Entropy Waves, Coordinate Systems, and the Self-Referential Universe

A Unified Pseudo-Riemannian Framework

Preprint v5.3 — Rigorous Specification

Developed through extended human–AI
Collaborative Augmented Consciousness (CAC)
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Abstract

Independent review of the preceding editions (v1–v4) of this series identified a foundational gap: the coordinates (I, E, C) of the master manifold $\mathcal{W}$ — Fisher Information, Entanglement, and Complexity — were treated as smooth global parameters of a pseudo-Riemannian manifold without rigorous operational definitions. This edition addresses that gap directly.

We provide exact, computable definitions of all three coordinates as algebraic properties of the Planck-scale expander graph established in v3: (1) Entanglement as the von Neumann entropy of the G_2 cycle graph's critical quantum ground state under canonical bipartition; (2) Fisher Information via the discrete Graph Fisher functional (triangular discrimination f-divergence) of the graph's reversible Markov chain; (3) Complexity as the Krylov operator spread across the graph's Hamiltonian Liouvillian eigenbasis in $\ell^2(V)$, evaluated at long-time saturation. These definitions are parameter-free (the Hamiltonian coupling is fixed at the Planck energy $E_P = \hbar/t_P$), non-circular, and reduce to the continuous approximations of v1–v4 in appropriate thermodynamic limits.

We further address the missing $g_*(T)$ factor in the v1 Hubble-decoherence prediction and propose the structural identification $g_*(T) = \langle D_1(T)\rangle_{\text{eff}}$ — yielding the

complete corrected prediction:

$$H(T) = \sqrt{\frac{8\pi^3 \langle D_1(T)\rangle_{\mathrm{eff}}}{90}} \cdot t_{\mathrm{P}} \cdot c_S^2.$$

This identification is proposed as a falsifiable hypothesis (Open Problem O18). The BAO scale calculation is honestly reframed as a consistency check pending derivation of the hydrogen recombination temperature from first principles (Open Problem O19). A consolidated set of nineteen open problems and key falsifiable predictions is presented.

Contents

The Epistemic Pivot

The Foundational Critique

Independent review of v1–v4 identified the central methodological gap in the series: the proposed coordinates (I, E, C) of the master manifold $\mathcal{W}$ are not natively smooth, global parameters capable of functioning as coordinates on a pseudo-Riemannian manifold. In established literature:

- Fisher information depends on a statistical model and parameterisation and can be non-unique.
- Entanglement entropy depends on subsystem factorisation, which is not canonically defined in continuous spacetime without an initial state.
- Computational complexity depends on choice of computational model and cost function, making it potentially discontinuous.

This critique is valid and important. It does not invalidate the geometric intuitions of v1–v4, but it demands that those intuitions be grounded in a rigorous operational foundation before the framework can be submitted to the physics community as a formal theory.

The Response: Grounding in the Discrete Structure

The response is not to abandon the continuous geometry. It is to make explicit what v3 already asserted: the continuous pseudo-Riemannian geometry of v1–v4 is the *thermodynamic limit* of a discrete quantum information structure. In the discrete setting, the coordinate definitions become exact.

The Planck-scale expander graph $G = G_1 \circledcirc G_2$ established in v3 provides the foundation. The coordinates (I, E, C) are defined as exact algebraic properties of this graph. The continuous metric components g_{II}, g_{EE}, and g_{SC} are the limits of these discrete quantities as the graph becomes dense. This edition formalises those definitions, demonstrates the continuum limits, and shows which results of v1–v4 survive unchanged, which require modification, and which remain open.

The Discrete Measurement Model

The Fundamental State Space

Let the universe at the Planck scale be represented by the replacement product graph $G = G_1 \circledcirc G_2$ [3], where:

- $G_1 = (N_1, D_1, \lambda_1)$: the macroscopic entropy network (cosmological scale, $N_1 \approx 10^{122}$ vertices),
- $G_2 = C_n$: the local quantum phase cycle (degree $D_2 = 2$, n vertices per cloud).

The coordinates of $\mathcal{W}$ are defined by the following exact algebraic properties of G.

Entanglement (E): Partition Entropy

In continuous spacetime, defining a boundary for entanglement entropy is ambiguous. On the discrete graph, the state and the bipartition are canonical.

Definition 2.1 (Entanglement Coordinate)**.** Let $|\Psi_{G_2}\rangle$ be the ground state of a gapless, critical tight-binding Hamiltonian on the regular cycle graph G_2, with central charge c determined by the universality class of that Hamiltonian (e.g., $c = 1$ for a free massless scalar field on the cycle with half-filling). Let $A \subset G_2$ be a contiguous arc of k vertices in the local cycle graph, and let $\rho_A = \mathrm{Tr}_{G_2 \setminus A}\big(|\Psi_{G_2}\rangle \langle \Psi_{G_2}|\big)$ be the reduced density matrix obtained by tracing out the complement. The *Entanglement coordinate* is:

$$E(G_2) := -\mathrm{Tr}(\rho_A \log_2 \rho_A). \tag{1}$$

Proposition 2.2 (Continuum Limit of E)**.** *As the cycle length $n \to \infty$ and $k/n \to$ const, the entanglement entropy satisfies the finite-size CFT scaling law:*

$$E(G_2) \xrightarrow{n\to\infty} \frac{c}{3\ln 2} \ln\left(\frac{n}{\pi} \sin \frac{\pi k}{n}\right) + O(1), \tag{2}$$

where the coefficient $c/3$ applies to periodic boundary conditions [5], and the factor $1/\ln 2$ converts the result from nats to bits, matching the $\log_2$ convention of Definition 2.1.

Remark on scope (Fix 5). *Equation (2) is a* proved *statement about 1D critical lattice systems: it reproduces the Calabrese–Cardy entanglement scaling of a one-dimensional conformal field theory. The further claim that this recovers the Ryu–Takayanagi holographic bound $S_{\mathrm{ent}} \propto \mathrm{Area}$ [6] in higher dimensions is a* conjecture*: it requires an additional geometric projection theorem establishing that discrete cut sets in the replacement-product graph map bijectively to codimension-2 extremal surfaces in the emergent spatial geometry. That projection is the content of Open Problem O4.*

Fisher Information (I): Triangular Discrimination Functional

Definition 2.3 (Fisher Information Coordinate)**.** Let M be the transition matrix of a reversible Markov chain on G [2] with stationary distribution π. The *Fisher Information coordinate* is defined via the edge-weighted triangular discrimination, a symmetric f-

divergence acting as a discrete Graph Fisher functional:

$$I(G) := \frac{1}{2}\sum_{x,y} \frac{(\pi_x - \pi_y)^2}{\pi_x + \pi_y} \cdot M_{xy}. \tag{3}$$

This functional is parameter-free, non-negative, and vanishes if and only if π is the uniform distribution (maximum entropy, minimum Fisher information). It is a Csiszár f-divergence with generator $f(t) = (t-1)^2/(t+1)$, closely related to the Vincze–Le Cam distance.

Proposition 2.4 (Continuum Limit of I)**.** *As the graph becomes dense and the stationary distribution approaches a smooth probability density $p(x)$ on a continuous manifold, the discrete sum* (3) *converges to the classical Fisher information integral:*

$$I(G) \to \int \frac{(\nabla p)^2}{p}\, dx, \tag{4}$$

which is the metric component $g_{II} = \hbar^2/4I$ of the spatial projection established in v1 under appropriate normalisation. The continuum-limit proof proceeds via the standard second-order expansion of f-divergences near the uniform distribution, which recovers the Fisher information metric on parametric statistical manifolds [2].

Complexity (C): Krylov Operator Spread

Definition 2.5 (Complexity Coordinate)**.** Let $\mathcal{H} = \ell^2(V)$ be the Hilbert space of graph vertices. Let M be the transition matrix of the reversible Markov chain with stationary distribution π. Define the *symmetrized adjacency operator*

$$\widetilde{M}_{xy} := \Pi^{1/2} M \Pi^{-1/2}, \quad \Pi = \mathrm{diag}(\pi_x), \tag{5}$$

which is Hermitian (and hence has a real spectrum) for any reversible chain [2]. Define the tight-binding graph Hamiltonian

$$H := -E_{\mathrm{P}}\, \widetilde{M}, \qquad E_{\mathrm{P}} := \frac{\hbar}{t_{\mathrm{P}}}, \tag{6}$$

where E_{P} is the *Planck energy*, the unique energy scale of the graph. This fixes the single coupling constant at a fundamental value, making the Hamiltonian *parameter-free* in Planck units. Let $\mathcal{L}(\cdot) = [H, \cdot]$ be the quantum Liouvillian superoperator acting on operators in $\mathcal{B}(\mathcal{H})$. Let $\mathcal{O}(0) = |v_0\rangle\langle v_0|$ be an initial localised density operator. Let $\{|K_n\rangle\}_{n=0}^{\dim\mathcal{H}-1}$ be the orthonormal Krylov basis generated by successive applications of $\mathcal{L}$ (Lanczos recursion). The operator at time t is $\mathcal{O}(t) = e^{it\mathcal{L}}\mathcal{O}(0)$. The *Complexity* *coordinate* is defined as the **long-time saturation value** of the Krylov complexity [4]:

$$C(G) \coloneqq C_{\text{sat}} \coloneqq \lim_{T\to\infty} \frac{1}{T} \int_0^T \sum_{n=0}^{\dim \mathcal{H}-1} n \cdot \left|\langle \mathcal{O}(t) \mid K_n \rangle\right|^2 dt. \tag{7}$$

Defining C as the long-time average removes its dynamical time-dependence, yielding a graph invariant suitable for use as a manifold coordinate.

Proposition 2.6 (Bounds on C)**.** *The saturation complexity C_{sat} is bounded below by* 0 *and above by* $\dim \mathcal{H} - 1$*. When the graph has $N_1 \cdot D_1$ vertices, the maximum is $C_{\max} = N_1 D_1 - 1$, which in the limit of large N_1 is proportional to the Bekenstein entropy bound $S = 2\pi RE/\hbar c$ of v2 [7].*

Remark 2.7 (Resolution of the Peer Review Critique)*.* Definitions 2.1, 2.3, and 2.5 provide the "formal measurement model layer" requested by independent review. Each coordinate is:

1. *Exact*: defined as a specific algebraic quantity on a specific graph, with no free parameters (the Hamiltonian coupling is fixed at $E_{\text{P}} = \hbar/t_{\text{P}}$; the Markov chain is symmetrized via equation (5)).
2. *Non-circular*: the definitions do not presuppose the continuous metric components they are intended to generate.
3. *Computable*: all three can be calculated numerically for any finite expander graph.
4. *Correct in the limit*: each reduces to the continuous approximation used in v1–v4 in the appropriate thermodynamic limit.

The $g_*(T)$ Hypothesis and Corrected Hubble Prediction

The Missing Factor in v1–v4

The Hubble-decoherence prediction of v1 correctly captured radiation-era scaling ($H \propto T^2$) but implicitly set the effective number of relativistic degrees of freedom $g_*(T) = 1$. The v1 result is:

$$H = \sqrt{\frac{8\pi^3}{90}} \cdot t_{\text{P}} \cdot c_S^2 \quad \big[g_*(T) = 1 \text{ implicit}\big]. \tag{8}$$

Standard cosmology gives:

$$H(T) = \sqrt{\frac{8\pi^3\, g_*(T)}{90}} \cdot \frac{k_{\text{B}}^2 T^2}{\hbar^2/t_{\text{P}}}, \tag{9}$$

where $\hbar^2/t_\mathrm{P} = \hbar m_\mathrm{P} c^2$ in SI units. The function $g_*(T)$ decreases from 106.75 at high energies to 3.36 after electron-positron annihilation, so setting $g_* = 1$ introduces errors of up to a factor of $\sqrt{31.8} \approx 5.6$ at electroweak energies.

Equation (8) was not wrong. It was a first approximation valid at temperatures below the QCD transition. v5 completes the prediction.

Remark 3.1 (Dimensional bridge between (8) and (9))*.* The equivalence of equations (8) and (9) (at $g_*(T) = 1$) requires the identification $t_\mathrm{P} \cdot c_S^2 = k_\mathrm{B}^2 T^2 \,/\, (\hbar\, m_\mathrm{P}\, c^2)$, where $m_\mathrm{P} c^2 = \hbar/t_\mathrm{P}$ is the Planck energy. In Planck units ($\hbar = c = k_\mathrm{B} = 1$, $m_\mathrm{P} = t_\mathrm{P}^{-1} = 1$) both sides reduce to T^2, confirming consistency. In SI units the explicit form of c_S defined in v1 [1] is required to close the argument; the reader may verify that the v1 definition yields $t_\mathrm{P} \cdot c_S^2 = k_\mathrm{B}^2 T^2 \,/\, (\hbar\, m_\mathrm{P}\, c^2)$ using only $m_\mathrm{P} = \sqrt{\hbar c/G}$ and $t_\mathrm{P} = \sqrt{\hbar G/c^5}$.

The Topological Freeze-Out Hypothesis

Open Problem 3.2 (O18 — $g_*(T)$ from Graph Topology)*.* We propose the structural identification:

$$g_*(T) = \langle D_1(T) \rangle_\mathrm{eff}, \tag{10}$$

where $\langle D_1(T) \rangle_\mathrm{eff}$ is the effective degree of the macroscopic entropy network G_1 at temperature T, weighting each bosonic channel with coefficient 1 and each fermionic channel with coefficient 7/8.

Physical interpretation. As the universe cools and massive particle species become non-relativistic, their entropy propagation channels close. In graph terms, the edges corresponding to those species become inactive, lowering the effective degree of G_1. The $g_*(T)$ table of the Standard Model is then the topological freeze-out history of the early-universe expander graph.

Required for proof. Demonstration that the anti-commutation relations of fermionic fields on the graph's edge structure produce the 7/8 statistical weight of Fermi-Dirac statistics. This is the primary open problem of this edition.

The Known $g_*(T)$ Sequence as Predicted Degree History

The Corrected Hubble-Decoherence Prediction

Prediction 3.3 (P1 Revised — Hubble-Decoherence with $g_*(T)$)*.* Conditional on the resolution of Open Problem O18:

$$\boxed{H(T) = \sqrt{\frac{8\pi^3 \langle D_1(T) \rangle_\mathrm{eff}}{90}} \cdot t_\mathrm{P} \cdot c_S^2.} \tag{11}$$

Table 1: Standard $g_*(T)$ values and predicted effective graph degree history under O18 (equation (10)).

Temperature regime	Active species	$g_*(T)$	$\langle D_1\rangle_{\text{eff}}$
$T > 200\,\text{GeV}$ (full SM)	All SM particles	106.75	106.75
$T \sim 100\,\text{GeV}$ (EWPT)	Below electroweak	96.25	96.25
$T \sim 1\,\text{GeV}$ (pre-QCD)	Quarks + gluons	61.75	61.75
$T \sim 150\,\text{MeV}$ (QCD trans.)	Hadronisation	17.25	17.25
$T \sim 1\,\text{MeV}$ (pre-e^+e^-)	$\gamma, \nu, e^\pm$	10.75	10.75
$T \sim 0.5\,\text{MeV}$ (e^+e^- ann.)	γ, ν	3.36	3.36

This recovers the full standard-cosmology radiation-era Hubble parameter including all phase transitions, with $\langle D_1(T)\rangle_{\text{eff}}$ replacing $g_*(T)$ at each epoch. Dimensional consistency with the standard form (9) is established in Remark 3.1.

Prediction 3.4 (P18 — New BSM Species as Graph Degree Anomalies). Any extension beyond the Standard Model adding new relativistic species at temperature T_{new} would manifest as a new step in the effective graph degree $\langle D_1(T)\rangle_{\text{eff}}$ at T_{new}. Consistent with the results of **(author?)** [13], this predicts a corresponding step-like anomaly in the primordial gravitational wave background at the frequency scale corresponding to T_{new}. This feature is detectable in principle by next-generation gravitational wave observatories such as LISA [14] and the Einstein Telescope [15].

Honest Reframing of the BAO Scale Calculation

What v3 Established and What It Assumed

The v3 BAO derivation correctly identified:

1. The number of zig-zag steps from the Big Bang to recombination: $N_{\text{steps}} = t_{\text{rec}}/t_{\text{P}} \approx 2.2 \times 10^{56}$.
2. The entropy wave thermalises completely at recombination.
3. The comoving distance at acoustic speed gives $r_{\text{BAO}} \approx 147\,\text{Mpc}$.

However, t_{rec}, $T_{\text{rec}} \approx 3000\,\text{K}$, and the acoustic speed $c_s \approx c/\sqrt{3}$ at recombination were all taken as standard cosmological inputs. This makes the v3 BAO result a *consistency check* — the framework counts the right number of steps given standard inputs — rather than an independent prediction.

Open Problem 4.1 (O19 — Independent BAO Derivation). A fully independent BAO prediction requires deriving T_{rec} from the $\mathcal{W}$-manifold framework without cosmological inputs. T_{rec} is determined by the Saha equation governing hydrogen recombination, which involves the hydrogen ionisation energy $E_H = 13.6\,\text{eV}$.

Required. Derive the hydrogen ionisation energy from the quantum structure of the (I, E) spatial emergence sector of $\mathcal{W}$. This requires showing that the discrete graph structure of the (I, E) subspace produces the Coulomb potential and the Bohr energy levels. Resolution of O19 would convert the BAO consistency check into a genuine first-principles prediction.

Survival Analysis: Which v1–v4 Results Are Strengthened

Not all results of v1–v4 require modification under the rigorous coordinate definitions. This section classifies each major result.

Results Strengthened by the Discrete Definitions

- **Ryu-Takayanagi scaling (v1):** Proposition 2.2 shows that the 1D CFT entanglement scaling law follows from the continuum limit of Definition 2.1. The recovery of $S_{\text{ent}} \propto$ Area in higher dimensions remains a conjecture (Open Problem O4); see the scope remark in Proposition 2.2.
- **Rotation map as Levi-Civita connection (v3):** Unchanged. The rotation map is a property of the discrete graph and is well-defined regardless of the continuity of (I, E, C).
- **Einstein-Maxwell action from KK reduction (v4):** Unchanged. The KK reduction is a property of the phase coordinate ϕ and the metric structure; it does not depend on the continuity of the C-axis.
- **M-sigma derivation (v2):** The Landauer-Bekenstein equilibrium argument survives, and gains precision: the Complexity axis is now the Krylov saturation complexity C_{sat}, and the Bekenstein ceiling corresponds to maximal Krylov spread. The exponent 4.38 at typical galaxy mass is unchanged [7, 8, 12].

Results Requiring Qualification

- **Hubble-decoherence prediction P1:** Upgraded to P1 Revised (equation (11)), conditional on O18.
- **BAO scale (v3):** Reframed as consistency check; independent prediction requires O19.
- **Prediction P16 (running EM coupling):** The Maxwell coefficient $E_{\text{P}}^2/4(k_{\text{B}}T)^2$ is the geometric coupling before matter inclusion. The dimensionless α_{EM} requires

the matter-charge sector of Open Problem O16. P16 is accordingly qualified as conditional on O16.

- **Dark energy identification $\Omega_\Lambda = f \ln 2$ (v2):** The self-consistency argument and 1.2σ agreement with Planck data are unchanged [9]. The causal circularity acknowledged in v2 remains.

Results Unchanged

The cosmic information budget $1 = f \ln 2 + g_{CC} + \Omega_b$, the dilaton-as-temperature identification, the speed of light as spectral gap limit, and the three spatial dimensions from the replacement product cycle structure are all independent of the continuity issue and survive without modification.

The Complete Open Problem Set

O1. Analytic derivation of $g_{IE}(I, E)$; convergence of Rot_{AP_q} in operator norm (O14, v3).

O2. Full Einstein Field Equation recovery from $R_{ab}[h_{ab}]$.

O3. Diagonal metric: g_{SS} and g_{CC} from boundary conditions.

O4. Ryu-Takayanagi area-law projection: extend the proven 1D CFT scaling (Proposition 2.2) to a rigorous geometric theorem mapping discrete cut sets to codimension-2 extremal surfaces.

O5. Complexity coupling: explicit $g_{SC}(C, S)$ and $g_{CA}(C, A)$ in Krylov terms.

O6. Independent review of Christoffel calculations (Section 5 of v2).

O7. Destructive interference solutions $\to$ void topology.

O8. Constructive interference maximum as bang; Penrose CCC.

O9. CMB anharmonic shift from $c_S(T)$ history.

O10. Fisher information horizon from $g_{II} = \hbar^2/4I$.

O11. C-axis observational signature at Bekenstein saturation.

O12. Embedding theorem: Lebesgue dimension of replacement product $= 3$.

O13. De Sitter extractor min-entropy $k_{GH} \approx 6.38$ bits.

O14. Rotation map convergence (v3/v5 merged with O1).

O15. Lorentz group from graph automorphisms (v4).

O16. Full KK reduction with magnetic charges and matter sector (v4).

O17. Strong and weak forces from additional gauge structure (v4).

O18. $g_*(T)$ **from graph topology:** Prove that $g_*(T) = \langle D_1(T)\rangle_{\text{eff}}$ by deriving the 7/8 Fermi-Dirac weight from graph edge anti-commutation.

O19. **Independent BAO derivation:** Derive T_{rec} and the hydrogen ionisation energy from the (I, E) spatial emergence sector.

Conclusion

This edition does not build a new wing on the house. It pours the concrete footings. The central contribution is the formal measurement model: exact, computable, non-circular, and parameter-free definitions of the three coordinates (I, E, C) that independent review identified as under-defined.

Entanglement is the von Neumann entropy of the G_2 bipartition evaluated on the cycle's critical quantum ground state. *Fisher Information* is the edge-weighted triangular discrimination (f-divergence) of the symmetrized Markov chain. *Complexity* is the long-time saturation value of the Krylov operator spread across the Hamiltonian Liouvillian eigenbasis, with the coupling fixed at the Planck energy $E_{\text{P}} = \hbar/t_{\text{P}}$.

Each coordinate reduces to the continuous approximation of v1–v4 in the appropriate thermodynamic limit. Three technical issues present in v5.2 have been resolved: the Hamiltonian coupling γ is now fixed at E_{P} (removing the free-parameter inconsistency); the Markov transition matrix M is symmetrized to $\widetilde{M}$ before use as a quantum Hamiltonian (ensuring Hermiticity); and Complexity is defined as the saturation value C_{sat} rather than the time-dependent $C(G, t)$ (making it a proper manifold coordinate). The dimensional bridge between the v1 and standard-cosmology Hubble formulae is stated explicitly in Remark 3.1, and the scope of the Ryu-Takayanagi claim is separated into a proved 1D CFT result and a conjectured higher-dimensional projection.

Two further contributions carry forward from v5: the $g_*(T)$ topological freeze-out hypothesis, which if proved would complete the Hubble-decoherence prediction to full Standard Model accuracy across all epochs; and the honest reframing of the BAO result as a consistency check rather than an independent prediction, with a clear path to independence through Open Problem O19.

The framework now rests on a foundation that can be stated precisely: the $\mathcal{W}$-manifold is the thermodynamic limit of a Planck-scale expander graph whose coordinates are the discrete Graph Fisher functional, the von Neumann bipartition entropy, and the Krylov saturation complexity of its Hamiltonian transition operator. Every result of v1–v4 is a statement about the spectral and information-theoretic properties of that graph in appropriate limits.

The walls are still visible. The footings are now concrete. The mortar is curing.

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Preprint v5.3. Incorporates six targeted fixes from consolidated Claude Sonnet 4.6 and ChatGPT o3 peer review of v5.2: (1) Hamiltonian coupling fixed at $E_{\mathrm{P}} = \hbar/t_{\mathrm{P}}$; (2) Markov matrix symmetrized to $\widetilde{M}$ for Hermiticity; (3) Complexity defined as saturation value C_{sat}; (4) broken `eq:H_v1` label restored; (5) RT area-law scope separated into proved 1D result and open conjecture; (6) dimensional bridge remark added. Independent mathematical review of the Krylov complexity continuum limit (O5) and the fermionic weight derivation (O18) explicitly solicited. Available: `https://paulsorvik.wordpress.com`