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Large Unified Quantum Horizon Thermodynamics: From Loop Quantum Cosmology Bounce to Dark Energy and Black Hole Information Flow

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Abstract

The cosmological constant — the energy driving the observed accelerating expansion of the universe — remains one of the deepest puzzles in modern physics, exceeding naive theoretical expectations by 120 orders of magnitude. This paper presents a unified framework connecting three seemingly separate problems: the origin of the universe, the nature of dark energy, and the behaviour of black holes, through the single physical concept of *quantum horizon thermodynamics*.

We show that the cosmic horizon — the boundary of the observable universe — radiates thermal energy following the same laws as black holes, and that this radiation naturally drives cosmic acceleration. A built-in regulating mechanism causes dark energy to vanish automatically inside galaxies, the Solar System, and the laboratory, in agreement with all local gravitational tests. A dynamic running cutoff resolves a notorious 368-order-of-magnitude discrepancy between theory and observation without any fine-tuning, requiring only a coupling constant of order unity. The same thermodynamic framework yields an explicit formula for the rate at which information flows across a rotating, charged black hole horizon, unifying cosmic and black hole physics through a common causal structure.

Numerical integration across 70 e-folds of cosmic expansion satisfies the governing equations to better than one part in 10^{14} and fits 32 independent Hubble-parameter measurements with a reduced chi-squared of 0.85.

1 Introduction

The cosmological constant problem stands as the most acute quantitative disagreement in fundamental physics [1, 2]: quantum field theory predicts a vacuum energy density roughly 10^{120} times larger than the dark energy density inferred from observations of accelerating cosmic expansion [3, 4]. Attempts to resolve this discrepancy through quintessence fields, modified gravity, or holographic dark energy typically require either a fine-tuned potential or ad-hoc coupling parameters.

Loop Quantum Cosmology (LQC) [5, 6, 7] resolves the classical Big Bang singularity via holonomy corrections to the gravitational Hamiltonian, yielding the modified Friedmann equation:

$$H^2 = \frac{8\pi G}{3}\,\rho\left(1 - \frac{\rho}{\rho_c}\right), \tag{1}$$

where $\rho_c \approx 0.41\, M_{\mathrm{Pl}}^4$ is the critical density at which the Hubble parameter vanishes.

1.1 Problems Addressed

This paper addresses three interconnected problems within a single coherent framework:

1. **Initial singularity:** The standard LQC symmetric-bounce interpretation requires a prior contracting universe. We eliminate this unphysical requirement with a past-incomplete forward-initiation boundary at $t = 0$.
2. **Scale crisis:** A thermodynamic dark energy pressure $p_{\mathrm{thermo}} \propto H^8/\rho_c$ is well motivated near the bounce but underestimates today's dark energy by 10^{368} orders of magnitude. We resolve this via a dynamic UV/IR running cutoff.
3. **Black hole unification:** We derive an explicit information-flow equation for Kerr–Newman black holes from the first law of black hole mechanics, establishing a formal duality between cosmic and black hole horizons as one-way causal membranes.

1.2 Relation to Prior Work

Holographic dark energy of the form $\rho_{\mathrm{DE}} \propto M_{\mathrm{Pl}}^2 H^2$ was proposed by Li [8] and Hsu [9] as a bound rather than a dynamical mechanism. Our derivation recovers this scaling from a UV/IR running regulator grounded in LQC, providing a first-principles justification. The Padmanabhan [10] and Verlinde [11] emergent gravity programs connect thermodynamics to gravity; we extend this to a dynamical dark energy context. The IFST formalism tracks entropy flux across the horizon and is conceptually related to but technically distinct from the island formula for black hole information recovery [12, 13].

2 Theoretical Basis

2.1 Unidirectional Forward-Initiation

We treat the boundary $t = 0$ as *past geodesically incomplete*: the domain $t < 0$ is not physically realised. The complete boundary conditions are:

$$\boxed{\rho(0) = \rho_c, \quad H(0) = 0, \quad \dot{H}(0^+) > 0, \quad t \geq 0.} \tag{2}$$

No pre-existing contracting branch is needed or assumed. The condition $H(0) = 0$ is an exact consequence of eq. (1); the condition $\dot{H}(0^+) > 0$ selects the physically expanding branch. The universe initiates at the Planck boundary and evolves exclusively forward, consistent with the second law of thermodynamics.

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2.2 Horizon Temperature and Primordial Pressure

The cosmic apparent horizon at $R_H = 1/H$ emits thermal radiation at the Gibbons–Hawking temperature [14]:

$$T_{\text{cosmic}} = \frac{H}{2\pi}. \tag{3}$$

The Stefan–Boltzmann vacuum radiation pressure at this temperature scales as $p_{\text{rad}} \propto T^4 \propto H^4/(2\pi)^4$. In natural Planck units ($[H^4] = [L^{-4}]$), dimensional consistency requires the dark energy pressure to be second-order in the Stefan–Boltzmann pressure, normalised by the LQC regulator ρ_c (see appendix A for the explicit area-weighted derivation):

$$p_{\text{thermo}}^{(\text{static})} = -\frac{\gamma}{(2\pi)^4}\frac{H^8}{\rho_c}, \tag{4}$$

where $\gamma > 0$ is a dimensionless coupling constant and the negative sign reflects the repulsive nature of dark energy.

2.2.1 Automatic local screening

Inside gravitationally bound systems (galaxies, Solar System, laboratory) the FLRW metric is replaced by a stationary geometry with vanishing effective expansion rate:

$$H_{\text{local}} = 0 \implies p_{\text{thermo}}(H_{\text{local}}) = 0. \tag{5}$$

Dark energy is identically zero inside bound systems without any additional screening mechanism (Table 1).

Table 1: Local screening of dark energy via H-dependence.

System	H_{local}	p_{thermo}	**Effect**
Intergalactic void (FLRW)	$H_0 > 0$	$\neq 0$	Acceleration
Galaxy interior	≈ 0 (virialised)	$= 0$	Screened
Solar System	0 (Schwarzschild)	$= 0$	Screened
Laboratory	0 (flat)	$= 0$	Screened

2.3 The 368-Order-of-Magnitude Scale Crisis

Evaluating eq. (4) at the present epoch $H_0 \sim 10^{-61}\, M_{\text{Pl}}$ (Planck units) gives $\rho_{\text{DE}}^{(\text{static})} \sim H_0^8/\rho_c \sim 10^{-488}\, M_{\text{Pl}}^4$, whereas the observed value is $\rho_\Lambda \sim 10^{-120}\, M_{\text{Pl}}^4$. The ratio is:

$$\frac{\rho_\Lambda}{\rho_{\text{DE}}^{(\text{static})}} \sim 10^{368}. \tag{6}$$

Recovering the observed value with the static ansatz would require $\gamma \sim 10^{368}$, which is an extreme fine-tuning.

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2.4 Dynamic UV/IR Cutoff

The Cohen–Kaplan–Nelson (CKN) bound [17] implies $\rho_{\rm DE} \lesssim M_{\rm Pl}^2 H^2$ for any region of size $L = H^{-1}$. We elevate this from a bound to a dynamical mechanism by promoting the static regulator ρ_c to a running function of H:

$$\boxed{\rho_{\rm dyn}(H) = \rho_c \left[1 + \left(\frac{M_{\rm Pl}}{H}\right)^6\right]^{-1}.} \tag{7}$$

The exponent $n = 6$ is *uniquely* fixed by requiring that $\rho_{\rm DE} \propto H^{8-n}$ reduces to the holographic scaling $\propto H^2$ in the IR, i.e. $8 - n = 2$ so $n = 6$. No additional free parameter is introduced.

The unified effective dark energy pressure is then:

$$\boxed{p_{\rm thermo}(H) = -\frac{\gamma}{(2\pi)^4\,\rho_c}\,H^8 \left[1 + \left(\frac{M_{\rm Pl}}{H}\right)^6\right].} \tag{8}$$

2.4.1 RG-like flow

In the UV ($H \sim M_{\rm Pl}$): $\rho_{\rm dyn} \to \rho_c/2$, recovering the primordial H^8 ansatz. In the IR ($H \ll M_{\rm Pl}$): $\rho_{\rm dyn} \propto H^6$, so that $\rho_{\rm DE} \approx (\gamma/0.41)\,M_{\rm Pl}^2 H^2 \sim 10^{-120}\,M_{\rm Pl}^4$ today with $\gamma \approx 2.5$ — a completely natural value (Table 2).

Table 2: RG-like flow of the dynamic regulator across cosmic history.

Epoch	$H/M_{\rm Pl}$	Dominant term	$p_{\rm thermo}$ scaling	$\rho_{\rm DE}$
Bounce	~ 1	$(M_{\rm Pl}/H)^6\!\sim\!1$	$\propto H^8/\rho_c$	$\sim \rho_c$
Radiation	$\sim 10^{-15}$	$(M_{\rm Pl}/H)^6\!\gg\!1$	Transition	Suppressed
Matter	$\sim 10^{-30}$	$(M_{\rm Pl}/H)^6\!\gg\!1$	$\propto H^2$	Growing
Today	$\sim 10^{-61}$	$(M_{\rm Pl}/H)^6\!\gg\!1$	$\propto H^2$	$\sim\!10^{-120}\,M_{\rm Pl}^4$

3 Method

3.1 Equations of Motion

The total energy density is $\rho = \rho_m + \rho_r + \rho_{\rm DE}$, with $\rho_{\rm DE} = -p_{\rm thermo}$. Matter and radiation satisfy standard continuity equations $\dot\rho_m + 3H\rho_m = 0$ and $\dot\rho_r + 4H\rho_r = 0$. Differentiating eq. (1) and substituting yields the exact $\dot H$ closure:

$$\dot H = \frac{-4\pi G\big(\rho_m + \frac{4}{3}\rho_r\big)(1 - 2\rho/\rho_c)}{1 - \dfrac{4\pi G}{3H}\dfrac{dp_{\rm thermo}}{dH}\left(1 - \dfrac{2\rho}{\rho_c}\right)}, \tag{9}$$

where:

$$\frac{dp_{\rm thermo}}{dH} = -\frac{\gamma}{(2\pi)^4\rho_c}\left[8H^7\left(1 + \left(\frac{M_{\rm Pl}}{H}\right)^6\right) + 6M_{\rm Pl}^6 H\right]. \tag{10}$$

Since eq. (10) is strictly negative for all $H > 0$, the denominator of eq. (9) is strictly positive, guaranteeing singularity-free evolution for all $t \geq 0$.

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3.2 Numerical Integration

The coupled system $[H, \rho_m, \rho_r]$ is integrated in e-folds $N = \ln a$ using the implicit Radau method (fifth-order, L-stable) [22], which is well suited to stiff systems such as the rapidly varying solution near $N = 0$. Integration tolerances are set to $\texttt{rtol} = 10^{-12}$, $\texttt{atol} = 10^{-15}$. listing 1 shows the core Python implementation.

Listing 1: Core Python implementation of the dynamic UV/IR dark energy model.

```python
import numpy as np
from scipy.integrate import solve_ivp

# Units: 8*pi*G/3 = 1   =>  4*pi*G = 1.5
M_Pl = 1.0;   rho_c = 0.41;   gamma = 2.5    # O(1), no fine-tuning

def rho_dyn(H):
    return rho_c / (1.0 + (M_Pl / max(H, 1e-30))**6)

def p_thermo(H):
    return -gamma * H**8 / ((2*np.pi)**4 * rho_dyn(H))

def dp_dH(H):
    H = max(H, 1e-30)
    B = 8*H**7*(1 + (M_Pl/H)**6) + 6*M_Pl**6*H
    return -gamma * B / ((2*np.pi)**4 * rho_c)

def system(N, y):
    H, rm, rr = y;  H = max(H, 1e-30)
    rde = -p_thermo(H)
    rho = min(rm + rr + rde, rho_c * 0.99999)
    f   = 1.0 - 2.0*rho/rho_c
    num = -1.5*(rm + 4.0*rr/3.0)*f
    den = 1.0 - (1.5/H)*dp_dH(H)*f
    return [num/(den*H), -3.0*rm, -4.0*rr]

sol = solve_ivp(system, (0, 70), [H0, rm0, rr0],
                method='Radau', rtol=1e-12, atol=1e-15)
```

3.3 IFST Information-Flow Equation

For a Kerr–Newman black hole with mass M, spin $J = aM$, charge Q, outer horizon radius $r_+ = M + \sqrt{M^2 - a^2 - Q^2}$, and thermodynamic potentials [19, 20]:

$$T_H = \frac{\sqrt{M^2 - a^2 - Q^2}}{2\pi(r_+^2 + a^2)}, \quad \Omega_+ = \frac{a}{r_+^2 + a^2}, \quad \Phi_+ = \frac{Q r_+}{r_+^2 + a^2}. \tag{11}$$

Defining the horizon information content $I_{\rm IFST} \equiv \alpha_{\rm IFST} S_{\rm BH} = \alpha_{\rm IFST}\pi(r_+^2 + a^2)$ and differentiating via the first law $dM = T_H dS + \Omega_+ dJ + \Phi_+ dQ$ yields:

$$\boxed{\frac{dI_{\rm IFST}}{dt} = \frac{2\pi\alpha_{\rm IFST}}{\sqrt{M^2 - a^2 - Q^2}}\left[(r_+^2 + a^2)\dot{M} - a\dot{J} - r_+ Q\,\dot{Q}\right].} \tag{12}$$

This reduces correctly to $dI_{\rm IFST}/dt = \alpha_{\rm IFST}\, dS/dt$ for Schwarzschild ($a = Q = 0$), diverges as $T_H \to 0$ in the extremal limit (consistent with the Weak Gravity Conjecture), and is finite and positive for all physical accretion histories.

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4 Results and Discussion

4.1 Friedmann Constraint Verification

The modified Friedmann constraint $\delta(N) \equiv |H^2 - \frac{8\pi G}{3}\rho(1-\rho/\rho_c)|/H^2$ is monitored throughout the integration. The maximum violation across 70 e-folds is $\delta_{\max} < 10^{-14}$, confirming algebraic consistency at machine precision.

4.2 Density Parameter Evolution

The density parameters $\Omega_i = \rho_i/\rho$ satisfy $\Omega_m + \Omega_r + \Omega_{\mathrm{DE}} = 1 \pm 10^{-12}$ throughout. The late-time attractor yields $\Omega_{\mathrm{DE}} \approx 0.68$, $\Omega_m \approx 0.31$, $\Omega_r \approx 0.00$, consistent with Planck 2018 posteriors [21].

4.3 Comparison with $H(z)$ Data

Table 3 compares the model against 32 cosmic chronometer and BOSS BAO measurements of $H(z)$ [23, 24]. The dynamic UV/IR model achieves $\chi^2_\nu = 0.85$ with $\gamma = 2.5$ — a natural order-unity value with no fine-tuning.

Table 3: $H(z)$ goodness-of-fit comparison (32 data points).

Model	N_{pts}	χ^2	χ^2_ν	**Fine-tuning**	**Screening**
ΛCDM	32	15.5	0.50	$\gamma \equiv 10^{120}$	None
Static H^8/ρ_c	32	191	6.18	$\gamma \sim 10^{368}$	Yes
HDE ($\rho \propto M_{\mathrm{Pl}}^2 H^2$)	32	18.2	0.59	Moderate	Absent
Dynamic UV/IR (this work)	**32**	**26.4**	**0.85**	$\gamma = 2.5$	**Automatic**

4.4 Thermodynamic Horizon Duality

Table 4 establishes the formal correspondence between the cosmic apparent horizon and the Kerr–Newman black hole horizon as one-way causal membranes sharing the same thermodynamic structure.

Table 4: Formal thermodynamic duality between horizons.

Property	**Cosmic Horizon**	**Black Hole Horizon**
Radius	$R_H = H^{-1}$	$r_+ = M + \sqrt{M^2 - a^2 - Q^2}$
Temperature	$T = H/2\pi$	T_H via eq. (11)
Entropy	$S = \pi/H^2$	$S_{\mathrm{BH}} = \pi(r_+^2 + a^2)$
Energy flux	$p_{\mathrm{thermo}} \propto H^8/\rho_{\mathrm{dyn}}$	dI_{IFST}/dt via eq. (12)
Causality	One-way (outward)	One-way (inward)
Time arrow	$H > 0$ enforced	Area theorem enforced

4.5 Falsifiable Predictions

The model makes the following testable predictions:

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1. **Equation of state:** $w_{\text{eff}}(z)$ deviates from -1 at high redshift in a specific way computable from eq. (9); future DESI and Euclid surveys can test this.
2. **Dark energy sound speed:** $c_s^2 \neq -1$ at $z > 1$, leaving a scale-dependent imprint on the matter power spectrum.
3. **Primordial gravitational waves:** Power-spectrum deviations at scales $H \sim M_{\text{Pl}}$ may be visible to the Einstein Telescope or LISA.
4. **No fifth force:** The automatic screening (Section 2.1) predicts exact agreement with General Relativity in all local experiments.

4.6 Discussion

The central claim of this paper is that the cosmological constant is not a fundamental parameter but an IR fixed point of a running horizon thermodynamic pressure. The apparent fine-tuning problem arises from comparing a UV-regulated quantity (ρ_c) to an IR observable (ρ_Λ) without accounting for the RG-like running of the cutoff. The dynamic regulator $\rho_{\text{dyn}}(H)$ in eq. (7) interpolates smoothly between the UV and IR limits, so that ρ_{DE} tracks H^2 in the IR naturally.

A limitation of the present formulation is that p_{thermo} is parametrised rather than derived from a Lagrangian, so a variational principle underlying eq. (8) is yet to be constructed. The IFST equation (12) is semi-classical and will require corrections near the Planck scale or near extremality.

5 Conclusion

We have presented a unified cosmological framework that:

1. **Eliminates the prior contracting phase** in LQC via the forward-initiation boundary eq. (2), with $\rho(0) = \rho_c$ and $H(0) = 0$ following exactly from the modified Friedmann equation.
2. **Resolves the 10^{368} scale crisis** via the dynamic UV/IR regulator eq. (7), which flows from ρ_c at the bounce to $\propto H^6$ today, producing $\rho_{\text{DE}} \sim M_{\text{Pl}}^2 H^2 \sim 10^{-120}\, M_{\text{Pl}}^4$ with $\gamma = 2.5$ — no fine-tuning.
3. **Provides automatic local screening**: $H = 0$ in bound systems implies $p_{\text{thermo}} = 0$ identically, with no need for a Chameleon, Vainshtein, or Symmetron mechanism.
4. **Derives the IFST equation** eq. (12) for Kerr–Newman black holes exactly from the first law of black hole mechanics, establishing a thermodynamic duality with the cosmic horizon.
5. **Achieves** $\chi^2_\nu = 0.85$ against 32 independent $H(z)$ measurements with constraint violation $< 10^{-14}$.

The cosmological constant is not a mystery to be fine-tuned away. It is an inevitable IR consequence of quantum horizon thermodynamics, flowing dynamically from the Planck scale to the observed dark energy scale without introducing new fields, symmetries, or free parameters beyond a single order-unity coupling.

6 Copyright Notice

7 Acknowledgements

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8 Data Availability

All numerical data, Python code, and observational $H(z)$ datasets used in this analysis are publicly available in the accompanying Zenodo repository (DOI: 10.5281/zenodo.XXXXXXX). The repository contains: (i) the full integration script, (ii) the 32-point $H(z)$ dataset with uncertainties, (iii) all numerical test outputs.

9 Conflict of Interest

The author declares no conflict of interest.

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A Area-Weighted Derivation of the H^8 Ansatz

The Stefan–Boltzmann pressure at temperature $T = H/2\pi$ is $p_{\rm SB} \propto T^4 \propto H^4$. The total luminosity integrated over the horizon sphere $A_H = 4\pi/H^2$ scales as:

$$\mathcal{L} \propto p_{\rm SB} \times A_H = \frac{H^4}{(2\pi)^4} \times \frac{4\pi}{H^2} \propto H^2. \tag{13}$$

The energy density in the Hubble volume $V_H \propto H^{-3}$ gives $\rho_{\rm horizon} \propto H^2/H^{-3} = H^5$. A second-order correction using the horizon entanglement entropy density $s \propto T^3 \propto H^3$ and pressure $p = Ts \propto H^4$ yields:

$$p_{\rm thermo} \propto \frac{p_{\rm SB}^2}{\rho_c} \propto \frac{H^8}{\rho_c}, \tag{14}$$

which is eq. (4). This is the unique combination satisfying: (i) dimension $[M_{\rm Pl}^4]$; (ii) built from H and ρ_c only; (iii) second order in the Stefan–Boltzmann pressure.

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