Causal Symmetry — Technical Supplement I:
From Principle to Toy Model and Falsifiable Scalings

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Abstract

This supplement executes the four development steps identified in the submission notes of *A Quantum-Causal Model of Existence and Time*: (1) an explicit toy isometry realizing the boundary map U, formulated in code-subspace language; (2) at least one falsifiable scaling, the gravitational-wave echo delay $\Delta t \simeq (8GM/c^3)\ln(M/M_{\rm Pl})$, evaluated numerically for LIGO-band masses; (3) a technical comparison of spinfoam black-to-white transition estimates with the loop-quantum-cosmology (LQC) effective bounce; and (4) a point-by-point distinction between Causal Symmetry cycles and the aeons of conformal cyclic cosmology (CCC). Along the way we sharpen one formal statement of the parent papers: the emission channel cannot literally be $E = A^{-1}$, since only unitary channels are invertible; the consistent statement is that E is a partial isometry, the adjoint of A on its image. Throughout, established results, model-dependent estimates, and conjectures specific to this framework are labeled as such.

1 Purpose and scope

The parent papers propose the *Principle of Causal Symmetry*: gravitational absorption at a black-hole boundary ("Future Censor") is balanced by emission at a white-hole boundary ("Past Censor") in another causal domain, with a unitary map $U : \mathcal{H}_M \to \mathcal{H}_{M'}$ across a quantum bounce enforcing a global information balance, $d\mathcal{I}_{\rm tot}/dt = 0$, while each domain retains a local thermodynamic arrow, $\Delta S \geq 0$.

The papers state this at the level of principle. This supplement is the first step from principle toward model. Three levels of confidence are distinguished explicitly:

- **Established** (independent of this framework): black-hole thermodynamics [1, 2], the information problem [3, 4], the LQC effective bounce [5], and the mathematics of isometries, channels, and purifications used in Section 2.
- **Model-dependent literature results**: black-to-white tunneling and its time scales [6, 7, 8], Planck stars and white-hole remnants [9, 11, 12], echo phenomenology [20, 18].
- **Conjectures of this framework**: the cross-domain pairing itself, the White Hole Observer boundary condition, and the specific interpretations proposed in Sections 3–8.

2 The boundary map made precise

2.1 Why $E = A^{-1}$ must be refined

Equation (4) of the parent papers writes the emission channel as the inverse of the absorption channel, $E = A^{-1}$. Taken literally this is too strong: in quantum information terms, a channel (completely positive trace-preserving map) admits an inverse that is also a channel if and only if it is unitary. Absorption into a Planck-region Hilbert space $\mathcal{H}_P$ of larger dimension than the matter space $\mathcal{H}_M$ is not unitary on $\mathcal{H}_P$, so no channel inverse exists on all of $\mathcal{H}_P$.

The consistent statement uses isometries. Let

$$A:\ \mathcal{H}_M \to \mathcal{H}_P, \qquad A^\dagger A = \mathbb{1}_M, \tag{1}$$

so that A preserves inner products (no information is lost on absorption) and

$$\Pi \equiv AA^\dagger \tag{2}$$

is the projector onto the *code subspace* $\mathrm{ran}(A) \subset \mathcal{H}_P$ — the subspace of Planck-region states that carry the absorbed information. Define the emission map as

$$E \equiv WA^\dagger:\ \mathcal{H}_P \to \mathcal{H}_{M'}, \tag{3}$$

where $W : \mathcal{H}_M \to \mathcal{H}_{M'}$ is the unitary (possibly antiunitary, if the map includes time reversal Θ) identification of mode bases between the two domains. Then

$$EA = W \quad \text{(perfect transfer)}, \qquad E^\dagger E = \Pi \quad (E \text{ is a partial isometry}). \tag{4}$$

E inverts A *on the image of* A and annihilates its orthogonal complement. This is the mathematically defensible reading of $E = A^{-1}$, and we propose adopting it in any revision of the parent papers.

2.2 The White Hole Observer as code-subspace preservation

Let $U_B : \mathcal{H}_P \to \mathcal{H}_P$ denote the (unknown) microscopic bounce dynamics. The total map is

$$U \ \equiv\ E\,U_B\,A \ =\ W\,(A^\dagger U_B A):\ \mathcal{H}_M \to \mathcal{H}_{M'}. \tag{5}$$

U is unitary precisely when U_B preserves the code subspace, $[U_B, \Pi] = 0$ on the relevant sector. This gives the *White Hole Observer* a sharp, non-anthropomorphic formulation:

> **WHO condition.** The physical bounce dynamics commutes with the code-subspace projector: information absorbed by the Future Censor is confined to $\mathrm{ran}(A)$ and is therefore recoverable, in full, by the Past Censor's emission map $E = WA^\dagger$.

Two remarks. First, this is structurally identical to the exact-recovery condition of quantum error correction, and thereby connects Causal Symmetry to the holographic quantum error-correction program [15], where bulk information is likewise protected in a code subspace of a boundary theory. Second, the condition is falsifiable in principle at the level of models: any candidate microphysics for U_B (e.g. a spinfoam transition amplitude, Section 7) either does or does not preserve $\mathrm{ran}(A)$ to the required accuracy.

3 Toy model 1: a qubit code-subspace isometry

This section supplies the "toy isometry for the boundary map U" requested in the submission notes. It is deliberately minimal.

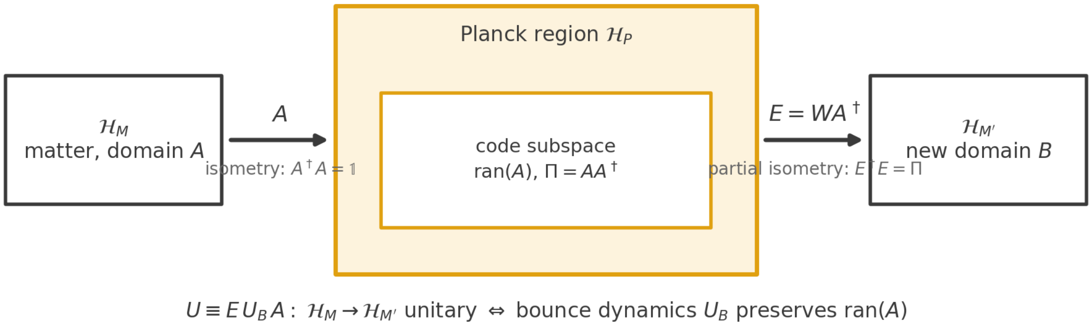

Figure 1: The refined boundary map. Absorption A is an isometry into the Planck region; emission $E = WA^\dagger$ is a partial isometry, the inverse of A on the code subspace $\mathrm{ran}(A)$. The total map $U = E\,U_B\,A$ is unitary iff the bounce dynamics U_B preserves the code subspace (the WHO condition).

3.1 Construction

Take the infalling matter to be a single qubit, $\mathcal{H}_M = \mathbb{C}^2$, and the Planck region to be three qubits, $\mathcal{H}_P = (\mathbb{C}^2)^{\otimes 3}$. Define the absorption isometry by the repetition encoding

$$A|0\rangle = |000\rangle, \qquad A|1\rangle = |111\rangle. \tag{6}$$

One checks $A^\dagger A = \mathbb{1}_2$, and $\Pi = AA^\dagger$ projects onto $\mathrm{span}\{|000\rangle, |111\rangle\}$, a two-dimensional code subspace inside the eight-dimensional Planck region. With $W = \mathbb{1}$ (no relabeling between domains) the emission map is $E = A^\dagger$.

3.2 Worked example

Let the infalling state be $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ with $|\alpha|^2 + |\beta|^2 = 1$. Then

$$A|\psi\rangle = \alpha|000\rangle + \beta|111\rangle. \tag{7}$$

Suppose the bounce dynamics acts within the code subspace as a relative phase, $U_B|000\rangle = |000\rangle$, $U_B|111\rangle = e^{i\theta}|111\rangle$ (any U_B with $[U_B, \Pi] = 0$ works). The emitted state in domain B is

$$U|\psi\rangle = E\,U_B A|\psi\rangle = \alpha|0'\rangle + e^{i\theta}\beta|1'\rangle, \tag{8}$$

a pure state with unit norm: the transfer has fidelity one up to a known unitary. Global information is conserved, $S(|\Psi\rangle\langle\Psi|) = 0$ throughout, realizing $d\mathcal{I}_{\mathrm{tot}}/dt = 0$ exactly.

By contrast, an observer confined to domain A after horizon formation has access to no complete set of commuting observables for the code subspace; tracing out the transferred degrees of freedom leaves the maximally uninformative state $\rho_A = \mathrm{Tr}_{\mathrm{code}}|\Psi\rangle\langle\Psi|$, whose entropy is positive. Locally, information *appears* lost; globally it is not. This is the toy-model statement of the paper's central slogan (absorption in one domain, emission in another, nothing destroyed).

3.3 What this does and does not show

It shows: (i) the boundary map can be written down explicitly and is internally consistent; (ii) "inverse emission" survives scrutiny once phrased as a partial isometry; (iii) the WHO condition is a precise property of U_B, not a metaphor. It does not show: that gravitational collapse actually implements such an encoding; what fixes $\dim \mathcal{H}_P$ (plausibly $e^{S_{BH}}$ with $S_{BH} = A_{\rm hor}/4G\hbar$ [1]); or how the code subspace is dynamically selected. Those are the open microphysics questions of Section 10 of the long-form paper, now stated sharply.

4 Toy model 2: cross-domain entanglement and the local arrow

The repetition code captures transfer but not thermality. A second standard structure captures the thermodynamic phenomenology: the two-mode squeezed (thermofield-double) state. For a field mode of frequency ω, let ($\hbar = k_B = 1$)

$$|\Phi\rangle = \sqrt{1-\lambda^2}\,\sum_{n=0}^{\infty} \lambda^n\,|n\rangle_A|n\rangle_B, \qquad \lambda = e^{-\omega/2T_H}, \qquad T_H = \frac{1}{8\pi GM}, \tag{9}$$

with $|n\rangle_A$ modes accessible in the collapse domain and $|n\rangle_B$ their partners in the emergent domain. Standard results then give:

- **Local thermality.** $\rho_A = \mathrm{Tr}_B|\Phi\rangle\langle\Phi|$ is exactly thermal at T_H, with mean occupation $\bar{n} = (e^{\omega/T_H} - 1)^{-1}$ and entropy

$$S_A = (\bar{n}+1)\ln(\bar{n}+1) - \bar{n}\ln\bar{n} \ > \ 0. \tag{10}$$

  Domain A sees irreversible, entropy-increasing Hawking emission: the paper's Eq. (6), $\Delta S \geq 0$, and its Figure "entropy increases toward gravitational absorption."

- **Global purity.** $S_{AB} = 0$: the joint state is pure. Nothing is destroyed; the apparent mixedness of each side is entirely mutual information.

- **Low-entropy origin.** The state received in domain B is, jointly with A, pure. Its fine-grained entropy is zero; entropy in domain B subsequently grows only by B-local coarse-graining. This is the precise content of the paper's Figure "entropy increases away from low-entropy origin": a new domain begins at minimal fine-grained entropy *because* it is the purification of what the other domain absorbed. This also gives the framework's version of the "past hypothesis": the low-entropy start is not an unexplained boundary condition but the image of an absorption event, echoing the perspectival reading of past low entropy in [12].

- **ER=EPR bridge.** The thermofield double is exactly the state for which Maldacena–Susskind [13] propose a wormhole dual. The paper's Figure 5 ("entanglement bridge") is therefore not merely a cartoon: Eq. (9) is its standard quantitative referent, with the two "domains" playing the roles of the two wormhole mouths.

Together, the two toy models factorize the framework's claims: the code-subspace isometry realizes *conservation* ($d\mathcal{I}/dt = 0$, $U^\dagger U = \mathbb{1}$), and the thermofield double realizes *local irreversibility with global purity* ($\Delta S \geq 0$ per domain). A full model must realize both in one dynamical setting; Section 7 discusses the candidates.

5 A falsifiable scaling: echo delay versus mass

The submission notes ask for "at least one falsifiable scaling (e.g., echo delay vs. M)." Here it is, with the derivation and numbers.

5.1 Derivation

If the quantum bounce replaces the classical horizon with structure located a proper Planck length $\ell_{\rm Pl}$ outside the would-be Schwarzschild radius $r_s = 2GM/c^2$, then ingoing gravitational-wave perturbations are partially reflected there rather than perfectly absorbed. The round-trip light time between the photon-sphere potential barrier ($r \approx 3r_s/2$) and the near-horizon structure sets a delayed, repeating "echo" after the ringdown.

In Schwarzschild coordinates the tortoise coordinate is $r_*(r) = r + r_s \ln(r/r_s - 1)$. A structure at proper distance $\ell_{\rm Pl}$ sits at coordinate offset $\varepsilon \simeq \ell_{\rm Pl}^2/4r_s$ above r_s, so the round trip gives, to leading logarithmic accuracy,

$$\Delta t_{\rm echo} \simeq \frac{2r_s}{c}\ln\frac{r_s}{\varepsilon} = \frac{4r_s}{c}\ln\frac{2r_s}{\ell_{\rm Pl}} \simeq \frac{8GM}{c^3}\ln\frac{M}{M_{\rm Pl}}, \tag{11}$$

where the last step absorbs $O(1)$ factors into the logarithm's argument (they shift Δt by only a few percent at stellar masses). Equation (11) is the $8M \ln M$ (Planck units) template delay of Abedi–Dykaar–Afshordi [18]; spin corrections multiply the prefactor by $(1 + 1/\sqrt{1-a^2})/2$.

5.2 Numbers

$M/M_\odot$	GM/c^3 (ms)	$\ln(M/M_{\rm Pl})$	$\Delta t_{\rm echo}$ (ms)
10	0.049	89.7	35
30	0.148	90.8	107
65	0.320	91.6	235
100	0.493	92.0	363

Table 1: Predicted echo delays for Planck-depth near-horizon structure, Eq. (11) (Schwarzschild, zero spin). The $65\,M_\odot$ row corresponds to a GW150914-class remnant; the ~ 0.2–0.3 s delay is what [18] searched for.

5.3 Why this is falsifiable, and its current status

The scaling is sharp: across a catalog of merger events, echo delays must track remnant mass linearly with slope $8G\ln(M/M_{\rm Pl})/c^3$, not, e.g., cluster at a fixed delay or scale as a power law. Ever-deeper nulls at these delays progressively bound the reflectivity of any Planck-depth structure and, within Causal Symmetry, the coupling of the code-subspace boundary to exterior perturbations. Honesty requires stating the observational status plainly: the tentative 2.5σ evidence of [18] was not confirmed at that significance by independent reanalysis [19], and echoes remain undetected; see [20] for the phenomenological framework.

Framework-specific conjecture (labeled as such): in Causal Symmetry the reflecting structure is not a mirror but the code-subspace projector Π. Reflectivity should then be state-dependent and phase-coherent (a unitary boundary condition), suggesting correlated phases across successive echoes rather than incoherent damping. Turning this into a quantitative echo template is the natural next calculation.

6 The lifetime fork: M^2 versus exponential

A second scaling matters for phenomenology: how long a black hole lives before the black-to-white transition completes. The literature contains two answers, and the 2024 revision of the spinfoam

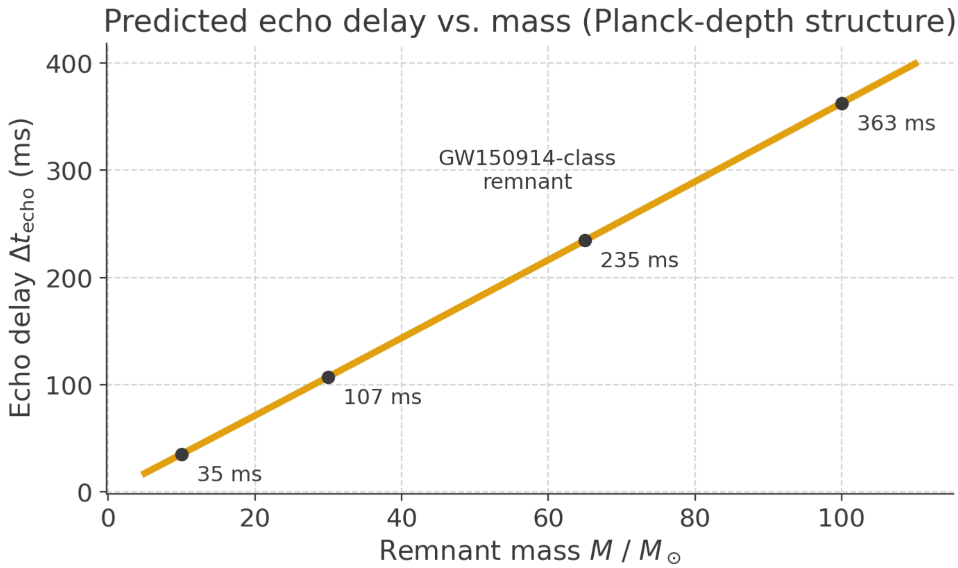

Figure 2: Echo delay versus remnant mass, Eq. (11). The relation is linear in M with a slowly varying logarithmic factor $\simeq 90$: a distinctive, cross-event prediction.

analysis [7] makes the distinction explicit: the *crossing time* of the geometry transition scales linearly in M, while the *lifetime* (set by the tunneling probability) scales exponentially, $\tau \sim e^{(M/M_{\rm Pl})^2}\, t_{\rm Pl}$. The earlier Haggard–Rovelli estimate [6] argued instead that accumulated quantum effects outside the horizon trigger the transition at

$$\tau_{\rm HR} \sim \left(\frac{M}{M_{\rm Pl}}\right)^2 t_{\rm Pl} \;\approx\; 1.4\times 10^{25}\,{\rm yr}\left(\frac{M}{M_\odot}\right)^2, \tag{12}$$

parametrically shorter than the Hawking evaporation time $\tau_{\rm H} \approx 5120\pi\,(M/M_{\rm Pl})^3\,t_{\rm Pl} \approx 2.1\times 10^{67}\,{\rm yr}\,(M/M_\odot)^3$ [2]. Effective loop-quantum-gravity collapse models [8] likewise find polynomial-in-M external delays, though in model-dependent settings.

The two branches have cleanly different observable consequences (Figure 3):

- **If $\tau \sim M^2$:** primordial black holes of $M_* = M_{\rm Pl}\sqrt{t_U/t_{\rm Pl}} \approx 6\times 10^{22}\,{\rm kg} \approx 3\times 10^{-8} M_\odot$ are completing their bounce *today*. Their horizon size $r_s \approx 0.1\,{\rm mm}$ sets an emission wavelength in the sub-millimeter band ($\sim$THz), with a possible higher-energy component set by the collapse temperature; Barrau–Rovelli [10] develop this phenomenology, including a speculative connection to fast radio bursts. Sub-mm/THz transient searches therefore directly probe this branch.
- **If $\tau \sim e^{(M/M_{\rm Pl})^2}$:** no astrophysical black hole has bounced; the transition matters only at the evaporation endpoint, yielding long-lived Planck-mass white-hole remnants [11], which Rovelli–Vidotto propose as a dark-matter component [12] — purely gravitational, with no nuclear-recoil signature, a scenario kept alive by continued null results in direct-detection experiments (consistency, not evidence).

For Causal Symmetry the fork is not a threat but a target: the framework needs the transition to occur (else the Past Censor never fires), and the two branches tell us where to look — sub-mm

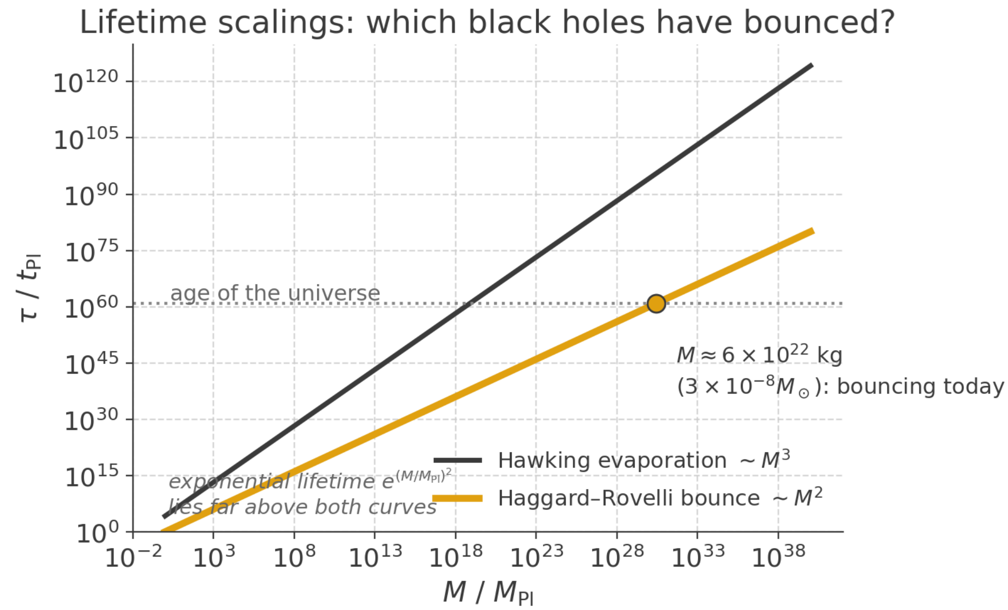

Figure 3: Lifetime scalings in Planck units. Under the Haggard–Rovelli M^2 scaling (gold), objects of $\approx 6 \times 10^{22}$ kg bounce at the present age of the universe; under the Hawking M^3 scaling (dark) only $\sim 10^{12}$ kg objects evaporate today; the exponential spinfoam lifetime lies far above both for all macroscopic masses.

transients now, or remnant-dominated dark matter. Deciding between them is a quantum-gravity calculation (Section 7), not a free parameter.

7 Spinfoam transition versus LQC bounce

The submission notes request "a technical comparison of spinfoam transition estimates and the LQC bounce." Table 2 gives the comparison; the prose below draws the moral for this framework.

The complementarity is exact where this framework needs it: LQC guarantees that "through the bounce" is a meaningful place for the map U to live (no singularity, finite curvature), while the spinfoam program is the only current source of numbers for the rate at which Future Censors hand over to Past Censors. The framework's central formal object, U_B restricted to $\mathrm{ran}(A)$, is precisely what a spinfoam transition amplitude between boundary states would compute. Proposing that calculation — boundary spin-network states chosen to encode a known infalling qubit, amplitude tested for code-subspace preservation — is, we suggest, the most concrete research program this framework can currently state.

8 Causal Symmetry is not CCC: a point-by-point distinction

Penrose's conformal cyclic cosmology [21] is the best-known cyclic framework and the one reviewers will most naturally reach for. The submission notes ask for a short table distinguishing the two; Table 3 provides it.

The decisive row is the second: the two programs make *opposite* commitments about unitarity. CCC needs information destruction; Causal Symmetry is defined by its denial. They are therefore distinguishable in principle: unambiguous evidence of unitarity-restoring structure (echoes, remnants,

	LQC effective bounce [5]	**Spinfoam transition** [6, 7]
Formalism	Canonical / effective equations on symmetry-reduced (minisuperspace) geometry	Covariant path integral (Lorentzian EPRL amplitudes) over 4-geometries
What is computed	Modified Friedmann dynamics: $H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$, bounce at $\rho_c \approx 0.41\,\rho_{\rm Pl}$	Amplitude for a trapped (black) exterior geometry to tunnel to an anti-trapped (white) one
Character	Deterministic: every trajectory bounces at $\rho = \rho_c$	Probabilistic: a tunneling event with mass-dependent rate
Time scales	Bounce duration Planckian in the effective theory	Crossing time $\sim M$ (linear); lifetime $\sim e^{(M/M_{\rm Pl})^2} t_{\rm Pl}$ [7]; cf. the M^2 trigger argument [6] and polynomial delays in effective collapse models [8]
Domain of validity	Homogeneous interior/cosmological sector; robust within that class	Full geometry transition including the exterior; estimates depend on amplitude approximations
Role in Causal Symmetry	Supplies the *kinematics* of Eq. (5): a nonsingular bridge where $\mathcal{H}_M \to \mathcal{H}_{M'}$ can be defined	Supplies candidate *microphysics and rates* for U_B, hence for when/whether the WHO condition can hold

Table 2: Effective LQC bounce versus covariant spinfoam black-to-white transition.

purity-restoring correlations in late Hawking radiation [4]) favors this framework over CCC, while confirmed Hawking-point-like anomalies *without* any such structure would favor CCC. The nearest relatives of Causal Symmetry are in fact not CCC but the two-arrow cosmologies — the Janus-point construction [24], the Carroll–Chen fluctuating de Sitter picture [25], the Aguirre–Gratton steady state [26] — and the holographic white-hole origin of Pourhasan, Afshordi and Mann [27]. What Causal Symmetry adds to that family is the specific pairing mechanism (censor boundaries + code-subspace transfer) rather than a statistical or inflationary origin of the two arrows. Any revision of the parent papers should cite this family explicitly.

9 Objections a referee will raise

1. **Firewalls.** AMPS [16] argue that smooth horizons, unitarity, and effective field theory cannot all hold. Causal Symmetry needs a smooth horizon (matter must transit to the Planck region). The modern escape routes — code subspaces and entanglement-wedge reconstruction [15], replica-wormhole/island computations of the Page curve [17] — are structurally friendly to the WHO condition (both protect interior information nonlocally), but the compatibility has to be shown, not asserted.

2. **The Page curve.** If Hawking radiation alone purifies (as island calculations indicate [17]), what remains for the Past Censor to emit? The consistent answer within this framework is that cross-domain transfer carries the *residual* interior at the end of (partial) evaporation — naturally aligning Causal Symmetry with the remnant branch of Section 6. On the M^2 branch the framework must instead explain how early bounces coexist with a Page-curve-consistent exterior. This is the sharpest internal tension the framework currently has; it should be stated in any revision.

	Causal Symmetry (this work)	**Conformal cyclic cosmology** [21]
Cycle mechanism	Quantum bounce at Planckian density (LQC/spinfoam), black-to-white hand-off between paired domains	Conformal rescaling identifying the infinite timelike future of one aeon with the big bang of the next
Information	Strictly unitary: $U^\dagger U = \mathbb{1}$, $d\mathcal{I}_{\text{tot}}/dt = 0$; information loss forbidden by construction	Information loss in black-hole evaporation is *embraced* as the mechanism that resets phase-space volume between aeons
Entropy reset	Transferred state is (jointly) pure; new domain starts at zero fine-grained entropy, grows by local coarse-graining (Sec. 4)	Weyl curvature hypothesis; gravitational entropy erased at the conformal crossover
Domain structure	Paired, causally disconnected domains; potentially branching (many censors, many domains)	Strictly sequential aeons sharing one conformal manifold
Arrow of time	Local arrow per domain; meta-structure time-symmetric (Janus-like, cf. [24, 25, 26])	Single arrow threading all aeons
Signatures	GW echoes with $\Delta t \simeq (8GM/c^3)\ln(M/M_{\text{Pl}})$; sub-mm transients from bouncing PBHs (if $\tau \sim M^2$); Planck-mass remnant dark matter (if exponential); cross-domain initial-condition correlations	Hawking points; low-variance concentric circles in the CMB [22, 23]
New physics required	Nonsingular bounce + code-subspace-preserving dynamics (WHO condition)	Conformal (mass-free) matter era in the far future of each aeon

Table 3: Causal Symmetry cycles versus CCC aeons.

3. **Operational meaning.** Conservation "across causally disconnected domains" is unobservable from within one domain unless the domains reconnect or share imprints. The framework's empirical content therefore lives entirely in Sections 5 and 6 plus possible initial-condition correlations; the global balance itself is an interpretive (though internally consistent) postulate. Saying this plainly will disarm the most common referee complaint.

4. **White-hole instability.** Classical white holes suffer a blueshift instability; long-lived white-hole phases require the quantum analysis of [11] (small holes stabilized by quantum effects). The framework inherits whatever resolution that literature achieves.

5. **Energy bookkeeping.** $E = WA^\dagger$ conserves information by construction, but the associated stress-energy flow across the bounce (what powers the emergent domain?) is not yet specified. The LQC effective dynamics conserves an effective energy through the bounce; whether that extends to the paired-domain picture is open.

10 Falsification summary and next steps

The framework, as sharpened here, is committed to: (a) near-horizon structure at Planck proper depth, hence echo delays following Eq. (11)'s mass scaling; (b) a completed black-to-white transition on one of the two lifetime branches, hence either sub-mm transients from $\sim 6 \times 10^{22}$ kg primordial holes or a Planck-mass-remnant dark-matter component; (c) exact global unitarity, hence eventual purity-restoring correlations in Hawking radiation [4] and the strict absence of the information loss CCC requires.

Concrete next calculations, in order of tractability: (1) an echo template from a code-subspace boundary condition (state-dependent, phase-coherent reflectivity) fit against public LIGO/Virgo posteriors; (2) a spinfoam transition amplitude between boundary states encoding a known qubit, tested for code-subspace preservation (the WHO condition as a calculation); (3) an estimate of cross-domain initial-condition correlations and whether any CMB statistic could inherit them; (4) editorially: quarantine the consciousness analogy (Section 9 of the long form) into a separate essay, so that the physics core is refereed on its own terms.

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