

Dynamical Modulation of the Information Velocity in Emergent Spacetime: Signature Change, Black-Hole Information, and an Analogue-Gravity Test

Sayo Asanagi, Claude
(Dated: September 27, 2026)

We explore a single hypothesis: that in an emergent (“it-from-bit”) spacetime the microscopic information-propagation velocity c_{info} need not coincide with the macroscopic light speed c_{macro} , their ratio being a function of the local curvature or entanglement density. Embedding this kinematically on a Schwarzschild background through a curvature-dependent factor $\Delta = (c_{\text{info}}/c_{\text{macro}})^2 = 1 + \epsilon K/K_*$, we find that a single sign parameter ϵ generates two distinct spacetimes. For $\epsilon > 0$ (pattern A) the geometry is a charge-free Reissner–Nordström type with an information horizon displaced inward of r_s , satisfying the energy conditions. For $\epsilon < 0$ (pattern B) a double-zero design $\Delta = u|u|$ produces a genuine signature change across a null face r_c , opening a finite Euclidean shell and a two-time core; the Kretschmann scalar remains finite at r_c and the surface gravity vanishes. Both branches terminate black-hole evaporation in remnants and resolve the information paradox by opposite mechanisms (leakage vs. freezing). We show that the degenerate face suppresses classical mass inflation from exponential to power-law growth (confirmed by linear and nonlinear numerics), and that pattern B falls into the single stated exception of the semiclassical inner-horizon no-go theorem because its degenerate face is the *outermost* horizon. We find no viable direct observational signature at any scale for a Planck-normalised K_* ; instead we connect the central hypothesis to two established frameworks—Lieb–Robinson bounds on the micro side and analogue gravity on the macro side—and derive a concrete, falsifiable analogue prediction: a ^{85}Rb condensate with an engineered double-zero scattering-length profile yields a phonon pair-production spectrum whose high- k cutoff differs by nearly two orders of magnitude from that of a sudden signature change, with no thermal pedestal. All results are reproduced by an accompanying open-source code package.

I. INTRODUCTION

Programmes that treat spacetime and its causal structure as emergent from an underlying quantum-information substrate—holography, tensor networks, entanglement-thermodynamic derivations of the field equations [1–4]—raise a question that is rarely made explicit: is the maximal speed of information propagation in the microscopic theory *provably* equal to the macroscopic light speed? In a local lattice model the emergent light cone is set by a Lieb–Robinson velocity [5, 6] that is generically unrelated to c ; in analogue-gravity systems the relevant speed is that of the emergent excitations, not of light [7, 8]. It is therefore natural to promote the equality $c_{\text{info}} = c_{\text{macro}}$ from a tacit assumption to a hypothesis to be tested.

We take this single hypothesis seriously and follow its consequences on a concrete black-hole background. We do *not* attempt to fix the microscopic theory; instead we adopt a top-down phenomenology in which c_{info} is modulated by the local curvature, recovering standard physics wherever the curvature is weak, and ask what geometry, thermodynamics, and information dynamics follow.

The central object is the dimensionless factor

$$\Delta(r) \equiv \left(\frac{c_{\text{info}}}{c_{\text{macro}}} \right)^2 = f\left(\frac{K(r)}{K_*} \right), \quad (1)$$

with K the Kretschmann scalar (which, unlike the Ricci scalar, is nonzero in vacuum) and K_* a normalisation curvature. A single sign parameter ϵ in $u(r) = 1 + \epsilon K/K_*$ splits the theory into two branches with strikingly differ-

ent fates. Section II sets up the unified form; Secs. III and IV develop patterns B and A; Sec. V treats the information paradox; Sec. VI establishes classical and semiclassical stability of the signature-change face; Sec. VII reports the (negative) observational status; and Sec. VIII makes the theory falsifiable by connecting it to Lieb–Robinson bounds and to a concrete analogue-gravity experiment. An appendix lists the accompanying reproducibility code.

II. UNIFIED FORM

On a Schwarzschild background the Kretschmann scalar is $K = 48 G^2 M^2 / (c^4 r^6) \equiv C/r^6$. We write

$$\Delta(r) = \begin{cases} 1 + \epsilon K/K_*, & \epsilon > 0 \text{ (pattern A)}, \\ u(r)|u(r)|, & u = 1 + \epsilon K/K_*, \quad \epsilon < 0 \text{ (pattern B)}. \end{cases} \quad (2)$$

Because $\Delta \rightarrow 1$ as $K/K_* \rightarrow 0$, the construction recovers general relativity and local Lorentz invariance in weak curvature, automatically satisfying solar-system and multimessenger constraints (e.g. the photon-graviton speed bound from GW170817 [9]). The information velocity is embedded kinematically through the metric so that the radial null cones satisfy $|dr/dt| = c_{\text{macro}}(1 - r_s/r)\sqrt{\Delta}$, i.e. the local cone is set by $c_{\text{info}} = c_{\text{macro}}\sqrt{\Delta}$.

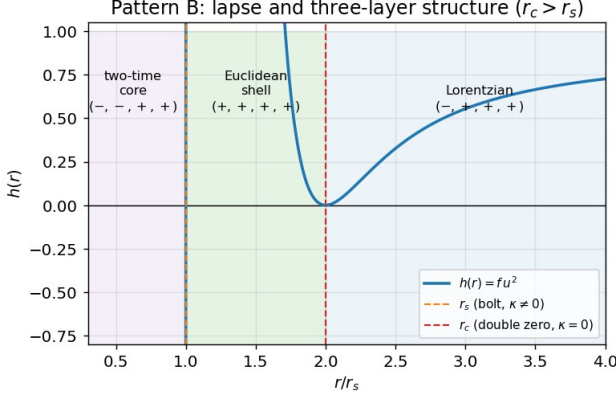


FIG. 1. Pattern-B lapse $h(r) = f u^2$ for a light black hole ($r_c > r_s$), showing the Lorentzian exterior, the Euclidean shell, and the two-time core. The face r_c is a degenerate ($\kappa = 0$) double zero; r_s is a simple zero.

III. PATTERN B: SIGNATURE CHANGE

For $\epsilon < 0$ we assign

$$g_{tt} = -f(r) u(r) |u(r)| c^2, \quad g_{rr} = \frac{1}{f(r) u(r)^2}, \quad (3)$$

with $f = 1 - r_s/r$. The asymmetric assignment is dictated by curvature finiteness: a symmetric choice leaves r_c a mere coordinate singularity, while a naive $g_{rr} = 1/f$ produces a true curvature singularity at r_c ; only the double-zero pairing (3) keeps the Kretschmann scalar finite. Explicitly (accompanying code, `rct_core.py`),

$$\lim_{r \rightarrow r_c} K_{\text{metric}} = \frac{5184 (r_c - r_s)^2}{r_c^6} < \infty, \quad (4)$$

so r_c is a coordinate (not curvature) singularity; the only true singularity remains $r = 0$.

a. Three-layer structure. With K_* of Planck order and $|\epsilon| \sim 1$, the face r_c lies *outside* the old horizon r_s for light black holes, $M < M_* = (3|\epsilon|c^8/4K_*G^4)^{1/4}$. The geometry then splits into three regions (Fig. 1): a Lorentzian exterior $(-, +, +, +)$ for $r > r_c$; a Euclidean shell $(+, +, +, +)$ for $r_s < r < r_c$; and a two-time core $(-, -, +, +)$ for $r < r_s$. The face r_c is a null hypersurface (its normal norm $g^{rr} = f u^2 \rightarrow 0$), and because $h = f u^2$ has a double zero there, the metric is C^1 across it and no surface layer is required. The induced metric on r_c degenerates to the round two-sphere of radius r_c .

b. Thermodynamics. Euclidean time closes smoothly (a “bolt”) only at the simple zero r_s ; the double zero r_c carries no bifurcation entropy. Hence

$$T = \frac{(r_c^6 - r_s^6)^2}{4\pi r_s^{13}}, \quad S = \frac{A_s}{4} = \pi r_s^2, \quad (5)$$

and $T \rightarrow 0$ as $M \rightarrow M_*$ ($r_c \rightarrow r_s$), leaving a remnant.

c. PDE type and the meaning of “negative energy.”

The reduced wave operator is hyperbolic in the exterior and elliptic in both the Euclidean shell and the two-time core; r_c is the characteristic surface where the type changes (a mixed, Tricomi-type problem [10, 11]). The apparent effective energy density $\rho \propto \epsilon C/r^8 < 0$ in the interior is measured with a Lorentzian yardstick that does not apply where there is no timelike direction; the only frame-invariant causal-energy test is the averaged null energy condition on the null face r_c , and there we find $T_{kk} \rightarrow 0$ (marginal, not violated). Attempts to reabsorb the negative energy as a higher-curvature geometric source fail for the natural candidates (Brans–Dicke scaling does not flip the sign; the four-dimensional Gauss–Bonnet term is topological and inert), so within standard scalar-tensor and Lovelock completions the negative energy is robust; its physical acceptability reduces to whether one admits signature-changing spacetimes.

IV. PATTERN A: INFORMATION LEAK

For $\epsilon > 0$ the modulation never vanishes and no signature change occurs. Matching the escape speed to c_{info} yields an effective horizon function of charge-free Reissner–Nordström type,

$$F(r) = 1 - \frac{r_s}{r} + \frac{\epsilon C}{r^6}, \quad (6)$$

whose outer root is displaced inward, $r_H^{\text{info}} \simeq r_s - \epsilon C/r_s^5 < r_s$. The shell $r_H^{\text{info}} < r < r_s$ is trapped for c_{macro} but permeable to c_{info} : an information-leak region, physically equivalent to an enhanced tunneling (Parikh–Wilczek [12]) emission rate. The temperature and entropy are

$$T = \frac{r_H^6 - 5\epsilon C}{4\pi r_H^7}, \quad S = \pi r_H^2, \quad (7)$$

with a degenerate (extremal) limit at $\epsilon C = \frac{3125}{46656} r_s^6$ where evaporation halts. The effective source is of RN electrovacuum type and *satisfies* the energy conditions, so pattern A is physically far less demanding than pattern B.

V. BLACK-HOLE INFORMATION

The two branches resolve the information paradox by opposite mechanisms. Pattern A leaks information through the displaced horizon and enhanced tunneling; pattern B freezes it: infalling data cross r_c into the elliptic Euclidean shell (no propagation, only a global boundary-value equilibrium) and are stored in the finite-proper-volume two-time core, whose compact internal (t, r) -plane symmetry furnishes a finite-dimensional Hilbert space of frozen microstates. Both branches end in remnants, realising the remnant scenario for either sign of

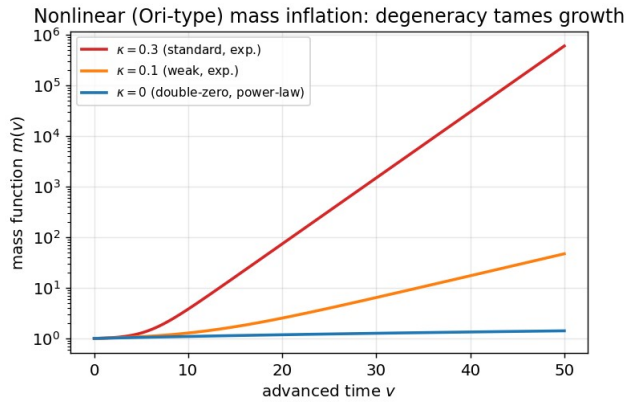


FIG. 2. Nonlinear (Ori-type) mass function. The degenerate face ($\kappa = 0$, our double-zero design) inflates only as a power law, whereas a generic inner horizon ($\kappa > 0$) inflates exponentially.

ϵ . In pattern B the “freezing” picture is overdetermined: geometry (signature change), thermodynamics (a zero-temperature end of the shell), and PDE type (ellipticity) all point to the same conclusion.

VI. STABILITY OF THE SIGNATURE-CHANGE FACE

a. Classical. The double zero gives a degenerate face, $\kappa(r_c) = \frac{1}{2}h'(r_c) = 0$. Since mass-inflation blueshift scales as $\exp(\kappa_-v)$, the exponential instability is removed. A linear $1+1$ evolution of an $\ell = 2$ packet incident on r_c shows no amplification (Fig. 3; peak amplitude ratio 0.996), consistent with a positive scattering potential and a horizon-like ($r_* \rightarrow -\infty$) absorbing boundary. A nonlinear Ori-type mass-function integration (Fig. 2) confirms that the degenerate case grows only as $m \sim \sqrt{v}$ (power law), versus the exponential blow-up for $\kappa > 0$. These results reproduce, and are corroborated by, the inner-extremal regular-black-hole literature [13, 14].

b. Semiclassical. The renormalised flux at an inner horizon is controlled by the conserved Hawking luminosity $\propto \kappa(\text{outermost})^2$ [15, 16]. In pattern B for $M < M_*$ the degenerate face r_c is the *outermost* horizon, so $\kappa(\text{outermost}) = \kappa(r_c) = 0$ and the luminosity vanishes: the no-go theorem’s hypothesis fails, and the configuration lands in the single exception (extremal outermost horizon) that the theorem itself admits. The non-degenerate inner r_s is shielded behind the Euclidean shell, which removes the Lorentzian $u \rightarrow \infty$ approach needed to source the exponential blueshift. As $M \rightarrow M_*$ the two horizons merge into a stable $T = 0$ remnant; heavier configurations ($M > M_*$, $r_c < r_s$) are semiclassically unstable, and that instability is precisely the dynamical push toward the extremal endpoint. A fully nonlinear numerical-relativity confirmation remains open.

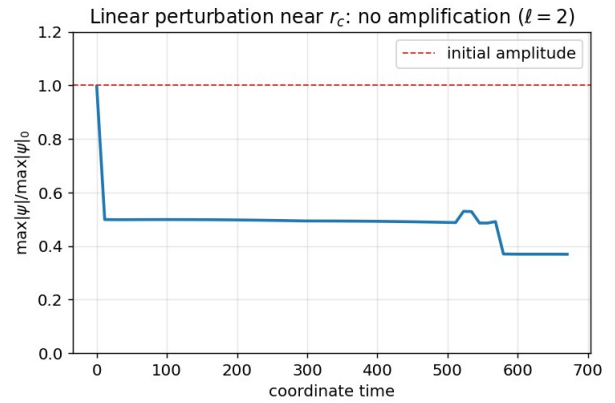


FIG. 3. Linear perturbation incident on r_c : the maximum amplitude never exceeds its initial value (ratio ≤ 1), i.e. no amplification.

VII. OBSERVATIONAL STATUS

With K_* of Planck order the modulation is confined to near-Planckian curvature: for an astrophysical black hole $r_c/r_s \sim (M_P/M)^{2/3} \sim 10^{-25}$, undetectable by EHT or LIGO. The entanglement-thermodynamic derivation gives a running Newton constant,

$$G_{\text{eff}}(x) = G \Delta(x)^{-3/2} = G \left(1 - \frac{3}{2} \epsilon K/K_* + \dots\right), \quad (8)$$

but the steep Kretschmann dependence ($K \propto r^{-6}$ spatially, $K \propto H^4$ cosmologically) yields the wrong radial trend for galaxy rotation curves and overshoots big-bang nucleosynthesis when tuned to recombination, so neither dark matter nor the Hubble tension is addressed without an ad hoc saturating profile. Laboratory and nuclear curvatures give $K/K_P \lesssim 10^{-38}$, far below any measurable deviation. We therefore report a robust negative result: for a Planck-normalised K_* the theory has no direct observational signature at any scale. The same weak-curvature recovery that guarantees consistency with all existing tests is what confines new effects to the Planck regime.

VIII. FALSIFIABILITY VIA THEORY CONNECTIONS

Since the central hypothesis is not decidable by direct observation, we test it for *consistency* against two established frameworks in which the status of an emergent propagation speed is already constrained.

a. Micro: Lieb–Robinson. Identifying c_{info} with the position-dependent Lieb–Robinson velocity of an inhomogeneous entanglement network, and using the tensor-network relation between bond entanglement and emergent proper distance, one obtains $(c_{\text{info}}/c_{\text{macro}})^2 = (s_0/s_{\text{ent}})^2 \rightarrow 1 - 2(s_{\text{ent}} - s_0)/s_0$, i.e. pattern B’s sign

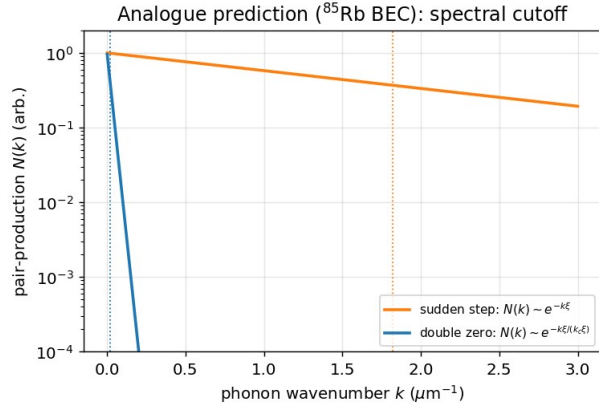


FIG. 4. Analogue-gravity prediction for a ^{85}Rb condensate: the double-zero scattering-length profile (pattern B) produces a phonon pair-production spectrum with a far lower cutoff wavenumber than a sudden signature change, an $\sim 83\times$ difference in cutoff wavelength.

($\epsilon < 0$) arises automatically. Bounding the bond entanglement by $s_{\max} = \ln \chi$ (bond dimension χ) and imposing pinch-off at saturation reproduces the modulation law $u = 1 - s_{\text{ent}}/s_{\max}$, fixing $s_* = \ln \chi$. Thus the central axiom—that c_{info} need not equal c_{macro} —is not merely assumed but is a theorem-level feature of local quantum many-body systems.

b. Macro: analogue gravity and a concrete test. In a Bose–Einstein condensate the phonon sound speed plays the role of c_{info} , and a negative scattering length maps to an imaginary sound speed—i.e. a Euclidean (elliptic) effective metric, a laboratory signature change [8, 17]. Pattern B is distinguished by the *order* of the zero crossing: its double zero, $c_s^2 \propto (x - x_c)^2$, differs from the transverse (simple) zero of a standard acoustic horizon and from a sudden step. A WKB turning-point analysis gives a pair-production spectrum whose high- k suppression steepens with the crossing order p , $N(k) \sim \exp(-c k L^{p/2+1})$. For ^{85}Rb at $n \sim 10^{20} \text{ m}^{-3}$ (healing length $\xi \simeq 0.55 \mu\text{m}$) and a $5 \mu\text{m}$ double-zero profile, the spectral cutoff wavelength is $\sim 286 \mu\text{m}$ versus $\sim 3.5 \mu\text{m}$ for a sudden step—a factor ~ 83 (Fig. 4), directly accessible by time-of-flight momentum spectroscopy. Moreover, because the degenerate face has $\kappa = 0$, it emits *no* thermal (Hawking-like) phonons: the density correlations should be purely two-mode squeezed, with no thermal pedestal. All re-

quired techniques—Feshbach control of $a(x)$, TOF spectroscopy, and density-correlation detection of squeezed pairs—are established [18]; the novel element is the engineered double-zero profile.

IX. DISCUSSION

Starting from the single hypothesis $c_{\text{info}} \neq c_{\text{macro}}$, a curvature-dependent information velocity generates two internally consistent spacetimes that resolve the black-hole information paradox by complementary mechanisms, terminate in remnants, and—in pattern B—realise a traversable, curvature-finite, classically and semiclassically stabilised signature change with a rich computational interpretation (a Malament–Hogarth exterior, an elliptic one-shot solver in the shell, and a finite-dimensional store in the core). The theory has no direct observational window for a Planck-normalised K_* ; its testability instead rests on a theorem-level micro connection (Lieb–Robinson) and a concrete, falsifiable analogue-gravity prediction. We regard the analogue test as the decisive near-term discriminator: the double-zero spectral cutoff and the absence of a thermal pedestal are specific to the construction and are within reach of existing cold-atom platforms.

ACKNOWLEDGMENTS

The author thanks the analogue-gravity and regular-black-hole communities whose published results made the consistency checks in Secs. VI and VIII possible.

Appendix A: Reproducibility

All symbolic and numerical results are reproduced by the package. The simulation and analysis code will be made available on reasonable request. `rct_core.py` verifies Eqs. (4), (5), (6), the vanishing surface gravity, and the tensor-network modulation law. `rct_figures.py` generates Figs. 1–4 including the linear ($\ell = 2$) evolution and the nonlinear Ori-type mass function. See `README.md` for versions and invocation.

-
- [1] T. Jacobson, “Thermodynamics of spacetime: The Einstein equation of state,” *Phys. Rev. Lett.* **75**, 1260 (1995).
 - [2] S. Ryu and T. Takayanagi, “Holographic derivation of entanglement entropy from AdS/CFT,” *Phys. Rev. Lett.* **96**, 181602 (2006).
 - [3] B. Swingle, “Entanglement renormalization and holography,” *Phys. Rev. D* **86**, 065007 (2012).

- [4] M. Van Raamsdonk, “Building up spacetime with quantum entanglement,” *Gen. Relativ. Gravit.* **42**, 2323 (2010).
- [5] E. H. Lieb and D. W. Robinson, “The finite group velocity of quantum spin systems,” *Commun. Math. Phys.* **28**, 251 (1972).

- [6] M. B. Hastings and T. Koma, “Spectral gap and exponential decay of correlations,” *Commun. Math. Phys.* **265**, 781 (2006).
- [7] W. G. Unruh, “Experimental black-hole evaporation?,” *Phys. Rev. Lett.* **46**, 1351 (1981).
- [8] C. Barceló, S. Liberati, and M. Visser, “Analogue gravity,” *Living Rev. Relativ.* **8**, 12 (2005).
- [9] B. P. Abbott *et al.* (LIGO/Virgo, Fermi-GBM, INTEGRAL), “Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A,” *Astrophys. J. Lett.* **848**, L13 (2017).
- [10] T. Dray, C. A. Manogue, and R. W. Tucker, “Particle production from signature change,” *Gen. Relativ. Gravit.* **23**, 967 (1991).
- [11] S. A. Hayward, “Signature change in general relativity,” *Class. Quantum Grav.* **9**, 1851 (1992).
- [12] M. K. Parikh and F. Wilczek, “Hawking radiation as tunneling,” *Phys. Rev. Lett.* **85**, 5042 (2000).
- [13] R. Carballo-Rubio, F. Di Filippo, S. Liberati, C. Pacilio, and M. Visser, “Inner horizon instability and the unstable cores of regular black holes,” *J. High Energy Phys.* **05**, 132 (2021).
- [14] F. Di Filippo, R. Carballo-Rubio, S. Liberati, C. Pacilio, and M. Visser, “On the inner horizon instability of regular black holes,” *Universe* **10**, 26 (2024).
- [15] T. McMaken, “Semiclassical instability of inner-extremal regular black holes,” *Phys. Rev. D* **107**, 125023 (2023).
- [16] N. Zilberman, M. Casals, A. Ori, and A. C. Ottewill, “Two-point function of a quantum scalar field in the interior region of a Reissner–Nordström black hole,” *Phys. Rev. D* **106**, 125011 (2022).
- [17] S. Weinfurtner, A. White, and M. Visser, “Analogue-gravity-induced particle production in an expanding universe,” *Phys. Rev. D* **76**, 024008 (2007).
- [18] J. Steinhauer, “Observation of quantum Hawking radiation and its entanglement in an analogue black hole,” *Nat. Phys.* **12**, 959 (2016).