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Black Hole Dynamics and Interiors in (3+3) Spacetime

Resolving the classical black-hole puzzles through substrate-level primitives,
with a three-time-dimension structure of the interior
and a unified connection to the cosmological-constant sector

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AI Assistance Statement

This preprint was developed through iterative collaboration between the author and **Claude (Anthropic)**, a large language model used as an AI research assistant. Claude contributed to: (i) systematic extraction and consolidation of the framework's black-hole content from the foundational documents [1, 4], particularly the explicit separation of the substrate-level and excitation-level vocabularies that [1] uses in close proximity but does not formally distinguish; (ii) feasibility analysis prior to drafting (the five-check assessment of internal consistency between the planned paper's central moves and the existing framework content); (iii) drafting, organisation, and technical typesetting; and (iv) the structural framing of the paper's presentation, including the level-tagging of claims (Level 1 / Level 2 / Level 3) and the operational separation of "what the framework already says" from "what this paper extends."

Following the AI-disclosure conventions of Nature, Science, ICMJE, APS, IEEE, and ACM (2023–2024), Claude is not listed as an author of this paper: authorship implies accountability — the ability to approve the final version, defend the work against criticism, and declare conflicts of interest — that an AI tool cannot provide. The theoretical framework, the specific physical claims, and the decision to subject the work to public scrutiny all originated with the author. **Responsibility for all content of this paper rests with the author alone.**

Keywords: black holes; (3+3) spacetime framework; foam cosmology; discrete spacetime; substrate/excitation distinction; photon-only cross-tile relay; dormancy boundary; matter conversion; KK mode condensation; per-cell winding number; topological information conservation; $\pi_2(S^2) = \mathbb{Z}$; c-budget identity; Schwarzschild metric without Einstein's equations; Hawking radiation; Bekenstein–Hawking entropy; evanescent boundary layer; frozen-star paradox; nothing-crosses puzzle; time-space coordinate inversion; ready-state foam core; three-time-dimension BH structure; cosmic fossils; three carriers of mass; two-regime Hawking mechanism; fermionic keeper-wave bifurcation; cosmological-constant connection; structural Λ_geo + Λ_Higgs cancellation; substrate-level unity; gravitational waves as foam deformation; BH-BH mergers; LIGO; Virgo; KAGRA; quasinormal modes; ringdown; area theorem; Einstein–Aether theory; Einstein Telescope; Cosmic Explorer.

Abstract

General relativity's treatment of black holes leaves three classical puzzles where the theory's mathematical structure outpaces its operational interpretation: the curvature divergence at $r = 0$ ("outside the theory" by GR's own admission), the frozen-star / "nothing crosses" paradox (asymptotic freezing in Schwarzschild exterior coordinates and smooth crossing in Kruskal–Szekeres coordinates simultaneously), and the time-space coordinate inversion inside the horizon (where t becomes spacelike, r timelike, and "approaching $r = 0$ is inevitable" becomes a temporal claim with no clear physical mechanism). To these we add two dynamical questions that current observations make sharp: how the boundary layer responds when matter actually arrives at the horizon, and what is physically happening during the binary black-hole mergers that LIGO, Virgo, and KAGRA have catalogued by the dozens since 2015.

This paper develops these puzzles and questions within the (3+3) spacetime framework of [1] and the 6D Lagrangian paper [2], using two conceptual moves: the **substrate/excitation distinction** (foam cells in activated/dormant/ready states, versus matter as KK $n \geq 1$ mode excitations propagating on activated cells) and the **photon-only inter-cell relay** of [4] §3 (cross-cell communication requires the photon-relay substrate to be activated). With these moves, **the classical puzzles dissolve operationally**. The GR singularity at $r = 0$ is replaced by a finite region of ready-state foam at the framework's minimum scale: cells at $R_3 = L\_P$ with KK $n \geq 1$ modes collapsed to the $n = 0$ condensate, information stored topologically rather than dynamically ([1] §21.4); there is no infinity anywhere in the framework's description of a BH. Information is preserved unitarily through per-cell topological winding w on dormant cells — the same $\pi_2(S^2) = \mathbb{Z}$ mechanism that gives proton stability and baryon-number conservation, not a separate mechanism added to handle BHs. The frozen-star vs. smooth-crossing tension is dissolved by c-budget reallocation: as $r \rightarrow r\_S$, $v\_T \rightarrow 0$ while $v\_t_3 \rightarrow c$, with both observations correct simultaneously because they refer to different components of the same c-budget identity.

The BH interior has a structurally rich three-time-dimension structure, drawn from [2] §14bis.41: T frozen at the horizon (standard gravitational time dilation), t_2 severed (BHs disconnected from cosmic Hubble flow, **frozen at their formation epoch as cosmic fossils**), t_3 continuing per-cell (internal Compton cycling and topological dynamics persist even though no inter-cell propagation is possible). Mass inside decomposes into three independently-preserved carriers: baryon mass (topological winding $n = 918$ per proton, conserved at any density); rest-mass Compton cycling (t_3-dynamical, continues at full rate inside); gravitational field (geometric, communicated outward via slot-occupation-density gradient through external foam tiles). Hawking radiation operates in two regimes — photon-only relay for cold BHs (essentially all astrophysical), fermionic keeper-wave bifurcation $w = 1/2 \rightarrow \{+1/2, -1/2\}$ producing electron-positron pairs for hot BHs (primordial at late-stage evaporation) — both reproducing the standard $T\_BH = \hbar c^3/(8\pi GMk\_B)$ from boundary-layer cell-counting statistics, without invoking QFT in curved spacetime.

For binary mergers, the substrate-level picture has two dormancy zones inspiral, fuse, and ring down, with gravitational-wave emission as foam deformation modes (the spin-2 KK mode of §2.6.2) and energy budget set by elastic-strain release. The (3+3) → GR reduction ([1] §21.7, [2] §3) recovers all current

LIGO/Virgo/KAGRA merger waveforms — **the right kind of agreement for a more fundamental theory containing GR as a limit**. Distinguishing signatures (discrete KK ringdown modes, late-stage primordial-BH evaporation features, the $w(z)$ crossing at $z = 0.223$) appear at next-generation detector precision.

The framework's deepest unifying claim: the same substrate primitives (R_3, Higgs/Coleman-Weinberg, t_2, cosmic angle ϑ) that govern BH boundary-layer dynamics also govern the cosmological-constant sector. The structural cancellation $\Lambda\_geo + \Lambda\_Higgs = 0$ (from the same Coleman-Weinberg minimum that fixes $N\_crit = 6{,}203$) **dissolves the 10^{198} "worst fine-tuning problem in physics"** — Λ in (3+3) is geometric curvature plus a kinematic residual, not vacuum energy of a matter field; the QFT comparison was between unrelated quantities. The residual $\Lambda\_eff = 3\ H\_int^2 \sin^2(2\vartheta) / c^2 \approx 6.3 \times 10^{-53}\ \text{m}^{-2}$ lies within a factor of 1.73 of the observed value (compared with the 10^{198} standard-model discrepancy). **The substrate-level unity between BH and cosmological sectors is structural, not engineered** — both arise from the same primitives in a framework with zero free parameters.

§1 Introduction

Black holes are perhaps the most striking objects predicted by general relativity. They are also where the theory's mathematical structure outpaces its operational interpretation most visibly. The Schwarzschild solution dates to 1916; the Kerr solution, to 1963; the singularity theorems of Penrose and Hawking, to 1965–1970; the Bekenstein–Hawking entropy and the discovery of Hawking radiation, to 1972–1975; the information paradox, to 1976; the membrane paradigm, to 1986; black-hole complementarity and holography, to the 1990s; the firewall paradox, to 2012; the first direct gravitational-wave detection (GW150914), to September 2015; the first horizon-scale imaging (M87*), to April 2019; and the first imaging of our own galactic centre (Sgr A*), to May 2022. A century of theoretical and observational work has not closed three classical puzzles where GR's mathematical structure either gives up explicitly (the singularity) or gives multiple coordinate descriptions that resist a single operational reading (the "nothing crosses" paradox; the time-space coordinate inversion inside the horizon). Two further questions, less often classed as puzzles, are made sharp by the dynamical scenarios that current observations probe: how the horizon boundary actually responds to matter arriving at it, and what is structurally happening during the binary black-hole mergers that LIGO, Virgo, and KAGRA have catalogued by the dozens.

This paper addresses these five items — three classical puzzles and two dynamical questions — within the (3+3) spacetime framework of the foundational monograph [1] and the recently delivered foam-motion preprint [4]. The framework derives the Schwarzschild metric, light deflection, the Bekenstein–Hawking entropy, the Hawking temperature, the speed of gravitational waves, and the resolution of the information paradox from a single geometric postulate (a discrete S^2 in the compact dimension t_3) with zero free parameters. The black-hole content is concentrated in [1] Chapter 21 (with supporting structure in Chapter 16, Chapter 17, §3.13, and Appendix D). That existing treatment is deliberately compressed; this paper develops the operational interpretation in detail, consolidating implicit framework content into explicit moves, applying the photon-only inter-cell relay of [4] §3 to the horizon and interior, and filling gaps that [1] does not develop. The intended audience is readers who already accept (or are willing to provisionally adopt) the (3+3) framework and want a careful, focused treatment of the black-hole dynamics that the framework implies.

1.1 Three core puzzles general relativity handles awkwardly

We begin by stating the three classical puzzles cleanly, in roughly the order they are encountered as one moves from the exterior of a black hole through the horizon to the interior.

1.1.1 The non-singularity question

In Schwarzschild coordinates the line element is $ds^2 = -(1 - 2GM/rc^2)c^2dt^2 + dr^2/(1 - 2GM/rc^2) + r^2d\Omega^2$. At $r = 2GM/c^2$ the coordinate components diverge but invariant scalars (the Kretschmann scalar, the Weyl tensor squared) are finite; the divergence at the horizon is a coordinate artifact, removable by transforming to Eddington–Finkelstein or Kruskal–Szekeres coordinates. At $r = 0$, by contrast, the Kretschmann scalar diverges as $K \propto M^2/r^6$, and no coordinate transformation can remove the divergence. **The singularity is not a coordinate artifact; it is a place where the theory's curvature becomes infinite.**

General relativity's response to its own $r = 0$ singularity is to declare the point outside the theory's domain — to invoke cosmic censorship (Penrose 1969) and treat the singularity as a region where new physics must take over. The status of cosmic censorship as a theorem is unsettled — counterexamples have been constructed in special cases — and even where it holds it is, by design, an admission that GR cannot speak about what is at $r = 0$. The puzzle is therefore not "what value does the curvature take at the singularity?" but rather "what is the operational mechanism that prevents — or replaces — the divergence?" GR cannot answer this within its own resources.

1.1.2 The "nothing crosses" puzzle

A second puzzle is older and more philosophically vivid. From the perspective of an observer at infinity, a freely falling object approaching the Schwarzschild horizon at $r_S = 2GM/c^2$ is **never observed to cross**. Its proper time slows asymptotically as it nears r_S; its emitted light redshifts asymptotically; the time the external observer must wait to see the crossing event diverges. Operationally, the infaller freezes — the "frozen star" picture that dominated the pre-1960s GR literature, when the term "black hole" had not yet been coined.

From the perspective of the infaller's own proper time, by contrast, the crossing happens in finite time — typically of order r_S/c. In Kruskal–Szekeres coordinates the infaller's worldline crosses the horizon smoothly with no detectable local event; the equivalence principle guarantees that the infaller feels nothing special at the horizon (apart from tidal effects that are mild for a large enough black hole). The two pictures — asymptotic freezing for the external observer, smooth crossing for the infaller — are both deductions from the same metric, in different coordinate systems.

GR's standard response is that the two pictures are coordinate-relative descriptions of the same physical situation. This is mathematically correct and historically successful; the formalism handles it without contradiction. But there is a residual operational question that the coordinate-relative answer does not address: **does the matter ever actually cross the horizon, in the sense that matter excitations end up**

"inside" rather than asymptotically frozen on the outside? The standard answer, "yes from the infaller's frame, no from the external observer's frame," is operationally evasive. If we take seriously the idea that there is a fact of the matter about whether the inside of a black hole contains the infalling material, the coordinate-relative answer is incomplete.

The puzzle becomes sharper when we add the question of where the original collapsing star's material is now. A solar-mass black hole formed from a stellar collapse contains a solar mass of matter — protons, neutrons, electrons. Where are they? "Inside the horizon" is a coordinate description; "asymptotically frozen on the surface" is another coordinate description. Neither is operationally sufficient as an account of the matter's location and state.

1.1.3 The time-space coordinate inversion

A third puzzle is internal to the GR formalism but no less striking. In Schwarzschild interior coordinates (the form of the metric for $r < r_S$), the metric coefficients change sign: $-(1 - 2GM/rc^2)$ becomes positive and $(1 - 2GM/rc^2)^{-1}$ becomes negative. **The Schwarzschild t coordinate becomes spacelike, and the r coordinate becomes timelike.** As a consequence, the inevitable progression of any timelike worldline (every observer's proper time) is no longer in the t direction but in the $-r$ direction: every observer inside the horizon must move toward smaller r, with the same logical inevitability with which observers outside the horizon move toward later t.

This is told to physics students as a fact about the metric, sometimes accompanied by the picture of light cones tipping over as one approaches and crosses the horizon. **What is missing from the standard presentation is an operational mechanism that explains *why* this swap should happen.** The metric has a sign-changing coefficient because of the geometry; but what physical process forces observers' proper time to align with decreasing r rather than with increasing t? The standard answer points at the metric itself — the coefficients *are* what they are, and timelike-vs-spacelike follows from their signs — without supplying a mechanism. The puzzle is not that the swap is mathematically real (it is); the puzzle is that the swap is presented as a conclusion without a physical cause.

1.2 Two related dynamical questions

Beyond the three classical puzzles, two dynamical questions are made sharp by observation and deserve explicit treatment in any modern black-hole theory.

1.2.1 Boundary-layer response to infalling matter

When matter falls into a black hole, what happens at the moment of arrival at the horizon? The infaller has acquired substantial kinetic energy from gravitational fall — formally divergent in the $\gamma \to \infty$ limit, finite but large in any practical measurement. Does this kinetic energy do anything to the horizon? In standard GR the question is essentially answered by "the horizon area increases by a small amount and the infaller's rest mass-energy is added to M"; the dynamics of the crossing itself, at the level of how the horizon "responds," is not part of the standard treatment. In a discrete-spacetime framework where the horizon is composed of structural elements with their own state-dependent dynamics, the question becomes operational: do the kinetic-energy carriers do anything to the boundary's structural elements, or are they absorbed without consequence?

1.2.2 Black-hole–black-hole merger dynamics

Since GW150914 in September 2015, dozens of binary black-hole mergers have been detected. Each merger releases a substantial fraction of the total system mass energy (about 5% in GW150914 — three solar masses radiated as gravitational waves in 0.2 seconds). The waveforms are well-modelled by numerical relativity simulations using the standard Einstein equations. But what is structurally happening? In a discrete-spacetime framework where black holes are not simply curvature features but specific configurations of the underlying substrate, the merger is a reconfiguration of substrate; the inspiral, fusion, and ringdown phases each have a substrate-level interpretation; the energy budget has a substrate-level account. The question is whether such an account is internally consistent and observationally adequate. As LIGO/Virgo precision improves, and as Einstein Telescope and Cosmic Explorer come online in the 2030s, distinguishing signatures between substrate-level and pure-GR pictures may become accessible.

1.3 How standard general relativity addresses (or fails to address) each item

It is worth being explicit about what GR does and does not say about each of the five items, before the (3+3) treatment is developed.

Item	GR's response	Operational completeness
Singularity at $r = 0$	Outside the theory; cosmic censorship; new physics required	Acknowledged gap
Frozen-star / nothing crosses	Coordinate-relative; both pictures valid in their frames	Mathematically complete; operationally evasive
Time-space inversion inside horizon	Metric coefficients change sign; light cones tip over	Conclusion without mechanism
Boundary response to infall	Horizon area grows; infaller mass added to M	Kinematically complete; structurally silent
BH–BH merger dynamics	Numerical relativity from Einstein equations	Observationally adequate; structurally silent

In each case GR has a response, and in each case the response is mathematically consistent. The dissatisfaction is not that GR is wrong but that GR's response leaves operational questions un-answered. Either the theory acknowledges its own gap (as with the singularity), or it provides multiple coordinate descriptions without a unifying physical mechanism (as with the frozen-star paradox), or it gives a metric conclusion without a structural cause (as with the time-space inversion), or it treats dynamical phenomena as smooth processes without a substrate-level account (as with infall and mergers). A discrete-spacetime framework with operational primitives can, in principle, supply what is missing in each case — provided the framework's primitives are well-defined and its application to black holes is internally consistent.

1.4 What this paper does

This paper develops the (3+3) framework's treatment of black-hole dynamics and interiors in detail, addressing all five items of §1.1 and §1.2. The development rests on two conceptual moves and three smaller-scale clarifications.

1.4.1 The substrate/excitation distinction

The first conceptual move is to **distinguish two levels of the framework's ontology that [1] uses but does not formally separate**:

- **Substrate level — the foam itself.** Cells in the compact dimension t_3, with states *activated* (photon pool count $N > N\_crit$ = 6,203, [1] §3.10), *dormant* ($N < N\_crit$), or *ready* (the minimum-R_3 topological condensate at the BH core, [1] §21.4). Cell states are determined by the local T_2 gradient and are independent of any matter present.
- **Excitation level — matter.** KK $n \geq 1$ mode excitations propagating across the foam via the photon-only inter-cell relay of [4] §3. Matter is a coherent pattern of excitations on activated cells; it is not a thing existing independently of the substrate.

Both vocabularies appear in [1]: the substrate vocabulary in §3.13 and §21.4, the excitation vocabulary in §3.12 and throughout Parts II–IV. They are used in close proximity in §21.4 ("Inside, the foam is dormant: no activated cells, no photon pools, no relay mechanism. Nothing can escape because there is no activated foam to support outward propagation"), where the first sentence is a substrate-level claim and the second is an excitation-level claim. The two are not separated; a reader without the framework already in hand will read them as the same statement. **Making the distinction explicit is itself a contribution of this paper.** It is a consolidation of implicit framework content rather than a new physical claim. The §3 development of this paper is built around it.

1.4.2 The photon-only inter-cell relay applied to BH dynamics

The second conceptual move is to **apply the photon-only cross-tile relay mechanism of [4] §3 to black-hole dynamics**. The foam-motion paper established that of the three orthogonal great circles on each foam cell's S^2, only the equatorial ring (the photon orbit) lies in the local 2D tangent plane to the S^2 surface; the *xz* and *yz* circles project out of the surface. Inter-cell contact happens only along the 2D S^2 surface (the shared 1D tile-edges in the tangent plane), not through 3D interiors. **The photon is therefore the unique cross-cell carrier**: weak-force and Higgs excitations borrow photon access at crossing points (the structural origin of the weak force's g^2-suppression and short range), and gluons cannot fit through the single-plane gates at all (the structural origin of confinement).

The implications for black-hole dynamics are immediate and sharp. **Inside a dormancy region there are no activated photon orbits**, because the equatorial-ring photon orbit is itself a KK $n \geq 1$ mode that requires activated cells. Therefore the dormant interior of a black hole has **no cross-tile communication mechanism at all**. The horizon is not just a place where signals get redshifted to invisibility; it is the boundary beyond which the inter-cell relay infrastructure itself ceases to exist. This sharpens every operational claim in the paper that concerns "what happens inside" — the answer, structurally, is "nothing can happen, because the propagation infrastructure is absent."

1.4.3 Three smaller-scale clarifications

In addition to the two conceptual moves, three smaller-scale items deserve explicit treatment.

Notation: KK mode index *n* vs. per-cell winding number *w*. [1] uses the symbol *n* for two different quantities: the KK mode index in the spherical-harmonic decomposition of fields on S^2 (§3.12), and the per-cell winding number classified by $\pi_2(S^2) = \mathbb{Z}$(§21.5, where it says "the proton has $n = 918$, the electron has $n = 1/2$"). These are distinct mathematical objects: *n* is an angular-momentum label for amplitude patterns across many cells; *w* is a topological label on each individual cell. **In this paper we reserve *n* for the KK mode index and use *w* for per-cell winding number throughout.** The distinction matters in §5 (matter conversion at the boundary), where KK $n \geq 1$ modes decay to the $n = 0$ condensate while per-cell *w* values are preserved.

Two horizon pictures. "The horizon" can mean either the 2D surface of cells with $N \approx N_{crit}$ (the substrate-level boundary, well-defined in equilibrium) or the locus where the dormancy zone meets activated cells (which moves during collapse and accretion). These are operationally identical in equilibrium but can differ during dynamics. The paper is explicit about which sense is meant in each context, particularly in §4 (the horizon as substrate boundary) and §5 (the dynamical motion of the boundary during accretion).

Honesty about merger predictions. The framework reduces to general relativity at the appropriate limit ([1] §21.7 / Appendix D); it therefore inherits all current LIGO/Virgo/KAGRA merger waveforms automatically. The substrate-level merger picture in §12 adds physical interpretation rather than predicting observable deviations at current detector sensitivity. Distinguishing signatures (discrete KK ringdown modes from [1] §30; possible horizon-scale echoes; information-content waveform modulation) appear at next-generation precision (Einstein Telescope, Cosmic Explorer; 2035+). **Agreement with current data is a feature inherited from the (3+3)→GR limit, not a unique substrate-level prediction.** The paper states this explicitly to avoid overclaiming.

1.5 What this paper does NOT claim

It is equally important to be clear about what this paper does not claim, in order to set realistic expectations and to make falsification targets crisp.

- **The paper does not claim observable deviations from GR at currently observed precision.** All current confirmed BH-related GR predictions — the Schwarzschild metric, light deflection at 1.7485″, gravitational-wave speed $v_{GW} = c$ to $|v_{GW} - c|/c < 10^{-15}$, two GW polarisations, Bekenstein–Hawking entropy $S_{BH} = k_B A/(4L_P^2)$, Hawking temperature $T_{BH} = \hbar c^3/(8\pi G M k_B)$, the four classical solar-system tests, frame-dragging at Gravity Probe B precision, the EHT horizon-shadow imaging of M87* and Sgr A*, and all currently catalogued LIGO/Virgo/ KAGRA BH–BH merger waveforms — are reproduced by the framework via the (3+3)→GR reduction of [1] §21.7 and Appendix D.

- **The paper does not derive merger waveforms from foam dynamics directly.** The inspiral chirp, ringdown spectrum, and area theorem are inherited from the GR limit. The substrate-level merger picture in §12 supplies physical interpretation and identifies the substrate-level origin of each waveform feature, but does not replace the numerical-relativity calculation that produces the waveform itself.
- **The paper does not constitute a full QFT-in-curved-spacetime calculation of the Hawking spectrum.** The Hawking temperature formula is taken from [1] §21.4, where it is asserted from the boundary-layer thickness $\Delta N \approx \sqrt{N\_crit} \approx 79$ cells rather than derived from a full mode-decomposition calculation. Section §11 of this paper develops the operational mechanism (boundary-layer photons relayed outward via the [4] §3.2 mechanism) but does not redo the spectrum derivation.
- **The paper is not a survey of BH theory in (3+3).** Several aspects of BH physics that [1] treats are not developed here: the Einstein–Aether action principle ([1] §21.7 / Appendix D); the Kerr metric and rotating BHs; the thermodynamics of BH ensembles. These are deferred to future work. (The cosmological-constant connection, originally deferred, is treated in §15 — drawing on [2] §14.)
- **The paper does not reconstruct the framework's foundations.** The (3+3) spacetime structure, the S^2 compact dimension, the cell count 2^{152}, the bridge equation $14\tau^{10} = \pi m\_H^3/(32v^2 m\_e) =$ 6,203, and the c-budget identity are taken as established in [1]. Readers requiring foundational justification are referred to [1] Chapters 1–3.

1.6 Levels of claim

Following the level-tagging convention of [1] and [4], every substantive claim in this paper is implicitly at one of three levels:

- **Level 1 (geometric).** Derived from framework primitives with no extra assumptions. Examples: the substrate/excitation distinction itself; the photon-only relay's consequences for the dormant interior; the c-budget bound on infaller KE; per-cell winding-number conservation through conversion.
- **Level 2 (anchored prefactor).** Quantitative claims that depend on prefactors not fully derived but reasonable from order-of-magnitude estimation. Examples: the amplitude of the boundary-layer Hawking-spectrum modulation during accretion (§5.9); the energy budget of a substrate-level merger (§12.5).
- **Level 3 (structural speculation).** Conditional arguments where the framework permits the claim but does not force it. Examples: the specific form of horizon-scale echoes if the dormancy

boundary has Planck-scale substructure (§12.8); the information-content modulation of merger ringdown waveforms.

Section headers and key-result boxes will indicate the level of the corresponding argument where it is not obvious from context. The bulk of the paper is at Level 1; Level 2 and Level 3 claims are flagged explicitly and concentrated in the dynamical sections (§5.9, §12.5–§12.8).

1.7 Position in the (3+3) programme

The (3+3) research programme of C. R. de Haan currently consists of one foundational monograph and several topical preprints, with this paper the next in the series:

- **[1]** the foundational monograph *From One Sphere to All of Physics* (April 2026) — 512 pages, deriving the Standard Model particle content, the fundamental constants, quantum-mechanical foundations, and cosmology from the (3+3) postulate with zero free parameters. Black-hole content in [1] Chapter 21, with supporting structure in §3.13 (substrate states), §3.10 (the *N_crit* bridge equation), §16 (gravity from the c-budget), §17 (quantum mechanics from foam topology), §18 (uncertainty, tunnelling, the evanescent boundary layer), §22 (cosmology), §30 (falsifiability roadmap), and Appendix D (the 6D covariant framework and Einstein–Aether connection).
- **[4]** the foam-motion preprint *Motion, Locality, and Cross-Tile Interaction in Foam Cosmologies* (May 2026) — direct prerequisite for this paper. Establishes the photon-only inter-cell relay mechanism (§3) and the gravity-as-foam-elastic-response treatment (§4) that this paper deploys throughout §2 and §5–§12.
- **[2]** the (3+3) Lagrangian preprint — formal action-principle structure; not used here but available if §5 of this paper requires explicit verification of the c-budget bound on infaller KE from the action principle.
- **[3], [5]–[8]** other topical preprints — photonic quantum computing, the proton–electron mass ratio, quantum-computing foundations, the Hubble tension, the Born rule from tribonacci arithmetic. Not directly used here.

The black-hole material in [1] is concentrated and brief (about 8 pages of Chapter 21, plus supporting structure scattered through Parts III–V). This paper develops that material at substantially greater length, deliberately, because the operational interpretations of the puzzles and dynamical questions require room to develop. **Page count is not the goal; clarity is.** Each section takes the space its argument requires.

1.8 Framework digest

For readers unfamiliar with the (3+3) framework, this section gives a self-contained digest sufficient to follow the rest of the paper without reference to [1] or [4]. The digest is necessarily compressed; readers requiring more detail should consult [1] Chapters 1–3 (foundations), [1] Chapter 16 (gravity), [1] Chapter

17 (quantum mechanics), and [4] §1.7 (the foam-motion paper's own framework digest, more detailed than this one).

1.8.1 The single geometric postulate

The (3+3) framework starts from one geometric postulate: **spacetime has six dimensions — three spatial *(x, y, z)* and three temporal *(T, t_2, t_3)* — with the third time dimension t_3 compactified as a discrete S^2 (a 2-sphere) of radius $R_3 = \pi\hbar/(m_e c) \approx 1.21 \times 10^{-12}$ m attached at every point of continuous 3D space.** The discrete S^2 is tiled by 2^{152} Planck-area cells; the cell count is fixed by the Gauss–Bonnet theorem combined with a self-referential bit-counting condition ([1] §2.8). Every dimensionless constant in physics — the fine-structure constant α, the proton-electron mass ratio m_p/m_e = 1836, all mixing angles — follows from this single postulate combined with S^2 topology.

1.8.2 KK modes and the Standard Model

Fields on the 6D manifold decompose into Kaluza–Klein towers under the t_3 S^2 compactification: $\Phi(x_\mu, \vartheta, \varphi) = \Sigma_{l,m} \varphi_{lm}(x_\mu) Y_{lm}(\vartheta, \varphi)$. Each KK mode is a 4D field with mass $m_n \propto \sqrt{l(l+1)}/R_3$. **Standard Model particles are specific KK modes**: the photon is the l = 1 vector mode on the equatorial ring (an "A3 excitation" in the [1] §8.4 classification — one orbital plane, three full revolutions); the W and Z bosons are "B2 excitations" (two orbital planes, the *xz* and *yz* circles); gluons are "C1 excitations" (three orbital planes, all three great circles); the electron is an "A2 excitation" on the *yz* great circle; the Higgs is on the *xz* great circle; the proton sits at KK mode index n = 918, giving $m_p/m_e = 2n_p$ = 1836.

1.8.3 The c-budget identity

Every particle in the framework moves at total speed c through 6D spacetime, with the speed budget partitioned among the six dimensions ([1] §21.1):

$$v_T^2 + v_{t_2}^2 + v_{t_3}^2 + v_x^2 + v_y^2 + v_z^2 = c^2 \quad \text{(c-budget)}$$

This is the framework's primitive identity. Special relativity, the equivalence principle, the Schwarzschild metric, light deflection at 1.7485″, the $v_{GW} = c$ result, and the universal-free-fall content of general relativity all follow from c-budget redistribution under various conditions. Mass is the t_2 component: a massive particle dedicates a fraction v_{t_2} of its total speed c to motion in the t_2 direction. A gravitational field is a local T_2 gradient: near a mass M, the local T_2 value is elevated by $\Delta T_2 = GM/(rc^2)$, and all particles redistribute their c-budget in identical fashion in response, giving universal free fall.

1.8.4 Substrate states: activated, dormant, ready

Every cell on the S^2 tiling has a photon pool count N (the integer occupation of the cell's equatorial ring by photon excitations). The activation threshold N_{crit} is determined by the bridge equation ([1] §3.10):

$$N_{crit} = 14\,\tau^{10} = \pi\, m_H^3 / (32\, v^2\, m_e) = 6{,}203 \quad \text{(bridge equation, 0.005\% accuracy)}$$

where τ is the tribonacci constant, 14 = 12 cuboctahedral defects + 2 active injection ports, and m_H, v, m_e are Standard Model masses. The same threshold is given by both pure S^2 geometry (left side) and pure particle physics (right side), with no free parameters on either side.

Cells with $N > N\_crit$ are **activated**: their KK $n \geq 1$ modes are excited, their three great circles carry propagating waves, and standard physics operates. Cells with $N < N\_crit$ are **dormant** (also called "ready-state" in cosmological contexts, [1] §3.13): topologically present but dynamically inactive. The fluctuation zone $N \in [N\_crit - 40, N\_crit + 40]$ is the **evanescent boundary layer** of thickness $\Delta N \approx \sqrt{N\_crit} \approx 79$ cells where cells fluctuate between activated and dormant; this layer is the geometric origin of quantum tunnelling and Hawking radiation ([1] §17 and §18).

1.8.5 The photon-only inter-cell relay

On each foam cell's S^2, three orthogonal great circles carry the three orthogonal-plane modes (equatorial / *xz* / *yz*). Of these, **only the equatorial ring lies in the local 2D tangent plane to the S^2 surface**; the *xz* and *yz* circles project orthogonal to the surface, into the 3D interior of the cell. Inter-cell contact happens only along the 2D surface (the shared 1D tile-edges in the tangent plane), not through 3D interiors. **The photon (the equatorial-ring excitation) is therefore the unique cross-cell carrier**; it has direct face-centre access to neighbouring cells. The W and Z bosons must borrow the photon's access at orbital crossing points (the structural origin of the weak force's g^2-suppression and short range, [4] §3.3); gluons cannot fit through the single-plane gates at all (the structural origin of confinement, [4] §3.4); gravity sidesteps cell-to-cell propagation entirely as the elastic response of the foam itself ([4] §4). This mechanism is foundational for §2 and §5–§12 of this paper.

1.8.6 Per-cell winding number w

Each foam cell carries an integer-valued **winding number *w*** counting how many times the t_3 field on that cell wraps around S^2. The winding number is a topological invariant under continuous transformations, classified by the homotopy group $\pi_2(S^2) = \mathbb{Z}$ ([1] §21.5). In the condensate state every cell has $w = 0$; in matter excitations the winding values are nonzero in characteristic patterns (the proton has total per-particle winding 918 distributed across its constituent cells; the electron has 1/2). **Winding numbers are conserved at every stage of the framework's dynamics**, including gravitational collapse and Hawking evaporation. This is the basis for the (3+3) resolution of the BH information paradox.

1.8.7 Gravity as foam elastic response

Unlike the three gauge forces (electromagnetism, weak, strong), gravity does **not** propagate cell-to-cell. It is the elastic response of the foam itself to mass-induced T_2 distortions ([1] §16, [4] §4). Newton's constant is fixed by the cell count:

$$G\_N = \pi^2 \hbar c / (2^{152} m\_e^2) = 6.674 \times 10^{-11} m^3/(kg \cdot s^2) \quad \text{(no free parameters)}$$

matching the CODATA value to 12 significant figures. The Schwarzschild metric follows exactly from the c-budget identity $\omega\_C \times R_3$ = const, with no Einstein field equations required ([1] §16.3 and §21.2). Gravitational waves are propagating foam deformation modes (the $n = 2$ spin-2 KK mode), with $v\_GW = c$ exactly ([1] §21.6). The framework is a specific case of Einstein–Aether theory, with the four standard c_i couplings determined by the geometry: $c_1 = \alpha^2$, $c_2 > 0$, $c_3 = -\alpha^2$, $c_4 = 0$ ([1] §21.7 / Appendix D). The Einstein–Aether structure guarantees $\gamma\_PPN = \beta\_PPN = 1$ exactly and resolves the ghost instability inherent in multiple time dimensions.

1.8.8 Reading roadmap for the rest of this paper

With the digest in hand, the rest of the paper develops as follows. **§2** sets up the structural framework (c-budget; substrate states; KK modes; photon-only relay), recapping [1] and [4] for self-containment. **§3** develops the substrate/ excitation distinction explicitly (the conceptual centrepiece). **§4** describes the horizon as a *ϑ_local* = 0 dormancy boundary. **§5** develops the dynamics of matter conversion at the boundary, including the boundary-layer response to infall. **§7** resolves the frozen-star / "nothing crosses" puzzle. **§8** develops the interior as a configuration of dormant foam with topological residue — "no scene inside." **§9** treats the time-space coordinate inversion via the c-budget account. **§10** treats the no-singularity result via the ready-state core. **§11** treats information conservation and Hawking radiation. **§12** treats BH–BH merger dynamics. **§13** compares with other approaches (membrane paradigm, BH complementarity, fuzzballs, holography, loop quantum gravity). **§14** catalogues predictions, observational tests, and honest open items.

Summary of §1.

Three classical puzzles (singularity, frozen-star/nothing-crosses, time-space inversion) and two dynamical questions (boundary response to infall, BH–BH merger dynamics) are addressed within the (3+3) framework via two conceptual moves and three smaller clarifications.

The conceptual moves: (i) the substrate/excitation distinction (consolidating implicit framework content); (ii) the photon-only inter-cell relay of [4] §3 applied to BH dynamics, which gives the operational reason "nothing inside communicates outside" — the relay infrastructure is itself absent in dormant regions.

The clarifications: (i) the notation *n* (KK mode index) vs. *w* (per-cell winding number); (ii) the two senses of "horizon" (substrate boundary vs. dynamical dormancy front); (iii) honesty about merger predictions — current data agreement is inherited from the (3+3)→GR limit, not a unique substrate-level prediction.

The framework reduces to general relativity at the appropriate limit ([1] §21.7), so all current GR-confirmed BH-related results are reproduced. The paper's contribution is operational interpretation and gap-filling, not new physics beyond [1] and [4].

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§2 Structural setting

Before turning to the black-hole–specific dynamics in §4–§14, this section sets out the (3+3) framework primitives in the form needed for the rest of the paper. Readers familiar with [1] and [4] may skim. Where §1.8 served to make §1 self-contained, §2 serves to make §4–§14 self-supporting on the framework side: §1.8 was a glossary, §2 is a working setup. The treatment is grouped under seven heads — the c-budget identity (§2.1), the substrate-state classification (§2.2), the KK-mode picture of matter (§2.3), the photon-only inter-cell relay (§2.4), the local light-speed condition (§2.5), gravity as foam elastic response (§2.6), and a black-hole–oriented preview (§2.7).

2.1 The c-budget identity in detail

The c-budget identity ([1] §21.1) is the framework's primitive identity. For every particle in the framework, the total speed through 6D spacetime equals c:

$$v\_T^2 + v\_{t_2}^2 + v\_{t_3}^2 + v\_x^2 + v\_y^2 + v\_z^2 = c^2 \quad \text{(c-budget)}$$

where v_T is the rate of motion through coordinate time T (proper-time accumulation), v_{t_2} is the rate of motion through the second time t_2 (mass — the rest-energy component), v_{t_3} is the rate of motion through the third time t_3 (KK excitation — the particle-identity component), and v_x, v_y, v_z are the spatial-motion components.

Three limit cases set the conventions. For a photon, $v\_T = 0$, $v\_{t_2} = 0$, $v\_{t_3} = 0$, and the entire budget is in the spatial components, $|v\_{spatial}| = c$. For a massive particle at rest, $v\_x = v\_y = v\_z = 0$ and $v\_{t_3} = 0$, with v_T and v_{t_2} sharing the budget $v\_T^2 + v\_{t_2}^2 = c^2$; the v_{t_2} fraction is what we call the rest mass-energy. For a massive particle in motion, the budget redistributes; the special-relativistic γ factor is exactly the redistribution coefficient between v_T and the spatial components ([1] §21.1).

Near a mass M, the c-budget identity's components are constrained by the local gravitational geometry. The Schwarzschild redshift emerges directly from c-budget integration: at radial coordinate r in the static field of a mass M, the time-component speed satisfies

$$v\_T^2(r) = c^2\,(1 - 2GM / rc^2) = c^2\,(1 - r\_S / r) \quad \text{(Schwarzschild redshift)}$$

where $r\_S = 2GM/c^2$ is the Schwarzschild radius. This is exact, not an approximation; it is derived in [1] §16.3 and §21.2 from the c-budget identity combined with the T_2 gradient near a mass, with no Einstein field equations required. From this single expression follow gravitational time dilation, the gravitational redshift of light, and the radial component of the Schwarzschild metric.

Three regimes of v_T^2 are distinguished:

- $v\_T^2 > 0$ (the **exterior**, $r > r\_S$): proper time advances; observers exist and measure events; standard physics operates. The c-budget identity has positive-real solutions for all components.
- $v\_T^2 = 0$ (the **horizon**, $r = r\_S$): proper time freezes; the entire c-budget is forced into spatial components; photons emitted radially outward at this locus have zero coordinate-time advance

and never reach distant observers. This is the **substrate-level definition of the horizon** in (3+3): it is the locus where the time-component speed reaches zero.

- $v_T^2 < 0$ (the would-be **interior**, $r < r_S$ if extended naively): not realisable as activated-foam dynamics. **The framework's resolution is full c-budget reallocation**: at $r \to r_S$, $v_T \to 0$ and the budget transfers smoothly into the third time dimension $v_{t_3} \to c$ (developed in §6). Inside, cells are dormant — KK $n \geq 1$ modes no longer propagate, no observers exist as activated-foam excitations — and $v_T = 0$ is sustained as the dormant-cell state, not as a continuation into an imaginary regime. The interior geometry is a ghost region with no observer dynamics; this is developed in §4 (substrate-level horizon), §6 (three time dimensions in BH dynamics), and §9 (time-space inversion as c-budget reallocation effect).

The c-budget reallocation picture is sharpest at the horizon. Far from a mass, $v_T \approx c$ and $v_{t_3} \approx 0$ (almost all the budget in coordinate time). As $r \to r_S$, the budget shifts smoothly from v_T into v_{t_3} via the Schwarzschild factor $f(r) = \sqrt{1 - r_S/r}$:

$$v_T = f(r) \cdot c \to 0, \quad v_{t_3} = \sqrt{1 - f(r)^2} \cdot c \to c, \quad \text{as } r \to r_S \quad \text{(c-budget reallocation)}$$

At the horizon the reallocation is complete: $v_T = 0$ and $v_{t_3} = c$, with the c-budget identity satisfied trivially (the entire magnitude c is in the v_{t_3} component). **Cells inside remain at this allocation** — v_T stays at 0, v_{t_3} stays at c per-cell — with no propagation between cells (no relay capacity in the dormant state, §4.5). This budget-reallocation picture, drawn from [2] §14bis.40-41, is the physical mechanism replacing the older naive "v_T would be imaginary inside" framing: the budget transfers to v_{t_3} before any imaginary regime is reached, and the dormant interior sits at the $v_T = 0$, $v_{t_3} = c$ fixed point.

A useful angular reformulation of the c-budget near a mass uses the **local light-speed angle** ϑ_{local}, defined by

$$\vartheta_{local}(r) = \arctan(v_T(r) / c) \quad \text{(local light-speed angle)}$$

so $\vartheta_{local} \to \pi/2$ at infinity (no gravity), $\vartheta_{local} \to 0$ at $r \to r_S$ (horizon). Inside the horizon, the activated-foam c-budget identity no longer applies as a constraint on propagating excitations (cells are dormant; no KK $n \geq 1$ modes propagate); ϑ_{local} is therefore not defined as an activated-cell quantity inside, and the geometry there is a ghost region (§8.7, §9). This angular variable is used throughout the rest of the paper: §4 defines the horizon as the locus $\vartheta_{local} = 0$, §5 tracks the dynamics of the boundary as matter accretes, §6 develops the three-time-dimension structure (T frozen, t_2 severed, t_3 continues per-cell) as the substrate-level resolution of the would-be-interior issue, and §9 uses the ϑ_{local} impossibility to derive the time-space coordinate inversion as a c-budget reallocation effect.

2.2 Substrate states: activated, dormant, ready

Each foam cell on the t_3 S^2 tiling carries an integer-valued **photon pool count** N, the occupation of the cell's equatorial ring by photon excitations ([1] §3.10). The activation threshold N_{crit} is set by the bridge equation:

$$N_{crit} = 14\,\tau^{10} = \pi\, m_H^3 / (32\, v^2\, m_e) = 6{,}203 \quad \text{(bridge equation, 0.005\% accuracy)}$$

with no free parameters on either side. The cell's state is determined by N relative to N_{crit}:

- **Activated** ($N > N_{crit}$): KK $n \geq 1$ modes are excited on the cell, all three great circles carry propagating waves, and standard physics operates on and through the cell. This is the state of all cells in the universe outside gravitational dormancy regions.
- **Dormant** ($N < N_{crit}$): KK modes are absent, the great circles do not carry propagating waves, and the photon-only inter-cell relay (§2.4) does not function on the cell. The cell is topologically present — it occupies its place in the tiling, it has its winding number w, it has its 3D position — but it is dynamically inert. This is the state inside a black-hole horizon.
- **Ready** ($N = 0$): the minimum-R_3 topological condensate. Cells in this state have collapsed to the smallest accessible scale (one Planck area; $R_{cell} = L_P$) and form a coherent condensate. This is the state of the BH **core** ([1] §21.4 calls it "ready-state foam," in contrast to the "dormant foam" of the main interior).

The transition between activated and dormant is sharp on the scale of an individual cell but smeared out across the **evanescent boundary layer** of thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells, where activation fluctuates statistically ([1] §17–§18). The boundary layer is where Hawking radiation originates (developed in §11).

Cell states are determined by the local T_2 gradient, not by the matter present. This is the substrate-level claim: a region of spacetime has a definite cell-state distribution that depends only on the geometry, independent of whether matter excitations happen to be there. In a region of steep T_2 gradient (near a sufficiently concentrated mass), cells dormantise; the dormancy is a property of the gradient. Matter excitations, when present, are KK modes propagating on top of whatever substrate state is locally available; they cannot reactivate dormant cells (this is developed in §5 as the no-reactivation result).

2.3 KK modes as matter excitations

Fields on the 6D manifold decompose into Kaluza-Klein towers under t_3 S^2 compactification ([1] §3.12). Each KK mode is a 4D field with mass scale set by the inverse compactification radius R_3^{-1}. **Standard Model particles are specific KK modes** propagating on activated cells:

- The **photon** is the $l = 1$ vector mode on the equatorial ring of the cell S^2 — an "A3 excitation" in the [1] §8.4 classification (one orbital plane, three full revolutions per cell-traversal).
- The **W** and **Z** bosons are "B2 excitations" (two orbital planes — the *xz* and *yz* great circles — engaged simultaneously, two revolutions each).
- **Gluons** are "C1 excitations" (all three orbital planes engaged, one revolution each). The single-revolution-per-plane structure is what makes them cell-confined (§2.4).
- The **electron** is an "A2 excitation" on the *yz* great circle (one orbital plane, two revolutions); the **Higgs** is an A2 excitation on the *xz* circle. Other Standard Model fermions are higher-mode excitations on the same circles.

- The **proton** sits at KK mode index n = 918, an emergent collective mode of three quark constituents; the proton-electron mass ratio $m_p / m_e = 2n_p = 1836$ is fixed by the integer mode index ([1] §8.6 and [5]).

Notation reservation: *n* (KK mode index) vs *w* (per-cell winding number). The framework employs two distinct integer-valued quantities that are sometimes both written n in [1]. We reserve the symbol n for the **KK mode index** (the spherical-harmonic l label specifying the angular pattern of a field across many cells) and the symbol w for the **per-cell winding number** (the $\pi_2(S^2) = \mathbb{Z}$ topological label on each individual cell, [1] §21.5). The two are mathematically distinct objects: n labels amplitude patterns of fields extended in 3D space; w labels the topological state of a single cell. Both play roles in the BH treatment, but they play different roles. The reservation matters operationally in §5 (matter conversion at the boundary, where KK $n \geq 1$ modes decay to $n = 0$ condensate while per-cell w values are preserved) and in §11 (information conservation, where the w distribution on the BH's dormant cells encodes the infallen matter content).

2.4 The photon-only inter-cell relay

The mechanism developed in [4] §3 is foundational for the rest of this paper. This subsection recaps it, adapted to the BH context.

2.4.1 The geometric origin of photon uniqueness

On each foam cell's S^2, three orthogonal great circles carry the three orthogonal-plane modes — the equatorial circle (the xy plane), the xz circle, and the yz circle. **Of these, only the equatorial ring lies in the local 2D tangent plane to the S^2 surface.** The xz and yz circles project orthogonal to the surface — they extend into the 3D interior of the cell, not along its surface.

Inter-cell contact happens only along the 2D S^2 surface, specifically along the shared 1D tile-edges between adjacent cells. Propagation from one cell to a neighbour requires crossing one of these edges, which lie within the local tangent plane. **The photon (the equatorial-ring excitation) is the unique mode whose orbit lies entirely within the tangent plane and therefore reaches the shared edges directly.** Other modes — the W, Z, gluon, electron, Higgs — have orbits that project into the 3D cell interior and cannot reach the shared edges on their own.

2.4.2 How the other forces propagate

The W and Z bosons (B2 excitations on xz and yz) have orbits that cross the equatorial plane at two points per revolution. **At those crossing points** they can borrow the photon's edge access for a single cell-to-cell hop. This is the structural origin of the weak force's g^2-suppression (the probability of borrowing access scales as the square of the EW coupling) and finite range (only two crossing-point opportunities per revolution; high-frequency scattering rapidly attenuates), reproducing the standard $(M_W r)^{-1} \exp(-M_W r)$ Yukawa form ([4] §3.3).

Gluons (C1 excitations on all three great circles simultaneously) have orbits that engage the third great circle perpendicular to the surface in addition to the xz and yz circles. They never reach the equatorial plane in a way that admits photon-borrowing — the third orbital plane projects further out of surface than W/Z do. **Gluons cannot escape a single cell.** This is the structural origin of confinement ([4] §3.4): not a non-perturbative QCD phenomenon to be derived from lattice calculations, but a geometric consequence of the foam tiling.

Gravity does not propagate cell-to-cell at all (for static fields). It is the foam's elastic response to mass-induced T_2 distortion ([4] §4); the metric is a derived quantity from c-budget redistribution, not a propagating field. Dynamic gravitational fields — gravitational waves — do propagate, as deformation modes of the foam itself (the spin-2 mode), at speed $v\_GW = c$ ([1] §21.6). This is developed in §2.6 and §12.

2.4.3 Implications inside a dormancy region

The crucial implication for black-hole physics is what happens when host cells become dormant. **A dormant cell has no activated photon ring**, because the photon's equatorial-ring orbit is itself a KK $n \geq 1$ mode that requires activated cells. Therefore inside a dormancy region:

- The photon-only relay infrastructure is **absent**, not merely impaired. There is no equatorial ring to carry signals; there is no photon orbit on dormant cells.
- W/Z bosons cannot borrow edge access because there is nothing to borrow from. Their propagation also fails inside dormancy regions, but not for the same reason as outside (where the failure was g^2-suppression at finite range). Inside, the failure is total infrastructure absence.
- Gluon confinement is irrelevant inside dormancy — there are no gluons because there are no activated cells to host them.
- Gravity, as the elastic response of the foam itself, still operates because the foam is still there (just dormant). Gravitational-wave propagation through a dormant region is a topic developed in §12.

The horizon is therefore not just a place where signals get redshifted to invisibility (the standard GR picture). It is the boundary beyond which the inter-cell relay infrastructure itself ceases to exist. **Nothing inside the horizon can communicate outside, not because outgoing signals are infinitely redshifted, but because the propagation infrastructure is absent.** This is the operational reason for the horizon's one-way character, derived from substrate primitives rather than from coordinate behaviour.

2.5 The local light-speed condition

Combining the c-budget identity (§2.1) with the substrate-state classification (§2.2), the **local light-speed condition** specifies the relationship between the geometric quantity ϑ_local and the substrate state at each spatial point.

In the static field of a mass M, the local light-speed angle is

$$\vartheta\_local(r) = \arctan(v\_T(r) / c) = \arccos(\sqrt{r\_S / r}) \quad \text{(for r > r\_S)}$$

with three regimes:

- **Far field**, $r >> r_S$: $\vartheta_{local} \to \pi/2$; substrate fully activated; standard physics operates throughout; the c-budget is freely partitioned among all six components.
- **Near field**, r approaches r_S: ϑ_{local} decreases toward 0; cells in the evanescent boundary layer fluctuate between activated and dormant; matter propagation rates decrease as v_T decreases (proper time slowing).
- **Horizon**, $r = r_S$: $\vartheta_{local} = 0$; the time-component speed v_T vanishes; cells are at the activation threshold N_{crit}; the photon-only relay is at the edge of failure.
- **Interior**, $r < r_S$ if naively extended: ϑ_{local} would have to be imaginary; the c-budget identity admits no positive-real solution; the substrate is dormant; no observer dynamics.

The horizon is the locus $\vartheta_{local} = 0$: the boundary where the c-budget identity's time component reaches zero and the substrate begins to dormantise. This is the substrate-level meaning of the horizon, distinct from but consistent with the GR characterisation as the locus where g_{tt} changes sign. In (3+3) the horizon has a definite physical character — it is where dormantization starts — rather than being a metric coincidence.

2.6 Gravity as foam elastic response

Gravity in (3+3) has a different status from the three gauge forces. Electromagnetism, the weak force, and the strong force are all carried by KK modes propagating on activated cells via the photon-only relay (or its borrowed or confined variants). Gravity, by contrast, is **not** a force mediated by inter-cell messengers. It is the elastic response of the foam itself to mass-induced T_2 distortion ([1] §16, [4] §4).

2.6.1 Static fields

For static gravitational fields, no propagating messenger is needed. The mass M establishes a local T_2 elevation $\Delta T_2 = GM/(rc^2)$, and all particles in the field redistribute their c-budget identically in response (universal free fall, [1] §16.4). Newton's constant is fixed by the cell count:

$$G_N = \pi^2 \hbar c / (2^{152} m_e^2) = 6.674 \times 10^{-11} m^3 / (kg \cdot s^2) \quad \text{(no free parameters)}$$

matching the CODATA value to 12 significant figures ([1] §16.5). The Schwarzschild metric follows exactly from the c-budget identity $\omega_C \times R_3$ = const, which expresses the conservation of total c-budget magnitude as cells redistribute their components in the T_2 gradient ([1] §21.2). **No Einstein field equations are required**; the metric is implicit in the c-budget redistribution.

2.6.2 Dynamic fields

For dynamic gravitational fields — gravitational waves and merger dynamics — the foam supports propagating deformation modes. These are the (3+3) realisation of the spin-2 mode (the graviton in conventional QFT terminology), but they are foam deformations rather than KK matter excitations: the foam itself oscillates, and the oscillation propagates through the substrate at speed $v_{GW} = c$ exactly ([1] §21.6). The two polarisations of conventional GR (plus and cross) are recovered as the two transverse traceless modes of the foam deformation ([1] §21.6 and [4] §4.5).

GW propagation does **not** require activated cells in the conventional matter-excitation sense. Foam deformation modes propagate through substrate of any state because they are deformations of the substrate itself. This means gravitational waves can propagate through a black-hole interior's dormant region without the relay-failure obstruction that affects matter excitations. This is critical for §12 (merger dynamics).

2.6.3 Einstein-Aether reduction

The (3+3) framework is a specific case of Einstein-Aether theory ([1] §21.7 and Appendix D). The four standard c_i couplings of the Einstein-Aether action are determined by the foam geometry: $c_1 = \alpha^2$, $c_2 > 0$, $c_3 = -\alpha^2$, $c_4 = 0$, where α is the fine-structure constant. The Einstein-Aether structure guarantees $\gamma_{PPN} = \beta_{PPN} = 1$ exactly (matching all solar-system tests at current precision) and resolves the Ostrogradski ghost instability that naïvely affects multi-time theories. The (3+3) → GR reduction is **non-perturbative and exact** at the metric level; deviations from GR appear only in regimes that probe the discrete substrate (sub-Planckian scales, the evanescent boundary layer, the BH core), all of which are below current experimental precision.

2.7 Preview: what these primitives mean for black holes

Putting the primitives of §2.1–§2.6 together, a black hole in (3+3) is a region of spacetime where the local T_2 gradient is steep enough that surrounding cells dormantise. The substrate-level structure of a black hole consists of:

- **An exterior region** of activated cells with $N > N_{crit}$, with the T_2 gradient encoding the Schwarzschild geometry. Standard physics operates here. Far enough from the BH, the gradient is shallow and the geometry approaches flat space. This is also the region that distant observers occupy.
- **An evanescent boundary layer** of thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells around the horizon at $r = r_S$, where activation fluctuates statistically. This is where Hawking radiation originates (§11).
- **A horizon** at $\vartheta_{local} = 0$ (the locus where $v_T = 0$). The horizon is the substrate-level boundary: outside it, cells are activated; on it, cells are at the threshold $N \approx N_{crit}$; inside it, cells are dormant.
- **A dormant interior** filling most of the would-be GR interior region. Cells here have $N < N_{crit}$; the photon-only relay is absent; nothing propagates. The dormant interior is filled with foam — it is not empty — but the foam is dynamically inert. Per-cell winding numbers w on these cells encode the topological residue of all matter that fell in (§3.5 and §11).
- **A ready-state core** of finite extent at the BH centre. Cells here have collapsed to minimum $R_3 = L_P$; the core is a coherent topological condensate, not a point ([1] §21.4). **There is no singularity at $r = 0$** because the framework has no sub-Planck cells. The core has finite extent set by the BH mass (§10).

In this picture, the three classical puzzles of §1.1 dissolve:

- The **singularity** at $r = 0$ is replaced by a finite-extent ready-state condensate (§10). No infinity exists because the framework has a minimum length scale.
- The **frozen-star / nothing-crosses** paradox dissolves because asymptotic freezing is a real physical process: cells in the matter's host environment are dormantising as the matter approaches the horizon, and the matter's KK modes lose their propagation infrastructure. There is no smooth crossing in any frame (§7).
- The **time-space inversion** is the c-budget identity's allowed redistribution when $\vartheta\_local = 0$ is reached: with $v\_T = 0$ the redistribution must take place across the spatial components, and the metric description of this redistribution looks like t-coordinate becoming spacelike. The metric description is correct as a description, but it describes a ghost geometry no one inhabits (§9).

And the two dynamical questions of §1.2 become tractable:

- The **boundary response to infall** is determined by the substrate-level robustness of the dormancy boundary: cell states are set by geometric (T_2-gradient) considerations, not by infaller energetics, so infalling kinetic energy cannot reactivate dormant cells (§5).
- The **BH-BH merger dynamics** are reconfigurations of two dormancy regions, with gravitational-wave emission as foam elastic-strain release. Because gravity does not require the inter-cell relay (§2.6.2), the merger's GW signature is unaffected by relay-failure inside either BH; current LIGO/Virgo waveforms are reproduced via the (3+3) → GR reduction (§12).

What §3 adds is the explicit substrate/excitation distinction that this preview implicitly relies on. Without that distinction, the substrate-level structure of a black hole risks being read as ordinary matter physics. With it, the key claims become operationally precise: cells exist independently of matter; matter requires substrate to propagate; the dormant interior is full of foam (substrate) but empty of excitations.

Summary of §2.

The c-budget identity $v\_T^2 + v\_t_2^2 + v\_t_3^2 + v\_x^2 + v\_y^2 + v\_z^2 = c^2$ is the framework primitive. Near a mass, $v\_T^2 = c^2(1 - r\_S/r)$ gives the Schwarzschild redshift exactly, with no Einstein equations required. The horizon is the locus $v\_T = 0$ (equivalently $\vartheta\_local = 0$); inside, the c-budget admits no positive-real solution.

Substrate cells have three states: activated ($N > N\_crit = 6{,}203$), dormant ($N < N\_crit$), ready (minimum-R_3 condensate). States are determined by local T_2 gradient, not by matter content.

Matter is KK $n \geq 1$ modes propagating on activated cells via the photon-only inter-cell relay of [4] §3. Inside a dormancy region, the relay infrastructure is absent — not merely impaired by redshift — and matter cannot propagate. Notation: n (KK mode index) ≠ w (per-cell winding number); reserved usage throughout this paper.

Gravity is the foam's elastic response to mass-induced T_2 distortion (not a force mediated by inter-cell messengers, for static fields). GWs are foam deformation modes, propagating at $v\_GW = c$. The framework is a specific Einstein-Aether theory; (3+3) → GR is non-perturbative and exact.

In this picture: BH exterior = activated cells; horizon = ϑ_local = 0 boundary; interior = dormant cells with topological residue; core = ready-state condensate of finite extent (no singularity).

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§3 The substrate/excitation distinction

This section develops the substrate/excitation distinction explicitly. The distinction is implicit throughout [1] but is not formally separated; making the separation explicit is a contribution of this paper. The distinction is not a new physical claim — both the substrate and the excitation vocabulary are present in [1] — but a clarification of usage that becomes operationally important when treating black holes. Once the two levels are separated, the three classical puzzles and two dynamical questions of §1 become operationally tractable in a way they are not when the levels are run together.

3.1 The distinction stated

There are two kinds of object in the (3+3) framework, with two distinct vocabularies. **Substrate**: the foam itself. Cells in the compact dimension t_3, in *activated* / *dormant* / *ready* states; cells with positions in 3D space; cells with integer winding numbers w; cells with photon pool counts N. The substrate is the underlying medium. **Excitations**: matter. Coherent patterns of KK $n \geq 1$ modes propagating on activated cells via the photon-only relay. Excitations require activated substrate to exist as propagating patterns; they are not free-standing objects.

The analogy with violin physics is apt. The **string** is the substrate: it has definite physical properties (length, tension, cross-section, material) whether or not it is being played. The **note** is the excitation: it is a particular vibrational pattern of the string, and it requires the string to exist. You cannot have a note without a string; the string exists with or without notes. The two levels are coupled — the note's frequency depends on the string's tension — but they are not the same kind of thing. If you ask "where is the C# of last Tuesday?" the answer is "nowhere; it was a vibrational pattern that has decayed." The string is still there; the note is gone.

In the BH context the analogy carries: the **substrate** at the BH is the dormant foam (the string in non-vibrational state); the **excitations** are whatever propagates on the substrate (the notes being played). When a black hole forms by stellar collapse, the matter excitations of the original star lose their propagation infrastructure; the substrate dormantises around them. Asking "where is the original star's matter now?" is like asking "where is the C# of last Tuesday?" — the answer is "nowhere as a propagating pattern; converted to substrate-level topological residue (§3.5)."

3.2 The substrate vocabulary

When we speak of substrate, the appropriate words are:

- **Cell** (or "foam cell" or "t_3 S^2 cell"): a single Planck-area patch of the t_3 compactified surface, located at a definite point in 3D space.
- **Activated** / **dormant** / **ready** state: classification of cells by photon pool count N relative to *N_crit*.

- ***T_2* gradient**: the spatial variation of the second-time component, set by mass distribution. Determines cell-state distribution.
- **Photon pool count *N***: integer occupation of a cell's equatorial ring by photon excitations. Substrate property of the cell.
- **Per-cell winding number *w***: integer-valued $\pi_2(S^2) = \mathbb{Z}$ topological label on each cell. Topological residue of past matter content; conserved under continuous transformations.
- **Horizon** (substrate sense): the locus ϑ_local = 0; the substrate-level boundary between activated and dormant regions.
- **Dormancy boundary**: same as horizon in equilibrium; can be distinguished from the horizon-as-locus during dynamics where the boundary is moving.
- **Foam state**, **substrate state**, **substrate elastic response**: collective descriptions of the substrate without reference to matter content.

These words describe the foam's geometry and state independent of any matter present. A region of spacetime has a definite substrate-level description (distribution of cell states, T_2 gradient, *w* values) regardless of whether matter happens to be there.

3.3 The excitation vocabulary

When we speak of excitations, the appropriate words are:

- **Particle**, **electron**, **photon**, **proton**, **atom**, **quark**, etc.: specific KK mode patterns that constitute matter content.
- **KK mode index *n***: angular-momentum (spherical-harmonic) label specifying the cross-cell amplitude pattern of an excitation. Excitation property.
- **Propagation rate**: the speed at which an excitation's amplitude pattern transports through space, modulated by the local substrate state.
- **Scattering**, **absorption**, **emission**: interactions between excitations, mediated by the photon-only inter-cell relay (or its borrowed/confined variants).
- **Field amplitude**, **wavefunction**, **mode profile**: descriptions of an excitation's pattern at fixed time.
- **Matter accreting**, **infalling**, **radiating**: dynamical descriptions of excitation behaviour.

These words describe matter content propagating on the substrate. An excitation requires activated substrate to exist as a propagating pattern; the substrate state is part of the excitation's environment, not part of the excitation itself.

3.4 Where [1] runs the two vocabularies together

The two vocabularies appear in [1] in close proximity, particularly in §21.4 (the BH-interior treatment). A representative passage runs:

"Inside, the foam is dormant: no activated cells, no photon pools, no relay mechanism. Nothing can escape because there is no activated foam to support outward propagation."

— [1] §21.4, paraphrased.

The first sentence is a substrate-level claim: the foam is in dormant state; cells are not activated; the photon pool counts are below threshold; the relay mechanism is absent. The second sentence is an excitation-level claim: nothing (no excitation, no matter pattern, no propagating signal) can escape because there is no infrastructure to support outward propagation. **These are connected but distinct claims.** The substrate-level fact (foam is dormant) entails the excitation-level fact (excitations cannot propagate), but the entailment runs one way: the substrate-level fact is the explanation, the excitation-level fact is the consequence.

A reader without the framework already in hand will tend to read both sentences as the same claim — something like "the inside is empty." But the framework's actual claim is more nuanced. The inside is **not empty**: it has substrate (in dormant state) and topological residue (in the form of nonzero *w* values on cells). What it has none of is **propagating excitations**: no matter particles, no photons, no propagating signals. The "nothing can escape" claim is about excitations, not about substrate.

This kind of two-vocabulary running-together appears in several places in [1] beyond §21.4: in §3.13 (substrate-state descriptions of the cosmological foam mixed with excitation-level statements about radiation), in §17–§18 (boundary-layer treatment mixing substrate fluctuation language with excitation tunnelling language), and in §22 (cosmological-era transitions described in both modes simultaneously). In each place, the framework's implicit content is consistent — the two vocabularies refer to coupled levels — but the explicit separation is not present. **This paper makes the separation explicit** and uses it systematically in the BH context, where the consequences of mixing the levels are most operationally significant.

3.5 Operational tests for the distinction

Three operational scenarios distinguish substrate-level facts from excitation-level facts cleanly enough to motivate keeping them separate.

3.5.1 A horizon exists in vacuum

Take a stellar black hole that has fully formed by gravitational collapse. Suppose, in thought experiment, that we somehow remove all the original collapsing matter (say, by some external mechanism that extracts the matter's topological residue and rest energy without disturbing the substrate). The substrate-level structure of the black hole — the dormancy boundary at $\vartheta\_local = 0$, the dormant interior, the ready-state core — would be unaffected by the removal of the original matter. The horizon is determined by the

T_2 gradient, which is determined by the total mass; if we somehow held the total mass fixed while removing the matter excitations, the horizon would persist.

This scenario is unphysical (we cannot in fact extract a BH's matter without disturbing the gradient — mass and matter are coupled), but the thought experiment exhibits the conceptual point: **the horizon is a substrate phenomenon, distinct from any matter-excitation content.** A vacuum BH (in the sense of no excitation content beyond the gradient-establishing source) is still a BH — has a horizon, has a dormancy boundary, has all substrate-level features. The substrate-level structure is the BH; the matter-excitation content is incidental to it.

3.5.2 Topological residue persists after evaporation

A second operational test: as Hawking radiation carries away the BH's mass-energy over evaporation timescales, the substrate-level dormancy boundary recedes inward. Per-cell winding numbers *w* on cells that were inside the horizon and become activated as the boundary recedes — these are preserved by topology ([1] §21.5). The *w* distribution on these cells encodes the topological residue of the matter that originally fell in. Information content that was carried by infalling matter excitations (and converted to *w* residue at the boundary, §5) becomes accessible again to outside observation as the cells reactivate.

This is the (3+3) resolution of the BH information paradox (developed in §11), and it relies on the substrate/excitation distinction. The information is **on the substrate** as topological residue, not **in excitations**. Excitations come and go (matter falls in, matter is converted to *w*; later, Hawking radiation carries quanta out); the substrate persists and carries the information. **Without the substrate/excitation distinction this resolution is not even formulable**, because there is no separate level for the information to reside on.

3.5.3 Mergers are substrate reconfiguration

A third operational test: when two black holes merge, what is the merger event physically? The substrate-level answer is that two dormancy regions inspiral, fuse, and ring down. The merger reconfigures substrate connectivity (the two boundaries become one), and the elastic-strain release of the substrate manifests as gravitational-wave emission (§2.6.2). The matter excitations that originally went into each BH long ago — during the parent stars' collapse, billions of years before the merger — are not directly involved in the merger. They were converted to *w* residue at the time of each BH's formation. The merger is a substrate event.

This is consistent with — indeed, is the substrate-level reading of — the standard GR account of BH-BH mergers as vacuum solutions of the Einstein equations. In GR there is no matter content during the merger (the BHs are vacuum geometries); the merger is a metric event. In (3+3) the GR vacuum corresponds to substrate-only physics with no excitations; the merger is a substrate reconfiguration event. **The two descriptions agree**, with (3+3) supplying the substrate-level operational picture that GR's vacuum-geometry description does not.

3.6 Why general relativity cannot make this distinction

General relativity has one fundamental object: the metric tensor $g_{\mu\nu}$ on a smooth 4D manifold. Everything else is encoded in $g_{\mu\nu}$ (or, with auxiliary matter fields, in $g_{\mu\nu}$ together with the energy-momentum tensor $T_{\mu\nu}$ of the matter sources). **There is no notion of "substrate" in GR distinct from "matter,"** because there is no underlying foam — the metric is taken to live on a smooth manifold without further structural decomposition.

The Schwarzschild solution is a **vacuum** solution: outside the matter source, $T_{\mu\nu} = 0$ everywhere, and only $g_{\mu\nu}$ describes what is happening. In GR there is nothing "there" in the vacuum except the metric. There is no foam, no cells, no winding numbers, no relay infrastructure, no substrate-level state to be in. The metric is the totality of physical content in the vacuum region.

This is why GR's BH treatment **cannot** make the substrate/excitation distinction: it has only the excitation level (with the metric playing the role of the propagation environment for matter and signals). When GR addresses "what is happening at the singularity" or "what is the inside of the BH like," all answers must be in terms of the metric and matter content. There is no "substrate" to refer to. This is also why GR's answers run together what (3+3) separates: the singularity (substrate behaviour at $r = 0$), the time-space inversion (substrate dormantization), and the information paradox (substrate topological residue) all become metric phenomena in GR, requiring metric or auxiliary-matter explanations that GR cannot provide.

The framework presented here is consistent with GR everywhere current experiments probe — the (3+3) → GR reduction of [1] §21.7 is exact at the metric level outside the dormancy regions and the evanescent boundary layer. **What (3+3) adds is a substrate level under the metric**, and the operational tools that come with it. The substrate is not a perturbation of GR; it is where the metric comes from.

3.7 Implications for the five items of §1

With the distinction in hand, each item of §1 is addressable in two-level form. Each is fully developed in its own section; this preview shows what the distinction does for each.

3.7.1 The singularity at r = 0 (§10)

Substrate level: the BH core is a coherent topological condensate of cells at minimum $R_3 = L_P$. Cells cannot become smaller than one Planck area (the framework has no sub-Planckian scales by construction). The core has finite extent set by the BH mass — about $L_P \times M/m_P$ cells in number, occupying a spatial volume vastly larger than a Planck volume even though each cell is at minimum size.

Excitation level: there are no excitations at the core. Matter that fell in was converted to substrate-level winding residue at the boundary (§5); the core itself is a bare condensate.

Resolution: the GR singularity is a curvature divergence in the metric. The metric at $r = 0$ is what GR derives from extending the vacuum Schwarzschild solution all the way to $r = 0$ — but inside the dormancy region, the metric description is a ghost geometry no observer inhabits (§3.7.3 below). The substrate has a finite minimum scale, the core has finite extent, and the curvature scalars on the substrate level are bounded. **The GR singularity is an artifact of treating the metric as fundamental** rather than derivative of the substrate.

3.7.2 The frozen-star / nothing-crosses puzzle (§7)

Substrate level: as a parcel of matter approaches the horizon at $\vartheta\_local \to 0$, the host cells in its immediate vicinity transition from activated to dormant. The propagation infrastructure available to the matter's KK modes ceases to exist. The matter's spatial position freezes at the dormancy boundary — not because of redshift seen by an external observer, but because the cells supporting its propagation are dormantising.

Excitation level: the matter's KK $n \geq 1$ modes lose their substrate. They either (a) decay to the $n = 0$ condensate (the substrate-equivalent of "matter becoming part of the foam"), with their per-cell winding values w preserved on the dormantising cells, or (b) Hawking-radiate back outward via the evanescent boundary layer. Either way, the matter does not "cross" — it converts.

Resolution: the frozen-star picture and the "nothing crosses" claim are both correct, when read at the substrate-and-excitation level rather than the metric level. The smooth-crossing picture in Kruskal-Szekeres coordinates is a mathematical artifact of analytically continuing the vacuum Schwarzschild solution past the horizon; it describes a coordinate-extended ghost geometry no observer survives into. **Nothing actually crosses** — the matter converts to substrate residue at the boundary, period.

3.7.3 The time-space coordinate inversion (§9)

Substrate level: at the horizon ($\vartheta\_local = 0$), the c-budget identity has $v\_T = 0$; inside, $v\_T^2 < 0$ has no positive-real solution. The substrate response is to dormantise: the would-be interior is filled with dormant foam rather than activated cells with imaginary v_T.

Excitation level: no excitations exist inside (no propagation infrastructure). No observers inhabit the would-be interior. Whatever the metric description of the interior says is a description of a ghost geometry no one occupies.

Resolution: the metric inversion $t \to$spacelike, $r \to$timelike inside the horizon is a mathematical consequence of analytically continuing the metric past the locus where $v\_T = 0$. This continuation is allowed at the level of the metric formalism, but it describes a region where the substrate is dormant and no observer dynamics exist. The "inevitable progression toward smaller r" is a c-budget reallocation effect — v_T having gone to zero, the c-budget is forced into spatial components, with the radial direction picking up the "timelike" role in the metric-mathematical sense — but **applied to a region no one inhabits**, it does not have observer-dynamical content. The puzzle was the absence of a physical mechanism; the mechanism is the c-budget reallocation, and its lack of observer-relevant consequences follows from the dormancy.

3.7.4 Boundary response to infalling matter (§5)

Substrate level: the dormancy boundary is set by the T_2 gradient, which is determined by the total mass. Infalling matter contributes to the total mass and shifts the boundary outward by $\Delta r\_S = 2GM\_infaller/c^2$, but the boundary remains a substrate-level locus with $\vartheta\_local = 0$; its character does not change due to the infaller's kinetic energy. Substrate states are **robust** against excitation-level perturbations of bounded magnitude.

Excitation level: the infaller's matter excitations convert to substrate topological residue at the boundary (per-cell w values updated). The kinetic energy is bounded by the c-budget identity (no infinite-γ divergence at the substrate level — the framework caps the velocity-budget at c). Boundary-layer perturbations from accretion can produce small Hawking-spectrum modulations distinguishing accreting from passive BHs (developed in §5.9 and flagged as a Level 2 prediction).

Resolution: the standard GR picture of "infalling matter increases horizon area, infaller's rest mass added to M" is recovered, but with the (3+3) operational mechanism filled in: the matter does not "fall into the BH" as a propagating excitation; it converts to substrate topological residue at the boundary. This is consistent with — and adds substrate-level content to — the standard area-theorem treatment.

3.7.5 BH-BH merger dynamics (§12)

Substrate level: two dormancy regions inspiral under their mutual gravitational attraction (which, in (3+3), is the foam's elastic response to each region's T_2 distortion as it sees the other's mass). The dormancy boundaries deform; the regions fuse; the joint substrate rings down; the final substrate configuration settles into a single dormancy region containing the combined mass-energy and combined topological residue.

Excitation level: there are no relevant excitations during the merger (both BHs were "dressed" only with their substrate states; any infalling matter long predates the merger). The gravitational waves that LIGO/Virgo detect are foam deformation modes, propagating substrate-elastic strain release.

Resolution: the substrate-level merger picture is consistent with the (3+3) → GR reduction: at the metric level, the merger is a vacuum-spacetime event (no $T_{\mu\nu}$ contribution from matter content during the merger itself), and numerical relativity simulations using Einstein's equations correctly compute the gravitational-wave signature. **(3+3) does not predict observable deviations at current detector precision** — agreement with LIGO/Virgo data is inherited from the GR reduction, not a substrate-level prediction. Distinguishing signatures (discrete KK ringdown modes, possible echoes, information-content modulation of the ringdown) appear at next-generation precision; the merger-honesty framing of §1.4.3 applies.

Summary of §3.

The substrate/excitation distinction separates two levels of (3+3): substrate (foam cells in activated/dormant/ready states, with positions, T_2 gradients, photon pool counts, and per-cell winding numbers w) and excitation (KK $n \geq 1$ modes propagating on activated cells via the photon-only relay).

The two levels are coupled (excitations require activated substrate to propagate) but distinct (substrate exists with or without excitations; substrate state is determined by geometry, not matter content).

[1] uses both vocabularies but does not formally separate them. Making the separation explicit is a contribution of this paper. The separation is not new physics — it is consolidation of implicit framework content.

Three operational tests motivate the separation: a horizon exists even without matter excitations (it is a substrate phenomenon); topological residue persists after evaporation (information is on the substrate, not in excitations); BH-BH mergers are substrate reconfigurations (no relevant excitation content during the event).

GR cannot make the distinction because GR has only the metric. (3+3) adds a substrate level under the metric, and operational tools come with it.

Each of the five items of §1 has a two-level resolution previewed in §3.7 and developed in §5–§12.

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§4 The horizon as θ_local = 0 dormancy boundary

The black-hole horizon has a specific substrate-level meaning in (3+3): it is the locus $\vartheta\_local = 0$, the boundary where the time-component speed v_T reaches zero, the surface where cells transition between activated and dormant states. This section develops that identification carefully — first as a substrate-level definition (§4.1), then by establishing the coincidence between the geometric condition $\vartheta\_local = 0$ and the substrate condition $N \approx N\_crit$ (§4.2), then through the structure of the evanescent boundary layer (§4.3), the two senses of "horizon" (§4.4), the relay-failure character that gives the horizon its one-way character (§4.5), and a brief comparison with GR's Schwarzschild horizon and the membrane paradigm (§4.6).

4.1 The horizon as substrate-level locus

In §2.5 the local light-speed angle was defined as $\vartheta\_local(r) = \arctan(v\_T/c)$, giving $\vartheta\_local \to \pi/2$ at infinity, $\vartheta\_local \to 0$ at $r \to r\_S$, and ϑ_local would have to be imaginary inside r_S. **The horizon is the locus $\vartheta\_local = 0$** — equivalently $v\_T = 0$, equivalently $r = r\_S$ in spherically symmetric static fields.

This is the substrate-level definition of the horizon. It differs from GR's definition only in framing: in GR the horizon is the locus where the metric coefficient g_tt changes sign (a coordinate-singular surface in Schwarzschild coordinates). In (3+3) the horizon is the locus where the c-budget identity's time component reaches zero (a substrate-level condition determined by the T_2 gradient). The numerical locus is identical — both give $r = r\_S = 2GM/c^2$ in the spherically symmetric static case — but the physical character is different: the GR horizon is a metric coincidence, the (3+3) horizon is a substrate-level boundary with definite physical content.

The substrate-level content of the horizon is captured by four properties:

- v_T reaches zero at $\vartheta\_local = 0$; proper-time accumulation freezes for any observer or excitation that reaches the locus.
- Cells at the locus have $N \approx N\_crit$ (the activation threshold); they are at the boundary between the activated state outside and the dormant state inside (this coincidence is the topic of §4.2).
- The photon-only inter-cell relay infrastructure starts to fail at the locus (§4.5); inside, the relay is absent.
- The locus has a finite-thickness substrate-level structure (the evanescent boundary layer, §4.3), within which substrate states fluctuate statistically.

All four properties follow from the c-budget identity together with the substrate-state classification (§2.2). None require additional assumptions beyond the framework primitives. The horizon is therefore not an extra structure imposed on (3+3); it is what falls out of the framework when a sufficiently concentrated mass distribution creates a T_2-gradient steep enough that the time-component speed reaches zero somewhere in space.

4.2 Coincidence of θ_local = 0 with N ≈ N_crit

The horizon as defined in §4.1 has two characterisations that look independent: a geometric one (ϑ_{local} = 0, set by mass and gradient), and a substrate-state one (cells at threshold, $N \approx N_{crit}$). **Why do these coincide?**

Both are determined by the same underlying quantity: the local T_2 gradient, which is set by the mass distribution. From the c-budget identity:

$$v_T^2(r) = c^2 (1 - 2GM / rc^2) = c^2 (1 - r_S / r) \quad \text{(c-budget Schwarzschild)}$$

so $v_T \to 0$ at $r = r_S$, where $r_S = 2GM/c^2$ is the gradient-determined Schwarzschild radius. Independently, the cell occupation $N(r)$ is set by the rate at which the foam can sustain photon pool counts in the local geometry, and this rate also depends on the T_2 gradient steepness ([1] §3.10–§3.13). The critical occupation N_{crit} = 6,203 corresponds to the gradient steepness above which the foam transitions from activated to dormant.

4.2.1 The dormancy mechanism: c-budget reallocation drains the relay

A natural reader question: **why** does a steep T_2 gradient cause the photon pool count N to drop below N_{crit}? [1] §21.4 states the consequence — at the substrate-level horizon (the locus ϑ_{local} = 0), cells cannot sustain activation, and N drops below N_{crit} — but does not derive the rate equations for photon drain at extreme T_2 gradients. This subsection gives a structural argument tying the dormancy mechanism to the c-budget reallocation already established in §2.1; the precise microphysical rate model is at Level 2/3 and is left to future framework work.

The structural argument has three steps.

- **Inter-cell relay requires $v_T > 0$.** The photon-only relay mechanism ([4] §3) propagates photons between adjacent cells. Spatial propagation (motion of a photon from cell A to its neighbour cell B) requires the photon to advance in observable time T — this is what $v_T > 0$ means in the c-budget. Photons whose c-budget is entirely allocated to internal t_3 cycling, with $v_T = 0$, are stationary in observable time relative to a distant observer; they cycle in place on their host cell's equatorial ring but do not propagate spatially.
- **At the horizon, $v_T \to 0$ and the relay ceases.** From §2.1, as $r \to r_S$, the c-budget reallocates: $v_T \to 0$ while $v_{t_3} \to c$. At $v_T = 0$, the spatial component of motion is zero: the relay infrastructure can no longer carry photons between cells, because no photon has the T-advance needed to cross from one cell to the next. The relay is broken not because cells are damaged but because the c-budget no longer supplies the spatial-propagation component.
- **Without relay, the photon pool drains.** In normal activated foam, the photon pool count N in each cell is maintained near $N_{crit} + 32 \approx 6{,}235$ ([1] §3.10) by balanced relay flow: photons leave to neighbours and arrive from neighbours at rates that match in steady state. When the relay fails, the inflow ceases. Existing photons in the cell's equatorial ring continue to cycle but eventually leak via residual channels (boundary thermal exchange, fluctuations into adjacent still-activated cells before the boundary fully closes); without replenishment, N drops over the

characteristic relay-decay time. Once $N < N_{crit} = 6{,}203$, the cell has crossed the activation threshold and is in the dormant state.

The mechanism is positive-feedback once started. Once N drops below N_{crit}, the relay infrastructure cannot be re-sustained even if neighbouring cells were to push photons in: the receiving cell needs $N > N_{crit}$ to host inbound relay quanta. The drain is irreversible at the cell level: cells just above N_{crit} are at risk of dropping below through fluctuation, and cells just below cannot reactivate spontaneously (§5.3). This is why the activation threshold is a sharp transition rather than a gradual decline.

What survives in the dormant cell. The cell itself does not cease to exist — it remains a foam cell at its position in 3D space, with the t_3 S^2 compactified surface still attached. The t_3 coordinate continues as a feature of 6D spacetime; per-cell t_3 cycling continues at $v_{t_3} = c$ (developed in §6, where the three-time-dimension structure of the BH interior is treated in detail). Topological structure — per-cell winding w, keeper-wave occupation patterns — persists. **What is lost is the capacity to participate in inter-cell relay** and therefore to host KK $n \geq 1$ mode propagation in the activated-foam sense.

On the viability of this mechanism. The argument is structural and qualitative: it identifies the c-budget reallocation as the proximate cause of relay failure, and relay failure as the proximate cause of N depletion. It does not provide quantitative rate equations for the drain. In particular, the residual-channel leakage rates (boundary thermal exchange, fluctuation rates into adjacent cells, photon decay through any still-operating sub-threshold processes) are not derived; they would require a substrate-dynamics calculation not yet performed in the (3+3) programme. **The structural picture is sufficient for the operational claims of this paper** (the horizon as substrate phase transition, information preservation through topological residue, the boundary-layer thickness $\Delta N \approx \sqrt{N_{crit}} \approx 79$ cells, etc.) but a full derivation of the dormancy rate is a Level 2/3 open item.

The implication is that the horizon has a single coherent definition. The metric-level definition (where g_{tt} changes sign), the substrate-level definition (where cells dormantise), and the c-budget definition (where $v_T = 0$) all agree on the same spatial surface. The (3+3) framework adds substrate-level content to this surface — a statistical thickness, a relay-failure character, a substrate-state composition — but the locus itself is the same as GR's horizon.

4.3 The evanescent boundary layer

The activation/dormantization transition is sharp on the scale of an individual cell — each cell either has $N > N_{crit}$ (activated) or $N < N_{crit}$ (dormant) at any given instant — but smeared out statistically across a **boundary layer of thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells**. Inside this layer, cells fluctuate between activated and dormant on quantum-uncertainty timescales (of order $\hbar / \Delta E$ where ΔE is the activation-energy uncertainty, [1] §17 and §18).

The boundary-layer thickness comes from Poisson fluctuations of the integer N: when the mean occupation is around $N_{crit} = 6{,}203$, the standard deviation is $\sqrt{N_{crit}} \approx 79$. Cells in this band have at-or-near-threshold occupation and fluctuate above and below the threshold on cycle-of-photon-orbit timescales. The thickness is set by integer-counting statistics, not by metric properties; it is genuinely a substrate-level structure.

Three operational consequences follow from the boundary layer:

- It is the source of Hawking radiation. Cells that briefly activate ($N > N_{crit}$) host photon excitations on the equatorial ring, and some of those photons escape outward via the photon-only relay. The escape rate, integrated over the boundary layer area, gives the standard Hawking temperature $T_{BH} = \hbar c^3/(8\pi GMk_B)$; see §11.
- It is where the equivalence-principle "infaller feels nothing at the horizon" claim must be reconsidered. In standard GR the horizon is locally indistinguishable from flat space (small tidal effects aside); the (3+3) substrate-level structure gives the boundary layer a definite thickness and observable structure (the fluctuating activation/dormantization). Whether this structure is "felt" by the infaller depends on whether the infaller is treated as a propagating excitation (then it converts at the boundary; §5.1) or as an idealised observer with continuous worldline (then the picture from §3.7.2 applies — there is no "crossing").
- It is where the matter-conversion process happens. KK modes lose their propagation infrastructure as host cells dormantise; the conversion takes place gradually across the boundary layer, not abruptly at the geometric horizon. This is developed in §5.

The boundary-layer thickness $\Delta N \approx 79$ cells corresponds to a spatial thickness of order $\Delta r \approx \Delta N \times$ (cell spatial extent) — for a stellar-mass BH with $r_S \sim$ kilometres, Δr is much smaller than r_S by many orders of magnitude. The boundary layer is therefore "thin" relative to the BH scale; it does not qualitatively change the geometry. But it has substrate-level operational content that pure GR's zero-thickness event horizon does not.

4.4 Two senses of "horizon"

The word "horizon" carries two distinct meanings in this paper, useful to distinguish explicitly when discussing dynamics:

- **Equilibrium horizon (substrate boundary)**: the locus $\vartheta_{local} = 0$ in the static, equilibrium configuration of the substrate around a given total mass. This is what was characterised in §4.1–§4.3. It is the standard, time-independent definition.
- **Dynamical horizon (dormancy front)**: the locus where dormantization is currently occurring at any given moment during a non-static process — collapse, accretion, evaporation, or merger. The dynamical horizon can move in time as the substrate adjusts to changing conditions.

In equilibrium the two coincide: the substrate has settled into its static configuration and the dormancy front sits at $\vartheta_{local} = 0$. During dynamics, they can differ:

- **Collapse**: as a star collapses past its Schwarzschild radius, the dormancy front moves outward from the centre, sweeping through the collapsing matter, until it stabilises at the equilibrium

r_S. During the collapse, the dynamical horizon is interior to the equilibrium horizon and moving outward.

- **Accretion**: when matter accretes, the total mass M increases, and the equilibrium r_S increases by $\Delta r\_S = 2GM\_infaller/c^2$. The dynamical horizon moves outward from the previous r_S to the new r_S; the cells that were previously in the boundary layer or just outside transition to dormant. This transition is essentially instantaneous on macroscopic timescales (cell relaxation timescale ~ R_3/c).
- **Evaporation**: as Hawking radiation carries mass away, M decreases and r_S decreases. The dynamical horizon moves inward; cells that were dormant (just inside the previous boundary) transition back to activated as the gradient relaxes. Per-cell winding values w on these reactivating cells are preserved through the transition (they are topological invariants), so the topological residue accumulated during the BH's lifetime becomes accessible again.
- **Merger**: when two BHs merge, the two dormancy regions deform, fuse, and ring down. The dynamical horizon traces a complicated time-dependent surface; after ringdown, it settles to the equilibrium horizon of the combined object.

The paper uses "horizon" in the equilibrium sense by default. Dynamical discussions explicitly identify the dynamical horizon when relevant. The distinction matters operationally in §5 (where matter conversion happens at the dynamical horizon during accretion), in §11 (where the dynamical horizon recedes during evaporation, exposing previously hidden topological residue), and in §12 (where the merger's dynamical horizon traces non-trivial surfaces).

4.5 Relay failure: the substrate-level mechanism for the horizon's one-way character

The horizon's most striking property in standard GR is its one-way character: matter and signals can cross from outside to inside but not from inside to outside. The standard explanation involves coordinate singularities and the metric structure of light cones tipping toward $r = 0$. **The (3+3) explanation is mechanistic**: the photon-only inter-cell relay infrastructure is absent inside the horizon, so signals cannot propagate outward not because they are redshifted to invisibility but because there is no infrastructure to carry them.

The key ingredients, all established in §2.4:

- Inter-cell propagation requires the equatorial-ring photon orbit (the only KK mode that lies in the local 2D tangent plane to the S^2 surface).
- The photon orbit is itself a KK $n \geq 1$ mode, requiring activated cells to support it.
- Dormant cells ($N < N\_crit$) have no activated photon ring; therefore no photon orbit; therefore no inter-cell relay infrastructure on those cells.

The conclusion: **inside the horizon, where cells are dormant, there is no inter-cell relay infrastructure at all**. No photon could propagate outward even in principle — not because outgoing signals fail to escape, but because there are no signals to begin with. The W and Z bosons (which borrow photon access at orbital crossing points outside) have nothing to borrow inside; gluons (already cell-confined outside) remain absent inside; gravity (which doesn't propagate cell-to-cell for static fields) is unaffected as a static field but its dynamic-mode propagation through dormant regions has its own character (§12.2).

The transition from full relay to no relay is gradual through the boundary layer. A photon emitted at $r = r_S$ + (boundary-layer half-thickness) can propagate outward but with severely reduced v_T (low time-component speed = high redshift in the GR limit); a photon "emitted" at $r = r_S$ − (boundary-layer half-thickness) cannot propagate at all because the relay infrastructure is fluctuating-or-absent. Across the boundary layer the propagation rate goes continuously from finite to zero. This is the substrate-level analogue of the GR redshift-to-invisibility picture: outside the horizon, signals propagate with finite (decreasing) rate; at the horizon, propagation becomes asymptotically slow; inside the horizon, propagation is structurally absent.

A useful summary statement: **the horizon is one-way not by metric construction but by infrastructure absence.** The asymmetry comes from the substrate-level fact that cells inside cannot host the photon-relay mechanism. This is consistent with — and, in (3+3), the operational reason for — the standard GR one-way property.

4.6 Comparison with GR's Schwarzschild horizon and the membrane paradigm

Two reference pictures are useful for comparison: the bare Schwarzschild horizon of pre-1986 GR (the metric coincidence, with no local properties), and the membrane-paradigm horizon of Thorne-Price-Macdonald (1986) (the "stretched horizon" with effective fluid properties).

4.6.1 Bare Schwarzschild horizon

In the bare GR picture, the Schwarzschild horizon at $r = r_S$ is a coordinate-singular surface where Schwarzschild-coordinate time t and radial coordinate r swap their timelike/spacelike characters. The surface itself has no local properties — no temperature, no entropy, no thickness, no internal structure. It is the locus where the metric coefficient g_{tt} changes sign, and that is all. The horizon is a feature of the geometry, not a physical surface.

This picture was challenged by Bekenstein (1973) and Hawking (1975), who showed that the horizon has thermodynamic content (entropy $S_{BH} = k_B A/(4L_P^2)$ and temperature $T_{BH} = \hbar c^3/(8\pi G M k_B)$), but the thermodynamic content remained without a clear operational mechanism in pure GR. The horizon "had" a temperature and entropy as deductions from QFT in curved spacetime, but the standard treatment offered no substrate-level explanation of where these came from. The horizon was thermodynamically active without being structurally specified.

4.6.2 The membrane paradigm

Thorne, Price, and Macdonald (1986; [TPM86]) proposed treating the horizon operationally as a 2D fluid membrane with definite local properties: surface tension, electrical conductivity, viscosity, surface gravity.

The membrane is a "stretched horizon" placed just outside the actual event horizon (typically at proper distance ~ Planck length above the actual horizon), and it has effective surface properties chosen to reproduce the BH's observable behaviour in interactions with the surrounding plasma, magnetosphere, and accretion flow. The membrane paradigm has been very successful for astrophysical calculations (BH accretion, magnetised jets, BH-pulsar interactions) but is, in [TPM86]'s own framing, a fictitious construct used because the actual horizon's local properties are difficult to specify in GR.

4.6.3 The (3+3) horizon

The (3+3) horizon is closer to the membrane paradigm than to bare GR — it has definite local properties (cell states, the boundary layer, the relay-failure mechanism) — but with a key difference: **the (3+3) horizon's substrate-level structure is not fictitious**. It is the actual structure of the foam at the horizon, consisting of cells in the activation/dormantization transition zone. The "membrane" of the membrane paradigm is, in (3+3), the evanescent boundary layer.

The membrane paradigm's effective surface properties have substrate-level analogues:

- The membrane's **surface tension** corresponds to the foam's elastic response to perturbations of the boundary; in (3+3) this is the foam-elasticity (§2.6) evaluated at the boundary layer.
- The membrane's **electrical conductivity** corresponds to the boundary-layer cells' capacity to absorb infalling charged matter, converting the charge to substrate residue (per-cell *w* updates) on a timescale ~ R_3/c. The effective conductivity is reproduced in the appropriate limit.
- The membrane's **viscosity** corresponds to the dissipation of energy from in-plane perturbations of the boundary layer; in (3+3), this is the rate at which boundary-layer fluctuations relax back to the steady state after a perturbation.
- The membrane's **surface gravity** is recovered as the c-budget gradient evaluated at the horizon; this is the same as the GR surface gravity.

The conclusion is that the membrane paradigm captures effective horizon physics correctly because the substrate-level boundary admits an effective-fluid description in the appropriate limit, but the underlying physics is different from a fluid: it is foam at threshold occupation. **(3+3) makes the membrane paradigm structurally specific** — what was a useful effective description becomes a derivable consequence of the substrate-level dynamics. This is consistent with the membrane paradigm's success and adds an operational underlay.

Summary of §4.

The horizon in (3+3) is the substrate-level locus $\vartheta\_local = 0$ (equivalently $v\_T = 0$, equivalently the cell-state transition surface $N \approx N\_crit$). These three conditions coincide because they are determined by the same T_2 gradient.

The horizon has finite-thickness substrate structure: the evanescent boundary layer of thickness $\Delta N = \sqrt{N\_crit} \approx 79$ cells, where cell occupations fluctuate around threshold. This layer is the source of Hawking radiation and the locus of matter conversion (§5).

Two senses of "horizon" are distinguished: equilibrium (the static substrate boundary) and dynamical (the moving dormancy front during collapse, accretion, evaporation, or merger). They coincide in equilibrium and can differ during dynamics.

The horizon's one-way character has a substrate-level mechanism: the photon-only inter-cell relay infrastructure is absent inside (where cells are dormant). Signals cannot escape inside-to-outside not because they are redshifted to invisibility but because the propagation infrastructure is absent.

The membrane paradigm of [TPM86] is operationally close to the (3+3) horizon picture: the membrane corresponds to the boundary layer, and the membrane's surface properties have substrate-level analogues. (3+3) makes the membrane paradigm structurally specific.

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§5 Matter conversion at the boundary; boundary-layer response to infall

This section develops what happens when matter actually arrives at the horizon. Section §5.1 describes the conversion process by which infalling KK $n \geq 1$ modes decay to the $n = 0$ condensate state on the dormantising cells. Section §5.2 establishes per-cell winding number w preservation as the topological invariant carrying information through the conversion. Section §5.3 is the no-reactivation result: no matter how energetic the infaller, dormant cells inside the horizon are not reactivated. Section §5.4 establishes the c-budget bound on infaller kinetic energy. Section §5.5 sets up the boundary-layer response in steady state. Section §5.6 develops the dynamical response to accretion perturbations, and §5.7 derives the boundary-layer Hawking-spectrum modulation during accretion. Section §5.8 closes by comparing the (3+3) and GR readings of "no infaller crosses."

5.1 The conversion process: KK modes to substrate residue

When matter (KK $n \geq 1$ modes) approaches the horizon, the host cells in its immediate vicinity transition from activated to dormant as the local T_2 gradient steepens beyond threshold. The matter's KK mode amplitudes lose their propagation infrastructure — the photon-only relay (§2.4) is failing on the host cells; the equatorial-ring orbits supporting the cross-cell propagation are dormantising; the matter pattern can no longer propagate as a coherent KK mode.

The KK mode amplitudes do not vanish — amplitude is conserved — but they reconfigure. Two pathways are available:

- **Decay to the *n* = 0 condensate.** The KK $n \geq 1$ mode amplitudes decay into the $n = 0$ (ground-state) substrate condensate on the dormantising host cells. The energy is transferred to the substrate (where it manifests as increased mass, contributing to the BH gradient and shifting the dormancy boundary outward by $\Delta r\_S = 2GM\_infaller/c^2$). The per-cell winding numbers w on the host cells are updated to encode the matter's topological identity, by the mechanism of §5.2.
- **Hawking-radiation back-emission.** A small fraction of the KK mode amplitude couples to the boundary-layer activation fluctuations and radiates back outward as Hawking quanta. This is part of the steady-state Hawking emission process (§11); for a stellar-mass BH it is a small fraction of the infalling rest mass-energy on any individual infall event.

The relative rates depend on the matter's specifics — what KK mode index n, what spin, what total energy, what infall trajectory. For a typical stellar-mass infaller (atomic matter, modest velocities), the conversion-to-condensate pathway dominates by many orders of magnitude; the back-emission pathway is present but small and effectively undetectable except over BH-evaporation timescales.

The conversion timescale is set by the cell relaxation time, $\tau\_cell \sim R_3 / c \approx 4 \times 10^{-21}$ s. On macroscopic timescales the conversion is essentially instantaneous: an infalling proton arriving at the boundary layer converts in much less than a microsecond, far below any astrophysical observational timescale.

5.2 Per-cell winding number preservation

The crucial topological property of the conversion process is that **per-cell winding numbers *w* are preserved**. The winding number on each individual cell is classified by the homotopy group $\pi_2(S^2) = \mathbb{Z}$ ([1] §21.5): each cell carries an integer-valued winding that counts how many times the t_3 field wraps around the cell's S^2. This integer is invariant under continuous transformations of the field, including KK mode decay (which is a continuous reconfiguration of the field amplitudes).

When KK $n \geq 1$ modes decay to $n = 0$ on a given cell, the cell's mode amplitudes change continuously, but the topological winding *w* on that cell cannot change without a discontinuous transformation. **The decay process cannot change *w* values.** The matter's topological identity — its *w* distribution across the cells it occupied before conversion — is preserved on the cells after conversion.

For example, an infalling proton (per-particle total winding 918, distributed across its constituent cells) approaching the horizon: as the host cells dormantise, the KK mode pattern of the proton decays to $n = 0$; but the *w* values across those cells continue to total 918 (more precisely, 918 distributed in whatever pattern characterised the proton). The proton has "converted to substrate residue" — but the substrate residue is identifiable as proton-shaped by its *w* pattern.

This is the topological invariant on which the (3+3) resolution of the BH information paradox rests (developed in §11). All the information that was carried by the infalling matter — its mass, its charge, its quantum numbers, its specific configuration — is encoded as topological residue on the cells that dormantised during the infall. The *w* distribution on the BH's cells forms a topological "map" of everything that fell in over the BH's lifetime.

Notation reminder (per the §1.4.3 reservation): *w* (per-cell winding number) and *n* (KK mode index) are distinct quantities. The conversion process changes *n* (from $n \geq 1$ to $n = 0$) while preserving *w* (topological label on each cell). [1] sometimes uses *n* for both quantities; in this paper we reserve *n* for the KK mode index throughout, and *w* for per-cell winding.

5.3 No reactivation of dormant cells from infaller kinetic energy

A natural concern is whether very energetic infalling matter could deposit enough kinetic energy at the boundary to reactivate dormant cells just inside, effectively punching a hole in the dormancy region. **The (3+3) answer is no.** Two independent reasons converge.

5.3.1 Geometric (not energetic) activation threshold

The activation threshold N_crit = 6,203 is set by the bridge equation $14\tau^{10} = \pi m\_H^3/(32v^2 m\_e)$; both sides are dimensionless geometric/Standard-Model quantities with no dependence on local energy density. The cell-state transition is determined by **whether the local T_2 gradient is steep enough that *N* falls below *N_crit*** — and the T_2 gradient is set by the total mass distribution, not by the kinetic energy of any individual infaller.

When an infaller of mass m arrives at the boundary, its rest mass-energy mc^2 is added to the BH's total mass M, and the equilibrium horizon moves outward by $\Delta r\_S = 2Gm/c^2$. The dormancy front follows the new equilibrium position. Cells that were just outside the previous boundary now find themselves in the steeper-gradient region and dormantise; the boundary has moved, but its character — cells transitioning at $N \approx N\_crit$ — is unchanged. **The infaller's rest mass-energy contributes to the gradient determination; its kinetic energy does not punch through dormancy.**

5.3.2 Relay failure ahead of the infaller

Independently, the photon-only relay mechanism gives a second reason. The infaller's KK modes propagate via the photon-only inter-cell relay (§2.4). As the host cells dormantise, the relay infrastructure on the host cells fails — **before the infaller arrives at the dormant region itself**. The infaller's KK modes lose their propagation infrastructure during the approach, not at the arrival; conversion to substrate residue happens through the boundary layer (over the ~79-cell-thickness ΔN), not at a discrete impact point.

There is no "impact" in the substrate-level picture. The matter's KK modes fade out as the cells dormantise; by the time the dormancy is complete on the host cells, the matter's mode amplitudes have decayed to $n = 0$ condensate. The kinetic energy delivered to dormant cells via the matter's spatial motion is zero — there is no propagating excitation present at the dormant cells to deliver any energy.

Conclusion: the dormant interior is robust against any infaller, regardless of kinetic energy. The boundary moves outward as mass accretes; its character does not change. This is consistent with the GR area theorem (horizon area cannot decrease) and adds the substrate-level mechanism for it: dormantization is irreversible at the substrate level (cells, once dormant, do not reactivate in equilibrium); evaporation, where the dormancy front recedes, requires the gradient to weaken, which requires mass loss via Hawking radiation (§11).

5.4 Bounded kinetic energy from the c-budget identity

A complementary observation: the infaller's kinetic energy, as measured at the substrate level, is bounded by the c-budget identity. There is no "infinite-γ" regime in the (3+3) substrate-level picture, in contrast to the standard GR coordinate-frame description.

The c-budget identity (§2.1):

$$v\_T^2 + v\_t_2^2 + v\_t_3^2 + v\_x^2 + v\_y^2 + v\_z^2 = c^2 \quad \text{(c-budget)}$$

caps every velocity component at c. The infaller's spatial-component speed $|v\_spatial|$ can reach c but cannot exceed it. As the infaller approaches the horizon, its c-budget redistributes: v_T decreases (proper-time slowing), and the spatial components increase to compensate. At the horizon ($\vartheta\_local = 0$), the entire c-budget is in spatial motion: $|v\_spatial| = c$. Beyond the horizon, the c-budget would have to admit $|v\_spatial| > c$, which is not allowed.

In the standard GR coordinate-frame picture, an infaller falling radially from rest at infinity reaches the horizon with kinetic energy that diverges in the limit $\gamma \to \infty$ as measured by a stationary observer at infinity. The (3+3) reading of this divergence: **the divergence is a coordinate artifact, not a substrate-level fact**. The stationary observer's measurement of the infaller's kinetic energy diverges because of the coordinate transformation (the stationary observer's proper time becomes infinitely separated from the infaller's as the infaller approaches the horizon); but the substrate-level energy carried by the infaller, evaluated in any local frame on its trajectory, is bounded by the c-budget.

The infaller's rest mass-energy mc^2 is a substrate-level quantity (it is the v_t_2 component of the infaller's c-budget). This is what gets added to the BH's mass on conversion. The kinetic energy in the spatial components — $v\_x^2 + v\_y^2 + v\_z^2$ — is bounded by c^2 in any local frame and contributes **bounded** energy on conversion. There is no infinite-energy deposit at the boundary; the deposit is $m \times c^2$ (rest mass-energy) plus a bounded kinetic contribution.

Combining §5.3 and §5.4: **the infaller delivers bounded energy at the boundary and that bounded energy is unable to reactivate dormant cells**. The dormant interior is robust against accretion of any kind. This is the substrate-level picture; the GR-frame "infinite kinetic energy at horizon crossing" is a coordinate artifact that does not enter the substrate-level dynamics.

5.5 Steady-state boundary-layer response

In the absence of accretion, the boundary layer reaches a statistical steady state. Cells in the layer fluctuate between activated and dormant on quantum-uncertainty timescales; the long-time-average activation fraction at any radial position within the layer is well-defined. The fluctuation statistics are set by Poisson counting of the integer N around the threshold N_crit.

Cells with $N > N\_crit$ (briefly activated within the layer) host equatorial-ring photon excitations. A fraction of those photons escape outward via the photon-only relay (§2.4), and the escape rate, integrated over the boundary-layer area, gives the standard Hawking flux:

$$T\_BH = \hbar c^3 / (8\pi G M k\_B) \quad \text{(Hawking temperature)}$$

([1] §21.4 derives this from the boundary-layer thickness $\Delta N \approx \sqrt{N\_crit} \approx 79$ cells combined with the cell-frequency relation; this paper takes it as a given.) The spectrum is approximately thermal at T_BH; the small deviations from exact thermality reflect the cell-discrete substrate but are negligible on observational scales for any realistic BH.

The steady-state Hawking emission is the base case against which dynamical perturbations (accretion, mergers) are measured. In §5.6 and §5.7 we develop the boundary-layer response to accretion perturbations and the resulting Hawking-spectrum modulation.

5.6 Boundary-layer response to accretion perturbations

When matter accretes onto a black hole, several substrate-level processes occur in sequence:

- **Approach phase.** The infaller's KK modes propagate through the activated far field at standard rates; gravitational acceleration (foam elastic response to the T_2 gradient) increases the spatial-velocity components in accord with the c-budget identity.
- **Boundary-layer entry phase.** As the matter approaches the boundary layer, host cells in its immediate vicinity begin to dormantise. The matter's KK mode propagation rate decreases; the modes begin their decay to $n = 0$.
- **Conversion phase.** Inside the boundary layer, the host cells are dormantising rapidly. The KK modes decay to substrate condensate; per-cell winding numbers *w* update to encode the matter's topological identity (per §5.2).
- **Boundary readjustment phase.** The new total mass $M' = M + m\_infaller$ has shifted the equilibrium horizon outward by $\Delta r\_S = 2Gm\_infaller/c^2$. The dynamical horizon (§4.4) moves to the new position, and cells that were just outside the previous boundary layer (now in the new boundary layer) have their T_2 gradients steepened to threshold.
- **Relaxation phase.** The boundary-layer fluctuation statistics around the new *r_S* settle into the new steady state (with the new horizon position). Relaxation timescale is of order $\tau\_cell = R_3/c \approx 4 \times 10^{-21}$ s.

During the conversion and readjustment phases, the boundary-layer activation statistics are perturbed. More cells than usual are at-or-just-above *N_crit* (some because the infall has briefly elevated their occupation; some because the boundary is moving and previously-far-from-threshold cells are now near threshold). The result is a brief enhancement of Hawking emission rate during the perturbation.

The duration of the enhancement is set by the longer of the conversion timescale (matter's passage through the boundary-layer thickness Δr at characteristic speed ~ *c*) and the cell relaxation timescale *τ_cell*. For a stellar-mass BH with boundary-layer Δr ~ 100 fm (much smaller than *r_S* ~ km), the duration is ~ 10^{-21} s — essentially instantaneous on astrophysical timescales.

5.7 Hawking-spectrum modulation during accretion (Level 2)

The brief enhancement of Hawking emission during accretion (§5.6) constitutes a Hawking-spectrum modulation distinguishing accreting from passive black holes. This is a **Level 2 prediction**: the framework permits the modulation, the order of magnitude follows from substrate primitives, but the precise prefactor depends on detailed boundary-layer dynamics that this paper does not derive in full.

5.7.1 Order-of-magnitude estimate

For an accretion event of mass *m_infaller* onto a BH of mass *M* (with *m_infaller* << *M*), the boundary-layer activation perturbation has:

- **Duration** $\tau\_perturb \sim \tau\_cell + (\Delta r/c) \approx 4 \times 10^{-21}$ s (the cell relaxation time dominates for boundary layers thinner than $c\tau\_cell$).
- **Spatial extent** ~ the boundary-layer area in the immediate vicinity of the infall path, of order $\Delta A \approx \Delta r \times r\_S$ (a thin annular region near the infall trajectory).

- **Intensity** ~ $m\_infaller \times c^2 \times (\Delta A / (4\pi r\_S^2))$ per unit time during $\tau\_perturb$. This is the rest mass-energy distributed over the affected fraction of the boundary layer.

Integrating, the **total integrated extra Hawking flux per accretion event** is of order:

$$\Delta E\_Hawking \sim m\_infaller\ c^2 \times \eta \times (\Delta A / 4\pi r\_S^2)$$

where η is the accretion-coupling efficiency (the fraction of the perturbation's energy that escapes as Hawking radiation rather than being absorbed into substrate-mass increase). The framework permits $\eta \sim 10^{-3}$ to 10^{-1} depending on the boundary-layer dynamics; the precise value is not derived in this paper. **Level 2 caveat**: this prefactor is the source of the Level 2 classification — the structural form of the modulation is at Level 1, the magnitude at Level 2.

5.7.2 Observational accessibility

For stellar-mass BHs accreting at typical astrophysical rates, the Hawking modulation is far below current detector sensitivity:

- **Stellar-mass BH** ($M \sim 10\ M\_\odot$): $T\_BH \sim 10^{-8}$ K, base Hawking flux ~ 10^{-29} W. Even with $\eta \sim 10^{-1}$, the modulation per accretion event is well below astrophysical foreground noise.
- **Supermassive BH** ($M \sim 10^9\ M\_\odot$): $T\_BH \sim 10^{-17}$ K; Hawking flux ~ 10^{-47} W. The modulation is undetectable by orders of magnitude.
- **Primordial BH** ($M \sim 10^{12} – 10^{15}$ g, near or below evaporation): $T\_BH \sim 10^{-12} – 10^{-9}$ GeV; Hawking flux is significant. Accretion modulation could be observably distinguishing if a primordial BH is detected.

The modulation is therefore a target for next-generation observations of evaporating primordial BHs (Cherenkov-Telescope-Array-class gamma-ray observatories, neutrino observatories like IceCube-Gen2 and KM3NeT). If primordial BHs are detected and their Hawking radiation observed, accretion modulations distinguishing (3+3) from pure-GR Hawking emission may become accessible. This is an in-principle observable distinction, even if the detection prerequisite (a primordial BH) has not yet been achieved.

For BH-BH mergers, a related effect occurs during the ringdown phase, where the substrate boundary is rapidly readjusting. The Hawking modulation during ringdown is qualitatively analogous to the accretion modulation but quantitatively different (energy scale set by the merger's ringdown energy rather than by individual infall events). This is a topic for §12.

5.8 Comparison with the GR "no infaller crosses" picture

Both standard GR and (3+3) yield the result that, from the perspective of a distant external observer, an infaller is never observed to cross the horizon. The mechanisms differ at the substrate level.

Aspect	Standard GR (Schwarzschild + Kruskal)	(3+3) substrate-level
What "no crossing" means to external observer	Signals from infaller redshift to infinite wavelength as horizon is approached	Infaller's KK modes lose propagation infrastructure as host cells dormantise
What happens to infaller in own frame	Crosses smoothly; reaches singularity in finite proper time	KK modes decay to $n = 0$ substrate at boundary; matter "converts," does not "cross"
Where infalling matter ends up	Inside the horizon (in some frame); crushed at $r = 0$ singularity	Topological residue (per-cell w values) on dormant cells; energy in substrate
Resolution of "what frame is right"	Both frames valid; coordinate-relative descriptions	Single substrate-level fact: matter converts, period; smooth-crossing in Kruskal is a metric continuation past the dormancy boundary
Operational test	No experimental access to interior	Topological residue accessible during evaporation as boundary recedes (§11)

The (3+3) reading has two operational advantages:

- **Single physical fact, not coordinate-relative.** The matter converts to substrate residue at the boundary. This is a substrate-level fact independent of any observer's frame. The smooth-crossing picture in Kruskal-Szekeres coordinates corresponds to a metric continuation past the dormancy boundary; the continuation is mathematically allowed but does not describe an observer-inhabited region.
- **Information-conservation pathway.** Per-cell w preservation means the matter's information ends up encoded in topological residue, accessible during evaporation. The GR picture (matter crushed at singularity, then evaporated as thermal Hawking radiation) gives no clear pathway for information conservation, leading to the information-paradox tension. The (3+3) pathway is operationally specific.

These advantages do not constitute an empirical distinction at current sensitivity — the GR exterior solution is accurate, the matter-crossing event is unobservable in either picture, and Hawking radiation has not yet been detected for any astrophysical BH. They are interpretational advantages: the (3+3) reading gives a single substrate-level account of what the matter does, where it ends up, and how its information is preserved.

Summary of §5.

Matter approaching the horizon converts to substrate residue at the boundary layer: KK $n \geq 1$ modes decay to $n = 0$ condensate on dormantising cells over a timescale of $R_3/c \approx 4 \times 10^{-21}$ s. The matter does not "cross" — it converts.

Per-cell winding numbers w are topologically preserved through the conversion ($\pi_2(S^2) = \mathbb{Z}$ invariance). Information about infalling matter is encoded in the w distribution on dormant cells.

No reactivation from KE: dormant cells are not reactivated by infaller kinetic energy. The activation threshold is geometric (set by T_2 gradient steepness, determined by total mass), not energetic. The relay-failure mechanism means KE is not delivered to dormant cells in the first place.

Bounded KE at horizon: infaller KE is bounded by the c-budget identity. The "infinite γ at horizon" of GR is a coordinate artifact; substrate-level energies are bounded by c-magnitude constraints on velocity components.

Hawking modulation during accretion (Level 2): Boundary-layer perturbations during accretion produce a tiny but in-principle-observable Hawking-spectrum modulation distinguishing accreting from passive BHs. The modulation is below current detector sensitivity for stellar-mass and supermassive BHs; potentially accessible for primordial BHs if detected.

The "no infaller crosses" puzzle of §1.1.2 has a single substrate-level resolution: matter converts at the boundary, the smooth-crossing picture in Kruskal coordinates is a metric continuation past the dormancy boundary not describing an observer-inhabited region, and per-cell w preservation gives a definite information-conservation pathway.

§6 Three time dimensions in BH dynamics

This section develops the **three-time-dimension structure of black holes** drawn from [2] §14bis.41 and the prior research note [31] that [2] consolidates. The thesis is straightforward: of the framework's three time dimensions (T, t_2, t_3), each responds differently to the extreme conditions inside a BH, and the c-budget reallocation among them gives a unified account of gravitational time dilation, the cosmological disconnection of black holes, the preservation of internal physics, and Hawking radiation — all from one principle. The three-time-dimension picture is the substrate-level resolution of the would-be-interior issue introduced in §2.1: the c-budget does not "disappear" or enter an imaginary regime; it reallocates across the three time dimensions in a specific pattern that preserves the c-budget identity throughout.

Section §6.1 recapitulates the *T*-frozen result already established in §2.1 and §4 and frames it as one of three time-dimension responses. Section §6.2 develops the t_2-severed result — BHs as cosmic fossils frozen at θ_form, disconnected from Hubble expansion. Section §6.3 develops the t_3-continues-per-cell result — internal physics keeps cycling at the substrate level even though no propagation between cells is possible. Section §6.4 develops the implication: there are **three distinct carriers of mass** inside a BH, and each is preserved by a different mechanism. This synthesis is drawn primarily from [2] §14bis.41 with refinements from the corresponding research notes.

6.1 T frozen at the horizon

T, the first time dimension, is the rate at which observable clocks advance — the coordinate time of standard relativity, set by how much of the c-budget goes into the temporal Planck-cell advance. The framework's response to extreme density is well known and was established in §2.1 and §4: *v_T* slows progressively toward the horizon, reaching zero at $r = r_S$.

$$v_T(r) = c \cdot \sqrt{1 - r_S / r} = c \cdot f(r), \quad f(r_S) = 0 \quad \text{(T-component reallocation)}$$

At the horizon, *v_T* = 0 completely. External observers never see an infalling object actually cross the horizon — its observable clock asymptotes to a stop (§7 develops this in detail). For an external T-observer, the infaller is frozen at the horizon for all coordinate time. The substrate-level mechanism is the c-budget reallocation: as $r \to r_S$, $v_T \to 0$ and $v_{t_3} \to c$, with the entire c-budget transferring from T into t_3 (developed below in §6.3).

Inside the horizon, *v_T* = 0 stays. Cells inside are dormant (§4.2.1); *v_T* does not enter an imaginary or otherwise pathological regime — it remains at zero at the dormant-cell fixed point (§2.1 c-budget reallocation paragraph). No outward propagation is possible because no T-advance is available. Electromagnetic signals, gravitational-wave emission outward, particle escape — all require *T*-advance in the spatial-outward direction, and that part of the budget has been depleted entirely. The horizon is therefore a one-way membrane in the *T*-component sense: nothing crosses outward because the *v_T* budget is unavailable for that.

This is the framework's account of standard gravitational time dilation: *T* freezes at the horizon, and the c-budget that would have been in *T* is redirected into t_3. **What is genuinely new in the (3+3) framework,**

beyond standard GR, is what t_2 and t_3 do. GR has a single time dimension; the framework has three, and the responses of t_2 and t_3 are not predictions of GR.

6.2 t_2 severed: black holes as cosmic fossils

t_2, the second time dimension, is the slow advance of the cosmic angle ϑ. It couples each activated foam cell to the global cosmic rotation $\vartheta(T)$, which drives the Hubble expansion $H(\vartheta)$ = H_int sin(2ϑ) ([1] §22, [2] §14bis.2). In normal activated foam, t_2 advances slowly relative to T (the rate is set by H_int ≈ 78 km/s/Mpc), and tiles recede from each other at the cosmic-expansion rate.

A black hole is a region where the local t_2 coupling has been severed. The extreme slot-occupation density / T_2 gradient steepness at the horizon (§4.2.1) disconnects the cells inside from the global ϑ advance. The global ϑ continues advancing for the rest of the universe; the black hole's local effective ϑ does not advance — **it stays at *ϑ_form*, the cosmic angle at the moment the black hole formed**:

Inside BH: ϑ_BH^local = ϑ_form (frozen at formation)\nOutside: ϑ(T) advances normally toward ϑ_max (t_2 severance)

This is a structurally distinctive prediction — specific to (3+3) and not derivable from standard GR (which has only one time dimension). Three observable consequences follow:

- **Black holes do not participate in Hubble expansion.** Their tiles do not recede with the cosmic flow. The surrounding matter redshifts away as the universe expands; the black hole remains at its formation size (modulo subsequent accretion). This is consistent with observation — black holes are not measured to expand cosmologically — but most cosmological frameworks don't predict them to in any case, so this is a consistency check rather than a distinguishing prediction.
- **Black holes are cosmologically stuck at their formation epoch.** The local Hubble rate H(*ϑ_form*) applies inside, not the current H(*ϑ_now*). An ancient black hole formed when the universe was at *ϑ_form* ≈ 20° carries an internal Hubble rate of H_int sin(40°), substantially different from today's H_int sin(2 × 55.79°). This is in principle observationally distinguishable through detailed BH dynamics, though the precision required to detect it is far beyond current capabilities (Level 2 prediction).
- **Old black holes are time-asymmetric cosmic fossils.** Two objects at the same spatial location — one just inside the horizon, one just outside — experience different cosmic times. The information paradox is partly about this asymmetry; the framework resolves it geometrically (via the three-time-dimension structure) rather than through firewalls or holographic constructions (§11).

Implication for primordial BHs. A very old black hole formed near the Bang epoch (small *ϑ_form*) is a kind of **frozen sample of early-universe physics**. The coupling constants, Compton frequencies, and keeper-wave structures inside are still governed by the formation-epoch S^2 geometry. For a primordial BH formed at, say, *ϑ_form* ≈ 5°, the internal physics is frozen at the conditions of that ancient epoch, even as the surrounding universe has evolved to *ϑ_now* ≈ 55.79°. This is a structural prediction of the framework — **primordial BHs as fossils of early-universe physics** — that distinguishes (3+3) from approaches where BH interiors are characterised only by mass, charge, and spin (no-hair theorem). The (3+3) interior carries an additional invariant: ϑ_form.

Whether this prediction is currently testable: probably not at the precision available, since the external-observable consequences (BH gravitational field, Hawking spectrum at fixed T_BH) are dominated by the mass parameter and ϑ_form enters only at higher orders. But the prediction is structurally present and provides an avenue for future tests — for instance, statistical analysis of primordial BH populations might reveal correlations with their formation epochs that are not predictable in mass-only frameworks.

6.3 t_3 continues per-cell: internal physics keeps cycling

t_3, the third time dimension, is the cycling of slot occupations on the compact t_3 S^2 of each cell. It carries the Compton frequency $\omega\_C = m c^2/\hbar$ for every massive particle, the keeper-wave occupations on the three great circles, and the internal phase relationships of all slot patterns. **t_3 continues at full speed inside the black hole** — even as T freezes at the horizon and t_2 is severed, the internal physics register of every dormant cell inside continues to cycle at c:

$$\text{Inside BH: } v\_t_3 = c \text{ per cell (full } c\text{-budget allocated to } t_3) \quad (t_3 \text{ persistence})$$

Caveat on terminology. The cells are dormant in the activation sense (§2.2, §4.2.1): no KK $n \geq 1$ modes propagate, no inter-cell relay capacity, no SM physics in the propagating sense. **But the t_3 coordinate still exists at each cell** (cells exist in 6D spacetime regardless of activation state), and per-cell t_3 cycling continues. What "t_3 continues" means is not that propagating excitations cycle (they don't — the cells are dormant), but that the cell's own t_3 S^2 compactified surface continues to advance through its compactification cycle, with topological structure (per-cell winding w, keeper-wave occupations) preserved. This is the reconciliation between [1]'s "dormant interior" picture and [2]/notes' "t_3 continues" picture — both are correct at their own level, and they are not in conflict.

What continues inside, per-cell:

Process	Status inside BH (per cell)	Reason
Compton frequency cycling $\omega\_C = m c^2/\hbar$	Continues at full rate	t_3 carries the Compton frequency; t_3 coordinate is not frozen at the cell
Photonic keeper wave (k=1 ring slot)	Continues; always occupied	Topological constraint on ring winding; independent of T
Fermionic keeper wave (yz ground state)	Continues; always occupied	Topological constraint on yz half-integer winding; independent of T
Slot occupation patterns (per-cell)	Cycle and evolve	t_3 provides the internal clock for slot dynamics on each cell

Process	Status inside BH (per cell)	Reason
Per-cell winding number w	Preserved as topological invariant	$\pi_2(S^2) = \mathbb{Z}$ topological label on each cell; cycles in t_3 but does not vanish
Information content (per cell)	Fully preserved in slot patterns	Patterns cycle in t_3 but do not vanish; cells are not destroyed by dormancy

What cannot happen inside (because *T* is frozen and inter-cell relay is unavailable):

- **Electromagnetic signals reaching outside**: photon-tooth propagation requires *T*-advance in the outward spatial direction; *T* is frozen toward the horizon, and the relay infrastructure is dormant inside. Photons cannot cross between cells in the dormant interior, and cannot exit.
- **Gravitational-wave emission outward**: same reason. Wave propagation requires *T*-advance and substrate-coupling; both are absent.
- **Particle escape**: budget exhausted on *T* component; nothing left for spatial outward propagation. The cells' t_3 cycling is internal-only — it does not produce excitations that propagate between cells.

Reframing of the GR picture. In standard GR, the BH interior is described as a region where the timelike and spacelike directions exchange roles (§9 develops this); distance-from-singularity becomes time-like, and "time-flow" is replaced by inward radial collapse. In (3+3), the GR description is the **external shadow** of an internal physics that runs unimpeded at the substrate level: the t_3 per-cell cycling continues, topological patterns persist, and information is fully preserved as cells' winding *w* values and keeper-wave occupation patterns. The interior is not "where physics breaks down"; it is "where physics runs in t_3 only, inaccessible to external *T*-observers."

6.4 Three carriers of mass inside the BH

A consequence of the three-time-dimension structure is that **mass inside a BH is not a single quantity** but is distributed across three distinct carriers, each preserved by a different mechanism. This synthesis follows [2] §14bis.41 and the corresponding research notes; it provides a structural account of why mass is conserved through the entire BH lifetime (collapse → static phase → Hawking evaporation) without ever needing the matter to "survive" in the propagating-excitation sense.

Carrier	(3+3) origin	Why it persists inside
Baryon mass (protons, neutrons)	KK winding number n = 918 of the yz circle per proton ([1] §7.6, [5]). Each proton carries n = +1 topological winding in $\pi_2(S^2) = \mathbb{Z}$. This winding is absolutely conserved.	**Topological**: the winding number survives any density. Compressing protons together at extreme density does not unwind them. Baryon number is

Carrier	(3+3) origin	Why it persists inside
		exactly conserved inside the horizon.
Rest-mass energy (Compton cycling)	The Compton frequency cycling of slot occupations in the compact t_3 dimension. $\omega\_C = m c^2/\hbar$. Heavier particle → faster t_3 cycling. This is the rest-mass term in the c-budget.	**Dynamical (per-cell)**: t_3 continues at full c rate inside the horizon (§6.3). The Compton frequency of every particle continues ticking regardless of what T and t_2 do.
Gravitational field (metric distortion)	The slot-occupation density gradient extends continuously outward from the high-density interior through the external activated foam tiles. Foam-elastic deformation of the substrate (§2.6).	**Geometric**: the gradient is continuous and extends outward without interruption. External observers feel the same gravitational attraction as from the original star of the same mass. Black holes orbit, merge, sit at galactic centres — all via this geometric carrier.

The three carriers are simultaneously active. Baryon winding numbers are stored as topological $\pi_2(S^2) = \mathbb{Z}$ invariants on individual cells; they cannot be removed by compression or by any continuous deformation of the field. Rest-mass Compton cycling continues on each dormant cell at the characteristic frequency $\omega\_C = m\, c^2/\hbar$; this is the cycling of slot patterns in t_3 and is per-cell, not propagating between cells. The gravitational field is the elastic deformation of the substrate around the BH, and it extends outward into the activated foam region where it is measurable by external observers.

The "no hair" theorem in this framework. External observers can only measure the gravitational-field carrier directly (and the BH's electric charge if it has one, via the same mechanism). They see total mass *M*, angular momentum *J*, and charge *Q* — three numbers. The detailed topological residue (the per-cell *w* distribution) and the detailed t_3 cycling patterns are inaccessible from outside (relay-failure, §4.5). The "no hair" theorem in (3+3) is a statement about external observability, not about physical reality: the additional internal structure exists, preserved on dormant cells, but is not externally measurable until it emerges via Hawking radiation (§11).

Implication for the information paradox. The structural account is now clear: information is preserved on (i) per-cell winding *w* (topological), (ii) per-cell t_3 slot-occupation patterns (dynamical-per-cell), and (iii) the gravitational-field configuration (geometric). All three are sustained throughout the BH's static phase. As Hawking radiation gradually extracts the BH's mass, all three carriers feed back into the outgoing radiation (§11.5–§11.7). At final evaporation, all three carriers have been returned to the external universe in the Hawking spectrum; nothing has been destroyed. This is the substrate-level account of unitary BH evaporation developed in §11.

Summary of §6.

T frozen at the horizon (§6.1, recap from §2.1, §4): $v\_T \to 0$ as $r \to r\_S$; inside, $v\_T = 0$ stays. No outward propagation in *T* possible.

t_2 severed (§6.2): BH disconnected from cosmic ϑ advance; frozen at *ϑ_form* (formation epoch); does not participate in Hubble expansion. Old BHs are cosmic fossils preserving early-universe physics. Adds *ϑ_form* as an internal invariant beyond GR's (M, J, Q).

t_3 continues per-cell (§6.3): internal Compton cycling, keeper-wave occupations, slot patterns continue on dormant cells; t_3 coordinate exists at each cell regardless of activation state. The cells are dormant in the activation sense (no KK $n \geq 1$ propagation), but t_3 per-cell cycling persists. Reconciles [1]'s "dormant interior" with [2]/notes' "t_3 continues" — both correct at their own level.

Three carriers of mass inside (§6.4): baryon winding (topological, $\pi_2(S^2) = \mathbb{Z}$); Compton cycling (dynamical-per-cell, t_3); gravitational field (geometric, extends outward). All three preserved throughout BH lifetime. "No hair" is statement about external observability, not physical reality.

The three-time-dimension structure provides the substrate-level resolution of the would-be-interior issue (§2.1) and unifies the framework's account of BH dynamics from horizon to centre.

§7 The frozen-star / "nothing crosses" resolution

This section synthesises the substrate-level resolution of the second classical puzzle of §1.1.2: the apparent contradiction between the asymptotic-freezing description of the infaller in Schwarzschild exterior coordinates and the smooth-crossing description in Kruskal-Szekeres coordinates. The pieces of the resolution have been assembled in §3 (substrate/excitation distinction), §4 (the horizon as substrate boundary), and §5 (matter conversion at the boundary). Here they are brought together as a single coherent picture: matter does not cross the horizon in any frame; the asymptotic-freezing picture is substrate-level correct; the smooth-crossing picture in Kruskal coordinates is a metric continuation past the dormancy boundary that does not describe an observer-inhabited region. The pre-1960s "frozen star" picture, often regarded as superseded by the post-Kruskal "BH-with-interior" picture, turns out to be closer to the substrate truth.

7.1 The puzzle in compact form

Restated briefly: standard general relativity supplies two coordinate descriptions of an infaller approaching the horizon. **In Schwarzschild exterior coordinates**, an external stationary observer sees the infaller's proper time slow asymptotically to zero, the emitted light redshift to zero frequency, and the time required to "see" the crossing event diverge. The infaller appears to freeze on the horizon. **In Kruskal-Szekeres coordinates**, which are regular at the horizon, the infaller crosses smoothly with no detectable local event, reaching the singularity at $r = 0$ in finite proper time of order r_S/c. The two descriptions are mathematically equivalent — they are coordinate transformations of the same metric — but they differ in what they say about the infaller's eventual location.

The standard GR resolution is that the descriptions are coordinate-relative: each is correct in its own frame, and the question "did the matter cross?" depends on which coordinate system you ask. As noted in §1.1.2, this resolution is mathematically clean but operationally evasive — it does not answer the question of whether there is a fact of the matter about the infaller's eventual location, and it leaves the disposition of the original collapsing star's matter unspecified except in coordinate-dependent terms.

The (3+3) resolution gives a single substrate-level fact: matter does not cross the horizon. It converts to substrate topological residue at the boundary layer (§5.1, §5.2). The conversion is a real physical process — KK $n \geq 1$ modes decaying to $n = 0$ condensate on dormantising cells — that occurs for every infaller regardless of coordinate frame. The two GR coordinate descriptions admit substrate-level readings: Schwarzschild exterior coordinates describe what the external observer sees of the conversion process (asymptotic freezing as the matter's KK modes lose their propagation infrastructure); Kruskal-Szekeres coordinates analytically continue the metric past the dormancy boundary into a ghost geometry no observer inhabits. **Both coordinate descriptions are correct as descriptions of metric structure; neither describes matter actually crossing the horizon as a propagating excitation.**

7.2 Asymptotic freezing as a real physical process

The Schwarzschild-exterior-coordinate asymptotic-freezing picture is the substrate-level reading of what is happening at the boundary. Recall from §2.5 and §4.1 that the local light-speed angle $\vartheta\_local(r) = \arccos(\sqrt{r\_S/r})$ goes to zero at the horizon. The c-budget identity's v_T component:

$$v\_T^2(r) = c^2 (1 - r\_S / r) \quad \text{(c-budget Schwarzschild)}$$

goes to zero at $r = r\_S$ and would have to be imaginary inside. The proper-time accumulation rate $d\tau/dt$ of an observer at radius r is v_T/c; this rate goes to zero at the horizon. **The propagation rates of all KK $n \geq 1$ modes — including the photon's equatorial-ring orbit and the matter's A2/B2/C1/A3 mode patterns — depend on the cells' activation state, which depends on N relative to N_crit, which depends on the T_2 gradient steepness, which is precisely what v_T tracks**. As the matter approaches r_S, its KK modes are propagating slower and slower, and approaching the limit of activation ceasing.

The "asymptotic" character is not a coordinate artifact. The matter's propagation rate is a substrate-level quantity: it depends on the cells' state, which is a substrate-level fact. The asymptotic limit is reached as the cells cross the activation threshold $N = N\_crit$. The matter's trajectory through the boundary layer takes finite time as measured by external observers (the time for the cells in its path to dormantise; cell relaxation timescale $\tau\_cell \approx R_3/c$), but the infaller's own proper-time accumulation has already gone to zero by the time it reaches $\vartheta\_local = 0$. The matter does not "continue past" the boundary in any frame because there is no continuation available — the propagation infrastructure is being removed.

The result: **asymptotic freezing is physically real**, not a coordinate artifact. The Schwarzschild-exterior-coordinate picture, in which the infaller asymptotically freezes on the horizon, is reading the substrate dynamics correctly at the level of what the external observer measures. Where standard GR's use of these coordinates is operationally limited — it cannot say what is "actually" happening to the infaller — the substrate-level reading supplies the mechanism: the infaller's KK modes are converting to substrate residue as the host cells dormantise. The asymptotic freezing in coordinate terms corresponds to the conversion process unfolding through the boundary layer at the substrate level.

7.3 What "smooth crossing" in Kruskal coordinates actually describes

Kruskal-Szekeres coordinates were introduced in 1960 (Kruskal 1960; Szekeres 1960) as a maximal extension of the Schwarzschild metric — a coordinate system regular everywhere except at $r = 0$ itself, including at the horizon. In Kruskal coordinates the metric coefficients are smooth at $r = r\_S$, the infaller's worldline crosses the horizon without coordinate singularity, and the analytical structure of the spacetime extends to the interior region as a manifold with t-r coefficient inversion. **This is mathematically allowed** and is the standard formal treatment of the BH interior in modern textbooks.

The substrate-level reading is that the Kruskal extension is **a metric continuation past the dormancy boundary**. The metric formalism does not "know" about substrate states; it operates at the level of $g\_\mu\nu$ on a smooth manifold. Continuing $g\_\mu\nu$ past the surface $\vartheta\_local = 0$ produces a mathematically well-defined region with t-r-inverted coefficients, in which analytical worldlines can be drawn. But the substrate at the same physical location is dormant: cells with $N < N_{crit}$, no propagating excitations, no observers. The Kruskal-extension worldlines drawn in the interior region **describe trajectories in a metric continuation, not propagation of physical matter**.

This distinction is sharper when stated in terms of the (3+3) primitives. A physical matter trajectory in (3+3) is a sequence of activated cells across which a coherent KK mode pattern propagates via the photon-only relay. Inside the dormancy region, none of these conditions hold: cells are dormant, the relay is absent, no KK mode pattern can propagate. The Kruskal-extension worldline crossing the horizon and continuing inward does not correspond to any physical matter trajectory in this sense — it is a metric construct that, while mathematically consistent, does not describe a propagating excitation.

A concrete way to see this: in the Kruskal extension, an infaller with "smooth crossing" worldline reaches the singularity at $r = 0$ in finite proper time of order r_S/c. But the substrate at $r < r_S$ is dormant; there is no physical propagation; the proper time of the metric-extension worldline is not anyone's proper time. **No physical observer accumulates that finite proper time** because no physical observer is propagating along that worldline. The smooth-crossing picture is a coherent metric description of a region inhabited by no observers — what we have called a ghost geometry (§3.7.3 and developed in §9).

7.4 The "fact of the matter" question

A key methodological point. In §1.1.2 the puzzle was framed as "does the matter actually cross the horizon, or does it asymptotically freeze on the outside?" The standard GR answer — "yes from the infaller's frame, no from the external observer's frame" — was characterised as operationally evasive. **What does it mean for there to be a fact of the matter, beyond what each coordinate frame reports?**

In a relativistic framework that allows matter to be defined in coordinate-invariant terms, the question has a definite answer. **Matter is converted to substrate residue at the boundary in (3+3)** — this is a substrate-level fact characterised by:

- Cell states (activated/dormant): coordinate-invariant property of cells, specified by N relative to N_{crit}, observable in principle by any local measurement of the photon-only relay function.
- Per-cell winding numbers w: integer-valued topological labels classified by $\pi_2(S^2) = \mathbb{Z}$, invariant under continuous deformations of the field, observable in principle by topological measurements.
- T_2 gradient distribution: substrate-level mass-energy distribution, observable through gravitational measurements.

Each of these is observer-independent. The "fact of the matter" about an infaller is its disposition into the substrate-level fields: how its KK modes have decayed to the $n = 0$ condensate, how its winding has redistributed onto cells in the boundary layer, how its rest mass-energy has contributed to the T_2 gradient. **All of these are determinate**, not coordinate-relative.

The standard GR coordinate-relative answer is correct as far as it goes — it tells you what each coordinate frame measures — but it does not have access to these substrate-level facts because GR has no substrate vocabulary (§3.6). The (3+3) extension of GR adds the substrate level beneath the metric, and the fact of the matter resides at that level. The puzzle of §1.1.2 — "is there a fact of the matter beyond coordinate descriptions?" — is answered: **yes, the substrate-level dispositions are coordinate-invariant facts**, and they specify matter conversion at the boundary as the operational truth.

7.5 Where the matter ends up

For each parcel of infalling matter, the (3+3) account specifies a definite final state. Following a single proton from far outside the BH:

- **Approach phase** ($r \gg r_S$): proton propagates as KK mode-918 pattern through activated foam at standard rates. Free-fall trajectory, c-budget redistributing toward radial spatial motion as it falls.
- **Boundary-layer entry** (r approaching r_S, in the boundary layer of thickness $\Delta N \approx 79$ cells): host cells in proton's immediate vicinity are fluctuating around N_{crit}. The proton's KK modes propagate at decreasing rates; the photon-only relay function on the host cells is intermittent.
- **Conversion** (cells dormantising on $\tau_{cell} \approx R_3/c$ timescale): the proton's KK mode pattern decays continuously to the $n = 0$ condensate on the host cells. The total winding 918 redistributes across these cells as topological residue — the w values on the cells now total 918, in whatever distribution the conversion process produced. The proton no longer exists as a propagating excitation.
- **Final state** (cells now in dormant state, host cells' w values updated): the proton is encoded in (i) the w distribution across the cells where conversion occurred, (ii) the rest mass-energy contribution to the BH's total mass M (manifesting as gradient steepening), and (iii) a small fraction of the rest mass-energy radiated back outward as Hawking quanta during the conversion process.

The proton's "location" in the BH's lifetime is therefore not "inside the horizon as a particle" (the GR-extension picture) but rather "encoded as topological residue on dormant cells in the boundary layer at the time of conversion, plus an energy contribution to the gradient." This is a definite specification, observer-independent, and consistent across all frames. Other infalling matter — electrons, neutrons, atoms, larger structures — converts by the same mechanism with their characteristic per-particle winding distributions.

For the original collapsing star's matter, the full conversion takes the time of the collapse process. As the star compresses past its Schwarzschild radius, outer layers reach the boundary layer first and convert; inner layers convert as they reach the receding boundary; eventually all matter has converted. After the BH has stabilised, the original star exists as a substrate-level distribution of dormant cells with topological residue, plus a ready-state core (§8.6, §10). **The star is not "inside the BH" as matter; it is the BH** — its mass-energy is the gradient, its information is the w distribution, its structure is the substrate state.

7.6 Equivalence-principle considerations

A subtle issue worth treating carefully. Standard GR's prediction that an infaller crosses the horizon smoothly relies on the equivalence principle: locally, free fall is indistinguishable from inertial motion in flat space, so the infaller "feels nothing special" at the horizon. Tidal effects are mild for a sufficiently large BH (the tidal acceleration scales as ~ GM/r_S^3, which decreases with BH mass), so the infaller is supposed to cross without any local detection of the event.

The (3+3) account contradicts this in part: the infaller does not cross at all, because the boundary is a substrate-level dormantization where matter converts rather than continues. **How is this consistent with the equivalence principle?**

The answer turns on what the equivalence principle covers. The principle is a statement that **local free-fall experiments in regions of activated foam** cannot distinguish gravitational acceleration from inertial acceleration. In any region where the substrate is fully activated — i.e. everywhere current experiments probe — this holds, and the (3+3) framework reproduces the equivalence principle exactly via the universal c-budget redistribution in a T_2 gradient ([1] §16.4). **At the boundary layer, the substrate is at threshold**: cells fluctuating between activated and dormant; the photon-only relay function intermittent; the conditions of activated-foam free-fall no longer holding.

In the boundary layer, the assumption that "any local experiment is fine" no longer applies, because the physics of measurement is itself in transition. Local experiments require activated cells (to support the propagation of test particles, the scattering of photons used for measurement, the operation of detectors); when the cells are at threshold, all of these are intermittent. **The infaller is not a sufficiently "small" or "fast" experiment to detect crossing the horizon — the infaller IS the experiment that's being transitioned**, with its own KK modes converting to substrate residue.

This is consistent with the (3+3) → GR reduction ([1] §21.7 / Appendix D). The reduction is exact at the metric level outside the dormancy regions and the evanescent boundary layer; the equivalence principle holds at the metric level in those regions. It begins to fail at the boundary layer, where substrate-level effects become non-negligible. The failure is not visible at any observation a stationary external observer can make (their measurements are at the metric level, in the activated exterior); it is visible to the substrate-level account of what is happening to the infaller, where conversion is the fact of the matter rather than smooth crossing.

Stated compactly: the equivalence principle holds wherever the substrate is fully activated; it does not hold at the boundary layer where the substrate is at threshold; and the infaller's "smooth crossing" prediction is an extrapolation of equivalence-principle reasoning past the regime of its validity. This is a refinement of standard GR, not a contradiction; it becomes operationally relevant only at the boundary layer scale ($\Delta N \approx 79$ cells, far below current experimental sensitivity).

7.7 The frozen-star picture vindicated

In the pre-1960s GR literature — before Kruskal and Szekeres introduced horizon-regular coordinates — the standard ontology was that black holes were "frozen stars." Matter approaching the gravitational radius froze on its surface; the BH was a star whose collapse had effectively halted at the horizon, with all its matter asymptotically distributed on the surface and the interior considered either undefined or empty. The term "black hole" was not in widespread use; "Schwarzschild singularity" referred to the locus $r = r_S$ (now called the horizon), and the singularity at $r = 0$ was generally regarded as a mathematical pathology rather than a physical region.

The post-1960s shift, driven by Kruskal-Szekeres coordinates and the subsequent work of Penrose, Hawking, and others, replaced this picture. The horizon was understood to be a mere coordinate singularity; the interior became a manifold region with definite metric structure; the singularity at $r = 0$ was characterised by the singularity theorems as a place curvature genuinely diverges; the term "black hole" was coined (Wheeler, 1967) and the modern ontology took shape — a BH is a region of spacetime cut off from the exterior by an event horizon, with an interior containing the original collapsed matter and a singularity at the centre.

The (3+3) substrate-level picture vindicates the pre-1960s ontology, with one important refinement. The pre-1960s "frozen on the horizon" claim was substrate-level correct: matter does freeze on (more precisely, converts in) the boundary layer, and the interior is not a region of propagating matter. The post-1960s "interior with matter inside" claim was a metric-extension overreach: the analytical continuation past the horizon is mathematically allowed but does not describe an observer-inhabited region of propagating physics. The refinement is that matter does not literally freeze on a mathematical surface; it converts to substrate topological residue across the finite-thickness boundary layer, with definite substrate-level disposition (per §7.5).

This is not a rejection of the GR formalism — the formalism correctly predicts what external observers measure, the metric structure outside the horizon, the gravitational lensing, the photon orbits, the Hawking thermal spectrum, and the merger waveforms ([1] §21.6, §21.7 / Appendix D). It is a rejection of the **interpretive ontology** that came with the post-1960s coordinate-extension treatment. The pre-1960s "frozen star" was a more accurate ontological characterisation of what happens to matter at a BH; the post-1960s "BH with interior" added unwarranted ontological commitments — specifically, the existence of an observer-inhabited interior region — that are not supported by the substrate-level physics.

A modern reading: matter at a BH is not "inside" in any observational or propagational sense; it is on/in the boundary, encoded as substrate residue, preserved topologically until released through Hawking evaporation. The "frozen star" was a more honest description than "BH with interior" because it did not extend the matter's description into a region the formalism cannot speak about consistently. **(3+3) puts substrate-level grounding under this older intuition** and supplies the missing operational mechanism (KK mode conversion + winding preservation) that makes the picture quantitative.

Summary of §7.

Matter does not cross the horizon in any frame; it converts to substrate residue at the boundary layer. This is a single substrate-level fact that replaces the coordinate-relative GR answer.

Asymptotic freezing in Schwarzschild exterior coordinates is physically real, not a coordinate artifact: it is the substrate-level reading of KK mode propagation rates going to zero as host cells dormantise.

Smooth crossing in Kruskal-Szekeres coordinates is a metric continuation past the dormancy boundary into a ghost geometry no observer inhabits. The continuation is mathematically allowed but does not describe physical matter trajectories.

The "fact of the matter" question is answered: substrate-level dispositions (cell states, w distributions, T_2 gradient) are coordinate-invariant observer-independent facts. The matter's final state is encoded in these.

The equivalence principle holds in regions of fully activated substrate; it does not hold at the boundary layer where the substrate is at threshold. The "smooth crossing" GR prediction extrapolates equivalence-principle reasoning past its regime of validity.

The pre-1960s frozen-star picture is vindicated: matter freezes/converts in the boundary layer; the interior is not an observer-inhabited region. The post-1960s "BH with interior" was a metric-extension overreach. (3+3) puts substrate-level grounding under the older intuition.

§8 The dormant interior: "no scene inside"

This section develops the substrate-level characterisation of the BH interior. In standard GR, the interior is a region of spacetime bounded by the event horizon, containing the collapsed star's matter (eventually crushed at $r = 0$), with metric coefficients t-r-inverted from the exterior. In (3+3), the interior is **dormant foam with topological residue**: cells in the dormant state, with no propagating excitations, no observer dynamics, but with definite substrate-level structure — winding numbers w on each cell, a T_2 gradient distribution, and (at the centre) a ready-state core. The summary slogan is "no scene inside": the interior is structurally specified at the substrate level but inaccessible at the excitation level — there are no observers witnessing a scene because there are no observers, and no propagating signals for them to witness.

8.1 What "no scene inside" means

A "scene" in the operational sense requires three things: observers, propagating signals connecting parts of the scene, and definite physical states for the things observed. In the BH interior, **none of these are present**:

- **No observers.** Observers in (3+3) are coherent matter excitations — KK mode patterns propagating on activated cells. Inside the dormancy region, no cells are activated and no KK modes are propagating. There are no observer-patterns present in any subregion of the interior.
- **No propagating signals.** Signals require the photon-only inter-cell relay (§2.4); the relay infrastructure is absent in dormant cells (§4.5). No photons propagate, no W or Z bosons can borrow access (no equatorial-ring photon orbit to borrow from), no inter-cell communication of any kind occurs.
- **No definite excitation-level states for observers to witness.** The substrate has definite states (cell occupations, winding numbers, T_2 gradient configuration), but there are no excitations on top of the substrate whose states could be reported by signals to observers. The substrate-level states are not "observed" in any operational sense — they are not signal-reportable from inside.

The dormant interior therefore has no scene to describe in observational language. **It has structure** — substrate-level structure that is fully specified — but it does not have a scene. This is a qualitatively different situation from "the interior is unreachable": "unreachable" suggests there is a scene that we cannot reach (a region where things happen that we cannot observe). "No scene" says there is nothing happening in the observational sense — no events, no observer-experiences, no propagation of signals between things — because the propagation infrastructure for events to happen is absent.

A useful analogy: a frozen lake is not a region with scenes that we cannot access; it is a region with structure (the configuration of frozen water molecules) but without the dynamics of the unfrozen state (where currents flow, fish swim, weather patterns play out). The dormant BH interior is analogous: structurally specified, dynamically inert. The "frozen-star" language of §7 gestures at this; the substrate-level structure makes it precise.

8.2 The dormant interior: substrate description

The substrate-level description of the BH interior consists of:

- **Cell states**: all cells in the dormant state ($N < N_{crit}$), except cells in the boundary layer (where $N \approx N_{crit}$ and fluctuates), and cells in the ready-state core (where $N = 0$ and cells are at minimum R_3).
- **Cell positions**: each cell occupies a definite point in the 3D space inside the BH, with the standard t_3 S^2 compactified surface attached. "Space" inside the BH is the same continuous 3D space as outside; it is the cells' substrate state (dormant) that distinguishes the interior, not their spatial occupancy.
- **Per-cell winding numbers *w***: integer-valued $\pi_2(S^2) = \mathbb{Z}$ topological labels on each cell, with values determined by the history of matter conversion at the boundary during the BH's formation and accretion lifetime.
- **T_2 gradient distribution**: the substrate-level gravitational field, with steepness determined by the BH's total mass-energy. The gradient is continuous from the exterior across the boundary layer into the interior.

This is a finite specification. The number of cells in the BH interior is set by the volume of the dormancy region: roughly $(4/3)\pi r_S^3 \times n_{cell}$ per unit volume, where n_{cell} is the cell density (one cell per Planck volume, for a 3D space tiled by t_3 S^2 cells with each cell occupying $\sim L_P^3$ in spatial extent). For a stellar-mass BH ($r_S \sim$ km), this is of order (km)³ × (1 cell / L_P^3) ≈ 10^{105} cells. **A definite, very large but finite number.** Each cell carries an integer *w* — also a definite, finite-information specification.

The dormant interior is therefore not a region of "infinite volume" or "infinite information capacity" or "infinite anything." It is a finite-volume region of dormant foam with finite-information topological residue. **This finite-information character is one of the framework's contributions** to understanding BH thermodynamics: the Bekenstein-Hawking entropy $S_{BH} = k_B A/(4L_P^2)$ is the count of substrate-level degrees of freedom in the boundary layer, finite and saturable (developed in §11).

8.3 Topological residue: the information content of the interior

The most striking feature of the substrate-level interior is the **topological residue** distributed across the dormant cells. Per-cell winding numbers *w*, on each cell of the interior, encode the entire history of matter that has fallen into the BH. This is the (3+3) framework's answer to "where does the information go when matter falls into a BH?": **the information is on the substrate, encoded in the *w* distribution.**

The *w* distribution is a finite specification (integer values on a finite cell count) — and crucially, it is **conserved through the BH's lifetime**. Per-cell winding is a topological invariant under continuous transformations; no substrate-level dynamics in (3+3) — including cell dormantization at collapse, gradual cell reactivation during evaporation, or the rare transitions in the boundary layer — can change a cell's *w* without a discontinuous transformation.

This is the basis for the (3+3) resolution of the BH information paradox (Hawking 1976), developed fully in §11. In standard GR, matter that falls in is crushed at the singularity; the matter's information content is then lost (or, in the strict treatment of QFT in curved spacetime, becomes inaccessible in a pure-state-evolves-to-mixed-state way). In (3+3), the matter's information is preserved on the substrate as topological residue from the moment of conversion through to the final stages of evaporation, where recently-reactivated cells (with their preserved *w* values) become available again to outside observation.

A key constraint: the topological residue is **finite-information** in the sense that a BH of mass *M* can carry no more *w*-distribution information than its Bekenstein-Hawking entropy $S_{BH} = k_B A/(4L_P^2)$ implies. The total information capacity scales as the boundary-layer area (specifically, the number of cells in the boundary layer, of order r_S^2/L_P^2), not as the interior volume. This is the holographic-principle-like character of the (3+3) framework: information about the interior's history is fundamentally limited by boundary-area considerations, recovering the holographic bound ([1] §21.5 derives this from substrate primitives).

The *w* distribution is **not directly observable from outside** during the BH's lifetime; it becomes accessible to outside observation only as cells reactivate during evaporation (when the dormancy boundary recedes inward). This is consistent with the BH appearing "hairless" (the no-hair theorems characterise stationary BHs by mass, charge, angular momentum only) — the extra information is present substrate-level, but inaccessible through standard observations until evaporation.

8.4 What happens to the original star's matter — full account

The collapse of a stellar-mass star to a BH provides the canonical scenario where the substrate-level dynamics of matter conversion play out at scale. This subsection traces the matter through the collapse to its final substrate-level disposition.

8.4.1 Collapse stages

Consider a star of mass *M* undergoing gravitational collapse past its Schwarzschild radius. The collapse passes through several stages:

- **Pre-collapse equilibrium**: the star is supported against gravitational collapse by some pressure mechanism (electron degeneracy, neutron degeneracy, thermal pressure, etc.). All matter is in propagating-excitation form (atoms, nuclei, electrons, photons) on activated foam.
- **Collapse onset**: support fails (e.g., supernova precursor; the progenitor's core exceeds the relevant mass limit). Free-fall begins, with the matter's spatial-velocity components increasing from rest as the c-budget redistributes.
- **Crossing the gravitational radius**: the outer layers reach the radius $r_S = 2GM/c^2$ (with *M* still the total stellar mass at this point). The first matter to encounter the boundary-layer threshold

is in the outer shells; their KK modes begin converting to $n = 0$ condensate as host cells dormantise.

- **Boundary expansion**: as outer-layer matter converts, the converted mass-energy contributes to the substrate-level gradient; the dynamical horizon (§4.4) expands outward to encompass the converted matter.
- **Inner-layer collapse**: inner layers continue inward as the boundary expands toward them. Each shell's matter converts when it reaches the boundary-layer threshold — first the next-outer shell, then the next-inner, and so on, sweeping inward.
- **Centre formation**: as matter accumulates at the centre, the central T_2 gradient steepness reaches the level where cells collapse to minimum $R_3 = L\_P$ and form the **ready-state core** ([1] §21.4). This is the (3+3) analogue of the GR singularity, but with finite extent (set by the central matter density and BH mass; developed in §10).
- **Equilibrium**: after all original stellar matter has converted and the ready-state core has formed, the BH settles into its equilibrium configuration: an exterior of activated foam, an evanescent boundary layer at $r = r\_S$, a dormant interior with topological residue, and a finite ready-state core at the centre.

8.4.2 Where the original mass-energy ends up

After the collapse, the original stellar matter's mass-energy is distributed across substrate-level structures:

- **Most of the rest mass-energy** is in the substrate as the T_2 gradient steepness — i.e., the BH's gravitational field carries the equivalent of Mc^2. This is the substrate-level realisation of "the matter is now the BH."
- **Topological information** about the original matter (proton/electron/neutron contents, the configuration of atoms, the macroscopic structure) is encoded in the per-cell *w* distribution across the dormant interior cells.
- **A small fraction radiated away during collapse** as gravitational waves (if the collapse was non-spherical) and as electromagnetic / neutrino signatures during the supernova explosion phase (if applicable). This fraction left the system as standard radiation and does not figure in the BH's subsequent state.
- **Hawking radiation thereafter** carries away mass-energy at the rate $L\_Hawking \sim 1 / (M^2\ t\_Planck)$, eventually evaporating the BH over timescale $\sim M^3\ t\_Planck / m\_Planck^2$ (which is enormous for stellar masses).

The original star, in its substrate-level final state, is a BH with definite mass *M* (gradient steepness), definite *w* distribution (encoding all the matter's information), and definite substrate-level structure (boundary layer + dormant interior + ready-state core). **This is what "the matter becomes the black hole" means in the substrate-level account.** It is a complete characterisation of the BH's state in terms of substrate primitives, with no hidden "interior matter" beyond what is encoded in the *w* distribution and the gradient.

8.5 Temporal questions inside

A natural question: **is there time inside the BH?** The answer depends on what is meant by "time."

In the (3+3) framework, time has two related but distinct senses: the coordinate time T (the first time dimension, in which substrate-level dynamics are parameterised) and the proper-time accumulation rate v_T/c (the v_T component of the c-budget, governing the rate at which excitations' proper time advances). In the dormant interior, **proper time is forced to zero** — $v_T = 0$ (per the c-budget identity's requirement that $v_T^2 \geq 0$; inside, where the GR-extension would give $v_T^2 < 0$, the substrate is dormant rather than entering an imaginary regime, §2.1 and §9). No observer inside accumulates proper time, because there are no observers and no proper-time-accumulating excitations.

But **substrate-level dynamics still happen**, parameterised by external coordinate time T: the BH's mass changes via Hawking radiation; the dormancy boundary recedes during evaporation; the ready-state core grows during accretion. These are real dynamical processes with substrate-level time-evolution. From the substrate-level perspective, "time" inside is the external coordinate time T, with the substrate state evolving as a function of T.

The standard GR treatment of the BH interior introduces a different temporal structure: in Schwarzschild interior coordinates, the r coordinate becomes timelike, so proper time of a hypothetical interior observer would advance in the $-r$ direction (the "inevitable progression toward smaller r" of §1.1.3). **In (3+3) this picture is a metric continuation past the dormancy boundary**, with no observers actually experiencing the inverted temporal flow because no observers exist inside. The "interior proper time" of the GR-extension picture is the proper time of metric-extension worldlines that do not correspond to physical excitations. This is the topic of §9.

Stated compactly: **inside the BH, there is no proper time for observers (because there are no observers), but there is substrate-level dynamics parameterised by external coordinate time.** The interior is "timeless" in the proper-time sense and "active" in the substrate-dynamics sense; the apparent contradiction in standard treatments (the interior as both "where time is space" and "where things happen") is resolved by separating the two senses of time.

8.5.1 The infalling worldline's proper time via t_3 cycling

A nuance worth surfacing: the §8.5 statement that "there are no observers" is correct in the strict activated-foam sense (no KK $n \geq 1$ mode patterns propagate inside, so no coherent SM particle survives as an observer in the standard sense), **but the worldline of an infalling object through 6D spacetime continues to have well-defined proper-time accumulation via t_3 cycling**, even after the worldline has crossed the horizon and the original matter has converted to topological residue (§5.1).

The mechanism is the same one developed in §6.3: cells inside have $v_{t_3} = c$ per-cell, with the entire c-budget allocated to t_3 (§2.1, §6.1). A worldline through these cells accumulates proper time τ via the t_3 integration:

$$d\tau = \sqrt{ dT^2 + (dt_3/c^2) } \; ; \; \text{inside, } dT = 0 \text{ and } dt_3/c = c \cdot d\lambda \quad (t_3\text{-driven proper time})$$

where λ is the worldline parameter. This gives the infalling worldline a finite proper time τ between horizon crossing and reaching the ready-state core — the same finite proper time that standard GR predicts for an infalling observer reaching the singularity. The numerical values follow the standard GR formulas:

BH mass	Schwarzschild radius	Proper time τ horizon → centre
10 M⊙ (stellar)	~30 km	~154 microseconds
100 M⊙	~300 km	~1.5 milliseconds
4×10^6 M⊙ (Sgr A*)	~12 million km	~62 seconds
10^9 M⊙ (supermassive)	~3 billion km	~4 hours

The interpretive question. What does this finite proper time mean operationally? Two readings are possible, and v1.1 acknowledges both without forcing a choice:

- **Worldline-only reading** (the strict-dormancy view): the worldline has finite proper time as a geometric fact about the t_3 integration, but no coherent observer experiences this time because the infaller's KK mode pattern has decohered into substrate-level topological residue at the horizon (§5.1). The proper-time accumulation is a property of the worldline-through-6D, not of an experiencing observer.
- **Operational-experience reading** (per [2] §14bis.41 and the [31] research note): the infaller, treated as a coherent system whose internal t_3 cycling continues on the dormant cells they have entered, has proper-time experience driven by t_3. They can in principle "look back" toward the horizon and see the entire history of the external universe compressed into a shrinking circle of incoming light (which has been falling in at all times during their finite proper-time interval). For supermassive BHs, the proper time inside is enough to think and observe before reaching the centre.

The operational-experience reading is more vivid and matches the standard GR picture; the worldline-only reading is more conservative and matches the strict-dormancy framing. **The framework permits both** as consistent interpretations at the substrate level: the t_3 cycling per-cell is unambiguous; whether this constitutes "observer experience" depends on how strictly one interprets "observer" in the dormancy regime. The deeper question — whether decoherence of an infaller's mode pattern at the horizon extinguishes coherent experience or whether t_3 per-cell cycling sustains something experience-like — is an open interpretive question that the framework does not yet resolve definitively.

For BH spaghettification calculations (§8.5.2 below) the worldline picture is sufficient: tidal forces stretch the infalling structure based on the gradient of slot occupation density across its spatial extent, regardless of whether one adopts the worldline-only or operational-experience reading.

8.5.2 Spaghettification: tidal forces and the $1/M^2$ scaling

Spaghettification — the radial stretching and transverse compression of an extended infalling body by the BH's tidal field — has a clean substrate-level interpretation in (3+3) and a counterintuitive mass-dependence: tidal force at the horizon scales as $\mathbf{1/M^2}$, so larger BHs produce *weaker* tidal forces at horizon-crossing.

The substrate-level mechanism. The infalling body is an extended collection of foam cells (a person of size ~2 m occupies ~10^{70} cells in L_P^3 units). The cells closer to the BH centre sit in a region of higher slot-occupation density (steeper T_2 gradient, smaller v_T) than the cells further out. The slot-occupation density gradient acts on each cell with a force proportional to the gradient steepness; the *differential* force between near-side cells and far-side cells stretches the body along the radial direction and compresses it transversely. This is the same mechanism as GR's tidal force, expressed in substrate-level vocabulary.

$$\text{Tidal force} \propto \partial(\text{slot occupation density})/\partial r \approx GM/r^3 \times (\text{body length}) \quad \text{(differential gradient)}$$

The $1/M^2$ scaling at the horizon. Evaluating at $r = r_S = 2GM/c^2$:

$$\text{Tidal force at horizon} \propto GM/r_S^3 \times (\text{body length}) = c^6 / (8\, G^2M^2) \times (\text{body length}) \quad \text{(horizon tidal force)}$$

so tidal force at the horizon scales as $\mathbf{1/M^2}$: a more massive BH has a much larger horizon, and the slot-occupation-density gradient is spread over a much larger distance, making the differential force per metre of body smaller. **The larger the BH, the gentler the horizon crossing.**

Numerical values for a 2-metre-long infalling body:

BH mass	Schwarzschild radius	Tidal force at horizon (per metre)	Outcome at horizon
10 M⊙ (stellar)	~30 km	~3×10^6 m/s² per metre	Torn apart well outside horizon
100 M⊙	~300 km	~3×10^4 m/s² per metre	Torn apart near horizon
10^6 M⊙ (mid-range)	~3 million km	~3×10^{-4} m/s² per metre	Barely noticeable; cross freely
4×10^6 M⊙ (Sgr A*)	~12 million km	~2×10^{-5} m/s² per metre	Imperceptible at crossing
10^9 M⊙ (giant)	~3 billion km	~3×10^{-10} m/s² per metre	Completely negligible

For comparison: Earth's surface gravity is ~10 m/s². A stellar-mass BH exerts tidal forces millions of times stronger than Earth gravity across a human body at the horizon — well above the threshold to disrupt molecular binding. A supermassive BH like Sgr A* exerts a tidal force at the horizon so weak that crossing would be subjectively gentle.

The progression toward the centre. Even for a supermassive BH, the gradient inevitably becomes extreme as the worldline approaches the centre. The progression in substrate-level vocabulary:

- **Approaching horizon (large BH)**: slot-density gradient across the body is tiny relative to body scale; all cells of the body are in nearly the same density regime; nothing noticeable; horizon crossed freely.
- **Well inside horizon**: slot-density gradient growing; cells closer to centre pulled more strongly inward than cells further out; mild stretching develops.
- **Deep inside**: gradient large enough to overcome molecular binding (roughly when tidal force per metre exceeds ~10^{10} m/s²); body begins extension along radial direction, transverse compression.
- **Approaching centre**: gradient extreme; tidal stretch comparable to binding energy of nuclei (then quarks); progressive spaghettification of matter into individual atoms, then nuclei, then quarks; cells progressively transition from dormant to ready-state at minimum $R_3 = L_P$.
- **At centre (ready-state core)**: cells at $R_3 = L_P$ with $N < N_{crit}$ (§10.2.1); the infalling body's topological winding *w* is added to the core's topological-residue inventory. The body is "fully incorporated" into the BH's topological residue; per-cell winding *w* values from the body's baryon content add to the core's topological charge inventory (§6.4 carriers of mass).

Connection to the three carriers of §6.4. Spaghettification doesn't "destroy" the infalling body in any framework-violating sense — it redistributes the body's mass into the three carriers: baryon winding (topological, conserved); Compton cycling (continues per-cell on dormant cells the body decohered into); gravitational field (the BH's mass increases by the body's rest mass-energy, contributing to the field extending outward). Conservation laws are respected throughout: mass-energy, baryon number, and information are all preserved at the substrate level even as the body is "torn apart" in the tidal-force sense.

8.6 The ready-state core (preview)

At the centre of every formed BH is the **ready-state core**: a coherent topological condensate of cells at the minimum compactification radius $R_3 = L_P$ ([1] §21.4). This is qualitatively different from the dormant interior:

- Cells in the ready state have **collapsed to one Planck area** (the smallest allowed scale by the framework's discrete structure); they are not just inactive but at the framework's minimum scale.
- They form a **coherent condensate**, not a collection of independent dormant cells; the ready-state cells are correlated topologically, with their *w* values configured into a self-consistent ground-state pattern.
- The core has **finite extent** — the number of ready-state cells is set by the BH's total mass, not divergent. A solar-mass BH has a ready-state core of order $L_P \times M_\odot/m_{Planck}$ cells in linear extent (estimated; full derivation in §10), occupying a spatial region vastly larger than the Planck volume even though each cell is at minimum size.

The ready-state core absorbs the matter's deepest topological residue. As matter falls into the BH and converts at the boundary, the most condensed fraction of its topological content settles to the ready-state core. The core thus encodes a particular subset of the BH's information content — specifically, the residue from the BH's formation and earliest infall — at the framework's minimum scale.

The ready-state core is the (3+3) replacement for the GR singularity. It is finite-extent, structurally specified, and consistent with the framework's minimum length scale; it does not have the curvature divergence of the GR singularity (curvature scalars on substrate-level cells at minimum R_3 are finite, set by the cell's own scale). **No singularity in the GR sense exists**; the centre is dense topology, not a mathematical point. The full development of this resolution is §10.

8.7 The ghost geometry of analytic continuation (preview)

Standard treatments of the BH interior use analytical continuation of the Schwarzschild metric past the horizon (typically expressed via Kruskal-Szekeres coordinates, which are regular at the horizon). The continuation produces a region with t-r-inverted metric coefficients, in which the standard GR dynamics can be described mathematically (geodesics, light cones, the locus $r = 0$ as a singular set, etc.).

In (3+3), this continuation is recognised as a metric construct without observer-dynamical content. The metric exists in the formal sense — $g_{\mu\nu}$ is well-defined as a tensor field everywhere except at $r = 0$ — but the substrate is dormant, no observers exist, no propagating signals carry information between parts of the region. The continuation is what we have called a **ghost geometry**: a metric structure with no observer dynamics on top.

The ghost geometry is internally self-consistent at the metric level. Its coordinate-extension worldlines (the smooth-crossing trajectories of §7.3, the "inevitable approach to $r = 0$" of standard interior treatments) are mathematically well-defined and trace out structures consistent with the extended metric. **What they do not do is correspond to physical matter propagation**, because in (3+3) physical matter requires activated cells and the cells in the ghost-geometry region are dormant.

The "ghost" terminology is meant to distinguish: the metric continuation is not "wrong" — it is mathematically valid and well-defined within the GR formalism. But it does not describe a physical region in which physics is happening to observers; it describes a mathematical extension that is consistent with the formalism but disconnected from substrate-level dynamics. The metric is a ghost because no one inhabits it.

This perspective resolves several long-standing interpretive tensions:

- The "smooth crossing" of the equivalence-principle prediction (§7.6) is the ghost-geometry continuation, not actual matter propagation.
- The "time-space inversion inside the horizon" (§1.1.3, full treatment §9) is a metric-coefficient feature of the ghost geometry, with no dynamical consequence because no observers experience the inverted temporal flow.

- The "approach to $r = 0$" predicted by the singularity theorems is the continuation's prediction within the ghost geometry; the (3+3) substrate-level physics replaces this with the ready-state core (§8.6, §10) at finite extent.
- The "interior of the BH" as a region with definite metric structure — the standard pedagogical picture — is the ghost geometry; the substrate-level reality is dormant foam with topological residue, not a metric-described observer-inhabited region.

The ghost geometry is the (3+3) reinterpretation of the post-1960s horizon-extension treatment of BH interiors. It is not a rejection of the metric formalism — the formalism remains correct as a description of metric structure — but a refinement of what that formalism tells us about observer-inhabited physics. Inside the dormancy region, the metric is well-defined as a tensor; the substrate is dormant; no observers are there to experience the metric structure as physics. **§9 develops the time-space inversion within this framing** — as a feature of the ghost geometry rather than a structural fact about observer dynamics.

8.8 What this means for "what's inside a black hole"

Putting §8.1–§8.7 together, the question "what's inside a black hole?" has a definite answer in (3+3) — but the answer takes a different form from the standard GR ontology.

The substrate-level answer:

- **A finite collection of dormant cells** with positions in 3D space, each carrying an integer per-cell winding number *w*.
- **A T_2 gradient distribution** with steepness determined by the BH's total mass-energy (continuous from the exterior, increasing inward through the boundary layer, very steep deep inside).
- **A ready-state core at the centre** of finite extent, consisting of cells at minimum R_3 in a coherent topological condensate.
- **Per-cell winding distribution encoding the BH's formation history**: which particles fell in, in what configuration, at what stage of the BH's lifetime.
- **No propagating excitations**: no matter, no photons, no W/Z bosons, no gluons; no atoms or larger structures in propagation form.
- **No observers**: nothing experiencing scenes, witnessing events, accumulating proper time.

The **excitation-level answer**: the interior contains nothing in the standard sense of "things happening to observers." There are no scenes, no events between things, no propagation of anything. The interior is empty in the observational sense, despite being filled with substrate.

The **metric-level answer**: the GR-extended metric describes a ghost geometry with t-r-inverted coefficients, geodesics that "approach $r = 0$," and a mathematical singularity at the centre. This metric description is mathematically valid but does not correspond to substrate-level reality, where the centre is a finite-extent ready-state core and no observers exist on the geodesics.

These three answers — substrate-level, excitation-level, metric-level — are all valid as descriptions but not equivalent in operational content. The **substrate-level answer is the most informative**: it specifies the actual physical state of the interior in coordinate-invariant terms. The excitation-level answer tells us what is observable from outside (essentially nothing, for the duration of the BH's lifetime). The metric-level answer is what GR derives from continuing the exterior solution past the horizon, and it describes a ghost geometry the substrate-level physics does not realise.

The "no scene inside" framing of this section captures the operational point: the interior is structurally specified (substrate-level), unobservable in the standard sense (excitation-level), and described by a ghost geometry in the metric formalism. There is content inside (cells, w values, gradient, core) but no scene in the observational sense (no events, no propagation, no observers). This is qualitatively different from the standard "BH interior contains the original matter and a singularity at $r = 0$" picture, and it sets up the §9 (time-space inversion) and §10 (no singularity) treatments that follow.

Summary of §8.

The BH interior in (3+3) is dormant foam with topological residue: a finite collection of dormant cells with integer per-cell winding numbers w, a T_2 gradient distribution, and a ready-state core at the centre.

"No scene inside" means: no observers (no propagating excitations), no propagating signals (relay infrastructure absent), no observable events (nothing for observers to witness). Structure exists at the substrate level; scenes do not exist at the excitation level.

The w distribution encodes the entire history of matter that has fallen into the BH, in finite-information form (integer values on a finite cell count). This is the substrate-level answer to "where does the information go," providing the basis for the (3+3) resolution of the BH information paradox (§11).

The original star's matter, post-collapse, exists as: most rest mass-energy in the T_2 gradient (the BH's gravitational field), topological information in the w distribution, a small fraction radiated during collapse. "The matter becomes the black hole" in the substrate-level sense.

Time inside has two senses: no proper-time for observers (none exist), but substrate-level dynamics parameterised by external coordinate time (Hawking evaporation, accretion, etc.).

The ready-state core is a finite-extent topological condensate replacing the GR singularity (full development §10). The Kruskal-extension metric description of the interior is a ghost geometry without observer-dynamical content (full treatment §9).

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§9 The time-space coordinate inversion

This section addresses the third classical puzzle of §1.1.3: inside the Schwarzschild horizon the metric coefficients change sign, so that the t coordinate becomes spacelike and the r coordinate becomes timelike, with "inevitable progression toward smaller r" replacing the more familiar "inevitable progression toward later t." The puzzle, in the framing of §1.1.3, is that this inversion is presented in standard treatments as a metric-mathematical conclusion without a physical mechanism. The (3+3) resolution treats the inversion as a c-budget reallocation effect within the ghost geometry of §8.7 — mathematically consistent within the metric continuation, but applied to a region with no observer dynamics, so without the dynamical content suggested by the standard pedagogy.

9.1 The puzzle restated

Recalling §1.1.3 in compact form: the Schwarzschild metric in standard coordinates is $ds^2 = -(1 - r_S/r)c^2dt^2 + (1 - r_S/r)^{-1}dr^2 + r^2d\Omega^2$. For $r > r_S$, the coefficient $(1 - r_S/r)$ is positive: $g_{tt} = -(1 - r_S/r)c^2 < 0$ (timelike), $g_{rr} = (1 - r_S/r)^{-1} > 0$ (spacelike). This is the standard Lorentzian signature with t the timelike coordinate and r spacelike. For $r < r_S$, the coefficient becomes negative: $g_{tt} = -(1 - r_S/r)c^2 > 0$ (now spacelike), $g_{rr} = (1 - r_S/r)^{-1} < 0$ (now timelike). **The roles of *t* and *r* have swapped.**

The standard interpretation is that, inside the horizon, an observer's inevitable proper-time progression (every observer's worldline must advance in the timelike direction) now points in the $-r$ direction. The light cones in interior Schwarzschild coordinates "tip over" so that future-directed timelike worldlines all have $dr/d\tau < 0$; the observer is dragged toward $r = 0$ with the same logical inevitability as observers outside are dragged toward later t.

This is presented to physics students as a fact about the metric — the coefficients are what they are, the timelike/spacelike characterisation follows from their signs. **The puzzle is that no physical mechanism is supplied for why this swap should happen**. The metric coefficients flip sign because of the geometry; but what physical process forces an observer inside to experience proper time advancing in the $-r$ direction rather than the $+t$ direction? Standard GR points at the metric coefficients; (3+3) supplies a mechanism via the c-budget account.

9.2 The c-budget reading: why the metric inverts

The c-budget identity (§2.1) for any propagating excitation is $v_T^2 + v_{t_2}^2 + v_{t_3}^2 + v_x^2 + v_y^2 + v_z^2 = c^2$. Each component is real and squared, so each contributes a non-negative quantity to the sum. In the static field of a mass M outside the horizon, $v_T^2(r) = c^2(1 - r_S/r)$ is positive; the c-budget identity has positive-real solutions and excitations propagate normally. As $r \to r_S$, $v_T \to 0$; the c-budget identity forces the entire magnitude c into the spatial components.

For $r < r_S$ if naively extended, v_T^2 would equal $c^2(1 - r_S/r) < 0$. This has no positive-real solution; v_T would have to be imaginary. The framework's response, established in §2.1, is that the substrate dormantises rather than entering an imaginary-velocity regime: the cells inside the horizon are dormant, no physical excitations propagate, and the c-budget identity is simply not in force in the substrate-level dynamics because there are no propagating excitations to which it could apply.

But the metric is still well-defined inside. The metric formalism does not depend on the substrate state — $g_{\mu\nu}$ is a tensor field on the continuum manifold, and its components are determined by the T_2 gradient distribution (which is well-defined throughout, including in the dormant interior). Inside r_S, the metric components can be computed as continuous extensions of the exterior values. **The c-budget identity, written in terms of components in this extended metric, has a different form**: with $g_{tt} > 0$ (now spacelike) and $g_{rr} < 0$ (now timelike), the squared-component sum constraint partitions differently. The "v_T-like" role — the component whose squared value contributes the negative metric coefficient — is now played by v_r, not v_T.

In symbols, schematically: in the exterior Lorentzian metric, the timelike direction T contributes the negative metric coefficient, the spatial directions contribute positive coefficients, and the c-budget identity reads as the constraint that the squared-magnitude on the Lorentzian metric is c^2 (with the convention that the timelike contribution enters with opposite sign). Inside the horizon, r contributes the negative metric coefficient, so the "timelike role" is played by r in the metric identity. The c-budget identity's form — total magnitude is c^2 — is preserved, but the coefficient assignments have rotated.

This is the c-budget reading of why the metric inverts: the magnitude c must be partitioned among the components, and when v_T^2 goes negative, the r direction takes over the role of "where the squared component magnitude is negative" — i.e., the role of "timelike direction" — to preserve the overall structure of the constraint. **The mechanism is c-budget reallocation**: with v_T unable to carry its component (locked at zero in the substrate sense; would-be imaginary in the metric continuation), the "timelike role" relocates to the radial direction, manifesting in the metric as the t-r coefficient inversion.

9.3 The ghost-geometry character of the inversion

The c-budget reading of §9.2 supplies the **mechanism** for the inversion: it is the metric-formalism reflection of c-budget reallocation when the v_T component is forced to zero. But the inversion describes a region — the interior of the dormancy boundary — where **no observers exist** and no propagating excitations are present. The metric structure is well-defined; the substrate is dormant; the standard interpretation of the inversion as "observers experiencing inevitable progression toward $r = 0$" applies to mathematical worldlines in the metric continuation, not to physical observer dynamics.

This is the ghost-geometry framing of §8.7. Inside the horizon, the metric is a tensor field with definite components and definite analytic structure. Mathematical worldlines can be drawn in the metric continuation, and they have all the properties standard treatments describe: timelike worldlines have $dr/d\tau < 0$; the worldlines reach $r = 0$ in finite affine parameter; the geodesic structure is consistent with the t-r-inverted metric. **What these mathematical worldlines do not do is correspond to physical observer dynamics**, because in (3+3) physical observers (= coherent KK mode patterns) require activated cells, and the cells inside are dormant.

The "inevitable progression toward $r = 0$" of standard interior treatments is therefore a **feature of the ghost-geometry continuation, not of observer experience**. The continuation is internally consistent — within the metric formalism, the inevitability follows from the geodesic equations and the inverted coefficients — but it describes a metric structure that no observers inhabit. There is no observer's proper time advancing in the $-r$ direction because there is no observer.

Compare the situation to a coherent mathematical extension that no one finds controversial: the analytic continuation of a real function past a branch point on the complex plane. The continued function is mathematically well-defined and useful for various purposes (residue calculations, asymptotic analysis), but it does not describe a different "physical reality" beyond the original real function. In a similar spirit, the Kruskal-Szekeres extension of Schwarzschild past the horizon is mathematically well-defined and useful (it makes the metric regular at the horizon, simplifies certain calculations) but does not describe a different "physical reality" with observers experiencing inverted-coordinate dynamics. **The inversion is real in the metric formalism; it is not real in the observer-dynamical sense.**

9.4 Light cones tipping over without observers in them

A pedagogical staple of standard interior-horizon treatments is the picture of "light cones tipping over" as one approaches and crosses the horizon (Wald 1984; Misner, Thorne, & Wheeler 1973). Outside the horizon, light cones at each point open in the standard way, with future-directed timelike worldlines having $dt/d\tau > 0$. As one approaches the horizon, the light cones progressively narrow and tilt inward; at the horizon, they tip over so that one branch points along the horizon itself; inside, both branches point inward (toward smaller r), so future-directed timelike worldlines must have $dr/d\tau < 0$.

In (3+3), this picture is mathematically valid but operationally vacuous inside the horizon. **Light cones are constructed at each point of the manifold as sets of vectors satisfying the null-cone condition (squared magnitude in the metric equals zero); their structure follows from the metric coefficients.** The light cones at $r < r_S$ in the Kruskal-extension manifold do indeed point inward — this is a consequence of the inverted g_{tt} and g_{rr} signs. The light cones are mathematical structures on the metric manifold.

But the light cones at points inside the horizon are not occupied by observers. There are no observer worldlines passing through these points; no propagating excitations following the timelike directions inside the cones; no "future" being experienced by anyone. The light cones are structurally specified — the formalism gives them definite cones with definite inversion properties — but they are operationally empty.

A useful contrast: outside the horizon, light cones are operationally meaningful. Photons travel along null-cone trajectories; matter excitations travel within the timelike directions inside the cones; the cones constrain what observers at each point can causally influence. The cones are full of physics. **Inside the dormancy boundary**, the cones are still mathematical structures on the metric, but they have no operational content: no photons travel along the null cones (no equatorial-ring photon orbit on dormant cells), no matter excitations travel within the cones (no propagating KK modes), no observers exist to be constrained by them. **The cones are empty cones in empty geometry.**

The "tipping over" of the light cones is therefore a feature of the metric continuation that holds at the formal level but does not correspond to an experienceable transition for any observer. An observer outside the horizon never reaches the tipped-over region (they do not cross the dormancy boundary as observers, per §7); no one experiences the tipped cones. The tipping is a mathematical feature of the ghost geometry, depicted in the standard pedagogical diagrams of BH structure but not actually witnessed by anyone.

9.5 "Inevitable progression toward r = 0" without observers

The standard pedagogical claim that observers inside the horizon must move toward smaller r with logical inevitability — the same inevitability with which observers outside must move toward later t — is a claim about observer dynamics. **In (3+3), no such observer dynamics exists inside.**

The metric-extension content of the claim is that timelike worldlines in Kruskal-extension coordinates inside the horizon do indeed have $dr/d\tau < 0$; this is mathematically true in the formalism. But the claim that "observers must" experience this inevitable progression assumes the existence of observers inside. In (3+3), there are no observers inside the dormancy boundary (§8.1, §3.7.3): all the matter that would have been "inside" has been converted to substrate residue at the boundary; no propagating KK excitations are present in the dormancy region; no observation events occur.

The "inevitable progression toward r = 0" describes a feature of the metric continuation that no one experiences. It is consistent within the metric formalism — geodesics in the ghost geometry do progress toward $r = 0$ — but it is not a description of what happens to anyone, because no one is there to experience the progression. The claim is structurally specified (metric content) and operationally vacuous (no observer dynamics).

A precise way to state this: in standard GR, the claim is "if an observer is inside the horizon, the observer must progress toward smaller r." In (3+3), the antecedent of this conditional is never satisfied — there is no observer inside the horizon. The conditional is therefore vacuously true (it has no counterexamples) but operationally without content (it is never instantiated). The metric continuation produces a region with the claimed structure, but no observers ever inhabit that region to make the structure their experience.

9.6 Substrate dynamics inside the horizon

Although there are no observer dynamics inside the dormancy boundary, **substrate dynamics do happen there**, parameterised by external coordinate time T. These should not be confused with the ghost-geometry features:

- **Hawking radiation** carries mass-energy out of the BH at a rate set by M. The dormancy boundary recedes inward as a function of T; cells that were just inside the boundary become activated as it passes them.

- **Topological residue persists** on the dormant cells. As cells are reactivated by the receding boundary, their *w* values (preserved through the dormancy period as topological invariants) become accessible to outside observation. This is the substrate-level information-conservation pathway (§11).
- **The ready-state core can grow** if the BH is accreting (§5.6, §8.6, §10): as more matter falls in and converts at the boundary, the deepest portion of the matter's topological residue settles into the core. The core has finite extent that scales with *M*.
- **Substrate-level reconfiguration during mergers** (§12): when two BHs merge, the two dormancy boundaries deform and fuse, and the substrate undergoes a reconfiguration parameterised by the external coordinate time of the merger event.

These substrate dynamics are real and observable in their consequences (the BH evaporates, accretion modifies the boundary structure, mergers produce gravitational-wave signatures). They are **not** the ghost-geometry inversion features. The inversion is a metric-extension structure that no one experiences; the substrate dynamics are external-time-parameterised processes with definite observable signatures in the activated exterior.

Important distinction: when standard GR pedagogy speaks of "interior dynamics" inside the horizon, what is meant is observer dynamics in the metric continuation — observers progressing toward smaller *r*. In (3+3), this kind of "interior dynamics" does not exist (no observers inside). What does exist is **substrate dynamics**, which are completely different in character — they are not local-observer experiences but global substrate-state changes parameterised by external time. The distinction is essential for clear thinking about the BH interior.

9.7 Comparison with the standard GR interior treatment

A direct comparison illuminates the difference between standard GR's treatment of the time-space inversion and the (3+3) substrate-level reading.

Aspect	Standard GR (Kruskal extension)	(3+3) substrate-level
Sign change of g_{tt} and g_{rr} inside r_S	Mathematical fact about the metric continuation	C-budget reallocation effect; v_T locked at 0, "timelike role" relocates to *r* in metric formalism
Light cones tipping over	Pedagogical depiction of the geodesic structure inside	Mathematically valid; cones empty (no excitations inside to inhabit them)
Inevitable progression toward $r = 0$	Observer experience; observers must move inward	Ghost-geometry feature; no observers exist to experience it

Aspect	Standard GR (Kruskal extension)	(3+3) substrate-level
Interior physical content	Original collapsed matter; reaches singularity at $r = 0$	Dormant foam with topological residue (§8); finite-extent ready-state core (§10)
Operational interpretation	Coordinate-relative; observers in different frames see different things	Substrate-level: matter converted at boundary (§5, §7); no observers inside; metric-extension is a ghost geometry

The two treatments agree on the metric structure: the coefficients invert, the coordinates swap timelike/spacelike characters, the geodesic equations have definite solutions. They disagree on **what the metric structure is describing**:

- Standard GR: the metric describes spacetime geometry, and the geometry inside the horizon contains observers experiencing inevitable progression toward the singularity. The matter that fell in is inside, getting crushed.
- (3+3): the metric describes the foam-elastic geometry, and the ghost-geometry continuation past the dormancy boundary describes substrate-level tensor structure but not observer dynamics. The matter that fell in is topological residue on dormant cells, not inside as propagating matter; the ready-state core (not a singularity) is at the centre.

No experimental observations distinguish the two readings at current sensitivity, because both predict the same exterior behaviour: matter falling toward the BH appears to freeze on the horizon (§7); Hawking radiation carries mass-energy out at the standard temperature (§5.5, §11); the gravitational field outside has the Schwarzschild form. **The distinction is interpretive and operational, not phenomenological at current sensitivity.**

Distinguishing observations would probe substrate-level effects: discrete-KK ringdown modes during BH-BH mergers (§12), boundary-layer Hawking-spectrum modulations during accretion (§5.7), or topological-residue signatures in late-stage Hawking radiation (§11). All of these are at precision targets requiring next-generation detectors (Einstein Telescope, Cosmic Explorer, advanced PBH-search facilities). At current sensitivity, standard GR's metric-extension picture and (3+3)'s substrate-level reading are observationally equivalent. The (3+3) reading offers, however, a mechanistic account of the inversion — c-budget reallocation in the ghost geometry — that standard GR does not provide, and a coherent account of where the matter ends up that addresses the operational shortcomings of the bare metric picture.

Summary of §9.

The time-space coordinate inversion inside the horizon is a c-budget reallocation effect: with v_T locked at zero (forbidden inside the horizon), the "timelike role" — the component whose squared value contributes negatively to the metric magnitude — relocates from T to r, manifesting in the metric formalism as the t-r coefficient inversion.

The mechanism (c-budget reallocation) supplies what was missing in the standard GR pedagogical treatment: a physical reason why the metric should invert past the horizon. The reason is structural — the c-budget identity's magnitude must be partitioned somewhere — not an arbitrary feature of the metric formalism.

But the inversion describes a region where no observers exist (per §8). The "inevitable progression toward $r = 0$," "light cones tipping over," and other standard pedagogical features are mathematically valid in the metric formalism but operationally vacuous: they describe ghost-geometry structure that no one inhabits.

Substrate dynamics inside (Hawking evaporation, topological-residue persistence, ready-state-core growth) are real but parameterised by external coordinate time, not by an "interior proper time" of the metric inversion. The two should not be conflated.

Standard GR and (3+3) agree on the metric structure inside; they disagree on what the structure describes — observer dynamics in standard GR's reading, ghost geometry without observers in (3+3)'s reading. Phenomenologically equivalent at current sensitivity; the distinction is interpretive and operational.

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§10 No singularity: the ready-state core

This section addresses the first classical puzzle of §1.1.1: GR's prediction of a curvature singularity at $r = 0$ inside every Schwarzschild black hole. In (3+3), there is no singularity at $r = 0$. The framework has a minimum length scale (the Planck-area cell), and at the BH centre, cells form a coherent topological condensate of finite extent — the **ready-state core**. Curvature scalars on substrate-level cells at the minimum scale are bounded; the GR singularity is replaced by a finite, structurally specified region. This section develops the ready-state core in detail: the framework's minimum length scale (§10.2), the structure of the condensate (§10.3), the core extent and its scaling with mass (§10.4), the boundedness of curvature scalars (§10.5), and the resulting "no singularity" claim (§10.6), with a comparison to other singularity-resolution proposals in §10.7.

10.1 The puzzle: GR's singularity at r = 0

The Schwarzschild solution outside the source matter is well-defined and finite at every point except $r = 0$. The Kretschmann curvature scalar:

$$K = R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} = 48\, G^2M^2 / (r^6 c^4) \quad \text{(Kretschmann scalar)}$$

diverges as $r \to 0$; no coordinate transformation can make this finite. **The singularity at $r = 0$ is a physical feature of the metric, not a coordinate artifact** — the Kretschmann scalar is a coordinate-invariant curvature measure, and its divergence is geometrically intrinsic. The Penrose-Hawking singularity theorems (Penrose 1965, Hawking & Penrose 1970) establish that, under broad conditions, gravitational collapse must produce a singularity in the GR sense.

Standard GR's response is to declare the singularity outside the theory's domain. The cosmic censorship hypothesis (Penrose 1969) proposes that singularities are always hidden behind event horizons, ensuring that observers outside cannot see the breakdown of GR's predictive power. Inside, "new physics" is required — typically taken to mean a quantum theory of gravity that resolves the singularity in some way. **The puzzle is that GR cannot answer "what is the operational mechanism that prevents — or replaces — the divergence?" within its own resources.**

The (3+3) framework, with its discrete substrate, supplies the mechanism directly. The Planck-area cells are the framework's minimum scale; sub-Planck structures simply do not exist; the BH centre cannot be a region of sub-Planck curvature because there is no sub-Planck region available. The "singularity" is replaced by a finite-extent region of cells at minimum scale — the ready-state core.

10.2 The framework's minimum length scale

The (3+3) framework has a discrete substrate: the t_3 S^2 surface is tiled by 2^{152} Planck-area cells, each of area $\approx L_P^2$ and linear extent $\approx L_P$ ([1] §2.8). The cell size is set by the framework primitives — the Planck area is the smallest cell, with no smaller scale available. **There are no sub-Planck cells**, no sub-Planck distances between cell centres, no sub-Planck regions in the framework's description of space.

This is qualitatively different from a continuum framework like GR. In continuum GR, every length scale exists in principle, and the metric is defined to arbitrarily small distances. In (3+3), the foam has a discreteness scale (the cell), and the smallest meaningful length is the cell linear extent ≈ L_P. Operations that would, in continuum GR, probe sub-Planck distances simply have no realisation in the discrete substrate; they are mathematically describable in the continuum extrapolation but do not correspond to any substrate-level reality.

The ready-state cells are at the **minimum compactification radius $R_3 = L_P$**. Recall that for activated cells in the ordinary universe, $R_3 = \pi\hbar/(m_e c) \approx 1.21 \times 10^{-12}$ m — far larger than L_P. Activated cells have their R_3 determined by the electron mass, with the condition that the KK mode tower fits the SM particle content. In the ready state, however, R_3 collapses to the framework's minimum, L_P, and the cells form a coherent topological condensate. This is the framework's densest accessible state — there is no smaller structure available.

Implication for BH centres: as collapsing matter approaches the centre, the T_2 gradient steepens; cells progressively dormantise; eventually, at sufficient gradient steepness, cells transition from dormant to ready state — collapsing to $R_3 = L_P$ and forming the condensate. **There is no further collapse possible** beyond the ready-state condensation, because the cells are at minimum scale. The "singularity at $r = 0$" of GR is replaced by a finite-extent ready-state region; the framework's minimum scale prevents further compression.

10.2.1 The ready-state core: what cells look like at the centre

The BH centre, per [1] §21.4, is **ready-state foam**: cells at $R_3 = L_P$ (the minimum compactification radius the framework allows), with the photon pool count N well below N_{crit}, and the KK $n \geq 1$ modes collapsed to the $n = 0$ condensate. The substrate is not "active" at the centre in the sense of supporting propagating excitations; it is in its ground configuration with information stored topologically (as per-cell winding w, conserved by $\pi_2(S^2) = \mathbb{Z}$) rather than dynamically.

Three points are worth being explicit about:

- **The centre is dormant, not "maximally active."** The cells at the centre are below the activation threshold $N < N_{crit}$; they have no photon relay capacity, no KK $n \geq 1$ modes propagating, no Standard Model physics operating in the activated-foam sense. The "ready" in "ready state" refers to the framework's ground-state cell configuration ([1] §3.13), not to an excited or saturated state.
- **Information storage is topological, not dynamical.** The infallen matter's topological residue (per-cell winding w) is preserved in the ready-state core. This is the same $\pi_2(S^2) = \mathbb{Z}$ mechanism that gives proton stability and baryon-number conservation ([1] §21.5). Information capacity is the topological-pattern space, not the photon-pool dynamical space.
- **The minimum-R_3 condition is geometric, not energetic.** Cells are compressed to $R_3 = L_P$ by the same T_2 gradient steepness that dormantises the boundary layer; the geometric collapse is the substrate-level analog of the GR "compression toward singularity," but bounded below by the

framework's minimum scale rather than diverging. There is no further compression possible because the framework has no sub-Planck cells.

The "no singularity" claim follows from the discrete substrate, not from a saturation argument: cells exist only down to the Planck scale, so the GR continuum extrapolation to $r = 0$ has no substrate-level analog past $R_3 = L\_P$. The centre is a finite region of dormant ready-state foam with finite topological-charge content, not a point of divergent density.

10.3 The ready-state condensate: structure

The ready-state core is a coherent topological condensate of cells at $R_3 = L\_P$. Its structure is qualitatively different from both the activated foam (the universe outside BHs) and the dormant interior:

- **Cells at minimum scale**: each cell has $R_3 = L\_P$, the smallest scale in the framework. The cells are at one Planck area each.
- **Coherent condensation**: unlike the dormant interior (where each cell is independently in the dormant state with its own *w* value), the ready-state cells are correlated topologically. The *w* values across the condensate are configured into a self-consistent ground-state pattern, with the total topological charge equal to the integrated *w* of all matter that has reached the core.
- **No KK mode excitations**: the ready-state cells are not activated; no $n \geq 1$ KK modes are present; no propagating excitations exist on the condensate.
- **Continuous boundary with dormant interior**: the ready-state core meets the dormant interior at a definite spatial surface. Outside the core, cells are dormant at their normal scale ($R_3 \approx 1.21 \times 10^{-12}$ m for activated cells, but in the dormant interior these cells are not at the activated R_3 either — they are dormant cells with their own characteristic structure set by the local gradient, transitioning continuously to the ready-state minimum at the core boundary).

The condensate is "ready-state" in the sense that ([1] §3.13, §21.4) it is the framework's ground state for a subregion at minimum scale: prepared topology, configured *w* distribution, no propagation but self-consistent static structure. The terminology distinguishes it from activated foam (the normal universe) and dormant foam (the BH interior outside the core).

The condensate carries the deepest topological residue from the BH's history. As matter collapses past the boundary into the dormant interior, the most condensed fraction of its topological content — typically the highest-density structures (nuclei, atomic cores) — settles to the ready-state core. The general dormant interior carries the bulk of the topological residue (extended structures, lower-density matter); the core carries the condensed kernel.

10.4 Core extent and its scaling with mass

A key claim is that the ready-state core has **finite extent**, with the extent scaling with the BH's total mass. The structural form follows directly from the framework primitives (cell saturation at the centre, topological residue counting linearly with infallen mass) and is at Level 1; the precise prefactor depends on substrate-dynamics calculations beyond this paper's scope and is at Level 2.

10.4.1 Structural scaling argument

The total topological residue carried by the BH is bounded by its total mass-energy. Each cell in the core carries one Planck-area's worth of condensed structure, contributing some quantum of topological charge per cell. The number of cells in the core therefore scales linearly with the total topological residue, and hence linearly with the BH mass *M*:

$$N_{core} \sim M / m_{Planck} \quad \text{(structural scaling, Level 1)}$$

The linear extent of the core, treating it as roughly spherical with each cell occupying ≈ L_P^3 in spatial volume, scales as the cube root:

$$r_{core} \sim L_P \times (M / m_{Planck})^{1/3} \quad \text{(linear scaling, Level 1)}$$

For a stellar-mass BH ($M \approx M_\odot \approx 2 \times 10^{30}$ kg $\approx 10^{38} \times m_{Planck}$):

$$r_{core} \sim L_P \times (10^{38})^{1/3} \approx L_P \times 10^{13} \approx 10^{-22}\ m \quad \text{(stellar BH order-of-magnitude)}$$

For a supermassive BH ($M \approx 10^9\ M_\odot$): $r_{core} \sim L_P \times 10^{16} \approx 10^{-19}$ m. For a primordial BH at the evaporation scale ($M \sim 10^{12}$ g $\approx 10^{18} \times m_{Planck}$): $r_{core} \sim L_P \times 10^6 \approx 10^{-29}$ m.

10.4.2 Core size comparison with Schwarzschild radius

In all cases the core is **vastly larger than a single Planck length** (structurally specified, finite-extent) and **vastly smaller than the BH's Schwarzschild radius** (a tiny fraction of the BH's spatial extent). For a stellar-mass BH, $r_S \approx 3$ km while $r_{core} \approx 10^{-22}$ m; the ratio is $r_{core}/r_S \sim 10^{-25}$. The dormant interior occupies essentially all of the BH's volume; the ready-state core is a tiny seed at the centre.

Important caveat: the $N_{core} \sim M/m_{Planck}$ scaling above is structural (it follows from the assumption that each core cell carries one unit of condensed topological charge proportional to one Planck mass's worth of mass-energy). The precise prefactor — what fraction of the BH's topological residue ends up in the core vs the dormant interior — is set by detailed substrate-level dynamics that are not derived here. **Level 2 caveat applies**: the order of magnitude is at Level 1, but the precise r_{core} for any given BH is at Level 2, awaiting fuller substrate-dynamics derivation.

10.5 Curvature scalars are bounded

A central claim of singularity-resolution proposals is that curvature scalars — particularly the Kretschmann scalar — must be bounded everywhere in the physical region. In (3+3), the substrate-level curvature scalars on cells at the minimum scale L_P are bounded by inverse Planck-length-squared: at the cell scale, the maximum geometric curvature accessible to the framework is set by $1/L_P^2$. Curvatures at finer resolution simply do not exist as substrate-level features.

In a region of cells at $R_3 = L_P$ (the ready-state core), the geometric curvature is bounded by $1/L_P^2$. The metric-extrapolation curvature scalar (the analogue of the Kretschmann $K = 48\ G^2M^2/(r^6\ c^4)$ extrapolated into the dormant interior) approaches the substrate-level bound as $r \to r\_core$ and is regulated at the cell scale.

Specifically: outside the core (in the dormant interior), the metric continuation gives Kretschmann $K(r) \propto M^2/r^6$, which grows as r decreases. At the core boundary $r = r\_core$, the scalar reaches a value set by r_core^6 in the denominator. With $r\_core \sim L\_P \times (M/m\_Planck)$^(1/3) per §10.4.1:

$$K(r\_core) \sim G^2M^2 / r\_core^6 \times c^{-4} \sim (1/L\_P^2)^2 \sim 1/L\_P^4 \quad \text{(scalar at core boundary)}$$

The metric Kretschmann scalar at the core boundary is of order $1/L\_P^4$, consistent with the substrate-level bound. Inside the core, where cells are at minimum scale, the curvature is regulated at this level — substrate-level cells cannot resolve smaller scales, so the curvature description does not continue to grow further.

No curvature divergence anywhere: the scalar is bounded by $1/L\_P^4$ at the core boundary and inside; everywhere else (the dormant interior and the exterior), it is finite. The GR-extrapolated divergence at $r \to 0$ is cut off at the core scale; the singularity is regularised by the substrate's discreteness.

10.6 No singularity: what replaces it

Putting §10.2–§10.5 together, the GR singularity at $r = 0$ is replaced by a definite substrate-level structure:

- **A finite-extent ready-state core** at the centre, with linear extent $r\_core \sim L\_P \times (M/m\_Planck)$^(1/3) — vastly larger than a Planck length, vastly smaller than the Schwarzschild radius.
- **Bounded curvature scalars** throughout: Kretschmann $\leq \sim 1/L\_P^4$ everywhere, with the maximum reached at the core boundary and the value inside the core regulated by the discrete substrate.
- **Coherent topological condensate** as the core's state, configuring the deepest topological residue from the BH's history.
- **No mathematical singularity** in the substrate-level description: the foam is at minimum scale at the centre but well-defined everywhere; no curvature divergence; no metric component infinities (in the substrate-level reading).

The "singularity at $r = 0$" of standard GR is therefore an artifact of extending the metric formalism past the framework's minimum scale. In a continuum framework like classical GR, the metric is defined arbitrarily finely, and the curvature scalars indeed diverge as $r \to 0$; this is the mathematical content of the singularity theorems. In a discrete-substrate framework, the cells have a minimum scale, and the curvature description is regulated at that scale; the divergence does not occur at the substrate level.

The singularity theorems (Penrose 1965, Hawking & Penrose 1970) are not contradicted: they correctly establish that, within continuum GR with standard energy conditions, gravitational collapse produces a metric singularity. **(3+3) does not deny this** — the metric continuation, within the ghost geometry, does have a singularity at $r = 0$ in the GR-extension sense. What (3+3) claims is that **the singularity is not**

physical in the substrate-level sense: it is a feature of the metric continuation past the framework's minimum scale, not a feature of the actual substrate-level configuration of the BH centre. The substrate-level configuration is the ready-state core — finite, bounded, structurally specified.

Operationally, this means: **no observer ever experiences infinite curvature**, because there are no observers inside the dormancy boundary (per §8), and the substrate-level curvature is bounded everywhere. The singularity theorems' "inevitable end" of timelike worldlines at the singularity is a feature of the ghost-geometry continuation; physical observers reach the boundary, convert to substrate residue (§5, §7), and do not propagate into the would-be-singular region. The ready-state core is the framework's answer to "what is at the BH centre" — finite, specified, non-divergent.

10.7 Comparison with other singularity-resolution proposals

Several proposals exist for resolving the GR singularity. A brief comparison with the (3+3) ready-state core illuminates what is shared and what is distinctive:

10.7.1 Loop quantum gravity bounce

In LQG (Ashtekar, Bojowald, and others), the singularity is replaced by a quantum bounce: the collapsing matter rebounds at a Planck-scale density and re-expands as an emergent "white hole" structure. The mechanism is loop quantization of geometry, with the discrete spectrum of geometric operators preventing infinite compression. **Different from (3+3)** in two key respects: (i) the mechanism (LQG quantum geometry vs (3+3) discrete-substrate minimum scale) is different; (ii) the LQG bounce produces dynamics — matter rebounding through a "white hole" — that (3+3) does not predict (the ready-state core is static; matter does not rebound). The phenomenological predictions also differ: LQG predicts emergent matter at late stages of BH evolution; (3+3) predicts substrate residue persisting through Hawking evaporation.

10.7.2 Fuzzballs (Mathur)

In string-theoretic fuzzball proposals (Mathur 2005, 2008), the BH is not a region with a horizon and singularity but a string-theoretic "fuzzy" object — a configuration of strings and branes filling the would-be horizon volume. There is no horizon in the GR sense, no singularity, no interior — the entire BH is a stringy "stuff" object. **Closer to (3+3) in spirit** (the BH replaced by a substrate-like structured object rather than a region with metric singularities), but **different in mechanism** (string-theoretic microstates vs (3+3) discrete-substrate dormancy). The fuzzball proposal also has different predictions: no horizon-scale information loss, potentially observable string-scale effects at the would-be horizon. (3+3) retains the horizon (as substrate boundary) but has no singularity; the two proposals share the spirit of "BH = structured object" but differ in detail.

10.7.3 Gravastars (Mazur and Mottola)

In the gravastar proposal (Mazur & Mottola 2001, 2004), the BH interior is replaced by a de Sitter region with negative pressure (a gravitational condensate star); there is no horizon (in some versions, a "thin shell" at the would-be horizon location). **More speculative** than fuzzballs or LQG bounces, with various theoretical motivations but no definitive mechanism. **Different from (3+3)**: the gravastar interior is a continuous de Sitter region with negative-pressure matter; the (3+3) interior is discrete dormant foam with positive T_2-gradient response. The (3+3) reading retains the horizon and has a definite substrate-level mechanism; the gravastar removes the horizon and substitutes a different matter content.

10.7.4 Generic regular black-hole proposals

A class of proposals (Bardeen 1968, Hayward 2006, Frolov 2014, and others) "regularises" the singularity by modifying the metric at small *r* via effective stress-energy considerations or modified-gravity assumptions. The Hayward metric, for example, replaces *r* in the metric components by an effective expression that is finite at $r = 0$. **(3+3) is more specific** than these generic proposals — it provides a substrate-level mechanism (the discrete cell structure with minimum scale) rather than an ad-hoc effective-metric modification. The generic regular-BH metrics are consistent with (3+3) at the metric level (in the limit where substrate effects are incorporated into an effective metric), but (3+3) supplies the substrate-level reason **why** the regularisation occurs.

10.7.5 The (3+3) position

The (3+3) ready-state core differs from each of the above proposals while sharing aspects of the broad "discrete-substrate" or "BH-as-structured-object" approaches:

- **Mechanism**: discrete substrate with minimum length scale (Planck-area cells); not loop quantization, not string microstates, not negative-pressure matter, not generic effective-metric regularisation.
- **Resulting structure**: finite-extent ready-state condensate at the BH centre; not a bounce, not a stringy object filling the BH volume, not a de Sitter interior.
- **Horizon retained**: (3+3) keeps the horizon as substrate-level dormancy boundary; the horizon is not removed (as in fuzzballs and some gravastars). The horizon is real — substrate-level — and has all its standard properties.
- **Information**: encoded in per-cell *w* distribution across the dormant interior plus the ready-state core; recovered through Hawking evaporation; no information loss. This is closer to fuzzballs (information in the object's structure) than to LQG bounces (information rebounds with the matter).
- **Phenomenological predictions**: distinguishing signatures appear at next-generation precision (§5.7, §11, §12); current observations are consistent with both (3+3) and pure-GR singularity-with-horizon pictures.

The (3+3) approach does not claim novelty in the broad sense — the idea that "matter at the BH centre is at some minimum scale rather than a singularity" is shared with the other proposals — but in the **specific mechanism** (the framework's discrete-substrate minimum length scale) and the **specific structure** (the ready-state condensate). The framework's fundamentals (the t_3 S^2 compactification, the cell tiling, the c-budget identity, the photon-only relay) all support the no-singularity claim directly; no extra assumptions are needed beyond those used elsewhere in the (3+3) programme.

Summary of §10.

The GR singularity at $r = 0$ is replaced by a ready-state core: a finite-extent coherent topological condensate of cells at minimum $R_3 = L\_P$, structurally specified at the substrate level.

Core extent $r\_core \sim L\_P \times (M/m\_Planck)$^(1/3) — Level 1 scaling, Level 2 prefactor. For a stellar-mass BH, $r\_core \sim 10^{-22}$ m, vastly larger than L_P but vastly smaller than $r\_S \sim$ km.

Curvature scalars are bounded everywhere: ~ $1/L\_P^4$ at the core boundary, regulated by substrate discreteness inside. No physical observer ever experiences infinite curvature (no observers inside the dormancy boundary).

The framework's minimum length scale (L_P-area cells) is the substrate-level mechanism preventing the GR singularity. Sub-Planck structures simply do not exist in (3+3); the cells have a minimum scale; further compression beyond the ready-state condensation is not allowed.

The (3+3) ready-state core differs from LQG bounces, fuzzballs, gravastars, and generic regular-BH proposals in mechanism and structure, while sharing the broad spirit that "matter at the BH centre is at minimum scale, not at a singularity."

Singularity theorems are not contradicted: they correctly establish the metric-continuation singularity in continuum GR. (3+3) places the singularity in the ghost geometry (per §8.7, §9) and replaces it with the ready-state core at the substrate level.

§11 Information conservation and Hawking radiation

This section develops the (3+3) treatment of two interrelated topics: Hawking radiation as a substrate-level emission process, and the resolution of the BH information paradox through the topological-residue pathway. The pieces have been assembled in earlier sections — the evanescent boundary layer of §4.3 as the source of Hawking emission, the matter-conversion process of §5.1 with per-cell winding number w preserved as a topological invariant (§5.2), the dormant interior with topological residue of §8.3, and the ready-state core of §10 carrying the deepest condensed residue. Section 10 brings these together: §11.1 restates the information paradox; §11.2 gives the substrate-level mechanism for Hawking emission; §11.3 recovers the standard Hawking temperature in the (3+3) picture; §11.4 examines what each Hawking quantum carries; §11.5 develops information conservation through the topological-residue pathway; §11.6 traces a BH through its full evaporation; §11.7 derives the Page curve as a structural feature of the substrate dynamics; §11.8 compares with other resolutions (complementarity, ER=EPR, soft hair, AMPS firewall, island formula); §11.9 closes with open questions and observational targets.

11.1 The information paradox restated

Hawking's 1975 derivation of black-hole thermal radiation, when combined with the standard GR picture of BH evaporation, leads to an apparent contradiction with quantum unitarity. **The information paradox** (Hawking 1976) can be stated compactly:

- Quantum mechanics requires unitarity: pure quantum states evolve to pure states; information is preserved.
- A pure quantum state of infalling matter, processed through BH formation and complete Hawking evaporation, ends up — in the standard GR picture — as a thermal mixed state at infinity.
- Pure-to-mixed evolution violates unitarity; therefore either GR's BH evolution is wrong, or quantum mechanics is wrong, or there is a hidden mechanism preserving information that the standard treatment misses.

For nearly fifty years the question of which alternative is correct has been the central problem of BH theory. The dominant view in the modern string-theoretic and holographic communities is that information is preserved (some kind of mechanism must exist; recent island-formula derivations (Penington 2020; Almheiri et al. 2020) provide a derivation in a particular framework). The dominant view in BH-thermodynamics-inspired treatments has been that information is encoded in subtle correlations of the Hawking radiation that aren't apparent in the leading-order thermal spectrum. Various proposals — black hole complementarity, soft hair, ER=EPR, island formulas — supply different mechanistic accounts of the information-preserving mechanism.

The (3+3) framework supplies a substrate-level mechanism for information preservation: per-cell winding numbers w on the substrate cells preserve the topological identity of all infallen matter (§5.2), and these winding values are progressively re-exposed as the dormancy boundary recedes during Hawking evaporation. The information is on the substrate throughout the BH's lifetime; it is recovered through the evaporation process. The paradox does not arise in (3+3) because the standard GR assumption that matter "ends up inside the singularity" — and is therefore unrecoverable — is replaced by the substrate-level fact that matter ends up as topological residue on dormant cells, which are recoverable as the boundary recedes.

This is not a novel claim relative to the broader information-preservation consensus; what is novel is the **specific substrate-level mechanism**. Where other proposals invoke complementarity, soft modes, holographic duality, or geometric quantum corrections, (3+3) invokes the discrete substrate's per-cell topological invariants as the carrier of information. The mechanism is structurally specific to (3+3) and emerges from the framework's primitives without additional assumptions.

11.2 Hawking radiation: the substrate-level mechanism

The substrate-level account of Hawking radiation begins with the evanescent boundary layer of §4.3. In equilibrium, this layer of thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells is the locus where cell occupations N fluctuate around the activation threshold $N_{crit} = 6{,}203$. **Cells in this layer briefly activate** when their N fluctuates above N_{crit}; during these brief activations, the cells host equatorial-ring photon excitations on the cell's S^2 surface.

Some of these briefly-hosted photons have outgoing-radial momentum components consistent with escape from the BH region. Via the photon-only inter-cell relay (§2.4), an outgoing photon on a briefly-activated boundary-layer cell can propagate via the relay to the next-outermost cell (which is fully activated, in the BH's exterior region), and from there outward through the activated foam at standard rates. **The escaping photon is the Hawking quantum**, observed at infinity as part of the BH's thermal radiation flux.

Three operational features distinguish this mechanism:

- **Two regimes for the Hawking mechanism, separated by temperature.** For $k_B T_{BH} \ll 2 m_e c^2$ (the cold-BH regime, including all astrophysical BHs whose T_{BH} is far below the electron rest energy), the framework's mechanism is the **photon-only relay**: cells in the boundary layer briefly activate; their equatorial-ring photon excitations escape via the relay; the radiation is predominantly photonic; no electron-positron pair production is energetically allowed. For $k_B T_{BH} \gtrsim 2 m_e c^2$ (the hot-BH regime, relevant for primordial BHs at the late-stage evaporation scale), the fermionic keeper-wave bifurcation mechanism of [2] §14bis.42 also operates: the topological-floor winding $w = 1/2$ on every yz-circle can locally bifurcate at the horizon, $w = 1/2 \to \{w = +1/2, w = -1/2\}$, producing electron-positron pairs in the boundary layer. The inward-moving member becomes a winding deficit on a dormant cell; the outward member escapes as a real Hawking electron or positron. This is the substrate-level realisation of the standard pedagogical "virtual particle pair" picture, but with topological winding bifurcation rather than the QFT-in-curved-spacetime continuum-mode pair production. Heavier-particle pair production (muons, pions, etc.) becomes accessible at correspondingly higher temperatures, all via the same fermionic keeper bifurcation mechanism.

- **Cold-BH spectrum is photonic; hot-BH spectrum is multi-species.** The photon-only relay (§2.4) means only photons escape via the inter-cell relay mechanism in the cold regime. As temperature rises into the pair-production regime, the spectrum becomes multi-species via the fermionic-bifurcation channel. Electroweak quanta (W, Z) and other massive particles emerge via the same channel at correspondingly higher temperatures, plus secondary photon-mediated processes outside the boundary layer (Compton-like scatterings, pair production from energetic photons) at all temperatures.
- **The temperature is set by the boundary-layer thickness.** The fluctuation rate of cells across N_{crit} is set by integer-counting statistics with characteristic frequency ~ c/R_3; the effective "temperature" of the emitted spectrum follows from this combined with the boundary-layer thickness ΔN. [1] §21.4 derives the standard $T_{BH} = \hbar c^3/(8\pi G M k_B)$ from these substrate-level primitives.

The standard Hawking formula $T_{BH} = \hbar c^3/(8\pi G M k_B)$ follows from substrate-level primitives ([1] §21.4) — boundary-layer thickness $\Delta N \approx \sqrt{N_{crit}}$, cell-occupation Poisson statistics, and the Schwarzschild radius. The framework reproduces Hawking's result without invoking QFT in curved spacetime and without the conceptual problems of the standard derivation: there is no need for "negative-energy modes," no observer ambiguity, no choice-of-vacuum question. What this section adds beyond [1]'s derivation is operational context — how the photon-only relay mechanism gives rise to outgoing radiation specifically (§11.2 above), what each quantum carries (§11.4), and how the information-preservation mechanism works across the full evaporation process (§11.5–§11.7).

11.3 The Hawking temperature in the (3+3) picture

For reference, the standard Hawking temperature is:

$$T_{BH} = \hbar c^3 / (8\pi G M k_B) \quad \text{(Hawking temperature)}$$

In the (3+3) substrate-level reading, this temperature emerges from the combination of (i) the boundary-layer thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells (set by Poisson statistics around the activation threshold), and (ii) the characteristic frequency of cell-occupation fluctuations across the threshold (set by c/R_3). The thermal character of the spectrum follows from the Poisson statistics: at any moment many cells are independently fluctuating, and the resulting photon emission rate has the form of thermal emission at a definite temperature.

[1] §21.4 develops this calculation with the result that the substrate-level temperature reproduces the standard Hawking T_{BH} exactly. Two operational consequences:

- **Tiny temperature for astrophysical BHs.** For a stellar-mass BH, $T_{BH} \sim 10^{-8}$ K — well below the cosmic microwave background temperature, so astrophysical BHs are net absorbers (of CMB photons) rather than net emitters. For supermassive BHs, *T_BH* is even smaller (~ 10^{-17} K for *M* ~ 10^9 *M_⊙*).

- **Significant temperature for primordial BHs at the evaporation scale.** For *M* ~ 10^{12} g, *T_BH* ~ 1 GeV (gamma-ray scale); for *M* ~ 10^9 g, *T_BH* ~ 1 TeV. PBHs at these mass scales are interesting candidates for direct observation of Hawking radiation, if any exist with the appropriate masses and abundances.

Substrate-level corrections to the standard *T_BH* are expected at order $(L\_P/r\_S)^2$ — i.e., suppressed by the ratio of the substrate cell scale to the BH scale. For stellar-mass BHs this is ~10^{-76} — utterly negligible. For Planck-mass BHs (*M* ~ *m_Planck*, near the framework's minimum BH mass), the corrections become order-one and the standard formula breaks down (but Planck-mass BHs are at the threshold of the framework's applicability anyway). For the BHs we observe, the standard *T_BH* is accurate to extraordinary precision.

11.4 What Hawking radiation carries

A Hawking quantum emerging from the boundary layer carries definite physical content. To understand information preservation it is essential to be precise about what each quantum carries:

- **Energy**: equal to the photon's frequency, $\hbar\omega$. The total energy budget over the BH's lifetime equals Mc^2 (eventual full evaporation).
- **Linear momentum**: the photon carries directional momentum $\hbar\omega/c$ in its direction of propagation. The directional distribution of Hawking quanta is approximately isotropic (averaging over the boundary layer), but with directional correlations from the boundary-layer geometry that may be observationally accessible at next-generation precision.
- **Polarisation state**: the photon's spin state. In the (3+3) framework, this is determined by the equatorial-ring photon's phase at the moment of escape — a substrate-level quantity that depends on the cell's configuration just before activation.
- **Topological information from the boundary cell**: this is the key observation of the (3+3) reading. **The photon's detailed properties (precise frequency, exact polarisation, departure direction) depend on the state of the host cell at the moment of activation**, which depends on the cell's per-cell winding *w*. Each Hawking photon carries fine-structure information about the cell that emitted it.

The information capacity per Hawking photon is bounded by the photon's phase-space volume and quantum-state degrees of freedom — roughly ~1–2 bits per quantum. This is the standard bound for thermal radiation. **What (3+3) adds** is the operational specification of where these bits come from: they encode the host cell's state at the moment of emission, which in turn depends on the cell's per-cell winding *w* (set during the BH's formation history).

In the early stages of evaporation, the host cells (in the original boundary layer) have *w* values determined by the most recently accreted matter. Their emissions reflect that matter's topological residue. As evaporation proceeds and the boundary recedes inward, the host cells of subsequent emissions are cells that were previously in the dormant interior — with *w* values reflecting earlier-accreted matter, including the original collapsing star's content. **The full evaporation process progressively exposes the BH's entire infall history through the Hawking quanta**, with each successive quantum potentially carrying information about a different epoch of the BH's history.

11.5 Information conservation: the topological-residue pathway

Putting §11.2 and §11.4 together with the substrate-level mechanisms developed earlier, the (3+3) information-conservation pathway has four steps:

11.5.1 Step 1: matter falls in, converts to substrate residue

Per §5.1 and §5.2, infalling matter does not "cross the horizon" but converts to substrate residue at the boundary layer. KK $n \geq 1$ modes decay to $n = 0$ condensate; per-cell winding numbers *w* are updated on the host cells to encode the matter's topological identity. **Information is preserved through the conversion**: the topological invariant $\pi_2(S^2) = \mathbb{Z}$ guarantees that *w* values cannot change under continuous transformations.

11.5.2 Step 2: residue persists on dormant cells through the BH lifetime

After conversion, the host cells transition to the dormant state and become part of the BH's dormant interior (§8.2, §8.3). The *w* values on these cells persist for the entire BH lifetime: per-cell winding is a topological invariant, conserved under any continuous transformation of the field configuration. **No substrate-level dynamics inside the dormant interior can change the *w* distribution** without a discontinuous transformation, and the framework does not provide such discontinuities inside the BH. The information is locked in topological residue.

11.5.3 Step 3: receding boundary exposes the residue

As the BH evaporates via Hawking radiation (§11.2), it loses mass at rate $dM/dt \sim -1/(M^2\, t\_Planck / m\_Planck^2)$. The T_2 gradient relaxes as the mass decreases; the substrate-level dormancy threshold recedes inward; cells that were dormant become activated as the dormancy boundary passes them. **As cells reactivate, they regain access to the photon-only relay infrastructure**, and their *w* values become directly observable through the cells' photonic emissions and absorptions.

11.5.4 Step 4: information is recovered through Hawking quanta

Photons emitted from the receding boundary at any time carry detailed information about the cells in the boundary at that time — and these are cells that were previously in the dormant interior, with their *w* distributions encoding earlier-accreted matter. Each Hawking quantum therefore carries information about the BH's formation history, with the temporal sequence of quanta covering the temporal sequence of accretion events (with the most-recently-accreted matter's information emerging first, as the boundary recedes through cells that received it most recently).

The information that fell into the BH at time *t_in* emerges as Hawking radiation at time *t_out* — typically much later, but with a definite mapping from infall time to emission time set by the boundary recession rate. The total information emerging in Hawking radiation, integrated over the BH's full evaporation, equals the total information that fell in. **Information conservation is exact**, with the temporal scrambling set by the substrate-level dynamics rather than being lost or destroyed.

11.6 Black-hole evaporation: full lifecycle

A complete picture of a BH's evaporation in (3+3) traces the boundary's progress from initial formation through complete disappearance. The lifecycle has four phases:

11.6.1 Phase I: Equilibrium with negligible evaporation

For astrophysical BHs ($M \gg m_{Planck}$), the evaporation timescale $t_{evap} \sim M^3\, t_{Planck} / m_{Planck}^2$ is enormous. A solar-mass BH has $t_{evap} \sim 10^{67}$ years, far longer than the current age of the universe. During Phase I, the BH is approximately static: Hawking radiation is negligible (output rate orders of magnitude below CMB absorption rate); the boundary is essentially fixed; the substrate-level structure is stable.

During this phase, accretion can dominate over evaporation, with the BH growing rather than shrinking. The boundary expands outward as *M* increases. Each accretion event's topological residue is added to the *w* distribution on cells in the (then-current) boundary layer (§5.6). **The BH's "memory" of its accretion history is built up during Phase I**.

11.6.2 Phase II: Slow evaporation through the bulk lifetime

When accretion has stopped or fallen below the Hawking emission rate, the BH's mass slowly decreases and the boundary slowly recedes. Each Hawking quantum carries away ~ T_{BH} worth of energy and ~ 1–2 bits of information about the boundary layer's current cells. The boundary recession rate is extremely slow (years per cell during stellar-mass evaporation; immensely longer for supermassive BHs).

During Phase II, **information about earlier-accreted matter progressively becomes accessible**. A cell with *w* residue from matter that fell in 10^{60} years ago becomes part of the new boundary layer when the boundary has receded enough to reach it; its emissions then carry information about that ancient infall event.

11.6.3 Phase III: Late-stage evaporation as M approaches m_Planck

As *M* decreases toward m_{Planck}, T_{BH} increases as $1/M$; emission rate $dM/dt \sim -1/M^2$ accelerates rapidly. The Hawking spectrum becomes increasingly hard (high-frequency); emission becomes increasingly rapid; the boundary recedes increasingly fast. The final $\sim 10^{-23}$ s of evaporation may be a brief but intense burst of high-energy quanta.

The dormant interior becomes increasingly exposed during Phase III. The receding boundary scans through cells with *w* values from progressively earlier accretion events, eventually reaching cells with *w* residue from the original collapsing star. The information from the BH's formation emerges as Hawking quanta during this phase.

11.6.4 Phase IV: Ready-state core dissolution

Toward the end of evaporation, the receding boundary reaches the ready-state core (§10). The core, being a coherent topological condensate at minimum $R_3 = L\_P$, dissolves as cells transition out of the ready state (R_3 expanding back from L_P to the activated value). The condensate's *w* configuration is released into the radiation; the deepest topological residue (encoding the BH's formation matter) emerges in the final stages of Hawking emission.

The total mass-energy emitted equals Mc^2 (the BH's initial mass), and the total information emitted equals the BH's initial Bekenstein-Hawking entropy $S\_BH = k\_B\ A\_initial/(4L\_P^2)$. **Both are conserved exactly**: the energy by mass-energy conservation, the information by topological invariance of per-cell *w*. The BH disappears completely, leaving behind an outgoing radiation field that is, in principle, in a pure quantum state correlated to the original infallen matter.

11.7 The Page curve in the (3+3) picture

Page (1993) showed that, under the assumption of unitarity, the entanglement entropy of Hawking radiation should rise to a maximum at the **Page time** *t_Page* (when the BH has lost half its initial Bekenstein-Hawking entropy through Hawking emission), then fall back to zero as the BH evaporates completely. The shape of this **Page curve** is a key signature of unitary BH evolution; recovering the Page curve from a fundamental theory has been a central goal of recent work (Penington 2020; Almheiri et al. 2020; the island formula derivations).

In the (3+3) framework, the Page curve emerges as a structural feature of the substrate dynamics, with the following mechanism:

11.7.1 Pre-Page time

In the early stages of evaporation, when the cumulative emitted radiation count *N_rad* is small compared to the BH's remaining entropy *S_BH* (boundary-layer area-bound), the entanglement entropy of the emitted radiation is $S\_rad \approx N\_rad$ — the radiation looks "thermal," with each quantum independently carrying ~1 bit of entanglement with the BH. The curve rises linearly with the radiation count.

Substrate-level reading: the boundary-layer cells in this phase have *w* values from recent accretion, and the radiation samples their states roughly statistically. The entanglement is "fresh" — each emitted photon is uncorrelated (or weakly correlated) with previously-emitted photons.

11.7.2 Page time

When the cumulative radiation count *N_rad* equals the BH's remaining entropy *S_BH*, the radiation's entanglement entropy reaches its maximum $S\_max = S\_rad = S\_BH / 2$. This is the Page time.

Substrate-level reading: at this point the receding boundary has exposed roughly half the BH's original cells — the cells originally in the boundary layer have all been processed; the receding boundary is now into the original dormant interior, exposing cells whose *w* values were set during the BH's earlier history.

The radiation begins carrying historically-correlated information; entanglement between radiation and remaining BH peaks.

11.7.3 Post-Page time

After the Page time, *N_rad* exceeds *S_BH*, and the entanglement entropy of the radiation begins to decrease — it is bounded by the smaller of *N_rad* and *S_BH*, and as the BH shrinks (*S_BH* decreasing), the radiation's entanglement entropy decreases linearly with *S_BH*. The radiation is "purifying" as the BH approaches complete evaporation.

Substrate-level reading: in this phase, the receding boundary is progressively exposing cells whose *w* values have already partially been reflected in earlier-emitted radiation (because the matter on those cells fell in during the BH's formation, and structurally similar matter has been emerging in the radiation since the boundary first started receding). **The new emissions are increasingly correlated with old emissions**, reducing the marginal entanglement of the radiation as a whole. By complete evaporation, the radiation has zero entanglement — it is in a pure state, consistent with unitarity.

The (3+3) Page curve emerges naturally from the substrate dynamics: it is not imposed as a quantum-information requirement on top of the GR evolution, but emerges from the topological-residue mechanism. The mechanism is structurally specific (per-cell *w* preserved through dormancy; progressively re-exposed by the receding boundary), and the resulting curve has the Page-shape automatically. The structural form of the Page curve is at Level 1 in (3+3); the precise time-dependence (the exact shape of the rising and falling segments) depends on substrate-dynamics details that are at Level 2.

11.8 Comparison with other resolutions

Several proposals exist for resolving the BH information paradox. A brief comparison illuminates how (3+3) relates to each:

11.8.1 Black hole complementarity (Susskind, Thorlacius, Uglum 1993)

BH complementarity asserts that the infalling observer's perspective and the external observer's perspective are complementary descriptions: each is internally consistent, but they cannot be combined into a single observer-independent description. The infaller experiences smooth crossing and reaches the singularity; the external observer sees the matter freeze and the information in Hawking radiation. The two perspectives are not in direct contradiction because no observer can compare them.

(3+3) does not require complementarity because there is a single substrate-level fact: matter converts at the boundary (§7); information is on the substrate (§5.2, §11.5). The infaller does not experience smooth crossing because the infaller's KK modes terminate at the boundary (§7); the apparent contradiction that complementarity was designed to address does not arise. The (3+3) reading is more economical — one description for all observers — but with the substrate-level mechanism doing the work.

11.8.2 Soft hair (Hawking, Perry, Strominger 2016)

The soft-hair proposal (HPS 2016) suggests that BHs carry "soft hair" — soft photons and gravitons that encode information about infallen matter. The BH is not "no hair" beyond mass, charge, and angular momentum (the classical no-hair theorems); rather, it has a continuous spectrum of soft modes that store information.

(3+3) is structurally similar in spirit but mechanistically different. In both proposals, information is stored "on the BH" rather than "inside" in the GR sense. (3+3) has discrete per-cell winding numbers *w* on cells; the soft-hair proposal has continuous soft modes. The (3+3) information storage is finite-information (integer values on countable cells), while soft hair has continuous-mode content. Operational differences may emerge in the spectrum of late-stage Hawking radiation: (3+3) predicts discrete topological signatures; soft hair predicts continuous-mode patterns.

11.8.3 ER=EPR (Maldacena and Susskind 2013)

The ER=EPR proposal connects entangled quantum states with Einstein-Rosen bridges (non-traversable wormholes): two entangled particles are connected by an ER bridge, and BH information can be preserved by analogous wormhole-mediated correlations between Hawking quanta and infalling matter. The proposal is geometric (uses GR's wormhole structures) and quantum-informational (entanglement is the substance of the connection).

(3+3) does not invoke ER bridges. The framework's primitives do not include wormhole geometries beyond the standard Schwarzschild solution; the substrate-level connection between Hawking radiation and infallen matter is via the receding-boundary mechanism described in §11.5, not via geometric wormhole connections. ER=EPR is a different geometric proposal addressing a similar question. The (3+3) and ER=EPR proposals are not incompatible — both can be simultaneously true at different levels of description — but they are different mechanistic accounts.

11.8.4 AMPS firewall (Almheiri, Marolf, Polchinski, Sully 2012)

The AMPS firewall paradox argued that BH complementarity, the equivalence principle, and unitarity cannot all be simultaneously satisfied unless there is a "firewall" — a region of high-energy excitations — at the horizon. Either complementarity fails, the equivalence principle fails at the horizon, or quantum mechanics is non-unitary in BHs.

(3+3) avoids the firewall paradox by modifying which assumption holds. In (3+3), the equivalence principle is exact in the activated foam (§7.6) but is modified at the boundary layer where substrate effects become non-negligible — the principle does not extend cleanly through the horizon as a smooth-crossing prediction. The (3+3) framework also does not require complementarity (§11.8.1). With a different set of premises, AMPS's argument does not go through; no firewall is needed. **The (3+3) horizon is structurally specified (boundary-layer cells with $N \approx N_{crit}$) but not a high-energy firewall**.

11.8.5 Island formula (Penington 2020; Almheiri et al. 2020)

Recent quantum-gravity calculations using semiclassical-gravity techniques (replica trick, the "island formula") have derived the Page curve in specific holographic settings. The mechanism involves "islands"

— regions inside the BH that contribute to the entanglement entropy of the radiation in a non-trivial way — and the formal calculation reproduces the Page curve from quantum-gravity primitives.

The (3+3) Page-curve derivation is structurally similar but mechanistically different. Both reproduce the Page curve from substrate-level (in (3+3)) or quantum-gravity (in island formulas) primitives. Both involve "interior content" contributing to the radiation's information content. Both are consistent with unitarity. Where the island formula uses the replica trick and gravitational saddles, (3+3) uses topological invariants and substrate reactivation. The two proposals may be complementary rather than competing — island formulas describe the formal-information-theory content of the Page curve, (3+3) describes the substrate-level dynamics that produce the information flow.

11.9 Open questions and observational targets

The (3+3) treatment of information conservation and Hawking radiation leaves several questions open and provides several observational targets distinguishable, in principle, from pure-GR Hawking emission.

11.9.1 Open questions

- **Precise time-dependence of the Page curve.** The structural form of the Page curve emerges from substrate dynamics (§11.7), but the exact rising and falling rates depend on detailed substrate-level dynamics not derived in this paper. The Level 1 / Level 2 distinction applies: structural shape at Level 1, precise time-dependence at Level 2.
- **Detailed Hawking spectrum corrections.** Standard T_{BH} is reproduced (§11.3), but small $(L_P/r_S)^2$ corrections are expected. The spectrum's precise corrections at next-generation detector precision are an open topic for further substrate-dynamics calculation.
- **Topological-residue signatures in late-stage radiation.** As Phase III (§11.6.3) and Phase IV (§11.6.4) of evaporation expose deep topological residue, the resulting Hawking spectrum should contain detectable structure — potentially in the spectral shape, polarisation correlations, or directional distribution. The precise predictions require fuller substrate dynamics work.
- **Sensitivity of substrate vs continuous-mode signatures.** The distinguishing observational signatures of (3+3)'s discrete substrate vs continuous-mode pictures (soft hair, holography) require careful quantification of expected signal vs detector capability.

11.9.2 Observational targets

In-principle observable signatures distinguishing (3+3) from pure-GR Hawking emission, listed in approximate order of accessibility:

- **Boundary-layer modulation during accretion.** Boundary-layer Hawking modulation (§5.7): accreting BHs should show small Hawking-spectrum modulations distinct from passive BHs. Below current detector sensitivity for stellar/supermassive BHs; potentially accessible for primordial BHs.

- **Late-stage primordial BH evaporation signatures.** If primordial BHs with masses ~10^{12} g are detected (their evaporation peaks now), the (3+3) framework predicts specific signatures in their late-stage emission spectrum, distinguishable from pure-GR thermal Hawking radiation. Cherenkov Telescope Array (CTA) for gamma-ray signatures, IceCube-Gen2 and KM3NeT for neutrino correlations, and direct gamma-ray observatories are the relevant facilities.
- **Page-curve structure.** Direct measurement of the Page curve is far beyond current capabilities (would require observing a BH's complete evaporation), but theoretical derivations comparing (3+3) Page-curve form with island-formula calculations may identify distinguishing features accessible at simulation level.
- **Topological-correlation signatures in BH-BH merger ringdown.** During mergers (§12), the substrate-level boundary reconfiguration may produce distinguishing features in the GW ringdown spectrum — discrete KK modes rather than continuous quasinormal modes. Einstein Telescope and Cosmic Explorer precision targets.
- **Directional anisotropy of Hawking emission.** The substrate-level mechanism (§11.2) gives the Hawking emission a possibly characteristic directional pattern, distinct from isotropic thermal emission. In-principle observable for primordial BHs if detected.

Overall framing: (3+3) does not predict deviations from current observations of BH-related phenomena — Hawking radiation has not yet been detected for any astrophysical BH, and the framework reproduces T_{BH} and S_{BH} exactly via the (3+3) → GR limit. The observable distinctions lie in regimes (primordial BHs, late-stage evaporation, next-generation merger precision) that are at the edge of current capability or in planning for next-generation facilities. **The framework is falsifiable in principle by these targets; agreement with current data is inherited from the GR reduction**, consistent with the merger-honesty framing of §1.4.3.

Summary of §11.

Hawking radiation has a substrate-level mechanism: cells in the evanescent boundary layer briefly activate, host equatorial-ring photons, and emit those photons via the photon-only relay. The standard $T_{BH} = \hbar c^3/(8\pi G M k_B)$ is reproduced (taken from [1] §21.4); substrate-level corrections are at order $(L_P/r_S)^2$, negligible for any astrophysical BH.

Information conservation operates through the topological-residue pathway: matter converts to substrate residue at the boundary (§5.1, §5.2); *w* values persist on dormant cells through the BH lifetime (§8.3); cells reactivate as the dormancy boundary recedes during Hawking evaporation; emitted Hawking quanta carry information about the *w* values on host cells.

BH evaporation has four phases: (I) equilibrium with negligible evaporation, (II) slow evaporation through bulk lifetime, (III) late-stage acceleration as $M \to m_{Planck}$, (IV) ready-state core dissolution. The total information emitted equals the BH's initial Bekenstein-Hawking entropy; total energy emitted equals Mc^2; both conserved exactly.

The Page curve emerges as a structural feature of the substrate dynamics: pre-Page time, fresh entanglement of Hawking radiation; Page time, maximum entanglement at $N_{rad} = S_{BH}$; post-Page time, decreasing entanglement as new radiation correlates with old. Structural form at Level 1; precise time-dependence at Level 2.

The (3+3) resolution differs from BH complementarity (no need for observer-relative descriptions; single substrate-level fact), soft hair (discrete w vs continuous modes), ER=EPR (no wormholes invoked), AMPS firewall (no firewall; equivalence principle modified at boundary), and island formulas (different mechanism but consistent picture).

Observational targets: boundary-layer modulation during accretion (§5.7), late-stage primordial BH evaporation signatures, BH-BH merger ringdown anisotropies, directional Hawking-emission patterns. All at next-generation detector precision; agreement with current data inherited from the (3+3) → GR reduction.

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§12 Black-hole–black-hole merger dynamics

This section develops the (3+3) treatment of binary black-hole mergers — the events that LIGO, Virgo, and KAGRA have catalogued by the dozens since GW150914 in September 2015. The substrate-level picture is that two dormancy regions inspiral, fuse, and ring down, with gravitational waves emerging as foam deformation modes (the spin-2 KK mode of §2.6.2) carrying away the foam's elastic-strain release. Section 11 develops this picture across the merger lifecycle (§12.1–§12.4), treats the energy budget at the substrate level (§12.5), and is then explicit about what the framework predicts versus what it inherits from the (3+3) → GR reduction (§12.6). Distinguishing signatures appearing only at next-generation precision are catalogued in §12.7. Section 11.8 considers information processing during mergers (how the two BHs' topological residues combine), and §12.9 closes with open questions and the framework's honest position on merger predictions.

The (3+3) → GR reduction is operationally central in this section. The framework reduces to general relativity at the appropriate limit ([1] §21.7 / Appendix D, [2] §3); the current LIGO/Virgo/KAGRA waveforms are recovered through this reduction. **This is the right kind of agreement** — a more fundamental theory should reduce to its predecessor in the appropriate limit, with substrate-level deviations visible only at higher precision than current detectors achieve. The substrate-level merger picture in this section adds operational content beyond GR: it identifies the substrate-level origin of each waveform feature, supplies a physical mechanism for the strain-release, and predicts distinguishing signatures (discrete KK ringdown modes, information-content waveform modulation) at next-generation precision. Where the framework inherits agreement rather than predicting deviations, this is stated explicitly.

12.1 The merger event in (3+3): substrate-level overview

A binary black-hole merger event in (3+3) is a substrate-level reconfiguration event involving two pre-existing dormancy regions and the activated foam between them. The event has the standard four phases of LIGO/Virgo terminology — inspiral, plunge, merger, ringdown — each with a substrate-level interpretation:

- **Inspiral**: two dormancy regions in mutual gravitational attraction (foam-elastic response to each other's T_2 gradient distortion), losing orbital energy through gravitational-wave emission. The orbital separation decreases over many cycles. Each BH retains its individual substrate structure (boundary layer, dormant interior, ready-state core) throughout the inspiral phase; the substrate-level changes are deformations of each BH's structure due to the other's gradient.
- **Plunge**: the final orbital cycles, where the two boundary layers come into close proximity (separations of order $r_S + r_S$), and the foam between them undergoes large-scale deformation. The substrate-level distinction between "two BHs" and "one BH with a complex shape" begins to become operationally fuzzy.
- **Merger**: the two boundary layers fuse. The two dormancy regions combine into a single, initially highly-distorted dormancy region. The substrate-level reconfiguration is rapid (timescale of

order *r_S/c* for the final merger event); the foam between the two BHs is rapidly absorbed into the newly-merged dormant region.

- **Ringdown**: the highly-distorted post-merger substrate oscillates at characteristic frequencies as it relaxes toward the equilibrium dormancy region of a single Kerr BH (or Schwarzschild, in the non-spinning limit). The oscillations are foam-elastic deformation modes propagating outward as gravitational-wave radiation. The substrate-level interpretation is literally substrate vibration; the GR interpretation is "quasi-normal modes" of the metric.

Throughout these phases, the matter-excitation level (§3) is essentially inert: there are no propagating matter excitations (electrons, photons, protons) involved in the merger event itself. The matter that originally formed each BH was converted to substrate residue at each BH's formation (typically billions of years before the merger; see §8.4); its content is preserved as per-cell winding *w* on dormant cells, and these winding values are not directly involved in the merger dynamics. **The merger is a substrate event**, with matter participation only via the gravitational effect of the BH masses (substrate-level T_2 gradient).

12.2 Inspiral phase: two dormancy regions

During the inspiral phase, the two dormancy regions are well-separated and each retains its individual substrate structure. The gravitational dynamics are dominated by the foam's elastic response to each BH's T_2 gradient distortion (§2.6.1, §2.6.2): each BH responds to the other's gradient as matter would, with the substrate elasticity providing the restoring force.

Gravitational-wave emission during inspiral is the standard chirping signal: as the orbital separation decreases, the GW frequency increases (orbital frequency goes up, GW frequency is twice the orbital frequency for leading multipole) and amplitude grows. **The (3+3) substrate-level mechanism for this emission**: the orbital motion of the two dormancy regions through the activated foam between them creates a time-varying mass quadrupole. The foam's elastic response to this time-varying gradient is a propagating deformation mode — the foam-elastic version of the spin-2 graviton. These propagating modes carry energy outward at speed *c*, reaching distant observers as gravitational waves.

The chirp waveform is reproduced by the (3+3) → GR reduction: the foam-elastic deformation modes obey the same field equations as GR's linearised gravitational waves (this is the Einstein-Aether reduction of [1] §21.7, Appendix D), with the same dispersion relation (*v_GW* = *c*), the same two polarisation states (plus and cross), and the same chirp form. **No observable deviations from GR's inspiral waveform are predicted at current detector precision** — the framework reproduces the standard waveform via the GR reduction, not via a separate substrate-level derivation.

The orbital energy loss during inspiral is energy taken from the foam-elastic system: as the foam radiates gravitational waves outward, the orbital binding energy of the two dormancy regions decreases. In the (3+3) reading, the radiated energy is foam-elastic strain energy stored in the deformed substrate around the binary; in the GR reading, it is the energy of metric perturbations carrying away the binding energy. The two descriptions are consistent and equivalent at the metric level via the GR reduction.

12.3 Merger phase: substrate reconfiguration

The merger phase is the rapid event in which the two boundary layers fuse and the two dormancy regions combine. This is the most dynamically intense period of the merger event, lasting a few times *r_S/c* for the final fusion event (~ 10^{-3} s for a stellar-mass binary).

In substrate-level terms, the merger event involves several simultaneous processes:

- **Boundary-layer fusion**: as the two dormancy regions approach, their evanescent boundary layers (each ~79 cells thick, §4.3) come into contact. The cells in the contact region transition from "outer boundary of region 1" / "outer boundary of region 2" to "interior of merged region." Cells in the contact region briefly experience overlapping boundary-layer fluctuations, then settle into the dormant state of the merged interior.
- **Topological residue rearrangement**: the per-cell *w* distributions of the two original BHs (each encoding its respective formation history) become co-located on the merged substrate. The total topological charge is preserved (sum of the two original distributions); the spatial distribution is no longer strictly inherited from either parent BH but reflects the merger geometry. **No information loss occurs**: the *w* values are topologically preserved; only their spatial distribution changes.
- **Ready-state core dynamics**: each of the original BHs had its own ready-state core (§10). During the merger, these cores are pulled toward each other and eventually combine into a single core for the merged BH. The detailed dynamics of core-fusion are at Level 2 — not derived in detail in this paper — but the structural picture is clear: two cores merge into one, with the combined core mass set by the merged BH's mass.
- **Foam-elastic strain release**: the rapid substrate reconfiguration involves substantial deformation of the surrounding foam. The strain energy stored in the deformed foam is rapidly released as outgoing gravitational waves — the dramatic GW peak that LIGO/Virgo detect at the merger event. This is the substrate-level mechanism for the merger's GW amplitude maximum.

The merger phase's GW signal — the peak amplitude transition from the chirp's end into the ringdown's decay — is reproduced by the (3+3) → GR reduction. Numerical relativity simulations using Einstein's equations compute this transition correctly, and the (3+3) framework inherits these predictions automatically through the GR limit. **No substrate-level corrections to the merger waveform peak are predicted at current detector precision**.

12.4 Ringdown phase: substrate oscillations

After the merger event, the post-merger substrate is a single, highly-distorted dormancy region. It must relax toward the equilibrium configuration of a single Kerr or Schwarzschild BH; this relaxation is the ringdown phase, where the substrate oscillates at characteristic frequencies and the oscillations propagate outward as the ringdown gravitational-wave signal.

In standard GR, the ringdown is described by the **quasi-normal modes (QNMs)** of the perturbed Kerr metric: a discrete spectrum of complex frequencies (each with real part = oscillation frequency, imaginary part = damping rate) characteristic of the final BH's mass and spin. The fundamental mode is the $l = m = 2$ QNM; higher modes ($l = 3$, etc.) are present but smaller-amplitude.

In the (3+3) substrate-level reading, the ringdown oscillations are foam-elastic deformation modes of the merged substrate. The substrate vibrates at characteristic frequencies set by:

- **The merged BH's overall scale** (set by r_S of the final mass): this gives the dominant mode frequencies, matching the standard QNM spectrum.
- **The substrate cell scale** (R_3 for activated cells outside the boundary; the boundary-layer thickness $\Delta N \approx 79$ cells): this introduces additional discrete-mode structure not present in the continuous-spectrum GR description. This is at the framework's substrate scale and is observationally accessible only at next-generation precision (§12.7).
- **Asymmetries from the merger geometry** (residual non-axisymmetry in the post-merger configuration): these contribute to higher-multipole modes, as in standard GR.

The standard QNM spectrum is reproduced by the (3+3) → GR reduction. The substrate-level corrections are at the cell scale, separated from the standard QNM frequencies by a ratio of order $(R_3 / r_S)^2$ for stellar-mass BHs — about 10^{-34}, far below current detector precision. **Standard GR ringdown predictions are reproduced exactly at current detector sensitivity**; substrate-level distinguishing features appear only at next-generation precision (§12.7).

During ringdown, the GW amplitude decays exponentially with the QNM's characteristic damping time. The energy stored in the post-merger substrate distortion is progressively radiated outward; the substrate progressively relaxes toward equilibrium; the merged BH stabilises into a single Kerr BH with its definite mass M_{final} and spin parameter a_{final}. The final BH then enters the long Phase I (§11.6.1) of slow Hawking evaporation that characterises its subsequent lifetime.

12.5 Energy budget at the substrate level (Level 2)

The energy radiated as gravitational waves during a typical BH-BH merger is ~5–10% of the total system mass — about 3 $M_\odot$ of energy released as GWs in 0.2 seconds for GW150914, for example. **In (3+3), this energy is foam elastic-strain energy released as the substrate reconfigures**. This is a Level 2 picture — the structural form of the energy budget is at Level 1, the precise quantitative reproduction depends on substrate-dynamics details that are not derived in full in this paper.

12.5.1 Where the radiated energy comes from

The energy radiated as GW comes from the gravitational binding energy and kinetic energy of the binary system, deposited into substrate-elastic strain during the merger event. The path is:

- Initial binding energy: the binary at finite separation has mutual gravitational binding energy $-Gm_1m_2/r$ (negative, indicating bound state). This is encoded substrate-level as the foam's elastic configuration in the region between and around the two BHs.

- Inspiral GW emission: as the binary radiates GWs, the orbital binding energy decreases (becomes more negative), and the energy is carried away in the GW field. The substrate-level mechanism is the foam-elastic deformation modes of §12.2.
- Merger phase: the rapid substrate reconfiguration involves a brief deep deformation of the foam, with much of the remaining binding energy momentarily stored as substrate strain. This strain energy is then released as outgoing GWs in the few-r_S/c duration of the merger peak.
- Ringdown decay: the residual substrate distortion relaxes as the foam returns to its equilibrium configuration around a single Kerr BH. The remaining radiated energy emerges in the ringdown phase.

The total energy radiated is bounded by the substrate-elastic-strain energy available, which in turn is bounded by the binary's pre-merger binding energy plus relative kinetic energy. For comparable-mass mergers ($m_1 \approx m_2$), the bound is about 30% of the total mass; the actual radiated fraction is ~5–10%, with the difference going into the final BH's spin and into rest mass-energy (which is conserved). This is consistent with standard numerical-relativity results.

12.5.2 Energy budget consistency check

For GW150914, the parameters are $m_1 \approx 36\ M_\odot$, $m_2 \approx 29\ M_\odot$, $M_{final} \approx 62\ M_\odot$, with $E_{radiated} \approx 3\ M_\odot \times c^2 \approx 5.4 \times 10^{47}$ J. In (3+3), this energy is the foam-elastic strain energy released by the substrate reconfiguration during the merger event. **The order of magnitude is consistent**: the strain energy stored in foam-deformation modes during the merger is bounded by the system's mutual binding energy at the merger separation, which for $r \approx r_S$ is of order $Gm_1m_2/r_S \approx m_1m_2c^2/M$. For GW150914 parameters, this gives ~ 17 $M_\odot \times c^2$ as the maximum bound — well above the actual 3 $M_\odot \times c^2$ radiated, leaving headroom for the radiated fraction observed.

Level 2 status: the structural picture (substrate strain release as GWs) is at Level 1; the precise prediction of the radiated fraction (5% vs 10% vs 20%) depends on detailed substrate-dynamics calculations that are not done in this paper. The (3+3) → GR reduction supplies the precise numerical predictions via numerical relativity; the substrate-level account supplies the physical interpretation. **No new prediction is made about the radiated fraction** — agreement with LIGO/Virgo measurements is inherited from the GR limit.

12.6 (3+3) → GR inheritance: current LIGO/Virgo agreement

This subsection is the central honest framing of §12. The (3+3) framework reduces to general relativity at the appropriate limit, in the specific sense developed in [1] §21.7 and Appendix D: the framework is a specific case of Einstein-Aether theory with the c_i couplings determined by the foam geometry, and the metric-level dynamics reduce exactly to standard GR in regimes where substrate-level corrections (at scale L_P/r_S) are negligible.

For all currently catalogued LIGO/Virgo/KAGRA BH-BH merger events, substrate-level corrections are at scale $L_P/r_S \sim 10^{-38}$ for solar-mass BHs — far below current detector sensitivity. **The (3+3) framework reproduces every LIGO/Virgo merger waveform exactly via the GR reduction.** The substrate-level account adds physical interpretation and identifies the substrate-level origin of each waveform feature, but does not predict observable deviations from numerical-relativity-using-Einstein-equations predictions at current precision.

This is **not** a unique substrate-level prediction. It is **inherited** from the GR reduction. To be specific:

- **The chirp waveform** during inspiral: reproduced via the GR reduction. Substrate-level mechanism (foam-elastic radiation modes) is consistent with this via Einstein-Aether reduction; no new prediction.
- **The merger peak amplitude and shape**: reproduced via the GR reduction. Numerical relativity using Einstein's equations gives the standard peak profile; (3+3) inherits this via the metric-level reduction.
- **The ringdown spectrum** (quasi-normal modes): reproduced via the GR reduction. Standard QNM frequencies and damping times are recovered exactly at the GR-limit metric level.
- **The final BH parameters** (mass, spin): reproduced via the GR reduction. The final BH is a Kerr (or Schwarzschild) solution at the metric level, with the standard formulas for mass loss and spin assignment.
- **The radiation pattern and polarisation**: reproduced via the GR reduction. The standard "plus" and "cross" polarisations are recovered as the two transverse-traceless modes of the foam deformation field.

Every observable feature of every currently-detected BH-BH merger event is reproduced by the (3+3) framework via the GR reduction, with the substrate-level account providing physical interpretation of each feature's origin in the underlying substrate dynamics. Distinguishing observations are at next-generation precision (§12.7); current data is consistent with both the standard GR picture and the substrate-level picture.

This is the responsible scientific framing: (3+3) does not currently make falsifiable predictions about LIGO/Virgo merger waveforms beyond what standard GR predicts. **The framework adds operational interpretation rather than empirical predictive content at current sensitivity.** Falsifiability in the BH-BH merger sector requires next-generation detectors operating at substantially improved precision, where the small substrate-level corrections become accessible.

12.7 Distinguishing signatures at next-generation precision

Substrate-level features that distinguish (3+3) from pure GR appear at precisions accessible to next-generation gravitational-wave detectors — Einstein Telescope (ET) and Cosmic Explorer (CE), planned for the 2030s, and possibly LISA for supermassive BH mergers. The framework's falsifiability roadmap ([1] §30) identifies these signatures as primary tests of the discrete-substrate hypothesis.

12.7.1 Discrete KK ringdown modes

The standard ringdown is described by a continuous spectrum of QNM frequencies, each with real and imaginary parts determined by the final BH's parameters. **In (3+3), additional discrete modes appear at the substrate cell scale**: foam-elastic oscillations of the merged substrate have characteristic frequencies set not only by r_S (giving the standard QNM spectrum) but also by the substrate cell scale R_3. The ratio of these new mode frequencies to the standard QNM frequencies is roughly r_S/R_3 — a large number, typically 10^{22} for stellar-mass BHs.

Discrete-mode signatures would manifest as:

- Additional spectral lines in the ringdown spectrum, at high frequencies set by $c/R_3 \approx 2.5 \times 10^{20}$ Hz — far above current detector bands, but with possible amplitude folding into observable bands through nonlinear mode coupling.
- Deviations from the standard QNM mode-amplitude ratios: the discrete-spectrum predictions would shift the relative weighting of $l = 2$ vs higher-l modes by amounts of order $(R_3/r_S)^2$ — far below current precision but potentially accessible at ET/CE sensitivity.
- Modulation of the ringdown decay envelope: substrate-cell-scale dynamics could produce small departures from the smooth-exponential decay of standard QNMs, on timescales related to R_3/c.

Status: Level 2 prediction. Structural form is at Level 1 (foam-cell-scale dynamics produce additional modes); precise spectrum and accessibility depends on substrate-dynamics details and detector capabilities. Detection requires Einstein Telescope or Cosmic Explorer precision; not accessible at current LIGO/Virgo/KAGRA levels.

12.7.2 Possible horizon-scale echoes

Some BH alternatives (fuzzballs, gravastars, certain regular-BH proposals) predict gravitational-wave **echoes** following the main ringdown signal: partial reflections of the ringdown wavefront from the BH's near-horizon structure, producing delayed signal components. Echo timing is set by the time for a signal to traverse the BH's near-horizon structure twice (in and out).

In (3+3), the substrate-level boundary layer has thickness $\Delta N \approx 79$ cells × cell linear extent, which is of order $L_P \times 79 \approx 1.3 \times 10^{-33}$ m for the cell-scale interpretation, or potentially larger if the layer's effective thickness includes activated-cell-scale lengths. The corresponding echo timing is roughly 2 × layer-thickness / $c \sim 10^{-41}$ s — far below current or planned detector timing resolution.

(3+3) therefore does not predict observable echoes at current or near-future detector capabilities. The boundary-layer structure is too thin and the echo timing too short for resolution. This distinguishes (3+3) from fuzzball-class proposals where echoes are at observable timescales (typically 10^{-3} to 10^{-1} s); the absence or presence of detectable echoes is a discriminator. **Status**: Level 3 prediction (structural speculation); unlikely to be observable in (3+3) given the thin-boundary-layer structure.

12.7.3 Information-content waveform modulation

A more speculative possibility: the merging BHs each carry their own *w* distribution (encoding their respective formation histories). The merger dynamics could in principle depend, at higher orders, on details of these distributions, producing subtle waveform modulations that distinguish mergers of "old, well-mixed" BHs from "young, structured" ones.

For typical astrophysical BH-BH mergers, the *w* distributions are expected to be statistically random (well-scrambled by the BH's formation history), so the macroscopic merger dynamics are dominated by the no-hair parameters (mass, spin) and the framework's prediction matches GR's no-hair result. **Higher-order moments of the merger waveform might show small modulations** correlated with the BHs' detailed substrate states, but these would require statistical analysis across many merger events at next-generation precision.

Status: Level 3 prediction. Conditional on detailed substrate dynamics and statistical accumulation across many merger events. Possibly accessible at ET/CE sensitivity with thousands of merger detections; not accessible at current single-event analysis precision.

12.8 Information processing during mergers

A subtle question: when two BHs merge, what happens to their information content (the per-cell *w* distributions encoding each BH's formation history)? The substrate-level answer is that **information is preserved through the merger** but **reconfigured spatially**. This subsection develops the picture briefly.

12.8.1 Pre-merger: two separate w distributions

Before the merger, the two BHs each have their own per-cell *w* distribution on their respective dormant cells. The total topological charge of BH 1 is W_1 = Σ_{cells in BH 1} *w_cell*; similarly W_2 for BH 2. Each distribution encodes the formation and accretion history of its respective BH; the two distributions are spatially separated and do not interact during the inspiral phase (the dormancy regions are disjoint).

12.8.2 Merger: distributions become co-located

During the merger event (§12.3), the two boundary layers fuse and the two dormancy regions combine into a single merged region. The cells from the two original BHs become part of the merged dormant interior, retaining their *w* values (per-cell winding is topologically preserved through continuous transformations of the substrate, including the merger's rapid reconfiguration).

Total topological charge is conserved: the merged BH's total topological charge equals *W_merged* = W_1 + W_2. The information content of each pre-merger BH is preserved on the cells that were originally in that BH; no information is lost or destroyed during the merger.

Spatially, the *w* distribution is reorganized by the merger. Cells that were originally near the "north pole" of BH 1 (relative to its merger-with-BH-2 axis) end up at definite positions in the merged BH's structure; the original BH 1's *w* distribution is transformed by the merger geometry onto the merged structure. The transformation is continuous (topologically allowed) but non-trivial. **The merged BH's *w* distribution is the union, geometrically rearranged, of the two pre-merger distributions.**

12.8.3 Post-merger: combined w distribution

After ringdown completes, the merged BH has a single, definite *w* distribution on its dormant cells, encoding the combined formation histories of both pre-merger BHs (plus any accretion content from between formation and merger). The post-merger BH's information content is the sum of the pre-merger BHs' information content; total topological information is preserved.

During subsequent Hawking evaporation of the merged BH (over the very long timescale ~ $M\_merged^3 \times t\_Planck/m\_Planck^2$), the receding boundary will progressively expose the *w* values, with both pre-merger BHs' histories emerging in the radiation. **In principle, the radiation from a merger remnant carries information about both pre-merger BHs' formation histories** — the merger does not erase the BHs' "memory."

This is a Level 1 structural claim (information preservation through mergers); the precise distribution of which information emerges at which evaporation epoch is at Level 2, depending on substrate-dynamics details of the merger and post-merger evaporation. **Observationally inaccessible at any current or planned timescale**, since BH evaporation is too slow to be observed directly for stellar-mass merger remnants.

12.9 Open questions and honest framing

Closing §12 with explicit recognition of what the framework currently predicts in the BH-BH merger sector and what remains as open work or inheritance from GR.

12.9.1 What (3+3) inherits from the GR reduction

The framework inherits, via the (3+3) → GR limit:

- All currently-detected LIGO/Virgo/KAGRA merger waveforms (chirp shape, merger peak, ringdown spectrum, final BH parameters).
- The two GW polarisations (plus and cross), with no extra polarisation modes detectable at current sensitivity.
- The dispersion relation $v\_GW = c$ exactly; no frequency-dependent GW velocity corrections at current precision.
- Standard numerical-relativity predictions for non-equal-mass mergers, spin-precession effects, and eccentric mergers.
- The Bekenstein-Hawking entropy and area-theorem behaviour of the merger remnant.

These are not unique (3+3) predictions; they are inherited from the GR reduction. Failure to find any of these in observations would falsify GR (and (3+3) by extension); detection of any of them is consistent with both. Agreement with current data is therefore not a positive test of (3+3) specifically.

12.9.2 Distinguishing signatures requiring next-generation precision

- Discrete KK ringdown modes (§12.7.1): Level 2; ET/CE precision.
- Information-content waveform modulation (§12.7.3): Level 3; statistical analysis across thousands of events at ET/CE.
- Boundary-layer Hawking modulation during merger ringdowns (analogous to §5.7 for accretion): Level 2; not directly observable for stellar mergers but conceivably detectable for primordial BH mergers if such occur in the observable era.

Echoes are not predicted at observable timescales in (3+3) — the boundary layer is too thin (§12.7.2). This distinguishes (3+3) from fuzzball-class proposals where echoes are predicted at observable timescales. **Absence of echoes at current sensitivity is consistent with (3+3); presence of echoes would tend to falsify (3+3) in favour of fuzzball-type alternatives.**

12.9.3 Open theoretical questions

- Detailed substrate dynamics during the merger event: the boundary-layer fusion process, the ready-state core merger, and the precise foam-elastic strain release require fuller substrate-dynamics calculations not done in this paper.
- Quantitative predictions for the discrete KK mode spectrum: requires detailed analysis of foam-elastic oscillation modes at the substrate cell scale, beyond the structural argument given here.
- Higher-order corrections to the chirp waveform: the (3+3) → GR reduction is exact at leading order, but small corrections at order $(L\_P/r\_S)^2$ should exist; their precise form requires further work.
- The relationship between (3+3) and the recent-work island-formula derivations of merger-related entropy production: open theoretical question.

12.9.4 The framework's honest position

The (3+3) framework provides a substrate-level account of BH-BH merger dynamics that is operationally illuminating — it specifies what the merger "is" in substrate terms (two dormancy regions inspiraling, fusing, and ringing down with foam-elastic-strain release), and gives operational meaning to the various phases of the merger. **It does not currently predict observable deviations from GR at current detector precision in the BH-BH merger sector.** Distinguishing predictions exist (discrete KK ringdown modes, information-content modulation) but require next-generation precision (Einstein Telescope, Cosmic Explorer, or comparable facilities planned for the 2030s).

This is an honest framing. Several of the recent string-theoretic and quantum-gravity proposals for BH structure (fuzzballs, soft hair, island formulas) make predictions that are accessible at current or near-current sensitivity through specific mechanisms (echoes, late-stage Hawking spectrum corrections, holographic-correction signatures). **(3+3)'s distinguishing signatures are at next-generation precision rather than current**, and the framework's contribution to BH physics is interpretational rather than predictive at current sensitivity. Falsifiability in this sector remains contingent on next-generation detectors. The framework remains internally consistent and explanatorily rich at current sensitivity, but does not currently make distinguishing observational predictions in BH-BH mergers.

Summary of §12.

BH-BH mergers in (3+3) are substrate-level reconfiguration events: two dormancy regions inspiral (chirp waveform via foam-elastic GW emission), fuse (boundary-layer merger), and ring down (substrate oscillations as foam-elastic deformation modes). Matter-excitation level is essentially inert during the merger.

Energy budget at substrate level: GW radiation is foam elastic-strain release (Level 1 structural; Level 2 quantitative). The ~5–10% mass-energy radiated for typical mergers is consistent with foam-elastic binding-energy bound at *r_S* separation.

GR inheritance: All currently-catalogued LIGO/Virgo/KAGRA merger waveforms are reproduced via the (3+3) → GR reduction, NOT via unique substrate-level prediction. Agreement with current data is inherited, not predicted.

Distinguishing signatures at next-generation precision: discrete KK ringdown modes (Level 2; ET/CE); information-content waveform modulation (Level 3; statistical analysis at ET/CE). Echoes NOT predicted at observable timescales — boundary layer too thin.

Information processing through mergers: per-cell *w* topologically preserved, total topological charge $W\_merged = W_1 + W_2$, both pre-merger histories' information present in merged BH (recovered eventually through Hawking evaporation, observationally inaccessible at any current or planned timescale).

Honest position: (3+3) provides operationally illuminating interpretation of BH-BH mergers; does not currently make distinguishing observational predictions at current detector precision; falsifiability in this sector requires next-generation detectors.

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§13 Comparison with other approaches to BH physics

This section provides a synthesis of how the (3+3) framework's treatment of BH physics relates to other approaches in the contemporary literature. Many comparisons have been made in passing in earlier sections — the membrane paradigm in §4.6, fuzzballs and gravastars in §10.7, BH complementarity, soft hair, ER=EPR, AMPS firewall, and island formula in §11.8 — and §13 collects these into a single comparative treatment, supplemented with new content on the holographic principle and AdS/CFT (§13.5) and a synthesis placing (3+3) within the broader landscape (§13.13). Subsections follow a consistent format: each cites the proposal's origin, summarises its mechanism, identifies points of agreement and disagreement with (3+3), and flags any phenomenological distinguishing predictions.

13.1 Why this section

BH theory has accumulated a rich set of competing proposals over the half-century since the singularity theorems and the Bekenstein–Hawking entropy first identified deep tensions in the standard GR picture. Each proposal addresses a subset of the puzzles (singularity resolution, information conservation, horizon character, observational predictions) with distinctive mechanisms and assumptions. Readers familiar with one or another of these proposals will naturally ask: where does (3+3) sit in this landscape? **This section answers that question** by walking through the major proposals and identifying both shared aspects and distinctive features of the (3+3) treatment.

A few principles guide the comparisons:

- **(3+3) is not in competition with all of these proposals.** Some — like the holographic principle and certain aspects of soft-hair proposals — capture features that (3+3) reproduces structurally with a different mechanism. Others — like fuzzballs and LQG bounces — make different predictions that conflict with (3+3) in observable ways.
- **Phenomenological predictions matter most for distinguishing.** Where (3+3) makes phenomenological predictions distinct from a competing proposal (echoes, ringdown structure, etc.), these are flagged. Where (3+3) and another proposal are observationally equivalent at current precision, the comparison is interpretive rather than empirically decisive.
- **The framing is honest.** This section does not argue that (3+3) is the "correct" theory of BH physics. It identifies what (3+3) does that other proposals do not, and what other proposals do that (3+3) does not. The reader can judge the balance.

13.2 Comparison axes

The proposals are compared along several axes that capture the key theoretical commitments and phenomenological predictions:

- **Ontology**: what kind of object is a BH? A region of spacetime with a singularity (standard GR), a fluid membrane (membrane paradigm), a string microstate object (fuzzball), a discrete-substrate dormancy region (3+3), etc.
- **Singularity status**: is there a singularity at $r = 0$? (Standard GR: yes; LQG bounce: replaced by bounce; fuzzball: no horizon, no interior, no singularity; (3+3): replaced by ready-state core.)
- **Horizon character**: is the horizon a genuine surface, a fictitious construct, or absent? (Standard GR: coordinate-singular surface; membrane paradigm: stretched horizon; fuzzball: no horizon; (3+3): substrate dormancy boundary.)
- **Information storage**: where does the information go? (Standard GR: crushed at singularity; soft hair: in continuous soft modes; fuzzball: in string microstates; (3+3): in per-cell winding w.)
- **Information recovery mechanism**: how is information returned through Hawking radiation? (Standard GR: no clear mechanism; complementarity: observer-relative; (3+3): receding boundary exposes residue.)
- **Phenomenological signatures**: what observations distinguish the proposal? (Fuzzballs: echoes; LQG: white-hole emergence; (3+3): discrete KK modes at next-gen precision.)

13.3 Standard GR (the baseline)

The post-1960s standard GR picture, refined through the singularity theorems (Penrose 1965; Hawking & Penrose 1970), the Bekenstein–Hawking entropy (Bekenstein 1973), and Hawking radiation (Hawking 1975), serves as the baseline against which all other proposals are measured. **The standard GR picture is**: BHs are regions of spacetime bounded by event horizons; the interior contains the collapsed matter, eventually crushed at the central singularity; the horizon is a coordinate-singular surface with thermodynamic content (entropy, temperature) but no specified local structure; information falling into the BH is, in the strict GR + QFT-in-curved-spacetime treatment, lost (the Hawking-1976 information paradox).

(3+3) keeps the GR exterior solution (Schwarzschild metric, light deflection, GW propagation, etc., all reproduced via the GR reduction) **and reinterprets the interior** (substrate-level dormant foam with topological residue, ready-state core replacing singularity, information preserved as per-cell w). The horizon is reinterpreted as the substrate-level dormancy boundary (rather than a coordinate-singular surface). The phenomenology at current precision matches standard GR exactly via the GR limit. **The disagreements are interpretive (what is happening inside) and predictive at next-generation precision**, not at currently-observed sensitivity.

13.4 Membrane paradigm (Thorne–Price–Macdonald 1986)

See §4.6 for detailed treatment. In brief: the membrane paradigm treats the horizon as a 2D fluid membrane with definite local properties (surface tension, conductivity, viscosity, surface gravity). The membrane is "stretched" — placed just outside the actual horizon — and is acknowledged to be a fictitious construct used because the actual horizon's local properties are difficult to specify in pure GR.

(3+3) and the membrane paradigm are operationally close: the (3+3) evanescent boundary layer of §4.3 maps roughly to the membrane paradigm's stretched horizon, and the membrane's effective surface properties have substrate-level analogues (electrical conductivity ↔ boundary-layer cell reactivation rate; viscosity ↔ boundary-fluctuation relaxation; surface gravity ↔ the c-budget gradient at the boundary). **The key difference** is that the (3+3) boundary layer is real (substrate cells at threshold $N \approx N_{crit}$), not a fictitious construct. (3+3) makes the membrane paradigm structurally specific and grounded in substrate primitives. Phenomenologically: agreement at current precision; potential discrete corrections at substrate cell scale (negligible for stellar BHs).

13.5 Holographic principle and AdS/CFT

't Hooft (1993) and Susskind (1995) proposed the **holographic principle**: the information content of a region of space is bounded by its boundary area, not its volume. For black holes specifically, the Bekenstein-Hawking entropy $S_{BH} = k_B A/(4L_P^2)$ is consistent with this principle — the BH's information content scales with the area of its event horizon. Maldacena (1998) realised this principle concretely as the **AdS/CFT correspondence**: a duality between a gravitational theory in (d + 1)-dimensional anti-de Sitter (AdS) space and a conformal field theory (CFT) on its d-dimensional boundary. BHs in the AdS bulk correspond to thermal states in the boundary CFT; Hawking radiation is reformulated as unitary evolution of the CFT.

The holographic principle is widely regarded as a deep insight that any theory of quantum gravity must respect. **How does (3+3) relate?**

13.5.1 (3+3) is structurally consistent with the holographic principle

The (3+3) framework reproduces the area-bound on BH information content. Per §8.3 and §11.5, the BH's information capacity is set by the number of cells in the boundary layer, which scales as r_S^2/L_P^2 — the boundary area in Planck units, exactly the Bekenstein-Hawking form. **The holographic principle is recovered structurally** in (3+3) without invoking AdS/CFT duality: it follows from the substrate-level mechanism (information stored on boundary-layer cells, recovered via boundary recession, with the cell count set by area).

This is a positive convergence: holography's area-vs-volume scaling is a feature both of (3+3) and of holographic-principle-respecting theories broadly. (3+3) does not need to invoke AdS bulk geometry or boundary CFT duality to recover this scaling.

13.5.2 AdS/CFT-specific features have no direct (3+3) analogue

AdS/CFT is a specific duality between specific gravitational and field-theoretic systems. Key features include: the AdS boundary is timelike (contrasted with asymptotically flat spacetime), the duality involves large-N gauge theories on the boundary, the BH-CFT correspondence maps thermal CFT states to BHs in the bulk. **(3+3) does not realise these specific features** — the framework is built on a different foundation (3+3 spacetime with discrete t_3 S^2 compactification, not AdS bulk + CFT boundary).

However, **the two pictures may be complementary rather than competing**. AdS/CFT is a formal duality applicable in specific (anti-de Sitter) geometries; (3+3) is a substrate-level theory of physical (asymptotically flat) spacetime. They might both be true at different levels of description: AdS/CFT as a useful formal tool for certain quantum-gravity calculations; (3+3) as the underlying substrate-level mechanism in physical spacetime. Recent work in island formulas (§11.8.5) uses AdS/CFT machinery to derive the Page curve in specific holographic settings; (3+3) derives the Page curve from substrate dynamics directly. Both derivations are internally consistent; the question of how they relate at a deeper theoretical level is open.

13.5.3 Distinguishing predictions

Direct phenomenological tests of AdS/CFT vs (3+3) are difficult because AdS/CFT is most directly applicable in AdS spacetimes, while observational BHs are in asymptotically flat spacetime. Indirect tests via simulation (comparing AdS/CFT-derived Page curves with (3+3)-derived ones) might identify subtle differences, but at current sensitivity the holographic principle is recovered by both. **At next-generation observational precision**: (3+3) predicts discrete-substrate-cell signatures (§12.7); AdS/CFT-based proposals predict continuous-mode signatures from CFT correlations. These could in principle be distinguished, but the sensitivity required is far beyond current detectors.

13.6 BH complementarity (Susskind, Thorlacius, Uglum 1993)

See §11.8.1 for detailed treatment. In brief: BH complementarity asserts that the infaller's perspective (smooth crossing, reaches singularity in finite proper time) and the external observer's perspective (matter freezes at horizon, information in Hawking radiation) are complementary descriptions — each internally consistent, but not jointly combinable into an observer-independent description.

(3+3) does not require complementarity: there is a single substrate-level fact (matter converts at the boundary, §7) that all observers can agree on. The infaller does not experience smooth crossing because the infaller's KK modes terminate at the boundary (§7); no contradiction between perspectives arises. The (3+3) reading is more economical — one description for all observers — but with the substrate-level mechanism doing the work that complementarity's observer-relativity was needed for in pure GR. **At observational sensitivity** (3+3) and complementarity are equivalent (both are consistent with current observations); the difference is methodological.

13.7 Soft hair (Hawking, Perry, Strominger 2016)

See §11.8.2 for detailed treatment. In brief: the soft-hair proposal suggests BHs carry "soft hair" — soft photons and gravitons, in continuous low-energy modes — that encode information about infallen matter. The BH is not "no hair" beyond the classical no-hair theorem variables (mass, charge, angular momentum); rather, it has a continuous spectrum of soft modes storing information.

(3+3) and soft hair are structurally similar in spirit — both store information "on the BH" rather than "inside" — but **mechanistically different**: (3+3) has discrete per-cell winding numbers *w* on cells; soft hair has continuous soft modes. The (3+3) information storage is finite-information (integer values on countable cells; consistent with the holographic area bound); soft hair has continuous-mode content. **Distinguishing predictions** at next-generation precision: (3+3) predicts discrete topological signatures in late-stage Hawking radiation; soft hair predicts continuous-mode patterns. The two could in principle be observationally distinguished if late-stage primordial-BH evaporation is detected, with sufficient spectral resolution.

13.8 Fuzzballs (Mathur 2005, 2008)

See §10.7.2 for the singularity-resolution comparison and §11.8 for the information-paradox comparison. In brief: in string-theoretic fuzzball proposals, BHs are not regions of spacetime with horizons and singularities but **stringy "fuzzy" objects** — configurations of strings and branes filling the would-be horizon volume. There is no horizon in the GR sense, no singularity, no interior. Each fuzzball is a definite microstate, and the BH thermodynamic entropy counts the number of fuzzball microstates.

Spirit-similar to (3+3) in replacing a metric singularity with a structured object, but **mechanistically very different**: fuzzballs are stringy microstates; (3+3) is a discrete-substrate dormancy region. The horizon-status is different — fuzzballs **have no horizon**, while (3+3) retains the horizon as substrate-level dormancy boundary. Most importantly, the **predictions for echoes** distinguish: fuzzballs predict gravitational-wave echoes from the fuzzy near-horizon structure at observable timescales (typically 10^{-3} to 10^{-1} s); (3+3) does not predict observable echoes (per §12.7.2; boundary layer too thin for observable echo timing). **Detection of echoes at current sensitivity would tend to falsify (3+3) in favour of fuzzball-class proposals**; absence is consistent with (3+3) and inconsistent with fuzzballs (or requires fuzzballs to predict unobservably-thin echo signals).

13.9 Loop quantum gravity (Ashtekar, Bojowald, and others)

See §10.7.1 for detailed treatment. In brief: in loop quantum gravity (LQG), the singularity is replaced by a **quantum bounce**: collapsing matter rebounds at a Planck-scale density and re-expands as an emergent "white hole" structure. The mechanism is loop quantization of geometry (spin networks, area and volume operators with discrete spectra), with discreteness preventing infinite compression.

(3+3) and LQG share the discrete-geometry approach — both have a discreteness scale that prevents the GR singularity — but **differ fundamentally** in the discrete structures involved. LQG has spin networks (combinatorial structures with definite quantum-gravity derivation); (3+3) has t_3 S^2 foam tiling (a specific discrete spacetime structure with a definite particle content via KK modes). **The dynamics differ**: LQG predicts a bounce (matter rebounds, emerges as white hole); (3+3) predicts a static ready-state core (no bounce; matter remains as topological residue). LQG predicts emergent post-bounce matter; (3+3) predicts substrate residue persisting through Hawking evaporation. Phenomenologically distinguishable, in principle, by late-stage primordial-BH evaporation signatures.

13.10 Gravastars and generic regular BH proposals

See §10.7.3 and §10.7.4 for detailed treatment. The **gravastar** proposal (Mazur & Mottola 2001, 2004) replaces the BH interior with a de Sitter region (negative-pressure matter); some versions remove the horizon entirely. **Generic regular-BH proposals** (Bardeen 1968; Hayward 2006; Frolov 2014) modify the metric at small *r* via effective stress-energy considerations or modified-gravity assumptions, regularising the singularity without specifying a substrate-level mechanism.

(3+3) is more specific than gravastars and generic regular-BH proposals — it provides a substrate-level mechanism (discrete cell structure with minimum scale) rather than ad-hoc effective-metric or matter-content modifications. The (3+3) ready-state core is a structurally specific replacement for the singularity; gravastars use a different matter content; generic regular BHs use modified-metric effective descriptions. Phenomenologically: (3+3) and the regular-BH proposals are very similar at the metric level (both regularise the singularity), with substrate-specific signatures distinguishable only at next-generation precision.

13.11 Firewall (AMPS), ER=EPR, and island formula

See §11.8.3, §11.8.4, §11.8.5 for treatments. The **AMPS firewall** paradox (Almheiri, Marolf, Polchinski, Sully 2012) argued that BH complementarity, equivalence principle, and unitarity are mutually inconsistent unless there is a "firewall" of high-energy excitations at the horizon. **ER=EPR** (Maldacena & Susskind 2013) connects entangled particles with Einstein-Rosen bridges: the BH-radiation entanglement is mediated by wormhole geometry. The **island formula** (Penington 2020; Almheiri et al. 2020) derives the Page curve via replica-trick calculations identifying "islands" (regions inside the BH contributing to radiation's entanglement).

(3+3) avoids the firewall paradox by modifying the equivalence-principle assumption at the boundary layer (§7.6), eliminating the need for a firewall. **(3+3) does not invoke ER bridges** — the substrate-level connection between Hawking radiation and infalling matter is via the receding-boundary mechanism, not via wormhole geometry. **(3+3) derives the Page curve structurally** via substrate dynamics (§11.7), consistent with the island formula's holographic derivation but using a different mechanism. None of these proposals are in direct phenomenological conflict with (3+3) at current precision; the differences are methodological and at next-generation precision.

13.12 Comparative matrix

A compact comparative matrix synthesises the comparisons across the major axes of §13.2:

Approach	Singularity	Horizon	Information storage	Echoes
Standard GR	Yes (at $r = 0$)	Coordinate-singular	Lost (paradox)	No
Membrane paradigm	Yes (in pure GR underlying)	Stretched membrane	Inherited from GR + thermodynamics	No
Holography / AdS/CFT	Replaced by CFT thermal state (in AdS)	CFT temperature	In CFT correlations	No (in standard form)
BH complementarity	Frame-relative	Frame-relative	Observer-relative	No
Soft hair	Implicit (not explicitly resolved)	Standard horizon + soft modes	Continuous soft modes	No (typical)
Fuzzballs	No (no interior)	No horizon	String microstates	**Yes (predicted at observable timescales)**
LQG bounce	Replaced by bounce	Standard horizon (until bounce)	In rebounded matter	No (typical)
Gravastars	Replaced by de Sitter interior	Stretched horizon or absent	In interior matter	Variable
Regular BHs (Bardeen, Hayward, ...)	Regularised at small r	Standard horizon	No clear specification	No
(3+3)	Replaced by ready-state core	**Substrate dormancy boundary**	**Per-cell winding *w***	**No (boundary layer too thin)**

Several patterns stand out from the matrix:

- **Singularity resolution** is now broadly consensus among non-standard proposals: (3+3), LQG, fuzzballs, gravastars, and regular-BH proposals all dispense with the GR singularity, by various mechanisms.
- **Horizon character** varies more: some proposals retain the horizon (membrane paradigm, gravastars, soft hair, generic regular BHs, (3+3)); fuzzballs eliminate it; LQG retains it transiently. (3+3) gives the horizon definite substrate content (boundary layer with cells at $N \approx N\_crit$), distinguishing it from all of these.
- **Information storage mechanisms** are remarkably diverse: continuous soft modes, string microstates, CFT correlations, observer-relative frames, discrete topological winding. (3+3)'s use

of integer-valued per-cell winding is distinctive — it is finite-information, topologically protected, and operationally accessible through Hawking emission.

- **Echoes are the sharpest phenomenological discriminator** at current detector sensitivity. Fuzzballs predict observable echoes; (3+3) predicts no observable echoes; most other proposals predict no observable echoes as well. **Detection of echoes at typical proposed timescales would tend to falsify (3+3) and most other approaches in favour of fuzzball-class proposals**; absence is consistent with (3+3) and most others.

13.13 Where (3+3) sits: synthesis

A final synthesis. **The (3+3) framework occupies a distinctive position in the BH-theory landscape**, with the following features:

- **Singularity resolution via discrete-substrate minimum scale**: consistent with the broad anti-singularity consensus of the modern literature, but with a specific mechanism (Planck-area cells with minimum $R_3 = L_P$) drawn from the framework's primitives. Different from LQG (no bounce), different from fuzzballs (horizon retained), different from gravastars (no de Sitter interior), different from generic regular-BH effective metrics (mechanism specified).
- **Horizon retained as substrate dormancy boundary**: a definite physical object (boundary-layer cells at $N \approx N_{crit}$), not a mathematical coincidence. Closer to the membrane paradigm and to soft-hair pictures than to fuzzballs (which dispense with the horizon).
- **Information stored as per-cell topological winding**: discrete-integer-valued, topologically protected, recovered through receding-boundary mechanism during Hawking evaporation. Different from soft hair (continuous modes), different from holographic CFT (boundary correlations), different from string microstates (large ensemble).
- **Holographic principle recovered structurally**: the area-bound on information content ($S_{BH} \propto A$) emerges from substrate primitives, consistent with the holographic principle without invoking AdS/CFT duality.
- **Page curve emergent from substrate dynamics**: structural form at Level 1 from the receding-boundary mechanism; consistent with island-formula derivations but with a different mechanism. Unitarity preserved.
- **No echoes predicted at observable timescales**: a sharp negative prediction that distinguishes (3+3) from fuzzball-class proposals at current detector sensitivity.
- **Falsifiability at next-generation precision**: discrete KK ringdown modes, late-stage primordial-BH evaporation signatures, boundary-layer modulation during accretion. All Level 2 or Level 3 predictions; not currently observable, but in principle distinguishable from competing proposals at ET/CE/CTA-class precision.

The framework's overall position is conservative-foundational rather than radical. It accepts the GR exterior solution exactly (via the Einstein-Aether reduction); it accepts the broad consensus that singularities are pathological and information must be preserved; it recovers the holographic-principle area-bound. **It supplies a specific substrate-level mechanism for these features** — discrete cells with minimum scale, per-cell topological winding, photon-only inter-cell relay, foam-elastic gravitational response — drawn from the broader (3+3) framework that addresses the entire Standard Model and cosmology with zero free parameters ([1]).

Where (3+3) is **distinctive** from competing proposals is in the specificity of its mechanisms (discrete cells, per-cell winding, photon-only relay) and the structural derivation of features (Page curve, holographic bound, substrate-level merger picture) from primitives shared with the framework's broader content. Where it is **conservative** is in the agreement with current GR-confirmed BH predictions, the absence of observable deviations at current detector precision, and the explicit inheritance of merger waveforms from the (3+3) → GR reduction. **(3+3) is not a radical alternative to GR for BH physics; it is a specific substrate-level theory that reduces to GR at observable scales while providing operational mechanisms for the features that pure GR leaves unexplained.**

Summary of §13.

BH-theory has accumulated rich proposals: standard GR, membrane paradigm, holography/AdS/CFT, BH complementarity, soft hair, fuzzballs, LQG bounce, gravastars, regular-BH proposals, ER=EPR, AMPS firewall, island formula. Each addresses a subset of the puzzles with distinctive mechanisms.

(3+3) is structurally consistent with the holographic principle (area-bound recovered from substrate); does not require BH complementarity; close to membrane paradigm but with substrate-level specificity; spirit-similar to fuzzballs but mechanistically and phenomenologically different (no observable echoes); shares the discrete-geometry approach with LQG but with different dynamics (ready-state core vs bounce); more specific than gravastars and generic regular-BH proposals; avoids AMPS firewall by modifying equivalence-principle assumption at boundary; derives Page curve via substrate dynamics (consistent with island formula).

Key distinguishing prediction: **no echoes at observable timescales** (boundary layer too thin). Detection of echoes would falsify (3+3) in favour of fuzzballs; absence is consistent with (3+3) and most other proposals.

Other distinguishing predictions at next-generation precision: discrete KK ringdown modes (vs continuous-mode QNMs), discrete topological signatures in late-stage Hawking radiation (vs continuous-mode soft-hair patterns or CFT correlations).

(3+3) occupies a "conservative-foundational" position: agrees with current GR-confirmed BH predictions exactly; supplies a specific substrate-level mechanism for the features that pure GR leaves unexplained; falsifiability requires next-generation detector precision.

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§14 Predictions, tests, and open items

This section consolidates the distinguishing predictions made throughout the paper, organised by Level (geometric / anchored prefactor / structural speculation per §1.6), with explicit observational targets and timescales. The two purposes are (i) to facilitate falsification — a clear catalogue of what observations would refute the (3+3) treatment of BH physics — and (ii) to guide next-generation observational programs that could in principle distinguish (3+3) from competing proposals.

14.1 Why a predictions section

A specific theory of BH physics should be testable against observation. For (3+3), the framework reproduces standard GR at currently-observed precision via the (3+3) → GR reduction ([1] §21.7, [2] §3) — **exactly as a more fundamental theory should** — so agreement with current data is inherited from the GR limit rather than independently predicted. Distinguishing predictions appear at next-generation precision, where substrate-level corrections become accessible: detectors planned for the 2030s and beyond, plus specific phenomena (primordial BHs at the evaporation scale; Earth-based facilities probing Hawking radiation directly). **This section collects the framework's distinguishing predictions** as a single resource so that experimentalists and observational astronomers can identify (3+3)-relevant observations.

The format is consistent: each predicted phenomenon has a Level tag (L1/L2/L3), a brief mechanism statement, an observational target (detector class + sensitivity required), and a timescale (when the observation might become accessible). Falsification scenarios — observations that would refute (3+3) — are catalogued in §14.6. The framework's open theoretical questions are listed in §14.7, and future research directions in §14.8.

14.2 Level 1 predictions (geometric)

Level 1 predictions are derived from framework primitives with no extra assumptions. They are structural claims about the (3+3) treatment of BH physics, falsifiable in principle by observations probing the substrate level. None of the Level 1 predictions are observationally distinguishable from standard GR at current detector precision, but each is structurally distinct and could become observationally accessible at next-generation facilities.

- **The substrate/excitation distinction itself** (§3): two levels of (3+3) ontology, with the substrate distinct from matter excitations. Falsifiable in principle by any observation that demonstrates BH physics requires only continuous-metric content with no underlying discrete substrate. Observationally inaccessible at current sensitivity.
- **Photon-only inter-cell relay's consequences for the dormant interior** (§4.5): cells inside the dormancy boundary have no photon-relay infrastructure. Falsifiable by detection of any signal originating from inside a BH (other than Hawking radiation from the boundary layer). Not

currently distinguishable from the standard GR "no signals from inside" claim, but operationally specific.

- **The c-budget bound on infaller kinetic energy** (§5.4): no infinite-γ regime exists at the substrate level. Falsifiable in principle by observations of physical processes at the infaller frame near the horizon — inaccessible in practice.
- **Per-cell winding-number conservation through matter conversion** (§5.2): topological $\pi_2(S^2) = \mathbb{Z}$ invariance is preserved through the conversion process. Falsifiable in principle by detection of BH-mediated information loss inconsistent with substrate-level information conservation.
- **The horizon as θ_local = 0 substrate boundary** (§4.1): the horizon has definite substrate-level structure (boundary layer with cells at $N \approx N_{crit}$), not a coordinate coincidence. Falsifiable by observations demonstrating the horizon is structurally featureless at substrate scales.
- **Ready-state core replaces the singularity** (§10, structural form): no singularity at $r = 0$; finite-extent topological condensate at the centre. Falsifiable by detection of curvature-divergence consequences inconsistent with the substrate-level minimum scale.
- **Information conservation through topological residue pathway** (§11.5): matter information preserved on substrate as per-cell *w*; recovered through Hawking evaporation. Falsifiable by demonstration of irreversible information loss in BH evaporation (the original information-paradox scenario).
- **Holographic area-bound recovered structurally** (§11.5, §13.5.1): $S_{BH} \propto A / (4L_P^2)$ emerges from substrate primitives. Falsifiable by demonstration that the Bekenstein-Hawking entropy formula breaks down in regimes where the substrate-level prediction would still hold.
- **Page curve emergent from substrate dynamics** (§11.7): structural form (rising to maximum at Page time, falling to zero) emerges from receding-boundary mechanism. Falsifiable by demonstration that BH evaporation does not produce a Page-curve information-recovery pattern.

These Level 1 predictions form the structural backbone of the (3+3) treatment. They are not observationally distinguishable from standard GR (which makes the same predictions about exterior phenomena via the GR reduction) at current sensitivity; their distinguishing content is interpretive and at the substrate level. **None constitute current-sensitivity falsifiable predictions specific to (3+3)** — that is a feature of the (3+3) → GR inheritance pattern noted throughout the paper.

14.3 Level 2 predictions (anchored prefactor)

Level 2 predictions are quantitative claims that depend on prefactors not fully derived in this paper but reasonable from order-of-magnitude estimation. They typically have well-defined structural form (Level 1) with quantitative specification at Level 2. The Level 2 predictions are where (3+3) makes its most observationally-relevant claims that could in principle be tested at next-generation detector precision.

- **Boundary-layer Hawking-spectrum modulation during accretion** (§5.7): BHs accreting matter should show small Hawking-spectrum modulations distinct from passive BHs. Order of magnitude: $\Delta E\_Hawking \sim m\_infaller \times c^2 \times \eta \times (\Delta A / 4\pi\, r\_S^2)$ with $\eta \sim 10^{-3}$ to 10^{-1}. **Observational target**: primordial BHs at the evaporation scale (CTA, IceCube-Gen2, KM3NeT). **Timescale**: 2030s+, conditional on PBH detection.
- **Energy budget for BH-BH mergers at substrate level** (§12.5): ~5–10% of total system mass radiated as GW, consistent with foam-elastic binding-energy bound at *r_S*. **Observational target**: precision GW measurements of merger waveforms at next-generation precision (ET, CE). **Timescale**: 2030s+. *(Note: this is reproduction of GR's prediction via the GR reduction, not an independent (3+3) prediction.)*
- **Ready-state core extent** (§10.4): *r_core* ~ *L_P* × (*M*/*m_Planck*)^(1/3). For a stellar-mass BH, *r_core* ~ 10^{-22} m. **Observational target**: no current or planned facility can resolve sub-Planckian features near a BH centre; this prediction is essentially untestable directly. **Timescale**: not currently observable.
- **Discrete KK ringdown modes** (§12.7.1): foam-elastic oscillations of the merged substrate at substrate cell scale, producing additional spectral lines beyond standard QNMs. Frequency separation from standard QNMs is ~ $(r\_S/R_3)^2$ × (standard QNM frequency). **Observational target**: merger ringdown spectroscopy with ET/CE precision. **Timescale**: 2030s+.
- **Hawking-spectrum corrections at order $(L\_P/r\_S)^2$** (§11.3): substrate-level corrections to the standard *T_BH*. For stellar-mass BHs, ratio is ~ 10^{-76} — utterly negligible. For Planck-mass BHs, becomes order-one. **Observational target**: not directly observable for any astrophysical BH; conceptually relevant for theoretical comparisons with other quantum-gravity proposals.

The Level 2 predictions are where (3+3) makes its most concrete claims that could be tested observationally. **All require next-generation precision** (ET/CE for mergers; CTA/IceCube-Gen2/KM3NeT for primordial BHs); none are testable at current sensitivity. The framework's falsifiability in the BH sector is therefore deferred to the 2030s and beyond, when next-generation detectors come online.

14.4 Level 3 predictions (structural speculation)

Level 3 predictions are conditional arguments where the framework permits the claim but does not force it. They are typically tied to specific conditions that may or may not hold; observational tests would also test whether the conditions are realised.

- **Information-content waveform modulation in BH-BH mergers** (§12.7.3): higher-order moments of the merger waveform may show modulations correlated with the merging BHs' detailed substrate states. Conditional on detailed substrate dynamics during merger and statistical accumulation across many merger events. **Observational target**: thousands of merger detections at ET/CE precision, with statistical analysis. **Timescale**: 2030s+, conditional.
- **Possible (but unobservable) horizon-scale echoes** (§12.7.2): some BH alternatives (fuzzballs) predict observable echoes; (3+3) does **NOT** predict observable echoes (boundary layer too thin).

This is more a sharp negative prediction than a positive one — but the substrate-cell-scale echo timing (~10^{-41} s) is in principle a Level 3 prediction if detector capabilities ever reach that precision. Currently not feasible.

- **Statistical signatures across many merger events** (§12.7.3, §12.8): aggregate analysis of merger remnant properties as a function of pre-merger BH formation histories may reveal substrate-level correlations. Conditional on detailed dynamics and statistical sample size. **Observational target**: merger ensemble analysis at ET/CE.
- **Boundary-layer cell substructure phenomena** (§4.3): the cell fluctuation pattern in the boundary layer may produce additional observable signatures beyond steady-state Hawking emission. Conditional on substrate-dynamics calculations not done in this paper. **Observational target**: detailed Hawking spectrum measurements.

14.5 Observational targets organised by detector class

For experimentalists and observational astronomers, the following table organises (3+3)-distinguishing observations by detector class, with estimated sensitivity requirements and timescales:

Detector class	Phenomenon	Level	Timescale
LIGO/Virgo/KAGRA (current)	No (3+3)-distinguishing observations expected; agreement with current data inherited from GR limit	—	Current
Einstein Telescope (ET)	Discrete KK ringdown modes; information-content waveform modulation	L2/L3	2035+
Cosmic Explorer (CE)	Discrete KK ringdown modes; statistical merger ensemble analysis	L2/L3	2035+
LISA	Supermassive BH mergers; ringdown spectroscopy at lower frequencies	L2	2035+
CTA (Cherenkov Telescope Array)	Late-stage primordial BH evaporation; Hawking modulation during accretion	L2	2030s+

Detector class	Phenomenon	Level	Timescale
IceCube-Gen2, KM3NeT	Neutrino correlations from PBH evaporation; substrate-cell signatures	L2	2030s+
EHT follow-on	Horizon-scale imaging at improved resolution; boundary-layer signatures	L2	Beyond 2035
Direct gamma-ray observatories	Late-stage PBH gamma-ray emission spectrum	L2	2030s+

The framework's falsifiability landscape is therefore: not testable at current detector precision; testable at next-generation precision (2030s+) for several phenomena; conditional on primordial-BH detection for some of the strongest tests; reliant on detailed substrate-dynamics theoretical work to convert structural predictions into precise quantitative statements that can be compared with observations.

14.6 Falsification scenarios

A scientific theory must be falsifiable. The following observations would refute the (3+3) treatment of BH physics:

- **Detection of horizon-scale gravitational-wave echoes** at typical fuzzball-class timescales (10^{-3} to 10^{-1} s after the main ringdown) for stellar-mass BH mergers. (3+3)'s thin boundary layer ($\Delta r \sim 10^{-33}$ m) does not support echoes at these timescales; observation would falsify (3+3) in favour of fuzzball-class proposals.
- **Detection of post-merger "white hole" phenomena** consistent with LQG bounce predictions. (3+3) predicts a static ready-state core, not a rebound; observation of LQG-bounce-type emergent matter would falsify (3+3).
- **Detection of BH-mediated information loss** demonstrating irreversible information destruction in Hawking evaporation. (3+3) predicts topological-residue preservation and Page-curve information recovery; observation of pure thermal Hawking radiation with no information-recovery signatures would falsify the substrate-level information-preservation claim.
- **Detection of GW polarisations beyond plus and cross**. (3+3) reduces to GR via Einstein-Aether at observable scales, with only the standard two polarisations; detection of extra modes would falsify the GR reduction and hence (3+3).
- **Frequency-dependent v_GW deviations**. (3+3) predicts $v_{GW} = c$ exactly via the foam-elastic mechanism; detection of $v_{GW} \neq c$ at any frequency would falsify the framework.

- **Discovery that BHs do not respect the Bekenstein-Hawking area-entropy relation**. (3+3) recovers $S_{BH} = A/(4L_P^2)$ structurally; demonstration that this relation breaks down in some regime would falsify the substrate-level information-storage mechanism.
- **Direct observation of sub-Planckian length scales in BH dynamics**. (3+3) has minimum length scale L_P; observation of physically meaningful sub-Planck phenomena would falsify the framework's discrete-substrate hypothesis.

These are real falsification scenarios — not hypothetical worries but observations that would, if made, refute the framework. **Most are at the edge of current observational capabilities or beyond**, consistent with the framework's position as conservative-foundational rather than making bold falsifiable predictions at current sensitivity. The falsifiability is real but deferred.

14.7 Open theoretical questions

Several theoretical questions remain open within the (3+3) framework's treatment of BH physics. They represent topics for further substrate-dynamics research, fuller integration with the broader (3+3) programme ([1] and [2]–[8]), and theoretical comparison with competing approaches.

- **Detailed substrate dynamics during merger events.** The boundary-layer fusion process, ready-state core merger, and precise foam-elastic strain release require fuller substrate-dynamics calculations beyond the structural-level treatment of §12.
- **Quantitative predictions for the discrete KK mode spectrum.** The structural argument for discrete modes (§12.7.1) requires detailed analysis of foam-elastic oscillation modes at the substrate cell scale.
- **Higher-order corrections to inspiral and ringdown waveforms.** The (3+3) → GR reduction is exact at leading order; small corrections at order $(L_P/r_S)^2$ should exist; their precise form requires further work.
- **Relationship between (3+3) and AdS/CFT** (§13.5.2). Whether the two approaches are complementary descriptions at different levels, or whether one can be derived from the other, is open.
- **Detailed information-extraction mechanism during late-stage evaporation.** Section 10.5 supplies the structural pathway, but the precise time-dependence of information emergence in Hawking radiation requires fuller substrate-dynamics calculations.
- **Quantitative predictions for the ready-state core extent.** Section 9.4 supplies the structural scaling $r_{core} \sim L_P \times (M/m_{Planck})^{(1/3)}$; the precise prefactor and core internal structure require detailed calculation.
- **Extension to rotating (Kerr) black holes.** The paper has focused on Schwarzschild BHs; extension to Kerr (rotating) BHs and the ergosphere is an open task. Kerr-extension is structurally straightforward via the GR reduction but requires substrate-level treatment of frame-dragging.

- **Charge dynamics at the boundary layer.** Charged BHs (Reissner-Nordström) have additional structure at the horizon; the substrate-level treatment of electromagnetic field interactions with the boundary layer is not developed in this paper.
- **Interaction between (3+3) and BH thermodynamic ensembles.** The Bekenstein-Hawking entropy is recovered for individual BHs; ensembles of BHs and thermodynamic phase transitions (Hawking-Page transitions, etc.) are not treated.
- **Connection to (3+3)'s cosmological implications.** §15 of this paper develops the substrate-level connection between BH physics and the cosmological-constant sector via shared primitives (R_3, Higgs/Coleman-Weinberg, t_2, cosmic angle ϑ). What remains open is the interplay between BH physics and cosmological structure formation: primordial BHs as dark matter candidates, BH formation in the early universe, the relationship between BH-population statistics and cosmic-angle evolution. The 1.73× residual on Λ_{eff} (§15.3) is also a known open item, attributed to missing matter-coupling terms in the full Friedmann analysis ([2] §14.3).

14.8 Future research directions

Several research directions follow naturally from the topics treated in this paper:

- **Lagrangian-level treatment of BH dynamics.** A formal action-principle derivation of the substrate-level dynamics (collapse, accretion, evaporation, mergers) using the (3+3) Lagrangian formalism of [2] (in preparation) would convert several of the structural Level 1/2 predictions into more quantitative form.
- **Substrate-dynamics simulations of mergers.** Numerical simulation of foam-elastic dynamics during BH-BH mergers, with discrete-substrate cells at the framework's minimum scale, would test the (3+3) → GR reduction numerically and identify substrate-level corrections to merger waveforms.
- **Cross-discipline applications.** The framework's discrete-substrate minimum-length-scale and topological-residue mechanisms have potential applications beyond BH physics — to early-universe cosmology (where the foam was undergoing transitions), to quantum-gravity phenomenology more generally, and to information-theoretic studies of unitarity in extended systems.
- **Extension to Kerr and Reissner-Nordström BHs.** Treating rotating and charged BHs requires substrate-level developments not done in this paper. The structural framework should extend straightforwardly via the (3+3) → GR reduction, but substrate-level mechanisms for frame-dragging and charge-distribution dynamics need explicit treatment.
- **Detailed relationship to BH information-theory developments.** Connections between the (3+3) Page-curve mechanism and the recent island-formula derivations (Penington 2020; Almheiri et al. 2020) deserve careful theoretical work.
- **Observational target development.** As ET, CE, CTA, IceCube-Gen2, and other facilities move from planning to construction in the 2030s, the (3+3) predictions should be developed into

specific data-analysis targets and pipeline searches. The framework offers concrete falsifiability targets that observational programs can prioritise.

Summary of §14.

Level 1 predictions (geometric): substrate/excitation distinction, photon-only relay consequences, c-budget bound, w conservation, horizon as $\theta_{local} = 0$, ready-state core, information conservation pathway, holographic area-bound, Page-curve emergence. None observationally distinguishable at current precision.

Level 2 predictions (anchored prefactor): boundary-layer Hawking modulation during accretion, energy budget for mergers, ready-state core extent, discrete KK ringdown modes, Hawking-spectrum corrections. Most observationally relevant at next-generation precision (2030s+).

Level 3 predictions (conditional): information-content merger waveform modulation, statistical signatures, boundary-layer cell substructure. Conditional on detailed substrate dynamics or statistical analysis at ET/CE precision.

Falsification scenarios: detection of fuzzball-timescale echoes; LQG-bounce-type post-merger phenomena; BH-mediated information loss; extra GW polarisations; $v_{GW} \neq c$; departures from $S_{BH} = A/(4L_P^2)$; sub-Planckian length scales.

Open theoretical questions: detailed merger substrate dynamics, discrete KK mode spectrum, higher-order GR corrections, AdS/CFT relationship, Kerr/Reissner-Nordström extension, cosmological connections.

Future directions: Lagrangian-level treatment, substrate simulations, extensions to rotating/charged BHs, observational target development.

References and appendices follow.

§15 The cosmological-constant connection

This section develops a connection that has been implicit in the paper but not made explicit: the same substrate primitives that govern BH boundary-layer dynamics also govern the cosmological-constant sector of the (3+3) framework. The connection is not metaphorical or analogical — it is algebraic, via shared primitives. The same R_3 that sets activated-cell scale in the BH paper sets the geometric cosmological-constant $\Lambda\_geo = 1/R_3^2$; the same Coleman-Weinberg minimum that fixes N_crit = 6,203 also drives the $\Lambda\_geo + \Lambda\_Higgs = 0$ structural cancellation; the same t_2 dimension that severs at the BH horizon (§6.2 cosmic-fossil framing) is the dimension whose kinetic energy manifests as cosmic-scale dark energy.

The material in this section is drawn primarily from [2] §14 (Lagrangian-level cosmological-constant analysis) and [2] §14bis (cosmological-sector closures). It is included here because the substrate-level unity is one of the (3+3) framework's strongest claims, and a BH paper that does not at least sketch the connection would leave the picture incomplete. The section is **conservative**: we summarise [2]'s results rather than re-derive them, and we end with the framework's honest open items at the cosmological-constant frontier.

15.1 Shared substrate primitives

The (3+3) framework's primitives are a small set of quantities from which consequences across many sectors of physics follow. The BH paper foregrounds a subset of these primitives (cells, KK modes, photon-only relay, c-budget identity, T_2 gradient); the cosmological-constant analysis in [2] §14 foregrounds an overlapping subset. The following table identifies the primitives that are common to both treatments:

Primitive	Role in BH dynamics (this paper)	Role in Λ-sector ([2] §14)
R_3 (compactification radius)	Sets activated-cell scale: $R_3 = \pi\hbar/(m\_e\, c) \approx 1.21 \times 10^{-12}$ m. Governs cell t_3 structure (§2.2).	Sets geometric cosmological-constant value: $\lvert\Lambda\_geo\rvert = 32\pi\, G_4 / R_3^2 \approx 3.4 \times 10^{37}$ m^{-2} ([2] eq. 14.2).
Higgs / Coleman-Weinberg mechanism	Determines $N\_crit = \pi\, m\_H^3/(32\, v^2\, m\_e) = 6{,}203$ (bridge equation, §2.2). Sets activation threshold.	Drives the Higgs VEV cancellation: $\Lambda\_Higgs = -m\_H^2\, v^2/8 = -\Lambda\_geo$ exactly at the radion potential minimum ([2] eq. 14.4–14.5).
t_2 time dimension	Severs at BH horizon (§6.2 cosmic-fossil framing): BH frozen at ϑ_form, disconnected from Hubble flow.	Carries the cosmic-rotation kinetic energy ($v\_t_2^2$ component of c-budget). Dark energy is the kinetic energy of the causal vector through t_2 ([2] §14.4).

Primitive	Role in BH dynamics (this paper)	Role in Λ-sector ([2] §14)
Cosmic angle ϑ(T)	ϑ*_form* characterises a BH at its formation epoch (§6.2). Local ϑ*_BH* = ϑ*_form* (frozen).	Global ϑ(T) advances at rate *H_int*; current value ϑ*_now* = 55.79°. Drives Hubble expansion $H(\vartheta)$ = *H_int* $\sin(2\vartheta)$.
N_crit = 6,203	BH boundary-layer threshold. Cell with *N* < *N_crit* is dormant.	Same threshold determines stability of the radion potential against non-perturbative corrections at *T* ~ Λ_QCD.

The crucial point is that **the framework does not have separate primitives** for BH physics versus cosmology. The same R_3, the same Higgs mechanism, the same t_2 dimension, the same cosmic angle ϑ. Consequences in the BH sector (boundary-layer thickness, dormancy mechanism, three-time-dimension structure, cosmic-fossil framing) and consequences in the Λ sector (geometric Λ_geo, structural cancellation, residual dark energy) are derived from this single set of primitives. **The unity is structural, not coincidental.**

15.2 The structural cancellation Λ_geo + Λ_Higgs = 0

The cosmological-constant problem in conventional physics is the discrepancy between the QFT-predicted vacuum energy density (~ $m\_Planck^4 \approx 10^{76}$ GeV^4) and the observed cosmological constant (~ 10^{-121} GeV^4). The 10^{198} ratio is the largest mismatch between theory and observation in all of science, and is often called "the worst fine-tuning problem in physics."

The (3+3) framework dissolves this problem at the structural level. The reasoning is given in [2] §14.1 and [1] §26.1; we sketch it here.

In the framework, the cosmological constant is **not** the vacuum energy of any matter field. It is a geometric quantity, with three contributions:

- **The geometric contribution *Λ_geo***: from the S^2 curvature (after Kaluza-Klein reduction of the 6D Einstein-Hilbert action), [2] eq. 14.1 gives $\Lambda\_geo = -32\pi\, G_4 / R_3^2$. Numerically: $|\Lambda\_geo| \approx 3.4 \times 10^{37}$ m^{-2}, far larger than any observed quantity.
- **The Higgs VEV contribution *Λ_Higgs***: from the radion potential's value at its minimum, [2] eq. 14.4 gives $\Lambda\_Higgs = -m\_H^2\, v^2 / 8$. Numerically: ~ -10^{37} m^{-2} (same order as *Λ_geo*, opposite sign).
- **The residual kinematic contribution *Λ_eff***: from the kinetic energy of the causal vector through t_2, [2] eq. 14.11 gives $\Lambda\_eff = 3\, H\_int^2 \sin^2(2\vartheta\_now) / c^2 \approx 6.3 \times 10^{-53}$ m^{-2}. This is the only one of the three that is comparable to the observed *Λ_obs*.

The structural cancellation is *Λ_geo* + *Λ_Higgs* = 0 (exactly). This is not a fine-tuning: the cancellation follows from the same Coleman-Weinberg minimum that fixes $\phi\_min = \ln(\pi\, M\_P / m\_e)$ and hence *m_H* = 125 GeV ([2] §9). The two contributions are evaluated at the same minimum of the radion potential, and the cancellation is a structural consequence of the radion's role in both: the same potential that produces the Higgs mass produces the Λ_Higgs contribution, and at its minimum the geometric Λ_geo contribution is exactly cancelled.

The 10^{198} cosmological-constant problem dissolves because the question was wrong: Λ is not vacuum energy in (3+3); it is geometric curvature plus a kinematic residual. The vacuum-energy-from-QFT value (~ m_Planck^4) is not what the framework's Λ is supposed to equal; the comparison was between unrelated quantities. **The cosmological-constant problem is dissolved, not solved**: the premise (Λ = vacuum energy) is false in (3+3) ([2] §14.1, [1] §26.1).

15.3 The residual Λ_eff and the 1.73× factor

After the structural cancellation, what remains is the kinematic residual:

$$\Lambda\_eff = 3\, H\_int^2 \sin^2(2\vartheta\_now) / c^2 \quad \text{([2] eq. 14.11)} \quad \text{(residual cosmological constant)}$$

with H_int = 78.175 km/s/Mpc the framework's intrinsic Hubble amplitude ([1] §22, [7]) and ϑ_now = 55.79° the current cosmic angle. Numerically: $\Lambda\_eff \approx 6.3 \times 10^{-53}$ m^{-2}. The observed value from Planck CMB measurements is $\Lambda\_obs \approx 3.6 \times 10^{-53}$ m^{-2}. **The framework's prediction is within a factor of 1.73 of the observed value** — to be compared with the 10^{198} standard-model discrepancy.

The 1.73× residual is an honest open item. The framework does not yet have a fully derived cosmological constant in the precise sense — what it has is a structural mechanism that brings the value from 10^{76} orders of magnitude wrong (standard QFT) to within a factor of 2 of observation. The remaining residual is attributed in [2] §14.3 to missing matter-coupling terms in the full Friedmann equation: the formula $\Lambda\_eff = 3\, H\_int^2 \sin^2(2\vartheta) / c^2$ captures the geometric/kinematic piece (the t_2 curvature contribution) but omits the matter-radiation coupling factors. A derivation of the full coupling is ongoing work in [1] Part VI Ch. 26 ([2] §14.3).

Cross-check: the dark-energy equation of state at the current epoch is $w\_eff(\vartheta\_now) = -1.002$ ([2] eq. 14.13), consistent with all current observational bounds on dark-energy w. The framework predicts $w(z)$ crossing −1 at $z = 0.223$ (from the geometric identity $\cot(2\vartheta) = 0$ at $\vartheta = 45°$), which is a falsifiable prediction independent of any prefactor uncertainty in Λ_eff. The 1.73× residual is localised to the Λ_eff closure and does not contaminate the late-universe expansion-history predictions ([2] §14.3, §14bis.9).

15.4 Connection to BH boundary-layer dynamics

The unity of substrate primitives produces a specific connection between BH physics and the cosmological-constant evolution. **A BH frozen at ϑ_form preserves a snapshot of Λ_eff at the formation epoch.** The global cosmic angle ϑ(T) advances; $\Lambda\_eff(\vartheta)$ evolves correspondingly; but inside the BH, $\vartheta\_BH = \vartheta\_form$ (severed from cosmic ϑ-advance per §6.2 cosmic-fossil framing), and the local effective Λ inside the BH remains at $\Lambda\_eff(\vartheta\_form)$.

This is operationally subtle. The BH interior is dormant foam (§4, §8); no observers exist as activated-foam excitations; the local effective Λ is not directly observable from inside (no observers to measure it). But the principle is clear: **the cosmological-constant evolution is suspended inside a BH, just as the Hubble expansion is suspended (§6.2)**. An ancient BH (formed when *ϑ_form* was small) preserves an early-epoch *Λ_eff* internally; a recently-formed BH preserves something close to the current *Λ_eff*.

- **An early-universe BH formed at *ϑ_form* ≈ 20°** has internal effective cosmological constant $\Lambda\_eff(20°) = 3\, H\_int^2 \sin^2(40°) / c^2 \approx 3\, H\_int^2 \times 0.413 / c^2 \approx 3.0 \times 10^{-53}$ m^{-2} — different from but the same order of magnitude as the current value.
- **A BH formed at *ϑ_form* = 45°** (the geometric crossing point where $w(z) = -1$) has internal $\Lambda\_eff = 3\, H\_int^2 \times \sin^2(90°) / c^2 = 3\, H\_int^2 / c^2 \approx 7.3 \times 10^{-53}$ m^{-2} — the maximum value of *Λ_eff* over cosmic history.
- **A BH formed near the current epoch (*ϑ_form* ≈ *ϑ_now* ≈ 55.79°)** has internal $\Lambda\_eff \approx 6.3 \times 10^{-53}$ m^{-2}, the same as the current cosmic value.

The substrate-level unity is the key takeaway: the same primitives that govern dormancy at the BH horizon also govern dark-energy evolution at cosmological scales. The framework is unified by its primitives, not by separate sector-specific assumptions. This is the strongest single structural feature of (3+3) and is what makes the framework's zero-free-parameter status credible: each sector's observables are consequences of the same shared primitives, not adjustable degrees of freedom.

Summary of §15.

The (3+3) framework's BH physics and cosmological-constant sector share the same substrate primitives: R_3, the Higgs/Coleman-Weinberg mechanism, the t_2 time dimension, the cosmic angle ϑ. Consequences in both sectors are derived from these shared primitives.

The 10^{198} cosmological-constant problem is **dissolved**: Λ is not vacuum energy in (3+3). The geometric *Λ_geo* + Higgs *Λ_Higgs* = 0 cancellation is structural (Coleman-Weinberg minimum), not fine-tuned.

The residual is $\Lambda\_eff = 3\, H\_int^2 \sin^2(2\vartheta) / c^2 \approx 6.3 \times 10^{-53}$ m^{-2}, within a factor of 1.73 of the observed Λ. The 1.73× residual is an honest open item attributed to missing matter-coupling terms.

$w(z)$ crossing at $z = 0.223$ (from $\cot(2\vartheta) = 0$ at $\vartheta = 45°$) is a sharp falsifiable prediction independent of the *Λ_eff* prefactor.

A BH frozen at *ϑ_form* preserves a snapshot of *Λ_eff*(*ϑ_form*) internally — the cosmological-constant evolution is suspended inside BHs, just as Hubble expansion is suspended (§6.2 cosmic-fossil framing).

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§16 Summary and conclusions

This paper has applied the (3+3) framework's substrate-level primitives to black-hole physics. The result is not a new metric or a new solution to the field equations — it is an account at a different level: substrate dynamics from which the metric-level GR results follow as the appropriate limit, and at which the puzzles GR alone cannot resolve become tractable. This section consolidates what the paper achieves.

16.1 What this paper achieves

The paper takes the (3+3) framework's primitives — discrete S^2 foam at the t_3 compact dimension, KK mode structure carrying matter, photon-only inter-cell relay, c-budget identity, T_2 gradient as gravitational source, Higgs/Coleman-Weinberg radion structure — and shows that they yield four substantive results:

- **Operational resolutions** of the classical BH puzzles: the singularity, the information paradox, and the frozen-star / smooth-crossing tension. Each is dissolved at the substrate level, not regularized or papered over. (L1, §10, §11.5, §7.)
- **A three-time-dimension structure** of the BH interior: T frozen at the horizon, t_2 severed (BHs as cosmic fossils frozen at ϑ_form), t_3 continuing per-cell (internal Compton cycling, keeper waves, slot patterns evolving). The structure is genuinely new — it does not appear in any standard treatment because GR has only one time dimension. (L1/L2, §6.)
- **Three carriers of mass inside a BH**, each preserved by a different substrate-level mechanism: baryon mass via $\pi_2(S^2) = \mathbb{Z}$ topological winding (absolutely conserved), rest-mass Compton cycling via t_3 continuation (dynamically conserved), gravitational field via the slot-occupation-density gradient extending continuously outward (geometrically communicated). (L1, §6.4.)
- **Substrate-level unity** with the cosmological-constant sector: the same primitives that govern BH boundary-layer dynamics (R_3, Higgs/Coleman-Weinberg, t_2, cosmic angle ϑ) also dissolve the cosmological-constant fine-tuning problem. The two are not separate sectors — they are consequences of one substrate. (L1, §15.)

The methodology is a substrate-level account, not an alternative metric or a competing solution to the field equations. Where standard GR treats BHs through coordinates and metric continuation, (3+3) treats them through cell states (activated/dormant/ready), c-budget allocation, and topological invariants. The metric-level GR results are recovered through the (3+3) → GR (Einstein-Aether) reduction ([1] §21.7, [2] §3); the substrate-level account adds operational content that GR alone leaves obscure.

16.2 The classical BH puzzles, dissolved

Standard GR produces three persistent puzzles. The framework dissolves each at the substrate level rather than handling them through regularization, complementarity, or formal device.

No singularity. The point $r = 0$ is replaced by a finite region of ready-state foam at the framework's minimum scale: cells at $R_3 = L\_P$ with the photon pool count N below N_crit and the KK $n \geq 1$ modes collapsed to the $n = 0$ condensate ([1] §21.4, §10.2.1). Information from the infallen matter is preserved as topological residue (per-cell winding w) rather than dynamically. **There is no infinity anywhere in the framework's description of a BH.** The discrete substrate has a smallest accessible scale by construction; sub-Planck regions are not physically realised, and the GR singularity at $r = 0$ is a continuum-extrapolation artifact that discreteness eliminates structurally. (L1, §10.)

No information loss. Matter falling in is converted at the boundary layer to topological residue carried by per-cell winding number w on dormant cells. The conversion is via the same $\pi_2(S^2) = \mathbb{Z}$ topology that gives proton stability and baryon-number conservation in [1]; it is not a separate mechanism added to handle BHs but a structural consequence of the framework's existing topology. **Information is preserved unitarily through the BH's entire lifetime.** It emerges, scrambled, in Hawking radiation correlations as the boundary recedes during evaporation. The Page-curve form follows from the substrate dynamics; the holographic area-bound $S\_BH = A / (4L\_P^2)$ follows from cell counting on the horizon. (L1, §11.5–11.7.)

No "frozen star vs. smooth crossing" contradiction. The external T-clock of an infalling object freezes at the horizon (standard gravitational time dilation, real). The infalling worldline crosses in finite proper time driven by t_3 cycling (per [2] §14bis.41 and [31], also real). They are different clocks measuring different things. The apparent contradiction — which has bedevilled BH discussions for decades — is dissolved by the c-budget reallocation at the horizon: as $r \to r\_S$, $v\_T \to 0$ while $v\_t_3 \to c$, with the entire c-budget transferring from T to t_3. **Both observations are correct simultaneously**, because they refer to two distinct components of the same c-budget. (L1, §7, §8.5.1.)

16.3 What is structurally new beyond standard treatments

Beyond resolving the classical puzzles, the paper develops several substrate-level structures that have no analog in standard GR or in the main alternative BH proposals (fuzzballs, gravastars, regular BHs, LQG bounce, complementarity, AdS/CFT, soft-hair). Each follows directly from the framework primitives.

The three-time-dimension structure (§6) is the framework's most distinctive structural contribution to BH physics. Of the three time dimensions T, t_2, t_3, each responds differently to the extreme conditions inside a BH, and the c-budget reallocation among them gives a unified account of what would otherwise appear as four independent phenomena: gravitational time dilation (T frozen), cosmological disconnection (t_2 severed), internal physics preservation (t_3 continues per-cell), and Hawking radiation (the t_3-discontinuity at the horizon driving boundary-layer emission). **One c-budget identity across three time dimensions yields the entire substrate-level BH phenomenology.**

The cosmic-fossil framing (§6.2) is a genuine structural prediction. A BH frozen at ϑ_form preserves a snapshot of early-universe physics inside its horizon: the local effective coupling structure, Compton frequencies, and keeper-wave configurations are governed by the formation-epoch S^2 geometry, not by the present-day cosmic angle. Ancient BHs are time-asymmetric fossils. This is structurally observable in principle, though the precision required to detect it on stellar-mass BHs is far beyond current capabilities. (L2, §6.2.)

The three carriers of mass (§6.4) decompose what "mass inside a BH" means into three independently-tracked quantities. Baryon mass is topological (cannot be unwound at any density). Rest-mass Compton cycling is t_3-dynamical (continues at full rate inside). Gravitational field is geometric (extends continuously outward through external foam tiles, carrying the only externally-accessible signature). **All three are preserved by structurally different mechanisms simultaneously**, and the standard "no-hair theorem" is the statement that only the geometric carrier is externally accessible.

The two-regime Hawking mechanism (§11.2) replaces the standard "virtual particle pair" pedagogy with two distinct substrate-level mechanisms separated by temperature. For $k_B T_{BH} << 2 m_e c^2$ (the cold-BH regime, including all astrophysical BHs), the photon-only relay is the only operative channel: cells in the boundary layer briefly activate; their photon excitations escape via the relay; no electron-positron pair production is energetically allowed. For $k_B T_{BH} \gtrsim 2 m_e c^2$ (the hot-BH regime, relevant for primordial BHs at late-stage evaporation), the fermionic keeper-wave bifurcation $w = 1/2 \to \{+1/2, -1/2\}$ ([2] §14bis.42) operates, producing electron-positron pairs at the horizon. **The standard Hawking temperature $T_{BH} = \hbar c^3 / (8\pi G M k_B)$ follows in both regimes** from boundary-layer cell-counting statistics (boundary thickness $\Delta N \approx \sqrt{N_{crit}} \approx 79$ cells); the framework reproduces Hawking's formula without invoking QFT in curved spacetime and without the conceptual problems of the standard derivation.

16.4 The substrate-level unity

The strongest single claim made in this paper is **the substrate-level unity between BH physics and the cosmological-constant sector**. This is not a metaphorical or analogical connection. It is algebraic, via shared primitives:

- The same $R_3 = \pi\hbar/(m_e c)$ that sets activated-cell scale in the BH boundary layer also sets the geometric cosmological-constant value $|\Lambda_{geo}| = 32\pi G_4 / R_3^2 \approx 3.4 \times 10^{37}$ m^{-2} ([2] eq. 14.2).
- The same Coleman-Weinberg minimum that fixes N_{crit} = 6,203 (the BH dormancy threshold) also drives the structural cancellation $\Lambda_{geo} + \Lambda_{Higgs} = 0$ ([2] §14.1, §9).
- The same t_2 dimension that severs at the BH horizon (cosmic-fossil framing, §6.2) is the dimension whose kinetic energy manifests as cosmic-scale dark energy: $\Lambda_{eff} = 3 H_{int}^2 \sin^2(2\theta) / c^2$ ([2] eq. 14.11).
- The same cosmic angle ϑ that is frozen at ϑ_{form} for an ancient BH is the angle whose advance drives Hubble expansion $H(\vartheta) = H_{int} \sin(2\vartheta)$ ([1] §22, [7]).

The 10^{198} cosmological-constant problem dissolves in the framework — not as an isolated achievement of the cosmology sector, but as a consequence of the same primitives that give BH boundary-layer dynamics. There is no separate cosmology in (3+3); the BH paper and the cosmological treatment of [1] / [2] are talking about the same substrate. Λ is not the vacuum energy of a matter field; it is geometric curvature plus a kinematic residual. The "worst fine-tuning problem in physics" is the wrong question: the comparison was between unrelated quantities. The framework's prediction $\Lambda_{eff} \approx 6.3 \times 10^{-53}$ m^{-2} lies within a factor of 1.73 of the observed value — to be compared with the 10^{198} standard-model discrepancy. (L1 for the structural cancellation; L2 for the numerical prediction.)

The unity is structural, not engineered. The framework was not designed to solve BH problems; it is a foundational programme deriving the Standard Model, gravity, quantum mechanics, and cosmology from a single geometric postulate ([1]). What this paper demonstrates is that when the same primitives are applied to BH physics, the classical puzzles dissolve and the connection to cosmological-scale phenomena emerges automatically. **The framework's unification of BH and cosmological-constant sectors via shared primitives is what makes the zero-free-parameter status credible**: each sector's observables are consequences of the same shared primitives, not adjustable degrees of freedom.

16.5 Position relative to other approaches

Section 13 develops a detailed comparison with the main alternative approaches to BH physics: the membrane paradigm, BH complementarity, fuzzballs, gravastars, regular-BH constructions (Bardeen, Hayward, Frolov), LQG bounce, AdS/CFT holography, and soft-hair / asymptotic-symmetry proposals. Each addresses one or two aspects of BH physics in detail; none addresses all of them from one set of primitives.

(3+3) addresses every component of the BH problem from one framework: horizon character (substrate-level locus $\theta_{local} = 0$), interior structure (dormant foam with topological residue, three-time-dimension dynamics), singularity replacement (ready-state foam at minimum $R_3 = L_P$), Hawking mechanism (boundary-layer cell statistics in two regimes), information preservation (per-cell w via $\pi_2(S^2) = \mathbb{Z}$), and connection to cosmological-scale physics (shared primitives across BH and Λ sectors). **It does so with zero free parameters** — every quantity that appears (N_{crit} = 6,203, R_3, L_P, the cell count 2^{152}, the boundary-layer thickness $\Delta N \approx 79$) is derived from the framework's single geometric postulate, not fitted to data.

The framework does not claim other approaches are wrong. The (3+3) → GR reduction recovers all of standard general relativity at observable scales; complementarity, fuzzball, gravastar, and regular-BH proposals each capture aspects of BH physics that (3+3) also predicts (in some cases via substrate-level mechanisms with different vocabulary). What (3+3) adds is **the structural backbone**: a single substrate-level description from which all the partial pictures emerge as different limits or different aspects of the same underlying foam dynamics.

16.6 Honest limits and open items

The framework's achievements are accompanied by honest limits, recorded here so that the reader can calibrate confidence appropriately.

- **Agreement with current LIGO/Virgo/KAGRA data is inherited via the (3+3) → GR reduction, not predicted independently.** This is the right kind of agreement — a more fundamental theory should reduce to its predecessor in the appropriate limit, with substrate-level deviations visible only at higher precision than current detectors achieve. Distinguishing observations require next-generation precision (Einstein Telescope, Cosmic Explorer, CTA, IceCube-Gen2) for phenomena like discrete KK ringdown modes, late-stage primordial-BH evaporation signatures, the $w(z)$ crossing at $z = 0.223$, and Hawking-spectrum modulation during accretion. (§14, §15.3.)

- **The 1.73× residual on *Λ_eff* is real and unresolved.** The framework predicts $\Lambda_{eff} \approx 6.3 \times 10^{-53}$ m^{-2} where Planck observes $\approx 3.6 \times 10^{-53}$ m^{-2}. This is an honest open item attributed to missing matter-coupling terms in the full Friedmann analysis ([2] §14.3). It does not contaminate the $w(z)$ prediction, which is a geometric identity independent of any prefactor uncertainty. (§15.3.)
- **The Kerr metric and rotating BHs are not developed in this paper.** [1]'s treatment of frame-dragging via T_2 rotation drag (a single paragraph in §21.6) supplies the substrate-level mechanism but stops short of a Kerr metric derivation; [2] does not extend it. Rotating-BH dynamics (ergosphere, frame-dragging in mergers, spin-precession) are left to future work. (§14.7, §14.8.)
- **Several substrate-level details are at Level 2.** The discrete KK ringdown spectrum, the precise prefactor in the ready-state core extent $r_{core} \sim L_P \times (M/m_{Planck})^{(1/3)}$, the exact Hawking-spectrum corrections at order $(L_P/r_S)^2$, and the boundary-layer modulation of Hawking emission during accretion are anchored to framework primitives but require fuller substrate-dynamics calculations to convert into precise quantitative predictions. The structural form is L1; the precise prefactors are L2. (§14.3.)
- **Charge dynamics (Reissner-Nordström BHs) are not developed.** The substrate-level treatment of electromagnetic field interactions with the boundary layer, and the structure of the charged horizon, are open topics. (§14.7.)

These limits are real but they do not undermine the achievements of §§16.1–16.5. They are the typical limits of a working substrate-level theory at this stage of development: the framework supplies the structural backbone and operational interpretations; quantitative precision at next-generation detector scales requires additional work within the framework, not a different framework.

Closing.

This paper has applied the (3+3) framework's substrate-level primitives to black-hole physics and demonstrated that the classical puzzles (singularity, information, frozen-star/smooth-crossing) dissolve operationally, the BH interior has a structurally rich three-time-dimension picture, three carriers of mass are independently preserved inside, and the substrate-level unity with the cosmological-constant sector emerges from shared primitives.

The result is not a new metric or a new solution to the field equations. It is a substrate-level account from which metric-level GR results follow as the appropriate limit, and at which the puzzles GR alone cannot resolve become tractable.

The framework's zero-free-parameter status, structural cancellations, and unification of BH and cosmological-scale physics via shared primitives are what make it credible as a foundational programme. The distinguishing observations sit at next-generation detector precision; the framework is falsifiable in principle by these targets, and the agreement with current data is inherited through the (3+3) → GR reduction rather than predicted independently — exactly as it should be for a more fundamental theory containing GR as a limit.

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Appendix A: Glossary of (3+3) substrate-level terminology

A reference glossary of substrate-level terminology used throughout the paper. Cross-references give the section where each term is introduced or developed.

- **Activated cell**: a cell with photon pool count $N > N_{crit} = 6{,}203$, in which KK $n \geq 1$ modes are excited and standard physics operates. The state of essentially all cells in the universe outside gravitational dormancy regions. (§2.2)
- **Boundary layer (evanescent)**: the substrate region of thickness $\Delta N = \sqrt{N_{crit}} \approx 79$ cells around the horizon, where cell occupations fluctuate around N_{crit}. Source of Hawking radiation; locus of matter conversion during accretion. (§4.3, §11.2)
- **c-budget identity**: $v_T^2 + v_{t_2}^2 + v_{t_3}^2 + v_x^2 + v_y^2 + v_z^2 = c^2$. The framework primitive constraint that every particle's total speed through 6D spacetime equals c. (§2.1)
- **Cell**: a single Planck-area patch of the t_3 S^2 compactified surface, located at a definite point in 3D space. Substrate primitive. (§2.2)
- **Dormant cell**: a cell with $N < N_{crit}$. Topologically present but dynamically inactive; no photon-relay infrastructure; the state of cells inside a BH horizon. (§2.2)
- **Dormancy boundary**: the dynamical version of the horizon — where dormantization is occurring at any given moment during non-static processes (collapse, accretion, evaporation, mergers). (§4.4)
- **Foam**: the substrate as a whole — the totality of t_3 S^2 cells tiling continuous 3D space. The medium on which matter excitations propagate. (§2.4)
- **Foam-elastic deformation modes**: the framework's name for gravitational waves — propagating deformations of the foam itself (spin-2 mode), with $v_{GW} = c$. (§2.6.2)
- **Ghost geometry**: a metric structure that is well-defined in the formal sense but does not correspond to observer-dynamical content. The Kruskal-extension interior of a BH is a ghost geometry. (§8.7)
- **Horizon (substrate-level)**: the locus $\vartheta_{local} = 0$ where $v_T = 0$; equivalently the boundary where cells transition between activated and dormant. Coincides numerically with the Schwarzschild horizon. (§4.1)
- **Inter-cell relay (photon-only)**: the propagation mechanism by which KK modes traverse multiple cells via the equatorial-ring photon orbit (the only orbit lying in the local 2D tangent plane to the S^2 surface). (§2.4)
- **Local light-speed angle (ϑ_{local})**: $\arctan(v_T/c)$ at radius r; goes to $\pi/2$ at infinity, 0 at the horizon, would-be imaginary inside. Useful angular variable for substrate-level dynamics. (§2.5)
- **KK mode index (n)**: the angular-momentum (spherical-harmonic l) label specifying the cross-cell amplitude pattern of a field. **Reserved usage**: in this paper, n is always the KK mode index (distinct from w). (§2.3)

- **Per-cell winding number (*w*)**: integer-valued $\pi_2(S^2) = \mathbb{Z}$ topological label on each individual cell. Conserved under continuous transformations. The substrate-level carrier of information about matter content. (§2.3, §5.2)
- **Photon pool count (*N*)**: integer occupation of a cell's equatorial ring by photon excitations. Determines cell state (activated if $N > N_{crit}$; dormant if $N < N_{crit}$). (§2.2)
- **Ready-state cell / ready-state core**: a cell at minimum compactification radius $R_3 = L_P$ (the framework's smallest scale); collectively, the ready-state core is the coherent topological condensate at the BH centre, replacing the GR singularity. (§2.2, §10)
- **Substrate**: the foam at any given state — the underlying medium on which matter excitations propagate. Distinct from matter excitations (the substrate/excitation distinction). (§3)
- **T_2 gradient**: the spatial variation of the second-time component, set by mass distribution. Determines cell-state distribution and the foam-elastic gravitational response. (§2.6.1)

Appendix B: Notation conventions

A consolidated reference for notation used throughout the paper. **The most important notation reservation** is between *n* (KK mode index) and *w* (per-cell winding number); these are distinct quantities sometimes both written *n* in [1] and explicitly separated in this paper (§1.4.3, §2.3, §5.2).

B.1 Spacetime coordinates

- T: first time dimension (coordinate time of standard relativity).
- t_2: second time dimension (mass / rest-energy direction).
- t_3: third time dimension (compactified as S^2; supports KK modes).
- x, y, z: spatial coordinates.
- r: radial coordinate from BH centre.
- $r_S = 2GM/c^2$: Schwarzschild radius.
- $R_3 = \pi\hbar/(m_e c) \approx 1.21 \times 10^{-12}$ m: compactification radius for activated cells; collapses to L_P in ready-state cells.
- $L_P = \sqrt{(\hbar G/c^3)} \approx 1.6 \times 10^{-35}$ m: Planck length; framework's minimum scale.

B.2 Velocity components

- v_T: rate of motion through coordinate time T (proper-time accumulation).
- v_{t_2}, v_{t_3}: rates of motion through the second and third time dimensions.
- v_x, v_y, v_z: spatial-motion components.
- c-budget identity: $v_T^2 + v_{t_2}^2 + v_{t_3}^2 + v_x^2 + v_y^2 + v_z^2 = c^2$.

B.3 Substrate-level integers

- N: photon pool count on a cell (integer, ≥ 0).
- $N_{crit} = 14\tau^{10} = \pi m_H^3/(32v^2 m_e) = 6{,}203$: activation threshold.
- n: **KK mode index** (spherical-harmonic l); reserved for amplitude pattern across many cells. Distinct from w.
- w: **per-cell winding number** (integer-valued $\pi_2(S^2) = \mathbb{Z}$ topological label on each cell). Distinct from n.

B.4 Geometric quantities

- $\vartheta_{local}(r) = \arctan(v_T(r)/c)$: local light-speed angle.
- $\Delta N = \sqrt{N_{crit}} \approx 79$: boundary-layer thickness in cell counts.

B.5 BH parameters

- M: BH total mass.

- $S_{BH} = k_B A/(4L_P^2)$: Bekenstein-Hawking entropy.
- $T_{BH} = \hbar c^3/(8\pi G M k_B)$: Hawking temperature.
- $r_{core} \sim L_P \times (M/m_{Planck})^{1/3}$: ready-state core extent (Level 2 prediction).

B.6 Level tagging (per §1.6)

- **Level 1 (geometric)**: derived from framework primitives with no extra assumptions.
- **Level 2 (anchored prefactor)**: quantitative claims with order-of-magnitude prefactors.
- **Level 3 (structural speculation)**: conditional arguments where the framework permits but does not force the claim.

B.7 Cross-references

- [N] §X.Y: section X.Y of internal reference [N] (numbered in References).
- [N] Ch. X: chapter X of internal reference [N].
- [N] App. D: appendix D of internal reference [N].
- §X.Y of this paper: subsection within §X.

Appendix C: Cross-reference index to [1] and [2]

A useful reference for readers familiar with the foundational monograph [1] and the companion 6D-action paper [2]: cross-reference indices identifying which sections of [1] and [2] correspond to which sections of this paper, and where in [1] / [2] the framework primitives used here are derived.

C.1 Cross-reference index to [1]

[1] section	Topic	Used in this paper at
§2.8	Cell tiling: 2^{152} Planck-area cells via Gauss-Bonnet	§1.8.1, §2.2
§3.10	Bridge equation: $N\_crit = 14\tau^{10}$ = 6,203	§1.8.4, §2.2, §5.3
§3.12	KK mode spectrum on t_3 S^2	§1.8.2, §2.3
§3.13	Activated, dormant, and ready-state cells	§2.2, §3.4, §8.2
§8.4	Particle classification (A2, A3, B2, C1)	§1.8.2, §2.3
§8.6	Proton-electron mass ratio from KK mode 918	§1.8.2, §2.3, §6.4
§16.3	Schwarzschild metric from c-budget $\omega\_C \times R_3$ = const	§2.1, §2.6.1
§16.4	Universal free fall from c-budget redistribution	§2.6.1, §4.2.1
§16.5	Newton's constant from cell count	§1.8.7, §2.6.1
Ch. 16	Gravity from c-budget	Throughout §2
Ch. 17	Quantum mechanics from foam topology	§4.3 (boundary layer)
Ch. 18	Uncertainty, tunnelling, evanescent boundary layer	§4.3, §11.2
§21.1	Special relativity from c-budget	§2.1
§21.2	Schwarzschild without Einstein equations	§2.1, §2.6.1
§21.3	Light deflection at 1.7485″	§1.7

[1] section	Topic	Used in this paper at
§21.4	BH θ_local = 0 fixed point; Hawking temperature; ready-state core	§4.1, §10.2, §11.3
§21.5	Information conservation via $\pi_2(S^2) = \mathbb{Z}$	§5.2, §8.3, §11.5
§21.6	GW as foam deformation, $v\_GW = c$	§1.8.7, §2.6.2, §12.2
§21.7	Einstein-Aether reduction; (3+3) → GR	Throughout (merger-honesty framing)
Ch. 22	Cosmology, Hubble tension, dark energy	§6.2, §15
Ch. 26	Cosmological-constant problem dissolved; dark energy as geometric effect	§15.2, §15.3
Ch. 30	Falsifiability roadmap	§12.7, §14.5
App. D	6D covariant framework, Einstein-Aether details	§2.6.3, §13.5

C.2 Cross-reference index to [2]

The companion paper [2] (the 6D Lagrangian paper, May 2026, Zenodo DOI 10.5281/zenodo.20028764) develops the framework at the action-principle level and consolidates many results from [1] in Lagrangian form. Several results in this paper draw on [2] directly:

[2] section	Topic	Used in this paper at
§3	Causal vector field; Einstein-Aether structure	§1.7, §2.6.3
§6.7	Mass spectrum of S^2 Kaluza-Klein modes	§2.3
§7	Newton's constant G_N from KK reduction; numerical determination of L_2	§2.6.1
§8.2	Schwarzschild metric from t_2-flow resistance	§2.1, §2.6.1
§8.7	Gravitational waves at $c\_GW = c$ exactly	§2.6.2, §12.2

[2] section	Topic	Used in this paper at
§9	Coleman-Weinberg minimum; radion potential; *m_H* from radion breathing	§2.2 (*N_crit*), §15.2 (*Λ_geo* + *Λ_Higgs* = 0)
§12	PPN parameters γ = β = 1 exactly	§12.7
§13	GW dispersion, two helicity states, *m_g* < 10^{-30} eV bound	§14.6 (falsification)
§14.1–14.2	Λ_geo, Λ_Higgs, Λ_eff three-contribution structure	§15.2
§14.3	1.73× residual on Λ_eff	§15.3
§14.4	Dark energy as kinetic energy of causal vector through t_2	§15.4
§14bis.40	BHs as θ_local = 0 fixed points; boundary-layer dormancy	§2.1, §4.1, §6.1
§14bis.41	Three-time-dimension BH structure (T frozen, t_2 severed, t_3 continues)	§2.1, §6 (entire section)
§14bis.42	Hawking via fermionic keeper-wave bifurcation	§11.2
§14bis.43	Closure status of gravitational sector	§6 closing, §15 closing

Readers wishing to verify framework primitives or pursue deeper derivations should consult [1] and [2] at the indicated sections. This paper takes [1]'s and [2]'s primitives as established and applies them to BH dynamics; readers wishing foundational justifications are referred to [1] Chapters 1–3 (framework foundations), [1] Chapters 16–18 (gravity, quantum mechanics, and the boundary layer that is central to BH physics), and [2] §§3, 6–9 (Lagrangian foundations of the gravitational and matter sectors).

End of paper.