

Time travel: a critical review

Permission, construction, and the acquisition problem

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Abstract

Backward time travel occupies an unusual position in physics: it is permitted by general relativity, not excluded by quantum mechanics, and yet no known construction is remotely buildable. This review argues that the standard summary—“forbidden by chronology protection”—is wrong in both directions. The no-go theorems are real but narrow: the quantum inequalities are proved for free, minimally coupled fields on controlled backgrounds; the Kay–Radzikowski–Wald theorem covers only compactly generated horizons and proves ill-definedness, not divergence; and the constructive counterexamples evade the hypotheses rather than the conclusions. At the same time, the engineering and acquisition barriers are stronger than usually stated. The best constructive model, the Ori (2005) compact vacuum core completed by a dust envelope, is an explicit, asymptotically flat vacuum-plus-dust *initial data set* whose computed test-field stress is quantum-benign at its local eikonal chronology horizon—many tens of orders below the unit-curvature stress at a metre-scale machine—conditional on the horizon being non-compactly generated. But its defining structure, a boost-holonomy identification, is not manufactured by any known classical route: the Carroll–Farhi–Guth–Olum, Geroch, and topological-censorship arguments block or constrain those routes, although the $3 + 1$ statement is an argument with a proof gap, not a theorem. The empirical channels are null or limited: the gravitational-wave relic survey gives a calibrated count limit at its operational threshold, not an idealized density bound, and the Gaia census is consistent with an astrophysical background under a composition-matched null, with no detection and no exclusion. The quantitative companion results cited here are preliminary and in preparation, not published. The conclusion is conditional and sharp: physics does not close the door; engineering and topology acquisition do. The open problems are four-dimensional backreaction, the state-selection principle, gauge-complete nonlinear stability, a $3 + 1$ acquisition theorem, and a survey with a measured efficiency.

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1 Introduction: two errors and one question

The question is old, the evidence is uneven, and the rhetoric is bad. On one side stands the textbook summary: Hawking’s chronology protection conjecture forbids time machines. On the other stands the enthusiast summary: the no-go theorems have cracks, so time travel is back on the table. Both summaries omit the hypotheses, and the hypotheses are the physics. This review is an audit of scope. Its thesis is a three-part conditional:

Physics does not forbid backward time travel; engineering and topology acquisition do. The strongest constructive model—the Ori (2005) compact vacuum core, completed by the hybrid dust-envelope construction—is quantum-benign at its computed chronology horizon but rests on a boost-holonomy identification whose known classical manufacture routes are blocked or constrained, with a $3 + 1$ proof gap. The observational channels are null or limited. The no-go theorems have verified cracks, but their scope is routinely overstated in both directions: they are narrower than the “time travel is forbidden” folklore, and weaker than the “the cracks reopen the door” counter-folklore.

The answer is therefore neither yes nor no. It is a separation of three questions that are usually conflated:

1. **Permission.** Is there a theorem that forbids closed timelike curves (CTCs) for all physically reasonable matter? No. Every rigorous result forbids a class of CTC-forming processes, and the class is the content.
2. **Construction.** Do explicit initial data exist that develop CTCs from vacuum and dust and are not obviously excluded by quantum effects? Yes, in a precise but limited sense: the Ori 2005 core and its hybrid completion are explicit, regular, asymptotically flat, and their computed test-field stress is negligible at the horizon. But initial data are not a machine, and “not obviously excluded” is not “stable under backreaction”.
3. **Acquisition.** Can the defining structure—the boost-holonomy identification—be created, inherited, nucleated, or reproduced? The classical theorems block or constrain the known creation routes from trivial data; the other routes are either cosmologically rare, exponentially suppressed, or require an existing machine. This is the real frontier.

The one-sentence spine of the review is: *the door is open; the corridor is built; the key is missing; and no one has seen the key.* Figure 1 is the same map.

1.1 Forward is measured; backward is not

The asymmetry is worth stating at the outset because it disciplines the language. Forward time dilation is an engineering fact. The Global Positioning System corrects roughly $38 \mu\text{s}$ per day, a combination of gravitational blueshift and orbital speed. Astronauts on the International Space Station accumulate a few milliseconds over a six-month mission; cosmonaut Sergei Avdeyev accumulated about 20 ms over his career. Muons in storage rings reach $\gamma \approx 29.3$, and optical clocks now resolve height differences at the millimetre scale. These are not interpretations; they are calibrations.

Backward time travel has no observation. The review will not pretend otherwise. What it has is a mathematical industry of exact solutions and a semiclassical industry of horizon stress computations, neither of which has produced a manufactured object. The empirical program is a search for relics, and that search is young.

1.2 The historical walls and their reframing

Three walls are usually named: exotic matter, chronology protection, and observation. Each is real. Each is also stated too crudely.

The *exotic-matter wall* is real, but it is not a single number. The laboratory Casimir energy at a 10 nm separation is about $4.3 \times 10^4 \text{ J/m}^3$ in magnitude. The wall and throat densities required

by macroscopic shortcut geometries are many tens of orders beyond any laboratory or solar-system resource. The often-quoted “forty orders” depends on the construction and on whether one compares density, total energy, or the volume–duration product. The robust statement, defended in §3, is that no known construction is within many tens of orders, and that the discount mechanisms proposed in the literature converge on the Planck scale or on beyond-Standard-Model infrastructure rather than on a laboratory source.

The *chronology-protection wall* is real, but the theorem usually invoked is narrower than its reputation. The Kay–Radzikowski–Wald (KRW) theorem [26] is about compactly generated Cauchy horizons, free linear fields, and a fixed background; Visser’s critical review remains the best guide to the interpretive forks [12]. It proves that the two-point function fails to be Hadamard at horizon points; it does not prove that the stress diverges, and it says nothing about non-compactly generated horizons. The Ori core is precisely the case where the horizon is believed—but not proven—to be non-compactly generated.

The *observational wall* is real, but it is currently a null without a calibrated efficiency. The gravitational-wave (GW) survey reported in the companion papers [88] counts candidate boost-holonomy pairs in the catalog volume; it does not measure a local relic density. The Gaia census [89] is consistent with an astrophysical background; it neither detects nor excludes relics.

1.3 The review’s new inputs

This review synthesizes five bodies of work, each reported in a companion paper. They are cited for the computations; the review does not re-derive them. Those papers are in preparation: every number attributed to them below is preliminary and is not presented as a published result.

- **P1: the full image-series tensor on the Ori core.** A 4×4 Jacobi transport, the frame-invariant eigenvalue structure $(-\frac{3}{2}, +\frac{1}{2}, +\frac{1}{2}, +\frac{1}{2})\mathcal{E}$, the Misner law $\mathcal{E} \propto \epsilon^{-2}$, and a chronology-horizon locus correction: $T = f$ is the timelike CTC boundary, not the horizon [85].
- **P2: the hybrid envelope.** An explicit umbilical slice family, certified constraint gates, a hand-off to Ori’s dust layers, and a mass law that separates density from total mass [86].
- **P3: the Xavier quotient.** A train-versus-pump classification, an on-generator discriminator, an off-generator stress computation, and a stability analysis in the analyzed sectors [87].
- **P4/P5: the relic surveys.** A sky-permutation-calibrated GW count limit and a composition-matched-calibrated full-sky Gaia radial-velocity pair census [88, 89].
- **P10/P12/P13: the laboratory and engineering ledgers.** A BEC design study with documented blockers, an acquisition audit, and a resource ledger [90, 91, 92].

Table 1 is the evidence ledger in miniature: every quantitative claim in the review traces to one of these rows or to a citation in the surrounding text.

1.4 Roadmap and status vocabulary

Section 2 fixes definitions and audits the classical no-go theorems. Section 3 audits the quantum inequalities. Section 4 audits chronology protection. Sections 5 and 6 present the constructive models. Section 7 treats quantum stress and state choice. Section 8 separates classical, semiclassical, and backreaction stability. Section 9 presents the observational constraints. Section 10 is the

Table 1: The evidence ledger: review-level numbers and their provenance. Companion papers are in preparation and are cited for computations, not as independent verification.

Source	Key numbers used in this review	Status
P1	Eigenvalues $(-\frac{3}{2}, +\frac{1}{2}, +\frac{1}{2}, +\frac{1}{2})\mathcal{E}$; $\mathcal{E} \propto \epsilon^{-2}$; $\epsilon_{\mathcal{H}} = a^2 \rho^2$; 5.3×10^{-18} and 1.78×10^{-13} J/m ³ ; nine-point ρ scan	Computed, test-field
P2	$H_1 = +0.765$, WEC = +0.728; 21/21 at $\pm 30\%$; retuned full-layer gates, $WEC(1 \text{ mm}) \geq +4.55 \times 10^{-6}$, $a_W^* = 0.0346$; $M_{\text{layer}} = 3.30 k_0 L_z$	Certified on gatefast band; full layer exhibited; $O(a)$ conjecture
P3	Train ratio 1.0000000000; pump $e^{-L/2\tau} = 0.9512294245$; on-generator rates +0.05000000, +0.15000000; off- $\mathcal{N}$ finite at $x_* = 0.1$	Computed; full stability open
P4	391 events, 282 with masses; 32,434 vs 32,806; corrected 30,343 vs 30,349; $\mu < 274$ (205); family $p = 0.539$; Stage-3 82/120, family 64/82, $p = 1.000$	Measured null; equality cut labelled; selection model
P5	33,812,183 RVs; 16,358 pairs; 939 permissive/135 strict; 171 of 1,177 above 3σ ; 173 vs 173.4, $p = 0.737$; 24/135, $p = 0.969$; 0 epoch pairs	Measured census; calibrated null (no excess)
P10	$V = \lambda c_s / (2\pi)$; S_Λ ; $2\pi R_0 = 314 \mu\text{m}$ image, $T \lesssim 0.08$ nK; $157 \mu\text{m}$ antipodal, $T \lesssim 0.16$ nK; B1–B9	Design study
P12	CFG/CFG0, Geroch, DJHT/Cutler, FSW, Minguzzi; routes A/B/C	Theorem/cited; routes scenario
P13	Canonical 4.0×10^{25} kg/m ³ , full envelope $2.9\text{--}5.4 \times 10^{27}$ kg ($1.5\text{--}2.8 M_J$); deep 778 kg/m ³ , $1.3\text{--}2.4 \times 10^{16}$ kg $\cdot L_z$; a -floor 2×10^{-17}	Exact/certified/extrapolated

conceptual pivot: acquisition, not assembly. Section 11 treats analogue experiments. Section 12 prices the machine. Section 13 lists open problems and falsifiers. Section 14 concludes.

Throughout, claims are tagged with a status vocabulary. The vocabulary is itself part of the review’s contribution, because the most common failure mode in this literature is to report a numerical check, a scaling law, and a theorem in the same voice. Table 2 fixes the vocabulary.

2 The general-relativistic framework and the classical no-go theorems

2.1 Definitions

A spacetime (M, g) contains a closed timelike curve if there is a smooth future-directed timelike curve $\gamma : S^1 \rightarrow M$. The chronology-violating region V is the set of points through which such a curve passes. Its boundary ∂V is the chronology boundary. A chronology horizon is a null hypersurface that separates a region admitting a global time function from one that does not; the standard example is the Cauchy horizon of Misner space [2]. Global hyperbolicity, the existence of a Cauchy surface, is equivalent to strong causality plus the requirement that $J^+(p) \cap J^-(q)$ be compact; a CTC is a failure of global hyperbolicity, but not every failure is a CTC.

Two distinctions do most of the work in this review. The first is *compactly generated* versus *non-compactly generated*. A Cauchy horizon is compactly generated if its generators, followed into the past, remain in a compact set. Misner space and Taub–NUT are compactly generated; a horizon whose generators escape to a non-compact matter region is not. The consistency problem—the grandfather paradox—is not this review’s subject. The standard results are that quantum

Table 2: Status vocabulary used throughout the review. The tag is part of the claim; removing it changes the claim.

Status	Meaning	Example
Theorem	Proved under stated hypotheses; the hypotheses are part of the claim.	KRW for compactly generated horizons; CFG in $2 + 1$ dimensions.
Exact	Closed-form result, independently checkable.	The Ori 2005 metric; the umbilical family at $a = 0$.
Certified	Numerical result with interval or tolerance bounds on a stated grid.	The C4 gate margins; the a_W^* interval certificate.
Exhibited	A construction shown numerically or by explicit profiles, without a general existence proof.	The C4 envelope; the $O(a)$ uniformity.
Extrapolated	A scaling law verified at accessible rungs and extended beyond them.	The deep-rung k_0 mass law.
Conjectured	A stated open claim with evidence but no proof.	Open-band $O(a)$ uniformity; full Xavier stability.
Cited Scenario	Relied on from the literature, not re-proved. A route consistent with known physics but with no demonstrated mechanism.	Ori 2007 outer layers; KRW. Primordial foam inheritance; quantum nucleation.

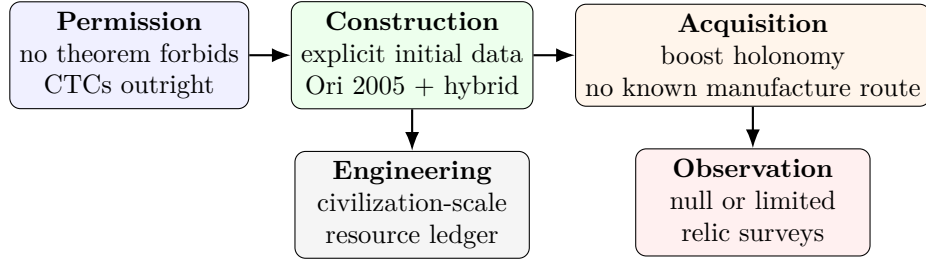


Figure 1: The review’s spine. Permission is a statement about theorems; construction is a statement about initial data; acquisition is a statement about topology. The arrows are logical dependencies, not a recipe.

mechanics generalizes consistently to nonchronal spacetimes [39], that postselected and multiple-history formulations avoid contradiction [67, 66], and that the question is one of state space, not of logic. One paragraph is enough; the physics is elsewhere.

The second is *chronology boundary* versus *chronology horizon*. In a quotient with a boost, the surface where the identified circles become null is not necessarily the null horizon that limits the domain of the covering space’s time function. The Ori core makes this distinction quantitative: the surface $T = f$ is the timelike boundary of the CTC region, and the local eikonal horizon lies below it by $\delta\mathcal{H} = a^2\rho^2 + O(a^3)$ [85]. Much confusion in the literature comes from calling both surfaces “the horizon”.

2.2 Light-cone tipping

The classical examples are variations on one mechanism: a metric coefficient changes sign, so a circle that was spacelike becomes timelike. In Gödel’s universe the rotation tips the light cones; in Kerr’s interior the ring singularity and the inner horizon do the same; in Tipler’s cylinder and van Stockum’s rotating dust the azimuthal circles close; in Gott’s pair of cosmic strings [4] the

Table 3: The classical no-go theorems and what they actually forbid. The “does not forbid” column is not a loophole list; it is the scope of the theorem.

Result	Hypotheses	What it forbids	What it does not forbid
Tipler (1976/77) [13]	Asymptotically flat, weak energy condition, non-compact Cauchy surface	CTCs without a singularity	Non-asymptotically-flat or energy-condition-violating constructions
Hawking (1992) [1]	Compactly generated chronology horizon; null energy condition along generators	A smooth compactly generated horizon without NEC violation	Non-compactly generated horizons; state choice; the backreacted endpoint
Carroll–Farhi–Guth (1992) [5]	Compactly supported data on $\mathbb{R}^3$; open universe	A CTC region from scratch; Gott pairs with timelike total momentum	Closed universes; non-Gott data; $3 + 1$ dimensions beyond the $2 + 1$ proof
Carroll–Farhi–Guth–Olum (1994) [6]	Edgeless non-compact slice; timelike total momentum	Evolution into a boost-holonomy configuration	Closed universes (pairs, not CTCs); the $3 + 1$ gap for the hybrid data class
Geroch (1967) [7]	Topology change between Cauchy surfaces	Topology change without CTCs, a singularity, or NEC violation	Quantum-gravity pricing; changes inside an existing CTC region
Friedman–Schleich–Witt (1993) [8]	NEC; simply connected asymptotic region	A traversable wormhole or causal access to an identification	NEC-violating throats; the existence of the identification as initial data
Deser–Jackiw–’t Hooft (1992) [9]; Cutler (1992) [10]	Two-defect Gott assembly; singular constraints	A smooth Cauchy surface generating the pair	A pre-existing pair; non-Gott holonomy
Minguzzi (2015) [11]	NEC; sourced spacetime	Compact Cauchy horizons in a non-empty sourced spacetime	Horizon-first tricks that violate the NEC; quantum-gravity escape

identification is a boost; in Morris–Thorne–Yurtsever wormholes [3] the conversion is achieved by moving one mouth relative to the other. The examples differ in matter content, topology, and the character of the horizon, and those differences are exactly what the no-go theorems care about.

2.3 The theorem table

Table 3 is the review’s central scope correction. Every row should be read with its hypotheses attached. The table is deliberately conservative: where the literature proves a $2 + 1$ -dimensional statement and the $3 + 1$ statement is folklore, the table says so.

2.4 What the table establishes

Four lessons follow.

First, *no theorem forbids CTCs outright*. Every result forbids a class of processes, and the class is the content. A reader who says “general relativity forbids time travel” has confused a collection of conditional theorems with a universal one.

Second, *the CFG/CFGO obstruction is the central acquisition obstruction*. Carroll, Farhi, and Guth showed that a pair of cosmic strings cannot be assembled into a Gott machine from compactly supported, asymptotically flat data with timelike total momentum; Carroll, Farhi, Guth, and Olum extended the energy-momentum analysis. The hybrid data class—regular, asymptotically flat, dust at rest, hence timelike total momentum—is squarely inside the intended scope. The closed-universe exception is not a route to a machine: it produces pairs, not CTCs, and it requires compact spatial topology, with the observed curvature fraction $\Omega_k = 0.001 \pm 0.002$ leaving little room. But the rigorous proofs are 2+1-dimensional. The 3+1 statement for this data class is binding by structural analogy and has not been challenged, but it is a gap, not a published theorem. The review states it as a gap every time it matters.

Third, *Geroch’s dichotomy is the reason the identification must be acquired*. If a spacetime undergoes a topology change between Cauchy surfaces, then it contains CTCs, a singularity, or a violation of the NEC. There is no fourth option in classical general relativity. A machine that installs a new identification from trivial data would be a topology-changing process without any of the three; Geroch’s theorem says it cannot exist classically. This is stronger and more general than the CFG energy argument.

Fourth, *topological censorship is not a prohibition on wormholes*. Friedman–Schleich–Witt says that, under the NEC, a simply connected asymptotic region cannot causally access a wormhole throat. It does not say that a wormhole cannot exist as initial data, and it does not forbid an NEC-violating throat. It explains why the pre-horizon region of a time machine is causally cloistered: the identification is hidden behind the horizon, which is both the machine’s legal hiding mechanism and the reason it cannot be installed from outside.

Minguzzi’s area theorem closes the remaining ordering loophole. Under the NEC, a compact Cauchy horizon cannot form in a non-empty sourced spacetime. One cannot “form the horizon first” and then let CTCs appear behind it, at least not in a classical sourced setting.

2.5 The Gott route, quantitatively

The Gott pair is the cleanest classical machine and the cleanest observational casualty. Two parallel cosmic strings moving with relative velocity v produce CTCs when $\gamma v > 1$; in terms of the string tension, the condition is $G\mu/c^2 \sim \mathcal{O}(1)$. The observed limits are many orders away. The Planck cosmic-string search gives $G\mu/c^2 \lesssim 10^{-7}$ and the NANOGrav pulsar-timing background gives $G\mu/c^2 \lesssim 10^{-10}$ [55, 56], while the Gott condition requires of order unity. That is seven to eleven orders short, depending on the bound and the string scenario.

Laboratory-scale defects are worse. An LHC-scale string has $G\mu/c^2 \sim 10^{-31}$, twenty-nine orders below the Gott condition at $\gamma v \sim 1$. Velocity cannot rescue the route, because the required boost factor is of order 10^{31} ; the Gott condition is scale-free in the string tension but not in the energy budget, and a metre-scale weak-string machine does not exist. This is one of the few places where the engineering verdict is not a matter of extrapolation: the numbers are separated by decades.

3 The quantum inequalities and the exotic-matter wall

3.1 The canonical bound

The quantum inequalities (QIs) are the precise version of the statement that negative energy must be transient and small. For a free massless scalar field in four-dimensional Minkowski space, the

Table 4: The verified cracks in the quantum inequalities. The status column says what kind of result the crack is.

Assumption	Counterexample or result	Status
Null energy condition at the quantum level	No null QI in 3 + 1 for free fields (Fewster–Roman) [18]	Theorem
State-independent bound for $\xi \neq 0$	Local averages unbounded below for non-minimally coupled scalars (Fewster–Osterbrink) [19]	Theorem
Free field	Static AWEC/QI violation in a self-consistent interacting model (Olum–Graham) [20]	Explicit model
Controlled background	QI bound diverges to $-\infty$ near horizons and singularities (Vollick) [22]	Theorem-level caveat
Flat-space sampling	Curved-space QIs are difference inequalities, not absolute bounds (Fewster; Fewster–Smith) [17, 21]	Theorem
Extrapolation to exotic metrics	The QIs used to rule out warp metrics are not the QIs that have been proved (Krasnikov) [24]	Critique
Interacting 4D theory	No state-independent QI for a realistic interacting 4D theory; 2D CFT is the rigorous exception (Fewster–Hollands) [23]	Open

Ford–Roman worldline bound is [14, 15]

$$\int_{-\infty}^{\infty} d\tau f_{\tau_0}(\tau) \langle T_{00} \rangle_{\text{ren}} \geq -\frac{3}{32\pi^2} \frac{1}{\tau_0^4}, \quad (1)$$

where f_{τ_0} is a smooth sampling function of width τ_0 normalized to unit integral. Equivalently, a negative-energy density ρ_- lasting for a proper time Δt satisfies $|\rho_-| \Delta t^4 \lesssim \hbar/c^3$ up to the numerical coefficient. A one-second pulse is capped at roughly 10^{-60} J/m³. This is a spectacular bound, and it is the reason the exotic-matter wall looks absolute.

But the bound is a theorem about a free, minimally coupled field in a Hadamard state on a controlled background, sampled along a timelike worldline. Every one of those clauses has been probed, and several have been broken.

3.2 The verified cracks

Table 4 collects the cracks. The table is not a list of loopholes to exploit; it is a list of hypotheses that are not theorems for the Standard Model. The distinction is the difference between “the QI does not apply” and “the QI is false”.

The application to wormhole throats was the original motivation [16]: the QI says that a traversable throat must be paid for by a transient negative-energy pulse, and the bill is what makes the geometry expensive.

The sharpest crack is the null one. Fewster and Roman showed that there is no null-averaged QI in four dimensions for free fields; the null energy condition is not enforced by quantum field theory at the quantum level [18]. This matters because chronology protection is usually phrased in

terms of the null energy along horizon generators. A theorem that does not exist cannot protect a horizon.

The second crack is state dependence. Fewster and Osterbrink showed that for a non-minimally coupled scalar there is no state-independent lower bound on local averages [19]. The conformal value $\xi = 1/6$ is inside the failing class. Since the Standard Model Higgs is non-minimally coupled to curvature in a curved background, the QI that is supposed to constrain a time machine does not straightforwardly apply to the matter we actually have.

The third crack is interactions. Olum and Graham exhibited a self-consistent interacting field theory whose domain-wall vacuum has static negative energy and violates the averaged weak energy condition [20]. No QI theorem exists for any realistic interacting four-dimensional theory. The 2026 state-independent quantum null energy inequalities of Fliss and Rolph [25] are an important advance—they extend the information-theoretic program to interacting theories in two and higher dimensions—but they are not the Standard Model, and they do not restore the flat-space QI.

The fourth crack is curvature. Vollick showed that the QI bound diverges to $-\infty$ near horizons and singularities [22]. The divergence is a statement about the sampling function’s support in a region where the geometric optics approximation fails; backreaction may cure it. But it means that the QI is weakest exactly where chronology protection needs it strongest.

3.3 What the QIs do not say

It is as important to state the negative results. The QIs do not give a pointwise bound: static negative energy is allowed, and the Casimir effect is the standard example. They do not give a spatial bound: a spatially organized negative-energy distribution can evade a worldline inequality. They do not bound the cosmological constant: the observed Λ violates the strong energy condition, $\rho + 3p < 0$, while saturating the null energy condition, $\rho + p = 0$ [55]. And they do not constitute a theorem for the Standard Model. The extrapolation from free, minimally coupled fields to the Standard Model is a conjecture, and the review should say so.

The discount end of the market is worth naming because it is where most “exotic matter is almost here” claims live. The Casimir effect is real and measured [77], and the dynamical Casimir effect has been observed in a superconducting circuit [78]. Casimir wormholes [76], long-throat constructions [75], and four-dimensional traversable wormholes with fermion Casimir energy [51, 52, 53] all lower the classical exotic-matter bill. Every one of them converges on the Planck scale, on a cold dark sector, or on beyond-Standard-Model infrastructure rather than on a laboratory source. The warp-drive literature makes the same point from the other side: Alcubierre’s original metric [70], Van Den Broeck’s reduced-energy variant [71], the physical warp-drive classification [73], and the generic null-energy violation proofs [74, 72] are all energy-condition ledgers, not build proposals.

The often-quoted “forty orders” is not a theorem either. It is a comparison between a laboratory Casimir energy and a macroscopic construction requirement. The comparison is real and the gap is enormous, but the number depends on the construction. The honest version is a scaling law: every discount mechanism proposed in the literature—Casimir wormholes, long throats, zero-classical-exotic-matter wormholes—converges on the Planck scale or on beyond-Standard-Model infrastructure. The wall is not a single number; it is a floor.

4 Chronology protection: the theorem and its scope

4.1 Hawking’s mechanism

Hawking’s conjecture [1] proposes that the laws of physics prevent the appearance of CTCs. The mechanism is semiclassical. On a chronology horizon whose generators are closed null geodesics, a null geodesic can wind around the generator repeatedly. Each circuit multiplies the energy by a boost factor e^h , with

$$h = -2 \oint \text{Re } \epsilon \, dt, \quad (2)$$

where ϵ is the shear or expansion along the generator. The stress tensor then behaves as Bd/s^4 in the distance s to the horizon, and the metric perturbation behaves as GBd/s^2 . Fed back through the semiclassical Einstein equations, the perturbation is supposed to destroy the horizon before CTCs form.

The mechanism is beautiful, and it is not a theorem. The wormhole chronology-horizon calculation of Kim and Thorne was the template [27], and Visser’s critique identified the renormalization and reliability ambiguities that KRW does not settle [30]. It assumes that the horizon is compactly generated, that the field is in a state with the relevant short-distance behavior, and that the semiclassical expansion remains reliable at the curvature scale where the divergence appears. Each assumption has been questioned.

4.2 The KRW theorem

Kay, Radzikowski, and Wald [26] put the compactly generated case on a rigorous footing. Their result: on a spacetime with a compactly generated Cauchy horizon, no quantum state can be Hadamard everywhere. The two-point function fails to be Hadamard at points of the horizon, and the renormalized stress tensor is singular or undefinable there.

The scope is the content. KRW is about compactly generated horizons. It is about linear scalar fields. It is about a fixed background. It proves ill-definedness, not divergence. It does not say that the horizon is destroyed, and it does not say what the backreacted geometry does. The theorem is often summarized as “chronology protection is proven”; that summary is wrong in three ways at once.

4.3 Non-compactly generated horizons

The constructive escape is to build a horizon that KRW does not cover. Ori and Soen’s cylindrical model, Krasnikov’s tubes, and Visser’s Roman ring are the standard examples [47, 32, 31]. In a Roman ring, individually innocuous wormholes are arranged so that the ensemble sits on the verge of chronology violation with arbitrarily small backreaction. The horizon is not compactly generated in the sense KRW requires, and the theorem is silent.

Whether the Ori 2005 core’s horizon is non-compactly generated is the load-bearing conditional of the entire constructive program. Ori himself suggests that the generators may emanate from the non-compact matter region, and that this must be verified by an explicit study of the Cauchy horizon [45]. The companion paper computes the local eikonal branch and shows that the stress is cut off at that branch, but it does not prove that the local branch is the global Cauchy horizon [85]. The review must say “conditional on the horizon being non-compactly generated” every time the finite-stress result is used.

4.4 State choice

The second escape is state choice. KRW says that no state is Hadamard everywhere; it does not say that every state has infinite stress at every point. Krasnikov constructed bounded-stress states in two-dimensional CTC spacetimes [32]. Li and Gott constructed a self-consistent vacuum for Misner space [33]. Cassidy analyzed the effective action [34]. Cramer and Kay showed that even the tuned states are ill-defined on the horizon [35].

The program’s adapted-state analysis on the two-dimensional Misner quotient makes the state band quantitative [84]. On the Misner quotient there are three natural states: the in-vacuum, which has the Hawking divergence with $B < 0$; the adapted cylinder or Milne vacuum, which is not zero—it carries a quotient-circle Casimir term $\pi^2/3\Lambda^2$ plus a Fulling residue $1/12$ —and is horizon-divergent; and a thermal state with inverse temperature β^* , which can have zero stress but only at a fine-tuned value. The ratio $R(\Lambda)$ of the adapted divergence coefficient to the in-vacuum one is 1.18, 1.42, 2.23, and 7.47 at $\Lambda = 0.5, 1, 2$, and 4. The natural adapted vacuum is worse than doing nothing. The zero-stress state is a fine-tuned thermal state with $2\pi\beta^*/\Lambda \approx 3.29$ and $\beta^*(2\pi) = 2.688$.

Li and Gott’s four-dimensional formula is $\langle T_{ab} \rangle \propto [(2\pi/b)^4 - 1]$, which vanishes only at $b = 2\pi$ [33]. The zero is a fine-tuning, not a generic property. Cramer and Kay’s objection survives: the tuned states are still ill-defined on the horizon [35]. The measure-zero set is the whole game.

4.5 Bosons, fermions, and mass

Klinkhammer showed that scalar and spinor divergences near closed null geodesics have the same tensorial structure and degree [28]. There is no generic cancellation for equal Bose–Fermi content. The supersymmetric $h = 0$ escape is Hawking’s own footnote, and it remains uncomputed in a realistic model.

Massive fields offer a verified self-regulation channel. Boulware [29] and Tanaka and Hiscock [36] showed that sufficiently massive fields can remain regular on the horizon. The result is model-dependent and not a generic escape, but it is a real crack. The bibliographic variant Phys. Rev. D **52**, 4503 (1995) is a different Tanaka–Hiscock paper on massive scalars in multiply connected flat spacetimes; the 1994 entry is the one used here.

4.6 The 2022–2026 frontier

Empanan and Tomašević have given the most important recent reformulation. In controlled holographic models, the chronology-violating region either decouples from the boundary theory or the null chronology horizon becomes a spacelike singularity under backreaction [37, 38]. Protection survives, but by a different mechanism than Hawking’s, and without Planck-scale physics in the model. The result is a benchmark, not a proof for the Ori metric.

Three 2026 developments sharpen the state-choice and mechanism debates. Rieger’s deck-equivariance classification of Misner-type spacetimes gives a precise criterion for quotient legality and non-compact generation [41]. Melton, Strominger, and Wang construct an invariant vacuum and Fock space on a time-periodic CTC quotient [42]. Lee, Nilsson, and Thakur show that modified-gravity corrections do not automatically protect chronology [43]. Senjaya formulates protection as a scalar quaresonance instability, a mechanism on the instability side rather than the horizon-stress side [44]. None of these closes the problem, but together they show that “chronology protection” is a family of mechanisms, not a single theorem. Table 5 collects them.

Table 5: The mechanisms of chronology protection and what each establishes.

Mechanism	What it establishes	Status
Hawking’s fountain	A compactly generated horizon has a pile-up; the stress grows as s^{-4}	Heuristic mechanism
KRW theorem	No Hadamard state on a compactly generated horizon; stress undefinable	Theorem (free fields, fixed background)
Non-compact horizons	KRW silent; Ori–Soen, Krasnikov, Roman rings evade the hypotheses	Existence/models
State choice	Tuned states can have zero stress at a point, but are ill-defined on the horizon	2D computation; 4D open
Massive fields	Sufficiently massive fields can remain regular on the horizon	Model-dependent
Holographic backreaction	The null horizon becomes a spacelike singularity in controlled models	Controlled models
Quasiresonance	Instability-side protection in a wormhole background	Model

5 Constructive machines I: the Ori core

5.1 The 2005 metric

Ori’s 2005 solution is the sharpest constructive challenge to the folklore [45]. The metric is

$$ds^2 = dx^2 + dy^2 - 2 dz dT + [f(x, y) - T] dz^2, \quad f(x, y) = \frac{a}{2}(x^2 - y^2), \quad (3)$$

with z cyclic, $z \sim z + L$. The determinant is exactly -1 , and the metric is Ricci-flat. The surface $T = f$ is where g_{zz} vanishes and the identification vector ∂_z becomes null. Crossing it, the circles of constant (x, y, T) change from spacelike to timelike, and CTCs appear. For $a \neq 0$ this surface is timelike—its normal has norm $a^2 \rho^2$ —like the CTC boundary of the Tipler–van Stockum family, and unlike a chronology horizon, which is null wherever smooth.

The exterior of the core is supported by matter satisfying the weak, dominant, and strong energy conditions. The dedicated geometric study of the Ori 1993/2005 spacetimes is Dietz, Dirmeier, and Scherfner [50]; Olum’s analysis of the Ori–Soen model is the main critique of the family [40]; Levanony and Ori show that extended objects can traverse four-dimensional Misner space on self-collision-free orbits [48]; and Ahmed, Al-Badawi, and Sakalli re-solve the core in a modified-gravity class, finding that the chronology-violating regions survive [83]. The last result delimits the “in GR” scope of the stress computation. The spacetime is asymptotically flat and topologically trivial. This is not a wormhole and not a warp bubble: it is a compact vacuum core with a boost-identified circle. Ori’s own open question is stability.

5.2 The 2007 envelope

The 2007 construction completes the initial data with a dust envelope [46]. The spacetime contains vacuum and dust only, is asymptotically flat, and has a well-posed initial-value problem. The core is pseudo-Schwarzschild, and its chronology horizon is, in Ori’s words, entirely generated by closed null geodesics. That is a Misner-like, quantum-hostile horizon.

The two papers are complementary halves. The 2005 core is quantum-benign but matter-incomplete; the 2007 envelope is matter-complete but quantum-hostile. The hybrid construction of §6 is the critical path that joins them.

5.3 The image-series stress

The companion paper P1 computes the image-series stress tensor on the 2005 core [85]. The method is exact transport of each image by the bitensor, with a full 4×4 Jacobi system. The longitudinal block has determinant exactly λ^2 , so the Van Vleck block is not assumed affine. The result, at the anchor and on the local eikonal chronology-horizon branch, is that the frame-invariant eigenvalues of $T^\mu{}_\nu$ are

$$\left(-\frac{3}{2}, +\frac{1}{2}, +\frac{1}{2}, +\frac{1}{2}\right) \mathcal{E} \quad (4)$$

up to the $O(a)$ transverse splitting, and the null energy along the image direction is $-\frac{3}{2}\mathcal{E}$. The energy-density proxy $\mathcal{E}$ is positive; the null energy is negative. The trace is zero to relative 7.3×10^{-17} at the anchor and 1.1×10^{-20} at the horizon, consistent with the exact vanishing of the local trace anomaly on this VSI pp-wave.

On approach to the horizon the stress follows the Misner law

$$\mathcal{E} \propto \epsilon^{-2}, \quad \min_n |\sigma_n| \approx 0.51 \epsilon, \quad (5)$$

where $\epsilon = f - T$ is the distance below the CTC boundary. The coefficient 0.51 is $4(\cosh \frac{L}{2} - 1)$, the exact Misner value, and it is constant to 0.1% over $\epsilon = 0.5 \rightarrow 10^{-3}$ and within 1% down to 10^{-4} .

5.4 The chronology-horizon locus correction

The most important result in P1 is a correction to the locus, not to the tensor. The surface $T = f$ is the timelike boundary ∂V of the CTC region, not the chronology horizon. The local eikonal horizon is the null surface $T = F$ with $|\nabla F|^2 = f - F$ and

$$F = f - a^2 \rho^2 + 4a^3(x^2 - y^2) + O(a^4), \quad \delta_{\mathcal{H}} = f - F = a^2 \rho^2 + O(a^3). \quad (6)$$

The horizon lies below ∂V , and the two surfaces coincide only in the degenerate Misner case $a = 0$. The stress is cut off at the horizon while still on its rising asymptote: at $\epsilon_{\mathcal{H}}$ the energy series is within 8–9% of its asymptotic constant, and the sharp turnover lies below the horizon. The only genuine singularity is on the single closed null geodesic at the origin.

A nine-point scan over $\rho = 0.10$ – 0.50 at $y = 0$ is a consistency check on the locus: because $\epsilon_{\mathcal{H}} = a^2 \rho^2$, the fitted ρ^{-4} law follows from the ϵ^{-2} law, and the CH/ ∂V ratio is a - and ρ -independent. The scan is not an independent measurement of the exponent; it is a check that the locus and the stress law are mutually consistent.

This is “protection without teeth.” The mechanism operates in form—there is a Misner-like pile-up and a horizon cut-off—but the magnitude is negligible. At $a = 0.02$ the energy-density proxy is $5.3 \times 10^{-18} \text{ J/m}^3$ and the largest full-tensor chart component at the horizon is $1.78 \times 10^{-13} \text{ J/m}^3$, about 55.4–55.7 orders below the unit-curvature stress. The often-quoted 6.6×10^{-5} is the ratio of the proxy to its formal past-horizon extrapolation on ∂V , not evidence of a cutoff.

5.5 Caveats

Four caveats travel with the result. First, it is a test-field computation: the metric is fixed, and the stress is not fed back. Second, it is conditional on the horizon being non-compactly generated; if the global horizon is compactly generated, KRW applies and the finite test-field result is not the relevant statement. Third, it is conditional on the Huygens truncation of the Hadamard form suggested by the exact Brinkmann pp-wave structure; the full four-dimensional mode sum is not

computed. Fourth, the global chronology horizon is not proven; only the local eikonal branch is computed.

None of these caveats makes the result wrong. They define its scope. The review’s claim is not “the Ori machine is quantum-safe”; it is “the best available test-field computation on the best available core finds a negligible stress at the local horizon, conditional on the horizon’s global character.”

5.6 The stability preview

The companion stability analysis (P1) finds geodesic ejection at rate $\mu - \frac{1}{4}$ with $\mu = \sqrt{a/2 + 1/16}$, tensor-transverse modes that are amplitude-neutral, and an h_{xy} gradient that piles up by $e^{L/2}$ per wrap onto the horizon [85]. The $h_{xx} - h_{yy}$ polarization is expelled for $a > 0$. There is no per-wrap amplifier in the analyzed sectors. The open sectors are $k_{\perp} \neq 0$, the full ten-component system, the quotient Cauchy problem, and nonlinear modes. Section 8 returns to this.

6 Constructive machines II: the hybrid and the Xavier core

6.1 The hybrid construction

The hybrid construction joins the 2005 vacuum core to Ori’s 2007 dust layers [86]. It requires three things: an umbilical hypersurface in the core on which the extrinsic curvature is pure trace, an explicit envelope layer satisfying the constraint inequalities against the core’s boundary data, and a matching to Ori’s outer layers. The companion paper delivers all three.

The umbilical slice family is

$$\tau = \tau_0 + \left(e - \frac{1}{4}\right) (x^2 + y^2) - \frac{a}{2}(x^2 - y^2), \quad (7)$$

with $K = k_0 h$ and $k_0 = 1/(2\sqrt{|\tau_0|})$. The family is exact at $a = 0$, with residual shear $1.08 a/(2|\tau_0|)$. The pure-trace reduction applies, and the C3 blocker is dissolved.

The C4 envelope is the numerical heart. The gates are $H_1 \geq 0$ and $H_1 \geq 2|M|$, checked on a fine grid with $\Delta r = 0.005$ and 48 azimuthal points. The minimum values are $H_1 = +0.765$ and $WEC = +0.728$; the construction passes all 21/21 single-knob perturbations at $\pm 30\%$. At $a = 0.02$ the sampled margins are $+0.763129$ and $+0.728189$, and the interval-certified lower bounds are $H_1 \geq 0.7468$ and $H_1 - 2|M| \geq 0.2736$ on the gatefast interior band. The derivative enclosure covers $a \leq a_W^* = 0.0346$. The retuned construction (a one-knob stage-1 onset delay $s_d = 1.5$ mm) is gate-positive over the full envelope layer $r > w$, including the innermost collar: at $a = 0.02$ the exact jets give $WEC(1\text{ mm}) \geq +4.550484 \times 10^{-6}$, a dense exact-jet scan is positive everywhere ($\min H_1 = \min WEC = +2.4 \times 10^{-12}$ at the innermost sampled shell), and the boundary torus $r = w$ is the exact vacuum continuation ($H_1 = 0$).

The hand-off to Ori’s layers is verified: a two-stage flattening drives the data onto Ori’s Layer-2 form with $H_1 = 6k_0^2$ to five decimals, and the Robertson–Walker dust density ε_0 matches. From that radius outward, Ori’s layers apply verbatim.

The honest summary is that the hybrid is *initial data for a time machine*, not a manufactured machine. Its evolution into CTCs is conditional on Ori’s existence theorem, which the companion cites rather than re-proves. Asymptotic flatness is inherited from Ori’s exterior layer; the ADM charges are not independently recomputed.

6.2 The machine-spec dials

The engineering translation is a set of dials, not a blueprint [92]. The size dial ρ_0 sets the scale; e sets the CTC threshold; a sets the wave strength, the geodesic ejection rate, and the horizon stress; τ_0 sets the depth, the total mass, and the lead time; L sets the loop scale.

The a -dial is the sharpest trade-off. Sending $a \rightarrow 0$ improves umbilicity, but the horizon stress scales as a^{-4} , so there is an a -floor of about 2×10^{-17} at metre scale. The canonical $a = 10^{-4}$ sits thirteen orders above the floor. At canonical values— $\rho_0 = 0.5$ m, $e = 0.1$, $a = 10^{-4}$, $\tau_0 = -1$ m², $L = 1$ —the assembly-to-CTC lead is $\sqrt{|\tau_0|}/c \approx 3.3$ ns, the loops are about 16 cm, and the full envelope mass is $2.9\text{--}5.4 \times 10^{27}$ kg, or $1.5\text{--}2.8 M_J$ (the vacuum tube alone is 6.45×10^{26} kg, or $0.34 M_J$). The compact-object wall estimate is $c^2 \rho_0 / 2G \approx 3.4 \times 10^{26}$ kg, or $0.18 M_J$, so the full envelope is about eight times the wall, not at it. Scaling up: kilometre scale is about 7×10^{29} kg, and AU scale about 10^{38} kg, or $5 \times 10^7 M_\odot$.

6.3 The mass law

The mass law is the most important engineering result, and it is easy to state incorrectly. At fixed ρ_0 and dimensionless z -period L_z , the dust density scales as k_0^2 but the total mass scales as k_0 , not k_0^2 . The certified C4-layer integral is

$$M_{\text{layer}} = 3.30 k_0 L_z \quad (8)$$

in geometrized units, because the z -orbit proper length grows as $1/k_0$. At the deep rung $k_0 \simeq 2.2 \times 10^{-12}$ the density is 778 kg/m³—sand or water—but the mass is asteroid-class: $1.3\text{--}2.4 \times 10^{16}$ kg $\cdot L_z$. The “tens of tons” figure requires picometre loops and is not usable. The canonical corner is not ordinary matter: $\varepsilon_0 = 4.0 \times 10^{25}$ kg/m³, with a peak of 1.17×10^{26} kg/m³, about 5×10^8 times nuclear saturation. The deep rung is ordinary density at asteroid mass, which is a different machine, not a cheaper version of the canonical one.

6.4 The Xavier core

Xavier’s metric [49] is

$$ds^2 = -2h(z, t) dt dz + [h(z, t) - f(x, y)] dz^2 + dx^2 + dy^2, \quad z \sim z + L. \quad (9)$$

It is vacuum. The z -circles switch from spacelike to timelike as a traveling wave drives $h < f$. It is locally flat if $f \rightarrow 0$. The geodesic identity is $\Gamma^t_{zz} \propto (h - f)$.

The companion analysis P3 classifies the quotient legality of $h = P(z)Q(z - 2t)$ under identifications $(z, t) \sim (z + L, t + cL)$ [87]. For pure z -shift ($c = 0$) the general legal profile is a train modulated by a pump, $h = e^{2at} p(z) q(z - 2t)$ with p, q L -periodic. It is z -dependent generically, has boost $b = aL$, and carries the Misner pile-up for $a \neq 0$. The trains—the boost-degenerate subfamily $a = 0$ with P and Q both L -periodic—are marginal. The pumps—the z -independent subfamily $p = q = 1$, $h = e^{2at}$ —carry the pile-up. Helical cores (mixed identification, P periodic and Q arbitrary) are a separate legal class, boost zero on the closed null generator, marginal, but not switchable.

The paper’s own $\text{sech}^2(k(z - 2t))$ and exponential examples do not descend to the pure- z quotient the paper imposes; they are legal only under a helical identification, which has no global time and is not a switchable machine. The train quotient is the machine-relevant one. This correction is one of P3’s main results.

Table 6: The constructive models. “Quantum” refers to the computed test-field stress at the local horizon; “matter” to whether the construction is completed with known matter.

Model	Matter	Horizon	Quantum	Status
Ori 2005	vacuum core	non-compact (probable)	benign at local CH	exact core; global CH open
Ori 2007	vacuum + dust	closed null geodesics	hostile	exact/cited
Hybrid (P2)	vacuum + dust	inherited	inherited	certified envelope; evolution cited
Xavier train (P3)	vacuum	switchable quotient	no pile-up on generator	exhibited; full stability open
Xavier pump	vacuum	switchable	Misner pile-up	computed

6.5 The on-generator discriminator

The monodromy measurement is clean. Over 24 circuits, the train’s affine circuit length is exactly constant (ratio 1.0000000000; $\lambda = 2/3$ at $z_* = 0$), while the pump’s shrinks geometrically at $e^{-L/2\tau}$ (ratio 0.9512294245 for $\tau = 10$, $L = 1$). The image sum diverges as ε^{-2} for the σ^{-1} weight and ε^{-4} for the σ^{-2} weight as $\varepsilon \rightarrow 0$, the same powers as exact Misner space. That divergence is the $\mathcal{N}$ -singularity of the closed null generator, not a core discriminator.

The genuine discriminator is on the generator. The train’s winding coefficients are bounded (measured log-rates $\equiv 0$ to 10^{-12}), while the pump’s grow at exactly $e^{+L/2\tau}$, and its spacing-weighted terms at $e^{+3L/2\tau}$ per circuit (measured rates +0.05000000 and +0.15000000). “Quantum silence” therefore means *no geometric pile-up*, not a finite on-generator two-point function. The off- $\mathcal{N}$ stress is finite at $x_* = 0.1$ and $t_* = 0.2499204$; its horizon limit is $\mathcal{O}(1)$ (degree zero in the horizon distance), and the near-axis scaling $S \sim C/x^2$ confines the divergence to the axis.

The train is classically neutral in the analyzed TT, profile, f -modulus, and vector-truncation sectors. The full ten-component, longitudinal/constraint, $\mathcal{O}(A\rho k_\perp)$, quotient-Cauchy, and nonlinear sectors remain open. Xavier is not stable in general; it is stable in the sectors that have been analyzed. Table 6 compares the constructive models.

7 Quantum stress and the state-selection problem

7.1 Why “the stress is finite” is not a well-posed statement

The stress tensor is not an operator-valued function of a point; it is a distribution, and its renormalized expectation value depends on the state. A statement that “the stress is finite at the horizon” is incomplete until the state is specified. The constructive literature sometimes slides from “there exists a state with finite stress” to “the horizon is benign,” and the slide is precisely where the state-choice loophole lives.

On the two-dimensional Misner quotient the three natural states can be written down. The in-vacuum has the Hawking divergence with $B < 0$. The adapted cylinder or Milne vacuum is not zero: it carries a quotient-circle Casimir term $\pi^2/3\Lambda^2$ plus a Fulling residue $1/12$, and it is horizon-divergent. The thermal state with inverse temperature β^* can have zero stress, but only at a fine-tuned value.

Table 7 collects the band [84]. The key number is the ratio $R(\Lambda)$ of the adapted divergence coefficient to the in-vacuum one: 1.18, 1.42, 2.23, and 7.47 at $\Lambda = 0.5, 1, 2$, and 4. The natural

Table 7: The state band on the two-dimensional Misner quotient. The “objection” column is not a refutation; it is the reason the state cannot be used as a generic protection argument.

State	Stress behavior	Status	Objection
In-vacuum	Hawking divergence, $B < 0$	2D computation	The generic state; diverges
Adapted cylinder/Milne	Casimir $\pi^2/3\Lambda^2$ plus Fulling $1/12$;	2D computation	Worse than in-vacuum ($R > 1$)
Thermal β^*	horizon-divergent Zero stress at $2\pi\beta^*/\Lambda \approx 3.29$	2D computation	Fine-tuned; Cramer–Kay ill-definedness
Li–Gott 4D	$\propto [(2\pi/b)^4 - 1]$; zero at $b = 2\pi$	Exact	Fine-tuned; zero only at $b = 2\pi$

adapted state is worse than the in-vacuum, not better. The zero-stress route is a fine-tuned thermal state with $2\pi\beta^*/\Lambda \approx 3.29$ and $\beta^*(2\pi) = 2.688$.

7.2 The four-dimensional extension

The four-dimensional status is weaker. Four-dimensional Misner space is stress-free at $b = 2\pi$. The Ori $f \neq 0$ core is VSI, the local trace anomaly vanishes, and the conical anomaly is computed, but no closed-form zero-stress state exists. The extension of the adapted-state construction to the full $f \neq 0$ core is open; Easson’s reduced Polyakov model gives state-dependent flux coefficients and a leading Cauchy-horizon divergence with cancellation conditions, a useful methodological comparator [82]. The exact status of the 4D adapted-state construction is not settled in the companion literature, and it is not quoted here as a result.

7.3 Renormalization ambiguity

There is a second layer of ambiguity: the renormalization prescription. The Ricci ambiguity, the Huygens truncation, and the difference between a chart component and a frame-invariant eigenvalue all matter. The companion paper is careful about this: the largest full-tensor chart component at the horizon is $1.78 \times 10^{-13} \text{ J/m}^3$, while the energy-density proxy is $5.3 \times 10^{-18} \text{ J/m}^3$. The chart component carries an extra $1/\sigma$ because the chart degenerates at the horizon; it scales as ϵ^{-3} while the eigenvalues scale as ϵ^{-2} . That is a chart effect, not a second physical divergence.

7.4 The missing principle

The state-selection principle is missing. Without it, any semiclassical-protection claim is incomplete. With it, the Li–Gott and Cassidy states might be excluded—or might not. The problem is not a technicality; it is the difference between “there exists a state in which the horizon is benign” and “the horizon is benign in the state the universe actually chooses.” The review lists it as one of the five open problems.

8 Stability: classical, semiclassical, and backreaction

8.1 Three different questions

“Is the machine stable?” is three questions in one. Classical stability asks whether small perturbations of the initial data grow. Semiclassical stability asks whether the renormalized stress backreacts to destroy the horizon. Backreaction stability asks what the endpoint of the semiclassical evolution is. The literature often answers one and is heard as answering another. Table 8 records the answer sector by sector.

8.2 Classical geodesic stability

On the Ori core the transverse geodesic equation gives

$$x'' + \frac{x'}{2} = \frac{a}{2}x, \quad (10)$$

so the per-unit- z growth rate is $\mu - \frac{1}{4}$ with $\mu = \sqrt{a/2 + 1/16}$. At $a = 0$ this is marginal Misner decay; for $a > 0$ it ejects. The closed null geodesic at the origin is attracting. The ejection is a classical focusing effect, not an instability of the metric.

8.3 Tensor stability

The tensor analysis is more encouraging. The TT amplitude is neutral for all a . The h_{xy} gradient grows by $e^{L/2}$ per wrap, which is a pile-up onto the horizon rather than an amplification of the metric perturbation. The Floquet spectrum lies on the unit circle. The $h_{xx} - h_{yy}$ polarization is expelled for $a > 0$. The profile sector is neutral. There is no per-wrap amplifier in the analyzed sectors.

The caveats are large: $k_{\perp} \neq 0$, off-core $\mathcal{O}(a\rho)$ terms, the quotient Cauchy problem, non-TT modes, and nonlinearity. The statement “no per-wrap amplifier” is a statement about the analyzed sectors.

8.4 Envelope stability and tolerance

The retuned C4 envelope passes both gates with margins, is robust under $\pm 30\%$ single-knob perturbations, and is gate-positive over the full envelope layer $r > w$ including the innermost collar. The late-time dust evolution is shared with Ori 2007 and is open.

8.5 Quantum stability

Two-dimensional backreaction is exactly zero on the Misner quotient. Four-dimensional backreaction is open. The Emparan–Tomašević result turns the null chronology horizon into a spacelike singularity in controlled holographic models [38]; that is the benchmark, not a proof for the Ori metric. The direct Einstein-gravity endpoint is uncomputed.

8.6 Xavier stability

The Xavier train is neutral in the TT, profile, f -modulus, and vector-truncation sectors. The transverse saddle $e^{\pm 0.2402}$ is a symplectic geodesic ejection, not a growing metric mode. The marginal $f_{\text{area}} > 2h_{\text{boost}}$ bound is the paper’s own caveat. The full system is open.

Table 8: Stability by sector. The table is deliberately granular; the honest answer to “is it stable?” is the list of open rows.

Sector	Result	Caveat
Geodesics	Ejection at $\mu - \frac{1}{4}$; attracting closed null geodesic	Classical focusing, not metric growth
TT tensor	Amplitude neutral; h_{xy} pile-up $e^{L/2}$ per wrap	$k_{\perp} = 0$
Polarization Profile	$h_{xx} - h_{yy}$ expelled for $a > 0$ Neutral	Full ten-component open Nonlinear open
C4 envelope	Retuned: gates pass over $r > w$; 21/21 at $\pm 30\%$	Continuum cell bound open
2D backreaction	Exactly zero	2D only
4D backreaction	Uncomputed	Main open problem
Xavier train	Neutral in analyzed sectors	Full system open
Quotient Cauchy	Compatible, not globally hyperbolic	IVP not posed in full

8.7 The quotient Cauchy problem

The constraints propagate with an $\mathcal{O}(a)$ truncation obstruction. The quotient is compatible but not globally hyperbolic. The initial-value problem is not posed in full. This is the technical reason the stability claims must be sector-by-sector.

9 Observation: relics, nulls, and what the surveys actually establish

9.1 The standard constraints

The observational baseline is a set of nulls and consistency checks, not a detection. The multi-messenger event GW170817 constrains the speed of gravitational waves to $|c_g/c - 1| \lesssim 10^{-15}$ [54]. There is no confirmed acausal signal in GW, gamma-ray burst, neutrino, or clock data. The Planck cosmic-string search and the NANOGrav pulsar-timing background constrain $G\mu/c^2$ at the 10^{-10} to 10^{-7} level, depending on the string scenario [55, 56], against the order-unity Gott condition. Cosmic rotation is bounded at $\omega/H_0 \lesssim 10^{-9}$. Nuclear-matter equations of state satisfy the dominant energy condition; dark energy violates the strong energy condition but not the null energy condition.

These constraints are strong, and they are not constraints on a local relic. They constrain the background, the defect population, and the propagation speed. A relic is a local region whose covering space is quotiented by a boost; it need not leave a cosmological imprint.

9.2 The boost-holonomy signature

The signature is exact and simple. A locally flat region whose covering space is quotiented by a boost of rapidity Λ produces a photon frequency ratio

$$r = \cosh \Lambda - n_z \sinh \Lambda, \quad (11)$$

which is exactly $e^{\pm\Lambda}$ for axial photons. The observable is a co-spatial spectral double image at a fixed, source-independent ratio, with no lens mass and no deflection. For gravitational waves, both source-frame masses scale by $e^{\pm\Lambda}$, while the mass ratio and effective spin χ_{eff} are unchanged;

the transverse-traceless amplitude is invariant, so there is no magnification, but $h \propto M_c^{5/3} f^{2/3} / D_L$ forces $D_L \propto M_c$, so the invariant combination is M_c/D_L , not D_L . Off-axis, the tilt can reach $\arctan(\sinh \Lambda)$, which is 27.5° at $\Lambda = 0.5$ and 49.6° at $\Lambda = 1$. The Gaia window is $1.0 \times 10^{-4} \lesssim \Lambda \lesssim 1.6 \times 10^{-3}$ through $\Delta RV = c(e^{\pm \Lambda} - 1)$; the GW window is $0.1 < |\Lambda| < 3$. The channels are complementary.

9.3 Cloistering

A pre-horizon pocket is a Rindler band. A generic stellar chord never enters it. The entry shell contains 3.8×10^{-51} stars for a 0.5 m pocket and 1.6×10^{-8} stars for a 1000 AU pocket. The OFF metre-scale relic is invisible. The channel opens for a wall optical depth $\tau_{\text{wall}} \gtrsim 0.1$ ly for stars, or $\tau_{\text{wall}} \gtrsim 0.002\text{--}0.02$ AU for GWs. The canonical 3 ns echo is below the event-separation threshold. This is not a failure of the survey; it is a statement about which relics are findable.

9.4 The GW null

The GW survey uses the GWTC-4.0/5.0 catalogs and their lensing baselines [58, 59]; it uses 391 events, 282 with source-frame masses and 281 with usable sky maps. Stage 1 finds 39,621 pairs; 32,434 survive, against a label-permutation median of 32,806 (two-sided $p \approx 0.10$, a mild deficit). The corrected M_c/D_L scaling cut at 3σ gives 30,343 candidates against a matched independent-pair null of 30,349 (two-sided $p \approx 0.96$), recovering 5,688 pairs the archived equality- D_L cut discarded; the archived equality cut gave 24,655. The corrected 51-event sky pilot gives $p = 0.75$; the full volume gives $p = 0.95$ over 30,311 mapped candidates, with largest candidate co-localization $C = 0.9513$. Of the corrected candidates, 3,669 have $C > 0.1$ (background 3,544), 96 have $C > 0.5$ (96.4), 4 have $C > 0.9$ (4.6), and 1 has $C > 0.95$ (1.5). The shared-base family statistic is $S = 2,697$; the nominal sky-permutation $p = 0.005$ falls to $p = 0.539$ under the composition-matched null. At posterior precision the corrected M_c/D_L scaling residual leaves 82 of 120 pairs (65 under the archived equality cut); the shared-base cluster is 64 of 82 at $|\Lambda_0| = 0.467$ with a Λ -permutation $p = 1.000$, so the posterior stage is null and the family test is precision-limited.

The calibrated 90% limits are the important numbers. At $C > 0.1$, $\mu < 274$ (the robust empirical value; 205 under the Gamma-Poisson model, which is not adequate at $C > 0.1$). At $C > 0.5$, $\mu < 17.3$ (20.9 conservative); at $C > 0.9$, $\mu < 4.50$ (4.95); at $C > 0.95$, $\mu < 3.10$ (3.23). The family test is degenerate at current parameter-estimation precision ($\sigma_\Lambda = 0.08\text{--}0.5$), so the shared-base cluster saturates. The archived-cut injection/selection model gives $\varepsilon_{\text{family}} \approx 1.8 \times 10^{-36}$, hence $N_{\text{relic}} < 1.5 \times 10^{38}$ (1.1×10^{38} under the Gamma-Poisson model) and no astrophysically meaningful density bound. The idealized $\mu < 2.3$ is the zero-observed case with negligible background; it is not the data-driven limit.

9.5 The Gaia census

The Gaia census uses the DR3 radial-velocity catalog [57], with 33,812,183 sources with published radial velocities. It finds 16,358 pairs at $\leq 1''$, of which 7,217 are astrometry-matched (44.1%). In the permissive sample, 1,177 of the 7,217 matched pairs are above 3σ in ΔRV , and 939 lie in the candidate zone. The strict all-six sample has 1,177 matched pairs, 171 above 3σ , and 135 in the candidate zone; the two 1,177 counts are different samples, and their equality is a numerical coincidence. The ΔRV median is 7.4 km/s, the 90th percentile is 41.6 km/s, the 99th percentile is 126.8 km/s, and the maximum is 489.5 km/s. The family statistic's largest cluster is 173 of 939, against a smooth expectation of 173.4; in the strict sample it is 24 of 135. It is not a cluster; it is the density itself, and the statistic is CDF-dominated. A composition-matched bootstrap (20,000

Table 9: The observational channels. The “what it establishes” column is deliberately narrower than the headline.

Channel	Statistic	Result	What it establishes
GW speed	$ c_g/c - 1 $	$\lesssim 10^{-15}$	Propagation speed, not background CTCs
Cosmic strings	$G\mu/c^2$	$\lesssim 10^{-10}$ – 10^{-7}	Gott route excluded by decades
GW pairs	μ at $C > 0.1$	< 274 (205 model)	Detectable-family count in catalog volume
GW strong	μ at $C > 0.9$	< 4.50 (4.95)	Strong-co-localization subset
GW relic number	$\varepsilon_{\text{family}}$ (archived cut); N_{relic}	1.8×10^{-36} ; $< 1.5 \times 10^{38}$	No density bound
Gaia pairs	family max	173/939 ($p = 0.74$); 24/135 ($p = 0.97$)	No excess; no detection/exclusion
Gaia epochs	epoch RVs	0 pairs	Data-limited, decisive test absent

draws holding the candidate count, sky positions, and pair identities fixed) gives null medians 179 (90% range 164–197) for the permissive sample and 28 (24–34) for the strict sample, with $p_{\text{excess}} = 0.737$ and 0.969; smooth Gamma/log-KDE models give 0.179/0.119 and 0.805/0.758, an assignment permutation gives $p = 1.00$, and real non-candidate controls give 0.63–0.86. No excess survives.

The decisive epoch test is data-limited. Data Release 3 has no epoch RVS spectra: in the EM-2 snapshot (524 tiles, 9,415 pairs; not the final census), 9 of 1,132 candidate sources have mean RVS, 0 have epoch RVs, and 0 pairs have both. The honest statement is “no detection, no exclusion.” The Gaia family statistic is now calibrated by a composition-matched null and shows no excess; it still supports no detection, exclusion, or density bound.

9.6 What the nulls do and do not establish

The GW null is a count limit in the surveyed catalog volume, not a density bound. The efficiency is unmeasured in the sense that matters for a population claim. The Stage-3 extractor and the corrected posterior cut are reproducible, and the family tests are now calibrated but precision-limited. The Gaia result reports no significant signal, no detection, and no exclusion.

The honest sentence is: *the survey has produced a null, not a bound on the local density of relics; the next step is an efficiency model or a sharper family statistic.* This sentence is less exciting than “time travel ruled out,” and it is the one the data support.

The observational strategy follows directly from the nulls. On the GW side, the O5/full-O4 re-run with better mass precision, a hierarchical family fit, and a sharper family statistic would convert the counting limit into a population statement; the present family test is saturated by $\sigma_{\Lambda} = 0.08$ – 0.5 even with the composition-matched null. On the electromagnetic side, a Gaia epoch-spectrum release or targeted multi-epoch spectroscopy of the 135 strict candidates would provide the decisive fixed-ratio test; DR3 cannot. A dedicated massless-lens or double-image survey with a calibrated family statistic would address the channel directly. None of these is guaranteed to find a relic; all of them sharpen the statement from “no detection” to “a bound, or a detection.” Table 9 summarizes the channels.

10 Acquisition: the conceptual pivot

10.1 The organ

The acquisition audit is reported in the companion paper P12 [91]; this section summarizes its logic. The defining structure of the machine is a boost-holonomy identification $z \sim z + L$ of rapidity $L/2$. The z -circle is spacelike before the horizon, null on it, and timelike after. The identification is causally cloistered before the horizon: a consequence of topological censorship, and the machine’s legal hiding mechanism. It is also the reason the machine cannot be installed from outside.

10.2 The four classical obstructions

Four independent results stand between “initial data exist” and “a machine can be assembled.”

1. **CFG/CFGO.** An open universe with compactly supported data and timelike total momentum cannot evolve into a boost-holonomy configuration [5, 6]. The hybrid data class is inside the intended scope. The rigorous proofs are $2 + 1$ -dimensional; the $3 + 1$ statement is a gap.
2. **Geroch.** A topology change between Cauchy surfaces requires CTCs, a singularity, or NEC violation [7]. Installing a new identification from trivial data would be a fourth option; classically, there is none.
3. **Deser–Jackiw–’t Hooft and Cutler.** A two-defect Gott assembly has singular or constrained data; a smooth Cauchy surface cannot generate the pair [9, 10]. A pre-existing pair is a different initial condition.
4. **Friedman–Schleich–Witt.** Under the NEC, a simply connected asymptotic region cannot causally access the identification [8]. The identification can exist as initial data; it cannot be reached from outside.

Minguzzi’s area theorem reinforces the horizon-first kill: under the NEC, a compact Cauchy horizon cannot form in a non-empty sourced spacetime [11]. The order of operations “form the horizon, then let CTCs appear” is not available classically.

10.3 The $3 + 1$ gap

The $3 + 1$ status deserves its own paragraph because it is routinely overstated. CFG and CFGO are rigorous in $2 + 1$ dimensions. The $3 + 1$ statement for the hybrid data class is binding by structural analogy and has not been challenged, but it is not a published theorem. A $3 + 1$ counterexample for a non-Gott data class would reopen a proof gap; it would not, by itself, provide a build route. The review states this as a gap, not a theorem, and lists a $3 + 1$ acquisition theorem among the open problems.

10.4 Route A: primordial inheritance

The first route is inheritance. Spacetime foam could produce a microscopic identification [64]; inflation could stretch it to macroscopic size while preserving topology; the pocket could survive 13.8 Gyr in vacuum; the survey could find it; and the hybrid construction plus Ori’s outer layers could wrap it. The machine window is $a \in (2 \times 10^{-17}, \sim 0.1)$, $e < 1/4$, $L = \mathcal{O}(1)$.

The route is consistent with known physics and has no demonstrated mechanism. The foam prior is not computed. The survival calculation is not done. The survey has not found a relic. Every arrow in the pipeline is a scenario, not a result.

10.5 Route B: quantum nucleation

The second route is nucleation. The Farhi–Guth and Farhi–Guth–Güven constructions are the template for creating a universe—or a region—by quantum tunneling [79, 80]. A Euclidean tunneling process could create the identification. No theorem forbids it. The amplitude is exponentially suppressed above the Planck scale, and the present-day ledger is unkind: the energy per particle is fifteen orders short, the energy density seventy-eight orders short, and the false-vacuum scale about sixty-eight to sixty-nine orders short. These are order-of-magnitude estimates, not theorems, but they are not close.

10.6 Route C: reproduction

The third route is reproduction. Inside an existing CTC region, Geroch’s price is already paid; topology change there is no longer forbidden; transport is not topology change. The modern traversable-wormhole constructions [51, 52, 53] are the closest controlled examples, and they respect boundary causality throughout. Andr  ka et al. sharpen the point with an extendible spacetime without CTCs whose every extension contains them: causal extension can be guaranteed only by adding structure, not by removing it [65]. The first machine still needs Route A or Route B. Krasnikov’s analysis of quantum inequalities and spacetime shortcuts is the cautionary version of the same route [81]. The black-hole-interior variant is formally a loophole but causally worthless: the inner horizon is a one-way membrane, the interior proper time at Sgr A* is about 62 s, and the tidal field at $10 M_\odot$ is about $10^7 g/m$. It is not a route to a usable machine.

10.7 The string route

The string route is the Gott pair, and it is the one route with a clean observational kill. The condition is $G\mu/c^2 \sim 1$; the observed bound is $\lesssim 10^{-10}$; LHC-scale defects are at 10^{-31} . The gap is twenty-nine orders at $\gamma v \sim 1$, and velocity cannot rescue it because the required boost is of order 10^{31} . The Gott condition is scale-free in the string tension but not in the energy budget.

10.8 The verdict

No present-day build route survives the audit. Each route considered here returns a kill or a constraint: CFG/CFG0, Geroch, DJHT/Cutler, topological censorship, Minguzzi, the string bound, the nucleation suppression, and the black-hole one-way membrane. The only live empirical task is the survey. The question is acquisition, not assembly. Table 10 lists the routes and their kills.

11 Analogue experiments: kinematics, not dynamics

11.1 The caveat

Analogue systems reproduce the kinematics of a curved metric; they do not reproduce the dynamics of general relativity. There is no real CTC, no backreaction, and no topology change. A flowing condensate can simulate a horizon because the phonon equation is a wave equation on an effective metric. It cannot simulate the Einstein equations that would destroy the horizon.

11.2 The platforms

The platforms are diverse: Bose–Einstein condensate horizons [62], optical fibers, hyperbolic metamaterials, temporal cloaking, superconducting-circuit dynamical Casimir effect [78], and quantum-

Table 10: The acquisition routes and their kills. “Status” is the strongest statement the evidence supports.

Route	Mechanism	Kill or obstruction	Status
A. Primordial	foam $\rightarrow$ inflation $\rightarrow$ survival $\rightarrow$ survey $\rightarrow$ wrap	No computed prior or survival rate	Scenario
B. Nucleation	Euclidean tunneling	15–78 orders short	Scenario
C. Reproduction	Inside an existing CTC region	Requires a first machine	Conjectured
String pair	Gott two-string assembly	$G\mu/c^2$ bound; 29 orders at LHC scale	Excluded
Black-hole interior	Inner-horizon CTC region	One-way membrane; 62 s; tides	Unusable
Classical assembly	Install the identification	CFG/CFG0; Geroch; FSW; DJHT	Theorem-level (2+1) / gap (3+1)

processor simulations of CTC-assisted computation [67, 68, 69]. Each tests a piece of the kinematics. None tests the semiclassical backreaction.

11.3 The BEC Misner design study

The companion design study P10 proposes a quasi-one-dimensional ^{87}Rb ring with radius $R(t) = R_0 - Vt$ and $V = \lambda c_s / (2\pi)$ [90]. In the acoustic regime the azimuthal phonons propagate on the Milne metric $ds^2 = -dT^2 + T^2 d\psi^2$ with $\psi \sim \psi + \lambda$. The ring realizes the quotient cylinder: in the covering space the boost orbit is a hyperbola, and the ring is the quotient circle obtained by identifying points along it. The ring’s $R = 0$ limit is a conical tip, not a compactly generated null horizon. The construction is a kinematic analogue of the image-sum geometry and does not test KRW in any dimension.

The measured quantities are the equal-time density correlation $G(\Delta\phi)$ and the angular-mode occupations. The stress coefficient

$$S_\Lambda = 2 \sum_{n \geq 1} \frac{q^n}{(1 - q^n)^2}, \quad q = e^{-\lambda}, \quad (12)$$

is inferred from the short-distance (coincidence-limit) scaling of G ; it is not the amplitude of the finite-separation image excess.

The design study has nine documented blockers (B1–B9), and the review carries them because presenting the proposal as a test would be a factual error: the sound speed was $\sqrt{2}$ too large in an earlier version, so V , the sweep time, the horizon temperature, the Bragg frequency, and the healing length were inconsistent (B1); the density correlation does not acquire S_Λ (B2); the infrared image is the $n = \pm 1$ term at the full ring $2\pi R_0 = 314 \mu\text{m}$, not $25 \mu\text{m}$, so it requires $T \lesssim 0.08 \text{ nK}$, while the antipodal correlation at $\pi R_0 = 157 \mu\text{m}$ requires $T \lesssim 0.16 \text{ nK}$ (B3); the 0.1–1 s phonon lifetime ignored Beliaev damping, with Bragg $\tau \sim 50 \mu\text{s}$ (B4); the fixed- q Bragg comb is not measurable as described (B5); the final ring has only $N(R_{\min}) \approx 2.1 \times 10^2$ atoms and ten azimuthal modes (B6); the ring $R = 0$ is a conical tip, not a compactly generated horizon (B7); the words “first,” “test,” and “calibration” overclaimed (B8); and the Ori/Xavier relation relied on unpublished or contested companion numbers (B9). The corrected design uses $c_s = \sqrt{gn/m} = \hbar/(\sqrt{2} m\xi) = 3.263 \text{ mm/s}$; at $\lambda = 1$ the sweep times are 96.3 and 93.2 ms, the horizon temperature is 25.1 nK, the image requirement $\ell_T \gtrsim 2\pi R_0$ needs $T \lesssim 0.08 \text{ nK}$, and the antipodal requirement $\ell_T \gtrsim \pi R_0$ needs

$T \lesssim 0.16$ nK; Beliaev damping gives $\tau \sim 25$ ms at $k\xi \sim 1$ and $50\text{--}70\ \mu\text{s}$ at $k\xi \sim 2.5$. The corrected design study is an honest feasibility study, not a ready proposal.

11.4 The verdict

The analogue program is the cheapest empirical handle on the mechanism. No experiment has been performed. The BEC proposal is a design study with a specific, documented feasibility gap. The 2026 optical proposal of Bermudez and Leonhardt [60] ties time travel to lasing and amplified vacuum fluctuations, which sets the quantum limits; Barceló et al. show that analogue systems can simulate CTCs only without a chronology horizon [61]; and the current analogue-gravity review [63] is the standard citation for “kinematics, not dynamics.”

12 The engineering ledger

12.1 The invoice

The companion ledger P13 separates the invoice into matter, wrap, placement, sourcing, and survey [92]. The separation matters because the dials are coupled: one cannot pay for the mass with the density, or for the survey with the wrap.

12.2 Matter

The canonical corner is not ordinary matter. At $k_0 = 0.499$ ($\tau_0 = -1\ \text{m}^2$) the hand-off density is $\varepsilon_0 = 4.0 \times 10^{25}\ \text{kg}/\text{m}^3$, with a peak of $1.17 \times 10^{26}\ \text{kg}/\text{m}^3$, about 5×10^8 times nuclear saturation. At the deep rung $k_0 \simeq 2.2 \times 10^{-12}$ the density is $778\ \text{kg}/\text{m}^3$ —sand or water—but the mass is asteroid-class, $1.3\text{--}2.4 \times 10^{16}\ \text{kg} \cdot L_z$. The density scales as k_0^2 , the total mass as k_0 at fixed ρ_0 and L_z , and $M_{\text{layer}} = 3.30\ k_0 L_z$. The “tens of tons” figure requires picometre loops and is not usable.

12.3 Mass and loop size

Mass and CTC loop size are tied through L_z : both scale linearly. Shrinking the loops is the only way to shrink the mass at fixed depth. The canonical design has a 3.3 ns lead, 16 cm loops, and a full envelope mass of $2.9\text{--}5.4 \times 10^{27}\ \text{kg}$ ($1.5\text{--}2.8\ M_J$); the vacuum tube alone is $M_{\text{tube}} \approx 6.45 \times 10^{26}\ \text{kg}$ ($0.34\ M_J$). The compact-object wall is $c^2 \rho_0 / 2G \approx 3.4 \times 10^{26}\ \text{kg}$ ($0.18\ M_J$), so the envelope is about eight times the wall. At kilometre scale the mass is about $7 \times 10^{29}\ \text{kg}$; at AU scale about $10^{38}\ \text{kg}$ ($5 \times 10^7\ M_\odot$).

12.4 The a -floor and the stress

The horizon backreaction gives an a -floor of about 2×10^{-17} at metre scale. The canonical $a = 10^{-4}$ sits thirteen orders above it. The horizon stress is about $8 \times 10^{-9}\ \text{J}/\text{m}^3$ at canonical values, fifty-plus orders below the unit-curvature density.

12.5 Wrap, placement, sourcing, survey

The wrap tolerates tens-of-percent density errors and decimetre radial placement at metre scale. The deep-slice assembly must be sited at $\gtrsim 0.008\text{--}0.12$ AU heliocentric and matched to the relic to about $7 \times 10^{-5}\ \text{m}/\text{s}$. The mass cannot be launched; it must be sourced in situ from an asteroid-class body (Eros scale). The survey, not the wrap, is the civilization-scale problem: a metre-scale OFF relic is cloistered, and the findable targets are $\gtrsim 0.1$ ly pockets or relics caught in the trigger epoch.

Table 11: The engineering ledger by rung, with the review’s status vocabulary attached. The density and the total mass scale differently; conflating them is the most common arithmetic error in popular accounts.

Rung	k_0	Density	Total mass	Resource class	Status
Canonical	0.499	$4.0 \times 10^{25} \text{ kg/m}^3$	$2.9\text{--}5.4 \times 10^{27} \text{ kg}$ ($1.5\text{--}2.8 M_J$)	Not ordinary matter	CERTIFIED
$\tau_0 = -100$	—	—	—	Not ordinary matter; 33 ns lead	CERTIFIED
Deep	2.2×10^{-12}	778 kg/m^3	$1.3\text{--}2.4 \times 10^{16} \text{ kg} \cdot L_z$	Asteroid industry	EXTRAPOLATED
Kilometre	—	—	$\sim 7 \times 10^{29} \text{ kg}$	Planetary	EXACT
AU	—	—	$\sim 10^{38} \text{ kg}$	Stellar	EXACT

12.6 The resource class

The canonical and $\tau_0 = -100$ rungs are not cheaper versions of the deep rung; they are different machines made of matter that does not exist. The deep rung is an asteroid-industry machine. The honest conclusion is that nothing on the matter side needs new physics, and everything on the acquisition side is unsolved. The ledger is civilization-scale, not physics-scale. Table 11 separates the rungs and their status.

13 Open problems and falsifiers

13.1 Theory

The theory agenda is short and well posed. Each item has a first step.

1. **Four-dimensional backreaction.** Evolve the semiclassical equations on the Ori quotient. Does the horizon survive? Two dimensions are exactly zero; four dimensions are open. *First step:* a mode-sum stress on the $f \neq 0$ core.
2. **State selection.** What picks the thermal β^* state, or excludes it? *First step:* a Euclidean or thermodynamic argument on the quotient.
3. **Gauge-complete and nonlinear stability.** $k_\perp \neq 0$, all ten components, the quotient Cauchy problem, nonlinear modes. *First step:* the full ten-component linear system.
4. **The $O(a)$ envelope theorem.** The uniformity is exhibited, not proved. *First step:* analytic error bounds on the profile family.
5. **The $3+1$ CFG gap.** Is there a $3+1$ counterexample for a non-Gott data class? *First step:* a careful statement of the hybrid data class in $3+1$.
6. **Interacting-field QIs.** Classify which interactions preserve or fail state-independent bounds. *First step:* the Olum–Graham mechanism as a template.
7. **Topology change in quantum gravity.** Is there a UV-complete no-go, or a consistent nucleation amplitude? *First step:* a controlled instanton calculation.
8. **Holographic protection.** A boundary argument that no unitary CFT dual develops a chronology horizon. *First step:* the Emparan–Tomašević models at finite coupling.

Table 12: Falsifiers of the five claims. “Kill” means the claim as stated is false; “weaken” means it survives in a narrower form.

Claim	Falsifier	Effect	Feasibility
C1 Permis- sion	A theorem forbidding CTCs for all reasonable matter and QG	Kill	Very low
C1	A proof that $3 + 1$ CFG/CFGO covers all data classes	Kill	Moderate
C1	A proof that topology change is impossible in QG	Kill	Low
C2 Cracks	A state-independent QI for $\xi \neq 0$	Kill one crack	Low
C2	A null QI in 4D for free fields	Kill one crack	Low
C2	KRW extended to non-compact horizons	Kill the constructive escape	Moderate
C3 Con- struction	A 4D backreaction that destroys the horizon	Kill	High priority
C3	A gauge-complete nonlinear instability with a per-wrap amplifier	Kill	Moderate
C3	A proof that the Ori CH is compactly generated	Kill the finite-stress relevance	Moderate
C4 Acqui- sition	A $3 + 1$ CFG counterexample for a non-Gott class	Weaken to $2 + 1$	Moderate
C4	A classical topology-change process from trivial data	Kill	Very low
C4	A traversable wormhole in inventory	Kill the premise	Low
C5 Obser- vation	A confirmed shared-base pair across independent pairs	Kill the null	Low
C5	A detected relic with the exact double-image signature	Kill the null	Low
C5	A confirmed acausal signal	Kill the premise	Very low

9. **Xavier full system.** The ten-component, longitudinal, quotient-Cauchy, and nonlinear sectors; the ignition-wave energy. *First step:* the constraint propagation.

10. **The survey efficiency model.** Turn the count limit into a density bound; a hierarchical family fit; a sharper Gaia family statistic with measured power. *First step:* an injection model with a measured selection function.

13.2 Experiment

The experimental agenda is equally short. The analogue horizon, the QI tests, the Casimir shaping, the GW re-run, and the dedicated lensing survey are the five live channels. None is guaranteed to reach a chronology horizon; all are well posed.

13.3 Falsifiers

The thesis is a conjunction of five claims (C1–C5). A single clean falsifier of any claim forces a rewrite, not a footnote. Table 12 separates kills from weakenings.

Table 13: The status of the central claims. “Established” means theorem or certified computation under stated hypotheses; “open” means a well-posed problem with no answer; “conjectured” means evidence without proof.

Claim	Status	Scope
No theorem forbids CTCs outright	Established	Every no-go is conditional
KRW for compactly generated horizons	Theorem	Free fields, fixed background, ill-definedness not divergence
CFG/CFGO obstruction	Theorem in 2 + 1; gap in 3 + 1	Hybrid class inside intended scope
Geroch topology-change dichotomy	Theorem	Classical GR
Topological censorship	Theorem	NEC; simply connected asymptotic region
QI cracks (null, ξ , interacting, curvature)	Established	Each is a theorem or explicit model; none is the Standard Model
Ori 2005 core	Exact	Vacuum, regular, asymptotically flat; stability open
Ori 2005 stress at local CH	Computed	Test-field, conditional on non-compact CH and Huygens truncation
Hybrid envelope	Certified	Numerical gates on a stated grid; $O(a)$ uniformity conjectured
4D backreaction	Open	2D is exactly zero
State-selection principle	Open	4D extension missing
Gauge-complete nonlinear stability	Open	Analyzed sectors neutral
Xavier full stability	Open	Train neutral in analyzed sectors
3 + 1 acquisition theorem	Open	2 + 1 proofs only
Relic detection	Null	Count limit, no density bound
Gaia census	Null, no exclusion	No epoch spectra
BEC chronology horizon	Design study	Nine documented blockers (B1–B9)

13.4 What is established, what is open, what is conjectured

Table 13 is the review’s summary ledger. It is the table a reader should photograph.

14 Conclusions

The five claims can now be stated in one sentence each.

C1, permission. No known theorem forbids CTCs outright; every rigorous no-go is conditional on compact generation, free or minimally coupled fields, open-universe data with timelike total momentum, or classical topology change.

C2, cracks. The quantum inequalities and chronology protection have verified cracks—no null QI in 4D, no state-independent QI for non-minimally coupled scalars, static violation in an interacting model, non-compact horizons beyond KRW—but the cracks are narrower than the counter-folklore. They do not reopen the door; they widen the frame.

C3, construction. The Ori 2005 core, completed by the hybrid dust envelope, is an explicit, vacuum-plus-dust, asymptotically flat, quantum-benign *initial data set* (ordinary density at the deep rung, not at the canonical corner). The stress at the local eikonal horizon is negligible in

the test-field computation, conditional on the horizon being non-compactly generated and on the Huygens truncation. The 4D backreaction is open, and the global horizon is not proven.

C4, acquisition. The defining structure, a boost holonomy, is not manufactured by any known classical route. CFG/CFG0, Geroch, Deser–Jackiw–’t Hooft, Cutler, Friedman–Schleich–Witt, and Minguzzi block or constrain those routes; the $3+1$ statement is an argument with a proof gap, not a theorem. The remaining routes are primordial inheritance, quantum nucleation, and reproduction; each is a scenario, not a mechanism.

C5, observation. The observational channels are null or limited. The GW survey gives a calibrated count limit of $\mu < 274$ detectable families at its operational threshold, not a density bound; the Gaia census is consistent with an astrophysical background under a composition-matched null, with no detection and no exclusion.

The answer to the question is therefore conditional and sharp: *physics does not close the door; engineering and topology acquisition do*. The best constructive model is quantum-benign, but no known route manufactures its defining identification. The no-go theorems have verified cracks, but their scope is routinely overstated in both directions. The open problems are the 4D backreaction, the state-selection principle, gauge-complete nonlinear stability, a $3+1$ acquisition theorem, and a survey with a measured efficiency.

What would change the answer? A 4D backreaction computation that destroys the horizon; a proof that the Ori horizon is compactly generated; a gauge-complete nonlinear instability with a per-wrap amplifier; a $3+1$ acquisition theorem; a confirmed relic; or a laboratory QI violation. Each is a well-posed target, and each is listed in Table 12. None is a reason to stop looking, and none is a reason to start claiming that a machine has been built.

The final caution is about tone. The review’s most likely failure mode is not being wrong about the physics but being read as advocacy. The engineering gap is enormous, the acquisition gap is unsolved, and the observational channels are null. The correct conclusion is not “time travel is possible” or “time travel is impossible.” It is the conditional: permission is not construction, and construction is not acquisition.

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