A Holographic Grammar of the Expanding Universe

2D Boundary as Ontological Substrate · 3D Bulk as Emergent Render · QFT as Grammar in Motion

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February 2026 · Version 9.4

Abstract

This paper proposes an ontological reinterpretation of the holographic principle in which the 2D boundary of de Sitter spacetime is treated as the primary physical substrate—an expanding qubit surface encoding all physical law as structural parameters (the *grammar*)—and the 3D bulk is its emergent geometric rendering. No new bulk dynamics are proposed. All cited equations are standard. The contribution is a reordering of their ontological status: boundary entanglement is primary; bulk spacetime is derived; quantum field theory in curved spacetime is the grammar in motion, described from inside the render.

Three concrete empirical claims distinguish this framework from standard ΛCDM:

1. **CMB phase structure.** Primordial fluctuations at low multipoles ($\ell \lesssim 10$) should exhibit weak but structured horizon-scale phase correlations not generically produced by single-field inflation, consistent with existing Planck 2018 large-angle anomalies. The framework predicts these anomalies will deepen rather than diminish with improved CMB polarization data (LiteBIRD, CMB-S4).
2. **Decoherence threshold.** Classical geometry requires a minimum boundary write-density, derived from axioms G1 and G3, yielding a minimum qubit activation count $N_{\min} \sim 10^{52}$. This manifests as a power deficit at $\ell \lesssim 10$ driven by proximity to the decoherence threshold during early inflation.
3. **Inflaton potential.** Four grammar axioms, no bulk physics, and no free parameters beyond the observed scalar amplitude A_s yield the E-model/Starobinsky potential with $n_s \approx 0.9678$ and $r \approx 0.00296$ for $N_e = 60$—consistent with Planck 2018 and testable by LiteBIRD (2030).

4. **Write-density gravity.** The dimensional mismatch between the 2D boundary (logarithmic Green's function) and the 3D bulk produces a $1/r$ gravitational acceleration correction with scale $a_w = cH_0/(2\pi) \approx 1.04 \times 10^{-10}$ m/s^2, yielding flat rotation curves and the baryonic Tully–Fisher relation ($v^4 = GMa_w$) with zero free parameters. The time-evolution prediction $a_w(z) = cH(z)/(2\pi)$ is testable by JWST.

If increasingly precise data exhibit purely Gaussian random phases at all scales, no threshold behavior for classicality, no information bounds associated with horizon growth, and no redshift-dependent acceleration scale, the framework is disfavored.

Contents

1 Ontological Scope

This paper does not propose new bulk dynamics, modifications to quantum field theory, or extensions to holographic entropy formulae. Every equation cited is standard. What is proposed is a reinterpretation of their ontological ordering:

> Boundary entanglement: primary. Bulk spacetime: derived. QFT in curved spacetime: the grammar in motion, described from inside the render.

The formal results of AdS/CFT—the Ryu–Takayanagi (RT) formula, Bogoliubov transformations, the Gibbons–Hawking temperature, the Page curve—are taken as given. The paper asks what these results imply if the boundary is not a convenient mathematical surface but the actual ontological substrate. The extension to dS/CFT is a prediction of the framework, not an assumed result. Where observational data are cited (DESI 2024, Yonsei 2025), they are noted as tentative and not yet at consensus significance.

1.1 The meta-argument

Three of the deepest unsolved problems in physics—the cosmological constant, the Hubble tension, and the failure to quantize gravity—have resisted solution for a combined total exceeding a century. The standard response has been to address each separately. This paper proposes that separate solutions constitute the wrong approach because the three failures share a single root cause: all three arise at the interface between bulk and boundary descriptions.

- The cosmological constant discrepancy is a dimensional mismatch between 3D volumetric QFT modes and a 2D surface quantity.
- The Hubble tension is a discrepancy between early-universe measurements probing global boundary structure and late-universe measurements probing local bulk geometry.
- Quantum gravity fails at the point where spacetime geometry—a derived quantity in this framework—is treated as fundamental and subjected to direct quantization.

The framework proposes a single ontological reordering from which all three failures become expected rather than anomalous. The historical analogy is the Copernican reordering: the failures of geocentric astronomy were not resolved by improved epicycles but by recognizing that the wrong object had been placed at the center. One hundred years of failure on quantum gravity—with increasingly sophisticated machinery—constitutes evidence that the machinery is aimed at the wrong target.

2 The Pre-Render State

This section establishes what exists before the first render, what triggers the first decoherence event, and why space is an output of the grammar rather than a pre-existing stage.

2.1 What exists before space

The pre-render state is the boundary qubit field in a condition of total, undifferentiated superposition—encoding every parameter of every physical law but having resolved none into a stable geometric output.

Exists	**Does not yet exist**
The boundary qubit field	Geometric space (no metric, distances, or causal structure)
All physical law as grammar parameters (coupling constants, field types, symmetry groups)	Field excitations (no particles, no quanta)
The entanglement structure of the grammar	Stable decoherence patterns (no classical objects)
Maximum superposition: all states simultaneously unresolved	Time as experienced (no sequential write-record)
The grammar's capacity to run	Any render output

The distinction between field types existing as grammar parameters and field excitations existing as render events is structurally essential. The fields exist in the sense that the rules of a formal system exist before any computation has been performed: fully specified, causally inert, containing within them every possible output.

2.2 The causal sequence

The ordering is significant. Expansion is not a consequence of decoherence—it is its cause.

1. **Boundary growth begins.** The qubit surface area increases. This is the primary event—ontologically prior to all else. There is no temporal "before" because time is the write-record, and no writes have yet occurred.
2. **New qubit modes activated.** As the boundary area grows, new qubit cells are added to the ledger via the Bogoliubov mechanism.
3. **First decoherence events cascade.** Interaction between existing boundary qubits and newly activated modes constitutes a mutual information exchange—

the grammar's definition of an observation event. The first write-events occur. The arrow of time begins.

4. **Space is rendered.** Stable decoherence patterns produce the first geometric structure. Following Van Raamsdonk (2010): entanglement between boundary regions generates geometric connectivity in the bulk.
5. **Write-density is maximum.** The qubit surface is small; every cell is simultaneously entangled with every other. No stable classical object can persist.
6. **Write-density falls with boundary growth.** As surface area increases, write-density per qubit decreases. The render cools. Successively more stable decoherence patterns become possible.

The Big Bang, in this framework, is the first moment at which the boundary produces a stable render output. The apparent singularity—infinite temperature, infinite density—is the render's description of the pre-render state projected backward along a time axis that did not yet exist. The singularity is the render's own extrapolation artifact, not a physical state.

2.3 Quantitative non-singularity: the minimum initial boundary

The non-singularity claim follows quantitatively from axiom G1. A boundary of zero area has zero information capacity—that is the pre-render state, not an initial physical condition. The first stable render requires a boundary of at least $A_0 = \ell_P^2$ (one Planck area). The corresponding minimum initial radius is:

$$r_{\min}(1\ \text{bit}) = \frac{\ell_P}{\sqrt{\pi}} \approx 9.1 \times 10^{-36}\ \text{m} \approx 0.56\ \ell_P \tag{2.1}$$

A more physically meaningful lower bound uses the Kolmogorov complexity of the grammar parameters—the minimum bit count required to specify the laws of physics. Estimates for the Standard Model plus General Relativity yield approximately 1000 bits, giving:

$$r_{\min}(1000\ \text{bits}) = \ell_P \sqrt{\frac{1000}{\pi}} \approx 18\ \ell_P \approx 2.9 \times 10^{-34}\ \text{m} \tag{2.2}$$

The initial state was a finite, information-carrying sphere of radius $r_0 \in [1, 18]\ \ell_P$, derived from G1 and the grammar-encoding requirement. A geometric singularity ($r = 0$) is excluded by G1 itself.

2.4 The boundary tracks the event horizon

The current boundary radius, derived from the observed de Sitter entropy $S_{dS} \sim 3 \times 10^{122}$ bits via the Bekenstein–Hawking relation, is:

$$r_{\text{now}} = \ell_P \sqrt{\frac{S_{dS}}{\pi}} \approx 1.58 \times 10^{26} \text{ m} \approx 16.7 \text{ Gly} \tag{2.3}$$

This matches the cosmological event horizon in ΛCDM ($\sim$16 Gly)—not the particle horizon ($\sim$46 Gly). The numerical correspondence between holographic entropy and the event horizon radius was noted by Susskind and Lindesay (2005) and formalized by Bousso's covariant entropy bound (1999). This framework adds a structural mechanism: the boundary is the future causal limit of what can ever be written to the ledger, which is precisely the event horizon's definition. This is consistent with the dS/CFT identification of the holographic dual on the future conformal boundary $\mathcal{I}^+$.

Quantity	**Value**	**Derivation**
Initial radius (1 bit)	$\sim 0.56\ \ell_P$	G1: $A_0 = \ell_P^2$
Initial radius (grammar-encoding)	$\sim 18\ \ell_P$	G1 + $\sim$1000 bit Kolmogorov complexity
Current radius	$\sim$ 16.7 Gly	G1 + $S_{dS} \sim 3 \times 10^{122}$
Horizon identified	Event horizon	Gibbons–Hawking / dS/CFT
Area growth factor	$\sim 3 \times 10^{119}$	Consistent with entropy growth

3 Initial Expansion: Three Grammar Mechanisms

The phrase "initial expansion" conceals three distinct questions with distinct answers in this framework.

3.1 The primal trigger: quantum tunneling

The pre-render state is the boundary qubit field at zero surface area: total superposition, all grammar parameters encoded, no write-events, no render, no time. The transition from zero to nonzero area is a quantum tunneling event:

$$|\psi_{\text{boundary}}\rangle = c_0|A = 0\rangle + c_1|A > 0\rangle \quad \longrightarrow \quad |c_1|^2 > 0 \tag{3.1}$$

This is consistent with Vilenkin's tunneling-from-nothing cosmology (1982) and the Hartle–Hawking no-boundary proposal (1983), but interpreted within the grammar framework: the first write-event is the superposition resolving, and the question "what happened before $t = 0$" is ill-formed because "before" is a write-record concept that presupposes the existence of prior writes.

3.2 The inflationary driver: inflaton as grammar parameter

In standard cosmology, the inflaton is an unexplained scalar field with a free potential shape. In this framework, the inflaton is a grammar parameter encoded in the boundary qubit field before the first render. Its potential shape is constrained by internal grammar consistency rather than fitted post hoc. Slow-roll corresponds to a large configuration space:

$$V(\phi) = \text{grammar parameter configuration energy at boundary area } A \tag{3.2}$$

$$\varepsilon = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1 \quad \Longleftrightarrow \quad \text{configuration space is large} \tag{3.3}$$

$$N_e \geq 60 \quad \Longleftrightarrow \quad \text{configuration-space depth from tunneling point to minimum} \tag{3.4}$$

3.3 Reheating: mode activation

Inflation ends when the inflaton parameter reaches its potential minimum. Reheating is the conversion of expansion-drive energy into write-events on the boundary—the oscillating inflaton decays by activating new Bogoliubov modes:

$$T_{\text{reheat}} \sim (\Gamma \cdot M_{Pl})^{1/2} \tag{3.5}$$

where Γ is the inflaton decay rate.

4 Ledger Persistence and Cyclic Re-initiation

Status: This section is speculative and not implied by known holographic dualities.

4.1 The asymmetry of the ledger

All write-events are permanent. The boundary ledger accumulates monotonically. A write-event, once recorded, is not reversed by the dissolution of the render it produced. The second law of thermodynamics, in grammar terms, states that the ledger only grows.

The pre-render and post-render states share conformal properties (scale-free, no mass, no clocks) but differ critically: the pre-render ledger is empty while the post-render ledger carries the full write-record of the preceding aeon.

4.2 Cyclic re-initiation

The post-render condition—full ledger, no active render, quantum system—is unstable. It resolves not by erasing the ledger but by initiating a new render:

$$\text{Ledger}(\text{render } N{+}1, t{=}0) = \text{Ledger}(\text{render } N, t{=}\infty) \tag{4.1}$$

$$\text{Constraint space}(\text{render } N{+}1) \subseteq \text{Constraint space}(\text{render } N) \tag{4.2}$$

The contraction map for the field parameter α is modeled phenomenologically:

$$\alpha_{N+1} = \alpha_N - \kappa(\alpha_N - \alpha_0) \tag{4.3}$$

$$\kappa = \frac{1}{\ln N_{\text{total}}} \approx \frac{1}{\ln(10^{122})} \approx 0.00356 \tag{4.4}$$

$$\alpha_0 = \sqrt{2/3} \quad \text{(thermodynamic attractor—zero computational shear)} \tag{4.5}$$

The notational convention is: κ denotes the contraction rate; γ (the G5 Inheritance Factor) denotes ledger-transfer fidelity. At $\gamma \to 1$ (perfect error correction), $\kappa = 1/\ln N_{\text{total}}$.

4.3 Distinction from Conformal Cyclic Cosmology

This framework differs from Penrose's CCC in several respects: what connects aeons (boundary ledger vs. conformal bulk geometry), whether a prior universe is required (no—the first render begins from an empty ledger), the status of the second law across aeons (globally monotone via the ledger), and observational signatures (grammar parameter constraints on physical constants vs. CMB rings from previous-aeon black holes).

The convergence on conformal geometry is likely not coincidental. What Penrose identifies as a conformal bridge between aeons corresponds, in this framework, to the boundary asserting itself as the render recedes.

5 The Fundamental Layer

The universe is a real-time 3D render generated by a 2D spherical boundary. This boundary surface is ontologically primary—it hosts a quantum field encoding all physical law as structural parameters. The 3D bulk is its emergent rendering.

2D Boundary (Primary)	3D Bulk (Derived)
Planck-scale qubit surface encoding all physical law	Emergent spacetime geometry
Entanglement is native	Classicality is a decoherence artifact
Permanent writes generate the arrow of time	Expansion mirrors boundary growth
Expanding boundary = growing storage capacity	Vacuum energy calculations are projection errors
Irreducible ground-state hum (Gibbons–Hawking)	Structure = decohered boundary write-patterns

Entangled particles are two decohered expressions of one continuous quantum field—not two objects signaling, but one event in two representations. Space is emergent; two "distant" particles in the bulk occupy a single coordinate in the grammar.

6 Core Grammar Axioms

Six axioms from which bulk physics is derived.

G1. Superposition.
Superposition is grammatically native to the boundary. Unobserved states are not hidden classical facts; they are genuinely unrendered.

G2. Decoherence.
Decoherence occurs when the grammar resolves a query from an interacting system. Any system capable of mutual information exchange qualifies; no privileged role for consciousness is assumed.

G3. Entanglement.
Two "distant" particles in the bulk share one coordinate in the grammar. Bell violations are not manifestations of non-locality; they reflect boundary unity projected through emergent bulk geometry.

G4. Time.
Time is the sequential record of interactions written to the grammar. The arrow of time is the irreversible accumulation of writes. No interaction implies no time.

G5. Resolution.
The Planck length is the grammar's resolution parameter—the maximum specificity per interaction. Heisenberg uncertainty is a grammar constraint on query resolution.

G6. Parsimony.

The grammar does not pre-render what is not required. Reality is exactly as specified as interactions demand.

7 QFT in de Sitter Spacetime

Every standard QFT result acquires a precise grammatical interpretation.

7.1 The vacuum as boundary ground state

An empty 3D bulk corresponds to the boundary qubits in their ground state: unresolved, in superposition, awaiting queries. Vacuum fluctuations are the boundary's qubit field in superposition:

$$E_0 = \tfrac{1}{2}\hbar\omega \text{ per mode} \quad \longleftrightarrow \quad \text{boundary qubit ground-state energy per unresolved cell} \tag{7.1}$$

7.2 Bogoliubov transformations as mode creation

As the 2D boundary grows, new qubit modes are added to the ledger. Particle creation under expansion is a bookkeeping artifact of boundary growth:

$$\hat{a}_{\text{out}} = \sum_k \left(\alpha_k \hat{a}_{\text{in}} + \beta_k \hat{a}_{\text{in}}^\dagger\right) \tag{7.2}$$

$$\langle N_{\text{out}}\rangle = \sum_k |\beta_k|^2 \quad \longleftrightarrow \quad \text{new boundary storage cells activated} \tag{7.3}$$

7.3 The Gibbons–Hawking temperature

Even a perfectly empty de Sitter bulk has an intrinsic temperature—the boundary's irreducible write rate, the minimum information cost of maintaining a render:

$$T_{GH} = \frac{\hbar H}{2\pi k_B} \tag{7.4}$$

where H is the Hubble parameter. As $H \to 0$, $T_{GH} \to 0$: the grammar approaches its own ground state.

7.4 Sphere-growth deceleration

As the boundary sphere grows, the same increment in area produces a decreasing increment in radius. The bulk's expansion rate naturally decelerates:

$$A = 4\pi r^2 \implies \frac{dA}{dt} = \text{const} \implies \dot{r} \propto \frac{1}{r} \implies \ddot{r} < 0 \tag{7.5}$$

Deceleration is geometric, not dynamical.

8 The Cosmic Microwave Background

Rapid early boundary growth stretched write-events across the qubit surface faster than decoherence could resolve them. These unresolved write-events became frozen grammar states. When expansion slowed and they re-entered the causal render horizon, they decohered into classical bulk structure:

$$P(k) \propto k^{n_s-1}, \quad n_s \approx 0.965 \tag{8.1}$$

$$|\delta_k|^2 = \frac{H^2}{2\varepsilon M_{Pl}^2} \tag{8.2}$$

$$\text{Freeze-out at } k = aH \quad \longleftrightarrow \quad \text{mode exits render horizon; grammar state suspended unresolved} \tag{8.3}$$

Near scale-invariance reflects uniform boundary write-density. The slight red tilt ($n_s < 1$) reflects a write-rate that marginally decreases as the boundary expands.

9 Ryu–Takayanagi and the Grammar's Geometry

9.1 The RT formula

$$S(A) = \frac{\text{Area}(\gamma_A)}{4G_N} \tag{9.1}$$

Entanglement entropy of boundary region A equals the area of the minimal bulk surface anchored to ∂A, in Planck units. The scaling with area rather than volume is precisely what this framework requires: if information were stored volumetrically in the bulk, entropy would scale with volume. It scales with the 2D surface because the 2D surface is where the information resides.

9.2 The de Sitter tension

The RT formula was derived in AdS/CFT—anti-de Sitter space with a timelike boundary, supported by 25 years of mathematical development. Our universe is de Sitter: positive cosmological constant, spacelike future boundary, no rigorously established CFT dual. This framework predicts that RT-like entanglement–area relations should generalize to de Sitter holography when a precise dual is established. This is a falsifiable prediction, not an assumed result.

10 The Cosmological Constant

Standard QFT calculates a vacuum energy density approximately 10^{120} times larger than the observed value of Λ. Every proposed resolution within bulk physics has failed. In this framework, the error is ontological: bulk QFT computes the shadow of boundary energy through an amplification factor introduced by dimensional reduction.

$$\rho_{\text{bulk,calc}} \sim M_{Pl}^4 \quad \text{(3D volumetric integration to Planck cutoff)} \tag{10.1}$$
$$\rho_{\text{observed}} \sim 10^{-120} M_{Pl}^4 \tag{10.2}$$
$$\text{Volume mode-count: } \ell_P^{-3} \quad \text{vs.} \quad \text{boundary area density: } \ell_P^{-2} \tag{10.3}$$
$$\text{Total mismatch: } \mathcal{O}(10^{120})\text{—geometric, not fine-tuning} \tag{10.4}$$

The 10^{120} discrepancy is a category error: the 3D vacuum energy and the observed Λ are not commensurate quantities.

11 Dissolved Problems

Several long-standing problems are artifacts of treating the bulk as ontologically primary.

The measurement problem. There is no collapse because there was no pre-existing classical state. Decoherence is the grammar resolving a query.

Quantum non-locality (Bell violations). Bell violations are the projection of boundary unity into emergent bulk geometry. The particles were never separated in the grammar.

The black hole information paradox. Information cannot be destroyed in a black hole: destruction in the render does not erase the boundary record. The Page curve, recovered via the island formula, is the boundary's write-history surfacing through Hawking radiation.

The arrow of time. Resolved by the irreversibility of writes to the boundary. Time-symmetric bulk laws generate a temporal arrow because writes are permanent and accumulate monotonically.

The fine-tuning problem. If physical constants are grammar parameters rather than brute facts, the question "why these constants?" becomes "what grammars are self-consistent?"—a mathematical rather than physical question.

12 Open Unifications

QM + GR unification. Both are bulk phenomena—renders of the boundary grammar under different interaction-density regimes. The framework does not quantize gravity; it identifies gravity as a render artifact of boundary geometry.

Hubble tension. A boundary write-rate inhomogeneity: early-epoch writes (CMB) and late-epoch writes (local H_0 measurements) sample different points on the boundary's growth curve.

Dark energy. The boundary's geometric expansion force misread as volumetric energy density.

Dark matter. Addressed quantitatively in Section 13 below.

Black hole entropy. The Bekenstein–Hawking entropy $S = A/4G$ is area-scaled—trivially correct in a framework where information resides on a 2D surface.

13 Write-Density Gravity: Emergent Dark Matter

New in v9.4. This section derives a gravitational acceleration correction from the 2D/3D dimensional mismatch inherent in the holographic grammar framework, producing flat rotation curves and the baryonic Tully–Fisher relation with zero free parameters.

13.1 Physical mechanism

The write-back mechanism operates as follows. Baryonic matter in the bulk generates decoherence events (thermal interactions, quantum measurements, particle collisions). Each decoherence event constitutes a write-event on the 2D boundary. Write-events modify the boundary's entanglement geometry. The bulk renders this modified geometry as gravitational curvature.

In regions of high baryonic activity (galaxies), write-density is high and the emergent gravitational binding is correspondingly enhanced. In voids, write-density is low, approaching the cosmic mean set by the Gibbons–Hawking background, and gravitational binding is correspondingly reduced.

13.2 The dimensional mismatch

The key mathematical result follows from a single fact: the 2D Laplacian has a logarithmic Green's function.

In the 3D bulk (standard Newtonian gravity):

$$\nabla^2\Phi = 4\pi G\rho \quad \Longrightarrow \quad G_3(r) = -\frac{1}{4\pi r} \quad \Longrightarrow \quad g_N = \frac{GM}{r^2} \tag{13.1}$$

On the 2D boundary (where write-density propagates):

$$\nabla^2_{2D}\,\rho_w = \text{source} \quad\Longrightarrow\quad G_2(r) = -\frac{1}{2\pi}\ln\left(\frac{r}{r_0}\right) \quad\Longrightarrow\quad \rho_w \propto \ln\left(\frac{R_{\max}}{R}\right) \tag{13.2}$$

The boundary's logarithmic write-density profile projects into the bulk as a gravitational potential correction via the Jacobson thermodynamic mechanism ($\delta Q = T\,\delta S$, $\delta S = c^3\delta A/4G$):

$$\Phi_{\text{write}}(r) = -\sqrt{GM\cdot a_w}\;\ln\left(\frac{r}{r_0}\right) \tag{13.3}$$

Taking the gradient:

$$\boxed{g_{\text{write}}(r) = \frac{\sqrt{GM\cdot a_w}}{r}} \tag{13.4}$$

This $1/r$ acceleration does not exist in standard 3D Newtonian gravity. It arises entirely from the dimensional mismatch between the 2D boundary and the 3D bulk.

13.3 The acceleration scale

The boundary has Gibbons–Hawking temperature $T_{GH} = \hbar H/(2\pi k_B)$. Each write-event carries thermal energy $\sim k_B T_{GH}$. The acceleration imparted per write-event per Compton momentum quantum ($\hbar/c$) is:

$$\boxed{a_w = \frac{k_B T_{GH}}{\hbar/c} = \frac{cH_0}{2\pi} \approx 1.04\times 10^{-10}\ \text{m/s}^2} \tag{13.5}$$

This is *not* a free parameter. It is derived from H_0 and c alone. Its value is within 13% of the empirical MOND acceleration constant $a_0 \approx 1.2\times 10^{-10}$ m/s^2—a coincidence ($a_0 \sim cH_0$) that has been noted since Milgrom (1983) but never satisfactorily explained. This framework provides the explanation: a_0 is the Gibbons–Hawking thermal energy of the cosmological boundary expressed as an acceleration.

13.4 Effective gravitational acceleration

The total effective acceleration is:

$$\boxed{g_{\text{eff}}(r) = \frac{GM(r)}{r^2} + \frac{\sqrt{GM(r)\cdot a_w}}{r}} \tag{13.6}$$

Regime I (Newtonian, $r \ll r_t$): $GM/r^2 \gg \sqrt{GMa_w}/r$, so $g_{\text{eff}} \approx GM/r^2$.
Regime II (write-density dominated, $r \gg r_t$): $\sqrt{GMa_w}/r \gg GM/r^2$, so:

$$v^2 = r\cdot g_{\text{eff}} \approx \sqrt{GM\cdot a_w} = \text{constant} \quad\Longrightarrow\quad \text{flat rotation curves} \tag{13.7}$$

The transition radius is:

$$r_t = \sqrt{\frac{GM}{a_w}} \tag{13.8}$$

13.5 The baryonic Tully–Fisher relation

In the write-density dominated regime:

$$\boxed{v^4 = GM \cdot a_w} \tag{13.9}$$

This is the baryonic Tully–Fisher relation with slope *exactly* 4, normalization set by H_0 and c, and zero free parameters. The observed slope is 3.85 ± 0.09 (McGaugh et al. 2000); the observed normalization is consistent within the systematic uncertainties of baryonic mass estimation.

13.6 Numerical results

Galaxy	M_b [$M_\odot$]	r_t [kpc]	$v_{\text{flat}}^{\text{pred}}$ [km/s]	$v_{\text{flat}}^{\text{obs}}$ [km/s]
Milky Way	5.0×10^{10}	8.2	162	220
NGC 3198	2.5×10^{10}	5.8	136	150
UGC 2885	1.0×10^{11}	11.6	193	300
DDO 154 (dwarf)	5.0×10^{7}	0.3	29	50

The predicted flat-velocity values are systematically 20–40% below observed values, indicating that the simple additive interpolation of Eq. 13.6 is not the correct interpolation function. The *functional form* (flat at large r, Keplerian at small r), the *scaling law* (Tully–Fisher slope 4), and the *acceleration scale* (within 13% of a_0) are all correct. The amplitude deficit is a calibration problem requiring refinement of the interpolation, not a structural failure of the mechanism.

13.7 Distinguishing predictions

The most important distinguishing prediction is the time-evolution of the acceleration scale:

$$a_w(z) = \frac{cH(z)}{2\pi} \tag{13.10}$$

At $z = 1$: $H(z{=}1) \approx 1.5\, H_0$, so $a_w(z{=}1) \approx 1.5\, a_w(z{=}0)$. At $z = 2$: $a_w(z{=}2) \approx 2.3\, a_w(z{=}0)$. Galaxy rotation curves at high redshift should show *stronger* write-density effects—flatter curves at smaller radii—than their low-redshift counterparts of similar baryonic mass.

Observable	Write-density	CDM	MOND
Tully–Fisher slope	4.0 exactly (derived)	∼3.5–4.0 (halo-dependent)	4.0 (postulated)
Normalization	Set by H_0: $a_w = cH/(2\pi)$	Free parameter per halo	a_0 = empirical constant
$a_0 \sim cH_0$ coincidence	Explained	Unexplained	Noted, unexplained
Time evolution	$a_w(z) \propto H(z)$	DM density evolves	a_0 constant
Empty voids	Reduced gravity	DM halos present	No MOND effect

13.8 Open challenges

Two observational tests pose challenges that must be addressed before the write-density mechanism can be considered a complete replacement for dark matter:

The Bullet Cluster. Gravitational lensing maps of the 1E 0657-56 cluster collision show that mass concentration is offset from the baryonic gas. If gravity tracks write-density and write-density tracks baryonic interactions, the strongest gravity should follow the gas. The observed lensing follows the galaxies instead. A possible resolution: the boundary ledger is permanent (axiom G4), so emergent gravity may reflect the *integrated* write-record rather than instantaneous write-density. The galaxies carry their accumulated write-history; the gas was stripped. This requires formalization.

CMB acoustic peaks. The relative heights of the acoustic peaks are exquisitely fit by cold dark matter that was gravitationally active before recombination. Any replacement mechanism must reproduce these peak ratios quantitatively. This has not yet been demonstrated for the write-density mechanism and represents the most demanding test.

14 Agency Within the Grammar

Agency is real but grammatically bounded. The grammar specifies the available phase space but not which state is selected. Interaction density determines the degree of agency: a system with low interaction density initiates no write-events; a system with high-complexity information exchange may constitute a high-density write-agent.

15 Empirical Signatures

Status	Signature	Description
Confirmed	Bekenstein bound	Entropy scales with area, not volume
Confirmed	CMB scale invariance	$n_s \approx 0.965$; slight red tilt consistent with decreasing write-rate
Confirmed	RT formula	$S = \text{Area}/4G$ in all tested holographic systems
Consistent	DESI 2024	Tentative weakening dark energy ($\sim$2–3σ from ΛCDM)
Testable	Planck-scale discreteness	Lorentz invariance deviations at ultra-high energies
Testable	Hubble tension interpolation	Intermediate-redshift H_0 measurements should interpolate smoothly
Testable	Island formula / Page curve	Analogue black holes in condensed matter
Predicted	Low-ℓ CMB phase structure	Structured non-Gaussian correlations at $\ell \lesssim 10$
Predicted	Write-density rotation curves	$a_w(z) = cH(z)/(2\pi)$ — time-dependent acceleration scale

16 The Event Horizon as Write-Saturation

16.1 ER = EPR as formal anchor

Under Susskind and Maldacena's ER = EPR conjecture, the interior field degrees of freedom of a collapsing black hole become maximally entangled with the horizon degrees of freedom, geometrically equivalent to a wormhole connecting interior to horizon. In grammar terms: the interior and horizon are complementary descriptions of one quantum system, connected by entanglement structure. Classical light cannot use the wormhole channel. That asymmetry is what the horizon is.

16.2 Capacity versus complexity

Write-saturation is a *local complexity constraint*, not a capacity limit. The exterior boundary has ample informational capacity; what it lacks is a simple operator—one accessible to a local, causal agent—that reconstructs the interior. This is the Harlow–Hayden result: decoding the interior from the radiation requires quantum computation of exponential complexity in the black hole entropy.

$$S_{BH} = \frac{A}{4G_N} \quad \longleftrightarrow \quad \text{scrambling depth required to saturate local write-capacity} \tag{16.1}$$

Caveat. The scrambling time formula and Hayden–Preskill theorem are derived in asymptotically AdS settings. In de Sitter spacetime, the natural temperature is the observer-dependent Gibbons–Hawking temperature. The scrambling time argument should be treated as indicative rather than directly applicable to a dS cosmological horizon.

Prediction. When a precise dS dual is established, the null surface of GR should correspond to the locus of zero local outward write-capacity—a local complexity constraint, consistent with global information recovery via the Hawking channel.

17 Predictions and Falsifiability

This framework makes concrete empirical claims that differ from standard ΛCDM with single-field slow-roll inflation.

17.1 Horizon-scale phase correlations in the CMB

Prediction. If classical spacetime is rendered from boundary entanglement, the earliest decoherence events impose global consistency constraints on primordial fluctuations. The largest-scale modes ($\ell \lesssim 10$) should exhibit weak but structured phase correlations deviating from random-phase Gaussian statistics.

Contrast with ΛCDM. Standard single-field slow-roll inflation predicts nearly Gaussian fluctuations with statistically random phases. Large-angle anomalies are attributed to cosmic variance.

Commitment on existing data. The Planck 2018 data exhibit anomalies at low multipoles—quadrupole-octopole alignment, hemispherical power asymmetry, suppressed large-angle correlations—at 2–3σ significance. The framework offers a structural reason: the largest-scale modes are most directly imprinted by global boundary consistency constraints and are therefore least likely to exhibit purely random Gaussian statistics. These anomalies are consistent with the prediction but do not confirm it. The framework commits to a directional bet: LiteBIRD's polarization data and CMB-S4's improved large-angle sensitivity will push these anomalies toward significance, not wash them out.

Falsifiability. If increasingly precise CMB analyses show low-ℓ phase statistics converging to Gaussian randomness, and if existing Planck anomalies weaken rather than strengthen, the hypothesis is disfavored.

17.2 Decoherence threshold for classical geometry

Prediction. Classical spacetime emergence requires a minimum write-density on the boundary. Below this threshold, quantum superposition dominates and no stable classical geometry persists.

Quantitative anchor. Axioms G1 and G3 jointly yield $N_{\min} \sim 10^{52}$ (full derivation in Appendix B). During inflation over N_e e-folds, boundary area grows as $A_{\text{end}}/A_{\text{start}} = e^{2N_e}$. Starting from the minimum initial boundary $A_0 = \ell_P^2$ (G1), the qubit modes activated during inflation are:

$$\Delta N = \frac{A_{\text{end}} - A_{\text{start}}}{\ell_P^2} = e^{2N_e} - 1 \approx e^{120} \approx 10^{52} \tag{17.1}$$

This manifests not as a sharp cutoff but as a power deficit at $\ell \sim 2$–5, where boundary write-density was closest to the minimum threshold during the first observable e-folds.

Falsifiability. If the primordial power spectrum is consistent with classical behavior arbitrarily close to the initial singularity—no threshold behavior, no low-ℓ deficit—the claim is disfavored.

17.3 Write-density acceleration scale

Prediction. The acceleration scale $a_w = cH(z)/(2\pi)$ evolves with redshift. Galaxy rotation curves at $z > 1$ should show systematically stronger write-density effects than low-redshift counterparts of similar baryonic mass.

Contrast. CDM predicts similar or weaker effects at high z. MOND predicts no evolution (a_0 is constant). This framework predicts a_w increases with z.

Falsifiability. If high-redshift galaxy kinematics (JWST) show no evolution of the acceleration scale, or if the acceleration scale decreases with z, the write-density mechanism is disfavored.

17.4 Boundary capacity and horizon entropy growth

Prediction. Horizon area growth constrains the rate of new classical information production per Hubble time. This imposes an upper bound on the emergence rate of classical degrees of freedom.

Falsifiability. If entropy production rates or mode emergence rates violate any bound implied by horizon area growth, the boundary-capacity interpretation is disfavored.

17.5 Summary of falsifiability commitments

1. Planck low-ℓ anomalies deepen with LiteBIRD and CMB-S4.
2. Write-density-driven power deficit persists at $\ell \lesssim 10$, anchored to $N_{\min} \sim 10^{52}$.

3. Entropy production bounded by horizon area growth.
4. Inflaton potential belongs to the Starobinsky class: $n_s \approx 0.9678$, $r \approx 0.00296$ for $N_e = 60$.
5. Acceleration scale $a_w = cH(z)/(2\pi)$ evolves with redshift (testable by JWST).

18 Historical Positioning

18.1 Three failures, one root cause

Problem	**Grammar reframing**
Cosmological constant	The 3D calculation is a projection of boundary energy through a dimensional amplification factor. A category error.
Quantum gravity	Gravity is not fundamental; it is the bulk's rendering of boundary write-topology. Quantizing it directly is quantizing a derived quantity.
Hubble tension	Early measurements probe global boundary write-rate; late measurements probe local bulk geometry. A genuine physical signal from boundary evolution.

18.2 Three claims likely to survive revision

(1) The boundary is not a mathematical convenience. The RT formula, Bekenstein–Hawking entropy, and Gibbons–Hawking temperature all behave as if the boundary is where the physics resides. Susskind–Lindesay (2005) and Bousso (1999) showed the holographic entropy of the observable universe recovers the event horizon radius.

(2) Gravity is a derived quantity. The emergent gravity program—Jacobson (1995), Verlinde (2011), Van Raamsdonk (2010)—converges on this conclusion from multiple independent directions.

(3) The cosmological constant problem is a category error. The 10^{120} discrepancy has resisted every solution that accepts the premise that 3D QFT vacuum energy and observed Λ are commensurate.

18.3 Relation to Penrose's Conformal Cyclic Cosmology

The frameworks converge on the significance of conformal geometry at temporal extremes and on the proposition that the question "what happened before the Big Bang" is answerable. They diverge on the mechanism: CCC posits a conformal bridge between classical bulk spacetimes; this framework posits a boundary ledger that never dissolved. CCC predicts CMB rings from previous-aeon black holes; this framework predicts grammar parameter constraints on physical constants.

18.4 The research agenda

Gap	What closes it	Timeline
dS/CFT dictionary	Rigorous dS/CFT correspondence	5–20 years
G4 derivation (α)	$\alpha = \sqrt{2/3}$ from first principles	Requires complete boundary theory
Inflaton potential class	LiteBIRD (n_s to ± 0.002, r below 0.001)	$\sim$2030
Hubble tension	Intermediate-z H_0 (DESI DR2/DR3)	3–7 years
Write-density amplitude	Correct interpolation function	Formal derivation needed
Bullet Cluster	Write-history vs. instantaneous density	Requires formalization
CMB acoustic peaks	Quantitative peak ratios from write-density	Not yet demonstrated

A Grammar-Derived Inflaton Potential

This appendix presents a toy-model realization of the grammar framework applied to single-field slow-roll inflation.

A.1 Consistency axioms

G1 (Finite Qubit Bound)

The boundary admits finite information capacity $N \sim A/\ell_P^2$, implying a compact inflaton configuration space and an asymptotic plateau: $\lim_{\phi\to\infty} V(\phi) = V_0$.

G2 (Monotone Write-Density)

Monotonically decreasing Hubble rate implies $V'(\phi) > 0$ for $\phi > 0$ and $V(0) = 0$ at the reheating endpoint.

G3 (Configuration-Space Depth)

At least $N_e \geq 60$ e-folds, constraining the potential's curvature scale.

G4 (Holographic Projection Factor)

The inflaton is the order parameter of a collective boundary mode. The kinetic term is induced by the Fisher information metric on the boundary state space: $\alpha = \sqrt{2/3}\, M_{Pl}^{-1}$.

G5 (Ledger Persistence)

Speculative. The boundary carries entanglement structure across render cycles with fidelity $\gamma \approx 1 - D_{KL}(P_{\text{final}} \| P_{\text{initial}}) / \ln N_{\text{total}}$.

A.2 Selected potential

The minimal functional form satisfying G1–G2 is the E-model/Starobinsky plateau potential:

$$V(\phi) = V_0 \left(1 - e^{-\alpha\phi}\right)^2 \tag{A.1}$$

with normalization V_0 fixed by the observed scalar amplitude A_s.

A.3 Slow-roll results

For $N_e = 60$ and $\alpha = \sqrt{2/3}$:

Leading-order approximations:

$$n_s \approx 1 - \frac{2}{N_e} = 0.9667, \qquad r \approx \frac{12}{N_e^2} = 0.00333 \tag{A.2}$$

Exact slow-roll integration:

$$\boxed{n_s \approx 0.9678, \qquad r \approx 0.00296} \tag{A.3}$$

Both values are consistent with Planck 2018 constraints ($n_s = 0.9649 \pm 0.0042$, $r < 0.036$). LiteBIRD (2030) will constrain r below 0.001, providing a definitive test.

B Derivation of the Decoherence Threshold

This appendix derives $N_{\text{min}} \sim 10^{52}$ and $\rho_{w,\text{min}}$ from axioms G1 and G3.

B.1 Boundary area scaling during inflation

During slow-roll inflation, $a_{\text{end}}/a_{\text{start}} = e^{N_e}$. Surface area scales as the square of the linear dimension:

$$\frac{A_{\text{end}}}{A_{\text{start}}} = e^{2N_e}, \qquad \frac{N_{\text{end}}}{N_{\text{start}}} = e^{2N_e} \tag{B.1}$$

B.2 Minimum initial boundary and $N_{\min}$

From G1, the minimum nonzero boundary area is $A_0 = \ell_P^2$. The total new qubit modes activated during inflation:

$$\Delta N_{\min} = (e^{2N_e} - 1) \cdot \frac{A_0}{\ell_P^2} = e^{120} - 1 \approx 10^{52} \tag{B.2}$$

B.3 Write-density threshold

The number of Planck-area cells on the boundary of a Hubble patch:

$$N_{\text{horizon}} = 4\pi \left(\frac{M_{Pl}}{H}\right)^2 \tag{B.3}$$

The minimum write-density for classical coherence:

$$\rho_{w,\min} = \frac{1}{N_{\text{horizon}}} = \frac{H^2}{4\pi M_{Pl}^2} = \frac{V(\phi)}{12\pi M_{Pl}^4} \tag{B.4}$$

Below this density, the grammar cannot maintain stable decoherence patterns across a causally connected region.

B.4 Connection to the CMB

Modes at $\ell \sim 2$–5 exited the horizon when boundary occupation was nearest $N_{\min}$ and write-density nearest $\rho_{w,\min}$. These modes experienced the weakest classical coherence. The framework predicts a power deficit at these scales—consistent with the $\sim$10% Planck 2018 deficit at $\ell = 2, 3$.

B.5 Boundary radius verification

From G1: $r = \ell_P \sqrt{N/\pi}$.

$$r_0(1 \text{ bit}) = \frac{\ell_P}{\sqrt{\pi}} \approx 9.1 \times 10^{-36} \text{ m} \tag{B.5}$$

$$r_0(1000 \text{ bits}) = \ell_P \sqrt{\frac{1000}{\pi}} \approx 2.9 \times 10^{-34} \text{ m} \tag{B.6}$$

$$r_{\text{now}} = \ell_P \sqrt{\frac{S_{dS}}{\pi}} \approx 1.58 \times 10^{26} \text{ m} \approx 16.7 \text{ Gly} \tag{B.7}$$

The current radius matches the cosmological event horizon ($\sim$16 Gly), not the particle horizon ($\sim$46 Gly). A geometric singularity ($r = 0$) is excluded by G1: zero area means zero information capacity.

C Ledger Persistence: Speculative Extension

Status: Not implied by known holographic dualities.

The contraction map for the field parameter α converges to the Starobinsky fixed point:

$$\alpha_{N+1} = \alpha_N - \kappa(\alpha_N - \alpha_0) \tag{C.1}$$

$$\kappa = \frac{1}{\ln(10^{122})} \approx 0.00356 \qquad \alpha_0 = \sqrt{2/3} \approx 0.8165 \tag{C.2}$$

Convergence to within 0.1% of α_0 requires $\sim$1930 render cycles. The physical motivation—computational shear minimization under the Bekenstein bound—is interpretive. The κ/γ distinction is maintained throughout: κ is the contraction rate; γ (G5) is ledger-transfer fidelity.

Acknowledgments

The author acknowledges the formal results of AdS/CFT, the RT formula, and the ER = EPR conjecture as the mathematical foundation on which this interpretive framework rests. The write-density gravity analysis benefited from comparison with the MOND literature (Milgrom 1983; McGaugh et al. 2000) and the emergent gravity program (Jacobson 1995; Verlinde 2011, 2016; Van Raamsdonk 2010).

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