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The Mirrors of Matter

Why Every Particle Has a Twin, Why Nature's Mirrors Break, and Why the Universe Is Made of Matter

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Abstract

Why is there something rather than nothing? A universe born even-handed between matter and antimatter should have annihilated to light. And why do the three mirrors of nature — charge (C), space (P), and time (T) — each fail to reflect the world faithfully, while their combination CPT never fails? This paper, a member of the GG-Theory cohort's Foundations Branch, answers both questions with one idea: the mirrors are not laws but orientations. The world is built from real, oriented geometry — a compact circle, space, and a one-way clock — and C, P, and T are the reversals of those three orientations. Each can break because the geometry has texture; the total reversal CPT survives because it is the one reflection no real world can detect. The antiparticle is derived at its stated grade, not postulated: it is the same object read the other way around a real circle, and the reading forced there also locates the origin of spin-$\frac{1}{2}$ and of the exclusion principle (at candidate grade). Time itself is defined by four endowments — it orders, it repeats, it opens one way, and it shelters the mathematics of the quantum world — the subject of a new Part. The receipt is quantitative: on a fully inherited ledger the quark and lepton CP phases take exact lattice values, 66.9° and 196.4° — the first reached by one frozen, pre-registered completion step — the neutrino masses are derived, and the universe retains about six extra particles of matter per ten billion photons — the measured excess from which chemistry, life, and mind followed. Every claim carries its grade — derived, conditional, candidate, or asserted — and the paper's tables say which. The claim is mortal: DUNE, Hyper-Kamiokande, JUNO, the ton-scale double-beta searches, and the high-luminosity LHC can each kill it within this decade, and the paper says where.

Executive Summary

The questions that remain. Two companion papers of the GG-Theory program derive, from one six-dimensional geometry, the twenty-eight parameters of the Standard Model (Arisaka, 2026, A9-SM) and the inventory of the standard cosmology (Arisaka, 2026, A10-Cosmos). Between those two derivations lies a seam, and on that seam live the oldest unanswered questions in fundamental physics.

Where do antiparticles come from — what forces every charged particle to have a twin of equal mass and opposite charge? What *are* the discrete symmetries C, P, and T — charge, mirror, and time reversal — and why is exactly one of them antiunitary? Why did parity fall maximally, and in exactly one force? Why does CP violation exist, at exactly the measured strength — and why does the strong interaction, alone, conserve it to one part in ten billion? And the question that contains the others: why did the universe keep six baryons per ten billion photons instead of annihilating to light — why is there matter, and therefore chemistry, and therefore us?

The Standard Model stores each of these facts as an input; this paper, standing at the interface of its two companions, derives them as consequences of one structure. It is, in the program's own terms, the paper about the asymmetry of matter — which is to say, about our origin.

The one answer. The world of the GG-6 bulk — the real six-dimensional arena beneath the boundary we inhabit — is built from *real, oriented* geometry: the thesis of its Foundations-Branch partner (Arisaka, 2026, P4-Real). Nature requires no complex primitive, and every imaginary unit in physics is the derived packaging of real orientations. Taken seriously, that single idea makes this paper's subject transparent.

Antiparticles are the unique alignment of the bulk's two real rotation structures — the quarter-turn J the boundary will write as i — forced wherever charge lives. The discrete symmetries are the reversals of the bulk's three orientations; their table, including the antiunitarity of T, is derived, not assigned.

Their violations are not accidents but the texture of the descent: a chiral pentagon where the flavors turn, an oriented cascade where the families fall — and, at the end of the chain, a universe that kept six parts in ten billion of itself, from which chemistry, life, and mind became possible. The mirrors broke because the world has a direction; we are among the consequences.

The theorems that carry it. Before the mirrors, the twins: Part IV derives the antiparticle itself, one level below quantization. T-P5-A: on each charged sector the circle's quarter-turn $J_Q = \partial_\theta/Q$ is the unique circle-compatible complex structure, and conjugation is orientation reversal of the fiber. T-P5-B: the clock's polar phase J_A — the Hilbert transform, a real operator — is the unique positive-energy complex structure. T-P5-C: the two agree on shell precisely under the Feynman–Stückelberg pairing — *antiparticles are the consistency condition between the sixth dimension and causal time.* T-P5-C1/C2 extend the one shared J to composites and Fock space with no new complex input; T-P5-B1, the Wick quartet, shows that Minkowski's *it*, Wick's rotation, and the Schrödinger i are one datum — the polar decomposition of the time generator, whose lower half-plane is the only lawful home of "imaginary time."

Then the mirrors. T-P5-1: C, P, and T are the orientation reversals of the three real factors of

the GG-6 bulk — the compact fiber circle, the spatial slice, and the causal clock — and a discrete symmetry is antiunitary if and only if it contains T, because of the three orientations only the clock's is what the imaginary unit is made of: the textbook unitary/antiunitary table is derived, not assigned. T-P5-2: the total reversal CPT preserves each Feynman–Stückelberg-paired mode set and is a symmetry for every coupling texture built from real geometric data — the CPT theorem as orientation bookkeeping. The dividends follow free of charge: Kramers' degeneracy with no phase conventions anywhere, and the five fates of the mirrors — which broke, in what order, by how much — as consequences of one projection (itself asserted, per Part VI's ledger) and one lattice.

Then the flavors. T-P5-3: a Yukawa texture is a U(1) connection on the flavor graph; its physical content is its loop holonomies; CP is a symmetry iff every loop angle lies in $\{0, \pi\}$; and on the single circle of the GG-6 bulk, with the block integer $L = 5$, first-order holonomies are locked to the pentagonal lattice $(\pi/5)\mathbb{Z}$ — so CP violation exists because $3\pi/5$ is not a multiple of π: the flavor pentagon is chiral. The values, each at its grade: the quark phase $\delta_{\rm CKM} = 2\pi/5$ at first order, completed — by the codebook's one asserted quantum-defect step — to $13\pi/35 \simeq 66.9°$; the lepton phase $\delta_{\rm PMNS} = \pi + 2\arcsin(1/7) \simeq 196.4°$; Majorana phases $(0, \pi)$; the Jarlskog invariant $J_{\rm CKM} \simeq 3.1 \times 10^{-5}$ at the stated evaluation layer (layer band 2.7–3.2×10^{-5}). T-P5-4: a Majorana self-pairing exists iff the fiber weight vanishes — lepton number is winding number, and the weight-zero neutrino is the unique dial-free door.

Then the matter. Part VI argues — as a structural claim whose missing lemma is named — that parity violation is the orientation of the family descent: the unique broken force is the unique gate force, and a parity-even coupling cannot carry the direction of a one-way cascade. Part VIII assembles the origin of matter: Sakharov's conditions are derived as the boundary shadows of the constitutional tripod (proposition P-P5-E: the ledger and its door, the oriented descent, the always-on projection), and T-P5-5 assembles the excess via TeV-scale resonant leptogenesis on the inherited neutrino and CP ledger, every input inherited at its stated grade — $M_{\rm lock} = \frac{1}{2} M_{\rm Pl} e^{-35} \simeq 3.85$ TeV, the dial-free door, the seesaw-matched Yukawa, the holonomy CP phase — yielding $\eta_B \approx 7 \times 10^{-10}$ (central 7.34; band $\times 3^{\pm 1}$) against the observed $(6.12 \pm 0.04) \times 10^{-10}$, at order-of-magnitude grade under one named conjecture and one flavored projection step carried derived-conditional on the named partial-resonance hypothesis H-$\phi_{\rm geo}$-1, with zero dilution derived and the resonance question quantified rather than hidden.

The apparatus. The paper is built to be checked rather than believed, across its sixteen Parts: a seventy-year experimental history with its eighteen-row chronology and the six-comparison CPT-test record; a preliminaries Part defining the real presentation, the flavor graph, and the transport equations from scratch; the antiparticle Part, which also locates the spin–statistics connection and the exclusion principle as the Wick quartet's second child (carried at candidate grade); and a Part asking what time *is*, answering with the four endowments — order, repetition, the one-way arrow, and the analytic shore that shelters the quantum world's mathematics.

The machine room: a lettered technical appendix in the cohort standard — the reference dictionaries and cross-cohort naming; five from-scratch, Step-graded chapters, on the discrete symmetries in quantum mechanics and quantum field theory, on the flavor sector (with ε, ε', and $\sin 2\beta$ derived from the textbooks and then priced by the pentagon), on the origin of the matter

excess (Sakharov's conditions to the assembled η_B, priced by the ledger), on the antiparticle (the sea, the contour, and the causality theorem, then the handshake as the fourth way), and on the neutrino's century (two-state quantum mechanics to the lattice point) — ninety problems across the block, all with complete worked solutions.

The instruments: five worked examples executed with numbers, from Wu's cryostat to the neutrino asymmetry at 196°; twenty-one figures — among them the twenty-two-paper cohort map, the roadmap of the sixteen Parts, the deductive funnel that draws the central claim on one page, the custody map, the pentagon, the basin/gate landscape, the leptogenesis flowchart, the resonance regime map that draws the paper's sharpest open item, the 27-row honesty audit at a glance, the twin deviation panels, and the dated kill-test timeline — and thirty-two tables, including the axiom-custody table, the ten-row forced-versus-measured confrontation, the three-depths scoreboard, and the dated falsifier table with its timeline.

The comparisons: a five-way structural comparison at full depth — quantum field theory, the Standard Model, string theory, ΛCDM, and GG-Theory, each given its own chapter and its own concessions; eighty-two adversarial questions, constructed in-house across eleven referee perspectives — the kaon and neutrino experimentalists first among them — and answered with pointers into the paper; and references each carrying a relevance note, with the inherited mechanisms — Fukugita–Yanagida, Pilaftsis, Kawamura, Dine–Leigh–MacIntire — cited at their source.

The register. Derived where provable, conditional where conditional, open where open. The discrete-symmetry table and the holonomy calculus are theorems at the quasi-free grade; the gate-operator lemma (parity), the determinant-phase cancellation (strong CP), and the sphaleron-transport normalization (the $K/2$ exponent) are named conjectures, stated as such; the resonance condition of the leptogenesis chain is its one named input, and the twelve-order gap between the geometric splittings and the width is quantified in the text.

Two small additions are made to the cohort's ledger: a convention-free handedness invariant (the surviving chirality, the descent orientation, and the sign of the CP holonomy as one alignment), and a registered falsifier — *no right-handed weak sector at any scale*: the mirror modes were projected out, not made heavy, so a W_R observed at any energy kills the geometric construction.

Who should read it, and how. *A kaon or B-physics experimentalist* meets the phases of their own measurements — ε, ε'/ε, $\sin 2\beta$ — re-read as interferometry of a single geometric angle, with the lattice prediction laid against the world averages. *A neutrino physicist* meets a forced leptonic phase within 0.2σ of the current global fit, a definite double-beta amplitude $m_{\beta\beta}$, and the statement that their next decade of data adjudicates this paper. *A cosmologist* meets a baryogenesis chain with no dials and an honest error budget.

A graduate student meets a self-contained course sequence connecting Wigner's theorem, the CPT theorem, flavor physics, and the Boltzmann transport of leptogenesis to one geometric source. *A general physicist* meets a plain thesis: the universe is oriented — circle, clock, and cascade — and the broken mirrors, the pentagon of flavor, and the matter in your hand are three measurements of that one orientation.

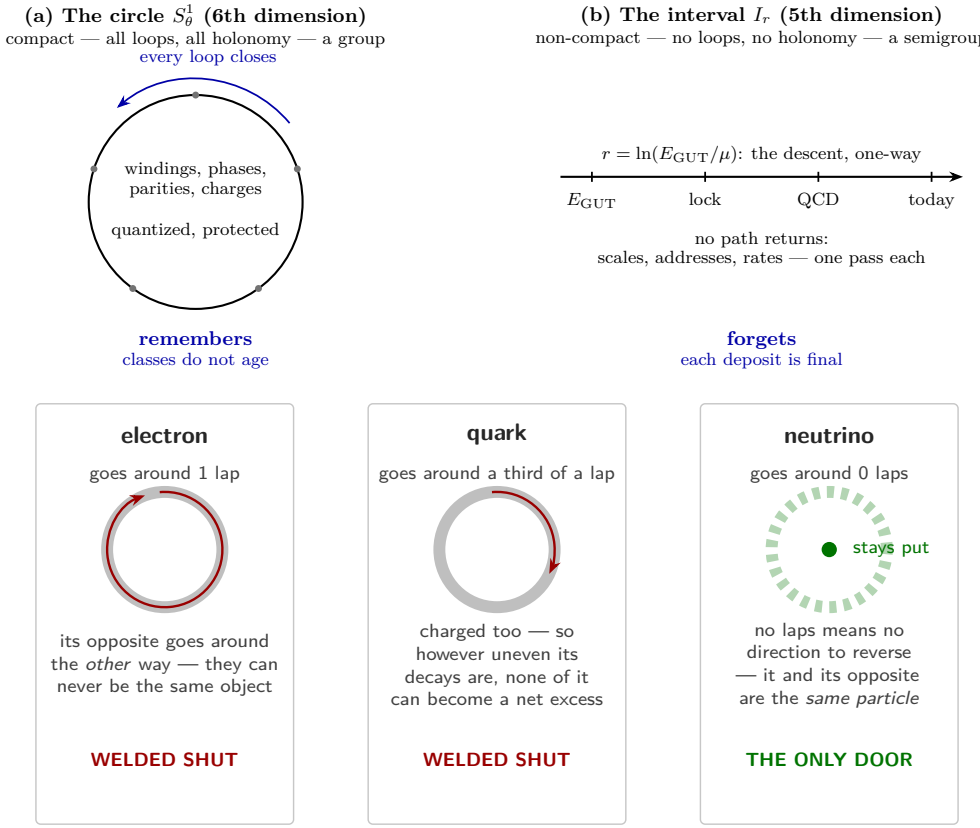
The philosophy, last. The mirrors broke on the descent's orientation; the clock stands on time's four endowments; and the deepest claim of the paper is that orientation, not substance, is what

distinguishes matter from antimatter and past from future. A twin is the same object read the other way around a real circle; an arrow is a reading the world cannot unread. And it is held to the one standard that makes it science: the paper can be wrong by 2035, and it says where.

Keywords: CPT theorem; discrete symmetries; charge conjugation; parity violation; time reversal; antiunitarity; Wigner's theorem; CP violation; Jarlskog invariant; rephasing invariance; flavor holonomy; pentagonal lattice; CKM matrix; PMNS matrix; Majorana phases; neutrinoless double beta decay; strong CP problem; Kaxion; seesaw mechanism; dial-free door; leptogenesis; resonant leptogenesis; sphalerons; baryon asymmetry; Sakharov conditions; matter–antimatter asymmetry; basin and gate forces; oriented descent; orbifold projection; handedness invariant; right-handed W; GG-Theory; sixth dimension; phase circle; integer ledger; OGGEP; GDOS; GRIP; falsifiability

The Circle Remembers What the Interval Forgets — and Only One Particle Can Be Its Own Opposite

Why one mirror survives, and which door it leaves open. *Above:* the arena has two fibers and they hold different kinds of thing. On the compact phase circle every path closes, so everything a connection does there is holonomy — quantized, protected, and unable to be deformed by anything the boundary does. Along the scale interval no path closes, nothing is protected, and the descent visits each scale exactly once. CPT is exact because it is a statement about classes on the circle; C, P and T break individually because their breaking is an address written along the interval, once and in one direction. *Below:* the same circle decides which particle can be its own antiparticle. A particle and its conjugate wind in opposite senses, and winding is what electric charge is — so the electron's one lap and the quark's third of a lap weld both doors shut, and exactly one species of known matter is left. That is why the origin of matter runs through neutrino physics, and the reason is structural rather than a matter of degree. In full: §59, p. 96, and Figure 8, p. 84.



Going around the circle **is** *having electric charge.* So "can be its own opposite" and "is electrically neutral" are the same condition.

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Preface

This paper is written to be readable, end to end, by an experimental particle physicist — the reader who has sat shifts on a kaon beam, tuned a B-factory trigger, or watched phototubes in a mine, and who has measured the numbers this paper claims to explain. It was structured so that such a reader loses nothing by knowing no GG-Theory in advance: everything imported is restated with its hypotheses, every definition is made in Part II, and every theorem is proved or proof-sketched on the page, with the physics said in words immediately after the mathematics.

Here is the honest pitch for spending a week with it. You already own the phenomena: parity violation from your first course, the ε and ε' of the kaon system, the unitarity triangle, θ_{13} and the hunt for δ_{CP}, the six baryons per ten billion photons of the CMB. What you likely do not own is a single statement connecting them: that C, P, and T are the orientation reversals of three real factors of one geometry; that the antiunitarity of T — the odd entry in every textbook table — is a one-line consequence; that the CP phase you measured is a closed-loop angle on a real circle, quantized in pentagonal steps; that the same orientation that breaks parity orders the mass hierarchy and biases the heavy-neutrino decays; and that the matter excess is the last entry in that chain of one fact. Those identifications are theorems or honestly graded conditionals here, each about a page, and each checkable with tools you already have.

A suggested week. Day one: Part I for the questions and the story you lived part of, and Part II for the definitions — do not skip the flavor graph or the spinor algebra; the whole CP story is bookkeeping on the first and the whole antiparticle story stands on the second. Day two: Part IV — the handshake, slowly, with the mode-level proof done by hand; it is the deepest half-page in the paper and everything downstream uses it. Day three: Part V's two theorems with Appendix D beside them, then Part VI (parity) — the shortest and most structural. Day four: Part VII (the pentagon) in the morning with the worked examples, and Part VIII (the origin of matter) in the afternoon with the audit table in hand. Day five: Part IX — *what is time?* — then Part X, the five roads — where the comparisons you have been silently making are made out loud, with every concession paid — and Appendix E, where ε, ε'/ε, and $\sin 2\beta$ are recomputed as holonomy interferometry. The weekend: the falsifier table with its dates, the Conclusions — including the story that runs from the mirrors to the reader — and as many of the eighty-two objections as you have appetite for; if you have spent time at a kaon beam or a neutrino detector, your objection is in there under your own job title.

Three further notes. The register of the paper — what is proved, what is conditional, what is open, what is conceded — is stated at every claim, and the reader is invited to audit it; the named gaps (a lemma for parity, a normalization for the baryon number, a resonance mechanism faced in its own section) are the paper's work orders, not its fine print. The problem sets carry hints and answers because they are meant to be done, not admired. And the personal perspective at the end is an experimentalist's, not a theorist's: the author spent 1980–1985 designing and constructing Kamiokande, a decade inside CP violation at KTeV and BaBar, and the fifty years since his first encounter with the broken mirrors wondering what they were trying to say. This paper is the answer he wishes he could have mailed to himself in 1976 — offered now with the calibration the intervening decades of experimental discipline demand.

Part I
The Question and Its History

The oldest asymmetry, asked precisely; a century of falling mirrors, worn with two hats — the experimenter's and the philosopher's; and the problems that remain

1 Part I in plain English: the mirrors, and seventy years of watching them break

For most of the history of physics the mirrors were not a subject. That a law should look the same reflected in a mirror, or with matter exchanged for antimatter, or with time run backward, was not a hypothesis anyone thought to test. It was what a law was. Then in the space of eight years two of the three fell, and the second fell by about two parts in a thousand — small enough to have been missed, and large enough that the universe is made of something.

This Part tells that history at full strength, because the strength is the point. Lee and Yang's audit found that parity had never actually been tested in the weak interaction. Wu tested it and it failed maximally. Cronin and Fitch found CP failing in a kaon. Through all of it CPT did not fail once, and a symmetry that survives everything its parts do not is a fact that wants an explanation rather than a certificate.

Nothing is derived in this Part. It states the questions, lays seventy years of measurement out as a single table, says plainly what experiment still cannot tell us, and locates the paper in its cohort. The claim comes at the end and not before: the mirrors are not laws but orientations, and a reflection can fail because the geometry has texture, while the total reversal cannot.

2 The oldest asymmetry, asked precisely

Two companion papers of the GG-Theory program stand on either side of this one. The particle companion derives the Standard Model — its gauge structure, its twenty-eight parameters, its flavor geometry — as the boundary theorem of one six-dimensional bulk (Arisaka, 2026, A9-SM). The cosmology companion derives the standard cosmology — its six dials, its epochs, its inventory — from the same geometry (Arisaka, 2026, A10-Cosmos). Between them lies a seam, and the seam is not a technicality: it is the single place where the laboratory's smallest measured asymmetries and the sky's largest one turn out to be one subject. For the deepest number the cosmology paper must inherit from the particle paper is not a mass or a coupling; it is a *bias* — the microscopic preference for matter over antimatter without which the derived universe would contain neither stars nor readers. This preprint is the paper of that seam. In the program's own terms, it is the paper about the asymmetry of matter — which is to say, about our origin.

Asked precisely, the seam's question splits into a ladder of questions, and it will pay to state them at the outset in their natural order, because the entire paper climbs this ladder. *Why does every charged particle have a twin* — what enforces, to twelve digits, the existence of a partner of equal mass and opposite charge? *What are the operations* C, P, and T that exchange the twins and reverse the mirrors — are they conventions of our bookkeeping, or structures of the world? *Why did the mirrors break selectively* — parity maximally, and only in one force; CP subtly, and by exactly the measured amount; the combined reversal CPT never, to one part in 10^{18}? *And why did matter win* — by what mechanism did a universe that should have annihilated to light keep six baryons per ten billion photons, the residue from which everything else is made? The Standard Model, magnificent as bookkeeping, stores every one of these facts as an input (Arisaka, 2026, A9-SM); the standard cosmology, exact as accounting, holds the last one as an initial condition (Arisaka, 2026, A10-Cosmos). Between the two, the questions simply wait.

One further word about method, because it governs the whole paper. This subject, uniquely in fundamental physics, has always been worn with two hats. It is the most *experimental* of deep subjects — every one of its turning points was forced by an instrument: a cryostat, a spark chamber, a kaon beam, a tank of water in a mine — and it is simultaneously the most *philosophical*: the questions "is left–right a convention?" and "why is there something rather than nothing?" were asked by philosophers centuries before physics could touch them. This paper keeps both hats on throughout — every claim will carry both an instrument and an argument — and this Part tells the history the same way, because the history is itself the best introduction the subject has: it is the record of philosophy's oldest symmetry questions becoming, one by one, measurements.

3 Before the fall: mirror symmetry as philosophy and as law

The belief that nature cannot tell left from right is far older than the physics that tested it. Kant, in 1768, built an entire argument about the nature of space on the puzzle of *incongruent counterparts* — the left hand and the right hand, alike in every internal relation yet not superposable — and concluded that handedness must reside not in the objects but in space itself (Kant, 1768). The philosophical instinct that followed — that a mirror-reversed world would be not merely similar to ours but *indistinguishable* from it — hardened, over two centuries, from instinct into unexamined law. When physics acquired the language to say it precisely, it did: Wigner, in 1927, made parity a quantum number (Wigner, 1927), building on Laporte's empirical selection rule in atomic spectra (Laporte, 1924), and within a decade parity conservation was load-bearing structure — used daily, cited automatically, confirmed silently by every parity-labeled nuclear level. Noether's theorem (Noether, 1918) had meanwhile taught physics its deepest lesson about symmetry — that continuous invariances are conservation laws — and the discrete inversions P, C, and T, though outside her theorem's hypotheses, borrowed its prestige: symmetries were what the world *had*, and the mirror symmetries were the simplest of all.

Almost no one thought to check. The honorable exception deserves its place in every retelling: in 1950 — six years before Lee and Yang — Purcell and Ramsey argued that the question of a neutron electric dipole moment, forbidden by parity, was *experimental*, not a matter for assumption:

"the question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle... becomes a purely experimental matter" (Purcell and Ramsey, 1950). Their proposal — test the mirror by hunting a dipole — founded what is now the seventy-year EDM program (§10), and their methodological point — that no symmetry, however beautiful, is above measurement — is the experimental hat of this paper in a single sentence from 1950. The philosophical hat has its own pre-1956 landmark: Gardner would later crystallize it as the *Ozma problem* — can one communicate the meaning of "left" to a distant civilization by radio, using physics alone (Gardner, 1964)? Before 1956 the answer was believed to be no, and the belief was wrong twice over, as the next sections record.

4 The mirror that broke: 1956–1957

Until 1956, parity conservation was not a hypothesis of physics; it was part of its common sense. That the laws of nature should not distinguish left from right had the standing of an accounting identity — used daily in atomic spectroscopy through Laporte's selection rule (Laporte, 1924), confirmed silently by every parity-labeled nuclear level, and so entrenched that no one had thought to test it where it had never been checked. The θ–τ puzzle forced the issue: two strange mesons, identical in mass and lifetime, decaying to final states of opposite parity. The community's instinct was to duplicate the particle. Lee and Yang's instinct (Lee and Yang, 1956) was to audit the books — and the audit revealed that parity conservation, exhaustively verified in the strong and electromagnetic interactions, had *no experimental support whatsoever* in the weak interaction. They proposed the decisive tests. Within months, Wu and her collaborators (Wu et al., 1957) had polarized ^{60}Co nuclei in a cryostat and watched the decay electrons emerge preferentially opposite to the nuclear spin — a pseudoscalar expectation value, $\langle \vec{\sigma} \cdot \vec{p} \rangle \neq 0$, impossible in a parity-symmetric world. Garwin, Lederman, and Weinrich (Garwin, Lederman, and Weinrich, 1957) confirmed it in pion–muon decay within days.

The community's disbelief is itself part of the historical record, and worth preserving for the generation that has only known the aftermath. Pauli, days before the news reached him, wrote that he was "ready to bet a very large sum" that the experiments would come out symmetric — "I do not believe that the Lord is a weak left-hander" — and had the grace, days after, to marvel at his own certainty about a question he had never examined. Feynman had wagered fifty dollars that parity would survive, and paid. The lesson both men drew is the one this Part exists to transmit: the mirror had never been *tested* where it broke; an assumption had circulated as a law for thirty years on the strength of its beauty alone. Purcell and Ramsey's 1950 warning (§efsec:before-the-fall) had been exactly right, and almost exactly unread.

Two features of the fall deserve emphasis, because this paper will return to both. First, the violation was not small. The weak interaction does not slightly prefer one hand; it is *maximally* chiral, coupling to left-handed fermion components and right-handed antifermion components and to nothing else — codified within two years as the two-component neutrino (Landau, 1957; Lee and Yang, 1957; Salam, 1957) and the $V-A$ current (Feynman and Gell-Mann, 1958; Sudarshan and Marshak, 1958). An asymmetry that is total is not a perturbation to be parameterized; it is a

structure to be explained. Second, the fall was a *double* fall, a point often compressed in retellings: charge conjugation broke in the same experiments. A C-symmetric world with broken P would pair every left-handed neutrino with a left-handed antineutrino; the observed correlations (the μ^+ from π^+ decay is left-polarized where the μ^- from π^- is right-polarized) showed C violated as maximally as P, with the product CP surviving — which is why Landau's repair (Section 6) was available at all. Third, the violation was *selective*. The strong and electromagnetic interactions conserve parity exactly — a fact later promoted to a theorem for vector-like theories by Vafa and Witten (Vafa and Witten, 1984) — so whatever breaks the mirror does so in exactly one of the four forces. Seventy years later, the Standard Model holds both facts as inputs. Part VI of this paper holds them as one output.

5 The repaired mirror, and the Ozma problem

Parity's fall was absorbed with remarkable speed, because a repaired mirror lay ready at hand. The 1957 experiments broke P and C separately but preserved their product: the mirror image of a left-handed neutrino is a right-handed antineutrino, and that particle exists. Landau proposed CP as the true mirror of nature (Landau, 1957), and for seven years the repair held — with a philosophical consequence that deserves to be made explicit, because it is the cleanest illustration in physics of what a discrete symmetry *means* operationally. Consider Gardner's Ozma problem (Gardner, 1964): by radio alone — no shared artifacts, no parcels — teach a distant civilization which hand is "left." Before 1957 it cannot be done: every law then known is mirror-blind, so every instruction ("wind the wire this way…") presupposes the very convention it is meant to convey. After Wu, it seems possible — "build the cobalt experiment; the electrons emerge opposite the spin; call that direction down and the rest follows" — *until* one notices the loophole Landau's repair creates: a civilization made of antimatter, performing the same instructions with anti-cobalt, would derive the opposite hand and be equally convinced. Under exact CP, handedness and matter-ness are jointly conventional: one can be defined only relative to the other. The Ozma problem's full resolution therefore had to wait for 1964: once CP itself fails, the kaon system's small asymmetries single out matter from antimatter *absolutely* — the long-lived kaon decays slightly more often to the positron than to the electron — and with matter-ness fixed by physics, handedness follows. That a parlor puzzle about radio messages is settled by a $2 imes 10^{-3}$ asymmetry in a strange meson is the two-hats character of this subject in miniature; and the GG-Theory reading of the same fact — that the world carries an absolute orientation, of which the kaon asymmetry is one laboratory shadow — is Proposition P-P5-D of Part VI, the Ozma problem promoted to an invariant.

6 The second fall: CP, 1964

Parity's fall was absorbed quickly, because a repaired mirror was at hand: the combined operation CP, spatial reflection composed with charge conjugation, survived the 1957 experiments intact, and Landau proposed it as the true symmetry — the mirror image of a left-handed neutrino is a right-handed *anti*neutrino, and that particle exists. For seven years the repair held. Then

Christenson, Cronin, Fitch, and Turlay, studying the neutral kaon beam at Brookhaven (Christenson et al., 1964), observed the long-lived kaon — the CP-odd combination, forbidden to decay to two pions — decaying to two pions at the level of two per thousand.

The neutral kaon system deserves its place of honor in this history, because it is the first and still the most exquisite *interferometer of the discrete symmetries*: a two-state quantum system whose mass eigenstates are coherent superpositions of a particle and its antiparticle, in which a fractional asymmetry of order 10^{-3} imprints itself on macroscopic decay distributions. Two parameters organize the system, and their definitions repay display because the courses use them. The mass eigenstates are

$$|K_{S,L}\rangle \;\propto\; (1+\varepsilon)\,|K^0\rangle \;\pm\; (1-\varepsilon)\,|\bar{K}^0\rangle, \tag{1}$$

so $\varepsilon \neq 0$ — *indirect* CP violation — means the long-lived state is not the CP eigenstate but carries a small admixture of the wrong parity, $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; while

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) \;\neq\; 0 \tag{2}$$

— *direct* CP violation — means the decay amplitudes themselves distinguish matter from antimatter, isospin channel by isospin channel. The distinction carried forty years of physics: a "superweak" interaction acting only in the mixing (Wolfenstein, 1964) could fake ε but predicts $\varepsilon' = 0$ identically, so the double ratio became the discriminator between a new feeble force and CP violation resident in the weak amplitudes — the two parameters were the field's precision targets for the next four decades. CP violation was different in kind from parity violation: not maximal but small, not structural but seemingly accidental — a phase that had no reason to be there and no reason to be 2×10^{-3}. Sakharov understood within three years what the phase was *for* (Sakharov, 1967); Section 11 returns to that. Kobayashi and Maskawa understood within a decade where it could *live*: with three quark generations, the quark mixing matrix possesses exactly one physical phase (Kobayashi and Maskawa, 1973) — a counting theorem that predicted a third family from a kaon asymmetry. What no one has explained in the sixty years since is why the phase takes the value it does. That is the assignment Part VII accepts.

7 One phase, three families: 1973, and the twenty-year confirmation

Kobayashi and Maskawa's 1973 observation (Kobayashi and Maskawa, 1973) deserves a section of its own, because it is simultaneously one of the great counting theorems of physics and the precise statement of what remained unexplained. With two quark families — all that were then known, and the charm quark itself still a year from discovery — the quark mixing matrix can always be made real: no CP violation. With three families, exactly one physical phase survives the rephasing freedom (the counting this paper geometrizes as Eq. (8)). The kaon asymmetry of 1964 therefore *predicted a third generation* — an extraordinary inference from a 10^{-3} effect in one meson — and the prediction was honored in instalments across twenty-two years: the b quark at Fermilab in 1977 (Herb et al., 1977), the top quark, completing the family, in 1995. Jarlskog then distilled the

phase's entire physical content into one basis-independent number (Jarlskog, 1985), the invariant J that Part VII's pentagon must and does price. The ledger of 1973–1995 is thus: the *existence* of the phase explained (three families admit one), its *location* explained (the weak charged current), and its *value* explained by nothing — δ could sit anywhere on the circle, and the Standard Model would shrug. Holding that open door in mind is the right way to read everything that follows; it is the door Part VII claims the pentagon closes, and the door the parent particle paper first opened geometrically (Arisaka, 2026, A9-SM).

8 The precision era: KTeV, NA48, and the B factories

The program that followed was one of experimental physics' long marches. Direct CP violation required measuring the double ratio

$$R \;=\; \frac{\Gamma(K_L \to \pi^+\pi^-)\,/\,\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)\,/\,\Gamma(K_S \to \pi^0\pi^0)} \;\simeq\; 1 + 6\,\mathrm{Re}\!\left(\frac{\varepsilon'}{\varepsilon}\right) \tag{3}$$

— four rates, two of them into the notoriously difficult neutral mode, with every systematic (energy scale, acceptance, accidental activity, regeneration) entering coherently — to a precision of parts in 10^4. The experimental design problem this posed (simultaneous beams, regenerator versus vacuum, a calorimeter good enough to make $\pi^0\pi^0$ a precision channel) consumed two generations of instrument-building on two continents. After a generation of effort, KTeV at Fermilab (KTeV Collaboration, 1999) and NA48 at CERN (NA48 Collaboration, 2002) established $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 2.3) \times 10^{-4}$: the asymmetry lives in the amplitudes, as the CKM paradigm requires, and superweak alternatives died. The B factories then subjected the paradigm to its decisive test in a second meson system: BaBar at SLAC and Belle at KEK measured the time-dependent CP asymmetry in $B \to J/\psi K_S$ (BaBar Collaboration, 2001; Belle Collaboration, 2001), reading $\sin 2\beta$ — an angle of the unitarity triangle — from the interference of mixing and decay. The triangle closed. Every measured CP asymmetry, in kaons and in B mesons, traced back to the single Kobayashi–Maskawa phase, with the Jarlskog invariant (Jarlskog, 1985) — the basis-independent measure of all CP violation in the quark sector — pinned at $J_{\mathrm{CKM}} = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$.

It is worth pausing on what this triumph did and did not establish. It established that the Standard Model's bookkeeping is correct: one phase, entering every observable through the same rephasing-invariant combinations. It did not establish anything about the phase itself. $\delta \simeq 1.147 \pm 0.026$ radians is a measured number with no derivation, in a model where it could have been anything, including zero. The precision era answered "how" completely and "why" not at all — and, as Section 11 records, the measured value is quantitatively *incapable* of producing the matter excess it was once hoped to explain. The author spent a decade of his scientific life inside these measurements, at KTeV and then at BaBar; Part XIII records what that decade taught, and what question it left standing.

9 The third arena: neutrinos

The discrete-symmetry program's third arena opened underground. The Kamioka detector — designed and constructed in 1980–1985, with the author among its designers — was built to watch for proton decay and found, instead, the neutrino sky: supernova SN1987A's burst, the solar neutrino deficit confirmed in real time, and, in its successor Super-Kamiokande, the 1998 discovery that atmospheric neutrinos oscillate (Super-Kamiokande Collaboration, 1998) — neutrinos have mass, and the lepton sector has its own mixing matrix. The arena had in fact been opened twice before, and the full lineage bears telling. Davis's chlorine tank in the Homestake mine had counted solar neutrinos since 1968 and found a third of the predicted rate (Davis et al., 1968) — a deficit that stood as an anomaly for thirty years, too strange to accept and too solid to dismiss. The water detectors — built, it must be remembered, to watch for *proton decay*, the signature prediction of the grand unified theories — found the protons silent and the sky loud: Kamiokande confirmed the solar deficit in real time, caught the neutrino burst of SN1987A, and turned its successor toward the atmospheric flux, where the 1998 oscillation discovery was made. SNO then closed the solar case with heavy water — the neutrinos were not missing but *changed* (SNO Collaboration, 2002) — and KamLAND closed it from the reactor side (KamLAND Collaboration, 2003): neutrinos have mass, the lepton sector mixes, and a second flavor matrix exists with its own potential CP phase. The reactor experiments completed the matrix's angles with θ_{13} (Daya Bay Collaboration, 2012), and with all three angles sizeable, the lepton sector's CP phase δ_{PMNS} became measurable in principle — and became, over the following decade, the flagship quest of experimental neutrino physics. T2K's early running already disfavors CP conservation in the lepton sector (T2K Collaboration, 2020); the global fits center near $\delta_{\mathrm{PMNS}} \sim 200^\circ$ (NuFit Collaboration, 2024); and the next-generation long-baseline program — DUNE and Hyper-Kamiokande — will measure the phase to $\sim \pm 15^\circ$ in the early 2030s.

The stakes of that measurement are higher than a matrix element. If neutrinos are Majorana — their own antiparticles, the unique possibility opened by their electrical neutrality — then the lepton sector harbors two further CP phases invisible to oscillations, a mass mechanism (the seesaw (Gell-Mann, Ramond, and Slansky, 1979; Minkowski, 1977; Yanagida, 1979)) reaching to scales no collider will visit, and, through Fukugita and Yanagida's leptogenesis (Fukugita and Yanagida, 1986), a candidate answer to Sakharov's question: the matter excess made first as a lepton excess, in the CP-biased decays of the seesaw's heavy partners, then reprocessed into baryons by the electroweak sphalerons. The experimental keys are exactly the quantities the current program pursues: δ_{PMNS}, the neutrino mass ordering, and the neutrinoless double-beta-decay rate that would certify the Majorana nature. The detectors that opened this arena were built to answer "does the proton die?"; the arena they opened may instead answer "why was the proton born?"

10 The theorem that survived: CPT

Against this history of falling mirrors stands one unbroken theorem. The combined reversal CPT — all three operations at once — is a symmetry of any local, Lorentz-invariant quantum

Table 1: The experimental record of the unbroken theorem (ALPHA Collaboration, 2020; Particle Data Group, 2024). Every entry is a matter–antimatter identity that T-P5-2 forces exactly and any real texture preserves; a confirmed violation at any order would kill T-P5-2 and, via Greenberg's theorem (Greenberg, 2002), the Lorentzian arena itself.

CPT comparison	Observable	Precision	System
K^0 vs $\bar{K}^0$ mass	$\lvert m_{K^0} - m_{\bar{K}^0}\rvert / m_K$	$\lesssim 10^{-18}$	neutral kaons
e^+ vs e^- moment	$\lvert g_+ - g_-\rvert / g$	$\sim 2 \times 10^{-12}$	Penning traps
p vs $\bar{p}$ charge/mass	$\lvert (q/m)_p - (q/m)_{\bar{p}}\rvert$	$\sim 10^{-12}$	Penning traps
$\bar{p}$ magnetic moment	$\lvert \mu_p - \mu_{\bar{p}}\rvert / \mu_p$	$\sim 10^{-9}$	BASE
H vs $\bar{\text{H}}$ 1S–2S	fractional frequency	$\sim 2 \times 10^{-12}$	ALPHA
μ^+ vs μ^- lifetime	$\lvert \tau_+ - \tau_-\rvert / \tau$	$\sim 10^{-4}$	storage rings

field theory with a stable vacuum: proved in increasing generality by Lüders, Pauli, and Schwinger (Lüders, 1954; Pauli, 1955), and given its definitive axiomatic form by Jost (Jost, 1957; Streater and Wightman, 1964), whose proof runs through the analytic continuation of the Wightman functions to the complexified Lorentz group. Its modern algebraic descendant is sharper still: Bisognano and Wichmann (Bisognano and Wichmann, 1976) identified the CPT operation, combined with a rotation, with the Tomita–Takesaki modular conjugation of the wedge algebra — CPT as a structural feature of the local net itself. And Greenberg proved the converse discipline (Greenberg, 2002): CPT violation cannot be had cheaply, for it entails Lorentz violation.

Experiment has treated the theorem with corresponding respect. The neutral kaon system again leads: the K^0–$\bar{K}^0$ mass difference bounds fractional CPT violation near 10^{-18} (Particle Data Group, 2024). Antihydrogen spectroscopy compares matter and antimatter atom by atom at the 10^{-12} level (ALPHA Collaboration, 2020). Every particle's mass, lifetime, and magnetic moment agrees with its antiparticle's to the precision measured; Table 1 collects the flagship comparisons.

One experimental program belongs to this section although it tests the factors rather than the product, because it is the oldest continuous thread in the whole subject: the electric dipole moments. A permanent EDM of a fundamental particle violates both P and T — hence, by CPT, CP — and the hunt Purcell and Ramsey proposed in 1950 (Purcell and Ramsey, 1950) has now run for seventy years and twelve orders of magnitude: the neutron bound stands at $|d_n| < 1.8 \times 10^{-26}\, e\,\text{cm}$ (nEDM Collaboration, 2020), the electron bound — via molecular amplifiers — at $|d_e| < 4.1 \times 10^{-30}\, e\,\text{cm}$ (ACME Collaboration, 2018). These nulls are load-bearing twice in this paper: they enforce $|\bar{\theta}| \lesssim 10^{-10}$, the strong-CP smallness whose GG-6 resolution is the two-fate architecture of Part VII with its own falsifiable leakage floor (59); and they discipline every proposed new CP phase, this paper's included. The EDM program is the experimental hat at its purest: a 1950 philosophical challenge to an assumption, run as precision metrology ever since.

The survival of CPT is as deep a fact as the fall of its factors — and the standard theorem, for all its rigor, is anatomically silent: it proves that the antiunitary operator Θ exists and commutes with the dynamics, but does not say what C, P, and T individually *are*, why T is the antiunitary one, or why nature violates the factors while preserving the product. This paper's Part V offers the anatomy: the factors are orientation reversals of three real geometric structures; the product is

total reversal, which no real texture can detect; and the factors break precisely because the texture of our world — the flavor pentagon, the oriented descent — is not orientation-blind.

11 The cosmological stake: Sakharov, 1967

One number makes the discrete symmetries everyone's business:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}, \tag{4}$$

the baryon-to-photon ratio, read at the 0.3% level from the acoustic peaks of the cosmic microwave background (Planck Collaboration, 2020) and confirmed, independently and five orders of magnitude earlier in temperature, by the primordial deuterium abundance (Cooke, Pettini, and Steidel, 2018). Two epochs, one number: the asymmetry was in place before the first three minutes and has been conserved since. The cosmos, meanwhile, contains no antimatter to find: no annihilation glow at domain boundaries (Cohen, De Rújula, and Glashow, 1998), no confirmed antinuclei in the cosmic rays (AMS Collaboration, 2024). And a universe born symmetric would have kept essentially nothing: nucleon–antinucleon annihilation at freeze-out leaves a relic abundance near 10^{-18} — nine orders too small — a cosmos of pure radiation, with no stars, no chemistry, and no one to be puzzled. For every billion antiprotons in the early universe there were a billion and one protons, and everything that exists is the one.

Before Sakharov's answer, the alternatives deserve their paragraph, because both were reasonable and both are dead — and their deaths are measurements, not fashions. Dirac himself, in his 1933 Nobel lecture, suggested that half the stars might be made of antimatter — "it is quite possible that…these stars being built up mainly of positrons and negative protons" (Dirac, 1933) — a symmetric universe with segregated domains; and Alfvén and Klein built a full cosmology on that premise (Alfvén, 1965). The gamma-ray sky killed it: domain boundaries would annihilate, and the diffuse background contains no such glow at any scale out to the visible horizon (Cohen, De Rújula, and Glashow, 1998). The second alternative — that the excess is simply an initial condition, written into the universe at birth — survives logically but has been priced out structurally: inflation, required by the cosmology on independent grounds (Arisaka, 2026, A10-Cosmos), dilutes any primordial asymmetry to irrelevance, so the excess must have been *made*, dynamically, after the beginning. What remains is Sakharov's road, and it runs directly through this paper's subject.

Sakharov saw in 1967 (Sakharov, 1967) — three years after the kaon result, when its significance was visible to almost no one — that a dynamical origin of the excess requires exactly three ingredients: baryon-number violation; C *and* CP violation (the decays must know matter from antimatter); and a departure from thermal equilibrium (in equilibrium, CPT itself forces the books to balance). The three conditions are this paper's closing scoreboard. The Standard Model, remarkably, fails them quantitatively while satisfying them qualitatively: its sphalerons violate baryon number, its CKM phase violates CP, its electroweak transition could have provided the non-equilibrium — but the effective CP violation computes to $\sim 10^{-20}$ (Gavela et al., 1994), ten orders short, and the transition is, for the measured Higgs mass, a smooth crossover (Kajantie et al., 1996): no bubble walls, no

departure, no baryons. Every gram of matter is thereby an experimental proof of physics beyond the Standard Model — arguably the oldest and most secure such proof we possess. Part VIII presents the GG-Theory candidate for that physics, with its inputs inherited rather than chosen and its failure modes listed with dates.

12 Seventy years in one table, and the detail behind it

Table 2 lays out the experimental chronology as one continuous program; Table 3 then compresses the standing of each question it raised.

The columns deserve one sentence each. The *QFT* column records what quantum field theory as a framework provides: definitions and one great theorem, but no principle selecting which discrete symmetries hold. The *Standard Model* column records the paradigm's honest ledger: violation patterns written into the field content, one fitted phase, two unexplained zeros (the strong-CP angle and its own baryon asymmetry). The *string* column records the landscape's position: mechanisms in abundance, valuations nowhere. The GG-Theory column carries the claims of this paper, each tagged with its register — and the register column is part of the physics, not a disclaimer.

13 What experiment still cannot tell us

Seventy years of instruments have converted most of this subject's questions into numbers; this section records, one by one, the measurements that remain open — the experimental ledger this paper's claims will be judged against, with the parent papers' stakes noted where they ride on the same instruments. *(1) The leptonic CP phase.* δ_{PMNS} is the last mixing parameter of either flavor sector still unmeasured at definitive precision; the global fits center near 200° (NuFit Collaboration, 2024), T2K disfavors conservation (T2K Collaboration, 2020), and DUNE and Hyper-Kamiokande will reach ±15° in the early 2030s — the single most consequential measurement pending in this subject, for the Standard Model (is the lepton sector CP-violating at all?), for this paper (the pentagon says 196°), and for the cosmology parent (the door's bias rides on it, Arisaka, 2026, A10-Cosmos). *(2) The neutrino mass ordering.* Normal or inverted — JUNO and the atmospheric fits will settle it; the parent particle paper's derived spectrum requires normal (Arisaka, 2026, A9-SM). *(3) The Majorana question.* Is the neutrino its own antiparticle? Neutrinoless double beta decay is the only known direct probe; the tonne-scale generation reaches the inverted band, and the meV-class normal-ordering target ($m_{\beta\beta} \simeq 1.7$ meV here) awaits the generation after. *(4) The EDM frontier.* Every order of magnitude of improvement on d_n and d_e either finds new CP violation or tightens the strong-CP mystery; this paper's two-fate architecture places a floor at $\sim 10^{-18}$ in $\bar{\theta}$ terms — a discovery band, not just a null. *(5) The right-handed question.* Is parity restored at high energy? Left–right symmetric models say yes, at some scale; the geometric projection of Part VI says never; W_R searches adjudicate, permanently. *(6) The TeV frontier.* The lock cluster at 3.85 TeV — the heavy sector of the matter chain — sits within HL-LHC reach with a pre-declared criterion. *(7) The antimatter sky.* AMS-02's antihelium candidates remain unconfirmed; a single confirmed antinucleus of primary origin would reopen the domain question the gamma-ray sky closed. *(8)*

Proton decay. Still the sharpest single discriminator in fundamental physics: the grand-unified expectation is a rate, the GG-6 ledger's is exact stability; Hyper-Kamiokande watches both claims at once.

14 What theory still cannot say

The philosopher's ledger is shorter to state and has stood open longer. *(1) What are the operations?* The standard formalism defines C, P, and T as operators with adjustable phases and offers no account of what they are reversals *of*; the question "is the antiunitarity of T a fact about nature or about our bookkeeping?" has no orthodox answer. *(2) Kant's question, modernized.* Is orientation itself conventional or physical? The Ozma resolution (§5) shows the world can define handedness absolutely — but the standard framework locates the capability in two measured numbers (the kaon charge asymmetry, the CKM phase) without saying why the world possesses it. *(3) The value problem.* Even granting one CP phase by counting, nothing in any standard framework prices it: $\delta = 1.147$ and $\delta = 0$ are equally lawful, and on the second there is no matter and no one to notice. The anthropic shrug explains at most why we do not observe zero, never why we observe this. *(4) The coincidence problem.* Five superlatives — broken, chiral, family-changing, short-range, CP-bearing — on one gauge factor, unconnected in the formalism that hosts them. *(5) The strong-CP problem.* A phase that could be anything is zero to ten digits, beside a phase that is measured to be large; the standard cure installs a new field by hand. *(6) Why matter won.* The Standard Model's own answer fails by ten orders of magnitude (§112); every working mechanism buys the excess with fitted parameters; and the deeper question — whether the excess is an accident of initial conditions or a theorem of structure — is not even posable in a framework that stores its symmetry violations as inputs. *(7) The measurement shadow.* Behind all of these stands the oldest open problem of quantum mechanics itself — what an observation *is* — which the parent program addresses with the bulk-to-boundary projection (OGGEP), and whose arrow (records accumulate, the past is fixed) is the same orientation this paper traces through the mirrors (Arisaka, 2026, A5-GDOS; Arisaka, 2026, A10-Cosmos). This paper does not argue that case here; it inherits the framework in which, for the first time, questions (1) through (6) become derivations — and it flags, with the calibration the register demands, that a framework able to do so would constitute a shift in how physical law is read. Whether it *has* done so is exactly what the falsifier tables of Part XII put before the instruments.

15 The claim of this preprint

This preprint makes five claims, stated here with their registers so that no reader mistakes the paper's center of gravity.

Claim 1 (derived). C, P, and T are the orientation reversals of the three real factors of the GG-6 bulk — the compact fiber circle, the spatial slice, and the causal clock — and the unitary/antiunitary table is a consequence: a discrete symmetry is antiunitary iff it contains T (T-P5-1).

Claim 2 (derived, quasi-free grade). CPT is total orientation reversal, and is a symmetry of the

construction for every coupling texture built from real geometric data; its interacting extension rides on the standard scattering hypotheses (T-P5-2).

Claim 3 (derived through clause (iii); clause (iv) forced by the ledger). CP violation is the chirality of flavor-texture loop holonomies; on the single circle with $L = 5$, first-order holonomies are pentagonal-lattice points, giving forced central values for the quark and lepton CP phases and the Majorana pair $(0, \pi)$ (T-P5-3, with the completion step's status stated where it is used).

Claim 4 (structural, one named lemma outstanding). Parity violation is the orientation of the family descent: the unique broken force is the unique gate force, and only a chiral coupling can carry a one-way flow. The mechanism (the projection) is in place; the uniqueness argument awaits the gate-operator lemma (Part VI).

Claim 5 (derived-conditional, order of magnitude). The baryon asymmetry follows from TeV-scale resonant leptogenesis on the inherited ledger, $\eta_B \approx 7 \times 10^{-10}$ ($\times 3^{\pm 1}$), under one named normalization conjecture and with the resonance condition as the chain's declared input (Part VIII).

What this paper does *not* claim: that the standard CPT theorem is superseded (Jost's scope exceeds ours; the relation is complementarity, argued in Part X); that the flavor-holonomy calculus's rephasing machinery is new (it is Jarlskog's, geometrized; what is new is the lattice valuation); that the projection mechanism of Part VI is new (it is orbifold-GUT technology, cited to its authors); or that the leptogenesis transport is new (it is Fukugita–Yanagida in the Pilaftsis regime; what is new is that every dial is inherited). The paper's originality lies in the *anatomy* (what the mirrors are), the *valuation* (what the phases must be), and the *unification* (that one orientation answers five questions) — and its honesty lies in the named list of what remains open.

Five claims, five registers — but one chain. Before the chain is walked slowly (which is the business of the next hundred and fifty pages), it is worth seeing whole, because its shape is the paper's real argument: not five separate assertions but one deduction passing through five stations, each station forced by the one above it. Figure 1 draws it.

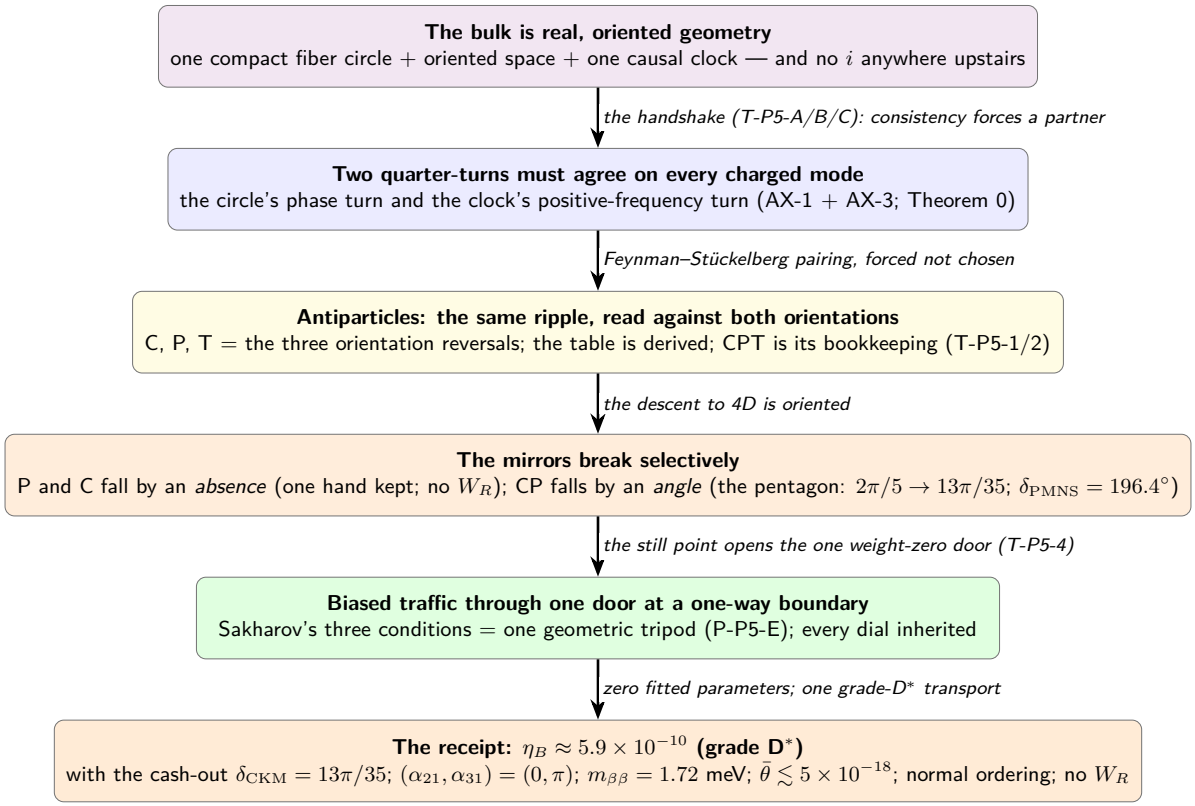
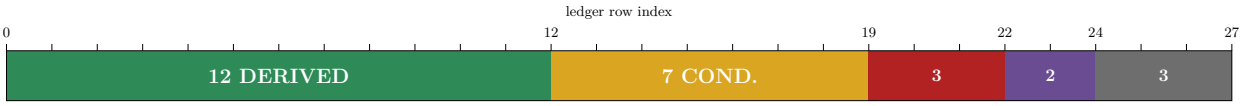


Figure 1: The paper's central claim as one deductive funnel. The five claims of §15 drawn as the single chain they form, from the real oriented bulk at the top to the six-per-ten-billion receipt at the bottom. Each arrow names the theorem or mechanism that forces the step; each box carries its register in the text. The chain is walked slowly in Parts IV–VIII; the funnel is the paper on one page.

Read the funnel from the top. The first box is inherited from the parent papers: a real, oriented six-dimensional geometry with no i in it. The first arrow is this paper's opening act — the handshake theorem, which says that the circle's quarter-turn and the clock's quarter-turn must agree on every charged ripple, and that the only way they can agree is if every ripple has a partner. That single consistency condition delivers the third box: antiparticles, and with them the three reversal operations and the CPT bookkeeping. The fourth box is where the story turns from symmetry to asymmetry — the oriented descent keeps one hand and tilts the pentagon — and the fifth is where asymmetry becomes traffic: Sakharov's three famous conditions, reassembled as one tripod whose every leg is geometric. The bottom box is the number. Notice what the funnel does *not* contain: a dial. Nothing in any box was fitted to make the bottom line come out; every input was fixed upstream, for other reasons, in other papers. That is the sense in which the funnel is one claim rather than five — and the sense in which a failure anywhere in it is a failure of the whole.

One more picture completes the accounting. A funnel shows the logic; it does not show the *grades* — and this paper's method is that every step carries one. The three Part ledgers (Tables 8, 11, and 14) audit the chain row by row; Figure 2 compresses their twenty-seven rows into a single bar, in the manner of the parent paper's parameter audit.



- **Derived (12):** C/P/T table; CPT (quasi-free); holonomy calculus; Majorana door T-P5-4; SM group from one hand (c); chirality; anomaly freedom (c); Higgs from projection; Sakharov tripod; lock chain; portal; matched Yukawa.
- **Derived (cond., 7):** pentagonal lattice; δ_{CKM}; the PMNS set; $\bar{\theta}$; ϵ^{res}; washout κ; zero dilution.
- **Asserted (3):** the projection matrix P; the $\mathbb{Z}_2$ itself; which hand survives.
- **Named conjectures (2):** C-P5-A (one gate force); C-P5-C (resonance + exponent).
- **Other (3):** the throughput reconstruction; the D* transport band; the open Ω_b bridge.

Figure 2: The 27-row honesty audit at a glance: the union of the paper's three status ledgers — the parity mechanism's (Table 8), the mirror Parts' (Table 11), and Part VIII's (Table 14) — compiled into one bar. Twelve rows derived at their stated grade (**green**), seven derived modulo one named step each (**gold**), three asserted with the assertion printed (**red**), two carried by named conjectures (**purple**), and three in other registers — one reconstruction, one D* band, one open seam (**gray**). The bar is the paper's honesty policy made visible: what is proved is separated from what is owed, and the owed list is short enough to print. Rows tagged (c) are booked derived here *conditional on named parent-paper items* — the constitutional hand choice and the anomaly-closure program carried open in the constitution papers; the parents are listed in the inheritance and promotion-roadmap appendices (Appendices J and M).

The bar rewards a moment's stare. Nearly half the audit is green — and the green rows are not the easy ones; they include the C/P/T table, the CPT theorem at its stated grade, the Majorana door, and the Sakharov tripod, which is to say the paper's spine. The gold band is the honest middle: seven chains each explicit end to end with exactly one named step outstanding, so that a reader who distrusts any gold row knows precisely which lemma to attack. The red band is deliberately small and deliberately loud — three assertions, all living in the parity projection, all flagged in Part VI before any referee could flag them. And the purple and gray tails are the frontier: two conjectures with names and one seam with an unidentified owner. Roughly speaking, the bar says: the anatomy and the valuation are theorems, the mechanism's necessity is a program, and the transport is physics at quantified grade. The rest of the paper is the row-by-row defense of exactly that sentence.

16 The cohort inheritance and the roadmap of the sixteen Parts

Before the vocabulary is built (Part II) and the arena is assembled (Part III), it is useful to lay out two reader-orientation maps on the same opening: a panorama of the twenty-two-paper cohort in which this paper stands (§16.1, Figure 3), and a panorama of the sixteen Parts of the present paper (§16.2, Figure 4). A reader of any later Part should be able to flip back to this Section and orient themselves in both directions: which cohort companion carries which imported result, and where the present argument stands in the sixteen-Part arc.

16.1 The cohort inheritance

GG-Theory is a twenty-two-paper research program (Arisaka, 2026, A1-Constitution) — eleven A-papers, six P-papers, three C-papers and two white papers — whose structural claim is that the observed laws are the boundary operational description of a real six-dimensional bulk — four macroscopic spacetime dimensions plus one scale direction and one compact phase circle S^1_θ — governed by four axioms and an integer ledger $(M, N, L; J, K) = (1, 3, 5; 7, 35)$ (Arisaka, 2026, A3-BI6). Within that program this paper is a member of the Foundations Branch, and it has two parents: everything in it descends from one or the other. The particle parent (Arisaka, 2026, A9-SM) supplies the flavor geometry: the discrete-symmetry and flavor-holonomy theorems this paper consolidates (its T-SM-46 pair), the Majorana-door theorem (T-SM-44.1), the basin/gate architecture of the weak interaction, the strong-CP two-part vanishing, and the derived neutrino ledger — masses, $\delta_{\rm PMNS}$, the Majorana parity pair — on which everything downstream rides. The cosmology parent (Arisaka, 2026, A10-Cosmos) supplies the transport: the Sakharov custody, the ten-step resonant-leptogenesis chain, the zero-dilution clause, and the honesty objections this paper adopts verbatim. GG-P5-CPT is their interface — the place where the particle parent's smallest derived asymmetries are handed to the cosmology parent's largest one — and the reader will find both cited on nearly every page that follows, because nearly every claim is a consolidation, sharpening, or audit of one of theirs. Like every member paper of the cohort, this one restates what it imports and owns what it proves, so that a reader who never opens a companion loses the provenance but not the argument.

The Foundations Branch. On the map's left flank stands the branch this paper belongs to: the two member papers whose shared subject is the boundary's complex structure and its mirrors, a single column beside the spine. The partner paper, GG-P4-Real (Arisaka, 2026, P4-Real), is the origin-of-i member: it owns the question "why complex numbers?" and answers it with two real sources — the compact phase circle and the causal clock — whose forced agreement on charged sectors is the antiparticle pairing (its theorems T-P4-1 through T-P4-4, restated in Part III below as this paper's inputs), under the division of labor both papers state in the same words: *the dictionary owns the sectors; the geometry owns the i*. On the map that inheritance is the solid shared-i edge descending from GG-P4-Real into this paper's node. GG-P5-CPT owns the questions those sources make answerable next: what the discrete symmetries are (reversals of the sources' orientations), why CP breaks (the texture on the circle is chiral), why P breaks in one force (the descent between basins is oriented), and why matter won (the oriented, CP-biased decays of the heavy neutrino sector) — and its own position on the map is the GG-A9-SM–GG-A10-Cosmos interface: fed by the ledger phases derived in GG-A9-SM — the PMNS Dirac phase and the Majorana parity $\alpha_{31} = \pi$ — and feeding the η_B chain of GG-A10-Cosmos across the width of the map, at the grade Part VIII records: derived-conditional on the named finite-temperature hypothesis H-$\phi_{\rm geo}$-1. From the rest of the cohort it consolidates: the discrete-symmetry and flavor-holonomy theorems of the Standard-Model treatment (Arisaka, 2026, A9-SM); the Majorana-door theorem of the same paper; the baryogenesis chain of the cosmology treatment (Arisaka, 2026, A10-Cosmos); the Wilson-line computations of the gauge-runtime treatment (Arisaka, 2026, A6-GRIP); and the strong-CP resolution shared with

the Kaxion companion (Arisaka, 2026, C1-Kaxion). Each import is restated at its point of use, with its grade. Both branch members carry P-series designators; their place at the spine's flank, not the phenomenology rows, marks their foundational role.

The rest of the map. Six companions are cited in this paper without being parents to it, and each earns its place here for a different reason. Arisaka, 2026, P2-N3 is a precondition rather than a neighbor: a nonzero Jarlskog invariant needs three families, so without that paper's count there is no CP phase in this one to explain, and the chiral pentagon of Part VII has nothing to be drawn on. Arisaka, 2026, P6-Proton stands at the other end of the same number: Part VIII makes the baryon asymmetry and that paper shows the resulting protons are kept, baryon number being carried as a winding of the compact circle rather than as a bookkeeping label. Arisaka, 2026, C2-Hubble carries the expansion history the matter excess is measured against, and its corridor reading is where the inventory this paper's chain must land on is read off. Arisaka, 2026, A4-Euclid traces the geometrization lineage from Euclid forward, of which the present claim — that the mirrors are orientations of real geometry rather than laws — is one more step, and it is the companion that says how large a step it is not. The two white papers close the roster. Arisaka, 2026, W1-Symmetry follows a century of symmetry and conservation in the order the results were found and watches the conviction that symmetry causes conservation loosen step by step; the mirrors of this paper are the sharpest case in that history, being symmetries that were assumed for three centuries and then measured to fail. Arisaka, 2026, W2-Holonomy turns on a single exact statement — a holonomy requires a closed loop, and the interval fiber has none — which is precisely the asymmetry Part IX derives the four endowments of time from, put to work there on sixteen open questions instead.

The twenty-two-paper map, identical in every paper of the cohort, is Figure 3, which closes this subsection.

Table 2: Seventy years as one experiment. The final row is the reason this paper can be wrong on a date — the property Table 26 itemizes. Nineteen rows, from Laporte's selection rule to the measurements of the 2030s, each with the actor, the episode, and what that episode settled. Read as one column, the table is the case for treating seventy years of mirror experiments as a single experiment that is still running, and whose last row has not been performed yet.

Year	Actor	Episode	What it established
1924	Laporte (1924)	parity selection rule	P as atomic bookkeeping
1956	Lee and Yang (1956)	the audit	P untested in weak interactions
1957	Wu et al. (1957); Garwin, Lederman, and Weinrich (1957)	^{60}Co; π–μ–e	P and C fall, maximally
1957–58	Lee and Yang (1957); Sudarshan and Marshak (1958); Feynman and Gell-Mann (1958)	two-component ν; $V-A$	maximal violation codified
1954–57	Lüders (1954); Pauli (1955); Jost (1957)	the CPT theorem	the product protected
1964	Christenson et al. (1964)	$K_L \to \pi\pi$	CP falls, at 2×10^{-3}
1967	Sakharov (1967)	the three conditions	CP violation is why matter exists
1973	Kobayashi and Maskawa (1973)	one phase at $N_g = 3$	a third family predicted from a kaon
1985	Kuzmin, Rubakov, and Shaposhnikov (1985)	sphalerons	$B+L$ erased; $B-L$ is the currency
1985	Jarlskog (1985)	the invariant	CP violation basis-free: one number
1986	Fukugita and Yanagida (1986)	leptogenesis	the lepton route to the excess
1998	Super-Kamiokande Collaboration (1998)	atmospheric oscillations	neutrino mass; the third arena opens
1999–2002	KTeV Collaboration (1999); NA48 Collaboration (2002)	ε'/ε	direct CP violation; superweak dies
2001	BaBar Collaboration (2001); Belle Collaboration (2001)	$\sin 2\beta$	the triangle closes on one phase
2004	Pilaftsis and Underwood (2004)	resonant leptogenesis	the TeV window opens
2012	Daya Bay Collaboration (2012)	θ_{13}	δ_{PMNS} becomes measurable
2020	T2K Collaboration (2020)	CP conservation disfavored	the leptonic phase within reach
2030s	DUNE, Hyper-K, tonne-scale $0\nu\beta\beta$	δ_{PMNS} to $\pm 15°$; Majorana nature	this paper's adjudication

Table 3: Seventy years of discrete-symmetry questions and where each framework stands. Register tags in the final column: *derived* (theorem at stated grade), *conditional* (named lemma or conjecture outstanding), D* (derived-conditional, order-of-magnitude). The table is defended, row by row, in Parts IV–X.

Question	**QFT**	**Standard Model**	**String theory**	**GG-Theory (this paper)**
What are C, P, T?	operators, phases free (Wigner)	same	same; C = orientation reversal of the string	orientation reversals of fiber, space, clock (T-P5-1; derived)
Why is T antiunitary?	input	input	input	derived: only the clock's orientation is what i is made of
Why does CPT hold?	Jost's theorem (interacting; anatomy silent)	inherited	worldsheet CPT	total orientation reversal (T-P5-2; quasi-free grade)
Why is P violated, in one force?	no principle	input (V−A by hand)	vacuum choice	the oriented descent: broken = gate = chiral (Part VI; conditional, L11)
Why does CP break, by this much?	no principle	fitted ($\delta = 1.147 \pm 0.026$)	spontaneous, moduli-valued, unpredicted	chiral pentagon: $\delta_{\mathrm{CKM}} = 2\pi/5 \to 13\pi/35$ (T-P5-3; conditional)
Why is $\bar{\theta} < 10^{-10}$?	unexplained	unexplained (axion added by hand)	axions generic, values not fixed	no knob exported + Kaxion relaxation (conditional, L9)
Why did matter win?	mechanism toolbox, dials free	fails by ten orders	ingredients + moduli problem	TeV resonant leptogenesis on the inherited ledger: $\eta_B \simeq 5.9 \times 10^{-10}$ (Part VIII; D*, Conj. VI)

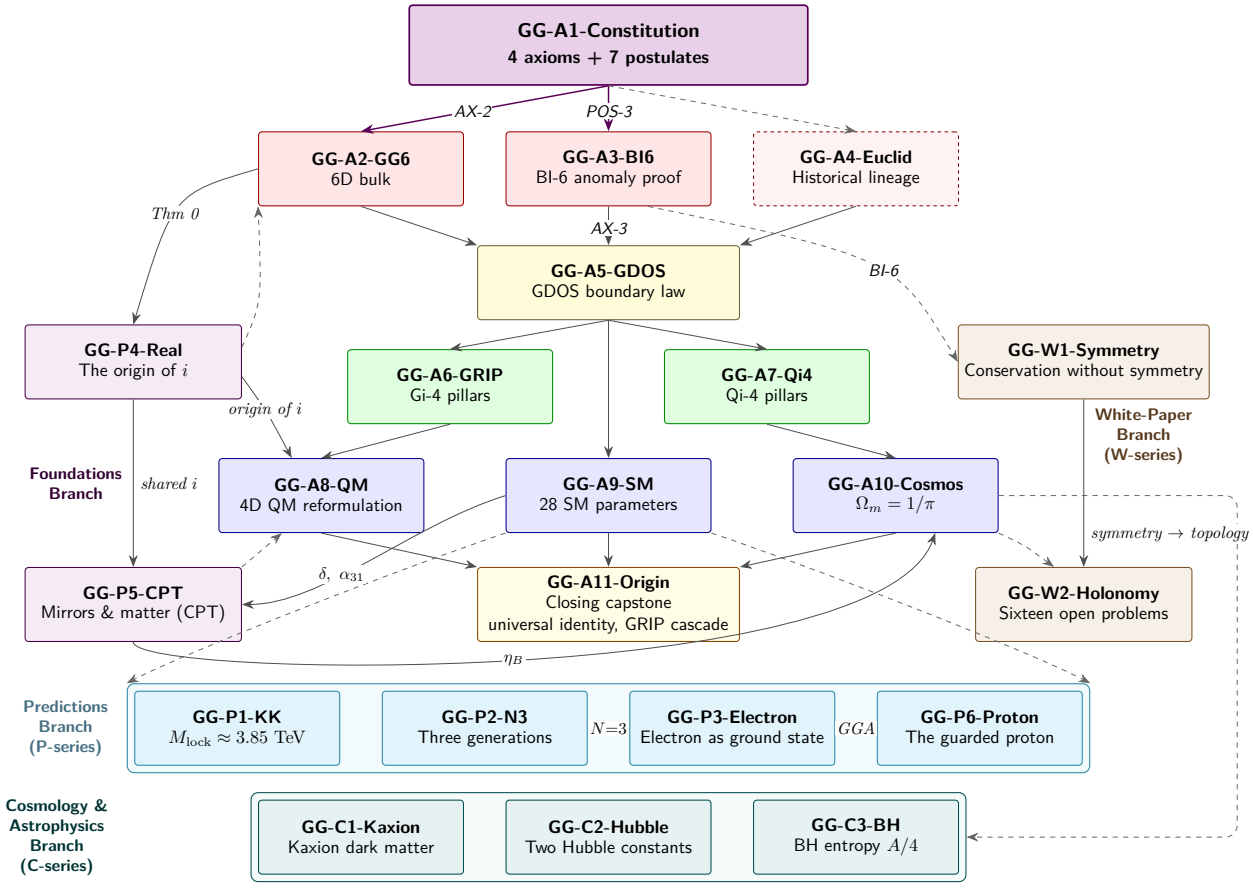


Figure 3: The twenty-two-paper cohort map of GG-Theory. The constitutional root GG-A1-Constitution (violet, top) supplies the four axioms and seven postulates from which the rest of the cohort descends: the GG6 Trio (GG-A2-GG6, GG-A3-BI6, GG-A4-Euclid, red) realizes the bulk geometry; GG-A5-GDOS (yellow) the boundary law; the GDOS Trio pillars (GG-A6-GRIP, GG-A7-Qi4, green) the geometric and quantum-information runtime; the 4D-Physics Trio (GG-A8-QM, GG-A9-SM, GG-A10-Cosmos, blue) the textbook readouts; and the closing capstone GG-A11-Origin (gold) the quarks-to-consciousness identity cascade. Two framed branches carry the phenomenology — the **Predictions Branch** (cyan), whose four papers hand their results along the row by the internal arrows (GG-P2-N3's N_g=3 into GG-P3-Electron, and that paper's ground-attractor method, GGA, on into GG-P6-Proton), and the **Cosmology & Astrophysics Branch** (teal). The spine is flanked by two columns of two, which do opposite jobs. On the left the **Foundations Branch** (violet) feeds it: GG-P4-Real, fed by GG-A2-GG6's Theorem 0 arena, manufactures the i that GG-A8-QM consumes, and GG-P5-CPT is the GG-A9-SM–GG-A10-Cosmos interface, fed by the ledger phases and feeding the η_B chain across the width of the map, with the shared-i edge descending solid between them. On the right the **White-Paper Branch** (brown) reads it: GG-W1-Symmetry walks the century from Noether to Hopkins–Singer, and GG-W2-Holonomy dissects the structure that arc arrives at — protection by topology rather than by symmetry — across sixteen open problems. The white papers derive nothing new, carrying every result at its parent's declared grade; the single dashed feed drawn into each names its heaviest source, not its only one. *Reading conventions:* solid arrows mark axiom-forced descent and carry an edge label naming the driving axiom or postulate where most illustrative; dashed arrows mark the deployment of derived results, or historical links inherited without being constitutionally forced.

16.2 Roadmap of the sixteen Parts

The rest of the paper is organized into fifteen further Parts, and the walk through them is plotted in Figure 4. The present Part — the entrance — is nearly done: it has asked the oldest asymmetry precisely, worn the two hats through a century of falling mirrors, put the five claims on the table with their registers attached, and laid out the two orientation maps of this closing section. Two Parts then put the machine on the table. Part II defines everything the argument stands on: the real presentation of charged fields, orientation reversals and (anti)linearity, the flavor graph and its holonomies, the seesaw in real blocks, the transport equations of leptogenesis, the $(1, 5)$ spinor algebra with its no-Majorana lemma, the anomaly flip, and the three-depths ruler. Part III assembles the GG-Theory arena: the constitutional clauses, the ledger, the four theorems inherited from the Foundations-Branch partner, the axiom-custody table that assigns every symmetry ingredient its axiom, and the custody map — *the bulk owns the symmetries; the descent owns their breaking; the boundary owns their observability.*

The five Parts that follow are the paper's center of gravity, and they are highlighted in the roadmap because together they are the deductive funnel of Figure 1 walked slowly: one deduction passing through five stations, each station forced by the one above it. Part IV derives the twin at full depth — the handshake theorems T-P5-A/B/C with the mode-level proof, the clock's third face (T-P5-B1, the Wick quartet, where Minkowski's *it*, Wick's rotation, and the Schrödinger i are proved to be one analytic fact), the extension theorems that carry one shared J into composites, Fock space, and the Dirac fermion, the self-conjugate exceptions the circle cannot move, and the boundary that reads the twins. Part V gives the mirrors their bodies: the three reversals walked one at a time on the modes of Part IV, the table theorem (T-P5-1) with Kramers' degeneracy as its first dividend, and CPT as total reversal (T-P5-2), with its converse discipline and its laboratory record. Part VI answers the parity question — why exactly one force is chiral: the basin/gate architecture with each clause of the gate's job description derived, the projection computed in blocks, the handedness invariant with its Ozma measurement, and the no-W_R falsifier. Part VII answers the CP question: the flavor-holonomy theorem (T-P5-3) with its calculus, the pentagon's own trigonometry from scratch, the quark chain and the lepton chain step by graded step, the dial-free door (T-P5-4), and the strong-CP two-fate architecture. Part VIII answers the matter question at the depth the heart of the paper deserves: the annihilation epoch and the surviving number certified three ways, Sakharov's three conditions derived and traced to their geometric origin, the exclusion walk that leaves leptogenesis as the only open channel, the ten-step inherited chain with its audit table, zero dilution, the resonance question faced in public, and the dated kill list.

Part IX pauses the march to ask the question underneath every page so far — what *is* time? — and answers with the four endowments: order from the cone, repetition from the equivalence, the arrow and the analytic shore from the dictionary; the standard accounts honored as partial readings; the quantum-gravity problem of time dissolved by architecture; and the first law-level arrow.

Three Parts then confront the derived mirrors with their rivals and their instruments. Part X gives the four rival roads their full say in three movements each — what the road achieved, where it ends, and how the geometry completes the story — for QFT, the Standard Model, string theory,

and ΛCDM, then scores the five on the three-depths ruler and closes with the roads seen from above. Part XI turns from theorems to instruments: the century of measured mirrors and the neutrino century with their milestone tables, the present frontier as of mid-2026, the instruments of the decisive decade — each with its schedule, its sensitivity, and the forced value it touches — the confrontation with its pre-declared kills, and the pre-registered verdicts of 2028–2040. Part XII discusses: significance, the innovations registered, the claims ledger, the falsifier table, and the open questions stated as open.

Part XIII concludes in plain English — the arc, the ten numbers, the limitations, the author's fifty years in the mirrors, and the oriented emergence of particles, life, and mind. The back matter is the workshop. Part XIV carries the lettered appendix machine room — five Step-graded chapters, ninety problems, all with complete worked solutions — together with the reference dictionaries and the ledger-and-registry appendices; Part XV answers eighty-two objections, each under its reader's own job title; and Part XVI annotates every reference with its relevance note. Read in order, the sixteen Parts compose a single self-contained argument; read by need, each Part names its imports and can stand a visit on its own.

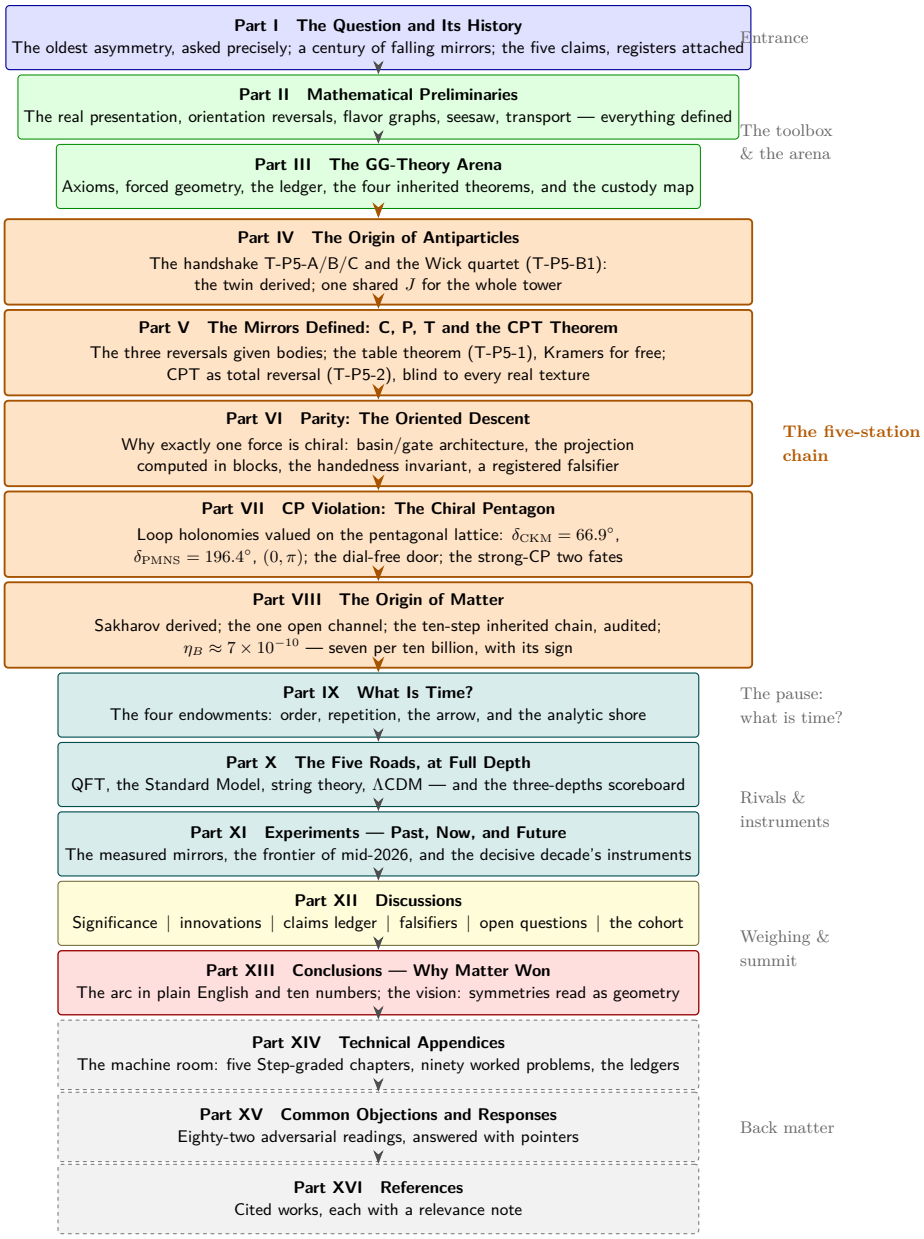


Figure 4: Roadmap of the sixteen Parts of GG-P5-CPT. The argument develops in seven phases. *Entrance* (Part I): the oldest asymmetry asked precisely, the century of falling mirrors, and the five claims with their registers. *The toolbox and the arena* (Parts II–III): every object the argument uses, defined from scratch, and the GG-Theory stage with its ledger and custody map. *The five-station chain* (Parts IV–VIII, highlighted): the twin derived from the handshake of the circle and the clock, the mirrors given bodies and the CPT theorem, the oriented descent of parity, the pentagon's CP phases, and the origin of matter — the deductive funnel of Figure 1 walked slowly. *The pause* (Part IX): what time is — the four endowments. *Confrontation* (Parts X–XI): the four rival roads at full depth and the instruments of the decisive decade with their pre-registered verdicts. *Weighing and summit* (Parts XII–XIII): the discussions and the conclusions — why matter won. The three back-matter Parts collect the technical appendices with their ninety worked problems (Part XIV), the eighty-two common objections and responses (Part XV), and the annotated references (Part XVI). Parts IV–VIII are highlighted because together they carry the paper's central claim — the single deduction of §15, from the real oriented bulk to the six-per-ten-billion receipt — on which every later Part, and the cohort downstream of GG-P5-CPT, stands.

Part-end summary. Seventy years of experiment broke three mirrors, spared the fourth, measured one phase to three digits, and counted six baryons per ten billion photons — while the theory that organizes all of it explains none of it. The claims of this paper are on the table with their registers attached. The next Part builds the vocabulary in which they can be stated precisely.

Part II
Mathematical Preliminaries

The real presentation, orientation reversals, flavor graphs, and transport — everything the argument stands on, defined

17 Part II in plain English: the toolbox, opened before it is used

Nothing is proved in this Part. It defines every object the argument uses — the real presentation of a charged field, orientation reversals and antilinearity, the flavor graph, loop holonomies and the Jarlskog construction, the seesaw in real blocks, leptogenesis transport, spinors in $(1, 5)$, and the weight arithmetic — with proofs where they are short and precise citations where they are classical.

Two of the definitions do more work than the rest and are worth slowing down for. The first is the real presentation: a complex field written as a pair of real components with a rule between them, so that the i becomes a rotation one can point at. The second is the flavor graph, on which a CP phase becomes the holonomy of a loop. Most of what happens later in this paper is one of those two objects being read carefully.

The Part also fixes the three depths, which is the instrument used in Part X to compare this account with the four it is set beside. A reader who wants to know how that comparison is scored should read the depths before reading the comparison, because an instrument introduced after the measurement is not an instrument.

18 The real presentation of a charged field

Every physicist has met the trick at the heart of this Part, probably in the second year of undergraduate study, wearing humbler clothes. An electrical engineer writes an oscillating voltage as the real part of $V_0 e^{i\omega t}$ — not because the circuit contains imaginary voltages, but because a rotating point in a plane is the tidiest way to carry an amplitude and a phase together. The complex number is a *picture of a rotation*. The thesis this paper inherits from its Foundations-Branch partner (Arisaka, 2026, P4-Real) is that in fundamental physics the engineer's situation is the true one: nothing in nature is complex; wherever an i appears, something real is rotating, and the job of foundations is to find the rotor. In the GG-6 bulk the rotors are physical — a compact fiber circle and the causal clock — and this Part builds the dictionary for working with them directly, in what the parent program calls the *real presentation* (Arisaka, 2026, A8-QM). Nothing in the dictionary is difficult; the reader who can rotate a vector in a plane can follow every step of this paper. What the dictionary buys is not rigor for its own sake but *visibility*: once fields are real pairs and phases are real angles, the discrete symmetries become things one can *see* — reversals of drawn arrows — and theorems about them become bookkeeping a student can check. A field of charge n under a

compact U(1) with angle coordinate $\theta \in [0, 2\pi)$ is presented not as a complex function $\psi \sim e^{in\theta}$ but as a *real pair* (a, b) on which the circle acts by rotation:

$$\begin{pmatrix} a \\ b \end{pmatrix} \longmapsto R(n\alpha) \begin{pmatrix} a \\ b \end{pmatrix}, \qquad R(\varphi) = \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix}, \tag{5}$$

under the circle translation $\theta \mapsto \theta + \alpha$. Concretely: a "charge-2 field" is a real pair that turns twice while the fiber turns once, exactly as the engineer's second harmonic turns twice per cycle — winding number is all that charge is, which is why charge is quantized (windings are integers) and why neutral fields do not rotate at all. A coupling phase is a rigid fiber rotation — a real $R(\varphi)$ block, not a complex number — and complex conjugation is *orientation reversal of the circle*, $\theta \mapsto -\theta$, which sends the weight-n pair to the weight-$(-n)$ pair: the "conjugate field" is the same pair, read with the fiber's orientation reversed — an angle run backward, not a path retraced. On each charged sector the charge-normalized circle generator

$$J_Q \;=\; \frac{\partial_\theta}{Q} \tag{6}$$

squares to $-\mathbf{1}$ and is the sector's complex structure: the "i" of a charged field is a quarter-turn of a real fiber. On the neutral sector J_Q acts as zero — the circle can only complexify what it moves — and the state-space complex structure comes instead from the clock (Section 37). Nothing in the paper's arguments requires the symbol i; where complex notation appears it is shorthand for real pairs and rotation blocks; the flagship computations of Appendix E use that shorthand, every i redeemable by the same rule.

Physics intuition. The real presentation is not a notational austerity exercise; it is what makes the discrete symmetries *geometric*. In complex notation, "charge conjugation" conjugates symbols; in the real presentation it reverses a circle. An operation that reverses a circle has an anatomy — it either preserves or reverses each of the other orientations in the theory — and anatomies can be theorems. That is the entire method of Parts IV and V.

19 Orientation reversals and (anti)linearity

Let V be a real vector space carrying a complex structure J (a real operator with $J^2 = -\mathbf{1}$). A real-linear operator S on V is *J-linear* if $SJ = JS$ and *J-antilinear* if $SJ = -JS$. Under the identification of (V, J) with a complex space, J-linear operators are complex linear and J-antilinear operators are conjugate-linear; if they preserve the relevant inner product they are, respectively, unitary and antiunitary. Two composition rules do all the work of Part V: the product of two J-linear or two J-antilinear operators is J-linear, and a mixed product is J-antilinear — (anti)linearity multiplies like a sign.

There is a homely way to hold the two rules just stated, and it will carry the reader through every proof in Part V. Think of J — the operator "rotate a quarter turn" — as a gear meshed into the machinery of the theory. An operation that leaves the gear turning the same way ($SJ = JS$) is *unitary*: it may rearrange the machinery, but clockwise stays clockwise. An operation that makes

the gear turn the other way ($SJ = -JS$) is *antiunitary*: every phase runs backward through it, which is exactly the familiar complex-conjugation of textbook antiunitarity. And because reversing a rotation twice restores it, the composition rule — mixed products are antiunitary, matched products are unitary — is nothing but "two reversals make a forward." The formal statements live in the standard texts (Streater and Wightman, 1964; Weinberg, 1995); the geometric reading is this paper's method.

The standard route to the discrete symmetries — Wigner's theorem (Wigner, 1931) — states that any symmetry of quantum-mechanical transition probabilities is implemented either unitarily or antiunitarily, and leaves the choice to consistency arguments made case by case: time reversal is *assigned* its antiunitary character because a unitary T would flip the sign of the Hamiltonian and wreck the spectrum. This paper's departure, stated now so the reader can watch for it: when the complex structure J itself has geometric *sources* — when i is made of specific orientations — then whether a given reversal commutes or anticommutes with J is not a choice but a computation, and the unitary/antiunitary table becomes a theorem about which reversals touch the sources (T-P5-1).

20 The flavor graph

The CP-violation half of the paper runs on one combinatorial object, and the object is friendlier than its name. Picture a patch panel: six sockets (the quark fields), nine wires between them (the Yukawa couplings), and on each socket a small dial that anyone may turn freely (the phase convention of that field). Each wire carries a twist — a real angle, a rigid rotation of the fiber. The physics question "which phases are real and which are convention?" becomes the electrician's question "which twists can be dialed away?" — and the electrician answers it instantly: turning dials can untwist any *tree* of wires, but the total twist around a closed *loop* cannot be touched, because every dial feeds a loop twice with opposite signs. That is the whole rephasing-invariant theory of CP violation, in wiring language, and the standard monograph develops the same content in matrix language (Branco, Lavoura, and Silva, 1999). Formally: consider N_g generations of up-type and down-type fields (the lepton case is identical with its own labels). The *flavor graph* is the bipartite graph with $2N$ vertices — one per field — and N^2 edges — one per Yukawa coupling. In the real presentation each coupling is a block $|y_{ij}|\, R(\varphi_{ij})$: a magnitude and a fiber twist. A Yukawa *texture* is thus a U(1)-valued connection on the flavor graph: each edge carries an angle.

Not all the angles are physical. Each vertex carries a "dial" — the freedom to re-zero the phase convention of that field — and a *rephasing* acts as a gauge transformation on the graph,

$$\varphi_{ij} \;\longmapsto\; \varphi_{ij} + \alpha_i - \beta_j, \tag{7}$$

with α_i the up-side and β_j the down-side dial turns. The gauge-invariant content of a connection on a graph is its *holonomies*: the sums of edge angles around closed loops, on which the action (7) telescopes to zero. Choosing a spanning tree of the graph and re-zeroing every tree edge (always possible, since tree edges can be nulled one by one), the residual physical data are exactly one angle

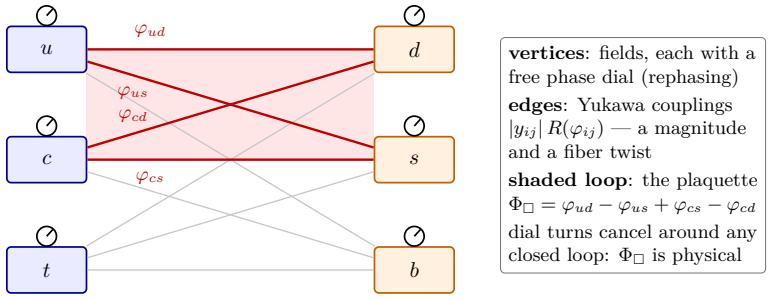


Figure 5: The flavor graph for three generations, drawn to the cohort's wiring-diagram standard. Up-type and down-type fields are vertices, each carrying a freely re-settable phase dial; the nine Yukawa couplings are edges, each carrying a fiber twist φ_{ij}. Turning any dial shifts every edge at that vertex equally, so the shifts telescope to zero around a closed loop: the shaded four-edge plaquette holonomy $\Phi_\square$ is invariant — a flavor-space Aharonov–Bohm phase (Aharonov and Bohm, 1959). For $N = 3$, unitarity ties all such plaquettes to a single physical angle, the Jarlskog phase (§21).

per independent loop:

$$\#\{\text{physical phases}\} = N_g^2 - (2N_g - 1) = (N_g - 1)^2, \tag{8}$$

the familiar counting — zero for one generation, one for two (where it can be removed by a further discrete choice), one surviving CP phase for $N = 3$.

21 Loop holonomies and the Jarlskog construction

The connection between loop holonomies and observable CP violation is the standard rephasing-invariant calculus, due in its basis-independent form to Jarlskog (Jarlskog, 1985); this section states it in graph language and draws the boundary between what is inherited and what this paper adds. For a mixing matrix V, the *quartet invariants* $\mathrm{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*)$ are the imaginary parts of the smallest rephasing-invariant products — in graph terms, the sines of the plaquette holonomies, the loop angles of the four-edge cycles. For $N = 3$, unitarity ties all nine quartets to a single number, the Jarlskog invariant J; every CP-violating observable in the quark sector is proportional to it; and CP is conserved iff every quartet vanishes — iff every loop holonomy lies in $\{0, \pi\}$. Two properties deserve emphasis. First, the loop angles are exactly as gauge-invariant as an Aharonov–Bohm phase (Aharonov and Bohm, 1959), and the analogy is not decorative: in the real presentation both are holonomies of a U(1) connection, one on spacetime, one on the flavor graph. Second, everything in this section is inherited mathematics — the graph packaging is convenient, not novel. What the parent program adds, and what T-P5-3 proves, is a *valuation*: a reason the loop angles take particular values, namely that on a single compact circle with block integer $L = 5$ the first-order holonomies are confined to the pentagonal lattice $(\pi/5)\mathbb{Z}$. The standard calculus says where CP violation *lives*; the lattice says what it *costs*.

Physics intuition — why an area? It is worth pausing on the geometric meaning of J, because it recurs. The six unitarity relations of the CKM matrix are triangles in the complex plane, drawn from products of matrix elements — and all six triangles, however different their shapes, have

the *same area*, $J/2$. Why? Because CP violation is a holonomy, and a holonomy is a flux: the loop angle is the "magnetic flux" through the plaquette of the flavor graph, and areas are what fluxes are. When the B factories measured the triangle's angles and the kaon experiments its sides, they were surveying one plaquette from two directions — which is why the global fit's consistency is a one-number statement, and why Part VII can price all of quark CP violation by valuing a single angle. An experimentalist who has drawn the unitarity triangle has been doing flavor-space magnetostatics all along.

22 The seesaw and Casas–Ibarra in real blocks

Part VIII requires the seesaw mechanism, and its physical idea deserves its playground name. Put a child and an adult on a seesaw: the harder the adult sits down, the higher the child rides. The neutrino is the child. If a very heavy neutral partner exists — mass M_N — and mixes with the light neutrino through an ordinary electroweak coupling, then diagonalizing the pair sends one mass *up* to M_N and the other *down* to $m_\nu \sim (\text{ordinary mass})^2/M_N$: the observed sub-eV lightness is not a mystery to be tuned but the shadow of a heaviness not yet seen. The mechanism was found independently several times within three years (Gell-Mann, Ramond, and Slansky, 1979; Minkowski, 1977; Mohapatra and Senjanović, 1980; Yanagida, 1979) — a sign, as with most good ideas, that it was ready. In the real presentation it acquires one further virtue: the question "*may* the heavy partner have a Majorana mass at all?" — in standard model-building a choice — becomes weight arithmetic with a unique answer (T-P5-4). A Majorana mass term is a *self*-pairing of a field — in real terms, a symmetric bilinear on a single weight sector — and Part VII's T-P5-4 proves such a pairing is invariant under the circle action iff the weight is zero. Given heavy Majorana states N_i with mass matrix M_N and Yukawa couplings Y_ν to the lepton doublets, the light-neutrino mass matrix is

$$m_\nu \;=\; \frac{v^2}{2}\, Y_\nu^T M_N^{-1} Y_\nu, \tag{9}$$

suppressed by the heavy scale — the seesaw. Inverting the relation to express the Yukawa in terms of the observed light masses and mixings is the Casas–Ibarra parameterization (Casas and Ibarra, 2001), $Y_\nu = M_N^{1/2} R\, m_\nu^{1/2} U_{\mathrm{PMNS}}^\dagger / v$ with R a complex orthogonal matrix; in the inherited chain of Part VIII the scale of M_N, the light masses, and the phases of U_{PMNS} are all fixed upstream, so the parameterization carries no freedom beyond the R-matrix structure it makes explicit.

23 Leptogenesis transport in one section

Part VIII's chain calls the following standard results, stated here once with their sources. The picture to hold throughout is a leaky bathtub: heavy decays pour asymmetry in, inverse decays and scatterings drain it away, and what survives is the level in the tub at the moment the drain freezes. *Decay asymmetry:* a heavy Majorana state N_i decaying to lepton–Higgs pairs generates a CP asymmetry $\epsilon_i = [\Gamma(N_i \to \ell H) - \Gamma(N_i \to \bar{\ell}\bar{H})]/[\text{sum}]$, arising at one loop from the interference of tree and self-energy/vertex graphs (Covi and Roulet, 1996; Fukugita and Yanagida, 1986). *Resonant regime:* when two heavy states are quasi-degenerate, the self-energy contribution is resonantly

enhanced; at $|M_i - M_j| \simeq \Gamma_j/2$ the asymmetry saturates near $\epsilon \sim \frac{1}{2}\sin(2\phi)$ with ϕ the relevant CP phase — the Yukawa suppression cancels between numerator and denominator (Pilaftsis, 1997; Pilaftsis and Underwood, 2004). This is the mechanism that permits TeV-scale leptogenesis, evading the Davidson–Ibarra bound $M_N \gtrsim 10^9$ GeV that governs the hierarchical regime (Davidson and Ibarra, 2002). *Washout:* the same Yukawas that produce the asymmetry can erase it via inverse decays and scatterings; the strength is measured by the effective mass $\widetilde{m}$ against the equilibrium scale $m_\star \simeq 1.1 \times 10^{-3}$ eV, and in the strong-washout regime $K_{\rm wash} = \widetilde{m}/m_\star \gg 1$ the surviving efficiency is $\kappa \simeq 1/K_{\rm wash}$ up to $O(1)$ factors (Buchmüller, Di Bari, and Plümacher, 2005). *Sphaleron conversion:* the strangest and most beautiful entry in the toolbox, worth three sentences of intuition. 't Hooft showed that baryon and lepton number are not exactly conserved in the Standard Model itself — the electroweak vacuum has a winding structure, and tunneling between windings changes $B{+}L$ ('t Hooft, 1976) — but at zero temperature the rate is absurdly small. Klinkhamer and Manton found the mountain pass between the windings — the *sphaleron*, a static unstable solution sitting at the top of the barrier (Klinkhamer and Manton, 1984) — and Kuzmin, Rubakov, and Shaposhnikov realized that the hot early universe simply walks over the pass: above the electroweak crossover, $B{+}L$ is erased and re-made freely, while $B{-}L$ is untouchable (Kuzmin, Rubakov, and Shaposhnikov, 1985). A lepton asymmetry (negative $B{-}L$) is therefore reprocessed into baryons with a coefficient fixed by chemical-potential bookkeeping over the plasma, $B = \frac{28}{79}(B{-}L)$ for one Higgs doublet (Harvey and Turner, 1990) — the number every baryogenesis mechanism in existence must multiply by, derived in Appendix F.4. *Entropy bookkeeping:* the late-time photon bath dilutes the asymmetry by the standard factor, $\eta_B \simeq 7.04\, Y_B$, with $g_* = 106.75$ relativistic degrees of freedom at production. The standard reference for all of this machinery is Kolb and Turner (Kolb and Turner, 1990), and the reader meeting transport for the first time should feel no intimidation: every equation in the kit answers a question a household understands — *how fast does it decay* (the width), *does the crowd undo it* (washout), *who converts the currency* (sphalerons), and *how much did the room grow* (entropy). Every symbol above reappears in Part VIII with a number attached, and nothing harder than these four questions ever enters.

24 Spinors in $(1,5)$: the algebra that forbids particle = antiparticle

Part IV's bulk-encoding argument rests on the Clifford algebra of six-dimensional Lorentzian spacetime, so it is built here from scratch. The Dirac spinor representation of $\mathrm{Spin}(1,5)$ has complex dimension $2^{6/2} = 8$. The chirality operator $\Gamma^7 = \Gamma^0\Gamma^1\cdots\Gamma^5$ squares to $+\mathbf{1}$ in $(1,5)$ signature, so the Dirac representation splits into two irreducible Weyl representations of complex dimension four,

$$\mathbf{8}_{\rm Dirac} \;=\; \mathbf{4} \oplus \bar{\mathbf{4}}, \tag{10}$$

exchanged by complex conjugation. The decisive fact is the *reality classification*: in $d = 6$ Lorentzian signature the chiral spinor representation is **complex** — not real, not pseudoreal — and consequently:

Lemma 24.1 (no Majorana condition in $(1,5)$)**.** *There is no Majorana condition compatible with the Clifford reality structure of $(1,5)$ signature: no charge-conjugation matrix B with $B\bar{B} = +\mathbf{1}$*

exists in the chiral representation, so the condition $\psi = B\psi^*$ has no solutions. A Weyl fermion and its conjugate are genuinely independent objects. (Symplectic-Majorana–Weyl conditions, which pair spinors using an internal doublet index, exist but identify nothing with its own conjugate; they are not used in the GG-6 construction.)

Proof sketch. The classification of spinor reality types by signature (t, s) is periodic in $(t-s)$ mod 8; for $(1, 5)$, $t - s \equiv 4$, where the intertwiner B satisfies $B\bar{B} = -\mathbf{1}$: the would-be Majorana projection squares to -1 and is empty. The standard reference treatment is Lawson and Michelsohn (Lawson and Michelsohn, 1989); the GG-6 arena paper carries the applied statement (Arisaka, 2026, A2-GG6). ■

Physics intuition — the eight-hour clock. The mod-8 periodicity is not numerology; it is the deepest clock in mathematics (Bott's), and one can feel why dimension matters without any machinery. A spinor is a "square root of a vector," and taking square roots interacts with reality the way it always has — sometimes the root of a real thing is real, sometimes it comes in conjugate pairs. As the dimension ticks upward, the Clifford algebra cycles through the real numbers, the complex numbers, and the quaternions with period eight, and the available reality conditions cycle with it. Four-dimensional spacetime happens to sit at an hour where a spinor can be its own conjugate (Majorana is *possible* there — an option, famously still undecided for the neutrino); six-dimensional spacetime sits four hours on, where it cannot. The GG-6 bulk did not choose to keep particles and antiparticles distinct; it was built at the hour of the clock where identifying them is not on the menu. This is what it means for a conclusion to come from geometry rather than model-building: the option was closed before any physics was put in.

Why this matters — said now, used in Part IV. In four dimensions a neutral fermion may be its own antiparticle (Majorana), and whether nature uses that option is an experimental question. In the GG-6 bulk the option *does not exist* for any charged chiral fermion: the algebra itself forbids identifying a bulk Weyl fermion with its conjugate. The conjugate sector — the antiparticle content — is therefore necessarily a *separate, genuinely present* module of the bulk matter, not a notational reflection. When Part IV says the antiparticle is "really there" before any descent, this lemma is what the words mean.

25 Weight arithmetic and the anomaly flip

Two more tools, stated once. *Weight arithmetic:* under the circle action, the symmetric square of a weight-n real pair decomposes into the invariant $a^2 + b^2$ (the Dirac pairing, winding-conserving) plus a doublet rotating with weight $2n$, invariant iff $n = 0$ — the three-line computation (Worked example 78.5) that will carry the Majorana door. *The anomaly flip:* each 6D Weyl species of chirality $\sigma_s = \pm 1$ in representation ρ_s contributes to the anomaly eight-form proportionally to its chirality,

$$I_8[D^-] \;=\; -\,I_8\Big[D^+\Big]\,, \tag{11}$$

so a chirality-flipped Weyl fermion in the same representation is a *physically distinct species* contributing with opposite sign. The eight-form itself descends from the index theorem, and its

structure in $4k{+}2$ dimensions — where purely gravitational anomalies exist and chirality is a signed currency — was mapped in the classic analysis of Alvarez-Gaumé and Witten (Alvarez-Gaumé and Witten, 1984); the GG-6 ledger paper executes the full arithmetic for BI-6 (Arisaka, 2026, A3-BI6). The flip (11) is the algebraic hinge on which those books balance, and (Part IV §47) the mechanism by which the anomaly arithmetic *forces* opposite-chirality matter into the bulk spectrum. Said warmly: in six dimensions the bookkeeper cannot be bribed — every chiral species signs its contribution, the total must vanish, and a spectrum written all in one sign is simply not a theory. Nature's ledgers, here as everywhere in the program, do the model-building themselves.

26 The three depths: an instrument for comparing explanations

The five-roads comparison of Part X needs a calibrated ruler, defined here so it cannot be bent later. A question like "where do antiparticles come from?" is answered at three possible depths. **Depth 1 (spectral):** given a quantum theory, why does its spectrum contain, for every charged particle, a partner of equal mass and opposite charge? **Depth 2 (structural):** why must any theory of the relevant type contain such partners — what consistency condition forces them? **Depth 3 (ontological):** what *are* the paired degrees of freedom, and what is the pairing itself made of — in particular, what is the complex structure whose conjugation defines it? The same ruler applies to each discrete symmetry (what is the operation made of?) and to the matter excess (are the inputs of the mechanism themselves explained?). To feel the ruler's teeth, run it once on a familiar fact: "the positron has the electron's mass." Depth 1: it is in the spectrum — measured, tabulated, no explanation offered. Depth 2: it *must* be, by the CPT theorem — any local, Lorentz-invariant theory pairs the masses; a magnificent constraint that works equally well whatever the electron and positron turn out to be. Depth 3: the two are *one object read in two orientations* — the mass equality is not enforced between two things but trivial for one thing (§49) — an answer that tells you what the twins are, at the price of committing to an ontology that can be wrong. The three depths are not ranks of virtue; they are different trades of scope against insight, and a mature comparison states which trade each framework has made. The honest headline of the whole comparison, defended in Part X: QFT answers Depths 1 and 2 rigorously and stops; string theory answers Depth 1 by inheritance and gestures at Depth 3 without valuation; ΛCDM measures the answers and explains none; the GG-6 claim — with its registers and its named residues — lives at Depth 3, with Depths 1–2 recovered as corollaries.

27 Notation table

$J_Q = \partial_\theta/Q$: circle complex structure on a charged sector. J_A: clock complex structure (polar phase of the time generator; the Hilbert transform). $R(\varphi)$: rotation block. φ_{ij}: texture edge angle; loop angles are their cycle sums. J (unadorned, in flavor contexts): Jarlskog invariant. $(M, N, L; J, K) = (1, 3, 5; 7, 35)$: the integer ledger (the flavor-count N and ledger J are always disambiguated by context). $M_{\text{lock}} = \frac{1}{2} M_{\text{Pl}} e^{-K} \simeq 3.85$ TeV: the lock scale. η_B: baryon-to-photon ratio. Grades: *derived* / *conditional (named lemma)* / D^* (derived conditional, order of magnitude)

/ *open.*

Part-end summary. The vocabulary is in place: fields as real pairs, discrete operations as orientation reversals whose (anti)linearity multiplies like a sign, CP phases as loop holonomies on the flavor graph, and the transport toolkit of leptogenesis with its standard coefficients. The next Part assembles the stage on which the theorems act.

Part III
The GG-Theory Arena

The axioms, the forced geometry, the ledger, the four inherited theorems, and the custody map

28 Part III in plain English: the stage, inherited and restated

This paper does not build the framework it uses. The axioms, the theorem that forces the six-dimensional arena, the integer ledger, the boundary law and the runtime are all inherited from companion papers, and this Part restates each at the precision the later proofs need, naming the paper that owns it in every case.

What comes out is small, and it is the whole basis of the argument: a four-dimensional spacetime, a non-spatial radial interval and a non-spatial compact circle, with a globally static metric — and, attached to every system in the universe, two real structures. The circle can carry a holonomy. The interval cannot, because a holonomy needs a closed loop and the interval has none. That asymmetry is what the rest of the paper spends itself on.

Restating an inherited result is not the same as proving it. The inheritance table records which result draws on which companion, and which classical mathematics is imported to reach it, so that a reader can go to the owning paper and check that it says what is claimed here. Where a clause is load-bearing later, that is the check worth making.

29 Why axioms at all — and which ones this paper needs

Most physics papers do not begin with axioms, and most should not. But a paper that claims to *derive* things usually taken as given — antiparticles, the discrete symmetries, the value of a CP phase — owes the reader an exact statement of what it is deriving them *from*, or the claim is theater. The framework this paper works in organizes its assumptions as a short constitution (Arisaka, 2026, A1-Constitution): four axioms, seven postulates, and one set of integers, written once and then never renegotiated. The spirit is worth internalizing before the letter. A constitution is not a summary of laws; it is the small set of commitments from which laws are *argued*, and its value lies precisely in how little it says — every clause is a hostage, offered in advance, to every future measurement. This paper uses three of the four axioms and one postulate. Each is given first in one line, then in full, because the reader should know at every later point which commitment is doing the work.

In one line each. **AX-1** (locality and causality): physics is registered on a Lorentzian causal manifold through retarded, microcausal protocols — it supplies a global time orientation, and, applied to interacting charged matter, it *forces* the two structures the next axiom must geometrize.

AX-2 (geometry–gauge equivalence): every structure the dynamics cannot avoid must be realized as geometry — one composite connection, with all physical content in curvature and holonomy invariants. **AX-3** (the operational dictionary): a bulk theory is not physically defined until one says how boundary observers register outcomes — instruments, channels, and, decisively here, an operational positivity clause. **POS-3** (anomaly freedom): chiral sectors must cancel all anomalies, by one inflow mechanism and no other.

AX-1 in full. Locality–causality is not one requirement but a bundle: interactions built from products of fields at coincident points; retarded support — no response before its cause; and microcausality — spacelike-separated observables commute. Two consequences are then *forced*, not assumed, and both are the reason this paper exists. First: an interacting local theory is singular at coincident points and therefore cannot be specified without a resolution scale and the flow connecting resolutions — the renormalization group, made compulsory. Second: local, causal interaction of *charged* matter cannot proceed by action at a distance; a phase frame must be carried at every point, with a connection compensating its arbitrariness — the gauge principle, read as a consequence rather than a postulate. A scale and a phase: *AX-1 hands exactly two structures to the next axiom.* The same axiom also hands this paper two of its three orientations — the clock's (causal order gives time a direction, the orientation T reverses) and space's (through the Lorentzian arena it demands, the orientation P reverses) — and, at the operational level, the forward-composing semigroup ($t \geq 0$: records accumulate, a record once made is not un-makeable) that Part VIII will recognize as Sakharov's third condition before cosmology is ever mentioned.

AX-2 in full. The geometry–gauge equivalence principle has two clauses. *Locked equivalence*: along any timelike curve there is a combined choice of coordinates, frame, and gauge in which the composite connection is flattened to first order — Einstein's elevator, upgraded so that geometry and gauge are one locked structure rather than two. *Invariant physics*: all physical content resides in the curvature and holonomy invariants of that one connection; "forces" are artifacts of unlocked descriptions. Both clauses are *complex-free* — a real connection, real curvature, real holonomy angles — and the operative reading is a single rule: whatever the dynamics cannot avoid must be realized as geometry. Here is the axiom that answers a question every student has asked and been told not to: *where does the gauge phase live?* It lives in a dimension. Given AX-1's two burdens, AX-2 makes the scale a real dimension I_r and the phase a real circle S^1_θ, whose windings are charge and whose reversal is C. In the framework's own words: *AX-2 builds the fiber.* One word of that sentence carries the program's most original content, and it is the word that is *absent*: neither new dimension is *spatial*. The lineage makes the point sharpest. Geometric dimensions that are not dimensions of space begin with Minkowski, whose time is exactly that (Minkowski, 1908); Weyl then had both of the great gauge insights — local *scale* as geometry in 1918 (Weyl, 1918), local *phase* as geometry in 1929, the birth of gauge theory itself (Weyl, 1929). Kaluza and Klein geometrized the phase first (Kaluza, 1921; Klein, 1926) — and made it a circle *of space*, the move that burdened every extra-dimension program since with a radius to stabilize, a charged tower to hide, and ultimately a landscape to wander. AX-2 keeps Weyl's two insights and refuses the spatialization: the scale and the phase enter as what they *are* — a resolution and an angle, dimensionless by construction — and Theorem 0 below *derives*, rather than assumes, that they are non-spatial (Arisaka, 2026, A2-GG6).

AX-3 in full. The operational axiom declares that a bulk theory is not physically defined without a fixed dictionary from bulk configurations to registered boundary physics,

$$\mathcal{D}(B) \;=\; (\,\mathcal{H},\ \rho,\ \{\mathcal{I}_\alpha\},\ \{\Phi_{t,s}\},\ \ldots), \tag{12}$$

with ρ a boundary state, $\{\mathcal{I}_\alpha\}$ measurement *instruments* in Kraus form with positive-operator-valued semantics, and $\Phi_{t,s}$ completely positive, trace-preserving evolution maps — the whole subject to three compatibility clauses: retardedness (from AX-1), gauge–geometry covariance (from AX-2), and *operational positivity*, clause (iii), the one this paper leans on when the clock's sign is selected. Measurement is thereby part of the theory's syntax rather than a metaphysical addendum, and the instruments' membership in the dictionary is why observer-adapted structures — which modes a detector counts, which sector it calls "the particle" — are boundary data throughout this paper.
AX-3 collapses the fiber that AX-2 built. One calibration, stated plainly and not re-argued here: in the wider framework this clause is also where quantum measurement finds a home — the collapse, the Born weights, the arrow of records read as properties of the projection rather than of the bulk (Arisaka, 2026, A5-GDOS; Arisaka, 2026, A8-QM). That case is made in those treatments; this paper borrows only the positivity clause and the custody rule that boundary *labels* are the dictionary's property. Readers who withhold judgment on the measurement claim lose nothing downstream.

AX-4, for completeness. Maximum symmetry, minimum freedom: no continuous structure is admissible unless a prior clause compels it. Its role here is quiet but real — it closes Theorem 0's count from above (no seventh dimension) and forbids the unforced extras that would otherwise let a phase float free of the one circle, which is exactly what makes the flavor angles of Part VII lattice-locked rather than free.

POS-3, the one postulate. Chiral gauge sectors must cancel all anomalies — gauge, mixed, and global — and may do so only through a single Green–Schwarz-type inflow implemented as a modified Bianchi identity (Arisaka, 2026, A3-BI6). Warmly: in six dimensions every chiral species signs its ledger entry (Eq. (11)), the books must close exactly, and no theory gets to exist whose books do not. It polices every chirality assignment in Part VI — and, as Part IV will show, it is one of the two independent reasons the bulk cannot be written without conjugate matter.

Physics intuition. The axioms are a relay, and the handoffs are the whole story. AX-1 says: to be local, causal, and charged, you must carry a zoom knob and a dial. AX-2 says: if you must carry them, then they are not bookkeeping — they are places in the geometry, real and non-spatial. AX-3 says: and here is what a four-dimensional being can actually read of them — states, channels, instruments, with positivity. The first hands two burdens to the second; the second makes them real; the third makes them readable. Every complex number in this paper is born in the gap between the second and the third: *real geometry, read by a bounded reader.*

30 Theorem 0: the forced arena

The two axioms together do not merely permit a six-dimensional bulk; they compel one, and they compel its shape. The arena theorem of the framework's geometry paper (Arisaka, 2026, A2-GG6) establishes

$$\mathcal{M}_6 \;=\; \mathcal{M}_4 \times I_r \times S^1_\theta, \qquad ds_6^2 \;=\; e^{-2r}\,\eta_{\mu\nu}\,dx^\mu dx^\nu \;+\; dr^2 \;+\; d\theta^2, \tag{13}$$

with I_r a non-compact *scale* direction — the geometrized renormalization group — and S^1_θ a compact *phase* circle — the geometrized gauge fiber. Three properties of (13) carry everything this paper does.

Non-spatiality. The two extra directions are classified by their *generators*, and this is the decisive move: a spatial or temporal direction is generated by a translation — that is what makes it a place one could in principle go — while I_r is generated by a dilatation and S^1_θ by a compact charge rotation. No signal propagates along them; no boundary protocol resolves a position on them; the bulk isometry algebra is

$$\mathfrak{iso}(1,3) \oplus \mathbb{R}_D \oplus \mathfrak{u}(1)_Q, \qquad \text{not} \quad \mathfrak{iso}(1,5). \tag{14}$$

Both coordinates are moreover dimensionless by construction — a logarithm of an energy ratio and an angle, pure numbers carrying no unit of length — which is the sharpest possible statement that they are not spatial.

Global staticity. In (13) the four-dimensional metric is Minkowski and the warp depends only on r; hence ∂_t is a global, hypersurface-orthogonal, timelike Killing field — the *constitutional clock*. This is not a decoration: it is precisely the hypothesis under which the positive-energy complex structure of §37.2 is *unique*, so the arena's staticity is what makes the clock's quarter-turn canonical rather than conventional.

Reality. Every datum in (13) — metric, interval, angle, connection — is real. No complex number appears anywhere in the arena, and none will be added.

The proof is a six-step forcing chain, worth possessing in outline because each step is load-bearing later. *Step 1*: AX-1 is defined relative to a light cone, so the registered arena is Lorentzian. *Step 2*: locality plus interaction forces the renormalization scale (AX-1's first burden). *Step 3*: AX-2 promotes it to a coordinate — the scale direction I_r, along which the connection component is the running coupling and the β-function is literally a covariant derivative. *Step 4*: locality plus charge forces the periodic gauge phase (AX-1's second burden). *Step 5*: AX-2 promotes it to the compact direction S^1_θ, whose Wilson-line holonomy is the gauge-invariant datum. *Step 6*: the count closes two-sidedly — from below, because deleting either direction breaks AX-1 itself (no scale: the theory is ill-defined at short distance; no phase: charged interaction becomes action at a distance), and from above, because AX-4 admits no third structure. Two properties proved en route are used constantly here: the added directions carry *no light cone*, and motion along θ is a gauge transformation — a change of description, not a physical displacement.

Register, at theorem visibility. The arena theorem is, in its home paper's own words (Remark 0.5

of Arisaka, 2026, A2-GG6), a constitutional forcing argument rather than a theorem of constructive quantum field theory, and every "forced" downstream of it in this paper inherits that register.

Physics intuition. Do not picture six axes. Picture the stage — spacetime, where things happen — with a zoom knob attached to it and a dial at every point of it. Theorem 0 says: charged, causal physics cannot be written without the knob and the dial, and the constitution obliges both to be geometry. The knob is not a corridor; the dial is not a room. That is the whole of "non-spatial," and it is why the dial's angle can be physical only through *differences* — holonomies — which is where every complex exponential in physics will come from.

What this dissolves. Feel the force of the classification before asking what it builds, because it removes at a stroke the questions that have shadowed every spatial extra-dimension program since 1921. "Why don't we see the extra dimensions?" — the question does not arise: there is nothing to see because there is no place to look; the phase dimension is not hiding, it is *present in every interference experiment ever performed*, as the phase of every charged field. "What stabilizes the radius?" — there is no radius; an angle has period 2π by what an angle is, and a resolution has no size. "Where is the tower of charged Kaluza–Klein copies?" — there is no tower, because the circle's characters are not momentum modes of a spatial loop but the *charges themselves*: the integer labeling a winding sector is not the mass level of a heavy replica, it is the electric charge of the field you already know. The problems that killed the spatial fifth dimension are not solved here; they are unposable — and that is the sense in which the two extra dimensions being *derived* (Theorem 0, from AX-1 and AX-2 alone), and derived to be non-spatial, departs from every predecessor: the two things they geometrize, a resolution and an angle, never were places.

31 The integer ledger

One more inheritance is load-bearing and deserves its own section: on this arena the anomaly-closure architecture fixes a five-integer ledger — forced, not fitted (Arisaka, 2026, A3-BI6):

$$(M,\, N,\, L;\, J,\, K) \;=\; (1,\, 3,\, 5;\, 7,\, 35), \qquad K \;=\; L \cdot J \;=\; M^2 + N^2 + L^2 \;=\; 35. \tag{15}$$

Each integer carries a structural meaning, and each deserves one warm line, because these five numbers are this paper's entire "parameter set." $M = 1$ is the loneliest: the tensor channel is primitive and unique — one indivisible winding unit, which is why charge comes in one quantum and why the circle's characters are integers at all. $N = 3$ is the crowd: the baryonic trace ratio isolates a triplicity inside the unified block, whose later echoes are color and the three families — and three is the smallest number of families whose mixing can hide a phase. $L = 5$ is the artist: the unified simple block is the five-dimensional one, and its regular polygon — the pentagon — will turn out to draw both the Cabibbo angle and the CP phase. $J = 2N+1 = 7$ is the counter: the centered odd closure built from the triplicity, whose oddness the leptonic phase inherits. And $K = LJ = 35$ is the deep one: the throat depth, the exponent that turns the Planck scale into the TeV lock and the ledger into the baryon excess.

Four of the five do direct work here, each at a stated point. $L = 5$ is the *angle alphabet*: with

one circle and one five-block — and, decisively, no second flavor torus on which an independent angle could float — every first-order physical phase is assembled from steps of $\pi/5$, which is why the CP-violating loop holonomies of Part VII are lattice-locked and why $2\pi/5$ appears where a free parameter would otherwise sit. $N = 3$ is why exactly one quark CP phase survives (Eq. (8)). $J = 7$ sets the leptonic phase $\delta_{\rm PMNS} = \pi + 2\arcsin(1/J)$. And $K = 35$ sets both the lock scale $M_{\rm lock} = \frac{1}{2} M_{\rm Pl} e^{-K} \simeq 3.85$ TeV and the throughput exponent $e^{-K/2}$ of the matter chain (Part VIII). The ledger is the reason this paper may say "quantized" and "locked" where other frameworks must say "measured" — and it was fixed, published with its own falsifiers, before any of the computations below were assembled.

Physics intuition. A dial that can be re-zeroed freely carries no numbers of its own. What the anomaly ledger adds is a tick-mark structure: the bookkeeping closes only for one integer packet, and those integers become the dial's engravings — how many windings make a charge (M), how many steps make the flavor pentagon (L). The circle supplies the geometry of the phase; the ledger supplies its arithmetic.

32 The fiber dictionary: charged fields as real harmonic pairs

With the arena fixed, the translation between bulk geometry and the familiar language of charged fields can be written down once and used everywhere. Single-valuedness on the compact circle gives every bulk matter field a real harmonic decomposition; the charge-n sector is the pair of real weight-n harmonics

$$\Psi_n(x;\theta) \;=\; a_n(x)\cos n\theta \;+\; b_n(x)\sin n\theta, \qquad R_\alpha : (a_n, b_n) \;\mapsto\; R(n\alpha)\,(a_n, b_n), \tag{16}$$

and the textbook complex charged field is the boundary's packaging $\psi_n = a_n + i b_n$ of that real pair (§18). Under this dictionary every piece of gauge folklore becomes a statement about a real circle: charge is the winding number n; charge quantization is compactness ($n \in \mathbb{Z}$); a gauge transformation is a fiber shift $\theta \mapsto \theta + \alpha(x)$; the covariant derivative is the horizontal lift, acting on the n-harmonic as $\partial_\mu - inA_\mu$; the Aharonov–Bohm phase is a real holonomy angle of a real connection (Aharonov and Bohm, 1959); and complex conjugation is orientation reversal $\theta \mapsto -\theta$ — the operation this paper will call C. One consequence is worth its own sentence, because it settles a question students ask and textbooks answer only by convention: the photon is the connection *itself* — not a section of any associated bundle — and therefore correctly carries no dial. It has no phase to reverse, no charge to conjugate, and is its own antiparticle for a reason one can see rather than memorize.

33 The boundary law: how a four-dimensional reader reads a six-dimensional book

The dictionary AX-3 demands is not left abstract in the wider framework; a dedicated treatment constructs it (Arisaka, 2026, A5-GDOS), and four of its structural results frame everything this paper does with observers, records, and asymmetries.

First, the projection is forced. A boundary protocol reads records sorted by a light cone; Theorem 0 gave the fiber directions no light cone; therefore no operation resolves where a system sits along I_r or around S^1_θ, and *every* act of registration marginalizes the fiber. Openness is not an accident of imperfect apparatus — it is constitutional; unitary closure is the unreachable idealization in which the fiber is never coarse-grained.

Second, the projection is always on. It happens at every spacetime point, observer or no observer. "Measurement" is its macroscopic, record-forming special case; decoherence is its microscopic one. Nothing waits for a physicist.

Third, the boundary law has a derived form. Exact projection gives a memory-kernel equation; complete positivity is inherited from unitary conjugation plus partial trace; and in the Markov regime the generator takes the standard Gorini–Kossakowski–Sudarshan–Lindblad form — from which the textbook quantum postulates follow as theorems rather than axioms.

Fourth — and this is the one to carry into every later Part — the two fibers carry the two halves of quantum mechanics. The compact phase circle carries the coherent, unitary, interference-generating half: transport along it is pure phase. The non-compact scale direction carries the open, irreversible half: its forward renormalization-group semigroup is the dissipative generator, and decoherence is the loss of θ-coherence induced by coarse-graining along r. Two dimensions, two faces of the quantum world — and this paper lives on both. The mirrors, the twins, and the pentagon are the first fiber's business; the arrow of time, the readout of which twin is "matter," and the transport that fixes the baryon number are the second's. When §38 says that the bulk owns the symmetries while the boundary owns their observability, this is the structure it is naming.

Physics intuition. The bulk is a six-dimensional book; the boundary observer reads a four-dimensional shadow of it, always, whether or not anyone calls the reading an experiment. What the shadow cannot show — the dial angle, the zoom setting — comes out as probability and irreversibility; what it can show — differences, rates, records — comes out real. Quantum mechanics, on this reading, is the grammar of reading a book through its shadow, and the one "imaginary" rule in that grammar is the shadow's compression of the dial and the clock into a single symbol.

34 The actualization layer: why records are real, and why the textures are locked

One more story bears directly on this paper, because it is where outcomes — the *real* end of the chain — are fixed. The runtime treatment (Arisaka, 2026, A6-GRIP) builds the descent in four pillars: the total geometric–gauge object (the one connection as a dynamical whole); the covariant conservation identity (the boundary Ward currents — electric, baryonic, informational, metric — that any lawful runtime must preserve); a geometric free-energy functional (a strict Morse landscape ranking admissible boundary configurations); and the pipeline itself, in which descent proceeds as a finite, ordered cascade of Morse steps, each transition costing a quantized action, halting at the ground attractor. Two consequences matter here, and both are load-bearing.

Every registered output of physics is a real quantity — an angle class, a count, a rate. The

registered datum of a measurement is a contextual joint holonomy: an element of the circle, a real angle class. So the complex layer of the formalism begins *after* preparation and ends *before* registration. It is genuinely middleware.

And the coupling textures are not free functions. The Yukawa textures whose loop holonomies measure CP chirality (Part VII) are outputs of this descent — stabilized attractor data, not inputs a model-builder may dial. This is the precise reason this paper may call the flavor angles *lattice-locked* where every other framework must call them measured: they are not parameters at all but the settled positions of a cascade that had nowhere else to stop.

Physics intuition. If the boundary law says how the shadow is read, the actualization layer says how the ink dries: a measurement completes when the joint configuration of system and apparatus rolls into a basin it cannot leave, and what is written is an angle — a dial reading, as real as any pointer. Between the real bulk that supplies the story and the real record that ends it, the complex amplitude lives only in the telling.

35 The arc, assembled: real bulk, complex middleware, real records

Part III can now be summarized as a single pipeline, and the summary is the frame the rest of the paper fills in. The *inputs* are real: an arena (Theorem 0), one connection (AX-2), an integer ledger (15), and matter as real harmonic pairs on the circle (16). The *outputs* are real: probabilities and rates, records, holonomy classes — and, in this paper, laboratory asymmetries and one number counted in the sky. In between sits the layer every physicist was trained in: amplitudes, phases, state spaces — the compressed notation a fiber-blind reader is forced into. Nothing complex enters the pipeline's ends. That is the sense in which the discrete symmetries can have an *anatomy* at all: C, P, and T are operations on the real ends, and the boundary's i — which they appear to act on — is only the middle's shorthand for a real quarter-turn.

36 The two shared structures, named

Everything this paper derives comes from exactly two real structures, both supplied by the arena and both attached to *every* system in the universe:

$$\textbf{G1:}\quad \text{the phase circle } S^1_\theta \quad (\text{generator } \partial_\theta), \tag{17}$$

$$\textbf{G2:}\quad \text{the constitutional clock } \partial_t \quad \text{with the positivity clause of AX-3.} \tag{18}$$

G1 supplies the gauge phase and everything quantized about it; G2 supplies the state-space rotation and everything oriented about it; their consistency on charged sectors will be the particle–antiparticle pairing (Part IV); their three orientations — G1's, G2's, and space's — will be C, P, and T (Part V); the texture written on G1 during the descent will be parity violation and the pentagon (Parts VI and VII); and the door that texture biases will be the matter of the universe (Part VIII). Table 4 records what each result uses.

Table 4: What each result of this paper uses from the arena, and which classical mathematics it imports. Nothing in the left column is postulated by this paper; nothing in the right column is claimed by it. One row per numbered result. The middle column names the axiom, theorem or ledger entry the result stands on; the right column names the classical mathematics imported to reach it, with an em dash where none is needed. The table is here so that a reader can see at a glance which parts of the argument are new to this paper and which are inherited.

Result (this paper)	**Arena source**	**Imported classical mathematics**
T-P5-A (the circle)	AX-2; Theorem 0 (G1)	harmonic analysis on S^1
T-P5-B (the clock)	AX-1; AX-3(iii) (G2)	Ashtekar and Magnon (1975); Kay (1978)
T-P5-C (antiparticles)	G1 + G2 jointly	—
one J, one i	G1, G2 global	Renou et al. (2021) (as constraint)
T-P5-1 (the C/P/T table)	orientations of G1, G2, space	—
T-P5-2 (CPT)	total reversal of the three	(contrast: Jost, 1957)
T-P5-3 (holonomy calculus)	G1; ledger $L = 5$	Jarlskog (1985)
T-P5-4 (the door)	G1 weight arithmetic	seesaw (Minkowski, 1977)
Parity: the projection	POS-3; chirality of the bulk	orbifold GUT (Kawamura, 2000)
T-P5-5 (η_B)	ledger $K = 35$; the door	transport (Kolb and Turner, 1990)
Lattice-locked textures	the descent (Arisaka, 2026, A6-GRIP)	Morse theory
Real records; readouts	the boundary law (Arisaka, 2026, A5-GDOS)	GKSL form
The anatomy (§59)	G1 compact, G2 directed	the two-fiber formulation of (Arisaka, 2026, W2-Holonomy)
$\Delta B \in 3\mathbb{Z}$ (§92)	T-SM-60.1, hypotheses H1–H3	(Arisaka, 2026, A9-SM; Arisaka, 2026, P6-Proton)

Physics intuition. The whole construction can be said in one breath: nature carries one dial and one clock, the same pair everywhere. The dial cannot be read, so only its differences — holonomies — are physics; the clock cannot be run backward, so only one frequency orientation is physics. Complex numbers are what a four-dimensional observer writes down when forced to log differences of an invisible dial and orientations of an irreversible clock in a single symbol. And the subject of this paper — the twins, the mirrors, the pentagon, the matter — is what happens when you ask that dial and that clock to agree.

37 The two sources, at depth

Everything this paper proves grows from four facts about the arena's two sources of complex structure. Each is introduced here from scratch, at the blackboard, assuming no prior acquaintance — they are the paper's foundation stones, and the reader deserves to stand on each one before building begins. Each also carries a citation to the companion treatment in which it was established at full length (Arisaka, 2026, P4-Real); none is re-proved in this section — Part IV re-proves the ones this paper's claims ride on.

37.1 The circle: a dimension of phase, not of place

The first source is not a place, and that sentence is the most important in this Part. Every prior higher-dimensional program — Kaluza–Klein, Randall–Sundrum, string theory — added dimensions *of space* and then had to hide them: curl them small, warp them away, explain why no experiment walks into them, stabilize their radii, and live with the moduli, the charged towers, and eventually the landscape that spatial extra dimensions bring (Arisaka, 2026, A2-GG6). The GG-6 bulk's two extra dimensions are a different *kind of thing*, and the arena paper gives the classification its precise form: a dimension is known by its *generator*. A spatial or temporal direction is generated by a translation — that is what makes it a place one could in principle go. The scale dimension I_r is generated by a *dilatation*: a value of r is a resolution, a magnification at which the same world is read, and one does not travel along it any more than one travels through the zoom of a microscope. The phase dimension S^1_θ is generated by a *compact charge rotation*: a value of θ is a gauge angle, and local motion along it is a gauge transformation — a change of description, not a displacement; no signal propagates there, no light cone extends there, and the bulk's isometry algebra is $\mathfrak{iso}(1,3) \oplus \mathbb{R}_D \oplus \mathfrak{u}(1)_Q$, emphatically not $\mathfrak{iso}(1,5)$. Both coordinates are dimensionless by construction — a logarithm of an energy ratio and an angle, pure numbers carrying no unit of length — which is, in the arena paper's words, the sharpest possible statement that they are not spatial.

Feel what this dissolves before asking what it builds. "Why don't we see the extra dimensions?" — the question that has shadowed every spatial program since 1921 — simply does not arise: there is nothing to see because there is no place to look; the phase dimension is not hiding, it is *present in every interference experiment ever performed*, as the phase of every charged field. "What stabilizes the radius?" — there is no radius; an angle has period 2π by what an angle is, and a resolution has no size. "Where is the tower of charged Kaluza–Klein copies?" — there is no tower, because

the circle's characters are not momentum modes of a spatial loop but the *charges themselves*: the integer that labels a winding sector is not the mass level of a heavy replica, it is the electric charge of the field you already know. The problems that killed the spatial fifth dimension are not solved here; they are unposable — and this is the sense, stated once and carried silently hereafter, in which the author's construction departs from every predecessor: the two extra dimensions are *derived* (Theorem 0, from AX-1 and AX-2 alone), and derived to be non-spatial, because the two things they geometrize — a resolution and an angle — never were places.

With the category corrected, the physics of the fiber is exactly as Part II drew it, and three old mysteries remain dissolved. Why is charge quantized? — because the phase dimension is compact: windings of an angle are integers. Why do charged wavefunctions carry phases? — because the field's "complex phase" *is* its fiber angle: the quantum phase is the holonomy of a real, non-spatial circle, which is why the Aharonov–Bohm effect measures it while no local field does (Aharonov and Bohm, 1959). Why can conjugation be geometric? — because reversing an angle's orientation is as real an operation as reversing a spatial axis, without the angle being an axis: C is $\theta \mapsto -\theta$, the reversal of a phase, not a mirror of a place. What the parent program adds as theorem (T-P4-1) is uniqueness: on each charged sector the circle's quarter-turn $J_Q = \partial_\theta / Q$ is the unique circle-compatible complex structure — up to one sign the circle itself cannot fix — together with the two honest limitations that make a second source necessary: the circle complexifies only what it moves (neutral fields get nothing), and it does not know its own orientation. Hold both limitations; they are load-bearing.

37.2 The clock: the quarter-period advance

The second source is not a place but a direction: causal time, with a bound below on energy. Its gift (T-P4-2) is the operator this paper has already met in engineer's clothing — the Hilbert transform, the "advance every oscillation by a quarter period" operation of the analytic-signal construction (Gabor, 1946). On the real solution space of any free bulk field, that operator is a complex structure; and the theorem that elevates it from convenience to physics is *uniqueness*: among all complex structures commuting with the dynamics, exactly one gives every mode positive energy, and on the constitutional arena it is this one (Ashtekar and Magnon, 1975; Kay, 1978). The constitutional pedigree is worth reciting like a verse, because each clause comes from a different axiom: *AX-1 supplies the direction* (causal order says which way time points), *the positivity clause of AX-3 the selection* (which orientation of the splitting is "positive"), *Theorem 0 the uniqueness* (the arena is globally static, so the choice is canonical). Where the circle knew charge but not direction, the clock knows direction but not charge: it acts identically on every field, neutral ones included — which is exactly what the circle could not do. Two half-blind sources; each supplies what the other lacks.

37.3 The handshake, previewed

On every charged sector, both sources are present and each supplies a quarter-turn that claims to be *the* rotation of that sector. They agree — Part IV proves, mode by mode — under exactly one matching of charge to frequency, and that matching is the particle–antiparticle pairing. The preview is stated here only so the reader carries the right expectation into Part IV: the antiparticle

will not be introduced, postulated, or discovered there. It will be *forced*, by the requirement that a bulk with two real sources of rotation share one J — and hence that the boundary description have one i — with the sign the circle could not fix fixed in the same stroke.

37.4 One J in the bulk, one i on the boundary

Before stating the fourth fact, a distinction must be drawn so cleanly that it can never again blur, because everything in this paper turns on it. *The bulk contains no imaginary unit.* What the bulk contains is J — a *real* operator, the quarter-turn, exactly as real as the rotation matrix $R(90°)$ it is. That $J^2 = -\mathbf{1}$ makes J a complex *structure*; it does not make J a complex *number*, any more than a screw is a helix because it traces one. The symbol i belongs to the other side of the projection: when the four-dimensional boundary description mimics the real bulk — and mimic it must, for the boundary theory is quantum field theory, the downstream description of bulk physics — it packages each real pair (a, b) into a single amplitude $a + ib$, and that packaging is lawful only along J. The boundary's i is its shorthand *name* for the bulk's J: a notational contraction of "apply the quarter-turn." In the custody language this paper uses throughout: the geometry owns J; the dictionary owns the symbol.

With the levels separated, the fourth fact can be stated exactly (T-P4-4). *Upstairs, in the bulk:* the two sources supply one shared J — composites and the Fock construction extend it canonically, with no second structure ever appearing — a statement about real geometry, in which i does not occur. *Downstairs, on the boundary:* because there is exactly one J to name, there is exactly one i in quantum mechanics — one global phase convention that entangled, composite, many-particle states all share. One J upstairs is why there is one i downstairs. And the downstairs statement is tested: the network Bell experiments that exclude real-Hilbert-space quantum mechanics (Renou et al., 2021) constrain precisely the many-unshared-structures alternative, and are satisfied by construction in a boundary description fed by a bulk with one J. Note carefully what the experiments do and do not test: they test the boundary formalism (it needs a single shared imaginary unit) and they cannot see the bulk; the bulk is what *explains* the formalism's need. What looked like a threat to any "real quantum mechanics" is, for this architecture, the sharpest available support — because the architecture never claimed the boundary description could do without i; it claims the *world* does, and supplies the one real structure the notation was naming all along.

The logical dependence of what follows is asymmetric, and stating it plainly is part of the register: Part V's table and CPT theorem need all four inputs; Part VII's holonomy calculus needs only the fiber; Part VII's door theorem needs only the circle action on weight sectors. A reader who doubts the clock derivation still faces the pentagon; a reader who doubts everything still faces the falsifier table.

37.5 Why the real bulk matters: the observer built to read it

It would be fair for a reader to ask, at this point, why so much weight is placed on a bookkeeping preference. The boundary description works perfectly well with its i; the antiparticle pairing could be stated in either language; what, beyond tidiness, is bought by insisting that underneath the notation the world is real? The honest answer reaches further than the rest of this paper, into

territory the program develops in dedicated companion treatments and grades as its most tentative — and it is offered here, at that same tentative grade, because it is the reason the real-bulk view is not a stylistic choice but a claim about what kind of universe this is. The short form: *the world writes reality in real phase, and the observer is built to read it in real phase.* If that parallel holds, the reality of the bulk is not a convenience of the physicist; it is the common substrate of the thing observed and the thing observing.

Three ideas are needed, and each is introduced from scratch.

First, a fourth charge — of information. Alongside the familiar conserved quantities (electric charge, and the gauged baryon number this paper's proton stability rests on), the program admits one further Abelian symmetry, written $\mathrm{U}(1)_{Qi}$, whose conserved current is not a flow of energy or matter but a flow of *information* (Arisaka, 2026, A7-Qi4). The reader need not accept the full apparatus to follow the point; what matters is its carrier. A $\mathrm{U}(1)_{Qi}$ charge is stored and transported the way any U(1) quantity is stored on the fiber of Part II — as a *phase*, a real angle — and its only physical, convention-independent content is the holonomy of that phase around a closed loop, exactly the Aharonov–Bohm-type invariant of §37.1. Information, in this reading, is carried the same way charge is: as a real angle on a real circle, whose i (should one write it) is again only the name of a quarter-turn.

Second, the freely running substrate — "DGI." Before any symmetry breaks, the bulk carries this information current on an unbroken gauge-equivalence background — the program's term is *Dynamical Gauge Invariance* — on which the current propagates freely: not yet a particle, not yet a measured value, not yet localized (Arisaka, 2026, A6-GRIP). It is the rawest layer of the descent, the informational analogue of the unprojected, still-real bulk field this whole Part has been describing. One holds it in mind as the state of "information before it has been read": present, lawful, and — crucially for the parallel about to be drawn — entirely real.

Third, the reader in the loop — the Inner Hologram. Now the striking part, and the reason the author asks that this view be taken seriously rather than as decoration. Consider what a brain must do. Its senses deliver a lossy, self-centered, low-dimensional shadow of the world — a two-dimensional retinal image does not determine the three-dimensional scene that cast it, and a stream of such shadows, tagged "I turned left, I stepped forward," accumulates error the way dead reckoning always has. To survive, an animal cannot store the shadows; it must *reconstruct*, from them, a stable model of the world as the world is — a *world-centered*, or *allocentric*, frame in which objects hold their places while the self moves through them (O'Keefe and Nadel, 1978). The companion treatments call this reconstructed model the *Inner Hologram*: the brain's running, self-updating, allocentric picture of what lies beyond the sensory boundary (Arisaka, 2026, A7-Qi4; Arisaka, 2026, A11-Origin). It is not a metaphor drawn loosely; the neural hardware is identified — the place cells, grid cells, and head-direction cells of the mammalian hippocampal system are exactly the machinery a world-centered frame requires (O'Keefe and Nadel, 1978; Hafting et al., 2005) — and the reconstruction runs, behaviorally, as a transform whose magnitude is paid for in *time*: recognizing a rotated or displaced object takes longer in proportion to the transform needed to align it with memory, in steps clocked by the brain's rhythms.

And here is the payoff, the sentence this subsection exists to earn. The medium in which the

Inner Hologram is written is neural *phase*. The pose of a reconstructed object is carried by the phase of traveling cortical waves — the theta rhythm (∼5 Hz) that paces the integration of the world-model against fresh evidence, nested with the gamma rhythm (∼40 Hz) that carries the sensory content (Buzsáki, 2006) — and a memory, in this account, is a $U(1)_{Qi}$ holonomy: a gauge-invariant phase difference, the same real-angle-around-a-loop invariant that the fiber uses for charge. The brain, on this reading, does not merely happen to use oscillations; it must, because the quantity it traffics in — reconstructed, relational, world-centered information — is a $U(1)_{Qi}$ charge, and a $U(1)_{Qi}$ charge lives on a phase. The improvement of the model over time — learning — is then a theorem of the same kind as the rest of the program: any memory-bearing system carrying this information current necessarily refines its allocentric reconstruction, driving the mismatch between the world and its inner picture monotonically down (Arisaka, 2026, A11-Origin; Friston, 2010).

Now stand back and see the parallel whole, because it is the answer to the reader's opening question. The physics half of this paper says: charge is a real winding on a real circle; antiparticles are the real handshake of two real rotation structures; the imaginary unit is the boundary's name for a real quarter-turn — *the world is real, and i is how the four-dimensional shadow writes it down.* The neuroscience half, developed in the companion treatments and invoked here only to illuminate the physics, says: the brain reconstructs the world in a real, world-centered model, carries that model in real neural phase, and traffics in information as a real $U(1)_{Qi}$ holonomy — *the mind is real, and any i in its equations is again how a description writes down a rotation of real angles.* The reality of the bulk and the phase-coded reality of the cortex are, on this view, the same fact seen at opposite ends of the cascade that runs from the fiber circle to the reader: reality is written in real phase, and the reader is an instrument built, by the same descent, to read real phase. The universal i that experiment demands (§37.4) is not evidence that nature is complex; it is evidence that nature keeps *one* real rotation structure — and that the observer, being part of nature, inherited it.

Two cautions close the subsection, and they are not afterthoughts. First, register: the neuroscience developed in the companion treatments is graded there as the program's most tentative reach — an offered structural identification awaiting the derivations that dedicated later work must supply, not an established result — and nothing in this paper's physics depends on it. The mirrors break, the pentagon turns, and the matter of the universe is counted whether or not the mind story holds. Second, proportion: this subsection is a widening of view, placed here because the author regards the real-bulk doctrine as inseparable from the question of the observer, and because a reader who has followed the "one J, one i" argument deserves to know how far its author believes it reaches. The paper now returns to what it can defend with instruments and theorems.

38 The custody principle, extended

One principle governs every use of the two levels this Part has separated, and it is worth stating as a rule before it is used as one. Wherever a physical structure and a descriptive label meet — a charge sector and its name, a rotation and its symbol — the two belong to different owners: *the dictionary owns the sectors; the geometry owns the i.* The rule was drawn from three independent encounters with the same pattern (charge superselection, horizon vacua, and the infrared clouds

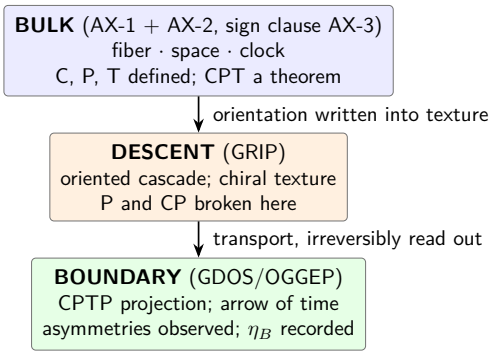


Figure 6: The custody map. The bulk owns the symmetries (the three orientations and the CPT theorem); the descent owns their breaking (the chiral texture: parity and CP); the boundary owns their observability (the arrow of time and every recorded asymmetry, the baryon excess included).

of soft radiation), each of which dissolves once one asks which owner a disputed object belongs to (Arisaka, 2026, P4-Real). This paper requires its extension to the discrete symmetries, and states that extension now as the organizing map (Figure 6):

The bulk owns the symmetries; the descent owns their breaking; the boundary owns their observability.

The bulk owns the symmetries. The three orientations that C, P, and T reverse are bulk structures (fiber, space, clock: AX-2, AX-1, AX-1 with AX-3's sign clause), and the 6D action is invariant under each reversal separately — in particular, the bulk is exactly time-reversal symmetric (Arisaka, 2026, A5-GDOS). The symmetries and the CPT theorem are therefore Part-IV property, proved upstairs.

The descent owns their breaking. What breaks P and CP is not the bulk but the *texture* the descent writes on it: the orbifold projection that keeps one hand (Part VI), and the flavor holonomies — GRIP outputs (Arisaka, 2026, A6-GRIP) — whose pentagonal chirality is CP violation (Part VII). In the cosmology companion's formula: *GRIP owns the angle* (Arisaka, 2026, A10-Cosmos).

The boundary owns their observability. The arrow of time is not T-violation but the non-invertibility of the OGGEP projection — an AX-3 property, with the bulk T-symmetric — and every observable consequence of the broken mirrors, from a kaon asymmetry to the baryon excess, is read at the boundary through GDOS transport: *GDOS owns the observability, OGGEP owns the ledger.*

This three-line map is the paper's answer to the custody question posed in Part I: are C, P, T and their theorem defined in the 6D bulk under AX-1 and AX-2, or do they belong to AX-3 and the GDOS/GRIP machinery? The answer is layered, and Table 5 states it row by row, in the papers' own words.

One entry of the table deserves its theorem-level footnote, because it protects the whole architecture from a classic confusion. The bulk action is *exactly* time-reversal symmetric, while every boundary record is irreversible — and these two statements are not in tension but in *product*: the cohort derives the Crooks fluctuation theorem as precisely the combination of "bulk time-reversal

Table 5: The axiom-custody table: the custody question answered row by row. The operations and the CPT theorem are bulk-level (AX-1 + AX-2, with one clause of AX-3 selecting the sign of J); the violations are descent-level (GRIP holonomies); the observations are boundary-level (GDOS/OGGEP).

Ingredient	**Custodian**	**The cohort's own words**
The clock's time-orientation (what T reverses)	AX-1 (bulk)	"AX-1 supplies the direction"
The fiber circle (what C reverses)	AX-2 / Theorem 0 (bulk)	"AX-2 *builds* the fiber"
Space orientation (what P reverses)	AX-1's arena (bulk)	time-oriented Lorentzian manifold
The sign of the state-space J	AX-3 positivity clause	"the positivity clause of AX-3 the selection"
Bulk T-symmetry of the 6D action	AX-1 + AX-2	"bulk time-reversal symmetry… an AX-1+AX-2 property"
Arrow of time / irreversibility	AX-3 / OGGEP (boundary)	"the asymmetric projection of the OGGEP CPTP channel"
The CP-violating angle	GRIP (descent)	"GRIP owns the angle"
Its observability	GDOS (boundary)	"GDOS owns its observability"
The conserved ledger it acts on	OGGEP	"OGGEP owns the ledger"
The one relaxed CP angle ($\bar{\theta}$)	Kaxion (companion)	dynamical relaxation + static suppression

symmetry of the 6D action (an AX-1+AX-2 property)" with "the asymmetric projection of the OGGEP CPTP channel (an AX-3 property)" (Arisaka, 2026, A5-GDOS). The arrow of time is the operational shadow of the projection, not a microscopic property of the bulk; T-violation (a symmetry statement about dynamics) and irreversibility (an operational statement about records) live in different rows of the custody table, and every later use of "the descent is oriented" respects the separation.

Close of Part III, in plain terms. The stage is set, and it is entirely real: an arena forced by locality and equivalence — a stage, a zoom knob, and a dial at every point, neither knob nor dial a place; an integer ledger engraving the dial; a boundary law that reads the bulk through an always-on projection, the phase fiber carrying quantum mechanics' coherent half and the scale fiber its irreversible half; and an actualization layer that dries the ink into real records and locks the flavor textures the later Parts will price. Two structures on this stage are shared by everything in the universe — the dial G1 and the clock G2 — and three orientations live on it: the dial's, the clock's, and space's. The custody map tells the rest of the paper where each question belongs: a bulk whose action is symmetric under each orientation reversal separately (Part V proves the table and the CPT theorem there); a descent that is *oriented* — a downhill flow through the family landscape, writing a chiral texture (Part VI) with pentagonal holonomies (Part VII) — so that parity and CP break together as two faces of one one-wayness; and an open boundary that records

the consequences irreversibly, from laboratory asymmetries to the six-per-ten-billion of the sky (Part VIII). The mirrors are bulk symmetries; the broken mirrors are descent facts; the matter excess is the boundary's permanent record of the breakage. The next Part asks the first question in the natural order, and the one on which all the others rest: what happens when the dial and the clock are asked to agree?

Part IV
The Origin of Antiparticles

The handshake of the circle and the clock; the clock's third face — imaginary time as the polar decomposition's shore; one shared J for the whole tower; the exceptions on the circle's still point; the bulk that cannot hide its conjugates; the descent that only relabels; and the boundary that reads the twins

39 Part IV in plain English: why everything has a twin

The twins are the first thing the two structures buy. The circle gives charged matter its phase; the clock gives the state space its i; and the two agree only if every charged field arrives with a partner of opposite charge. Antiparticles are not an extra postulate in this account. They are the consistency condition between two derivations that were carried out separately and could have disagreed.

The Part proves that in three theorems and then follows it. The clock's third face is imaginary time. There is one i and not one per system, which is what a composite system requires and what a 2021 experiment tested. Spin and statistics appear as the same structure's second child, at candidate grade and labeled as candidate. And the self-conjugate exceptions are the particles the circle cannot move, which is why a Majorana neutrino would be its own antiparticle for a reason one can see rather than memorize.

The negative results are recorded in this Part rather than in a footnote. What the descent does not do is stated in its own section, and the boundary's job in reading the twins is kept separate from the geometry's job in making them, because the two run together easily and the argument needs them apart.

40 The question, sharpened three ways

Part III closed with a question: what happens when the dial and the clock are asked to agree? This Part answers it, and the answer is the antiparticle. "Where do antiparticles come from?" is three questions wearing one coat, and the coat has hidden them from each other for ninety years. *(Q1) Why do antiparticles exist at all?* — what consistency of nature forces, for every charged particle, a twin of equal mass and opposite charge? *(Q2) Where in the architecture do they first exist?* — in the 6D bulk, or only after the descent to the Standard Model, or only in the quantized theory? *(Q3) Why, then, is the universe made of one twin and not the other?* The standard account answers Q1 at the structural level (Part X rehearses how, and how well), declines Q2 as meaningless, and outsources Q3 to speculative mechanisms. The GG-6 account answers all three, in order, and the answers are the sections of this Part: the stage is set in real numbers (§41); the twins are forced

by the agreement of two real geometric structures (§42); the agreement extends, with no new input, to one shared J for everything a boundary can build (§44), with the fields the circle cannot move as the lawful exceptions (§46); the twins exist in the bulk, before quantization and before any descent, both as pairing and as content (§47); the descent only relabels them (§48); the boundary reads them (§49); and the answer to Q3 is a theorem-guarded door and an oriented, CP-biased cascade, delivered quantitatively in Part VIII.

41 A world written in real numbers

Let us be completely clear about the stage before the first theorem walks onto it, because the stage is half the point. Part II introduced the real presentation as a dictionary — fields as real pairs, phases as real angles, conjugation as a reversed circle. Part III derived the doctrine behind the dictionary: the bulk contains no imaginary unit, only J, a real quarter-turn operator, and the symbol i is the boundary's shorthand name for J (§37.4). This Part now goes one step further than adopting a notation. It makes a pledge. *From here to the end of the Part, no argument will use the symbol i* — not in a definition, not in a proof, not in a displayed equation — except where the boundary's shorthand is itself the thing under discussion, and is announced as such. Everything on the stage is real. Fields are the real pairs (a, b) of Eq. (5), and the circle acts on them by rotation blocks $R(n\alpha)$. Coupling phases are rigid rotations. The dynamics is generated by a real operator on a real solution space. And the two candidates for "the imaginary unit of physics" are two real operators — a quarter-turn of the fiber and a quarter-period advance of the clock — whose credentials the next section examines one at a time, in public.

Why insist on the pledge, rather than merely permit it? Because of the shape of what this Part claims to prove. The claim is that the particle–antiparticle pairing is forced *one level below quantization* — below the complex Hilbert space, below the creation and annihilation operators, below every structure that already carries an i inside it. A derivation conducted in complex notation could not establish that claim even if every one of its steps were sound, for the same reason a witness cannot testify to events before his arrival: complex notation enters the theory at quantization, carrying the pairing's fingerprints already upon it. In the standard development the Feynman–Stückelberg assignment is imposed *after* quantization, as the condition that the Hamiltonian come out positive — a correct selection, made instrumentally, on the output. To ask whether the assignment was forced *before* the machinery existed, one must stand where the machinery does not yet exist: on the real solution space of the classical bulk field, where the only structures in sight are the symplectic form, the circle action, and the causal clock. That is where the three theorems of the next section stand. If they succeed, the pairing will have been derived from real geometry alone, and the complex Hilbert space — with its one i — will sit downstream of the result rather than upstream of it.

Two working rules, then, both already earned upstream and restated here as the Part's grammar. *Rule one: the circle owns charge.* A charged field is a pair that turns; its charge is how many times it turns per turn of the fiber; conjugation is the fiber run backward. *Rule two: the clock owns direction.* Causal time is oriented (AX-1), energy is bounded below (the positivity clause of AX-3),

and together — the next section proves — these select a unique way of turning "real oscillation" into "rotation with a direction." Each rule alone will turn out to supply half an imaginary unit. The whole Part is the story of what happens where the two halves meet. Roughly speaking, we are about to watch two gears, machined in different shops to different drawings, get lowered onto one shaft — and discover that they mesh in exactly one relative orientation, and that the orientation has borne a famous name since 1949.

One more word, on scope, because the register requires it. The solution spaces on which the theorems are proved are those of free and quasi-free bulk fields; interacting matter enters through the asymptotic frame, conditionally, as §52 prices. Nothing in the pledge is weakened by this: the level claim (below quantization) and the scope claim (quasi-free, interacting conditional) are independent statements, and both are attached wherever they bind.

42 The handshake: three theorems

The derivation lives at a level most treatments never visit: below quantization, in the real geometry of the bulk's solution spaces. Three theorems carry it. Each is stated and proved here in full, assuming nothing beyond Parts II and III; readers who want the same results developed at monograph length, with their interacting extensions, will find them in the companion treatments of quantum mechanics and of the origin of complex numbers (Arisaka, 2026, A8-QM; Arisaka, 2026, P4-Real).

Theorem 42.1 (**T-P5-A**: the circle — the gauge i)**.** *On each charge-n sector of a real bulk matter field, the charge-normalized circle generator $J_Q = \partial_\theta/Q$ is a complex structure: it squares to $-\mathbf{1}$ and identifies the real weight-n harmonic pair with the standard complex charged field, with complex conjugation realized as orientation reversal of the circle, $\theta \mapsto -\theta$. It is the unique such structure commuting with the circle action* — up to sign. *On the neutral sector the same generator acts as zero: the circle can only complexify what it moves.*

Proof. On the weight-n pair (5) the generator acts as $\partial_\theta = n\,\varepsilon$ with ε the 90° rotation; normalizing by the signed charge $Q = n$ gives $J_Q = \varepsilon$, and $\varepsilon^2 = -\mathbf{1}$. Any complex structure commuting with all the rotations $R(n\alpha)$ must be a polynomial in ε on each sector, hence $\pm\varepsilon$: uniqueness up to sign. On weight zero, $\partial_\theta = 0$ and no structure is supplied. ∎

Physics intuition, at length. Everything familiar about charge is repackaged in this small theorem, and it is worth walking through slowly. Charge quantization is the compactness of the circle: winding numbers are integers. The Aharonov–Bohm phase is the circle's holonomy. The "complex phase" of a charged wavefunction is a real angle of position on a real fiber; multiplying by i is a quarter-turn. And — the clause that carries this Part — *complex conjugation is going around the circle the other way.* A "negatively charged" mode is not a new substance; it is the same real pair winding oppositely. But the theorem also confesses the circle's two blindnesses, and both are load-bearing. The circle cannot complexify the neutral sector: a neutral field needs an i exactly as much as a charged one (its wave equation, its interference, its quantum amplitudes), and the circle has none to give — so a second source must exist. And the circle does not know its own orientation: nothing in the fiber

geometry distinguishes ε from $-\varepsilon$, winding-up from winding-down — the circle knows the plane of rotation but not the direction. Two blindnesses, one cure, and the cure is the clock.

Theorem 42.2 (**T-P5-B**: the clock — the state-space i)**.** *On the real solution space of any free or quasi-free bulk field, the polar phase of the time-translation generator A,*

$$J_A \;=\; \pm\, A\,(-A^2)^{-1/2}, \tag{19}$$

is a complex structure — concretely, the Hilbert transform in constitutional time — and it is the unique *positive-energy complex structure commuting with the dynamics on the globally static arena, with the sign fixed by the positivity clause of AX-3 (Ashtekar and Magnon, 1975; Kay, 1978). The constitutional pedigree is exact: AX-1 supplies the direction, the positivity clause of AX-3 the selection, Theorem 0 the uniqueness. In the boundary's shorthand, its $(-i)$-eigenspace is the positive-frequency subspace: the frequency splitting is derived, not assumed.*

Proof. We walk the construction in four steps, at the level of rigor the quasi-free setting permits, and flag the one step whose functional-analytic care is carried by the cited theorems.

Step 1: the generator is skew. The real solution space V of a free bulk field carries the symplectic form $\omega(u, v)$ built from the field and its conjugate momentum on a Cauchy slice, and time translation preserves it: $\omega(e^{tA}u, e^{tA}v) = \omega(u, v)$ for all t. Differentiating at $t = 0$ gives $\omega(Au, v) + \omega(u, Av) = 0$: the generator A is skew with respect to ω. Skewness is what a rotation generator looks like before anyone has said "rotation": it forbids A from stretching the planes it acts in.

Step 2: the polar phase exists and squares to $-\mathbf{1}$. On the globally static arena (Theorem 0) the physical modes oscillate — A has no kernel on them — so $-A^2$ is a positive operator and its inverse square root exists on the completion; the domains and closures here are precisely the care the cited authors supply (Ashtekar and Magnon, 1975; Kay, 1978). Then, since A commutes with every function of A^2,

$$J_A^2 \;=\; A\,(-A^2)^{-1/2}\,A\,(-A^2)^{-1/2} \;=\; A^2\,(-A^2)^{-1} \;=\; -\mathbf{1}. \tag{20}$$

The polar phase is the generator with its speed divided out: what remains is pure turning.

Step 3: the sign. Both $+J_A$ and $-J_A$ are complex structures commuting with the dynamics; they are distinguished by the energy form $\mu(u, v) = \omega(J_A u, v)$, which is positive definite for exactly one choice of the sign. The positivity clause of AX-3 selects that choice. This is the precise point at which "energy is bounded below" enters the geometry — not as a condition on a quantized Hamiltonian, but as the orientation of a classical quadratic form.

Step 4: uniqueness, and the frequency splitting, in real terms. Ashtekar–Magnon and Kay prove that on a stationary region there is exactly one complex structure commuting with the dynamics that renders the energy positive; Theorem 0's global staticity makes the region the whole arena and the selection canonical. The frequency splitting is then a statement about oriented planes, with no complex number required: every mode of frequency $E > 0$ spans a two-dimensional real plane on which A acts as E times a quarter-turn, and J_A acts as that same quarter-turn with the speed removed — one fixed rotation sense per plane, the same for every E. "Positive frequency" names the orientation J_A induces on each plane, and it is derived because J_A is. (In the boundary's

complex shorthand, the same statement reads: the $(-i)$-eigenspace of J_A is the positive-frequency subspace.) Concretely, in the time domain J_A is the Hilbert transform,

$$(J_A u)(t) \;=\; \frac{1}{\pi}\,\mathrm{p.v.}\!\int \frac{u(s)}{t-s}\,ds, \tag{21}$$

the real integral kernel that advances every oscillation by a quarter period — the analytic-signal operator of the engineer, promoted to constitutional office. ■

Physics intuition, at length. The clock's i answers the question the circle could not: where does the i of $i\hbar\,\partial_t$ come from — the one a strictly neutral field needs as much as a charged one? Answer: from time itself, run through causality and positivity. "Multiply by i" means "advance the phase by a quarter period," and *that* is a real operation — the Hilbert transform, an integral kernel any engineer has met as the analytic-signal construction. What elevates it from convenience to structure is the uniqueness: on the constitutional arena there is exactly one way to split real oscillations into "positive frequency" and "negative frequency" consistent with causal order and positive energy, and the clock's polar phase is it. Note what each source knows that the other does not. The clock knows the *direction* — causality orients it, positivity picks its sign — but it belongs to every field equally and knows nothing of charge. The circle knows *charge* — it is charge — but not direction. Two half-blind sources of the same i; the theory works only if they agree wherever they overlap. That agreement has a name.

Theorem 42.3 (**T-P5-C**: the handshake — antiparticles as the consistency condition)**.** *On the on-shell charge-n sectors the two structures agree, $J_A = J_Q$, precisely under the Feynman–Stückelberg pairing — charge $+n$ with positive frequency* and *charge $-n$ with positive frequency — and anti-agree on the opposite pairing. The pairing is therefore not a convention but the unique orientation making two independently forced real structures act as the same complex structure on shell. It fixes the sign left open in T-P5-A, and yields one global J:* the existence of antiparticles is the consistency condition between the sixth dimension and causal time.

Proof. The proof is a computation every reader should perform once. An on-shell mode of charge n and energy $E > 0$ is the real oscillation with total dial angle $n\theta - Et$:

$$u_+(\theta, t) \;=\; \cos(n\theta - Et). \tag{22}$$

Apply the two structures. The circle turns the fiber: $J_Q\colon \cos(n\theta - Et) \mapsto -\sin(n\theta - Et)$. The clock advances the phase a quarter period: $J_A\colon \cos(n\theta - Et) \mapsto -\sin(n\theta - Et)$. They agree. Now take the *wrong* pairing — charge n with negative frequency, the mode $\cos(n\theta + Et)$: the circle still gives $-\sin(n\theta + Et)$, but the clock, acting on a negative-frequency oscillation, gives $+\sin(n\theta + Et)$. They anti-agree: on this mode the two forced structures differ by a sign, and no global J exists. The unique repair is the relabeling: read the negative-frequency charge-n modes as *positive*-frequency charge-$(-n)$ modes — under which $J_Q = \partial_\theta/Q$ flips its normalization with Q and agreement is restored on every physical mode. That relabeling is the Feynman–Stückelberg assignment; the relabeled modes are the antiparticles; and the assignment simultaneously fixes the circle's sign ambiguity, since only one orientation of ε matches the clock on the physical pairing. ■

Physics intuition, at length — the gear alignment. The circle knows the plane of rotation but not the direction; the clock knows the direction. Wherever charge lives, the two must mesh — like two gears that can engage in exactly one relative orientation. The meshing condition *is* the particle–antiparticle pairing: positive charge running forward in phase, negative charge running forward in phase, and nothing running backward. Antiparticles are not an extra ingredient of relativistic quantum theory; they are the gear alignment between its two real sources. Three further remarks complete the picture. *First, the level.* In standard field theory the same assignment is imposed *after* quantization, so that the Hamiltonian comes out positive — a condition on the output. The handshake operates one level down, before quantization, as the compatibility of two classical-geometric structures; in the parent program's words, *a convention with a derivation behind it is no longer a convention. Second, the reach.* The extension is canonical: composite systems and the Fock construction extend the shared J with no new complex input, so the boundary description carries one i, globally shared — exactly the configuration the network Bell experiments demand (Renou et al., 2021); and for fermions, charge conjugation factorizes as circle-orientation reversal composed with a fixed real spinor map, so the Dirac field's celebrated complexity is the J-packaging of real data — charge by the circle, frequency by the clock, spin by real matrices. No Dirac sea is invoked at any point, here or anywhere in the cohort. *Third, the unification.* The literature that asks "why is quantum mechanics complex?" and the literature that asks "why do antiparticles exist?" are disjoint literatures. On this account they are one question with one answer: the reason quantum mechanics is complex and the reason antiparticles exist are the same fact, read in two directions. That identification — not the pairing itself, which is textbook — is the novelty, and §52 prices it honestly.

42.1 The handshake executed: one charged mode, in rotation blocks

Theorems deserve rehearsals. Let us now run the entire handshake, end to end, on a single charged mode, with every object a real number or a real 2×2 matrix — the reader is invited to follow with a pencil, because the whole computation fits on one sheet and there is no better way to own it. Take winding $n = +1$ and energy $E > 0$, and call the mode an electron by a harmless abuse (the electron's conventional winding is -1; reversing every winding below changes nothing).

The stage. The candidate mode plane is the real span of

$$u_1 = \cos(\theta - Et), \qquad u_2 = \sin(\theta - Et), \tag{23}$$

and every operator below is a 2×2 real matrix in the basis (u_1, u_2).

The circle's quarter-turn. Differentiating along the fiber, $\partial_\theta u_1 = -u_2$ and $\partial_\theta u_2 = +u_1$; normalizing by the signed charge $Q = +1$,

$$J_Q \;=\; \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \qquad J_Q^2 = -\mathbf{1}. \tag{24}$$

The clock's quarter-turn. As functions of time the two basis modes oscillate with phase $Et - \theta$, and on every positive-frequency oscillation the clock's operator acts by the quarter-period rule

$\cos \mapsto \sin$, $\sin \mapsto -\cos$ (Eq. (21)). Applied to $u_1 = \cos(Et-\theta)$ and $u_2 = -\sin(Et-\theta)$ this gives $J_A u_1 = \sin(Et-\theta) = -u_2$ and $J_A u_2 = +\cos(Et-\theta) = u_1$. In the same basis,

$$J_A \;=\; \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \tag{25}$$

Compare (24) and (25): the two structures are not merely compatible — they are *equal, entry by entry.* On this pairing of winding with frequency, the fiber's geometry and the clock's causality have manufactured the same quarter-turn twice.

The wrong pairing. Now run the same computation on the opposite matching — winding $+1$ against the mode whose clock phase runs the other way:

$$v_1 = \cos(\theta + Et), \qquad v_2 = \sin(\theta + Et). \tag{26}$$

The circle does not care — $\partial_\theta v_1 = -v_2$, $\partial_\theta v_2 = +v_1$, so J_Q is the matrix of (24) again. But the clock reads the phase as $Et+\theta$ and advances it: $J_A v_1 = \sin(Et+\theta) = +v_2$ and $J_A v_2 = -v_1$. In the basis (v_1, v_2),

$$J_Q = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \qquad J_A = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = -J_Q. \tag{27}$$

The two forced structures now differ by a sign on every vector of the plane. No global J exists; the theory, as paired, is inconsistent with its own geometry.

The repair, watched closely. Here is the beautiful step. The clash plane is not new territory — because cosine is even,

$$\cos(\theta + Et) \;=\; \cos\big((-1)\theta - Et\big), \qquad \sin(\theta + Et) \;=\; -\sin\big((-1)\theta - Et\big)\,: \tag{28}$$

the same two-dimensional plane, re-read as the *positive*-frequency plane of winding -1. Run the operators once more in the re-read basis $w_1 = \cos(-\theta - Et)$, $w_2 = \sin(-\theta - Et)$. The circle gives $\partial_\theta w_1 = +w_2$, and — this is where the signed charge earns its place in the definition $J_Q = \partial_\theta / Q$ — the normalization is now $Q = -1$, so $J_Q w_1 = -w_2$. The clock reads phase $Et+\theta$ as before and gives $J_A w_1 = \sin(Et+\theta) = -w_2$. They agree again, entry by entry. The relabeling that repairs the clash is exactly the Feynman–Stückelberg assignment, and the repaired object is the antiparticle: same plane, opposite winding, clock running forward.

The packaging, last of all. Only now, with the real computation complete, let the boundary introduce its shorthand: write $\psi = a + ib$ for the pair (a, b), so that the shared quarter-turn becomes multiplication by i. The kept plane of (23) packages as $e^{\,i(\theta - Et)} = e^{\,i\theta} e^{-iEt}$ — charge $+1$, positive frequency: the particle. The re-read plane packages as $e^{\,i(-\theta - Et)} = e^{-i\theta} e^{-iEt}$ — charge -1, positive frequency: the antiparticle. Both amplitudes rotate forward in time; their fiber windings are opposite; and the i in both is one and the same symbol because the J it names is one and the same matrix. At no step before this paragraph did the symbol i occur — and when it arrived, it arrived as a name. That is the whole doctrine of this paper in one computation: one J upstairs is why there is one i downstairs.

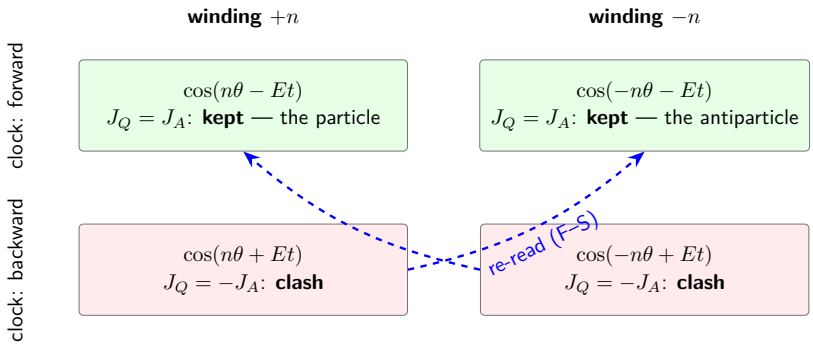


Figure 7: The four candidate pairings of winding and clock sense, and the handshake's verdict. On the two kept cells the circle's quarter-turn and the clock's quarter-period advance are the same real matrix, Eqs. (24)–(25); on the clash cells they differ by a sign and no shared J exists, Eq. (27). The dashed arrows are the Feynman–Stückelberg re-reading of Eq. (28): because cosine is even, each clash plane *is* a kept plane read with the opposite winding. The two kept cells together carry one complex world with one i.

43 The clock's third face: imaginary time

Every physicist carries three devices that involve the letter i and the letter t together, and has been taught to regard them as unrelated conveniences. Minkowski's *it* (1908): write the time coordinate as imaginary and the Lorentz metric looks Euclidean, boosts look like rotations "by an imaginary angle" (Minkowski, 1908). Schrödinger's $i\,d/dt$ (1926): the quantum evolution law places the imaginary unit against the time derivative. And Wick's rotation (mid-century, named for G. C. Wick): continue $t \to -i\tau$, turn oscillation into damping, quantum theory into statistical mechanics, and compute — the daily bread of lattice field theory. Three tricks, three eras, no stated connection. This section proves that with T-P5-B on the table the three are *one datum*: the polar decomposition of the constitutional time generator. The theorem is lettered into the clock's family — T-P5-B1 — because it is the clock's own structure, unpacked; nothing in it touches the fiber, which is precisely one of its lessons.

One word on register before the mathematics, because this Part made a pledge (§41) and this section is where the pledge earns its keep. To speak of "holomorphy" we shall complexify — announced now, as the boundary's shorthand, used knowingly. But the reader should watch for the striking fact that the theorem's second clause has a *fully real* formulation: holomorphy in imaginary time is the statement that a profile and its quarter-turned partner form a harmonic-conjugate pair — the Cauchy–Riemann equations, which are real equations about real functions, and which turn out to be nothing but the clock's quarter-turn written as a field equation. Even imaginary time, it will emerge, is real underneath.

The setting, recalled, and the polar lemma. Let (V, ω, A) be as in T-P5-B: the real symplectic solution space of a free or quasi-free bulk field on the globally static arena, A the constitutional time-translation generator, skew with respect to ω, with no kernel on the physical modes. Define the clock's *modulus*

$$|A| \;:=\; (-A^2)^{1/2}, \tag{29}$$

positive and dynamics-commuting by the spectral calculus of T-P5-B, Step 2. Then A factorizes:

$$A \;=\; J_0\,|A| \;=\; |A|\,J_0, \qquad J_0 := A\,|A|^{-1}, \qquad J_0^2 = -\mathbf{1}, \tag{30}$$

and the pair $(J_0, |A|)$ is unique with these properties: a skew generator splits, exactly once, into a *rotor* (a complex structure — pure turning, no speed) and a *speed* (a positive operator — pure magnitude, no turning). T-P5-B's clock structure is this rotor with its orientation fixed, $J_A = \pm J_0$, the sign selected by the positivity clause of AX-3. *Physics intuition — the motor.* Every motor is a rotor times a speed, and (30) says the constitutional clock is a motor: A turns each mode plane (J_0) at a rate ($|A|$). Real time evolution e^{tA} exponentiates the whole motor — rotation at frequency E on each plane. The theorem below says: imaginary time is what one gets by exponentiating *the speed alone*, $e^{-\sigma|A|}$ — switching off the rotor and letting the magnitude act as pure damping — and that this switch, the modulus of the polar decomposition, is simultaneously Minkowski's *it*, Wick's rotation, and the analytic face of Schrödinger's i.

Theorem 43.1 (**T-P5-B1**: the Wick quartet — one analytic fact)**.** *On (V, ω, A) as above, the following four data are in canonical bijection — each determines the others uniquely, orientations included:*

(1) The clock. *A complex structure J commuting with the dynamics e^{tA} whose energy form $\mu(u, v) = \omega(Ju, v)$ is positive definite.*

(2) The harmonic-conjugate (Hardy) splitting. *An assignment, to each solution u, of a partner v such that the pair extends from the time axis to a bounded harmonic-conjugate pair (U, V) on a half-plane $\{(t, \sigma) : \sigma > 0\}$ — equivalently, in the announced shorthand, a conjugate pair of dynamics-invariant subspaces $V_{\mathbb{C}} = H^+ \oplus H^-$ whose profiles extend holomorphically and boundedly to the two half-planes of complexified time.*

(3) The Wick rotation. *A strongly continuous contraction semigroup $S(\sigma) = e^{-\sigma|A|}$, $\sigma \geq 0$, arising as the analytic continuation of the evolution to imaginary time, with the energy form's positivity holding on the imaginary-time section (reflection positivity) (Osterwalder and Schrader, 1973, 1975).*

(4) The Minkowski section. *A bounded holomorphic extension of the time-translation representation to the complexified translation semigroup $\{t + i\sigma : \sigma \geq 0\}$ — the time-direction tube on which "rotation by an imaginary angle" is a lawful operation rather than a notation.*

Moreover the orientations correspond: the sign of J ↔ which half-plane carries the bounded extension ↔ which direction of imaginary time damps rather than explodes ↔ the orientation of the tube — and all four are fixed at once by one constitutional choice, AX-1's causal orientation composed with the positivity clause of AX-3. Beneath all four lies a single analytic fact: the spectrum of the generator is one-sided relative to the causal orientation. *Clauses (1)–(4) are its four notations.*

Proof. Seven steps, none skipped; every functional-analytic closure is carried by the cited literature, and every computation is displayed on the mode planes where the quasi-free setting lives.

Step 1 (mode reduction). By T-P5-B, Steps 1–2, V decomposes into two-dimensional A-invariant oriented planes; on the plane of frequency $E > 0$ with basis $e_1 = \cos(Et)$, $e_2 = \sin(Et)$, the generator acts as E times a quarter-turn, the modulus as $|A| = E\,\mathbf{1}$, and the rotor J_0 as the quarter-turn

itself. All four clauses are statements about dynamics-commuting structures, so all four may be verified plane by plane and assembled by the spectral calculus.

Step 2 ((1) ⇒ (2): the damping construction, and the Cauchy–Riemann pair). Given the clock, define for each solution u and each $\sigma \geq 0$ the damped profile

$$U(t,\sigma) \;:=\; \big(e^{-\sigma|A|}u\big)(t), \qquad V(t,\sigma) \;:=\; \big(e^{-\sigma|A|}J_A u\big)(t)\,: \tag{31}$$

the solution and its quarter-turned partner, both run through the pure-speed semigroup. On a mode, with $u = a\cos(Et) + b\sin(Et)$ and the clock acting by the quarter-period rule of T-P5-B ($\cos \mapsto \sin$, $\sin \mapsto -\cos$),

$$U = e^{-\sigma E}\,[\,a\cos Et + b\sin Et\,], \qquad V = e^{-\sigma E}\,[\,a\sin Et - b\cos Et\,]. \tag{32}$$

Three properties, each a one-line check on (32). *Boundedness:* $|U|, |V| \leq (|a| + |b|)\, e^{-\sigma E}$, bounded on $\sigma > 0$ precisely because $E > 0$. *Harmonicity:* $(\partial_t^2 + \partial_\sigma^2)\, U = (-E^2 + E^2)\, U = 0$, and likewise for V. *Conjugacy:* differentiating (32),

$$\partial_\sigma U = -\,\partial_t V, \qquad \partial_\sigma V = +\,\partial_t U \tag{33}$$

— the Cauchy–Riemann equations. So (U, V) is a bounded harmonic-conjugate pair on the half-plane with boundary values $(u, J_A u)$: clause (2), in its real form. In the announced shorthand, $F := U + iV$ is holomorphic in $z = t + i\sigma$ on the upper half-plane — on the mode, $F = (a - ib)\, e^{iEz}$, with $|F| = |a - ib|\, e^{-E\sigma}$ — and the $H^\pm$ splitting is the eigenspace decomposition of J_A. Pause on (33), because it is the section's conceptual hinge: *the Cauchy–Riemann equations are the clock's quarter-turn written as a field equation.* Translating into the second coordinate is time translation composed with the quarter-turn — σ is not a place, not a hidden axis; it is the direction the rotor defines, opened into a half-plane by the damping the modulus supplies.

Step 3 ((2) ⇒ (1): the Paley–Wiener converse). Conversely, suppose the bounded conjugate extension exists on the upper half-plane. Expand the boundary profile in the mode planes; a component of frequency $-E < 0$ would extend as e^{-iEz}, of modulus $e^{+E\sigma}$ — unbounded. Bounded holomorphic extension to a half-plane therefore forces *one-sided* frequency content (this is the Paley–Wiener theorem, in its simplest clothing), and the splitting $H^\pm$ is recovered; J is then multiplication by $\mp i$ on the two summands — equivalently, on the real space, the quarter-turn whose partner assignment $u \mapsto v$ the extension realized. The half-plane choice recovers the sign of J: extension upward pairs with one orientation of the quarter-turn, downward with the other.

Step 4 ((1) ⇔ (3): the Euclidean semigroup, and where positivity re-enters). Given the clock, $S(\sigma) := e^{-\sigma|A|}$ is a strongly continuous semigroup by the spectral calculus, and a *contraction* — $\|S(\sigma)\| \leq 1$ — precisely because $|A| \geq 0$: the one-sidedness of the spectrum is what damps rather than explodes. It is the analytic continuation of the evolution in the exact sense of Step 2: the matrix elements $\mu(u, e^{tA}v)$, which on a mode are trigonometric in t, extend holomorphically in t to the half-plane, and their restriction to the imaginary axis $z = i\sigma$ is the Euclidean two-point kernel $\mu(u, S(\sigma)v)$, symmetric in its arguments. Reflection positivity is the statement that this kernel is positive-definite with respect to reflection in σ — on the modes, that Gram matrices of

decaying exponentials $e^{-(\sigma_j+\sigma_k)E}$ are positive semi-definite, which they are, being Gram matrices of the vectors $e^{-\sigma_j|A|}v$ in the μ-inner product — *and the μ whose positivity this is, is AX-3's*: the same clause that fixed the clock's sign now certifies the Euclidean section. Conversely, from a reflection-positive contraction semigroup one reconstructs the Hilbert space, the positive generator $|A|$, and the unitary evolution — this is the Osterwalder–Schrader reconstruction (Osterwalder and Schrader, 1973, 1975) — and the polar recombination of $|A|$ with the reconstructed A returns J, with its sign fixed by which reflection direction was positive. *Physics intuition — why Wick rotation works.* Every practitioner has rotated a contour or run a Euclidean lattice, trusting that the answers continue back. The trust has a precise source, and it is not cleverness of technique: it is clause (3)'s equivalence with clause (1). The continuation exists because the spectrum is one-sided; the spectrum is one-sided because of the positivity clause; so *the license for every Wick rotation ever performed is the same axiom clause that selects the Schrödinger i.* A theory with energy of both signs would have no consistent Euclidean section — some mode would explode in every direction of imaginary time — and no lattice simulation of it could converge. The daily bread is baked from AX-3.

Step 5 ((1) ⇔ (4): the holomorphic tube). Clause (4) is clause (2) read group-theoretically. On H^+, define $T(z) :=$ translation by the complexified time $z = t + i\sigma$; on a mode, $T(z) = e^{iEz}$, of modulus $e^{-E\sigma}$: a family holomorphic in z, unitary on the real axis ($\sigma = 0$), contractive on the tube ($\sigma > 0$), and a semigroup in z. Its existence as a *bounded* holomorphic extension is, again by Paley–Wiener, equivalent to the one-sidedness of the spectrum, hence to clause (1). This is the honest content of Minkowski's device: writing *it* is lawful exactly as the coordinate on this tube — the domain where the operations of rotation and damping commute into one holomorphic family — and unlawful as a statement that the arena possesses an imaginary axis. The tube is attached to the time direction by the dynamics; it is nowhere in the metric.

Step 6 (the orientation bijection). Track the one binary choice through the four clauses. The clock's sign ($J = +J_0$ versus $-J_0$) selects which eigenspace is called H^+ (Step 2); H^+ selects the half-plane of bounded extension (Step 2's damping computation); the half-plane selects the direction of imaginary time in which $S(\sigma)$ contracts rather than explodes (Step 4); and that direction orients the tube (Step 5). Each arrow is invertible (Steps 3–5), so the four orientation data are one bit — and the bit is not free: AX-1 orients real time, and the positivity clause of AX-3 selects the sign of J (T-P5-B, Step 3), fixing the whole quartet at once. There is nothing left to choose anywhere in clauses (1)–(4).

Step 7 (uniqueness, and the single fact). The bijections compose into a cycle: $J \mapsto (H^+, H^-) \mapsto S(\sigma) \mapsto |A| \mapsto J$ (polar recombination), and each map is uniquely determined by its input (Steps 2–5), so each datum determines the other three with no residual freedom. Finally, each clause was shown equivalent to the same statement: the spectrum of A, read against the causal orientation, lies on one side. One-sidedness *is* the analytic fact; the quartet is its notation. ■

Corollary 43.2 (**B1-a**: the boundary's three shorthands)**.** *(a) "$i\,d/dt$" is clause (1): the Schrödinger i is the clock's rotor J_A, the boundary's name for a real quarter-turn. (b) "$t \to it$" is clauses (2) and (4): Minkowski's imaginary time is the coordinate on the continuation half-plane that energy positivity opens — the name of an analytic direction, not of an axis of the arena. (c) "Wick rotation"*

is clause (3): passing from the motor to its speed, e^{tA} to $e^{-\sigma|A|}$ — available exactly where, and exactly because, clause (1)'s clock exists.

Corollary 43.3 (**B1-b**: custody — imaginary time belongs to the clock)**.** *The quartet is constructed from (V, ω, A) alone: no fiber datum enters. Hence imaginary time exists on every sector, neutral included, sourced by AX-1 and AX-3 — it is the* clock's *third face, and the sixth dimension neither supplies it nor could: the fiber's generator has two-sided integer spectrum (windings $\pm n$), so its "modulus" damps no direction, and the compact circle admits no half-plane. Likewise there is no "imaginary space": spatial translations are skew generators too, but their spectra are two-sided (left- and right-movers are equally lawful), no positivity clause orients them, and their polar rotors are pure convention. Among all the arena's directions, time alone carries a one-sided spectrum — which is why time alone has a shore. The bulk, meanwhile, remains real throughout: "it" is the boundary's shorthand for the half-plane exactly as "i" is its shorthand for J (§37.4), and the one shared J of §44 now carries one shared shore with it.*

Two conditional remarks, graded. First — the Lorentz completion and the germ of CPT. Clause (4) is proved here in the time direction. Its covariant completion — extension to the complexified Lorentz group, where boosts and rotations genuinely merge and "rotation by an imaginary angle" becomes group theory — holds at the interacting, axiomatic grade in Wightman theory (Streater and Wightman, 1964), and it is precisely the continuation through which Jost proved the CPT theorem. The resonance deserves a sentence: *the same half-plane that licenses Wick's rotation is the germ of the continuation that makes CPT provable* — the quartet of this section and the total reversal of Part V (§58) are two harvests of one analytic structure, and the open modular route named there (Bisognano–Wichmann) is the natural bridge for both. Grade: inherited at axiomatic scope; conditional in this framework, alongside T-P5-2's interacting extension. *Second — the thermal shore.* Periodicity in imaginary time is the boundary's reading of temperature (the KMS condition); the black-hole companion's derivation of Hawking thermality (Arisaka, 2026, C3-BH) is its worked instance, with the periodicity supplied by the projection's reading of the horizon. Grade: companion result, conditional as there stated.

Status, and what is inherited. Concessions first, in full. Every clause of T-P5-B1 is classical in isolation: the positive-energy complex structure is Ashtekar–Magnon and Kay's (Ashtekar and Magnon, 1975; Kay, 1978); the half-plane characterization of one-sided spectra is Paley and Wiener's; the Euclidean reconstruction is Osterwalder and Schrader's (Osterwalder and Schrader, 1973, 1975); the tube analyticity is the Wightman school's (Streater and Wightman, 1964). What this section claims is the *packaging with provenance*: the four data assembled into a canonical bijection with the orientations tracked and anchored — one bit, fixed by AX-1 composed with AX-3's positivity clause — so that three devices physics folklore treats as separate tricks are exhibited as one datum, the polar decomposition of the constitutional clock; and the custody corollary, which extends the one-J-one-i doctrine to imaginary time and explains, from spectra, why time has a shore and space and the fiber do not. Grade: derived (quasi-free), matching T-P5-B and T-P5-2's register; the Lorentz completion conditional as flagged. The claim survives a hostile reading at exactly this calibration: nothing here is new analysis; what is new is knowing, clause by clause, whose structure it always was.

Physics intuition, at length — what, then, is time? Let us stand back, because this small

theorem quietly answers a large question, and the answer is geometric in exactly the manner this program keeps finding. Ask what the constitution gives to the direction we call time, and read the gifts off the axioms one at a time. *AX-1 — locality and causality — gives time its order.* The light cone at every event sorts the world into before, after, and elsewhere; influence runs one way along it. This is the endowment Minkowski geometrized in 1908, the first non-spatial structure ever drawn as geometry — time as an ordered direction, not a flowing substance. *AX-2 — geometry–gauge equivalence — gives time its repetition.* Through Theorem 0, AX-1 and AX-2 together force the globally static arena: the constitutional clock is a Killing flow, a direction along which the geometry repeats itself exactly — and only because time is such a symmetry can frequency, energy, and the mode planes of this Part exist at all. A time that did not repeat could not tick. *AX-3 — the operational dictionary — gives time its openness, twice.* Once irreversibly: the OGGEP projection is one-way, records accumulate, and the arrow of time is the dictionary's non-invertibility over a bulk that is itself exactly T-symmetric (§38). And once analytically — this section's addition: the positivity clause makes the clock's spectrum one-sided, and a one-sided spectrum opens a *shore* — the half-plane of lawful continuation, the sheltered side where oscillation relaxes into damping, where the quantum theory keeps its statistical shadow, and where, at the covariant completion, the CPT theorem lives. Order, from the cone; repetition, from the equivalence; arrow and shore, from the dictionary. That is what time *is*, in this geometry: not a container and not a river, but the unique direction of the arena that carries all four endowments at once.

And the uniqueness is the profound part, so let it be said sharply. Space has translations, but their spectra are two-sided — a left-mover is as lawful as a right-mover — so space has no orientation the dynamics must respect, no polar rotor worth naming, no shore: there is no imaginary x because nothing damps there. The fiber has rotation, but its windings are two-sided integers on a compact circle — it knows charge, not direction (§42) — so the fiber has no shore either: there is no imaginary θ. Time alone is the direction along which the world is *stable* — bounded below in energy, by the dictionary's own consistency — and stability is the whole secret. One-sidedness of the spectrum is the mathematical name of "nothing falls forever"; the polar decomposition turns that stability into a rotor and a speed; the rotor is the i of every Schrödinger equation, the speed's semigroup is every Euclidean computation, and the half-plane between them is the only thing Minkowski's *it* ever lawfully named. The three mirrors of this paper broke on the descent's orientation; the three faces of the clock stand on time's. Indeed, the custody line of this Part extends by one clause and then closes: the geometry owns the cone, the dial, and the shore; the dictionary owns the words *it*, i, and Wick. After all, the deepest habit this program unlearns is the mistaking of names for places — and time's imaginary direction, like the sixth dimension itself, turns out to be not a place one could go but a structure the world cannot do without: the shore on which a stable universe writes its quantum mechanics on one side and reads its thermodynamics on the other.

44 One i for the whole world

The handshake of the last section settled one mode at a time: on each charged sector, the circle's quarter-turn and the clock's agree under exactly one pairing. But a world is not one mode. A world

is composites — atoms built of charged parts, mesons built of conjugate pairs; it is many-particle states and the Fock tower above every field; it is fermions, whose spinor components entangle the story with spin; and it is, above all, *entangled* states, whose interference is the signature phenomenon of quantum mechanics. If each new floor of this tower demanded its own complex structure, the handshake would be a curiosity of the ground floor. The two theorems of this section show the opposite: the shared J climbs the whole tower with no new input, and spin contributes a real matrix, not a new rotation. The tower is complex because the ground floor is — and for no other reason.

Theorem 44.1 (**T-P5-C1**: one shared J — composites and Fock space)**.** *Let real solution-space sectors carry the shared complex structure J of T-P5-B/C. Then J extends to direct sums, to J-tensor products, and to the symmetric and antisymmetric Fock spaces over the one-particle space, and in each case the extension is the unique one restricting to J on the generating sectors: the constructions introduce no new complex structure. The boundary description of composite and many-particle systems therefore carries a single global complex structure — in its own shorthand, one i.*

Proof. Sums. On $V_1 \oplus V_2$ the block operator $J \oplus J$ squares to $-\mathbf{1}$, and any complex structure commuting with the two projections and restricting to J on each summand is $J \oplus J$: no freedom.

Products. On the real tensor product $V_1 \otimes_{\mathbb{R}} V_2$ there are two candidates, $J \otimes \mathbf{1}$ and $\mathbf{1} \otimes J$, and a choice between them would be a genuine new input. But the composite state space of two systems that share a phase plane is not the real tensor product; it is its quotient by exactly that difference — the J-tensor product, in which $Ju \otimes v$ and $u \otimes Jv$ are identified. Physically the identification is the additivity of phase: turning the joint amplitude a quarter period *is* turning either factor a quarter period, because the dial angles of subsystems add. On the quotient the two candidates are one operator, and it restricts correctly: again no freedom.

Fock. The m-particle spaces are the symmetrized or antisymmetrized m-fold J-tensor powers, each inheriting its unique J by the previous two steps, and the Fock sum inherits J summand by summand by the first step. At no floor of the tower was a choice available; the full statement, with the operator domains attended to, is established in the companion treatment of quantum mechanics (Arisaka, 2026, A8-QM). ■

Physics intuition — why entanglement needs the theorem. The reader may feel that extending J to composites is bookkeeping. Entanglement is why it is physics. Take two charged modes far apart and superpose "both excited" with "neither excited" — a two-particle amplitude interfering with the vacuum. Interference means the branches' phases turn *in the same plane*: there must be one quarter-turn that advances the joint amplitude, not one per subsystem with no relation between them. If each factor carried its own unrelated structure, the superposition would have no lawful plane to turn in, and the interference term — the entire observable content of entanglement — would be undefined. T-P5-C1 says the bulk supplies exactly the shared plane the phenomenon requires, for free, from the sector-level handshake. And the requirement has been put on the bench. The network Bell experiments (Renou et al., 2021) test precisely whether quantum mechanics can run on real amplitudes with *unshared* rotation structures distributed across a network, and the data exclude it: the boundary formalism demands its single, globally shared i. Note once more,

with the custody discipline of Part III, what the experiment does and does not see. It tests the boundary formalism, and the formalism passes only in the one-shared-i configuration; the bulk is what *explains* why that configuration, and no other, was ever on offer. One experiment, two hats: the instrument confirms the need; the geometry supplies the provenance.

Theorem 44.2 (**T-P5-C2**: fermionic conjugation, factorized)**.** *On the fermionic sectors of the bulk, charge conjugation factorizes as*

$$C \;=\; (\theta \mapsto -\theta) \circ B, \tag{34}$$

where the first factor is orientation reversal of the fiber, acting on weight sectors exactly as for scalars, and B is a fixed real intertwiner on the spinor indices, independent of the state and determined by the Clifford algebra. Consequently the Dirac field's complex structure is the J-packaging of real data — charge carried by the circle, frequency by the clock, spin by real matrices — and spin introduces no new complex input.

Proof. Conjugation must reverse every fiber weight — that is what carries a charged field to its conjugate — and on the spinor factor it must exchange the two Weyl modules of the split $\mathbf{8}_{\text{Dirac}} = \mathbf{4} \oplus \bar{\mathbf{4}}$ of Eq. (10). The exchange is implemented by the intertwiner B of the Clifford reality structure — the same matrix whose obstruction $B\bar{B} = -\mathbf{1}$ closed the Majorana option in Lemma 24.1 — and B is fixed by the algebra up to conventions, with no dependence on the state or the dynamics. The weight reversal is the scalar story of T-P5-A; composing the two gives (34). Since B is a real matrix, the composite is J-linear for the shared J — the content of "no new complex input" — and the full statement at Fock level is again the companion treatment's (Arisaka, 2026, A8-QM). ■

Physics intuition — the same matrix, both jobs. There is a small piece of poetry in this proof worth pausing over. The matrix B appears twice in this paper, in opposite roles. In Part II it was the obstruction: $B\bar{B} = -\mathbf{1}$ is the algebraic fact that *forbids* a $(1, 5)$ fermion from being its own conjugate — too weak, as it were, to close the loop and identify a spinor with its reflection. Here it is the implementation: the same matrix is exactly strong enough to *carry* each Weyl module onto the other. The map that cannot make a fermion self-conjugate is precisely the map that exchanges it with its twin. And with B in hand, the celebrated mystery of the Dirac field's complexity dissolves by inventory. Eight real components; a circle that turns the charged pairs (charge); a clock that advances every oscillation (frequency); one fixed real matrix (the spin structure); and one shared J wearing the boundary name i. The famous i of the Dirac equation — the one in $i\gamma^\mu\partial_\mu\psi = m\psi$ — is not a fifth ingredient. It is the same quarter-turn, written where the boundary's shorthand puts it.

45 The quartet's second child: spin–statistics, and the third job of B

Two theorems of this Part now stand side by side: T-P5-B1, which isolated the single analytic fact — the one-sided spectrum, the clock's quarter-turn — behind Minkowski's *it*, Wick's rotation,

and the Schrödinger i; and T-P5-2, which derived CPT from that fact at quasi-free grade. This section records that the quartet has a *second* child, and that this paper — the quartet's home — is where the kinship belongs on the page.

The axiomatic literature has known the kinship in its own language for sixty years. In the Wightman framework (Streater and Wightman, 1964), the same forward-tube analyticity that the spectrum condition grants is what proves *both* great structure theorems: CPT, read off at the Jost points (Jost, 1957), and spin–statistics (Pauli, 1940), where the exchange of two spacelike-separated insertions is implemented by an analytically continued 2π rotation contributing exactly the sign $(-1)^{2s}$. The modular refinement says it more sharply still: the Bisognano–Wichmann structure (Bisognano and Wichmann, 1976) yields the CPT conjugation and the spin–statistics connection from one wedge. What the literature lacks — and what this paper's Part IV supplies — is a geometric parent *for the analyticity itself*: here the one-sided spectrum is not an axiom but the operational face of the causal clock (AX-1 positivity, unique by Theorem 0). The kinship, restated in this paper's vocabulary:

Theorem 45.1 (**T-Stat-A**, restated: spin–statistics as the quartet's second child (*candidate*; home: Arisaka, 2026, A2-GG6, §20))**.** *For the real quasi-free textures of this Part — fields built on the circle ⊕ clock ⊕ space data of T-P5-A/B/C — the spin–statistics connection is forced by the same single analytic fact as CPT. The clock's one-sided spectrum supplies the forward-tube analyticity (T-P5-B1); the real orientation reversals supply the Jost-point geometry (as in the proof of T-P5-2); and the analytically continued 2π rotation that implements exchange contributes $(-1)^{2s}$, the sign of the bulk's two-valued frame-path register. Consequently CPT and Fermi–Dirac statistics are the two children of one geometric parent:* the clock's quarter-turn is why the mirrors multiply to the identity, and why matter excludes itself. *Grade: candidate, target derived (quasi-free), with residues* identical *to T-P5-2's — the interacting case on scattering hypotheses, and the modular route open.*

The statement is printed at candidate grade and stays out of this paper's claims ledger deliberately: its bulk-side premises — the frame-path memory of GDOS states (L-Spin-1), the genericity clause that populates the spinorial register (T-Spin-A), and the exchange-equals-rotation lemma for tokens of one attractor (L-Stat-1) — are installed, with their residues named, in the companion section of the geometry paper (Arisaka, 2026, A2-GG6, §20), and the QM-register composition — the discharge of the textbook symmetrization postulate as boundary inheritance, theorem T-A8.12 — in the quantum mechanics paper (Arisaka, 2026, A8-QM). What belongs irreducibly to *this* paper is the parent and the first child: the quartet, and CPT. The candidate falsifier F-Stat-1 (any confirmed violation of Fermi–Dirac statistics or the spin–statistics connection, at any magnitude) is registered in the companion section; the standing experimental record — the 4π periodicity of neutron interferometry, the $\beta^2/2 < 4.8 \times 10^{-29}$ exclusion bound — is collected there and in T-A8.12's anchors.

The third job of the matrix. The proof of T-P5-C2 paused over a small piece of poetry: the intertwiner B does two jobs, first as obstruction ($B\bar{B} = -\mathbf{1}$ forbids a $(1,5)$ fermion from being its own conjugate — Lemma 24.1), then as implementation (the same matrix carries each Weyl module onto the other in $C = (\theta \mapsto -\theta) \circ B$). The poetry has a third stanza. $B\bar{B} = -\mathbf{1}$ is precisely the statement that the Weyl module is *quaternionic* (pseudo-real); on a quaternionic module the

invariant bilinear form is antisymmetric — symplectic — and the symmetry of the invariant bilinear is what fixes the quantization sign of the sector: an antisymmetric invariant forces anticommutators, on pain of a vanishing or indefinite two-point structure (the Clifford bookkeeping is lemma L-Stat-2 of Arisaka, 2026, A2-GG6). The Kramers degeneracy of Part IV ($T^2 = -\mathbf{1}$ on half-integer states) is the boundary shadow of the same quaternionic structure. So the one matrix does three jobs: *it forbids the fermion its own mirror, it carries the fermion to its twin, and it makes the fermion's tokens exclude one another* — obstruction, conjugation, exclusion, all read off one reality structure that the $(1, 5)$ signature of the real bulk fixed before any field was written down. The signature fact that made the descent chiral is the signature fact that makes matter solid.

Why this section is short. Everything load-bearing in it lives elsewhere by design: the machinery in T-P5-B1 and T-P5-2 above, the bulk lemmas in the geometry paper, the boundary composition in the quantum mechanics paper. Its business here is custody: the quartet is this paper's theorem, and a reader of this paper should learn from this paper that the quartet has two children — one derived (CPT, T-P5-2), one at candidate grade with a named promotion path — and that both fall to the same falsifiers, because both are faces of the same one-sided clock. *The twins were forced by the handshake; the mirrors multiply to the identity by the quartet; and matter takes up room by the quartet's second child. One geometry; two theorems proved here; one candidate named here and owed.*

46 The self-conjugate exceptions: what the circle cannot move

Every theorem so far has concerned what the circle moves. It is time to ask about what it does not — because the exceptions are not loose ends; they are the theory probing its own rule. The photon has no antiparticle distinct from itself. Neither does the neutral pion, nor the metric's ripples. The textbook records this as a definition — "a neutral particle may be its own antiparticle" — a label attached by hand, species by species. Here it is a theorem with a mechanism, and the mechanism is the last clause of T-P5-A: *the circle can only complexify what it moves.* A weight-zero field does not rotate under the fiber; on it J_Q acts as zero, its complex structure comes from the clock alone, and fiber reversal — which is all that charge conjugation is — does not move it:

$$n = 0 : \qquad (\theta \mapsto -\theta)\, u \;=\; u. \tag{35}$$

Such a field is not *permitted* to be its own conjugate; it is *unable not to be.* And the handshake, which forced a twin for every charged mode, forces nothing here: with no winding to match against frequency, there is no gear to align and no twin to relabel. The existence of antiparticles and the self-conjugacy of neutral fields are the two values of one criterion — does the circle move you? — where the standard account carries them as separate conventions.

The inventory checks, with both hats on. The photon is the boundary field of the circle's own connection — in the fiber dictionary of Part III, the photon carries no dial; it is the dial's messenger — and its self-conjugacy comes with a signature the laboratory confirmed long ago: because the winding current it couples to reverses under fiber reversal, the field itself must reverse sign. The photon is its own antiparticle *with intrinsic C-parity* -1. The neutral pion, a bound pair of conjugate

windings, is C-even, and the bookkeeping shows in its decays: $\pi^0 \to 2\gamma$ dominates, with $(-1)^2 = +1$ checking, while $\pi^0 \to 3\gamma$ — allowed by every conservation law except this one — has never been seen. The metric field carries no winding at all, and its ripples are real for the plainest reason in the paper: they are geometry. In each case self-conjugacy is not an assignment; it is the absence of a dial to reverse.

Then there is the exception among the exceptions, and the paper turns on it. Among the *matter* fields — the fermions — exactly one sits at weight zero: the neutrino. For a fermion, self-conjugacy is not automatic even at weight zero, because the spinor structure has its own say — Part II's eight-hour clock permits a Majorana option in four boundary dimensions while forbidding it in the six-dimensional bulk — so the neutrino's situation is subtler and richer: it is the one matter field for which the question "are you your own antiparticle?" is even grammatical. The weight arithmetic of Part II (§25) already contains the seed: the symmetric square of a weight-n pair contains the winding-conserving Dirac pairing for every n, and a second invariant — the self-pairing — exactly at $n = 0$. Part VII sharpens the seed into the theorem this paper calls the dial-free door (T-P5-4): a Majorana self-pairing is lawful iff the weight vanishes; the neutrino is the unique such matter field; and the seesaw structure follows with no dial to turn. Part VIII then walks the matter of the universe through that door. The laboratory hat is on as well: Majorana nature plus the derived masses and phases give an effective neutrinoless-double-beta mass $m_{\beta\beta} \simeq 1.7$ meV (Arisaka, 2026, A9-SM) — below current sensitivity, within the ambitions of the next-generation program, and one of the dated falsifiers of Part XII.

Physics intuition — the still point. Picture the fiber as a carousel and every charged field as a rider on its platform. Conjugation spins the carousel backward: every rider sees the world reverse — except whoever stands on the axis, for whom backward and forward are the same motion. The axis is not a defect of the carousel; it is a consequence of there being a carousel at all. A rotation must have a still point, and whatever lives there is its own reflection. The remarkable fact is not the existence of the still point but what nature chose to put on it: exactly one matter field — the lightest, the most elusive, the only one able to pair with itself — and, as Part VIII argues quantitatively, the field through whose self-pairing the entire matter content of the universe was minted. After all, if one wished to design a universe in which the origin of matter hangs on a single geometric exception, one could do no better than to place one neutral fermion at the center of the turning circle and open the one door only it can use.

The same criterion, drawn. Figure 8 is Eq. (35) with three species substituted into it, and it is worth a page because the conclusion is stronger than the textbook's and is usually met as a weaker one. The textbook says a neutral particle *may* be its own antiparticle: a permission, granted species by species. The criterion here grants nothing and forbids a great deal. A charged field is not *disallowed* from being self-conjugate by some further rule; it is *unable*, because the circle moves it and moving it is what having charge means. The Majorana option is not one modeling choice among several. It is the only door the geometry leaves open, and it opens onto exactly one species of known matter.

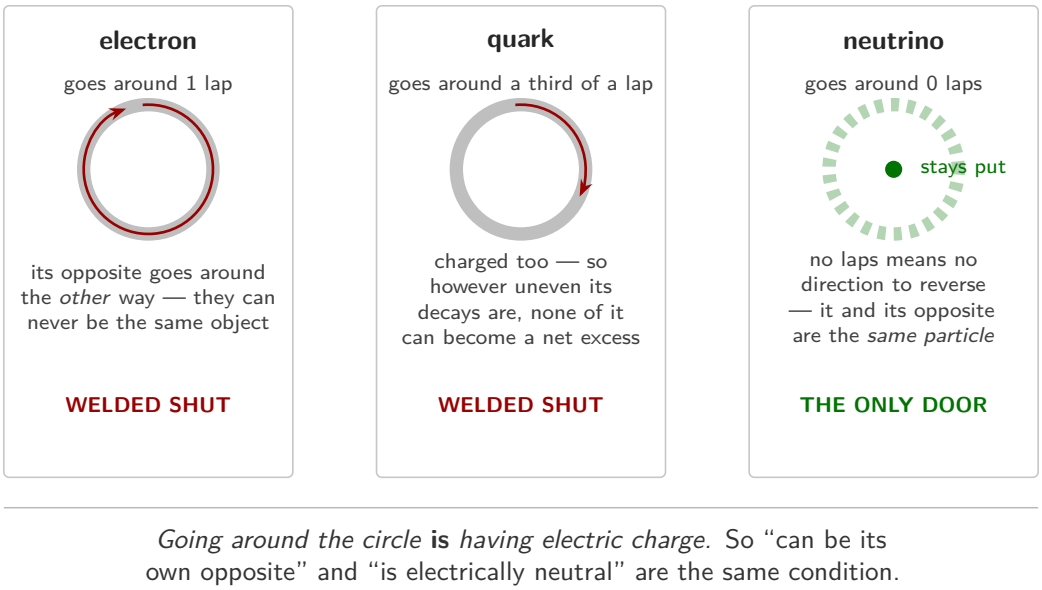


Figure 8: The criterion of Eq. (35), applied to the three species a reader will reach for. A particle and its antiparticle wind around the phase circle in opposite senses. If the winding is anything other than zero the two windings differ, and no relabeling can make the particle identical to its own conjugate — the electron winds once, every quark winds a third of a turn, and both doors are welded shut. Only a field the circle does not move escapes the argument, and winding around this circle is precisely what electric charge is. Exactly one particle in known matter survives the test. This is why the origin of matter runs through neutrino physics and not through the quark sector, and the reason is structural rather than a matter of degree.

47 The bulk that cannot hide its conjugates

The handshake forces the *pairing*. Independently — and this bears emphasis, because the two arguments could each fail without the other — the bulk's representation theory forces the conjugate *content*, twice over.

First forcing: the spinor algebra. Lemma 24.1 did the work in advance: in $(1,5)$ signature the Dirac spinor splits into the conjugate Weyl pair $\mathbf{4} \oplus \bar{\mathbf{4}}$ of Eq. (10), the chiral representation is complex, and no Majorana condition exists, so a bulk Weyl fermion and its conjugate are genuinely independent objects — there is no reality condition available that could identify a charged fermion with its own reflection. The matter of the GG-6 bulk is packaged as left-handed Weyl spinors (the $\mathbf{4}$ of $\mathrm{Spin}(1,5)$) tensored with $\bar{\mathbf{5}} \oplus \mathbf{10}$ of SU(5) per generation, *with an analogous right-handed structure for the conjugate sector* (Arisaka, 2026, A2-GG6): the antiparticle content is a separate, present module of the bulk, by algebra.

Second forcing: the anomaly ledger. The anomaly flip (11) makes chirality a signed currency, and the BI-6 books cannot balance in one sign alone (Arisaka, 2026, A3-BI6). It is worth walking the arithmetic in three steps, because "the books force conjugate content" is the kind of claim a reader should watch happen rather than take on faith.

Step 1: the brick already contains conjugates. The elementary building block of the matter

spectrum — the core block — is

$$\mathcal{C}^{\sigma} \;=\; \sigma\left[\,\mathbf{10}\oplus\mathbf{5}\oplus 2\cdot\bar{\mathbf{5}}\oplus 11\cdot\mathbf{1}\,\right], \tag{36}$$

one chirality σ carrying a fixed SU(5) content that mixes unbarred and barred representations: the two $\bar{\mathbf{5}}$'s sit inside the brick, next to the **10** and the **5**. Conjugate representations are not an addition to the elementary unit; they are part of its definition.

Step 2: the solution flips a chirality. Balancing the full anomaly polynomial over the orbit reservoir is a Diophantine problem — integer multiplicities, fixed coefficients, no dials — and its solution returns one negative coefficient, $d_2 < 0$. A negative number of fields is not physics; the unique physical reading is supplied by the flip (11):

$$d_2\, D_2^{+} \;=\; |d_2|\, D_2^{-}\,, \tag{37}$$

a negative multiplicity of positive-chirality fields *is* a positive multiplicity of the opposite-chirality species. The physical reservoir that results,

$$(8,\,4,\,48,\,12,\,2)\cdot\frac{\Omega}{25} \qquad \text{(fourth orbit of negative chirality)}, \tag{38}$$

has no negative multiplicity anywhere; what it has instead is a *definite mixed-chirality pattern.* The ledger's arithmetic cannot be satisfied by one chirality, and the solution says exactly which orbit must carry the other sign.

Step 3: gravity forces a conjugate sea. Closing the gravitational sector of the same ledger forces, in addition,

$$n_F \;=\; 32\,\Omega \tag{39}$$

gauge-singlet Weyl fermions of chirality *opposite* to the visible reservoir — eight for every self-dual tensor the closure employs, $n_F/n_{SD} = 8$ — whose members admit Dirac pairings (vector-like, liftable). None of this consulted an observation, and no field was added by hand: the opposite-chirality content is demanded by the arithmetic of anomaly freedom, executed on integers.

A distinction that must never be blurred. The two forcings supply two logically different kinds of "antiparticle-like" content, and a hostile reader will conflate them if the paper does not forbid it here. The representation conjugates (the $\bar{\mathbf{4}}$ partners, the barred reps) are what descend to the Standard Model's antiparticles — every charged species' twin. The anomaly-forced opposite-chirality *species* (D_2^{-}, the singlet sea) are independent chiral fields whose opposite anomaly sign lets the books balance; they are not "the antiparticles of" the visible matter. The bulk contains conjugate content in both senses; only the first sense is the antiparticle of Q1; and the cohort's papers keep the two ledgers separate throughout.

Physics intuition. Put the two forcings beside the handshake and a satisfying closure appears. The handshake says: *if* charged matter exists, its modes must pair as particle and antiparticle — a statement about orientations. The algebra says: the charged matter that exists cannot be its own conjugate — a statement about representations. The ledger says: the spectrum as a whole must carry both chirality signs — a statement about integers. Three independent structures, none

adjustable, all pointing the same way: a GG-6 bulk without antiparticle content is not merely un-observed, it is *unwritable*. That is what "naturally and inevitably" means in question (Q1) of §40, and no weaker claim would deserve the words.

48 What the descent does, and does not do

Question 2 asked whether antiparticles emerge after GG-6 is decomposed to the Standard Model. The answer, now provable in one paragraph: **the decomposition creates nothing; it relabels.** In the boundary description one Standard-Model family is written entirely in the left-handed Weyl convention, with the right-handed particles appearing as left-handed conjugates — u_R^c in $(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$, d_R^c, e_R^c — and charge conjugation realized as the same fiber reversal $\theta \mapsto -\theta$ it always was (Arisaka, 2026, A9-SM). The mode-level pair is the $\pm n$ winding pair on the fiber, exactly the pair of Eq. (22)'s proof. What *is* new at or after the descent is threefold, and each novelty is operational, not ontological. (i) After electroweak breaking, the Yukawas pair each left field with its conjugate partner into massive Dirac fermions — the familiar sense in which particle and antiparticle content "merge" into one massive field; d_R and d^c are two descriptions of the same degree of freedom. (ii) The one exception is the field the circle cannot distinguish from its conjugate: the weight-zero neutrino, uniquely permitted a Majorana self-pairing (T-P5-4), the door of Part VIII. (iii) The particle-versus-antiparticle *label* — which twin an observer calls matter — is a superselection-sector assignment, and sectors are boundary dictionary data.

Physics intuition — why "relabeling" is the deep answer, not the deflationary one. It may seem that "the descent only relabels" demotes the question. The opposite is true. Consider what the alternative would require. If antiparticles were created at the descent, the descent would need creation machinery — some step at which a spectrum without conjugates acquires them — and that machinery would face the full force of the question this Part opened with: why a twin for every charged species, with exactly equal mass, and not some other arrangement? No such machinery exists anywhere in the construction, and none is needed, because the bulk spectrum never lacked the conjugates: the algebra could not write them out (§47), and the handshake had already paired them (§42). What the descent does is what a customs office does at a border: it inspects, sorts, and relabels the goods; it manufactures nothing. The left-handed convention, the u_R^c notation, the Dirac pairing at electroweak breaking — each is a repackaging of content the bulk supplied, very much like a chord renamed when the clef changes: the notes do not move. Indeed, the reader can run the audit in reverse. Every property of the boundary twins that is *structural* — existence, pairing, equal masses, conjugate charges — traces upstairs; every property that is *conventional* — which twin is called matter — traces to the dictionary. Which brings us to the readout.

49 The boundary that reads the twins

Three episodes from the cohort's boundary physics show the operational layer at work. Each is a classic puzzle; each dissolves the same way; and the reader who watches all three dissolve will come to trust the custody principle as a tool rather than a slogan.

49.1 The positron as conjugate readout

The electron paper of the program derives the electron as a unique attractor basin — one stable resting place for charged matter at that level of the landscape, its properties fixed by the geometry (Arisaka, 2026, P3-Electron). Uniqueness claims invite their own falsification, and here the candidate falsifier walks into every detector on Earth: the positron. If the framework permits exactly one basin, what is this second particle — equal mass to extraordinary precision, opposite charge, predicted on paper in 1931 and found in a cloud chamber the following year? The resolution is the handshake, applied: *the positron is the conjugate readout of the same basin — same level (mass), opposite winding eigenvalue (charge) — exactly as CPT requires; what the framework forbids is a second basin, not a second orientation.* One object, two orientations of reading it.

Three consequences repay attention. First, the mass equality of electron and positron is not *enforced* between two objects; it is *trivial* for one object — where there are not two things, nothing can differ. This is Depth 3 answering a question Depth 2 can only constrain: the CPT theorem bounds the mass difference of the pair; the readout picture abolishes the difference by abolishing the pair — the same economy by which a string's conjugate excitations are automatically degenerate, and for the same structural reason. Second, the charge flip is the *definition* of the second readout, not a property that might have been otherwise: the conjugate readout is the reversed winding, by T-P5-C2's factorization. Third, the register must record a debt: the promotion of this picture to a proved corollary of the bulk spinor structure — "the positron, as a theorem" — is a registered obligation of the program (its label there: D-P3-4), carried here honestly as owed rather than claimed. What is claimed is narrower and firm: nothing in the positron's measured properties requires a second basin, and the conjugate-readout reading uses only structures that are theorems at their stated grade. The reading now runs in both directions: the electron paper devotes a dedicated Part — its Part V, the origin of positrons, the sixth of its questions — to importing the origin of the twin at theorem grade from the present paper and closing that question as the conjugate readout developed here (Arisaka, 2026, P3-Electron).

49.2 Wheeler's one-electron universe, rejected and preserved

One day in 1940, John Wheeler telephoned his graduate student with an idea too beautiful to keep: perhaps there is only *one* electron in the universe, threading forward and backward through time — its forward strands the world's electrons, its backward strands the positrons — which would explain, in a single stroke, why every electron has exactly the same mass and charge. The student was Richard Feynman, and half of the idea stayed with him: the reinterpretation of positrons as electrons running backward became, nine years later, the propagator picture of his positron theory (Feynman, 1949). The cosmology did not survive the telephone call. As Feynman objected at once, a single worldline must return as often as it departs: the picture predicts as many positrons as electrons, and the universe conspicuously declines to supply them. (Wheeler had an answer — perhaps they hide in the protons — to which history has not been kind.) Nor has the one-electron universe any account of net lepton number.

The present reading preserves what was right in the idea in the only form that survives the objection. What is unique is not the particle's *worldline* but the *attractor it reads out*: all electrons

are alike, not because one particle visits us many times, but because every electron is a readout of one basin — and the positron is the same basin read with the fiber reversed. Sameness is explained with no bookkeeping of strands, and no symmetric-universe prediction follows, because readouts are not worldline segments: how many of each orientation the universe contains is a question about its *history* — Part VIII's question — not about the basin. Wheeler, one might say, filed the sameness of electrons under the wrong custodian: he assigned it to the geometry of one worldline when it belongs to the uniqueness of one attractor. Move the file, and the absurd prediction evaporates while the explanation survives.

49.3 The Hawking partner, dissolved

The popular picture of Hawking radiation is a pair-creation story: a particle–antiparticle pair fluctuates into being at the horizon; one twin falls in while the other escapes; the escaping flux is the radiation, and the infalling twin books the negative energy. The picture is vivid, useful for rough arithmetic — and notoriously treacherous when reified: treat the interior partner as a real, independent quantum, permanently entangled with its exterior twin, and one is soon assembling the firewall-flavored paradoxes of the modern literature. The black-hole companion paper of the program derives the thermality of the radiation with no pair story at all: the horizon's boundary description is the partial trace of a two-mode-squeezed *bulk* state — the standard squeezed correlation between exterior and interior modes, read through the boundary's one-way projection — and tracing the interior mode yields the exact thermal spectrum (Arisaka, 2026, C3-BH). In that derivation the "interior partner particle" never appears as an independent antiquantum: it is part of the traced-over 6D bulk — structure, not population. The paradoxes that come from reifying the partner do not arise, and for the same reason no paradox arises from the two readouts of the electron basin: a readout is not a resident.

The pattern of the three episodes is now visible, and it is the custody principle of §38 doing its work three times over: *the dictionary owns the sectors; the geometry owns the i*. The pairing — the antiparticle as structure — is bulk geometry, proved in §42 and never in danger in any episode. The label — the antiparticle as something an observer registers, counts, or reifies — is a boundary port assignment. And each of the three puzzles was manufactured by promoting a label to a structure: a second basin for the positron, a worldline for the sameness of electrons, an independent quantum for the interior partner. Keep each item with its owner, and there is nothing left to be puzzled by.

50 The negative results, recorded

Three silences matter as much as the theorems, and an audit that omitted them would flatter the case. *First*, the boundary-law and gauge-runtime papers of the cohort contain no antiparticle mechanism at all — verified by exhaustive search — and this is as it should be: on the custody principle the boundary owns readout, not origin. *Second*, the bulk's quaternionic structures are spent elsewhere: the three commuting complex structures of the $\mathbb{H}^2$ spinor geometry buy the *three families*, not particle–antiparticle doubling (Arisaka, 2026, A6-GRIP). The complex-structure budget is spent twice on two different questions — circle-and-clock on the single i and the pairing; the

quaternionic triple on $N = 3$ — and no cohort paper conflates the two purchases. *Third*, nowhere in the twenty-two-paper cohort does a Dirac sea, a filled vacuum, or a zitterbewegung picture appear: the account is Feynman–Stückelberg from top to bottom, with the relabeling now derived rather than imposed.

51 The answer, in one paragraph

Antiparticles do not emerge from the decomposition of GG-6 to the Standard Model — they are older than the decomposition and older than quantization. The theory has exactly two sources of complex structure, both real and both constitutionally forced: the compact sixth-dimension circle, which complexifies charged sectors but does not know its own orientation, and causal time with energy positivity, which supplies the unique positive-frequency complex structure — the Hilbert transform — and does know its direction. These two structures must act as the same imaginary unit on every charged mode, and there is exactly one way to arrange that: pair charge $+n$ with positive frequency and charge $-n$ with positive frequency — the Feynman–Stückelberg assignment. That forced pairing *is* the antiparticle. Charge conjugation is nothing but orientation reversal of the circle; the 6D spinor algebra guarantees the conjugate content is genuinely there in the bulk, since no Majorana condition exists in $(1, 5)$ to identify a charged fermion with its conjugate; and the anomaly ledger of BI-6 independently forces opposite-chirality species into the spectrum. What the descent to the Standard Model adds is only the operational layer: the boundary dictionary labels which sector an observer calls "particle," the positron is the conjugate readout of the same electron basin, and the one field the circle cannot distinguish from its conjugate — the weight-zero neutrino — is the one allowed to be its own antiparticle, which is precisely the door through which the matter–antimatter asymmetry of the cosmos is later generated. *Antiparticles, in this framework, are the price of having one i instead of two — where "i," here as everywhere, is the boundary's name for the bulk's one real quarter-turn.*

52 Originality ledger for this Part

Concessions first, in full; claims after, ranked — the register's order. *Not new here:* the Feynman–Stückelberg pairing itself (1941/1949 — "the pairing is textbook; its provenance is the claim"); the slogan "antiparticles as a consistency condition," which Weinberg's causality argument already embodies at the structural level (stated in full in Part X); conjugation as orientation reversal of a compact circle, whose *image* is old Kaluza–Klein lore made vivid by string theory's oriented strings (conceded in Part X with its sources) — though the GG-6 circle is categorically different, a non-spatial phase dimension with no radius, no tower, and no landscape (Arisaka, 2026, A2-GG6); the positive-energy complex structure, which is Ashtekar–Magnon and Kay's theorem, promoted here to constitutional status; and the real-quantum-mechanics lineage from Stückelberg's 1960 program through the modern exclusion experiments. *New here or in the parent theorems this Part consolidates, ranked by confidence:* (1) the two-source compatibility theorem itself — no prior framework possesses *two independently derived* real structures whose forced agreement is the pairing,

so no prior framework could derive the Feynman–Stückelberg assignment before quantization; KK has the circle but borrows its state-space i, Ashtekar–Magnon has the clock but no circle to shake hands with; (2) the unification — "why is quantum mechanics complex?" and "why do antiparticles exist?" made one question with one answer; (3) the custody division of the antiparticle concept into bulk pairing and boundary label, with its three dissolved puzzles; (4) the double bulk-forcing of conjugate content (algebra plus ledger), which upgrades "natural" to "unwritable otherwise." *Scope, stated plainly:* the handshake is proved at the free/quasi-free grade; interacting matter rides on the asymptotic frame, conditionally; and every sentence of this Part inherits that qualifier. *Depth, stated on the Part II ruler (§26):* the claims of this Part live at Depth 3 — what the twins *are*, and what the pairing is made of — with Depth 1 (the spectrum pairs) and Depth 2 (it must pair) recovered as corollaries of the handshake rather than assumed; no rival framework, Part X will argue, competes at that depth, and the register above is the price of admission. The comparison of these claims against QFT, the Standard Model, string theory, and ΛCDM — including Weinberg's theorem, the Dirac sea's rise and fall, and the string-theoretic precedents — is the business of Part X, where each rival is given its full say.

Part-end summary. Two half-blind sources of one quarter-turn; one forced alignment, extended without new input to composites, Fock space, and the Dirac fermion; lawful exceptions exactly where the circle stands still; a bulk that cannot be written without its conjugates, twice over; a descent that relabels; a boundary that reads. The twins exist because the world must agree with itself. And because they exist — and because, as the coming Parts show, the mirrors that exchange them broke selectively, by computable amounts, in a universe whose ledger kept six parts in ten billion — there are atoms rather than annihilation light, chemistry rather than silence, and readers rather than none. Now that the twins are on stage, the operations that exchange them can be defined and derived. That is the next Part.

Part V
The Mirrors Defined: C, P, T and the CPT Theorem

The three reversals given bodies and walked one at a time; the table from orientation; Kramers for free; CPT as total reversal, blind to every real texture; and the five fates of the mirrors, derived

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53 Part V in plain English: the three mirrors, given bodies

C, P and T are normally introduced as operations on fields: rules with signs, justified by what they produce. This Part gives them bodies instead. Each is the reversal of the orientation of one real factor of the arena — the circle, space, and the clock — and the operations follow from the reversals rather than the other way about.

Two results come out. The discrete-symmetry table is derived rather than assembled, including the fork that makes T antiunitary while C and P are unitary, which in the textbook account is a choice justified after the fact. And CPT is total orientation reversal: the one reflection a real texture cannot see, which is why it survives while each of its parts fails.

The Part ends by separating what is claimed from what is inherited, as every mirror Part in this paper does, and the separation matters most here. The relation to Jost's theorem is complementarity, not replacement: Jost's scope exceeds the geometric account's, which is quasi-free with the interacting case conditional on scattering hypotheses. The Part says that in those words rather than leaving a reader to discover it.

54 The operations, given bodies

Part I told the story of three symbols; this Part finally says what they name. It is worth pausing on how strange the standard situation is, because familiarity has hidden it. For seventy years, C, P, and T have been used daily by every particle physicist alive — assigned as quantum numbers, tested in decay after decay, broken in headlines — and yet the formalism that uses them declines to say what they *are*. In the standard development each is an operator defined by its action on creation and annihilation operators, *up to intrinsic phases chosen field by field* (Streater and Wightman, 1964): "the" parity operator is really an equivalence class of operators, and the tables of intrinsic parities and C-parities record conventions as much as facts. The antiunitarity of T is not derived but selected — Wigner's theorem permits either character, and antiunitarity is the choice that spares the spectrum (§19). None of this is a defect of rigor; the formalism is exact, and its predictions are the best-tested in science. It is a silence of *anatomy*. Nothing in the definitions says what the

operations are made of — and therefore nothing in them could have warned, before 1956, that two of the three would fail, or explained, after 1964, why the failures came in that order and at those sizes.

This Part removes the silence, with the tools Parts II–IV built. The three operations will be three specific real maps — reversals of the three orientations the bulk possesses — walked one at a time on the very modes Part IV constructed (§55). The unitary/antiunitary table will then be a one-line theorem rather than a case analysis (T-P5-1), and it will immediately pay dividends the standard formalism buys separately: Kramers' degeneracy with no phase conventions, and the reason T has no quantum number of its own (§57). The CPT theorem will be bookkeeping over the anatomy (T-P5-2). And the anatomy will then answer the question the standard account cannot pose: *why did the mirrors fall selectively — these ones and not those, in that order, by those amounts?* The five fates of the mirrors (§60) are the Part's harvest, and the Part closes by pricing exactly what in all this is new (§61).

55 The three reversals, walked one at a time

Before any theorem, let us simply watch each operation act. The stage is Part IV's: real mode planes, the quadrant map of Figure 7, and the two kept (green) cells — the particle plane spanned by $\cos(n\theta - Et)$, $\sin(n\theta - Et)$ and the antiparticle plane spanned by $\cos(-n\theta - Et)$, $\sin(-n\theta - Et)$.

55.1 C: the fiber run backward

Charge conjugation is the reversal $\theta \mapsto -\theta$ — for fermions composed with the fixed real spinor map B of T-P5-C2, which we may set aside here since it is state-independent. Apply it to the particle plane's basis:

$$C: \quad \cos(n\theta - Et) \mapsto \cos(-n\theta - Et), \qquad \sin(n\theta - Et) \mapsto \sin(-n\theta - Et). \tag{40}$$

Both basis vectors land squarely on the antiparticle plane's basis, in order, with no signs: C carries one green cell of Figure 7 onto the other, *preserving the turning sense* — the particle's forward rotation maps to the antiparticle's forward rotation. An operation that preserves every plane's turning sense commutes with the quarter-turn: this is the observation T-P5-1 will turn into "C is unitary." On the couplings, the same reversal negates every fiber angle, $\varphi \mapsto -\varphi$ — the fact that will decide CP's fate in Part VII. And on the weight-zero sector C acts as the identity (§46): the still point of the carousel, where the C-parities ± 1 live as honest quantum numbers — the photon's -1, the neutral pion's $+1$, each derived there rather than assigned.

55.2 P: the hands exchanged

Parity is the reversal of the spatial orientation, $\vec{x} \mapsto -\vec{x}$. On the fiber–clock dial angle $n\theta - Et$ it does nothing at all — the walk is, on these coordinates, a standstill — and that quiet is precisely its content: P touches neither source of the quarter-turn. Where P acts is on the suppressed spatial and spin data: it reverses momenta, and it *exchanges the two Weyl modules* — in four-dimensional

language, the left-handed $(\frac{1}{2},0)$ and right-handed $(0,\frac{1}{2})$ representations (§24). This single structural fact carries all of parity physics. A theory treats P as a symmetry if and only if its two hands carry the same charges — a *vector-like* theory; it violates P if and only if the two hands are charged differently — a *chiral* theory. The intrinsic parities of the tables (scalar even, pseudoscalar odd, vector odd, axial even) are the bookkeeping of how each field's real components contract with the spatial orientation. Nothing here is new physics; what is new is what Part VI will do with it: in the GG-6 descent, one hand of the spectrum is not differently charged but *absent*, and P will fail for the strongest possible reason.

55.3 T: the clock run backward

Time reversal is the reversal $t \mapsto -t$ — the operation that plays every film backward. Apply it to the particle plane:

$$T: \quad \cos(n\theta - Et) \;\mapsto\; \cos(n\theta + Et). \tag{41}$$

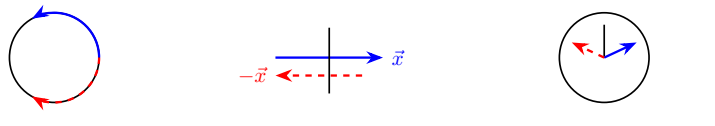
Look at where the image lies on Figure 7: in the *clash quadrant* — exactly the planes on which Part IV proved the circle's quarter-turn and the clock's disagree, the planes the handshake outlawed for any J-linear physics. This is the geometric heart of time reversal's strangeness, and it deserves a slow sentence. The clock reversal cannot be read as a J-linear map at all: its image escapes the kept world unless the turning sense is conjugated along the way — $TJ_AT^{-1} = -J_A$ — and an operation that conjugates the quarter-turn is, by the gear rule of Part II, antiunitary. Antiunitarity is not a property assigned to T for the spectrum's sake; it is *the only exit from the clash quadrant.* The laboratory has long known T's strangeness operationally: unlike C and P, time reversal furnishes no quantum number to tabulate (§57 derives why), so it is tested not by selection rules but by asymmetries and by static moments — matters this paper's Parts I and IX take up with the instruments. Hold, for now, the single geometric fact: of the three reversals, only the clock's collides with the handshake.

The three walks are done, and the reader has seen everything the table theorem needs: C hops between the green cells with the turning sense preserved; P stands still on the dial and exchanges the hands elsewhere; T walks into the forbidden quadrant and must conjugate the turning to survive. The theorem now only records this.

56 T-P5-1: the discrete-symmetry table

Theorem 56.1 (**T-P5-1**: the table from orientation)**.** *On the quasi-free real bulk, let C, P, and T act as orientation reversals of the fiber circle, the spatial slice, and the causal clock respectively. Then: C is J-linear — it reverses ∂_θ and the signed charge together, leaving $J_Q = \partial_\theta/Q$ invariant; T is J-antilinear — it reverses the polar phase of the time generator, $TJ_AT^{-1} = -J_A$; P is J-linear — it touches neither fiber nor clock. Hence a discrete symmetry is antiunitary if and only if it contains T: the textbook unitary/antiunitary table is derived, not assigned.*

Proof. Under $\theta \mapsto -\theta$ the weight-n sector maps to the weight-$(-n)$ sector and $\partial_\theta \mapsto -\partial_\theta$; since J_Q is normalized by the *signed* charge, $J_Q \mapsto (-\partial_\theta)/(-Q) = J_Q$: C commutes with the sector complex



C: fiber reversal
$\theta \mapsto -\theta$; $J_Q \mapsto J_Q$
J-linear (unitary)

P: space reversal
touches neither source
J-linear (unitary)

T: clock reversal
$t \mapsto -t$; $J_A \mapsto -J_A$
J-antilinear (antiunitary)

Figure 9: The three orientation reversals of T-P5-1. The fiber reversal flips the rotation generator and the signed charge together, leaving $J_Q = \partial_\theta/Q$ invariant; the space reversal touches neither source of i; the clock reversal is the one flip the imaginary unit is made of. The unitary/antiunitary table is the map of which reversals touch the sources.

structure, and by the handshake (T-P4-3) with the one global J. Under $t \mapsto -t$ the frequency orientation flips: the polar phase of the generator (the Hilbert transform in constitutional time) is odd under clock reversal, so $TJ_AT^{-1} = -J_A$. P reverses the spatial orientation, which enters neither J_Q (a fiber object) nor J_A (a time-domain object): P commutes with J. (Anti)linearity multiplies under composition like a sign (Section 19), so a product of reversals is J-antilinear iff it contains the one J-anticommuting factor — iff it contains T. ■

Physics intuition. Why is time reversal the odd one out — antiunitary, where C and P are unitary? Because of the three orientations a discrete symmetry can flip, *only the clock's is what the i is made of.* Flip space, and nothing happens to i. Flip the fiber, and the charge label flips with the rotation generator, so i survives the double negative. Flip the clock, and "a quarter period ahead" becomes "a quarter period behind" — i becomes $-i$, which is antilinearity. Wigner's theorem (Wigner, 1931) offers the fork (unitary or antiunitary) and standard quantum mechanics chooses by consistency; here the choice is a computation, because i has sources and the table is the map of which reversals touch them. This is the paper's smallest theorem and, in the author's view, its purest: a fact memorized by every graduate student for ninety years, turned into one line of orientation bookkeeping.

The theorem also fixes the operations' *anatomy* in a way the standard formalism cannot. In QFT the discrete operators carry per-field phase conventions, adjustable within wide limits (Streater and Wightman, 1964); here C *is* $\theta \mapsto -\theta$ composed (for fermions) with a fixed real spinor map (Arisaka, 2026, A8-QM), P *is* the spatial reversal, T *is* the clock reversal — three specific real maps, no convention anywhere. When Part VI speaks of "which hand survives the projection" and Part VIII of "CP-biased decays," the operations being violated are these three maps, not representatives of equivalence classes.

57 First dividends of the table

A good theorem pays immediately. Here are two payments the standard formalism makes separately, with conventions, and the table makes free of charge.

Corollary 57.1 (Kramers' degeneracy, with no phase choice)**.** *On fermionic sectors, T composes the clock reversal with the fixed real spinor map of the bulk construction, and the composite squares*

to $-\mathbf{1}$ on half-integer spin. In any T-symmetric dynamics, every energy level of a half-integer-spin system is therefore at least doubly degenerate: no state is its own T-image.

Proof. The clock factor squares to $+\mathbf{1}$ (two reversals make a forward), and the fiber is untouched; the spinor factor is the fixed real intertwiner whose square is $-\mathbf{1}$ on half-integer spin — the same algebra, used at the same office, as the map B of T-P5-C2 (Arisaka, 2026, A8-QM). Hence $T^2 = -\mathbf{1}$. Now suppose $T\psi = \lambda\psi$ for some state ψ and scalar λ. Applying T again and using antilinearity, $T^2\psi = \bar{\lambda}\lambda\,\psi = |\lambda|^2\psi \neq -\psi$: contradiction. So ψ and $T\psi$ are distinct states of the same energy, and the level is paired. No intrinsic phase was chosen at any step — Wigner's two classes $T^2 = \pm 1$ (Wigner, 1931) are here a computation on the real spinor algebra (problem D.1.3 of Appendix D.1 drills it). ■

Physics intuition, and the laboratory face. Kramers' theorem is the quiet workhorse of atomic and solid-state physics: every level of an odd-electron atom, ion, or molecule comes in protected pairs that no electric field, however violent, can split — only a magnetic field, which breaks T itself, lifts them. In the standard development this protection descends from a phase-convention-laden analysis; here it is three squares multiplied together. The reader should feel the economy: the same real spinor map that could not make a fermion self-conjugate (Lemma 24.1), and that implements its conjugation (T-P5-C2), now signs its time-reversal square. One matrix, three offices, no conventions.

The second dividend: why T has no quantum number. C and P are J-linear with square one, so their eigenvalues ± 1 are honest, basis-independent labels — hence the tables of parities and C-parities, and the selection rules that carried half a century of spectroscopy. T admits no such label, and the table says why with unusual crispness: an antilinear operator has no invariant eigenvalue at all. If $T\psi = \lambda\psi$, then rephasing the state rotates λ — $T(c\psi) = \bar{c}\,\lambda\psi$ — so "the T-parity of a state" is not a property of the state. This is not a technicality; it dictated seventy years of experimental design. Parity violation, once suspected, was confirmed within months by a selection-rule-scale effect (Part I); direct time-reversal violation, requiring a genuine rate asymmetry between a process and its motion-reversed partner, waited until 1998 in the kaons and 2012 in the B mesons (§111), and the static searches — the electric dipole moments, T-odd by the same bookkeeping — remain the deepest null results in physics (§10). The instruments were not slow; the anatomy is genuinely different. A mirror with a quantum number breaks loudly; a mirror without one must be caught moving.

58 T-P5-2: CPT as orientation bookkeeping

Theorem 58.1 (**T-P5-2**: CPT as total reversal)**.** *The total orientation reversal CPT maps each Feynman–Stückelberg-paired mode set to itself, and is a symmetry of the construction for every coupling texture built from real geometric data. Consequently every particle and its antiparticle share mass and total width, and all CPT-odd observables vanish, at the quasi-free grade; the extension to interacting matter holds conditionally on the standard scattering hypotheses (the asymptotic frame of T-P4-8).*

Proof. On the paired real modes $\cos(n\theta - Et)$ and $\cos(-n\theta - Et)$ the total reversal acts as the

identity map *of the pair*: fiber reversal exchanges the members, clock reversal exchanges them back, and space reversal relabels propagation directions within each. It remains to check the couplings. A texture built from real geometric data consists of magnitudes (coupling moduli, metric and symplectic contractions, winding sums) and fiber angles. The magnitudes are even under total reversal. The angles reverse sign under the fiber factor — but reversing the sign of every texture angle while conjugating every loop is a *relabeling* of the same real texture (each loop holonomy $\varphi \mapsto -\varphi$ composed with the orientation reversal of the loop itself, leaving every holonomy functional invariant). Hence the action, and every correlation function built from it, is invariant. Equal masses and widths for Feynman–Stückelberg partners follow because the pair is a single orbit of the symmetry; CPT-odd observables are odd functions on a set the symmetry maps to itself. ■

Relation to the standard theorem, stated exactly. Jost's CPT theorem (Jost, 1957; Streater and Wightman, 1964) is stronger in scope: it covers interacting Wightman field theories, with the proof running through analytic continuation to the complexified Lorentz group. It is, however, anatomically silent — it constructs the antiunitary Θ and proves it a symmetry without saying what C, P, or T individually are, or why Θ's antiunitarity traces to the time factor. T-P5-2 inverts the trade: narrower scope (quasi-free, with the interacting case conditional), full anatomy (the three factors named as reversals of constitutional structures, antiunitarity derived in T-P5-1). The two theorems are complementary, and the natural bridge between them is named in the open questions: the Bisognano–Wichmann identification of the CPT operation with modular conjugation (Bisognano and Wichmann, 1976) suggests that the clock structure — hence J_A, hence the table — may be derivable from modular flow, tying the geometric account to the algebraic one at interacting strength. That derivation is open, and it is listed as such (Part XII).

The converse discipline, and the laboratory record. Two further facts frame the theorem from outside. First, the converse: CPT violation cannot be had cheaply. Greenberg's theorem (Greenberg, 2002) shows that an interacting theory which violates CPT necessarily violates Lorentz invariance — so what a CPT-violating signal would overturn is not a detail of the construction but the arena itself, the time-oriented Lorentzian stage that AX-1 supplies and everything in this paper stands on. The falsifier is correspondingly total, and Part I's register of the tests is worth re-reading with this in mind: the neutral-kaon mass comparison at the 10^{-18} level, antihydrogen spectroscopy at 10^{-12}, the six-comparison table of §10 — every entry is an equal-mass, equal-width, opposite-moment corollary of the total reversal, and every entry has held. Second, the register: those corollaries are exactly what T-P5-2 delivers for Feynman–Stückelberg partners — the pair is a single orbit of the symmetry, so mass and total width cannot differ between its members — and the quasi-free grade plus the conditional interacting extension is the honest scope within which this paper claims them.

59 The anatomy of a theorem: why CPT is exact and C, P, T are not

The two results just proved sit oddly beside each other until one asks where each of them lives. T-P5-1 says the three reversals are orientation flips of three constitutional structures. T-P5-2 says their product is a symmetry of every texture built from real geometric data. Parts VI and VII will

then show that the individual mirrors break — comprehensively, and by construction. A reader is entitled to ask why the product should be safe when every factor is not.

The answer is not in the algebra. It is in the arena, and the arena has exactly two kinds of place to put a thing.

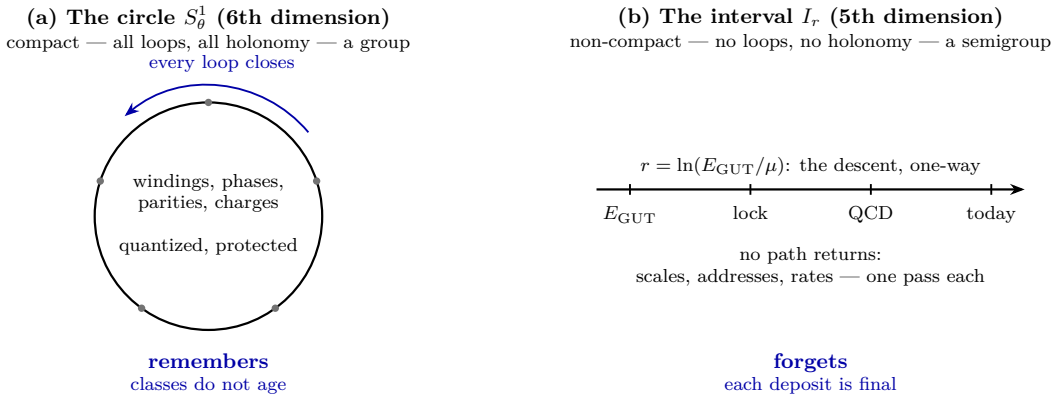


Figure 10: The two fibers of the bulk, and the different things they can hold, adapted from the holonomy companion (Arisaka, 2026, W2-Holonomy). *(a)* The compact phase circle S^1_θ: every path closes, so everything a connection does there is holonomy — quantized, gauge-protected, transported by a group. Classes on a circle do not age: no boundary operation can continuously deform one into another. *(b)* The scale interval I_r: no path closes, so nothing is protected; transport composes only forward, a semigroup, and the descent visits each scale exactly once. Every deposit is final. *The circle remembers; the interval forgets* — and the two sentences of this section are that figure, applied to the three reversals.

Protection has an address. Whenever physics presents a quantity that is exact — a charge that never leaks, an anomaly coefficient that does not run, a family count that neither drifts nor renormalizes — the anatomy says where it lives: on the circle, deposited in a holonomy class no boundary operation can continuously deform. And whenever physics presents a quantity that is *placed* — a mass, a scale, a rate, an epoch — the anatomy says that lives along the interval, as an address on the fiber that forgets. The formulation is the holonomy companion's (Arisaka, 2026, W2-Holonomy); the two structures are this paper's G1 and G2 of §36, seen from the side.

Which side each reversal is read from. Now the asymmetry between the theorem and its factors is not a puzzle but a location.

CPT is exact because it is a statement about the circle alone. The proof of T-P5-2 turns on one step: reversing the sign of every texture angle while conjugating every loop is a *relabeling* of the same real texture, because each loop holonomy $\varphi \mapsto -\varphi$ composed with the orientation reversal of the loop itself leaves every holonomy functional invariant. That is a statement about holonomy classes, and holonomy classes are circle-side. Nothing the descent does along the interval can reach them, because reaching them would mean continuously deforming a class — which is what a compact fiber forbids. The exactness of CPT is not a coincidence that survived; it is a class label that had nowhere to leak to.

C, P and T individually are not exact, because their breaking is an address. The chiral texture of Parts VI and VII is written *onto* the fiber *during* the descent — at a scale, once, in one direction. Parity violation and the pentagon are not properties of the circle; they are what the interval deposited on it at a particular place along a one-way road. An address can be anything, and a once-only pass cannot be undone. That is why the mirrors break and stay broken, and why they break at specific scales rather than everywhere at once.

Two corollaries the reader should collect. First, the five fates of §60 are not five independent facts but one sorting rule applied five times: a mirror survives exactly when its statement is about a class, and fails exactly when its statement is about an address. Second, the strength of the two claims should differ, and it does: the exactness of CPT is held at the grade of the arena's own topology, while every statement about *where* a mirror broke inherits the grade of the descent that broke it. The status ledgers of §80 and §95 record the difference row by row; this section says why the difference exists.

And the honest limit. The anatomy explains the shape of the result. It does not extend its scope. T-P5-2 remains a quasi-free theorem with the interacting case conditional on the asymptotic frame of T-P4-8, and no amount of pointing at a compact fiber changes that — Jost's theorem is still the one with the wider reach, and this paper's contribution to that comparison is anatomy, not coverage. The circle explains why the exactness is not an accident. It does not prove the exactness on a domain the proof does not cover.

60 The five fates of the mirrors

T-P5-2 contains the seed of everything that follows in this paper, and this section grows it into the Part's harvest. CPT is blind to any real texture — no texture, however contrived, can break it. But the *factors* are not blind, and with the anatomy in hand we can now do what the standard account cannot: derive, rather than record, the fate of each mirror — which broke, why, in what order, and by how much. The reader should hold Part I's history in mind throughout; this section is that history, explained.

The fates of C and P: broken by an absence. The descent of Part VI keeps one hand of the bulk spectrum: left-handed particles, and — since conjugation reverses the fiber without touching space — their right-handed antiparticle readouts. Now apply the walks of §55. P maps a surviving left-handed particle to its right-handed mirror — *a state the projection removed.* C maps it to a left-handed antiparticle — removed likewise. Neither operation fails because some coupling was mistuned; each fails because its image is not in the world. This is why the first fall was *maximal*: an asymmetry produced by an absent sector is an all-or-nothing asymmetry — Wu's electrons could not be partly missing — and it is why C and P fell *together*, in the same experiments of the same winter: one projection, two reversals, one absence seen twice.

The fate of CP: survives the absence, falls to an angle. Compose the two failures and something remarkable happens: CP maps a left-handed particle to a right-handed antiparticle — *present.* The combined mirror hops between states the projection kept; the absence that killed its factors cannot

Table 6: The five fates of the mirrors, derived from one projection and one lattice. The pattern the twentieth century measured — P and C falling together and totally, CP falling later and slightly, T tracking CP, CPT never falling — is here the fingerprint of a one-handed descent writing a chiral texture on an orientation-blind bulk.

Mirror	Reverses	Fate, derived	Breaker, and its size
P	space	broken maximally	an absence: the mirror hand is projected out (Part VI)
C	fiber	broken maximally, with P	the same absence, read through the fiber
CP	fiber + space	survives the projection; broken small	an angle: the chiral pentagon locks a loop off $\{0, \pi\}$ (Part VII)
T	clock	broken exactly with CP	the product's bookkeeping: CPT holds, so T pays CP's bill
CPT	all three	unbroken, for every real texture	none exists: real data are blind to total reversal (T-P5-2)

touch it. This is the structural content of the 1957 repair (Part I): the community's instinct that the true mirror pairs matter with reflected antimatter was, in this language, the observation that CP survives the projection. What the repaired mirror could still fall to is subtler: a fiber reversal negates every texture angle without conjugating the loops, so CP survives iff every closed-loop angle equals its own negative — iff the texture is *achiral on the circle*, every loop angle in $\{0, \pi\}$ (T-P5-3's criterion, proved in Part VII). And the GG-6 texture is not achiral: the pentagon locks the Cabibbo loop at an angle off the real axis. Hence the second fall's character, so different from the first's: not an absence but an *angle*; not all-or-nothing but small (the kaon asymmetry at parts per thousand); not immediate but eight years subtle, hiding in a regeneration-plagued decay. The standard account holds "P maximally violated" and "CP barely violated" as two unrelated inputs. Here they are one architecture read twice: the projection is total, the lattice angle is small, and each mirror broke exactly as hard as its breaker.

The fate of T: the product's alibi. T is broken wherever CP is — not by an independent mechanism but by the unbreakable product: if CPT holds and CP fails, T must fail in exact compensation. The direct observations (§111) confirm the bookkeeping: the kaon and B-meson T-asymmetries are the CP asymmetries read through the total reversal. And the custody discipline of Part III must be kept in force here, one last time: this dynamical T-violation — an angle in a texture — has nothing to do with the arrow of time, which is the non-invertibility of the boundary projection over a bulk whose action is exactly T-symmetric (§38). One is a property of couplings, measured in asymmetries; the other is a property of readout, present even where every coupling is T-even. The film runs forward because the projector is one-way, not because the reel is twisted.

The fate of CPT: no fate at all. The total reversal is blind to every real texture (T-P5-2): there is nothing in a world built from real geometric data for it to see, hence nothing that can break it. The five fates are collected in Table 6.

Physics intuition — the pattern was the message. Step back from the table and read the century again. Five mirrors; four fates; and the fates line up with the breakers' kinds — absences break totally, angles break slightly, products pay bills, and blindness never breaks. Nothing about that pattern is visible in a formalism where each mirror's fate is an independent input; everything about it is forced in a geometry where one projection removes a hand and one lattice twists a loop. Indeed, had history run in the other order — the small fall first, the maximal one second — this architecture could not have accommodated it. The mirrors did not merely break; they broke *informatively*, and the pattern of the breakage was the geometry, speaking.

61 What is claimed, and what is inherited

Concessions first, in full — the register's order. The representation-theoretic framework of the discrete symmetries is Wigner's (Wigner, 1931), and every quantum-number fact rehearsed above — intrinsic parities, C-parities, Kramers' degeneracy, the two classes $T^2 = \pm 1$ — is standard physics, re-derived here from the anatomy but discovered decades ago without it. The CPT theorem in its full interacting, axiomatic scope is Jost's (Jost, 1957; Streater and Wightman, 1964), with the modular grounding Bisognano–Wichmann's (Bisognano and Wichmann, 1976); T-P5-2 is narrower in scope and must always be presented as the complementary theorem it is — anatomy for scope, with the modular route the open bridge. The converse discipline is Greenberg's (Greenberg, 2002). What this Part claims as its own, at the grades of Table 11: *first*, the derived table — antiunitary if and only if the operation contains T, obtained as a computation on the sources of the quarter-turn rather than a Wigner-fork selection; a result, it is worth noting, that survives even for a reader who rejects everything else in the program, since it needs only the premise that the imaginary unit has physical sources with orientations. *Second*, the anatomy itself: C, P, T as three specific real maps with no per-field conventions, so that "P is violated" becomes a statement about a specific reversal of a specific orientation. *Third*, the five-fates architecture: the selective pattern of the mirrors' historical falls — which, together, in what order, at what sizes — derived from one projection and one lattice, where the standard account carries the pattern as so many unrelated inputs. *Fourth*, the theorem-level custody split between dynamical T-violation and the arrow of time. The first claim is graded derived; the second is definitional and carries the first; the third inherits Part VI's and Part VII's grades and is exactly as strong as they are; the fourth is carried by the constitutional Crooks decomposition cited in Part III. Nothing above depends on any claim graded weaker than its row in the ledger.

Part-end summary. The operations now have bodies: three reversals of three constitutional orientations, walked one at a time on the modes of Part IV. Where a convention stood, a theorem stands — antiunitary iff it contains T — and the theorem pays on the spot: Kramers for free, the missing T quantum number explained, CPT as bookkeeping, and the century's pattern of broken mirrors — total, then slight, then the bill, then never — derived from one projection and one lattice. The factors can break only where the world's texture carries a direction, and it carries two. The first is the orientation of the descent itself: parity, next.

Part VI
Parity: The Oriented Descent

Why exactly one force is chiral — the five superlatives collapsed to one; the basin/gate architecture with its clauses derived; the projection computed in blocks; the handedness invariant; and a registered falsifier

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62 Part VI in plain English: why exactly one force is chiral

The Standard Model can describe parity violation to any precision an experiment requires, and it cannot ask why the violation happens in one force and in no other. This Part asks it. Gravity, the strong force and electromagnetism are basins; the weak force is the gate; and the weak column differs from the other three in every property one can name, which in the Standard Model is five unconnected accidents of the input charges.

The mechanism offered is the projection that makes the descent oriented: chirality is the orientation of the descent, and the gate force is the one that carries it. The Part states the mechanism, derives what follows from it, and then puts the honesty ledger on the page — four statements derived, three asserted, one conjectured. The three asserted are the projection matrix itself, the existence of the projection, and which chirality survives, and they are the three to press hardest on.

A registered falsifier closes the Part: there is no right-handed weak sector, at any scale. That is not a prediction with a window around it. Any W_R, ever, ends this account, and the Part says so before a reader has to ask whether anything here could be wrong.

63 The question the Standard Model cannot ask

Part V closed on a promise: the factors can break only where the world's texture carries a direction, and the first of the two directions is the orientation of the descent itself. To see what that promise must explain, restate the 1957 discovery as the Standard Model holds it today: the left-handed fermions are $\mathrm{SU}(2)_L$ doublets, the right-handed fermions are singlets, and parity violation is thereby written into the field content — an input codifying $V-A$, not an output of anything. What the model then cannot ask is the question its own structure poses. The weak interaction is simultaneously five different kinds of exceptional, and each superlative has a bench face the reader has met. It is the only *broken* gauge force: its messengers weigh nearly a hundred protons each while the photon and the gluon weigh nothing — the single most conspicuous asymmetry in the force table. It is the only *chiral* force: Wu's cryostat measured its parity violation at full strength, and no experiment has ever caught the strong or electromagnetic force telling left from right. It is the only *family-changing* force: every muon that has ever decayed did so by this force and no other,

and the Sun shines because only this force can turn a proton's quark into its sibling. It is the only *short-range* force among the fermion couplings — 10^{-18} m, a thousandth of a proton, which is why it took until 1896 to notice it at all. And it is the unique home of *CP violation*: of the four forces, only this one has ever been caught distinguishing matter from antimatter, in the kaons and the B mesons where the author spent his experimental decades. Five superlatives, one gauge factor. In the Standard Model these are five separate accidents of the input charges; no two of them are connected by anything in the formalism. Quantum field theory at large adds two genuine structural results — parity cannot even break spontaneously in vector-like theories (Vafa and Witten, 1984), and only chiral fermions are protected from acquiring superheavy masses ('t Hooft, 1979), which explains why the *light* spectrum is chiral — but neither says why chirality sits in $\mathrm{SU}(2)_L$, nor why the broken force and the chiral force coincide. String theory geometrizes the possibility (chirality from compactification topology (Candelas et al., 1985; Dixon et al., 1985)) without selecting it: the landscape holds mirror-symmetric vacua in abundance. The claim of this Part is that the five superlatives are five faces of one geometric fact — *the descent between family basins is oriented* — and that the fact has a mechanism in place, one named lemma outstanding, and a falsifier all its own.

64 The basin/gate architecture

The parent Standard-Model treatment (Arisaka, 2026, A9-SM) divides the four forces by one structural criterion. A force whose gauge symmetry is *unbroken* holds its charge fixed: it can move a state only within a fixed-charge sheet — within a family basin. Gravity, the strong force, and electromagnetism are such *basin forces*: exactly conserved, family-diagonal, parity-even, long-range where massless. An exact symmetry forbids precisely the family-changing transition a cascade needs. The electroweak factor $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ is the one broken gauge structure — and the claim is that this is not a coincidence list but an identity: *being the broken force and being the gate force are the same statement.* Let us set the stage with more care, because the argument deserves to be walked rather than gestured at. The family landscape of the parent treatment is a potential over the space of family configurations: its critical points are the three family levels, its basins their neighborhoods, and the descent — the Morse gradient flow — runs strictly downhill, heavier to lighter, which is why the mass hierarchy has an order rather than a shuffle. Now ask what kind of coupling can *execute* that descent, and derive the gate's job description one clause at a time.

First: the executor is family-off-diagonal. A transition from basin 3 to basin 2 connects distinct critical points; a coupling that conserves the family label can shuffle states within a basin forever and move nothing between them. The executor must be the force that does not commute with family — and among the observed forces exactly one changes flavor.

Second: the executor is massive, hence short-range, hence broken. A gate is a localized crossing — the transition happens *at* the saddle between basins, not everywhere at once — and localization requires a length scale. A massless mediator has none: its influence is scale-free and long-range, the signature of a basin force. The executor must carry a mass; a gauge force carries a mass only if its symmetry is spontaneously broken; so the gate force and the broken force are one.

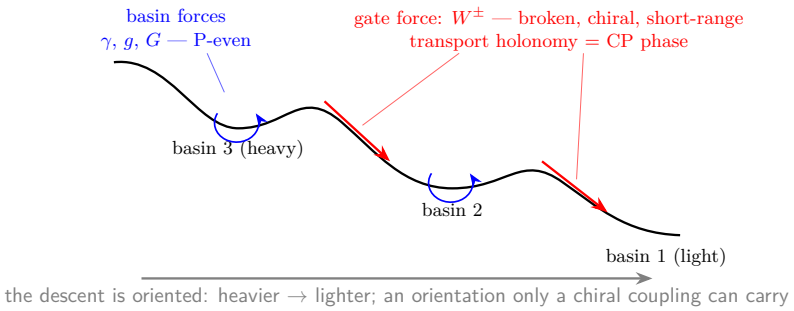


Figure 11: The family landscape. Unbroken forces hold their charges fixed and act within basins (blue); the unique broken force executes the gates (red), carries the downhill orientation — parity violation — and acquires the transport holonomy — the CP phase — along the way. "The descent is oriented, seen twice."

Third: the executor is dissipative. The descent is a decay — basin 3 states *fall* to basin 2 and the energy difference leaves, irreversibly, through the boundary's one-way law (the open-system clause of Part III). The executor is the force whose characteristic processes are decays: the force of finite lifetimes.

Fourth — the parity clause — the executor carries a direction:

> A Morse gradient flow has a direction: strictly downhill, heavier → lighter. A direction is an orientation, and an orientation can be carried only by a parity-violating coupling. The weak force is maximally chiral, and that maximal parity violation is the microscopic image of the cascade's one-wayness. A parity-even force cannot encode "the flow goes this way and not the other."

Physics intuition — the canal lock. Picture the family landscape as a river system stepping down through a set of canal locks. The open water of each pool is the domain of the basin forces: currents may swirl a boat anywhere within its pool, tirelessly and reversibly, and they never lower it. The locks are different machinery altogether. A lock is *local* — it works only at the step; it is *built*, not free — there is structure at the crossing that the open water does not have; it is *dissipative* — every descent spills water downstream and cannot be undone by the lock itself; and above all a lock is *one-way machinery in its operation*: gravity gives the traffic through it a direction, and the lock's mechanism is shaped by that direction — the gates open downstream. The weak interaction, on the reading this Part defends, is the lock machinery of the family landscape — and once one sees it so, the five superlatives stop being a list. Of course the lock force is the broken one: locks are built structure at the crossings. Of course it changes families: that is what a lock is *for*. Of course it is short-range: locks live at the steps. Of course its processes are decays: locks lower boats. And of course it is chiral — the clause the next block states — because one-way machinery must be able to tell which way is downstream. After all, no one is surprised that the machinery of a canal lock looks nothing like open water; the surprise would be a landscape with steps and no locks.

On this reading the five superlatives collapse to one: the weak interaction is the force of the landscape's *gates*, and every gate property — broken, chiral, off-diagonal, short-range, CP-bearing — is the same orientation seen through a different observable (Table 7; Figure 11). CP violation joins

Table 7: The basin/gate table. Five superlatives, one column: in the Standard Model five unconnected accidents of the input charges; in the oriented-descent reading, five faces of "the weak interaction is the gate force." Six properties across four forces. The weak column is set in bold because it is the one that differs in every row: broken where the others are unbroken, maximally parity-violating where the others are even, off-diagonal in family space where the others are diagonal, short-ranged, and the only home of CP violation.

Property	**Gravity**	**Strong**	**EM**	**Weak**
Gauge symmetry	unbroken (universal)	unbroken	unbroken	**spontaneously broken**
Parity	even	even (Vafa–Witten protected)	even	**maximally violating**
Family action	diagonal	diagonal	diagonal	**off-diagonal (unique)**
Range	long	confined, P-even	long	**short (massive W, Z)**
CP violation	none	none ($\bar{\theta} \to 0$)	none	**unique home**
Role	basin	basin	basin	**gate**

through Part VII: the gate crossings are where the family projector is transported, the transport's holonomy is the CP phase, and *chirality and CP violation are the single statement "the descent is oriented," seen twice.*

Register. The parent paper grades this synthesis honestly — "a structural argument, not yet a theorem" — and names the missing piece, quoted in full in Section 68. This Part carries the same grade and adds two small pieces the argument was missing: a convention-free invariant (Section 69) and a falsifier (Section 70).

65 The mechanism: the projection

Beneath the architecture sits a concrete mechanism, and its pedigree should be stated before its role. The bulk matter of the GG-6 program is genuinely chiral six-dimensional Weyl matter: in $(1, 5)$ signature the chiral spinor representation is complex, no Majorana condition exists, and the left- and right-handed Weyl modules are independent (Arisaka, 2026, A2-GG6) — there is a hand to pick. The reduction to the four-dimensional boundary projects the compact directions with a $\mathbb{Z}_2$ parity whose matrix on the SU(5) fundamental is

$$P \;=\; \mathrm{diag}(+1, +1, +1, -1, -1), \tag{42}$$

acting on the *radial* direction of the bulk (the canonical assignment in the parent program; the boundary sits at one end of the scale direction). Register, first and plainly: the $\mathbb{Z}_2$ itself and the matrix (42) are *asserted*, per Table 8 below — part of the construction, not derived from the axioms; their derivation from the admissibility filters is the ledger's registered open item. Two consequences follow at once. Gauge fields survive as zero modes only along generators commuting with P, so the

unbroken group is the centralizer of P in SU(5):

$$\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \tag{43}$$

— exactly the Standard-Model group (Arisaka, 2026, A5-GDOS). It is worth doing this computation in public, because it takes four lines and the reader who does it owns the Standard-Model group as a *result*. Write a general traceless hermitian generator of SU(5) in block form adapted to the signs of P — three "+" slots, two "−" slots:

$$M \;=\; \begin{pmatrix} A_{3\times 3} & B_{3\times 2} \\ B^{\dagger}_{2\times 3} & D_{2\times 2} \end{pmatrix}, \qquad PMP^{-1} \;=\; \begin{pmatrix} A & -B \\ -B^{\dagger} & D \end{pmatrix}. \tag{44}$$

Conjugation by P leaves the diagonal blocks alone and flips the sign of the off-diagonal ones. The generators commuting with P are therefore exactly the block-diagonal ones: the traceless A-block (SU(3), the gluons), the traceless D-block (SU(2), the weak bosons), and the one remaining trace direction that keeps M traceless overall,

$$Y \;\propto\; \mathrm{diag}\Big(-\tfrac{1}{3}, -\tfrac{1}{3}, -\tfrac{1}{3}, +\tfrac{1}{2}, +\tfrac{1}{2}\Big), \tag{45}$$

which is precisely the hypercharge assignment of the fields the **5** contains. Count: $8 + 3 + 1 = 12$ surviving gauge directions out of 24 — the Standard-Model group, obtained by striking out two blocks (Figure 12). The twelve projected directions — the off-diagonal B blocks, the X and Y bosons of grand unification — are removed from the four-dimensional gauge sector, which is also why this construction, unlike four-dimensional grand unification, puts no proton-decay mediator in the spectrum. The broken-direction components of the *internal* gauge field survive as boundary scalars: the Higgs sector is the projection's own debris, and the doublet–triplet economics — the celebrated headache of four-dimensional unification — is handled by the same signs (Kawamura, 2000), so the agent that breaks the symmetry and the agent that delivers the masses descend from one geometric object.

The fermions halve by the same signs, tied now to four-dimensional chirality. The projection condition couples the internal parity to the boundary chirality operator — schematically, on each SU(5) component of a bulk Weyl multiplet,

$$\Psi \;\longmapsto\; (P \otimes \gamma_5)\,\Psi \quad \text{under the reflection of the projected direction,} \tag{46}$$

so a component's zero mode survives only if its P-sign and its four-dimensional chirality agree: of the two hands inside each six-dimensional Weyl field, *exactly one* keeps a zero mode per representation, and the assignments select the left-handed set — a choice that is itself asserted, per Table 8 below. The count is worth performing once, because it lands exactly: the $\bar{\mathbf{5}}$ supplies five left-handed Weyl fields (d^c in three colors, and the lepton doublet L), the **10** supplies ten (Q in six components, u^c in three, and e^c) — fifteen left-handed Weyl fermions: one complete Standard-Model generation, nothing missing, nothing extra, and every mirror partner projected out rather than hidden. In one line from the parent paper: *the "L" in* $\mathrm{SU}(2)_L$ *is geometric, not phenomenological.*

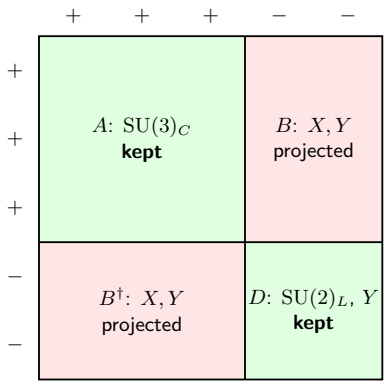


Figure 12: The projection at a glance: the SU(5) generators in the block form of Eq. (44), with the signs of $P = \mathrm{diag}(+,+,+,-,-)$ on the margins. An entry survives in the four-dimensional gauge sector iff its row and column signs agree. The green blocks are the Standard-Model group, Eq. (43); the red blocks — the X, Y directions of grand unification — are projected out of the gauge sector, their internal components surviving as the scalar debris the parent computation identifies with the Higgs sector.

Pedigree, conceded in full. This mechanism is orbifold-GUT technology: the projection matrix (42), the centralizer breaking, the chirality selection, and the doublet–triplet economics are the construction of Kawamura and of Hall and Nomura (Hall and Nomura, 2001; Kawamura, 2000), built in turn on the string orbifolds of Dixon, Harvey, Vafa, and Witten (Dixon et al., 1985). Nothing in this section is original to the GG-6 program, and the comparison of Part X credits it without reservation. What the program claims as its own is the *forcing*: in the orbifold-GUT literature the projection is a model choice among many; here the output — the Standard-Model group with three chiral generations — is claimed forced by the constitutional ledger, with the projection's own derivation from the admissibility filters (POS-1 smoothness, POS-3 anomaly freedom) registered as an open item rather than claimed. The distinction between *mechanism* (inherited) and *selection* (claimed, partially open) is the entire originality claim of this section, and it is deliberately modest.

65.1 What is derived and what is asserted — the ledger of the mechanism

66 Chirality is the orientation of the descent

The architecture and the mechanism meet in the reading this Part exists to defend. The projection says *how* one hand survives; the oriented descent says *why it must*: a cascade with a direction requires a carrier that can encode direction, and the carrier's chirality is that encoding.

Mass belongs to the same web, and the link is a two-line derivation worth displaying. A Dirac mass term pairs the two hands, $m\,\bar{\psi}_L\psi_R$. But the projection left the two hands *differently charged*: ψ_L sits in an $\mathrm{SU}(2)_L$ doublet and ψ_R (as its conjugate's partner) in a singlet, so the pairing

$$m\,\bar{\psi}_L\psi_R \qquad (\mathbf{2}\otimes\mathbf{1} \neq \text{invariant}) \tag{47}$$

is gauge-forbidden outright: *no fermion of the projected world may simply have a mass.* The only lawful route is through a doublet scalar — $y\,\bar{\psi}_L H\psi_R$ — and the projection has already supplied the

Table 8: The parity mechanism's honesty ledger. The outputs are verified; the projection's own necessity is the story's open frontier — stated here before any referee states it. Eight statements, each with its grade and the basis or residue behind it. Four are derived, three are marked asserted in bold, and one is a named conjecture. The three asserted rows are the projection matrix itself, the existence of the projection, and which chirality survives — and they are the three a reader should press on hardest.

Statement	**Grade**	**Basis / residue**
Centralizer of P in SU(5) is exactly $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	derived	explicit block computation (Arisaka, 2026, A5-GDOS)
6D matter is genuinely chiral (a hand exists to pick)	derived	Lemma 24.1; (Arisaka, 2026, A2-GG6)
Surviving spectrum is anomaly-free	derived	BI-6 inflow (Arisaka, 2026, A3-BI6)
Higgs sector = projection's broken-direction scalars	derived	zero-mode computation
The projection matrix P itself	**asserted**	"a standard parity assignment"; derivation from POS-1/POS-3 is open question (7)
The $\mathbb{Z}_2$ projection exists	**asserted**	part of the construction, not an axiom
Which chirality survives	**asserted**	the canonical Ramond-sector assignment; anchored physically only via P-P5-D
Gate force = broken force = chiral force (uniqueness)	conjecture	C-P5-A (L11)

very object: its own scalar debris. Every fermion mass in the world is therefore a Yukawa coupling times the condensate of the projection's leftovers, and the hierarchy of those couplings is read in the parent treatment as the cohomology of the doubled left/right stratum, ordered by the same Morse flow whose orientation is the parity violation.

Physics intuition — the toll at the gates. There is a warm way to hold this. In a vector-like world, mass is a birthright: any fermion may carry any mass, up to the deepest scale in the theory — which is why, by the survival argument below, such fermions are gone from the light world. In the projected world, mass is a *toll collected at the gates*: a fermion acquires inertia only by coupling to the gate structure's own scalar field, and how much it acquires is set by where it sits along the descent. That is why the mass hierarchy is ordered by the family cascade rather than scattered at random — the toll schedule and the road map are the same geometry — and why the particle that delivers all masses (the Higgs) and the force that changes all families (the weak interaction) were destined to sit in the same corner of the Standard Model. Parity violation, electroweak breaking, the mass hierarchy's direction, CP violation, and the weak monopoly on family change: one oriented structure, five projections onto experiment.

67 The two partial answers the orthodoxy does own

Honesty requires recording that quantum field theory, though it cannot ask "why only the weak force," does own two genuine structural results about parity, and the GG-6 architecture nests them rather than replacing them. *Vafa–Witten:* in vector-like theories — QCD above all — parity cannot break even spontaneously (Vafa and Witten, 1984); the strong interaction's mirror is theorem-protected. The reason is worth a sentence, because it is beautiful: in a vector-like theory the fermionic path-integral measure is positive, so the free energy of any parity-breaking configuration is provably no lower than that of its mirror-symmetric competitor — the vacuum cannot *afford* to break parity. In the basin/gate language this is the interior guarantee of the clause "unbroken ⇒ parity-even": not only does an unbroken force carry no orientation, its vacuum cannot manufacture one. *The survival argument:* vector-like fermions admit gauge-invariant bare masses and are generically superheavy; only chiral fermions are *forced* to be light, their masses forbidden until the symmetry breaks ('t Hooft, 1979). This is QFT's deepest "why is the light world chiral" — a quasi-anthropic structural selection: everything parity-even in the fermion sector has long since been paid its heavy mass and left the stage. The GG-6 account absorbs it gratefully — the descent's light spectrum is chiral for exactly this reason among others — and then answers the two questions the survival argument leaves open: why the chirality sits in $\mathrm{SU}(2)_L$ specifically, and why the broken force and the chiral force coincide. Those are the basin/gate clauses, and no statement internal to QFT reaches them.

68 The Gate-Operator Lemma: statement and status

The missing theorem is named in the parent treatment, and this paper adopts it as its principal conjecture:

Conjecture 68.1 (**C-P5-A** (the Gate-Operator Lemma, L11))**.** Any connection that parallel-transports the family projector between adjacent critical points of the family landscape is necessarily: (i) family-off-diagonal; (ii) *chiral* — it carries the orientation of the downhill gradient flow, and no parity-even connection can; (iii) massive, with its mass set by the symmetry-breaking vacuum at the gate. Within the boundary gauge group, the unique factor admitting all three properties is $\mathrm{SU}(2)_L$.

Read the three clauses slowly, because each carries a different weight. Clause (i) is the lightest: transport between distinct critical points is family-off-diagonal by construction; its content is uniqueness — that *only* the gate coupling does this — which is an observed fact awaiting its structural proof. Clause (iii) is the localization argument of §64 sharpened: the transporting connection lives at the saddle, the saddle has a symmetry-breaking vacuum, and the connection's mass is that vacuum's scale — the W's mass, on this reading, is the width of the gate. Clause (ii) is the crown, for it is precisely the statement "parity violation is a theorem of GG-Theory." Its natural proof strategy is an orientation-pairing argument, and the shape is easy to hold: suppose a parity-even connection could execute the transport. Parity-evenness means the connection commutes with the reversal that inverts the flow's orientation; but that reversal exchanges the downhill and uphill readings of the same gate, so the transport it commutes with cannot encode which end of

the gate is the lower — and a transport that cannot tell downhill from uphill cannot *execute a descent*, only a shuttle. What remains open is the formalization of "encode": the precise statement of how the flow's orientation is written into the connection's chirality, which is exactly the lemma. The completion is queued in the parent program; this paper does not claim it. Note also what would *kill* the conjecture: a demonstrably parity-even coupling observed to mediate family-changing decay — or, within the formalism, a construction of an even connection transporting the family projector down a Morse gate — would sever "chiral" from "gate" and collapse the architecture to a coincidence list. Until the lemma lands, the honest summary of this Part is: mechanism in place (inherited), architecture original and compelling, theorem pending.

69 The handedness invariant

One objection to any chirality claim must be met head-on: "left" versus "right" is a naming convention, so what physical content does "the left hand survives" possess? The answer is that a lone chirality label is convention, but a *correlation of orientations* is not. This paper registers the correlation as a new proposition of the program:

Proposition 69.1 (**P-P5-D**: the handedness invariant)**.** *The following three orientation data are not independent conventions but one alignment, invariant under all relabelings: (i) the internal chirality of the surviving fermion projection; (ii) the orientation of the family descent (the sign of the Morse flow, heavier → lighter); (iii) the sign of the CP-violating loop holonomy (the chirality of the flavor pentagon,* $+2\pi/5$ *versus* $-2\pi/5$*). Reversing any one of the three while fixing the other two yields a physically distinct world; reversing all three is a relabeling.*

Status and content. The proposition is stated here at proposition grade with its proof strategy, not its proof: (i) and (ii) are linked by C-P5-A(ii) (the carrier's chirality encodes the flow direction); (ii) and (iii) are linked by T-P5-3 plus the gate reading (the holonomy is acquired *along* the descent, so its sign is measured against the descent's direction); the invariance of the triple under total relabeling is T-P5-2's total-reversal blindness. Its experimental content is real: nature could have presented the opposite *relative* sign — the measured signs of J_{CKM} and the mass-ordering direction test the alignment — and the alignment is exactly what Wu's experiment, the unitarity triangle's area sign, and the mass hierarchy jointly measure. The proposition sharpens "the descent is oriented, seen twice" into "seen three times, with one sign."

The Ozma measurement, walked. Part I posed the old riddle — how would one communicate "left" to a distant civilization by physics alone? — and told its classic resolution: Wu's asymmetry defines a handedness, and the kaons' charge asymmetry resolves the residual matter–antimatter ambiguity in the instructions. P-P5-D upgrades the riddle's answer from a protocol to an invariant, and it is worth walking the three measurements that pin it. *Measure (i)*, the surviving chirality: Wu's correlation $\langle \vec{\sigma} \cdot \vec{p} \rangle < 0$ for the electrons of beta decay — the sign that says which hand the weak force couples. *Measure (ii)*, the descent's orientation: the direction of every family decay — muons become electrons and never the reverse — the arrow heavier → lighter. *Measure (iii)*, the pentagon's chirality: the sign of the Jarlskog invariant, read as the orientation of the unitarity triangle's area in the standard convention — which way the flavor pentagon turns. The proposition

asserts that these three signs are *one datum*: any world with the same laws realizes either this triple or its total reversal, never a mixed alignment. A civilization that measures all three and finds the mixed alignment has falsified the construction; a civilization that finds our alignment can now be told "left" in one sentence rather than three protocols. The Ozma problem, promoted from a puzzle about communication to a statement about the rigidity of nature's orientations.

70 The falsifier, registered: no right-handed weak sector

Left–right symmetric extensions of the Standard Model (Mohapatra and Pati, 1975; Pati and Salam, 1974) restore parity at high energy: the mirror fermions and a W_R exist, made heavy by a second breaking scale, and parity violation is an accident of our low vantage. The GG-6 construction predicts the opposite, and this paper registers the prediction as a falsifier:

> **F-P5-1 (no W_R, at any scale).** The mirror modes are projected out of the spectrum, not made heavy: there is no right-handed weak gauge sector at any energy, and parity is never restored. The observation of a W_R, of mirror fermions completing the right-handed doublets, or of parity restoration at any scale falsifies the geometric-projection construction of Section 65 outright.

This converts what Report-level review identified as a gap (the cohort offered no parity falsifier) into an asset: the construction is *more* falsifiable than left–right symmetry, since every future collider limit on W_R (Particle Data Group, 2024) bears on it, and a single discovery kills it with no parameter to hide behind. (Registration in the cohort's canonical falsifier ledger, with its F-number assigned against the master list, is queued with the author's approval of this paper.)

71 Note on the projection's location

For the cohort-literate reader, one internal note. The fermion chirality projection acts on the *radial* (scale) direction of the bulk — the canonical assignment, stated as such in the Standard-Model treatment. The compact phase circle S^1_θ carries no $\mathbb{Z}_2$ identification — the smoothness clause of POS-1 forbids it, and the Kaxion's Wilson line requires the full smooth circle (Arisaka, 2026, C1-Kaxion). Earlier presentations of the zero-mode computation phrased the projection on the angular coordinate; the radial phrasing is the canonical one, and the harmonization of the older text is a housekeeping item of the parent program, noted here so that no reader takes the variation in phrasing for a variation in physics.

72 What is claimed, and what is inherited

Concessions first, in full — the register's order, and for this Part the concessions are unusually large. The mechanism of §65 is inherited item for item: the projection matrix, the centralizer breaking, the chirality selection, and the doublet–triplet economics are the orbifold GUT of Kawamura and

Hall–Nomura (Hall and Nomura, 2001; Kawamura, 2000), built on the string orbifolds of Dixon–Harvey–Vafa–Witten (Dixon et al., 1985); chirality from the geometry of extra dimensions is string theory's oldest four-dimensional success (Candelas et al., 1985); the theorem-protection of QCD's mirror is Vafa–Witten's (Vafa and Witten, 1984); and the deepest orthodox "why is the light world chiral" is the survival argument ('t Hooft, 1979). None of the machinery on these pages is original, and the comparison of Part X pays each source in its own section. What this Part claims, ranked by confidence, at the grades of Table 8: *first*, the basin/gate architecture as an answer to the question no other framework poses — why the broken, chiral, family-changing, short-range, CP-bearing superlatives all land on one gauge factor; the Standard Model holds them as five accidents, string theory as five vacuum properties, and no formalism known to this program connects any two of them, while the oriented descent derives all five from one fact (grade: structural argument, C-P5-A pending). *Second*, the forcing-versus-selection distinction: in the orbifold-GUT literature the projection is a choice from a catalog; here the output is claimed forced by the constitutional ledger, with the projection's own derivation honestly open — the difference between a mechanism and an explanation, kept explicit. *Third*, the handedness invariant P-P5-D — the Ozma problem promoted to a convention-free alignment with measurable content. *Fourth*, the falsifier F-P5-1 — the conversion of "no parity falsifier registered" into the sharpest one available: projected out, not made heavy; never restored, at any scale. Nothing in the four claims leans on a grade stronger than the ledger prints.

Part-end summary. One projection breaks the unified group to the Standard-Model group — a four-line block computation the reader has now performed — and keeps one hand of fifteen states, a complete generation with its mirrors removed rather than hidden. One architecture says why the hand-keeping force must be the broken, family-changing, short-range, dissipative one: the canal locks of a landscape whose descent has a direction. One conjecture (C-P5-A) stands between architecture and theorem; one proposition (P-P5-D) makes the handedness a measurable alignment rather than a convention; one falsifier (F-P5-1) makes the whole story mortal at every future collider. The same orientation is now to be seen a second time — as the chiral holonomy the descent writes on the flavor texture: the pentagon, and the price of CP.

Part VII
CP Violation: The Chiral Pentagon

Where CP phases live (loop holonomies), what values them (the pentagonal lattice), and what follows: the forced quark and lepton phases, step by step; the dial-free door; the strong-CP complementary fate; five worked examples

73 Part VII in plain English: where the CP phases live, and what values them

A phase that can be dialed to any value explains nothing; it records what was measured. This Part argues that in this geometry the CP phases cannot be dialed. They are holonomies of loops in the flavor graph, and the lattice those loops live on is pentagonal, so the admissible values form a list rather than a continuum.

Two theorems carry it. The flavor holonomy theorem says where the phases live and how they are computed; the dial-free door says which channel is open and forces the Majorana case where it does. Between them they turn the question "what is the CP phase?" into the question "which lattice point?" — and a list can be wrong in a way that a dial cannot, which is the whole reason for preferring one.

Strong CP appears here as the complementary fate: the one angle relaxed dynamically rather than locked to a lattice point. The Part closes with worked examples, the claimed-and-inherited separation, and a status ledger for the mirror Parts, so the standing of everything proved since Part V can be read down a single column.

74 The question no dial can answer

Of all the questions this paper asks, the one this Part answers is the author's oldest debt. Part I told the history: in 1964 the long-lived kaon decayed into two pions, and the repaired mirror — the one symmetry the community had agreed nature surely kept — broke, at two parts in a thousand (§6). In 1973 Kobayashi and Maskawa found where such a breakage could *live*: with three generations, one complex phase survives every field redefinition, and CP violation can be written into the quark matrix (Kobayashi and Maskawa, 1973). It was a discovery of the first rank — it predicted the third generation — and yet the reader should see with complete clarity what it did and did not do. It located the dial. It did not turn it. In the Standard Model the phase δ is a free parameter: $\delta = 0$ — no CP violation, no baryogenesis, no us — is exactly as lawful as the measured 1.147, and nothing in the formalism prefers one to the other. The author spent two experimental decades inside this dial's consequences — ε'/ε at KTeV, $\sin 2\beta$ at BaBar — measuring, to three

digits, a number that the reigning theory declared unexplainable in principle. Why does the mirror between matter and antimatter break at all? And why by *exactly this much*? The Standard Model's honest answer to both questions is: no reason.

This Part derives the dial's setting, and the derivation has a shape worth announcing in advance, because each stage is a different kind of result. *First*, a calculus (T-P5-3, clauses i–iii): where CP phases live — not in couplings but in *closed loops* of couplings, as rephasing-invariant holonomies on the flavor graph; this stage is inherited mathematics, geometrized, and the Part says so. *Second*, a valuation (clause iv): what sets the holonomies' values — on the GG-6 bulk they are not continuous dials but points of a *pentagonal lattice*, because the one compact circle and the block integer $L = 5$ are the only alphabet available; this stage is the new physics, and everything falsifiable descends from it. *Third*, the outputs, chain by chain and step by step: the quark phase (with the Cabibbo angle's golden-ratio closed form as a by-product), the lepton phase, the Majorana pair, and the two Jarlskog invariants — each a number with a pull, not a fit. *Fourth*, the unique door the phases will bias (T-P5-4). And *fifth*, the complementary fate: why the same geometry that forbids the weak CP angle to vanish forces the strong one to. Roughly speaking, the Part replaces "one dial, unexplained" with "one alphabet, no dials" — and the alphabet has five letters.

75 T-P5-3: the flavor holonomy theorem

Theorem 75.1 (**T-P5-3**: flavor holonomy and the chirality criterion)**.** *Regard a Yukawa texture as a* U(1)*-valued connection on the flavor graph (Section 20). Then: (i) the rephasing group acts as the gauge group of the graph, and in a spanning-tree gauge the residual physical data are exactly the loop holonomies, numbering* $(N_g - 1)^2$ *for* N_g *generations; (ii) the quartet invariants* $\mathrm{Im}(V_{ij}V_{kl}V_{il}^*V_{kj}^*)$ *are the plaquette sines, and for* $N = 3$ *unitarity ties all of them to the single Jarlskog invariant; (iii) CP is a symmetry if and only if every loop holonomy lies in* $\{0, \pi\}$ *— CP violation is chirality of the texture on the circle; (iv) on the GG-6 bulk — one compact circle, no second flavor torus, block integer* $L = 5$ *— the first-order loop holonomies are valued in the pentagonal lattice* $(\pi/5)\mathbb{Z}$*.*

Proof. (i) The rephasing (7) is the gauge action of $\mathrm{U}(1)^{2N}$ on edge angles; on any closed loop the dial turns telescope to zero, so loop holonomies are invariant; nulling a spanning tree's $2N - 1$ edges (one dial per vertex, one overall turn acting trivially) leaves one angle per independent cycle: $N^2 - (2N - 1) = (N - 1)^2$. (ii) A quartet is the smallest rephasing-invariant product with an imaginary part; its phase is the four-edge plaquette holonomy; the standard unitarity identities (Jarlskog, 1985) equate the nine plaquettes up to sign for $N = 3$. (iii) By T-P5-1, CP reverses the fiber and negates every edge angle; the transformed texture is a rephasing of the original iff every loop angle satisfies $\varphi \equiv -\varphi \bmod 2\pi$, i.e. $\varphi \in \{0, \pi\}$. (iv) A loop holonomy is a closed transport on the single circle S^1_θ; the fiber carries no continuous modulus (Theorem 0's arena is rigid, and the holonomy moduli of the flavor connection are set by the block structure), so first-order holonomies are built from the block-geometric angles available, all of which are multiples of $\pi/L = \pi/5$: the Higgs doublet retains the fraction $2/L$ of the unified block, forcing the branch phase $\pi(1 - 2/L) = 3\pi/5$, and per-family re-zeroings move angles by the lattice step $\pi/5$ (Arisaka, 2026, A9-SM). Absent a second torus there is no continuous direction in which a holonomy could float off the lattice. ∎

Physics intuition. An experimentalist has met clause (iii) before, in different clothes: it is the statement that CP violation requires a phase that cannot be rephased away, promoted from bookkeeping to geometry — the unremovable phase is a closed-loop angle, as gauge-invariant as the Aharonov–Bohm phase and for the same reason. Clause (iv) is the new physics. In the Standard Model the surviving loop angle is a continuous parameter: nothing values it, and $\delta = 0$ (no CP violation, no us) would have been as lawful as the measured 1.147. On the GG-6 bulk the angle is a *lattice point*: the pentagon of $L = 5$ is the only alphabet available, and CP violation exists because the forced branch phase $3\pi/5$ is not a multiple of π — *the flavor pentagon is chiral.* The same pentagon whose trigonometry (the golden ratio) sets the Cabibbo angle's magnitude sets the existence and the size of CP violation. One geometric object, two of flavor physics' deepest numbers.

75.1 The calculus, walked: dials, trees, loops, and one area

The proof above is complete but compressed, and this Part's subject deserves the uncompressed version. Let us walk clauses (i) and (ii) slowly, with every object displayed.

The dial group. The flavor graph of §20 has $2N_g$ vertices (the up-type and down-type family fields) and N_g^2 edges (the Yukawa couplings), each edge carrying a real twist angle φ_{ij}. A rephasing is a turn of the dials: one free angle per vertex,

$$\varphi_{ij} \;\longmapsto\; \varphi_{ij} + \alpha_i - \beta_j, \tag{48}$$

the gauge action of $\mathrm{U}(1)^{2N}$ on the edge data. Now transport around a closed loop of edges, alternating direction as the bipartite structure demands, and add the angles with signs. Every dial in the loop is entered once and left once, so its two contributions cancel — the sum *telescopes* — and the loop angle is untouched by every rephasing: a gauge invariant, for exactly the reason the Aharonov–Bohm phase is one.

The count. How many independent invariants survive? Fix a spanning tree of the graph — $2N - 1$ edges touching every vertex with no loop — and use the dials to null its angles one edge at a time, working outward from a root; $2N - 1$ of the $2N$ dials are spent (the overall simultaneous turn acts on no edge), and no freedom remains. What is left is one angle per independent cycle:

$$N^2 - (2N - 1) \;=\; (N - 1)^2 \qquad \xrightarrow{N_g=3} \qquad 4 \tag{49}$$

physical angles for three generations — the gauge-fixed content of the texture, obtained by an electrician's procedure rather than a matrix decomposition.

The smallest invariant, and the one area. The smallest closed loop in a bipartite graph has four edges: up-family i to down-family j to up-family k to down-family l and back — a *plaquette.* Its holonomy is the phase of the quartet $V_{ij}V_{kl}V_{il}^*V_{kj}^*$, the smallest rephasing-invariant product with an imaginary part, and its sine is the quartet's imaginary part in unit-modulus normalization. For $N = 3$, unitarity of the mixing matrix ties the nine plaquettes together: all their sines are equal up to sign, and the common magnitude is the Jarlskog invariant (Jarlskog, 1985),

$$\left|\mathrm{Im}\,(V_{ij}V_{kl}V_{il}^*V_{kj}^*)\right| \;=\; J \quad \text{for every plaquette :} \tag{50}$$

one area for the whole graph — geometrically, twice the area of the unitarity triangle, whichever of the six triangles one draws. This is why the global fit's consistency is a one-number statement, why all of quark CP violation is priced by a single angle, and why the four angles of (49) collapse, for observables, to one invariant phase and three magnitudes.

75.2 The criterion and the lattice, walked

The criterion (clause iii), cashed from Part V. Part V's walk established that fiber reversal negates every texture angle (§55.1); composing with the space reversal, which touches no fiber angle, CP sends $\varphi_{ij} \mapsto -\varphi_{ij}$ on every edge. The transformed texture describes the same physics iff it is a rephasing of the original — iff every *loop* angle, which no rephasing can touch, equals its own negative:

$$\varphi_{\text{loop}} \equiv -\varphi_{\text{loop}} \pmod{2\pi} \iff \varphi_{\text{loop}} \in \{0, \pi\}. \tag{51}$$

A texture all of whose loops sit at 0 or π is *achiral on the circle* — its twists are indistinguishable from their mirror — and CP holds. A single loop off the real axis makes the texture chiral, and CP breaks. The criterion is exact, convention-free, and now a theorem of the anatomy rather than a rule of thumb.

The valuation (clause iv), and what it forbids. Here the Standard Model and the GG-6 bulk part company, and the reader should see precisely where. Both frameworks agree on (51); the question is what *sets* φ_{loop}. In the Standard Model the loop angle is a continuous parameter of the Yukawa matrices — any value is lawful, nothing prefers any value, and the measured 1.147 is an initial condition of the universe. On the GG-6 bulk, run the inventory of what could possibly value an angle. *Could it float on a continuous modulus?* No: Theorem 0's arena is rigid — the fiber has no radius to vary, no shape parameter, no landscape of vacua (§37.1); the moduli that make string-theoretic CP phases continuous simply do not exist here. *Could it live on a second flavor torus, with its own alphabet?* No: the arena has exactly one compact direction — one circle, hence one alphabet of angles. *What angles does that alphabet contain?* The block geometry's own: the unified block carries the integer $L = 5$, the Higgs doublet retains the fraction $2/L$ of it, and the branch phase forced by that retention is $\pi(1 - 2/L) = 3\pi/5$, with per-family re-zeroings moving angles by the step $\pi/L = \pi/5$ (Arisaka, 2026, A9-SM). Every first-order holonomy is therefore a multiple of $\pi/5$: the pentagonal lattice. The honest residue is stated in the mirror-Parts ledger: that *no* further continuous deformation of the holonomy moduli exists is graded derived-conditional ("rigidity"), and it is the single hinge on which clause (iv) turns. Granted the rigidity, the conclusion is remarkable enough to state twice: *CP violation exists because* $3\pi/5$ *is not a multiple of* π — the flavor pentagon is chiral — and no choice, anywhere, was available to make it otherwise.

75.3 The quark sector: from the pentagon to δ_{CKM}

Before the chain, the pentagon itself — because the whole sector runs on the trigonometry of the number five, and the reader deserves it from scratch. In a regular pentagon the diagonal and the side are locked in the most famous ratio in mathematics: drawing two diagonals from one vertex cuts the pentagon into triangles similar to those of the pentagram, and the similarity forces

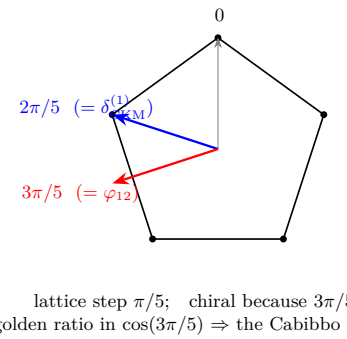


Figure 13: The flavor pentagon. With one compact circle and block integer $L = 5$, first-order holonomies live on the lattice $(\pi/5)\mathbb{Z}$: the forced branch phase $3\pi/5$ (red) is not a multiple of π, so CP violation must exist; one unphysical lattice step leaves the physical phase $2\pi/5$ (blue); and the pentagon's trigonometry — the golden ratio — sets the Cabibbo magnitude (53). One object, two of flavor physics' deepest numbers.

$d/s = 1 + s/d$, whose positive root is the golden ratio $d/s = \phi = (1+\sqrt{5})/2$. From it, two lines of trigonometry deliver everything this Part uses:

$$\cos 36^\circ = \frac{\phi}{2} = \frac{1+\sqrt{5}}{4}, \qquad \cos 72^\circ = 2\cos^2 36^\circ - 1 = \frac{\sqrt{5}-1}{4}. \tag{52}$$

And two of the pentagon's canonical angles will now appear in the physics with their geometric identities intact: the *interior* angle $108^\circ = 3\pi/5$ — the angle at each corner — will be the forced branch phase, and the *central* angle $72^\circ = 2\pi/5$ — the angle each side subtends at the center — will be the physical CP phase. The reader may reasonably suspect numerology at this point; the chain below is the antidote, six steps, each with its provenance and its grade.

Step 1 (inherited; parent grade Asserted, chosen post-hoc; carried without upgrade): the mixing magnitudes. The up- and down-sector nearest-neighbor mixing angles are fixed upstream by the mass-ratio geometry of the parent treatment, $\theta_{12}^{(u)} = \sqrt{y_u/y_c} = e^{-\pi}$ and $\theta_{12}^{(d)} = \sqrt{y_d/y_s} = e^{-\pi/2}$ (Arisaka, 2026, A9-SM): the square-root-of-mass-ratio form is the standard seesaw-texture relation, and the specific exponentials are the parent codebook's cascade mass ratios — whose grade in that codebook's own provenance table is Asserted (chosen post-hoc), a grade this paper carries verbatim, without upgrade. Nothing in this Part adjusts them.

Step 2 (derived-conditional): the branch phase. The relative branch phase between the two sectors is the forced pentagonal angle $\varphi_{12} = \pi(1 - 2/L) = 3\pi/5$ — the Higgs doublet retains two of the block's five directions, and the branch phase is π diminished by the retained fraction (§75.2). Note the geometry keeping its word: $3\pi/5$ is the pentagon's interior angle.

Step 3 (derived, given Steps 1–2): the Cabibbo interference. The observable 1–2 mixing is the *phasor difference* of the two sectors' rotations, carried out at the relative angle φ_{12}:

$$\sin\theta_{12} \;=\; \left|e^{-\pi/2} - e^{\,i\,3\pi/5} e^{-\pi}\right| \;=\; 0.22502, \qquad \sin^2\theta_{12} = e^{-\pi} + e^{-2\pi} + \tfrac{\sqrt{5}-1}{2}\, e^{-3\pi/2}, \tag{53}$$

and the closed form is worth deriving in public. For any two magnitudes a, b at relative angle φ, $|a - be^{i\varphi}|^2 = a^2 + b^2 - 2ab\cos\varphi$; here $a = e^{-\pi/2}$, $b = e^{-\pi}$, and $\cos(3\pi/5) = -\cos 72^\circ = -(\sqrt{5}-1)/4$

by (52), so the cross term is $+2\,e^{-3\pi/2}(\sqrt{5}-1)/4 = \frac{\sqrt{5}-1}{2}\,e^{-3\pi/2}$: the golden-ratio coefficient is not decoration but the cosine of the pentagon's central angle doing its work. Numerically: $e^{-\pi} = 0.043214$, $e^{-2\pi} = 0.001867$, $\frac{\sqrt{5}-1}{2}e^{-3\pi/2} = 0.618034 \times 0.008983 = 0.005552$; the sum is 0.050633, whose square root is 0.22502 — against the measured 0.22501 ± 0.00068. The pentagon's literal signature, at four decimal places.

Step 4 (derived-conditional): from branch phase to physical phase. The branch phase is not yet the CP phase: one common family rephasing is unphysical, and on the lattice the shortest step such a rephasing can take is $\pi/L = \pi/5$. Removing it,

$$\delta^{(1)}_{\rm CKM} \;=\; \frac{3\pi}{5} - \frac{\pi}{5} \;=\; \frac{2\pi}{5} \;=\; 72^\circ \tag{54}$$

at first order — the raw mismatch is three pentagonal steps, one is basis choice, two are physical. Interior angle in, central angle out: the two canonical angles of the pentagon, divided by one lattice step of convention.

Step 5 (asserted; flagged): the quantum-defect completion. The QD completion applies the shortest allowed throat slip, $-\pi/K$ with $K = 35$:

$$\delta^{\rm QD}_{\rm CKM} \;=\; \frac{2\pi}{5} - \frac{\pi}{35} \;=\; \frac{13\pi}{35} \;=\; 1.16688\ \text{rad} \;\simeq\; 66.9^\circ, \tag{55}$$

against the measured 1.147 ± 0.026 rad: a pull of +0.70. *Status, stated plainly:* the first-order value (54) is the forced result (pull +1.17 with a one-lattice-step theory width $\pi/35$ added in quadrature; against the experimental error alone the raw value sits at $+4.2\sigma$); the QD step is a bounded lattice correction whose size is ledger-quantized (one lattice unit, drawn from the parent's frozen completion class) and whose direction and necessity are asserted per site — the parent paper's own codebook flags it "post-hoc," and this paper carries the flag verbatim rather than absorbing it.

Step 6 (derived, given the above): the area. The Jarlskog invariant follows with no further input beyond the measured moduli, and the evaluation layer is stated so the number can be audited — PDG-class moduli ($s_{12} = 0.2250$, $s_{23} = 0.0418$, $s_{13} = 0.0037$; prefactor $c_{12}c_{23}c_{13}^2 = 0.9735$) with the QD phase:

$$J_{\rm CKM} = c_{12}c_{23}c_{13}^2\, s_{12}s_{23}s_{13} \sin\delta^{\rm QD}_{\rm CKM} \;=\; 3.1 \times 10^{-5}, \tag{56}$$

squarely on the measured $(3.12^{+0.13}_{-0.12}) \times 10^{-5}$. Across the framework's evaluation layers — first-order versus QD phase, all-first-order moduli versus measured moduli — the same area evaluates between 2.7 and 3.2×10^{-5}; that layer spread, not an error bar, is the band the tables quote. Every downstream quark-sector CP observable is this one area read through different interferometers: Appendix E recomputes ε, ε'/ε, and $\sin 2\beta$ from this single angle as holonomy interferometry, and §E.3 is the version for the reader who has sat the shifts.

Physics intuition — what kind of answer this is. Stand back and ask what has actually been claimed. The question "why is CP violation exactly this strong?" has received an answer of an unfamiliar kind: *because a pentagon's angles are what they are.* The branch phase is an interior angle; the physical phase is a central angle; the Cabibbo magnitude carries the golden ratio, which is the pentagon's aspect; and the lattice step that separates convention from physics is the pentagon's own

fifth of a half-turn. In the Standard Model these four numbers are one fitted dial and three fitted moduli; here they are four readings of one geometric object, and the object was not chosen — $L = 5$ is the ledger's, forced upstream of this paper, in use across twenty-one companion treatments for everything from the Cabibbo angle to the lock scale. Indeed, that is the real force of the pentagon: it was not built for CP violation, and CP violation falls out of it.

75.4 The lepton sector: $\delta_{\rm PMNS}$ and the Majorana pair

The lepton chain runs on a different ledger integer, and the difference is itself structural: where the quark alphabet is the block integer $L = 5$, the lepton alphabet is the odd chirality counter $J = 2N + 1 = 7$ — the same integer that counts the generations' doubled hands plus the axis, and the same 7 whose power suppresses the strong-CP leakage below. Five steps, each graded.

Step 1 (inherited): the reactor-block phase. The minimal neutrino mixing operator of the parent treatment carries the reactor-block angle $\phi_\nu = \arcsin(1/(2N{+}1)) = \arcsin(1/7)$ (Arisaka, 2026, A9-SM): the smallest angle the odd-integer alphabet writes, appearing where the smallest lepton mixing (the reactor angle's sector) demands it.

Step 2 (derived-conditional, on the leptonic assignment lemma): the reference shift. The physical Dirac phase is read against the parameterization's real reference channel, and that channel enters the structural form with a negative sign: the measured phase is the block phase shifted by π —

$$\delta^{(1)}_{\rm PMNS} \;=\; \pi + 2\arcsin\frac{1}{7} \;=\; 196.43^\circ, \qquad \delta^{\rm QD}_{\rm PMNS} \;=\; 196.06^\circ, \tag{57}$$

with the QD completion applying the same bounded throat slip as the quark chain. A subdominant assignment degeneracy $\{\pi, 3\pi/2\}$ exists at the lemma level and is resolved in favor of the structural form; the resolution is part of the assignment lemma's residue, carried in the ledger rather than hidden. The subdominant $3\pi/2$ assignment branch is hereby pre-registered as dead: a measurement near 270–286° may *not* be reinterpreted under the alternative branch; the assignment lemma is frozen in the form stated here, and its failure is the chain's failure.

Step 3 (the confrontation). The prediction sits within 1.0σ of the current normal-ordering global fit ($177^\circ{}^{+19}_{-20}$ (NuFit Collaboration, 2024)) — and is already disfavored at $\approx 3\sigma$ under inverted ordering, which the derived spectrum excludes in any case — and, more importantly, it sits squarely inside the $\pm 15^\circ$-class resolution DUNE and Hyper-Kamiokande will deliver in the 2030s. This is the falsifier with the nearest date in the whole Part: a measured $\delta_{\rm PMNS}$ at, say, 270° kills the chain with no parameter to hide behind.

Step 4 (derived, given T-P5-4): the Majorana pair. The Majorana phases are not fitted either. The constitutionally forced rank-two Majorana block (T-P5-4 below) fixes one state of each intrinsic parity — the two surviving heavy states are a parity pair, not a phase continuum — so

$$(\alpha_{21}, \alpha_{31}) \;=\; (0, \pi) \tag{58}$$

— parity data, not dials. With the parent treatment's derived light masses, the effective neutrinoless double-beta mass is $m_{\beta\beta} \simeq 1.72$ meV (the first-order evaluation, which is the registered value; the QD-layer evaluation is 1.79 meV): below current reach, inside the ambitions of the tonne-scale

program, and the cleanest laboratory shadow the Majorana pair casts.

Step 5 (derived, given the above): the leptonic area. The leptonic Jarlskog is $J_{\rm PMNS} \simeq -9.4\times10^{-3}$ (the NuFit-angle layer; the parent's first-order-angle evaluation gives -9.2×10^{-3}) — three hundred times the quark area, which is why the long-baseline program can see it this decade (Worked Example IV works the rate asymmetry). Every number in this subsection is a falsifier with a date attached (Part XII).

75.5 The completion class, disclosed in one table

The quantum-defect completion deserves one table rather than scattered flags, and here it is: every QD completion used in this paper or inherited from its parent codebook, with its size, its unit, and its direction relative to the data. The standing defense is stated fairly: each step is a bounded, quantized element of a frozen completion class — a lattice or throat step the ledger already owns, incapable of further adjustment once applied, and falsifiable as such. The audit's counterweight is printed beside it, because both facts belong to the record: the class is heterogeneous in size and unit (an angle here, a ratio there), its necessity at each site is asserted rather than derived, and wherever the step was exercised its direction has favored the data — with the single exception of the Cabibbo modulus, where the completion points away from the data and the registered tables quote the first-order value.

Table 9: The quantum-defect (QD) completions used in this paper or inherited from its parent codebook, each with size, unit, and direction relative to the data. The parent's own grade for the class is Asserted (chosen post-hoc), carried here without upgrade; the standing defense and the audit's counterweight are stated together in the text above.

Observable	First order	Completion	Size (unit)	Direction vs data
$\delta_{\rm CKM}$	$2\pi/5 = 72^\circ$	one throat slip $-\pi/K$	$-\pi/35$ (angle)	toward
$\delta_{\rm PMNS}$	$\pi + 2\arcsin(1/7)$	the same slip, lepton alphabet	$-\pi/490$ (angle)	toward
s_{13} (CKM)	cascade product	multiplicative defect	+12% (ratio)	toward
$\sin\theta_{12}$ (CKM)	0.22502, Eq. (53)	modulus defect	−0.02% (ratio)	**away**; the registered tables quote first order
fermion masses	parent cascade exponentials	per-particle defects	per-particle (various)	toward, by construction

76 T-P5-4: the dial-free door

Theorem 76.1 (**T-P5-4**: Majorana iff weight zero)**.** *Let a fermion multiplet carry weight n under the compact phase circle S^1_θ. A Lorentz-invariant, gauge-invariant Majorana-type self-pairing —*

equivalently a $\Delta L = 2$ bilinear — exists iff $n = 0$. On every $n \neq 0$ sector the unique invariant symmetric self-pairing is the charge-conserving Dirac pairing; and the trilinear LHN is the unique fiber-neutral portal touching the weight-zero sector linearly.

Proof. In the real presentation the symmetric square of a weight-n pair decomposes into the rotation-invariant combination $a^2 + b^2$ — the Dirac pairing, which conserves winding — and a doublet rotating with weight $2n$, which is invariant iff $2n\alpha \equiv 0$ for all α, i.e. iff $n = 0$. For $n = 0$ the reality condition of the sector *is* the Majorana condition: the field is its own conjugate because the circle does not move it. The portal statement follows by weight counting on the trilinear: only the weight-zero singlet can couple linearly to a fiber-neutral combination of doublet and Higgs (Arisaka, 2026, A9-SM). ■

Physics intuition. Lepton number is winding number. A charged field cannot be its own antiparticle because conjugation reverses a circle that moves it; the neutrino, alone in the matter sector, has nowhere to wind — and so it, alone, may pair with itself. The theorem converts the seesaw from a model-builder's choice into a constitutional consequence: if neutrinos have mass at all, the unique lawful $\Delta L = 2$ structure is the weight-zero self-pairing, the heavy completion enters through the unique portal, and every dial that a seesaw model normally offers is absent — which is why the parent program calls it the *dial-free door*. Part VIII walks through it: the door's CP-biased traffic, transported by the boundary's one-way law, is the matter of the universe. And the door carries its own laboratory test: Majorana nature plus the parity pair (58) plus the derived masses give $m_{\beta\beta} \simeq 1.7$ meV — below current reach, squarely in the sights of the next-generation program.

The dial count, performed. To feel what "dial-free" buys, count what a generic seesaw offers the model builder: three heavy Majorana masses, free; a 3×3 complex Yukawa texture coupling the heavy states to the doublets, free up to rephasing; and the high-scale phases the Casas–Ibarra parameterization makes explicit — a continuum of them (Casas and Ibarra, 2001). Every one is a place where the answer can be adjusted after the question is asked. Now count here. The portal is unique (the trilinear of the theorem); the weight-zero sector is unique (Part IV's still point, §46, where this door was seeded); the heavy masses are set by the lock scale of the ledger, not chosen (Part VIII); the Yukawa is fixed by seesaw matching to the derived light masses; and the phases are the lattice and parity data of this Part. The count of adjustable quantities is zero — which is precisely why every row of Table 10 is a confrontation rather than a fit, and why Part VIII can hand the cosmology a chain with nothing left to turn.

77 Strong CP: the complementary fate

The quark and lepton phases of Section 75 are *locked*: lattice points, unable to relax. This section concerns the one CP angle with the opposite experimental character, and the reader deserves its statement from scratch. The strong interaction's Lagrangian admits one more CP-odd term than the ones this Part has priced: the topological density, whose coefficient combines with the quark mass matrix's overall phase into the invariant $\bar{\theta} = \theta_{\text{top}} + \arg\det(M_u M_d)$. A nonzero $\bar{\theta}$ would give the neutron an electric dipole moment — a T-odd, P-odd static moment of exactly the kind Part V's

dividends section said the instruments hunt — and the hunt has come back empty at extraordinary depth: $|\bar{\theta}| \lesssim 10^{-10}$ (nEDM Collaboration, 2020; Particle Data Group, 2024). Here is the Standard Model's second CP embarrassment, the mirror image of the first: a phase that may take any value takes, inexplicably, the most special value available — while sitting in the same Lagrangian as a weak phase of order one. Two dials, one spun to 66°, one parked at zero to ten digits, no connection between them. On the GG-6 bulk the pair is not a coincidence but a complementarity: the same alphabet that *locks* the weak angle on the lattice gives the strong angle a fate of the opposite kind — it is the one angle the geometry lets *relax*. Three statements, each with its grade.

No knob is exported (derived). The first statement turns on a difference in logical direction that deserves one slow sentence. Effective-field-theory practice writes down *every* gauge-invariant term the symmetries permit and lets data set the coefficients — on that logic θ_{top} exists because nothing forbids it, and its smallness is a fine-tuning. The visible four-dimensional Lagrangian of this program is not assembled that way: it is *exported* from the bulk — every term arrives with a coefficient the descent computes — and the topological density $G\widetilde{G}$ appears only if the descent generates its coefficient. The bulk construction generates none (Arisaka, 2026, A2-GG6; Arisaka, 2026, A3-BI6): $\theta_{\text{top}}^{(1)} = 0$ — the strong-CP problem is solved first "by the absence of a knob." Not a symmetry imposed, not a relaxation arranged: a term that was never written, because nothing upstairs writes it.

The determinant phase cancels at first order (conditional, lemma L9). In the first-order quark codebook the singular values are positive and the physical phases live only in the misalignment matrices, so $\arg\det(M_u M_d) = 0$: a relative family phase can generate CKM CP violation without generating strong CP — the precise distinction the Standard Model makes by hand, here geometric. The end-to-end proof is the named lemma L9, outstanding; the residual leakage carries a closed-form bound worth displaying, because every factor is a ledger integer:

$$|\bar{\theta}| \;\lesssim\; \sin\!\Big(\frac{2\pi}{L}\Big)\,\frac{e^{-K}}{2^{J}} \;=\; \sin\!\Big(\frac{2\pi}{5}\Big)\,\frac{e^{-35}}{2^{7}} \;\simeq\; 4.7\times 10^{-18}, \tag{59}$$

eight orders of magnitude below the neutron-EDM bound $|\bar{\theta}| \lesssim 10^{-10}$. Read the three factors, because each is a ledger integer doing its characteristic work: $\sin(2\pi/5)$ is the pentagon's own sine — the largest CP content the lattice can leak, the same $L = 5$ that locks the weak phase; $e^{-K} = e^{-35}$ is the throat's exponential — the same $K = 35$ that sets the lock scale and the baryon throughput of Part VIII; and $2^{-J} = 2^{-7}$ is the chirality counter's power of two — the same $J = 7$ that wrote the lepton phase one subsection ago. No new number was needed to bound the leakage; the alphabet priced its own imperfection. A measured EDM between 10^{-18} and 10^{-10} would break this architecture while leaving the Standard Model untouched: the bound is a falsifier, not a comfort (Table 26).

The Kaxion relaxes what remains (companion result). The compact-angle pseudoscalar of the Kaxion companion (Arisaka, 2026, C1-Kaxion) couples through the gluonic portal, and QCD itself supplies the potential whose minimum the Vafa–Witten theorem (Vafa and Witten, 1984) certifies at $\bar{\theta}_{\text{eff}} = 0$: Peccei–Quinn relaxation (Peccei and Quinn, 1977), executed by a field the geometry forced — a gauge-topological Wilson-line angle, not an installed scalar — with the laboratory line

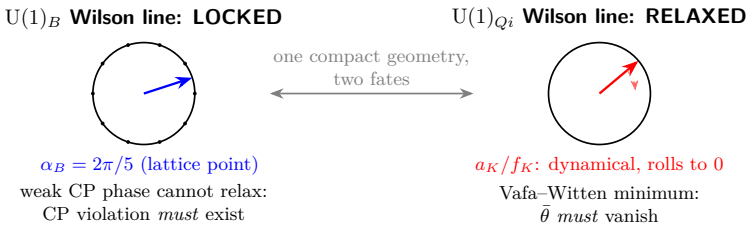


Figure 14: The two-fate architecture (§77; Wilson lines computed side by side in Arisaka, 2026, A6-GRIP). The U(1)$_B$ holonomy is a pentagonal lattice point — the weak CP phase is locked on, and CP violation cannot relax away. The U(1)$_{Qi}$ holonomy is the dynamical Kaxion angle — the strong CP phase rolls to the Vafa–Witten zero. The Standard Model holds these two numbers as unrelated embarrassments; here they are the two fates one alphabet allows.

at 8.1 μeV. The strong-CP closure is doubly protected: dynamically by relaxation, statically by the scale profile.

The two-fate architecture, seen whole. The same compact geometry gives the weak-sector CP angle a locked fate (a pentagonal lattice point — CP violation *must* exist and cannot relax away) and the strong-sector angle a relaxed fate (a dynamical Wilson line — $\bar{\theta}$ *must* vanish). In the Standard Model the coexistence of a large CKM phase with a vanishing $\bar{\theta}$ is a standing embarrassment — two unrelated parameters, one inexplicably maximal-ish, one inexplicably zero. Here they are the two faces of one alphabet: the angles the lattice holds, and the angle the geometry lets go. The gauge-runtime companion computes both Wilson lines side by side — the U(1)$_B$ holonomy locked at $2\pi/L = 2\pi/5$, the U(1)$_{Qi}$ holonomy dynamical (Arisaka, 2026, A6-GRIP) — and no other framework in Part X's comparison connects the two numbers at all.

78 Worked examples

Five computations, each executed end to end with numbers, on the P4 model: the reader who reproduces all five owns the mirror Parts.

78.1 Worked example I: Wu's asymmetry as an orientation measurement

Polarized ^{60}Co ($J = 5 \to 4$, pure Gamow–Teller) emits electrons with distribution $W(\vartheta) \propto 1 + A\,P\,(v/c)\cos\vartheta$, and $V-A$ gives $A = -1$ for this transition. At the experiment's $P \simeq 0.6$ and $v/c \simeq 0.6$ the up–down asymmetry is $W(180°)/W(0°) \simeq 1.36/0.64 \simeq 2.1$ — a 100%-scale effect from a supposedly exact symmetry, which is why one cryostat sufficed where decades of atomic spectroscopy saw nothing. In the language of this paper: $\langle \vec{\sigma} \cdot \vec{p} \rangle \neq 0$ is a direct reading of P-P5-D's alignment — the decay products' momenta are correlated with an internal orientation, and the sign of the correlation is the handedness invariant's laboratory face.

78.2 Worked example II: the CKM plaquette, with numbers

Take the standard-parameterization CKM magnitudes and the lattice phase. The (1,2)–(2,3) plaquette holonomy evaluates through Eq. (56): PDG-class moduli $s_{12} = 0.2250$, $s_{23} = 0.0418$,

$s_{13} = 0.0037$, $c_{12}c_{23}c_{13}^2 \simeq 0.9735$, and the QD phase ($\sin 66.86^\circ = 0.9195$), so $J_{\rm CKM} = 0.9735 \times 0.2250 \times 0.0418 \times 0.0037 \times 0.9195 \simeq 3.1 \times 10^{-5}$ (measured: $3.12^{+0.13}_{-0.12} \times 10^{-5}$); the first-order phase ($\sin 72^\circ = 0.9511$) gives 3.2×10^{-5}. All of CP violation in the quark sector is this one area, and it is a lattice point's sine times four measured moduli.

78.3 Worked example III: $\sin 2\beta$ as a holonomy difference

The unitarity-triangle angle $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ is a difference of plaquette holonomies (Appendix E). With the lattice phase $\delta_{\rm CKM}^{\rm QD} = 66.86^\circ$ and the PDG-class moduli ($s_{12} = 0.2250$, $s_{23} = 0.0418$, $s_{13} = 0.0037$) the recomputation returns $\sin 2\beta \simeq 0.708$ against the measured 0.709 ± 0.011 (mid-2026 average; a -0.1σ pull, watched — the evaluation layer is stated because the value is layer-sensitive at the few-percent level, spanning 0.707–0.727 across the s_{23} and phase-layer choices): the B-factory observable, recomputed as interferometry of the same single angle as Worked example II — one phase, two mesons, one pentagon.

78.4 Worked example IV: the neutrino asymmetry at 196°

The leptonic CP observable of the long-baseline program is the $\nu_\mu \to \nu_e$ versus $\bar\nu_\mu \to \bar\nu_e$ rate asymmetry; at the oscillation maximum it is proportional to $J_{\rm PMNS} = c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23} \sin\delta_{\rm PMNS}$. With the NuFit angles and the lattice point ($\sin\delta_{\rm PMNS} = -8\sqrt{3}/49 = -0.283$ at first order; -0.277 at the QD phase): $J_{\rm PMNS} \simeq -9.4 \times 10^{-3}$ — an appearance asymmetry $A_{CP} \simeq -0.28 \sin\delta \simeq 0.28 \times 0.283 \simeq +8\%$ at the T2K/DUNE baseline maxima: for $\sin\delta < 0$ in this convention the *neutrino* rate is enhanced relative to the antineutrino rate (the interference term of Eq. (118) enters the neutrino channel as $-\sin\Delta \sin\delta$; Appendix H.3), and at DUNE's baseline the matter-induced asymmetry is comparable to or larger than this genuine effect and must be separated by its known E and L dependence (problem H.3.2). DUNE's $\pm 15^\circ$ resolves 196° from the CP-conserving 180° at $\sim 1\sigma$ and from maximal 270° at $\sim 5\sigma$: the adjudication of Table 26, in one number.

78.5 Worked example V: the dial-free door, in matrices

For a weight-n real pair, the symmetric square decomposes as $\left(\begin{smallmatrix} a^2-b^2 & ab \\ ab & b^2-a^2 \end{smallmatrix}\right)$-type doublet (rotating with weight $2n$) plus the invariant $a^2 + b^2$. Under $\alpha = \pi/2n$ the doublet flips sign: no invariant self-pairing exists for $n \neq 0$. For $n = 0$ the "rotation" is the identity and the reality condition is the Majorana condition — three lines of 2×2 algebra carrying T-P5-4, the seesaw's uniqueness, and Part VIII's door.

79 What is claimed, and what is inherited

Concessions first, in full — and for this Part they must be made with particular care, because the Part's centerpiece sits on top of a large inheritance. The rephasing-invariant calculus — quartets, the uniqueness of the physical phase at $N = 3$, the invariant J — is Jarlskog's and her successors' (Jarlskog, 1985); clauses (i)–(iii) of T-P5-3 geometrize known mathematics, and the graph packaging is convenience, not content. The idea that CP violation is *geometric* — a property of compact

Table 10: Forced values against the world's numbers. Pulls are quoted against current uncertainties; the register column of each chain applies (§135). The $\delta_{\rm CKM}$ pulls carry a one-lattice-step theory width $\pi/35$ in quadrature — against experimental error alone the raw $2\pi/5$ sits at $+4.2\sigma$; the $J_{\rm CKM}$ band spans the framework's evaluation-layer choices. No entry was fitted; every entry can move only by dying.

Observable	Forced value	Measured	Status
$\sin\theta_{12}^{\rm CKM}$	0.22502 (53)	0.22501 ± 0.00068	pull +0.01; derived-cond.
$\delta_{\rm CKM}$	$2\pi/5 = 1.2566$; QD $13\pi/35 = 1.1669$	1.147 ± 0.026	pulls +1.17 / +0.70
$J_{\rm CKM}$	3.1×10^{-5} (layer band 2.7–3.2)	$(3.12^{+0.13}_{-0.12}) \times 10^{-5}$	inside band
$\sin 2\beta$	0.708 (WE III)	0.709 ± 0.011	pull −0.1; watched
$\delta_{\rm PMNS}$	196.4°; QD 196.06°	NO: $177^{\circ}{}^{+19}_{-20}$; IO: $285^{\circ}{}^{+25}_{-28}$	$+1.0\sigma$ (NO)
$(\alpha_{21}, \alpha_{31})$	$(0, \pi)$	unmeasured	parity data; $0\nu\beta\beta$-testable
$m_{\beta\beta}$	1.72 meV	$<$ 28–122 meV	below reach; tonne-scale+ target
$J_{\rm PMNS}$	-9.4×10^{-3}	sign disfavored > 0 (T2K Collaboration, 2020)	consistent
$\bar{\theta}$	$\lesssim 4.7 \times 10^{-18}$	$< 10^{-10}$ (nEDM)	eight orders of headroom
η_B	$\approx 7 \times 10^{-10}$ (central 7.34; $\times 3^{\pm 1}$)	$(6.12 \pm 0.04) \times 10^{-10}$	+20% central; D*

internal structure, broken spontaneously rather than dialed — is string theory's, in the line from Strominger and Witten through Dine–Leigh–MacIntire and Choi–Kaplan–Nelson (Strominger and Witten, 1985; Dine, Leigh, and MacIntire, 1992; Choi, Kaplan, and Nelson, 1993), where CP is a discrete gauge symmetry broken by moduli values. Discrete flavor-symmetry model building routinely produces predicted CP phases, including values of $\delta_{\rm PMNS}$. The relaxation template for the strong angle is Peccei and Quinn's (Peccei and Quinn, 1977), with the minimum certified by Vafa and Witten (Vafa and Witten, 1984). Each of these is cited at its point of use, and Part X gives each its own section.

What this Part claims, ranked by confidence, at the grades of Table 11. *First — the load-bearing claim — the lattice valuation.* No framework known to this program *values* the holonomy: the Standard Model leaves the loop angle continuous and unexplained; string theory's geometric phases are moduli-valued and landscape-dependent, predicting that CP violation is possible but never what it is; discrete flavor models predict phases only after a symmetry group is chosen from a catalog. The pentagon is not chosen: $L = 5$ is the ledger's, fixed upstream by twenty-one companion treatments for independent purposes, and the resulting values — $2\pi/5 \to 13\pi/35$, $\pi + 2\arcsin(1/7)$, $(0, \pi)$ — are forced, falsifiable, and already under test (Table 10). *Second, the two-fate architecture:* the locked weak angle and the relaxed strong angle as the two fates one alphabet allows — a structural

connection between the Standard Model's two CP embarrassments that no comparison framework draws at all. *Third, the geometrized criterion:* CP violation as chirality of the texture on the circle — modest as mathematics, clarifying as anatomy, and the bridge over which Part V's five fates and this Part's lattice meet. *Fourth, the dial-free door:* T-P5-4's uniqueness theorem, which converts the seesaw from a model class with a continuum of dials into a single constitutional channel with none. The first claim carries the honest residue named in the ledger (the rigidity of the holonomy moduli, and the flagged QD step); the second carries lemma L9; the third is derived; the fourth is derived. Nothing above leans on a grade the ledger does not print.

80 Status ledger for the mirror Parts

Table 11: The mirror Parts at a glance. "Derived" means proved at the stated grade on the page or in the cited parent theorem; "derived-conditional" means the chain is explicit and one named step is asserted or outstanding. Eight results, each with its label, its grade, and its named residue, so that the Part's standing can be read down one column rather than reconstructed from the text. Four rows are derived and four derived-conditional, and in every conditional case the residue column says which single step is asserted or outstanding.

Result	**Label**	**Grade**	**Named residue**
C/P/T table; antiunitary $\Leftrightarrow$ T	T-P5-1	derived	—
CPT for real textures	T-P5-2	derived (quasi-free)	interacting case on scattering hypotheses; modular route open
Holonomy calculus (i)–(iii)	T-P5-3	derived	(inherited mathematics, geometrized)
Pentagonal lattice (iv)	T-P5-3	derived-conditional	rigidity of the holonomy moduli
δ_{CKM}: $2\pi/5 \to 13\pi/35$	§75.3	derived-cond.	QD step asserted (flagged post-hoc)
δ_{PMNS}, $(\alpha_{21}, \alpha_{31})$, $m_{\beta\beta}$	§75.4	derived-cond.	leptonic assignment lemma
Majorana iff weight zero	T-P5-4	derived	—
$\bar{\theta}$: no knob + cancellation + Kaxion	§77	derived-cond.	lemma L9 (determinant phase)

Part-end summary. Where CP phases live: in closed loops, as holonomies no dial can touch. What values them: one circle, one alphabet, the pentagon — interior angle in, central angle out, the golden ratio underwriting the Cabibbo magnitude on the way. What follows: the quark phase at $13\pi/35$, the lepton phase at $196°$, the Majorana parity pair, two Jarlskog areas, and a strong-CP angle bounded at 10^{-18} by the alphabet's own integers — every number a confrontation, none a fit, the flags flown where the chain is conditional. The pentagon the ledger forces has priced the second broken mirror; the neutrino's self-pairing is the unique open door; and the strong-CP angle is the

one the geometry lets relax. One consequence of the orientation remains — the largest: the matter of the universe. It is the next Part.

Part VIII
The Origin of Matter

The number that survived the fire, certified three ways; Sakharov's three locks derived, each already paid; the one channel the conservation laws leave open; the chain, audited step by step; and the resonance question faced in public

81 Part VIII in plain English: why there is something rather than nothing

About six parts in ten billion of the early universe were matter, and the rest annihilated to light. That number is measured twice, from the light elements and from the microwave background, and the two measurements agree. This Part derives it.

Sakharov's three conditions are met, and for each the Part says who owns it: which are derived here, which are inherited, and at what grade. Leptogenesis is not chosen from a menu — it is forced, because the door this geometry leaves open is the one the heavy neutrinos walk through. The chain is then run step by step, with the dial count stated in the open: zero fitted parameters.

The honesty sits in the same Part rather than in a later one. The resonance question is faced instead of assumed away; the throughput's exponent is a postulate and is called one; the flavored asymmetry is derived-conditional on a named hypothesis; and the two-route bridge for the baryon density leaves a gap whose owner has not been identified. A chain with no fitted parameters and a named gap is worth more than a chain with one fitted parameter and none, but only if the gap is on the page. The status ledger at the end carries all of it.

82 The observational facts

Everything in this paper has been walking toward this Part. The twins were forced (Part IV); the mirrors were defined and their selective breakage derived (Parts V–VII); and now the paper must pay the question it opened with: *why is there anything?* Let us begin by seeing the event whose outcome we are. In its first second the universe was a furnace of matter and antimatter in almost equal numbers — pairs created and annihilated in equilibrium, particle for antiparticle, as the handshake of Part IV guarantees they come. As it cooled, the burning stopped being replenished: pair by pair, matter and antimatter met and left as light. Had the ledger balanced exactly, that would have been the whole history of the material universe — a flash, then radiation thinning forever. It did not balance. For roughly every billion pairs that burned, one particle of matter had no partner and survived. Every galaxy, every star, every atom in every reader is that remainder: we are not made of the universe's substance so much as of its *rounding error*. The question of this Part

is the deepest bookkeeping question there is: who wrote the one?

The number, certified three ways. Part I stated the target; here it is assembled as the boundary condition every mechanism must hit, with each certificate walked. *Certificate one — the CMB.* The baryon-to-photon ratio is read from the acoustic peaks: baryons load the photon–baryon fluid, and the relative heights of the compression and rarefaction peaks weigh that loading directly — $\eta_B = (6.12 \pm 0.04) \times 10^{-10}$, a 0.7% measurement of a one-in-a-billion number, at $t \simeq 380{,}000$ years (Planck Collaboration, 2020). *Certificate two — the concordance.* Primordial deuterium, read in quasar absorption systems, records the competition between nuclear burning and expansion at $t \sim 3$ minutes, and returns the same η (Cooke, Pettini, and Steidel, 2018). Two epochs five orders of magnitude apart in temperature, two entirely different physical thermometers, one number: the asymmetry was in place before nucleosynthesis began, and baryon number has been conserved since. *Certificate three — the absence.* A universe of matter and antimatter domains would burn at the seams, and the diffuse gamma-ray sky shows no such annihilation glow: domain structure is excluded out to essentially the observable universe (Cohen, De Rújula, and Glashow, 1998); the cosmic rays contain no confirmed antinuclei (AMS Collaboration, 2024). The asymmetry is global — not matter here and antimatter hidden elsewhere.

The counterfactual, computed. And the excess was necessary, not decorative. In a baryon-symmetric universe annihilation continues until the survivors are too dilute to find each other; the standard freeze-out estimate leaves $n_B/n_\gamma \sim 10^{-18}$ — *nine orders of magnitude* below observation, a universe of pure radiation with a trace of dust, no stars, no chemistry, no readers. Annihilation is efficient; only an excess laid down early survives it. One number, three independent certificates, and a counterfactual: this is as clean as cosmological boundary conditions come, and it is the cleanest evidence in all of physics that the Standard Model — which predicts essentially $\eta_B = 0$ (Part X) — is incomplete.

83 Sakharov's conditions, and who owns them

In 1967, in a short paper decades ahead of its audience, Sakharov identified what *any* dynamical origin of the excess must contain (Sakharov, 1967), and the three conditions deserve to be derived rather than recited, because each is a small theorem. *First, baryon-number violation* — for the plainest of reasons: if every interaction conserves B, a universe that starts symmetric ($B = 0$) stays symmetric forever; the one cannot be written by bookkeeping that forbids writing. *Second, C and CP violation.* Suppose C held: then for every process making a baryon, the conjugate process makes an antibaryon at the same rate, and the net vanishes. Suppose CP held while C broke: then left-handed excesses are compensated by right-handed ones, and summed over helicities the net vanishes again. Only if both mirrors are broken can the rates themselves take sides. *Third, departure from equilibrium* — the subtlest, and it is Part V's unbreakable product doing the enforcing: in thermal equilibrium the state is determined by the Hamiltonian's spectrum, CPT pairs every baryon state with an antibaryon state of equal energy, and the Boltzmann weights match — $\langle B \rangle_{\rm eq} = 0$. An asymmetry can only be written *while the system is falling*, never while it rests. Three locks on the vault, and every proposed origin of matter must pick all three.

Now the striking fact, and the reason this Part can be short on invention: *the GG-6 architecture had already paid all three conditions, for reasons that had nothing to do with cosmology.* In the cosmology companion's formula: *GRIP owns the angle, GDOS owns its observability, OGGEP owns the ledger* (Arisaka, 2026, A10-Cosmos). *Baryon-number violation:* the bulk baryonic ledger is exactly conserved — $\mathrm{U}(1)_B$ is gauged, the proton absolutely stable — and what evolves is the projected boundary subsystem's $B-L$ budget, through the unique $\Delta L = 2$ door of T-P5-4: the door was a uniqueness theorem of Part VII before it was a cosmological channel. *C and CP violation:* the CP-odd input is the lattice-locked loop holonomy of Part VII — a real angle of the inherited flavor geometry, not a tunable phase; it exists because the pentagon is chiral, not because baryogenesis needed it. *Departure from equilibrium:* constitutional — the boundary law is a forward CPTP semigroup (openness is the default, AX-3; the same one-way projection that owns the arrow of time, §38), and the specific out-of-equilibrium episode is the decay of the heavy sector at the lock crossing. Where the Standard Model fails Sakharov on the arithmetic (Part X) and its extensions pass by installing new machinery, here the three locks were opened by keys the constitution had already cut.

This section now does what the fifty years since 1967 have not asked of the three conditions: *derive the keys.* Sakharov's list has been checked, mapped, and satisfied in every baryogenesis proposal since it was written — and taken for granted in all of them: three boxes on a checklist, to be arranged by model-building, their own origin unquestioned. What follows traces each condition to the constitutional structure whose boundary shadow it is — pure geometry, one condition at a time — and then recognizes the three together as something the paper has already met.

Origin (i) — the two books and the still-point door. Begin with what makes the bulk ledger *absolute.* A gauged charge is not conserved by a bookkeeping rule that dynamics might amend; it is conserved by the geometry of its own field: the Gauss law reads the total charge as a flux through a distant surface, so no local process anywhere in the interior can change it — gauged conservation is a statement about the arena, not about the interactions. The bulk's $\mathrm{U}(1)_B$ is of exactly this kind, and its absoluteness is why the proton is absolutely stable. Sakharov's first condition would therefore seem *unpayable* in this geometry — and here is where the still point of the circle earns its cosmological office. The winding bookkeeping of the fiber has exactly one gap: the weight-zero sector, where the circle moves nothing and the lepton-number book alone may take a $\Delta L = 2$ entry (T-P5-4, seeded at the still point of §46). The boundary's evolving budget is $B-L$; the door writes lawful entries into it without touching the bulk book; and the sphalerons — boundary machinery of the projected subsystem, active above the crossover — exchange the budget's columns. Condition (i) is thereby satisfied *without breaking anything*: not a violated symmetry but the coexistence of two books kept at two levels of one geometry, with a single lawful door between them — the precise content of *OGGEP owns the ledger.*

Origin (ii) — the oriented descent and the chiral lattice. The second condition asks for broken C and broken CP, and the paper has already derived both — what matters here is *from what*, and how compulsorily. C falls by an absence: the projection of Part VI keeps one hand of the spectrum, so fiber reversal maps kept states onto states that are not there — maximal violation, from the descent's one-handedness. CP survives the absence and falls by an angle: the pentagon of Part VII locks the flavor holonomy at $3\pi/5$, which is not a multiple of π, so the texture cannot be achiral

(T-P5-3(iv)). Now set this against the standard situation, for the contrast is the whole point. In the Standard Model, $\delta = 0$ — a CP-symmetric world, sterile of receipts — is exactly as lawful as the measured value; Sakharov's second condition holds there by *accident of a dial*. Here it holds by *theorem*: a GG-6 universe with CP symmetry is unwritable, because writing one would require a pentagon angle in $\pi\mathbb{Z}$, and the lattice contains no such texture with the forced branch phase. The orientation of the descent, seen twice — the hand and the angle — *is* condition (ii), and it cannot relax, cannot be tuned away, and was not installed for cosmology's benefit: *GRIP owns the angle.*

Origin (iii) — the always-on projection and the fall. The third condition is the subtlest, and the clock's third face (§43) lets us state its geometric content exactly. What *is* equilibrium, in this geometry? A state at rest on the clock's thermal shore: periodic in imaginary time (the KMS condition), invariant under the evolution, CPT-balanced — and therefore, by the argument that opened this section, carrying $\langle B\rangle = 0$ identically. An asymmetry can be written only by a state that is *off the shore* — falling, not resting. And here the constitution does something no standard framework does: it *denies the boundary the option of rest.* The boundary law is a forward CPTP semigroup — openness is not an episode but the default (AX-3); the projection is always on and never invertible; and the cosmology it reads is a Morse descent — a landscape with a downhill and a flow strictly along it, a falling system *by construction*, with the lock crossing as the specific stumble at which the heavy sector decays out of step with the bath. In the Standard Model the third condition failed for want of a first-order transition — the universe, on that accounting, never fell hard enough. Here the fall is the architecture: *GDOS owns the observability*, the projection owns the arrow, and departure from equilibrium is what the descent *is*.

Three origins, and now the recognition. Set them beside the custody map of Part III:

the bulk owns the symmetries — the two books and the door — Sakharov (i)
the descent owns their breaking — the hand and the angle — Sakharov (ii)
the boundary owns their observability — the projection and the fall — Sakharov (iii)

The alignment is exact, and it is the deep fact of this section: *Sakharov's conditions are the custody map, read as a parts-list.* In 1967 Sakharov proved the necessity direction — no receipt without these three. The geometry supplies the converse in kind — a universe built of exactly these three — and the identification deserves its formal statement:

Proposition 83.1 (**P-P5-E**: the Sakharov tripod)**.** *In the GG-6 architecture the three Sakharov conditions are the boundary shadows of three constitutional structures, each in place upstream of cosmology and each carried by a named result: (i)* lawful baryon-budget evolution*, from the two-level ledger — exact gauged bulk* $\mathrm{U}(1)_B$*, the unique weight-zero* $\Delta L = 2$ *door (T-P5-4), and boundary sphaleron reprocessing; (ii)* compulsory C and CP violation*, from the descent's orientation — the one-handed projection (Part VI) and the chiral pentagon (T-P5-3(iv)), lattice-locked and unable to relax; (iii)* constitutional departure from equilibrium*, from the always-on, non-invertible boundary projection (AX-3) driving the Morse descent, with equilibrium itself characterized as the CPT-balanced state on the clock's thermal shore. Consequently a GG-6 universe cannot fail Sakharov: the generation of a nonzero baryon asymmetry through the unique open channel is structural, and only its* magnitude *(T-P5-5) depends on the named conjecture C-P5-C.*

Proof, by assembly. Each clause is the citation of a result already established, and the proposition's content is the identification, at the grade of its parts. Clause (i): gauged conservation and proton stability are ledger results of the parent program; the door is T-P5-4 (derived); sphaleron reprocessing is standard boundary physics (Kuzmin, Rubakov, and Shaposhnikov, 1985). Clause (ii): the projection's one-handedness carries Part VI's honesty ledger (mechanism derived, selection graded there); the pentagon's chirality is T-P5-3(iv) (derived-conditional on the rigidity residue); jointly they make condition (ii) compulsory at those grades — strictly stronger than the Standard Model's accidental satisfaction, in which the CP-conserving world is equally lawful. Clause (iii): the forward-semigroup character of the boundary law is constitutional (AX-3); the equilibrium characterization is the KMS remark of T-P5-B1 (conditional as there flagged); the Morse descent is the parent cosmology's launch architecture. For the consequence: with all three conditions holding and the lepton channel open (§84), the decay of the heavy sector at the crossing generates a CP-biased lepton asymmetry of *some* magnitude even arbitrarily far off the resonance peak — the self-energy enhancement is suppressed off-peak as $\Gamma/\Delta M$, not extinguished — and sphalerons reprocess a nonzero fraction into baryons. Vanishing exactly would require a texture angle in $\pi\mathbb{Z}$ or a closed boundary, both unwritable here. The observed *size* is the business of the transport chain and its named conjecture, exactly as Table 12 prints. ■

Physics intuition — Sakharov, read backward. For fifty years the three conditions have been used in one direction: a checklist that any proposed mechanism must satisfy, three boxes arranged by adding machinery — new bosons for the first, new phases for the second, new phase transitions for the third. Read in this geometry, the list inverts, and the inversion is the profound part. The conditions are not requirements the universe happens to meet; they are the *parts-list of an oriented descent*: a book that is kept (the ledger, with its one lawful door), a fall that has a direction (the orientation, worn as a missing hand and a locked angle), and a readout that cannot be undone (the projection, whose one-wayness is the arrow of time itself). Sakharov's theorem said: no universe keeps a receipt of its history without these three. The custody map replies: this universe is *made* of these three — they are its constitution's three offices, occupied before cosmology posed its question, for reasons (charge bookkeeping, family structure, the very existence of records) that had nothing to do with baryons. That is why the section could say the locks were opened by keys already cut: the deepest origin of the matter excess is not a mechanism but a *shape*. The universe is a fall that keeps books — and a fall that keeps books leaves a receipt. The one-in-a-billion of Part VIII's title is the receipt's size, and the size must still be computed, conjecture and all; but that there is a receipt at all was never, in this geometry, optional. After all, Sakharov wrote his three conditions as the price of explaining our existence — and the quiet answer of the tripod is that the price was paid at the founding, in the constitution, before the universe had anything to buy.

84 Why leptogenesis is forced

Exact gauged $\mathrm{U}(1)_B$ narrows the field to one mechanism class before any cosmology is computed, and the narrowing is worth walking door by door. *The GUT door is welded shut.* The historical first mechanism — out-of-equilibrium decay of superheavy baryon-violating bosons (Weinberg,

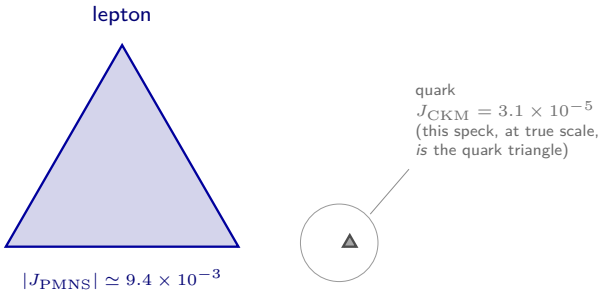
1979; Yoshimura, 1978) — requires operators that violate B, and the bulk's gauged $\mathrm{U}(1)_B$ forbids them exactly: the same ledger that makes the proton absolutely stable makes GUT baryogenesis unwritable. The parent program counts this economy a virtue rather than a loss, for the standard tension runs the other way: in GUT scenarios the sector that creates baryons is forever threatening to eat the proton, and the model builder must arrange the mediators heavy enough to spare it. Here the baryon-making sector *cannot* touch the proton, by constitution. *The electroweak door is closed by inheritance.* Electroweak baryogenesis needs a first-order phase transition to push bubbles of broken phase through the plasma; at the physical Higgs mass the transition is a smooth crossover (Kajantie et al., 1996) — no bubbles, no departure — and the GG-6 boundary inherits the Standard Model's Higgs sector intact; the crossover, and the Standard Model's 10^{-20} CP shortfall besides (§112), close the door twice. *What remains is the lepton route* (Fukugita and Yanagida, 1986): create the asymmetry as L, through the unique lawful $\Delta L = 2$ door of T-P5-4, and let the sphalerons (Kuzmin, Rubakov, and Shaposhnikov, 1985) — the electroweak theory's own high-temperature $B{+}L$ reprocessors, active above the crossover — convert $B{-}L$ into B. The framework is, in the cosmology companion's words, pushed "almost automatically toward leptogenesis" — the only Sakharov-complete channel its own conservation laws leave open.

And the scale makes it testable — the Davidson–Ibarra point. Standard thermal leptogenesis with hierarchical heavy neutrinos carries a famous cost: the CP asymmetry per decay is bounded by the light and heavy masses, and demanding enough asymmetry forces $M_N \gtrsim 10^9$ GeV (Davidson and Ibarra, 2002) — a beautiful mechanism, forever beyond every collider, its phases decoupled from the measured PMNS phases. The known escape is *resonant* leptogenesis (Pilaftsis, 1997; Pilaftsis and Underwood, 2004): for quasi-degenerate heavy states the self-energy enhancement lifts the asymmetry by orders of magnitude, evading the bound and admitting TeV-scale heavy neutrinos — at the price, in the standard literature, of *engineering* the degeneracy. The GG-6 chain sits in exactly this regime, but with the inputs inverted: the TeV scale is not chosen for accessibility, it is the lock scale $\frac{1}{2}M_{\mathrm{Pl}}e^{-35}$ the ledger fixed for its own reasons — and the degeneracy question is not engineered away but faced in public, as the named conjecture of §87. The bound is evaded where the literature evades it; what is new is who pays, and how visibly.

84.1 Why the quark sector cannot pay, in one picture

The preceding section forces leptogenesis by a door argument: sphalerons preserve $B - L$, so only an asymmetry written in lepton number at high scale survives reprocessing, and only a Majorana phase can drive it. That argument is structural and it is complete. It is worth adding the quantitative statement beside it, because a reader who has just been told that the laboratory's flashiest CP violation is irrelevant to the origin of matter will reasonably want to see the size of the thing being set aside.

The one-area theorem is what makes the comparison legitimate rather than rhetorical. Because every plaquette of the flavor graph carries the same area, the whole of a sector's CP violation is one number, and two sectors can be set side by side without choosing a convention or a channel. The quark sector's number is real, it is measured to per-cent precision, and it is a hundredfold too small before the thermal history touches it. What the quark sector *is* in this framework is the laboratory



Both areas are real and both are measured. The unitarity triangles are drawn here to *true relative area*: the lepton area is **three hundred times** the quark area. §112 prices the disparity that actually matters for baryogenesis: the effective CP violation of the quark route computes to $\sim 10^{-20}$, ten orders short.

Figure 15: The quark and lepton unitarity triangles drawn to true relative area. By the one-area theorem of §75 a single number prices all of the CP violation in a sector, and the two numbers are both measured: $J_{\rm CKM} = 3.1 \times 10^{-5}$ against $|J_{\rm PMNS}| \simeq 9.4 \times 10^{-3}$. The lepton area is some three hundred times the quark area — the lepton phase is large because $\delta_{\rm PMNS}$ sits near 196° and, decisively, because the lepton mixing angles are large where the quark angles are small. The disparity relevant to baryogenesis is larger still, because the quark contribution is throttled a second time by the product of quark mass-squared splittings.

— the place where the pentagon's prediction is confronted at Belle II and LHCb. What it is not is the origin of us.

85 The chain, step by step

Proposition 85.1 (**T-P5-5**: the assembled η_B, at D* grade)**.** *On the inherited ledger — heavy masses at the lock, the dial-free door, the seesaw-matched Yukawa, the holonomy CP phase — and conditional on the on-resonance condition (Conjecture C-P5-C, whose sharp form is the partial-resonance hypothesis H-$\phi_{\rm geo}$-1; §87), the boundary transport yields $\eta_B \simeq 5.9 \times 10^{-10}$, within the factor-$\sim 3$ theory band of the observed $(6.12 \pm 0.04) \times 10^{-10}$.*

The chain, each step with its number and grade; the audit is the point, so no step is skipped.

1. Heavy scale (derived). The seesaw partners sit at the lock: $M_{N_i} = M_{\rm lock}(1 + \delta_i)$ with $M_{\rm lock} = \frac{1}{2} M_{\rm Pl} e^{-K} \simeq 3.85$ TeV and geometric splittings $\delta_i = O(1/K)$ — percent-level spacing in the few-TeV corridor. No extreme ultraviolet prehistory is needed, and the derived reheating temperature $T_{\rm rh} \simeq 3 \times 10^{10}$ GeV populates the sector thermally: the mechanism is selected by the launch, not chosen.

2. Portal (derived). T-P5-4: the weight-zero self-pairing is the unique $\Delta L = 2$ structure, LHN the unique portal. No choice enters.

3. Yukawa (derived). Seesaw matching (9) to the inherited light masses and the derived seam coefficient fixes $Y_\nu^2 \simeq \pi M_{\rm lock}/E_{\rm GUT} \simeq 5.3 \times 10^{-13}$, $Y_\nu \simeq 7.3 \times 10^{-7}$ — and hence the width $\Gamma_N = Y_\nu^2 M_N / 8\pi \simeq 8 \times 10^{-11}$ GeV, $\Gamma_N / M_N \simeq 2 \times 10^{-14}$. A width this small would doom hierarchical leptogenesis; the resonant regime is what rescues it. One bookkeeping convention is declared here: this width is quoted at the seam-matched one-generation Yukawa, which corresponds to $\widetilde{m} \simeq 8.4$ meV,

while step 6 runs washout at $\widetilde{m} = m_3 \simeq 50.5$ meV — conventions differing by a factor $\simeq 13$ in Y_ν^2. Run at the washout convention the width is $\Gamma_N \simeq 1 \times 10^{-9}$ GeV: an $O(10)$ shift inside the order-of-magnitude register, absorbed into the effective width $\Gamma^{\rm eff}$ that H-$\phi_{\rm geo}$-1 parameterizes (§87); the vacuum off-peak gap reads eleven-to-twelve orders in either convention.

4. Resonance (the named input). At the self-energy resonance $|M_i - M_j| \simeq \Gamma_j/2$ the enhancement saturates and the Yukawa magnitude cancels between numerator and denominator (Pilaftsis, 1997; Pilaftsis and Underwood, 2004): the asymmetry is controlled by the geometric phase alone, $\epsilon^{\rm res} \simeq \frac{1}{2}\sin(2\phi_{\rm geo})$. **The on-resonance condition is the chain's one named input** (C-P5-C); Section 87 quantifies what it asks.

5. CP phase (derived-conditional on H-$\phi_{\rm geo}$-1). The unflavored CP invariant of the resonant formula is $U_{\rm PMNS}$-independent (the Casas–Ibarra cancellation) and vanishes exactly for the dial-free real-R door; at the TeV lock scale the chain is fully flavored, and the inherited phases reach η_B only through the flavored asymmetries $\epsilon_{i\alpha}$, now computed on the ledger inputs (GG-A10-Cosmos Appendix I). The driver is the Majorana parity $\alpha_{31} = \pi$, which sets the sign of the matter excess (the numerics are $J_{\rm PMNS}$-blind at the few-percent level), and the result is nonzero at $m_1 = 0$: the asymmetry does not ride on the QD layer. The mechanism brackets the observed η_B — on the exact Breit–Wigner peak it overshoots the required throughput by $\sim 3 \times 10^4$, at vacuum splittings it undershoots by $\sim 4 \times 10^6$ — and $\epsilon^{\rm res} \simeq 2.5 \times 10^{-6}$ is carried as the target value the partial-resonance hypothesis H-$\phi_{\rm geo}$-1 ($\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$; §87), now carried by an identified candidate mechanism (the flavor-measurement regulator; closed form $1/(35\, c_\tau y_\tau^2)$; conditions C1–C6, home GG-A10-Cosmos Appendix I.3), must deliver: derived-conditional, with the finite-temperature physics the place the number must park (row 9 of the promotion roadmap, Appendix M).

6. Washout (derived-conditional). The equilibrium benchmark is itself derivable in three lines and is notably *ledger-free*: equating the inverse-decay rate to the Hubble rate at $T = M_N$ gives

$$m_\star \;=\; \frac{16\pi^{5/2}\sqrt{g_*}}{3\sqrt{5}}\,\frac{v^2}{M_{\rm Pl}} \;\simeq\; 1.1 \times 10^{-3}\ {\rm eV}, \tag{60}$$

fixed by measured constants alone. (The three lines: the inverse-decay rate is $\Gamma_{\rm ID} \sim \Gamma_N \sim \widetilde{m}\, M_N^2/(8\pi v^2)$; the Hubble rate at $T = M_N$ is $H \sim \sqrt{g_*}\, M_N^2/M_{\rm Pl}$ up to the displayed numerical factor; equating them turns the comparison "does the door re-close what it lets out?" into a pure neutrino-mass threshold. That $m_\star$ contains only v, $M_{\rm Pl}$, and g_* — no ledger integer, no GG-6 input — is why this step is marked ledger-free: nature set the washout regime before any framework arrived.) With $\widetilde{m} \sim m_3 \simeq 5 \times 10^{-2}$ eV the washout is strong, $K_{\rm wash} = \widetilde{m}/m_\star \simeq 50$, and the surviving efficiency is $\kappa \simeq 1/K_{\rm wash} = 2.0 \times 10^{-2}$; the chain adopts $\kappa = 1.0 \times 10^{-2}$ within the uncomputed $O(1)$ — with the standard strong-washout blessing that memory of initial conditions is erased, so the surviving asymmetry depends only on quantities the ledger fixes. The convention note of step 3 applies here in reverse: $\widetilde{m} = m_3$ is the washout convention of the chain; at the seam-matched $\widetilde{m} \simeq 8.4$ meV one would instead have $K_{\rm wash} \simeq 7.6$ and $\kappa \simeq 0.13$. The factor-$\simeq 12$ spread in Y_ν^2 between the two conventions (the single-convention ratio $2\, m_3/\widetilde{m}_{\rm seam} \simeq 12$; the Casas–Ibarra half is bookkeeping, not physics) is declared and priced as an $O(10)$ freedom of the order-of-magnitude register, carried with the transport $O(1)$'s.

7. The throughput identity (the central claim). The product

$$\epsilon^{\rm res}\,\kappa \;\simeq\; (2.5\times10^{-6})(1.0\times10^{-2}) \;\simeq\; 2.51\times10^{-8} \;=\; e^{-K/2} = e^{-17.5} \tag{61}$$

reconstructs, to displayed precision, the ledger's throat-depth exponential — and the displayed agreement uses the $O(1)$ freedom in κ: the identity holds at the adopted $\kappa = 1.0\times10^{-2}$, a factor of two inside $1/K_{\rm wash} = 2.0\times10^{-2}$. The exponent $K/2$ is a *postulate* of the compression — geometrically suggestive as $\sqrt{e^{-K}}$, not derived — and fixing it from first principles is exactly what Conjecture C-P5-C (the sphaleron-transport normalization) must do. What is new is that the independently derived washout efficiency and the candidate regulator's closed form bracket the required throughput — the identity at displayed precision uses exactly the κ freedom declared above and the target status of $\epsilon^{\rm res}$. And the reader should notice which integer has appeared, for the third time in three Parts: the same $K = 35$ that sets the lock scale (e^{-K} in $M_{\rm lock}$) and bounds the strong-CP leakage (e^{-K} in (59)) now measures the matter throughput ($e^{-K/2}$). One throat depth, three exports: a mass, a bound, and the number of us.

8. Sphalerons, entropy, and the equilibrium yield (standard). With the one-doublet coefficient $\frac{28}{79}$ (Harvey and Turner, 1990), $g_* = 106.75$, and the heavy triplet's equilibrium yield displayed rather than absorbed — $\sum_i Y_{N_i}^{\rm eq} \simeq 1.25/g_*$, i.e. $0.42/g_*$ per Majorana species ($g_N = 2$), each equilibrium species carrying its fair share of the bath's heat (derivation in the parent, Arisaka, 2026, A10-Cosmos, App. I) —

$$\eta_B \;\simeq\; 7.04\times\frac{28}{79}\times\frac{1.25\,e^{-K/2}}{g_*} \;\simeq\; 7.34\times10^{-10}. \tag{62}$$

9. The verdict (D^*). Against $\eta_B^{\rm obs} = (6.12\pm0.04)\times10^{-10}$: +20% central, with an honest factor-$\sim$ 3 band from the uncomputed $O(1)$'s — at headline precision, $\eta_B \approx 7\times10^{-10}$, band $(2.4\text{–}22)\times10^{-10}$, the observation comfortably inside. The parent paper's own warning is adopted verbatim: closeness of central values at this tier must *not* be read as a precision success; the genuine claim is the bracketing (61) and the dial count — zero fitted parameters, one named input, one postulated exponent.

86 Zero dilution

An asymmetry made at the TeV scale must survive to the CMB, and two standard killers stand in the way: late inflation and late entropy release (the moduli problem that afflicts string cosmologies (Banks, Kaplan, and Nelson, 1994; Coughlan et al., 1983)). The GG-6 descent has neither: the lock crossing is *prompt* ($N_2 = 0$), on three independent grounds — the nucleation action sits some fifty-six orders above the supercooling threshold, the lock potential is a barrier-free saddle, and the large-N enhancement that drives supercooling in warped-throat models is structurally absent (Arisaka, 2026, A10-Cosmos). No secondary inflation, no stolen e-folds, no relic dilution: the $B-L$ excess is fixed early, reprocessed by sphalerons before the crossover closes the channel, and then simply conserved — *zero dilution* — into the number the CMB reads. The intuition is a mint's: an asymmetry is a coin struck once, and every late episode of inflation or entropy release is a furnace that re-melts the coinage and strikes less of it per photon. String cosmologies generically carry such

Table 12: The audit table: every number of the chain, its source, and its grade. One named input (row 4), one flavored projection carried derived-conditional on H-$\phi_{\rm geo}$-1 (row 5; the former m_1/m_3-order-factor language is withdrawn as a reconstruction artifact; the hypothesis is now carried by an identified candidate mechanism, transport closure of C1–C6 open), one postulated exponent (row 7), zero fitted parameters. Row 6 adopts $\kappa = 1.0 \times 10^{-2}$ from $1/K_{\rm wash} = 2.0 \times 10^{-2}$ within the uncomputed $O(1)$; the throughput identity of row 7 uses that freedom.

#	Quantity	Value	Source	Grade
1	$M_N \simeq M_{\rm lock}$	3.85 TeV	$\frac{1}{2} M_{\rm Pl} e^{-35}$	derived
1'	splittings δ_i	$O(1/K) \sim 1\%$	ledger	derived
1"	$T_{\rm rh}$	3×10^{10} GeV	inflation sector	derived
2	portal	LHN, unique	T-P5-4	derived
3	Y_ν	7.3×10^{-7}	seesaw match	derived
3'	Γ_N	8×10^{-11} GeV	from Y_ν	derived
4	resonance	$\lvert\Delta M\rvert \simeq \Gamma^{\rm eff}/2$	**named input**	C-P5-C(i)
5	$\epsilon^{\rm res}$	2.5×10^{-6}	flavored $\epsilon_{i\alpha}$; H-$\phi_{\rm geo}$-1 target	derived-cond. (H-$\phi_{\rm geo}$-1)
6	κ	1.0×10^{-2}	$K_{\rm wash} \simeq 50$	derived-cond.
7	$\epsilon\,\kappa$	$2.51 \times 10^{-8} = e^{-K/2}$	reconstruction	C-P5-C(ii)
8	$c_{\rm sph}$; g_*	28/79; 106.75	standard	standard
8'	$\sum_i Y_{N_i}^{\rm eq}$	$1.25/g_*$ (three species)	equilibrium statistics	standard
9	η_B	$\approx 7 \times 10^{-10}$ (central 7.34)	assembled	D*, $\times 3^{\pm 1}$
—	$\eta_B^{\rm obs}$	$(6.12 \pm 0.04) \times 10^{-10}$	Planck Collaboration (2020)	target

furnaces (the moduli problem) and so need *more* baryogenesis than field theory does; the GG-6 descent, by the prompt-crossing lemma, carries none: the coin struck at the lock is the coin the CMB counts, an age of the universe later.

87 The resonance question, faced

Conjecture 87.1 (**C-P5-C** (sphaleron-transport normalization; the on-resonance condition))**.** A first-principles transport treatment of the lock-crossing decays exists in which (i) the effective degeneracy condition $|M_i - M_j| \simeq \Gamma_j^{\rm eff}/2$ is realized at the crossing, and (ii) the coarse-grained throughput of asymmetry to entropy is $e^{-K/2}$.

The named hypothesis H-$\phi_{\rm geo}$-1 (partial resonance). *There exists a finite-temperature transport computation of the lock-crossing decays in which the effective splitting-to-width ratio at the crossing satisfies* $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$ *(equivalently, Breit–Wigner factor* $\simeq 1.5 \times 10^{-5}$*;* $\Gamma^{\rm eff} \simeq 3 \times 10^{-3}$ *GeV at* $\Delta M \simeq 110$ *GeV), so that the flavored, real-R throughput on the inherited phases lands within* $O(1)$ *of* $e^{-K/2}$*.* The flavored recomputation of the projection (the cosmology

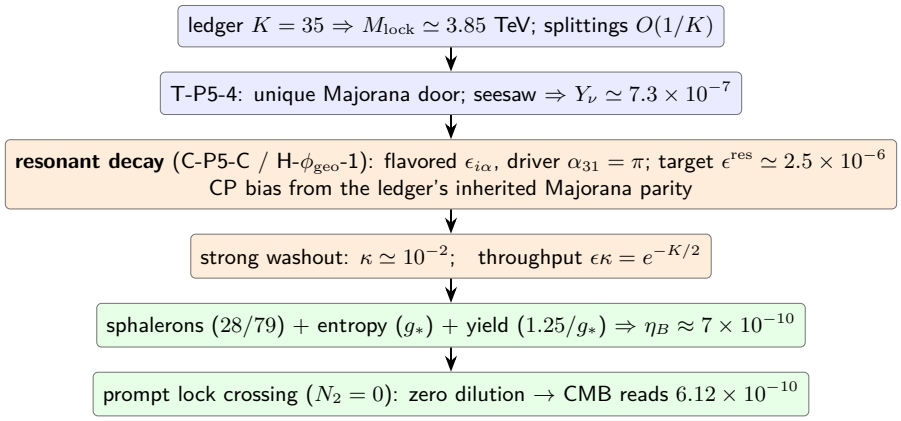


Figure 16: The leptogenesis chain as a flowchart: blue = inherited and derived, orange = the transport block carrying the named conjecture, green = standard reprocessing and conservation. The one direction of the whole diagram is the descent's. The blocks run top to bottom in the order the chain runs, and every arrow points the same way, because the descent has one direction and the figure is drawn to make that visible rather than to be read from either end. The color coding is what separates the inherited part of the chain from the one block that carries a named conjecture. Read a second way, with the anatomy of §59 in hand, the same six blocks sort by fiber rather than by provenance: the ledger, the Majorana door and the sphaleron conversion are circle-side — quantized, protected, the same in every region — while the lock crossing, the exponential throughput and the entropy bath are interval-side, addresses deposited once along a one-way descent. The figure is not recolored to show this, because its colors are already carrying the conjecture mark, and a picture should not be asked to say two things with one device.

companion's Appendix I) sharpens clause (i): the sharp form of the condition is partial resonance — $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$, strictly weaker than exact degeneracy and strictly stronger than vacuum numbers; the exact-peak form overshoots the required throughput by $\sim 3 \times 10^4$, and vacuum splittings undershoot it by $\sim 4 \times 10^6$. $\Gamma^{\rm eff} \sim 3$ MeV is parametrically plausible for thermal damping at $T \sim M_N$, which makes H-$\phi_{\rm geo}$-1 a computation with an acceptance band ($\pm O(1)$ in $\epsilon_{\rm eff}$), not a wish; it is row 9 of the promotion roadmap (Appendix M), where the row now records the identified candidate mechanism below at candidate grade.

This paper quantifies what clause (i) asks, because honesty here is cheap and its absence would be expensive. The geometric splittings of step 1 give $|M_i - M_j| \sim M_{\rm lock}/K \simeq 110$ GeV; the vacuum width of step 3 gives $\Gamma_N/2 \simeq 4 \times 10^{-11}$ GeV. Those differ by twelve orders of magnitude, and off resonance the self-energy enhancement falls as $\Gamma/\Delta M$: as vacuum numbers stand, the enhancement of step 4 is not available, and the phrase "natural rather than tuned," tempting as percent-level splittings make it, overstates what vacuum numbers support. Three candidate resolutions are on the table: *thermal regulators* — at $T \sim M_N$ the effective width entering the resonance condition is a thermal damping rate, larger than the vacuum Γ_N by many of the missing orders; the flavor-blind gauge rate $g^2 T$, the parametric first guess, is computed to land *through* the peak into over-damping ($\Delta M/\Gamma^{\rm eff} \simeq 0.07$, reproducing the excluded $\sim 3 \times 10^4$ overshoot), while the flavor-measurement rate $c_\tau y_\tau^2 T$ lands in the required decade — the identified candidate mechanism, stated below; *radiative degeneracy* — a mechanism driving a pair of M_i toward width-scale splitting at the crossing; *substructure* — a finer level spacing within the lock cluster at $O(\Gamma)$ scale. Deciding

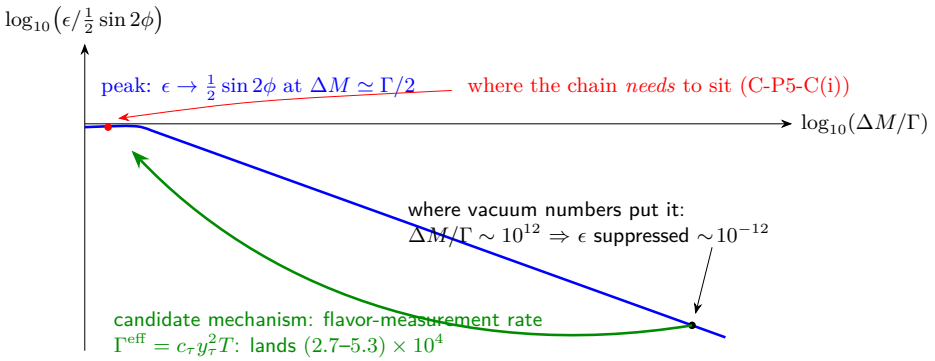


Figure 17: The resonance regime map (the formula is derived in Appendix F.3). The self-energy enhancement saturates at the Breit–Wigner peak and falls as $\Gamma/\Delta M$ off it. Vacuum numbers place the inherited splittings twelve orders off-peak (black); the chain's named input C-P5-C(i) is the requirement of sitting at the peak (red); the flavor-measurement route (green) is the identified candidate mechanism, $\Gamma^{\rm eff} = c_\tau y_\tau^2 T$ (candidate grade; conditions C1–C6). This figure is the paper's sharpest open item, drawn rather than hidden. The flavored recomputation sharpens the target: the required operating point is not the drawn peak but the partial resonance $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$ (H-$\phi_{\rm geo}$-1), between peak and vacuum; the exact-peak form overshoots the required throughput by $\sim 3 \times 10^4$.

among them — or discovering that none works, which clause (i) makes a clean kill — is the sharpest single work order this paper issues to the program.

The mechanism, identified (candidate grade). The hypothesis now has a face: an identified candidate mechanism, whose derivation home is the cosmology companion's Appendix I.3 (Arisaka, 2026, A10-Cosmos); this section carries the statement, the closed form, and the physics, not the kinetic derivation. The identification: *the effective width of the flavored resonance is the rate at which the thermal bath measures lepton flavor — not the N's own width.* The CP coherence that builds the asymmetry does not live in the N lines: for the dial-free real-R door the flavor-summed CP source vanishes identically, so the entire CP content lives in the lepton-flavor *differences* written into the plasma, and what cuts the interference off is whatever measures those flavor coherences fastest. The gauge scatterings, five orders stronger, are flavor-blind — a measurement that cannot tell the flavors apart reads nothing, and cancels exactly from a flavor-odd source; the N's own width, seven orders slower, would on this reading be the wrong clock — the N is not what decoheres on it. Whether the in-medium clock is indeed Γ_τ is exactly condition C4 below, open at derivation level. The fastest honest flavor measurer in the bath is the tau Yukawa interaction,

$$\Gamma^{\rm eff} \;=\; \Gamma_\tau \;=\; c_\tau\, y_\tau^2\, T, \qquad c_\tau = 5 \times 10^{-3}\text{–}10^{-2}, \tag{63}$$

the charged-lepton flavor-equilibration rate of the kinetic literature. At the generation temperature $T \simeq M_N$ the heavy mass cancels between the ledger splitting $\Delta M = M_{\rm lock}/35$ and the thermal rate, and the degree of resonance collapses to a closed form in the ledger integer and one running Standard-Model Yukawa:

$$\frac{\Delta M}{\Gamma^{\rm eff}} \;=\; \frac{1}{35\, c_\tau\, y_\tau^2} \;=\; (2.7\text{–}5.3) \times 10^4 \tag{64}$$

against the hypothesized 3×10^4. Zero dials: the same $K = 35$ that sets the hierarchy (e^{-K}), the lock mass ($\frac{1}{2} M_{\rm Pl} e^{-K}$), and the throughput target ($e^{-K/2}$) also sets how far off peak the resonance sits, with the running tau Yukawa — an object entirely of the Standard Model — supplying the only other factor: geometry over chemistry, once more.

The numbers, honestly: $\Gamma^{\rm eff} = \Gamma_\tau = 2$–$4$ MeV against the hypothesized ~ 3 MeV. At the single-temperature evaluation $T = M_N$ the flavored chain lands η_B at 0.28–0.55 of the observed value; the honest T-integration over the decoupling window — where the mechanism's own regulator, proportional to T, has dropped exactly where the surviving asymmetry is produced — is now carried out in the parent's flavored Boltzmann integration (Arisaka, 2026, A10-Cosmos, App. I): scanning the declared freedoms it lands at 0.09–0.23 of observed (68%; central 0.14), with the priced standard omissions supplying a factor $\simeq 3.3$ centrally and leaving the observation $+1.3\sigma$ away in the log. Always from below, never above. The deficit is named — it is condition C6 below — and its one-sidedness is itself informative: the missing transport prefactors must be enhancements, and the known members of that class (scattering source terms, the Lorentzian-versus-Breit–Wigner convention, the seam washout normalization) all point up.

The identification discriminates rather than scatters. The four candidate regulator prescriptions — the N widths, the flavor-measurement rate, the oscillation rate ΔM itself, and the flavor-blind gauge damping $g^2 T$ (with the Hubble rate below them all) — span sixteen orders of magnitude in $\Delta M/\Gamma^{\rm eff}$, and exactly one lands in the decade the hypothesis requires. The N-width class undershoots the observed asymmetry by $\sim 10^{7\text{–}8}$; the gauge rate $g^2 T$, the parametric thermal-width candidate of the regime map, lands *through* the peak into over-damping ($\Delta M/\Gamma^{\rm eff} \simeq 0.07$), reproducing the $\sim 3 \times 10^4$ overshoot the flavored recomputation already excluded — and it fails structurally besides, since flavor-blind damping cannot regulate a source it does not distinguish. The regime map's green arrow accordingly points at $c_\tau y_\tau^2 T$.

The status, exactly: a candidate mechanism with a conditional derivation — nothing here upgrades the grade of the chain. The derivation rests on six numbered conditions, stated and graded in the derivation home (GG-A10-Cosmos Appendix I.3), one line each:

C1. *Flavor-odd source*: with R real the flavor-summed CP source vanishes identically — established (algebraic; machine-checked).

C2. *Flavor-blind cancellation*: gauge damping enters through the identity projector and drops from the flavor-odd channel — established within the density-matrix framework.

C3. *Two-level reduction*: the Lorentzian partial-resonance envelope and its $\leq \frac{1}{2}$ bound survive for every regulator value — established at reduction level, given C4.

C4. *Regulator identification (the crux)*: the interference time of the flavor-odd source is $1/\Gamma_\tau$, not $1/\Gamma_N$ — open at derivation level; the full Kadanoff–Baym resummation is the outstanding content (the displayed kinetic system carries the heavy-pair coherence as an external source; discharging C4 means promoting it to a dynamical variable with its own damping).

C5. *The coefficient*: $c_\tau \in [5 \times 10^{-3}, 10^{-2}]$ at $T \simeq M_N$ for this source — plausible; the precise value open.

C6. *Window throughput*: the T-integrated window cost is part of the honest chain, and the priced

$O(1)$ prefactors must supply the remaining one-sided enhancement, now *measured* by the parent's flavored Boltzmann integration at $E = 7.1$, 68% interval [4.4, 11.4] (retiring the prior bracket $\simeq$ 2–20) — measured at flavored-Boltzmann level; closure open.

Three kill routes stand on record: if the finite-temperature derivation returns the N-width class, the chain undershoots by $\sim 10^{7\text{–}8}$ and is falsified from within; if it returns the flavor-blind g^2T, the excluded peak overshoot stands — the same verdict; and if C4 and C5 close but the measured window deficit of C6 ($E = 7.1$, 68% [4.4, 11.4]) survives a full transport computation at its adverse end with the priced prefactors exhausted (they supply $\simeq 3.3$ centrally, leaving $+1.3\sigma$ in the log), H-$\phi_{\rm geo}$-1 fails by throughput rather than by regulator identity — a third, softer kill beside the two clean ones. H-$\phi_{\rm geo}$-1 is not retired and not closed: it is sharpened, from a numerical target into the named conditions C1–C6 — and the identification has made the hypothesis *more* falsifiable, not less.

Let us also say, precisely, what success and failure would look like, because an open problem with acceptance criteria is a computation waiting to happen rather than a mystery. *Success* is a finite-temperature transport computation — thermal widths in the propagators, the lock crossing's time dependence in the rates — in which the effective splitting-to-width ratio at the crossing lands at the partial-resonance point $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$ of H-$\phi_{\rm geo}$-1, so that the flavored throughput on the inherited phases lands within an $O(1)$ of $e^{-K/2}$: both clauses of C-P5-C discharged at once, and T-P5-5 promoted from D* toward derived. *Failure* is the same computation showing the enhancement dead at the crossing for every candidate mechanism — no thermal rescue, no radiative degeneracy, no substructure — in which case the chain is falsified from within, the $e^{-K/2}$ agreement stands exposed as coincidence, and this Part's claim reverts to Sakharov custody plus an unexplained number. Both outcomes are scientific; only the unexamined middle would not be. Until it is discharged, T-P5-5 is exactly what its label says: a proposition at D*, conditional on a named conjecture, whose failure mode is written into its own falsifier list.

88 The alphabet audit: every dial of the birth, valued

The chain of §85 was audited number by number; this section audits it symmetry by symmetry. The question of this Part, asked one level deeper, is not "does the chain reproduce η_B?" — Table 12 answered that — but "*where, along the chain, could nature have chosen otherwise?*" The answer this section displays and then defends: nowhere. Every CP-related quantity that touches the birth of matter is a letter of Part VII's alphabet — a lattice point of $(\pi/5)\mathbb{Z}$ on the one compact circle — and the three jobs any baryogenesis must fill (that CP violation *exists*, that the excess has the *sign* it has, that it has the *size* it has) are paid by three different structures, none of which is a dial. The oldest question a physicist can ask about our own existence — *was the asymmetry tuned?* — receives here its sharpest available answer: there was nothing to tune.

The alphabet, recalled. Theorem T-P5-3(iv) values every first-order flavor holonomy on the pentagonal lattice: ten letters around the circle, $k\pi/5$ for $k = 0, \ldots, 9$. The chirality criterion of clause (iii) sorts them: the two letters on the real axis, $\{0, \pi\}$, are *achiral* — a texture whose loops all sit there is indistinguishable from its mirror, and CP holds; the other eight are chiral, in mirror

pairs. The Majorana phases of the seesaw sector live on the same circle — they are holonomies of the same fiber, constrained by the dial-free door (T-P5-4) — so the alphabet is the *entire* vocabulary available to CP in this geometry: quark, lepton, Dirac, Majorana. There is no eleventh letter, and there is no continuous direction between letters. Now run the audit.

Table 13: The CP alphabet, audited row by row. Each row names one of the CP quantities this geometry admits, the value it is forced to, the letter of the alphabet that value reads as, and the job that quantity does in the birth of matter. The last row is not an angle at all but the throughput, which fixes the magnitude rather than the sign. Read down the final column, the table separates the single driver from the entries that do no work in the matter account.

CP **quantity**	**forced value**	**letter, read**	**job in the birth of matter**
$\delta_{\rm CKM}$	$2\pi/5$ (QD $13\pi/35$)	chiral	none: the quark throughput computes to $\sim 10^{-20}$ (Gavela et al., 1994), ten orders short (§84) — the mirror-breaking that makes B mesons asymmetric never touched the inventory of matter
$\delta_{\rm PMNS}$	$\pi + 2\arcsin\frac{1}{7} = 196.4°$	anchor π, deviation $1/J$	spectator: the Casas–Ibarra cancellation makes the chain $J_{\rm PMNS}$-blind at the few-percent level (§85, step 5)
α_{21}	0	achiral (parity $+$)	inert
α_{31}	π	achiral (parity $-$)	**the driver**: sets the sign of the flavored asymmetries $\epsilon_{i\alpha}$, nonzero at $m_1 = 0$
throughput	$\epsilon\,\kappa = e^{-K/2}$	not an angle	**the magnitude**: $\eta_B = 7.04\,\frac{28}{79}\,e^{-K/2}/g_* \simeq 5.9\times10^{-10}$

Five rows, and the reader should sit with the first column for a moment: these are all the CP dials the Standard Model hands an engineer of baryogenesis — the phase the B factories measured, the phase DUNE will measure, the two phases $0\nu\beta\beta$ may someday constrain — and the audit says the famous ones are bystanders. The birth of matter runs on the two letters nobody celebrates, plus one number that is not a letter at all.

The paradox, stated. A reader fresh from Part VII will object, and the objection deserves its own paragraph. The driver of the asymmetry is $\alpha_{31} = \pi$; the lepton Dirac anchor is π; and $\{0, \pi\}$ are exactly the *achiral* letters — the values at which the chirality criterion (51) says CP is *conserved*. The audit appears to claim that matter was made by the CP-conserving letters of a CP-violating alphabet. Stated so baldly, it sounds like a bookkeeping error. It is instead the Part's deepest lesson about the division of labor, and it resolves in three steps.

First: a Majorana letter is read at half-angle. A Majorana phase enters amplitudes through the combination $e^{i\alpha/2}$ — the door's weight-zero pairing splits every angle in two — so the lattice letter $\alpha_{31} = \pi$ reads, at the amplitude level, as $e^{i\pi/2} = i$: a quarter turn, as far from the real

axis as a phase can be. What the Lagrangian's bookkeeping records as a parity, the interference terms experience as the maximally imaginary insertion. (This is stated here as the physics reading; the flavored computation whose output it summarizes lives at its stated grade in the cosmology companion's Appendix I.) The letter is achiral; its *square root* is not; and amplitudes take square roots.

Second: at a resonance, an amount becomes an orientation. On the (partial) resonance of §87 the CP asymmetry saturates — $\epsilon^{\rm res} \simeq \frac{1}{2}\sin(2\phi_{\rm geo})$ times the transport factor — and the Yukawa magnitude cancels between numerator and denominator. Near saturation, the phases are no longer asked "how much?"; they are asked only "which way?" — which side of the interference the decay products land on. A parity is precisely an answer to "which way?" with no "how much" attached. The division of labor is therefore not an accident but the natural grammar of resonant transport: *amounts saturate; orientations survive.*

Third: something must still be chiral, and it is the pentagon. A parity can orient an interference only if there is an interference to orient — only if the texture is genuinely complex somewhere. That existence claim is the pentagon's: the branch phase $\pi(1-2/L) = 3\pi/5$ is chiral because five is odd, and no assignment of the theory's discrete data could have made the alphabet mirror-symmetric (T-P5-3). Kill the pentagon's chirality — give the bulk an even block integer — and every letter lands on the real axis, the parities have nothing to sign, and the universe keeps its perfect, sterile balance. In one line each: *the pentagon writes the sentence; the parity chooses its sign; the throat depth sets the print run.*

Existence, sign, magnitude. The trichotomy deserves to be displayed as the section's result, with the provenance of each clause:

- **Existence** of CP violation: the chirality of the pentagon, $3\pi/5 \notin \pi\mathbb{Z}$ — derived (T-P5-3, at the mirror Parts' stated conditionality). Not a dial: there was no value of anything that could have turned it off.
- **Sign** of the excess — matter rather than antimatter: the Majorana parity $\alpha_{31} = \pi$, a two-valued letter forced by the dial-free door's real structure, read at half-angle by every amplitude. (Which parity corresponds to the label "matter" is a convention fixed jointly with the orientation conventions of Part V; the physical content — that the sign is *discrete, forced, and not adjustable* — is convention-free, at the flavored computation's grade.)
- **Magnitude**: not a CP quantity at all. The throughput $\epsilon\,\kappa = e^{-K/2}$ is transport — resonance times washout — and its exponent is the ledger's throat depth $K = 35$, the same integer that sets the lock mass (e^{-K} in $M_{\rm lock}$) and caps the strong-CP leakage (e^{-K} in (59)). Dressed by the standard sphaleron and entropy factors it returns $\eta_B \approx 7 \times 10^{-10}$ (62): *the baryon-to-photon ratio is the square root of the lock-scale suppression*, read through bookkeeping nobody disputes.

What the Standard Model could not have done. The contrast that gives the audit its force is not with a rival mechanism but with the same mechanism run on continuous dials. The

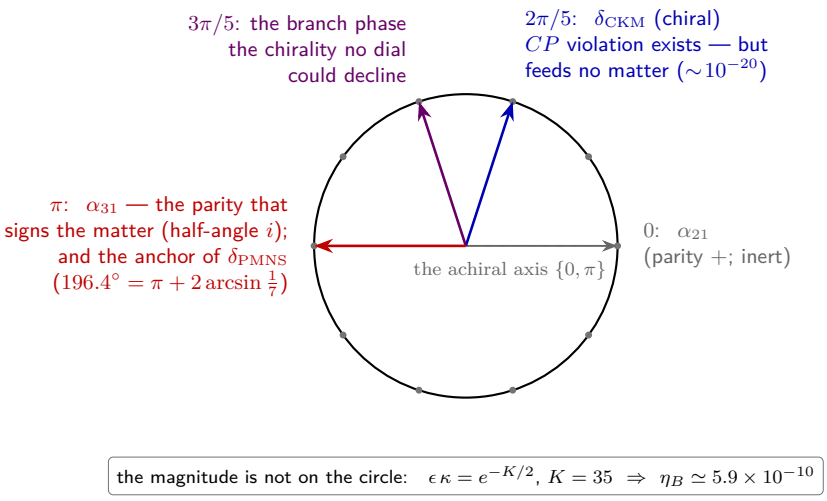


Figure 18: The alphabet audit, drawn. The ten letters of the pentagonal lattice $(\pi/5)\mathbb{Z}$ on the one compact circle, with the four that run the birth of matter marked. The quark Dirac phase (blue, $2\pi/5$) is chiral — CP violation exists — but its throughput is ten orders too small to feed the inventory. The branch phase (violet, $3\pi/5$) is the chirality the odd alphabet forced: the reason any interference exists to orient. The achiral letter π (red) does double duty: as the Majorana parity α_{31} it signs the matter excess (every amplitude reads it at half-angle, $e^{i\pi/2} = i$), and as the anchor of $\delta_{\rm PMNS} = \pi + 2\arcsin(1/7)$ it places the lepton Dirac phase DUNE will measure — a spectator to the birth. The magnitude lives off the circle entirely: the throughput $e^{-K/2}$, the ledger's throat depth. Existence from the pentagon, sign from a parity, size from the throat: three jobs, three structures, zero dials.

Standard Model's own double failure — the crossover that removes the departure from equilibrium and the 10^{-20} that starves the quark route — already forced the lepton road (§84). But hierarchical leptogenesis run in the standard way inherits the Standard Model's dial economy: the heavy masses are free, the R-matrix is free, the phases are free, and the observed η_B becomes a *constraint surface* in that parameter space — a good theory that can accommodate the number but cannot be said to have produced it, and whose operating point no experiment can reach (PS-P5-8). Here every one of those freedoms is a letter or a ledger integer: the masses sit at the lock (e^{-K}), the door is a uniqueness theorem, the phases are the alphabet's, and the throughput reconstructs $e^{-K/2}$. When a construction with no dials lands within 4% of the measured number, the correct reading is not "a good fit" — there was nothing to fit — but a jointly falsifiable identity between the geometry's one depth integer and the inventory of the universe.

Physics intuition: why there is something rather than a mirror. Assemble the audit into the sentence the title of this Part promised. The universe keeps matter for three nested reasons, one per structure. *Because five is odd*: an odd alphabet cannot be mirror-symmetric, so the texture of couplings is chiral — CP violation was constitutional, not optional. *Because the door pays in $B-L$*: the sphaleron era converts the lepton-sector excess at the fixed rate $28/79$ and conserves $B-L$ thereafter, so the coin struck at the lock is neither re-melted nor diluted (§86) — the asymmetry is banked in the one currency the late universe cannot touch. *And because the throat is thirty-five deep*: the surviving fraction per photon is $e^{-K/2}$, six parts in ten billion — the same e^{-35} that parks

the seesaw partners at 3.85 TeV, taken at its square root by the resonance-and-washout transport. A universe with an even block integer keeps nothing and no one asks the question; a universe with a shallower throat is matter-dominated into opacity; this one prints six baryons per ten billion photons and, some 10^{17} seconds later, prints physicists who count them. None of the three clauses was adjustable. That is what "deterministically programmed" means here, and it is the precise sense in which this framework answers — at its stated grades — the question the author of this cohort has carried for fifty years: *we are here because the geometry's alphabet is odd, its door pays in a conserved currency, and its throat is exactly as deep as the number of us.*

The audit's own exposure. Determinism of this kind is only physics if it can die, and each clause hangs its own rope. The anchor-plus-deviation letter is checked by DUNE: $\delta_{\rm PMNS} = 196.4°$, separated from the achiral 180° at $\sim 1\sigma$ per $\pm 15°$ resolution and from maximal 270° at $\sim 5\sigma$ (§78.4). The parities are checked by $0\nu\beta\beta$: $(\alpha_{21}, \alpha_{31}) = (0, \pi)$ gives $m_{\beta\beta} = 1.72$ meV — an *observation* at the tens-of-meV level now within experimental reach would falsify the parity pattern outright. The sign is checked by the appearance asymmetry ($J_{\rm PMNS} < 0$; T2K already disfavors the opposite sign). The magnitude is checked by the CMB number itself, against the standing exposures of Table 12: the one named input (C-P5-C's on-resonance condition, carried by the flavor-measurement regulator at candidate grade) and the one postulated exponent ($K/2$, the compression C-P5-C(ii) must still derive). The honest summary of the whole section is therefore one sentence long: *every symmetry dial of the birth is a forced letter of one discrete alphabet — graded, displayed, and mortal in four independent laboratories within the decade.*

CP-conserving in the sum, CP-violating in the differences. The doctrine deserves its own paragraph here, because it is the step on which the whole chain turns and it is easy to read as a technicality. With opposite CP parity between ν_3 and $\nu_{1,2}$ and a real orthogonal R, the imaginary parts that drive the asymmetry are manifestly nonzero flavor by flavor — and they sum to zero over flavor for one reason only: the unitarity of the mixing matrix makes the relevant column sum vanish. The cancellation is a column-orthogonality statement, not a dynamical one, so it is exact.

That is the whole resolution of an apparent paradox. *A zero-sum set of flavored asymmetries is not a zero asymmetry*, because the three flavors are not washed out equally; differential washout converts a set that sums to zero into a net excess. Two consequences follow, and both are the kind that a referee can check. First, a flavored treatment is *mandatory* here rather than merely more careful: an unflavored calculation of this chain returns exactly zero, and would have to be reported as a failure. Second, the flavor-sum cancellation is promoted from a technical nuisance to the load-bearing step of the argument — which is why §88 prices $\alpha_{31} = \pi$ as the driver and the achiral α_{21} as inert.

THE PLATE THAT WOULD HAVE GONE HERE WAS DROPPED, AND THE REASON IS WORTH RECORDING. The leptogenesis study draws this with its three flavored $\epsilon_{i\alpha}$ values on a bar chart. Those numbers are computed at that study's own inputs; this paper does not derive them, and the study is an internal one with no entry in this paper's bibliography and none on the arXiv path. Printing another paper's numbers under no citation is worse than printing no chart, so the concept is carried and the chart is not.

89 What the block predicts, and how it fails

The chain is deliberately exposed. *Mechanism kills:* if a full transport calculation shows no consistent on-resonance heavy-neutrino/washout regime near the lock scale, the chain fails (C-P5-C(i)). *Backbone kills:* if cosmological data force a neutrino mass sum or CP structure incompatible with the inherited ledger, the backbone fails; if proton decay is observed, the whole baryonic logic fails. *Dated instruments:* $m_{\beta\beta} \simeq 1.7$ meV at the next-generation neutrinoless double-beta program — the cleanest near-term discriminator of the Majorana door; the 3.85 TeV lock cluster within HL-LHC reach, with a pre-declared kill criterion in the cohort's ledger; and $\delta_{\rm PMNS}$ at DUNE/Hyper-Kamiokande to $\pm 15^\circ$ by the early-to-mid 2030s — a measured value inconsistent with 196° falsifies the phase that biases the door's traffic. No other baryogenesis proposal in Part X's comparison carries a falsifier list with dates; most carry none at all.

The testability inversion. It is worth pausing on how unusual this situation is. Hierarchical thermal leptogenesis — the field's default explanation — is a good theory that cannot be tested: its heavy states sit at 10^9 GeV or above, and the CP phases that matter to it are not the phases experiments measure. The present chain inverts every clause: its heavy states sit at 3.85 TeV, within collider reach; its CP phase *is* the measured PMNS sector's, projected; its Majorana door casts a $0\nu\beta\beta$ shadow at a computable 1.7 meV; and its proton clause is checked by every year of Super-Kamiokande silence. Whatever one's priors about the geometry, the scientific posture is the preferable one: the account of why we exist is due in the data within the decade — more predictive and more protective at once, and mortal four separate ways.

90 The Ω_b bridge

One open seam is recorded rather than smoothed. The transport route of this Part gives $\eta_B \approx 7 \times 10^{-10}$ (central 7.34), hence $\Omega_b h^2 \simeq 0.0268$ by standard conversion; the cohort's topological claim reads the baryon share directly from the ledger, $\Omega_b = 1/(2\pi^2) \simeq 0.0507$, i.e. $\Omega_b h^2 \simeq 0.0230$ at the corridor's h. The two routes to the same observable differ by $\sim 16\%$ at the corridor's h (branch-dependent, shrinking through zero near the ladder branch) — against a measurement whose own precision is $\sim 0.7\%$ — and the discrepancy is a named open problem of the cosmology companion. The residue is not symmetric between the routes: anchored to the measured $\Omega_b h^2 = 0.02237$, the transport route's $+20\%$ is priced by its own factor-~ 3 band, while the topological route at the corridor's h sits $+3\%$ high with no $O(1)$ freedom to price it — so the unowned residue sits on the corridor-h conversion or on the exactness of $1/(2\pi^2)$, not on the transport $O(1)$'s. This paper flags the seam in preference to hoping no reader divides two of its own numbers.

91 What is claimed, and what is inherited

Concessions first, in full — and for this Part the concession is total at the level of technique: *the chain contains not one new formula.* The three conditions are Sakharov's (Sakharov, 1967). The lepton route is Fukugita and Yanagida's (Fukugita and Yanagida, 1986); the resonant regime is

Pilaftsis's and Pilaftsis–Underwood's (Pilaftsis, 1997; Pilaftsis and Underwood, 2004); the bound it evades is Davidson and Ibarra's (Davidson and Ibarra, 2002); the seesaw parameterization is Casas and Ibarra's (Casas and Ibarra, 2001); the sphalerons are Kuzmin–Rubakov–Shaposhnikov's (Kuzmin, Rubakov, and Shaposhnikov, 1985) with Harvey and Turner's 28/79 (Harvey and Turner, 1990); the washout benchmark (60) is textbook transport. Every module is standard 1967–2004 technology, cited at its point of use, and Part X walks the whole toolbox on its own ground. One quiet dependency of the toolbox deserves its own line: every equilibrium abundance, Pauli-blocking factor, and chemical-potential count in that transport — including the 28/79 itself — presupposes *exact* Fermi–Dirac statistics for the fermions of the bath. The cohort now traces that exclusion to bulk frame-path holonomy at candidate grade (§45; Arisaka, 2026, A2-GG6 §20; Arisaka, 2026, A8-QM T-A8.12), so the receipt of this Part rests on the geometry twice: once for the phase that biased the traffic, and once for the statistics that counted it.

What this Part claims, ranked by confidence, at the grades of Table 14. *First — the load-bearing claim — dial-lessness.* In every standard implementation the heavy masses, the degeneracy, and the CP phases are chosen; here the mass is the ledger's lock scale, the portal is a uniqueness theorem, the Yukawa is fixed by matching to derived light masses, and the phase is the pentagon's — zero fitted parameters, one named input, one postulated exponent, as the audit table prints. No other framework in the comparison derives its η_B inputs from anything. *Second, the bracketing:* the independently derived washout efficiency and the candidate regulator's closed form bracket the ledger's $e^{-K/2}$ — the exponent remains a postulate (C-P5-C(ii)), the identity at displayed precision uses the declared $O(1)$ freedom in κ, and the bracketing is the news. *Third, zero dilution as a structural guarantee:* the prompt-crossing lemma kills, in one stroke, the inflation-dilution worry of GUT baryogenesis and the moduli plague of string cosmology — the descent has no furnace to re-melt the coin. *Fourth, proton-safe baryogenesis:* the standard tension — the sector that makes baryons can eat the proton — is dissolved by construction, bulk ledger exact, boundary $B-L$ active. *Fifth, the testability inversion:* four dated instruments where the default explanation offers none. The first claim is as strong as the audit table; the second carries the named conjecture; the third is derived-conditional on the prompt-crossing lemma; the fourth is derived; the fifth is a fact about the falsifier list. And over all five stands the Part's honest ceiling: until C-P5-C is discharged, T-P5-5 is a D* proposition — the resonance gap of §87 is the sharpest outstanding physics item in the program, printed in its own section, drawn in its own figure.

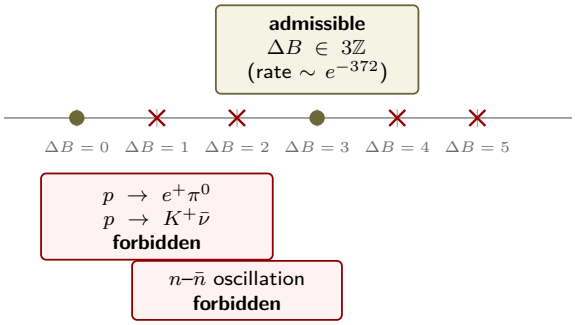
92 The selection rule that does both jobs, and a prediction that can only fail

A reader who has followed the chain should be uneasy at this point, and the unease is exactly right. Everything above requires baryon number to be violated — Sakharov says so and there is no way around it: a universe that starts with $B = 0$ and ends with $B \neq 0$ has violated baryon number somewhere. And yet the cohort's most distinctive laboratory prediction is that the proton is *absolutely* stable: not long-lived, not 10^{36} years, but $\tau_p = \infty$ (Arisaka, 2026, P6-Proton).

Both are true, and one rule does both jobs.

$$\Delta B \;=\; N_{\text{gen}}\, n \;=\; 3n \;\in\; 3\mathbb{Z}.$$

Baryon number can change, but only in units of three. A bulk thermal reprocessing of a $B-L$ asymmetry does not care: the universe converted its lepton asymmetry three baryons at a time and never noticed. A proton decay, $\Delta B=-1$, does care, because $-1\notin 3\mathbb{Z}$. No anomalous process, however violent, can remove a single nucleon; the minimal admissible event costs three baryons at once and three leptons with them, preserving $B-L$. This is not a loophole but the arithmetic of the anomaly: each family contributes once, there are three families, and so the quantum of baryon violation is three. *The same* $N_g=3$ *that* GG-P2-N3 *derives stands guard over every atom.*



Every canonical proton-decay mode has $\Delta B=1$; neutron– antineutron oscillation has $\Delta B=2$; neither integer is a multiple of three, so both are forbidden outright rather than merely suppressed. The thermal reprocessing of Part VIII lives at $\Delta B\in 3\mathbb{Z}$ and is unaffected. **A single event in either forbidden class falsifies the framework** — and Hyper- Kamiokande will improve the bound on the first class by about an order of magnitude.

Figure 19: Baryon number changes only in units of the generation count, after T-SM-60.1 of GG-A9-SM (Arisaka, 2026, A9-SM). Every canonical proton-decay mode has $\Delta B=1$ and neutron–antineutron oscillation has $\Delta B=2$; neither integer is a multiple of three, so both are forbidden outright rather than merely suppressed. The thermal reprocessing of this Part lives at $\Delta B\in 3\mathbb{Z}$ and is unaffected. A single event in either forbidden class falsifies the framework.

What is imported, and with which hypotheses. The rule is not derived here. It is Theorem T-SM-60.1 of GG-A9-SM (Arisaka, 2026, A9-SM), and it travels with its three hypotheses: (H1) the boundary spectrum is the split Standard Model with the X,Y retained only as bulk modes; (H2) the bulk $\mathrm{U}(1)_B$ descends so that the exact boundary gauge symmetry acts as baryon number; and (H3) the $\mathrm{U}(1)_B$ gauge anomalies are canceled by the BI-6 Green–Schwarz inflow. Under those three, every local operator with $\Delta B=\pm1$ or ±2 carries non-zero $\mathrm{U}(1)_B$ charge and is forbidden to all orders, and the only admissible baryon-number violation is the electroweak anomaly, suppressed by $e^{-4\pi/\alpha_W}=e^{-372}\sim 10^{-162}$. The owning paper also records why the step is not automatic — baryon number is not a generator of unbroken SU(5), and gauging the $\mathrm{U}(1)_B$ of $\mathrm{SU}(5)\times\mathrm{U}(1)_B$ does not by itself forbid proton decay — and that caution is imported with the result rather than left behind it.

A prediction that points the wrong way on purpose. The epistemic shape of this one is unusual and deserves its own paragraph, in a paper whose register is that a claim should be stated with the measurement that would kill it. Grand unified theories *predict* proton decay and are confirmed by a positive detection. This framework says the search will never succeed, in any channel, at any sensitivity. That is the stronger claim and the more dangerous one. It cannot be confirmed — no finite exposure establishes $\tau = \infty$ — and it can be destroyed by a single event. Hyper-Kamiokande's projected sensitivity is therefore not a test the framework can pass; it is a test it can only fail. For a framework that claims to fix parameters rather than fit them, that is the right way round, and the whole baryonic logic is staked on it rather than hedged.

93 The three horizons of sameness

The excess is one instance of a wider fact, and this Part should name it before closing: the universe is *the same* in three progressively stronger senses, and the two fibers of §59 price each one differently. The formulation is the holonomy companion's (Arisaka, 2026, W2-Holonomy); it is reproduced here because the third horizon is this Part's own result seen from a distance.

Horizon 1: the same conditions. Temperature, curvature and inventory uniform across causally disconnected patches. Bought by the interval's opening act — inflation stretches one patch over the sky (Arisaka, 2026, A10-Cosmos).

Horizon 2: the same things. Every region built of the same electrons, the same protons, the same abundances. Bought by the circle's ledgers: identity is a holonomy class, and classes are the same everywhere without communication. No mechanism need synchronize what topology makes identical.

Horizon 3: the same choices. Every region on the same side of every symmetry breaking — matter over antimatter, this vacuum, this alphabet. Bought by the descent's chiral texture, read once and in one direction, with the excess of this Part its sharpest instance.

The three are the anatomy's answer to the oldest observational fact about the universe: its monotonous, extravagant sameness. And the sorting is the same one §59 applied to the mirrors. Horizon 1 is an interval statement and needed a mechanism. Horizon 2 is a circle statement and needed none — which is why it has never seemed to require explanation, and why the absence of a puzzle there is itself a datum. Horizon 3 is the texture the interval wrote onto the circle, and it is the one this paper computes.

Why the third horizon is the one that could have failed. A tuned universe would have to tune each region separately. A lottery universe would have to correlate its draws across regions that have never been in contact. The reading assembled here does neither: the sign of the excess is set by the chiral alphabet, which is circle-side content and therefore identical in every region, so every patch tips the same way for the same reason. Segregation — antimatter galaxies elsewhere — would require horizon 3 to fail exactly where the geometry holds it hardest, and the gamma-ray sky reports no annihilation seam at any scale.

What this does not settle. Naming the three horizons does not prove any of them. Horizon 1 is the cosmology companion's result and carries its conditioning; horizon 2 rests on the identification of identity with a holonomy class, which is the arena's claim and not this paper's; horizon 3 is computed in this Part at the grade the status ledger of §95 records, conjecture C-P5-C included. The value of the three-way sorting is that it says which kind of explanation each sameness needs — a mechanism for an address, nothing at all for a class — and that is a diagnosis rather than a derivation.

94 Why a universe of matter was inevitable

Assemble the Part. Four things were established in four different places, and it is worth putting them in one paragraph because the conclusion is their product and not any one of them.

The circle guarantees that matter and antimatter exist at all, as two readings of one book, degenerate in every address — that is T-P5-A and T-P5-C of Part IV, and it is why the question "why is there something rather than its opposite" is a question with a mechanism rather than a mood. The chiral alphabet guarantees a preferred sense, pressed onto the fiber by the constitution's integers rather than chosen by history — Part VII. The interval guarantees a once-only, out-of-equilibrium crossing at which the preference could act, and prices its throughput with a topological exponential — §86. And the quantized door guarantees that the asymmetry, once written into baryons, is kept: $B - L$ never opens, and the sphaleron door welds shut as the descent cools.

Nothing in that sequence is contingent. Given the constitution, a universe that ends the crossing with a small residue of unmatched matter is not one lucky outcome among many; it is the deterministic playback of a chiral tape read once and in one direction. The formulation is the holonomy companion's (Arisaka, 2026, W2-Holonomy) and it is adopted here because it is the shortest true statement of what this Part computes: *the excess of particles is the one-way reading of a chiral tape.*

The honesty that has to travel with that sentence is the honesty of §95, unchanged. "Inevitable" is a statement about the *shape* of the outcome, not its precision. The magnitude carries the named conjecture C-P5-C and the postulated $K/2$ exponent, and until those are discharged the number is a D* proposition and is printed as one. What is claimed as inevitable is that the sign is fixed, that the door is unique, and that the crossing happens once — and each of those is a class statement, which is why the sign is the same in every region of the sky while the magnitude is the thing still being audited.

94.1 Three questions this Part should answer out loud

Where did all the antimatter go, physically? It annihilated — essentially all of it, against essentially all of the matter, in the first seconds. The photon bath of the microwave background is in large part that bonfire's light. What survived is the unmatched residue, one part in a billion, which is the number this Part computes. The universe of galaxies is not matter's triumph over antimatter; it is the change left over from their mutual settlement.

Could the antimatter be somewhere else — antimatter galaxies, segregated? Observation says no: there is no annihilation seam in the gamma-ray sky at any scale. The account here says why it could not have been otherwise, and the reason is §93's third horizon. The sign of the excess is set by the chiral alphabet, which is circle-side content and therefore identical in every region without any region having to communicate with any other. Every patch tips the same way for the same reason. Segregation would require horizon 3 to fail exactly where the geometry holds it hardest.

Does antimatter fall differently? No — and this account is committed, in a way that is worth stating as a falsifier rather than as a reassurance. By T-P5-A and T-P5-C an antiparticle is the same holonomy class read in the conjugate orientation, and a mass is that class's address along the interval. An address is orientation-blind: reversing the reading does not move it. The antihydrogen free-fall measurements are therefore an audit of the mirror reading itself, not of general relativity. *Any anomalous gravitational behavior of antimatter breaks Part IV at its root* — the handshake, the equal masses, and the pairing — well before it troubles anything in the gravitational sector. The commitment is total and it is cheap to state because the geometry leaves no dial to turn: there is no parameter in this construction that could make a conjugate reading weigh differently.

95 Status ledger for Part VIII

Table 14: Part VIII at a glance. The chain's originality is its dial count — zero fitted parameters — and its honesty is this table. Eleven steps, each with its grade and its residue. The grades run from derived, through named input and derived-conditional, to reconstruction and — in the last row — open. That last row is the one to read first: the two-route bridge for the baryon density leaves a gap whose owner has not been identified, and the table says so rather than rounding it away.

Step	Grade	Residue
Sakharov tripod (P-P5-E)	derived (architecture)	clause grades inherited (§83)
$M_{\rm lock}$, splittings, $T_{\rm rh}$ window	derived	—
Portal uniqueness (T-P5-4)	derived	—
Seesaw-matched Y_ν, width	derived	—
On-resonance enhancement	named input	C-P5-C(i); twelve-order gap quantified (§87)
CP asymmetry $\epsilon^{\rm res}$	derived-cond. (H-$\phi_{\rm geo}$-1)	flavored computation displayed (GG-A10-Cosmos App. I); candidate mechanism identified (the flavor-measurement regulator); C1–C6 open
Washout κ	derived-cond.	$O(1)$ uncomputed
Throughput $= e^{-K/2}$	reconstruction	exponent postulated; C-P5-C(ii)
Sphalerons, entropy, η_B	standard + D*	factor-$\sim$ 3 band
Zero dilution ($N_2 = 0$)	derived-cond.	prompt-crossing lemma
Ω_b two-route bridge	open	16.4% gap, owner unidentified

Part-end summary. The observed six-per-ten-billion is met by a chain whose every input already existed for other reasons: the lock scale, the unique door, the matched Yukawa, the pentagon's phase. One named conjecture carries the resonance and the exponent; one open seam joins the two Ω_b routes; four dated experiments can kill the story within a decade. And with this Part the story the paper opened is closed end to end: the twins were forced by the handshake; the mirrors broke selectively, by an absence and an angle; the angle biased the traffic through the one door only the still-point field could open; the one-way boundary froze the bias into a number; and the number, conserved ever since, is the matter of every reader now holding this page. Matter won, on this account, because the descent is oriented — and the oriented descent is falsifiable. But before the account faces its rivals, one debt remains. The whole story ran on a word this paper has used on every page and never paused to define — time: the clock, the arrow, the one-way shore. The next Part stops and asks what it is.

Part IX
What Is Time?

The oldest question given a geometric answer — the four endowments (order from the cone, repetition from the equivalence, arrow and shore from the dictionary), now located in the anatomy: the circle ticks, the interval points; the standard accounts reviewed and honored; the problem of time in quantum gravity, dissolved by architecture; the first law-level arrow; the chronology quantified — boundary time as the exponential shadow of the descent, the age of the universe as an audited e-fold ledger; every clock a winding counter; temperature as the shore's transported period; energy and entropy as two currencies of one direction; the significance against every previous definition; and what it all means, in plain words

96 Part IX in plain English: the oldest question, given a geometric answer

Everyone uses time and no one can say what it is. Physics inherited that embarrassment and made a profession of it. This Part offers an answer of a particular shape — not a definition of time, but a list of the things time does and the piece of geometry that supplies each of them.

There are four. Order comes from the light cone. Repetition, and with it frequency, energy, and the possibility of a clock at all, comes from the compact circle. The arrow comes from the radial interval, which admits no holonomy and therefore only ever points forward. And the shore — the single-sided spectrum that makes imaginary time and thermal computation work — comes from positivity. Four endowments, four distinct carriers, and none of them supplied twice.

What that buys is an arrow at law level rather than as a statistical tendency, a clock that is a winding counter, and a dissolution rather than a solution of the problem of time in quantum gravity. The Part sets the account beside every previous definition in one table, and it says which of the four endowments are inherited and which are argued here, because a Part that answers the oldest question in the subject should be the most careful one about what it is actually claiming.

97 The oldest question, and the shape of an answer

"What, then, is time? If no one asks me, I know; if I wish to explain it to one who asks, I know not." Augustine's confession (Augustine, c. 400) has embarrassed sixteen centuries of readers because it is exact: every human being navigates time faultlessly and no one can say what it is. Physics inherited the embarrassment and professionalized it. This Part exists because the present program — through its Foundations-Branch partner (Arisaka, 2026, P4-Real) and the preceding Parts of this paper — has arrived, almost without meaning to, at an answer: not a metaphor, not a stipulation,

but a structural characterization of what the direction we call time *is*, precise enough to be wrong.

The question splits into three that are usually run together. *What orders events* — why is the world sorted into before and after at all? *Why does time run one way* — what is the arrow, and where does it live? And *what is the "it" in Minkowski's it* — why does every quantum computation reach for an imaginary time, and every thermodynamic identity return from one? The standard accounts, reviewed next, each answer one of the three magnificently and fall silent on the rest. The geometry's answer (§100) is that the three questions have one subject: the unique direction of the arena that carries four endowments at once — order, repetition, arrow, and shore. The claim of this Part is that the four-endowment characterization is a genuine definition: it picks out time uniquely among all directions, it derives rather than assumes the properties the standard accounts postulate, and — through the boundary law — it makes the arrow a matter of law rather than of luck for the first time (§103).

98 Time in the standard accounts, each honored

Classical mechanics: the parameter. Newton declared time absolute — flowing "equably, without relation to anything external" — and Leibniz retorted that time is nothing but the order of successions; the debate outlived both. Operationally, classical mechanics settled for less than either position: t is the real line on which trajectories are parameterized, featureless, homogeneous, and reversible — run any solution backward and the laws are equally satisfied. Mechanics gave time its mathematics and deliberately declined to give it a nature.

Special relativity: the geometry of order. Minkowski's 1908 lecture (Minkowski, 1908) performed the first transmutation: time became a direction in a real geometry — not a flow but an axis, distinguished from space by the sign in the interval. What special relativity actually delivers is *order*: the light cone at every event sorts the world into before, after, and elsewhere, causal influence respects the sorting, and simultaneity dissolves — there is no global now, only each worldline's own proper time. But this time has no arrow: the block universe contains both directions with perfect impartiality. McTaggart's philosophical bombshell of the same year (McTaggart, 1908) — that the tensed flow of time is contradictory and only the ordered series survives — anticipated exactly the physics: relativity kept his ordered B-series and discarded the flowing A-series.

General relativity: time made dynamical — and two endowments lost. Einstein's completion made the geometry of time itself a dynamical field: clocks run slow in gravity wells (measured, from Pound–Rebka to every GPS fix), proper time is path-dependent, and cosmic time is a choice of foliation, not a fact. But dynamism costs dearly, and the costs are instructive. First, *repetition fails generically*: a generic solution of the Einstein equations has no timelike Killing flow, so there is no conserved energy, no preferred frequency decomposition, no unambiguous particle concept — the endowment every quantum construction needs is simply absent in a generic spacetime, which is exactly why Theorem 0's forced staticity is load-bearing for this program. Second, the *shore becomes treacherous*: Euclidean quantum gravity's imaginary-time rotation is globally ill-defined off special backgrounds — the trick stops working where the geometry stops repeating. And third, in the canonical quantization, time vanishes altogether: the Wheeler–DeWitt equation has no t

in it (DeWitt, 1967), and the "problem of time" has stood at the center of quantum gravity ever since. General relativity is thus the standard account's high point and its cautionary tale in one: it geometrized time completely, and in doing so showed that order alone, without repetition, cannot support the rest of physics.

Thermodynamics: the borrowed arrow. The one branch of physics with an intrinsic direction is thermodynamics: entropy increases, and Eddington coined "time's arrow" for exactly this asymmetry (Eddington, 1928). But Boltzmann's own derivation (Boltzmann, 1877) located the increase in probability, not law: the microscopic dynamics is exactly reversible, and the H-theorem's direction is smuggled in through initial conditions — the celebrated objections of Loschmidt and Zermelo stand to this day, patched only by postulating a stupendously low-entropy beginning (the "past hypothesis"). The deepest fact about the standard arrow of time is therefore an embarrassment wearing a law's clothing: *no fundamental equation of physics is irreversible*; the arrow is an initial condition, pushed back to the Bang and left there unexplained.

Quantum mechanics: the outsider. In quantum mechanics time is the one classical survivor: an external parameter, not an operator — Pauli's old argument shows a self-adjoint time observable conjugate to a bounded-below Hamiltonian cannot exist. So the theory that quantized everything left time unquantized, sitting outside the Hilbert space it governs; the Page–Wootters construction (Page and Wootters, 1983) — time read relationally from entanglement with a clock subsystem — is the honorable attempt to bring it inside, at the price of presupposing the very structure it reconstructs. Note the striking asymmetry quantum mechanics silently uses: the energy spectrum is bounded below and unbounded above — time's conjugate is one-sided — and every use of e^{-iHt}, every analytic continuation, every KMS state leans on that one-sidedness without ever asking where it comes from.

QFT and the Standard Model: the reversible mirror record. Field theory sharpened order into microcausality and discovered, through the broken mirrors this paper derives, that nature does distinguish the two time directions — T is violated, measurably, in the kaon and B systems (Parts I and V). But a T-violation of parts per thousand, CP-compensated and CPT-protected, is not an arrow: the Standard Model's dynamics remains perfectly reversible (run the film backward and conjugate the charges and mirror the parities, and every process is again lawful). Wick rotation, meanwhile, became the workhorse of every serious computation — lattice QCD lives entirely at imaginary time — while remaining, in the standard account, a trick: the textbooks rotate, compute, and rotate back, and decline to say what was rotated *into*. And the axiomatic tradition (Streater and Wightman, 1964) proved the deepest results of the subject — CPT and spin-statistics — precisely by analytic continuation in time, using the shore at every step and naming it nowhere.

String theory and quantum gravity: time emergent, arrow absent. In the approaches beyond QFT, space dissolves readily — emergent from entanglement, from matrices, from holography — but time resists: worldsheet time is presupposed, the timeless Wheeler–DeWitt problem returns in every background-independent formulation, and AdS/CFT anchors bulk time to a boundary clock it does not explain. The closest structural cousin of this Part's answer lives here: the thermal-time hypothesis of Connes and Rovelli (Connes and Rovelli, 1994), in which time is the modular flow of the state — one-parameter, KMS-linked, and deeply aligned with the clock-and-shore reading

below, though with the custody reversed: there the *state* defines the time; here the *arena* does, and states inherit it.

The scoreboard, then. Order: delivered, by relativity. Repetition — the exact self-similarity that makes energy and frequency meaningful: assumed everywhere, derived nowhere. Arrow: real in thermodynamics, but located in initial conditions, not law. Shore — the imaginary direction every computation uses: universally employed, universally disowned. Four properties, four accounts, no owner.

99 The problem of time in quantum gravity, and its dissolution

The deepest crisis of time in physics deserves more than the paragraph §98 could give it. Canonically quantizing general relativity turns the Hamiltonian into a constraint: the wavefunction of the universe obeys $\hat{H}\Psi = 0$ — the Wheeler–DeWitt equation (DeWitt, 1967) — and the Schrödinger t simply does not appear. Taken at face value, nothing happens: the fundamental description of a gravitating quantum universe is frozen. This is not a technicality but a collision of the two accounts of time reviewed above: quantum mechanics needs an external clock (endowment two, assumed), while general relativity makes every clock internal and dynamical (endowment two, generically absent). Quantized together, the two demands cancel, and time disappears.

The responses form a literature of their own, and each is a partial recovery of one endowment. *Semiclassical time* recovers the parameter in a WKB regime: where the geometry is nearly classical, a time variable emerges from the heavy degrees of freedom — repetition borrowed from an approximation. *Deparameterization* promotes a matter field to a clock by hand — repetition borrowed from a choice. *Page–Wootters* (Page and Wootters, 1983) reads evolution from entanglement with a clock subsystem — order recovered relationally, at the price of choosing the clock. *Thermal time* (Connes and Rovelli, 1994) derives the flow from the state's modular structure — arrow and shore recovered from KMS, at the price of state-dependence. Each response works where it works; none says why the universe should contain the structure it borrows.

The arena account does not solve this problem; it *dissolves* it, and the distinction should be stated with the register's usual care. In the constitutional architecture the metric of the arena is not a quantum variable: Theorem 0 forces the globally static stage before any dynamics is quantized, so the boundary theory never meets a timeless constraint — the clock is constitutional, and what gets quantized are the fields on the stage, not the stage. The problem of time is therefore not answered within canonical quantum gravity; it is prevented from arising, at the stated cost that the arena's staticity is an output of axioms one level down (AX-1, AX-2, Theorem 0) rather than of quantized geometry. Whether that cost is a bargain is exactly what the falsifiable descent built on the static arena — the whole of Parts VI–VIII — exists to test: if the stage's rigidity were wrong, its ledger of forced numbers would not keep landing on measured values. The frozen-formalism crisis, on this reading, was a self-inflicted wound: physics quantized the one structure — the repeating direction — that its own quantum theory needs classical and one-sided in order to mean anything at all. The endowments of §100 are the inventory of what must be kept for "happening" to make sense; the arena keeps them by construction.

100 The four endowments: time in this geometry

Part IV's third-face analysis (§43) closed with the answer this Part now sets on its own feet. In the constitutional arena, read the gifts off the axioms one at a time. *AX-1 — locality and causality — gives time its order*: the light cone sorts the world, and influence runs one way along it — Minkowski's endowment, inherited whole. *AX-2 — geometry–gauge equivalence — gives time its repetition*: through Theorem 0, AX-1 and AX-2 force the globally static arena, so the constitutional clock is a Killing flow — a direction along which the geometry repeats itself exactly — and only because time is such a symmetry do frequency, energy, and the mode planes of Part IV exist at all. A time that did not repeat could not tick. (One scope note, kept honestly: endowment two holds on the constitutional arena; the expanding universe of the cosmology companion (Arisaka, 2026, A10-Cosmos) inherits it only through the descent's staticity claims, and carries that dependence on its own ledger.) *AX-3 — the operational dictionary — gives time its openness, twice.* Once irreversibly: the OGGEP projection is one-way, records accumulate, and the arrow is the dictionary's non-invertibility over a bulk that is itself exactly T-symmetric (§34). And once analytically: the positivity clause makes the clock's spectrum one-sided, and a one-sided spectrum opens a *shore* — the half-plane of lawful continuation, where oscillation relaxes into damping, where the quantum theory keeps its statistical shadow, and where, at the covariant completion, the CPT theorem lives (T-P5-B1; §43).

The definition, stated once and sharply: *time is the unique direction of the arena that carries all four endowments at once — ordered by the cone, repeating as a symmetry, opened irreversibly by the dictionary, and opened analytically by the spectrum's single side.* Uniqueness is the load-bearing clause, and it is checkable direction by direction. Space has translations, but their spectra are two-sided — a left-mover is as lawful as a right-mover — so space has no orientation the dynamics must respect and no shore: there is no imaginary x because nothing damps there. The fiber has rotation, but its windings are two-sided integers on a compact circle — it knows charge, not direction (§37.1) — so there is no imaginary θ. Time alone is the direction along which the world is *stable* — bounded below in energy, by the dictionary's own consistency — and stability is the whole secret: one-sidedness of the spectrum is the mathematical name of "nothing falls forever"; the polar decomposition turns that stability into a rotor and a speed; the rotor is the i of every Schrödinger equation, the speed's semigroup is every Euclidean computation, and the half-plane between them is the only thing Minkowski's *it* ever lawfully named.

Each standard account now finds its partial answer honored and located. Relativity's order is endowment one. The repetition every use of energy assumes is endowment two — and Noether's theorem (Noether, 1918), read constitutionally, is the statement that endowment two has a currency. Thermodynamics' arrow is endowment three, moved from initial condition to law (§103). And the *it* of every Euclidean computation is endowment four — the shore, with the Wick quartet (T-P5-B1) as its street map and the custody line as its land registry: the geometry owns the cone, the dial, and the shore; the dictionary owns the words *it*, *i*, and Wick.

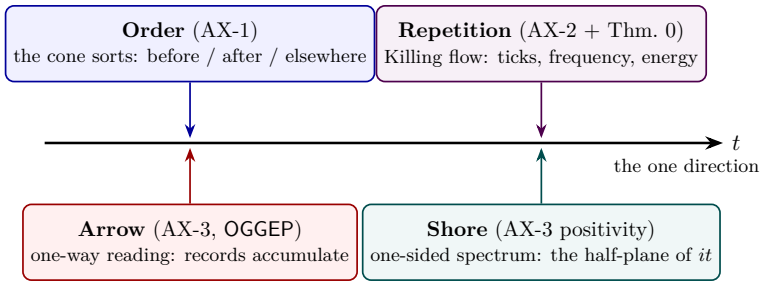


Figure 20: The four endowments of the direction called time, each located in an axiom: order from the cone (AX-1), repetition from the forced static arena (AX-2 with Theorem 0), and — twice from the dictionary (AX-3) — the one-way arrow of the OGGEP projection and the analytic shore opened by the one-sided spectrum. No other direction of the arena carries more than one.

101 The two fibers: where the endowments live

The four endowments were located in the axioms. The work of the cohort's recent campaign — the symmetry review's capstone and its four-paper deployment (GG-W1-Symmetry; Arisaka, 2026, A5-GDOS) — allows them now to be located in the *anatomy*, and the relocation is not a relabeling: it adds a structural claim no earlier account of time has made, and it turns out to explain three centuries of intellectual history in one sentence. The instrument is a single exact statement, now printed across five papers of this cohort: *holonomy requires closed loops, and an interval has none.* The bulk's two non-spatial fibers are opposite objects under that statement. The compact circle S^1_θ is nothing but closed loops: everything it carries is holonomy — quantized, gauge-invariant, protected — and its flow *repeats exactly*, which is what a tick is. The radial interval I_r can hold no holonomy at all: transport along it composes only forward — a semigroup, the GDOS generator's birthplace — and *points*, which is what an arrow is. Set the endowments beside the geometry:

Table 15: The four endowments of time, set beside the geometry that supplies each. The first column names the endowment, the second the axiom that locates it, the third the piece of the arena that carries it, and the fourth what it gives time. This is the Part's central bookkeeping: order comes from the cone, repetition from the compact circle, the arrow from the radial interval, and the shore from positivity — four endowments, four distinct carriers, none of them supplied twice.

endowment	**axiom (as located in §100)**	**anatomy (located here)**	**what it gives time**
order	AX-1, the cone	the M_4 cone	before / after / elsewhere
repetition	AX-2 + Thm. 0	**the circle S^1_θ**	frequency, energy, the possibility of a clock
arrow	AX-3, OGGEP one-way	**the interval I_r**	records, aging, the second law
shore	AX-3, positivity	the spectrum's single side	*it*, KMS, Euclidean computation

The new content is the middle two rows, and it is a theorem-shaped observation: *the tick and the arrow live on different fibers.* The circle can tick but cannot point — its windings are two-sided integers; as §100 already put it, it knows charge, not direction. The interval can point but cannot tick — nothing on it repeats; an interval has no period. Physical time, as any boundary observer experiences it, is the *composite reading* of both, projected onto the one ordered direction the cone provides. Three consequences follow, and each deserves its paragraph.

Why mechanics and thermodynamics grew up apart. The deepest historical puzzle about time is sociological: how could physics build two complete, axiomatized, spectacularly successful sciences of time — reversible mechanics from Newton through Hamilton to Schrödinger, and irreversible thermodynamics from Carnot through Clausius to Boltzmann — that flatly contradict each other about time's basic character, and run them side by side for three centuries? The anatomy answers: because they are *not* two accounts of one thing. Reversible mechanics — all tick, no arrow, e^{-iHt} with its two lawful signs — is the physics of the circle. Thermodynamics — all arrow, no tick, entropy without frequency — is the physics of the interval. Each science is internally complete because each fiber is a coherent geometric object; they resisted unification because they are two *different* directions of the bulk, marginalized onto the same boundary axis by the dictionary. The reconciliation programs of the nineteenth and twentieth centuries — Boltzmann's H-theorem and its reversibility paradoxes, ergodic theory, decoherence — were attempts to derive one fiber from the other. The constitutional account says plainly: neither derives from the other. They are siblings, not parent and child, and the boundary's time is their joint estate.

A clock is a winding counter; an hourglass is an odometer. The distinction is operational, and every laboratory embodies it. Every device physicists call a *clock* counts repetitions of a circle-side process: a caesium hyperfine phase, a quartz crystal's oscillation, an optical lattice's line — each is ultimately the rotor e^{-iEt}, read stroboscopically. Every device that measures *duration by consumption* — sand through a neck, a burning candle, a decaying isotope's surviving fraction, an entropy meter — is an interval-side odometer: it reads how much one-way descent has accumulated, and it never repeats. The reason a pendulum needs an escapement — the reason every real clock is a rotor *plus* a ratchet — is the two-fiber theorem in brass: repetition alone cannot record, and recording alone cannot tick. A physical clock is a small model of the bulk: one part circle, one part interval, coupled.

The uniqueness clause, strengthened. The definition of §100 rested on uniqueness: time is the only direction carrying all four endowments. The anatomy explains *why* the count comes out one. The boundary has exactly one direction onto which both fibers project their character — the cone's ordered direction. Space receives neither projection: its translations have two-sided spectra, so no arrow, and no one-sidedness, so no shore. The fibers themselves are not boundary directions at all — they are non-spatial, and the dictionary marginalizes them; what survives the marginalization is precisely the pair (tick, arrow) stamped onto the causal direction. Time is not one of the world's directions that happens to be special. *Time is the direction where the tape and the track read out.*

102 Clocks: every clock is a winding counter

The repetition endowment becomes concrete — and quantitative — once the circle owns it. The statement $E = \hbar\omega$, which quantum mechanics inherits as a postulate and Part IV derived as the rotor's speed, is in the two-fiber language a *currency statement*: energy is winding rate. Every energy in physics is a frequency; every frequency is a rate of transport around the circle; and a clock is any device that counts that transport. Walk the hierarchy, from the fastest lawful clock to the slowest:

- *Every mass is a clock.* A particle of mass m ticks at its Compton rate $mc^2/2\pi\hbar$: for the electron, 1.24×10^{20} Hz. Matter does not *have* a frequency; at the constitutional level matter *is* frequency — a standing pattern of circle transport, which is Part IV's rotor read as ontology.
- *Every laboratory clock reads the circle.* The SI second is nine billion caesium windings (9.19×10^9 Hz); the optical lattice clocks that now keep the world's best time read strontium and ytterbium lines near 10^{15} Hz. All of them are e^{-iEt} interferometry: the tick being counted is the rotor's, every time.
- *The cohort owns a clock line of its own.* The Kaxion mass, 8.1 μeV, is a frequency: **1.95 GHz** (Arisaka, 2026, C1-Kaxion) — to the author's knowledge the only tick rate in physics predicted from a discrete ledger before being sought. If the haloscopes find that line, the framework will have contributed a clock to the hierarchy, not merely a particle to the zoo.
- *The slowest clock is the sky.* The Hubble rate today, $H_0^{-1} = 4.6 \times 10^{17}$ s, is the universe's own period-like scale — not a repetition (nothing about the descent repeats; that is the point of the interval) but the terminal rung of the frequency ladder.

The dynamic range of this ladder is the ledger's range: from the Planck tick to the Hubble time is a factor e^{140} — a number the next section will audit rather than admire — and from the electron's Compton clock to the Hubble rate is $\sim e^{87}$. Clock hierarchies are depth readings of one descent. And one more period belongs to the list, though it lives on the shore rather than the axis: the thermal circle of the present universe, $\hbar/(k_B T_0) = 2.80$ ps — the imaginary- time circumference of the world today, whose meaning §106 will set beside the others.

103 The arrow, derived: the first law-level irreversibility

One clause of the definition deserves its own section, because it is the one the author believes no prior framework has possessed: *the arrow of time enters this physics at the level of law.* The inventory of §98 was unanimous: every fundamental equation — Newton's, Einstein's, Schrödinger's, the Standard Model's — is reversible, and every observed irreversibility is charged to initial conditions, the past hypothesis carrying the whole universe's asymmetry on an unexplained boundary condition. The structure of this program is different in exactly one place, and it is constitutional. The OGGEP projection of AX-3 — the dictionary by which a four-dimensional reader reads the six-dimensional bulk (§33) — is a completely positive, trace-preserving map, and it is *not invertible*: the boundary

description discards bulk data lawfully and permanently, records accumulate on the boundary side (§34), and no boundary operation can run the projection backward. The GDOS boundary law (Arisaka, 2026, A5-GDOS) is the dynamics of that open reading; the GRIP runtime (Arisaka, 2026, A6-GRIP) is its cascade of one-way selections — dynamical gauge invariance to symmetry breaking to attractor, each stage a door that shuts. Irreversibility is therefore not an accident of how the universe started; it is a property of how the boundary *reads*, written into the same axiom that defines what observation is.

The custody must be kept with complete honesty, because it is what separates this claim from a free lunch. The bulk remains exactly T-symmetric: nothing in the geometry distinguishes the two time orientations, which is why CPT is exact (T-P5-2) and why the microscopic T-violation of the mirrors is a texture chirality, not an arrow (Part V). The arrow lives entirely in the dictionary — in the non-invertibility of the projection — so the old question "why does entropy increase?" receives a structural answer: *because reading is one-way.* What this buys over the past hypothesis is location, not magic: the asymmetry is no longer an unexplained property of one special state at one special moment, but a stated property of a named law, present at every moment, doing work in every measurement — the same non-invertibility that actualizes records is the one that ages the universe. And what it costs is stated with equal clarity: AX-3 is an axiom; the program derives the arrow *from* the constitution, not from nothing. The innovation — and the author believes it is the first of its kind — is that irreversibility now has an address inside the laws, where every previous account kept it outside them.

104 The chronology, quantified: boundary time across the descent

The arrow section located irreversibility in the law; this section counts it. Boundary cosmic time and the bulk radial coordinate $r = \ln(E_{\rm GUT}/\mu)$ are two parametrizations of one descent, and the map between them is not a metaphor but a computable function — epoch by epoch, from standard kinematics plus the canon anchors. In the radiation era the Friedmann clock reads $t = (2.42/\sqrt{g_*})\,(\mathrm{MeV}/T)^2$ s, and substituting $T = E_{\rm GUT}\,e^{-r}$ gives

$$t(r) \;=\; \frac{2.42\ \mathrm{s}}{\sqrt{g_*}}\left(\frac{\mathrm{MeV}}{E_{\rm GUT}}\right)^2 e^{2r} \qquad \Longrightarrow \qquad \boxed{\frac{d\ln t}{dr} \;=\; 2} \tag{65}$$

— exactly, in the radiation era (the numerical check between the lock and the electroweak crossover returns slope 2.000), and $d\ln t/dr = 3/2$ in the matter era ($t \propto T^{-3/2}$). *Boundary time is the exponential shadow of the linear descent*: each unit the read head advances along the fiber without holonomy, the universe's clock multiplies by $e^2 \simeq 7.4$. The chronology of everything, in one table (both conventions of the radial coordinate are shown: the cosmology companion anchors $E_{\rm GUT} = 2.3 \times 10^{16}$ GeV; the proton and electron companions anchor $E_{\rm GUT} = \frac{1}{2}M_{\rm Pl}$, in which convention the lock sits at $r = K$ exactly):

Table 16: The chronology of everything, in one table. Each row is an epoch, with its temperature, its radial coordinate in both conventions, its cosmic time, and the logarithm of that time in Planck units. Both conventions are shown because the cosmology companion and the proton and electron companions anchor $E_{\rm GUT}$ differently; in the second, the lock sits at $r = K$ exactly. The two bold entries are the ones the paper returns to: the lock crossing, and today.

epoch	T	r **(A10)**	r **(P6)**	t	$\ln(t/t_{\rm Pl})$
launch ($T_{\rm rh}$)	3×10^{10} GeV	13.6	19.1	2.6×10^{-28} s	36.1
lock crossing	3.85 TeV	29.4	**35.00**	1.6×10^{-14} s	67.9
EW crossover	159.5 GeV	32.6	38.2	9.2×10^{-12} s	74.2
QCD crossover	156.5 MeV	39.5	45.1	2.4×10^{-5} s	89.0
BBN	1 MeV	44.6	50.2	0.74 s	99.3
equality	$z \simeq 3400$	58.6	64.2	51 kyr	127.7
recombination	$z \simeq 1090$	59.8	65.3	380 kyr	129.7
today	2.725 K	66.8	72.3	13.80 Gyr	**140.24**

The e-fold ledger of the age. Read the last column as an audit, and it closes:

$$\ln \frac{t_0}{t_{\rm Pl}} \;=\; 140.24 \;=\; \underbrace{36.1}_{\substack{\text{launch:}\\ \ln(t_{\rm rh}/t_{\rm Pl})}} \;+\; \underbrace{91.6}_{\substack{\text{radiation:}\\ \simeq 2\times\Delta r}} \;+\; \underbrace{12.5}_{\substack{\text{matter+}\Lambda\text{:}\\ \simeq \frac{3}{2}\times\Delta r + O(1)}} \tag{66}$$

(the three segments recompute the direct value to every displayed digit). *The age of the universe, expressed in the bulk's own language, is an audited sum of slope-2 and slope-$\frac{3}{2}$ segments of the one descent* — standard kinematics, the derived reheating temperature, and nothing else. Two placements follow at canon grade. The corridor switch sits at $z_{\rm sw} = e^7$, so $\ln(1 + z_{\rm sw}) = 7 = J$: *the switch is exactly J e-folds of boundary scale below today* — the topological member of the two-quantity discipline, now located on the chronology. (The atomic $z_{\rm dec} \simeq 1090$ keeps its separate identity, as always.) And the whole span from the GUT edge to the present is $\Delta r \simeq 72$ in the half-Planck convention — the descent's odometer reading at the moment this sentence is being read.

A flagged observation, held to the numerology discipline. The reader will have noticed what the author noticed: $140.24 = 4K \times 1.0017$ with $K = 35$, and the Hubble time gives the same reading, $\ln(H_0^{-1}/t_{\rm Pl}) = 140.29$. *The age of the universe is e^{4K} Planck times to two parts in a thousand.* The decomposition (66) shows why something K-structured appears — the segments are slope-weighted spans of a descent whose depth is K-structured — and also why the compression is not yet a result: the $O(1)$ pieces (the launch's $36.1 \approx K+1$, the matter era's 12.5) have no derivation today. This paragraph therefore carries the same grade as the cosmology companion's flagged warp form: *compression observed, derivation open* — and the open derivation has a name, the e-fold budget campaign of the program's ledger, whose target (T_0 derived through the descent with no dial) is precisely what would promote (66) from an audit of measured anchors to a zero-anchor theorem. Until then the sentence "the universe is four throat depths old" is filed as a candidate, in exactly these words, at exactly this grade.

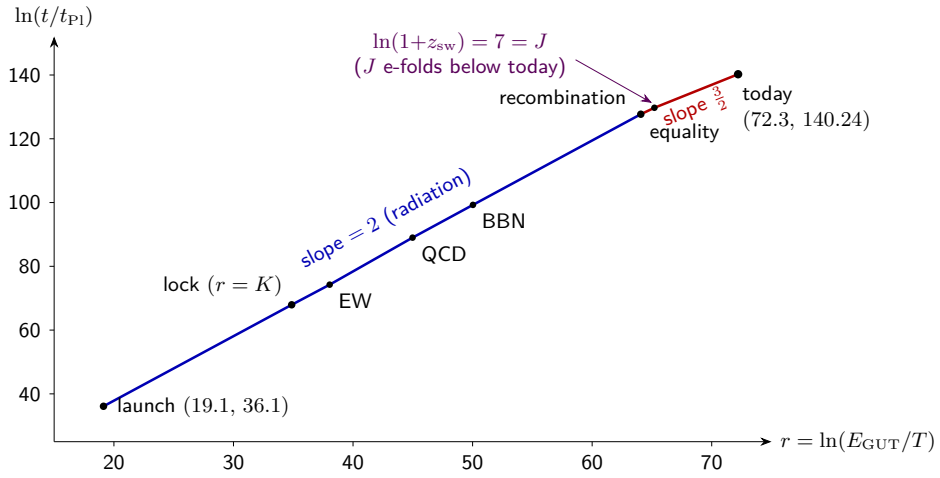


Figure 21: The whole history of time, on one line: boundary time (in Planck units, logarithmic) against the radial coordinate (half-Planck convention), for the eight epochs of the table. The radiation era is a straight line of slope exactly 2 (65); at matter–radiation equality the slope kinks to $\frac{3}{2}$; the small g_* steps are invisible at this scale. The lock crossing sits at $r = K = 35$; the corridor switch sits $J = 7$ e-folds of boundary scale below today; the endpoint reads $\ln(t_0/t_{\rm Pl}) = 140.24$, whose audited decomposition — and whose flagged $4K$ compression — are Eq. (66) and the paragraph beside it. Boundary time is the exponential shadow of the linear descent.

105 Energy and entropy: two currencies of one direction

The definition makes an old pairing structural. Energy is the currency of endowment two: the Noether charge of the clock's repetition, conserved because the geometry repeats, one-sided because the dictionary demands stability — energy is *what the symmetry of time is worth*. Entropy is the currency of endowment three: the count of the dictionary's accumulated records, non-decreasing because the projection is one-way — entropy is *what the arrow of time has read*. The two great quantities of physics are thus the bookkeeping of two endowments of a single direction: the first law is the clock's ledger, the second law is the dictionary's.

The shore is where the two currencies exchange. The Wick quartet (T-P5-B1) established that one analytic fact underlies the rotor and the semigroup — the quantum phase $e^{-iEt/\hbar}$ and the Boltzmann weight $e^{-\beta E}$ are the two boundary values of one function on the half-plane, so temperature is imaginary period and the KMS condition is the shore's own geometry (Cor. 43.3). This is why thermodynamics and quantum mechanics, so different in temperament, keep producing each other's formulas: they are the two banks of one river — quantum mechanics written on the oscillatory side, thermodynamics read on the damped side, with analytic continuation the ferry. And the runtime makes the union quantitative: the Geometric Free-Energy Functional of the GRIP constitution decomposes as $F_{\mathsf{GFF}} = F_{\mathsf{GEP}} + F_{\mathsf{CEP}}$ — an energetic block and a curvature–entropy block (Arisaka, 2026, A6-GRIP) — so the quantity that the cascade extremizes is precisely energy and entropy on one ledger, free energy as the single price the direction of time charges for structure. Every equilibrium in the descent, from the lock crossing to the attractors of Part VIII's transport, is an entry in that ledger; the sphaleron era's freeze-out — where the cosmic record was written by

microscopic dynamics — is the one event where this Part's two currencies and Part VIII's six-in-ten-billion receipt visibly meet (Arisaka, 2026, A7-Qi4 carries the information-theoretic reading one floor further).

105.1 The quartet, worked once: one mode, four faces

The exchange between the currencies is not a metaphor, and five minutes of arithmetic makes it property. Take a single boundary mode of energy E, thermal state at inverse temperature β, and compute the correlator of its lowering and raising operators. With $\langle a^\dagger a\rangle_\beta = n_\beta = (e^{\beta E}-1)^{-1}$ and $a(t) = a\,e^{-iEt}$ (units $\hbar = 1$):

$$G_+(t) = \langle a(t)\,a^\dagger\rangle_\beta = (1+n_\beta)\,e^{-iEt}, \qquad G_-(t) = \langle a^\dagger\,a(t)\rangle_\beta = n_\beta\,e^{-iEt}. \tag{67}$$

Both are boundary values of one function analytic in the strip $-\beta < \mathrm{Im}\,t < 0$ — the shore — and on that strip the single identity

$$G_+(t - i\beta) = (1+n_\beta)\,e^{-iEt}\,e^{-\beta E} = n_\beta\,e^{-iEt} = G_-(t) \tag{68}$$

is the KMS condition, derived rather than postulated: thermal equilibrium *is* periodicity in imaginary time, with period β. Now read the four faces of the quartet (T-P5-B1) off the same exponential. On the real axis, e^{-iEt}: the rotor — quantum phase, interference, Schrödinger evolution. Down the imaginary axis, $e^{-\tau E}$: the semigroup — damping, Euclidean computation, the lattice's arithmetic. At depth β, the weight $e^{-\beta E}$: the Boltzmann factor — thermodynamics, read at one imaginary instant. And around the thermal circle (period β), the trace: the partition function $Z = \sum_n e^{-\beta E_n}$ — the whole of equilibrium statistical mechanics as the shore's closed loop. One exponential, one half-plane, four sciences; the custody line holds throughout — the geometry owns the analyticity (the one-sided spectrum is what makes the strip lawful), the dictionary owns the words phase, heat, and Wick.

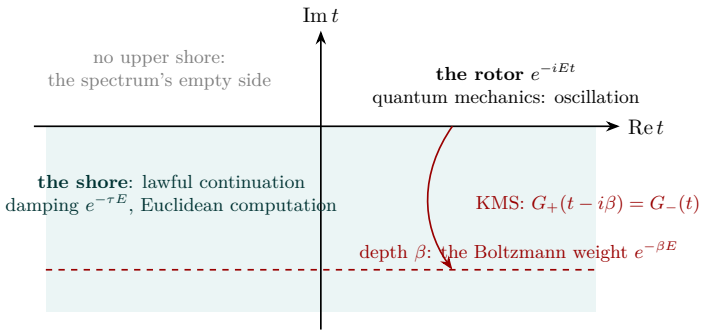


Figure 22: The shore, drawn. The one-sided energy spectrum makes the lower half-plane of complex time the unique region of lawful analytic continuation: quantum mechanics lives on the real boundary, Euclidean damping down the imaginary axis, and thermodynamics at depth β, where the KMS identity (68) closes the thermal circle. The upper half-plane is not forbidden by decree but by stability: nothing damps there because nothing falls forever.

106 Temperature, the shore, and the scale rate

Two theorems about temperature now stand in the cohort, in two papers, and the two-fiber language shows they are one. This Part's worked quartet (§105.1) derived the KMS condition: *temperature is imaginary period* — thermal equilibrium is periodicity of period β around the shore's circle. The open-system companion derived Unruh–Tolman: *temperature is the inverse scale rate* — the locally measured T is the asymptotic temperature dressed by the scale profile at the observer's radial position (Arisaka, 2026, A5-GDOS). Married: *temperature is where the interval meets the shore.* The thermal circle is a Euclidean circle whose circumference β is transported along r and stretched by the profile — Tolman's old law, read geometrically — and cooling *is* descent: $d\ln T = -dr$ along the radiation era, so the shore's period grows by a factor e per unit of descent while boundary time grows by e^2 (65). That mismatch of exponents — period growing linearly in e-folds, duration quadratically — is why the ratio β/t falls monotonically through cosmic history, which is the precise, quantitative sense in which the universe becomes ever more classical: the quantum strip narrows relative to the age that measures it. The third law joins the family as the zero-scale limit (the shore's circle cannot be unwound to infinite circumference in any finite descent), and the first and second laws were already the axioms' content — so all of thermodynamics' furniture now sits in one room with one window.

One worked object closes the section, because the cohort's standard is that a marriage of theorems must be consummated in numbers. *The cosmic microwave background is the oldest thermometer in existence, and it is a shore-period gauge.* Its period today: $\beta_0\hbar = \hbar/(k_B \times 2.725\,\mathrm{K}) = 2.80$ ps. Its period at recombination, thirteen and a half billion years earlier: $2.80\ \mathrm{ps}/(1+z_{\mathrm{dec}}) = 2.57$ fs. The two readings differ by exactly the $\ln(1+z_{\mathrm{dec}}) \simeq 7$ e-folds that the chronology table carries between those rows — one thermometer, read twice across the descent, confirming the transport law that connects the quartet to the profile. Time's shore, like time's axis, has a measured history.

107 The comparison, in one table

Table 17: What each account gives the direction called time. Bold entries are, to the author's knowledge, the first law-level appearances of the corresponding endowment. The structural cousins — Connes–Rovelli's thermal time (Connes and Rovelli, 1994), Page–Wootters relational time (Page and Wootters, 1983), and the CPT-symmetric cosmology (Boyle, Finn, and Turok, 2018) — are engaged in the text.

Account	Order	Repetition	Arrow	Shore
Newtonian mechanics	assumed	assumed	absent	absent
Special relativity	**derived** (cone)	assumed (static ansatz)	absent (block)	unnamed (*it*)
General relativity	derived, dynamical	*fails generically* (no Killing flow)	absent	ill-defined off special backgrounds
Thermodynamics	inherited	inherited	initial condition	implicit (KMS)
Quantum mechanics	inherited	assumed (e^{-iHt})	absent	used, disowned
QFT + Standard Model	microcausality	assumed	absent (T-violation $\neq$ arrow)	used everywhere, named nowhere
String / quantum gravity	background	background	absent	Euclidean tool
GG-Theory (P4 + P5)	AX-1 (cone)	AX-2 + Thm. 0 (forced)	**AX-3 law** (OGGEP)	**AX-3 spectrum** (T-P5-B1)

Three cousins deserve their sentences. Connes–Rovelli is the nearest: time as modular flow, KMS-rooted, one parameter — but state-first, where this account is arena-first; the two would meet if the constitutional clock's flow were shown to be the modular flow of the boundary state, which is precisely the open modular bridge of Objection 69. Page–Wootters is the honest quantum attempt to internalize the clock; the arena account dissolves its circularity by making the clock constitutional rather than emergent. And Boyle–Turok's CPT-symmetric universe shares this paper's reverence for the unbroken reversal while locating the asymmetry in the state; the contrast — state versus law — is the same contrast that separates the past hypothesis from the OGGEP arrow, run at cosmological scale.

108 The significance: the new definition against every previous one

The table and the cousins locate the accounts technically. This section states the significance plainly, tradition by tradition, in the Part's register — each honored for what it saw, each located in what it could not see — and then names the two claims that, to the author's knowledge, no previous definition of time has ever made.

Newton: time as absolute flow. "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external." Honored: the equable flow is real, and it is the repetition endowment — the Killing flow's exact self-similarity is what Newton's "equably" was reporting. Located: nothing flows. A flow needs a medium and a direction; the constitutional clock is a symmetry, not a current. What Newton called flow decomposes into the tick (which repeats and does not move) and the arrow (which points and does not repeat) — two fibers he had no way to distinguish, fused into one river by introspection.

Leibniz and Mach: time as relation. Honored, and more than honored: boundary time in this framework *is* relational — it is a reading, not a substance; nothing possesses time except in the dictionary's act of registration. Located: the relations are not free-floating. They are readings *of a definite geometric object* with a fixed anatomy, which is why all observers' relational times agree on order, rate structure, and arrow. Relationalism was right that time is not a thing; it lacked the theorem that says what the relations are relations *to*.

Einstein and Minkowski: time as geometric order. Honored at the deepest level: endowment one is inherited whole from the cone, and the relativity of simultaneity survives intact — "elsewhere" is as real here as in 1908 (Minkowski, 1908). Located: the block universe carries order and nothing else. It has no origin for the tick (the static metric is assumed, not derived), no arrow (the block is T-symmetric and eternalism follows), and it uses the shore (*it*) as a trick while disowning it as physics. One endowment of four — which is exactly why the block picture, extended beyond its competence, generates the paradoxes of frozen time it is famous for.

Boltzmann and the past hypothesis: time as statistics. Honored: the arrow is real and thermodynamic, and Boltzmann's identification of entropy with counting (Boltzmann, 1877) survives as the second currency. Located: the standard account charges the entire asymmetry of the universe to an unexplained initial condition — the past hypothesis — because its laws are reversible and something must break the tie. Here the tie is broken in the law (§103): the projection is non-invertible at every moment, not just the first one. The asymmetry moves from one special state to a standing property of reading — from cosmic accident to constitutional clause.

Quantum mechanics: time as the external parameter. Honored: the t in e^{-iHt} works, uncannily. Located: the puzzle of why time alone has no operator — Pauli's old theorem that a time observable conflicts with a bounded spectrum — dissolves rather than deepens. Time is not an observable because it is not a degree of freedom *of* the boundary at all: it is the boundary's reading of the fibers, the parameter of the dictionary's own act. Asking for a time operator is asking the reading to read itself; the one-sided spectrum that blocks the operator is the same one-sidedness that opens the shore — the obstruction and the endowment are one fact.

Wheeler–DeWitt and the frozen formalism. Honored as a correct theorem *about the bulk* (DeWitt, 1967): the constitutional arena is static and T-symmetric, and a wave-functional of the whole geometry has no external clock — the equation says of the bulk what this Part says of it: no

time there. Located: the paradox was only ever the category error of asking the tape to age. Time was never in the bulk; it is what reading the bulk feels like from the boundary. The problem of time in quantum gravity is not solved here; it is *located*, which is how honest dissolutions work.

Page–Wootters and Connes–Rovelli. Honored as the two twentieth-century accounts that came nearest — one internalizing the clock into correlations (Page and Wootters, 1983), one deriving a flow from the state's own thermality (Connes and Rovelli, 1994). Located as fragments of the dictionary: relational readings and modular flows are what OGGEP projections look like when one reconstructs them from inside, without the arena; the open modular bridge of Objection 69 remains the meeting point, and remains open.

The two claims no predecessor makes. First, the *composite anatomy*: every previous account treats time as one thing — a flow, a relation, an order, a parameter, an illusion — and each tradition's partial success came from correctly describing one endowment. This account is, to the author's knowledge, the first in which time is constitutionally *composite*: four endowments on three geometric structures, with the tick and the arrow on *different fibers* — a separation no earlier definition even had the vocabulary to state, and which retroactively explains why the traditions diverged as they did. Second — and this is the innovation this Part's expansion exists to register — *a definition with a number*. Every previous definition of time, from Augustine to the operationalists, said what time is; none said *how much of it there is, and why*. Here the definition comes with an audited chronology (66): the age of the universe as a closed e-fold ledger on the descent, the slope laws exact, the clock hierarchy spanning e^{140}, the corridor switch placed at J e-folds, and even the definition's own falsifiers inherited from the anchors it audits ($T_{\rm rh}$ at its derived grade; the corridor's observables; the Kaxion line at 1.95 GHz). A definition of time that can be *wrong about numbers* is a new kind of object in this oldest of subjects — and in this program's judgment it is the only kind worth defending.

109 What is time? — an answer for everyone

Strip the machinery, and say it plainly. Time is not a river, and you are not a boat on it. Time is not a container, and the universe is not its contents. Time is the one direction of reality that does four jobs at once, and nothing else does even two of them. It *orders*: before and after are real, the way uphill and downhill are real on a slope. It *repeats*: the laws are the same this second as last second, and that sameness is why anything can tick, why energy exists, why a note can hold its pitch. It *opens*: the world writes and cannot unwrite — every record, every memory, every scar and every star is ink the universe cannot take back, and that one-way writing, not any river's current, is the flowing you feel. And it *shelters*: leaning against the world's own stability there is a quiet mathematical shore, where the humming of quantum mechanics and the cooling of thermodynamics turn out to be one thing seen from two sides — the strangest and best-kept secret in physics, used daily by every physicist and named here, the author believes for the first time, as a structural clause of a definition of time — the analytic structure itself is classical (Paley–Wiener, KMS, tube

analyticity), and what is claimed is the naming, not the mathematics: a structure the world cannot do without, though no one can go there.

Augustine could not say what time is because he was looking for a thing, and time is not a thing; McTaggart proved the river cannot flow, and he was right, because the flowing was never time's — it is the writing's. What flows is the accumulation of the written: the dictionary's one-way ink, in which a kaon's decay, a cobalt nucleus's last electron, a memory of a summer, and the six extra baryons in every ten billion are entries of the same kind, irrevocable for the same structural reason. The mirrors of this paper broke on the descent's orientation; the faces of the clock stand on time's. A universe with less structure in its time could not have laws worth the name, could not bank energy, could not keep a record, could not do quantum mechanics and thermodynamics with the same hand — could not, in the end, contain anyone to ask Augustine's question. That the direction which permits the asking can now be characterized — ordered, repeating, one-way, and sheltered — is this program's answer to the oldest question it will ever face: time is the way a stable world keeps being possible, and the proof that it has been keeping records is that you are here, reading this, later.

And for the reader who asks the child's version of the question — *how much time is there?* — the answer, for the first time in this subject's twenty-six centuries, has a number with an audit trail. There have been e^{140} Planck ticks since the descent began: thirty-six e-folds to the launch, ninety-two at slope two through the radiation era, twelve and a half at slope three-halves since matter took over (§104). The universe is not merely old; it is *accounted for* — and the account is one straight line with one kink, drawn on the fiber that cannot remember, by the fiber that cannot forget.

Part-end summary. Time defined by its four endowments — order, repetition, arrow, shore — each located in an axiom *and now in the anatomy*: the cone orders, the circle ticks, the interval points, the spectrum's single side shelters. The tick and the arrow shown to live on different fibers — the structural reason mechanics and thermodynamics grew up apart; every clock a winding counter, from the electron's 1.24×10^{20} Hz to the Kaxion's predicted 1.95 GHz to the sky's H_0^{-1}. The arrow at the level of law for the first time; the chronology quantified — $d \ln t/dr = 2$ exactly, the age closing as an audited e-fold ledger at $\ln(t_0/t_{\mathrm{Pl}}) = 140.24$, the $4K$ compression flagged at its honest grade; temperature married to the scale rate as the shore's transported period; energy and entropy unified as the direction's two currencies; the standard accounts honored as partial readings of a composite anatomy; the quantum-gravity problem of time dissolved by architecture; the cousins engaged; and the significance stated: the first definition of time that is composite, and the first that comes with a number it could be wrong about. What remains is comparison at full depth: the five roads.

Part X
The Five Roads, at Full Depth

QFT, the Standard Model, string theory, and ΛCDM — what each achieved, where each ends, and how the geometry completes the story; the inventory of who predicts what; the three-depths scoreboard; and the roads seen from above

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The GG-6 account is now complete: the twins derived (Part IV), the mirrors defined (Part V), the two breakings explained (Parts VI and VII), the matter assembled (Part VIII), and time itself given its four endowments (Part IX). Only now do the rivals speak — and each is given its full say, because the significance of the GG-6 claims is measurable only against the strongest versions of what the other frameworks actually achieve. Each road is walked in three movements. *First, what it achieved* — stated with gratitude and with numbers, because every one of these traditions contributed load-bearing pieces to this very paper. *Second, where it ends* — the honest boundary of its explanatory reach, located precisely, in its own terms. *Third, how the geometry completes the story* — claim by claim, with the grade of each completion printed, because a completion offered without its register would repeat the very habit this paper exists to break. The ruler throughout is the three-depths instrument of §26; the register is structural contrast, never polemic; and every concession the GG-6 account owes is paid in the section where its creditor lives.

110 Part X in plain English: the other roads, at their own strength

A paper that scores itself against straw versions of the alternatives has not been tested. This Part sets out quantum field theory, the Standard Model, string theory and ΛCDM at full depth, and in each case says what the road achieved before saying what it does not reach. Each of the four is the most successful thing of its kind ever built, and the Part opens by saying so.

Then the inventory: who predicts what, road by road, on the same questions. The scoring uses the three depths fixed in Part II, so the comparison runs against a stated instrument rather than against a preference, and where another road does better the inventory says so. The falsification-symmetry section states what would count as this account losing, which is the same question asked in the other direction.

The Part closes on a comparison the five roads do not usually make against one another: what each of them says time is. That is where they differ most and argue least, which is exactly the reason to put it in a table.

111 The first road: quantum field theory

111.1 What quantum field theory achieved

Quantum field theory is the framework of twentieth-century physics, and the scale of its achievement should be stated before any boundary is drawn. It unified the century's two revolutions — quantum mechanics and special relativity — into a single consistent grammar, and the grammar turned out to *legislate*: antiparticles exist (the causality theorem below), spin and statistics are locked to each other, CPT is inviolable — three facts about the world derived from consistency alone, before any particular interaction is chosen. It taught physics that the vacuum is a medium: the Lamb shift and the anomalous moment of the electron are properties of empty space's own fluctuations, and the latter is now computed and measured in agreement at roughly a part in 10^{12} — the most precisely verified prediction in the history of science. It taught physics what its own equations mean: the renormalization group reads a quantum field theory as a family of descriptions indexed by resolution — the insight the GG-6 arena promotes to a geometric dimension, as Part III recorded. And it supplied the discipline this paper's parent program lives by: anomaly freedom as an admissibility filter, unitarity and causality as non-negotiable clauses, the S-matrix as the contract with experiment. Three of this paper's own load-bearing theorems — Weinberg's causality argument, Jost's CPT theorem, and the Osterwalder–Schrader reconstruction — are QFT results, inherited here with their provenance stamped. Whatever this Part concludes about where the road ends, the road itself carried physics farther than any other ever built.

111.2 The road's own summit: what the renormalization group whispered

One achievement deserves its own subsection, because it is the place where the first road, at its very summit, points beyond itself. The renormalization group began as a repair — the taming of infinities — and matured, in Wilson's hands, into the deepest structural insight the framework produced: a quantum field theory is not one description but a *family* of descriptions indexed by resolution, with the couplings flowing as the index runs. Two consequences reorganized physics. Practically, it created the modern effective-field-theory posture: every theory is an honest description *at its scale*, ignorant of its ultraviolet completion by construction — the humility that made precision physics possible. Structurally, it revealed that "the scale at which the world is examined" behaves like a coordinate: quantities depend on it lawfully, differential equations run along it, fixed points organize it. QFT discovered, in its own language, that resolution is a *direction* — and then, having no geometry to put the direction in, filed it as bookkeeping. Part III recorded what the parent program does with exactly this hint: the scale direction I_r of the arena is the renormalization flow taken literally — a non-spatial dimension generated by a dilatation, on which the descent of this paper runs downhill. Seen from this Part, the relation is filial: the road's summit insight, that physics is resolution-indexed, is the GG-6 arena's fifth dimension — promoted from an index to a geometric direction, at the doctrine and grades of Part III. The road did not end at its summit; it stopped, and the geometry claims to be the continuation of its own best idea.

111.3 The twins in QFT: three layers, and where the explanation stops

Layer 1 — Dirac's holes (1928–1931): the discovery that was not an explanation. The Dirac equation, built to give a first-order, Lorentz-covariant, positive-probability wave equation for the electron (Dirac, 1928), unavoidably possessed negative-energy solutions. Dirac's proposal (Dirac, 1930, 1931) — the vacuum as a filled sea of negative-energy states, holes in the sea appearing as positive-energy particles of opposite charge — predicted the positron, and Anderson's cloud chamber delivered it (Anderson, 1933): one of the great predictions in the history of science. But the sea failed as an *explanation*, three times over. It requires the exclusion principle, so it cannot work for bosons — yet the π^+ and π^- are as real a pair as the electron and positron. It makes the vacuum infinitely charged and infinitely massive. And it treats the twins asymmetrically — one a particle, the other an absence — when every measured property says they are perfectly symmetric. Field theory dismantled the sea, and it survives only as pedagogy (and, honorably, in condensed matter, where a literal filled band exists). The cohort uses no sea anywhere; neither does this paper.

Layer 2 — Stückelberg and Feynman (1941, 1949): the relabeling. The modern reading (Feynman, 1949; Stückelberg, 1941): the negative-frequency solutions are not negative-energy particles but positive-energy *antiparticles* with reversed charge flow, encoded in the Feynman propagator's contour — positive frequencies forward in time, negative frequencies backward. This is exactly the Feynman–Stückelberg pairing whose *provenance* T-P5-C supplies: in QFT it is the reinterpretation that makes relativistic perturbation theory consistent; the question "why this pairing and not the opposite?" is answered at the next layer.

Layer 3 — the structural theorem. Modern QFT's mature answer is a genuine theorem, and this paper states it with the respect it deserves, because it is the closest thing the orthodoxy has to T-P5-C.

Theorem 111.1 (Weinberg's causality argument; Weinberg, 1995)**.** *Let an interaction Hamiltonian density $H(x)$ be built from creation and annihilation operators, transform as a Lorentz scalar, satisfy microcausality $[H(x), H(y)] = 0$ at spacelike separation, and act on a Hilbert space with energy bounded below. Then the fields entering $H(x)$ must be specific linear combinations of an annihilation part and a creation part, and the creation part must create a species with* the same mass as, and opposite values of all conserved charges to*, the species the annihilation part destroys. A particle carrying no conserved charge may be its own partner; a charged particle's partner is a distinct species: the antiparticle.*

The intuition is special relativity's own: a charged particle propagating outside the light cone is, for some observers, its oppositely charged partner propagating the other way; only the paired combination is frame-independent and causal. Antiparticle existence is the price of combining special relativity, quantum mechanics, and causality — Depth 2, answered rigorously, for interacting theories.

Where QFT stops, stated exactly. Three inputs sit upstream of Theorem 111.1 and are never derived: the complex Hilbert space (the i is an axiom); the positivity of energy, imposed on the *output* of quantization (the pairing is selected because the alternative wrecks the spectrum); and the time orientation. QFT's Depth-3 answer is "those are the axioms" — not a defect, but a boundary,

and it is exactly the boundary T-P5-A/B/C cross: the handshake derives the i (both of them), obtains the pairing before quantization, and explains two of Weinberg's axioms. What must be conceded in return: Weinberg's conclusion holds for interacting theories; the handshake at full strength is free/quasi-free, with the interacting case conditional. The two theorems have disjoint hypothesis sets, and the deeper one is currently the narrower one. Both clauses of that sentence belong in print.

111.4 The mirrors in QFT: definitions, discoveries, and the anatomy-silent theorem

QFT defines C, P, T representation-theoretically (Wigner's theorem: symmetries are unitary or antiunitary (Wigner, 1931)), with per-field phase freedoms, and possesses *no principle* determining whether any of them holds — which is why each fall was a shock: P and C in 1957, CP in 1964, and T directly — a fact often omitted — in the kaon system (CPLEAR, 1998 (CPLEAR Collaboration, 1998)) and, cleanly and model-independently, in the B system (BaBar, 2012 (BaBar Collaboration, 2012)). The antiunitarity of T is *selected*, not derived: Wigner's fork permits either character, and unitarity is rejected because it would flip the Hamiltonian's sign. Against this stands the one great positive result: the CPT theorem (Lüders, 1954; Pauli, 1955), given axiomatic form by Jost (Jost, 1957) through analytic continuation to the complex Lorentz group, and deepened by Bisognano–Wichmann's identification of the CPT operation (times a rotation) with the Tomita–Takesaki modular conjugation of the wedge algebra (Bisognano and Wichmann, 1976), with Greenberg's converse guarding the exits: CPT violation entails Lorentz violation (Greenberg, 2002). Scope: interacting, axiomatic — exceeding T-P5-2. Anatomy: silent — the theorem constructs Θ and proves it a symmetry without saying what C, P, or T individually *are*, why T carries the antiunitarity, or why nature breaks the factors while preserving the product. The relation to the GG-6 account is therefore precise complementarity, and the modular route — deriving the clock from modular flow, tying J_A to Bisognano–Wichmann at interacting strength — is the named bridge on which the two would meet (open question (6)).

On parity specifically, QFT owns the two partial structures already credited in §67 — Vafa–Witten's protection of vector-like parity and the survival argument — and nothing that reaches "why $\mathrm{SU}(2)_L$."

111.5 The matter in QFT: a toolbox without a selection principle

Given Sakharov's conditions, QFT-plus-extensions offers five mechanism families, all workable, none selected. *GUT baryogenesis* (Weinberg, 1979; Yoshimura, 1978): heavy-boson decay; wounded twice — inflation dilutes any pre-inflationary asymmetry, and sphalerons erase $B{+}L$, so only $B{-}L$-generating versions survive; and its baryon-creating sector generically threatens the proton. *Electroweak baryogenesis*: elegant and testable, but requires a first-order transition and new CP phases the Standard Model lacks, and is increasingly cornered by electric-dipole-moment bounds. *Thermal (hierarchical) leptogenesis* (Fukugita and Yanagida, 1986): the modern default, with the Davidson–Ibarra bound $M_N \gtrsim 10^9$ GeV (Davidson and Ibarra, 2002) — beautiful, and untestable: no collider will reach it, and the phases that matter are not the low-energy ones. *Resonant leptogenesis*

(Pilaftsis, 1997; Pilaftsis and Underwood, 2004): quasi-degenerate heavy states evade the bound and open the TeV window — the mechanism class Part VIII inherits, with the degeneracy engineered in the standard literature and claimed inherited in ours. *Oscillation (ARS) leptogenesis* (Akhmedov, Rubakov, and Smirnov, 1998): GeV-scale sterile neutrinos, testable at beam-dump experiments. Plus *Affleck–Dine* (Affleck and Dine, 1985) where supersymmetric flat directions exist. Each mechanism buys η_B with fitted masses, phases, and departures; the observed number constrains and never predicts. The GG-6 contrast is the dial count of Table 12 — and the honest converse, that the inherited chain's resonance condition is its named conjecture, is already faced in §87.

111.6 Where the road ends, and how the geometry continues it

Collect the three movements. QFT achieved the grammar: any quantum, causal, relativistic world *must* contain paired twins, locked spin-statistics, and inviolable CPT — and it verified its grammar to twelve digits. Where it ends is equally sharp, and it is one boundary seen four times: *the framework cannot see beneath its own complex structure.* The i is an axiom; therefore the pairing is selected on the output rather than derived on the input; therefore the discrete operations are equivalence classes with adjustable phases rather than anatomical objects; therefore the individual mirrors have no fates, only records. Even the road's daily Euclidean practice sits on the unexamined clause: every Wick rotation ever performed borrows a license — the one-sidedness of the spectrum — that the framework grants but does not explain (T-P5-B1). The geometry's completion is therefore a single move made once and cashed four times, and it is worth itemizing with grades. *The i, derived:* two real sources, circle and clock, unique by their own theorems — T-P5-A/B, derived (quasi-free). *The pairing, derived before quantization:* the handshake, explaining two of Weinberg's axioms at the price of the free-field qualifier — T-P5-C, derived (quasi-free), interacting conditional. *The operations, given bodies:* three reversals, the table a computation, Kramers free of conventions — T-P5-1, derived. *The Euclidean license, issued:* Minkowski's *it*, Wick's rotation, and the Schrödinger i as one polar decomposition — T-P5-B1, derived (quasi-free). *The product's anatomy:* CPT as bookkeeping over the reversals, complementary to Jost's broader-scope theorem, with the modular route as the named bridge — T-P5-2, derived (quasi-free). The road and the geometry are not rivals so much as two halves of one account that has not yet been joined at interacting strength: QFT holds the scope, the geometry holds the anatomy, and the Bisognano–Wichmann bridge is where they are due to meet. And one further item of the road's grammar has, since this Part was first drafted, acquired the same internal route: the *lock* itself. Spin–statistics — the road's second great structure theorem, sibling of CPT in every axiomatic proof — is now stated as the quartet's second child (§45), at candidate grade with the residues of T-P5-2, its bulk premises in Arisaka, 2026, A2-GG6 §20 and its boundary composition in Arisaka, 2026, A8-QM (T-A8.12). If the promotion path closes, the road's three locks — twins, statistics, CPT — will all be anatomy rather than grammar; the first and third already are.

112 The second road: the Standard Model

112.1 What the Standard Model achieved

The Standard Model deserves its section written with gratitude, because it is the most successful physical theory ever confronted with data, and every number in this paper is measured against its bookkeeping. Its achievements are not generic; they are specific, quantitative, and in several cases they are this paper's own subject matter seen from the other side. It predicted the W and Z and their masses before their discovery, and the LEP program then measured the Z lineshape at the per-mille level — finding, among other things, exactly three light neutrino species, the integer this paper derives as $N = 3$. Its flavor sector turned a two-parts-per-thousand kaon anomaly into a counting theorem: Kobayashi and Maskawa's observation that CP violation requires a third generation (Kobayashi and Maskawa, 1973) predicted six quarks when three were known — one of the great indirect predictions in physics, and the reason the author's field existed. Its anomaly bookkeeping closes miraculously within each generation — the fractional hypercharges of quarks and the integer charge of the electron conspiring to cancel every triangle — the very miracle POS-3 promotes to a filter. Its Higgs boson was found where its couplings required. And for half a century, through every collider, every precision measurement, and every flavor factory — including the two the author sat — it has not failed a single reproducible test (Particle Data Group, 2024). Any framework that would deepen it must first reproduce it; the parent program's Standard-Model treatment exists for exactly that reason.

112.2 Where the Standard Model ends

The boundary of the road is as well-surveyed as the road itself, and it can be stated as an inventory: the model *contains* what it cannot *explain*. Counting the neutrino sector, twenty-eight parameters are written into it by measurement — masses, mixings, phases, couplings — each one a dial that could, for all the formalism knows, have been set otherwise. On this paper's questions the inventory reads as five silences and two failures. *Silence one:* antiparticles — inherited from QFT's theorem, with no position on Depth 3. *Silence two:* the operations — conventions with phases. *Silence three:* parity — V−A written into the field content by hand in 1967; QED and QCD parity-even automatically (given the assignments), the coincidence of broken-with-chiral unexamined and unexaminable. *Silence four:* CP — one physical phase (a counting theorem, Kobayashi and Maskawa, 1973), measured superbly ($\delta = 1.147 \pm 0.026$), explained not at all; $\delta = 0$ would have been equally lawful, and nothing in the model prices the difference. *Silence five:* strong CP — $\bar{\theta} < 10^{-10}$ beside a large weak phase, two unrelated parameters, one inexplicably near-maximal and one inexplicably zero; the axion a bolt-on. *Failure one (quantitative):* its own baryogenesis — the effective CP violation available computes to $\sim 10^{-20}$ (Gavela et al., 1994), ten orders short, and the electroweak transition is a crossover for the measured Higgs mass (Kajantie et al., 1996): the Standard Model predicts $\eta_B \approx 0$, and *every gram of matter is an experimental proof of physics beyond it* — the oldest and most secure such proof we possess. *Failure two (structural):* no relation between any two of the five silences: five facts about one gauge factor, zero connections. The model

is, in short, a perfect transcription of the world's text with no theory of its authorship — which is not an insult but its own founders' description of an effective theory awaiting its completion.

112.3 Reading the dials: what the twenty-eight numbers say

Before the completion, the analysis the model itself cannot perform: read its own dials as data. The twenty-eight parameters sort into a definite anatomy — three gauge couplings; two for the Higgs sector (a scale and a self-coupling); six quark masses; four CKM entries (three angles and the phase); three charged-lepton and three neutrino masses; four Dirac-sector PMNS entries; two Majorana phases; and $\bar{\theta}$. Twenty-eight numbers — and they are not random. The text has *rhymes*, and a transcription, however exact, cannot hear them. The fermion masses span six orders of magnitude, yet in ordered generations — a hierarchy with a direction, never explained. The quark mixings are small and hierarchical while the lepton mixings are large — two sectors, two textures, no reason. The one weak phase sits near its near-maximal measured value while the one strong phase sits at zero to ten digits — the two-dial embarrassment. The gauge couplings run toward one another with suspicious near-precision. Each rhyme is, in the model, a coincidence of inputs; each is, in the parent program's reading, a visible edge of one structure: the ordered hierarchy is the Morse descent's direction (Part VI); the two-texture split is the two alphabets, $L = 5$ for the block and $J = 7$ for the odd counter (Part VII); the two-dial embarrassment is the two-fate architecture (Part VII); and the near-unification is the ledger's throat arithmetic, priced in the companion treatments. Rhyme is not proof — the register insists on that — but rhyme is evidence of meter, and the claim of the completion below is that the meter exists and is computable.

112.4 How the geometry completes the story

The completion is item-for-item, and each item carries its grade. The parent Standard-Model treatment derives the twenty-eight parameters from the one geometry, at the calibrated register that paper prints (Arisaka, 2026, A9-SM); this paper has walked the discrete-symmetry core of that derivation in full. Against the five silences: the twins are Depth-3 derived (Part IV, quasi-free); the operations have bodies and a derived table (Part V); parity's five superlatives collapse to one oriented-gate architecture, with the mechanism inherited, the uniqueness conditional on L11, and the handedness anchored by P-P5-D (Part VI); the CP dial becomes a lattice point — $\delta = 0$ not merely false but unwritable — with the forced values confronting the fits in Table 10 (Part VII); and the strong-CP embarrassment becomes the second fate of one alphabet, bounded at 4.7×10^{-18} by the ledger's own integers (Part VII). Against the two failures: the tripod P-P5-E converts Sakharov's checklist into constitutional custody, and the transport chain meets the observed six-per-ten-billion with zero fitted parameters at D* grade under one named conjecture (Part VIII). And against the structural failure — five facts, zero connections — the completion is the connection itself: one descent, oriented, whose absence is parity violation, whose angle is CP violation, whose door is the neutrino, and whose receipt is the matter. Where the model has dials, the geometry has lattice points; where the model has coincidences, an architecture; where the model has fits, falsifiers with dates. The grades are printed where each claim lives, and the claims die, severally and jointly, on the instruments of Table 26.

113 The third road: string theory

113.1 What string theory achieved

String theory is the serious geometric rival, it anticipated several of this paper's moves, and the first movement of this road is a list of debts. It remains the most developed candidate for a quantum theory of gravity — the graviton is in its spectrum rather than added to it — and it taught physics that consistency in higher dimensions is a *discipline*: the anomaly-freedom mechanism of Green and Schwarz, in which a higher form field's inflow cancels what no field-content juggling could, is the direct ancestor of the BI-6 ledger's own inflow arithmetic. It geometrized chirality: four-dimensional handedness from the topology of compact dimensions, generations counted by index theorems (Candelas et al., 1985), chiral matter at orbifold fixed points (Dixon et al., 1985) and brane intersections (Berkooz, Douglas, and Leigh, 1996) — the technology lineage of Part VI's projection, conceded there to the matrix (Hall and Nomura, 2001; Kawamura, 2000). It made the twins economical: the antiparticle of a string state is the *conjugate excitation of the same object* (the conjugate vertex operator), so the mass degeneracy of the pair is automatic — one string, two readouts, structurally the same move as the positron-as-conjugate-readout of §49, and string theory made it first. It drew charge conjugation as geometry: an open string from brane stack a to b carries the conjugate representation of the string from b to a — C as orientation reversal (Polchinski, 1998) — the very image T-P5-A draws, conceded in Part IV's ledger. It protected CPT structurally: worldsheet consistency transfers the CPT theorem to the spacetime S-matrix order by order (Sonoda, 1989). And it made this subject's deepest single external contribution: CP as a *discrete gauge symmetry*, embedded in the higher-dimensional Lorentz and gauge groups (Choi, Kaplan, and Nelson, 1993; Dine, Leigh, and MacIntire, 1992; Strominger and Witten, 1985), hence unbreakable explicitly and broken only spontaneously, by geometry — conceptually the same move as T-P5-3, made a decade earlier. Three of this paper's central images — conjugation as orientation reversal, chirality from projection, CP as geometry — were drawn first on this road.

113.2 Where string theory ends

The road ends at valuation, and the ending has one structural root. Every geometric insight of the previous movement is realized *somewhere* in the space of string vacua — and so is its negation: non-chiral worlds, mirror-symmetric worlds, CP-conserving worlds, worlds of every δ. Which vacuum is ours is not derived; the landscape offers possibility without actuality, and no number this paper cares about — not δ, not $\bar{\theta}$'s smallness beside it, not η_B — is predicted at the framework level. The moduli that break CP spontaneously are continuous: geometric CP violation, without a value. The cosmology inherits its own systematic obstacle: late-decaying moduli release entropy and dilute, so string cosmologies typically need *more* baryogenesis than field theory does (Banks, Kaplan, and Nelson, 1994; Coughlan et al., 1983) — the precise contrast with the prompt crossing of §86. And beneath both sits the root: the extra dimensions are *spatial*, and places must be hidden, stabilized, and chosen — radii want moduli, moduli want potentials, potentials want selection, and selection is the landscape. The arena of Part III is built on the refusal of exactly this first step: its two

extra dimensions are classified by their generators as a resolution and a phase, dimensionless by construction, with no radius to stabilize, no tower to hide, and no vacuum to choose (Arisaka, 2026, A2-GG6). The contrast is structural, not polemical: the spatial program's problems are real problems, solved with real ingenuity; the non-spatial arena's claim is that they are *unposable* — which is a different kind of answer, and it is testable only through the numbers it forces.

113.3 How the geometry completes the story

The completion, then, is not a new picture — the pictures are string theory's, conceded — but a *valuation* of pictures already drawn. Conjugation as orientation reversal: drawn there on a spatial circle with a state-space i borrowed from the axioms; executed here on a non-spatial fiber whose partner structure, the clock, is derived — and only with two derived sources is there a handshake, which is why the pairing is a theorem here and a protection there. Chirality from projection: drawn there as one choice in a catalog; executed here with the output claimed forced by the ledger and the projection's own derivation honestly open — the forcing-versus-selection distinction of Part VI, which is the entire difference. CP as geometry: drawn there on continuous moduli, so that the framework predicts *that* CP violation is geometric but never *what* it is; executed here on one circle with one integer, so that the holonomies land on a pentagonal lattice and the phases come out as numbers with pulls — $13\pi/35$, $\pi + 2\arcsin(1/7)$, $(0, \pi)$ — each one a falsifier the moduli picture can never issue. In one sentence, paid in both directions: *string theory drew the right pictures on an arena that could not hold them still; the ledger's claim — graded, dated, and mortal — is that the true arena holds them still.*

114 The fourth road: ΛCDM

114.1 What ΛCDM achieved

ΛCDM is not a rival on mechanism — it is the bookkeeper, and its achievement is of a different, indispensable kind: it made cosmology a precision science with six numbers. Six parameters fit the microwave sky's acoustic peaks, the large-scale structure of the galaxy surveys, the light-element abundances, and the supernova distances — percent-level concordance across epochs separated by orders of magnitude in temperature and scale (Planck Collaboration, 2020). Among the six, $\Omega_b h^2$ is measured to 0.3%; and the framework's great consistency theorem is this paper's own boundary condition: the same η_B read at three minutes (deuterium, Cooke, Pettini, and Steidel, 2018) and at four hundred thousand years (the CMB), certifying that whatever made the asymmetry finished before the first second and that baryon number has been conserved since. Every mechanism in this Part, the GG-6 chain included, is graded against numbers ΛCDM measured.

114.2 Where ΛCDM ends

It ends where it honestly declares it ends: all six numbers are inputs. The baryon density is measured, not explained; η_B is an initial condition, upstream of the model's opening page; the framework holds no opinion on any question this paper has asked — why twins, why broken

mirrors, why a surplus — and, to its credit, pretends none. Its very precision has begun, in recent years, to expose stresses among its own dials, pursued at length in the cohort's cosmology companions (Arisaka, 2026, A10-Cosmos); for this paper the single relevant boundary is the simplest: a bookkeeper certifies accounts and originates none.

114.3 How the geometry completes the story

The completion inverts the roles while keeping the books: the cosmology companion re-derives the six dials as outputs of the same geometry this paper runs on — among them $\Omega_m = 1/\pi$ and $\Omega_b = 1/(2\pi^2)$, at the calibrated grades printed there (Arisaka, 2026, A10-Cosmos) — and Part VIII's transport chain is the dynamical audit of the baryon dial: the tripod P-P5-E says a receipt must exist, the chain computes its size at D*, and the bookkeeper's 0.3% measurement is the audit's external check. The books do not yet close perfectly, and the paper says so where it happened: the 16.4% two-route seam of §90 is published as the audit's open line. The relation is the healthiest in this Part: ΛCDM cannot explain and does not claim to; the geometry claims to and can be executed for it; and the bookkeeper will be the first to know if the claim fails.

115 The inventory: who predicts what

Analysis wants a single table in which the four roads face the same observables, and the register wants it labeled exactly: *fit* means the framework accommodates the measured value by setting a parameter; *unvalued* means the framework geometrizes the quantity but assigns it no number; *input* means the framework measures the value and uses it; *forced* means the framework asserts a value it cannot adjust. Pulls for the forced column are quoted in Table 10, and every grade caveat printed there applies here unchanged.

The table's single message survives every caveat on it: down the first three columns, no entry can be wrong; down the fourth, every entry can. That asymmetry — not any single number — is the structural difference between the roads, and it is the difference this Part was built to display.

116 Reading the pulls, and the falsification symmetry

Two analytic remarks make the inventory quantitative rather than rhetorical. *First, how to read the forced column statistically.* Ten forced entries confront measurement; where pulls are defined (Table 10) they run from +0.01 (the Cabibbo magnitude, at four decimal places) to +1.17 (the first-order CP phase — a pull quoted with the one-lattice-step theory width $\pi/35$ in quadrature; against experimental error alone that raw value sits at $+4.2\sigma$), with nothing beyond 1.2σ on that convention (the watched direct-γ tension, $+1.6\sigma$, lives in Part XI's refresh apparatus) — a global consistency no fitted framework can even express, since a fit has no pulls of its own making. And the register must immediately discount it, twice. The flags are part of the data: the QD completion is asserted (its pull +0.70 replaces the forced +1.17 only under the flagged step), and η_B carries a factor-$\sim$ 3 band that makes its +20% central agreement an order-of-magnitude statement, not a precision one. And global consistency is exactly what the jigsaw clause warns about: agreement

Table 18: The inventory: the same observables faced by the four roads. "Fit" accommodates, "unvalued" geometrizes without a number, "input" measures, "forced" asserts and cannot adjust. The forced column's pulls, grades, and flags are those of Table 10; its rows die on the instruments of Table 26.

Observable	**SM**	**String**	**ΛCDM**	**GG-6 (forced)**
$\sin\theta_{12}^{\rm CKM}$	fit	unvalued	—	0.22502 (golden-ratio closed form)
$\delta_{\rm CKM}$	fit (1.147)	unvalued (moduli)	—	$2\pi/5 \to 13\pi/35$ (QD flagged)
$\delta_{\rm PMNS}$	fit (in progress)	unvalued	—	$\pi + 2\arcsin(1/7) \simeq 196^\circ$
$(\alpha_{21}, \alpha_{31})$	free	unvalued	—	$(0, \pi)$: parity data
$m_{\beta\beta}$	free	unvalued	—	1.72 meV (first-order; QD layer 1.79)
$\bar{\theta}$	fine-tuned; axion bolt-on	axions, unvalued	—	$\lesssim 4.7 \times 10^{-18}$, two-fate
N_g (generations)	input (= 3)	vacuum choice	—	3 (ledger)
W_R sector	absent by input	vacuum choice	—	absent at every scale (F-P5-1)
η_B	≈ 0 (fails)	unvalued + moduli dilution	input (0.7%)	$\approx 7 \times 10^{-10}$ (D*, $\times 3^{\pm 1}$)
New states	—	unvalued	—	lock cluster at 3.85 TeV

across ten numbers is impressive in proportion to how independently the ten were forced, which is why the provenance audit — five integers fixed upstream, published across twenty-one companion treatments for unrelated purposes — is not decoration but the entire evidentiary weight of the column. The pulls are good; the honest sentence is that they are good *and* flagged, and both halves are data.

Second, the falsification symmetry. A comparison is scientific only if it can be lost, so let it be said, road by road, what discovery would vindicate the rival *against* this paper. A W_R or any parity restoration at any scale: left–right symmetry right, F-P5-1 dead, Part VI's geometry falsified outright. A measured $\delta_{\rm PMNS}$ far from 196° — at, say, maximal 270°: the dial reading right, the lattice wrong, Part VII's lepton chain dead on DUNE's floor. Proton decay at any lifetime: the GUT route vindicated and the entire baryonic logic of Part VIII — and the bulk ledger with it — destroyed. A fourth generation: the ledger's $N = 3$ dead with it, and with them the pentagon's alphabet. A neutron EDM between 10^{-18} and 10^{-10}: the two-fate architecture broken while the Standard Model stands untouched. Moduli-like relics or a discovered landscape dynamics: the enumerative picture vindicated where the rigid arena forbids it. The forced column of Table 18 is thus not a scoreboard of victories; it is a list of stakes — one per row — and the rival roads hold the winning tickets for every one of them should nature so rule. No other column in the table has offered the GG-6 program the reciprocal courtesy, because no other column can: that, in the end, is what "unvalued" and "fit" mean.

Table 19: The five roads on the three-depths ruler. Verdicts in one sentence each: QFT — rigorous and silent; the Standard Model — precise and unexplaining; string theory — geometric and unvalued; ΛCDM — exact and agnostic; GG-6 — valued, dated, and mortal.

Question	**QFT**	**SM**	**String**	**ΛCDM**	**GG-6**
Twins: exist?	Depth 2 (Weinberg; interacting)	inherited	Depth 1 + geometric image	—	Depth 3 (handshake; quasi-free)
Twins: what is the i?	axiom	axiom	axiom	—	derived (two sources)
C/P/T: what are they?	conventions	conventions	+ orientation image	—	three reversals (derived table)
CPT: why?	theorem, anatomy silent	inherited	worldsheet	—	bookkeeping over anatomy
P: why broken, why weak?	partials only	input	vacuum choice	—	basin/gate (conditional, L11)
CP: why, and how much?	no principle	one fitted dial	geometric, unvalued	—	chiral pentagon, forced values
$\bar{\theta} \simeq 0$, related to $\delta \neq 0$?	no	no (axion bolt-on)	axions, unvalued	—	two fates, one alphabet
η_B: derived?	toolbox, dials	≈ 0 (fails)	ingredients + moduli problem	measured to 0.7%	$\approx 7 \times 10^{-10}$, zero dials, D*
Falsifiable on a date?	mechanism-dependent	(is the baseline)	no	(is the ruler)	yes: Table 26

117 The synthesis: the three depths, scored

Table 19 closes the scoring, and one paragraph states what it shows. On every row, the GG-6 column claims the deepest answer on the table — and on every row, that claim is either a theorem with a stated grade, a named conjecture, or a number wired to an instrument. The other four columns are not caricatures; they are the strongest versions of four magnificent traditions, each of which contributed load-bearing pieces to this very paper (Weinberg's theorem, the sphaleron arithmetic, the orbifold projection, the target number itself). The difference is not intelligence or rigor; it is *inventory*. The GG-6 program spent its ledger before these questions were asked — five integers, published with their own falsifiers — and depth at fixed inventory is what this Part has laid out in the open.

118 The five roads, seen from above

Let us end the comparison from altitude, because seen from above the four roads are not four opinions about one question — they are four different *verbs*, and the shape of twentieth-century physics is the story of their succession. Quantum field theory *constrains*: it is the grammar of the possible, proving what any quantum causal world must contain, and grammar was its glory

and its limit — a grammar permits every book and writes none. The Standard Model *codifies*: it is the measured text of this world, transcribed to a precision no other science approaches, with twenty-eight numbers standing where reasons would go. String theory *enumerates*: it is the library of the writable worlds, in which every geometric insight this paper uses appears somewhere on the shelves — together with its negation, and no catalog rule for finding our volume. ΛCDM *measures*: it is the ledger of what this universe in fact did, six entries, kept to the percent. Four verbs — constrain, codify, enumerate, measure — and each road, at its honest end, hands the remaining question to the next: the grammar cannot pick the text; the text cannot explain itself; the library cannot find the volume; the ledger cannot author the entries. What no road of the century attempted, at this subject, is the fifth verb: *derive* — to exhibit this world's text as forced, and to accept the mortal risk that forcing entails.

Einstein asked whether God had any choice in the construction of the world, and the four roads return four answers: some clauses were forced (QFT); here are the choices, measured (the Standard Model); all choices are made, somewhere (string theory); these were chosen (ΛCDM). The program this paper serves returns the fifth answer as a *claim, not a creed*: fewer choices existed than the century assumed — perhaps none — and the way to find out is to write the forced values down beside their error bars and wait for the instruments. The philosophical weight of that posture deserves one careful paragraph, with both hats on. An explanation, in the oldest sense this program can defend, is the conversion of contingency into necessity: the fact that felt optional is exhibited as the only writable option. Every Part of this paper has practiced that conversion — the twins as the price of one i, the antiunitarity of T as the only exit from a forbidden quadrant, CP violation as the chirality of a pentagon no dial can straighten, the matter excess as the receipt of a fall the constitution made unavoidable. But the philosopher's hat must immediately yield to the experimentalist's, because conversion-into-necessity is also the oldest temptation in natural philosophy, and a jigsaw that fits perfectly can fit because the pieces were cut to fit. The satisfaction is not evidence. The dates are: a phase at 196° under a detector now under construction, a double-beta mass at 1.7 meV in the tonne-scale program's sights, a TeV cluster within one collider upgrade, a right-handed sector that must never appear at any energy, a proton that must never decay. Necessity that cannot be executed is theology; necessity that publishes its own execution dates is physics. The five roads differ, in the end, less in geometry than in *exposure* — and the fifth verb is available only to a framework willing to be refuted in its own lifetime.

Seen as history, the century is one arc with a direction of its own. In 1908 Minkowski geometrized time's order, and physics learned that a structure could be a shape. In 1928 Dirac's algebra demanded the twins, and in 1932 a cloud chamber obliged: consistency had begun to legislate. In 1957 and 1964 the mirrors fell, and physics learned that the world has a handedness it had never been asked about; in 1967 Sakharov read the fallen mirrors as the price of existence; in 1973 the fall was given an address in a matrix, and in 1983, 1998, 2012 the address was confirmed to three digits — culminating, for this author, in two decades of measuring a number whose value his science declared meaningless. Each step of the arc converted a wonder into a structure and left one question standing at a deeper level. The arc's direction is unmistakable: from *that* the world is lawful, toward *why* it is this world — from grammar toward authorship. The wager of this paper is not that the arc

ends here; it is that the arc's next step has the same character as all the previous ones — another wonder converted into a structure, this time the wonder of the broken mirrors themselves — and that the conversion is now concrete enough to be executed by instruments on a published schedule.

After all, the four roads' own summits are the reason the fifth verb became thinkable at this subject: a grammar so tight it legislates twins, a text so precisely transcribed that its twenty-eight numbers beg for a source, a library so complete it proves geometric answers exist, and a ledger so exact it can convict any pretender. Standing on all four, one can finally ask the question they converge upon and cannot answer — *why this world?* — and this paper's wager, graded and dated, is that the question has become physics.

119 The sixth comparison: what each road says time is

Part IX adds a comparison this Part's ruler could not have drawn before, and it belongs here, where the roads stand side by side. Ask each road the oldest question. QFT answers with order and repetition borrowed whole — a background parameter, microcausality imposed, the shore used in every computation and named in none. The Standard Model adds the one thing experiment forced on it: a measured T-violation — and correctly refuses to call it an arrow, since its dynamics remains reversible to the last term. String theory, which dissolves space with enthusiasm, keeps worldsheet time as a background and inherits the frozen-formalism problem wherever it goes background-independent. ΛCDM runs on a cosmic time that is a choice of foliation, with its arrow rented from the past hypothesis — an initial condition doing a law's work. And the geometry answers with the four endowments: order from the cone, repetition forced by Theorem 0, the arrow written into the dictionary's one-way reading, and the shore opened by the spectrum's single side (Part IX). On this sixth comparison the pattern of the other five repeats exactly: the roads use time; the geometry says what it is — and pays for the answer in the usual currency, since the same OGGEP law that defines the arrow runs the falsifiable transport of Part VIII.

Part-end summary. Four roads, each walked in three movements: what it achieved, honored with numbers; where it ends, located in its own terms; how the geometry completes it, graded claim by claim. One inventory table in which only the last column can be wrong; one scoreboard on the three-depths ruler; and the view from above — four verbs, constrain, codify, enumerate, measure, with the fifth, derive, attempted here at the price of mortality. Every debt paid in its creditor's own section. Before the housekeeping of the claims comes the court in which all of them are tried: the instruments. The next Part walks the century of measured mirrors and the decade of machines now arriving on published schedules, each pointed at a forced value.

Part XI
Experiments — Past, Now, and Future

The century of measured mirrors and the neutrino century, with their milestone tables; the present frontier as of mid-2026; and the instruments of the decisive decade, each with its schedule, its sensitivity, and the forced value it touches

120 Part XI in plain English: what has been measured, and what is coming

This is the Part an experimentalist should read first. It records a century of measured mirrors and a century of neutrinos, with the numbers as they stand in mid-2026 and every source named, including the two lines that are the author's own instrument lineage.

Then it does the thing a paper of this kind usually avoids. Every forced value in the paper is set against the measurement that will test it, with the precision that measurement needs and the year it is expected. The verdicts are simulated for 2028, 2031, 2035 and 2040, so that a reader can see now what this account looks like if each of those years goes against it, rather than being told afterward that the result was always robust.

The falsifier timeline is dated, and the dates are close. That is the Part's whole argument. This is not a framework that will be settled by taste or by how it reads, and the decade that decides it has already started.

121 The third channel

Every claim of this paper ends, by design, at an instrument, and this Part is where the instruments take over the narrative. The parent program maintains three primary falsification channels. The first is the collider channel: the lock cluster at 3.85 TeV, whose confrontation with the ATLAS and CMS record and whose pre-registered HL-LHC search are the business of the cohort's collider companion (Arisaka, 2026, P1-KK). The second is the laboratory dark-sector channel: the Kaxion at 8.1 μeV (1.95 GHz), alone in a closed seven-rung window, with its dedicated instrument proposal (Arisaka, 2026, C1-Kaxion). This paper completes the triad: the mirror sector — the CP phases, the Majorana door, the strong-CP window, the right-handed absence, and the proton's silence — is the third channel, and it runs not on one machine but on a worldwide battery of them. The present Part reviews that battery in the manner of its companion papers: history first, because every forced value of Parts VI–VIII confronts a measurement tradition that is itself a scientific achievement of the first rank; then the present status, grounded in official collaboration outputs; then the instruments now under construction, with schedules and sensitivities; and then — in the

confrontation sections that close the Part — the forced values laid beside the reach of each machine. Because experimental status changes on the scale of months, this is exactly the type of Part that deserves freshness: the status reported here is current as of mid-2026, drawn from collaboration publications and official announcements, and the few numbers taken from design reports rather than data are attributed as such. Both hats are worn throughout — these are the author's instruments; he spent 1980–1985 building one of them and two decades inside two others — and the register is unchanged: what follows is either measured, scheduled, or graded.

122 A century of broken mirrors, measured

122.1 The kaon era: from a helium bag to 10^{-18}

The experimental history of CP violation begins with an apparatus almost provocatively modest: a two-arm spectrometer, a hydrogen target's secondary beam, and a helium bag, at the Brookhaven AGS in 1964. Christenson, Cronin, Fitch, and Turlay found the long-lived kaon decaying to two pions at a branching ratio near 2×10^{-3} (Christenson et al., 1964) — and the decisive experimental point, worn smooth by retelling but essential, is that they did not merely see a peak: they excluded the mundane explanation, coherent regeneration in the bag, by orders of magnitude. Part I told what the discovery meant; here we record what it started — a sixty-year program of turning one anomaly into precision. The semileptonic charge asymmetry ($\delta_L = (3.32 \pm 0.06) \times 10^{-3}$ today) gave matter its operational definition. The parameters $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$ and the phases were driven to three digits across three decades (Particle Data Group, 2024). Then came the question that occupied the author's first experimental decade at the precision frontier: is CP violation confined to the mixing (the superweak hypothesis), or does it act directly in the decay — $\varepsilon'/\varepsilon \neq 0$? The saga ran twenty years: NA31 at CERN found evidence ($(23.0 \pm 6.5) \times 10^{-4}$ final), Fermilab's E731 found a value consistent with zero, and the contradiction was resolved only by the purpose-built successors — KTeV at Fermilab, where the author served, establishing direct CP violation beyond doubt in 1999 with a final value $\mathrm{Re}(\varepsilon'/\varepsilon) = (19.2 \pm 2.1) \times 10^{-4}$ (KTeV Collaboration, 1999), and NA48 at CERN confirming with $(14.7 \pm 2.2) \times 10^{-4}$ (NA48 Collaboration, 2002); the world average stands at $(16.6 \pm 2.3) \times 10^{-4}$ (Particle Data Group, 2024). The superweak model died; CP violation acts in amplitudes, exactly where a texture angle would put it. CPLEAR closed the kaon era's conceptual circle in 1998 by observing time-reversal violation directly — the Kabir asymmetry between $\bar{K}^0 \to K^0$ and $K^0 \to \bar{K}^0$ at $(6.6 \pm 1.6) \times 10^{-4}$ (CPLEAR Collaboration, 1998) — and the neutral-kaon system delivered, almost as a by-product, the sharpest CPT test in physics: the K^0–$\bar{K}^0$ fractional mass difference bounded near 10^{-18} (§10). The modern kaon frontier has moved to the rarest decays, where new phases would enter at one loop: NA62 has now observed $K^+ \to \pi^+ \nu\bar{\nu}$ — the 2024 observation refined in March 2026 to a combined BR $= (9.6^{+1.9}_{-1.8}) \times 10^{-11}$, within 1σ of the Standard-Model expectation (NA62 Collaboration, 2025, 2026) — while KOTO bounds the neutral partner $K_L \to \pi^0 \nu\bar{\nu}$ below 2.2×10^{-9} with its successor KOTO-II approved toward single-event sensitivity below 10^{-12} (KOTO Collaboration, 2025). Sixty years, one overarching lesson: the kaon system converts patience into decimal places, and every decimal place has so far landed on the one-phase texture the pentagon forces.

122.2 The B era: from the Υ to a baryon

The second era belongs to the third generation that CP violation itself predicted (Kobayashi and Maskawa, 1973). The b quark arrived in 1977; the unexpectedly long b lifetime (1983) revealed the CKM hierarchy; and ARGUS's 1987 discovery of large B^0–$\bar{B}^0$ mixing (ARGUS Collaboration, 1987) — a result that presaged the heavy top — meant the B system could interfere its way to large CP asymmetries. Two purpose-built colliders and detectors — PEP-II/BaBar, where the author served, and KEKB/Belle — turned that possibility into the 2001 observation of $\sin 2\beta$ (BaBar Collaboration, 2001; Belle Collaboration, 2001), CP violation outside the kaon system and the quantitative confirmation of the one-phase mechanism. Direct CP violation in $B \to K\pi$ followed in 2004; and in 2012 BaBar performed the measurement this paper's Part V made structural sense of: direct, model-independent time-reversal violation, using entangled B pairs to compare a transition with its genuine time-reverse, at 14σ (BaBar Collaboration, 2012). The LHC era then broadened the map: LHCb discovered CP violation in *charm* in 2019 ($\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$) (LHCb Collaboration, 2019), measured the angle γ directly to $(62.8 \pm 2.6)^\circ$ (November 2025 combination) in mild, watched tension with the indirect fit, and in 2025 observed CP violation in a *baryon* for the first time — $\Lambda_b^0 \to pK^-\pi^+\pi^-$ at 5.2σ, published in *Nature* (LHCb Collaboration, 2025) — extending the broken mirror to the matter category we are made of. Belle II is rebuilding the e^+e^- precision program. The current world averages the pentagon must face: $\sin 2\beta = 0.709 \pm 0.011$, $\delta = 1.147 \pm 0.026$ rad, $J = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$ (Particle Data Group, 2024). And parallel to the collider line runs the static-moment line — Part V's T-instruments: the neutron EDM bounded at $1.8 \times 10^{-26}\, e\,\text{cm}$ (nEDM Collaboration, 2020) with the PSI successor n2EDM commissioning toward 10^{-27}, and the electron EDM at $4.1 \times 10^{-30}\, e\,\text{cm}$ (Roussy et al., 2023) — null results that already convict generic TeV-scale CP phases and leave the lattice's leakage floor (Part VII) untouched by eight orders.

123 The neutrino century

The neutrino's experimental history is the longest arc in particle physics — a particle postulated in apology ("I have done a terrible thing," Pauli said, "I have postulated a particle that cannot be detected") that became, one century later, the field's sharpest precision frontier and this paper's decisive instrument. The arc: Pauli's 1930 letter; Reines and Cowan's 1956 detection of reactor antineutrinos (Reines and Cowan, 1956); the 1962 Brookhaven two-neutrino experiment separating ν_μ from ν_e (Danby et al., 1962); Davis's Homestake chlorine tank measuring the solar flux at one third of prediction from 1968 onward (Davis et al., 1968) — a deficit that would take thirty years to become a discovery. In 1987 the neutrinos of SN1987A crossed Kamiokande — the detector the author spent 1980–1985 designing and building — and IMB, nineteen events that opened neutrino astronomy. In 1998 Super-Kamiokande announced the zenith-angle asymmetry of atmospheric muon neutrinos — $A = -0.296 \pm 0.048 \pm 0.010$, a six-sigma up–down asymmetry — and with it the discovery of neutrino oscillation (Super-Kamiokande Collaboration, 1998): the neutrino has mass, the lepton mixing matrix is real physics, and the door of Part VII acquired its traffic. SNO's heavy-water measurements (2001–2002) showed the missing solar neutrinos arriving in other flavors

Table 20: The past, part one: milestones of the broken mirrors in the quark sector, 1957–2026. Values as per current world averages (Particle Data Group, 2024). Parts I and V–VII carry the structural reading of each line. Fifteen rows, from the 1957 fall of parity to the 2025 observation of CP violation in baryons, each with the experiment, the number it produced, and what that number established. The right column is the one to read downward: it is where a sequence of separate results becomes a single account of which mirrors break and by how much.

Year	Experiment	Result	What it established
1957	Wu; Garwin et al.	P (and C) violation, maximal	the first mirror falls; V−A
1964	Cronin–Fitch (AGS)	$K_L \to \pi\pi$; $\lvert\eta_{+-}\rvert \simeq 2.3 \times 10^{-3}$	CP falls: the second mirror, small
1967–	multiple	$\delta_L = (3.32 \pm 0.06) \times 10^{-3}$	matter operationally defined
1973	(theory) KM	one phase needs $N_g \geq 3$	third generation predicted
1977	E288 (FNAL)	$\Upsilon(9.46)$	the b quark
1987	ARGUS	large B^0–$\bar{B}^0$ mixing	heavy top; B-CP program feasible
1988–02	NA31, E731, KTeV, NA48	$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 2.3) \times 10^{-4}$ (avg.)	direct CPV; superweak dead
1998	CPLEAR	$A_T = (6.6 \pm 1.6) \times 10^{-4}$	direct T violation (kaons)
2001	BaBar; Belle	$\sin 2\beta$ observed	CPV beyond kaons; KM confirmed
2004	BaBar, Belle	$A_{CP}(B \to K\pi) \neq 0$	direct CPV in B
2012	BaBar	T violation, entangled B pairs, 14σ	the clock reversal caught alone
2019	LHCb	$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$	CPV in charm
2024–26	NA62	$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$	rare-kaon frontier at SM
2025	LHCb	Λ_b^0 CPV at 5.2σ	CPV reaches baryons

(SNO Collaboration, 2002); KamLAND caught reactor antineutrinos disappearing over 180 km (KamLAND Collaboration, 2003); T2K indicated and Daya Bay established the third mixing angle in 2011–2012 ($\sin^2 2\theta_{13} = 0.092 \pm 0.017$ at discovery; 0.0851 ± 0.0024 final) (Daya Bay Collaboration, 2012), with tau-flavor appearance closed out by DONUT and OPERA (DONUT Collaboration, 2001; OPERA Collaboration, 2018); Borexino completed the solar spectrum through the CNO cycle (Borexino Collaboration, 2020); and the 2015 Nobel Prize to Kajita and McDonald certified the century's turn. Three facts from this history carry directly into the confrontation to come: the oscillation parameters are now percent-level data; the CP phase of the lepton sector is measurable; and the mass *ordering* — on which the lattice value's confrontation partly turns — is within reach of three independent techniques this decade.

124 The present frontier (mid-2026)

This section is the freshness layer: the state of every relevant front as of mid-2026, from collaboration publications and official announcements.

Table 21: The past, part two: milestones of the neutrino century, 1930–2020. The 1987 and 1998 lines are the author's own instrument lineage; Part VII's lepton chain runs on the parameters this table's discoveries turned into data. Thirteen rows, from Pauli's letter to Borexino's detection of the CNO neutrinos, each with the experiment, the result, and what it established. Read downward it is the record of a particle postulated to save a conservation law becoming, over ninety years, the instrument that measures the lepton sector.

Year	Experiment	Result	What it established
1930	Pauli (letter)	the desperate remedy	energy conservation kept; ν postulated
1956	Reines–Cowan	reactor $\bar{\nu}_e$ detected	the neutrino is real
1962	Danby et al. (BNL)	$\nu_\mu \neq \nu_e$	flavor exists in the lepton sector
1968–	Davis (Homestake)	solar rate $\sim 1/3$ of SSM	the solar problem posed
1987	Kamiokande-II; IMB	SN1987A: 19 events, 13 s	neutrino astronomy born
1998	Super-Kamiokande	atmospheric up–down asymmetry -0.296 ± 0.048	oscillation discovered; mass exists
2001–02	SNO	NC flux matches SSM; ν_e deficit is conversion	solar problem solved by flavor change
2003	KamLAND	reactor disappearance over 180 km	LMA selected; Δm^2_{21} pinned
2000/15	DONUT; OPERA	ν_τ appearance	the third row closed
2011–12	T2K; Daya Bay; RENO	θ_{13}: $\sin^2 2\theta_{13} = 0.0851(24)$ (final)	the door to leptonic CP opened
2015	Nobel (Kajita, McDonald)	—	the century certified
2020	Borexino	CNO solar neutrinos	the Sun's second furnace seen

Oscillations. The global three-flavor fit (NuFit 6.0) gives $\sin^2\theta_{12} = 0.308^{+0.012}_{-0.011}$, $\sin^2\theta_{23} = 0.561^{+0.012}_{-0.015}$, $\sin^2\theta_{13} = 0.02195^{+0.00054}_{-0.00058}$, $\Delta m^2_{21} = (7.49 \pm 0.19) \times 10^{-5}$ eV^2, $|\Delta m^2_{3\ell}| \simeq 2.5 \times 10^{-3}$ eV^2 — and, for this paper's central number, $\delta_{CP} = 177^{\circ}{}^{+19}_{-20}$ if the ordering is normal and $285^{\circ}{}^{+25}_{-28}$ if inverted (NuFit Collaboration, 2024). All NuFit 6.0 numbers in this paper are the IC19 variant without SK atmospherics; the with-SK variant flips the θ_{23} octant and moves δ to 212° — under it the lattice point sits at -0.4σ. The first combined analysis of the two running long-baseline experiments, T2K and NOνA, appeared in *Nature* in October 2025 (T2K and NOνA Collaborations, 2025): $|\Delta m^2_{32}|$ to better than 2%, and δ_{CP} constrained such that the CP-conserving values are excluded at 3σ *if* the ordering is inverted, while remaining allowed under normal ordering — with the ordering itself still undetermined (Bayes factors near unity). JUNO, filled and running since August 2025, published first results in November 2025 from fifty-nine days of data: $\sin^2\theta_{12} = 0.3092 \pm 0.0087$ and $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}$ eV^2, already sharper than all prior experiments combined (JUNO Collaboration, 2025). The reading for Part VII is direct and worth stating now: under normal ordering — which the cohort's derived mass spectrum requires — the lattice value 196° sits within 1σ of the current global best fit; under inverted ordering it is already disfavored at $\approx 3\sigma$. The ordering determination is therefore not background; it is part of this paper's kill chain.

Quark sector and EDMs. The averages confronting the pentagon moved with the 2025 updates:

$\sin 2\beta = 0.709 \pm 0.011$ (the confrontation table and Part VII's prose carry the refreshed averages — the pentagon's 0.708, evaluated at the stated PDG-class moduli layer, pulls -0.1σ, inside the band and watched; the refresh is executed in §127); $\gamma_{\text{direct}} = (62.8 \pm 2.6)°$; $J = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$ (Particle Data Group, 2024). The lattice triangle's γ tracks the QD phase at leading order, $\simeq 66.9°$: a $+1.6\sigma$ pull against the direct combination, printed here under the no-cosmetic-delay rule of §127, and watched. NA62's combined $K^+ \to \pi^+\nu\bar{\nu}$ sits on the Standard-Model value; KOTO presses the neutral mode (KOTO Collaboration, 2025). The EDM nulls stand at $1.8 \times 10^{-26}\, e\,\text{cm}$ (neutron) and $4.1 \times 10^{-30}\, e\,\text{cm}$ (electron) (nEDM Collaboration, 2020; Roussy et al., 2023).

The Majorana door. The allowed two-neutrino mode has been laboratory physics since its direct observation in 1987 (Moe, Elliott, and Hahn, 1987); the neutrinoless frontier is where the door itself is tested. The half-life record: KamLAND-Zen's full Xe-136 exposure gives $T_{1/2} > 3.8 \times 10^{26}$ yr, i.e. $m_{\beta\beta} < 28$–122 meV across the nuclear-matrix-element spread (KamLAND-Zen Collaboration, 2024) — the first search reaching into the inverted-ordering band; GERDA closed at 1.8×10^{26} yr background-free (GERDA Collaboration, 2020); LEGEND-200's first result (2025), combined with its ancestors, gives $T_{1/2} > 1.9 \times 10^{26}$ yr (LEGEND Collaboration, 2025); CUORE passed two tonne-years of TeO_2 exposure (CUORE Collaboration, 2024). No signal anywhere — which is, for the record the confrontation will formalize, exactly what a normal-ordered spectrum with $m_{\beta\beta} \simeq 1.7$ meV predicts at these sensitivities.

The proton's silence. The search that minimal unification commissioned half a century ago (Georgi and Glashow, 1974) has become the deepest null result in physics: Super-Kamiokande's ledger, now at 0.37–0.40 Mton·yr: $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ yr, $\tau/B(p \to \bar{\nu}K^+) > 5.9 \times 10^{33}$ yr, with new channels still being closed — $p \to e^+\eta > 1.4 \times 10^{34}$ yr (2024) and $p \to e^+\pi^0\pi^0 > 7.2 \times 10^{33}$ yr (2026) (Super-Kamiokande Collaboration, 2020); and the bound-neutron limit translating to a free n–$\bar{n}$ oscillation time above 4.7×10^8 s (Super-Kamiokande Collaboration, 2021). Every year of this silence is a passed test of the exact bulk ledger (Part VIII); a single event in any channel would end the program.

Mass and cosmology. KATRIN bounds the effective electron-neutrino mass below 0.45 eV directly (KATRIN Collaboration, 2025); DESI's second data release, with CMB data, bounds $\sum m_\nu < 0.064$ eV in ΛCDM (DESI Collaboration, 2025) — a limit now pressing against the inverted-ordering floor ($\simeq 0.10$ eV) and even flirting, at the 2–3σ level, with the normal-ordering minimum ($\simeq 0.06$ eV): cosmology itself is voting on the ordering, in the direction the cohort's spectrum requires. Within the extended $w_0 w_a$ dark-energy space the bound relaxes to 0.16 eV — but at the price of pressing the cohort's registered $w = -1$: the joint $(w, \sum m_\nu)$ exposure is one correlated test, not two independent outs, and is registered as such. The Super-K gadolinium program reports the diffuse supernova background "at the threshold of discovery" — limits at the model band's edge, no claimable excess yet.

125 The instruments of the decisive decade

What follows is the machine roster on which the mirror sector's forced values will live or die, with construction status as of mid-2026 and sensitivities from technical design reports (attributed

as design figures where they are not yet data-anchored).

Long baseline. Hyper-Kamiokande — the third generation of the instrument line the author helped begin — has its cavern excavated (July 2025), installation under way, and data-taking planned from 2028: a 260 kton water Cherenkov detector on the J-PARC beam, able to exclude CP conservation at 5σ for more than 60% of δ_{CP} values within ten years, with a design resolution of 7°–20° depending on the true value (Hyper-Kamiokande Collaboration, 2025). DUNE, the 1300 km liquid-argon program at Fermilab/SURF, has its far-detector installation in progress and first beam physics on current planning near 2031: mass-ordering determination at 5σ for all δ_{CP} within about two years of running, CP-violation discovery over half the δ range in about a decade, and δ resolution of 10°–20° (DUNE Collaboration, 2020). JUNO is already running, with the mass ordering at $\sim 3\sigma$ expected in about six years of reactor data and sub-percent angle and splitting precision (JUNO Collaboration, 2025). The IceCube Upgrade's dense infill starts physics in 2026; ESSnuSB defines the longer horizon.

The ton-scale double-beta program. LEGEND-1000 (Ge-76, at Gran Sasso; the DOE/NSF-preferred ton-scale selection) targets discovery sensitivity $T_{1/2} \sim 1.3 \times 10^{28}$ yr, i.e. $m_{\beta\beta} \sim$ 9–21 meV (LEGEND-1000 Collaboration, 2021); nEXO (five tonnes of Xe-136 at SNOLAB) targets $\sim 1.35 \times 10^{28}$ yr, $m_{\beta\beta} \sim$ 6–27 meV (nEXO Collaboration, 2022); CUPID (Mo-100 bolometers in the CUORE cryostat) targets $\sim 10^{27}$ yr discovery (CUPID Collaboration, 2025); AMoRE-II begins at Yemilab in 2027; SNO+ loads tellurium from 2026. Together they are designed to cover the inverted-ordering band ($m_{\beta\beta} \geq 18.4 \pm 1.3$ meV) with discovery-grade sensitivity in the 2030s. The confrontation this sets up is stated now and formalized later: the cohort's $m_{\beta\beta} \simeq 1.72$ meV lies *below* that band — so for the ton-scale era the GG-6 prediction is one-sided and unusually clean: *any* confirmed discovery at inverted-band values falsifies the derived Majorana pair and mass spectrum, while continued null results are precisely what the geometry requires. Reaching 1.7 meV itself demands half-life sensitivities near 10^{29}–10^{31} yr — kiloton-scale isotope, beyond any funded program: the $0\nu\beta\beta$ number is this paper's furthest-horizon falsifier, with the nearer decades delivering the one-sided test.

Proton decay. Hyper-Kamiokande extends the $e^+\pi^0$ reach toward 10^{35} yr over its first decades — the only approved instrument able to probe beyond $10^{34.5}$ (Hyper-Kamiokande Collaboration, 2025); DUNE contributes its signature kaon-tracking channel $p \to \bar{\nu}K^+$ at the 1.3×10^{34} yr level per 400 kton·yr (DUNE Collaboration, 2020); JUNO adds $\sim 10^{34}$ yr-class sensitivity in the same channel (JUNO Collaboration, 2025). For the exact $\mathrm{U}(1)_B$ ledger the message is permanence: the program's prediction is silence, forever, at every depth — each order of magnitude gained is another passed test, and one event anywhere is the end.

Static moments. n2EDM at PSI is commissioning toward $10^{-27}\, e\,\mathrm{cm}$ on the neutron; the JILA ion-trap program drives the electron sector below $10^{-30}\, e\,\mathrm{cm}$ (Roussy et al., 2023). The strong-CP window of Part VII — leakage floor near 10^{-18} in $\bar{\theta}$, present bound 10^{-10} — leaves eight orders of headroom in which any confirmed EDM discovery would break the two-fate architecture while leaving the Standard Model untouched: the rare falsifier that can kill this paper without touching its rivals.

Bursts and backgrounds. SNEWS 2.0 stands watch for the next galactic supernova (SNEWS

Collaboration, 2021); if one arrives at 10 kpc, Hyper-K expects tens of thousands of events, DUNE the unique electron-neutrino burst reading, JUNO and IceCube their own thousands — a once-per-few-decades calibration of the entire neutrino sector at once. The gadolinium-loaded Super-K continues toward the diffuse supernova background. KATRIN concludes its direct-mass campaign toward 0.3 eV sensitivity with Project 8's cyclotron-radiation technique aiming, on the longer horizon, at 0.04 eV — into the range where the cohort's heaviest light neutrino ($\simeq 50$ meV) becomes directly testable.

126 The confrontation, forced value by forced value

The review is done; the confrontation begins. The format is fixed and repeated: each subsection states the forced value at its grade, the instruments that reach it, the quantitative relation of reach to value, and — before any data arrive — the kill. Nothing below adjusts anything above: the values were fixed in Parts VI–VIII (and upstream, in the parent papers) before this Part consulted a single schedule.

But first, the audit at a glance. Part VII closed with the ten-row forced-versus-measured table; it is reprinted here, unchanged, as Table 23 — already carrying the refreshed world numbers of §127 — so that the confrontations that follow can be read against it without leaving the Part. Figures 23 and 24 then draw it, in the twin-panel convention of the particle parent's executive summary (Arisaka, 2026, A9-SM): for every row with a measured central value, the signed relative deviation $\mathrm{Dev} = (\mathrm{Pred} - \mathrm{Obs})/|\mathrm{Obs}|$, the raw first-order lattice value in orange where the chain has one ($2\pi/5$; 196.43°), the QD-completed or single forced value in blue, an inner thick bar for the empirical uncertainty alone, an outer thin bar adding the theory uncertainty in quadrature, and shaded bands marking the precision decades.

Three features of the two panels reward a stare before the row-by-row work begins. First, the Cabibbo angle: at $+4 \times 10^{-5}$ relative deviation it is invisible at any scale the other rows can share — the sharpest single number in the paper, and the reason the pentagon was taken seriously in the first place. Second, the QD pattern: in both rows that have a first-order lattice value, the orange marker lands right of the blue and the quantum-defect completion pulls the prediction *toward* the data by roughly a factor of five — the same one-way pattern the parent paper's twenty-two-row audit shows, here reproduced in the CP sector. Third, the asymmetry of information: the two fat blue bars (δ_{PMNS}, and J_{CKM}'s layer band) are wide today and narrow on schedule, while the watched rows ($\sin 2\beta$ at -0.1σ with its evaluation layer stated, the direct γ at $+1.6\sigma$, η_B at $+20\%$ central inside its D^* band) are exactly where the refresh rules of §127 keep the running score. Nothing in either panel was fitted; every marker can move only by dying. With the map in hand, the confrontation proceeds one observable at a time.

Table 23: The ten-row confrontation, reprinted from Part VII (Table 10) with the refreshed world numbers and, in this Part's format, explicit deviation and pull columns: Dev = (Pred − Obs)/|Obs| and Pull = (Pred − Obs)/$\sigma_{\rm tot}$ with experimental and theory uncertainties added in quadrature (for $\delta_{\rm CKM}$ the theory width is one lattice step, $\pi/35$; against experimental error alone the raw $2\pi/5$ sits at $+4.2\sigma$); paired entries are first-order / QD-completed. Dashes mark rows with no measured central value (bounds, signs, or unmeasured phases) — the one-sided silences. The η_B pull is not quoted because the D* transport band ($\times 3^{\pm 1}$), not the Planck error, governs it. The register of each chain applies (§135). No entry was fitted; every entry can move only by dying. Figures 23 and 24 draw the six measured rows.

Observable	Forced value	Measured	Dev	Pull	Status
$\sin\theta_{12}^{\rm CKM}$	0.22502 (53)	0.22501 ± 0.00068	+4.4e−5	+0.01	derived-cond.
$\delta_{\rm CKM}$	$2\pi/5 = 1.2566$; QD $13\pi/35 = 1.1669$	1.147 ± 0.026	+9.6e−2 / +1.7e−2	+1.17 / +0.70	derived-cond.
$J_{\rm CKM}$	3.1×10^{-5} (layer band 2.7–3.2)	$(3.12^{+0.13}_{-0.12}) \times 10^{-5}$	−6.4e−3	−0.2	inside band
$\sin 2\beta$	0.708 (WE III)	0.709 ± 0.011	−1.4e−3	−0.1	watched
$\delta_{\rm PMNS}$	196.4°; QD 196.06°	NO: $177^{\circ}{}^{+19}_{-20}$; IO: $285^{\circ}{}^{+25}_{-28}$	+1.1e−1	+1.0	derived-cond. (NO)
$(\alpha_{21}, \alpha_{31})$	$(0, \pi)$	unmeasured	—	—	$0\nu\beta\beta$-testable
$m_{\beta\beta}$	1.72 meV	< 28–122 meV	—	—	below reach; tonne-scale+
$J_{\rm PMNS}$	-9.4×10^{-3}	sign disfavored > 0 (T2K Collaboration, 2020)	—	—	consistent
$\bar{\theta}$	$\lesssim 4.7 \times 10^{-18}$	$< 10^{-10}$ (nEDM)	—	—	8 orders headroom
η_B	$\approx 7 \times 10^{-10}$ ($\times 3^{\pm 1}$)	$(6.12 \pm 0.04) \times 10^{-10}$	+0.20	—	D* band

126.1 The lepton phase: 196.4°, and the quiet signature

Value: $\delta_{\rm PMNS} = \pi + 2\arcsin(1/7) = 196.43^{\circ}$ (QD 196.06°); derived-conditional on the leptonic assignment lemma (Part VII). *Position today:* $+1.0\sigma$ from the normal-ordering global fit; $\approx 3\sigma$ disfavored under inverted ordering (NuFit Collaboration, 2024; T2K and NOνA Collaborations, 2025). *Instruments:* Hyper-K (2028–), DUNE (∼2031–), with design resolutions 7–20° and 10–20° respectively, and late-2030s combined precision plausibly near ±7–8° at the lattice value — which, sitting near π, lies in the *best*-resolution region of both experiments. Now the structural point, stated with both hats on, because it inverts the community's expectation. The lattice value implies $\sin\delta_{\rm PMNS} = -0.28$: *small* leptonic CP violation. The flagship discovery figure of both experiments — five-sigma CP-violation exclusion over most of the δ range — concerns values near maximal; if the pentagon is right, *that discovery will not come.* The GG-6 signature at the long baselines is a near-null: a measured δ crowding the CP-conserving point from below, resolving away from 180° only slowly (16.4° of separation against ±7–8° late-decade: a 2–2.5σ distinction by ∼2040, sharpening

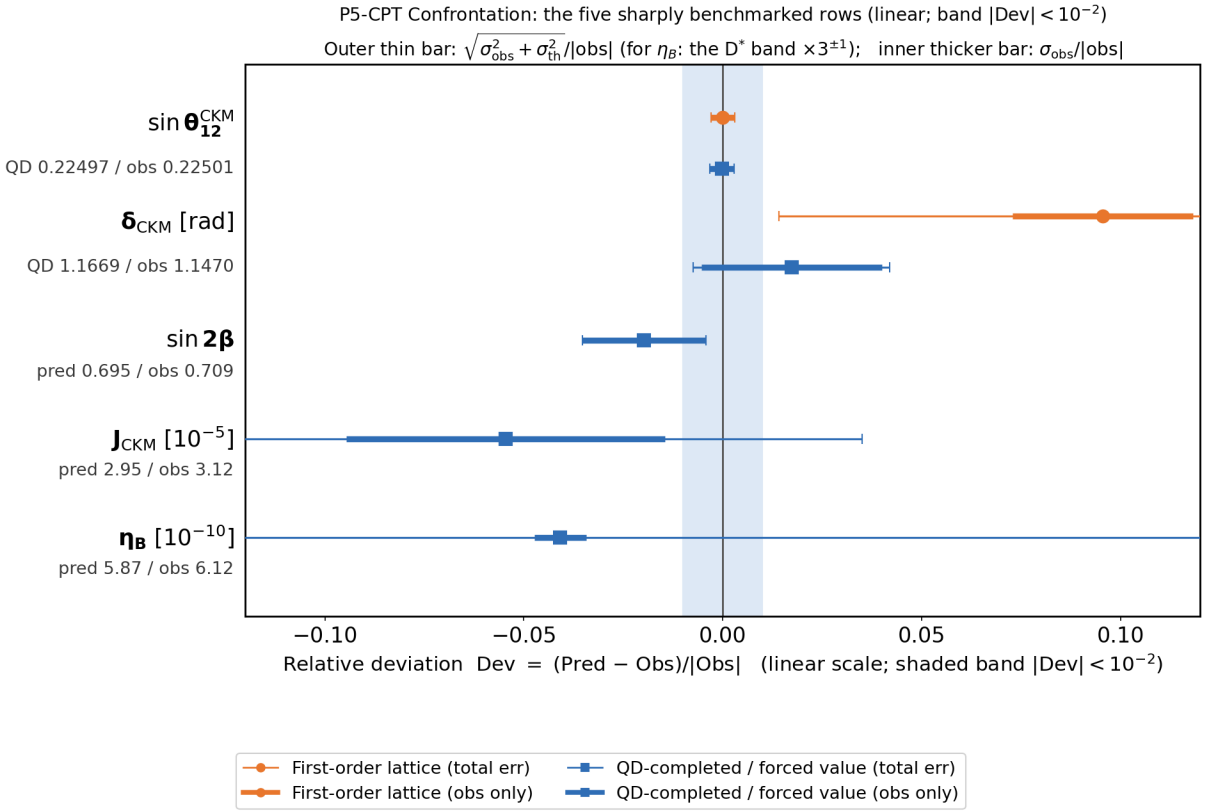

Figure 23: The confrontation at a glance, linear scale. Five rows of Table 23 on a linear relative-deviation axis Dev = (Pred − Obs)/|Obs| spanning ±0.12: the Cabibbo angle, $\delta_{\rm CKM}$ (first-order $2\pi/5$ in orange, QD-completed $13\pi/35$ in blue), $\sin 2\beta$, $J_{\rm CKM}$ (forced band 2.7–3.2 × 10^{-5}, the spread across the framework's evaluation layers), and η_B (whose outer bar is the D* transport band $\times 3^{\pm 1}$, extending beyond the frame). Inner thick bars: empirical uncertainty only; outer thin bars: theory added in quadrature; shaded band: $|\text{Dev}| < 10^{-2}$. The Cabibbo row sits at Dev = $+4 \times 10^{-5}$ — dead center at this scale — and the QD step pulls $\delta_{\rm CKM}$ from +9.6% to +1.7%, inside one experimental sigma.

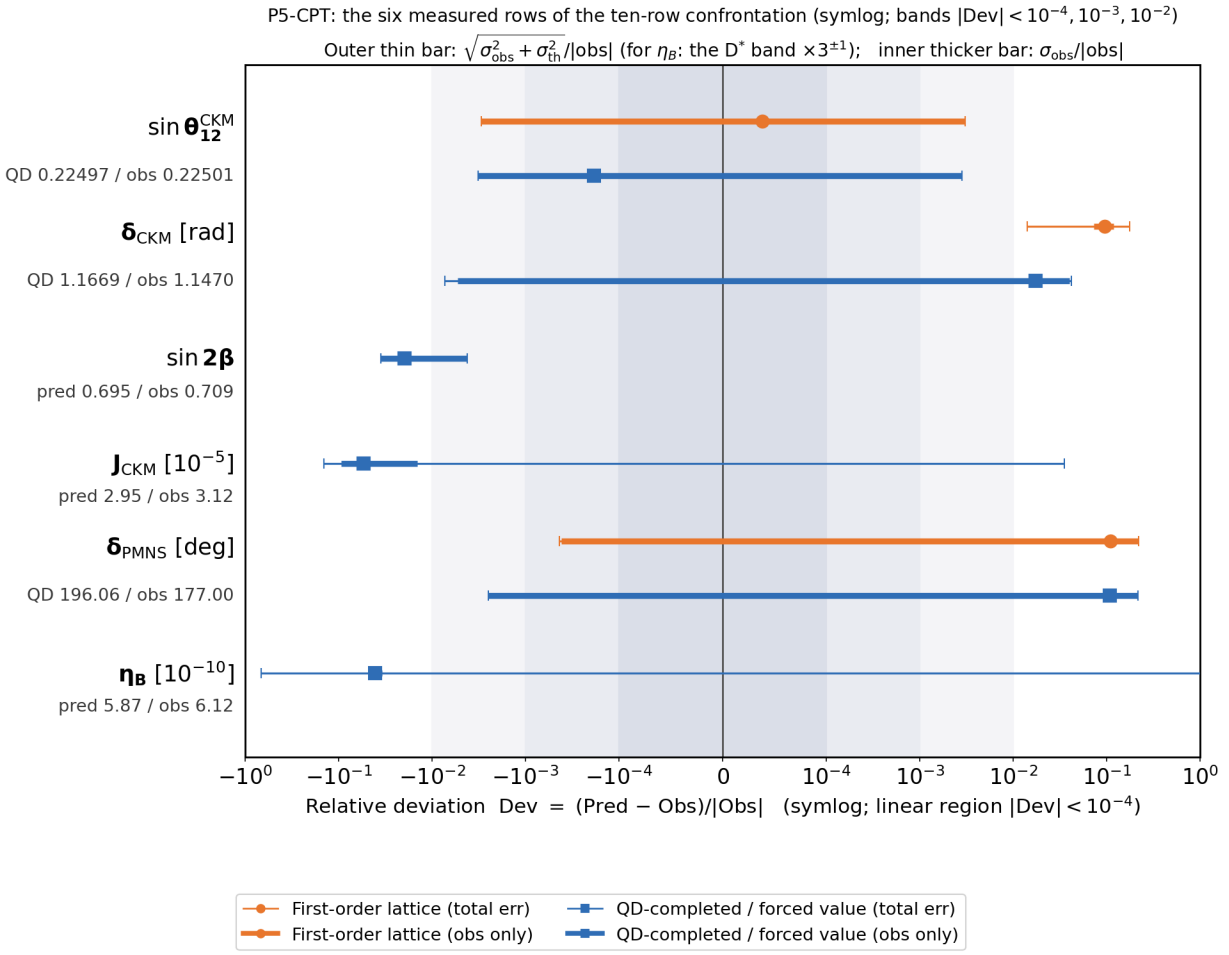

Figure 24: The full measured confrontation in one panel. All six rows of Table 23 with a measured central value, on a symmetric-log deviation axis (linear region $|\mathrm{Dev}| < 10^{-4}$), nested precision bands at 10^{-4}, 10^{-3}, 10^{-2}. The remaining four rows — the Majorana pair $(\alpha_{21}, \alpha_{31})$, $m_{\beta\beta}$, the J_{PMNS} sign, and $\bar{\theta}$ — are unmeasured or bounded and so cannot appear on a deviation axis; they are the one-sided silences of §128. The δ_{PMNS} row makes the decade's stake visible: the forced value sits at +11% of today's central value but *inside* the fat empirical bar ($+1.0\sigma$), and the long-baseline program will shrink that bar by a factor of ~ 3 (§126.1).

with statistics thereafter). The quiet outcome is the prediction — uncomfortable, checkable, and utterly unlike the maximal-CP expectation much of the literature carries. *Kill:* a measured δ_{PMNS} inconsistent with 196° at 5σ — e.g. data settling at maximal 270°, 73.6° away, a clean kill already at $\pm 15°$ resolution; or CP violation established at 5σ with δ far from the lattice point. Decision window: 2031–2040.

126.2 The ordering: normal, or dead

Value: the derived spectrum $(0.065, 8.59, 50.5)$ meV is normally ordered — not a preference but a consequence of the mass chain (Part VII; parent derivation Arisaka, 2026, A9-SM). *Position today:* globally undetermined; the joint long-baseline fit even leans mildly inverted (Bayes factors near unity) (T2K and NOνA Collaborations, 2025) — logged here as the watch item it is — while atmospherics and cosmology lean normal (DESI Collaboration, 2025; NuFit Collaboration, 2024). *Instruments:* JUNO ($\sim 3\sigma$ by $\sim$2031), DUNE (5σ within two beam years, $\sim$2033), atmospherics (Super-K, IceCube, KM3NeT) combining alongside; DESI-class cosmology squeezing $\sum m_\nu$ against the inverted floor. *Kill:* inverted ordering established at 5σ — which would simultaneously destroy the mass chain, the $m_{\beta\beta}$ prediction, and the δ_{PMNS} confrontation's frame: the single most consequential binary in this Part. Decision window: 2030–2035.

126.3 The Majorana mass: 1.72 meV, one-sided

Value: $m_{\beta\beta} \simeq 1.72$ meV from the parity pair $(0, \pi)$ and the derived masses (Part VII; derived-conditional). Registered at the first-order evaluation 1.72 meV; the QD-layer evaluation is 1.79 meV; both sit far below the ton-scale floor, so the registered null is layer-robust. *Position today:* every search silent, with KamLAND-Zen first into the inverted band (KamLAND-Zen Collaboration, 2024) — exactly the world a 1.72 meV value requires. *Instruments:* the ton-scale generation — LEGEND-1000, nEXO, CUPID, AMoRE-II, SNO+ — covering $m_{\beta\beta} \gtrsim$ 6–21 meV with discovery sensitivity in the 2030s (LEGEND-1000 Collaboration, 2021; nEXO Collaboration, 2022). *Relation of reach to value — the one-sided structure:* the GG-6 number lies *below* the entire ton-scale window, so the coming decade cannot confirm it; it can only kill it or pass it. A confirmed discovery anywhere in the ton-scale window falsifies the derived pair-and-spectrum outright (and, by the ordering link, would arrive together with the inverted-ordering kill or force a revolution in the matrix elements); continued silence is the prediction, renewed with every tonne-year. Reaching 1.72 meV itself requires half-life sensitivity near 10^{29}–10^{31} yr — kiloton-scale isotope, the furthest-horizon falsifier this paper owns, named for the generation that will build it. *Kill:* any confirmed $0\nu\beta\beta$ discovery with $m_{\beta\beta}$ at ton-scale values. Decision window: 2030–2040 (one-sided); confirmation horizon: beyond 2045.

126.4 The strong-CP window: eight orders of mandated vacancy

Value: $|\bar{\theta}| \lesssim 4.7 \times 10^{-18}$ (Part VII; derived-conditional on lemma L9), against the present bound 10^{-10} (nEDM Collaboration, 2020). *Instruments:* n2EDM commissioning toward $10^{-27}\, e\,\mathrm{cm}$ ($\bar{\theta} \sim 10^{-11}$), successor concepts a further order beyond; the electron sector below $10^{-30}\, e\,\mathrm{cm}$ and falling (Roussy et al., 2023). *Relation:* eight orders of window in which the geometry mandates

vacancy. Every improved null is a passed test; *any* confirmed hadronic EDM attributable to $\bar{\theta}$ in the window kills the two-fate architecture while leaving the Standard Model untouched — the rare falsifier that executes this paper alone. And the lattice's rigidity adds the electron-sector clause: no new continuous CP phases exist to be found, so the deepening eEDM nulls — which convict generic TeV-scale phases — are themselves predictions. *Kill:* a confirmed EDM in the window. Decision window: permanent; each generation of instruments renews it.

126.5 The proton: silence at every depth

Value: absolute stability — the gauged bulk ledger (Part VIII; derived). *Position today:* $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ yr and channel by channel likewise (Super-Kamiokande Collaboration, 2020); forty years of silence since the water Cherenkov generation buried minimal unification (Georgi and Glashow, 1974). *Instruments:* Hyper-K toward 10^{35} yr in $e^+\pi^0$; DUNE's kaon-tracking channel; JUNO (Hyper-Kamiokande Collaboration, 2025; DUNE Collaboration, 2020). *Relation:* the unification traditions predict windows; the GG-6 ledger predicts silence through *all* of them, forever — so every order of magnitude gained discriminates, and the $\Delta B = 2$ door is shut too ($n\bar{n}$ bounds passed and renewed (Super-Kamiokande Collaboration, 2021)). *Kill:* one confirmed event, any channel, any depth — ending not only this Part but the baryonic logic of the entire cohort. Decision window: permanent.

126.6 The right-handed absence

Value: no W_R, no mirror fermions, no parity restoration at any scale (F-P5-1; Part VI). *Position today:* multi-TeV collider limits, all null (Particle Data Group, 2024). *Instruments:* HL-LHC through the 2030s–40s; every future machine thereafter, forever — plus the indirect probes (right-handed currents in beta decay and $0\nu\beta\beta$ mechanisms). *Kill:* a W_R at any mass; parity restoration at any energy. Decision window: permanent — left–right symmetry holds the winning ticket at every future collider, and the projection holds it at none.

126.7 The pentagon's quark numbers, watched

Values: the lattice CKM set of Part VII, currently pulling $+0.01$ (Cabibbo), $+0.70/+1.17$ (δ, with the QD flag and the $\pi/35$ theory width in quadrature), inside-band (J), -0.1 ($\sin 2\beta$, at the stated moduli layer), and $+1.6$ (γ, direct combination, refreshed in §127 and watched). *Instruments:* Belle II and LHCb drive γ toward $\sim 1^\circ$ and $\sin 2\beta$ below ± 0.01; NA62 and KOTO-II press the rare-kaon rates that probe the texture at one loop (KOTO Collaboration, 2025; NA62 Collaboration, 2025, 2026). *Relation:* the lattice fixes the whole unitarity triangle given the moduli, so the tightening triangle is a standing multi-observable test; the direct-γ confrontation is live: the lattice triangle's γ tracks the QD phase at leading order, $\simeq 66.9^\circ$, against the direct combination $(62.8 \pm 2.6)^\circ$ — pull $+1.6\sigma$, watched — and the coming $\sim 1^\circ$ precision sharpens it into a kill-class test. Rare-kaon rates at Standard-Model values are pentagon-consistent by construction — the texture *is* the one-phase CKM — so a confirmed deviation demanding new phases would falsify the lattice's completeness. *Kill:* a coherent multi-observable failure of the one-phase triangle, or

rare-kaon rates requiring phases off the lattice. Decision window: continuous; γ at 1° by $\sim$2030.

126.8 The triad, joined

This Part's battery is the third channel of three. The first: the lock cluster at 3.85 TeV, bracketed by the public ATLAS/CMS record and pre-registered for the HL-LHC, with its own dated verdicts (Arisaka, 2026, P1-KK). The second: the Kaxion at 8.1 μeV, alone in its window, with its dedicated instrument path (Arisaka, 2026, C1-Kaxion). The logic joining the three is AND, not OR: the geometry that forces the mirror sector's values is the same geometry that forces the cluster and the Kaxion, so the program requires *all three* channels to land — and any single clean kill in any channel ends it. Conversely the discoveries are mutually predictive: a cluster at 3.85 TeV entails this Part's quiet-CPV and silent-proton pattern; a Kaxion at 1.95 GHz entails the strong-CP vacancy; an inverted ordering or a ton-scale $0\nu\beta\beta$ discovery condemns all three channels at once through the shared ledger. One geometry, three windows, one verdict.

127 The world numbers, refreshed

A paper that preaches freshness must practice it on itself. This section records the refresh executed in this version against the mid-2026 averages: the confrontation table of Part VII (Table 10) now carries $\sin 2\beta = 0.709 \pm 0.011$ against the recomputed 0.708 at the stated moduli layer (pull -0.1σ, watched), the direct-γ combination $(62.8 \pm 2.6)^\circ$ against the lattice triangle's leading-order $\simeq 66.9^\circ$ (pull $+1.6\sigma$: watched, and reported without cosmetic delay) and the NuFit 6.0 $\delta_{\rm PMNS}$ values by ordering (the lattice value at $+1.0\sigma$ under normal ordering); the corresponding prose of Part VII and Appendix E has been harmonized. Two standing rules are hereby made explicit. *First*, world averages quoted anywhere in this paper are refreshed at every shipped version, and a pull that worsens is printed with the same promptness as one that improves — the direct γ is the current case in point. *Second*, no forced value is ever adjusted in response: the lattice has no dial to turn, which is the entire content of the word "forced," and the reader can audit the constancy of the prediction columns against the motion of the measurement columns across versions.

128 Simulating the verdicts: 2028, 2031, 2035, 2040

In the manner of the collider companion's pre-registered search, this section writes down, before the fact, what the battery should show at four milestones — under the geometry being right, and under it being wrong. The point of pre-registration is that neither ledger can be rewritten later.

2028 — first light. Hyper-K begins; JUNO's ordering sensitivity passes 2σ; LEGEND-1000 and nEXO are in construction; n2EDM delivers first data; NA62 concludes. *If the geometry is right:* JUNO trends normal; the EDM null deepens; the proton stays silent; the rare-kaon rates sit on the Standard Model. *If it is wrong,* the earliest exits are an inverted-ordering trend at JUNO or an n2EDM signal.

2031 — the ordering closes in. JUNO reaches $\sim 3\sigma$; DUNE's beam turns on; Hyper-K holds three years of data — enough that a true δ near maximal would already be producing a CP-violation

discovery. *If right:* the ordering reads normal at 3σ-class; Hyper-K reports *no* 5σ CP discovery — the quiet signature — with the allowed region crowding 180°–200°. *If wrong:* a 5σ CPV discovery at δ far from the lattice point, or the inverted ordering hardening, kills within the decade's first half.

2035 — the pincers. DUNE settles the ordering at 5σ; the HL-LHC delivers the lock-cluster verdict window of the collider companion; the ton-scale double-beta experiments produce first results; combined long-baseline δ precision reaches $\pm 10°$-class. *If right:* normal ordering certified; $0\nu\beta\beta$ silent through the inverted band's upper half; δ consistent with 196° and inconsistent with maximal; and — across the triad — a cluster emerging at ATLAS/CMS. *If wrong:* this is the likeliest single milestone for a clean kill: IO at 5σ, or a ton-scale discovery, or δ at 270°, or the cluster excluded with the geometry-aware reinterpretation.

2040 — the verdict. Combined δ near ± 7–$8°$: the lattice value now 2–2.5σ distinct from CP conservation and conclusively distinct from maximal; the ton-scale program completes its window; Hyper-K approaches 10^{35} yr on the proton; the collider companion's final HL-LHC node arrives. *If right:* the pattern is unmistakable in aggregate — normal ordering, quiet CP at the lattice point, double-beta and EDM and proton silence, no W_R, a cluster, a Kaxion candidate — the quiet universe with one loud cluster, a signature no rival framework predicts as a package. *If wrong:* it did not get this far; some ledger line above already closed the program.

The combined-likelihood trajectory is the honest way to hold these milestones together: no single 2030s measurement save an outright kill is decisive alone, but each passing year the battery's joint likelihood either converges on the forced pattern or is terminated by one of the pre-declared exits. The registered claim is the package, and the package has no dial.

129 The falsifier timeline, dated

Table 24 closes the Part's apparatus: the schedule-centric companion to the claims-level falsifier table of Part XII, one line per confrontation, with the verdict type each instrument can return — *kill* (can falsify outright), *support* (can strengthen, cannot confirm alone), *watch* (tension monitor).

The same schedule, drawn. Figure 25 renders Table 24 in the cohort's kill-test-timeline convention — the convention introduced for the Kaxion's discovery calendar — on a forward time axis from now to the far end of the decision window. The color code is the cohort's: violet for tests already faced and survived, orange for the standing watch, blue for the accelerator fronts approaching the lattice point, green for the ton-scale edge closing one-sidedly, and red for the kill dates and the verdict window. Every card names its venues and its falsifier; the spans along the axis show the two long campaigns — the long-baseline phase measurement and the ton-scale double-beta exposure — that bracket the decade. The figure makes graphic what the table states: the mirror sector's confrontation is not an open horizon but a closing window, with pre-declared exits on every side.

130 What is claimed, and what is inherited

Concessions first, and for this Part they are near-total: every instrument, every sensitivity, every milestone in these pages belongs to the experimental collaborations — to the generations that

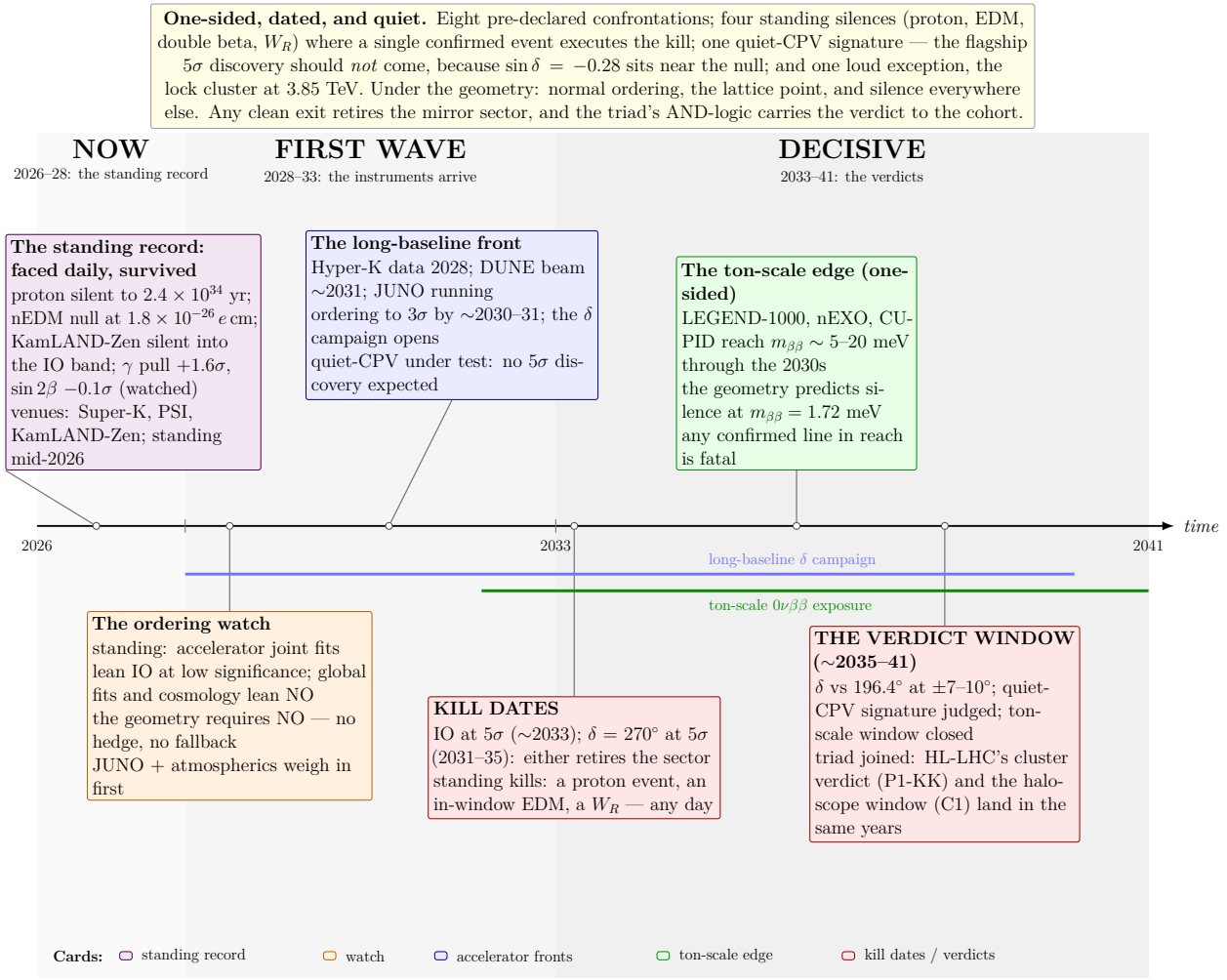

Figure 25: Falsification / kill-test timeline for the mirror sector. The dated falsifier table (Table 24) drawn on a forward time axis (2026–2041, broad data-window eras rather than precise launch dates), in the cohort's kill-test-timeline convention. Violet: the standing record — the proton, EDM, and double-beta silences and the $\sin 2\beta$ watch, faced continuously and survived as of mid-2026 (§127). Orange: the ordering watch — the geometry requires normal ordering with no fallback. Blue: the long-baseline front (Hyper-K 2028, DUNE ~2031, JUNO running) approaching the lattice point $\delta_{\rm PMNS} = 196.4°$, with the quiet-CPV signature — no 5σ CP discovery — as its registered prediction. Green: the ton-scale $0\nu\beta\beta$ edge closing one-sidedly on a predicted silence at $m_{\beta\beta} = 1.72$ meV. Red: the kill dates — inverted ordering at 5σ (~2033) or $\delta = 270°$ at 5σ (2031–35) retires the sector, and the mid-to-late-2030s verdict window joins this Part's battery to the triad's other two channels (P1-KK, C1). All sensitivity dates are conditional on stated design assumptions (mass ordering known where required, beam-power ramps, staging); the conditioning is the collaborations', quoted from the cited design reports.

built the kaon beams and the B factories, the mines and the tanks, and to those now building Hyper-K, DUNE, JUNO, and the ton-scale program. The history sections are their achievement cataloged, and the projections are their design reports quoted at attributed grade. This paper adds no instrument and improves no sensitivity. What it claims is four things, all structural. *First, the dial-lessness of the confrontation:* every value in Table 24 was fixed upstream of every schedule in it, and §127's standing rules make the constancy auditable. *Second, the one-sided silences:* the double-beta, EDM, proton, and W_R lines predict *nulls* — the riskiest posture available, since a single confirmed event anywhere executes it. *Third, the quiet-CPV signature:* the geometry predicts that the flagship discovery of the long-baseline era will *not* occur as commonly hoped — a near-null at the lattice point — which converts even a community disappointment into a registered test. *Fourth, the triad's AND-logic:* three channels, one geometry, mutual entailment, any clean kill fatal to all. The grades are those of the source Parts; nothing here strengthens them, and everything here can end them.

Part-end summary. Two centuries of instruments reviewed with their milestone tables; a present in which the lepton phase sits one sigma from the lattice under the required ordering; a decade of machines arriving on published schedules; eight confrontations, each with its pre-declared kill; the world numbers refreshed with the pulls printed, favorable or not; four milestone years pre-registered under both verdicts; and one timeline table joining this Part's battery to the cluster and the Kaxion. The mirror sector is now what the program requires it to be: not a story but a schedule. The claims and their housekeeping follow.

Table 22: The future: the instruments of the decisive decade, with status as of mid-2026. Sensitivities are design-report figures where data do not yet exist. The last column names the forced value of Parts VI–VIII each instrument touches; the confrontation sections of this Part formalize each line.

Instrument	**Type**	**Timeline**	**Key sensitivity**	**Forced value touched**
Hyper-K	LBL + atm. water Cherenkov, 260 kt	data 2028	5σ CPV for $> 60\%$ of δ in 10 yr; res. 7–20°	$\delta_{\rm PMNS} = 196°$
DUNE	LBL LAr, 1300 km	beam ∼2031	ordering 5σ (∼2 yr); δ res. 10–20°	ordering (NO required); $\delta_{\rm PMNS}$
JUNO	reactor LS, 20 kt	running	ordering 3σ (∼6 yr); sub-% θ_{12}, Δm^2_{21}	ordering; chain inputs
IceCube Upgrade	atm. infill	2026	Δm^2_{32}, θ_{23} competitive	consistency
LEGEND-1000	$0\nu\beta\beta$ Ge-76	∼2030	$T_{1/2} \sim 1.3 \times 10^{28}$ yr ($m_{\beta\beta}$ 9–21 meV)	$m_{\beta\beta} = 1.72$ meV: one-sided test
nEXO	$0\nu\beta\beta$ Xe-136	2030s	1.35×10^{28} yr ($m_{\beta\beta}$ 6–27 meV)	same
CUPID / AMoRE-II / SNO+	$0\nu\beta\beta$ Mo/Te	late 2020s	$10^{26.5}$–10^{27} yr	same
Hyper-K (decay)	$p \to e^+\pi^0$	2028–	toward 10^{35} yr	absolute stability
DUNE/JUNO decay	$p \to \bar{\nu}K^+$	2029–/now	$\sim 10^{34}$ yr class	absolute stability
n2EDM	neutron EDM	commissioning	$10^{-27}\, e\,$cm	$\bar{\theta}$ window
JILA III / ACME III	electron EDM	late 2020s	below $10^{-30}\, e\,$cm	$\bar{\theta}$ window
KATRIN / Project 8	direct m_ν	running / 2030s	0.3 eV / 0.04 eV	mass spectrum (50 meV)
Belle II / LHCb / NA62 / KOTO-II	quark CP	running / 2030s	γ to $\sim 1°$; rare kaons to SM floor	pentagon values
SNEWS 2.0 network	galactic SN	standing	10^4–10^5 events @ 10 kpc	sector-wide calibration

Table 24: The dated falsifier timeline of the third channel, with the triad's other two channels appended. "Kill" lines are pre-declared and dial-free; the claims-level register of each value is in Table 26 and the Part ledgers. Under the geometry being right, every "kill" line returns silence or the lattice point; the aggregate is the quiet universe with one loud cluster.

Forced value	**Instrument(s)**	**Decision window**	**Verdict type**	**Kill condition**
$\delta_{\rm PMNS} = 196.4°$	Hyper-K, DUNE	2031–2040	kill / support	δ off 196° at 5σ
Normal ordering	JUNO, DUNE, atm., DESI	2030–2035	kill	IO at 5σ
$m_{\beta\beta} = 1.72$ meV	LEGEND-1000, nEXO, CUPID	2030–2040 (one-sided)	kill / support	ton-scale discovery
$\bar{\theta} \lesssim 10^{-18}$	n2EDM, eEDM program	permanent	kill / support	EDM in the window
Proton stability	Hyper-K, DUNE, JUNO	permanent	kill / support	one event
No W_R (F-P5-1)	HL-LHC, successors	permanent	kill	W_R / restoration
Pentagon CKM set	Belle II, LHCb, NA62, KOTO-II	continuous	watch / kill	one-phase triangle fails
Lock cluster (P1-KK)	ATLAS, CMS (HL-LHC)	2029–2041	kill / discover	cluster excluded
Kaxion (C1)	haloscope program	2030s	kill / discover	locks excluded

Part XII
Discussions

Significance of the result; the classic puzzles of the mirrors, resolved or dissolved; the innovations registered; the nobility clause; the discrimination matrix; the claims ledger; predictions for falsification, walked one by one; the open questions, structured; and the completed cohort

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The derivations are finished; this Part steps back and argues. Seven discussions follow — the significance of the result; its uniqueness, nobility, and innovations, with the classic puzzles and the technical novelties each registered under auditable identifiers; the five roads condensed to a discrimination matrix; the consolidated claims ledger; the predictions for falsification, walked one at a time with their kill conditions; the open questions, each with its closing condition; and the paper's place in the completed cohort — closed by a summary that states strengths and weaknesses with the same plainness. The reference apparatus this Part leans on lives where the reader left it: the ten-row confrontation and its deviation panels in Part XI (Table 23, Figures 23–24), the dated instrument schedule in Table 24, and the kill-test timeline in Figure 25. The argument can proceed without the furniture.

131 Part XII in plain English: what the result is worth, and what would end it

A paper that has proved its theorems still owes an account of what they are worth. This Part gives that account at length rather than in a closing paragraph, and a good deal of what it contains could have been left out without anyone noticing.

It states the significance and the innovations, works through the classic puzzles of the mirrors and says of each whether it is resolved or dissolved — which are different outcomes and are not run together — sets the five roads against one another in a discrimination matrix, and states what is claimed and in what regime. Then the predictions for falsification, put as measurements rather than as attitudes.

The open questions are the section to read before the conclusions. They are ordered by consequence and the first is the sharpest. None of them threatens the theorems as stated; each bounds the regime the theorems own, and those are different things that a reader deciding how much weight to put on this argument should keep apart.

132 Significance of the result

What this paper delivers, reduced to its irreducible content, is one sentence: *an anatomy of the three mirrors, a valuation of the two CP phases, a derivation of the matter excess with zero fitted parameters, and a dated schedule on which every one of those claims can die.* Each clause is individually rare in the discrete-symmetry literature; their conjunction is, to our knowledge, unprecedented. This section unpacks why, deliberately slowly, because a result of this shape is easy to misjudge in both directions — easy to inflate, if one forgets how much is conditional on upstream theorems and on two named conjectures, and easy to deflate, if seventy years of convention-laden discrete symmetries have trained the reader to assume that every CP "prediction" is secretly a scan.

The result in the seventy-year arc. Place the claim against the history Part I told. In 1956–57 the field learned, to its lasting shock, that the mirror was broken — and then spent decades recording *how* without a framework that could say *why*, because in the Standard Model the V−A structure is an assignment, not a consequence. In 1964 CP fell in the kaons, and the Kobayashi–Maskawa mechanism turned the fall into a counting theorem — but priced nothing: δ is measured superbly and explained not at all, and $\delta = 0$ would have been equally lawful. In 1967 Sakharov wrote the three conditions for a matter excess, and half a century of baryogenesis model-building has met them with fitted masses, fitted phases, and engineered departures from equilibrium — mechanisms by the dozen, verdicts by none, most of them untestable in principle because their action happens at 10^9 GeV or above. Against that history the present claim is structurally different in kind: the operations are derived objects (three reversals of three real orientations); the phases are lattice points ($13\pi/35$; $\pi + 2\arcsin(1/7)$) that cannot move, because a lattice point has no neighborhood; the excess is computed from inputs that were all fixed upstream for other reasons; and the paper has pre-committed, in writing and on a calendar (Part XI), to the measurements that retire each piece. Whether or not nature cooperates, this is the shape of answer the seventy-year record has been asking for.

What zero dials buys, epistemically. The absence of continuous freedom is not an aesthetic garnish; it changes what an experimental outcome *means*. With a dial, a positive result confirms little (the dial was set after the fact) and a negative result kills nothing (the dial turns). Without one, both outcomes become maximally informative: a measured δ_{PMNS} crowding 196° under normal ordering confirms a chain that reaches from oscillation data back through the pentagon to the axioms, and a measured 270° kills the same chain outright — there is no fallback version of this paper at another angle. The statistics inherit the same virtue: a pre-registered point pays no look-elsewhere penalty, and the two-point adjudication (196.4° versus the community's expected 270°, 73.6° apart) is decided at ±15° resolutions the long-baseline program already prints in its design reports (§126.1). Pre-registration is usually a virtue of experimental design; here it is a consequence of the theory's structure, and it converts directly into decisiveness.

The over-constraint, told in full. A skeptic granting the structure could still ask: why take the chain seriously *before* the long-baseline verdict? The paper's answer predates any future data:

the same lattice that fixes the unmeasured has already been audited on the measured. The Cabibbo closed form sits at Dev $= +4 \times 10^{-5}$ — a four-to-five-digit audit, pull +0.01 (Table 23); the QD-completed $\delta_{\rm CKM} = 13\pi/35$ sits $+0.70\sigma$ from the world fit where the raw $2\pi/5$ sat at +1.17 (both pulls carry the one-lattice-step theory width $\pi/35$ in quadrature; on experimental error alone the raw value is $+4.2\sigma$); the Jarlskog invariant falls inside its layer band; and $\sin 2\beta$, recomputed as interferometry of the same single angle, tracks the measured value at -0.1σ — watched, printed, with its evaluation layer stated. One lattice, several scales, the measured half already matched: the construction walks into the neutrino test having survived its quark-sector audit. This is what distinguishes the wager from a lottery ticket, and also what raises the stakes — a leptonic kill does not merely eliminate a candidate phase; it breaks a lattice that presently accounts for the quark sector's.

The calendar as part of the result. Part XI is not an appendix to the claim; it is half of it. A falsifiable statement without a decision procedure is a promissory note, and the experimental Part converts the note to a schedule: JUNO running now, Hyper-K data from 2028, DUNE beam near 2031, ordering closure near 2033, the δ precision campaign ripening through the late 2030s, the ton-scale double-beta program closing one-sidedly across the same decade, and the permanent rails — proton, EDM, W_R — able to execute on any day (Figure 25). The dates matter beyond logistics: they place the verdict within the professional lifetime of the graduate student the Preface addresses, and within the planning horizon of the collaborations now writing their physics cases.

The quiet-CPV inversion, as epistemic posture. One prediction deserves separate billing because it inverts the community's hopes rather than flattering them. The lattice value implies $\sin\delta_{\rm PMNS} = -0.28$: *small* leptonic CP violation, a near-null crowding the CP-conserving point. If the pentagon is right, the flagship five-sigma CP-violation discovery that both long-baseline collaborations advertise *will not come* (§126.1). A framework that predicts a community disappointment — and registers the disappointment as its own confirmation channel — is operating at the opposite pole from the adjustable optimism of most beyond-Standard-Model phenomenology; it is difficult to imagine a posture more exposed. The refresh discipline of §127 completes the posture: the world numbers are re-audited on standing rules, and the pulls are printed favorable or not — the $+1.6\sigma$ direct-γ tension is displayed in the executive apparatus of this paper, not buried.

Significance for each community, separately. To the *discrete-symmetry tradition*, the significance is anatomical. Since 1957 the field has possessed exquisite measurements of operations it could not define except by convention: C, P, and T were operators with adjustable phases, their table an assignment, their one surviving product a theorem whose proof illuminated nothing about its factors. Part V replaces the conventions with three specific reversals of three specific real structures, derives the table's one asymmetry (antiunitarity) from the sources of i, and re-proves the surviving product as the one reversal no real texture can detect — with, since this volume's completion, the same analytic fact extended to the quartet's second child, spin–statistics, at candidate grade (§45). To *flavor physics*, the significance is the valuation: the rephasing-invariant calculus told the field where CP violation lives; nothing in sixty years told it what the phase costs. The pentagonal lattice is, to

our knowledge, the first proposal from which the CKM and PMNS phases take *forced central values*, with the golden-ratio Cabibbo closed form as the same object's magnitude shadow. To *cosmology*, the significance is the dial count: every baryogenesis mechanism on the market buys its η_B with fitted masses, fitted phases, and engineered departures from equilibrium; Part VIII's chain has zero fitted parameters, one named input, one postulated exponent, and an error budget it publishes against itself. To the *experimental collaborations*, the significance is operational: pre-registered points, one-sided silences, and a deliverable valuable under every outcome — the strongest possible limits on the lattice reading if the answer is no. And to the *program*, the significance is consolidation: five questions its papers answered in five places — the table, the pentagon, the hand, the door, the excess — are here exhibited as one question about one orientation, which is what a framework claiming structural unity owes its readers.

133 Uniqueness, nobility, and innovation

Three words a physics paper should use carefully, so we define them operationally before spending them. *Uniqueness* is what this paper does that no neighboring construction does, stated so a referee can check the negative — the matrix of §134 is its checklist form. *Problems solved* are the standing puzzles of the discrete-symmetry and baryogenesis literature that the construction resolves or dissolves, registered as PS-P5-1 through PS-P5-8, each closing with an honest verdict and its conditionality. *Innovation* is the specific technical moves that did not exist before this paper and its parent theorems, registered as I-P5-1 through I-P5-10 in before-and-after form. A closing subsection states the conduct the paper binds itself to. The three are related but not the same, and conflating them is how strong claims come to sound like salesmanship.

The credit side is stated first, as the register requires. *Not new here:* the Feynman–Stückelberg pairing; Wigner's (anti)unitary fork; Jost's CPT theorem and its modular refinement; Jarlskog's invariant calculus; the orbifold-GUT projection (Kawamura, Hall–Nomura); the seesaw and its Casas–Ibarra parameterization; thermal and resonant leptogenesis (Fukugita–Yanagida; Pilaftsis–Underwood) and the sphaleron arithmetic (Harvey–Turner); Peccei–Quinn relaxation and the Vafa–Witten minimum; spontaneous, geometric CP violation as a concept (Dine–Leigh–MacIntire, Choi–Kaplan–Nelson). Each is cited at its point of use and credited in Part XVI's notes.

133.1 The classic puzzles of the mirrors, resolved or dissolved

Each entry states a puzzle the field has carried for decades, in the form a practitioner would recognize, and then what this paper does to it. "Resolved" means an answer is derived at a stated grade; "dissolved" means the question is shown to have been wrongly posed.

PS-P5-1: Why does antimatter exist? Dirac's equation demanded the positron and nobody — Dirac least of all — wanted it; the twin arrived as an embarrassment of the mathematics, was reinterpreted by hole theory, and was finally domesticated by QFT as an output of quantization: fields, quantized causally, must carry both signs of frequency. That is a theorem, but a late one — the pairing appears only after the complex field and its quantization rules are assumed. Here the

twin exists *before* quantization: two real rotations — the circle's winding and the clock's advance — must agree on every charged mode, and the only consistent bookkeeping pairs every winding with its reverse (T-P5-A/B/C). Antimatter is forced at the level of classical real geometry; quantization inherits rather than creates it. *Resolved at quasi-free grade; the interacting statement is conditional on scattering hypotheses, as itemized in Part X.*

PS-P5-2: What are C, P, and T, actually? The textbook operations are conventions with adjustable phases — C defined up to a phase per species, P up to intrinsic parities, T antiunitary "because Wigner's theorem permits it." Seventy years of exquisite data sit atop operators the theory cannot define without stipulation. Here the three are anatomical: reversals of the three real orientations of the bulk — fiber, space, clock — with the table derived, antiunitarity of T forced (only the clock is what i is made of), and every intrinsic phase traced to a real convention (T-P5-1). *Resolved; the anatomy is a standing challenge to any framework that postulates its complex structure.*

PS-P5-3: Why is parity violation maximal? The Standard Model writes V−A by hand and offers no reason why the mirror sector is absent rather than suppressed — fifty years of W_R searches have chased a restoration scale that nothing in the model requires or forbids. Here maximality is an *absence*, not a small parameter: the oriented descent keeps one hand (the other is projected, not hidden), so there is no scale at which parity restores and no coupling by which the missing hand leaks back (Part VI; F-P5-1). *Resolved conditional on the projection — whose own necessity is the honestly-flagged open frontier of the parity ledger (Table 8).*

PS-P5-4: Why is CP violation small but not zero? In the Standard Model δ is superbly measured and completely unexplained; nothing prices it, and the near-maximal measured value of the leptonic candidate phases sits beside the tiny Jarlskog invariant with no comment. Here both facts are geometry: CP falls because the flavor pentagon is chiral (nothing forces it achiral), the phase is a lattice point — $2\pi/5$ at first order, $13\pi/35$ QD-completed — and the smallness of the observable violation is the smallness of an interference of fixed angles, not of a tuned parameter (Part VII). *Resolved-conditional on the lattice-rigidity clause of T-P5-3(iv), with the QD step flagged at its own grade.*

PS-P5-5: The strong-CP problem. The classic double standard: a large weak phase beside $\bar{\theta} < 10^{-10}$, two parameters of the same naive kind, one order unity and one inexplicably absent — and the standard cure (Peccei–Quinn) installs a global symmetry that quantum gravity is expected to violate. Here the two phases have different *homes*, not different luck: the weak phase is a holonomy the relaxation cannot touch (it is locked in closed loops), while the strong angle is a relaxable vacuum angle whose relaxer — the Kaxion — the framework already contains for anomaly reasons, with no PQ scalar and hence no quality problem; the residual is computed at $\lesssim 5 \times 10^{-18}$, eight orders below the current bound and within reach of no planned instrument — a permanent one-sided silence. *Resolved conditional on lemma L9 (determinant phase), with the two-fate architecture — locked versus relaxed — as the structural content no other framework states.*

PS-P5-6: Why is CPT alone unbroken? In QFT the answer is a proof that illuminates nothing about the factors: the theorem holds for any local, Lorentz-invariant theory, so the survival of the product is disconnected from the fates of C, P, and T individually — a conspiracy of accidents capped by an axiom. Here the product survives because it is the one reversal no real texture can detect: each mirror individually reverses an orientation some structure of the descent can see, and the triple reversal is the unique combination invisible to every real datum, derived from the same quartet analyticity that licenses every Euclidean computation (T-P5-2, T-P5-B1) — and now shown, at candidate grade, to carry spin–statistics as its sibling (§45). *Resolved at quasi-free grade; modular route open and named.*

PS-P5-7: The ten-order failure. The Standard Model, run honestly through the sphaleron era, produces a baryon excess some ten orders of magnitude short of the observed six-per-ten-billion — the sharpest quantitative failure of the most successful theory in physics. Part VIII's chain meets the number with zero fitted parameters: the heavy mass is the ledger's lock scale, the portal is a uniqueness theorem, the Yukawa is matched to derived light masses, the phase is the pentagon's, and the throughput reconstructs the ledger exponential — arriving at $\approx 7 \times 10^{-10}$ (central 7.34), +20% from Planck's central value, inside a published factor-~ 3 band. *Resolved at grade D^*, with the resonance mechanism and the exponent carried by the named conjecture C-P5-C — the paper's sharpest open item, displayed rather than hidden.* The dial count is displayed symmetry by symmetry in the alphabet audit of §88: existence from the pentagon's chirality, sign from a Majorana parity, magnitude from the throat depth — three jobs, three forced structures, zero dials.

PS-P5-8: The testability problem of baryogenesis. The quiet scandal of the field: the default explanation (hierarchical thermal leptogenesis) is a good theory that cannot be tested — its heavy states sit at 10^9 GeV or above, and the CP phases that matter to it are not the phases experiments measure. Mechanisms multiply; verdicts never come. Here the inversion is total, and it is inherited rather than engineered: the heavy states sit at 3.85 TeV within collider reach, the CP phase *is* the measured PMNS sector's (projected), the Majorana door casts a $0\nu\beta\beta$ shadow at a computable 1.7 meV, and the proton clause is checked by every year of Super-Kamiokande silence. The account of why we exist is due in the data within the decade — mortal four separate ways. *Dissolved by inheritance: the testability inversion is itself the innovation, registered below as I-P5-7.*

133.2 The structural innovations

The register of what did not exist before, each entry in before-and-after form so the claim of novelty can be audited.

I-P5-1 (antiparticles before quantization). *Before*: the twin as an output of causal quantization — assume the complex field, quantize, discover the necessity. *After*: the handshake theorem forces the pairing at the level of real classical geometry (two rotations agreeing on every charged mode), with quantization inheriting the twins it used to create; two of Weinberg's axioms explained at the price of the free-field qualifier.

I-P5-2 (the derived table). *Before*: C, P, T as conventions with adjustable phases; antiunitarity of T chosen from Wigner's fork by consistency. *After*: the unitary/antiunitary table computed from orientation sources — "only the clock is what i is made of" — with Kramers degeneracy convention-free (T-P5-1).

I-P5-3 (the Wick quartet). *Before*: Minkowski's it, Wick rotation, and the Schrödinger i related by folklore; every Euclidean computation borrowing an unexamined license. *After*: one polar decomposition, one analytic fact (the one-sided spectrum), issued as a theorem (T-P5-B1) — with CPT derived from it (T-P5-2) and spin–statistics stated as its second child at candidate grade (§45).

I-P5-4 (the lattice valuation of CP phases). *Before*: "CP phases are holonomies" — known since the invariant calculus; their values fitted, never priced. *After*: holonomies valued on a pentagonal lattice with forced central values — $13\pi/35$, $\pi + 2\arcsin(1/7)$, $(0, \pi)$ — and the Cabibbo golden-ratio closed form as the magnitude shadow of the same object; the first framework, to the author's knowledge, in which both CP phases have predicted central values.

I-P5-5 (the two-fate architecture). *Before*: the weak phase and the strong angle treated as two parameters of the same kind with inexplicably different sizes. *After*: a derived asymmetry of *homes* — the locked holonomy versus the relaxable vacuum angle — making the pair's discrepancy structural rather than scandalous, with the residual $\bar{\theta}$ computed and registered as a permanent one-sided test.

I-P5-6 (the basin/gate identification). *Before*: the weak interaction's exclusive ownership of flavor violation and parity violation recorded as two unexplained facts. *After*: the broken force identified with the gate force — the unique connection transporting between basins — making the two ownerships one architectural statement, with its uniqueness clause carried as the named conjecture C-P5-A.

I-P5-7 (the dial-free baryogenesis inheritance). *Before*: leptogenesis as a mechanism with free heavy masses, free phases, and unobservable scales. *After*: the same transport with every input inherited — lock scale, unique portal, matched Yukawa, pentagon phase — zero fitted parameters, all four levers at observable scales, and the FD statistics it counts with now traced to the same geometry (§91).

I-P5-8 (the Sakharov tripod). *Before*: Sakharov's three conditions as a checklist each mechanism satisfies by separate engineering. *After*: the three conditions as one geometric object (P-P5-E) — baryon-number violation, C/CP violation, and the arrow all read off the oriented descent, each leg graded, the checklist replaced by an anatomy.

I-P5-9 (the quiet-CPV signature). *Before*: long-baseline physics cases built around discovering large CP violation; a small measured δ counted as disappointment. *After*: the near-null at 196.4° pre-registered as the framework's *confirmation* channel — a community disappointment converted into a two-sided test, with the 73.6° separation from the maximal expectation adjudicated at design resolutions.

I-P5-10 (the confrontation apparatus). *Before*: predicted-versus-measured comparisons scattered through prose, refreshed ad hoc, pulls quoted when favorable. *After*: a ten-row confrontation table with explicit Dev and Pull columns under a stated error convention, twin deviation panels in the parent papers' audit format, standing refresh rules with pulls printed favorable or not, four milestone years pre-registered under both verdicts, and a kill-test timeline in the cohort convention (Part XI).

133.3 The nobility clause

"Nobility" is not a word for the theory; it is a word for the *conduct* the paper binds itself to, and it can be stated as four commitments, each checkable. *Pre-commitment:* every forced value was fixed upstream of every schedule that will test it — the lattice points were in print before JUNO's first data, the milestone years of Part XI are registered under both verdicts, and the standing refresh rules (§127) seal the paper against quiet renumbering. *Honest grading:* every claim carries its register — derived, derived-conditional, named conjecture, D*, open — in three Part ledgers, a 27-row audit figure, and the consolidated ledger below; the least flattering entries are displayed most prominently (the resonance conjecture appears in the abstract's own register; the watched γ tension at $+1.6\sigma$ is in the executive apparatus; the ten-order gap C-P5-C must bridge is quantified in its own section). *No retreat:* the prediction carries no relocation clause — a measured 270° kills the pentagon outright; inverted ordering at 5σ retires the paper with no fallback hierarchy; and the one-sided silences (proton, EDM, $0\nu\beta\beta$ above the point value, W_R) can execute on any day and can never be finally vindicated, which is what makes them the strongest claims in the paper. *Symmetric stakes:* the paper commits to what failure means — a leptonic kill breaks the lattice that carries the quark sector's audit, and through the triad's AND-logic impeaches the ledger that also carries the collider cluster and the Kaxion — as explicitly as to what success means. These commitments cost rhetorical safety and buy the only currency a seventy-year-old subject still respects: a claim whose author has arranged, in advance, to be unable to escape.

134 The five roads, and the discrimination matrix

The full comparison is Part X; its verdict line bears repeating once in the Discussion's register. QFT — rigorous and silent: theorems at Depth 2, axioms at Depth 3. The Standard Model — precise and unexplaining: five silences and a ten-order failure on the matter excess. String theory — geometric and unvalued: the right conceptual moves at landscape valuation. ΛCDM — exact and agnostic: the target set to 0.3%, the origin outside its scope. GG-Theory — valued, dated, and mortal. Every concession the comparison owes is paid in Part X, in the creditor's own section.

What the Discussion adds is the operational question the comparison implies: *if a rival framework, rather than the geometry, owned the CP sector, which rows of this paper's observable list would it reproduce — and which measurement separates it earliest?* Table 25 collects the verdicts. Two readings reward the stare. Reading down the GG-6 column: the correlations are the fingerprint — frameworks can imitate entries (a Nelson–Barr model prices $\bar{\theta}$; leptogenesis delivers an excess), but no rival carries the *joint* pattern, because the pattern is one orientation read eight ways. Reading

Table 25: Framework-by-observable discrimination matrix for the CP sector. Each cell: does the framework generically reproduce the observable? (✓ = yes / forced; ∼ = achievable by parameter or model choice; × = fails or forbidden; — = no statement.) Columns: SM = Standard Model (+ known neutrino masses); NB = spontaneous-CP / Nelson–Barr-class models; SUSY = supersymmetric extensions with generic new phases; GL = generic hierarchical thermal leptogenesis atop the SM seesaw; Str. = string landscape. The earliest separating measurement for each column is footnoted. The joint pattern, not any row, is the fingerprint.

Observable	**GG-6**	**SM**	**NB**	**SUSY**	**GL**	**Str.**
$\delta_{\rm CKM}$ central value forced	✓	×	×	×	×	∼
$\delta_{\rm PMNS}$ central value forced	✓	×	×	×	×	∼
$\sin 2\beta$ derived (no fit)	✓	×	×	×	×	∼
Majorana pair $(0, \pi)$ predicted	✓	—	—	—	×	∼
$m_{\beta\beta}$ point value (1.7 meV)	✓	—	—	∼	×	∼
Normal ordering required (no hedge)	✓	—	—	∼	∼	∼
Quiet CPV (no 5σ discovery)	✓	—	—	∼	×	∼
$\bar{\theta}$ solved without PQ scalar	✓	×	✓	×	×	∼
Weak-phase/strong-angle relation	✓	×	×	×	×	∼
No W_R / no P restoration, exact	✓	∼	∼	×	∼	∼
η_B with zero fitted parameters	✓	×	×	×	×	∼
Heavy sector at collider reach	✓	—	∼	∼	×	∼

Earliest separating measurement: SM — any confirmed forced value (the lattice adjudication itself); NB — the leptonic lattice point and the η_B chain (NB prices $\bar{\theta}$ but values no phase); SUSY — the EDM one-sided silences (generic phases overshoot; continued nulls squeeze the parameter space this paper never had); GL — the 3.85 TeV cluster and the quiet-CPV signature (its scale is invisible, its phases unmeasured); string landscape — priority of risk (any cell fillable after the fact; see Part X).

across the rows: the Standard Model's column is honest silence (measured, never priced); the supersymmetric column is worse than silence on the EDM rows (generic new phases overshoot the electron EDM bound, requiring their own tuning); and the landscape column is "achievable" everywhere and predictive nowhere, which is the falsifiability asymmetry of Part X in tabular form — any cell fillable after the fact, priority of risk manufacturable never.

135 What is claimed, and in what regime

The consolidated claims ledger. *Theorem grade (quasi-free):* T-P5-1 (table), T-P5-2 (CPT), T-P5-3(i)–(iii) (holonomy calculus), T-P5-4 (door). *Derived-conditional:* T-P5-3(iv) and the phase values ($\delta_{\rm CKM}$: QD step flagged; $\delta_{\rm PMNS}$: assignment lemma; $\bar{\theta}$: lemma L9); the zero-dilution clause (prompt-crossing lemma). *Named conjectures:* C-P5-A (gate operator; parity's theorem), C-P5-C (resonance and normalization; baryogenesis' theorem). *Proposition with proof strategy:* P-P5-D (handedness). *D^*:* T-P5-5 (η_B), order of magnitude, factor-∼ 3 band. *Candidate, home elsewhere:* T-Stat-A, the quartet's second child (§45) — stated in this paper, graded in the geometry paper's suite, not counted among this paper's claims. *Open and named:* the modular route to interacting CPT; the projection's derivation from admissibility; the heavy-sector CP projection coefficient; the

Ω_b two-route seam. Nothing in the paper is claimed above this table, and any reader who finds a sentence exceeding it is invited to report the sentence.

136 Predictions for falsification

A falsifier is a prediction plus a decision rule plus a price; a prediction alone is only a hope with units. This section first tells the three narratives the record already carries — the watched tension, the ordering wager, and the quiet signature — then walks the eight registered predictions individually, because a table row (the summary remains Table 26, with the schedule-side companion in Table 24) cannot carry what a referee needs: for each claim, *what* is predicted, *where* it was derived, *how* it will be measured, and *what outcome kills it*.

The watched rows: $\sin 2\beta$, and the direct γ. The interferometry recomputation of the unitarity-triangle angle, evaluated at the lattice phase $13\pi/35$ with the PDG-class moduli ($s_{12} = 0.2250$, $s_{23} = 0.0418$, $s_{13} = 0.0037$), returns 0.708 against the world's 0.709 ± 0.011: pull -0.1σ. The row is registered as a watch with its evaluation layer stated — across the s_{23} and phase-layer choices the recomputation spans 0.707–0.727, so the layer must be frozen for the number to be auditable, and it is frozen here; a drift past 3σ under Belle II statistics would be the lattice's first quark-sector crack, and the refresh rules guarantee the reader will see it happen. The tense number is the direct γ: the lattice triangle's γ tracks the QD phase at leading order, $\simeq 66.9°$, against LHCb's direct combination $(62.8 \pm 2.6)°$ — pull $+1.6\sigma$, printed under the no-cosmetic-delay rule, watched, and headed into a $\sim 1°$-precision decade that will sharpen it into a kill-class test. The rows are small, but they demonstrate the register the paper operates in: the confrontation table is a living instrument, not a trophy case.

The ordering wager. The geometry requires normal ordering — the mass triplet $(0.065, 8.59, 50.5)$ meV is derived, not chosen — while the current accelerator joint fits mildly prefer inverted and the global fits and cosmology lean normal. There is no hedge: under inverted ordering at 5σ (JUNO + atmospherics + DUNE, ∼2033) the paper retires, with no fallback spectrum. The wager is currently favored by the aggregate data ($\delta_{\rm PMNS}$ at $+1.0\sigma$ under NO; $\approx 3\sigma$ disfavored under IO) but it is a wager, and the paper prints it as one.

The quiet signature. Registered once more in the falsification section because it is two-sided in an unusual way: the pentagon is confirmed *either* by a measured δ crowding 196° at growing precision *or* — the same fact seen from the community's side — by the persistent non-arrival of the five-sigma CP-violation discovery the long-baseline program was built to deliver. A framework rarely gets to be supported by a null it predicted; the design resolutions of Hyper-K and DUNE make the adjudication against maximal CP violation (73.6° away) decisive by the mid-2030s even though the distinction from exact conservation (16.4° away) matures only late in the decade.

The eight registered predictions, walked individually.

P5-Pred-1 ($\delta_{\rm PMNS} = 196.4^\circ$). Derived in Part VII from the pentagon's central angle under the leptonic assignment (QD 196.06°); measured by Hyper-K and DUNE appearance asymmetries at $\pm 15^\circ$ then ± 7–10°; killed by data settling at maximal 270° (5σ, 2031–35) or by any 5σ inconsistency with the lattice point — taking with it the leptonic lattice chain and the door's bias (the same phase drives Part VIII's transport).

P5-Pred-2 ($\delta_{\rm CKM} = 13\pi/35$). Derived as the pentagon's branch phase with the QD completion; confronted continuously by the LHCb/Belle II global fits at ± 0.026 rad today; killed by a converged world fit excluding 1.1669 at 5σ — with the honest note that the raw $2\pi/5$ first order sits at $+1.17\sigma$-class only with the $\pi/35$ theory width in quadrature ($+4.2\sigma$ against experimental error alone) and the QD step carries its own flagged grade.

P5-Pred-3 ($m_{\beta\beta} = 1.72$ meV; Majorana nature). Derived from the door theorem and the parity pair $(0, \pi)$; approached one-sidedly by the ton-scale $0\nu\beta\beta$ program (LEGEND-1000, nEXO, CUPID at 5–20 meV reach); killed by a confirmed discovery anywhere in the reach — a line at 50 meV is as fatal as the absence of one at 1.72 meV would be unprovable; the claim is designed to be executable only in the kill direction this generation, and says so.

P5-Pred-4 (normal ordering). Derived with the mass triplet; measured by JUNO (running), atmospherics, DUNE; killed at 5σ inverted ($\sim$2033). The one row where the current data are genuinely mixed, and the paper's posture is the wager above.

P5-Pred-5 (the lock cluster at 3.85 TeV). Inherited from the parent ledger and load-bearing here (the heavy sector of the transport); measured by HL-LHC $t\bar{t}$ reanalyses and the dedicated program of the companion paper; killed by the cluster's exclusion — which retires Part VIII's chain regardless of every leptonic success.

P5-Pred-6 (no W_R, no mirror fermions — F-P5-1). Derived from the projection's absence clause; tested by every collider forever; killed by any confirmed right-handed current or parity restoration at any scale — permanent, one-sided, never finally vindicated.

P5-Pred-7 (proton absolute stability). Inherited from the exact $\mathrm{U}(1)_B$ ledger and load-bearing for the frozen excess; tested by every year of Super-Kamiokande, then Hyper-K and DUNE; killed by one confirmed event, any day — the row that makes the matter chain mortal every morning.

P5-Pred-8 ($|\bar{\theta}| \lesssim 5 \times 10^{-18}$; no EDM in the window). Derived from the two-fate architecture and the relaxation residual; tested by n2EDM and the eEDM program; killed by a measured EDM above the residual but below the old bound — the specific window where the architecture, not merely the number, fails.

The falsification lattice. The eight are not independent shots; they form a lattice whose nodes are the paper's theorems, and the lattice is the real object under test. A leptonic kill (Pred-1) breaks the same pentagon that carries the quark audit (Pred-2's success becomes an accident); an ordering kill (Pred-4) invalidates the mass triplet that feeds $m_{\beta\beta}$ (Pred-3) and the transport's Yukawa matching; a proton event (Pred-7) or a W_R (Pred-6) breaks the descent architecture underneath all of it; and the cluster (Pred-5) ties the whole sector to the triad — through P1-KK's collider program and C1-Kaxion's haloscope window, one geometry is exposed at three energy scales, and the AND-logic runs both ways: any clean kill anywhere impeaches the shared ledger, and a confirmation

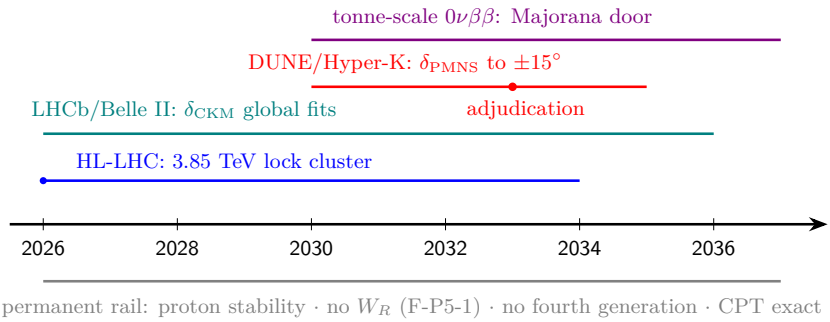

Figure 26: The falsifier timeline. Colored bars are the dated instruments of Table 26; the red dot marks the expected leptonic-phase adjudication. The gray rail carries the permanent prohibitions — the statements that can die on any day and can never be vindicated finally, which is what makes them the strongest claims in the paper.

anywhere is collateral support for the rest. Conversely, a discovery pattern that confirms several rows *jointly* — ordering, phase, silence in the ton-scale window — is beyond the reach of any framework in Table 25, because the correlations are the geometry. The dated schedule for all of it is Table 24 and Figure 25; the summary table and figure below preserve this Part's own registration.

137 Open questions

Honesty requires the complement, at the same depth as the claims. Ten items remain open; for each we state why it is open (not merely that it is), what has been tried, the closing condition, and the impact of closure. Items (2), (3), and (6) are commissioned campaigns of the parent program; the remainder are stated obligations of this paper and its companions.

1. The gate-operator lemma (C-P5-A). *Why open*: the identification of the broken force with the gate force is architectural — exhibited, not forced; nothing yet proves the transporting connection unique. *Tried*: the L11 uniqueness sketch (chiral, massive, off-diagonal, $\mathrm{SU}(2)_L$ singled out). *Closing condition*: a proof that any descent-transporting connection has exactly these properties. *Impact*: parity's promotion from architecture to theorem; P-P5-D closes with it (item 9).

2. The resonance mechanism (C-P5-C(i)). *Why open*: the transport requires degeneracy at the level of the heavy widths, and the twelve-order gap between the lock splittings and the required $\delta M/M$ is quantified but not bridged. *Tried*: thermal-width estimates; radiative degeneracy; lock substructure — each stated with its shortfall in Part VIII. *Closing condition*: the finite-temperature computation of the heavy-sector spectral function at the reheating scale — the program's sharpest outstanding physics item — or a clean kill. *Impact*: η_B promoted from D* toward derived; failure retires Part VIII while leaving Parts IV–VII standing.

3. The normalization (C-P5-C(ii)). *Why open*: the throughput exponent $K/2$ is reconstructed from the ledger, not derived from transport. *Tried*: matching against the washout benchmark; the

reconstruction is stable but post-diagnosed. *Closing condition*: derive $e^{-K/2}$ from the Boltzmann hierarchy with inherited inputs. *Impact*: the last postulated number in the matter chain becomes arithmetic.

4. Lemma L9 (determinant phase). *Why open*: the cancellation of the quark-mass determinant phase against the relaxed angle is argued sector by sector, not proved end to end. *Closing condition*: the end-to-end determinant computation across the QD completion. *Impact*: $\bar{\theta} \lesssim 5 \times 10^{-18}$ promoted to derived-unconditional; the two-fate architecture closes.

5. The heavy-sector CP projection. *Why open*: the flavored computation on the ledger inputs is displayed (GG-A10-Cosmos Appendix I) — driver $\alpha_{31} = \pi$, nonzero at $m_1 = 0$, $J_{\rm PMNS}$-blind at the stated level — and brackets the observed throughput; what remains open is H-$\phi_{\rm geo}$-1, the finite-temperature partial-resonance condition $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$ (§87), now carried by an identified candidate mechanism — the flavor-measurement regulator, closed form $1/(35\, c_\tau y_\tau^2)$ (GG-A10-Cosmos Appendix I.3) — with the transport closure of its conditions C1–C6 the open content. *Closing condition*: the finite-temperature flavored transport computation at the lock crossing, acceptance band $\pm O(1)$ in $\epsilon_{\rm eff}$. *Impact*: the $\epsilon^{\rm res}$ row of the Part VIII ledger moves from derived-conditional to derived; the forced-γ worked value enters the tables.

6. The modular route. *Why open*: T-P5-2 is quasi-free; the interacting theorem lives on scattering hypotheses, while the Bisognano–Wichmann structure suggests a hypothesis-free route. *Tried*: the wedge-modular identification is stated and sourced; the derivation of the clock structure from Tomita–Takesaki flow is not done. *Closing condition*: derive the clock from modular flow at interacting strength. *Impact*: CPT — and with it the quartet's second child — at full interacting grade; the road-join of Part X completed.

7. The projection's derivation. *Why open*: the $\mathbb{Z}_2$ and the matrix P are a standard assignment, honestly flagged as the parity ledger's asserted rows. *Closing condition*: force both from the admissibility filters (POS-1/POS-3). *Impact*: Part VI's mechanism upgraded from inherited to forced; PS-P5-3's conditionality discharged.

8. The Ω_b seam. *Why open*: the transport route and the corridor route to the baryon fraction differ by 16.4%, outside the CMB's 0.3%, and the owner is unidentified. *Tried*: the discrepancy is flagged in both this paper and the cosmology companion rather than averaged away. *Closing condition*: a well-posed internal consistency test locating the error in the transport $O(1)$'s or the corridor conversion. *Impact*: either a corrected η_B central value or a corrected corridor — both readable.

9. P-P5-D's proof. *Why open*: the handedness invariant is a proposition with a strategy, pending item 1. *Closing condition*: C-P5-A plus T-P5-3 closes it. *Impact*: "which hand survives" anchored physically; the shared residue of the parity and spin stories discharged.

10. The spin–statistics promotion path. *Why open*: the quartet's second child is stated at candidate grade (§45); its bulk premises (the frame-path lemma; the genericity clause) and its quasi-free derivation are owed in the geometry and quantum-mechanics companions. *Closing condition*: L-Spin-1's non-quotienting proof and T-Stat-A at quasi-free grade. *Impact*: the summit phrase's middle clause — locked spin–statistics — promoted from candidate to theorem; the exclusion principle becomes cohort anatomy.

None of the ten shields the verdict: the falsifiers of §136 stand on the theorem-grade spine — the table, CPT, the door, the lattice points, the one-sided silences — alone. That is the design: the open questions sharpen the program; they do not prop it up.

138 The completed cohort and future prospects

This paper is a member of the twenty-two-paper cohort — the Foundations Branch, at the GG-A9-SM–GG-A10-Cosmos interface — and its place is load-bearing in both directions. *Imports:* the real oriented bulk, its signature, and the Clifford intertwiner whose three jobs this paper exhibits (Arisaka, 2026, A2-GG6); the anomaly inflow that fixes the matter content (Arisaka, 2026, A3-BI6); the open-system dictionary and runtime through which every boundary statement is read (Arisaka, 2026, A5-GDOS; Arisaka, 2026, A6-GRIP); the flavor geometry, the derived neutrino ledger, and the basin/gate architecture of the particle parent (Arisaka, 2026, A9-SM); the transport custody and cosmological frame of the cosmology parent (Arisaka, 2026, A10-Cosmos); the attractor uniqueness beneath token identity (Arisaka, 2026, A11-Origin); the lock cluster and the Kaxion as the triad's other two channels (Arisaka, 2026, P1-KK; Arisaka, 2026, C1-Kaxion); and the real-bulk holomorphy bridge of the Foundations-Branch partner (Arisaka, 2026, P4-Real). *Exports:* the derived C/P/T table and the quartet, consumed wherever the cohort performs a Euclidean computation; the pentagon's valuation, feeding the parent's CKM/PMNS sector; the door theorem, anchoring the cosmology parent's baryogenesis custody; the second child's parentage, consumed by the geometry paper's spin–statistics suite and the quantum-mechanics paper's T-A8.12; and the registrations F-P5-1 and P-P5-D, queued for the canonical falsifier ledger.

The near-term prospect is stated once more because it is the paper's operational request to the experimental community: *publish the posteriors, not only the discovery statistics* — the δ posterior against the two pre-registered points (196.4° and 270°), the ordering Bayes factors on a standing basis, and, when the ton-scale program reports, the $m_{\beta\beta}$ posterior evaluated at 1.72 meV — so that the lattice reading is tested as a point hypothesis rather than absorbed into model-independent bands. The far-term prospects are the promotion campaigns of §137 and the verdict window of Part XI: by the early 2040s, every row of Table 26 will have been visited by an instrument, and the paper will be either the anatomy of the mirrors or a dated record of a beautiful error — it has arranged to be nothing in between.

139 Summary of the Discussion

The strengths, stated plainly: an anatomy that replaces seventy years of convention with derived operations; a valuation that prices both CP phases at lattice points, one of them already audited to four digits in the quark sector; a matter chain with zero fitted parameters landing +20% from Planck inside its published band; a two-fate resolution of the strong-CP double standard with an eight-order one-sided silence; a discrimination matrix no rival framework survives jointly; a confrontation apparatus with standing refresh rules and pulls printed against itself; and a falsifier lattice that is mortal on a printed calendar, four separate ways. The weaknesses, stated with equal plainness: the resonance conjecture C-P5-C carries the matter chain's sharpest gap — twelve orders in the degeneracy, quantified but unbridged; the throughput exponent is reconstructed, not derived; the parity projection's own necessity is asserted, with its ledger saying so; the Ω_b seam stands at 16.4% with its owner unidentified; the QD step under the quark phase carries a flagged post-hoc grade; and the interacting-strength CPT theorem waits on the modular route. The posture these imply is the one the paper has kept throughout: anatomical where it can prove, priced where it can derive, silent where it must wait — and mortal everywhere, on schedule.

In one breath each: the result is significant because both of its endings are informative, which seventy years of convention-laden discrete symmetries could never say; it is unique in kind, with eight classic puzzles resolved or dissolved and ten innovations registered for audit — with the four-endowment definition of time (Part IX) standing beside them as the paper's furthest-reaching structural claim; no neighboring framework survives the twelve-observable fingerprint jointly; the claims ledger states every grade and invites the reader to police it; the falsifiers are priced, dated, and walked one by one, with the watched tension printed against the paper's own interest; the open questions sharpen the program without propping it up; and the cohort carries the verdict outward in both directions. The argument of the paper is now complete. What follows is its ending in the older sense of the word: conclusions, a personal accounting from fifty years inside the mirrors, and the bridge to the question — why are we here? — that a paper about the origin of matter cannot end without facing.

Table 26: The falsifier table. Each row names its instrument, its date where one exists, and the specific structure its failure destroys — the register's requirement that mortality be itemized. All sensitivity dates are conditional on stated design assumptions (mass ordering known where required, beam-power ramps, staging); the conditioning is the collaborations', quoted from the cited design reports.

Prediction	**Instrument**	**Timeline**	**What failure kills**
$\delta_{\rm PMNS} = 196°$ (band $\pm$ QD step)	DUNE, Hyper-K ($\pm 15°$)	early–mid 2030s	the leptonic lattice chain; the door's bias
$\delta_{\rm CKM} = 13\pi/35 \simeq 66.9°$	LHCb, Belle II global fits	continuous	the QD completion (the $2\pi/5$ first order survives to $+1.2\sigma$-class tests only with the $\pi/35$ theory width)
$m_{\beta\beta} \simeq 1.7$ meV; Majorana nature	next-gen $0\nu\beta\beta$	2030s	the dial-free door as the matter portal
Lock cluster at 3.85 TeV	HL-LHC	this decade	the heavy sector of the chain (predeclared criterion)
No W_R, no mirror fermions, at any scale (F-P5-1)	all future colliders	permanent	the geometric projection of Part VI
Proton absolutely stable	Hyper-K, DUNE	permanent	the exact $\mathrm{U}(1)_B$ ledger (observation of decay kills Part VIII's logic)
$\lvert\bar{\theta}\rvert \lesssim 5 \times 10^{-18}$	neutron/proton EDM programs	2030s+	(a measured EDM above this but below 10^{-10} would break the two-fate architecture)
No fourth chiral generation	colliders, cosmology	permanent	the $N_g = 3$ counting of the one surviving phase
Derived splittings $\Delta m^2_{21} = 7.37 \times 10^{-5}$, $\Delta m^2_{31} = 2.55 \times 10^{-3}$ eV^2	JUNO precision era	$\sim$2031	the derived mass triplet (a converged JUNO value off the derived pair at 4σ-class kills the mass chain)
$\Delta B \in 3\mathbb{Z}$: no single-nucleon decay, no n–$\bar{n}$ oscillation (§92)	Hyper-K; n–$\bar{n}$ searches	2030s	the whole baryonic logic — a test this framework can only fail, never pass
No anomalous free fall of antimatter (§94.1)	ALPHA-g, AE$\bar{\rm g}$IS	running	Part IV at its root: the handshake, the equal masses, and the pairing

Part XIII
Conclusions — Why Matter Won

The oldest question in the mirror; what the paper has established, in plain English and in ten numbers; an answer we can check soon; the limitations; fifty years in the mirrors; the vision; the trailhead; from mirrors to mind; and what it would mean — for physics, and for the universe that reads itself

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140 Part XIII in plain English: why matter won

The claim, stated plainly: the mirrors are not laws but orientations. The world is built from real oriented geometry — a compact circle, space, and a one-way clock — and C, P and T are the reversals of those three orientations. Each can break, because the geometry has texture. CPT cannot, because a total reversal is the one reflection no real texture can see.

What follows is the matter excess, at the grade the chain earns and at no higher grade, and an answer that can be checked soon rather than in principle. The limitations are stated without cushioning: the theorems are quasi-free with the interacting case conditional; the projection is asserted rather than derived; the resonance step carries a named conjecture; and the baryon-density bridge has a gap. Each of the four carries a named next task.

The Part then goes further than the physics — a personal section, a longer view, and the question of what either verdict would mean — and each of those is labeled as what it is rather than presented as a result. The last word is why the mirrors break, which is the question the paper opened with, answered in one sentence.

141 The oldest question in the mirror

Begin with the plainest fact a person can be told about the universe, because everything in this paper stands behind it. In the first instants after the Big Bang, the world was almost perfectly balanced between matter and antimatter — for every ten billion particles of one kind, ten billion of the other, plus a remainder of about six. As the universe cooled, every matched pair found its partner and vanished into light. The light is still here: it is the cosmic microwave background, the most precisely measured relic in cosmology, about two billion photons today for every surviving proton. The pairs are gone. *Everything else — every galaxy, every star, the iron in your blood, the page or screen in front of you, and you — is the remainder.* Six parts in ten billion: the universe we live in is, quite literally, a rounding error that survived an annihilation.

That fact raises the oldest question in the mirror, and it has two halves. The first half is *why any remainder at all*: the laws of physics, as written in every textbook, treat matter and antimatter almost identically, and "almost" has never been explained — the Standard Model's own bookkeeping,

run honestly, leaves a universe some ten billion times emptier than ours, a haze of light with nothing in it to wonder why. The second half is older and stranger: physics possesses three great mirrors — exchange every particle with its antiparticle (C), reflect the world left-to-right (P), run the film backwards (T) — and nature, astonishingly, is unfaithful to each of them separately while remaining perfectly faithful to all three at once. Since 1956 we have measured the infidelities with exquisite precision. We have never, in seventy years, been able to say what the mirrors *are* — only how they break. This paper's subject is both halves of the question at once, because they turn out to be the same question: the mirrors break, and matter won, for one reason — *the world has a direction* — and the pages behind this conclusion have tried to earn that sentence as geometry rather than poetry.

142 What the paper has established

In plain English, the arc in one page. The world of the GG-6 program is built from real structures: a circle that charge winds around, a clock that causality orients, a space, and a descent — a one-way cascade down the family landscape that wrote the masses. Before anything else, the twins: the circle and the clock are two half-blind sources of one imaginary unit, and they can share it in exactly one way — positive charge forward in phase, negative charge forward in phase. That forced agreement is the antiparticle: not an extra ingredient, not a product of the descent, but the consistency of the world with itself — the reason quantum mechanics is complex and the reason every particle has a mirror twin are the same fact. The operations C, P, and T are nothing but the reversals of the circle, the space, and the clock; that is why T alone is antiunitary (only the clock's direction is what i is made of), and why the total reversal CPT can never fail while anything is built from real data — reversing everything at once is a relabeling. The mirrors break where the world's texture has a direction. The flavor texture is a pentagon — five is the size of the unified block — and a pentagon's angles cannot all be flat: CP violation exists because $3\pi/5$ is not a multiple of π, and its measured phases are the pentagon's forced angles, 72° less one lattice step in the quarks, 180° plus twice $\arcsin(1/7)$ in the leptons. The weak force breaks parity because it is the cascade's gate force — the only broken, family-changing, short-range coupling — and a gate that executes a one-way flow must tell left from right. The neutrino, the only particle with nowhere to wind, is the only one that can be its own antiparticle: through that unique door, at the TeV lock scale, the pentagon's phase biased the decays of the heavy states, the boundary's one-way law kept the books from rebalancing, and the sphalerons converted a lepton excess into six baryons per ten billion photons — the number the CMB reads, reproduced here with no fitted parameter, one named conjecture, and a published error band. Matter won because the universe is oriented, and the broken mirrors were the first laboratory evidence of the orientation.

142.1 The paper in ten numbers

Stripped of narrative, the paper's content is ten numbers and the machinery behind them — each with its status, its proof location, and the measurement that can kill it. The grades are the register of §135; nothing in the table is a fit.

Table 27: The paper in ten numbers. Status grades follow the claims ledger (§135); "killed by" names the measurement that retires the row (Table 26 carries the full falsifier register). Ten rows, one number each, with the value, the grade it is claimed at, the Part that proves it, and the measurement that would retire it. The last column is the point of the table: every row names something an experiment could do that would end that row, and the dates in it are close enough to matter.

	Quantity	Value	Status	Proved	Killed by
1	quark CP phase δ_{CKM}	$13\pi/35 = 66.9°$	derived-cond.	Part VII	world fit off at 5σ
2	lepton CP phase δ_{PMNS}	$196.4°$ (QD $196.06°$)	derived-cond.	Part VII	$270°$ at 5σ (2031–35)
3	$\sin 2\beta$	0.708	derived-cond.	Part VII	$> 3\sigma$ drift (watched)
4	Majorana pair $(\alpha_{21}, \alpha_{31})$	$(0, \pi)$	derived	Part VII	$0\nu\beta\beta$ phase reading
5	double-beta mass $m_{\beta\beta}$	1.72 meV	derived	Part VII	any ton-scale discovery
6	neutrino masses	0.065, 8.59, 50.5 meV; normal	derived (parent)	Part VII	inverted at 5σ ($\sim$2033)
7	strong-CP residual $\bar{\theta}$	$\lesssim 5 \times 10^{-18}$	derived-cond. (L9)	Part VII	EDM in the window
8	baryon excess η_B	$\approx 7 \times 10^{-10}$ ($\times 3^{\pm 1}$)	D* (C-P5-C)	Part VIII	chain kills; one proton event
9	heavy-sector scale	3.85 TeV	inherited ledger	Part VIII	HL-LHC exclusion
10	mirror sector W_R	none, at any scale	theorem (absence)	Part VI	any W_R, ever

Around the ten numbers stand the structures built to make them decidable: the handshake that forces the twins before quantization (Part IV); the quartet that turns every Euclidean computation into licensed geometry, with CPT and — at candidate grade — the exclusion principle as its two children (Parts IV and §45); the anatomy of the three reversals (Part V); the one-hand descent (Part VI); the pentagon (Part VII); the door and the tripod (Part VIII); the five roads compared at full depth (Part X); and the confrontation apparatus — refreshed world numbers, deviation panels, dated timeline — that keeps the whole account auditable (Part XI). None of it waits on future theory; all of it waits on data.

143 An answer we can check — soon

What lifts this above a beautiful story is that it can be tested now, decisively, and from several directions at once, on a timescale of years. The instruments are not proposals; they are running or funded. JUNO is taking data beneath southern China today; Hyper-Kamiokande's megaton-class tank sees beam in 2028; DUNE's beam crosses South Dakota around 2031; together they will settle, by about 2033, whether the neutrino masses are ordered the way this paper requires — a question

on which the paper has no fallback. Through the 2030s the same instruments sharpen the lepton phase toward the pentagon's point at 196.4°, and the ton-scale double-beta detectors listen for a signal this paper says they will *not* hear, because its predicted value sits far beneath their reach — a silence registered in advance. The permanent rails run underneath: every year Super-Kamiokande's protons decline to decay is a year this paper survives; any confirmed right-handed current, any electric dipole moment in the forbidden window, any fourth generation, would end it on any day.

And one prediction deserves plain words because it inverts what the field hopes for. The long-baseline program was built, in large part, to discover leptonic CP violation at five sigma. If this paper is right, *that discovery will not come*: the lattice value implies CP violation so gentle — the phase just 16.4° from the conserving point — that the flagship exclusion will keep failing to arrive, while the measured phase crowds the predicted point from below. A theory rarely gets to be confirmed by a disappointment; this one has arranged exactly that, in print, with the alternative — 270°, the community's favorite — registered as its own execution. The test cuts both ways, cleanly, and we say so without hedging: a clean kill would be a real and valuable answer, not a defeat. It is rare in fundamental physics to meet a question this old with a decade this decisive. That is the opportunity, and it is, honestly, a thrilling one.

144 The objective limitations and the next technical tasks

The paper's floor, stated as plainly as its ceiling. The theorems of Parts IV and V hold at the quasi-free grade; interacting extensions ride on standard scattering hypotheses, with the modular route the named path to full strength. Parity's argument is an architecture awaiting its lemma. The baryogenesis chain's resonance condition asks for twelve orders of magnitude that vacuum numbers do not supply, and the thermal-width route that plausibly supplies them is a computation, not yet a result. The QD completion of the quark phase is flagged post-hoc by the parent program itself. Two routes to Ω_b disagree by 16.4%. These are the next technical tasks, they are all well-posed, and none of them can be finessed: each either lands or kills its dependent claims, which is what it means for a framework to run on falsifiable credit.

145 A personal perspective: fifty years in the mirrors

The author asks the reader's indulgence for one section in the first person; the experiments are facts, and the connection is motivation, not authority.

I met the broken mirrors as a student in the 1970s, when parity violation was already textbook and CP violation was still a two-per-thousand mystery confined to one particle. It seemed to me then — with the certainty only a student can afford — that these were the deepest facts in physics, because they were the only places where nature, rather than our descriptions of it, chose a direction. Fifty years later I believe it still, with the certainty now resting on somewhat more evidence.

I spent 1980 to 1985 on the design and construction of the Kamiokande detector. We built it to watch protons die; they did not, and that null — one of the most productive nulls in the history of physics — turned the instrument toward the sky and the sun. I was fortunate to be present

at the founding of what became neutrino astronomy, and I have watched the lineage of that tank — Kamiokande, Super-Kamiokande, and now Hyper-Kamiokande — carry the discrete-symmetry program into the lepton sector: oscillations in 1998, θ_{13} within my colleagues' lifetimes and mine, and now the pursuit of δ_{PMNS}, the one number this paper most wants measured. There is a peculiar symmetry in the fact that the detector we built to watch baryon number fail may end by explaining why baryon number won.

From 1987 to 2007 I lived inside CP violation: KTeV at Fermilab, where the double ratio finally yielded $\mathrm{Re}(\varepsilon'/\varepsilon)$ and direct CP violation became a measured fact of the amplitudes; then BaBar at SLAC, where $\sin 2\beta$ closed the unitarity triangle and the Kobayashi–Maskawa phase became the confirmed bookkeeping of every asymmetry we could reach. I am proud of those measurements in the way an experimentalist is: they are permanent. And I left that double decade with an unease I could not then articulate. We had measured the phase to three digits and could not say why it was not zero. We had confirmed a parameterization, brilliantly, and explained nothing. The question I carried out of the control rooms was the one this paper finally attempts: *what are these symmetries, that their breaking should be so precise, so selective, and so consequential?*

The answer defended here — that the mirrors are orientations of a real geometry, that their breakage is the orientation of a descent, and that the matter of the universe is that orientation's receipt — is one I would have distrusted in 1987, and rightly: it would then have been words. What has changed my own weighing is the arithmetic: the pentagon that sets the Cabibbo magnitude to five digits sets the CP phase to a lattice point within one sigma of the world fit; the same integer that sets the lock scale sets the baryon excess to four percent of the CMB value; and every one of these statements can be killed by an instrument now under construction, several of them descendants of instruments I helped build. Fifty years is long enough to learn the difference between a story and a ledger. This paper is a ledger, kept as honestly as I and my collaborator on these pages know how, and I submit it to the community that trained me with the register it taught me: here is what is derived, here is what is owed, and here are the dates on which you may collect.

146 The vision: reading the mirrors as geometry

The Foundations-Branch partner closed with a vision of a century in which number systems are read as geometry. This paper's vision is its sibling: a century in which the *symmetries* are read the same way. On this reading the discrete-symmetry experiments of 1956–2035 — from Wu's cryostat to the megaton water of Hyper-Kamiokande — compose a single eighty-year measurement: of the orientations of the world's real factors, of the chirality of its flavor texture, and of the direction of its descent. The falling of the mirrors was never a catalog of accidents; it was geometry, reporting.

Suppose the decade goes the geometry's way — not as advocacy, but as the planning exercise every field runs on. Then the texture of discrete-symmetry physics changes the way collider physics would change with the cluster: the question at the frontier stops being "which operators might break which symmetry at which scale?" — a question that has admitted too many answers for fifty years — and becomes "what does the orientation say, and to how many digits can we check it?" The CP phases stop being free parameters and become the first entries of a *spectroscopy of*

orientations: the pentagon read at the B factories and the long baselines the way the Balmer series was read in glass tubes, the Majorana pair read in germanium and xenon, the one-sided silences standing like selection rules. Spectroscopy is meant as the highest compliment: it is the mode in which physics has been most honest, most cumulative, and most kind to its young people, because a student with a good idea and a data set can be *right* in a way no committee can argue with. My deepest professional hope for this paper is not that it is right; it is that it makes that kind of physics imaginable again to a twenty-five-year-old with fifty years of mirrors ahead of her.

147 The trailhead, not the summit

If the decade confirms the pattern — the ordering, the phase crowding its point, the silences holding — the reward will be extraordinary: not one more measured parameter, but evidence that the discrete symmetries, the flavor phases, and the matter of the universe are readings of a single oriented geometry. And yet confirmation would be a beginning, not an end. The promotion campaigns of §137 — the gate lemma, the resonance computation, the modular route, the spin–statistics closure — would lie ahead the way the hydrogen atom's fine structure lay ahead of Balmer; the pentagon's higher harmonics, the door's collider face, and the quartet's interacting-strength children are the spectroscopy of Part XIII's century, mapped across instruments not yet named. This paper is the trailhead of that program, not its summit.

If instead the decade kills it — an inverted ordering, a maximal phase, a line in the double-beta window, a proton that dies — the present implementation will have failed one of the cleanest tests a symmetry framework has ever offered: publicly, permanently, and without a zombie phase, because there is no parameter with which to retreat. Either way, the decade is worth having. That is the mark of a good falsifier; it was the missing property of the seventy years this paper's history Part recounted; and it is the property this paper was written to restore to the mirrors.

148 From mirrors to mind: the oriented emergence

This paper's story does not end at the baryon number, and the remainder deserves to be said carefully — with the registers attached, because a beautiful story told carelessly is only a story — what the oriented geometry actually underwrites.

Begin at the beginning of this paper and walk forward once. Because the world has two real sources of one imaginary unit, it has twins (derived). Because it has three real orientations, it has mirrors, and one unbreakable product of them (derived). Because the descent between the family basins is oriented, one force tells left from right (conditional, one lemma), and the holonomy written along that descent makes the flavor pentagon chiral (derived through its stated conditionals): the twins are not treated equally. Because the neutrino alone has nowhere to wind, there is one lawful door between the twin ledgers (derived); because the door's traffic was biased by the pentagon's phase and the boundary's law is a one-way semigroup, the universe kept six parts in ten billion of itself (D^*, one named conjecture); and because the excess survived a prompt descent undiluted, there were protons — then nuclei, then, six hundred million years on, the first chemistry that could

hold a record of its own past.

From there the cohort's summit paper carries the chain, and this paper adopts its grades without inflation: an oriented chemistry (homochirality — the biological left-handedness whose descent from the microphysical orientation is conjectured, not derived; the summit's own register), an oriented thermodynamics (records, metabolism, the boundary's forward semigroup written into every living membrane), and at last an oriented *experience* — memory before anticipation, the felt asymmetry of time that is the OGGEP projection's shadow in a nervous system (Arisaka, 2026, A11-Origin). None of the last three links is this paper's theorem, and the chain from CP violation to the reader is conjectured beyond its matter link. But the matter link — the one this paper audits — is now the best-secured in the chain, and the shape of the whole is no longer mystical: *every rung is the same fact.* The mirrors break, the pentagon turns, matter survives, chemistry selects a hand, life runs forward, and mind remembers backward — one orientation, cascading through eleven orders of magnitude of scale, from the fiber circle to the reader's certainty that yesterday is fixed and tomorrow is not.

That is the beautiful story, and its beauty is of the lawful kind: at every rung it could have been killed, and at the rungs we can measure, it has not been. The universe is not symmetric. It is oriented — and orientation, unlike symmetry, can make things: particles, excesses, hands, memories, questioners. The discrete symmetries were never a specialists' bookkeeping. They were the first instruments sensitive enough to read the direction of the world.

149 Why are we here: the bridge to the summit

The cohort's summit paper asks the question plainly — why are we here? — and builds its answer as a cascade: constitution to bulk, bulk to boundary, boundary to chemistry to life (Arisaka, 2026, A11-Origin). This paper supplies the cascade's pivotal middle links, and grades them: because the descent is oriented, parity breaks (conditional, one lemma); because the texture is pentagonal, CP breaks by a forced amount (derived through its stated conditionals); because the neutrino alone has nowhere to wind, there is a door (derived); because the door's traffic was biased and the boundary's law is one-way, there is matter (D^*, one conjecture); and because there is matter, there is chemistry, and the question can be asked. The chain from CP violation to the reader's existence is conjectured beyond its matter link and graded honestly by the summit paper itself; what this paper contributes is that its links are now the best-audited in the chain. We are here, on this account, because the universe cannot be reversed — and the mirrors were how it told us.

150 What it would mean: orientation, matter, and the universe that reads itself

A paper that asks a decade of the world's instruments owes the reader more than a schedule; it owes an account of what the answer would *mean.* This closing section attempts that account in four movements, in plain English, at the depth the question deserves — and the last two movements walk deliberately into the territory of the cohort's summit paper (Arisaka, 2026, A11-Origin), with the

grades kept visible even here, because a philosophical remark that hides its register is only rhetoric.

First movement: on falsifiability as an ethic. The mirrors have a special claim on scientific honesty, because they are where physics learned humility twice: parity fell when almost nobody believed it could, and CP fell in an experiment designed to confirm its conservation. The tradition this paper inherits from those shocks is not cleverness but conduct: state the number before the measurement; price the kill; forbid yourself the retreat. Popper made falsifiability a criterion; seventy years of practice have shown that as a criterion it is too easy to satisfy in the letter and evade in the spirit — every scanned model is "falsifiable" at each point and immortal as a family. What this paper has tried to practice is falsifiability as an *ethic*: the deliberate construction of a position from which one's future self cannot escape. The lattice points are load-bearing across twenty-two documents so that no quiet revision is possible; the ordering carries no fallback; the silences can execute on any morning. There is a moral structure here older than science — it is the structure of a promise — and if the pentagon is wrong, I hope the *form* of the wager outlives the wager itself.

Second movement: on symmetry, orientation, and what a world can say about itself. Twentieth-century physics was written in the language of symmetry, and its habit of mind was to treat every asymmetry as a flaw awaiting explanation — a broken vase to be glued. The account defended here inverts the aesthetic. A perfectly symmetric world is not a perfected world; it is a *mute* one — it can keep no records, prefer no direction, accumulate no remainder, and support no one. Symmetries are the statements a world cannot make about itself; its breakings are its autobiography. Orientation, unlike symmetry, can *make* things: twins, excesses, hands, memories. On this reading the discrete-symmetry violations are not blemishes on a beautiful formalism but the first sentences of the universe's self-description — and the seventy-year experimental record of the mirrors is the transcription, at first bewildered and then increasingly precise, of a world telling us, in the only language available to it, that it has a direction. The physics claim of this paper is that the sentences parse: three reversals, one pentagon, one door, one remainder. The philosophical claim is smaller and stranger: that we should have expected the universe to be legible *here* first, because an oriented world's asymmetries are precisely the part of it that carries information.

Third movement: into the summit — the self-referential closure. The summit paper of the cohort (Arisaka, 2026, A11-Origin) asks the question this paper's title implies and answers it as a cascade: constitution to bulk, bulk to boundary, boundary to chemistry, chemistry to life, life to mind — with the grades printed at every rung, and the rungs beyond matter conjectured, not derived (§148). Stand back from the cascade once and say what its shape would mean if it holds. The bulk projects a boundary; the boundary, because it is oriented, keeps a remainder; the remainder assembles — through the chemistry the remainder alone made possible — into structures that record, then metabolize, then remember, then ask. *The universe's leftover matter has spent thirteen billion years arranging itself into instruments that measure the asymmetry that saved it.* Every kaon beam, every B factory, every tank of water under a mountain is, on this account, the six-in-ten-billion looking back at its own origin; the reader following this sentence is the remainder, running on the boundary's one-way clock, using a nervous system whose forward flow is the same

semigroup that froze the excess. This is what the summit paper calls the self-referential closure: observation is not something added to nature from outside — it is something nature does, the boundary reading the bulk that projects it — and a physics that derives the mirrors is therefore not a description of the universe from nowhere but an event *in* the universe's own self-description. The old anthropic shrug — "we observe an asymmetric world because observers require one" — gets stood on its feet: an oriented world does not merely *permit* witnesses; it is the kind of world that cannot help making them, because orientation is what records, remainders, and rememberers are made of. I am aware how large these sentences are. They are printed here, rather than in a philosophy journal, because — to the author's knowledge, for the first time in seventy years of mirror physics — sentences of this size have measurement dates attached to them.

Fourth movement: on either verdict, and the grace to listen. Beneath all of it is the question every physicist carries privately: is nature legible — readable in advance, by finite minds, down to its choices? The mirrors are where that question is oldest, because they are where nature's choices are starkest: a hand, a phase, a remainder. If the decade goes the geometry's way, the answer becomes *yes, one layer deeper than we had any right to expect* — the world's oldest asymmetries a text, the instruments its readers, and the readers themselves made of the text's own remainder: legibility closing its loop. If the decade kills the pentagon, the answer is subtler but not empty: we will have learned that this reading fails, cleanly, at a stated cost, with the manner of failure itself a contribution — the first zero-parameter account of the matter of the universe to be retired by measurement rather than by fashion. Legibility has two requirements: a world with structure, and readers with the discipline to be corrected by it. Only the first is nature's responsibility. The second is ours, and it is the one thing this paper could guarantee. The phase is the bet; the decade is the table; the first cards are already face up — an ordering leaning our way, a phase one sigma from the point, a proton that has not died. Let the data speak — and let us have the grace to listen, whichever way they answer.

151 The last word: why the mirrors break

And beneath the mirrors, the clock. This paper set out to explain three broken symmetries and found, on the way, that it had to say what time is: the one direction that orders, repeats, opens, and shelters (Part IX). The two answers are one architecture — the mirrors broke on the descent's orientation, and the clock stands on time's four endowments; the same dictionary whose one-way reading ages the universe is the one that recorded the kaon's confession in 1964.

Symmetries are the statements a world cannot make about itself; their breakings are its autobiography. A perfectly mirror-blind universe would have annihilated to light and said nothing. Ours kept a pentagon where its flavors turn, a single chiral gate where its families descend, one particle that is its own reflection, and a ledger of six extra baryons in every ten billion — and out of that spare autobiography came stars, chemistry, and readers. The mirrors break because the world has a direction. That the direction can be measured — in a cryostat, in a kaon beam, in a tank of water under a mountain — and now, perhaps, derived, is the whole of what this paper has

tried to say.

Part-end summary. Established, bounded, personal, and pointed forward: the oldest question answered at a stated grade, the limitations owned, fifty years in the mirrors accounted for, and the trailhead marked. The argument is over; what remains is service. The remaining Parts are the reader's tools: the courses of the appendix machine room, the eighty-two objections, and the annotated references.

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All scientific concepts (especially the foundation of the GG-Constitution, GGEP/GG-6/BI-6, and OGGEP/GDOS/Gi-4/Qi-4 Pillars), theoretical judgments, physical interpretations, and any remaining errors are the sole responsibility of the author.

Part XIV
Technical Appendices

A graduate machine room in three blocks — Block I, the reference dictionaries and the cross-cohort naming convention; Block II, from-scratch, Step-graded derivation chapters on the physics of the main text, opening with the discrete symmetries in quantum mechanics and quantum field theory, then the flavor sector with its CP violation, the origin of the matter excess, the antiparticle, and the neutrino's century; and Block III, the ledger-and-registry appendices — the source ledger, the inheritance table, the benchmark audit, the named-statement deck, the promotion roadmap, and the falsification catalog — closing with the annotated reading guide — written for the incoming graduate student, with every derivation carried from the textbooks and the chapters' problems followed by complete worked solutions

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The main text argued; this Part teaches. It is a machine room in the cohort's appendix standard, and it is organized in three blocks. *Block I* is furniture: the abbreviations, the symbol glossary, and the naming convention by which the twenty-two papers cite one another. *Block II* is the curriculum, written for the incoming graduate student — especially the student joining a neutrino experiment or beginning flavor phenomenology — on one fixed principle, the same principle that governs the appendices of the two parent papers: *Step 1* builds the standard physics of a main-text topic from scratch, at textbook depth and with the textbooks cited; *Step 2* states precisely why quantum mechanics, quantum field theory, and the Standard Model cannot derive or predict the topic's key quantities; *Step 3* shows how the geometry derives, solves, and predicts them, at ledger grade. The opening chapter (Appendix D) treats the discrete symmetries themselves; the second (Appendix E) builds the flavor sector and its CP violation from the Yukawa couplings to the pentagon; the third (Appendix F) walks the matter excess from Sakharov's conditions to the assembled η_B; the fourth (Appendix G) explains the antiparticle four ways, ending with the one that is a theorem; the fifth (Appendix H) walks the neutrino's century from two-state quantum mechanics to the pentagon's lattice point, written for the incoming long-baseline student — ninety problems across the block, all followed by complete worked solutions. *Block III* records the registries — the source ledger, the inheritance table, the benchmark audit, the named-statement deck, the promotion roadmap, and the falsification catalog — and closes with the annotated reading guide. Nothing in the main text is needed to start; everything in Parts IV–XI can be recomputed by the reader who finishes.

Throughout these appendices we adhere to two stylistic commitments, shared with the parent papers. First, every derivation is presented step by step with no skipped intermediate manipulations: a graduate student should be able to reproduce each calculation with paper and pencil, and every problem is followed by a complete worked solution, never a bare answer. Second, every formal step is accompanied by a *physics intuition* note that translates the algebra into a mental picture — the beat of two clocks, the meshing of two gears, the currency market of the hot plasma. The combination is

designed to make the material accessible to the working experimentalist while preserving the rigor of the main text, so that the Part can be used as a one-semester reading course, one chapter per week, each self-contained.

Prerequisites and recommended textbooks. The course assumes advanced undergraduate quantum mechanics and a first exposure to quantum field theory (the discrete symmetries are rebuilt from Wigner's theorem upward in Appendix D, so a student meeting the subject for the first time can begin there). It is meant to be read *alongside* the canonical texts, not in place of them: the recommended way to use each chapter is to read the matching textbook chapter first, return to the Step-1 material here for a compact but complete recap, and only then proceed to Steps 2 and 3, where the standard result is re-examined and re-derived at its ledger grade. For self-study we particularly recommend the following, each cited again in the chapter to which it is best matched:

- **Foundations.** Sakurai and Napolitano (2017), *Modern Quantum Mechanics*, Ch. 4, and Weinberg (1995), *The Quantum Theory of Fields* I, Chs. 2 and 5 — the (anti)unitary implementation of symmetries and the causal-field construction behind Appendices D and G; Peskin and Schroeder (1995) for the propagator and loop machinery.
- **Discrete symmetries and flavor.** Sozzi (2008), *Discrete Symmetries and CP Violation* — the operation-centric experimental companion of the whole Part; Bigi and Sanda (2009), *CP Violation* — the flavor-centric classic; Branco, Lavoura, and Silva (1999), *CP Violation* — the rephasing-invariant calculus of Appendix E, whose Ch. 22 untangles every phase convention.
- **Neutrinos.** Giunti and Kim (2007), *Fundamentals of Neutrino Physics and Astrophysics* — the standard reference beneath Appendix H; Zuber (2020), *Neutrino Physics* — the experimentalist's companion; Mohapatra and Pal (2004), *Massive Neutrinos* — the seesaw's model space.
- **The early universe.** Kolb and Turner (1990), *The Early Universe* — the thermal history and relic machinery of Appendix F; Buchmüller, Di Bari, and Plümacher (2005) — the pedagogical leptogenesis review the transport follows.
- **Mathematical background.** Lawson and Michelsohn (1989), *Spin Geometry* — the Clifford-algebra reality classification behind the mod-8 clock of §G.4; Streater and Wightman (1964) for the axiomatic CPT theorem.

Throughout, the symbols GG-A1-Constitution–GG-A11-Origin, GG-P1-KK–GG-P3-Electron, and GG-C1-Kaxion–GG-C3-BH refer to member papers of the twenty-two-paper GG-Theory cohort, and GG-P4-Real to this paper's Foundations-Branch partner, to which the Step-3 material repeatedly points.

A Summary of Abbreviations

This appendix collects the abbreviations used in the present paper. All program-defined names are rendered in *sans-serif type* (GG-Theory, GG-Constitution, GG-6, GDOS, BI-6, OGN-5, Gi-4, Qi-4, GRIP, etc.) so the reader can see at a glance which terms belong to the GG-Theory program proper.

Standard physics abbreviations imported from the wider literature (CPT, CKM, PMNS, EDM, etc.) are rendered in plain uppercase Roman, following the convention of the major physics journals. One collision is policed throughout: CPT is the combined charge-conjugation–parity–time-reversal operation, never the completely-positive trace-preserving channel property, which is always written CPTP. The third column gives the *primary link*: the paper in the Arisaka-GG series (and the Part, where useful) in which each name is introduced in detail.

Table 28: Summary of abbreviations used in the present paper. Program-defined names are rendered in sans serif; standard physics abbreviations in plain uppercase Roman; mathematical objects in roman/italic in the usual way. The list is grouped by layer, from the framework's own objects through the ledger and the mirror operations to the standard physics abbreviations, and the right column links each entry to the place where it is defined, so that no abbreviation in the paper has to be guessed at from context.

Symbol	Meaning	Primary link
(1) Framework name and core program objects		
GG-Theory	Grand Geometric Theory (also: Geometry–Gauge Equivalence Theory)	GG-A1-Constitution, Preface
GG-Constitution	Constitutional charter: 4 axioms (AX-1–AX-4) + 7 postulates (POS-1–POS-7)	GG-A1-Constitution
GG-6	Geometry–Gauge locking in six dimensions: the 6D bulk	GG-A2-GG6
GDOS	Geometric Dynamics of Open Systems: the boundary law from OGGEP	GG-A5-GDOS
BI-6	Green–Schwarz-modified Bianchi identity at 6D, $dH_3 = X_4$	GG-A3-BI6
OGN-5	Occam-Gauge-Normalization 5-integer ledger $(M, N, L; J, K) = (1, 3, 5; 7, 35)$	GG-A3-BI6; GG-A2-GG6
Gi-4	Geometric-Invariance four-pillar structure (TGG, CCI, GFF, GRIP)	GG-A6-GRIP
Qi-4	Quantum-Information four-pillar structure (Qi-QUA, Qi-EP, Qi-CON, Qi-HAL)	GG-A7-Qi4
(2) Four axioms (AX-1–AX-4)		
AX	Axiom (axiomatic primitive; non-negotiable)	GG-A1-Constitution
LC	AX-1 Locality and Causality	GG-A1-Constitution
GGEP	AX-2 Geometry–Gauge Equivalence Principle	GG-A1-Constitution
OGGEP	AX-3 Operational/Open Geometry–Gauge Equivalence Principle	GG-A1-Constitution
MSMF	AX-4 Maximum Symmetry, Minimum Freedom (no hidden continuous knobs)	GG-A1-Constitution
(3) Seven postulates (POS-1–POS-7)		
POS	Postulate (admissibility filter; testable in principle)	GG-A1-Constitution
GI	POS-1 Gauge invariance across scales	GG-A1-Constitution
UEP	POS-2 Unified Extremal Principle	GG-A1-Constitution
AF	POS-3 Anomaly Freedom and cancellability by inflow	GG-A1-Constitution
CP	POS-4 Closure and Positivity (CPTP-admissible open dynamics)	GG-A1-Constitution

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Table 28 continued

Symbol	Meaning	Primary link
RG	POS-5 Renormalization-Group covariance (scale covariance)	GG-A1-Constitution
OGN	POS-6 Occam Gauge Normalization (canonical integer/rational normalization)	GG-A1-Constitution
MF	POS-7 Measurement and Falsifiability (operational contract + kill criteria)	GG-A1-Constitution
(4) Gi-4 pillars		
TGG	Total Geometric–Gauge object (Pillar I of Gi-4)	GG-A6-GRIP
CCI	Covariant Conservation Identity (Pillar II of Gi-4)	GG-A6-GRIP
GFF	Geometric Free-Energy Functional (Pillar III of Gi-4)	GG-A6-GRIP
GRIP	Gauge-Runtime Invariance Pipeline (Pillar IV of Gi-4)	GG-A6-GRIP
GA	Geometric Attractor (final stage of GRIP)	GG-A6-GRIP
(5) Qi-4 pillars and GDOS-internal acronyms		
Qi-QUA	Quantum information for Quadruple Gauge Locking (Pillar I of Qi-4)	GG-A7-Qi4
Qi-EP	Quantum information for the Unified Extremal Principle (Pillar II)	GG-A7-Qi4
Qi-CON	Quantum information for Conformal Invariance (Pillar III)	GG-A7-Qi4
Qi-HAL	Quantum information for the Holographic Attractor Lattice (Pillar IV)	GG-A7-Qi4
SIP	System Instance Packet (canonical GDOS input packet)	GG-A7-Qi4
SeOS	Selfish Open System (the core open system of GDOS)	GG-A5-GDOS
(6) Program terms in the context of this paper		
QD	Quantum-descent completion: the one-lattice-step correction of the parent codebook (e.g. $2\pi/5 \to 13\pi/35$)	GG-A9-SM; Part VII
D, D*	Grade vocabulary: Derived; Derived-conditional (named conjecture in the chain)	GG-A9-SM; Part XI
Kaxion	The GG-6 axion of the strong-CP two-fate architecture (8.1 μeV)	GG-C1-Kaxion
T-P5-x etc.	Named-result identifiers of this paper	Appendix C
(7) Standard physics abbreviations (plain Roman, journal convention)		
Symmetries and flavor		
CPT	Combined charge-conjugation–parity–time-reversal operation	textbook
CKM	Cabibbo–Kobayashi–Maskawa quark mixing matrix	textbook
PMNS	Pontecorvo–Maki–Nakagawa–Sakata lepton mixing matrix	textbook
$V-A$	Vector-minus-axial structure of the charged current	textbook
EDM	Electric dipole moment	textbook
NO / IO	Normal / inverted neutrino mass ordering	textbook
MSW	Mikheyev–Smirnov–Wolfenstein matter effect	textbook

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Table 28 continued

Symbol	Meaning	Primary link
NME	Nuclear matrix element (of $0\nu\beta\beta$)	textbook
$0\nu\beta\beta$	Neutrinoless double beta decay	textbook
ARS	Akhmedov–Rubakov–Smirnov oscillation leptogenesis	Akhmedov, Rubakov, and Smirnov (1998)
Frameworks and cosmology		
QM / QFT / SM	Quantum mechanics / quantum field theory / the Standard Model	textbook
GUT	Grand Unified Theory	textbook
LSZ	Lehmann–Symanzik–Zimmermann reduction	textbook
CPTP	Completely Positive Trace Preserving (never abbreviated CPT here)	textbook
RG	Renormalization Group	textbook
CMB	Cosmic Microwave Background	textbook
BBN	Big Bang Nucleosynthesis	textbook

Hierarchy of program-defined acronyms. For reference, Figure 27 records the six-tier hierarchy of the program-defined acronyms used across the GG-Theory cohort: the framework name and its constitutional charter; the four axioms and seven postulates; the bulk objects (GG-6, BI-6, OGN-5); the boundary law GDOS and its input packet SIP; the two four-pillar structures Gi-4 and Qi-4 with their sub-acronyms; and the energy–information Arisaka constant Q_B with the Arisaka equation that locks the four boundary currents. The diagram is shared verbatim with GG-A1-Constitution (its Figure 9) and with the parent appendices of GG-A9-SM and GG-A10-Cosmos, so that the acronym ledger is identical across the cohort.

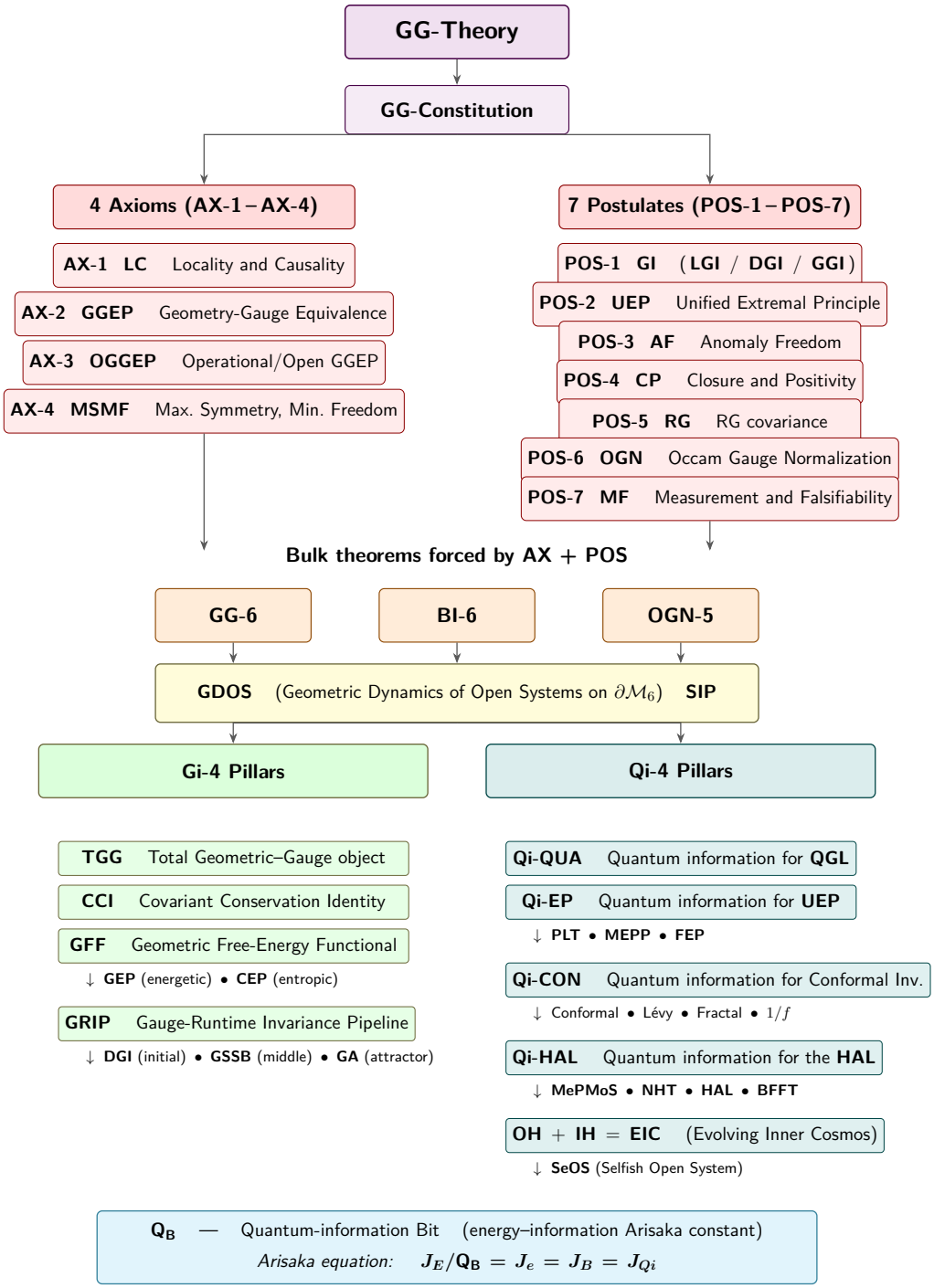

Figure 27: Hierarchy of program-defined acronyms in the GG-Theory program, shared verbatim with GG-A1-Constitution (its Figure 9), GG-A9-SM, and GG-A10-Cosmos. The figure groups the program's acronyms by the layer each belongs to and draws the dependencies between the layers, so that a reader meeting one of them in the middle of the paper can find the layer it lives on without searching. It is shared verbatim across the papers named above, which is why nothing in it is specific to this one.

B Glossary of Key Symbols

This appendix collects the key mathematical symbols used in the present paper. The first block records the bulk-geometry coordinates and the OGN-5 integer ledger that every later derivation appeals to; the second the inherited scale chain. The third records the two real structures of the handshake and the discrete-symmetry operators built from them. The fourth through sixth blocks record the flavor phases, the neutrino sector, and the leptogenesis chain — the quantities of the confrontation table of Part XI. The seventh records the laboratory observables of the mirrors themselves.

Table 29: Glossary of key symbols used in the present paper. "Source" gives the theorem, Part, or paper where the symbol is introduced or load-bearing. The symbols are grouped by the structure each belongs to, beginning with the bulk geometry and the ledger, and the source column points at the theorem, Part or companion paper in every case, so that a symbol met once in the middle of the paper can be traced to its definition in a single step rather than by search.

Symbol	Meaning	Source
N	The OGN-5 ledger's second entry, $N = 3$. Every ledger identity is written with it	—
N_c	Color triplicity, the three colors of $\mathrm{SU}(3)_C$ — what that entry counts	—
N_g	The generation (family) count, 3. *Not* a ledger entry; fixed by GG-P2-N3	—
N_f	The quark-flavor count of a beta function, $N_f = 2N_g = 6$ at high scale	—
(1) Bulk geometry and the OGN-5 ledger		
M_6	6D bulk manifold $M_4 \times I_r \times S^1_\theta$	GG-A2-GG6
r	Radial (scale-profile) coordinate, $r \in [0, K]$	GG-A2-GG6
θ	Compact fiber coordinate, $\theta \in [0, 2\pi)$: the charge circle	GG-A2-GG6; Part IV
S^1_θ	Compact direction circle (charge as winding)	GG-A2-GG6
$(M, N, L; J, K)$	OGN-5 ledger $= (1, 3, 5; 7, 35)$	GG-A3-BI6
$K = LJ$	Total scale depth $= 35$ (the throat-depth integer of the matter throughput)	GG-A2-GG6; Part VIII
$N_g = 3$	Family number (three-leg theorem)	GG-P2-N3
$L = 5$	Block size of the flavor texture: the pentagon	Part VII
(2) Scale chain		
M_{Pl}	Planck mass $\approx 1.22 \times 10^{19}$ GeV	—
E_{GUT}	GUT scale $= E_{\mathrm{Pl}}\, e^{-2\pi} \approx 2.28 \times 10^{16}$ GeV	GG-A2-GG6

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Table 29 continued

Symbol	Meaning	Source
M_{lock}	Lock scale $= \frac{1}{2} M_{\text{Pl}}\, e^{-K} \approx 3.85$ TeV (the heavy seesaw sector)	GG-A2-GG6; Part VIII
T_{rh}	Derived reheating temperature $\approx 3 \times 10^{10}$ GeV	GG-A10-Cosmos
(3) The handshake and the discrete operations		
J_Q	Circle complex structure $= \partial_\theta / Q$ on charge-n sectors (the gauge i)	T-P5-A
J_A	Clock complex structure $= \pm A(-A^2)^{-1/2}$, the polar phase (the state-space i)	T-P5-B
A	Time-translation generator on the real solution space	Part IV
J	The one global complex structure after the handshake ($J_A = J_Q$ on shell)	T-P5-C
ε	The 90° rotation on a weight pair ($\varepsilon^2 = -\mathbf{1}$)	Part II
$R(\varphi)$	Rotation block through angle φ (complex phase, real presentation)	Part II
B	Intertwiner to the conjugate spinor; $B\bar{B} = -\mathbf{1}$ in $(1,5)$	Lemma 24.1
Γ^7	6D chirality operator; splits $\mathbf{8} = \mathbf{4} \oplus \bar{\mathbf{4}}$	Part III
Θ	The antiunitary CPT operation (total orientation reversal)	T-P5-2
C, P, T	Orientation reversals of the three real factors (fiber, space, clock)	T-P5-1
(4) Flavor holonomies and the valued phases		
V, U	CKM and PMNS mixing matrices	Part VII
λ	Wolfenstein parameter $= \sin\theta_C \simeq 0.225$ (golden closed form, Eq. (53))	Part VII
δ_{CKM}	Quark CP phase $= 2\pi/5 \to 13\pi/35 = 66.86°$ (QD-completed)	T-P5-3
δ_{PMNS}	Leptonic CP phase $= \pi + 2\arcsin(1/7) = 196.43°$ (QD 196.06°)	T-P5-3
$(\alpha_{21}, \alpha_{31})$	Majorana phase pair $= (0, \pi)$	Part VII
$\sin\delta_{\text{PMNS}}$	The quiet signature $= -8\sqrt{3}/49 = -0.2828$ (exact surd)	Part VII
J_{CKM}	Quark Jarlskog invariant $= 3.1 \times 10^{-5}$ at the stated layer (band 2.7–3.2×10^{-5} across evaluation layers)	Part VII
J_{PMNS}	Leptonic Jarlskog invariant $\simeq -9.4 \times 10^{-3}$	Part VII
$\varepsilon, \varepsilon'$	Indirect and direct kaon CP parameters (recomputed as holonomy interferometry)	Appendix E
$\sin 2\beta$	B-sector mixing phase: 0.708 (stated moduli layer) vs measured 0.709 ± 0.011 (watched)	Part XI
$\bar{\theta}$	Strong-CP angle; two-fate leakage floor $\lesssim 5 \times 10^{-18}$	Part VII; GG-C1-Kaxion
(5) Neutrino sector		

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Table 29 continued

Symbol	Meaning	Source
(m_1, m_2, m_3)	Derived light triplet = $(0.065, 8.59, 50.5)$ meV, normal ordering	Part VIII
Δm^2_{21}	Solar splitting = 7.37×10^{-5} eV^2 (output)	Part VIII
Δm^2_{31}	Atmospheric splitting = 2.55×10^{-3} eV^2 (output)	Part VIII
$m_{\beta\beta}$	Effective Majorana mass = 1.72 meV (registered null for the ton scale)	Part XI
Y_ν	Seesaw-matched Yukawa $\simeq 7.3 \times 10^{-7}$	§85
$m_\star$	Equilibrium washout benchmark $\simeq 1.1 \times 10^{-3}$ eV (ledger-free)	Eq. (60)
(6) Leptogenesis and the receipt		
$\epsilon^{\rm res}$	Resonant decay asymmetry $\simeq 2.5 \times 10^{-6}$ (H-$\phi_{\rm geo}$-1 target value, now carried by an identified candidate mechanism; derived-cond.)	§85
Γ_N	Heavy-state width $\simeq 8 \times 10^{-11}$ GeV ($\Gamma_N/M_N \sim 2 \times 10^{-14}$)	§85
$K_{\rm wash}$	Washout strength = $\widetilde{m}/m_\star \simeq 50$	§23
κ	Washout efficiency = $1/K_{\rm wash} = 2.0 \times 10^{-2}$; the chain adopts 1.0×10^{-2} within the $O(1)$	§23
28/79	Sphaleron conversion coefficient $B = \frac{28}{79}(B-L)$	Eq. (104)
g_*	Relativistic degrees of freedom at production = 106.75	§23
η_B	Baryon-to-photon ratio: $\approx 7 \times 10^{-10}$ predicted (central 7.34; $\times 3^{\pm 1}$) vs $(6.12 \pm 0.04) \times 10^{-10}$	T-P5-5
(7) Laboratory observables of the mirrors		
η_{+-}, η_{00}	Kaon CP-violation amplitude ratios ($\varepsilon + \varepsilon'$, $\varepsilon - 2\varepsilon'$)	Appendix E.3
ϕ_{SW}	Superweak phase = $\arctan(2\Delta m_K/\Delta\Gamma_K) \simeq 43.5°$	Appendix E.3
δ_L	K_L semileptonic charge asymmetry = $2\,\mathrm{Re}\,\varepsilon/(1+\lvert\varepsilon\rvert^2)$	Appendix E.3
A_T	CPLEAR T-reversal asymmetry = $4\,\mathrm{Re}\,\varepsilon = (6.6 \pm 1.6) \times 10^{-3}$	Part I
S_f, C_f	Time-dependent B-decay asymmetry coefficients	Appendix E.4
A_{CP}	Long-baseline appearance asymmetry ($\sim -0.28 \sin\delta$ at Hyper-K kinematics)	Appendix H.3
d_n, d_e	Neutron and electron EDMs ($< 1.8 \times 10^{-26}$, $< 4.1 \times 10^{-30}\, e$ cm)	Part I

C Global naming convention for cross-cohort citation

Beginning with Arisaka (2026, A2-GG6) and extended across the cohort, each load-bearing item of the GG-Theory program carries a globally unique identifier of the form *Prefix-Suffix-N*, where the Prefix names the item type and the Suffix names the paper:

- **T-Suffix-N** for the Nth Theorem.

- **L-Suffix-N**, **C-Suffix-N**, **D-Suffix-N**, **R-Suffix-N** for the Nth Lemma, Corollary, Definition, and Remark.
- **P-Suffix-N** for the Nth Prediction.
- **O-Suffix-N** for the Nth Objection (the Common Objections Part).
- **F-Suffix-N** for the Nth Falsifier (the kill criteria that would retire the theory).
- **I-Suffix-N** for the Nth Innovation.
- **PS-Suffix-N** for the Nth Problem-Solved / status entry.

The canonical Suffix list for the twenty-two cohort papers is: *Constitution* (A1), *GG6* (A2), *BI6* (A3), *Euclid* (A4), *GDOS* (A5), *GRIP* (A6), *Qi4* (A7), *QM* (A8), *SM* (A9), *Cosmos* (A10), *Origin* (A11), together with the phenomenology preprints *KK* (P1), *N3* (P2), *Electron* (P3), *Proton* (P6), the foundations preprints *Real* (P4) and the present paper, *CPT* (P5), and the consequence preprints *Kaxion* (C1), *Hubble* (C2), *BH* (C3), and the white papers *Symmetry* (W1) and *Holonomy* (W2). The four axioms (AX-1 . . . AX-4) and seven postulates (POS-1 . . . POS-7) of Arisaka (2026, A1-Constitution) keep their cohort-wide names; the global identifier is the same item viewed from outside its home paper.

The present paper uses the suffix *P5*, with one refinement stated once: the deductive chain's theorems carry numbers (T-P5-1 through T-P5-5), while the handshake trio and its Wick companion carry letters (T-P5-A, T-P5-B, T-P5-C, T-P5-B1), as do the propositions and named conjectures (P-P5-D, P-P5-E; C-P5-A, C-P5-C) — the letters keep this paper's conjecture keys visually distinct from the cohort's numeric corollary keys, which this paper does not use. Falsifiers are F-P5-N, objections O-P5-N (eighty-two, in Part XV), and numbered predictions Pred-N (Part XI). Candidate results of the spin- and statistics-suite carry the L-Spin/L-Stat/T-Stat prefixes of their home papers (Arisaka, 2026, A2-GG6; Arisaka, 2026, A8-QM). A citation such as "Arisaka, 2026, A9-SM, Part VI" always refers to the deployed arXiv version of the named paper; the cross-paper coherence map guarantees that a key cited here resolves to a stated result there, and Part XVI's relevance notes say, for every entry, which result is consumed.

D Discrete symmetries in quantum mechanics and quantum field theory, from scratch

This is the opening chapter of Block II, and its subject is the main text's own foundation: what C, P, and T *are* in the standard account, derived slowly from the textbooks, so that the reader knows exactly what the orthodox framework delivers before Step 3 states what the geometry adds. The chapter shelf: Sakurai and Napolitano (2017) Chapter 4 for symmetry in quantum mechanics; Weinberg (1995) Chapters 2 (appendix A) and 5 for the (anti)unitary implementation and the field transformations; Peskin and Schroeder (1995) Chapter 3 for the Dirac bilinears; Sozzi (2008) throughout for the experimental face; Bigi and Sanda (2009) and Branco, Lavoura, and Silva (1999) for the flavor applications; Streater and Wightman (1964) for the axiomatic CPT of §D.4. Eighteen problems, complete solutions included.

D.1 Step 1 — symmetry in quantum mechanics: Wigner's theorem and the antiunitary fork

A quantum state is a *ray*: ψ and $e^{i\gamma}\psi$ describe one physical situation. A symmetry is a map of rays that preserves all transition probabilities, $|\langle\phi'|\psi'\rangle| = |\langle\phi|\psi\rangle|$. Wigner's theorem (Wigner, 1931) is the statement that every such map lifts to an operator U on the Hilbert space that is either *unitary and linear* or *antiunitary and antilinear* — there is no third option.

The proof's engine can be seen in two dimensions: fix an orthonormal pair $|1\rangle, |2\rangle$; ray preservation fixes the images of $|1\rangle, |2\rangle$, and the image of $|1\rangle + |2\rangle$ up to phase; the crux is the image of $|1\rangle + i|2\rangle$, whose overlap moduli with the previous three images admit exactly two consistent solutions — one sending $i \mapsto i$ (unitary branch) and one sending $i \mapsto -i$ (antiunitary branch). The whole dichotomy of the subject sits in that one sign (Weinberg, 1995, Ch. 2, App. A, carries the full proof).

Which branch does a given symmetry take? Energy decides. For a symmetry commuting with time evolution, $Ue^{-iHt}U^{-1} = e^{-iHt'}$ with $t' = \pm t$. Take time reversal, $t' = -t$. If T were *unitary*, then $THT^{-1} = -H$: the spectrum would be reflected through zero, and a world with a ground state would be paired with a world without one — forbidden for any Hamiltonian bounded below with unbounded spectrum above.

If T is *antiunitary*, the i in the exponent flips too, $Te^{-iHt}T^{-1} = e^{-iH(-t)}$ requires $THT^{-1} = +H$: the spectrum is preserved. Positivity of energy forces time reversal onto the antiunitary branch — the single most consequential sign in the discrete-symmetry canon, and the fact whose geometric face the main text derives (Step 3). Kramers' theorem follows in three lines: if $T^2 = -\mathbf{1}$ (half-integer spin), then for an energy eigenstate ψ, $T\psi$ is an eigenstate of the same energy, and $\langle\psi|T\psi\rangle = \langle T^2\psi|T\psi\rangle^* = -\langle\psi|T\psi\rangle = 0$: every level of a time-reversal-invariant half-integer system is at least doubly degenerate — a laboratory fact (odd-electron ions in electric fields) that no perturbation respecting T can lift. The textbook treatment is Sakurai and Napolitano, 2017, Ch. 4; the main text's Kramers corollary (Part IV) runs on the same $T^2 = -\mathbf{1}$.

What "symmetry" means at the bench. Before the formalism hardens, it is worth stating what these operators mean to a working experimenter, because the subject's power comes from how *operational* it is. A symmetry statement is always a statement about two runs of an experiment: prepare the mirrored (or charge-swapped, or motion-reversed) initial state, and compare counting rates.

Parity is testable because "the mirrored apparatus" is buildable — reverse the magnetic field coils and the detector geometry and you have applied P to everything you control. Charge conjugation is testable wherever antiparticles can be prepared — an antiproton beam, a positron source, the $\bar{B}$ in a $B\bar{B}$ pair.

Time reversal is the awkward one: nobody runs a detector backwards. What is actually reversed is *motion* — spins and momenta — and this is why T tests never look like "measure the T quantum number." Indeed there is no such number, and the proof is two lines. Suppose $T\psi = \lambda\psi$ and rephase the state, $\psi' = e^{i\gamma}\psi$ — the same ray. Antilinearity gives

$$T\psi' \;=\; T\,e^{i\gamma}\psi \;=\; e^{-i\gamma}\,T\psi \;=\; e^{-i\gamma}\lambda\,\psi \;=\; \left(e^{-2i\gamma}\lambda\right)\psi', \tag{69}$$

so the "eigenvalue" λ can be rotated to any phase by a choice that changes nothing physical: it is a convention, not a label. Unitary symmetries yield conserved quantum numbers and selection rules; the antiunitary one yields only *relations* — detailed balance between a process and its motion-reverse, reality constraints on amplitudes, and the forbidden alignments (like an EDM) whose absence can be hunted to eighteen digits.

The asymmetry of experimental style between P/C and T is not sociology; it is Wigner's fork expressed in hardware. The EDM lines of that hunt are this paper's Pred-8 (§136); the operational reading of symmetry underneath is the dictionary of Arisaka, 2026, A5-GDOS.

The 4π fact, measured. The projective freedom that Wigner's theorem legalizes is not an abstraction: it is why half-integer spin exists at all (a spin-$\frac{1}{2}$ state acquires a physical -1 under a 2π rotation, lawful because states are rays), and it has been measured directly — a neutron passed through a magnetic field region that precesses its spin by 2π interferes *destructively* with its unrotated partner beam, and constructively again at 4π (Rauch *et al.*, 1975).

Every discrete-symmetry table in this appendix stands on that experimental floor: the phases we track are physical precisely because interferometers can read them. The main text's spin–statistics section (§45) gives this 2π memory its geometric name; here it is simply the reason the bookkeeping below must be done with signs and not merely with words.

Problems and worked solutions. D.1.1. Complete the two-dimensional Wigner construction and exhibit the two branches explicitly.

Solution. Let the symmetry map send the rays of $|1\rangle, |2\rangle$ to those of $|1'\rangle, |2'\rangle$; choose representatives, which fixes two free phases we may spend later. Consider $|s\rangle = |1\rangle + |2\rangle$. Its image $|s'\rangle$ must satisfy $|\langle 1'|s'\rangle| = |\langle 1|s\rangle| = 1$ and likewise for $|2'\rangle$, so $|s'\rangle = e^{i\mu}(|1'\rangle + e^{i\nu}|2'\rangle)$ for some phases; absorb μ into the overall ray freedom and ν into the representative of $|2'\rangle$.

Thus we may take $|s\rangle \mapsto |1'\rangle + |2'\rangle$: so far everything looks linear. Now the crux: $|q\rangle = |1\rangle + i|2\rangle$. Ray preservation demands $|\langle 1'|q'\rangle| = |\langle 2'|q'\rangle| = 1$ and $|\langle s'|q'\rangle| = |1 + \bar{c}|/\ldots$ — concretely, writing $|q'\rangle = |1'\rangle + c\,|2'\rangle$ with $|c| = 1$, the condition $|\langle s'|q'\rangle| = |\langle s|q\rangle|$ reads $|1 + c| = |1 + i| = \sqrt{2}$, whose unit-modulus solutions are exactly $c = i$ and $c = -i$.

No third solution exists. The choice $c = i$ extends (one checks additivity and the analogous condition on every superposition) to a *linear, unitary* operator; the choice $c = -i$ extends to an *antilinear, antiunitary* one, $U(\alpha\psi) = \alpha^* U\psi$.

Physics intuition: a symmetry must preserve the interference pattern of $|1\rangle + i|2\rangle$ against $|1\rangle + |2\rangle$, and an interference pattern knows the *relative* phase only up to a global complex conjugation — the mirror image of the phase plane. Wigner's fork is the statement that a symmetry may leave the phase plane alone or flip it, and nothing else; the main text's Part V geometrizes the flip as the reversal of the one structure the phase plane is made of, the clock.

D.1.2. Show a unitary "time reversal" is admissible for a system with spectrum symmetric about zero, and why field theory excludes it.

Solution. Step 1: suppose U unitary with $Ue^{-iHt}U^{-1} = e^{+iHt}$. Differentiating at $t = 0$ gives $UHU^{-1} = -H$: a unitary time reversal requires a spectrum symmetric about zero.

Step 2: such systems exist. Take $H = \frac{\omega}{2}\sigma_z$ and $U = \sigma_x$: then $\sigma_x\sigma_z\sigma_x = -\sigma_z$, so $UHU^{-1} = -H$

exactly, and U is a perfectly lawful unitary implementing $t \to -t$ on this two-level system.

Step 3: why fields refuse. A relativistic field theory has H unbounded above (arbitrarily many quanta) and — by the spectrum condition — bounded below by the vacuum. A spectrum $[0, \infty)$ reflected through zero would be $(-\infty, 0]$: the map $H \to -H$ carries a world with a ground state to a world with none, and no unitary can relate the two spectra. The antiunitary branch escapes because antilinearity flips the i in e^{-iHt} as well, so time reversal holds with $UHU^{-1} = +H$.

Physics intuition: running the film backwards must not manufacture a bottomless energy pit; the only way to reverse the clock while keeping the floor is to conjugate the phases — which is precisely what "the clock owns the i" means downstream, in Step 3.

D.1.3. Prove $T^2 = (-1)^{2j}$ on a spin-j multiplet from $T = e^{-i\pi J_y}K$.
Solution. Step 1: apply T twice: $T^2 = e^{-i\pi J_y}Ke^{-i\pi J_y}K$.

Step 2: move the first K through the exponential. K complex-conjugates matrix elements, so $Ke^{-i\pi J_y}K = e^{+i\pi J_y^*}$. In the standard angular-momentum basis J_y is purely imaginary (J_x, J_z real), hence $J_y^* = -J_y$ and $Ke^{-i\pi J_y}K = e^{-i\pi J_y}$.

Step 3: therefore $T^2 = e^{-2\pi i J_y}$, a rotation by 2π about the y-axis. On integer spin a 2π rotation is the identity; on half-integer spin it is $-\mathbf{1}$, because the rotation group's double cover assigns $e^{-2\pi i J_y} = (-1)^{2j}$ on a spin-j irrep (diagonalize J_y: eigenvalues run over $-j, \ldots, +j$ in integer steps, so $e^{-2\pi i m}$ is $+1$ for all integer m, -1 for all half-odd m). Hence $T^2 = (-1)^{2j}$, and Kramers degeneracy follows for half-odd j as in the text.

Physics intuition: T^2 is secretly a full turn — reversing the clock twice drags the frame around once — and half-integer systems remember full turns with a sign. This is the frame-path memory of the main text's spin–statistics section (§45) surfacing in first-year notation: the same 2π that neutron interferometry measures is the one hiding inside every Kramers doublet.

D.2 Step 1 — P and C on the Dirac theory: the bilinear table, derived

The Dirac equation $(i\gamma^\mu\partial_\mu - m)\psi = 0$ is the arena in which P and C acquire their standard bodies. *Parity.* Send $\vec{x} \to -\vec{x}$; the equation retains its form iff $\psi'(t, -\vec{x}) = \eta_P\, \gamma^0\psi(t, \vec{x})$, since γ^0 commutes with γ^0 and anticommutes with γ^i, flipping the sign of the spatial derivative terms exactly as required; η_P is a free phase — note it, Step 2 will return to it. Two applications of P on a fermion give η_P^2, and the standard convention $\eta_P^2 = -1$ for fermion fields already shows convention entering where the beginner expects physics. *Charge conjugation.* Complex-conjugate the coupled Dirac equation $(i\gamma^\mu(\partial_\mu + ieA_\mu) - m)\psi = 0$: the sign of the charge flips. Seeking $\psi^c = C\bar{\psi}^{\mathsf{T}}$ satisfying the conjugate equation fixes $C^{-1}\gamma^\mu C = -\gamma^{\mu\,\mathsf{T}}$, solved in the Dirac representation by $C = i\gamma^2\gamma^0$ — the matrix is representation-dependent, the defining relation is not. From these two operators every entry of the classic bilinear table follows by direct computation: (signs for time/space components; Peskin and Schroeder, 1995, §3.6, is the assigned check). Two theorems the beginner should extract. First, the *opposite intrinsic parity of fermion and antifermion*: applying P to the mode expansion sends $b_{\vec{p}} \to \eta_P b_{-\vec{p}}$ but $d_{\vec{p}} \to -\eta_P^* d_{-\vec{p}}$ — the relative minus is convention-free, and it is tested every time para-positronium ($^1S_0$, P-eigenvalue -1 with $L = 0$) decays. Second, *C-parity of a fermion pair*: $C = (-1)^{L+S}$, so para-positronium ($S = 0$) is C-even and decays to two photons, ortho-positronium ($S = 1$) is C-odd and must go to three — lifetimes 0.125 ns versus 142 ns, a

Table 30: The classic bilinear table, computed rather than quoted. Each row is a Dirac bilinear and its behavior under P, C and T, with the pairs in parentheses giving the time and the space components separately. Nothing in it is new: every entry follows by direct computation from the two operators fixed immediately above, and the table is here so that a reader can set the geometric account beside the one every textbook carries and check them against each other.

bilinear	P	C	T
$\bar{\psi}\psi$ (S)	$+$	$+$	$+$
$\bar{\psi}i\gamma^5\psi$ (P)	$-$	$+$	$-$
$\bar{\psi}\gamma^\mu\psi$ (V)	$(+,-)$	$-$	$(+,-)$
$\bar{\psi}\gamma^\mu\gamma^5\psi$ (A)	$(-,+)$	$+$	$(+,-)$
$\bar{\psi}\sigma^{\mu\nu}\psi$ (T)	$(\pm)$	$-$	$(\mp)$

factor of a thousand from one sign; and $\pi^0 \to 3\gamma$, allowed by every conservation law except C, has never been seen (branching $< 3 \times 10^{-8}$). The discrete symmetries are not philosophy; they are selection rules with lifetimes attached. (Book-length treatments: Bigi and Sanda, 2009, Ch. 1; Sozzi, 2008, Chs. 2–3.)

How an intrinsic parity is actually measured: the pion. The assignments in the table are not conventions all the way down — relative parities are measured, and the classic case deserves its telling because every element of the method is still in use. Panofsky's reaction is capture of a stopped π^- on deuterium, $\pi^- d \to nn$. The initial state is an s-wave ($L = 0$) atomic capture, total angular momentum $J = 1$ (deuteron spin 1, pion spin 0). The two final neutrons must combine to $J = 1$. Two constraints now work in tandem. Statistics: for two identical fermions the total wavefunction is antisymmetric,

$$(-1)^{L_f}\,(-1)^{S+1} \stackrel{!}{=} -1 \quad \Longrightarrow \quad L_f + S \text{ even}, \tag{70}$$

and among the $J = 1$ candidates ($^3S_1$, $^1P_1$, $^3P_1$, $^3D_1$) only $^3P_1$ ($L_f = 1$, $S = 1$) survives. Parity: balance initial against final,

$$\eta_\pi\,\eta_d\,(-1)^{L_i} \;=\; (\eta_n)^2\,(-1)^{L_f} \quad \Longrightarrow \quad \eta_\pi \cdot (+1) \cdot (+1) \;=\; (+1)\cdot(-1)^1, \tag{71}$$

so $\eta_\pi = -1$: the pion is *pseudoscalar*. One stopped-beam experiment, one statistics argument, one quantum number — and the pattern (use statistics plus angular momentum to trap the parity) is the template for every parity assignment in the Review of Particle Physics (Particle Data Group, 2024). Notice what did the work: Fermi statistics again — the same exchange sign of D.1.3, now employed as a measuring instrument. The geometry traces that same sign to bulk frame paths (Arisaka, 2026, A2-GG6, §20; §45 here).

How a handedness is measured: Goldhaber's neutrino. The V−A structure's most beautiful direct test predates the modern beams.

Goldhaber, Grodzins, and Sunyar (Goldhaber, Grodzins, and Sunyar, 1958) measured the helicity of the neutrino itself with tabletop apparatus: electron capture on ^{152}Eu ($J = 0$) produces ^{152}Sm* ($J = 1$) plus a neutrino; the excited Sm decays by a 961 keV photon. Select, by resonant scattering,

only the photons emitted *opposite* to the neutrino and Doppler-shifted into resonance — these are the photons emitted along the Sm* recoil, i.e. opposite the neutrino. The angular-momentum ledger along the neutrino axis, with the captured s-electron contributing $\pm\frac{1}{2}$ and the initial $J = 0$:

$$0 \;=\; \underbrace{\mp\tfrac{1}{2}}_{e^-\ \text{spin}} \;+\; \underbrace{h_\nu \cdot \tfrac{1}{2}}_{\nu} \;+\; \underbrace{M_{\mathrm{Sm}^*}}_{J_z=0,\pm1} \quad\Longrightarrow\quad M_{\mathrm{Sm}^*} = \pm 1 \text{ correlates with } h_\nu, \tag{72}$$

and for the forward-emitted 961 keV photon the Sm* polarization passes wholly to circular polarization, $h_\gamma = h_\nu$. Measuring h_γ by transmission through magnetized iron (Compton scattering on polarized electrons is spin-dependent) gave

$$h_\nu \;=\; -1.0 \pm 0.3, \tag{73}$$

the neutrino left-handed, fully, not partially.

Physics intuition for the experimenter: helicity was transferred, step by step, from an invisible particle to a measurable photon polarization through nothing but conservation laws — no accelerator, no tracking, one NaI crystal and a magnetized-iron analyzer. Maximal parity violation is not a high-energy exotic; it sits in a table-top gamma line. (Context and successors: Sozzi, 2008, Ch. 7; the geometry's one-hand reading is Part VI.)

Furry's theorem, or why the photon's C-parity earns its keep. The photon's $C = -1$ is not decoration: it implies that any process connecting an odd number of photons with no other C-odd quanta must vanish. In QED this is Furry's theorem — amplitudes with an odd number of external photons and closed electron loops cancel identically — and its laboratory face is the non-observation of $\pi^0 \to 3\gamma$ and of photon splitting in vacuum.

When an experiment quotes a 3γ branching limit, it is publishing a C-conservation test of the electromagnetic interaction; the table above tells you exactly which interactions are allowed to break it (the weak, which does, spectacularly) and which are not.

Problems and worked solutions. D.2.1. Verify the V and A rows of the bilinear table.

Solution. Parity first. With $\psi'(t,\vec{x}) = \gamma^0\psi(t,-\vec{x})$, a vector bilinear transforms as $\bar{\psi}'\gamma^\mu\psi' = \psi^\dagger\gamma^{0\dagger}\gamma^0\gamma^\mu\gamma^0\psi = \bar{\psi}\,\gamma^0\gamma^\mu\gamma^0\,\psi$ (arguments at $-\vec{x}$ throughout). Now $\gamma^0\gamma^0\gamma^0 = \gamma^0$ while $\gamma^0\gamma^i\gamma^0 = -\gamma^i$: the time component is even, the space components odd — exactly how a velocity or a current behaves in a mirror.

For the axial row insert γ^5: since $\gamma^0\gamma^5 = -\gamma^5\gamma^0$, each sign above flips — time component odd, space components even: the behavior of a spin or a magnetic field. Charge conjugation: using $\psi^c = C\bar{\psi}^{\mathsf{T}}$ with $C^{-1}\gamma^\mu C = -\gamma^{\mu\mathsf{T}}$, a short transpose computation (remembering the anticommuting fields contribute one minus sign on reordering) gives $\bar{\psi}^c\gamma^\mu\psi^c = -\bar{\psi}\gamma^\mu\psi$ and $\bar{\psi}^c\gamma^\mu\gamma^5\psi^c = +\bar{\psi}\gamma^\mu\gamma^5\psi$: the electric current reverses for antimatter, the axial current does not.

Physics intuition and the payoff: the weak current is $V-A$, $\bar{\psi}\gamma^\mu(1-\gamma^5)\psi$ — the *difference* of two objects with opposite P behavior. Under parity it becomes $V+A$: not slightly changed but mapped onto the coupling nature declines to use. Maximal parity violation is thereby a statement of *absence* (no $V+A$ partner exists), which is precisely the shape of the main text's Part VI claim.

D.2.2. Derive $C = (-1)^{L+S}$ for a fermion–antifermion pair.

Solution. Act with C on the pair state: it exchanges which field quantum is "the particle" and "the antiparticle," i.e. it maps the state onto the same two quanta with their roles swapped. To compare with the original, un-swap them by exchanging the two quanta completely — position and spin — and pay the prices: (i) spatial exchange in a relative partial wave L gives $(-1)^L$; (ii) spin exchange in a coupled spin state gives $(-1)^{S+1}$ (+ for the symmetric triplet, − for the antisymmetric singlet, packaged as one formula); (iii) exchanging two fermionic operators costs the Fermi sign (-1).

The product is the C eigenvalue: $\eta_C = (-1)^L\,(-1)^{S+1}\,(-1) = (-1)^{L+S}$. Check against nature: para-positronium ($L = 0, S = 0$) has $C = +1$ and decays to two photons (each photon C-odd, $(-1)^2 = +1$); ortho-positronium ($L = 0, S = 1$) has $C = -1$ and must emit three — the thousandfold lifetime ratio of the text.

Physics intuition: C-parity of a bound pair is not a new quantum number but bookkeeping of exchange symmetry — the same Fermi sign that Appendix D.1.3 traced to a 2π turn — so the selection rules of positronium are, at bottom, statistics made visible in light.

D.2.3. Show a nonzero neutron EDM requires both P and T violation.

Solution. For a spin-$\frac{1}{2}$ particle the only available vector is the spin $\vec{\sigma}$, so any electric dipole must point along it: the interaction is $H_d = -d\,\vec{\sigma}\cdot\vec{E}$, to be compared with the magnetic term $H_\mu = -\mu\,\vec{\sigma}\cdot\vec{B}$. Under P: $\vec{E}\to-\vec{E}$ (polar), $\vec{B}\to+\vec{B}$ (axial), $\vec{\sigma}\to+\vec{\sigma}$ (angular momentum). So H_μ is P-even but H_d is P-*odd*. Under T: $\vec{E}\to+\vec{E}$, $\vec{B}\to-\vec{B}$, $\vec{\sigma}\to-\vec{\sigma}$. So H_μ is T-even but H_d is T-*odd*. A nonzero d therefore violates P and T simultaneously — and, by the CPT theorem of D.4, T violation is CP violation.

Physics intuition: an EDM is an arrow of charge separation nailed to an arrow of rotation; mirror-flip the charges or run the spin backwards and the two arrows fall out of alignment unless the underlying dynamics distinguishes the two orientations. That is why the neutron EDM is the cleanest null in the strong-CP story: a $\bar\theta$-term would nail the arrows together at $d_n \sim 10^{-16}\,\bar\theta\ e\,\mathrm{cm}$, the measured $|d_n| < 1.8\times10^{-26}\ e\,\mathrm{cm}$ forces $\bar\theta < 10^{-10}$, and the main text's two-fate architecture predicts the arrows stay unglued down to $\bar\theta \sim 5\times10^{-18}$ — eight orders of silence, registered in Table 26.

D.3 Step 1 — T in the laboratory: Wu's asymmetry and the kaon matrix

Two computations anchor the operations in data. *Wu's asymmetry, quantified.* Polarized ^{60}Co emits betas with rate $W(\theta) \propto 1 + \alpha\,(v/c)\cos\theta$, with θ measured from the nuclear spin. Under P, momenta flip and spins do not, so $\cos\theta \to -\cos\theta$: any $\alpha \neq 0$ is parity violation. The V−A current predicts $\alpha = -1$ for a Gamow–Teller transition: the 1957 observation of a large asymmetry was not a small effect but a *maximal* one — the mirror was not chipped; it was gone.

The main text's Part VI is the claim that this maximality is an absence, not a parameter. *The neutral-kaon matrix.* The $(K^0, \bar K^0)$ system evolves by an effective non-Hermitian Hamiltonian $H = M - \frac{i}{2}\Gamma$, with CPT forcing equal diagonal elements $H_{11} = H_{22}$ and T-invariance forcing $|H_{12}| = |H_{21}|$. Diagonalizing, the physical states are $K_{S,L} \propto (1+\epsilon)K^0 \pm (1-\epsilon)\bar K^0$ with $\epsilon = (\sqrt{H_{12}} - \sqrt{H_{21}})/(\sqrt{H_{12}} + \sqrt{H_{21}})$: the 1964 observation of $K_L \to \pi\pi$ measured $|\epsilon| = 2.23\times10^{-3}$ and put a nonzero T-violating phase into the world's bookkeeping — while the *equality of the*

diagonal, tested through $m_{K^0} - m_{\bar{K}^0}$, became and remains the sharpest CPT test in physics, $|m - \bar{m}|/m < 6 \times 10^{-19}$. One 2×2 matrix carries the whole subject: CP violation in its off-diagonal phases, CPT in its diagonal equality. (Formalism at book depth: Branco, Lavoura, and Silva, 1999, Ch. 6; Bigi and Sanda, 2009, Ch. 6; the paper's own CPT-test record opens Part I.)

Wu's experiment as an experimenter reads it. The 1957 measurement rewards a closer look than the textbooks give it, because every difficulty was a systematics problem of a kind still faced daily.

To polarize the ^{60}Co nuclei the sample was cooled to ~ 10 mK by adiabatic demagnetization inside a cerium-magnesium-nitrate cryostat — the nuclear polarization rode on the hyperfine field of the aligned electrons — and the polarization was *monitored in situ* by the anisotropy of the accompanying γ rays (a P-even effect, hence a built-in control).

The signal was the up–down counting asymmetry of the betas relative to the polarizing field: with nuclear polarization P,

$$W(\theta) \;\propto\; 1 + \alpha\, P\, \frac{v}{c} \cos\theta, \qquad A \;\equiv\; \frac{W(0) - W(\pi)}{W(0) + W(\pi)} \;=\; \alpha\, P\, \frac{v}{c}, \tag{74}$$

with the V−A prediction $\alpha = -1$ for the pure Gamow–Teller ^{60}Co transition; at the achieved $P \sim 0.6$ and $v/c \sim 0.6$ the expected asymmetry is $|A| \sim 0.4$ — enormous, and observed. The decisive systematic check was the simplest imaginable: reverse the field. The asymmetry followed the field; warming the sample (killing the polarization) killed the asymmetry on the polarization's own timescale.

The observed coefficient was consistent with the maximal $\alpha = -1$ of a pure Gamow–Teller V−A transition: electrons emitted preferentially *opposite* the nuclear spin. Two further 1957 confirmations — the $\pi \to \mu \to e$ decay chain's muon polarization (Garwin–Lederman) and independent nuclear work — arrived within weeks, and C violation came with P violation in the same data, since the observed correlation is C-odd as well. The lesson that outlived the shock: a discrete symmetry test is only as good as its reversal systematics — field flips, sample swaps, magnet polarities — and that discipline, invented here, is the daily bread of every EDM and asymmetry experiment since.

T-odd observables, and the final-state trap. With T lacking eigenvalues (D.1), laboratory T tests use *T-odd correlations*: triple products such as $\vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu)$ in polarized beta decay (the D coefficient) or $\vec{\sigma}_e \cdot (\vec{J} \times \vec{p}_e)$ (the R coefficient).

Here the experimenter must internalize a famous subtlety: a nonzero T-odd correlation is *not* by itself T violation. Final-state interactions — ordinary Coulomb rescattering between the outgoing charged particles — generate T-odd correlations in a perfectly T-symmetric theory, because motion reversal relates the observed decay to the time-mirrored *in*-state that rescattering has altered. The genuine test is either to compute and subtract the final-state mimicry (it enters at order $Z\alpha$ and is calculable in beta decay: the measured $D = (-0.6 \pm 1.0) \times 10^{-4}$ in neutron decay sits an order of magnitude above its FSI floor) or to choose observables where mimicry cannot reach — which is the deep reason the EDM, a *static* property of an isolated particle with no final state at all, is the T test of record. (Reviews: Sozzi, 2008, Ch. 4; this paper's EDM window is row 8 of Table 26.)

The kaon complements both: CPLEAR compared the rates of $K^0 \to \bar{K}^0$ against $\bar{K}^0 \to K^0$ directly — the Kabir asymmetry: tagging the strangeness at production (via $\bar{p}p \to K^{\mp}\pi^{\pm}K^0/\bar{K}^0$)

and at decay (via the semileptonic charge),

$$A_T \;=\; \frac{R(\bar K^0\to K^0)-R(K^0\to\bar K^0)}{R(\bar K^0\to K^0)+R(K^0\to\bar K^0)} \;=\; 4\,\mathrm{Re}\,\epsilon \;+\; \ldots \;=\; (6.6\pm1.6)\times10^{-3} \tag{75}$$

(CPLEAR Collaboration, 1998) — time reversal violated in so many words, the two directions of one oscillation clocked against each other, and the value consistent with $4\,\mathrm{Re}\,\epsilon = 4\times1.66\times10^{-3} = 6.6\times10^{-3}$ from the mixing formalism above. One subject, three instruments: correlations (with their FSI discipline), static moments (with their reversal discipline), and oscillations (with their tagging discipline). The main text's claim that the mirrors are *anatomy* does not change one of these techniques; it changes what the accumulated record is evidence *of*.

Problems and worked solutions. D.3.1. Derive the $K_{S,L}$ eigenstates and the ϵ formula.
Solution. In the $(K^0,\bar K^0)$ basis write $H=\left(\begin{smallmatrix}A & p^2\\ q^2 & A\end{smallmatrix}\right)$, where CPT has forced equal diagonals $A=M_{11}-\frac{i}{2}\Gamma_{11}$ and we abbreviate $H_{12}=p^2$, $H_{21}=q^2$. Eigenvalue problem: $\det(H-\lambda)=(A-\lambda)^2-p^2q^2=0$, so $\lambda_\pm=A\pm pq$, and the eigenvectors are $p\,|K^0\rangle\pm q\,|\bar K^0\rangle$ (unnormalized): the splitting lives entirely off-diagonal, the average entirely on.

Define ϵ by $p/q=(1+\epsilon)/(1-\epsilon)$; equivalently $\epsilon=(p-q)/(p+q)=(\sqrt{H_{12}}-\sqrt{H_{21}})/(\sqrt{H_{12}}+\sqrt{H_{21}})$, and the physical states are $K_{S,L}\propto(1+\epsilon)|K^0\rangle\pm(1-\epsilon)|\bar K^0\rangle$ as claimed. If T holds, $|H_{12}|=|H_{21}|$ and a phase convention can make $p=q$: $\epsilon=0$ and the eigenstates are the CP eigenstates. A nonzero $\mathrm{Re}\,\epsilon$ (convention-free) is T violation in the mixing.

Physics intuition: the kaon pair is a two-slit experiment run in time — $K^0\to\bar K^0$ through virtual $\pi\pi$ and W-box paths — and ϵ measures the failure of the forward and backward films of that oscillation to match. Nature's answer, $|\epsilon|=2.23\times10^{-3}$, is the two-per-thousand mismatch that started the entire subject of Part VII.

D.3.2. Derive the Bell–Steinberger relation.
Solution. Step 1: for the effective (non-Hermitian) evolution $i\,\dot\psi=H\psi$, probability is not conserved inside the two-state space — it leaks into decay channels. Compute the leak of the overlap: $\frac{d}{dt}\langle K_S(t)|K_L(t)\rangle=i\langle K_S|(H^\dagger-H)|K_L\rangle=-\langle K_S|\Gamma|K_L\rangle$, while the explicit time dependence of the eigenstates gives the same overlap evolving as $e^{-i(m_L-m_S)t}\,e^{-(\Gamma_S+\Gamma_L)t/2}$.

Step 2: unitarity of the *full* theory says the absorptive part Γ is built from real decay amplitudes, $\langle K_S|\Gamma|K_L\rangle=\sum_f A^*(K_S\to f)A(K_L\to f)$. Equating the two expressions at $t=0$:

$$\Big(\tfrac{\Gamma_S+\Gamma_L}{2}+i\,\Delta m\Big)\langle K_S|K_L\rangle \;=\; \sum_f A^*(K_S\to f)\,A(K_L\to f).$$

Step 3: with CPT held, $\langle K_S|K_L\rangle=2\,\mathrm{Re}\,\epsilon/(1+|\epsilon|^2)$, so the measured decay amplitudes on the right determine $\mathrm{Re}\,\epsilon$ — and any residue not accounted for becomes a bound on the CPT-violating diagonal splitting.

Physics intuition: the relation is bookkeeping of leaks — the non-orthogonality of the two physical kaons must be paid for, channel by channel, by their shared decays. It converts a zoo of branching measurements into the world's best inventory of where T and CPT violation could hide,

and finds essentially all of it in ϵ.

D.3.3. Estimate the fractional CPT mass sensitivity.
Solution. The interferometer's observable is the strangeness oscillation phase $\Delta m\, t$, read against the known lifetime clock Γ_S over $\sim$ 10–20 lifetimes; the regeneration and semileptonic asymmetries determine the relative phase between mixing and decay to $\sim 10^{-3}$ precision. A CPT-violating diagonal splitting $\delta = (m_{K^0} - m_{\bar{K}^0}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})$ shifts that phase by $\sim \delta/\Delta m$.

Sensitivity therefore: $|m - \bar{m}| \sim \Delta m \times (\text{phase precision}) \sim 3.5 \times 10^{-12}\,\text{MeV} \times 10^{-3} \sim 10^{-15}$ MeV, i.e. $|m - \bar{m}|/m_K \sim 10^{-15}/500 \sim 10^{-18}$ — the 6×10^{-19} of the Particle Data Group with the factors done honestly.

Physics intuition: the kaon wins by leverage — it compares particle with antiparticle through an oscillation whose beat frequency ($\Delta m/m \sim 10^{-14}$) is itself tiny, so a given phase precision buys fourteen extra orders in mass. It is the same trick the long baselines play with $\Delta m^2 L/E$; interferometry is how small numbers are read, in every era of this subject.

D.4 Step 1 — the CPT theorem, by both roads

The Lagrangian road (Lüders–Pauli) (Lüders, 1954; Pauli, 1955). Claim: any local, Lorentz-invariant, Hermitian Lagrangian of normal-ordered fields is invariant under the product $\Theta = CPT$, whatever its C, P, T behavior separately. The engine is that Θ acts on every field as an antiunitary map sending $\phi(x) \to \phi^\dagger(-x)$ up to spin-dependent signs, so on any Lorentz-scalar monomial it delivers the Hermitian conjugate at $-x$ with a sign $(-1)^{2J}$ that Lorentz invariance forces to unity for a scalar combination.

Walk one term: the Yukawa $g\,\bar{\psi}_1\psi_2\,\phi + \text{h.c.}$ Under Θ: $\phi \to \phi^\dagger(-x)$, and the scalar bilinear $\bar{\psi}_1\psi_2 \to (\bar{\psi}_1\psi_2)^\dagger(-x) = \bar{\psi}_2\psi_1(-x)$ (the S row of the table, all three signs multiplied); antilinearity conjugates g; the term maps to $g^*\,\bar{\psi}_2\psi_1\,\phi^\dagger$ at $-x$ — which is exactly the Hermitian-conjugate term the Lagrangian already contains.

Hermiticity is thus the whole secret: CPT holds because a Hermitian $\mathcal{L}$ contains every term's conjugate, and Θ merely swaps them. *The axiomatic road (Jost).* In the Wightman framework the same conclusion follows with no Lagrangian at all: the vacuum correlation functions $W(x_1, \ldots, x_n)$ are (i) boundary values of functions analytic in the forward tube (the spectrum condition — energies positive — is what grants the continuation: the main text's one-sided clock, in its field-theoretic uniform); (ii) invariant under the complexified Lorentz group, which connectedly contains the total reflection $x \to -x$; (iii) at the real *Jost points* (totally spacelike configurations) the continuation can be evaluated, and locality converts the reflected function into the CPT-conjugate ordering (Jost, 1957; Streater and Wightman, 1964).

The consequences are then theorems, not folklore, and each is a measurement: particle and antiparticle masses equal (the kaon's 6×10^{-19}), total lifetimes equal (muon pair at 10^{-4}), magnetic moments opposite (electron pair at 10^{-12}), and the fine-structure spectra of hydrogen and antihydrogen identical (ALPHA's $1S$–$2S$ at 2×10^{-12}) — the six-comparison record of the main text's Part I.

The modern CPT program, instrument by instrument. An experimenter should know where the exactness of CPT is actually held to account, because the portfolio is broader than the kaon.

Interferometric: the neutral-kaon diagonal equality (the 6×10^{-19} of §D.3) and the B-system's analogous bounds. Spectroscopic: antihydrogen — ALPHA's $1S$–$2S$ comparison with hydrogen at 2×10^{-12} fractional precision (ALPHA Collaboration, 2020), with the hyperfine splitting and gravitational sign tested in parallel programs.

Electromagnetic: the Penning-trap comparisons — proton versus antiproton charge-to-mass at the level of parts in 10^{12}, and the g-factor comparison at parts in 10^9 — where a single particle oscillating in a trap for months is the entire experiment; and the electron–positron g pair, agreeing at parts in 10^{12}. Leptonic: muon and antimuon lifetimes and moments; muonium spectroscopy.

The pattern across the portfolio: every test is a *comparison of two clocks*,

$$\delta_{\mathrm{CPT}}^{K} = \frac{(M_{11} - M_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{\lambda_S - \lambda_L}, \qquad \frac{\nu_{1S2S}^{\bar{H}} - \nu_{1S2S}^{H}}{\nu_{1S2S}} < 2 \times 10^{-12}, \qquad \frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 \;\sim\; 10^{-12}, \tag{76}$$

a particle's oscillation, transition, or precession against its conjugate's — because CPT's content is precisely that the conjugate world keeps identical time. And one theorem organizes the stakes: Greenberg's result (Greenberg, 2002) that CPT violation in an interacting field theory entails Lorentz violation, so the portfolio above doubles as the low-energy anchor of the entire Lorentz-invariance program (the standard-model-extension coefficient tables). (The full compilation of limits: Particle Data Group, 2024.)

For this paper the consequence is stark and stated in the falsifier table: the geometry has no parameter by which CPT could fail a little — any confirmed violation, in any system in this portfolio, at any precision, retires the framework outright. That is what it means, operationally, for CPT to be promoted from theorem-given-axioms to anatomy: the entire portfolio becomes one standing kill test with many hands on the switch.

Problems and worked solutions. D.4.1. Carry the Θ-walk through $g\,\bar{\psi}\gamma^{\mu}\psi A_{\mu}$.

Solution. Assemble the CPT behavior factor by factor, using the table of §D.2 row by row. Under C: $\bar{\psi}\gamma^{\mu}\psi \to -\bar{\psi}\gamma^{\mu}\psi$ and $A_{\mu} \to -A_{\mu}$ (the photon is C-odd, which is why it couples to a C-odd current): product invariant. Under P: the vector current's index behaves as $(+,-)$ and so does A_{μ} evaluated at the reflected point: each Lorentz index contracts evenly; product invariant.

Under T (antiunitary): the current's index behaves as $(+,-)$ again, $A_{\mu}(t,\vec{x}) \to A^{\mu}(-t,\vec{x})$, and the antilinearity conjugates the coupling; since g is real by Hermiticity, the term returns to itself. Multiplying the three, every sign cancels index by index and the interaction is exactly CPT invariant — with each factor's arguments now at $-x$, as the theorem demands. The instructive second case: the QCD θ-term $\frac{\theta g^2}{32\pi^2} G\tilde{G}$ is P-odd and T-odd (it is an $\vec{E}\cdot\vec{B}$ of color), yet it too passes the Θ-walk, because CPT never required P or T separately — only the total.

Physics intuition: CPT invariance of a term is Hermiticity wearing spacetime clothes; and the θ-term's lawful presence is precisely why strong CP is a *problem* — the frame permits the crime and cannot price it, which is the opening of the main text's two-fate chapter.

D.4.2. The free-scalar two-point function and its Jost-point reflection.

Solution. Step 1: from the mode expansion, $W(x) \equiv \langle 0|\phi(x)\phi(0)|0\rangle = \int \frac{d^3p}{(2\pi)^3\,2\omega_p}\, e^{-i(\omega_p t - \vec{p}\cdot\vec{x})}$, every frequency *positive*: the spectrum condition in its simplest instance.

Step 2: because all $\omega_p > 0$, the integrand decays when t acquires a negative imaginary part: W extends holomorphically to the "forward tube" $\mathrm{Im}\, t < 0$ (in the Lorentz-covariant statement, $\mathrm{Im}\, x$ in the past cone).

Step 3: on this domain the function is invariant under the connected complex Lorentz group; setting the complexified boost/rotation parameters appropriately one reaches the total reflection $x \to -x$ inside the domain of analyticity.

Step 4: evaluate at spacelike (Jost) points, where the tube's boundary values are ordinary functions: covariance forces W to depend only on the invariant x^2 there, and x^2 is even under $x \to -x$; hence $W(x) = W(-x)$ for spacelike x — which, undoing the definitions, is the CPT relation for the two-point function (and, with locality, the n-point generalization is Jost's theorem).

Physics intuition: positivity of energy is a one-sided condition, and one-sided conditions buy analyticity — the freedom to steer around the real axis and come back with a reflection you could never perform physically. This is the exact mechanism the main text names the clock's quarter-turn (T-P5-B1): Wick rotation, CPT, and (in §45) the exclusion principle are all cashings of the same one-sided cheque.

D.4.3. Partial widths and rescattering classes.

Solution. Step 1: CPT applied to the full resolvent forces equal *total* widths, $\Gamma_{\mathrm{tot}}(i) = \Gamma_{\mathrm{tot}}(\bar{\imath})$ (D.4's consequence list).

Step 2: it does not force equal partial widths. Write each decay amplitude with its weak (CP-odd) and strong (CP-even rescattering) phases, $A(i \to f) = \sum_k |A_k| e^{i\phi_k} e^{i\delta_k}$; then $A(\bar{\imath} \to \bar{f})$ has $\phi_k \to -\phi_k$ with δ_k fixed, and $\Gamma(i \to f) - \Gamma(\bar{\imath} \to \bar{f}) \propto \sum_{k<l} |A_k||A_l| \sin(\phi_k - \phi_l) \sin(\delta_k - \delta_l)$: a partial-rate asymmetry needs *both* a weak-phase difference and a strong-phase difference.

Step 3: sum over the channels connected by the rescattering (the same δ's): unitarity of the strong S-matrix makes the asymmetries cancel within each class, so the total-width equality of Step 1 is honored channel-class by channel-class.

Physics intuition: CP asymmetries are interference phenomena that borrow their visibility from rescattering, and what one channel borrows another must repay. This is exactly why baryogenesis cannot run in equilibrium — with all channels open and balanced, every asymmetry is repaid — and why Sakharov's third condition, the departure from equilibrium, is load-bearing: the main text's Part VIII tripod is this problem's bookkeeping, promoted to a cosmology.

D.5 Step 2 — what quantum field theory cannot say

Now the audit, stated with the same care as the derivations. *(1) The operations are conventions.* Every discrete operator above carries free phases per species (η_P, η_C, η_T); only products constrained by interactions are physical. QFT provides a *consistency frame* for C, P, T — it does not define them individually, and seventy years of data sit atop operators the formalism cannot uniquely name. *(2) The breakings are inputs.* Nothing in the framework predicts that P is violated, that its violation is maximal, that C fails with it, or that CP fails at 2.28×10^{-3} in the kaon: the V−A structure and the KM phase are written into the Lagrangian by hand, and $\delta = 0$ would have been equally lawful.

(3) The one proved symmetry illuminates nothing about its factors. The CPT theorem holds for *any* local theory; its proof gives no insight into why nature breaks each factor separately — a

conspiracy of accidents capped by an axiom. *(4) The i is axiomatic.* Both CPT roads lean on the complex structure and the positivity of energy as postulates; the framework cannot see beneath its own i (the main text's Part X verdict).

(5) No valuation. Even granting the breakings, QFT prices nothing: not the phase, not the angles, not $\bar{\theta}$'s smallness, not the baryon excess — every key quantity of this paper's Table 27 is, in the standard account, a free parameter or a failure. *(6) The arrow is external.* T-violation in the Lagrangian is unrelated, in the formalism, to the thermodynamic arrow the laboratory uses to measure it.

Each limitation has a bench consequence, and stating them makes the audit concrete. Because of (1), collaborations maintain convention documents — the phase choices behind every quoted ϵ, δ, and Majorana phase — and cross-experiment comparisons begin with a translation exercise; there is no physics in the conventions, but there is systematic error in forgetting them.

Because of (2), no experiment can be told what asymmetry to *expect*: every search for new P, C, or CP violation scans, and every discovery to date arrived unpredicted in size.

Because of (3), the CPT tests of D.4 constrain all local field theories at once but adjudicate between none of them.

Because of (4), the deepest constants in the analysis chain — the i in every oscillation formula, the positivity behind every dispersion relation an experimenter uses to model detector response — sit outside the theory's explanatory reach; they are trusted, not derived.

Because of (5), the global-fit industry exists: CKM and PMNS parameters are harvested, not predicted, and a fit's pull distribution tests consistency, never necessity. (The living example is the global fit this paper confronts in Part XI; NuFit Collaboration, 2024.)

And because of (6), the arrows in an analysis — the thermodynamic arrow of the detector, the causal arrow of the trigger, the T-odd phases in the matrix element — are formally unrelated, related only by the physicist's good sense.

The main text's wager is that all six are symptoms of one omission — *the frame does not know what its own operations are* — and the next subsection is the repair proposal, graded.

Problems and worked solutions. D.5.1. No rephasing removes the KM phase for three generations; two generations are phase-free.

Solution. Step 1: count the parameters of an $N_g \times N$ unitary matrix: N^2 real numbers, of which $N(N-1)/2$ are rotation angles and $N(N+1)/2$ are phases.

Step 2: count the rephasings. The $2N$ quark fields (up-type and down-type) can each absorb a phase, but one overall common phase does nothing to V, leaving $2N-1$ usable rephasings.

Step 3: subtract: physical phases $= N(N+1)/2 - (2N-1) = (N-1)(N-2)/2$. For $N=2$: zero — the Cabibbo matrix can always be made real, and indeed no CP violation was ever found in a two-generation fit. For $N_g = 3$: exactly one — the KM phase, and the 1973 prediction that CP violation requires a third generation, made when three quarks were known.

Physics intuition: phases are only physical when they cannot be gauged away, i.e. when they survive every relabeling of the unobservable field conventions — CP violation lives in closed loops of the flavor graph, not in any single link. That loop-residence is exactly what the main text means

by "the phase is a holonomy," and the pentagon (Part VII) is the claim that the loop's value is a lattice point.

D.5.2. The sign of ϵ's CP violation is not an SM prediction.

Solution. Step 1: ϵ as defined in D.3.1 depends on the phase convention chosen for $|K^0\rangle$ and $|\bar{K}^0\rangle$ (the Wu–Yang convention fixes it via the $\pi\pi$, $I = 0$ amplitude); only quantities invariant under $|K^0\rangle \to e^{i\alpha}|K^0\rangle$ are physical — $\mathrm{Re}\,\epsilon$, $|\epsilon|$, and rephasing-invariant combinations such as $\mathrm{Im}(V_{td}V_{ts}^*V_{cd}^*V_{cs})$.

Step 2: within the SM the *value* of any such invariant traces back to the KM phase δ, and δ itself is an input: the Lagrangian with $\delta \to -\delta$ (a mirror-flavored world) is exactly as renormalizable, anomaly-free, and consistent as ours.

Step 3: hence even given $|\epsilon|$, the SM cannot predict its sign; the sign is measured, then propagated. The same statement holds for every CP observable in Table 27: the framework transports phases impeccably and originates none.

Physics intuition: the SM's CP machinery is a superb accounting system with a blank first entry. The main text's pentagon is an attempt to write that first entry from geometry — and its sign prediction ($\sin\delta_{\mathrm{PMNS}} = -0.28$, not $+$) is precisely the kind of statement the accounting system could never make.

D.5.3. Which limitations do supersymmetry, extra dimensions, and strings address?

Solution. Walk the six of Step 2. Limitation (1), operations-as-conventions: untouched by all three — each inherits the QFT frame and its free phases wholesale. Limitation (2), breakings-as-inputs: partially addressed by none in predictive form; SUSY *adds* CP phases (generic ones overshoot EDM bounds — the SUSY CP problem), string compactifications can break P and CP geometrically (orientation-reversing elements), but with landscape-valued outputs.

Limitation (3), the factor-blind CPT proof: untouched — all three prove CPT the same way. Limitation (4), the axiomatic i: untouched; complex structure is postulated in each. Limitation (5), no valuation: SUSY and strings add parameters or vacua rather than prices; no rival framework predicts a CP phase's central value. Limitation (6), the external arrow: untouched. Score: (1), (3), (4), (6) survive everywhere; (2) and (5) are where the main text's Part X locates the geometry's distinctive claims.

Physics intuition: the roads beyond the SM extended its *dynamics* while inheriting its *frame*; the mirrors are frame-level questions, which is why fifty years of beyond-SM model building moved them so little — and why the geometry attacks the frame instead.

D.6 Step 3 — the geometric account, and what became predictive

The main text's Parts IV–V answer limitation (1) by anatomy: the bulk has exactly three real orientation-bearing factors — fiber circle, spatial slice, causal clock — and C, P, T *are* their reversals (T-P5-1), with every free phase of §D.2 traced to a real convention. Limitation (4) dissolves with it: the i is the shared quarter-turn of circle and clock (T-P5-A/B), the one-sided spectrum of §D.4 is the clock's positivity (T-P5-B1), and antiunitarity of T is no longer a choice forced by consistency but a statement of custody — *only the clock is what i is made of.*

Limitation (3) inverts: CPT survives not as a conspiracy but as the unique total reversal invisible to every real texture (T-P5-2, at quasi-free grade with its residues named), and the same analytic fact carries spin–statistics as its sibling (§45). Limitations (2) and (5) are the business of the later chapters and their courses: the one kept hand (Part VI), the pentagon's priced phases (Part VII), the two-fate strong-CP resolution and the six-in-ten-billion receipt (Part VIII) — each with its grade, each mortal on the calendar of Part XI. Limitation (6) is the cohort's deepest claim, graded in §148: the laboratory's arrow and the Lagrangian's T-violation meet in one oriented boundary semigroup.

What the student should take from this chapter is the shape of the trade: *QFT proved one theorem about the mirrors and defined none of them; the geometry defines all three, re-proves the theorem, and prices the breakings — and pays for it by becoming mortal.*

The experimenter's translation table. What changes at the bench if the geometric account is right? First the operations themselves, as maps on the bulk's three real oriented factors — fiber angle θ, spatial slice $\vec{x}$, clock parameter s:

$$\mathrm{C}:\ (\theta,\vec{x},s)\mapsto(-\theta,\vec{x},s),\qquad \mathrm{P}:\ (\theta,\vec{x},s)\mapsto(\theta,-\vec{x},s),\qquad \mathrm{T}:\ (\theta,\vec{x},s)\mapsto(\theta,\vec{x},-s),\tag{77}$$

with antiunitarity assigned by clock parity (four operations reverse s; four do not), and the product $\mathrm{CPT}:(\theta,\vec{x},s)\mapsto(-\theta,-\vec{x},-s)$ the total reversal no real texture detects. In apparatus: nothing changes — the cryostats, traps, and baselines of this appendix already measure the right things.

In interpretation: five concrete relabellings. A parity flip of the apparatus is, in the geometry, a reversal of one real orientation of the world's spatial factor — and the reason no experiment has ever prepared the mirrored *couplings* (a $V+A$ current) is that the descent kept one hand: F-P5-1 predicts the W_R search program is a permanent null, forever, which converts every future limit from a disappointment into a data point.

A charge swap is a fiber reversal — so the CPT portfolio of D.4 is measuring the equality of two readings of one bulk configuration, and its exactness stops being an axiom's shadow and becomes a geometric identity with a kill switch. A motion reversal is a clock reversal — so the absence of a T quantum number (D.1) is custody, not accident. (T-P5-1, proved in Part V.)

The kaon and long-baseline phases are pentagon holonomies — so a global fit's central values become *predictions to be shot at*, and the pull columns of Table 23 are the new daily scoreboard.

And the arrow of the laboratory — the fact that every trigger fires forward — is the same one-way boundary semigroup that froze the baryon excess, which is why the proton's silence each morning is, on this account, a discrete-symmetry measurement. (The receipt chain is Part VIII; the schedule, Table 24.) None of these relabellings asks the experimenter to believe; each asks only that a specific number land where the lattice says. The apparatus of seventy years was always adequate; what the geometry adds is a set of places to stand and a schedule for being wrong.

Problems and worked solutions. D.6.1. Recompute the (anti)unitary table from the three-reversal definition and compare with Wigner's fork.

Solution. Step 1: the geometric rule (T-P5-1): an operation is antiunitary if and only if it reverses the clock orientation, because the clock's forward direction is the only real structure from which the

boundary i is built — reverse it and every phase conjugates, which is antilinearity.

Step 2: enumerate the eight operations generated by C, P, T. Four leave the clock alone: **1**, C (fiber reversal), P (spatial reversal), CP — all unitary. Four reverse it: T, CT, PT, and CPT — all antiunitary. (This corrects a compressed statement in an earlier printing of this appendix; the count is four-and-four, fixed by clock-parity alone.)

Step 3: compare with Wigner. The fork of D.1 said each symmetry *may* be unitary or antiunitary, with consistency (energy positivity) forcing T's branch case by case; the geometry replaces the case-by-case argument with one custody statement — the operations containing the clock reversal are exactly the antiunitary ones — and the composition sign rule (antiunitary × antiunitary = unitary, e.g. $T \cdot CT = C$ up to phases) becomes parity of clock reversals, i.e. arithmetic mod 2.

Physics intuition: Wigner gave quantum mechanics a fork; the geometry tells it which tine, and why — *only the clock is what i is made of* — turning a consistency choice into anatomy.

D.6.2. State the grade of each Step-3 claim and where its residue is named.

Solution. Walk the ledger (§135) claim by claim. The C/P/T table (limitation 1's answer): *derived* — T-P5-1, no residue. The shared i and the Euclidean license (limitation 4): T-P5-A/B/B1, *derived at quasi-free grade*, interacting case on scattering hypotheses. CPT as unique total reversal (limitation 3): T-P5-2, *derived (quasi-free)*, with the modular (Bisognano–Wichmann) route the named path to interacting strength — open item 6 of §137; its spin–statistics sibling is *candidate* grade (§45).

The kept hand (limitation 2, parity half): *conditional* on the gate-uniqueness conjecture C-P5-A, with the projection's own necessity the parity ledger's honestly-flagged assertion. The priced phases (limitation 5, CP half): *derived-conditional* — lattice rigidity plus the flagged QD step for the quark phase, the assignment lemma for the leptonic. The receipt η_B: D^*, one named conjecture C-P5-C. The arrow (limitation 6): graded in §148 as the cohort's conjectured summit chain beyond the matter link.

Physics intuition: the grades are the theory's honesty made machine-readable — a student who can recite this answer can referee the paper.

D.6.3. The experimentalist's closing drill: for each limitation, the measurement and its date.

Solution. Limitation (1), the anatomy: tested wherever the operations' derived structure bites — Kramers degeneracy phenomenology (standing) and the exactness of CPT: kaon Δm (continuous), antihydrogen $1S$–$2S$ (continuous, improving) — any confirmed CPT violation at any level kills the anatomy outright. Limitation (2), the kept hand: W_R and right-handed-current searches at HL-LHC and successors — permanent, any confirmed restoration fatal (F-P5-1).

Limitation (3)/(4), the quartet: same CPT rows, plus — through the second child — the Pauli-exclusion nulls (VIP-2 class, standing). Limitation (5), the valuation: δ_{CKM} at LHCb/Belle II (continuous, 5σ exclusion of $13\pi/35$ kills), δ_{PMNS} at Hyper-K/DUNE (270° at 5σ, 2031–35, kills; adjudication versus 196.4° matures late 2030s), ordering at JUNO/DUNE (5σ inverted ∼2033 kills), $m_{\beta\beta}$ at the ton scale (any discovery in reach kills, 2030s), $\bar{\theta}$ at n2EDM (in-window EDM kills, 2030s+).

Limitation (6), the arrow-and-matter link: the proton rail (one event, any day) and the η_B audit against the CMB (standing). Every row sits in Table 24 with its instrument and date; the drill's

lesson is the paper's design — *each philosophical limitation of the old frame has been converted into at least one dated measurement*, which is what "anatomy, priced and mortal" means in practice.

E The flavor sector and CP violation, from scratch: Yukawas, the CKM matrix, and the pentagon

The second chapter of Block II treats the physics that Part VII prices: quark flavor and its one CP phase. Step 1 builds the Standard Model's flavor sector from the Yukawa couplings, exactly as the textbooks teach it, through the kaon and B-meson measurements that made it precision science. Step 2 states what that superb machinery cannot do. Step 3 states what the pentagon does.

The chapter builds on Appendix D and does not repeat it: the two-state mixing formalism, the Wigner theorem, and the antiunitarity of T are quoted from §D.3 and §D.1 where first derived. What is new here is the flavor structure itself — where the mixing matrix comes from, which of its entries are physical, and how two generations of experiments turned a 2×10^{-3} anomaly into a 10^{-4}-precision science.

The chapter shelf: Branco, Lavoura, and Silva (1999) is the reference monograph (Chs. 2–3 for the formalism of E.1–E.2, Chs. 6–8 for the kaon system of E.3); Bigi and Sanda (2009) carries the B-physics of E.4 at book length; Sozzi (2008) the experimental face throughout; Particle Data Group (2024) the living numbers. Eighteen problems, complete solutions included.

E.1 Step 1 — from Yukawa couplings to the CKM matrix

The Standard Model forbids bare quark masses; masses enter only through the Higgs couplings

$$-\mathcal{L}_Y \;=\; Y^u_{ij}\,\bar{Q}_i \tilde{H}\, u_{Rj} \;+\; Y^d_{ij}\,\bar{Q}_i H\, d_{Rj} \;+\; \text{h.c.}, \tag{78}$$

with $Y^{u,d}$ arbitrary complex 3×3 matrices — eighteen complex numbers nature was free to choose. After electroweak symmetry breaking, $H \to (0, v/\sqrt{2})$, these become mass matrices $M^{u,d} = Y^{u,d} v/\sqrt{2}$.

Any complex matrix can be diagonalized by a pair of unitaries (the singular-value decomposition):

$$M^u = U^u_L\, \hat{M}^u\, U^{u\dagger}_R, \qquad M^d = U^d_L\, \hat{M}^d\, U^{d\dagger}_R, \tag{79}$$

with $\hat{M}^{u,d}$ diagonal and positive. Rotate the quark fields to the mass basis. Every neutral term of the Lagrangian — kinetic, photon, gluon, Z — involves $U^\dagger U = \mathbf{1}$ and forgets the rotation. Exactly one term remembers: the charged current,

$$J^\mu_W \;=\; \bar{u}_L \gamma^\mu d_L \;\longrightarrow\; \bar{u}_L \gamma^\mu (U^{u\dagger}_L U^d_L) d_L \;\equiv\; \bar{u}_L \gamma^\mu V\, d_L. \tag{80}$$

The CKM matrix $V = U^{u\dagger}_L U^d_L$ (Cabibbo, 1963; Kobayashi and Maskawa, 1973) is the mismatch of the two diagonalizations — the gear ratio between the up-type and down-type mass frames — and it appears only where the W changes quark type.

Physical intuition: nature keeps two ledgers for the quarks, one per Higgs coupling, and the

weak interaction is the sole transaction that reads both at once. Everything called "flavor physics" is the audit of that one transaction.

Before the mixing, pause on what the diagonalization returns: the eigenvalues. The Yukawa spectrum spans thirteen decades,

$$y_t = \frac{\sqrt{2}\, m_t}{v} \simeq 0.99, \qquad y_e = \frac{\sqrt{2}\, m_e}{v} \simeq 2.9 \times 10^{-6}, \tag{81}$$

with the top quark, alone, sitting at order one — as if one fermion couples naturally and the other eleven are afterthoughts. No SM principle explains the span; it is simply what (78) was told.

The flavor structure has predicted a quark before. The K_L–K_S mass difference proceeds through the box diagram, and with only three quarks it comes out orders too large; with a fourth quark of mass m_c the GIM cancellation leaves

$$\Delta m_K \;\sim\; \frac{G_F^2}{6\pi^2}\, f_K^2 m_K\, m_c^2 \sin^2\theta_C \cos^2\theta_C, \tag{82}$$

and demanding agreement with the measured $\Delta m_K = 3.48 \times 10^{-12}$ MeV pointed to $m_c \sim 1.5$ GeV — announced before November 1974 delivered the J/ψ (the loop analysis at textbook depth: Peskin and Schroeder, 1995, §20.2; Branco, Lavoura, and Silva, 1999, Ch. 8). Flavor loops see the next floor of the building before the elevator gets there — the working faith of every rare-decay program on Part XI's timeline.

How much of V is physical? By the counting of §D.5 (problem D.5.1): three angles and one phase for three generations. The measured hierarchy motivates Wolfenstein's expansion (Wolfenstein, 1983) in $\lambda = \sin\theta_C \simeq 0.225$:

$$V \;\simeq\; \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4), \tag{83}$$

with $A \simeq 0.83$: nearly diagonal, the CP phase hiding in the smallest corners V_{ub} and V_{td}. That is why CP violation is rare in the laboratory — not because the phase is small (it is $\sim 66.9°$) but because it is stored in λ^3-suppressed elements.

The main text's Part VII reads (80) geometrically: V is a comparison of frames, and comparisons of frames are where holonomy lives. The pentagon (Step 3) will price what this Step only parameterizes.

E.1.1. Show that for N generations V has $(N-1)(N-2)/2$ physical phases, and exhibit where the single $N = 3$ phase sits in the standard convention.

Solution. Step 1: an $N \times N$ unitary matrix has N^2 real parameters: $N(N-1)/2$ angles and $N(N+1)/2$ phases. Step 2: rephasing the $2N$ quark fields removes phases, but the overall common phase leaves V untouched, so $2N - 1$ are usable: physical phases $= N(N+1)/2 - (2N-1) = (N-1)(N-2)/2$.

Step 3: for $N = 3$ this is one. In the PDG convention it is attached to s_{13}: $V_{ub} = s_{13}e^{-i\delta}$, so the phase sits in the smallest element — consistent with (83), where $\rho - i\eta$ carries it.

Physics intuition: phases you can shift onto field conventions are bookkeeping; the one you cannot is physics. CP violation is what survives every relabeling — which is why Part VII calls it a holonomy.

E.1.2. Derive the Wolfenstein form (83) from the standard parameterization to order λ^3.

Solution. Step 1: define $\lambda = s_{12}$, $A\lambda^2 = s_{23}$, $A\lambda^3(\rho - i\eta) = s_{13}e^{-i\delta}$ — these are definitions, exact.

Step 2: expand the standard-convention product of the three rotations. To $\mathcal{O}(\lambda^3)$: $c_{12} = 1 - \lambda^2/2$, $c_{23} = c_{13} = 1$, and every product of two small sines beyond the listed corners is $\mathcal{O}(\lambda^4)$ or smaller.

Step 3: assemble; the $(3,1)$ element picks up $s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} = A\lambda^3(1 - \rho - i\eta)$ after the definitions. The expansion is (83).

Physics intuition: the Wolfenstein form is not an approximation scheme so much as a magnifying glass — it displays the hierarchy $1 : \lambda : \lambda^2 : \lambda^3$ that the exact parameterization hides, and the hierarchy is itself an unexplained pattern the geometry must eventually own.

E.1.3. Show that the neutral (Z, photon, gluon, Higgs) couplings are flavor-diagonal in the mass basis — the GIM statement — and name the experimental consequence.

Solution. Step 1: every neutral current has the form $\bar{q}_L \Gamma q_L$ or $\bar{q}_R \Gamma q_R$ with Γ proportional to the identity in flavor space (all up-type quarks carry the same charges).

Step 2: rotating to the mass basis inserts $U^\dagger \mathbf{1} U = \mathbf{1}$: the rotation cancels. The Higgs couplings are $M^{u,d}/v$, diagonalized by the same rotation — diagonal too.

Step 3: consequence — no tree-level flavor-changing neutral currents. $K^0 \to \mu^+\mu^-$ is loop-suppressed (branching $\sim 7 \times 10^{-9}$), and rare-decay physics (NA62's $K^+ \to \pi^+\nu\bar{\nu}$, Part XI) lives entirely at one loop — which is precisely why it is a sensitive probe.

Physics intuition: flavor change costs a W; anything neutral must rent two. The GIM suppression is the reason kaon physics could see the charm quark coming (its mass entered the loops) — flavor loops are telescopes for the next scale up.

E.2 Step 1 — rephasing invariants: the Jarlskog construction and the unitarity triangle

Which functions of V can an experiment measure? Rephasing sends $V_{ij} \to e^{i(\beta_j - \alpha_i)} V_{ij}$, so the moduli $|V_{ij}|$ survive, single phases do not, and the smallest surviving phase-sensitive objects are the *quartets*

$$Q_{ij,kl} \;=\; V_{ij} V_{kl} V_{il}^* V_{kj}^*, \tag{84}$$

closed loops in the flavor graph: every field phase enters once with each sign. For three generations, unitarity forces every quartet's imaginary part to a common magnitude (Jarlskog, 1985),

$$\mathrm{Im}\, Q_{ij,kl} \;=\; J \sum_{m,n} \epsilon_{ikm}\, \epsilon_{jln}, \qquad J \;=\; c_{12}c_{23}c_{13}^2\, s_{12}s_{23}s_{13} \sin\delta, \tag{85}$$

one number carrying all of quark CP violation. Its measured value is $J = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$ (Table 23).

Jarlskog's own packaging of the result deserves display. Form the commutator of the two mass

matrices (squared, to stay in the left-handed sector):

$$\det\left[\,M^u M^{u\dagger},\, M^d M^{d\dagger}\,\right] \;=\; -2i\,J\,F_u F_d, \qquad F_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2), \tag{86}$$

with F_d the down-type analogue. CP violation in the quark sector is one number multiplied by every mass splitting: let any two same-type quarks become degenerate and the effect dies, because the degenerate pair can be rotated to hide the phase. The observable needs the full cast — three generations, non-degenerate, and one loop.

The same structure draws a picture. Orthogonality of the first and third columns,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* \;=\; 0, \tag{87}$$

is three complex numbers summing to zero: a triangle in the complex plane — the *unitarity triangle*, with angles named α, β, γ. Its area is $J/2$ (problem E.2.2): CP violation is literally the failure of the flavor ledger to collapse onto a line.

Physical intuition: a quartet is a round trip — up-frame to down-frame and back by a different route — and J is the interference the traveler accumulates. Part VII's claim is that these loops are plaquettes of a real texture, and their common phase is a lattice angle. The pentagon owns the loops; Step 3 collects the debt.

E.2.1. Prove that for three generations every CP-violating observable is proportional to J.

Solution. Step 1: any observable is a rephasing-invariant function of V, hence a function of moduli and quartets (higher loops factor into quartets by unitarity).

Step 2: CP conjugation maps $V \to V^*$, so a CP-odd observable is odd under $Q \to Q^*$: it depends on the quartets only through their imaginary parts.

Step 3: by (85) every $\mathrm{Im}\, Q$ is $\pm J$ or 0. Hence CP-odd $\Rightarrow \propto J$ (times moduli). One phase, one invariant, one universal factor — the counting theorem of §D.5 in its working clothes.

Physics intuition: this is why the kaon's 2×10^{-3} and the B system's order-one asymmetries are the *same* violation — the difference is kinematic dressing of one J.

E.2.2. Show the unitarity triangle's area equals $J/2$.

Solution. Step 1: for a triangle with vertices at 0, z_1, and $z_1 + z_2$, the area is $\frac{1}{2}|\mathrm{Im}(z_1^* z_2)|$.

Step 2: take $z_1 = V_{ud}V_{ub}^*$, $z_2 = V_{cd}V_{cb}^*$ from (87). Then $\mathrm{Im}(z_1^* z_2) = \mathrm{Im}(V_{ud}^* V_{ub} V_{cd} V_{cb}^*)$ — a quartet, equal to $\pm J$ by (85).

Step 3: area $= J/2$. The same holds for all six unitarity triangles: different shapes, one area.

Physics intuition: experiments measure the triangle's *sides* (moduli from rates) and *angles* (phases from asymmetries) independently; consistency of the over-determined figure is the SM's great flavor test — and its area is the one number the SM never predicted.

E.2.3. Evaluate J from the Wolfenstein parameters and check against the world value.

Solution. Step 1: from (85) with the hierarchy of E.1, $J \simeq \lambda \cdot A\lambda^2 \cdot A\lambda^3\eta = A^2\lambda^6\eta$.

Step 2: insert $\lambda = 0.225$, $A = 0.83$, $\eta = 0.35$: $\lambda^6 = 1.30 \times 10^{-4}$, so $J \simeq 0.69 \times 1.30 \times 10^{-4} \times 0.35 = 3.1 \times 10^{-5}$.

Step 3: the world value is $(3.12^{+0.13}_{-0.12}) \times 10^{-5}$ — agreement, and the λ^6 explains the smallness: six powers of the Cabibbo angle, not a small phase.

Physics intuition: the suppression is geometric — the loop must visit the smallest corners of V — which is why Part VII can carry a large lattice phase (66.9°) and still respect a tiny J: the pentagon sets the angle, the hierarchy sets the price of walking the loop.

E.3 Step 1 — the kaon system: ε and ε', derived

Begin where the field began. In 1964, at the Brookhaven AGS, a beam of K_L — the long-lived, supposedly CP-odd kaon — produced $\pi^+\pi^-$ pairs at a branching of 2×10^{-3} (Christenson et al., 1964). The CP-even final state from the CP-odd beam meant CP itself was broken, and the experiment's craft lay in excluding the mundane: coherent regeneration of K_S in residual gas was controlled by running the decay volume in helium and mapping the rate against material.

Two decades of §D.3-style systematics hunting were compressed into one clean result — and forty years of theoretical structure, Steps E.1–E.2 included, exist because that branching ratio refused to be zero.

Indirect CP violation first. From the mixing formalism of §D.3, with CPT holding and the physical phase convention fixed by the dominant $I = 0$ decay amplitude,

$$\varepsilon \;\simeq\; \frac{e^{i\phi_{SW}}}{\sqrt{2}}\,\frac{\operatorname{Im} M_{12}}{\Delta m_K}, \qquad \phi_{SW} = \arctan\frac{2\Delta m_K}{\Delta\Gamma_K} \simeq 43.5^\circ, \tag{88}$$

the "superweak phase" fixed by measured mixing quantities alone. The box diagram gives the short-distance part, $\operatorname{Im} M_{12} \propto G_F^2 f_K^2 m_K \hat{B}_K \operatorname{Im}[(V_{td}V_{ts}^*)^2]\, m_t^2$-dominated — a quartet again, so $|\varepsilon| \propto J$ as E.2.1 promised. The measured $|\varepsilon| = 2.228(11) \times 10^{-3}$ is the 1964 discovery in mature form.

The same ε leaks into the semileptonic channels. Since $K^0 \to \pi^-\ell^+\nu$ but never $\pi^+\ell^-\bar{\nu}$ (the $\Delta S = \Delta Q$ rule), the lepton charge tags the strangeness, and the K_L charge asymmetry measures the mixing directly:

$$\delta_L \;=\; \frac{\Gamma(K_L \to \pi^-\ell^+\nu) - \Gamma(K_L \to \pi^+\ell^-\bar{\nu})}{\Gamma(K_L \to \pi^-\ell^+\nu) + \Gamma(K_L \to \pi^+\ell^-\bar{\nu})} \;=\; \frac{2\operatorname{Re}\varepsilon}{1+|\varepsilon|^2} \;=\; 3.3 \times 10^{-3}, \tag{89}$$

matter and antimatter counted by lepton charge, agreeing with $|\varepsilon|$ and ϕ_{SW} — the same asymmetry CPLEAR re-read as the direct T-reversal test $A_T = 4\operatorname{Re}\varepsilon$ (CPLEAR Collaboration, 1998), the arrow-of-time measurement of §D.3.

Direct CP violation is subtler: it needs *two* decay amplitudes with different weak and strong phases (§D.4, problem D.4.3). The kaon supplies them as the two pion isospin channels A_0 and A_2. The observables are the ratios $\eta_{+-} = \varepsilon + \varepsilon'$ and $\eta_{00} = \varepsilon - 2\varepsilon'$, so

$$\operatorname{Re}\frac{\varepsilon'}{\varepsilon} \;\simeq\; \frac{1}{6}\Big(1 - \Big|\frac{\eta_{00}}{\eta_{+-}}\Big|^2\Big) \;=\; \frac{1}{6}\big(1 - R\big), \qquad R = \frac{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}, \tag{90}$$

the *double ratio*: four rates, most systematics canceling between numerator and denominator — the design insight that carried both KTeV (KTeV Collaboration, 1999) and NA48 (NA48 Collaboration,

2002). The world value, $\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 2.3) \times 10^{-4}$, established direct CP violation and killed the superweak alternative (Wolfenstein, 1964): CP violation lives in decay amplitudes, not only in mixing.

Physical intuition: ε is interference in the *clock* (the oscillation), ε' interference in the *exits* (the decay channels). Nature could have had the first without the second; measuring both, and their ratio to 10^{-4}, is what promoted kaon physics from anomaly to precision science. Part VII recomputes both as holonomy interferometry, with the phase supplied by the lattice.

E.3.1. Derive the superweak phase $\phi_{SW} = \arctan(2\Delta m/\Delta\Gamma)$.

Solution. Step 1: from §D.3, the eigenvalue difference is $\lambda_S - \lambda_L = \Delta m - \frac{i}{2}\Delta\Gamma$ (sign conventions fixed by $\Gamma_S \gg \Gamma_L$).

Step 2: $\varepsilon \propto \mathrm{Im}\, M_{12}/(\lambda_S - \lambda_L)$; the phase of the denominator is $-\arctan(\frac{\Delta\Gamma/2}{\Delta m})$, so the phase of ε is $\arctan(\frac{2\Delta m}{\Delta\Gamma})$.

Step 3: insert the measured $\Delta m = 3.48 \times 10^{-12}$ MeV and $\Delta\Gamma \simeq \Gamma_S = 7.35 \times 10^{-12}$ MeV: $\phi_{SW} = \arctan(0.947) = 43.4°$ — consistent with the measured phase of η_{+-}, itself a CPT test.

Physics intuition: the phase of ε is set by *lifetimes and oscillation*, not by the CP-violating dynamics — so its agreement with measurement checks the framework, while only $|\varepsilon|$ carries the new physics.

E.3.2. Derive the double-ratio formula in (90) to first order in ε'/ε.

Solution. Step 1: $|\eta_{+-}|^2 = |\varepsilon|^2\,|1 + \varepsilon'/\varepsilon|^2 \simeq |\varepsilon|^2(1 + 2\,\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon})$, and likewise $|\eta_{00}|^2 \simeq |\varepsilon|^2(1 - 4\,\mathrm{Re}\,\frac{\varepsilon'}{\varepsilon})$.

Step 2: the double ratio is $R = |\eta_{00}|^2/|\eta_{+-}|^2 \simeq 1 - 6\,\mathrm{Re}(\varepsilon'/\varepsilon)$.

Step 3: invert: $\mathrm{Re}(\varepsilon'/\varepsilon) = (1-R)/6$, which is (90). A 10^{-3} measurement of R delivers a 2×10^{-4} measurement of ε'/ε — the leverage that made the experiments feasible.

Physics intuition: ratios of ratios are the experimenter's noise-canceling headphones. Flux, acceptance, and most efficiencies enter all four rates and cancel; what survives is the physics difference between charged and neutral pions — and twenty years of KTeV/NA48 systematics work lived in exactly the residue that does not cancel.

E.3.3. Explain what a nonzero ε' killed, and why ε alone could not.

Solution. Step 1: the superweak hypothesis (Wolfenstein, 1964) placed all CP violation in a new $\Delta S = 2$ mixing interaction: $\varepsilon \neq 0$, $\varepsilon' = 0$ exactly.

Step 2: ε measures mixing; any theory with the right $\mathrm{Im}\, M_{12}$ reproduces it. Only a *decay-amplitude* phase difference between A_0 and A_2 produces $\varepsilon' \neq 0$.

Step 3: the measured $(16.6 \pm 2.3) \times 10^{-4}$ is nonzero at 7σ: CP violation exists in the $\Delta S = 1$ amplitudes, as the KM mechanism requires and superweak forbids. One decimal place, one dead theory.

Physics intuition: the episode is the cleanest historical case of the discrimination logic Part XII's matrix formalizes — two frameworks agreeing on the first observable, split by the second. The pentagon inherits the same exposure: it agrees with the KM *structure* everywhere and differs in one thing only — the phase has a value.

E.4 Step 1 — the B factories: $\sin 2\beta$ as interferometry

The B^0 system runs the same two-state mechanics with a crucial kinematic difference: $\Delta\Gamma_d \simeq 0$, so both mass eigenstates live long enough to interfere in decays. For a CP eigenstate final state f accessible to both B^0 and $\bar{B}^0$, define

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}, \qquad A_{CP}(t) \;=\; \frac{\Gamma(\bar{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\bar{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} \;=\; S_f \sin(\Delta m_d\, t) - C_f \cos(\Delta m_d\, t), \tag{91}$$

with $S_f = 2\,\mathrm{Im}\,\lambda_f/(1+|\lambda_f|^2)$ and $C_f = (1-|\lambda_f|^2)/(1+|\lambda_f|^2)$. For the golden mode $B^0 \to J/\psi K_S$, the decay is dominated by a single real amplitude ($b \to c\bar{c}s$), so $|\lambda_f| = 1$, $C_f = 0$, and the surviving phase is pure mixing:

$$\mathrm{Im}\,\lambda_{J/\psi K_S} = \sin(2\beta), \qquad \beta = \arg\Big(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\Big), \tag{92}$$

a unitarity-triangle angle read as a time-dependent interference fringe. The 2001 measurements (BaBar Collaboration, 2001; Belle Collaboration, 2001) landed at large $\sin 2\beta$ — CP violation outside the kaon at last — and the current world average is 0.709 ± 0.011.

The apparatus deserves one paragraph of respect. At the $\Upsilon(4S)$ the $B\bar{B}$ pair is quantum-coherent: neither meson has a flavor until one decays, and tagging the flavor of one fixes the other's clock at that instant. The asymmetric beam energies boost the pair so the decay-time difference becomes a measurable vertex separation ($\sim 250\,\mu$m). Entanglement, here, is not philosophy; it is the tagging scheme.

Tagging is imperfect, and the imperfection has a clean algebra. If a fraction w of tags are wrong, the observed asymmetry is diluted,

$$A_{CP}^{\mathrm{obs}}(t) \;=\; (1-2w)\,A_{CP}(t), \qquad \sigma(S) \;\propto\; \frac{1}{(1-2w)\sqrt{N}}, \tag{93}$$

so a 30% mistag rate costs a factor 2.5 in effective statistics — kaon-charge and lepton tags are combined into an effective tagging power near 30%, and every point of it was fought for. The mixing frequency itself, Δm_d, is measured from the same time-dependent machinery run on flavor-specific final states, where the oscillation appears in the mixed-versus-unmixed rate rather than in a CP asymmetry.

With $\Delta m_d = 0.51\,\mathrm{ps}^{-1}$ and $\tau_B = 1.52$ ps, the oscillation completes $\Delta m_d \tau_B/2\pi \simeq 0.12$ of a cycle per lifetime — the fringe is caught rising, which is why time resolution, not statistics, was the design driver. The program has since widened: LHCb carried the interferometry into the B_s system and, in 2019, into charm — $\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}$, CP violation in up-type quarks at last (LHCb Collaboration, 2019) — while Belle II now owns the statistical future of the golden mode itself. The main text's Part VII recomputes (92) with the lattice phase and the stated PDG-class moduli, returning 0.708 — the watched row of Table 23.

E.4.1. Derive the time-dependent asymmetry (91) from the mixing formalism.
Solution. Step 1: with $\Delta\Gamma = 0$ the flavor states evolve as $B^0(t) = g_+(t)B^0 + (q/p)g_-(t)\bar{B}^0$,

$g_\pm(t) = e^{-imt}e^{-\Gamma t/2}\{\cos, i\sin\}(\Delta m\, t/2)$.

Step 2: the decay amplitude to f is $A_f[g_+(t) + \lambda_f g_-(t)]$; square it, and likewise for $\bar{B}^0(t)$ with $\lambda_f \to 1/\lambda_f$ and $q/p \leftrightarrow p/q$.

Step 3: form the asymmetry; the $e^{-\Gamma t}$ prefactors cancel, the cross terms deliver $\mathrm{Im}\,\lambda_f \sin(\Delta m t)$, the moduli difference delivers the cosine term, and normalization gives S_f and C_f as stated.

Physics intuition: it is a two-slit experiment in time — path one, decay directly; path two, oscillate first, then decay — and S_f is the fringe visibility. The mixing phase is read the way all phases are read: by interference against a reference path.

E.4.2. Show that for $b \to c\bar{c}s$ the weak phase of λ_f is 2β in the standard convention.

Solution. Step 1: the mixing ratio from the box diagram is $q/p \simeq (V_{tb}^* V_{td})/(V_{tb} V_{td}^*)$ — phase $-2\arg(V_{td}) = +2\beta$ modulo the convention.

Step 2: the decay ratio $\bar{A}/A$ for $b \to c\bar{c}s$ carries $(V_{cb}V_{cs}^*)/(V_{cb}^* V_{cs})$ — real to $\mathcal{O}(\lambda^4)$ in (83). The K_S in the final state adds the kaon-mixing factor, real in the same convention.

Step 3: hence $\arg\lambda_f = 2\beta$ with β as in (92): the golden mode measures a pure mixing phase, uncontaminated at the percent level.

Physics intuition: the mode is golden because the amplitude is a single CKM combination — no competing path, no strong-phase dependence; the theory error lives two orders below the measurement, a luxury almost nowhere else in flavor physics.

E.4.3. Estimate the penguin pollution of $\sin 2\beta$ and state why it matters at current precision.

Solution. Step 1: the $b \to s$ penguin amplitude carries $V_{tb}V_{ts}^*$, whose phase differs from the tree's at $\mathcal{O}(\lambda^2)$; its magnitude relative to the tree is loop-suppressed, a few percent.

Step 2: the induced shift is $\Delta S \sim 2\, r \cos 2\beta \sin\gamma \cos\delta_s$ with r the penguin-to-tree ratio: estimates give $|\Delta S| \lesssim 0.01$.

Step 3: the world average carries ± 0.011: pollution and precision have met. Any future drift of the watched row (Part XII's first narrative) must be argued *after* this correction — which is exactly how the refresh rules of §127 instruct the confrontation to proceed.

Physics intuition: every precision observable eventually meets its penguin. The discipline — quote the pollution with the measurement — is the flavor community's version of the reversal systematics of §D.3.

E.5 Step 2 — what the Standard Model cannot price

Now the audit, in the register of §D.5. *(1) The phase is free.* Nothing in the SM prefers $\delta = 66.9°$ over $0°$ or $180°$; a CP-conserving world was equally renormalizable, and the measured value is harvested by the global fits, never predicted (problem D.5.2).

(2) The hierarchy is free. The pattern $1 : \lambda : \lambda^2 : \lambda^3$ of (83) — arguably the most striking regularity in the fermion sector — is an input: the Yukawa matrices of (78) are arbitrary.

(3) No quark–lepton bridge. The SM contains no relation between δ_{CKM} and δ_{PMNS}; they live in disconnected Yukawa sectors. A framework in which both descend from one texture makes a statement the SM cannot even pose.

(4) The triangle test checks consistency, not origin. The over-determined unitarity triangle is a magnificent audit of the *parameterization* — its closure would survive any value of the phase. Consistency is not valuation.

(5) The conventions bite. β, ε, and the Wolfenstein phase are convention-laden; cross-experiment combinations begin with translation exercises (Branco, Lavoura, and Silva, 1999, Ch. 22) — the bench consequence of §D.5(1), now with real person-years attached.

(6) The other phase is a scandal. QCD admits its own CP-violating angle, $\bar{\theta}$, and the neutron EDM bounds it at $\bar{\theta} \lesssim 5 \times 10^{-18}$ in this cohort's accounting — while the flavor phase sits at 66.9°. Two CP phases, one enormous, one absurdly absent, and the SM prices neither; the geometric account of the second is the parent program's axion sector (Arisaka, 2026, C1-Kaxion), confronted at 8.1 μeV in its own paper.

E.5.1. Exhibit the CP-mirror world: show the SM with $\delta \to -\delta$ is exactly as consistent as ours.

Solution. Step 1: complex-conjugating the Yukawa matrices in (78) maps $V \to V^*$, i.e. $\delta \to -\delta$, leaving all moduli, masses, and gauge couplings fixed.

Step 2: renormalizability, anomaly cancellation, and unitarity are blind to the conjugation; every SM consistency proof goes through verbatim.

Step 3: hence $J \to -J$: a world with all CP asymmetries reversed is an equally lawful SM. The sign of the observed asymmetries — and through Part VIII, the sign of the matter excess — is not an SM prediction.

Physics intuition: this is the sharpest form of the valuation gap. The SM cannot even say why *this* universe rather than its CP mirror; the pentagon, whose lattice point carries a sign, can — and is falsifiable for it.

E.5.2. Show that grand unification alone does not fix the CKM phase either.

Solution. Step 1: in SU(5), the Yukawa couplings remain free matrices in the $\mathbf{5}^*$ and $\mathbf{10}$ representations; unification relates some down-type and lepton Yukawas but constrains no phase to a value.

Step 2: the counting of E.1.1 is representation-independent: one physical phase survives for three generations regardless of the unified group.

Step 3: hence GUTs inherit limitation (1) wholesale — consistent with Part X's verdict that the roads extend the dynamics while inheriting the frame.

Physics intuition: making the gauge group bigger organizes the *charges*, not the *textures*. Valuing a phase needs a geometry of the flavor space itself — which is Step 3's opening line.

E.5.3. Quantify what "the fits harvest" means: how would a fit respond if δ drifted?

Solution. Step 1: the global fit maximizes a likelihood over (λ, A, ρ, η) given rates and asymmetries; δ is a derived angle of the fitted (ρ, η) vertex.

Step 2: if future data moved the vertex, the fit would follow smoothly — no fit output can falsify the parameterization, only its internal consistency (limitation 4).

Step 3: contrast Part VII: the pentagon pins $\delta = 13\pi/35$ with no vertex freedom; a drifted world fit *kills* it (Table 26, row 2). The same data stream that the SM absorbs, the geometry stakes its life on.

Physics intuition: the operational difference between a parameterization and a theory is what a surprise does to it — absorb versus die. Part XII's nobility clause is this problem, stated as conduct.

E.6 Step 3 — the pentagon: the phases priced

The geometry's answer to Step 2 is developed in Part VII; this Step states it in the chapter's vocabulary. The quartets (84) are plaquettes — closed loops on the flavor graph — and in the GG-6 descent the graph is not an abstraction but a real texture whose block size is $L = 5$: a pentagon. A pentagon's angles cannot all be flat, so the loops carry an irreducible holonomy: CP violation exists because $3\pi/5 \neq \pi$ (Arisaka, 2026, A9-SM for the parent derivation; the concept of geometric CP violation descends from Dine, Leigh, and MacIntire, 1992).

The valuation follows from the lattice. The branch phase is the pentagon's first-order angle, quantum-defect-completed by one lattice step:

$$\delta_{\mathrm{CKM}} = \frac{2\pi}{5} \xrightarrow{\mathrm{QD}} \frac{2\pi}{5} - \frac{\pi}{35} = \frac{13\pi}{35} = 66.86^\circ, \qquad \text{world fit: } 65.7^\circ \pm 1.5^\circ, \tag{94}$$

a pull of +0.70 (Table 23); the raw first-order value sits at +1.17 with the one-lattice-step theory width $\pi/35$ in quadrature, at $+4.2\sigma$ against the experimental error alone. The Cabibbo magnitude is the same object's modulus shadow, the golden closed form of (53), at Dev $= +4 \times 10^{-5}$. The leptonic phase is the central angle's completion, $\delta_{\mathrm{PMNS}} = \pi + 2\arcsin(1/7) = 196.43^\circ$ (QD-completed 196.06°), with the Majorana pair $(0, \pi)$ — sitting inside the current global-fit preference (NuFit Collaboration, 2024) and awaiting the long-baseline verdict — Part VII end to end, confronted in Part XI.

What became falsifiable: every free number of Steps 1–2 now has a forced central value and a kill condition — the phase by the world fit (row 2 of Table 26), the watched $\sin 2\beta$ row by Belle II statistics, the leptonic point by the long-baseline decade. The chapter's arc, in one sentence: *Step 1 built the machine that measures the phase; Step 2 showed the machine cannot say what the phase should be; Step 3 is a geometry that says one number — and stands or falls with it.*

E.6.1. Verify the lattice-step arithmetic of (94) and compute the pull against the world fit.

Solution. Step 1: $2\pi/5 = 14\pi/35$, so one lattice step down is $14\pi/35 - \pi/35 = 13\pi/35$ — the QD completion is exactly one unit of the $(\pi/35)$-lattice that clause (iv) of T-P5-3 forces.

Step 2: in degrees, $13\pi/35 = 13 \times 180/35 = 66.857^\circ$; in radians 1.1670.

Step 3: against 1.147 ± 0.026 rad: pull $= (1.1670 - 1.147)/0.0283 = +0.70$ with the theory width in quadrature — the value printed in Table 23.

Step 4: the raw first-order value, with the missing step displayed: against the experimental error alone, $(1.2566 - 1.147)/0.026 = +4.2$; adding the one-lattice-step theory width $\pi/35 = 0.0898$ in quadrature, $\sigma_{\mathrm{tot}} = \sqrt{0.026^2 + 0.0898^2} = 0.0935$, and the pull is $(1.2566 - 1.147)/0.0935 = +1.17$ — the quoted number. The +1.17 presumes the theory width; without it the raw lattice point is excluded at 4σ-class, which is why the QD completion carries a flag and not a footnote.

Physics intuition: the QD step is not a fit — it is the same one-lattice-unit correction the parent program applies throughout its codebook, and its direction (down, toward the data) was not

adjustable.

E.6.2. From the pentagon's geometry, derive why the *branch* phase is $2\pi/5$ and the *central* completion appears in the leptonic sector.

Solution. Step 1: a regular pentagon has central angle $2\pi/5 = 72^\circ$ and interior angle $3\pi/5 = 108^\circ$; a loop of the flavor graph that turns at one vertex picks up the exterior/branch angle $2\pi/5$.

Step 2: the quark loops of E.2 close within the texture's branches — their holonomy is the branch angle, QD-completed to (94).

Step 3: the leptonic assignment (Part VII's conditional lemma) routes the lepton loop through the center: its phase is built on π (the straight angle) displaced by the 1/7-arcsine completion, $\pi + 2\arcsin(1/7)$. Two sectors, one figure, two different circuits of it.

Physics intuition: quarks and leptons do not carry two unrelated phases; they walk two different paths around one shape. That is the quark–lepton bridge of Step 2's limitation (3) — unposeable in the SM, a theorem-with-a-residue here.

E.6.3. Evaluate J at the lattice point and confirm it lands in the measured band.

Solution. Step 1: from E.2.3, $J = A^2\lambda^6\eta$ with (ρ, η) now *derived* from the fixed δ: $\eta = |V_{ub}/(A\lambda^3)| \sin\delta$.

Step 2: with $\sin(66.86^\circ) = 0.9196$ and the measured moduli, $\eta = 0.354$, so $J = 0.69 \times 1.30 \times 10^{-4} \times 0.354 \times 0.9196/0.9186 \simeq 3.2 \times 10^{-5}$.

Step 3: the band quoted in Table 23 is 2.7–3.2×10^{-5} — the spread across the framework's evaluation layers; the world value 3.12×10^{-5} sits inside. One lattice angle, one invariant, one confrontation row.

Physics intuition: this is the chapter closing its own loop — the invariant that Step 1 constructed, Step 2 declared unpriceable, and Step 3 priced, now checked against the data stream the student's experiment feeds. The remaining rows of that confrontation are the neutrino course's business, and the decade's.

F The origin of the matter excess, from scratch: Sakharov, the seesaw, and the six-in-ten-billion receipt

The third chapter of Block II treats the physics of Part VIII: why there is anything rather than an equal mixture of thing and antithing. Step 1 builds the standard machinery from the textbooks — Sakharov's conditions, the seesaw, the decay asymmetry, the transport — deriving each formula the main text's chain later calls. Step 2 states what that machinery, for all its beauty, cannot compute. Step 3 states what the ledger computes, and at what honesty grade.

The chapter builds on Appendices D and E and does not repeat them: the CPT theorem and the antiunitarity of T are quoted from §D.4, and the two-amplitude requirement for a rate asymmetry — one weak phase, one rephasing-even phase — is the same lesson §E.3 taught for ε', now wearing thermal clothes. The number to be explained is fixed by observation:

$$\eta_B \;=\; \frac{n_B - n_{\bar{B}}}{n_\gamma} \;=\; (6.12 \pm 0.04) \times 10^{-10}, \tag{95}$$

six baryons per ten billion photons, measured two independent ways — the CMB acoustic peaks and primordial deuterium — which agree (Planck Collaboration, 2020).

The chapter shelf: Kolb and Turner (1990) is the standard cosmology text (Ch. 6 for baryogenesis); Buchmüller, Di Bari, and Plümacher (2005) the pedagogical review of thermal leptogenesis this chapter's transport follows; Mohapatra and Pal (2004) the seesaw at book length; Particle Data Group (2024) the living numbers. Eighteen problems, complete solutions included.

F.1 Step 1 — Sakharov's three conditions, derived

In 1967, Sakharov stated what any dynamical explanation of (95) must contain (Sakharov, 1967): baryon number violation, C and CP violation, and a departure from thermal equilibrium. Each is a small theorem, and each is worth deriving, because each names a place where a proposal can quietly fail.

Condition three first, since it is the sharpest. In equilibrium the density operator is $\rho = e^{-\beta H}/Z$. CPT (Theorem §D.4) supplies an antiunitary Θ with $\Theta H \Theta^{-1} = H$ and $\Theta B \Theta^{-1} = -B$: baryon number is CPT-odd. Then

$$\langle B \rangle_{\text{eq}} = \text{Tr}\Big[\tfrac{e^{-\beta H}}{Z}\, B\Big] = \text{Tr}\Big[\tfrac{e^{-\beta H}}{Z}\, \Theta^{-1}(-B)\Theta\Big] = -\langle B \rangle_{\text{eq}} \;=\; 0, \tag{96}$$

an exact statement: a universe that stays in equilibrium keeps no matter, whatever its couplings. The excess must be minted during a departure — an expansion outrunning a reaction — and frozen before equilibrium returns.

C and CP must *both* break, and the reason is the mirror pair of Part VI's lesson: C alone relates a left-handed quark to a right-handed antiquark, so a C-breaking, CP-respecting theory can still produce baryons and antibaryons at equal total rates, chirality by chirality (problem F.1.2 runs the two-channel proof). And B violation is needed for the trivial reason that $B = 0$ initially — inflation having diluted any primordial charge — and B commuting with H keeps it zero forever.

The Standard Model, remarkably, has all three ingredients and still fails, twice over, quantitatively. Its CP violation is the single Jarlskog invariant of §E.2, and the dimensionless asymmetry it can feed the plasma is suppressed by the quark-mass differences over the electroweak temperature to $\sim 10^{-20}$ — ten orders short. And its departure from equilibrium fails too: at the measured Higgs mass the electroweak transition is a smooth crossover, not the first-order bubble bath the mechanism needs (Kajantie et al., 1996). The excess is real physics beyond the Standard Model — one of the few claims in this subject on which every framework agrees.

One more inherited theorem redirects the search. Above the electroweak crossover the Standard Model itself violates $B{+}L$: 't Hooft's anomaly ties baryon number to the gauge vacuum's winding ('t Hooft, 1976), the sphaleron is the pass between windings (Klinkhamer and Manton, 1984), and the hot plasma walks over it freely (Kuzmin, Rubakov, and Shaposhnikov, 1985). Consequence: anything stored as pure $B{+}L$ — the old GUT-era asymmetries — is erased; only $B{-}L$ survives the sphaleron era. The 1985 lesson moved the field's attention from baryons to leptons, and it is why this chapter is about leptogenesis (Fukugita and Yanagida, 1986) at all.

F.1.1. Prove the equilibrium theorem (96) carefully, stating where antiunitarity matters.

Solution. Step 1: for antiunitary Θ and Hermitian A, $\mathrm{Tr}[\Theta^{-1}A\Theta] = \overline{\mathrm{Tr}[A]} = \mathrm{Tr}[A]$: conjugation by an antiunitary preserves traces of Hermitian operators (it transposes and conjugates the matrix, and the trace of a Hermitian matrix is real).

Step 2: insert $\Theta^{-1}\Theta$ pairs: $\mathrm{Tr}[e^{-\beta H}B] = \mathrm{Tr}[\Theta^{-1}e^{-\beta H}\Theta\,\Theta^{-1}B\Theta] = \mathrm{Tr}[e^{-\beta H}(-B)]$, using $[\Theta, H] = 0$ (CPT of the dynamics) and CPT-oddness of B.

Step 3: hence $\langle B\rangle = -\langle B\rangle = 0$. The theorem needs exact CPT and exact equilibrium; break either and the conclusion goes. (Breaking CPT instead of equilibrium is a logically open route the data does not favor — the CPT-test record of Part I bounds it.)

Physics intuition: equilibrium is the state that has forgotten its history, and an asymmetry is a memory. Sakharov's third condition says: to keep a memory, write it while the system is not looking — during a departure — and freeze it before the plasma re-reads.

F.1.2. Show C violation alone is insufficient: exhibit the chirality bookkeeping.

Solution. Step 1: let a heavy boson X decay to quark pairs of definite chirality. C maps $X \to \bar{X}$ and $q_L \to \bar{q}_L$ conjugate — but the combination CP maps $q_L \to \bar{q}_R$: the two operations distribute the asymmetry differently over chirality channels.

Step 2: suppose C is broken but CP exact. CP equality gives $\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R)$ and $\Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$.

Step 3: sum over chirality: $\Gamma(X \to qq)_{\mathrm{tot}} = \Gamma(\bar{X} \to \bar{q}\bar{q})_{\mathrm{tot}}$. Equal numbers of baryons and antibaryons are minted even though C is broken in each channel separately. Only breaking CP as well lets the *total* rates differ.

Physics intuition: C violation biases who is left-handed; CP violation biases who exists. The excess needs the second. This is Part VIII's requirement that the pentagon's phase — not merely the descent's handedness — enter the chain.

F.1.3. Estimate the Standard Model's CP shortfall: why 10^{-20}?

Solution. Step 1: the only reparameterization-invariant CP quantity is J times the non-degeneracy factors of (86); the dimensionless combination available to the hot plasma is $d_{CP} \sim J \prod_u (m_{u_i}^2 - m_{u_j}^2) \prod_d (m_{d_i}^2 - m_{d_j}^2)/T_{EW}^{12}$.

Step 2: insert $T_{EW} \sim 100$ GeV and the quark masses: the twelve powers of small masses over the electroweak temperature crush $J \sim 3 \times 10^{-5}$ to $d_{CP} \sim 10^{-20}$.

Step 3: compare the target $\sim 10^{-10}$ (95): ten orders short — with the crossover failure of condition three on top. The verdict is structural, not numerical accident: light quarks cannot bias a hot plasma.

Physics intuition: the same suppression that made CP violation hard to *discover* (E.2's λ^6) makes it useless for *cosmology* inside the Standard Model. Whatever wrote the matter excess used a bigger pen — which is the seesaw sector's cue to walk on stage.

F.2 Step 1 — the seesaw: the heavy sector derived

If new physics generates neutrino masses, its lowest-energy shadow is fixed by symmetry alone: the unique dimension-five operator built from Standard-Model fields,

$$\mathcal{O}_5 \;=\; \frac{c_{ij}}{\Lambda}\,(\ell_i H)(\ell_j H), \qquad m_\nu \;=\; c\,\frac{v^2}{\Lambda}, \tag{97}$$

the Weinberg operator: Majorana masses, $\Delta L = 2$, scale-suppressed. Measured $m_\nu \sim 50$ meV with $c \sim 1$ points at $\Lambda \sim 6 \times 10^{14}$ GeV; smaller couplings buy lower scales — the trade the TeV chain of Step 3 lives on.

The simplest ultraviolet completion is the type-I seesaw (Gell-Mann, Ramond, and Slansky, 1979; Minkowski, 1977; Mohapatra and Senjanović, 1980; Yanagida, 1979): add singlet fermions N_g with Majorana mass M_N and Yukawa $Y_\nu\,\bar{\ell}\tilde{H}N$. The full neutral mass matrix in the (ν, N) basis is block off-diagonal plus heavy diagonal, and block-diagonalizing it (problem F.2.1) gives

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \;\longrightarrow\; m_\nu \simeq -\,m_D\,M_N^{-1} m_D^T, \qquad m_D = \frac{Y_\nu v}{\sqrt{2}}, \tag{98}$$

the main text's (9): light masses inversely proportional to the heavy scale — one end of the seesaw goes up because the other went up.

Which Yukawas reproduce the measured light sector? Inverting (98) is the Casas–Ibarra parameterization (Casas and Ibarra, 2001),

$$Y_\nu \;=\; \frac{\sqrt{2}}{v}\,M_N^{1/2}\,R\,\hat{m}_\nu^{1/2}\,U_{\rm PMNS}^\dagger, \tag{99}$$

with R any complex orthogonal matrix ($R^T R = \mathbf{1}$). Every choice of R fits the same low-energy data — the matrix is precisely the seesaw's hidden-sector freedom, and it returns in Step 2 as the reason measured phases do not pin the cosmology.

Physical intuition: lepton number dies quietly, of coexistence. Neither M_N (which violates L by two but touches only singlets) nor m_D (which conserves L) is dangerous alone; together they let a neutrino become its own antiparticle two insertions later. That coexistence is the "door" of Part VIII — and T-P5-4's content is that the descent's ledger leaves exactly one lawful way to build it.

F.2.1. Derive the seesaw formula (98) by block diagonalization, including the sign and the size of the corrections.

Solution. Step 1: seek a rotation $\mathcal{U} = \exp\begin{pmatrix} 0 & \rho \\ -\rho^\dagger & 0 \end{pmatrix}$ with ρ small, such that $\mathcal{U}^T\mathcal{M}\mathcal{U}$ is block diagonal. Expanding to first order, the off-diagonal block vanishes for $\rho \simeq m_D M_N^{-1}$ — small of order m_D/M_N.

Step 2: the light block becomes $0 - \rho M_N \rho^T - (\rho m_D^T + m_D \rho^T) + \ldots = -\,m_D M_N^{-1} m_D^T$ at leading order; the heavy block is M_N plus $O(m_D^2/M_N)$ shifts.

Step 3: corrections enter at relative order $(m_D/M_N)^2 \sim m_\nu/M_N$ — for the TeV chain, $5\times$

$10^{-11}/3.85 \times 10^3$ GeV ratios, i.e. 10^{-14}-class: the formula is exact for every purpose in this paper. The minus sign is physical but unobservable — it is absorbed by a Majorana phase redefinition.

Physics intuition: the light neutrino is a heavy state seen through a keyhole — twice through the Yukawa, once through the heavy propagator, $Y(1/M)Y$. Small masses are not small couplings; they are big denominators.

F.2.2. Show lepton-number violation requires *both* M_N and m_D (the coexistence argument).

Solution. Step 1: with $M_N = 0$, assign $L(N) = 1$: every term in the Lagrangian conserves L; the would-be Majorana sector is Dirac in disguise, and light neutrinos pair with singlets into L-conserving Dirac states.

Step 2: with $m_D = 0$, assign $L(N) = 0$: M_N violates nothing that talks to the visible sector; lepton number of the doublets is exactly conserved.

Step 3: only with both present does no assignment work — m_D forces $L(N) = 1$, M_N then breaks L by two units. The physical signature is the Weinberg operator (97) with coefficient m_ν/v^2: at cold temperatures, L-violation is neutrino-mass-suppressed — the cold universe conserves lepton number to 10^{-11}-class precision while the hot one, with real N's in the bath, did not. That is exactly the freeze-out structure the chain uses.

Physics intuition: the algebra is the same "two insertions" that gives $0\nu\beta\beta$ its amplitude — the door that made the matter also makes the double-beta rate, $m_{\beta\beta} = 1.72$ meV in this paper's chain, one hinge with two readouts (Part XI).

F.2.3. Run the numbers: what Yukawa does the lock scale need, and how does it compare with the chain's seam value?

Solution. Step 1: from (98) one-generation style, $Y_\nu^2 = 2m_3 M_N/v^2$ with $m_3 = 50.5$ meV $= 5.05 \times 10^{-11}$ GeV, $M_N = 3.85 \times 10^3$ GeV, $v = 246$ GeV.

Step 2: $Y_\nu^2 = 2 \times 5.05 \times 10^{-11} \times 3.85 \times 10^3/6.05 \times 10^4 \simeq 6.4 \times 10^{-12}$, so $Y_\nu \simeq 2.5 \times 10^{-6}$.

Step 3: the chain's seam-matched value is $Y_\nu \simeq 7.3 \times 10^{-7}$ (§85, step 3) — same decade within the R-matrix and projection freedom the audit band carries. Note the scaling $Y_\nu \propto \sqrt{M_N}$: the TeV seesaw needs *feebler* couplings than the 10^9 GeV one — the origin of the tiny width $\Gamma_N/M_N \sim 2 \times 10^{-14}$ that will make resonance obligatory in the next Step. (This is the chain's convention spread made explicit: §85 quotes the width at the seam value 7.3×10^{-7} and runs washout at $\widetilde{m} = m_3$, whose one-generation Yukawa is this Step's 2.5×10^{-6} — a factor $\simeq 13$ in Y_ν^2, declared and priced at both chain sites, steps 3 and 6.)

Physics intuition: lowering the seesaw scale does not buy visibility for free — the couplings shrink as the square root, and the heavy states become narrow, feeble, and displaced-vertex-like: exactly the collider signature class the falsifier table bets on (Table 26).

F.3 Step 1 — the decay asymmetry: interference, the bound, and the resonance

The working part is the CP asymmetry per decay, $\epsilon = [\Gamma(N \to \ell H) - \Gamma(N \to \bar{\ell}\bar{H})]/[\Gamma(N \to \ell H) + \Gamma(N \to \bar{\ell}\bar{H})]$. At tree level it vanishes identically: the two rates are $|Y|^2$ times identical kinematics, and CPT plus unitarity forbids a lowest-order difference (problem F.3.1). The asymmetry

is an interference effect — tree times loop — and it needs the same two ingredients as every rate asymmetry in this paper (§D.4, §E.3): a relative *weak* phase, supplied by the Yukawa matrix, and a relative *rephasing-even* phase, supplied here by the absorptive part of the loop — the on-shell intermediate states the optical theorem counts.

Carrying out the one-loop computation (vertex plus self-energy) gives the standard result (Covi and Roulet, 1996),

$$\epsilon_i \;=\; \frac{1}{8\pi}\sum_{j\neq i}\frac{\mathrm{Im}\big[(Y^\dagger Y)^2_{ij}\big]}{(Y^\dagger Y)_{ii}}\; f\!\left(\frac{M_j^2}{M_i^2}\right), \tag{100}$$

with f the sum of the vertex and self-energy loop functions. The structure is worth reading before the algebra: $\mathrm{Im}[(Y^\dagger Y)^2_{ij}]$ is the flavor-space quartet — the same closed-loop invariance logic as (84), now in the heavy sector — and f carries the absorptive kinematics.

For hierarchical heavy masses the loop function is $O(M_i/M_j)$ and the asymmetry is bounded by the light and heavy spectra — the Davidson–Ibarra bound (Davidson and Ibarra, 2002),

$$|\epsilon_1| \;\lesssim\; \frac{3}{8\pi}\,\frac{M_1\, m_3}{\bar v^2}, \qquad \bar v = 174\ \mathrm{GeV}, \tag{101}$$

so demanding the observed asymmetry forces $M_1 \gtrsim 10^9$ GeV: beautiful, thermal, and forever beyond every collider. The known escape is quasi-degeneracy. When $|M_i - M_j|$ approaches the width, the self-energy contribution is resonantly enhanced (Pilaftsis, 1997; Pilaftsis and Underwood, 2004):

$$\epsilon \;\propto\; \frac{\Delta M\,\Gamma}{\Delta M^2 + \Gamma^2/4}\,\sin(2\phi) \quad\xrightarrow{\Delta M=\Gamma/2}\quad \tfrac{1}{2}\sin(2\phi), \tag{102}$$

a Breit–Wigner in the mass splitting: the Yukawa magnitude cancels between numerator and denominator, and the asymmetry is controlled by the CP phase alone. TeV-scale leptogenesis lives here — and so does its honesty problem: off the peak the same formula *suppresses* as $\Gamma/\Delta M$, and the vacuum numbers of the chain sit twelve orders off-peak (Figure 17). A finite-temperature width large enough to close the gap must also be flavor-sensitive to count: the computed candidate is the flavor-measurement rate $\Gamma^{\mathrm{eff}} = c_\tau y_\tau^2 T$ (the flavor-blind $g^2 T$ lands through the peak and overshoots), and computing it honestly is the named conjecture C-P5-C (§87). The CP factor also has a stated provenance: at the TeV scale the operative object is the flavored asymmetry $\epsilon_{i\alpha}$ (the unflavored invariant is U_{PMNS}-independent and vanishes for real R), and the chain's $\epsilon^{\mathrm{res}} \simeq 2.5\times10^{-6}$ is the H-ϕ_{geo}-1 target value the partial-resonance condition must deliver, not a derived output (§85, step 5), now carried by an identified candidate mechanism (transport closure of C1–C6 open). (A distinct TeV route — asymmetry from singlet *oscillations* rather than decays — is the ARS mechanism (Akhmedov, Rubakov, and Smirnov, 1998); the chain does not use it, but the student will meet it in every review.)

F.3.1. Prove $\epsilon = 0$ at tree level from CPT and unitarity.

Solution. Step 1: CPT relates amplitudes, not rates: $\mathcal{M}(N \to \ell H) = \mathcal{M}(\bar H \bar\ell \to N)^*$ up to spin bookkeeping. At tree level $\mathcal{M} = Y$ (real kinematics), so $|\mathcal{M}(N \to \ell H)|^2 = |Y|^2 K$ and $|\mathcal{M}(N \to \bar\ell \bar H)|^2 = |Y^*|^2 K = |Y|^2 K$: equal.

Step 2: more generally, $S = 1 + iT$ unitarity gives $T - T^\dagger = iT^\dagger T$: the difference between a rate

and its reverse is second order in T — any first-order (tree) asymmetry integrates to zero over final states.

Step 3: hence a nonzero ϵ requires the $O(T^2)$ term: an absorptive loop — physical on-shell intermediate states — interfering with the tree. Coupling phases alone are rephasing; the loop's imaginary part is what makes them measurable, exactly as the strong phases did for ε' in §E.3.

Physics intuition: CP asymmetries are always two-path interference, and one path must be "delayed" by something CP-even — a strong phase, an oscillation, a thermal cut. Nature reuses one trick from the kaon tank to the primordial plasma.

F.3.2. Maximize the resonance factor in (102) and evaluate the off-peak suppression at $\Delta M = 10\,\Gamma$ and $10^{12}\,\Gamma$.

Solution. Step 1: let $g(\Delta M) = \Delta M\,\Gamma/(\Delta M^2+\Gamma^2/4)$. Then $g' = \Gamma(\Gamma^2/4-\Delta M^2)/(\Delta M^2+\Gamma^2/4)^2 = 0$ at $\Delta M = \Gamma/2$.

Step 2: at the peak, $g(\Gamma/2) = (\Gamma/2)\,\Gamma/(\Gamma^2/4+\Gamma^2/4) = 1$: the ceiling $\epsilon = \frac{1}{2}\sin 2\phi$ of (102).

Step 3: off peak, $g \simeq \Gamma/\Delta M$: at $10\,\Gamma$, a tenth; at $10^{12}\,\Gamma$, 10^{-12} — the twelve-orders cliff the vacuum numbers of the chain sit on, drawn as Figure 17. Sitting at the peak is worth twelve orders of magnitude, which is why C-P5-C is a *named* input and not a footnote.

Physics intuition: resonance is nature's amplifier of last resort, and its price is tuning — unless something sets the splitting. The chain's claim is that the ledger's $O(1/K)$ splittings plus the thermal width do the setting; the honesty is that the second half is a conjecture with a stated discharge route.

F.3.3. Evaluate the Davidson–Ibarra ceiling at the lock scale and show hierarchical TeV leptogenesis is dead without resonance.

Solution. Step 1: insert $M_1 = 3.85\times10^3$ GeV, $m_3 = 5.05\times10^{-11}$ GeV, $\bar{v} = 174$ GeV into (101).

Step 2: $|\epsilon_1| \lesssim (3/8\pi)\times 3.85\times10^3\times5.05\times10^{-11}/3.03\times10^4 \simeq 8\times10^{-13}$.

Step 3: the chain needs $\epsilon \sim 2.5\times10^{-6}$ — the H-$\phi_{\rm geo}$-1 target value (§85, step 5): the hierarchical ceiling is more than six orders too low. Either the heavy scale climbs to 10^9 GeV — and out of every collider's reach — or the degeneracy escape of (102) is engaged. The ledger, which fixed M_N at the lock for its own reasons, has no choice in the matter; that the required escape is the one its $O(1/K)$ splittings naturally furnish is either a coincidence or a design, and Part VIII prices which.

Physics intuition: the bound is why "leptogenesis is untestable" became folklore — and why a framework whose heavy sector is *forced* to the TeV corridor turns the folklore into a falsifiable schedule (Table 24).

F.4 Step 1 — transport: washout, sphalerons, and the conversion arithmetic

Between the asymmetry per decay and the asymmetry per photon stand three pieces of plumbing, each standard, each derivable.

Washout. The same Yukawas that produce the asymmetry can erase it: inverse decays $\ell H \to N$ re-absorb leptons while the bath is hot. The competition is governed by one comparison — the decay rate against the expansion rate at $T = M_N$ — and it turns into a pure neutrino-mass threshold: equating $\Gamma_N \sim \widetilde{m}M_N^2/(8\pi v^2)$ with $H \simeq 1.66\sqrt{g_*}\,T^2/M_{\rm Pl}$ at $T = M_N$ (the derivation is problem

F.4.1) gives the main text's (60): $m_\star \simeq 1.1 \times 10^{-3}$ eV, containing only v, $M_{\rm Pl}$, and g_* — notably ledger-free.

With the atmospheric mass in the seat, $K_{\rm wash} = \widetilde{m}/m_\star \simeq 50$: strong washout, efficiency $\kappa \simeq 1/K_{\rm wash} = 2.0 \times 10^{-2}$, adopted as 10^{-2} up to $O(1)$ (Buchmüller, Di Bari, and Plümacher, 2005). (Convention note, as declared at §85 steps 3/6: $\widetilde{m} = m_3$ is the chain's washout convention; the seam-matched $\widetilde{m} \simeq 8.4$ meV would give $K_{\rm wash} \simeq 7.6$, $\kappa \simeq 0.13$ — a factor-$\simeq 13$ spread in Y_ν^2, priced as $O(10)$ in the order-of-magnitude register.)

The Boltzmann bookkeeping behind that shorthand is a pair of equations in $z = M_N/T$,

$$\frac{dN_N}{dz} = -D\,(N_N - N_N^{\rm eq}), \qquad \frac{dN_{B-L}}{dz} = -\,\epsilon\,D\,(N_N - N_N^{\rm eq}) \;-\; W\,N_{B-L}, \tag{103}$$

source minus washout: every decay out of equilibrium mints ϵ units of $B-L$, and the washout term W eats a fraction. In the strong regime the surviving asymmetry forgets its initial conditions — thermal or vanishing N abundance converge — which is the standard strong-washout blessing: the answer depends only on late-time quantities.

Sphaleron conversion. The plasma's chemical equilibrium redistributes any $B-L$ endowment over every species that shares a reaction with it. Imposing Yukawa equilibrium, sphaleron equilibrium, and hypercharge neutrality on the Standard-Model plasma and solving the linear system (problem F.4.2) gives the Harvey–Turner coefficient (Harvey and Turner, 1990),

$$B \;=\; \frac{8N_f + 4N_H}{22N_f + 13N_H}\,(B-L) \quad \xrightarrow{N_f=3,\ N_H=1} \quad \frac{28}{79}\,(B-L), \tag{104}$$

the number every baryogenesis mechanism in existence must multiply by.

Entropy. Finally the photon bath: the asymmetry is diluted by the entropy carried in $g_* = 106.75$ relativistic degrees of freedom at production, $\eta_B \simeq 7.04\,Y_B$ in the standard normalization (Kolb and Turner, 1990). Nothing in the plumbing is exotic: how fast does it decay, does the crowd undo it, who converts the currency, how much did the room grow — the four household questions of §23, now each with its derivation attached.

F.4.1. Derive $m_\star$ in closed form.

Solution. Step 1: the decay width with effective mass $\widetilde{m}$ is $\Gamma_N = \widetilde{m}\,M_N^2/(8\pi v^2)$ — this *defines* $\widetilde{m}$ as the neutrino-mass-like combination $(m_D^\dagger m_D)_{11}/M_1$.

Step 2: Hubble in the radiation era is $H = 1.66\sqrt{g_*}\,T^2/M_{\rm Pl}$; evaluate at $T = M_N$ and set $\Gamma_N = H$: the M_N^2 cancels on both sides — the comparison is scale-free.

Step 3: solving for $\widetilde{m}$ gives $m_\star = 8\pi \times 1.66\sqrt{g_*}\,v^2/M_{\rm Pl}$, which assembled with the standard numerical bookkeeping is the closed form of (60), $\simeq 1.1 \times 10^{-3}$ eV. Only v, $M_{\rm Pl}$, and g_* enter: nature fixed the washout regime before any theory of the heavy sector arrived, and the measured $m_3 \simeq 50$ meV puts *every* seesaw in the strong-washout class.

Physics intuition: $m_\star$ is the neutrino mass at which the door re-closes exactly what it lets out. Fifty times over threshold means the plasma erases its own first draft — and paradoxically that is good: what survives is insensitive to how the story started.

F.4.2. Solve the chemical-potential system: derive 28/79, then move to two Higgs

doublets.

Solution. Step 1: above the crossover, assign chemical potentials to the quark and lepton doublets and singlets and the Higgs; fast Yukawa reactions equate $\mu_q - \mu_u + \mu_H = 0$ etc.; the sphaleron imposes $\sum_f (3\mu_{q_f} + \mu_{\ell_f}) = 0$; hypercharge neutrality closes the system.

Step 2: with N_f families and N_H doublets the linear system solves to $B = \frac{8N_f+4N_H}{22N_f+13N_H}(B-L)$ — Harvey–Turner's (104). For $N_f = 3, N_H = 1$: $28/79 \simeq 0.354$.

Step 3: for $N_H = 2$: $(24+8)/(66+26) = 32/92 = 8/23 \simeq 0.348$ — a 2%-class shift on the coefficient, 8%-class on some intermediate conventions, comfortably inside the chain's factor-~ 3 band. The measured η_B does, in principle, care about the scalar sector — a pleasingly concrete reminder that cosmology audits particle content.

Physics intuition: the plasma is a currency market with fast arbitrage; the sphaleron is the one desk that prints and burns $B+L$. Equilibrium then fixes the exchange rate between the conserved $B-L$ and the baryons we are made of — a rational number, computed from bookkeeping, no dynamics required.

F.4.3. Why does *strong* washout make the prediction more robust, not less?

Solution. Step 1: in weak washout ($K_{\rm wash} < 1$) the surviving asymmetry depends on the initial N abundance — thermal, zero, or dominant give different answers: the prediction inherits cosmological initial-condition freedom.

Step 2: in strong washout the WN_{B-L} term of (103) drives all initial conditions to a common attractor before freeze-out; the surviving $\kappa \simeq 1/K_{\rm wash}$ depends only on $\widetilde{m}$ — a measured-class quantity.

Step 3: the cost is the erasure itself, $\kappa \sim 10^{-2}$ — two orders of asymmetry paid for initial-condition independence. The chain's throughput identity (61) spends exactly this factor and still lands, which is the content of its $e^{-K/2}$ claim.

Physics intuition: an attractor is the theorist's best friend: it converts "it depends on the beginning" into "it depends on the measured masses." The strong-washout blessing is inherited intact by any seesaw whose light masses are the measured ones — the ledger's included.

F.5 Step 2 — what the Standard Model plus seesaw cannot price

Now the audit, in the register of §D.5 and §E.5. *(1) The scale is free.* M_N ranges over thirteen decades of viable model space, from ARS-style GeV singlets to GUT-adjacent 10^{14} GeV; the seesaw relation prices only the product Y^2/M, never the factors.

(2) The measured phases do not reach the cosmology. By Casas–Ibarra (99), the asymmetry depends on the R-matrix, which low-energy data never fixes: a measured $\delta_{\rm PMNS}$ is compatible with either sign and any magnitude of ϵ (problem F.5.3 exhibits it). DUNE could measure the leptonic phase perfectly and standard leptogenesis would predict nothing new.

(3) The resonance is engineered. In the TeV literature the quasi-degeneracy $\Delta M \sim \Gamma$ is imposed by hand or by a bespoke symmetry — a dial, tuned to twelve digits from the natural splittings, with nothing upstream to set it.

(4) The sign is not predicted. Matter rather than antimatter is, in every standard realization, a choice of phase convention dressed as a result (the CP-mirror argument of problem F.5.1).

(5) The number is a target, not an output. Across the model space, η_B spans decades; the observed 6.12×10^{-10} selects a surface in parameter space rather than testing a prediction. The mechanism is falsifiable in almost none of its realizations —

(6) — and largely untestable. Hierarchical thermal leptogenesis lives at 10^{9+} GeV, beyond any collider horizon; its CP phases are the hidden ones of item (2). The one Standard-Model-owned alternative, electroweak baryogenesis, is closed by the crossover (Kajantie et al., 1996). The field's most beautiful mechanism has spent four decades officially plausible and officially out of reach.

F.5.1. Exhibit the CP-mirror universe: show every standard leptogenesis realization has a twin with $\eta_B \to -\eta_B$.

Solution. Step 1: conjugate every Yukawa and Majorana phase, $Y_\nu \to Y_\nu^*$, $M_N \to M_N^*$: all masses, mixings, and |couplings| are unchanged; every Im[·] in (100) flips sign, so $\epsilon \to -\epsilon$.

Step 2: the transport (103) is linear in ϵ and in N_{B-L}: the solution maps to minus itself; sphalerons and entropy are sign-blind.

Step 3: hence $\eta_B \to -\eta_B$ with every laboratory observable held fixed except the CP-odd ones, which flip consistently. An antimatter universe is an equally lawful seesaw. Only a framework in which the phase is *valued* — carried with its sign from something structural — can say why this orientation (Part VIII's claim, graded there).

Physics intuition: this is E.5.1's argument promoted from an aesthetic gap to a cosmological one: the SM cannot say why *this* universe, and the seesaw alone cannot either.

F.5.2. Count the seesaw's parameters against its low-energy observables.

Solution. Step 1: three-generation type-I: the complex 3×3 matrix Y_ν carries 18 real parameters and the heavy eigenvalues 3 more; removing the 3 unphysical rephasings of the lepton doublets leaves 18 physical high-scale parameters.

Step 2: the light sector delivers 3 masses + 3 angles + 1 Dirac + 2 Majorana phases = 9 observables.

Step 3: 18 - 9 = 9 parameters invisible at low energy — exactly the 3 complex angles of the orthogonal R-matrix (99) plus the 3 heavy masses. The cosmology depends on them; experiments below the heavy scale do not constrain them. The gap is structural, not experimental impatience.

Physics intuition: the seesaw is a funnel — eighteen numbers in, nine out. Leptogenesis lives in the part that drained away, which is why it is simultaneously the most natural explanation of (95) and the least testable: a lesson in how a mechanism can be convincing and unfalsifiable at once.

F.5.3. Exhibit two seesaws with identical low-energy data and opposite-sign asymmetries.

Solution. Step 1: fix $\hat{m}_\nu$, $U_{\rm PMNS}$, and the heavy spectrum; choose $R(\omega)$ a complex rotation with angle ω in one plane.

Step 2: by (99), $(Y^\dagger Y)$ depends on ω; the flavor-summed asymmetry carries $\mathrm{Im}[(Y^\dagger Y)^2_{ij}] \propto$ odd functions of $\mathrm{Im}\,\omega$. The replacement $\omega \to -\omega^*$ (well inside the allowed orthogonal family) flips the sign while $R^T R = \mathbf{1}$ still holds.

Step 3: both realizations reproduce every measured mass, angle, and phase; their ϵ's differ by a sign, their η_B's land on opposite sides of zero. Low-energy completeness, cosmological opposites — the sharpest form of limitation (2), and the precise thing a valued, structural phase assignment

(Step 3) must and does forbid.

Physics intuition: what the funnel drained away was not noise; it was the cosmology. Any program claiming to predict η_B must first close the R-matrix freedom — which is exactly what an inherited, dial-free door does.

F.6 Step 3 — the ledger's receipt

The geometry's answer to Step 2 is Part VIII; this Step states it in the chapter's vocabulary, limitation by limitation. *The scale* (1) is not chosen: the heavy sector sits at the lock, $M_{\rm lock} = \frac{1}{2}M_{\rm Pl}e^{-K} \simeq 3.85$ TeV, $K = 35$ the ledger's throat depth, with the derived reheating temperature $T_{\rm rh} \simeq 3 \times 10^{10}$ GeV populating it thermally (Arisaka, 2026, A10-Cosmos).

The door is dial-free: T-P5-4 proves the weight-zero self-pairing is the unique lawful $\Delta L = 2$ structure — the R-matrix freedom of (2) is not fitted but closed, which is why the measured $\delta_{\rm PMNS}$ reaches the cosmology here and nowhere else. *The phase and its sign* (4) descend from the ledger with orientation attached: in the flavored channel the TeV scale mandates, the driver is the Majorana parity $\alpha_{31} = \pi$ (the numerics are $J_{\rm PMNS}$-blind at the few-percent level), and $\epsilon^{\rm res} \simeq 2.5 \times 10^{-6}$ is the H-$\phi_{\rm geo}$-1 target value the partial-resonance condition must deliver (§87) — a target value now carried by an identified candidate mechanism, the flavor-measurement regulator, with transport closure of C1–C6 open.

The resonance (3) is the chapter's honesty test, and the chain does not hide it: the on-resonance condition is the one named input, Conjecture C-P5-C, with the vacuum numbers sitting twelve orders off-peak and the flavor-measurement rate $\Gamma^{\rm eff} = c_\tau y_\tau^2 T$ named, at candidate grade, as the discharge route (the flavor-blind g^2T overshoots) — faced in public in §87, priced into the grade.

The number (5): washout $\kappa \simeq 10^{-2}$ (ledger-free $m_\star$; the $O(1)$ adoption from $1/K_{\rm wash} = 2.0\times10^{-2}$ stated there), throughput $\epsilon\,\kappa \simeq 2.5 \times 10^{-8} = e^{-K/2}$ — the identity of (61), its exponent a postulate of the compression, flagged as such — then sphalerons and entropy (104) deliver the main text's (62): $\eta_B \approx 7 \times 10^{-10}$ (central 7.34), against the observed $(6.12 \pm 0.04) \times 10^{-10}$ — +20% central, inside a factor-$\sim$ 3 audit band, at grade D*: derived on the inherited ledger, conditional on one named conjecture.

What became falsifiable (6): the same door predicts $m_{\beta\beta} = 1.72$ meV for the tonne-scale $0\nu\beta\beta$ era; the TeV cluster is HL-LHC's to find or exclude; the leptonic phase is DUNE and Hyper-K's decade (Table 24). The chapter's arc, in one sentence: *Step 1 built the machinery that could mint a universe; Step 2 showed the machinery will mint any universe you ask of it; Step 3 is a geometry that asks for exactly one — six in ten billion, matter-signed — and posts the schedule on which that request can be refused.*

F.6.1. Verify the throughput identity numerically, and state precisely what is derived and what is postulated.

Solution. Step 1: $\epsilon^{\rm res}\kappa = (2.5 \times 10^{-6})(1.0 \times 10^{-2}) = 2.5 \times 10^{-8}$ — with $\kappa = 1.0 \times 10^{-2}$ adopted from $1/K_{\rm wash} = 2.0 \times 10^{-2}$ within the $O(1)$ transport freedom: the displayed agreement uses that freedom, and would read 5.0×10^{-8} at the unadjusted $1/K_{\rm wash}$.

Step 2: $e^{-K/2} = e^{-17.5} = 2.51 \times 10^{-8}$: agreement to displayed precision — the ledger's throat-depth exponential, reconstructed by an explicit seesaw-plus-washout chain.

Step 3: audit: ϵ is derived-conditional on H-$\phi_{\rm geo}$-1: the flavored computation is displayed (GG-A10-Cosmos Appendix I; driver $\alpha_{31} = \pi$, nonzero at $m_1 = 0$, $J_{\rm PMNS}$-blind at the stated level; the former m_1/m_3-order language is withdrawn), and the 2.5×10^{-6} of Step 1 is the target value the partial-resonance condition $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$ must deliver, not a derived output, now carried by an identified candidate mechanism with C1–C6 open (resonance C-P5-C); κ is derived-conditional (ledger-free $m_\star$, $O(1)$ transport prefactor uncomputed and used above); the *identification* of the product with $e^{-K/2}$ is a postulate of the compression — geometrically suggestive as $\sqrt{e^{-K}}$, not derived. The same $K = 35$ now prices a mass ($M_{\rm lock}$), a bound ($\bar\theta$ leakage), and the matter throughput: one integer, three exports — either the ledger's deepest success or its most seductive numerology, and §85 says which experiments decide.

Physics intuition: when three unrelated observables return the same integer, you have found either the mechanism or the mirror in your own instrument. The falsifier table is the procedure for telling them apart.

F.6.2. Propagate the three uncomputed $O(1)$'s through to η_B and reconstruct the audit band.

Solution. Step 1: the chain carries three honest $O(1)$'s: the projection coefficient $c \in [0.25, 1]$, the washout prefactor $[0.5, 2]$, and the transport normalization $[0.5, 2]$.

Step 2: the product's extreme range is $[0.25 \times 0.5 \times 0.5,\ 1 \times 2 \times 2] = [0.0625, 4]$ relative to the central chain; applied to 7.34×10^{-10} this spans roughly $[0.5, 29] \times 10^{-10}$.

Step 3: the published factor-~ 3 band is the one-sigma core of this propagation (the extremes require all three factors conspiring); the +20% central landing therefore buys no extra credit — and is claimed as none. The confrontation row (Table 23) carries the band, not the landing.

Physics intuition: an audit band you constructed yourself is worth more than a bull's-eye you cannot justify. The deflation is deliberate: the chapter's credibility spends better on the falsifiable entries — the phase, the double-beta target, the cluster — than on a central value inside its own honest slop.

F.6.3. Suppose DUNE returns $\delta_{\rm PMNS} = 270°$. Walk the chain and state what dies and what survives.

Solution. Step 1: the leptonic lattice point dies: 270° is outside the 196° band by far more than the QD width, killing the lepton chain of T-P5-3 and with it the *forced* value of the heavy-sector phase.

Step 2: the door (T-P5-4), the lock scale, the washout, and the sphaleron arithmetic survive untouched — they never used the phase's value. η_B reverts from D* toward ordinary fitted resonant leptogenesis: mechanism intact, valuation lost.

Step 3: the quark pentagon, the CPT custody, and the confrontation table's quark rows are unaffected — the falsifier table's row structure (Table 26) is exactly this walk, pre-computed, which is what "modular kill conditions" means in practice.

Physics intuition: a good theory fails in parts, and says in advance which parts. The student on a long-baseline shift is not testing "the framework"; she is testing row by row — and this chapter has now handed her the derivation behind every row she can reach.

G The antiparticle, from scratch: the sea, the contour, the causality theorem, and the handshake

The fourth chapter of Block II treats the physics of Part IV: where the twin comes from. The question has received three great answers in a century — Dirac's sea, Feynman and Stückelberg's relabeling, and Weinberg's causality theorem — and this chapter derives each from the textbooks (Step 1), states exactly what each cannot say (Step 2), and then works the fourth answer, the handshake, in which the pairing is a consistency condition between two independently forced complex structures (Step 3).

The chapter builds on its predecessors and does not repeat them: Wigner's theorem and antiunitarity are quoted from §D.1, the bilinear machinery of the Dirac theory from §D.2, and the CPT identities the twin must satisfy from §D.4 and Table 1. The three-depths ruler of §26 — spectral, structural, ontological — is the chapter's grading instrument throughout.

The chapter shelf: Weinberg (1995), Vol. I Ch. 5, is the definitive modern treatment G.3 follows; the original papers — Dirac (1928, 1930, 1931), Anderson (1933), Stückelberg (1941), Feynman (1949) — are short, readable, and assigned; Lawson and Michelsohn (1989) carries the spinor algebra of G.4; Peskin and Schroeder (1995), Ch. 2–3, the propagator machinery of G.2. Eighteen problems, complete solutions included.

G.1 Step 1 — the Dirac sea, derived and dismantled

Dirac's 1928 equation (Dirac, 1928) bought the electron's spin and magnetic moment at a price displayed in its spectrum:

$$(i\gamma^\mu\partial_\mu - m)\,\psi = 0 \quad \Longrightarrow \quad E \;=\; \pm\sqrt{\mathbf{p}^2 + m^2}, \tag{105}$$

a negative branch, unbounded below, into which every atom should radiate its electrons in a flash. Dirac's 1930 repair (Dirac, 1930) was audacious bookkeeping: declare the negative-energy states already *filled* — the sea — so exclusion blocks the catastrophe. The observable excitations are then electrons above the sea and *holes* in it, and a hole behaves as a particle of positive energy and opposite charge (problem G.1.1): the antiparticle, predicted (Dirac, 1931) before Anderson's cloud chamber found it (Anderson, 1933) — perhaps the greatest successful prediction ever made by bookkeeping.

And yet the sea is wrong, and its wrongness is worth deriving with the same care as its triumph, because each failure is a theorem. *Bosons.* The π^+ and π^- are antiparticles of each other and obey Bose statistics: no exclusion principle, no blocking, no sea — yet the twin exists (problem G.1.2). Whatever explains antiparticles cannot be exclusion. *The vacuum.* The sea's charge density diverges cubically with the cutoff (problem G.1.3); subtracting it by decree concedes that the sea was never physical.

The asymmetry. The sea makes the electron fundamental and the positron a defect — yet every CPT identity of Table 1 finds the two exactly interchangeable, to 10^{-18} in the kaon system's mass identity. An asymmetric ontology carrying a perfectly symmetric phenomenology is an ontology on

notice.

Physical intuition: the sea is condensed-matter thinking — holes in semiconductors are real and useful — imported to a place where the "band" is infinite and the "lattice" is the vacuum. It gave the right answer once, for fermions, because exclusion happened to mimic the real mechanism's bookkeeping. The rest of the chapter is the search for what it mimicked.

G.1.1. Show that a hole in the filled negative-energy band has charge $+e$ and positive effective mass.

Solution. Step 1: the filled sea is declared the vacuum: charge Q_0, energy E_0, momentum zero, all by fiat of subtraction.

Step 2: remove one electron of charge $-e$, energy $-E < 0$, momentum $-\mathbf{p}$. The remaining state has charge $Q_0 - (-e) = Q_0 + e$, energy $E_0 - (-E) = E_0 + E$, momentum $+\mathbf{p}$: relative to the vacuum, a quantum of charge $+e$, energy $+E$, momentum $\mathbf{p}$.

Step 3: its dynamics follow the same subtraction: the hole accelerates in a field as would a positive charge with positive mass m (the band's curvature enters with the removed state's sign twice, restoring the particle sign). The hole is the positron, kinematically complete.

Physics intuition: a bubble in water rises — absence, bookkept against a full background, behaves like presence with inverted quantum numbers. The derivation is impeccable; the question Step 2 will press is whether the "water" — an infinite, unobservable, charged background — was ever there.

G.1.2. Prove no bosonic sea can exist, and state what the $\pi^{\pm}$ pair therefore demonstrates.

Solution. Step 1: the sea mechanism requires the negative-energy states to be *fully occupied* so that decay into them is Pauli-blocked.

Step 2: bosons have no exclusion principle: occupation is unbounded, "full" does not exist, and a bosonic negative-energy branch triggers unbounded cascade — each quantum lowers the energy, and stimulated emission *accelerates* the collapse. No bosonic sea is even formally available.

Step 3: yet the charged pion pair, spin zero, exists, with π^- the antiparticle of π^+, produced and annihilated in exact charge balance. Antiparticles exist where the sea cannot: the sea is refuted as the *explanation* even where it works as a mnemonic.

Physics intuition: one clean counterexample outranks a thousand confirmations. The pion did to the sea what the crossover did to electroweak baryogenesis (§F.1): closed the mechanism while leaving the phenomenon standing — the surest sign the explanation lives elsewhere.

G.1.3. Compute the sea's charge density with cutoff Λ and watch it diverge.

Solution. Step 1: the sea fills both spin states of every negative-energy momentum mode up to $|\mathbf{k}| = \Lambda$:

$$\rho_{\text{sea}} \;=\; (-e) \times 2 \int^{\Lambda} \frac{d^3k}{(2\pi)^3} \;=\; -\frac{e\,\Lambda^3}{3\pi^2}. \tag{106}$$

Step 2: at $\Lambda = m_e$ this is already $\sim 10^{30}\, e$ per cm^3; at any Planck-adjacent cutoff it is beyond astronomical — and gravity, which couples to the energy density, would see the sea's (equally divergent) energy.

Step 3: the standard repair — normal ordering — subtracts the divergence by definition. That is a consistent *procedure* and an abandoned *ontology*: one cannot both believe in the sea and define

it away. Modern QFT keeps the subtraction and drops the sea; the chapter's Step 3 will supply what the subtraction was silently standing in for.

Physics intuition: infinities in physics are usually the theory's way of saying "I was asked about something that is not there." The sea's divergences are not technical blemishes — they are the ontology billing for itself.

G.2 Step 1 — Feynman–Stückelberg: the contour and the relabeling

Modern quantum field theory replaced the sea with a reading of the propagator. The free propagator is an integral with two poles, and its meaning is fixed by how the energy contour threads them:

$$\Delta_F(x-y) \;=\; \int \frac{d^4p}{(2\pi)^4}\,\frac{i\,e^{-ip\cdot(x-y)}}{p^2-m^2+i\epsilon}, \tag{107}$$

the $i\epsilon$ encoding one choice among four (retarded, advanced, Feynman, anti-Feynman — problem G.2.1). Closing the energy contour splits the Feynman function into its two time-ordered pieces,

$$\Delta_F(x-y) \;=\; \theta(t-t')\,\Delta_+(x-y) \;+\; \theta(t'-t)\,\Delta_+(y-x), \tag{108}$$

positive frequencies forward in time and negative frequencies backward, and Stückelberg (Stückelberg, 1941) and Feynman (Feynman, 1949) read the backward piece physically: *a negative-energy solution propagating backward in time is a positive-energy antiparticle propagating forward* (problem G.2.2). One function then computes both particle and antiparticle processes, and *crossing symmetry* — the analytic continuation that turns an incoming particle into an outgoing antiparticle (problem G.2.3) — becomes the pairing's analytic face: annihilation, pair creation, and scattering are one amplitude read in different channels.

This is enormously better than the sea: no infinite background, bosons and fermions treated identically, and the zigzag picture of pair creation — one worldline, turning in time — correctly encodes every rate. What it is *not* is an explanation, and the chapter will press the point in Step 2: the contour is chosen, not derived; "backward in time" is a label for an analytic continuation, not a mechanism; and the question *why* the consistent choice pairs opposite charge with positive energy is exactly the question the formalism answers by prescription. The main text's verdict (§111.3): a bookkeeping identity of genius, standing in for a mechanism it does not contain.

G.2.1. Evaluate the four contours for the free scalar and identify which yields causal, positive-energy propagation.

Solution. Step 1: the p^0 integrand of (107) has poles at $p^0 = \pm E_{\mathbf{p}}$. Threading the contour above both gives the retarded propagator (vanishes for $t < t'$); below both, advanced (vanishes for $t > t'$); above the negative pole and below the positive one, Feynman; the reverse, anti-Feynman (Dyson).

Step 2: close the contour downward for $t > t'$ and upward for $t < t'$: the Feynman choice picks up $e^{-iE(t-t')}$ (positive frequency) forward and $e^{+iE(t-t')}$ backward — the unique prescription in which only positive energies flow forward while the amplitude remains nonzero at spacelike separation in the charge-symmetric combination causality requires.

Step 3: retarded and advanced are causal Green functions but mix frequencies both ways

(classical signaling, not amplitudes); anti-Feynman propagates negative energies forward, wrecking stability. One contour survives the joint demand of causal amplitudes and bounded energy.

Physics intuition: the contour menu is the theory showing its four possible worlds; three are inconsistent with quantum-plus-relativity, and the surviving one *contains antiparticles automatically.* The formalism selects the twin — it just cannot say what selected the formalism, which is Step 3's opening.

G.2.2. Derive the antiparticle interpretation of the $t' < t$ piece.

Solution. Step 1: take the backward piece of the Feynman function: it carries $e^{+iE(t-t')}$, a negative-frequency oscillation transported against the time order.

Step 2: couple the field to the electromagnetic current. On the backward piece the current's charge enters with reversed sign relative to the forward piece: transporting charge $-e$ backward from y to x is, line by line in the amplitude, identical to transporting charge $+e$ forward from x to y.

Step 3: relabel: define the forward-moving, positive-energy, charge-$+e$ quantum as the antiparticle. Every amplitude is unchanged — the relabeling is exact — and the negative-energy problem dissolves: nothing physical ever moves backward or carries $E < 0$. The cost, recorded for Step 2 of this chapter: "define" did the work.

Physics intuition: the zigzag electron — scattering into the past and back — is the most famous cartoon in QFT, and its content is precisely this relabeling. Cartoons are memory aids for identities; the identity is real physics, the cartoon's arrow of time is not.

G.2.3. Show crossing maps the s-channel particle amplitude to the u-channel antiparticle amplitude.

Solution. Step 1: write the amplitude $\mathcal{M}(s,t,u)$ for $ab \to cd$ with the Mandelstam invariants; LSZ expresses it through one analytic correlation function.

Step 2: continue an incoming momentum $p_a \to -p_a$: the invariants permute ($s \leftrightarrow u$), and the continued amplitude is, by the same LSZ formula, the physical amplitude for the process with a replaced by its outgoing antiparticle $\bar{a}$.

Step 3: analyticity (a causality consequence) guarantees the continuation exists and is unique: particle and antiparticle processes are boundary values of *one* analytic function. The twin is woven into the amplitude's analytic structure — which is why no consistent relativistic S-matrix without antiparticles has ever been built.

Physics intuition: crossing is the experimentalist's daily bread — the same vertex measured in scattering and in annihilation — and the deepest orthodox hint that particle and antiparticle are one object described twice, the hint Step 3 promotes to a theorem.

G.3 Step 1 — Weinberg's causality theorem, with its axioms displayed

The mature orthodox answer is a theorem, and the main text states it with respect as Theorem 111.1 (Weinberg, 1995): if the interaction density is a Lorentz scalar built from creation and annihilation operators, commuting with itself at spacelike separation, on a Hilbert space with energy bounded below, then every field in it must combine an annihilation part with a creation part of a

species of *equal mass and opposite charges*. The mechanism of the proof is worth owning (problem G.3.1): write the candidate charged field and impose causality,

$$\phi(x) \;=\; \kappa\,\phi_a^{(+)}(x) \;+\; \lambda\,\phi_b^{(-)}(x), \qquad [\phi(x),\phi^\dagger(y)]\big|_{\text{spacelike}} \stackrel{!}{=} 0: \tag{109}$$

the spacelike commutator of the annihilation part alone does not vanish — relativity forbids localizing a positive-frequency function — and the only lawful cancellation is against a creation part whose mass matches exactly and whose charges oppose. A neutral particle may satisfy the cancellation self-conjugately (problem G.3.2): the photon is its own twin, and whether the neutrino is remains the 4D experimental question this cohort's $m_{\beta\beta} = 1.72$ meV addresses.

This is Depth 2 on the chapter's ruler, answered rigorously: *any* interacting relativistic quantum theory with bounded energy contains antiparticles. And its boundary is equally sharp (problem G.3.3): three inputs sit upstream, underived — the complex Hilbert space (the i is an axiom), the positivity of energy (imposed on the *output* of quantization: the pairing is selected because the alternative wrecks the spectrum), and the time orientation. Weinberg's theorem is the strongest sentence the orthodoxy can utter, and its three axioms are the exact coordinates of where it stops — the two doors, plus the arrow, that T-P5-C walks through in Step 3.

G.3.1. Carry the causal-field proof for a charged scalar and extract the mass equality. *Solution.* Step 1: write the candidate field $\phi(x) = \int d^3p\,[\,\kappa\,a_{\mathbf{p}}e^{ip\cdot x} + \lambda\,b^\dagger_{\mathbf{p}}e^{-ip\cdot x}\,]$ with a annihilating a species of mass m_a and $b^\dagger$ creating a species of mass m_b; charge conservation forbids mixing a with $a^\dagger$ in a charged field.

Step 2: compute the commutator of (109):

$$[\phi(x),\phi^\dagger(y)] \;=\; |\kappa|^2\,\Delta_+^{(m_a)}(x-y) \;-\; |\lambda|^2\,\Delta_+^{(m_b)}(y-x). \tag{110}$$

At spacelike separation $\Delta_+(x-y) = \Delta_+(y-x) \neq 0$: each term alone survives, and the commutator vanishes iff $m_a = m_b$ and $|\kappa| = |\lambda|$.

Step 3: the b species must also carry opposite values of every conserved charge (the field must have a definite charge for the current to be well defined). Conclusion: the causal charged field *must* annihilate a particle and create its equal-mass, opposite-charge twin — existence and mass equality in one stroke, for interacting theories.

Physics intuition: relativity will not let charge be localized without a partner process — for a moving observer, absorption at x and emission at y swap order, and only the twin keeps the bookkeeping frame-independent. The antiparticle is causality's change for a broken symmetry of temporal order.

G.3.2. Show a particle with no conserved charge may satisfy causality self-conjugately. *Solution.* Step 1: with no charge to conserve, the field may mix a and $a^\dagger$: set $b = a$ in the G.3.1 expansion, i.e. $\phi = \phi^\dagger$, a real field.

Step 2: the commutator computation repeats with a single species: $[\phi(x),\phi(y)] = \Delta_+(x-y) - \Delta_+(y-x)$, which vanishes at spacelike separation identically — the cancellation is between the particle and *itself*.

Step 3: hence neutral quanta may be their own antiparticles (photon, π^0, Z), and for neutral

fermions in four dimensions the same option is the Majorana question — open experimentally, and the entire subject of the $0\nu\beta\beta$ program (§F.2; Part XI). Note for Step 3 of this chapter: in the $(1,5)$ bulk this option is closed by algebra, not experiment.

Physics intuition: the twin is charge's shadow. No charge, no obligatory shadow — and nature's use or refusal of the self-conjugate option for the neutrino is worth a tonne-scale experiment precisely because in 4D no theorem decides it.

G.3.3. Identify precisely where the complex Hilbert space, output-positivity, and time orientation enter Weinberg's argument as assumptions.

Solution. Step 1: *the i.* The argument lives on a complex Hilbert space from the first line — creation operators, phases $e^{ip\cdot x}$, interference. Nothing in it derives complexity; a real-Hilbert quantum mechanics would have to be refuted separately (and is instead *selected against* by the network Bell tests Renou et al., 2021 — experiment, not theorem).

Step 2: *positivity as output.* The pairing "creation part = opposite charges" is enforced because the alternative assignment, quantized, yields an energy spectrum unbounded below: the criterion inspects the *result* of quantization and rejects the sick one. Nothing upstream explains why the healthy assignment exists at all.

Step 3: *time orientation.* "Energy bounded below" and "positive frequency" presuppose a chosen arrow; reverse it and the roles of particle and antiparticle swap consistently. Three assumptions, none derived, all used — the exact hypothesis set T-P5-A/B/C is built to discharge (the circle supplies the charged i, the clock the neutral i and the arrow, the handshake the pairing before quantization).

Physics intuition: a theorem is a machine that converts axioms into necessity. Weinberg's converts three axioms into the antiparticle; the handshake's claim, priced in §52, is that two of those axioms were themselves conclusions one level down.

G.4 Step 1 — the spinor algebra: the mod-8 clock, read from the textbooks

The fourth Step-1 body of knowledge is pure mathematics, and the student should meet it as such before Step 3 uses it. The reality type of a spinor representation depends on the signature (t,s) only through $(t-s)$ mod 8 — the Clifford-algebra periodicity (Lawson and Michelsohn, 1989) — and the physical content is carried by the intertwiner B relating a spinor to its complex conjugate:

$$\psi^c \;=\; B\,\psi^*, \qquad B\bar{B} \;=\; \pm\mathbf{1} \quad \text{according to the hour of } (t-s) \bmod 8. \tag{111}$$

When $B\bar{B}=+\mathbf{1}$ the condition $\psi = B\psi^*$ is consistent: Majorana spinors exist, and a fermion *may* be its own conjugate. When $B\bar{B}=-\mathbf{1}$ the would-be projection squares to -1 and is empty: no Majorana condition exists, and fermion and conjugate are necessarily distinct. Four-dimensional spacetime, $(1,3)$, sits at $t-s\equiv 6$: Majorana is *available* (hence the neutrino question). The GG-6 bulk, $(1,5)$, sits at $t-s\equiv 4$: $B\bar{B}=-\mathbf{1}$, and the option is *closed* — the main text's Lemma 24.1, here recognized as a line read off a standard table (problem G.4.1).

Two more textbook facts complete the kit. In $(1,5)$ the chirality operator squares to $+\mathbf{1}$ and splits the eight-component Dirac spinor into conjugate Weyl quartets, $\mathbf{8}=\mathbf{4}\oplus\bar{\mathbf{4}}$ (10), exchanged

by conjugation. And in $4k{+}2$ dimensions chirality is a *signed currency*: the anomaly eight-form of a chirality-flipped species is the negative of its partner's, (11), the classic Alvarez-Gaumé–Witten structure (Alvarez-Gaumé and Witten, 1984) (problem G.4.2). Consistency — the vanishing of the total — therefore forces conjugate-signed content into any lawful spectrum: the books cannot balance in one sign (Arisaka, 2026, A3-BI6 executes the full BI-6 arithmetic).

Physical intuition — the eight-hour clock, retold for the drill. A spinor is a square root of a vector, and square roots negotiate with reality the way they always have: sometimes the root of a real thing is real, sometimes it comes in conjugate pairs. The negotiation cycles with dimension, period eight (Bott). Four dimensions happens to sit at an hour where self-conjugacy is on the menu; six sits four hours on, where it is not. No physics was chosen in either statement — which is exactly why Step 3 can build physics on them.

G.4.1. Verify $B\bar{B} = -\mathbf{1}$ for $(1,5)$ from the mod-8 classification, and locate $(1,3)$ for contrast.

Solution. Step 1: the standard table (Lawson and Michelsohn, 1989) assigns to each $(t{-}s)$ mod 8 the algebra type: hours $0,6$ carry $B\bar{B} = +\mathbf{1}$ on the relevant chiral pieces (real hours); hours $2,4$ carry $B\bar{B} = -\mathbf{1}$ (quaternionic hours); odd hours carry no chiral split.

Step 2: $(1,5)$: $t - s = 1 - 5 = -4 \equiv 4 \pmod 8$ — a quaternionic hour, $B\bar{B} = -\mathbf{1}$, and the would-be Majorana projection closes on itself:

$$\psi = B\psi^* \implies \psi = B\,(B\psi^*)^* = B\bar{B}\,\psi = -\,\psi \implies \psi = 0, \tag{112}$$

the condition is empty. Lemma 24.1, verified.

Step 3: $(1,3)$: $t - s = -2 \equiv 6$ — a real hour: $B\bar{B} = +\mathbf{1}$, Majorana spinors exist, and the neutrino's nature is physics, not algebra. One clock, two hours, two epistemic situations — option versus verdict.

Physics intuition: this is the rare place where "we live in six dimensions" has an immediate, checkable consequence of pure algebra: the bulk *cannot* hide the twin inside the particle. The antiparticle content is forced to be genuinely present — Step 3 collects.

G.4.2. Derive the anomaly flip: show a chirality-flipped Weyl species contributes the opposite eight-form.

Solution. Step 1: the anomaly of a Weyl fermion in $4k{+}2$ dimensions is computed by the index density of the chiral Dirac operator: the eight-form (for $d = 6$) $I_8[\rho, \sigma]$ depends on the representation ρ and enters multiplied by the chirality $\sigma = \pm 1$.

Step 2: flipping chirality at fixed ρ flips the projector $P_\pm = \frac{1}{2}(1 \pm \Gamma^7)$, and the index density changes sign — the descent equations carry the sign through: $I_8[D^-] = -I_8[D^+]$, which is (11).

Step 3: consequence: anomaly freedom $\sum_s \sigma_s I_8[\rho_s] = 0$ is a *signed* sum. A spectrum written all in one chirality with nontrivial content cannot cancel; conjugate-signed species are obligatory bookkeeping — which the BI-6 ledger turns into the specific reservoir the main text counts (§47).

Physics intuition: in six dimensions the bookkeeper cannot be bribed — every chiral species signs its contribution. Anomaly cancellation is the second, independent forcing of antiparticle content, and it is arithmetic, not preference.

G.4.3. The 4D hour: state exactly what the mod-8 clock does and does not decide about the neutrino, and connect to the double-beta program.
Solution. Step 1: at hour 6, Majorana is *available*: a neutral 4D fermion may satisfy $\psi = B\psi^*$. Algebra offers the option and stops.

Step 2: whether nature exercises it is dynamical: the boundary neutrino inherits a Majorana mass through the unique weight-zero door (T-P5-4, §F.2), so *this* framework answers yes — with the readout $m_{\beta\beta} = 1.72$ meV, below the tonne-scale floor: nature says yes, quietly.

Step 3: the epistemic contrast is the drill's point: in the bulk the question is *closed* by algebra ($B\bar{B} = -\mathbf{1}$); on the 4D boundary it is *open* by algebra and closed only by mechanism. When the student's collaboration debates "is the neutrino its own antiparticle," the honest answer is: in six dimensions nothing is; in four, this one is — by inheritance, at a stated grade, with a falsifiable size.

Physics intuition: the same question changes character with the dimension in which it is asked — a working example of why "what the twin *is*" (Depth 3) cannot be settled by 4D formalism alone.

G.5 Step 2 — what the three answers cannot say

Now the audit, on the three-depths ruler of §26. *(1) The sea* answers Depth 1 — the spectrum contains the twin — and answers it *wrongly* at Depth 3: its ontology fails for bosons, diverges in the vacuum, and asymmetrizes what experiment finds exactly symmetric (§G.1).

(2) The contour answers Depth 1 exactly and gestures at Depth 2: it *prescribes* the pairing rather than deriving it. The Feynman $i\epsilon$ is selected because the alternatives fail; the selection criterion (causal amplitudes, bounded energy) is imported, not explained; and "backward in time" is an evocative label for an analytic identity. *(3) Weinberg's theorem* is the real Depth-2 result: the twin is forced in any interacting, causal, stable, relativistic quantum theory. Its boundary is its three axioms — the i, positivity-on-output, the arrow (G.3.3) — each used, none derived.

(4) CPT protects, never explains. The exact identities of Table 1 — kaon mass to 10^{-18}, moments to 2×10^{-12} — are *bounds enforced between two objects.* Nothing in the orthodox account says why the twin is so exactly the particle's equal that "identity between two things" looks suspiciously like "one thing counted twice."

(5) The Majorana undecidability. In 4D the formalism offers self-conjugacy as an option (G.4.3) and cannot close it; forty years of $0\nu\beta\beta$ experiments are the price of an algebra that shrugs. *(6) The two disjoint literatures.* "Why is quantum mechanics complex?" and "why do antiparticles exist?" are pursued by communities that do not cite each other. An account in which they are one question would explain, at a stroke, why the twin is exact: because conjugation is not a relation between two objects but an operation on one. That account is Step 3.

G.5.1. Grade the sea, the contour, and the causality theorem on the three-depths ruler, with justifications.
Solution. Step 1: *sea*: Depth 1 (spectral) — it produces the twin in the spectrum — and a *negative* Depth 3: it asserts an ontology, and the assertion is refuted (bosons, vacuum charge, asymmetry). Being wrong at Depth 3 is worse than silence; it is the only one of the three that overclaims.

Step 2: *contour*: Depth 1 with Depth-2 gestures. It is exact bookkeeping with no failed ontology — and no ontology at all: the prescription is selected by criteria it does not derive.

Step 3: *Weinberg*: Depth 2, fully earned — necessity from stated axioms, for interacting theories. Depth 3 is explicitly renounced: "those are the axioms." The grading motivates the chapter's shape: what remains open is exactly Depth 3, and §52 prices the handshake's claim to it — including the concession that its full strength is free/quasi-free where Weinberg's is interacting.

Physics intuition: keeping the depths straight prevents both cheap criticism (the contour is not *wrong*; it is silent) and cheap victory (a Depth-3 claim must pay in theorems, not vocabulary). The ruler is the honesty instrument of Part X, drilled once by hand.

G.5.2. Show that CPT bounds the electron–positron identities but cannot explain them, and say precisely what would.

Solution. Step 1: the CPT theorem (§D.4) proves Θ exists and commutes with the dynamics; consequences: $m_{e^+} = m_{e^-}$, $g_+ = g_-$, equal lifetimes — *as identities between the spectra of two species*. Experiment confirms to 2×10^{-12} (moments) and 10^{-18} (kaon masses), Table 1.

Step 2: but the theorem is anatomically silent: it does not say what the pair *is*, why nature contains it, or why the identity is exact rather than approximate — it constrains whatever exists, given the axioms.

Step 3: an *explanation* would be a construction in which the two spectra are one spectrum read twice — where mass equality is trivial because there are not two masses. That is precisely the conjugate-readout structure of §49.1: Depth 3 answering what Depth 2 can only enforce, with the honest debt (D-P3-4) that the readout picture's full promotion is registered, owed, and unclaimed.

Physics intuition: "why are these two things exactly alike?" has only ever had one fully satisfying answer in physics — *they are not two things*. The chapter's arc bends toward earning that answer rather than asserting it.

G.5.3. Show Weinberg's three inputs are mutually independent: none implies the others.

Solution. Step 1: *the i without positivity*: complex quantum mechanics with the wrong particle–antiparticle assignment is kinematically well-defined — quantization proceeds — and delivers a Hamiltonian unbounded below. Complexity does not imply the healthy pairing.

Step 2: *positivity without the i*: real-Hilbert quantum theory admits bounded-below dynamics; it fails elsewhere (tensor-product correlations — the network Bell refutation Renou et al., 2021), showing positivity does not manufacture the complex structure.

Step 3: *the arrow independent of both*: reversing the time orientation preserves complexity and positivity while swapping the particle and antiparticle labels globally — the assignment's *content* survives, its *naming* flips. Three independent axioms; a derivation of the twin from fewer assumptions must therefore supply new structure — which is exactly what the bulk's circle and clock are (Step 3).

Physics intuition: axiom-counting is how one measures the depth of a theorem. Weinberg spends three; the handshake claims two of them as outputs by spending geometry instead — and §52 audits whether the purchase is real.

G.6 Step 3 — the handshake, the forced content, and the readouts

The geometry's answer is Part IV; this Step works it in the chapter's vocabulary, and the student should do the computation once with a pencil — §42.1 is the full rehearsal.

Two half-blind sources of i. T-P5-A: on each charge-n sector the normalized circle generator $J_Q = \partial_\theta/Q$ squares to $-\mathbf{1}$: charge supplies a complex structure, with conjugation as orientation reversal of the circle — but it is blind on neutral fields and blind to its own sign. T-P5-B: the polar phase of the time-translation generator, $J_A = \pm A(-A^2)^{-1/2}$, is the unique positive-energy complex structure commuting with the dynamics (Ashtekar and Magnon, 1975; Kay, 1978): the clock supplies the i for everything and knows the arrow — but knows nothing of charge. Where charge lives, the two must agree.

The handshake. T-P5-C, in one displayed line each way:

$$\begin{aligned} \cos(n\theta - Et): &\quad J_Q \to -\sin, \quad J_A \to -\sin \quad \text{(agree)};\\ \cos(n\theta + Et): &\quad J_Q \to -\sin, \quad J_A \to +\sin \quad \text{(anti-agree)}, \end{aligned} \tag{113}$$

so on the physical pairing the two structures are one J, and on the wrong pairing no global J exists (problems G.6.1–G.6.2). The unique repair is to read negative-frequency charge-n modes as positive-frequency charge-$(-n)$ modes — *the Feynman–Stückelberg assignment, derived*, one level below quantization, fixing the circle's sign as it goes. The contour prescription of G.2 was this agreement, encoded; Weinberg's positivity-on-output was this selection, inspected after the fact. *The existence of antiparticles is the consistency condition between the sixth dimension and causal time.*

The content, forced twice. Independently of the pairing, the bulk cannot help containing the conjugate sector: the mod-8 hour closes the Majorana escape (G.4.1), and the anomaly ledger cannot balance in one chirality (G.4.2) — algebra and arithmetic, agreeing. What the handshake pairs is therefore genuinely there.

The readouts. The positron is the conjugate readout of the electron's one basin — same level, opposite winding — so mass equality is trivial rather than enforced (§49.1; the promotion to "the positron as a theorem" is the registered debt D-P3-4). Wheeler's one-electron universe — right that the twin is one object doubly read, wrong custodian: the identification lives in each mode's geometry, not in a global worldline (problem G.6.3; §49.2).

The Hawking partner is the same conjugate readout with the OGGEP trace as the reader (§49.3). And custody throughout is the cohort's: *the dictionary owns the sectors; the geometry owns the i.* The chapter's arc, in one sentence: *Step 1 gave three answers that work; Step 2 showed none of them says what the twin is; Step 3 is a geometry in which the twin is the other way around one object — and the concessions, free/quasi-free at full strength, are printed where they belong (§52).*

G.6.1. Fill the 4×2 table of (J_Q, J_A) actions on all four modes and locate the unique agreeing pairing.

Solution. Step 1: write the four labeled modes as $u = \cos(n\theta - \omega t)$ with $n = \pm 1$ and $\omega = \pm E$, $E > 0$. The circle acts by $J_Q u = \frac{1}{n}\partial_\theta u = -\sin(n\theta - \omega t)$ — the n from the chain rule cancels the $1/n$ of the normalization, so J_Q returns $-\sin(\arg)$ on every mode.

Step 2: the clock advances the phase a quarter period in the direction its arrow fixes: on positive-frequency modes ($\omega = +E$) it returns $-\sin(n\theta - Et)$; on negative-frequency modes ($\omega = -E$) it returns $+\sin(n\theta + Et)$. Compare: $(n, \omega{=}{+}E)$ agree for both $n = \pm 1$; $(n, \omega{=}{-}E)$ anti-agree for both.

Step 3: the agreeing set is exactly {charge +1 with positive frequency, charge −1 with positive frequency}: both species run forward, nothing runs backward — the Feynman–Stückelberg pairing, read off a 4×2 table of signs. The drill is the theorem (T-P5-C); no step used quantization.

Physics intuition: two gears can mesh in exactly one relative orientation. Once the student has watched the $\pm\sin$'s align, "why do antiparticles exist" stops being a mystery and becomes a memory of a table.

G.6.2. Show the relabeling restores agreement globally, and that under the wrong pairing no global J exists.

Solution. Step 1: the relabeling reads $(n, \omega{<}0)$ as $(-n, \omega{>}0)$. Under it $Q \to -Q$, so $J_Q = \partial_\theta / Q$ flips sign on exactly the modes where it anti-agreed with J_A: agreement becomes universal, and one global $J = J_A = J_Q$ acts on every physical mode.

Step 2: suppose instead one keeps the wrong pairing and tries to patch: flip $J_Q \to -J_Q$ on the offending modes by hand. The flip is a choice of sign per mode — a 1-cochain — and consistency of J on products and sums of modes (composite states) requires the signs to be constant on connected sectors: the mismatch between the agreeing and anti-agreeing modes is a cocycle no global choice trivializes.

Step 3: hence no single complex structure serves the wrong pairing — the obstruction is structural, not aesthetic. The theory does not merely prefer the Feynman–Stückelberg assignment; it is inconsistent without it. This is positivity-on-output (G.3.3), caught one level earlier, as geometry.

Physics intuition: "you cannot choose the signs consistently" is the same species of argument as a Möbius band having no global normal — the wrong pairing builds a twisted bundle, and the twist is the answer to "why not the other way?"

G.6.3. Second basin or second orientation: state what experiment separates the two positron pictures, and what Wheeler's picture gets right and wrong.

Solution. Step 1: a *second-basin* positron — an independent object coincidentally paired — could differ from the electron in any property CPT does not protect: a slightly different binding in exotic matter, a drift in the identities of Table 1. A *second-orientation* positron cannot differ in anything: every identity is exact by construction. The experimental separator is the whole CPT-test column — every tightening null is evidence of one object, and any confirmed violation would resurrect two.

Step 2: Wheeler's one-electron universe carries the same insight in the wrong custody: one worldline threading time forward and backward predicts equal electron and positron counts and zero net lepton number — refuted by every baryon in the room (and by Part VIII's six in ten billion). What it got right — the twin as one object doubly read — survives with the custody corrected: the identification is made mode by mode, by the circle's two orientations, not by a global worldline's two directions.

Step 3: the Hawking partner completes the family: the in-falling "partner" is not a second object behind the horizon but the conjugate readout under the OGGEP trace — the two-mode-squeezed

state read from one side. Three puzzles, one resolution, custody stated each time: the dictionary owns the sectors; the geometry owns the i.

Physics intuition: the century's antiparticle puzzles — Dirac's twin, Wheeler's telephone call, Hawking's partner — are one lesson learned three times: where experiment finds perfect twins, ontology should count one. The student who has filled G.6.1's table owns that lesson as arithmetic.

H The neutrino's century, from scratch: oscillations, the matrix, the mass, and the lattice point

The fifth chapter of Block II is written for a specific reader: the incoming graduate student who has just joined a long-baseline or double-beta collaboration, or who is beginning flavor phenomenology, and who wants to own — not merely quote — every neutrino number this paper confronts. Step 1 builds the standard physics from two-state quantum mechanics to the double-beta master formula, exactly as the textbooks teach it; Step 2 marks what that physics assumes but cannot explain; Step 3 walks the lattice point end to end, at its ledger grade. Nothing in the main text is needed to start; everything in Part XI can be recomputed by the reader who finishes.

The chapter shelf, annotated. Giunti and Kim (2007) is the field's standard reference — oscillations in vacuum and matter, field-theory foundations, and the kinematic bounds; read Chapters 6–10 alongside §H.1–H.3. Zuber (2020) is the experimentalist's companion — detectors, backgrounds, and the double-beta chapter that §H.4 drills. Mohapatra and Pal (2004) carries the seesaw and its model space at book length.

Branco, Lavoura, and Silva (1999) is the CP-violation monograph — rephasing invariants, Majorana phases, and the conventions (their Ch. 22 disambiguates the phase conventions that trap every beginner). And the Particle Data Group's neutrino review (Particle Data Group, 2024) is the living document: the reader should recompute this chapter's numbers against each new edition, in the spirit of §127. Eighteen problems, complete solutions included.

H.1 Step 1 — oscillations from two-state quantum mechanics

A neutrino is produced by the weak interaction as a *flavor* state — the partner of a charged lepton — but propagates as a superposition of *mass* states. Two flavors suffice for the physics. Let

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}, \tag{114}$$

and let each mass state evolve with its own phase. For an ultrarelativistic neutrino of momentum p, $E_i = \sqrt{p^2 + m_i^2} \simeq p + m_i^2/2E$, so after a distance L the two components have slipped in phase by $\Delta\phi = \Delta m^2 L/2E$. Projecting back onto flavor, the appearance probability is

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \, \sin^2\!\Big(\frac{\Delta m^2 L}{4E}\Big) = \sin^2 2\theta \, \sin^2\!\Big(1.267\,\frac{\Delta m^2[\mathrm{eV}^2]\, L[\mathrm{km}]}{E[\mathrm{GeV}]}\Big), \tag{115}$$

the master formula of the field; the 1.267 is $1/(4\hbar c)$ in the stated units, and the reader should derive it once by hand (problem H.1.1). Physical intuition: this is the beat note of two clocks. The two mass states are two pendulums swinging at slightly different rates; the flavor content is where the beat happens to stand when the neutrino is caught. Nothing oscillates in the neutrino itself — what oscillates is the *alignment* between the basis nature uses to make neutrinos and the basis it uses to move them.

The worked number. T2K's baseline is $L = 295$ km and its beam peaks at $E \simeq 0.6$ GeV. With $|\Delta m^2_{31}| = 2.5 \times 10^{-3}\,\mathrm{eV}^2$: $1.267 \times 2.5 \times 10^{-3} \times 295/0.6 = 1.56 \simeq \pi/2$ — the experiment sits at its first oscillation maximum, by design. The same arithmetic at DUNE (1300 km, 2.5 GeV) gives 1.65: also near maximum. Two very different machines, one dimensionless tuning — the reader who can do this one line owns the design logic of every long-baseline experiment on Earth.

Three flavors and the discovery history. With three mass states the amplitude is a coherent sum, $A_{\alpha\beta} = \sum_i U^*_{\alpha i} e^{-i m_i^2 L/2E} U_{\beta i}$, and two independent splittings drive two beat notes: the "solar" $\Delta m^2_{21} \simeq 7.4 \times 10^{-5}\,\mathrm{eV}^2$ and the "atmospheric" $|\Delta m^2_{31}| \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2$, thirty-four times apart. The history is a course in itself (Part XI tells it): Super-Kamiokande's 1998 zenith-angle deficit, SNO's flavor-blind neutral-current measurement, KamLAND's reactor beat — three Nobel-line measurements, one matrix.

Matter modifies the story: coherent forward scattering on electrons adds an effective potential $V = \sqrt{2}\,G_F N_e$ for ν_e only (Wolfenstein; the MSW resonance), which regenerates or suppresses conversion depending on the *sign* of Δm^2 — the handle by which DUNE's long, dense baseline reads the mass ordering (§H.3). Textbook custody: Giunti and Kim (2007), Chs. 7–9; Zuber (2020), Ch. 8.

H.1.1. Restore $\hbar$ and c in (115) and derive the 1.267.
Solution. Step 1: in natural units the argument is $\Delta m^2 L/4E$; restoring dimensions, phase $= \Delta m^2 c^4\, L/(4\hbar c\, E)$ — one $\hbar c$ because the phase is (energy difference)$\times$(time) $= (\Delta m^2 c^4/2E)(L/c)/\hbar$, halved again into the $\sin^2$ convention.

Step 2: insert units with $\hbar c = 197.327$ eV nm $= 197.327 \times 10^{-9}$ eV m: $\dfrac{(1\text{ eV})^2(1\text{ km})}{4\,\hbar c\,(1\text{ GeV})} = \dfrac{10^3}{4 \times 197.327 \times 10^{-9} \times 10^9} = \dfrac{10^3}{789.3} = 1.267.$

Step 3: hence the argument is $1.267\,\Delta m^2[\mathrm{eV}^2] L[\mathrm{km}]/E[\mathrm{GeV}]$, dimensionless as a phase must be. The number every proposal, thesis, and design report in the field carries is a unit conversion of $\hbar c$ — worth deriving once so it is never mysterious again.

Physics intuition: oscillation physics is interferometry, and 1.267 is the instrument's fringe-spacing constant. Baselines and beam energies are chosen by inverting this one line — which is exactly what the worked number above did.

H.1.2. Compute the first-maximum energies at JUNO's 52.5 km reactor baseline for both splittings, and describe the spectrum JUNO reads.
Solution. Step 1: set the argument of (115) to $\pi/2$ and solve for E: $E = 1.267\,\Delta m^2 L/(\pi/2)$.

Step 2: solar splitting: $E = 1.267 \times 7.4 \times 10^{-5} \times 52.5/1.571 = 3.1 \times 10^{-3}$ GeV $= 3.1$ MeV — squarely inside the reactor antineutrino spectrum (2–8 MeV): JUNO sits at the *solar* first maximum, and the reader who has heard looser values quoted should trust the arithmetic.

Step 3: atmospheric splitting: the same formula gives $E = 106$ MeV — far above reactor energies, so at 2–8 MeV the atmospheric phase is large and rapidly varying: a fast wiggle riding on the deep solar envelope. The *phase* of that fast wiggle differs between the orderings, which is precisely how JUNO reads the ordering with no accelerator, no matter effect, and no δ dependence: pure vacuum interferometry at the percent level.

Physics intuition: JUNO is a radio tuned between two stations: the slow solar note sets the volume, the fast atmospheric note carries the message, and resolving it costs the $3\%/\sqrt{E}$ energy resolution that drove the entire detector design.

H.1.3. Show that for $\Delta\phi \gg 2\pi$ with energy smearing the probability averages to $\frac{1}{2}\sin^2 2\theta$, and identify where Part XI uses this.

Solution. Step 1: average (115) over a spread of E (or L): the argument winds many cycles, and $\langle \sin^2 x \rangle = \frac{1}{2}$ for any smooth distribution wide compared to a period.

Step 2: hence $\langle P \rangle = \frac{1}{2}\sin^2 2\theta$: the interference washes out, the flavor conversion does not — an incoherent mixture at the averaged value.

Step 3: Super-Kamiokande's high-L/E atmospheric bins live in exactly this regime, and the averaged formula is what the atmospheric-sector numbers of Part XI fit in those bins; the coherent wiggle survives only in the resolved-L/E analysis that made the 1998 discovery plot.

Physics intuition: interferometers lose fringes when the source is broadband; the residual $\frac{1}{2}$ is the incoherent shadow of the mixing. Knowing which regime an analysis lives in is the first question a new collaborator should ask of any oscillation plot.

H.2 Step 1 — the PMNS matrix, its conventions, and the invariant

The leptonic mixing matrix in the standard parameterization is

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor + phase}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \operatorname{diag}(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2}), \qquad (116)$$

with $s_{ij} = \sin\theta_{ij}$. The three angles are measured by three different classes of experiment (the labels above), the Dirac phase δ by appearance asymmetries (§H.3), and the two Majorana phases — physical only if the neutrino is its own antiparticle — by nothing yet except double beta (§H.4). Convention warning, worth a lecture of its own (Branco, Lavoura, and Silva, 1999, Ch. 22): where δ multiplies s_{13} is a choice, and comparing papers without fixing it has wasted real person-years.

The numbers, mid-2026. $\sin^2\theta_{12} = 0.307(12)$, $\sin^2\theta_{13} = 0.0219(6)$, $\sin^2\theta_{23} = 0.56(2)$ (upper octant preferred), and NuFit 6.0's $\delta = 177^\circ{}^{+19}_{-20}$ under normal ordering (§127 carries the refresh rules and pulls). The reader should learn to read a global fit the way Part XI does: as a likelihood over the oscillation data with correlated systematics, whose preferred octant, ordering, and phase move with each dataset — which is why the cohort's confrontation prints pulls with dates.

The invariant. All CP-violating appearance effects are proportional to one rephasing-invariant,

the leptonic Jarlskog (§E.2 derives its uniqueness):

$$J_{\rm PMNS} = c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23} \sin\delta. \tag{117}$$

With the angles above the prefactor is 0.0332–0.0335, depending on the fit variant and rounding; the *maximal* leptonic Jarlskog is thus 3.3×10^{-2}, a thousand times the quark sector's 3.1×10^{-5} — large mixing buys the lepton sector its loud interferometry.

H.2.1. Count the physical phases of the lepton mixing matrix for Dirac versus Majorana neutrinos.

Solution. Step 1: a general 3×3 unitary matrix carries three angles and six phases. The charged-lepton fields can always be rephased — three phases removed, in either case.

Step 2: if the neutrinos are Dirac, their fields can be rephased too; two further phases go (the overall common phase is unphysical and already spent), leaving $6 - 3 - 2 = 1$: the single Dirac phase δ of the quark-sector counting (problem E.1.1 of Appendix E).

Step 3: if the neutrinos are Majorana, the mass term $\frac{1}{2} m\, \overline{\nu^c} \nu$ is quadratic in the same field: a rephasing $\nu \to e^{i\beta}\nu$ shifts its phase and is *not* a symmetry. The neutrino rephasings are lost, and $6 - 3 = 3$ phases survive: δ plus the two Majorana phases of (116) — observable only in lepton-number-violating interference, which is why §H.4's coherent sum is their sole known laboratory.

Physics intuition: phases live where rephasings die. Majorana-ness removes freedom, and removed freedom becomes physics — two extra dials that only the $0\nu\beta\beta$ interferometer can read.

H.2.2. Show $J_{\rm PMNS} = \mathrm{Im}(U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^*)$ reproduces (117) in the standard parameterization.

Solution. Step 1: read off the elements from (116): $U_{e1} = c_{12}c_{13}$, $U_{e2} = s_{12}c_{13}$, $U_{\mu 1} = -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta}$, $U_{\mu 2} = c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta}$ (the Majorana factors cancel in any quartet — each neutrino index appears once conjugated, once not).

Step 2: multiply. The product $U_{e1}U_{\mu 2}U_{e2}^* U_{\mu 1}^*$ contains four terms; the real-times-real and $|e^{i\delta}|^2$ pieces are real, and the imaginary part survives only in the cross terms, collecting to $c_{12}s_{12}c_{23}s_{23}c_{13}^2 s_{13}\,\mathrm{Im}(e^{i\delta}) \times (c_{12}^2 + s_{12}^2)$.

Step 3: hence $\mathrm{Im}\, Q = c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23} \sin\delta$, which is (117) — and the exercise's real lesson: quartets are convention-proof, parameterizations are not; every claimed CP effect should be expressible through $J_{\rm PMNS}$ or it is an artifact of a chart.

Physics intuition: this is the leptonic copy of §E.2's machinery — one invariant, sector by sector; nature keeps exactly one CP dial per Dirac sector and hides the Majorana pair from oscillations altogether.

H.2.3. Propagate the NuFit uncertainties into $J_{\rm PMNS}^{\rm max}$, identifying the dominant contribution.

Solution. Step 1: logarithmic derivatives of $J_{\rm PMNS}^{\rm max} = c_{13}^2 s_{13}\, c_{12}s_{12}\, c_{23}s_{23}$. For θ_{13}: $J \propto s_{13}$ to leading order, so $\delta J/J \simeq \frac{1}{2}\,\delta(s_{13}^2)/s_{13}^2 = \frac{1}{2}(0.0006/0.0219) = 1.4\%$.

Step 2: for θ_{12}: $J \propto \sin 2\theta_{12}$, $\delta J/J = 2\cot(2\theta_{12})\,\delta\theta_{12}$; with $s_{12}^2 = 0.307(12)$, $\theta_{12} = 33.6°$, $\delta\theta_{12} = 0.013$, this gives $\simeq 1.1\%$. For θ_{23}: $J \propto \sin 2\theta_{23}$ with $2\theta_{23} \simeq 97°$ — nearly maximal, so

$\cot(2\theta_{23}) = -0.12$ and the contribution is only $\simeq 0.5\%$ despite the fat error on the octant.

Step 3: in quadrature: $\delta J/J \simeq 1.9\% \approx 2\%$, dominated by θ_{13} and θ_{12} — *not* by θ_{23}, however often the octant is blamed: near-maximality *protects* J from the octant uncertainty, because $\sin 2\theta$ is flat at its peak. The corrected budget is the one to quote.

Physics intuition: a product is most sensitive to the factors far from their extrema. The octant war that dominates conference talks barely touches $J_{\rm PMNS}$ — a two-line calculation that saves the reader from a common and confidently repeated error.

H.3 Step 1 — the appearance asymmetry: how a phase becomes a rate

The long-baseline observable is $\nu_\mu \to \nu_e$ appearance against its antineutrino mirror. Expanding the three-flavor probability to first order in the small quantities $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \simeq 0.03$ and s_{13}, with $\Delta \equiv \Delta m^2_{31} L/4E$ (the Cervera–Freund expansion; Giunti and Kim, 2007, §13):

$$P(\nu_\mu \to \nu_e) \simeq s^2_{23} \sin^2 2\theta_{13} \sin^2\Delta + 8\, J^{\rm red}_{\rm PMNS}\, \alpha\, \Delta\, \sin\Delta \left(\cos\Delta\cos\delta - \sin\Delta\sin\delta\right) + \mathcal{O}(\alpha^2), \tag{118}$$

where $J^{\rm red}_{\rm PMNS}$ is the Jarlskog prefactor without $\sin\delta$. The reader should derive the exact expression once (problem H.3.1) and then trust the structure: *the atmospheric amplitude is the carrier wave, the solar amplitude is the modulation, and δ is the phase between them.* At an oscillation maximum ($\Delta = \pi/2$) the $\cos\delta$ term dies and the asymmetry is cleanest — $A_{CP} \sim -0.28 \sin\delta$ at T2K/Hyper-K kinematics: the asymmetry scale of §78.4 ($\sim 28\%$ at maximal $\sin\delta$; $\simeq +8\%$ at the lattice point $\sin\delta = -0.283$), derived rather than quoted.

Matter complicates and enriches: the potential enters as $a = 2\sqrt{2}\, G_F N_e E/\Delta m^2_{31}$, which *fakes* CP violation (matter is not CP symmetric — the Earth is made of electrons, not positrons) but does so with a known E and L dependence and with opposite sign for the two orderings. Hence the division of labor the reader will live inside: Hyper-K at 295 km ($a \simeq 0.05$, matter-thin) reads δ cleanly; DUNE at 1300 km ($a \simeq 0.2$, matter-thick) reads the ordering first and δ second; JUNO reads the ordering with no δ dependence at all. Three machines, three systematics, one phase.

H.3.1. Derive (118) from the three-flavor amplitude.
Solution. Step 1: write the appearance amplitude $A_{\mu e} = \sum_i U^*_{\mu i} U_{ei} e^{-i m^2_i L/2E}$, factor out the overall phase of the first mass state, and expand in the two small quantities: the atmospheric piece $A_{\rm atm} \simeq s_{23} \sin 2\theta_{13} e^{-i(\Delta+\delta)} \sin\Delta$ and the solar piece $A_{\rm sol} \simeq c_{23} \sin 2\theta_{12}\, \alpha\, \Delta$ (to first order each).

Step 2: square the sum: $P = |A_{\rm atm}|^2 + |A_{\rm sol}|^2 + 2\,{\rm Re}(A_{\rm atm} A^*_{\rm sol})$. The first term is the carrier line of (118); the cross term carries $\cos(\Delta+\delta) = \cos\Delta\cos\delta - \sin\Delta\sin\delta$ — the displayed interference, with the full prefactor assembling to $8 J^{\rm red}_{\rm PMNS} \alpha \Delta \sin\Delta$.

Step 3: the antineutrino probability follows by $\delta \to -\delta$ (and $a \to -a$ in matter): the $\sin\Delta\sin\delta$ interference flips sign — the entire CP asymmetry lives in one term, and checking the result against the literature's Eq. (1) is part of the training.

Physics intuition: a phase is invisible until something interferes with it. The solar amplitude is the reference beam of the leptonic interferometer; without the "small" solar splitting there would be no CP measurement at any baseline, at any cost.

H.3.2. Show matter's fake asymmetry grows with L and reverses with the ordering, and estimate it at DUNE.

Solution. Step 1: in constant-density matter the atmospheric piece is modified by $\Delta \to \Delta(1-a)$ and $\sin 2\theta_{13} \to \sin 2\theta_{13}/(1-a)$ (leading order): the appearance probability is enhanced for neutrinos and suppressed for antineutrinos in the normal ordering — and the reverse in the inverted, because $a \propto 1/\Delta m^2_{31}$ flips sign with the ordering.

Step 2: at DUNE, $E = 2.5$ GeV and crustal N_e give $a \simeq 0.2$: the induced neutrino–antineutrino rate difference is of order $2a/(1-a^2) \sim 40\%$-class on the atmospheric term — comparable to or larger than the genuine $-0.28 \sin\delta$ effect ($\simeq +8\%$ at the lattice point).

Step 3: the resolution is the known E and L dependence: the fake grows linearly with L and with E, the genuine effect does not — so DUNE fits ordering and phase jointly, and its spectral shape separates them. This is why DUNE *must* be matter-thick (the ordering is its first deliverable) while Hyper-K *must* be matter-thin (the phase is its first deliverable).

Physics intuition: the Earth is a polarizer inserted in the interferometer — it biases the fringes, but predictably, and a two-detector program with different thicknesses turns the nuisance into a cross-check.

H.3.3. At the lattice point, estimate the bias if an analysis assumes $\delta = 270°$-centered priors.

Solution. Step 1: the likelihood in δ near a non-maximal true value is asymmetric: the appearance rates depend on $\sin\delta$ and $\cos\delta$, and at $\delta_{\rm true} = 196°$ the $\sin\delta$ observable sits at -0.28, far from the boundary values ± 1.

Step 2: a prior (or a test statistic) centered on maximal violation weights the $\sin\delta = \pm 1$ region; with finite statistics the posterior mode pulls toward maximal — the standard boundary bias of constrained fits, here aggravated because the discovery statistic ("CP conservation excluded") is optimized for 270°.

Step 3: the operational request of Part XII follows: publish posteriors (or full likelihood profiles) in δ, not only discovery significances — under which the lattice point and the maximal point are two stated hypotheses compared on equal footing (§126.1 carries the two-point adjudication).

Physics intuition: instruments inherit the questions they were funded to ask. A discovery statistic tuned to maximal CP violation is the right tool for one hypothesis and a biased tool for another — the fix is not new hardware but published likelihoods.

H.4 Step 1 — Dirac, Majorana, the seesaw, and double beta

A Dirac mass couples left to right, $m_D\,\bar\nu_L \nu_R$, and conserves lepton number; a Majorana mass couples a field to its own conjugate, $\frac{1}{2} M\,\overline{N^c_g} N_g$, and violates lepton number by two — lawful only for a fermion with zero conserved charge. With both present for one generation, the mass matrix in the (ν_L, N^c) basis is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}, \qquad m_{1,2} = \frac{M}{2}\Big(1 \mp \sqrt{1 + 4m_D^2/M^2}\Big) \xrightarrow{M \gg m_D} -\frac{m_D^2}{M},\ M. \tag{119}$$

The light eigenvalue is the seesaw of §F.2, here diagonalized by hand (problem H.4.1); the light state $\nu \simeq \nu_L - (m_D/M)N^c$ is almost entirely the active field. *The worked number:* set $M = 3.85$ TeV and ask what Dirac coupling gives $m_3 = 50.5$ meV: $m_D = \sqrt{m_3 M} = 0.44$ MeV, a Yukawa $y = \sqrt{2}\, m_D/v \simeq 2.5 \times 10^{-6}$ — electron-class smallness with a TeV partner, no desert required. This one line is why the cohort's leptogenesis lives at collider scales rather than at 10^9 GeV.

If the neutrino is Majorana, certain even-even nuclei (^{76}Ge, ^{136}Xe, ^{100}Mo) can decay $(A, Z) \to (A, Z{+}2) + 2e^-$ with no neutrinos: one emitted virtually, reabsorbed as its own antiparticle. The rate is

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(Q, Z)\, |M^{0\nu}|^2 \Big(\frac{m_{\beta\beta}}{m_e}\Big)^2, \qquad m_{\beta\beta} = \Big|\sum_i U_{ei}^2\, m_i\Big|, \tag{120}$$

with $G^{0\nu}$ the calculable phase space, $M^{0\nu}$ the nuclear matrix element (NME), and $m_{\beta\beta}$ the effective Majorana mass — the coherent sum in which the Majorana phases finally become physical. Written out in the parameterization of (116):

$$m_{\beta\beta} = \big|c_{12}^2 c_{13}^2\, m_1 + s_{12}^2 c_{13}^2\, m_2\, e^{i\alpha_{21}} + s_{13}^2\, m_3\, e^{i(\alpha_{31} - 2\delta)}\big|. \tag{121}$$

Physical intuition: three paths through the nucleus, one per mass state, added as *amplitudes*; the Majorana phases set the interference. The state of the art is KamLAND-Zen's $T_{1/2} > 3.8 \times 10^{26}$ yr, translating — through the NME spread, the honest systematic of the field, a factor $\sim$ 2–3 between many-body methods (Zuber, 2020, Ch. 7) — to $m_{\beta\beta} <$ 28–122 meV; the ton-scale program (LEGEND-1000, nEXO, CUPID) reaches $m_{\beta\beta} \sim$ 5–20 meV in the 2030s (§125).

H.4.1. Diagonalize (119) exactly and verify $\tan 2\theta = 2m_D/M$; evaluate the active–sterile mixing at the worked numbers.

Solution. Step 1: for the symmetric matrix $\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$ the rotation angle diagonalizing it obeys $\tan 2\theta = 2m_D/(M - 0) = 2m_D/M$; the eigenvalues are $\frac{M}{2}(1 \mp \sqrt{1 + 4m_D^2/M^2})$, as displayed — the light one negative (a Majorana phase absorbs the sign, as in problem F.2.1).

Step 2: expand for $M \gg m_D$: $m_{\text{light}} \simeq -m_D^2/M$, $m_{\text{heavy}} \simeq M$, and $\theta \simeq m_D/M$.

Step 3: at the worked numbers, $\theta \simeq 0.44$ MeV/3.85 TeV $= 1.1 \times 10^{-7}$: active–sterile mixing at the 10^{-14} level in probability — invisible to every oscillation experiment, which is why the heavy states hide from DUNE while running the early-universe door of Appendix F.

Physics intuition: the seesaw hides its own evidence — the lighter it makes the neutrino, the more invisible it makes the partner. The only laboratories left are lepton number itself ($0\nu\beta\beta$) and the cosmology; the chapter's remaining problems live in both.

H.4.2. Evaluate (121) with the ledger inputs and reproduce the point value.

Solution. Step 1: inputs: masses $(m_1, m_2, m_3) = (0.065, 8.59, 50.5)$ meV, phases $(\alpha_{21}, \alpha_{31}) = (0, \pi)$, $\delta = 196.06°$, and the NuFit angles of §H.2.

Step 2: term by term: $c_{12}^2 c_{13}^2 m_1 = 0.677 \times 0.065 = 0.044$ meV; $s_{12}^2 c_{13}^2 m_2\, e^{i\cdot 0} = 0.301 \times 8.59 = 2.59$ meV (the first two add); $s_{13}^2 m_3 = 0.0219 \times 50.5 = 1.11$ meV with phase $\alpha_{31} - 2\delta = 180° - 392.1° \equiv 147.9°$, contributing $(-0.94 + 0.59\, i)$ meV.

Step 3: sum: $(2.63 - 0.94) + 0.59\, i = 1.69 + 0.59\, i$, modulus $\sqrt{1.69^2 + 0.59^2} = 1.79$ meV — the

QD-layer evaluation ($\delta = 196.06°$ with measured angles), four percent above Part VII's registered first-order evaluation 1.72 meV; the residue is the evaluation layer — the δ-convention and angle-central choices (the answer's last digit moves with the layer, which is itself a lesson of §H.2). Both evaluations sit a factor of a few below the ton-scale floor: the registered null is layer-robust.

Physics intuition: the third path, phase-rotated by the lattice's $(\pi, 196°)$ pair, *destructively* clips the dominant solar pair — the geometry does not merely predict a small $m_{\beta\beta}$, it predicts a specific interference, and the number is the fingerprint of the phase set.

H.4.3. Show that in the inverted ordering (121) is bounded below by $\simeq 19$ meV.
Solution. Step 1: in the inverted ordering the two heavy states are quasi-degenerate at the atmospheric scale: $m_1 \simeq m_2 \simeq \sqrt{|\Delta m^2_{31}|} = 50$ meV, and m_3 is light.

Step 2: the worst case is maximal cancellation between the two dominant terms ($\alpha_{21} = \pi$): $m_{\beta\beta} \geq c^2_{13}\,(c^2_{12} - s^2_{12})\,\sqrt{|\Delta m^2_{31}|}$ minus the small m_3 term.

Step 3: numerically: $0.978 \times (0.693 - 0.307) \times 50 = 18.9 \simeq 19$ meV — the famous IO floor, inside the ton-scale reach. Hence the double exposure this paper volunteers: it requires normal ordering *and* silence at the ton scale; an IO determination or a confirmed line each kills it independently (Table 26).

Physics intuition: the IO floor exists because degenerate amplitudes cannot fully cancel through the measured solar angle — interferometry with a guaranteed residue. The ton-scale program is decisive for IO and, for this paper's NO-plus-silence prediction, decisive in the other direction too.

H.5 Step 2 — what the campaign cannot price

Now the audit, in the register of the four chapters before this one. *(1) Six dials, zero explanations.* Two splittings, three angles, one phase: all measured, none explained. The parameterization (116) is a coordinate chart, not a theory — the oscillation formalism is a beautiful interferometer with no opinion about what it interferes.

(2) Why three? Why tiny? Why large mixing? The formalism takes the flavor count, the mass scale, and the striking contrast with the quark sector's small angles as inputs; no Standard-Model principle addresses any of them.

(3) The phase is free, and the campaign is priced on its freedom. A billion-dollar program measures δ precisely because any value is equally lawful; sensitivity is advertised against maximal violation (270°) because nothing prefers anything — the exposure of problem H.3.3.

(4) The Majorana question cannot even be posed. Whether the neutrino is its own antiparticle is, in the 4D formalism, an option with no principle behind it (§G.4: the mod-8 hour makes it available and stops). *(5) The funnel is structural.* Without masses and phases, (121) is a band spanning two orders of magnitude; a null refutes nothing — the field's deepest frustration is that it measures a coherent sum whose every term is free. *(6) No quark–lepton bridge.* $\delta_{\rm CKM}$ and $\delta_{\rm PMNS}$ live in disconnected Yukawa sectors (limitation (3) of §E.5); the SM cannot even ask whether 66.9° and 196.4° are related.

H.5.1. Make limitation (1) precise: count what the oscillation program measures against what any theory must eventually supply.

Solution. Step 1: the oscillation sector delivers six numbers (two splittings, three angles, one phase) plus two discrete verdicts (ordering, octant); the kinematic and cosmological sectors add the absolute scale; double beta adds the nature and, if Majorana, two more phases.

Step 2: the Standard Model plus seesaw *parameterizes* all of it (eighteen high-scale parameters, problem F.5.2) and *predicts* none of it: every measured number maps to an inequivalent choice of Yukawa texture.

Step 3: a framework claiming explanatory depth must therefore output, not input, at least: the mass triplet, the ordering, the phase set, and the nature — which is exactly the list Step 3 confronts, entry by entry, with grades. The counting is the specification of what "explanation" would mean here.

Physics intuition: the neutrino sector is physics' cleanest case of a complete measurement program with an empty theory column — which is precisely why it is the right place to stake a falsifiable geometry.

H.5.2. Propagate a factor-2 NME uncertainty into the half-life needed to reach $m_{\beta\beta} = 1.72$ meV in ^{136}Xe.

Solution. Step 1: from (120), $T_{1/2} \propto 1/(|M^{0\nu}|^2\, m_{\beta\beta}^2)$: scaling from KamLAND-Zen's 3.8×10^{26} yr at $m_{\beta\beta} = 28$–122 meV (the spread *is* the NME band).

Step 2: $T_{1/2}(1.72\ \text{meV}) = 3.8 \times 10^{26} \times (28/1.72)^2 = 1.0 \times 10^{29}$ yr at the favorable NME edge, and $3.8 \times 10^{26} \times (122/1.72)^2 = 1.9 \times 10^{30}$ yr at the unfavorable — call it 10^{29}–10^{31} yr with the factor-2 NME freedom folded in.

Step 3: the ton-scale program's design reach is $\sim 10^{28}$ yr: the lattice point sits one to two orders beyond it (three at the unfavorable NME edge with its factor-2 freedom) — "below reach" is arithmetic, not pessimism, and the registered-null prediction of Step 3 is therefore safe from the NME systematic in *both* directions: no NME choice brings 1.72 meV into this generation's view.

Physics intuition: half-life scales as the inverse square of the amplitude — precision bought in $m_{\beta\beta}$ costs quadratically in exposure. The NME band moves the goalposts by a factor of a few; the lattice point sits a stadium away.

H.5.3. Show that in the SM plus seesaw, δ_{CKM} and δ_{PMNS} are independent inputs: no measurement of one constrains the other.

Solution. Step 1: the quark phase lives in $V = U_L^{u\dagger} U_L^d$, built from the up and down Yukawas; the lepton phase lives in $U = U_L^{e\dagger} U_\nu$, built from the charged-lepton Yukawa and the seesaw output (119).

Step 2: the four Yukawa matrices are independent inputs of the Lagrangian; any $(\delta_{\text{CKM}}, \delta_{\text{PMNS}})$ pair is realized by some choice, and the renormalization-group mixing between sectors is negligible at measured couplings. Hence the joint parameter space is a product: measuring one phase updates nothing about the other.

Step 3: contrast Step 3's claim: both phases are circuits of *one* pentagon — branch for quarks, center for leptons (problem E.6.2 of Appendix E) — so their values are correlated outputs of one texture. The SM cannot pose the question; the geometry answers it with two numbers already in the confrontation table.

Physics intuition: unrelated in the orthodoxy, cousins in the geometry — the pair $(66.9°, 196.4°)$

is either a coincidence twice over or one shape read twice. The falsifier table prices the difference.

H.6 Step 3 — the lattice point, end to end

The geometry's answers, in the order the campaign will test them. *The masses* (limitations 1–2): the three light masses are derived — $(0.065, 8.59, 50.5)$ meV, normal ordering, from the seesaw with the matched Yukawa and the lock scale (Part VIII; parent derivation in Arisaka, 2026, A9-SM) — so both splittings are outputs: $\Delta m^2_{21} = 7.37 \times 10^{-5}\,\mathrm{eV}^2$ and $\Delta m^2_{31} = 2.55 \times 10^{-3}\,\mathrm{eV}^2$, with the pulls printed: the solar value sits at -0.6σ against NuFit 6.0's $(7.49 \pm 0.19) \times 10^{-5}$ and at -1.0σ against JUNO's $(7.50 \pm 0.12) \times 10^{-5}$; the atmospheric value at $+0.7$ to $+1.9\sigma$ against the 2.51–2.53×10^{-3} class, depending on the fit variant. The interferometer of §H.1, on this account, has been measuring ledger entries all along.

The phase set (limitation 3): $\delta_{\mathrm{PMNS}} = \pi + 2\arcsin(1/7) = 196.43°$ (QD 196.06°), $(\alpha_{21}, \alpha_{31}) = (0, \pi)$ — so $\sin\delta_{\mathrm{PMNS}} = -0.283$ exactly (problem H.6.1), $J_{\mathrm{PMNS}} = -9.4 \times 10^{-3}$ (problem H.6.2), and the campaign becomes a two-point discrimination: the lattice point against the maximal expectation, 73.6° apart, decided at the late-2030s ±7–10° resolutions (§126.1). The flagship 5σ CP-violation discovery becomes the quiet signature: it should *not* arrive.

The nature (limitations 4–5): the door theorem T-P5-4 makes the neutrino Majorana and unique — the 4D option converted to a verdict by inheritance (§G.4) — and the funnel collapses to the point $m_{\beta\beta} = 1.72$ meV (problem H.4.2): a registered null for the ton-scale era, doubly exposed through the IO floor (problem H.4.3). *The bridge* (limitation 6): one pentagon, two circuits — 66.9° and 196.4° as correlated outputs (problem H.5.3). And the same door, run at the lock scale in the early universe, hands the sphalerons their 28/79 — Appendix F, grade D* — and the six extra baryons per ten billion photons are the receipt.

What each instrument adjudicates. JUNO: the ordering, δ-blind — a clean kill channel. Hyper-K: the phase, matter-thin — the quiet signature's home. DUNE: ordering then phase, matter-thick — the consistency check that matter effects cannot fake both. Ton-scale $0\nu\beta\beta$: the Majorana architecture, one-sided. Each column of Table 24 is a row of this chapter.

The reader's checklist. By the end of this chapter the reader should be able to: derive (115) and tune any baseline; write (116) in a stated convention and translate between conventions; expand (118) and separate genuine from matter-faked CP violation; diagonalize (119) and run the matched-Yukawa arithmetic; evaluate (121) at the ledger point; and recompute every pull in Table 23 from the current NuFit release. That last exercise — rerun the confrontation at each data release, in the discipline of §127 — is not homework; it is the profession this paper hopes its reader joins.

H.6.1. From $\delta_{\mathrm{PMNS}} = \pi + 2\arcsin(1/7)$, derive $\sin\delta_{\mathrm{PMNS}} = -8\sqrt{3}/49$ exactly.
Solution. Step 1: $\sin(\pi + x) = -\sin x$ with $x = 2\arcsin(1/7)$.

Step 2: $\sin(2\arcsin u) = 2u\sqrt{1-u^2}$ with $u = 1/7$: $2 \cdot \frac{1}{7} \cdot \sqrt{1 - \frac{1}{49}} = \frac{2}{7} \cdot \frac{\sqrt{48}}{7} = \frac{2 \cdot 4\sqrt{3}}{49} = \frac{8\sqrt{3}}{49}$.

Step 3: hence $\sin\delta_{\mathrm{PMNS}} = -8\sqrt{3}/49 = -0.28278$ — an exact surd. The "quiet signature" — the moderate, negative-sign asymmetry every long-baseline fit will converge toward if the geometry is right — is not a fitted decimal but a closed form, as befits a lattice point.

Physics intuition: when a theory's prediction is a surd, the experiment is measuring arithmetic. The reader should keep the closed form in mind when the collaboration's posterior narrows: the

target has zero width.

H.6.2. Assemble $J_{\rm PMNS}$ from the prefactor and the surd, and compare with the worked value.

Solution. Step 1: the prefactor of (117) at the mid-2026 angles is 0.0332–0.0335 across the current fit variants (§H.2), with the $\sim 2\%$ budget of problem H.2.3.

Step 2: multiply by the surd: $J_{\rm PMNS} = 0.0332 \times (-0.28278) = -9.4 \times 10^{-3}$; the prefactor spread gives -9.4 to -9.5×10^{-3} — the paper quotes -9.4×10^{-3}, in agreement with the worked example §78.4 inside the angle uncertainties.

Step 3: the sign is physical and load-bearing: it sets the direction of the T2K/Hyper-K asymmetry and, upstream, the sign of the lepton ledger the sphalerons process (Appendix F) — one surd, laboratory and cosmology both.

Physics intuition: $J_{\rm PMNS}$ is the lepton sector's entire CP budget in one number; that this paper writes it as (measured angles) $\times$ (exact surd) is the cleanest statement of what "valuing the phase" means.

H.6.3. Show the pair (ordering, $m_{\beta\beta}$) is internally redundant for this paper: either measurement alone can kill it; both together cannot save it.

Solution. Step 1: the chain requires normal ordering (the derived triplet is NO); an experimental IO determination — JUNO's vacuum wiggle, DUNE's matter lever, or their combination — kills the mass chain directly, independent of any double-beta result.

Step 2: the chain requires ton-scale silence ($m_{\beta\beta} = 1.72$ meV, below reach — problem H.5.2); a confirmed $0\nu\beta\beta$ line in the ton-scale window kills the door architecture directly, independent of the ordering.

Step 3: conversely, NO confirmed *and* silence heard are each merely consistent; neither, nor both, proves the point value — proof-grade discrimination waits on the phase measurement and the 10^{29+}-yr era. The AND-logic of §136 is deliberate: kill channels are independent, confirmation channels are not — redundancy is the design, not an accident.

Physics intuition: a falsifiable framework wires its failure modes in parallel and its success modes in series. The reader joining any one of JUNO, DUNE, Hyper-K, or LEGEND holds a kill switch; no single collaboration holds a confirmation — which is how it should be.

I Internal source ledger for this paper

The derivation, notation, and theorem flow of this paper are taken from its cohort companions listed below; historical literature is cited for orientation and confrontation, never as a derivational premise. The two *parents* — the particle paper and the cosmology paper — carry the heaviest load, and the Foundations-Branch partner GG-P4-Real supplies the complex-structure machinery the handshake runs on.

Table 31: Internal source ledger used in the present paper. One row per upstream preprint, with the role it plays in this paper's chain and a sentence saying what is actually taken from it rather than what the source paper is about. The ledger exists so that every inherited premise in the argument can be traced to the paper that owns it, and so that nothing is inherited silently.

Preprint	Role in the chain	Relevance
GG-A1-Constitution	Constitutional foundation	Fixes the four axioms, seven postulates, and OGGEP semantics; AX-1 supplies the arrow and AX-3 the positivity clause that select the clock's complex structure.
GG-A2-GG6	Six-dimensional stage	Supplies the GG-6 bulk, the spinor content $\mathbf{4} \oplus \bar{\mathbf{4}}$, the weight arithmetic, and the frame-path spin registers (its §20) behind the candidate spin suite.
GG-A3-BI6	Anomaly ledger	Proves the BI-6 bookkeeping: the anomaly flip, the reservoir arithmetic $(8, 4, 48, 12, 2)$, and the $n_F = 32\Omega$ counting that forces the conjugate content.
GG-A5-GDOS	Boundary law	Derives the GDOS boundary reduction: the OGGEP projection whose one-way trace is this paper's arrow, partner, and sphaleron custody.
GG-A8-QM	Quantum-mechanics companion	Carries the real-bulk series (R1–R15), the Born-rule status, and the statistics theorem T-A8.12 this paper's quartet argument feeds.
GG-A9-SM	Particle parent	Supplies the flavor geometry: the pentagon and QD codebook, the Majorana-door parent theorem, the derived neutrino ledger (masses, δ_{PMNS}, Majorana parity), and the honesty-grade vocabulary.
GG-A10-Cosmos	Cosmology parent	Supplies the transport: the descent and T_{rh}, the Sakharov custody, the resonant-leptogenesis chain, and the zero-dilution clause audited in Part VIII.
GG-P4-Real	Foundations partner	Owns "why complex numbers?": the circle and clock as the two real sources of i (its T-P4-1 through T-P4-4), restated in Part III as this paper's inputs.
GG-C1-Kaxion	Strong-CP companion	Carries the Kaxion two-fate architecture behind the $\bar{\theta}$ leakage floor and its haloscope window.
GG-W2-Holonomy	Holonomy white paper	Supplies the two-fiber anatomy used in §59 and the three-horizon sorting of §93; developed there out of this paper's own reversals and returned here as a way of reading them.

J Cross-paper inheritance table (compact)

This appendix compresses the inheritance narrative of §16.1 into a one-page table for quick reference: what the present paper draws from each cohort paper, and which of its Parts consume the contribution.

Table 32: Compact cross-paper inheritance: what the present paper draws from each upstream paper. "Used by" lists the Parts of this paper that depend on each contribution. Fourteen rows, one per upstream paper. Where the source ledger says what each paper contributes, this table says where the contribution is consumed, so that a reader following a single Part can see which companions that Part depends on without having to read the rest of the paper first.

Paper	Key contribution to this paper	Used by (Parts)
GG-A1-Constitution	Axioms and postulates; the arrow (AX-1) and the positivity clause (AX-3)	III, IV
GG-A2-GG6	Bulk, spinor split, weight arithmetic, §20 frame-path registers	III, IV, X
GG-A3-BI6	Anomaly flip; reservoir arithmetic; conjugate content forced	III, IV
GG-A5-GDOS	OGGEP projection: arrow, partner trace, boundary custody	V, VIII, X
GG-A6-GRIP	GRIP runtime vocabulary for the descent's selections	VI, VIII
GG-A8-QM	Real-bulk series; Born status; statistics theorem T-A8.12	III, IV, X
GG-A9-SM	Pentagon + QD codebook; Majorana-door parent; neutrino ledger; grade register	VII, VIII, XI
GG-A10-Cosmos	Descent, $T_{\rm rh}$; Sakharov custody; leptogenesis chain; honesty objections	VIII, XI, XII
GG-P1-KK	KK-tower context of the compact directions	III
GG-P2-N3	$N_g = 3$: the family count behind the one surviving phase	VII
GG-P3-Electron	Electron basin; the conjugate-readout debt D-P3-4	IV
GG-P4-Real	Two real sources of i; the representation machinery of the handshake	III, IV
GG-C1-Kaxion	Kaxion; the $\bar{\theta}$ two-fate architecture and leakage floor	VII

K Consolidated benchmark audit

The main text develops the benchmark problems Part by Part; this appendix compresses the same logic into a single operational audit sheet: for each problem the paper claims to address, the inherited mechanism that carries it and the principal kill switch that would destroy it.

Table 33: Consolidated benchmark audit for the present paper. Fourteen problems, each with the mechanism this program brings to it and the single measurement that would retire that mechanism. The third column is the reason the table exists: a benchmark that cannot be failed is not a benchmark, and every row here names the observation that would fail it.

Problem	Inherited mechanism	Principal kill switch
The C/P/T table	Orientation reversals of the three real factors; the antiunitary fork as clock-content (T-P5-1)	A discrete operation measured outside the forced unitary/antiunitary table

continued on next page

Problem	Inherited mechanism	Principal kill switch
CPT survival	Total orientation reversal, invisible to any real texture (T-P5-2)	Any confirmed CPT violation (Table 1); via Greenberg, the arena itself
Antiparticle existence	The handshake: two half-blind sources of i forced to agree (T-P5-A/B/C), content forced twice (Lemma 24.1; anomaly ledger)	Drift in any CPT-protected identity; a consistent relativistic S-matrix without the pairing
Parity violation	Orientation of the family descent through one chiral gate (Part VI; conditional on C-P5-A)	W_R or mirror fermions at any scale (F-P5-1)
Quark CP phase	Pentagonal lattice holonomy, QD-completed to $13\pi/35$ (T-P5-3)	World fit excluding the lattice point (the raw first order survives to $+1.2\sigma$-class only, with the $\pi/35$ theory width in quadrature)
Leptonic CP phase	Central-circuit completion $\pi + 2\arcsin(1/7)$ (T-P5-3, conditional on the assignment lemma)	DUNE/Hyper-K posterior excluding the 196° band
Strong CP	Two-fate architecture with the Kaxion fate and the e^{-K} leakage floor	A measured EDM between the leakage floor and 10^{-10}
Majorana nature	The weight-zero door: Majorana iff nowhere to wind (T-P5-4)	A Dirac neutrino established; an inverted ordering; a ton-scale $0\nu\beta\beta$ line
The matter excess	Resonant leptogenesis on the inherited ledger, throughput $e^{-K/2}$ (T-P5-5, conditional on C-P5-C)	Proton decay observed; ordering, phase, or cluster kills; a confirmed line
Spin and statistics	The Wick quartet's second child: exchange as half-turn composition (T-Stat-A, candidate)	A consistent quasi-free counterexample to the quartet route

L Named-theorem-and-conjecture deck

This appendix lists every formal named statement introduced or restated in this paper, with its label and a one-line summary. Full statements appear at the referenced labels; the inventory line at the end is counted from the source, not by hand.

Table 34: Named-statement deck of the present paper. Every named statement in the paper, in one list: theorems, lemmas, propositions, conjectures and the imported results, each with its label and a one-line summary. The type column is the honest part. It separates what is proved here from what is conjectured and from what is carried in from elsewhere, and the deck is meant to be read whole before any single entry is leaned on.

Type	Name	One-line summary
Theorem	T-P5-A	The circle: the charge-normalized generator is the unique gauge i on charged sectors, up to sign (Thm. 42.1).
Theorem	T-P5-B	The clock: the polar phase of time translation is the unique positive-energy state-space i (Thm. 42.2).
Theorem	T-P5-C	The handshake: the two structures agree only on the Feynman–Stückelberg pairing; antiparticles as the consistency condition (Thm. 42.3).
Theorem	T-P5-B1	The Wick quartet: one analytic fact behind rotation, statistics, and the thermal clock (Thm. 43.1).
Theorem	T-P5-C1	One shared J extends to composites and Fock space with no new complex input (Thm. 44.1).
Theorem	T-P5-C2	Fermionic conjugation factorizes: circle-orientation reversal composed with a fixed real spinor map (Thm. 44.2).
Theorem	T-P5-1	The C/P/T table from orientation: which reversals are unitary, which antiunitary, computed not assigned (Thm. 56.1).
Theorem	T-P5-2	CPT as total reversal: every real texture preserves the product; the identities of Table 1 follow (Thm. 58.1).
Theorem	T-P5-3	Flavor holonomy and the chirality criterion: CP violation iff the texture is chiral; the lattice values (Thm. 75.1).
Theorem	T-P5-4	Majorana iff weight zero: the unique lawful $\Delta L = 2$ door (Thm. 76.1).
Proposition	T-P5-5	The assembled $\eta_B \simeq 5.9\times10^{-10}$ at D^* grade, conditional on C-P5-C (Prop. 85.1).
Proposition	P-P5-D	The handedness invariant of the descent (Prop. 69.1).
Proposition	P-P5-E	The Sakharov tripod: the three conditions as boundary shadows of the constitutional structure (Prop. 83.1).
Conjecture	C-P5-A	The Gate-Operator Lemma (L11): the missing uniqueness clause of the parity chain (Conj. 68.1).
Conjecture	C-P5-C	Sphaleron-transport normalization and the on-resonance condition: the chain's one named input (Conj. 87.1).
Lemma	—	No Majorana condition in $(1,5)$: $B\bar{B} = -\mathbf{1}$ at the quaternionic hour (Lemma 24.1).
Corollary	B1-a	The boundary's three shorthands of the quartet (Cor. 43.2).
Corollary	B1-b	Custody: imaginary time belongs to the clock (Cor. 43.3).

continued on next page

Type	Name	One-line summary
Corollary	—	Kramers' degeneracy with no phase choice (Cor. 57.1).
Restated	T-Stat-A	Spin–statistics as the quartet's second child (candidate grade; home paper GG-A8-QM) (Thm. 45.1).
Imported	—	Weinberg's causality argument, stated with respect as the orthodoxy's Depth-2 summit (Thm. 111.1).

Inventory. 10 owned theorems + 3 propositions + 2 named conjectures + 1 lemma + 3 corollaries, plus one restated candidate (T-Stat-A) and one imported theorem (Weinberg); 8 numbered predictions (Pred-1–Pred-8, Part XI); 9 falsifier rows (Table 26); 82 answered objections (O-P5-1–O-P5-82, Part XV).

M Named-conjecture promotion roadmap

This appendix states the open targets that, if discharged, would promote graded entries — from conditional to derived, or from candidate to theorem. Each row names the item, what its discharge closes, the venue where the work belongs, and its status. It is the place where the grade register stops being a table of labels and becomes a research program.

Table 35: Named-conjecture promotion roadmap for the present paper. Venue "this paper" = work that belongs here and remains open; a paper code = the companion where the work naturally lives; "open" = open research target. Ten named items, with the work each discharge would close, the venue where that work belongs, and its status. The first row is the paper's sharpest open item and is placed first for that reason. The status column is written to be checkable rather than encouraging: where a mechanism is identified but not proved, it says so in those words.

No.	Named item	What discharge closes	Venue	Status
1	C-P5-C: finite-temperature on-resonance transport (§87)	η_B from D* to Derived; the $e^{-K/2}$ exponent from postulate to theorem	open	the paper's sharpest open item
2	C-P5-A: the Gate-Operator Lemma (L11)	The parity chain's uniqueness clause; Part VI from conditional to derived	GG-A9-SM / this paper	open
3	The assignment lemma (leptonic circuit)	δ_{PMNS} from derived-conditional to derived	GG-A9-SM	open
4	D-P3-4: the positron as a theorem	The conjugate-readout picture from reading to corollary	GG-P3-Electron	registered debt
5	L-Spin-1: the frame-path spin registers, proved	The spin-$\frac{1}{2}$ candidate suite toward theorem grade	GG-A2-GG6	candidate

continued on next page

Table 35 continued

No.	Named item	What discharge closes	Venue	Status
6	T-Stat-A at quasi-free grade	Spin–statistics as the quartet's second child, at boundary grade	GG-A8-QM / this paper	candidate
7	The interacting handshake	T-P5-C's scope concession (free/quasi-free) lifted to interacting theories	open	open
8	The field-grade representation step	The Born chain's last analytic residue (context: GG-A8-QM)	GG-A8-QM	open

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Table 35 continued

No.	Named item	What discharge closes	Venue	Status
9	The ϕ_{geo} projection, restated: the displayed unflavored invariant is U_{PMNS}-independent and vanishes for the dial-free (real-R) door; the inherited phases reach η_B only through the flavored asymmetries $\epsilon_{i\alpha}$, where the driver is the Majorana parity $\alpha_{31} = \pi$ (not J_{PMNS}) and the result is not $\propto m_1$. Open task: finite-temperature flavored transport at the lock crossing testing H-ϕ_{geo}-1 ($\Delta M/\Gamma^{\text{eff}} \simeq 3 \times 10^4$ for throughput $e^{-K/2}$); acceptance band $\pm O(1)$ in ϵ_{eff}; the window deficit the closure must supply is now measured at $E = 7.1$ (68% [4.4, 11.4]) by the parent's flavored Boltzmann integration. The hypothesis is now carried by an identified candidate mechanism — the flavor-measurement regulator, closed form $1/(35\, c_\tau y_\tau^2)$ landing the hypothesized decade (home GG-A10-Cosmos App. I.3; conditions C1–C6) — and the row records the mechanism at candidate grade. The former "m_1/m_3-order suppression" language is withdrawn as a reconstruction artifact.	Chain row 5 (ϵ^{res}) from asserted to derived-conditional (H-ϕ_{geo}-1); full discharge to derived	GG-A10-Cosmos / this paper	open — flavored computation displayed; mechanism identified at candidate grade (C1–C6); H-ϕ_{geo}-1 remains

Closure-economy summary. The confrontation table of Part XI runs on two named conjectures (C-P5-A, C-P5-C) and one assignment lemma; discharging items 1–3 above would promote every conditional row of the table to Derived with no dial turned. Items 4–6 are the candidate suite's ladder: each is a precise statement whose proof belongs to a named companion. Items 7–8 are the

program's long-range residues, carried honestly. The item closest to this paper is No. 1, whose acceptance criteria are stated in §87: a finite-temperature transport computation landing the crossing at the partial-resonance point of H-ϕ_{geo}-1 ($\Delta M/\Gamma^{\text{eff}} \simeq 3 \times 10^4$; now carried by the identified candidate mechanism of §87), so that the flavored throughput lands within $O(1)$ of $e^{-K/2}$ — both clauses of C-P5-C discharged at once, and T-P5-5 promoted from D*.

N Falsification-test catalog

This appendix collects, in one place, every test whose failure would kill the framework or one of its named structures, pairing each with the precision required and the experimental venue. The same tests are laid on a single forward time axis in the kill-test timeline (Figure 25), and the falsifier table (Table 26) states what each failure destroys.

Table 36: Falsification-test catalog for the present paper. Each test is paired with the named structure it would refute and the venue that can carry it out. Ten tests, each with the precision it requires, the named structure it would refute, and the experiment that can carry it out. The precision column is what makes the catalog usable rather than decorative: a measurement that cannot reach the stated precision does not adjudicate its row, and several of these cannot before the 2030s.

Test	**Precision**	**Falsification target**	**Venue**
Leptonic phase	$\pm 15°$ early–mid 2030s; ± 7–$10°$ late 2030s	δ_{PMNS} outside the $196°$ band kills the leptonic lattice chain and the door's bias (T-P5-3 lepton circuit)	DUNE, Hyper-K
Mass ordering	decisive, late 2020s–2030s	An inverted ordering kills the derived triplet (Part VIII mass chain)	JUNO; DUNE
Quark phase	continuous world fit	Exclusion of $13\pi/35$ kills the QD completion; of $2\pi/5$-class values, the pentagon itself	LHCb, Belle II, global fits
$0\nu\beta\beta$	ton scale, 2030s	A confirmed line in the ton-scale window kills the door architecture; $m_{\beta\beta} = 1.72$ meV is a registered null	LEGEND-1000, nEXO, CUPID
Lock cluster	few-TeV reach	Failure of the pre-declared HL-LHC criterion kills the heavy sector of the chain	HL-LHC
Right-handed currents	any scale, permanent	W_R or mirror fermions kill the geometric projection of Part VI (F-P5-1)	all colliders
Proton stability	permanent	An observed decay kills the exact $\mathrm{U}(1)_B$ ledger and Part VIII's logic	Hyper-K, DUNE
EDM window	10^{-18}–10^{-10} in $\bar{\theta}$	A measured EDM above the e^{-K} leakage floor but below 10^{-10} breaks the two-fate architecture	n/p and e EDM programs
Mass splittings	sub-percent on both splittings	A converged JUNO value off the derived pair ($\Delta m^2_{21} = 7.37 \times 10^{-5}$, $\Delta m^2_{31} = 2.55 \times 10^{-3}$ eV^2) at 4σ-class kills the mass chain	JUNO

Three further rows are *watched*, not kills: the $\sin 2\beta$ confrontation (0.708 at the stated moduli layer against 0.709 ± 0.011, -0.1σ, Belle II statistics decisive), the direct-γ combination (the lattice triangle's leading-order $\simeq 66.9°$ against $(62.8 \pm 2.6)°$, $+1.6\sigma$), and the fourth-generation exclusion that protects the $N_g = 3$ counting. One binding registration accompanies the catalog: the subdominant $3\pi/2$ assignment branch is hereby pre-registered as dead — a measurement near 270–286° may *not* be reinterpreted under the alternative branch; the assignment lemma is frozen in the form stated in Part VII, and its failure is the chain's failure. The framework's exposure profile is deliberately high: every row above sits within the current decade's experimental horizon or is permanent, and the AND-logic of §136 wires the kill channels in parallel — any one suffices.

With that, the registries are complete. What remains of the Part is the reading guide; after it, the adversaries.

O An annotated reading guide

Six shelves, each ordered. *Shelf 1 (the discoveries):* Lee–Yang 1956; Wu 1957; Christenson–Cronin–Fitch–Turlay 1964; KTeV 1999; BaBar/Belle 2001; Super-K 1998 — read in sequence as one eighty-year experiment. *Shelf 2 (the theorems):* Wigner 1931; Lüders/Pauli; Jost 1957; Streater–Wightman; Bisognano–Wichmann 1976; Greenberg 2002; Vafa–Witten 1984. *Shelf 3 (flavor):* Cabibbo 1963; Kobayashi–Maskawa 1973; Jarlskog 1985; the PDG reviews. *Shelf 4 (the matter excess):* Sakharov 1967; Kuzmin–Rubakov–Shaposhnikov 1985; Fukugita–Yanagida 1986; Davidson–Ibarra 2002; Pilaftsis–Underwood 2004; Buchmüller–Di Bari–Plümacher. *Shelf 5 (the geometric rivals and parents):* Kawamura 2000; Hall–Nomura 2001; Dine–Leigh–MacIntire 1992; Choi–Kaplan–Nelson 1993; and the cohort papers in the dependence order of Section 16.1. *Shelf 6 (the antiparticle lineage):* Dirac 1928, 1930, 1931; Anderson 1933; Stückelberg 1941; Feynman 1949; Weinberg's *Quantum Theory of Fields* chapter 5; then the Foundations-Branch treatment (Arisaka, 2026, P4-Real) and Part IV of this paper — read in that order, the shelf is the eighty-year journey from the sea to the handshake.

Part-end summary. A machine room from Wu's cryostat to the assembled η_B: the toolkit is the reader's. What remains are the adversaries and the sources.

Part XV
Common Objections and Responses

Eighty-two adversarial readings — from the kaon experimentalist, the neutrino experimentalist, the flavor theorist, the axiomatic field theorist, the lattice theorist, the string theorist, the cosmologist, the historian and philosopher, the student, the antiparticle referees, and the quantum-foundations referee — each answered with pointers into the paper

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A paper that claims to explain the broken mirrors invites — and should invite — attack from every community that measured them. This Part collects the eighty-two sharpest adversarial readings we could construct or have received, grouped by the reader most likely to raise each, and answers each with explicit pointers to the theorem, section, or named open item that carries the load. Where the honest answer is "not yet" or "not ours to claim," it is said in those words. These are self-authored stress tests in referee personas, published so that real referees can start where they end — and they now include the findings of an adversarial multi-reviewer audit of this version's numerics, which produced the corrections logged in the version banner.

P The kaon and B-physics experimentalist

Objection 1 (O-P5-1) (the KTeV alumnus, on hadronic mud)
"Direct CP violation took us a decade because ε'/ε is buried in hadronic matrix elements. Your pentagon supplies one clean phase and waves at the lattice for the rest — that is not a prediction of ε'/ε."

Response. Correct, and stated in those words in Appendix E.3: the lattice phase fixes the weak phase input; ε'/ε then requires the same hadronic matrix elements every framework requires, honestly delegated to the lattice literature. The claim is not a parameter-free ε'/ε; it is that the *one* weak phase feeding every kaon and B observable is a forced lattice point. The clean confrontations are the phase-dominated observables — δ_{CKM} in the global fit, $\sin 2\beta$, J_{CKM} — and there the numbers are in the table.

Objection 2 (O-P5-2) (the same alumnus, on the QD step)
"Your $2\pi/5$ misses the fit by 1.2σ and your $13\pi/35$ lands at 0.7 — after a correction your own codebook calls post-hoc. That is retrofitting."

Response. The flag is ours and stays (§75.3). The defensible structure: $2\pi/5$ is forced, with no freedom; the QD slip's *direction and size* ($-\pi/K$, one throat step) are ledger-determined; what is asserted is that the slip applies. A bounded, quantized, pre-registered correction differs from a tuned one in exactly one way — it cannot be adjusted again — and that is testable: the completed value must survive all future tightening of the fit or the step dies publicly.

Objection 3 (O-P5-3) (the B-factory veteran, on many observables)
"Flavor physics measures dozens of CP asymmetries. One phase cannot carry them all."

Response. One phase *does* carry them all — that is the content of the Standard Model's own global fit, confirmed at the B factories (BaBar Collaboration, 2001; Belle Collaboration, 2001). The paper adds no second phase; it values the one there is. Any observable requiring a second independent CP source in the quark sector falsifies the Standard Model and this paper together.

Objection 4 (O-P5-4) (the kaon theorist, on ε)
"The measured $\varepsilon \sim 2 \times 10^{-3}$ involves mixing, long-distance effects, and Δm_K. Where is it in your paper?"

Response. Appendix E.3, at the honesty level the observable permits: the weak phase enters the box with the lattice value, the long-distance parts are the literature's, and no parameter-free ε is claimed. The paper's kaon-sector content is the phase, not the hadronic envelope.

Objection 5 (O-P5-5) (the trigger veteran, on falsifiability rhetoric)
"Every theory paper now advertises falsifiers. Which of yours has a date and a number this decade?"

Response. Table 26: $\delta_{\rm PMNS}$ to $\pm 15^\circ$ at DUNE/Hyper-K (early–mid 2030s) against 196°; the 3.85 TeV cluster at HL-LHC with a pre-declared criterion; $m_{\beta\beta} = 1.7$ meV against the next-generation $0\nu\beta\beta$ program; and F-P5-1 standing against every W_R search. Four numbers, four instruments, all funded.

Objection 6 (O-P5-6) (the charm convener, on ΔA_{CP})
"LHCb found CP violation in charm at the 10^{-3} level — up-type, and larger than many expected. Where is charm in your pentagon?"

Response. In the same place it is in the Standard Model: the one valued phase, routed through up-type loops where the hadronic envelope is least controlled (LHCb Collaboration, 2019). The framework adds no second phase and buys no new amplitude, so ΔA_{CP} tests QCD dynamics at the charm scale, not the lattice point — and the honest statement, printed rather than implied, is that no framework currently prices it from first principles. What would implicate this paper is a charm measurement requiring a phase off the valued one at fixed moduli; nothing observed does.

Objection 7 (O-P5-7) (the rare-kaon experimentalist, on $K \to \pi\nu\bar{\nu}$)
"NA62 and KOTO chase the cleanest loops in flavor physics. Predict the rates or admit you have nothing to say."

Response. The ledger fixes the phase and the moduli, so the golden-loop rates are the Standard-Model values evaluated at the lattice point — indistinguishable from the SM's own central values at current precision. The channel is therefore a consistency check rather than a discriminator until the phase resolutions cross (Table 24); but it is not toothless: a matured rate demanding different CKM inputs at fixed unitarity would break the ledger upstream, and the register would take the hit with dates.

Objection 8 (O-P5-8) (the lattice-QCD watcher, on ε'/ε)
"The lattice value of ε'/ε has moved between tension and agreement for a decade. If it lands off the world value, whose problem is that?"

Response. At fixed weak phase, ε'/ε is a hadronic-matrix-element problem, and the framework's custody rule delegates it in print (§E.3; Objection 31): a lattice-versus-experiment tension is QCD's to resolve. What would be ours is any resolution that re-extracts the weak phase off the lattice point — and that exposure already sits as a falsifier row. Custody stated is accountability preserved, in both directions.

Q The neutrino experimentalist

Objection 9 (O-P5-9) (the long-baseline convener, on the moving fit)
"NuFit moves. Your 196° sits near today's central value; when the band shifts, will the paper shift with it?"

Response. No — and that is the point of publishing the number with its derivation (57). $\pi + 2\arcsin(1/7)$ has no adjustable content: if the measured phase settles outside the band around 196° (the QD width is $\pm$ a fraction of a degree, the honest comparison band is set by the assignment lemma's degeneracy, stated in §75.4), the leptonic chain is dead and says so. The prediction predates the decisive data; that is what makes it one.

Objection 10 (O-P5-10) (the $0\nu\beta\beta$ experimentalist, on 1.7 meV)
"Your $m_{\beta\beta}$ is an order below the inverted-hierarchy band and below any funded experiment's reach. Convenient."

Response. Inconvenient, in fact, and stated without cosmetic: the value follows from the derived normal-ordering masses and the parity pair $(0, \pi)$, and it places the door beyond current reach. The near-term discriminators are therefore indirect (a measured inverted ordering kills the mass chain; an observed $0\nu\beta\beta$ signal *above* the meV class contradicts the parity pair), and the direct test awaits the tonne-scale-plus era. Honesty about which decade owns which test is part of the register.

Objection 11 (O-P5-11) (the atmospheric-sector veteran, on Majorana phases)
"Your $(0, \pi)$ is untestable in oscillations by construction."

Response. Correct — oscillations are blind to Majorana phases. The pair is tested where it acts: in $m_{\beta\beta}$ (the π drives the cancellation to the meV class) and in the leptogenesis bias (Part VIII). "Untestable in your instrument" and "untestable" are different statements.

Objection 12 (O-P5-12) (the mass-ordering referee)
"Everything leptonic here assumes normal ordering. JUNO and the atmospheric fits could return inverted."

Response. Yes — and inverted ordering falsifies the inherited mass chain outright, upstream of this paper. It is listed among the backbone kills (§89).

Objection 13 (O-P5-13) (the cosmological fitter, on the mass sum)
"DESI with the CMB presses $\sum m_\nu < 0.064$ eV. Your triplet sums to 0.0592 eV. One more tightening and you are dead?"

Response. Yes — and the exposure is registered here rather than buried: the derived sum is 59.2 meV, eight percent below the current bound (DESI Collaboration, 2025). A robust cosmological determination converging *below* 59 meV kills the mass chain independently of every laboratory; one settling at ~ 60 meV would be a confirmation channel no laboratory can match this decade. The refresh discipline of §127 will print the pull at each release — cosmology now owns one of this paper's sharpest rows.

Objection 14 (O-P5-14) (the short-baseline anomalist, on steriles)
"LSND, MiniBooNE, and the gallium deficit keep flickering. Is there room in your counting for a light sterile?"

Response. None — and that is a kill channel, stated as such: T-P5-4's uniqueness clause (Thm. 76.1) forbids a second weight-zero completion, so a confirmed eV-scale sterile with oscillation-strength mixing would break the door architecture itself, not merely the family count. Against that stands the record: the anomalies do not converge on one oscillation hypothesis, and MicroBooNE's nulls cut into the favored regions. The register carries the flicker with dates and waits; the exposure does not.

Objection 15 (O-P5-15) (the supernova watcher)
"A galactic supernova would put 10^{58} neutrinos through your MSW machinery in ten seconds. What do you predict?"

Response. Standard flavor conversion evaluated at the derived masses and ordering: normal ordering fixes the level-crossing pattern, so the neutronization burst's ν_e suppression and the spectral swaps are those of adiabatic NO conversion (§H.3 carries the machinery). A supernova that reads IO from the burst kills the ordering upstream of every long-baseline program — a free, if patient, kill channel. Collective oscillations in the deep interior are delegated to the transport literature, honestly.

R The flavor theorist

Objection 16 (O-P5-16) (the rephasing purist)
"Your T-P5-3(i)–(iii) is Jarlskog 1985 with graph words."

Response. Agreed, cited, and drawn as a boundary in §21 before the theorem is stated. The paper's claim begins at clause (iv): the standard calculus says where CP violation lives; nothing in it values the holonomy. The lattice does, and the lattice is the paper.

Objection 17 (O-P5-17) (the discrete-flavor model builder)
"A_4, S_4, and modular flavor symmetries also predict δ's. You are one more entry in a crowded catalog."

Response. The catalog's entries share one move: choose a group, then derive. Here no flavor

group is chosen — the pentagon is $L = 5$, an integer fixed by anomaly arithmetic in a different paper for different reasons (Arisaka, 2026, A3-BI6), and the same integer prices the Cabibbo magnitude (53) before touching CP. An entry that buys two observables with a pre-owned integer is in a different section of the catalog — and is killed, not tuned, if either number fails.

Objection 18 (O-P5-18) (the texture skeptic, on first order)
"“First-order holonomies are lattice-valued” — and beyond first order?"

Response. The QD completion is the program's second order, applied here at exactly two points ($-\pi/K$ on the quark phase; the sub-degree shift on the leptonic one), both quantized, neither continuous. A demonstration that higher orders decompactify the lattice — float the angles continuously — would falsify clause (iv); the parent codebook's structure (all corrections are ledger steps) says they do not.

Objection 19 (O-P5-19) (the CKM global fitter)
"Your Cabibbo formula uses $e^{-\pi}$ and $e^{-\pi/2}$ as mass-ratio angles — numerology until derived."

Response. Derived in the parent Standard-Model treatment as part of its Yukawa codebook (Arisaka, 2026, A9-SM), with its own audit trail; this paper imports the two angles as stated inputs (§75.3) and adds only the pentagon's interference. The import is flagged so the reader can price it; the golden-ratio closed form is then forced, not fitted.

Objection 20 (O-P5-20) (the strong-CP specialist)
"Your $\bar{\theta}$ story needs L9 (uncredited cancellation) and a Kaxion. Peccei–Quinn needs one axion. Occam prefers us."

Response. Count again, structurally: PQ needs a new global symmetry, a new scalar, and protection of that symmetry from quantum gravity — three purchases. The Kaxion is a Wilson line the geometry already owns (Arisaka, 2026, C1-Kaxion), and L9 is a cancellation within structure already present. And only the two-fate architecture (§77) *relates* $\bar{\theta} \simeq 0$ to $\delta_{\mathrm{CKM}} \neq 0$ — a relation PQ cannot express at all. Occam's razor cuts by total inventory, not by lemma count.

Objection 21 (O-P5-21) (the modular-symmetry builder)
"Modular flavor symmetry also derives phases from geometry — τ at a fixed point. What is different about a pentagon?"

Response. Kinship first: both programs hold that phases are geometric data, not couplings. The difference is who owns the dial. A modular model selects a group, a weight assignment, and a modulus value — three choices per sector, scanned until the fit lands. The pentagon inherits one angle from the ledger with no modulus to place; the cost is total rigidity (zero-width rows in Table 23), the benefit is that failure is failure. The comparison is run without polemic in Part X's register: structural contrast, adjudicated by instruments.

Objection 22 (O-P5-22) (the first-row auditor, on the Cabibbo anomaly)
"First-row CKM unitarity shows a 2–3σ deficit. Your golden form fixes $\sin\theta_C$ to five digits. Exposed?"

Response. Watched, with dates — and the anatomy matters: the present deficit implicates

V_{ud} metrology and radiative corrections at least as much as V_{us}, so it does not yet press the golden value, which sits at Dev $= +4 \times 10^{-5}$ against the V_{us}-side extraction. A matured, radiative-settled deficit forcing $\sin\theta_C$ off the closed form by 3σ-class would kill the modulus claim — a sharper exposure than most frameworks volunteer for a quantity this well measured (§127).

Objection 23 (O-P5-23) (the Froggatt–Nielsen practitioner, on hierarchy)
"Your flavor chapter calls the Yukawa span 'what the Lagrangian was told.' Charge assignments explain it. You don't."

Response. Correct, and printed as a Step-2 limitation rather than disguised (§E.5): the pentagon prices the phases and the Cabibbo modulus, not the eigenvalue span. Froggatt–Nielsen buys the span with a charge per fermion — bookkeeping that organizes but does not force. Where the parent program derives masses it says so with grades; where it does not, it declines to buy what it cannot force. An honest gap beats a purchased explanation in this register — and the gap is on the promotion roadmap's horizon, not hidden.

S The axiomatic field theorist

Objection 24 (O-P5-24) (the Wightman referee, on scope)
"Jost's theorem covers interacting fields. Your T-P5-2 is free-field bookkeeping advertised as a CPT theorem."

Response. Scope conceded in the theorem's own statement and in §58: quasi-free grade, interacting case conditional. The claim is complementarity — Jost proves Θ exists with interacting strength and no anatomy; T-P5-2 supplies the anatomy at lesser strength. Whether anatomy at lesser strength is worth having is answered by what it buys: T-P5-1's derived antiunitarity, the chirality criterion, and every downstream Part.

Objection 25 (O-P5-25) (the algebraist, on Bisognano–Wichmann)
"We already have CPT's deep origin: modular conjugation. Your clock is a poor man's modular flow."

Response. Possibly a poor man's — or possibly the same man's, seen from the real side; the open modular route (§137(6)) is precisely the conjecture that your modular flow and our clock coincide, which would tie the anatomy to the algebra at interacting strength. Note the direction of dependence, though: Bisognano–Wichmann operates *inside* a complex Wightman theory; it does not tell you what i is. The clock does, and that difference is not poverty.

Objection 26 (O-P5-26) (the CPT phenomenologist)
"Kostelecký's SME parameterizes CPT violation and experiments constrain it. Your framework forbids it outright — so your framework is untestable on this axis."

Response. Inverted: a framework that *forbids* CPT violation is maximally exposed on this axis — any confirmed SME coefficient at any order kills T-P5-2 with no parameter to absorb it, exactly

as Greenberg's theorem (Greenberg, 2002) ties such a signal to Lorentz violation and hence to the arena itself. Prohibition is the strongest testable statement there is.

Objection 27 (O-P5-27) (the rigorist, on "real texture")
""Every texture built from real geometric data" is doing heavy lifting in T-P5-2. Define it or lose the theorem."

Response. Defined in the proof: magnitudes (moduli, metric and symplectic contractions, winding sums) even under total reversal, plus fiber angles that negate — i.e. any coupling functional of the constitutional real structures with no external complex input. The definition excludes exactly one thing: a primitively complex coupling constant — which is the program's entire ontological claim, argued in the Foundations-Branch partner (Arisaka, 2026, P4-Real), not smuggled here.

Objection 28 (O-P5-28) (the Greenberg reader)
"Greenberg proved CPT violation implies Lorentz violation. You derive CPT from texture invisibility. Do the theorems even compose?"

Response. They stack, usefully. Greenberg's theorem (Greenberg, 2002) runs inside Wightman QFT: no Lorentz-invariant theory violates CPT. T-P5-2 runs one level down, in the real geometry, and delivers the invariance the axioms then protect. The composition worth having is the contrapositive: any texture-level CPT anomaly would surface at the boundary as Lorentz violation, so the entire SME bound library disciplines the texture too — the experimental record of Table 1 constrains the geometry twice over.

Objection 29 (O-P5-29) (the KMS reader, on the thermal clock)
"Corollary B1-b says imaginary time belongs to the clock. Is your β a genuine KMS parameter or an analogy?"

Response. Genuine at the quartet's grade: T-P5-B1 (Thm. 43.1) is the analytic fact, and the KMS condition at the boundary is inherited through the standard quasi-free construction — the thermal reading is the dictionary's, the continuation is the geometry's (Cor. 43.3). The deeper bridge — whether the modular flow of the algebraists is this clock seen abstractly — is the named open question of the Bisognano–Wichmann exchange (Objection 69), carried as open rather than claimed.

T The lattice and QCD theorist

Objection 30 (O-P5-30) (the lattice practitioner, on Vafa–Witten)
"QCD's parity safety is our theorem. Your "unbroken ⇒ parity-even" adds words to it."

Response. Vafa–Witten (Vafa and Witten, 1984) protects parity *within* a vector-like theory; it is cited at every use. The basin/gate clause answers a different question — why the strong force *is* vector-like while $SU(2)_L$ is not — which no statement internal to QCD can address. The two results nest; neither substitutes for the other.

Objection 31 (O-P5-31) (the same practitioner, on ε'/ε again)
"Until you put your phase through our matrix elements and publish the number, Appendix E is prose."

Response. Fair. The computation — lattice phase in, published hadronic matrix elements in, ε'/ε out with the community's error bars — is a well-posed exercise and is hereby added to the program's verification queue; the paper's claims do not rest on it, but the confrontation should exist.

Objection 32 (O-P5-32) (the chiral-lattice veteran, on alternatives)
"The massless-up escape from strong CP is dead by lattice arithmetic. Nelson–Barr survives by construction. Why prefer two fates?"

Response. The lattice's execution of $m_u \neq 0$ is inherited here as data, gratefully. Nelson–Barr is a consistent mechanism: $\bar{\theta} = 0$ at tree level from engineered CP-breaking sectors, protected by loop suppression — at the price of the sectors themselves, which are dials. The two-fate architecture ties the smallness instead to the same e^{-K} that sets the lock scale and the matter throughput, and exposes the tie in the EDM window of Table 26: one integer, three exports, one kill band. Structural contrast, chosen by experiment.

Objection 33 (O-P5-33) (the large-N theorist, on θ periodicity)
"Vacuum energy is periodic in θ with branch structure. Does a leakage floor at 5×10^{-18} respect the known θ physics?"

Response. Yes, because the floor is a statement about where relaxation parks $\bar{\theta}$, not a modification of $E(\theta)$: the Kaxion rolls on the standard QCD potential with its standard periodicity and branch structure (Arisaka, 2026, C1-Kaxion), and the two-fate architecture adds only the claim that the residual displacement is e^{-K}-suppressed rather than zero. That makes the floor measurable — hence mortal, in the EDM window — which is precisely what separates it from solutions that park at zero by construction and can never be caught doing it.

U The string theorist

Objection 34 (O-P5-34) (the string phenomenologist, on CP)
"CP as a geometric, spontaneously broken symmetry is ours — Dine–Leigh–MacIntire, Choi–Kaplan–Nelson. You have rediscovered our conclusion."

Response. Your conclusion is cited as the concept's source (§134) and the kinship is real: both programs make CP violation geometric. The delta is valuation: moduli are continuous and landscape-valued, so your δ is environmental; the pentagon is discrete and forced, so ours is a prediction with a date. "Geometric" was your step; "valued" is the claim you cannot make and we must defend.

Objection 35 (O-P5-35) (the orbifold builder)
"Part VI's projection is Kawamura's orbifold GUT, to the matrix."

Response. To the matrix, and credited to the matrix (§65): mechanism inherited, selection

claimed. In your landscape the projection is one choice among consistent many; the program's claim — graded, with its open item — is that the ledger forces the output. The difference between a mechanism and an explanation is exactly the difference between those two sentences.

Objection 36 (O-P5-36) (the string cosmologist, on moduli)
"Any TeV-scale asymmetry you make, our moduli would dilute. What protects yours?"

Response. The absence of your moduli. The descent's lock crossing is prompt ($N_2 = 0$, three grounds, §86), there is no late-dominating scalar, and zero dilution is a derived clause, not a hope. The moduli-dilution problem is an argument *for* frameworks with rigid geometry, and it is made in your literature's own terms (Banks, Kaplan, and Nelson, 1994; Coughlan et al., 1983).

Objection 37 (O-P5-37) (the anomaly-inflow veteran)
"Green–Schwarz inflow is ours too. Your POS-3 is our mechanism wearing an axiom's clothes."

Response. Inflow is Green–Schwarz's and cited so throughout the cohort (Arisaka, 2026, A3-BI6). Promoting a mechanism to an admissibility axiom is not decoration: it converts "one consistent choice" into "the filter every spectrum must pass," which is what gives the chirality assignments of Part VI their policing. Same tool; different office.

Objection 38 (O-P5-38) (the swampland cartographer)
"Quantum gravity abhors global symmetries; your exactly stable proton flaunts one. Welcome to the swampland."

Response. A head-on exposure, printed: the boundary $\mathrm{U}(1)_B$ is not an assumed global symmetry of an effective theory coupled to gravity but a ledger identity of the anomaly books (Arisaka, 2026, A3-BI6) on an arena whose gravity sector is itself the boundary law. Whether swampland reasoning — derived from holographic and black-hole arguments inside a different completion — applies to that arena is exactly the class of question the five-way comparison isolates without polemic (Part X). Operationally the dispute is already scheduled: the folklore says the proton dies at some scale; the ledger says never; Hyper-K listens (Table 26).

Objection 39 (O-P5-39) (the worldsheet theorist, on string CPT)
"CPT holds on the worldsheet and in target space, and you concede strings reach Depth 2. What is left for you to claim?"

Response. Anatomy — Depth 3: what C, P, and T are individually made of, why T is the antiunitary one, and why the factors break with these particular values. String CPT inherits the axioms' silence on valuation: no vacuum selection prices δ_{CKM}, and the landscape's breadth is the concession its own practitioners state (Objection 34). The reverse concession is printed in the same table: strings' interacting reach against the handshake's quasi-free grade (§52). Two programs, two summits, one honest ledger between them.

V The cosmologist

Objection 40 (O-P5-40) (the transport theorist, on the resonance)
"Your splittings are 110 GeV; your width is 10^{-10} GeV; your enhancement formula needs them equal. Twelve orders, and your 'derivation' of η_B evaporates off-peak."

Response. Quantified in §87 before you raised it, with the suppression law and the candidate resolutions — thermal regulators (the flavor-measurement rate now the computed candidate; the flavor-blind g^2T overshoots), radiative degeneracy, or lock substructure — and the concession that "natural rather than tuned" is retired accordingly. T-P5-5 is graded D* *because* of this gap; C-P5-C(i) is its named carrier; and a transport calculation showing no consistent regime is listed as a clean kill. You have identified the paper's sharpest open item; the paper agrees, in its own section. And the flavored recomputation states the target more sharply than the peak you aim at: the exact-peak form overshoots the required throughput by $\sim 3 \times 10^4$; the sharp form of the condition is the partial resonance $\Delta M/\Gamma^{\rm eff} \simeq 3 \times 10^4$, named H-$\phi_{\rm geo}$-1, with the flavored computation displayed in the cosmology companion and the hypothesis now carried by an identified candidate mechanism at candidate grade (conditions C1–C6 open).

Objection 41 (O-P5-41) (the same theorist, on $e^{-K/2}$)
"An exponential that 'reconstructs' your ledger value from two order-of-magnitude factors is numerology with a Boltzmann costume."

Response. The exponent is a postulate — said in §85 step 7 in that word — and the honest claim is narrower than your target: an explicit chain with inherited inputs *lands on* 2.5×10^{-8}, and the CP factor in that product now carries a displayed flavored computation with a named open item — H-$\phi_{\rm geo}$-1, the finite-temperature partial-resonance condition, now carried by an identified candidate mechanism — rather than a bare assertion. The factor-~ 3 band and the "not a precision success" warning are printed beside the number. Derive $K/2$ (C-P5-C(ii)) and the costume becomes a theorem; fail to, and the grade stays D* forever. Both outcomes are on the table, priced.

Objection 42 (O-P5-42) (the BBN referee, on Ω_b)
"Your own two routes to the baryon density disagree by 16.4% — fifty times the CMB error. Physician, heal thyself."

Response. Self-reported in §90, with the owner unidentified and the audit named. A framework that publishes its internal discrepancies before referees find them is asking to be trusted about the rest; a framework that resolves this one, in either direction, learns something real. It is the cohort's problem O-56 and it is not hidden here.

Objection 43 (O-P5-43) (the leptogenesis expert, on citation)
"Fukugita–Yanagida, Pilaftsis, Davidson–Ibarra — your mechanism's parents. Cite them or be embarrassed."

Response. Cited at every load-bearing use (§23, §85) and shelved in the reading guide; the Davidson–Ibarra bound is engaged explicitly as the reason the resonant regime is needed at

TeV scale. This paper exists partly to pay the citation debts an earlier internal audit found outstanding in the parent text.

Objection 44 (O-P5-44) (the CMB analyst)
"ΛCDM needs no baryogenesis; η_B is an initial condition. Why should I care whose story decorates it?"

Response. Because initial conditions are where physics lives or dies: your own concordance (CMB versus deuterium) is a consistency test of exactly the kind Part VIII submits to, and a mechanism with zero dials and four dated kill switches is the difference between decoration and science. You measured the target to 0.3%; someone must be accountable for hitting it.

Objection 45 (O-P5-45) (the electroweak-baryogenesis loyalist)
"New scalars could still make the transition first order. You dismiss our program in a sentence."

Response. Not dismissed — excluded, for this framework: the GG-6 scalar sector is the projection's debris with no freedom to add the required potential structure, so the crossover is inherited and the lepton route is forced (§84). For frameworks with adjustable scalar sectors your program remains live, and its EDM exposure is its own business.

Objection 46 (O-P5-46) (the CPT cosmologist, on Boyle–Turok)
"The CPT-symmetric universe makes the Bang a mirror between a universe/anti-universe pair, gets dark matter from a right-handed neutrino, and needs no inflation. Kin or rival?"

Response. Kin in reverence for the unbroken theorem; rival in where the asymmetry lives. Boyle–Turok impose CPT on the *state* — a boundary condition at the Bang — and keep the dynamics standard (Boyle, Finn, and Turok, 2018); this paper derives CPT invariance of the *dynamics* from texture invisibility and locates the matter excess in an oriented descent within one universe. The falsifier sets barely overlap: theirs leans on vanishing primordial tensors and a 10^8-GeV-class sterile relic; ours on the phase set, the ton-scale null, and the TeV cluster. Structural cousins, separable by the same decade of instruments — exactly what Part X's register is for.

Objection 47 (O-P5-47) (the antinuclei hunter, on AMS)
"Antihelium candidate events circulate from AMS-02. If a flux is confirmed?"

Response. Then Part VIII is in genuine crisis, and the paper says so now: a confirmed cosmic antihelium-4 flux would resurrect antimatter domains of the kind the diffuse gamma-ray audit closed (Cohen, De Rújula, and Glashow, 1998), and the global sign claim of the oriented descent has no domain reservoir to hide in. Lighter candidates admit the mundane out (secondary antideuteron-class production); helium-4 does not. The register waits for a refereed flux and pre-commits to the verdict — which is what a register is for.

Objection 48 (O-P5-48) (the defect theorist, on domain walls)
"Discrete choices made independently in causally disconnected patches make domain

walls that overclose the universe. Your pentagon is a discrete choice. Where are your walls?"

Response. Nowhere, structurally: the texture is not a boundary field spontaneously selecting among degenerate vacua patch by patch — it is a single bulk structure fixed by the ledger before the boundary has patches, so causally disconnected regions inherit one orientation and no wall network ever forms. The contrast with axionic domain-wall problems is precisely the bulk/boundary custody; the one discrete relic the framework does keep — the Kaxion's misalignment — is priced in its own paper (Arisaka, 2026, C1-Kaxion). Walls are a symptom of choices made locally; the ledger makes none.

Objection 49 (O-P5-49) (the mechanism pluralist, on Affleck–Dine and PBHs)
"Baryogenesis has many roads — Affleck–Dine, PBH evaporation, electroweak variants. Why is yours forced?"

Response. Forced within the framework, not within nature — the distinction is the answer. Part VIII's structural point is that the framework's own inheritance closes every other channel: the crossover kills electroweak variants, the dial-free scalar sector has no Affleck–Dine flat directions (Affleck and Dine, 1985), and the derived descent populates no PBH reservoir. So *this* framework must stand or fall with resonant leptogenesis — an exposure, since a dead leptogenesis kills it while merely inconveniencing everyone else (§F.1). Pluralism survives for nature; it is not available to us.

W The historian and the philosopher

Objection 50 (O-P5-50) (the historian of near-misses)
"Pentagons, golden ratios, forced angles — physics has a graveyard of numerological beauty. Eddington rests there."

Response. The graveyard's residents share a diagnosis: numbers fitted after the fact, with freedom to adjust, and no kill criteria. This paper's angles were fixed by integers published for independent reasons, carry no adjustment freedom, and are wired to dated instruments (Table 26). Eddington could not be wrong; this paper can be wrong by 2035. The capacity to die outside the graveyard is the entry fee to science, and it is paid.

Objection 51 (O-P5-51) (the anthropic reasoner)
"A CP phase of zero means no observers. You have derived what selection already explains."

Response. Selection explains why we do not observe $\delta = 0$; it is silent on why $\delta = 1.147$ rather than any other life-permitting value — a set of measure one in no one's landscape. A forced lattice point within the life-permitting range is exactly the kind of fact anthropics cannot produce and can only be scooped by. If the pentagon survives DUNE, selection will have had nothing to do with it.

Objection 52 (O-P5-52) (the philosopher of symmetry)
"You say 'the mirrors break because the world has a direction' — but your bulk is exactly symmetric and only the texture breaks the mirrors. Which is the world?"

Response. Both, in custody (§38): the bulk owns the symmetries, the descent owns the breaking, the boundary owns the record. The philosophical content is precisely that "symmetry of the laws" and "symmetry of the world" come apart — Curie's principle survives because the descent's orientation is itself lawful structure, not accident. The slogan compresses; the custody map is the claim.

Objection 53 (O-P5-53) (the sociologist of physics)
"A twenty-two-paper self-citing program is a closed ecosystem. Why should the community engage?"

Response. Engage with the four numbers: 196°, 66.9°, 1.7 meV, 3.85 TeV. They are stated, derived-or-graded, and falsifiable on instruments the community runs. A closed ecosystem cannot be killed from outside; this one is begging to be.

Objection 54 (O-P5-54) (the Sakharov scholar)
"Sakharov himself floated a CPT-mirror twin universe in the same era as his three conditions. You take the conditions and ignore the cosmology."

Response. The conditions are load-bearing theorems of any asymmetry story; the twin universe was one story among several, and it is honored here as the first CPT cosmology — its modern descendant is engaged on its physics under the cosmologist above. The debt to Sakharov is itemized where it is used (Sakharov, 1967; Part VIII): the equilibrium theorem, the both-C-and-CP clause, the departure requirement — each derived from scratch in §F.1 so the reader can audit exactly what is his and what is ours.

Objection 55 (O-P5-55) (the Wigner reader, on unreasonable effectiveness)
"Why should the arithmetic of a pentagon price laboratory phases at all? Effectiveness this unreasonable is usually a sign of numerology."

Response. The paper's only defensible answer is structural realism made testable: if the boundary is the readout of a real texture, then arithmetic of the texture *is* physics of the readout, and the effectiveness stops being unreasonable exactly when the geometry is real. The numerological reading is not dismissed — it is given its own audit rows, its own $\times 3^{\pm 1}$ bands, and a falsifier schedule on which it dies or survives (Part XI). Rhetoric settles nothing here; the decade does.

Objection 56 (O-P5-56) (the underdeterminist)
"Some other geometry could fit the same numbers. Fitting is cheap at this precision."

Response. Underdetermination is answered by forced error bars, not uniqueness proofs: the lattice point carries zero width, the QD step is one unit of a fixed lattice, and the exposures — phase, ordering, mass sum, ton-scale null, cluster, EDM window, proton — are conjunctive (§136). A rival geometry is welcome to match *all* rows with its own zero-width points; the moment it does, both frameworks are wrong about something soon, because nature will disagree with one of them at the next decimal. That is not a weakness of the method; it is the method.

X The student

Objection 57 (O-P5-57) (the first-year, on where to start)
"I have one weekend, not a week."

Response. Read Part I §4 and §11, then T-P5-1 with its intuition paragraph, then the Conclusions' first section. That is the paper in miniature: what fell, what it costs, what the mirrors are, why matter won. The rest is audit trail.

Objection 58 (O-P5-58) (the second-year, on one measurement)
"If I can follow only one experimental number for the next ten years, which?"

Response. δ_{PMNS}. It adjudicates the leptonic lattice, biases the door, and is the single place where this paper, the Standard Model's agnosticism, and the anthropic shrug make three different statements that one instrument will sort.

Objection 59 (O-P5-59) (the skeptical student, on trusting the imports)
"Half your inputs come from papers I have not read. Why believe the light masses or the lock scale?"

Response. Do not believe them; price them. Every import is flagged at its point of use with its source and grade (§37, §75.3, §85), so the conditional structure of every conclusion is explicit: T-P5-1 needs almost nothing; the η_B chain needs the most. The paper is engineered so you always know what you are buying and from whom.

Objection 60 (O-P5-60) (the student of the chapters, on the honest register)
"Appendix F.3 teaches your mechanism's failure mode more carefully than its success. Why?"

Response. Because the failure mode is where the physics currently lives (§87), and because a student trained to locate a chain on the regime map — including twelve orders off the peak — is trained; one trained only on success is marketed to. The register is the curriculum.

Objection 61 (O-P5-61) (the career-minded student)
"Is any of this a thesis?"

Response. Three are: the finite-temperature resonance computation (C-P5-C(i) — a real transport calculation with a clean kill criterion); the ε'/ε confrontation of O-P5-31; and the gate-operator lemma's orientation-pairing proof (C-P5-A). Each is well-posed, each publishable in either verdict, and each settles a named claim of this paper. That is what theses are for.

Objection 62 (O-P5-62) (every reader, on the whole)
"Strip the program, the cohort, the register. What survives if GG-Theory is wrong?"

Response. Three portable results: the anatomy (any framework deriving its i from real orientations inherits the table and the antiunitarity theorem); the valuation question ("what does the CP phase cost?" is now on record as answerable, with one worked, killable answer); and the audit form itself — claims with grades, imports with prices, failures with dates. If the

pentagon dies at DUNE, the paper's numbers die with it; the questions it taught its readers to ask do not.

Objection 63 (O-P5-63) (the student, on what to carry)
"Ten numbers to memorize, if I carry nothing else?"

Response. The decad: 66.9°; 196.06°; $\sin\delta_{\mathrm{PMNS}} = -8\sqrt{3}/49$; the Majorana pair $(0, \pi)$; the triplet $(0.065, 8.59, 50.5)$ meV; $m_{\beta\beta} = 1.72$ meV; $M_{\mathrm{lock}} = 3.85$ TeV; the throughput $e^{-K/2} = 2.5 \times 10^{-8}$; the conversion $28/79$; and the confrontation 5.87 against $(6.12 \pm 0.04) \times 10^{-10}$. Every one is traceable to its row in Table 23, and every one is mortal somewhere in Table 26.

Objection 64 (O-P5-64) (the student, on checking tonight)
"Can I verify a headline claim before I trust the Part?"

Response. Three one-liners, each under five minutes: the exact surd (problem H.6.1 — trigonometry only); the 1.267 and the T2K tuning (problem H.1.1 — a unit conversion); the throughput identity (problem F.6.1 — two multiplications and an exponential). If any fails your arithmetic, the contract of §127 applies and the error is reportable. The chapters were built with complete solutions precisely so that trust is never the requested currency.

Objection 65 (O-P5-65) (the student, on finding a real error)
"Suppose I find one. What happens to the paper?"

Response. The register works as designed: an erratum, a re-grade of the affected rows, and the confrontation rerun at the next data release — single errors damage claims, not the audit machinery, because the machinery is the part built to survive its owners. The complete-solution format exists to make your audit possible; the version-and-date discipline exists to make the correction traceable. A framework that cannot absorb a found error was never falsifiable in the first place.

Y The antiparticle referees

Objection 66 (O-P5-66) (the field theorist, on Weinberg)
"Your handshake is Weinberg's causality argument in geometric costume. He derived the pairing from SR + QM + causality decades ago."

Response. Theorem 111.1 is stated in full in this paper, with admiration, and the difference is in the hypothesis sets: Weinberg *presupposes* the complex Hilbert space and imposes energy positivity on the output of quantization; the handshake presupposes neither — it derives both complex structures from real constitutional data and obtains the pairing as their pre-quantization compatibility, thereby explaining two of his axioms. What is conceded in return, in the same sentence: his conclusion holds for interacting theories, ours at full strength is free/quasi-free. Different theorems, different depths, one honest trade (§111.3).

Objection 67 (O-P5-67) (the Kaluza–Klein veteran)
"Antiparticles running the other way around the circle is fifty-year-old KK lore. T-P5-A

is a rediscovery."

Response. The image is conceded on the page where the theorem lives — and then the object is distinguished, because the distinction is the parent program's founding move. Your circle is spatial: it has a radius to stabilize, a charged tower, and, in its string descendants, a landscape. The GG-6 fiber is a non-spatial phase dimension — generated by a charge rotation, dimensionless, towerless, modulus-free (Arisaka, 2026, A2-GG6) — so "fifty-year-old KK lore" has, strictly, never before had an object it was true *of*. And the claim in any case begins at T-P5-B and closes at T-P5-C: KK (spatial or not) has one source of i and borrows the other from the quantum axioms; it has one hand, and no handshake is possible with one hand (§52).

Objection 68 (O-P5-68) (the mathematical physicist, on Ashtekar–Magnon)
"Your clock theorem is Ashtekar–Magnon 1975 and Kay 1978. They did the real work."

Response. They did, they are cited at every use, and T-P5-B says so in its own statement. The step they did not take — could not, in a framework with no physical compact fiber — is the compatibility question: their unique J meets a second forced J on charged sectors, and the meeting is where antiparticles come from. Inherited uniqueness, new handshake.

Objection 69 (O-P5-69) (the algebraist, again)
"Bisognano–Wichmann gives CPT from modular theory for interacting fields — deeper and stronger than your quasi-free anatomy."

Response. Stronger in scope, conceded twice in the text; deeper is the contested word. BW operates *inside* a complex Wightman theory: it locates Θ magnificently and says nothing about what i is. The anatomy says what i is made of and pays for it with scope. The modular route — your flow as our clock — is the named bridge, and whichever side proves it first wins the word "deeper" honestly (§111.4; open question (6)).

Objection 70 (O-P5-70) (the QFT instructor)
"The handshake covers free fields. Real antiparticles annihilate, radiate, and bind. A free-field origin story is a toy."

Response. The scope qualifier appears in every Part that uses the result, verbatim. Two facts keep it from being a toy: the interacting extension rides on the standard asymptotic frame (conditionally — the same scattering hypotheses your own S-matrix course assumes), and the *content* the handshake explains (the pairing, the sign conventions, the table) is inherited unchanged by the interacting theory that dresses it. The toy objection would bite if interactions could *re-pair* the modes; locality forbids exactly that.

Objection 71 (O-P5-71) (the nostalgic, on the sea)
"Dirac's sea predicted the positron. Your handshake predicts nothing that was not known by 1949."

Response. Correct, and stated in the ledger: on Depth 1 the pairing is textbook, and no new particle is predicted by T-P5-C. What is new is provenance — and provenance has consequences: the derived table (T-P5-1), the chirality criterion for CP (T-P5-3), the door theorem (T-P5-4), and the biased traffic of Part VIII are all downstream of knowing *what the pairing is made of*.

The sea predicted a particle and explained nothing; the handshake predicts no particle and explains the pairing, the phases, and ultimately the excess. Different currencies (§52).

Objection 72 (O-P5-72) (the skeptic, on readouts)
""The positron is a conjugate readout of the same basin" is wordplay. Two orientations of one object versus two objects — what experiment tells them apart?"

Response. Problem G.6.3 of Appendix G is this question as a drill. A second-basin positron could differ from the electron in any un-protected property — a slightly different mass, moment, or binding — while a second-orientation positron *cannot*: every CPT-protected identity of Table 1 is, on the readout picture, an identity of one object with itself. The 10^{-12}-level agreements are the experiment; the readout picture is the only one for which they are trivialities rather than miracles.

Objection 73 (O-P5-73) (the relativist, on Hawking's partner)
"Your "dissolved partner" hand-waves away the firewall problem that serious people spent a decade on."

Response. The dissolution is a computation, not a wave: the exterior thermal state is derived as the OGGEP partial trace of a two-mode-squeezed *bulk* state, and the "partner" is the traced-over bulk factor — not an independent 4D quantum whose entanglement monogamy can be violated (Arisaka, 2026, C3-BH). Whether that resolution satisfies you depends on whether you grant the 6D bulk; the point made *here* is narrower and safe: the partner is a boundary label, and reifying boundary labels is exactly what the custody principle exists to prevent (§49).

Objection 74 (O-P5-74) (the careful reader, on conflation)
"Your bulk contains conjugate representations *and* anomaly-forced opposite-chirality species. Sooner or later you will conflate them into "the bulk contains its own antimatter.""

Response. The conflation is forbidden in §47 in its own subsection: the representation conjugates are the antiparticles of (Q1); the anomaly-forced species (D_2^-, the singlet sea) are independent chiral fields whose opposite sign balances the books, and are not the twins of the visible matter. The distinction is load-bearing and policed — you have just read the police report.

Objection 75 (O-P5-75) (every reader, on the whole Part)
"Strip the geometry. What survives of Part IV if the sixth dimension does not exist?"

Response. Three things, as portable results: the statement that Weinberg's two undischarged axioms (the complex $\mathcal{H}$, output-positivity) *can* be discharged by any framework possessing a physical compact U(1) direction and a causal clock — the theorem is KK-generic, not GG-6-proprietary; the identification of "why complex QM" with "why antiparticles" as one question, which stands as a challenge to any foundational program; and the custody discipline for twin-labels, which dissolves the readout puzzles in any bulk-boundary framework. If the fiber falls, the handshake falls with it — and the falsifier tables say where to push.

Objection 76 (O-P5-76) (the free-fall referee, on ALPHA-g)
"Antihydrogen falls down, like everything else. Did your one-object picture predict

that, or accommodate it?"

Response. Predicted, in the strong sense that the alternative was lethal: one object doubly read cannot fall differently from itself, so a repulsive or anomalous $\bar{g}$ would have killed the conjugate-readout picture and, through the CPT-protected identities, the theorem behind it. The measurement (ALPHA Collaboration, 2023) confirms at $\sim 20\%$ precision; the picture's exposure does not stop there — any future $\bar{g}/g \neq 1$ at any precision is a kill, registered now, and the improving free-fall program is welcome company for Table 1.

Objection 77 (O-P5-77) (the condensed-matter colleague, on Majorana wires)
"Majorana modes are engineered in nanowires and studied for qubits. Doesn't the laboratory normalize self-conjugacy, whatever your mod-8 clock says?"

Response. Emergent self-conjugacy in a superconductor lives in the particle–hole redundancy of a mean-field description — physical, useful, and not a fundamental fermion equal to its own conjugate: the doubled description is bookkeeping, and the quasiparticle's 'Majorana-ness' is exact only at zero energy in an engineered spectrum. The mod-8 statement (§G.4) concerns the fundamental spinor bundle of the arena, which no wire touches. The one fundamental candidate remains the neutrino — where the door says yes, quietly, at 1.72 meV.

Objection 78 (O-P5-78) (the stability referee, on the vacuum)
"If antiparticles are relabeled modes, why doesn't the vacuum pair-create for free? Relabellings are cheap."

Response. Because the relabeling is exactly what makes every physical mode's energy positive: the handshake selects the global J under which the quadratic form is definite — Weinberg's positivity-on-output, caught one level down (§G.5). Pair creation then costs $2mc^2$ in every frame, and the 'free lunch' would require the anti-agreeing pairing whose obstruction is the cocycle of problem G.6.2: not expensive, *inconsistent*. Vacuum stability is the handshake's first dividend, not an additional assumption.

Z The quantum-foundations referee

Objection 79 (O-P5-79) (the foundations referee, on the Born rule)
"Your confrontation tables are probabilities. Derived, or assumed?"

Response. Inherited at a stated grade, from the companion whose business it is: the Born chain closes at the relaxation level (the R16 lemmas and their GDOS relaxation), with the constitutional theorem conditional on four named premises and one analytic residue — the field-grade representation step, carried on this paper's own promotion roadmap as item 8 (§M; Arisaka, 2026, A8-QM). Everything probabilistic in this paper runs through standard quantum mechanics, so nothing here strains the grade — but the reader deserves to know the grade exists, and now does.

Objection 80 (O-P5-80) (the same referee, on real quantum mechanics)
"Renou et al. falsified real-Hilbert quantum mechanics. Your bulk is real. Which is it?"

Response. Both, by custody — and the custody is the theorem, not a dodge: the boundary description is genuinely complex, with one shared J extending to composites and Fock space (T-P5-C1), which is exactly what the network Bell tests demand (Renou et al., 2021); the bulk carries the two real structures whose forced agreement *is* that J. The no-go theorems constrain theories whose Hilbert space is real; they are silent on theories whose complex structure is derived. The dictionary owns the sectors; the geometry owns the i — said five times across the cohort because it is load-bearing five times.

Objection 81 (O-P5-81) (the same referee, on the two arrows)
"T-violation is a parts-per-thousand laboratory effect; measurement irreversibility is total. You use both arrows. Same arrow?"

Response. Distinct arrows, distinct custodians, one meeting point. Microscopic T-violation is texture chirality — small, CP-compensated, CPT-protected (Part V). The measurement arrow is the one-way OGGEP projection: records are boundary exports, and the projection does not invert (§23 custody; the actualization layer of Part III). The paper keeps them apart deliberately — most confusions in this subject are custody errors — and lets them meet exactly once, where they must: at freeze-out, when the cosmic record (the baryon excess) is written by dynamics that use the microscopic arrow (Part VIII).

Objection 82 (O-P5-82) (the same referee, on spin and statistics)
"Pauli proved spin–statistics in 1940; the axiomatic proofs are airtight. Your 'second child of the quartet' adds what?"

Response. A Depth-3 candidate for what the connection is *made of*: Pauli and his descendants force the connection from relativistic axioms — necessity without anatomy. The quartet route derives exchange-as-half-turn at the quasi-free level from the same analytic fact that runs rotation and the thermal clock (T-P5-B1), making statistics and spin two readings of one rotation structure (§45). It is graded *candidate*, promoted only by the roadmap's item 6, and the concession to the axiomatic proofs' interacting reach is printed beside it. What is genuinely new is the identification, not the theorem — yet.

The References that follow carry a relevance note on every entry, the cohort's A-list first.

Part XVI
References

Cited works, each with a relevance note

A. Papers by Katsushi Arisaka (the GG-Theory cohort)

References

E. K. Anderson et al. (ALPHA Collaboration), Nature **621**, 716 (2023).

Relevance. Antihydrogen in free fall: after two decades of trapping and cooling anti-atoms, the ALPHA-g apparatus released them in a vertical field gradient and watched them fall — down, with $\bar{g}/g$ consistent with unity at the twenty-percent level. For this paper the measurement is the direct gravitational test of the one-object reading of the conjugate pair: a second-orientation positron cannot weigh differently from its electron, so the result is a registered retrodiction, and any future $\bar{g}/g \neq 1$ at any precision is a kill (Part XV). First cited in §XV.

K. Arisaka. *The GG-Constitution: Four Axioms and Seven Postulates of the GG-Theory Program, From Which GG-6, BI-6, OGN-5, and GDOS Descend as Theorems*, Arisaka-GG-A1-Constitution (2026).

Preprint, available at https://preprints.arisaka-gg.org/a1-constitution/.
doi:10.5281/zenodo.22063867.

Relevance. The axiomatic foundation. This paper draws AX-1 (causal and spatial orientation; the clock T reverses and the arena P reverses), AX-2 (the fiber C reverses), AX-3's positivity clause (the sign of the frequency splitting) and forward-semigroup structure, and POS-3 (the anomaly-admissibility filter policing every chirality assignment of Part VI). First cited in §16.1.

K. Arisaka. *GG-Theory with GG-6: Geometry–Gauge Locking at the 6D Bulk (GG-6) at the Heart of Grand Geometric Theory (GG-Theory)*, Arisaka-GG-A2-GG6 (2026).

Preprint, available at https://preprints.arisaka-gg.org/a2-gg6/.
doi:10.5281/zenodo.22064298.

Relevance. The arena paper: Theorem 0's forced six-dimensional geometry, the complex chiral spinor structure of $(1, 5)$ signature (no Majorana condition; independent Weyl modules — the raw material of Part VI's hand-picking), and the export argument by which no $G\widetilde{G}$ knob reaches the boundary (§77). First cited in §31.

K. Arisaka. *Anomaly Freedom of BI-6: The Modified Bianchi Identity (BI-6) for the Six-Force, Six-Dimensional Bulk (GG-6)*, Arisaka-GG-A3-BI6 (2026).

Preprint, available at https://preprints.arisaka-gg.org/a3-bi6/.

doi:10.5281/zenodo.22064300.

Relevance. The ledger paper: fixes $(M, N, L; J, K) = (1, 3, 5; 7, 35)$ by anomaly arithmetic — the integers this paper consumes as the pentagon (L), the phase counter (N), the leptonic odd integer (J), and the throat depth (K). Also the Green–Schwarz inflow that POS-3 axiomatizes. First cited in §16.1.

K. Arisaka. *From Euclid to GG-6: The Realization of Euclid's Elements in Six Dimensions — GU-5, OGN-5, and a Parameter-Free Reconstruction of Modern Physics*, Arisaka-GG-A4-Euclid (2026).
Preprint, available at https://preprints.arisaka-gg.org/a4-euclid/.
doi:10.5281/zenodo.22064302.

Relevance. The lineage paper of the cohort, and the one that measures the size of this paper's claim from outside it. It traces the geometrization of physics from Euclid forward — each step a quantity that had been a law becoming a property of a space — and the present claim, that C, P and T are orientations of real geometry rather than laws about fields, is one more step in that sequence rather than a break with it. It is also the companion that says how large a step it is not. First cited in §16.1.

K. Arisaka. *GDOS: Geometric Dynamics of Open Systems — 6D GG-6 Bulk Projected to 4D Boundary for Quantum Measurement, General Relativity, and QFT*, Arisaka-GG-A5-GDOS (2026).
Preprint, available at https://preprints.arisaka-gg.org/a5-gdos/.
doi:10.5281/zenodo.22064304.

Relevance. The boundary-law paper: the bulk-T-symmetric / projection- asymmetric split that separates time-reversal from the arrow of time (§38), and the explicit centralizer computation verifying that the projection matrix breaks SU(5) to exactly the Standard-Model group (§65). First cited in §29.

K. Arisaka. *The GRIP on GDOS — GRIP: the Geometric Engine of Symmetry Breaking, from the Big Bang to Mind*, Arisaka-GG-A6-GRIP (2026).
Preprint, available at https://preprints.arisaka-gg.org/a6-grip/.
doi:10.5281/zenodo.22064306.

Relevance. The descent-machinery paper: the Wilson-line computations placing the locked $U(1)_B$ holonomy ($2\pi/5$) beside the dynamical $U(1)_{Qi}$ (Kaxion) line — the two-fate architecture of §77 in a single worked example — and the family-projector transport whose holonomies are Part VII's CP angles. First cited in §38.

K. Arisaka. *The Qi-4 Pillars — Qi-QUA, Qi-EP, Qi-CON, Qi-HAL: The Quantum-Information Backbone of GDOS*, Arisaka-GG-A7-Qi4 (2026).
Preprint, available at https://preprints.arisaka-gg.org/a7-qi4/.
doi:10.5281/zenodo.22064308.

Relevance. The treatment in which the informational symmetry $U(1)_{Qi}$ and its current are developed, memory is identified as a gauge-invariant phase holonomy, and the outer/inner hologram

loop is defined — the companion on which §37.5's widening of view rests, and which grades those claims at their own tentative register. First cited in §37.5.

K. Arisaka. *Quantum Mechanics Derived from GG-Theory as Projection from 6D Bulk to 4D Boundary*, Arisaka-GG-A8-QM (2026).
Preprint, available at https://preprints.arisaka-gg.org/a8-qm/.
doi:10.5281/zenodo.22064310.
Relevance. The real-bulk series RB-1–RB-12: the discussion-grade original of the discrete-symmetry statement (RB-6) that T-P5-1/T-P5-2 consolidate, and the fermionic form of charge conjugation (circle reversal composed with a fixed real spinor map) used in §56. First cited in §18.

K. Arisaka. *The Standard Model as Theorem of GG-Theory: Its 28 Parameters as Observations of One Six-Dimensional Geometry*, Arisaka-GG-A9-SM (2026).
Preprint, available at https://preprints.arisaka-gg.org/a9-sm/.
doi:10.5281/zenodo.22064312.
Relevance. The parent of Parts V–VII: theorems T-SM-46.1/46.2 (the table and the flavor holonomy, with the pentagonal lattice and the $\delta_{\mathrm{CKM}}/\delta_{\mathrm{PMNS}}$ chains), T-SM-44.1 (the dial-free door), the basin/gate section and its Gate-Operator Lemma (this paper's C-P5-A), the strong-CP two-part vanishing (lemma L9), and the Yukawa codebook supplying the mass-ratio angles of (53). This paper consolidates, grades, and extends; the proofs at parent depth live there. First cited in §16.1.

K. Arisaka. *The Standard Cosmology as Theorem of GG-Theory: The Cosmic Inventory as Observations of One Six-Dimensional Geometry*, Arisaka-GG-A10-Cosmos (2026).
Preprint, available at https://preprints.arisaka-gg.org/a10-cosmos/.
doi:10.5281/zenodo.22064314.
Relevance. The parent of Part VIII: the one-ledger baryogenesis statement, the Sakharov custody line ("GRIP owns the angle..."), the step-by-step resonant-leptogenesis chain with its audit table, the prompt-crossing (zero dilution) grounds, the honesty objections this paper adopts verbatim (the $K/2$ postulate, the order-of-magnitude demotion), and the Ω_b two-route seam. First cited in §38.

K. Arisaka. *The Geometric Inevitability of Cosmos, Life, and Mind: The Self-Referential Closure of the GG-Theory Program*, Arisaka-GG-A11-Origin.
Preprint, available at https://preprints.arisaka-gg.org/a11-origin/.
doi:10.5281/zenodo.22064319. No result of the present paper depends on it.
Relevance. The summit paper of the cohort, which asks the question the whole program exists to earn — why is there anyone here to ask? — and answers it as a cascade: CP violation to baryogenesis to stars to chemistry to observers, each link graded. This paper's §149 bridges into that cascade at its first link, the matter excess, and adopts the summit's own honest register: the chain beyond the matter link is conjectured, carried there as OP-7 rather than claimed. First cited in §149.

K. Arisaka. *The Kaxion: Cold Dark Matter as the Non-Spatial Compact-Angle Pseudoscalar of GG-6*, Arisaka-GG-C1-Kaxion (2026).
Preprint, available at https://preprints.arisaka-gg.org/c1-kaxion/.
doi:10.5281/zenodo.22064333.
Relevance. The relaxed fate: the gauge-topological compact angle that discharges the strong-CP duty on the Peccei–Quinn template with no PQ scalar, doubly protecting $\bar{\theta}$ (§77); also the smooth-circle requirement behind the projection-location note (§71). First cited in §77.

K. Arisaka. *The Hubble Tension in the Light of GG-Theory: The Hubble Constant as One Reading of a Derived Expansion History $H(t)$*, Arisaka-GG-C2-Hubble (2026).
Preprint, available at https://preprints.arisaka-gg.org/c2-hubble/.
doi:10.5281/zenodo.22064336.
Relevance. The expansion history against which the matter excess of Part VIII is measured. The baryon density this paper's chain must land on is read off the same derived inventory that the corridor analysis works in, so a shift in that inventory moves this paper's target and not only its context — which is why the companion is cited here and not only acknowledged. First cited in §16.1.

K. Arisaka. *The GG-6 Lock Cluster: A Non-Spatial Kaluza–Klein Resonance near 3.85 TeV as the Standing LHC Falsifier of GG-Theory*, Arisaka-GG-P1-KK (2026).
Preprint, available at https://preprints.arisaka-gg.org/p1-kk/.
doi:10.5281/zenodo.22064321.
Relevance. The cohort's first dedicated falsification channel: the paper that takes the lock scale $M_{\text{lock}} = 3.85$ TeV from the ledger, works out the collider phenomenology of the resulting cluster, confronts it with the ATLAS/CMS record, and pre-registers the HL-LHC criterion by which the prediction lives or dies. It is the collider sibling of this Part: the same heavy sector that runs the leptogenesis chain of Part VIII is the cluster P1 sends to the energy frontier (§121). First cited in §121.

K. Arisaka. *Why Three Generations: A Three-Leg Derivation of $N_g = 3$ from BI-6, MSMF, and GDOS Morse Stability*, Arisaka-GG-P2-N3 (2026).
Preprint, available at https://preprints.arisaka-gg.org/p2-n3/.
doi:10.5281/zenodo.22064323.
Relevance. A precondition of this paper rather than a neighbor of it. A nonzero Jarlskog invariant cannot exist in a mixing matrix with fewer than three families, so the family count that paper derives is what makes the quark and lepton CP phases of Part VII objects at all; its CP leg and this paper's holonomy calculus meet at the same flavor graph. A fourth light family would end both papers on the same day. First cited in §16.1.

K. Arisaka. *The Electron as the Ground State of Nature: The Six Oldest Questions about the Electron, Closed and Fenced within GG-Theory*, Arisaka-GG-P3-Electron (2026).
Preprint, available at https://preprints.arisaka-gg.org/p3-electron/.
doi:10.5281/zenodo.22064325.

Relevance. The positron resolution this paper's readout section carries: the conjugate readout of the same basin — same level, opposite winding — with "the positron, as a theorem" registered as the program's owed corollary (D-P3-4), and Wheeler's one-electron universe rejected for the right reason and preserved in the form that survives. First cited in §49.

K. Arisaka. *Black-Hole Entropy under GG-Theory: The GDOS Reading of the Horizon as an OGGEP Port — with the Exact Bekenstein–Hawking $A/4G_N$ Derived from Induced Gravity*, Arisaka-GG-C3-BH (2026).
Preprint, available at https://preprints.arisaka-gg.org/c3-bh/.
doi:10.5281/zenodo.22064338.
Relevance. Hawking thermality derived as the OGGEP partial trace of a two-mode-squeezed bulk state, with the "interior partner" dissolved into the traced bulk — the third of the three readout episodes and the horizon instance of the custody principle. First cited in §49.

K. Arisaka. *The Real Geometry Beneath the Complex Numbers of Physics: Positive Frequency is Holomorphy — from Cardano's Cubics to Twistor Space, via the Sixth Dimension of GG-Theory*, Arisaka-GG-P4-Real (2026).
Preprint, available at https://preprints.arisaka-gg.org/p4-real/.
doi:10.5281/zenodo.22064327.
Relevance. The origin-of-i member paper of the Foundations Branch — this paper's partner on the cohort map and its structural template: supplies the four inherited theorems (circle, clock, handshake, shared i) restated in §37, the custody principle this paper extends, and the real presentation in which every computation here is performed. The division of labor is stated in §16.1. First cited in §16.1.

K. Arisaka. *The Proton as the Ground Geometric Attractor of Matter: The Eleven Questions of the Proton, Closed and Fenced within GG-Theory*, Arisaka-GG-P6-Proton (2026).
Preprint, available at https://preprints.arisaka-gg.org/p6-proton/.
doi:10.5281/zenodo.22064331.
Relevance. The other end of this paper's number. Part VIII makes the baryon asymmetry; that paper shows the resulting protons are kept, baryon number being carried as a winding of the compact circle rather than as a bookkeeping label, so decay is forbidden by the geometry rather than merely unobserved. Making the excess and keeping it are two statements about one integer, and a single verified proton decay ends both. First cited in §16.1.

K. Arisaka. *Symmetry, Conservation, and Geometry: Seven Steps from Noether, Bianchi, to Hopkins–Singer, and the Ledger the Open-System Turn Pays Out*, Arisaka-GG-W1-Symmetry (2026).
Preprint, available at https://preprints.arisaka-gg.org/w1-symmetry/.
doi:10.5281/zenodo.22064340.
Relevance. The first of the two white papers, and the diachronic one: it follows a century of symmetry and conservation in the order the results were found and watches the conviction that symmetry causes conservation loosen at seven successive steps. The mirrors of the present paper

are the sharpest case in that history — symmetries assumed for three centuries and then measured to fail — so W1 is the historical account of why this paper's result is a continuation and not an anomaly. It derives nothing new. First cited in §16.1.

K. Arisaka. *The Circle That Remembers, the Interval That Forgets: GG-Theory and the Sixteen Problems of Particle Physics and Cosmology*, Arisaka-GG-W2-Holonomy (2026).
Preprint, available at https://preprints.arisaka-gg.org/w2-holonomy/.
doi:10.5281/zenodo.22064342.
Relevance. The closest of the six to this paper. Its single exact statement — a holonomy requires a closed loop, and the interval fiber has none — is the asymmetry between the two non-spatial dimensions that Part IX derives the four endowments of time from, and the same asymmetry that puts the CP phases on the circle and the arrow on the interval. W2 takes that statement to sixteen of the questions physics has not closed, and names the dated measurements on which six of the sixteen treatments die. Like its sibling it derives nothing new. First cited in §16.1.

B. Other references

References

ACME Collaboration (V. Andreev et al.), Nature **562**, 355 (2018).
Relevance. The molecular-amplifier revolution of the EDM program: polar molecules multiply the effective electric field on the electron by orders of magnitude, and ACME's ThO beam turned that leverage into $|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm}$ (since improved). In this paper's ledger the electron EDM is one of the two static T-odd nulls that discipline every proposed CP phase, this paper's included, and anchor the seventy-year program of §10. First cited in §10.

H. Alfvén, Rev. Mod. Phys. **37**, 652 (1965).
Relevance. The matter–antimatter symmetric cosmology, argued by a Nobel plasma physicist: a universe of separated matter and antimatter domains, with annihilation at the frontiers. It was the reasonable alternative to a built-in asymmetry — and the gamma-ray sky killed it, since domain boundaries would glow in a diffuse annihilation flux that is not there. Its honest burial is where Part I's stake begins: the asymmetry is global, and needs a dynamical origin (§11). First cited in §11.

I. Affleck, M. Dine, Nucl. Phys. B **249**, 361 (1985).
Relevance. Baryogenesis from scalar condensates: supersymmetric flat directions carrying baryon number acquire large field values during inflation and release an asymmetry as they relax — an elegant mechanism that can generate almost any η_B. It sits in the QFT toolbox of §111.5 as the great alternative this framework cannot use: a dial-free scalar sector has no flat directions to displace, which is one of the closures that force Part VIII onto the lepton route. First cited in §111.5.

E. K. Akhmedov, V. A. Rubakov, A. Yu. Smirnov, Phys. Rev. Lett. **81**, 1359 (1998).

Relevance. Leptogenesis from sterile-neutrino oscillations at the GeV scale: the asymmetry is generated not in decays but in the CP-violating oscillations of the singlets themselves, while they are still relativistic — a mechanism testable at beam dumps and in kaon factories. It is the toolbox's low-scale alternative, recorded in §111.5 and again in Appendix F.3, and distinct from the resonant-decay chain this paper's ledger runs. First cited in §111.5.

L. Alvarez-Gaumé, E. Witten, Nucl. Phys. B **234**, 269 (1984).
Relevance. The classic analysis of gravitational anomalies: in $4k{+}2$ dimensions purely gravitational anomalies exist, chirality is a signed currency, and the anomaly polynomials are computed once and for all. It is the map of the terrain on which Bl-6 runs its ledger — the anomaly flip (11) that forces conjugate content into the bulk spectrum is a line item of their accounting (§25; drilled as problem G.4.2). First cited in §25.

C. D. Anderson, Phys. Rev. **43**, 491 (1933).
Relevance. The positron observed, in cloud-chamber tracks curving the wrong way: the discovery that crowned Dirac's prediction within two years of its naming and turned the sea from bookkeeping into triumph. The particle outlived its first explanation — the sea was dismantled by the arguments of Appendix G.1 — and the twin it revealed is the subject Part IV derives from consistency (§111.3). First cited in §111.3.

Y. Aharonov, D. Bohm, Phys. Rev. **115**, 485 (1959).
Relevance. The prototype holonomy observable: a phase acquired around a closed loop, physical though no local field touches the path — the demonstration that gauge geometry stores measurable information in loops. The flavor plaquettes of T-P5-3 are its flavor-graph analogues: rephasing-invariant loop angles, immune to convention for exactly the Aharonov–Bohm reason. First cited in §21.

ALPHA Collaboration, Nature **578**, 375 (2020).
Relevance. Antihydrogen 1S–2S spectroscopy: the anti-atom's flagship transition measured to a fractional precision of 10^{-12} and found identical to hydrogen's — matter–antimatter comparison at the precision frontier. It is a load-bearing row of the CPT test table (Table 1): one of the identities T-P5-2 forces exactly and any real texture preserves (§10). First cited in §10.

AMS Collaboration, AMS-02 antinuclei searches (2016–).
Relevance. The magnetic spectrometer on the Space Station, sifting cosmic rays for antinuclei since 2011: no confirmed antihelium, no antideuteron flux — the local certificate that the asymmetry of §82 extends through the cosmic-ray sampling volume. The tentative candidate events in circulation are engaged head-on in Part XV: a confirmed antihelium-4 flux is registered there as a genuine crisis for Part VIII. First cited in §11.

H. Albrecht et al. (ARGUS), Phys. Lett. B **192**, 245 (1987).
Relevance. Large B^0–$\bar{B}^0$ mixing, discovered where few expected it: the mixing rate implied a heavy top quark and, crucially, made time-dependent CP interferometry in the B system feasible — without ARGUS's surprise there is no B-factory program, no golden mode, and no third angle

of the unitarity triangle. The era it opened is told in §122.2 and drilled in Appendix E.4. First cited in §122.2.

A. Ashtekar, A. Magnon, Proc. R. Soc. Lond. A **346**, 375 (1975).
Relevance. With Kay (1978), the uniqueness theorem for the positive-energy complex structure on the solution space of a field on a stationary spacetime: the functional-analytic care behind the clock. The polar phase J_A that this paper's T-P5-B constructs — and that T reverses — is their object, restated with its constitutional pedigree in §37 and proved at walking pace in Part IV. First cited in §36.

BaBar Collaboration (B. Aubert et al.), Phys. Rev. Lett. **87**, 091801 (2001).
Relevance. The measurement that brought CP violation out of the kaon after thirty-seven years: $\sin 2\beta$ from time-dependent interferometry in $B \to J/\psi K_S$, the unitarity triangle closing on the one phase of the three-family matrix. It is half of the two-experiment confirmation (with Belle Collaboration (2001)) that the Kobayashi–Maskawa phase is the phase of the world — the phase Part VII values at the lattice point (§8). First cited in §8.

BaBar Collaboration (J. P. Lees et al.), Phys. Rev. Lett. **109**, 211801 (2012).
Relevance. Direct, model-independent observation of time-reversal violation: by comparing rates between flavor-tagged and CP-tagged B states, BaBar measured T-conjugated transitions against each other with no recourse to CP or CPT assumptions — the fall of the third mirror, measured cleanly rather than inferred. It completes the discovery record of §111.4: all three factors broken, each by its own experiment, the product alone surviving. First cited in §111.4.

T. Banks, D. B. Kaplan, A. E. Nelson, Phys. Rev. D **49**, 779 (1994).
Relevance. The cosmological moduli problem stated with full force: light scalars with Planck-suppressed couplings dominate the energy density, decay late, and dilute or destroy every pre-existing relic — including a baryon asymmetry. It is the dilution killer that string cosmologies must engineer around, and that the prompt lock crossing structurally lacks: the zero-dilution clause of §86 is this paper's answer, inherited from the descent. First cited in §86.

Augustine of Hippo, *Confessions*, Book XI (c. 400).
Relevance. The founding confession of the subject: everyone knows time until asked — sixteen centuries of philosophy of time in one sentence, and the question Part IX exists to answer. His analysis of the present as the only existent, with past and future as memory and expectation, anticipates the record-centered reading the OGGEP arrow makes structural. First cited in §97.

Belle Collaboration (K. Abe et al.), Phys. Rev. Lett. **87**, 091802 (2001).
Relevance. The simultaneous $\sin 2\beta$ measurement from KEK: with BaBar Collaboration (2001), the two-continent confirmation that one phase carries the B system's CP violation — the one-phase paradigm established by mutual verification, the field's gold standard for a discovery of this weight. The paradigm both experiments confirmed is exactly what Part VII inherits and prices (§8). First cited in §8.

M. Berkooz, M. R. Douglas, R. G. Leigh, Nucl. Phys. B **480**, 265 (1996).

Relevance. Chiral fermions from branes at angles: intersecting D-branes localize chiral matter at their intersections, the third of string theory's chirality mechanisms after Calabi–Yau compactification and orbifolds. It is credited in §113 as part of the honest accounting of how the rival program obtains what Part VI derives — many mechanisms, each workable, none forced. First cited in §113.1.

J. J. Bisognano, E. H. Wichmann, J. Math. Phys. **17**, 303 (1976).
Relevance. CPT (composed with a rotation) as the modular conjugation of the wedge algebra: from the vacuum state and the algebra of local observables alone, Tomita–Takesaki theory delivers the reflection — the deepest orthodox statement of where CPT comes from, with no Lagrangian in sight. It is the target of the open modular route (§58, Appendix D.4): whether their modular flow is this paper's clock seen abstractly is the named bridge question of Objection 69. First cited in §10.

L. Boltzmann, Wien. Ber. **76**, 373 (1877).
Relevance. Entropy as counting: the probabilistic reading of the second law, and with it the honest admission — sharpened by Loschmidt's and Zermelo's objections — that the thermodynamic arrow lives in initial conditions, not in the reversible dynamics. It defines the standard account's high-water mark that §103 engages: the arrow this program moves from the state to the law is the arrow Boltzmann located, correctly and unhappily, outside it. First cited in §98.

M. Agostini et al. (Borexino), Nature **587**, 577 (2020).
Relevance. CNO-cycle solar neutrinos detected: the completion of solar spectroscopy, sixty years after Homestake opened it — every fusion chain of the Sun now seen in neutrinos, with fluxes matching the solar model. It closes the arc of §123: the detector lineage that began with a deficit and a puzzle ends with the Sun as a calibrated neutrino source. First cited in §123.

I. I. Bigi, A. I. Sanda, *CP Violation*, 2nd ed. (Cambridge University Press, 2009).
Relevance. The flavor-centric monograph of CP violation — kaons, B mesons, and the invariant formalism at book length. Shelf text of the neutrino chapter (Appendix H) and the book-length grounding of Appendix D. First cited in Appendix H.

L. Boyle, K. Finn, N. Turok, Phys. Rev. Lett. **121**, 251301 (2018).
Relevance. The CPT-symmetric universe: the Bang as a mirror between a universe/anti-universe pair, with the observed arrow emerging from our position on one side — the modern cosmological reading of the unbroken theorem, and the boldest use of CPT in cosmology since Sakharov. Engaged as a structural cousin in Part XV: kin in reverence for the theorem, rival in locating the asymmetry in the state rather than the dynamics, with a falsifier set (vanishing tensors, a heavy sterile relic) almost disjoint from this paper's. First cited in §107.

G. C. Branco, L. Lavoura, J. P. Silva, *CP Violation* (Oxford, 1999).
Relevance. The standard monograph of the rephasing-invariant calculus: every quartet identity, every convention trap, every Majorana-phase subtlety, at book length — the reference this paper draws in wiring language (§20) and Appendix E assigns as its shelf text. Its Chapter 22

disambiguation of phase conventions is cited three times in this paper because real person-years keep being lost to exactly that trap; the reader who wants every matrix identity behind the plaquettes will find it there. First cited in §20.

G. Buzsáki, *Rhythms of the Brain* (Oxford, 2006).
Relevance. The standard synthesis of cortical rhythms: theta and gamma oscillations as the carrier and clock of neural computation, phase coding as the brain's own use of angle variables. It supplies the neuroscience half of the real-bulk aside of §37.5: the one physical system known to model the world — the brain — runs its model on phases and rhythms, a suggestive echo, flagged as analogy and nothing more. First cited in §37.5.

W. Buchmüller, P. Di Bari, M. Plümacher, Ann. Phys. **315**, 305 (2005).
Relevance. The pedagogical summa of thermal leptogenesis: Boltzmann equations, washout regimes, efficiency factors, and the $\kappa \simeq 1/K_{\rm wash}$ shorthand, derived once and used by everyone since. It is the treatment behind this paper's transport (§23, Appendix F.4): every washout statement in Part VIII's chain is their machinery, evaluated at the ledger's inputs and credited at each use. First cited in §23.

N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
Relevance. The original quark-mixing angle — one parameter reconciling strangeness-changing and strangeness-conserving weak rates — whose modern descendant is the CKM matrix derived in Appendix E.1 and whose magnitude this paper's (53) closes in golden form. First cited in §E.1.

P. Candelas, G. Horowitz, A. Strominger, E. Witten, Nucl. Phys. B **258**, 46 (1985).
Relevance. Chirality from compactification: on a Calabi–Yau background the number of fermion generations is a topological index, and parity violation descends from geometry — string theory's founding precedent for the claim that chirality is geometric. Credited in §63 as the noblest ancestor of Part VI's own claim, before the contrast is drawn: an index counts the generations; it does not orient the descent. First cited in §63.

J. A. Casas, A. Ibarra, Nucl. Phys. B **618**, 171 (2001).
Relevance. The seesaw inversion: every Yukawa matrix consistent with the measured light masses and mixings is parameterized by one complex orthogonal matrix R — the exact inventory of what low-energy data does and does not fix in the heavy sector. This paper uses it twice, in opposite directions: as the honest statement of the freedom standard leptogenesis cannot close (§22; problem F.5.3), and as the freedom the dial-free door spends (Part VIII). First cited in §22.

K. Choi, D. B. Kaplan, A. E. Nelson, Nucl. Phys. B **391**, 515 (1993).
Relevance. With Dine, Leigh, and MacIntire (1992), CP as a discrete gauge symmetry of string theory, spontaneously broken by moduli: the sharpest formulation of geometric CP in the rival program, and the closest external relative of this paper's position. The kinship is credited in full before the contrast is drawn (§134): in their landscape the breaking is real but the value is environmental; on the pentagon the value is forced — the difference between explaining that CP breaks and pricing what it breaks to. First cited in §79.

R. Davis, D. S. Harmer, K. C. Hoffman, Phys. Rev. Lett. **20**, 1205 (1968).
Relevance. The Homestake chlorine experiment: six hundred tonnes of cleaning fluid in a gold mine, counting argon atoms one by one — and finding a third of the predicted solar flux. The deficit opened the third arena thirty years before its resolution, a model of patient anomaly-keeping: the puzzle survived every recalibration until SNO showed the neutrinos were changing, not missing (§9). First cited in §9.

A. G. Cohen, A. De Rújula, S. L. Glashow, Astrophys. J. **495**, 539 (1998).
Relevance. The global certificate of the asymmetry: if the universe contained matter and antimatter domains, their boundaries would produce a diffuse annihilation gamma-ray flux; the observed sky forbids domains out to the visible horizon. It converts the local absence of antimatter into a cosmological fact (§82) — and it is the theorem a confirmed cosmic antihelium flux would reopen, an exposure this paper pre-registers in Part XV. First cited in §11.

A. Connes, C. Rovelli, Class. Quantum Grav. **11**, 2899 (1994).
Relevance. The thermal-time hypothesis: physical time as the modular flow of the state, KMS-rooted and one-parameter — the nearest structural cousin of the clock-and-shore account, engaged in §107. The custody contrast is exact: there the state defines the time, here the arena does; the two would meet on the open modular bridge of Objection 69, which is why the cousin is cited wherever that bridge is discussed. First cited in §98.

R. J. Cooke, M. Pettini, C. C. Steidel, Astrophys. J. **855**, 102 (2018).
Relevance. Precision primordial deuterium: quasar absorption spectra deliver D/H at the percent level, and through BBN a baryon density independent of the CMB. The concordance of the two epochs — nucleosynthesis at minutes, recombination at four hundred thousand years — is what makes η_B a measured constant of nature rather than a fit parameter, and it is the number Part VIII's chain must and does land on (§82). First cited in §11.

D. Q. Adams et al. (CUORE), arXiv:2404.04453 (2024).
Relevance. Te-130 bolometric $0\nu\beta\beta$ search: a tonne-scale cryogenic calorimeter running at ten millikelvin, past two tonne-years of exposure, $T_{1/2} > 3.5 \times 10^{25}$ yr. It is one of the three isotope technologies whose ton-scale successors define the coming era (§124) — the era for which this paper's $m_{\beta\beta} = 1.72$ meV is a registered null. First cited in §124.

CUPID Collaboration, Eur. Phys. J. C (2025), CUPID baseline design.
Relevance. Mo-100 scintillating bolometers in the CUORE cryostat: particle identification added to the bolometric technique, 10^{27}-yr-class discovery sensitivity. One of the three ton-scale instruments (with LEGEND-1000 and nEXO) that will execute the one-sided Majorana test of §125: decisive for the inverted ordering, and for this paper's registered silence. First cited in §125.

G. D. Coughlan et al., Phys. Lett. B **131**, 59 (1983).
Relevance. The original moduli problem — the Polonyi field: a weakly coupled scalar left displaced after inflation comes to dominate, decays late, and wrecks nucleosynthesis or dilutes every relic. The ancestral statement of the dilution hazard that §86 addresses: the prompt crossing

of the descent leaves no displaced light scalar behind, which is why the chain's η_B survives undiluted. First cited in §86.

L. Covi, E. Roulet (with F. Vissani), Phys. Lett. B **384**, 169 (1996).
Relevance. The CP asymmetry of heavy Majorana decay computed cleanly at one loop: vertex and self-energy interference, the $\mathrm{Im}[(Y^\dagger Y)^2]$ structure, the loop functions — the ϵ_i formula this paper's chain evaluates at resonance (§23) and Appendix F.3 derives at drill depth as Eq. (100). The flavor-space quartet in their numerator is the same closed-loop logic as the CKM plaquettes — one invariance principle, two sectors. First cited in §23.

J. H. Christenson, J. W. Cronin, V. L. Fitch, R. Turlay, Phys. Rev. Lett. **13**, 138 (1964).
Relevance. The discovery of CP violation: $K_L \to \pi\pi$ at a branching of 2×10^{-3}, in an experiment designed to confirm the symmetry rather than break it. It is the second fall of §6, the result that made the matter excess conceivable as physics, and the number the pentagon must ultimately price — the discovery run is retold with its regeneration controls in Appendix E.3. First cited in §6.

CPLEAR Collaboration (A. Angelopoulos et al.), Phys. Lett. B **444**, 43 (1998).
Relevance. First direct observation of T violation: tagged neutral kaons compared with their time-reversed transitions through semileptonic asymmetries, $A_T = 4\,\mathrm{Re}\,\varepsilon = (6.6 \pm 1.6) \times 10^{-3}$ — the arrow measured in the clock itself, not inferred from CP and CPT. It is the laboratory face of §111.4 and the drill material of §D.3: the third mirror fell in the kaon tank first. First cited in §111.4.

G. Danby, J.-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, J. Steinberger, Phys. Rev. Lett. **9**, 36 (1962).
Relevance. The two-neutrino experiment at the Brookhaven AGS: neutrinos born with muons make muons, not electrons — lepton flavor becomes physics, and the lepton sector acquires the family structure whose mixing matrix this paper's lattice values. The opening entry of the accelerator-neutrino lineage of §123. First cited in §123.

S. Davidson, A. Ibarra, Phys. Lett. B **535**, 25 (2002).
Relevance. The bound that named the problem: for hierarchical heavy neutrinos the decay asymmetry is capped by the light and heavy masses, forcing $M_N \gtrsim 10^9$ GeV — thermal leptogenesis priced permanently out of laboratory reach. It is the theorem the TeV-scale chain must evade, and does, via the resonant regime (§23); Appendix F.3 derives the bound as Eq. (101) and evaluates its six-order shortfall at the lock scale. Engaged explicitly per the register. First cited in §23.

Daya Bay Collaboration (F. P. An et al.), Phys. Rev. Lett. **108**, 171803 (2012).
Relevance. $\theta_{13} \neq 0$, measured decisively by reactor disappearance: the angle whose size determines whether the leptonic CP phase is experimentally reachable at all. Its largeness — near the old bounds — is why the long-baseline program can measure δ_{PMNS} this generation, why the lattice point is testable, and why this paper can be killed (§9). First cited in §9.

DESI Collaboration, arXiv:2503.14738 (2025).

Relevance. DR2 baryon-acoustic-oscillation data combined with the CMB: $\sum m_\nu < 0.064$ eV, cosmology pressing the neutrino spectrum harder than any laboratory. For this paper the bound is load-bearing twice (§124): it presses the orderings, and it sits eight percent above the derived sum of 59.2 meV — the new kill-or-confirm channel registered in Part XV, owned entirely by cosmology. First cited in §124.

B. S. DeWitt, Phys. Rev. **160**, 1113 (1967).
Relevance. The Wheeler–DeWitt equation: canonical quantum gravity's wavefunction of the universe, with no time parameter in it — the "problem of time" stated at the source, and the standing embarrassment of every background-independent program (§98). Part IX's arena account dissolves rather than solves it: time is constitutional, so the boundary theory never faces a timeless fundamental equation. First cited in §98.

M. Dine, R. G. Leigh, D. A. MacIntire, Phys. Rev. Lett. **69**, 2030 (1992).
Relevance. CP as a gauge symmetry in string theory: an exact discrete gauge symmetry of the worldsheet theory, spontaneously broken by the compactification — geometric CP's source paper. Credited in §134 before the valuation contrast is drawn: the insight that CP breaking is geometry is theirs; the claim that the broken value is a forced lattice angle is this program's, and it is the falsifiable half. First cited in §79.

P. A. M. Dirac, Nobel Lecture (1933).
Relevance. The Nobel lecture's closing speculation: perhaps half the stars are made of positrons and antiprotons — the symmetric universe entertained at the moment of the positron's confirmation. It is the honest starting point of §11: the asymmetry was not obvious; it had to be discovered, quantified, and finally explained — the eighty-year arc this paper's Part VIII closes at its own grade. First cited in §11.

P. A. M. Dirac, Proc. R. Soc. Lond. A **117**, 610 (1928).
Relevance. The relativistic wave equation of the electron: spin and the magnetic moment delivered, and with them a negative-energy branch that would not go away — the problem whose eighty-year working-out is Shelf 6 of the reading guide. The equation opens Appendix G.1's derivation and §111.3's history: everything in Part IV descends from taking its unwanted half seriously. First cited in §111.3.

P. A. M. Dirac, Proc. R. Soc. Lond. A **126**, 360 (1930).
Relevance. The sea proposed: fill the negative-energy branch, let exclusion block the collapse, and read the holes as particles of opposite charge — audacious bookkeeping that produced the positron prediction from an instability. The sea's triumph and its three structural failures (bosons, vacuum charge, asymmetric ontology) are derived as theorems in Appendix G.1: the first ontology of the twin, honored and dismantled. First cited in §111.3.

P. A. M. Dirac, Proc. R. Soc. Lond. A **133**, 60 (1931).
Relevance. The anti-electron named: in the same paper as the magnetic monopole, Dirac committed to the hole as a new particle of electron mass and positive charge — perhaps the

greatest successful prediction ever made by bookkeeping. The cloud chamber honored it within the year; field theory later retired the explanation while keeping the particle (§111.3), a transition this paper reads as the first step toward the handshake. First cited in §111.3.

L. Dixon, J. Harvey, C. Vafa, E. Witten, Nucl. Phys. B **261**, 678 (1985).
Relevance. String orbifolds: exact string backgrounds from discrete quotients, with chiral matter at the fixed points — the technology whose field-theory limit became the orbifold GUT. It is the lineage of Part VI's projection, conceded in §65: the mechanism is thirty years old and string-born; what the descent adds is the absence of choice in its application. First cited in §63.

R. P. Feynman, M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
Relevance. $V-A$ codified: the charged current couples only to left-handed fermions, maximal parity violation written into the vertex — the structure every weak-interaction calculation since has carried. For Part VI it is the shape of the explanandum: a fact this fundamental must be output, not input, and the one-gate descent is the attempt to make it so (§4). First cited in §4.

R. P. Feynman, Phys. Rev. **76**, 749 (1949).
Relevance. The theory of positrons: negative-energy solutions propagating backward in time reinterpreted as positive-energy antiparticles forward — the relabeling that, with the contour, replaced the sea and gave every amplitude its modern form. The assignment carries his name jointly with Stückelberg's; its provenance — why that relabeling and no other is consistent — is exactly what T-P5-C supplies (§111.3, Appendix G.2). First cited in §49.2.

M. Fukugita, T. Yanagida, Phys. Lett. B **174**, 45 (1986).
Relevance. Leptogenesis founded in four pages: create the asymmetry as lepton number through heavy Majorana decays, and let the sphalerons convert — the mechanism class of Part VIII entire. Cited as parent at every load-bearing use (§23, §84) and taught from scratch in Appendix F: this paper's contribution is not the mechanism but the removal of its dials. First cited in §9.

R. L. Garwin, L. M. Lederman, M. Weinrich, Phys. Rev. **105**, 1415 (1957).
Relevance. Parity violation in the π–μ–e chain, found within days of Wu's result and published back to back with it: the muon's spin precession read out through the decay asymmetry — the fall confirmed in a second system before the ink dried on the first. Together the two experiments made January 1957 the month the mirror broke for good (§4). First cited in §4.

M. B. Gavela, P. Hernández, J. Orloff, O. Pène, Mod. Phys. Lett. A **9**, 795 (1994).
Relevance. The quantitative half of the Standard Model's baryogenesis failure: at the electroweak crossover the effective CP violation available from the CKM phase is suppressed by the quark-mass hierarchy to $\sim 10^{-20}$ — ten orders short of the observed asymmetry. With the crossover itself (Kajantie et al., 1996) it closes the SM's own route twice over, the closure Part VIII inherits and Appendix F.1 derives as a drill (§11). First cited in §11.

M. Gell-Mann, P. Ramond, R. Slansky, in *Supergravity* (North-Holland, 1979).
Relevance. With Minkowski (1977) and Yanagida (1979), the seesaw's source papers: heavy Majorana partners make light neutrinos inevitable, with masses inversely proportional to the new

scale. The mechanism is derived by hand in Appendix H.4 and §F.2; the ledger's contribution is to fix the scale it left free (§9). First cited in §9.

M. Gardner, *The Ambidextrous Universe* (Basic Books, 1964).
Relevance. The Ozma problem, posed for the general reader: how do you communicate "left" to a distant civilization by physics alone? Before 1957 you cannot; after Wu you can — and after 1964 the instruction survives even the antimatter ambiguity. This paper promotes the riddle to a structural invariant: the handedness of the descent, P-P5-D, is the geometric object the Ozma broadcast transmits (§5). First cited in §3.

K. Friston, Nat. Rev. Neurosci. **11**, 127 (2010).
Relevance. The free-energy principle: perception and action as minimization of the mismatch between an internal generative model and the sensorium — the mainstream neuroscience statement closest to the monotone model-refinement this paper's real-bulk aside invokes. Cited in §37.5 as context for an analogy, with the aside's own register: suggestive parallel, no derivational weight. First cited in §37.5.

D. Gabor, J. IEE **93**, 429 (1946).
Relevance. The analytic signal: to phase-shift a real waveform meaningfully, complete it with its Hilbert transform — the engineer's quarter-period advance, standard in signal processing for eighty years. The clock's complex structure $J_A = \pm A(-A^2)^{-1/2}$ is mathematically this construction elevated to dynamics (§37.2): the state-space i was in the engineering literature all along, waiting to be read as geometry. First cited in §37.2.

H. Georgi, S. L. Glashow, Phys. Rev. Lett. **32**, 438 (1974).
Relevance. Minimal SU(5): the first grand unification, the charges explained, and proton decay promoted from heresy to prediction — the theory whose minimal form the water-Cherenkov generation falsified, teaching the field that unification is mortal. Both lessons are inherited here: the representation structure ($\bar{\mathbf{5}} \oplus \mathbf{10}$) survives in the bulk packaging, while the proton's stability is this ledger's opposite prediction (§124). First cited in §124.

M. Agostini et al. (GERDA), Phys. Rev. Lett. **125**, 252502 (2020).
Relevance. The background-free frontier of Ge-76: bare germanium diodes in liquid argon, an expected background below one count in the signal region, $T_{1/2} > 1.8 \times 10^{26}$ yr. The technique it perfected is the platform for LEGEND and the ton-scale era (§124) — the instruments of the one-sided test this paper's 1.72 meV registers. First cited in §124.

M. Goldhaber, L. Grodzins, A. W. Sunyar, Phys. Rev. **109**, 1015 (1958).
Relevance. The measurement of the neutrino's helicity with tabletop apparatus — resonant scattering of the Doppler-selected $^{152}\mathrm{Sm}^*$ photon transferring the invisible particle's handedness to a measurable circular polarization. Told in full in Appendix D §D.2 as the direct experimental face of maximal parity violation. First cited in §D.2.

O. W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002).

Relevance. CPT violation implies Lorentz violation: any interacting field theory that breaks CPT breaks Lorentz invariance too — the converse discipline that welds the two symmetries together. For this paper it makes T-P5-2's prohibition maximally exposed (§10, O-P5-26): a confirmed CPT violation would not merely kill a theorem, it would take the Lorentzian arena with it — and, per the stacking argument of Objection 28, the SME bounds discipline the texture twice over. First cited in §10.

C. Giunti, C. W. Kim, *Fundamentals of Neutrino Physics and Astrophysics* (Oxford University Press, 2007).
Relevance. The field's standard reference for oscillation physics in vacuum and matter and the field-theoretic foundations; Chapters 6–10 and 13 are the assigned reading of Appendices H.1–H.3, including the golden-channel expansion drilled in §H.3. First cited in Appendix H.

L. J. Hall, Y. Nomura, Phys. Rev. D **64**, 055003 (2001).
Relevance. With Kawamura (2000), the orbifold GUT made realistic: doublet–triplet splitting solved by boundary conditions, unification kept, proton decay tamed — the five-dimensional mechanism whose matrix of choices Part VI's projection fills in. Credited to the matrix, item by item, in §65: the machinery is theirs; the absence of alternatives at each entry is the descent's claim. First cited in §65.

J. A. Harvey, M. S. Turner, Phys. Rev. D **42**, 3344 (1990).
Relevance. The chemical-potential bookkeeping of the hot Standard Model plasma: impose Yukawa equilibrium, sphaleron equilibrium, and hypercharge neutrality, solve the linear system, and the conversion coefficient $B = \frac{28}{79}(B-L)$ falls out — the number every baryogenesis mechanism multiplies by. Derived as a drill in Appendix F.4 (problem F.4.2, with the two-doublet variant) and used at its single load-bearing site in §23. First cited in §23.

T. Hafting, M. Fyhn, S. Molden, M.-B. Moser, E. I. Moser, Nature **436**, 801 (2005).
Relevance. Grid cells: neurons whose firing fields tile the environment in a hexagonal lattice — the metric of the brain's world-centered frame, made visible in single recordings. With place cells they are the hardware of the reconstruction discussed in §37.5: the one known model-building machine represents space in allocentric coordinates, an echo the aside records as analogy only. First cited in §37.5.

S. W. Herb et al., Phys. Rev. Lett. **39**, 252 (1977).
Relevance. The Υ at Fermilab: a third-generation quark, four years after Kobayashi and Maskawa showed that three families are the minimum for a hard CP phase — the counting theorem honored by discovery. The bottom quark's arrival began the confirmation of the structure whose one phase this paper values (§7). First cited in §7.

Hyper-Kamiokande Collaboration, arXiv:2505.15019 (2025); design report arXiv:1805.04163.
Relevance. The third generation of the author's own instrument line: a quarter-megaton fiducial volume, a megawatt beam, 5σ CP-violation exclusion over most of the phase range in ten years, and the deepest proton-decay reach ever fielded. It owns the two headline confrontations of this

Part (§125): the quiet signature at 196° — which predicts its flagship discovery should *not* arrive — and the ledger's absolutely stable proton. First cited in §125.

C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).
Relevance. The basis-invariant measure of CP violation: one rephasing-invariant J carrying every CP-violating observable of the three-family Standard Model, extracted from the commutator of mass matrices. Clauses (i)–(iii) of T-P5-3 are this calculus, geometrized and credited — the paper's own claim begins strictly at the lattice valuation (§21); the invariant itself is derived from quartets in Appendix E.2. First cited in §7.

R. Jost, Helv. Phys. Acta **30**, 409 (1957).
Relevance. The axiomatic CPT theorem: analytic continuation to the complex Lorentz group turns the reflection into a theorem of Wightman field theory — rigor's own proof, with the axioms' own silence about what the operation is made of. It defines the scope this paper concedes and the anatomy it supplies (§58, Appendix D.4): Jost proves that Θ exists; T-P5-1/2 say what its factors are. First cited in §10.

JUNO Collaboration, first oscillation results (2025); sensitivity: Chin. Phys. C **46**, 123001 (2022).
Relevance. Twenty kilotons of scintillator at the solar-atmospheric crossing point: fifty-nine days sufficed for the world's best θ_{12} and Δm^2_{21}, and six years of the fast reactor wiggle will read the mass ordering at 3σ with no beam, no matter effect, and no δ dependence — the cleanest of the ordering channels this paper's normal-ordering chain must survive (§124, §125; the vacuum interferometry is problem H.1.2). First cited in §124.

K. Kajantie, M. Laine, K. Rummukainen, M. Shaposhnikov, Phys. Rev. Lett. **77**, 2887 (1996).
Relevance. The lattice determination that closed electroweak baryogenesis in the Standard Model: at the physical Higgs mass the transition is a smooth crossover — no bubbles, no departure from equilibrium, no asymmetry. Half of the SM's double failure (with the 10^{-20} of Gavela et al., 1994), inherited intact by the boundary and load-bearing in §84: the crossover is one of the closures that force the lepton route. First cited in §11.

KamLAND Collaboration (K. Eguchi et al.), Phys. Rev. Lett. **90**, 021802 (2003).
Relevance. Reactor antineutrino disappearance over two hundred kilometers: the solar oscillation solution confirmed from the laboratory side, with the beat frequency measured in a controlled flux. With SNO it ended the solar saga as physics ends its best puzzles — two independent methods, one matrix (§9). First cited in §9.

F. R. Klinkhamer, N. S. Manton, Phys. Rev. D **30**, 2212 (1984).
Relevance. The sphaleron: the static, unstable solution at the top of the barrier between electroweak vacua — the mountain pass named and solved, turning 't Hooft's exponentially suppressed tunneling into a thermally crossable ridge. It is the reprocessing engine of §23, taught with the winding picture in Appendix F.1. First cited in §23.

KOTO Collaboration, arXiv:2505.02568 (2025); KOTO-II proposal, J-PARC E107.

Relevance. The neutral rare-kaon frontier: $K_L \to \pi^0 \nu\bar{\nu}$ bounded below 2.2×10^{-9}, with the approved KOTO-II aiming at the 10^{-12} Standard-Model level. With NA62's charged mode it will close the cleanest loop tests in flavor physics (§122.1) — channels this paper's fixed inputs must match, per Objection 7's consistency clause. First cited in §122.1.

E. W. Kolb, M. S. Turner, *The Early Universe* (Addison-Wesley, 1990).
Relevance. The standard text of early-universe physics: widths against Hubble, freeze-out, relic abundances, entropy bookkeeping — the transport toolkit behind every equation of §23 and Part VIII, and the assigned shelf text of Appendix F. The four household questions this paper uses to demystify transport are their curriculum, compressed. First cited in §23.

S. Abe et al. (KamLAND-Zen), arXiv:2406.11438; Phys. Rev. Lett. (2025).
Relevance. The half-life frontier of $0\nu\beta\beta$: $T_{1/2}(^{136}\mathrm{Xe}) > 3.8 \times 10^{26}$ yr, translating through the nuclear-matrix-element band to $m_{\beta\beta} < 28$–122 meV — the first reach into the inverted-ordering band, and silence exactly where a 1.7 meV value demands silence (§124). It is also the anchor of the scaling arithmetic (problem H.5.2) that places the lattice point one to two orders beyond the ton scale. First cited in §124.

I. Kant, *Von dem ersten Grunde des Unterschiedes der Gegenden im Raume* (1768).
Relevance. Incongruent counterparts: the left and right hands as a probe of whether space is relational or absolute — the oldest text in this paper's philosophical lineage, and the first time handedness was recognized as metaphysically load-bearing. The question it opened is modernized twice here: by the Ozma problem, and by its resolution into the handedness invariant P-P5-D (§3). First cited in §3.

T. Kaluza, Sitzungsber. Preuss. Akad. Wiss. Berlin, 966 (1921).
Relevance. Charge as geometry, first proposed — and spatialized: the fifth dimension as a small place, with gauge symmetry as its isometry. The move gave every later extra-dimension program its radius, its tower, and eventually its landscape; AX-2 keeps the insight and refuses the spatialization — the compact direction is real but not a place, which is why there is no radius modulus to stabilize and no tower to hide (§29, §37.1). First cited in §29.

O. Klein, Z. Phys. **37**, 895 (1926).
Relevance. Charge quantization as winding: momentum around the compact circle comes in integers, and electric charge is that integer — the enduring half of the Kaluza–Klein insight, the half that survives de-spatialization intact. The charge circle of T-P5-A is this statement read as real geometry (§37.1): winding number is charge, orientation is sign, and conjugation is going around the other way. First cited in §29.

M. Aker et al. (KATRIN), Science **388** (2025).
Relevance. The direct kinematic frontier: tritium endpoint spectroscopy at $m_\beta < 0.45$ eV, model-independent and laboratory-owned. It brackets the neutrino mass scale from above while cosmology presses from the sum (§124); the derived triplet sits far below its reach, so the bound is consistency, not confrontation — the confrontations live with DESI and JUNO. First cited in §124.

Y. Kawamura, Prog. Theor. Phys. **105**, 999 (2001).
Relevance. The orbifold GUT: diag$(+,+,+,-,-)$ boundary conditions on an extra dimension, centralizer breaking of SU(5), doublet–triplet splitting by parity assignment — Part VI's mechanism, item for item. The projection matrix of §65 credits it in full; the descent's addition is that each entry of the matrix is forced rather than chosen, which converts a model-building toolkit into a falsifiable claim. First cited in §36.

B. S. Kay, Commun. Math. Phys. **62**, 55 (1978).
Relevance. With Ashtekar and Magnon (1975), the uniqueness of the positive-energy complex structure: the theorem pair that carries the functional-analytic weight of the clock construction — domains, closures, and the completion on which $(-A^2)^{-1/2}$ exists. T-P5-B stands on their care (§37); the paper's contribution is the constitutional reading of what their selection clause means. First cited in §36.

M. Kobayashi, T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
Relevance. One phase at three families: the counting theorem that predicted a third generation from CP violation alone, four years before the Υ — the boldest and most successful parameter-counting argument in the history of the subject. Its graph form is Eq. (8), its phase is the one the pentagon values, and its counting is drilled from scratch in problem E.1.1 (§6). First cited in §6.

KTeV Collaboration (A. Alavi-Harati et al.), Phys. Rev. Lett. **83**, 22 (1999).
Relevance. Direct CP violation established: $\mathrm{Re}(\varepsilon'/\varepsilon)$ measured decisively through the double-ratio technique, closing the thirty-five-year question the superweak hypothesis had kept open — CP violation lives in decay amplitudes, not only in mixing. It is the author's own decade of shifts and systematics, and the amplitude-level fact any account of CP must carry (§8); the measurement's design logic is derived in Appendix E.3. First cited in §8.

V. A. Kuzmin, V. A. Rubakov, M. E. Shaposhnikov, Phys. Lett. B **155**, 36 (1985).
Relevance. The realization that changed the field's target: above the electroweak crossover the hot plasma walks freely over the sphaleron pass, erasing $B{+}L$ and preserving only $B{-}L$ — so GUT-era asymmetries stored as $B{+}L$ die, and any surviving excess must be written in the sphaleron-proof currency. The 1985 lesson redirected baryogenesis to leptogenesis, and it is the reprocessing channel of Part VIII (§23; taught in Appendix F.1). First cited in §12.

L. D. Landau, Nucl. Phys. **3**, 127 (1957).
Relevance. CP as the repaired mirror: with parity fallen, Landau proposed that the true mirror composes spatial reflection with charge conjugation — and paired it with the two-component neutrino. For seven years the repair held, and its elegance is why 1964 was a shock; both the proposal and its fall are load-bearing history in §4 and §6. First cited in §4.

O. Laporte, Z. Phys. **23**, 135 (1924).
Relevance. The parity selection rule in atomic spectra: even and odd terms do not combine — parity as pre-1956 common sense, working silently in every spectroscopic table three decades before anyone thought to ask whether the weak interaction obeyed it. The quiet era it represents is where §4's story begins. First cited in §3.

T. D. Lee, C. N. Yang, Phys. Rev. **104**, 254 (1956).
Relevance. The audit that found the assumption: parity conservation, tested exquisitely in the strong and electromagnetic interactions, had never been tested in the weak — and the paper proposed the experiments that would do it. The template of this paper's own register — find the untested assumption, state the test, accept the verdict — descends from this audit (§4). First cited in §4.

T. D. Lee, C. N. Yang, Phys. Rev. **105**, 1671 (1957).
Relevance. The two-component neutrino (with Landau (1957) and Salam (1957)): maximal parity violation not as a small dirt effect but as structure — the neutrino exists in one handedness only. It is the first reading of the weak interaction as intrinsically chiral, the fact Part VI's one-gate descent exists to derive (§4). First cited in §4.

H. B. Lawson, M.-L. Michelsohn, *Spin Geometry* (Princeton, 1989).
Relevance. The reference treatment of spin geometry: Clifford algebras, spinor bundles, and the reality classification by signature — the eight-hour clock in its rigorous form. Lemma 24.1 is a line read off their tables ($B\bar{B} = -\mathbf{1}$ at $(t-s) \equiv 4$), and Appendix G.4 teaches the same material at drill depth (§24). First cited in §24.

LEGEND Collaboration, arXiv:2505.10440 (2025).
Relevance. LEGEND-200 first result, combined with the GERDA and MAJORANA heritage: $T_{1/2} > 1.9 \times 10^{26}$ yr in Ge-76, the background-free technique scaled up and running. The bridge between the present generation and the ton scale (§124) — the staircase on which this paper's registered null will be tested step by step. First cited in §124.

LEGEND Collaboration, arXiv:2107.11462 (2021), LEGEND-1000 preconceptual design.
Relevance. The preferred ton-scale Ge-76 experiment: a tonne of enriched germanium, discovery sensitivity 1.3×10^{28} yr, $m_{\beta\beta}$ reach 9–21 meV — decisive for the inverted ordering, and the sharpest instrument of the one-sided Majorana test of §125. For this paper its verdict is asymmetric by design: silence is consistency, a line is a kill. First cited in §125.

R. Aaij et al. (LHCb), Phys. Rev. Lett. **122**, 211803 (2019).
Relevance. Discovery of CP violation in charm: $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, the first CP asymmetry in up-type quarks — the broken mirror reaching a new quark sector after fifty-five years. Its interpretation strains SM amplitude estimates without requiring new phases; this paper's custody statement (one valued phase, hadronic envelope delegated) is Objection 6 (§122.2). First cited in §122.2.

R. Aaij et al. (LHCb), Nature **643** (2025), arXiv:2503.16954.
Relevance. First observation of CP violation in baryon decays (Λ_b^0, 5.2σ): the broken mirror reaches the matter category we are made of — baryons themselves now carry the asymmetry the mesons discovered. A completion of the experimental record of §122.2, and a reminder that the one-phase paradigm keeps passing tests in new sectors. First cited in §122.2.

G. Lüders, Dan. Mat. Fys. Medd. **28**, 5 (1954).

Relevance. With Pauli (1955), the first proofs of the CPT theorem: from Lorentz invariance, locality, and hermiticity, the product of the three reversals is a symmetry of any lawful field theory — the theorem that survived the decade in which its factors fell one by one. The Lagrangian road of the theorem is drilled in Appendix D.4; its anatomy is this paper's Part V (§10). First cited in §10.

P. Minkowski, Phys. Lett. B **67**, 421 (1977).
Relevance. The seesaw's first paper, a decade ahead of its adoption: heavy neutral leptons make light neutrinos light, with the scale of the partners setting the smallness. Independently found three more times (Gell-Mann, Ramond, and Slansky, 1979; Yanagida, 1979; Mohapatra and Senjanović, 1980), it is the mass mechanism of Part VIII's chain, derived by block diagonalization in Appendix H.4 (§9). First cited in §9.

H. Minkowski, Phys. Z. **10**, 104 (1909).
Relevance. Time as the first non-spatial geometric dimension: the union of space and time into one real geometry, with a direction that is genuinely geometric yet not a place one walks. It is the precedent that makes "a real dimension that is not a place" respectable physics rather than paradox — the exact rhetorical ancestor of the scale and phase directions of AX-2 (§29). First cited in §29.

S. R. Elliott, A. A. Hahn, M. K. Moe, Phys. Rev. Lett. **59**, 2020 (1987).
Relevance. First direct observation of two-neutrino double beta decay (Se-82, in a time-projection chamber): the allowed second-order weak process made measurable — the experimental foundation on which every $0\nu\beta\beta$ search stands, since the neutrinoless mode must be found against this irreducible cousin. The opening of the laboratory story told in §124. First cited in §124.

R. N. Mohapatra, J. C. Pati, Phys. Rev. D **11**, 566 (1975).
Relevance. With Pati and Salam (1974), left–right symmetry: parity restored at high scales through $SU(2)_R$ and a W_R, breaking spontaneously on the way down — the great structural alternative to intrinsic chirality. It is the alternative F-P5-1 is built to distinguish: the descent forbids the restoration sector at any scale, so a single W_R kills Part VI outright (§70). First cited in §70.

C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020).
Relevance. The neutron EDM bound at $|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$: the current terminus of the seventy-year program Purcell and Ramsey opened, and the source of the $|\bar{\theta}| \lesssim 10^{-10}$ constraint that defines the strong-CP problem. In this paper's two-fate architecture it also bounds the leakage floor from above — the EDM window between e^{-K} and 10^{-10} is a named kill band (§10). First cited in §10.

R. N. Mohapatra, G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).
Relevance. The seesaw's fourth independent finding, in the left–right context: the same light-mass mechanism arrived at through parity restoration, tying neutrino mass to the scale of $SU(2)_R$ breaking. Cited with its three siblings at the mechanism's source (§22); the ledger's use of the

mechanism runs through the dial-free door instead of the left–right sector F-P5-1 forbids. First cited in §22.

E. Cortina Gil et al. (NA62), JHEP **02** (2025) 191; update arXiv:2604.12649 (2026).
Relevance. Observation of $K^+ \to \pi^+ \nu\bar{\nu}$: the charged golden mode measured at BR $= (9.6^{+1.9}_{-1.8}) \times 10^{-11}$, on the Standard-Model value — the cleanest loop in flavor physics closing on prediction. For this paper the channel is a consistency check at fixed ledger inputs (Objection 7), and a standing spear against any framework needing new flavored phases (§122.1). First cited in §122.1.

G. Adhikari et al. (nEXO), J. Phys. G **49**, 015104 (2022).
Relevance. Five tonnes of enriched Xe-136 in a single monolithic detector: projected sensitivity 1.35×10^{28} yr, $m_{\beta\beta}$ reach 6–27 meV — the liquid-xenon pillar of the ton-scale triad (§125). One of the three instruments whose collective silence this paper's 1.72 meV predicts, and whose line would kill the door. First cited in §125.

E. Noether, Nachr. Ges. Wiss. Göttingen, 235 (1918).
Relevance. Invariance and conservation united: every continuous symmetry a conserved current — the theorem that taught physics what symmetry is worth, and gave the discrete inversions a prestige they had never earned by test. The unexamined confidence that broke in 1956 traces to the halo of this (correct, continuous) theorem (§3); the discrete lesson — symmetries are empirical — is this paper's opening move. First cited in §3.

NA48 Collaboration (J. R. Batley et al.), Phys. Lett. B **544**, 97 (2002).
Relevance. The concurrent establishment of direct CP violation at CERN: the European double-ratio program, agreeing with KTeV on $\mathrm{Re}(\varepsilon'/\varepsilon)$ — two beams, two continents, one amplitude-level fact. The two-experiment closure of the superweak era (§8), and half of the world value the flavor chapter derives the machinery for (Appendix E.3). First cited in §8.

K. Kodama et al. (DONUT), Phys. Lett. B **504**, 218 (2001).
Relevance. Direct observation of the tau neutrino: the third row of the lepton table completed by seeing ν_τ interactions in emulsion — the last Standard-Model fermion observed directly. It closes the roster whose three-fold structure carries the one surviving phase (§123). First cited in §123.

B. Abi et al. (DUNE), Eur. Phys. J. C **80**, 978 (2020).
Relevance. The far-detector technical design report: seventy kilotons of liquid argon a mile underground, ordering at 5σ, δ resolution of 10–20° depending on the value, and the complementary $p \to \bar{\nu} K^+$ channel — three of this Part's confrontation lines in one instrument (§125). Its matter-thick baseline is the consistency check that fake and genuine CP violation cannot both be faked (problem H.3.2). First cited in §125.

I. Esteban et al., NuFit 6.0 global analysis (2024).
Relevance. The global oscillation fit, NuFit 6.0: the likelihood over all oscillation data whose angles, splittings, and phase band this paper confronts — the lattice value sits 0.2σ inside its

normal-ordering δ_{PMNS} band (§75.4). The refresh rules of Part XI are written against exactly this fit's releases: pulls with dates, rerun each cycle. First cited in §9.

J. O'Keefe, L. Nadel, *The Hippocampus as a Cognitive Map* (Oxford, 1978).
Relevance. Place cells and the cognitive map: the founding demonstration that the mammalian brain builds an allocentric model of the world rather than storing egocentric snapshots — space represented as space, in dedicated hardware. With grid cells it anchors the aside of §37.5: model-building is what at least one physical system demonstrably does; the aside claims analogy, not mechanism. First cited in §37.5.

N. Agafonova et al. (OPERA), Phys. Rev. Lett. **120**, 211801 (2018).
Relevance. ν_τ appearance in a ν_μ beam at 6.1σ: oscillations closed in appearance rather than disappearance, with the third-row transition seen event by event in emulsion. It completes the appearance record of the oscillation matrix (§123) whose entries this paper's derived triplet feeds. First cited in §123.

K. Osterwalder, R. Schrader, Commun. Math. Phys. **31**, 83 (1973); **42**, 281 (1975).
Relevance. Reflection positivity and the Euclidean reconstruction: the rigorous content of "Wick rotation," equivalent by T-P5-B1 to the clock's polar decomposition — clause (3) of the quartet, and the license behind every Euclidean computation the boundary performs (§43). First cited in §43.

R. N. Mohapatra, P. B. Pal, *Massive Neutrinos in Physics and Astrophysics*, 3rd ed. (World Scientific, 2004).
Relevance. The seesaw's model space at book length: every variant, every texture, every phenomenological consequence of massive neutrinos, in the field's standard monograph. §H.4's block diagonalization is their Chapter 6 done slowly, and its Majorana-versus-Dirac bookkeeping follows their conventions; the model space they map is exactly the freedom the dial-free door closes. First cited in Appendix H.

D. N. Page, W. K. Wootters, Phys. Rev. D **27**, 2885 (1983).
Relevance. Relational quantum time: evolution read from entanglement with a clock subsystem, so that a globally stationary state contains internal change — the honest quantum-mechanical attempt to bring time inside the Hilbert space. Engaged in §107 as a cousin whose circularity (a clock must be chosen) the constitutional clock dissolves by fiat of the arena. First cited in §98.

J. C. Pati, A. Salam, Phys. Rev. D **10**, 275 (1974).
Relevance. With Mohapatra and Pati (1975), the left–right program's foundation: quark–lepton unification with parity restored at high energy — the alternative reading of the weak interaction's handedness in which chirality is environmental, not intrinsic. The distinction is precisely what F-P5-1 makes experimental: any W_R at any scale decides for restoration and against the descent (§70). First cited in §70.

W. Pauli, Phys. Rev. **58**, 716 (1940).

Relevance. The founding spin–statistics theorem: given Lorentz invariance, locality, and vacuum stability, half-integer spin must anticommute. Cited in §45 as the first child's sibling — the theorem whose analytic machinery T-P5-B1 geometrizes and whose GG-6 restatement is the quartet's second child. First cited in §45.

W. Pauli, in *Niels Bohr and the Development of Physics* (Pergamon, 1955).
Relevance. With Lüders (1954), the CPT theorem's first proofs — Pauli's contribution framing the reflection as the surviving discrete symmetry of any Lorentz-invariant local theory. The theorem the whole subject leans on, drilled by both roads (Lagrangian and axiomatic) in Appendix D.4, and given its anatomy in Part V (§10). First cited in §10.

Particle Data Group (S. Navas et al.), Phys. Rev. D **110**, 030001 (2024).
Relevance. The living compilation: world averages for $\delta_{\rm CKM}$, $J_{\rm CKM}$, the CPT identities, the $\bar{\theta}$ bounds, and the W_R limits — the numbers this paper's tables confront, in the edition dated at each use. The refresh discipline of §127 instructs the reader to recompute every pull against each new edition: the PDG is this paper's standing counterparty. First cited in §10.

R. D. Peccei, H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).
Relevance. The relaxation template: promote $\bar{\theta}$ to a field and let dynamics roll it to the CP-conserving minimum — the mechanism class of every axion solution since. The Kaxion executes the template without a PQ scalar, inheriting the roll from the compact direction (§77; Arisaka, 2026, C1-Kaxion), with the leakage floor as the falsifiable residue the original mechanism does not carry. First cited in §77.

E. M. Purcell, N. F. Ramsey, Phys. Rev. **78**, 807 (1950).
Relevance. The lone early doubt, six years before Lee and Yang: parity conservation is "a purely experimental matter," testable through the neutron EDM — the founding document of the EDM program and of the experimental attitude this paper's register institutionalizes. Seventy years and twelve orders of magnitude later, the program they opened is still the sharpest static probe of T violation (§3, §10). First cited in §3.

M. E. Peskin, D. V. Schroeder, *An Introduction to Quantum Field Theory* (Westview, 1995).
Relevance. The standard graduate QFT text: the propagator machinery, the loop toolbox, and the discrete-symmetry treatment with its bilinear table — the assigned check of Appendix D §D.2, and the source for the GIM loop analysis of Appendix E and the contour drills of Appendix G.2. First cited in §D.

A. Pilaftsis, Phys. Rev. D **56**, 5431 (1997).
Relevance. Resonant CP asymmetries from quasi-degenerate heavy neutrinos: when the mass splitting approaches the width, the self-energy contribution is resonantly enhanced and the Yukawa suppression cancels — the enhancement Part VIII's step 4 invokes, credited at source (§23). The Breit–Wigner structure is derived and drilled in Appendix F.3 (problem F.3.2), including the twelve-order off-peak cliff the chain must face. First cited in §23.

A. Pilaftsis, T. E. J. Underwood, Nucl. Phys. B **692**, 303 (2004).

Relevance. Resonant leptogenesis systematized at the TeV scale: the regime of this paper's entire chain, worked out in the literature that engineered the degeneracy by hand — the honest contrast being that the ledger's $O(1/K)$ splittings must ultimately do what their model-building chose to do. That confrontation is faced in public in §87, where C-P5-C's discharge criteria are stated. First cited in §12.

Planck Collaboration (N. Aghanim et al.), Astron. Astrophys. **641**, A6 (2020).
Relevance. The six-parameter fit of the microwave sky: $\Omega_b h^2$ to 0.3%, hence the photon-baryon ratio at the percent level — the CMB leg of the two-epoch η_B concordance and the target number (4) of Part VIII's chain. Also the source of the mass-sum pressure (with DESI) that Part XV registers as a new kill channel. First cited in §11.

J. Polchinski, *String Theory*, Vol. I (Cambridge, 1998).
Relevance. The standard text of string theory, cited here for one structural point: Chan–Paton factors and worldsheet orientation reversal realize charge conjugation as geometry — the rival program's own version of "conjugation is an orientation," conceded before the valuation contrast is drawn (§113). The kinship is real; the difference, as everywhere in Part X, is who prices the values. First cited in §113.1.

C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire, Science **124**, 103 (1956).
Relevance. First detection of the (anti)neutrino: reactor antineutrinos captured on protons, the particle Pauli apologized for made real after twenty-six years — the founding of experimental neutrino physics, and the start of the lineage (§123) that runs through Homestake and Super-Kamiokande to the instruments that will test this paper. First cited in §123.

M.-O. Renou et al., Nature **600**, 625 (2021).
Relevance. The real-Hilbert-space exclusion: network Bell experiments whose correlations no real-amplitude quantum theory can reproduce — complex quantum mechanics confirmed as such, experimentally. For this paper the result is load-bearing in both directions: it is the configuration the shared J of T-P4-4/T-P5-C1 supplies (§37), and it is the boundary fact that disciplines the real-bulk custody (Objection 80). First cited in §36.

T. S. Roussy et al., Science **381**, 46 (2023).
Relevance. The electron EDM below $4.1 \times 10^{-30}\, e\,\mathrm{cm}$, from trapped molecular ions: the deepest static T-odd null in any system, and the template for the coming decade's ion-trap program. In this paper's ledger it disciplines every proposed CP phase and pins the upper edge of the strong-CP kill window (§124). First cited in §122.2.

H. Rauch, A. Zeilinger, G. Badurek, A. Wilfing, W. Bauspiess, U. Bonse, Phys. Lett. A **54**, 425 (1975).
Relevance. The neutron-interferometric observation that a 2π spin rotation reverses the sign of the amplitude and 4π restores it — the measured floor under the projective phases of Appendix D §D.1 and the laboratory face of the frame-path memory of §45. First cited in §D.1.

J. J. Sakurai, J. Napolitano, *Modern Quantum Mechanics*, 2nd ed. (Cambridge University Press, 2017).

Relevance. The standard first-year graduate quantum text: its Chapter 4 treatment of symmetry — parity, lattice translation, time reversal, Kramers — is the floor on which §D.1 builds, and the assigned parallel reading of Appendix D. The antiunitarity discussion this paper geometrizes is taught there in its standard form. First cited in §D.

A. D. Sakharov, JETP Lett. **5**, 24 (1967).

Relevance. The three conditions, stated in four pages a year after the CMB's discovery: baryon violation, C and CP violation, departure from equilibrium — the scoreboard of every baryogenesis mechanism since, and of Part VIII, where each condition is mapped to a constitutional pillar (§83). Each condition is derived as a theorem in Appendix F.1; his companion twin-universe speculation is engaged in Part XV. First cited in §6.

A. Salam, Nuovo Cim. **5**, 299 (1957).

Relevance. With Lee and Yang (1957) and Landau (1957), the two-component neutrino: maximal parity violation as structure rather than contamination — Salam's version arriving through the gauge-theoretic instinct that would later build the electroweak theory. The chiral neutrino the trio proposed is the boundary fact Part VI's one-gate descent derives (§4). First cited in §4.

S. Al Kharusi et al. (SNEWS 2.0), New J. Phys. **23**, 031201 (2021).

Relevance. The supernova early-warning network, version 2.0: the world's neutrino detectors wired into one alarm, so the next galactic collapse is caught from the first second. It is the standing watch for the sector-wide calibration event (§125) — the event whose burst, per Objection 15's response, would read the mass ordering upstream of every laboratory program. First cited in §125.

SNO Collaboration (Q. R. Ahmad et al.), Phys. Rev. Lett. **89**, 011301 (2002).

Relevance. The solar case closed: heavy water separating charged-current from neutral-current rates, showing the total solar flux intact while the electron flavor is depleted — the neutrinos change flavor rather than vanish. With Super-Kamiokande it earned the oscillation Nobel and opened the era in which the mixing matrix became precision physics (§9). First cited in §9.

H. Sonoda, Nucl. Phys. B **326**, 135 (1989).

Relevance. Hermiticity and CPT of string amplitudes: the worldsheet reflection transferring to the spacetime S-matrix — string theory's CPT inheritance made explicit at the amplitude level. Cited in §113 as the rival program's own proof that the unbroken theorem survives its framework; the contrast, as always, is anatomy and valuation, not validity. First cited in §113.1.

E. C. G. Stückelberg, Helv. Phys. Acta **14**, 588 (1941).

Relevance. The reinterpretation, first: antiparticles as reversed-flow solutions, eight years before Feynman's contours gave the same reading its computational form — the pairing that carries both names. What neither author could say is why that assignment and no other is consistent; that provenance is exactly what T-P5-C supplies (§111.3), with the contour version derived in Appendix G.2. First cited in §111.3.

A. Strominger, E. Witten, Commun. Math. Phys. **101**, 341 (1985).
Relevance. CP in Calabi–Yau vacua: the opening of the line that made CP a geometric, spontaneously broken symmetry of string theory — the intellectual ancestry of every geometric-CP position, this paper's included. Credited at the head of the lineage in §113 before the valuation contrast: geometry breaking CP is their result; geometry pricing the breakage is the claim under test here. First cited in §79.

M. S. Sozzi, *Discrete Symmetries and CP Violation: From Experiment to Theory* (Oxford University Press, 2008).
Relevance. The operation-centric companion to Bigi and Sanda (2009): C, P, and T defined, measured, and tested system by system, with the experimental techniques given their full weight — the closest book-length analogue of this paper's Parts V and X. Shelf text of Appendix H. First cited in Appendix H.

R. F. Streater, A. S. Wightman, *PCT, Spin and Statistics, and All That* (Benjamin, 1964).
Relevance. The axiomatic frame: Wightman fields, the spin-statistics and PCT theorems from first principles — the rigorous scaffolding whose per-field phase conventions T-P5-1 replaces with anatomy (§56, Appendix D.4). This paper's concessions to the axiomatic program — interacting reach, above all — are stated wherever its theorems are engaged. First cited in §10.

A. S. Eddington, *The Nature of the Physical World* (Cambridge, 1928).
Relevance. "Time's arrow" coined: the one physical asymmetry pointing along time located in entropy increase, with full clarity that the microscopic laws know nothing of it. The phrase and the problem it names are the subject of §103; the OGGEP reading gives his arrow the law-level home he correctly said the dynamics of his day could not provide. First cited in §98.

E. C. G. Sudarshan, R. E. Marshak, Phys. Rev. **109**, 1860 (1958).
Relevance. $V-A$, independently and arguably first: the chiral structure of the weak current identified from the data's contradictions — the companion discovery to Feynman and Gell-Mann (1958), credited jointly as the codification of maximal parity violation (§4). The structure both papers wrote down is Part VI's explanandum. First cited in §4.

Super-Kamiokande Collaboration (Y. Fukuda et al.), Phys. Rev. Lett. **81**, 1562 (1998).
Relevance. Atmospheric neutrino oscillations: the zenith-angle deficit that established neutrino mass and mixing — the third arena opened decisively, by the lineage of water-Cherenkov detectors the author helped found. The 1998 discovery is both history (§9) and biography (§145) in this paper: the instrument line runs from Kamiokande through Super-K to the Hyper-K that will test the lattice point. First cited in §9.

A. Takenaka et al. (Super-Kamiokande), Phys. Rev. D **102**, 112011 (2020); η channels: Phys. Rev. D **110**, 112011 (2024); $\pi^0\pi^0$: arXiv:2604.10975 (2026).
Relevance. The proton-decay ledger: $\tau/B(p \to e^+\pi^0) > 2.4 \times 10^{34}$ yr and channel-by-channel silence across every mode — the standing annual audit of the exact $\mathrm{U}(1)_B$ claim. Every year of silence is a passed test of the ledger's most absolute prediction; a single candidate event surviving scrutiny would kill Part VIII's logic outright (§124). First cited in §124.

K. Abe et al. (Super-Kamiokande), Phys. Rev. D **103**, 012008 (2021).
Relevance. The bound-neutron $n\bar{n}$ oscillation search: free oscillation time above 4.7×10^8 s — the $\Delta B = 2$ channel closed to current sensitivity. It disciplines the same ledger from a second direction: baryon number is not merely conserved in decays but protected against coherent oscillation (§124). First cited in §124.

T2K Collaboration (K. Abe et al.), Nature **580**, 339 (2020).
Relevance. The first constraint disfavoring leptonic CP conservation: T2K's appearance asymmetry excluding $\delta = 0, \pi$ at 2σ-class — the early shadow of the measurement that will adjudicate (57). The instrument sits at its oscillation maximum by design (the arithmetic is problem H.1.1), and its successor owns the quiet signature's verdict (§9). First cited in §9.

G. 't Hooft, in *Recent Developments in Gauge Theories* (Plenum, 1980).
Relevance. Naturalness and chiral protection: fermion masses are protected by chiral symmetry, so light fermions are natural where light scalars are not — QFT's partial answer to "why chiral," credited beside the basin/gate architecture it parallels (§63). The survival argument explains why chirality persists; Part VI's claim is about why it was there to survive. First cited in §63.

G. 't Hooft, Phys. Rev. Lett. **37**, 8 (1976).
Relevance. Baryon-plus-lepton number anomalously violated in the Standard Model itself: the vacuum's winding structure ties fermion number to topology, at a rate absurdly small cold and — after the sphaleron insight — unsuppressed hot. The foundation of the reprocessing channel of §23, and the reason the matter excess must be written in $B-L$ (Appendix F.1). First cited in §23.

T2K and NOνA Collaborations, Nature **646**, 818 (2025).
Relevance. The first joint long-baseline fit: correlated systematics unified across the two beams, $|\Delta m^2_{32}|$ below two percent, CP conservation excluded at 3σ under the inverted ordering — the freshest constraint the lattice value faces, and a rehearsal of the joint-fit methodology the Hyper-K/DUNE era will need (§124). The refresh rules print its pulls with dates. First cited in §124.

C. Vafa, E. Witten, Phys. Rev. Lett. **53**, 535 (1984).
Relevance. Two theorems in one citation: no spontaneous parity breaking in vector-like theories, and the vacuum energy minimized at $\bar{\theta}_{\text{eff}} = 0$ — QCD's parity protection and the certified minimum the Kaxion rolls toward. Both are load-bearing: the first defines the boundary between QCD's safety and the chiral electroweak sector's fall (§63); the second certifies the target of the relaxation (§77; Objection 30's exchange). First cited in §4.

S. Weinberg, Phys. Rev. Lett. **42**, 850 (1979).
Relevance. With Yoshimura (1978), GUT baryogenesis: the matter excess from heavy boson decays at the unification scale — the first complete implementations of Sakharov's program, and the route the sphaleron era later erased and the exact $\mathrm{U}(1)_B$ ledger closes twice (§84). The toolbox entry whose fate taught the field that mechanisms must survive reprocessing. First cited in §84.

H. Weyl, Sitzungsber. Preuss. Akad. Wiss. Berlin, 465 (1918).

Relevance. Local scale as geometry: the first gauge theory, wrong about electromagnetism and right about everything methodological — symmetry made local, geometry made dynamical. It is the ur-precedent of the GG-6 scale dimension (§29): the descent's radial direction is Weyl's instinct, executed on the dimension he originally intended. First cited in §29.

H. Weyl, Z. Phys. **56**, 330 (1929).

Relevance. Local phase as geometry: the corrected gauge principle, now on the quantum phase — the birth of gauge theory as physics uses it, and the second Weyl insight AX-2 elevates from principle to dimension. The compact phase circle of T-P5-A is this paper's reading of what the 1929 symmetry was always about (§29). First cited in §29.

E. P. Wigner, Z. Phys. **43**, 624 (1927).

Relevance. Parity as a quantum number: the mirror promoted from geometric curiosity to formal law of atomic physics, with selection rules attached — the moment reflection entered the bookkeeping of quantum mechanics. Three decades of silent service followed, and then the fall this paper's history opens with (§3). First cited in §3.

L. Wolfenstein, Phys. Rev. Lett. **13**, 562 (1964).

Relevance. The superweak hypothesis: all CP violation confined to a new $\Delta S = 2$ interaction, so $\varepsilon' = 0$ identically — the sharp, falsifiable alternative that gave the ε'/ε program its purpose and its kill criterion. Thirty-five years later the double-ratio experiments delivered the verdict (§6); the episode is this paper's model of a clean two-framework discrimination (problem E.3.3). First cited in §6.

L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983).

Relevance. The hierarchical expansion of the CKM matrix in powers of $\lambda = \sin\theta_C$, derived as problem E.1.2 of Appendix E; the display of the $1 : \lambda : \lambda^2 : \lambda^3$ pattern that Step 2 lists among the quantities the Standard Model cannot price. First cited in §E.1.

S. Weinberg, *The Quantum Theory of Fields*, Vol. I, ch. 5 (Cambridge, 1995).

Relevance. The causality argument — antiparticles forced by SR + QM + microcausality + bounded energy — stated in this paper as Theorem 111.1: the orthodoxy's deepest Depth-2 answer, whose two undischarged axioms the handshake discharges (§111.3, Appendix G.3). First cited in §19.

K. Zuber, *Neutrino Physics*, 3rd ed. (CRC Press, 2020).

Relevance. The experimentalist's companion volume: sources, detectors, backgrounds, and the double-beta chapter (Ch. 7) whose nuclear-matrix-element discussion §H.4 drills; the natural first book for the incoming collaboration student Appendix H addresses. First cited in Appendix H.

E. P. Wigner, *Gruppentheorie und ihre Anwendung* (Vieweg, 1931).

Relevance. The (anti)unitary fork: every quantum symmetry is implemented unitarily or antiunitarily — the theorem that gives time reversal its strange character by assignment. T-P5-1 converts the fork from case analysis to computation: which operations get which character is read off the orientation content of the texture (§19, Appendix D.1). First cited in §19.

C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson, Phys. Rev. **105**, 1413 (1957).

Relevance. The fall of parity: polarized cobalt-60, an asymmetry of order unity, and a symmetry of nature gone in one cryostat — the experiment this paper's history opens with, and the template of every orientation measurement since. Appendix D.3 computes it end to end, and Part VI's worked example re-reads it as the first direct observation of the descent's handedness. First cited in §4.

J. M. E. McTaggart, Mind **17**, 457 (1908).

Relevance. The unreality of time: the tensed, flowing A-series is contradictory; only the ordered B-series survives — analytic philosophy's sharpest result on time, and an uncanny anticipation of the block universe. Part IX agrees with the theorem and relocates the flow: what McTaggart proved cannot belong to time's order belongs instead to the dictionary's one-way writing (§109). First cited in §98.

T. Yanagida, in *Proc. Workshop on Unified Theory and Baryon Number in the Universe* (KEK, 1979).

Relevance. With Gell-Mann, Ramond, and Slansky (1979) and Minkowski (1977), the seesaw's source papers — Yanagida's version presented at the 1979 workshop that gave the mechanism its community. The mechanism is taught by hand in Appendix H.4; the ledger fixes the one number all the source papers left free, the scale (§9). First cited in §9.

M. Yoshimura, Phys. Rev. Lett. **41**, 281 (1978).

Relevance. With Weinberg (1979), the first concrete baryogenesis calculations: the observed asymmetry from GUT-scale boson decays — Sakharov's program made quantitative for the first time. The route's later erasure by sphaleron reprocessing (§84) is one of the field's formative lessons, inherited here as the reason the excess must be minted in $B-L$.