

An Information-Theoretic Approach to Entropic Gravity in a Cyclic Topology

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February 2026

Abstract

I propose a cosmological model where the observable universe is treated as a holographic projection on a regularized horn torus topology. Unlike standard Friedmann-Lemaître-Robertson-Walker (FLRW) metrics that begin at a dimensionless singularity, my model introduces a Planck-scale throat ($l \approx 1.6 \times 10^{-35}$ m) at the central conjunction. This non-zero geometry acts as a conduit for information preservation, linking a prior "Big Crunch" phase to the current epoch, thereby resolving the information loss paradox.

I posit that spacetime is an emergent information-theoretic substrate in which General Relativity and the Standard Model arise as effective descriptions. In this framework, the speed of light (c) represents the fundamental rate of information propagation. Gravitational time dilation is reinterpreted as an entropic effect: regions of high mass-energy density exhibit higher holographic entropy, resulting in a localized slowing of proper time relative to the background metric. Cosmic expansion is driven by the relaxation of the toroidal boundary, effectively increasing the system's entropy capacity ($S \propto A$).

Ideas similar to those explored here, such as horn torus topologies in cosmology, cyclic universes with toroidal geometry, regularized singularities at the Planck scale, and entropic or information-theoretic approaches to gravity and cosmic expansion, have been investigated in prior works [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

1 Introduction

The quest for a unified description of the universe that reconciles general relativity (GR) with quantum mechanics has led to various speculative frameworks. This paper builds on holographic principles and entropic gravity to propose an emergent cosmology on a regularized horn torus manifold. Horn torus topologies, characterized by hyperbolic geometries, have been discussed in cosmic topology literature as potential models for negatively curved spaces [1, 2]. Cyclic cosmologies incorporating toroidal elements have also been explored, offering alternatives to singular Big Bang models [3, 4, 1].

By regularizing the central singularity at the Planck scale, I avoid infinities in curvature, a concept echoed in loop quantum cosmology and scalar-field frameworks for singularity resolution [14, 5, 6]. The information-theoretic lens draws from entropic gravity theories, where

gravity emerges from entropy gradients, and extends to cosmic scales to explain expansion without ad hoc dark energy [11, 10, 9, 8, 7].

This approach emphasizes the universe as a dynamic, information-preserving system, with emergent phenomena arising from holographic entropy bounds and thermodynamic principles.

To clarify the holographic projection, I invoke a bulk-boundary correspondence inspired by AdS/CFT duality [16]. Here, operators on the toroidal boundary encode bulk fields via tensor network structures [17], where boundary bits correspond to bulk quanta through quantum error-correcting codes. Specifically, the mapping relates boundary correlation functions to bulk expectation values, e.g., $\langle O(\mathbf{x})O(\mathbf{y}) \rangle_{\text{boundary}} \sim G(\mathbf{x}, \mathbf{y})_{\text{bulk}}$, ensuring that local bulk dynamics, such as particle interactions, arise from non-local boundary correlations, providing a mechanism for emergence. The T^2 surface of the horn torus acts as a series of nested holographic screens, where as the universe expands, observers transition from inner to outer screens, increasing the available Hilbert space and thus the number of possible quantum states.

2 The Planck-Scale Throat and Information Conservation

The central singularity of the classical horn torus is replaced by a minimal surface area, a "disk" of diameter l_P (Planck length).

2.1 The Throat

This structure functions as a bridge between the collapsing phase of a previous cycle and the expansion phase of the current one. Similar regularizations at Planck scales have been proposed to resolve Big Bang singularities [5, 6].

2.2 Resolution

By imposing a minimum length cutoff, I avoid the infinite curvature singularities of classical GR. Matter and information traversing this throat are "compressed" to the holographic limit but are not destroyed, emerging as the initial conditions of the Big Bang. This preserves information across cycles, addressing the black hole information paradox through holographic encoding [7].

3 The Emergent Information Flow in Spacetime

I reinterpret the metric of spacetime not as a fundamental background, but as the output of an underlying information-theoretic system governed by holographic principles.

3.1 Speed of Light (c)

This is defined as the causal information processing limit, consistent with causal limits in entropic gravity frameworks [11]. In this model, space and time emerge as dimensions that organize information processing while maintaining causality, with c setting the conversion between spatial and temporal intervals.

3.2 Mass as Information Density

Matter is defined as a localized region of high information density, per the Bekenstein bound and holographic entropy [8, 9].

3.3 Time Dilation

Following the holographic principle, a region with high mass (high entropy density) induces curvature that manifests as time dilation. This is an entropic effect, where higher entropy regions evolve at a different rate relative to low-entropy backgrounds.

Formalism: If the system has an entropy production rate Ω , and a volume contains N bits of information, the local flow of time Δt scales as $\Delta t \propto N/\Omega$, derived from thermodynamic considerations.

4 Entropy and The Expanding Boundary

The torus structure itself remains topologically static; however, the holographic boundary (the outer wall) undergoes radial growth.

4.1 Entropic Drive

As the radius of the torus's outer section increases, the surface area A grows. Since the maximum entropy is bounded by area ($S \leq A/4G$), this expansion allows the universe to transition from a low-entropy state (at the throat) to a high-entropy state. Entropic gravity theories link this to cosmic acceleration [10, 11, 15].

4.2 Emergent Gravity

The tendency of the system to maximize entropy manifests macroscopically as the "force" of gravity and the expansion of space.

5 Mathematical Framework

In this section, I formalize the information-theoretic interpretation of spacetime dynamics. My goal is to derive an "Information-Theoretic Metric" that maps the emergent properties of the regularized horn torus manifold to observable gravitational phenomena.

5.1 Foundations: Holographic Entropy, Variational Principles, and Information Load

The model is grounded in the holographic principle. For any spherical region the boundary area A bounds the entropy via

$$S \leq \frac{A}{4l_P^2},$$

where l_P is the Planck length. We interpret S as the instantaneous information content and $A/4l_P^2$ as the total computational capacity of the local spacetime substrate.

To derive the emergent dynamics we maximize the entropy subject to energy and conservation constraints using the action

$$\mathcal{A} = \int \left(S - \lambda \left(\int \rho_S dV - S_{\text{total}} \right) - \mu \left(\frac{dS}{dt} - \Omega(1 - f(\rho_S)) \right) \right) dt,$$

where ρ_S is the entropy (information) density, λ, μ are Lagrange multipliers, and $f(\rho_S) \approx \kappa \rho_S$ encodes the linear response of high-density regions (motivated by Landauer's principle and microcanonical fluctuations).

Extremizing with respect to ρ_S yields the equilibrium condition

$$\frac{\delta S}{\delta \rho_S} = \lambda + \mu \Omega \frac{\delta f}{\delta \rho_S}.$$

Identifying the information density ρ_S with the local “entropy debt” imposed by mass-energy leads to a Poisson-like equation $\nabla^2 \Phi \propto \rho$ in the weak-field limit, recovering Newtonian gravity as an entropic effect.

Link to Capacity and Load. We now promote these ideas to a local processing picture. A spherical holographic screen of radius r has a discrete channel capacity given by the number of Planck patches:

$$\mathcal{C}(r) = \frac{4\pi r^2}{l_P^2}.$$

A central mass M imposes an information load

$$\mathcal{I}(r) = \frac{8\pi M c r}{\hbar}$$

on this screen. The ratio \mathcal{I}/\mathcal{C} directly measures the fractional occupation of the vacuum's processing resources and will serve as the source term in the metric derivation below.

5.2 Derivation of the Information-Theoretic Metric

The metric tensor $g_{\mu\nu}$ measures the processing latency of the information substrate. Proper time τ advances more slowly where the vacuum is occupied encoding mass-energy.

Definition 1 (Fundamental Clock): The universe ticks at the Planck time $t_P = l_P/c$.

Definition 2 (Channel Capacity): A spherical holographic screen at radius r has total capacity

$$\mathcal{C} = \frac{4\pi r^2}{l_P^2}.$$

Definition 3 (Information Load): The load imposed by central mass M is

$$\mathcal{I} = \frac{8\pi M c r}{\hbar}.$$

The local proper-time flow is the idle fraction of capacity:

$$\frac{d\tau}{dt} = \sqrt{1 - \frac{\mathcal{I}}{\mathcal{C}}}.$$

When $\mathcal{I} \rightarrow \mathcal{C}$, proper time halts (event horizon).

Substituting the definitions:

$$\frac{\mathcal{I}}{\mathcal{C}} = \frac{8\pi M c r / \hbar}{4\pi r^2 / l_P^2} = \frac{2M c l_P^2}{\hbar r}.$$

Using $l_P^2 = \hbar G / c^3$ (i.e., the emergent coupling $G = l_P^2 c^3 / \hbar$) we obtain

$$\frac{\mathcal{I}}{\mathcal{C}} = \frac{2GM}{rc^2},$$

and therefore

$$\frac{d\tau}{dt} = \sqrt{1 - \frac{2GM}{rc^2}},$$

exactly the Schwarzschild time-dilation factor. Gravity and the metric structure emerge purely from the ratio of holographic information load to channel capacity; G appears only at the final step when converting to laboratory units.

5.3 Derivation of MOND from Holographic Saturation

At high accelerations the screen operates far above the cosmic de Sitter noise floor and the standard \mathcal{I}/\mathcal{C} ratio recovers Newtonian gravity. At low accelerations the incremental load $\Delta\mathcal{I}$ contributed by baryonic matter becomes comparable to or smaller than the background capacity set by the de Sitter horizon (minimum temperature $T_{\min} \approx \hbar H_0 / (2\pi k_B)$, corresponding to $a_0 \approx cH_0$).

In this regime the effective capacity acquires a constant background term $\mathcal{C}_{\text{bg}} \propto T_{\min}$, and the response to an additional load becomes nonlinear. The change in proper-time flow is no longer linear in $\Delta\mathcal{I}$ but follows

$$\delta\left(\frac{d\tau}{dt}\right) \propto \sqrt{\frac{\Delta\mathcal{I}}{\mathcal{C}_{\text{bg}}}},$$

because the screen's bit-update rate is limited by thermal fluctuations at the noise floor (analogous to modified equipartition below a critical temperature in entropic MOND derivations).

For a test particle the effective acceleration $g_{\text{eff}} = |\nabla\Phi|$ then satisfies

$$g_{\text{eff}} \approx \sqrt{g_N a_0},$$

where $g_N = GM/r^2$ is the Newtonian acceleration from the baryonic mass. This is the deep-MOND regime: rotation curves flatten ($v^4 \propto Ma_0$) and the baryonic Tully–Fisher relation emerges naturally. The same saturation mechanism explains the external-field effect and the Bullet-Cluster-like separation of entropic “wakes” from baryons without particulate dark matter.

The transition is governed by the interpolation function implicit in the full \mathcal{I}/\mathcal{C} dynamics, recovering Newtonian behavior when $g_N \gg a_0$ and MOND behavior when $g_N \ll a_0$, all within the same first-principles information-processing framework.

5.4 Regularization at the Planck-Scale Throat

A standard Horn Torus is defined by a major radius R and minor radius r where $R = r$. This creates a singularity at the center. I introduce a regularization parameter $\epsilon \approx l_P$ (Planck length).

The regularized metric for the manifold is:

$$ds^2 = -c^2 dt^2 + d\rho^2 + \rho^2 d\phi^2 + (R + \rho \cos \theta)^2 d\psi^2$$

subject to the constraint $R = r + \epsilon$. This metric describes the line element in coordinates where ρ is the radial distance from the axis, preventing divergence at $\rho = 0$.

The “Throat” is defined at the coordinate limit where the torus would self-intersect. Instead of a point, I find a minimal surface area:

$$A_{\text{throat}} \approx 4\pi^2(l_P)r$$

This non-zero area allows for a finite flux of entropy $\dot{S} < \infty$, resolving the information loss paradox associated with a zero-dimensional Big Bang singularity.

5.5 Asymptotic Approach to FLRW Metric

To address the observed flatness, I demonstrate that the horn torus metric approaches the flat FLRW form at observable scales. The regularized metric is:

$$ds^2 = -c^2 dt^2 + d\rho^2 + \rho^2 d\phi^2 + (R + \rho \cos \theta)^2 d\psi^2,$$

with $\rho \geq l_P$. For large R (major radius) and observers at $\rho \ll R$, expand $(R + \rho \cos \theta)^2 = R^2 + 2R\rho \cos \theta + \rho^2 \cos^2 \theta$. Neglecting higher-order terms $\mathcal{O}(\rho^2/R^2)$, the metric approximates $ds^2 = -c^2 dt^2 + d\rho^2 + \rho^2 d\phi^2 + R^2 d\psi^2 + 2R\rho \cos \theta d\psi^2$. Rescaling $\psi' = R\psi$, this becomes approximately flat $ds^2 = -c^2 dt^2 + d\rho^2 + \rho^2 d\phi^2 + dz^2$ (with $z = \rho \cos \theta$), which is Minkowski in cylindrical coordinates. Incorporating expansion via a scale factor $a(t)$ on the spatial part yields the flat FLRW metric $ds^2 = -c^2 dt^2 + a(t)^2(dr^2 + r^2 d\Omega^2)$, consistent with $\Omega_k \approx 0$. This expansion demonstrates how the local metric becomes independent of the global curvature for large R .

5.6 Quantum Extensions and Testable Predictions

The framework aligns with holographic cosmology, predicting deviations in high-energy regimes observable in CMB anisotropies or gravitational waves.

For CMB: Topology suppresses power at low multipoles. Specifically, the quadrupole ($l = 2$) is reduced by $\sim 20\%$ compared to Λ CDM due to finite toroidal size, matching Planck observations of low large-scale power [12]. This reduction occurs because the topology limits the wavelength of fluctuations, cutting off power below certain scales.

6 Observational Consistency

6.1 Why a Horn Torus? Compatibility with Flat Universe

Planck data indicate a nearly flat universe ($\Omega_k \approx 0$), while horn tori exhibit hyperbolic curvature. However, away from the throat, the geometry approximates flatness if the major radius R is large compared to the observable horizon (~ 46 Gly). The throat’s Planck-scale regularization introduces negligible curvature locally, consistent with observations [1].

6.2 Suppression of Matched Circles in CMB Observations

Toroidal topologies predict matching circles in CMB if the fundamental domain is smaller than the last scattering surface. In my horn torus model, the non-compact hyperbolic nature (infinite in the “horn” direction) and large domain size suppress such signatures. Observers far from the throat (as we are) see no repeats, aligning with null searches [12].

The absence of correlated antipodal regions in the CMB is due to the hyperbolic metric’s exponential expansion, diluting topological imprints beyond the particle horizon.

6.3 Addressing Entropic Gravity Criticisms

Entropic gravity faces scrutiny for the Bullet Cluster, where lensing mass separates from gas, suggesting collisionless dark matter. However, in this framework, entropy gradients create a “wake” with finite relaxation time $\tau \sim \ell/c$ (where ℓ is the system scale), allowing the gravitational potential to lag behind collisional baryons during high-speed encounters (~ 1000 km/s), thus permitting spatial separation without particulate dark matter [11]. This lag is modeled as a retarded potential in the entropic force law, $F(t) = \int_{-\infty}^t dt' K(t-t') T \nabla S(t')$, with kernel K encoding memory effects. The integral incorporates past entropy gradients, allowing the potential to persist after baryons have moved.

For planetary orbits, accelerations exceed a_0 , so entropic corrections are negligible, matching GR/Newtonian predictions precisely.

In cluster collisions, the entropic potential’s nonlocal nature decouples from baryonic dissipation, reproducing weak lensing maps consistent with observations.

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