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Article

Is Gravity Fundamental? A Physical Interpretation of the Cosmological Constant Through Black Hole Cosmology

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Abstract

Recent decades have established that gravity may be emergent rather than fundamental. Jacobson derived Einstein's equations from thermodynamic principles, Verlinde proposed entropic gravity, and Padmanabhan developed extensive thermodynamic interpretations. However, these frameworks lack a concrete physical mechanism for the cosmological constant Λ —the deepest unsolved problem in physics, with a 10^{120} discrepancy between observation and quantum field theory. This paper provides a physical interpretation of Λ by combining emergent gravity with black hole cosmology. The central hypothesis is that the universe exists within a black hole in a parent universe, where steady matter infall from the exterior manifests as constant energy density ρ_Λ in the interior, providing a concrete, order-of-magnitude physical pathway. In weak-field and homogeneous limits, dynamics are governed by $\nabla^2\Phi = 4\pi G(\rho_m - 2\rho_\Lambda)$, where $\rho_\Lambda = \Lambda c^2/(8\pi G)$, demonstrating gravity as an interference effect. This framework is mathematically equivalent to Λ CDM, reproducing $H_0 = 67.43$ km/s/Mpc, $q_0 = -0.549$, and $z_{\text{trans}} = 0.67$. Rather than solving cosmological paradoxes, this interpretation naturalizes them through open-system energetics and inevitable transition dynamics, offering potentially testable implications while remaining equivalent to Λ CDM at the background level.

Keywords: emergent gravity; cosmological constant; black hole cosmology; dark energy; Λ CDM; physical interpretation; spacetime generation

1. Introduction

1.1. The Emergent Gravity Paradigm

Einstein's geometric paradigm has dominated for over a century: spacetime curvature caused by matter-energy ($G_{\mu\nu} = 8\pi GT_{\mu\nu}$). However, the past three decades have witnessed a conceptual shift suggesting gravity is not fundamental but *emergent*—arising from deeper microscopic processes.

Jacobson (1995) [1] demonstrated that Einstein's equations can be derived from the first law of thermodynamics ($\delta Q = TdS$) applied to local causal horizons, establishing that gravitational dynamics reflect thermodynamic principles.

Verlinde (2010, 2016) [2,3] proposed that gravity is an entropic force arising from holographic screens, with dark energy explained through elastic response to entropy displacement.

Padmanabhan (2002–2015) [4,5] developed comprehensive thermodynamic interpretations, demonstrating that gravitational field equations can be expressed in purely thermodynamic language.

1.2. The Unresolved Problem: Physical Origin of Λ

Despite profound advances, existing emergent gravity frameworks share a fundamental limitation: they do not provide a concrete physical mechanism for the cosmological constant—the 10^{120} discrepancy between observed vacuum energy density and quantum field theory predictions.

The standard Λ CDM model describes observations successfully but remains conceptually divided:

- **Gravity (G):** Matter attracting matter through spacetime curvature
- **Dark Energy (Λ):** A constant energy density causing cosmic acceleration

This creates profound conceptual challenges:

1. **The Cosmological Constant Problem:** Why is $\rho_\Lambda \sim 10^{-26} \text{ kg/m}^3$, while quantum field theory predicts $\rho_{QFT} \sim 10^{94} \text{ kg/m}^3$?
2. **The Coincidence Problem:** Why do ρ_m and ρ_Λ have comparable magnitudes today after 13.8 billion years of evolution?
3. **Energy Conservation Question:** If ρ_Λ is constant while volume V expands, how is the total energy $E = \rho_\Lambda V$ accounted for?

1.3. *This Work: A Physical Interpretation*

This paper provides a physical interpretation by combining:

1. **Emergent Gravity:** Following Jacobson, Verlinde, and Padmanabhan, gravity emerges from underlying processes
2. **Black Hole Cosmology:** Following Pathria (1972), Smolin (1992), and Poplawski (2010) [6–8], the universe may be the interior of a black hole—a mathematical equivalence between Schwarzschild black hole interiors and expanding FLRW universes

The key innovation is recognizing that black hole cosmology provides a physical mechanism: steady matter infall into a black hole from the exterior, when viewed from the interior, manifests as constant energy density—the observed ρ_Λ .

1.4. *Distinction from Prior Work*

Table 1. Comparison with prior emergent gravity frameworks.

Theory	Mechanism	Λ Treatment
Jacobson (1995)	Thermodynamic ($\delta Q = TdS$)	Not addressed
Verlinde (2010)	Entropic force, holographic screen	Not addressed
Verlinde (2016)	Elastic response to entropy displacement	Phenomenological
Padmanabhan (2010–2015)	Thermodynamic language	Remains abstract
This work	External energy influx	Physical mechanism

While previous theories use entropy and information as abstract principles, this work identifies external energy influx as the concrete physical process, transforming emergent gravity from philosophical insight to a picture with potentially testable implications.

2. Theoretical Framework

2.1. *The Open System Hypothesis*

The framework rests on three postulates:

Postulate 1 (Open System): The 4D universe is an open system embedded within a larger structure—a “Meta-Universe” (e.g., parent universe or external spacetime).

Postulate 2 (Nature of ρ_Λ): The Meta-Universe provides continuous, steady energy influx into the universe. This constant injection rate, per unit volume, is ρ_Λ .

Postulate 3 (Nature of Time/Space): This energy injection process drives both the flow of time and the creation of space.

2.2. *Physical Mechanism: Black Hole Cosmology*

2.2.1. The Mathematical Equivalence

The Schwarzschild solution describes a black hole. Inside the event horizon, the roles of time and radial coordinates exchange. An observer crossing the horizon experiences entry into a region appearing as an expanding universe.

This equivalence, developed by Pathria (1972), Smolin (1992), and Poplawski (2010) [6–8], reveals:

- Big Bang singularity $\leftrightarrow$ Black hole singularity ($r = 0$)
- Cosmic expansion $\leftrightarrow$ Infall toward singularity
- Event horizon $\leftrightarrow$ Boundary separating interior from exterior

Important caveat: This mathematical equivalence between Schwarzschild interior and FLRW metrics is established at the level of coordinate transformations and metric signatures. The physical interpretation—particularly the relationship between exterior and interior observers across the horizon—remains a subject of ongoing investigation in black hole thermodynamics and involves subtleties regarding information, causality, and the nature of the singularity. The order-of-magnitude arguments presented here should be understood in this context.

2.2.2. Quantitative Connection: $\dot{M}_{ext} \rightarrow \rho_\Lambda$

Consider matter falling into a black hole at rate $\dot{M}_{ext}$ in the exterior frame. The key is understanding how this appears to interior observers.

Time dilation at horizon: For exterior observers, matter takes infinite time to cross the horizon due to gravitational time dilation. The time dilation factor at the Schwarzschild radius r_s is:

$$\frac{dt_{ext}}{dt_{int}} \rightarrow \infty \quad \text{as } r \rightarrow r_s \quad (1)$$

Energy flux transformation: From the interior perspective, the exterior infall rate $\dot{M}_{ext}$ appears “frozen” at the horizon but continuously contributes energy. The key is understanding the rate at which this manifests in the interior frame.

For a black hole of radius $r_s \sim ct_0$ (where t_0 is the universe age), the accumulated mass from exterior infall over exterior time must satisfy:

$$M_{BH} \sim \int_0^{t_{ext}} \dot{M}_{ext} dt_{ext} \quad (2)$$

However, from the interior frame, this accumulated mass appears distributed over interior time. The interior energy influx rate per unit interior volume is:

$$\Gamma_{in} \sim \frac{M_{BH}}{t_{int} \cdot V_{int}} \quad (3)$$

Here t_{int} denotes the interior cosmic time related to the exterior time by horizon time-dilation; this mapping **smears** the exterior $\dot{M}_{ext}$ into a constant interior-frame influx.

Due to the relationship between exterior and interior time scales (set by the horizon time dilation), this reduces to an effective constant energy density:

$$\rho_\Lambda \sim \frac{M_{BH}}{V_{int}} \sim \frac{c^2}{Gr_s^2} \quad (4)$$

where the last step uses $M_{BH} \sim r_s c^2 / G$ (Schwarzschild relation). This constant density, combined with the continuity equation $\dot{\rho}_\Lambda + 3H(\rho_\Lambda + p_\Lambda) = 0$, requires $p_\Lambda = -\rho_\Lambda$ for consistency.

Numerical correspondence: For $r_s \sim ct_0 \sim 10^{26}$ m:

$$\rho_\Lambda \sim \frac{c^2}{G(ct_0)^2} \sim \frac{1}{Gt_0^2} \sim 10^{-26} \text{ kg/m}^3 \quad (5)$$

This is of the same order as the observed critical density $\rho_{crit} \sim 10^{-26} \text{ kg/m}^3$.

Constancy of ρ_Λ : The key insight is that time dilation at the horizon creates an effective “steady state” from the interior perspective. Exterior infall rate $\dot{M}_{ext}$ becomes “smeared” across interior cosmic time due to infinite time dilation, manifesting as constant ρ_Λ .

While this is an order-of-magnitude argument rather than rigorous derivation, it demonstrates that black hole cosmology naturally produces the correct scale for ρ_Λ .

2.3. The Unified Field Equation

Dynamics in the weak-field and homogeneous limits considered here are governed by a single scalar field Φ —the Spacetime Generation Potential:

$$\nabla^2\Phi = 4\pi G(\rho_m - 2\rho_\Lambda) \tag{6}$$

Connection to standard notation: In the Newtonian limit of General Relativity with cosmological constant, the Poisson equation is:

$$\nabla^2\Phi = 4\pi G\rho_m - \Lambda c^2 \tag{7}$$

Therefore, the relationship is:

$$\rho_\Lambda = \frac{\Lambda c^2}{8\pi G} \tag{8}$$

This makes explicit that ρ_Λ is simply the energy density form of the cosmological constant, with Λ having dimensions $[\text{length}]^{-2}$. The factor of 2 in the field equation arises from the standard definition.

Sign convention: With $\Phi < 0$ near masses (attractive), $-2\rho_\Lambda$ acts as a negative source, creating a “potential hill” in empty space.

All motion follows the gradient:

$$\vec{a} = -\nabla\Phi \tag{9}$$

2.4. Physical Interpretation

Empty Space (The Hill): In voids, $\rho_m \approx 0$:

$$\nabla^2\Phi \approx -8\pi G\rho_\Lambda < 0 \tag{10}$$

This is a “potential hill”—objects accelerate away from each other (cosmic acceleration).

Matter Regions (The Interference): Near mass, total energy density is $\rho_{total} = \rho_m + \rho_\Lambda$. This high-energy state interferes with spacetime generation, slowing local time flow and creating a “potential well”:

$$\nabla^2\Phi \approx 4\pi G\rho_m > 0 \tag{11}$$

Objects move toward regions where time flows slowest—this is gravity.

2.5. Time Flow and Emergence

In General Relativity’s weak-field approximation, the metric is:

$$g_{00} \approx -(1 + 2\Phi/c^2) \tag{12}$$

The proper time relation is:

$$\frac{d\tau}{dt} \approx 1 + \frac{\Phi}{c^2} \tag{13}$$

where $d\tau$ is proper time (experienced locally) and dt is coordinate time. With $\Phi < 0$ near matter:

$$\frac{d\tau}{dt} < 1 \Rightarrow \text{Time flows MORE SLOWLY} \tag{14}$$

The spatial volume creation rate is proportional to the time flow rate. **Physical interpretation:** Matter creates regions where spacetime generation is hindered. Objects naturally move toward slow-time regions to maximize their proper time ($\delta \int d\tau = 0$)—this is gravity as an emergent phenomenon.

3. Mathematical Verification

3.1. Derivation of FLRW Equations

By applying the field equation to the homogeneous and isotropic FLRW metric, the standard Friedmann equations are derived:

First Friedmann Equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho_m + \rho_\Lambda) \tag{15}$$

Second Friedmann Equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 2\rho_\Lambda) \tag{16}$$

where $\rho_m = \rho_{m,0}a^{-3}$ and $\rho_\Lambda = \text{const.}$
The constancy of ρ_Λ requires (from energy-momentum conservation $\nabla_\mu T^{\mu\nu} = 0$):

$$p_\Lambda = -\rho_\Lambda \tag{17}$$

This negative pressure is not an assumption but a mathematical consequence of constant density in expanding spacetime.

3.2. Energy Conservation in the Open System

In standard General Relativity with closed systems, energy-momentum is conserved:

$$\nabla_\mu T^{\mu\nu} = 0 \tag{18}$$

In this framework, the 4D universe is an open system. The effective conservation equation includes a source term representing influx from the Meta-Universe:

$$\nabla_\mu T^{\mu\nu}_{4D} = J^{\nu}_{influx} \tag{19}$$

where J^{ν}_{influx} represents the energy-momentum flux from the exterior. For the background cosmology:

$$J^0_{influx} \sim \rho_\Lambda H \tag{20}$$

This expresses that energy is conserved in the total system (Meta-Universe + Universe), with the apparent “creation” being transfer across the boundary (event horizon).

3.3. Numerical Verification

Because the background equations are **by construction** identical to Λ CDM, the numerical curves coincide once $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$ are chosen; the contribution here is interpretive rather than predictive.

Table 2. Model predictions vs. Planck 2018 observations [11]. $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$ are inputs; H_0 , q_0 , and z_{trans} follow by construction; the contribution is interpretive rather than predictive.

Observable	Model	Planck 2018	Deviation
H_0 (km/s/Mpc)	67.43	67.4 ± 0.5	$+0.06\sigma$
q_0	-0.549	-0.55 ± 0.05	$+0.02\sigma$
$\Omega_{m,0}$	0.300	0.315 ± 0.007	(Input)
$\Omega_{\Lambda,0}$	0.700	0.685 ± 0.007	(Input)
z_{trans} ($q = 0$)	0.67	~ 0.7	Consistent

Important note: This framework is mathematically equivalent to Λ CDM for background cosmology. The numerical agreement reflects this equivalence, not new predictions. The contribution is providing physical interpretation, not modifying the mathematical structure.

4. Discussion

4.1. Physical Interpretation of the Paradoxes

Rather than claiming to “solve” the paradoxes, this framework provides physical interpretations that *naturalize* them:

4.1.1. Energy Conservation

Standard Puzzle: If ρ_Λ is constant while V expands, total energy $E = \rho_\Lambda V$ appears to be created from nothing.

Physical Interpretation: The universe is an open system. Energy is conserved in the combined system (Meta-Universe + Universe). The “creation” is energy transfer across the boundary, expressed mathematically as $\nabla_\mu T_{4D}^{\mu\nu} = J_{influx}^\nu$.

4.1.2. The Cosmological Constant Problem

Standard Puzzle: Why is $\rho_\Lambda \sim 10^{-26} \text{ kg/m}^3$, while quantum field theory predicts $\rho_{QFT} \sim 10^{94} \text{ kg/m}^3$?

Physical Interpretation: This is a category error. These are fundamentally different quantities:

- ρ_{QFT} = Theoretical vacuum energy *within* the 4D universe
- ρ_Λ = Rate of energy influx *from* the Meta-Universe

There is no reason they should be equal. ρ_Λ is a fundamental constant characterizing the coupling between universe and Meta-Universe. The black hole cosmology interpretation suggests $\rho_\Lambda \sim c^2/(Gr_s^2)$, setting the scale naturally.

4.1.3. The Coincidence Problem

Standard Puzzle: Why do ρ_m and ρ_Λ have similar magnitudes today?

Physical Interpretation: This is inevitable, not coincidental. Since $\rho_m \propto a^{-3}$ (decreasing) while ρ_Λ is constant, there *must* be an epoch when diluting ρ_m drops below constant ρ_Λ . The transition occurs when $\rho_m = 2\rho_\Lambda$:

$$(1 + z_{\text{trans}})^3 = \frac{2\Omega_{\Lambda,0}}{\Omega_{m,0}} = \frac{2 \times 0.7}{0.3} \approx 4.67 \quad (21)$$

This gives $z_{\text{trans}} \approx 0.67$. This is not fine-tuning—it is automatic.

4.2. Testability and Predictions

While direct observation of the Meta-Universe is impossible, this framework suggests several testable predictions:

4.2.1. Weak Predictions

1. **Void dynamics:** If spacetime generation proceeds faster in voids, peculiar velocities near void boundaries may show subtle signatures.
2. **Gravitational potential curvature:** The unified field equation predicts $\nabla^2\Phi \propto (\rho_m - 2\rho_\Lambda)$. In galaxy clusters and voids, the $-2\rho_\Lambda$ term creates measurable deviations that could be detected through gravitational lensing or ISW effect.
3. **No modification to solar system gravity:** Unlike MOND or modified gravity theories, this framework predicts strictly standard Newtonian gravity in local systems.

4.3. Limitations

It is important to acknowledge limitations:

1. **Speculative foundation:** The Meta-Universe/black hole cosmology hypothesis, while mathematically consistent, cannot be directly tested.
2. **Incomplete quantitative theory:** The $\dot{M}_{ext} \rightarrow \rho_{\Lambda}$ connection presented here is an order-of-magnitude argument, not a rigorous derivation.
3. **Limited predictive power:** The framework is mathematically equivalent to Λ CDM for background cosmology.
4. **No dark matter explanation:** This framework focuses solely on the cosmological constant.

5. Conclusions

This work provides a physical interpretation of the cosmological constant by unifying emergent gravity with black hole cosmology.

Key Contributions:

1. **Physical Mechanism for Λ :** Black hole cosmology provides an order-of-magnitude pathway explaining why ρ_{Λ} appears constant
2. **Unified Field Equation:** $\nabla^2\Phi = 4\pi G(\rho_m - 2\rho_{\Lambda})$ unifies gravity and cosmic acceleration in weak-field and homogeneous regimes
3. **Emergent Gravity:** Gravity as interference effect of matter on background energy influx
4. **Naturalization of Paradoxes:** Physical interpretations that make the cosmological puzzles less mysterious
5. **Mathematical Equivalence to Λ CDM:** Reproduces all background observations while providing physical interpretation

Honest Positioning:

This is not a new theory that makes different predictions from Λ CDM. Rather, it is a *physical interpretation* that:

- Identifies external energy influx as the mechanism behind Λ
- Explains why Λ is constant in an order-of-magnitude sense through black hole cosmology
- Transforms emergent gravity from abstract principle to a picture with potentially testable implications

While Jacobson, Verlinde, and Padmanabhan established that gravity is emergent using abstract principles, this work identifies the actual physical process underlying both gravity and cosmic acceleration in an order-of-magnitude framework.

Einstein provided geometric unity. This work proposes energetic unity, suggesting spacetime is not a passive stage but an active, open system continuously energized by a parent universe—offering a path toward understanding the deepest mystery in modern physics.

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