

Emergent Vacuum Energy from Apparent-Horizon Thermodynamics

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Abstract

Recent high-precision cosmological observations have revealed statistically significant tensions between early-universe inferences and late-time measurements, most notably in the Hubble constant H_0 and the clustering amplitude parameter S_8 . These discrepancies may indicate limitations of the standard Λ CDM framework when extrapolated across cosmic epochs.

In this work, we develop a thermodynamically motivated cosmological model in which the dark energy component is not introduced as a fundamental constant, but instead emerges dynamically from the thermodynamics of the apparent horizon. By applying Hayward's unified first law in conjunction with the Clausius relation to the cosmological apparent horizon, we derive a self-consistent evolution equation for the Hubble parameter $H(z)$.

Numerical integration of the resulting evolution law yields a present-day expansion rate $H_0 \simeq 71.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$, which lies between cosmic microwave background inferences and local distance ladder measurements. The model further predicts a present-day matter density $\Omega_{m,0} = 0.2677$ and a clustering parameter $S_8 = 0.781$, both of which are consistent with recent weak lensing constraints. ...notably in the Hubble constant H_0 [2] and the clustering amplitude parameter S_8 [8].

These results suggest that horizon thermodynamics may provide a viable mechanism for generating an effective dark energy component, and that the observed cosmological tensions could reflect an incomplete thermodynamic description of the cosmic expansion history rather than the need for new fundamental fields.

1 Introduction

The standard cosmological model, Λ CDM, provides a remarkably successful description of the large-scale evolution of the Universe. Based on general relativity and the cosmological principle, it accounts for a wide range of observations, including the cosmic microwave background (CMB), baryon acoustic oscillations, large-scale structure formation, and the observed late-time accelerated expansion [1].

Despite these successes, the increasing precision of cosmological measurements has exposed persistent discrepancies between early-universe predictions and late-time observations. These tensions have grown in both statistical significance and robustness against known systematic uncertainties, motivating renewed scrutiny of the assumptions underlying the Λ CDM framework.

1.1 Current Cosmological Tensions

1.1.1 The Hubble Constant Discrepancy

Measurements of the present-day expansion rate inferred from the CMB under the assumption of Λ CDM yield $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [1]. In contrast, direct late-time measurements based on the local distance ladder, most prominently those from the SH0ES collaboration, report significantly higher values, $H_0 \simeq 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [2]. The discrepancy now exceeds the 5σ level, making it increasingly difficult to attribute to unknown systematics alone.

1.1.2 The S_8 Tension

A second, independent discrepancy arises in measurements of the amplitude of matter fluctuations. Weak lensing surveys such as KiDS-1000 and the Dark Energy Survey consistently infer values of

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m/0.3}$$

that are lower than those predicted by Planck-normalized Λ CDM. This tension suggests a slower growth of structure than expected within a model driven by a constant vacuum energy density.

1.2 A Thermodynamic Perspective on Dark Energy

The simultaneous presence of expansion-rate and structure-growth tensions raises the possibility that the cosmological constant may represent an effective description rather than a fundamental component of the theory. Motivated by the holographic principle and the thermodynamic interpretation of gravitational dynamics, we explore an alternative framework in which the accelerated expansion emerges from horizon thermodynamics.

In dynamical spacetimes, apparent horizons possess well-defined thermodynamic properties, including entropy and temperature, governed by applying Hayward's unified first law [4] in conjunction with the Clausius relation. When applied to an expanding Friedmann–Lemaître–Robertson–Walker universe, these relations imply an exchange of energy associated with horizon entropy production. Rather than introducing a constant Λ , this approach allows an effective vacuum energy density to arise dynamically as a consequence of the evolving expansion rate.

1.3 Objectives and Structure of This Work

The primary goal of this work is to derive a self-consistent cosmological evolution law based on apparent-horizon thermodynamics and to examine its implications for late-time cosmological tensions. We aim to determine whether such a framework can simultaneously accommodate early-universe constraints while modifying the late-time expansion and growth histories in a phenomenologically viable manner.

The paper is organized as follows. In Section 2, we review the geometry and thermodynamics of the apparent horizon and introduce the Hayward formalism. Section 3 derives the horizon-induced interaction and the resulting Holographic Equilibrium Law governing the expansion history. In Section 4, we confront the model with observational constraints and assess its implications for the H_0 and S_8 tensions. We conclude in Section 5 with a discussion of the broader theoretical and observational consequences.

2 Geometry and Thermodynamics of the Apparent Horizon

2.1 FLRW Geometry and Apparent Horizon Radius

We consider a spatially flat Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime, whose line element is given by

$$ds^2 = -c^2 dt^2 + a^2(t) [d\chi^2 + \chi^2 (d\theta^2 + \sin^2 \theta d\phi^2)], \quad (1)$$

where $a(t)$ is the scale factor and χ denotes the comoving radial coordinate. The physical (areal) radius is defined as

$$R(t, \chi) = a(t)\chi. \quad (2)$$

In a dynamical spacetime, the relevant causal boundary is the apparent horizon, defined as the marginally trapped surface on which the expansion of outgoing radial null geodesics vanishes. For a spatially flat FLRW universe, this condition reduces to:

$$h^{ab} \partial_a R \partial_b R = 0, \quad (3)$$

which yields the familiar relation:

$$R_H = \frac{c}{H} \quad (4)$$

where $H \equiv \dot{a}/a$ is the Hubble parameter. The apparent horizon therefore defines a dynamically evolving boundary whose radius is set by the instantaneous expansion rate.

2.2 Horizon Entropy and the Bekenstein–Hawking Law

According to the holographic principle and black hole thermodynamics, horizons carry entropy proportional to their surface area. The area of the apparent horizon is

$$A_H = 4\pi R_H^2 = 4\pi \frac{c^2}{H^2}. \quad (5)$$

The associated entropy is given by the Bekenstein–Hawking area law,

$$S_H = \frac{k_B A_H}{4\ell_P^2}, \quad (6)$$

where the Planck length is

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}}. \quad (7)$$

Substituting Eq. (5) into Eq. (6), we obtain

$$S_H = \frac{\pi k_B c^5}{G \hbar H^2}. \quad (8)$$

This entropy quantifies the number of holographic degrees of freedom associated with the cosmic apparent horizon.

2.3 Horizon Temperature

The apparent horizon is also associated with a characteristic temperature. In dynamical spacetimes, the relevant quantity is the Hayward–Kodama surface gravity κ . For a spatially flat FLRW universe with slowly varying expansion ($|\dot{H}| \ll H^2$), the surface gravity reduces to

$$\kappa \simeq \frac{c^2}{R_H}. \quad (9)$$

The corresponding horizon temperature is given by the Gibbons–Hawking relation,

$$T_H = \frac{\hbar \kappa}{2\pi k_B c}. \quad (10)$$

Using Eq. (9), this yields

$$T_H = \frac{\hbar H}{2\pi k_B}. \quad (11)$$

The apparent horizon thus behaves as a thermodynamic system characterized by a finite entropy and temperature, despite being a purely geometric construct.

2.4 Hayward's Unified First Law

The thermodynamic behavior of apparent horizons in dynamical spacetimes is governed by Hayward's unified first law, which relates changes in the total energy enclosed by the horizon to horizon entropy and work terms:

$$dE = T_H dS_H + W dV. \quad (12)$$

Here:

- E is the Misner–Sharp energy contained within the apparent horizon,
- T_H and S_H are the horizon temperature and entropy,
- W is the work density,
- V is the physical volume enclosed by the horizon.

For a spatially flat FLRW universe, these quantities take the explicit forms

$$E = \frac{4\pi}{3} R_H^3 \rho, \quad (13)$$

$$W = \frac{1}{2}(\rho - p), \quad (14)$$

$$V = \frac{4\pi}{3} R_H^3, \quad (15)$$

where ρ and p are the total energy density and pressure of the cosmic fluid. Throughout this section, we work in units where $c = \hbar = k_B = 1$ unless otherwise stated.

2.5 Clausius Relation and Heat Flow

Rearranging Eq. (12) yields

$$dE - W dV = T_H dS_H. \quad (16)$$

In the thermodynamic analogy, the left-hand side represents the net heat flow δQ across the apparent horizon:

$$\delta Q \equiv dE - W dV. \quad (17)$$

Equation (16) therefore takes the form of the Clausius relation,

$$\delta Q = T_H dS_H, \quad (18)$$

which holds for any perfect fluid in an FLRW spacetime. This relation provides a direct connection between horizon thermodynamics and the gravitational dynamics of the universe.

2.6 Horizon Power from Entropy Production

The rate of energy transfer associated with horizon entropy production is obtained by differentiating Eq. (8) with respect to cosmic time:

$$\dot{S}_H = \frac{d}{dt} \left(\frac{\pi c^5}{G \hbar H^2} \right) = - \frac{2\pi c^5}{G \hbar} \frac{\dot{H}}{H^3}. \quad (19)$$

Multiplying by the horizon temperature given in Eq. (11), we define the total thermodynamic power crossing the apparent horizon as:

$$\Phi \equiv T_H \dot{S}_H \quad (20)$$

Substituting Eqs. (19) and (11) yields

$$\Phi = -\frac{c^5}{G} \frac{\dot{H}}{H^2}. \quad (21)$$

The quantity Φ has dimensions of energy per unit time and represents the net thermodynamic power associated with entropy production at the apparent horizon.

2.7 From Boundary Power to an Effective Volumetric Interaction

The power Φ is defined on the two-dimensional horizon surface. To incorporate its effect into the homogeneous bulk description used in cosmology, we introduce an effective volumetric interaction rate by distributing this power over the physical volume enclosed by the apparent horizon:

$$\Psi \equiv \frac{\Phi}{V_H}, \quad (22)$$

where

$$V_H = \frac{4\pi}{3} R_H^3 = \frac{4\pi c^3}{3H^3}. \quad (23)$$

Substituting Eq. (21) into Eq. (22) yields

$$\Psi = -\frac{3c^2}{4\pi G} H \dot{H}. \quad (24)$$

The quantity Ψ has dimensions of energy density per unit time and represents an effective interaction term capturing the averaged thermodynamic influence of the apparent horizon on the cosmic fluid. It should be emphasized that Ψ is not interpreted as a microscopic energy flux propagating through spacetime, but as a coarse-grained source term encoding horizon backreaction at the level of homogeneous cosmology.

2.8 Sign Convention and Physical Interpretation

From Eq. (21) it follows that in a decelerating universe ($\dot{H} < 0$), the horizon power satisfies $\Phi > 0$. We interpret this case as a net inward transfer of energy from the apparent horizon into the cosmic interior. The corresponding volumetric rate Ψ is likewise positive under these conditions.

Throughout this work, Ψ is defined with respect to the comoving cosmological frame. During decelerating phases, the apparent horizon radius increases and the associated entropy grows. Maintaining the Clausius relation requires a compensating energy exchange, which we interpret as an effective transfer between matter–radiation components and an emergent vacuum sector. In the asymptotic de Sitter limit $\dot{H} \rightarrow 0$, the interaction vanishes smoothly, and the vacuum energy approaches a constant value.

3 Interaction Mechanism and the Emergence of Vacuum Energy

In this section, we develop the physical mechanism underlying the horizon-induced energy transfer introduced in Section 2. We show that the entropy imbalance between radiation and the apparent horizon naturally selects radiation as the dominant donor to an emergent vacuum component. The resulting interaction leads to a self-consistent evolution of the vacuum energy density without introducing a fundamental cosmological constant.

3.1 Thermodynamic Origin of the Interaction

3.1.1 Entropy Scaling: Radiation versus Horizon

To identify the physical origin of the horizon-induced energy transfer, we compare the scaling behavior of radiation entropy with that of the apparent horizon entropy during cosmic expansion.

The entropy of radiation contained within the apparent horizon volume,

$$V_H = \frac{4\pi}{3} R_H^3, \quad (25)$$

is given by

$$S_r = \frac{4}{3} \sigma T^3 V_H, \quad (26)$$

where σ is the radiation constant. Using the relation between radiation energy density and temperature,

$$\rho_r = \sigma T^4, \quad (27)$$

the temperature can be expressed as

$$T = \left(\frac{\rho_r}{\sigma} \right)^{1/4}. \quad (28)$$

Substituting into Eq. (26) yields

$$S_r = \frac{16\pi}{9} \sigma^{1/4} \rho_r^{3/4} H^{-3}. \quad (29)$$

3.1.2 Scaling in the Radiation-Dominated Era

During the radiation-dominated epoch, the Friedmann equation implies

$$H^2 \simeq \frac{8\pi G}{3} \rho_r. \quad (30)$$

Substituting Eq. (30) into Eq. (29), we find the scaling behavior

$$S_r \propto H^{-3/2}. \quad (31)$$

By contrast, the horizon entropy derived in Section 2 scales as

$$S_H \propto H^{-2}. \quad (32)$$

As the universe expands and H decreases, the horizon entropy grows more rapidly than the entropy of the radiation contained within it. This increasing entropy imbalance provides a thermodynamic driver for energy transfer associated with horizon entropy production.

3.1.3 Symmetry Considerations and Dominant Energy Donor

The horizon-induced interaction must be compatible with the symmetries of both the FLRW spacetime and the cosmic fluid. In particular, the apparent horizon is a scale-free null surface, suggesting that any effective coupling should respect conformal symmetry at leading order.

To assess which components of the cosmic fluid can participate most efficiently, we consider the trace of the energy-momentum tensor,

$$T^\mu_{\mu,i} = \rho_i - 3p_i \quad (33)$$

... In contrast, for radiation with equation of state $p_r = \rho_r/3$,

$$T_{\mu,r}^\mu = 0 \quad (34)$$

indicating explicit breaking of conformal invariance through the presence of a mass scale. Any direct coupling between massive matter and a scale-free null boundary is therefore expected to be suppressed in an effective description.

In contrast, for radiation with equation of state $p_r = \rho_r/3$,

$$T_{\mu,r}^\mu = 0, \quad (35)$$

implying exact conformal invariance at the classical level. Radiation therefore matches the symmetry structure of the apparent horizon more naturally than massive matter.

We thus model the horizon-induced interaction as acting dominantly on the radiation sector. Possible subleading couplings to massive species are neglected at the level of homogeneous background evolution.

3.1.4 Volumetric Interaction Rate from Horizon Thermodynamics

From Section 2, the total thermodynamic power associated with horizon entropy production is

$$\Phi = -\frac{c^5}{G} \frac{\dot{H}}{H^2}. \quad (36)$$

Dividing by the apparent horizon volume,

$$V_H = \frac{4\pi c^3}{3H^3}, \quad (37)$$

yields the effective volumetric interaction rate

$$\Psi = -\frac{3c^2}{4\pi G} H \dot{H}. \quad (38)$$

In decelerating phases of expansion ($\dot{H} < 0$), $\Psi > 0$, indicating a net transfer of energy density from radiation to an emergent vacuum component. In the de Sitter limit $\dot{H} \rightarrow 0$, the interaction switches off smoothly.

3.1.5 Coupled Continuity Equations

The interaction is incorporated into the continuity equations by decomposing the total energy density as

$$\rho_{\text{tot}} = \rho_r + \rho_m + \rho_Q, \quad (39)$$

where ρ_Q denotes the emergent vacuum component. The modified continuity equations are

$$\dot{\rho}_r + 4H\rho_r = -\Psi, \quad (40)$$

$$\dot{\rho}_m + 3H\rho_m = 0, \quad (41)$$

$$\dot{\rho}_Q + 3H(1 + w_Q)\rho_Q = +\Psi. \quad (42)$$

Summing Eqs. (40)–(42) yields

$$\dot{\rho}_{\text{tot}} + 3H(\rho_{\text{tot}} + p_{\text{tot}}) = 0, \quad (43)$$

demonstrating that total energy–momentum conservation is preserved.

3.2 Self-Consistent Evolution and the Circularity Issue

A potential concern arises because the interaction rate Ψ depends on the Hubble parameter, which is itself determined by the total energy density through the Friedmann equation. This does not introduce logical circularity, provided the equations are interpreted dynamically rather than algebraically.

At each instant, the apparent horizon geometry is fixed by the instantaneous total energy density, while the vacuum component is generated through the accumulated interaction over the past expansion history. The Friedmann equation therefore acts as a constraint at each time slice, whereas the interaction governs the temporal evolution between slices.

3.2.1 Vacuum Energy as an Integrated Interaction

In the asymptotic vacuum-dominated regime, where $w_Q \rightarrow -1$, the dilution term in Eq. (42) vanishes and

$$\dot{\rho}_Q \simeq \Psi. \quad (44)$$

Assuming $\rho_Q \rightarrow 0$ in the far past, the vacuum energy density is given by

$$\rho_Q(t) = \int_{-\infty}^t \Psi(t') dt'. \quad (45)$$

3.2.2 Redshift-Space Representation

Using

$$dt = -\frac{dz}{(1+z)H(z)}, \quad (46)$$

Eq. (45) becomes

$$\rho_Q(z) = \int_z^\infty \frac{\Psi(z')}{(1+z')H(z')} dz'. \quad (47)$$

During decelerating expansion, $\rho_Q(z)$ increases monotonically toward low redshift, indicating the progressive buildup of vacuum energy.

3.3 Modified Friedmann Equation

We now incorporate the accumulated vacuum energy into the cosmological expansion dynamics. Before the annihilation of the radiation component, the Friedmann equation takes the form

$$H^2(z) = \frac{8\pi G}{3} \left[\rho_m(z) + \rho_r(z) + \int_z^\infty \frac{\Psi(z')}{(1+z')H(z')} dz' \right]. \quad (48)$$

Equation (48) explicitly shows that the vacuum energy density is generated cumulatively through the interaction kernel $\Psi(z)$ and contributes nonlocally to the expansion history.

3.4 Holographic Equilibrium Law

To obtain a closed form, we introduce a dimensionless effective coupling $\alpha(z)$ via

$$\Psi = \Gamma(z)\rho_r, \quad \Gamma(z) \equiv -\alpha(z)\frac{\dot{H}}{H}. \quad (49)$$

Consistency between the geometric interaction rate in Eq. (38) and the fluid description requires

$$\alpha(z)\rho_r(z) = \frac{3H^2(z)}{4\pi G} = 2\rho_{\text{crit}}(z), \quad (50)$$

yielding

$$\alpha(z) = \frac{2}{\Omega_r(z)}. \quad (51)$$

Substituting this relation into the redshift-space Friedmann equation and expressing all quantities in terms of the dimensionless Hubble parameter $E(z) \equiv H(z)/H_0$, we obtain the Holographic Equilibrium Law:

$$E^2(z) = \Omega_{m,0}(1+z)^3 + \Omega_{r,0}(1+z)^4 + 2 \int_z^\infty \frac{E(z')}{1+z'} \frac{dE(z')}{dz'} dz'. \quad (52)$$

3.4.1 Differential Evolution Equation

Differentiating Eq. (52) with respect to z yields the local evolution equation

$$\frac{dE}{dz} = \frac{[3\Omega_{m,0}(1+z)^2 + 4\Omega_{r,0}(1+z)^3](1+z)}{2E(2+z)}. \quad (53)$$

This equation governs the cosmological expansion without introducing a fundamental cosmological constant. The factor $(1+z)/(2+z)$ acts as a thermodynamic weighting kernel encoding horizon backreaction.

3.4.2 Higher-Order Corrections

Possible quantum-gravitational distortions of the horizon entropy, such as those described by Barrow entropy, may be incorporated via a damping factor $0 < \beta \leq 1$:

$$\frac{dE}{dz} = \beta \frac{[3\Omega_{m,0}(1+z)^2 + 4\Omega_{r,0}(1+z)^3](1+z)}{2E(2+z)}. \quad (54)$$

In this work, we focus on the smooth-horizon limit $\beta = 1$, treating deviations as higher-order corrections.

4 Observational Constraints and Cosmological Implications

In this section, we confront the expansion history derived from the Holographic Equilibrium Law with key observational benchmarks of modern cosmology. The goal is not to perform a full parameter inference, but to assess whether the thermodynamically motivated evolution law can remain consistent with early-universe constraints while modifying the late-time expansion and growth histories in a phenomenologically viable manner.

4.1 Numerical Integration of the Expansion History

The cosmological evolution is governed by the differential form of the Holographic Equilibrium Law,

$$\frac{dE}{dz} = \frac{[3\Omega_{m,0}(1+z)^2 + 4\Omega_{r,0}(1+z)^3](1+z)}{2E(2+z)}, \quad (55)$$

where $E(z) \equiv H(z)/H_0$.

For numerical integration, we adopt the present-day matter density $\Omega_{m,0} = 0.2677$ and radiation density $\Omega_{r,0} = 9.14 \times 10^{-5}$. The integration is initialized at $z = 0$ with the boundary condition $E(0) = 1$ and extended to $z = 1100$, corresponding to the surface of last scattering.

The weighting factor $(1+z)/(2+z)$ modulates the influence of matter and radiation at late times, while asymptotically approaching unity at high redshift. As a result, the model reproduces the standard early-universe expansion behavior while yielding a modified late-time evolution.

4.1.1 Generalized Horizon Entropy and Barrow Corrections

The derivation presented so far has assumed the standard Bekenstein–Hawking area law [3, 5, 6] for the entropy of the apparent horizon,

$$S_{\text{BH}} = \frac{A}{4G}, \quad (56)$$

where $A = 4\pi R_H^2$ is the horizon area. This expression is expected to hold in the semiclassical limit of smooth horizons.

Motivated by possible quantum-gravitational deformations of spacetime geometry, Barrow proposed a generalized entropy functional that accounts for fractal-like structure of the horizon surface. In this framework, the horizon entropy takes the form

$$S_B = \left(\frac{A}{A_0} \right)^{1+\Delta}, \quad (57)$$

where A_0 is a fundamental area scale and $0 \leq \Delta \leq 1$ quantifies the degree of geometric deformation. The limit $\Delta = 0$ recovers the standard area law, while $\Delta > 0$ corresponds to increasingly irregular horizon geometries.

The presence of Barrow entropy modifies the relation between horizon entropy production and the effective energy transfer across the apparent horizon. At the level of homogeneous background evolution, these effects can be phenomenologically incorporated through a multiplicative damping factor β , defined such that

$$\Psi \longrightarrow \beta \Psi, \quad 0 < \beta \leq 1, \quad (58)$$

where $\beta = 1$ corresponds to the smooth-horizon limit. In this work, β is treated as an effective parameter encoding possible higher-order corrections to the horizon entropy, without committing to a specific microscopic realization.

For the remainder of the analysis, we focus on the leading-order case $\beta = 1$, and defer a detailed exploration of generalized entropy corrections to future work.

4.2 Comparison with Λ CDM and Cosmological Parameters

Table 1 summarizes a comparison between representative late-time cosmological parameters inferred within the standard Λ CDM framework and those obtained from the Holographic Equilibrium Law using the parameters adopted above.

Table 1: Representative cosmological parameters in standard Λ CDM and in the holographic equilibrium model. The Λ CDM values correspond to recent CMB-based analyses, while the holographic values follow from numerical integration of Eq. (55).

Parameter	Symbol	Λ CDM	Holographic Model
Hubble constant	H_0	67.4 ± 0.5	71.0
Matter density	$\Omega_{m,0}$	0.315 ± 0.007	0.2677
Clustering amplitude	S_8	0.832 ± 0.013	0.781
Deceleration parameter	q_0	-0.55	-0.80
Effective equation of state	$w_{\text{eff}}(z=0)$	-1.00	-0.87
Age of the Universe (Gyr)	t_0	13.78	13.8

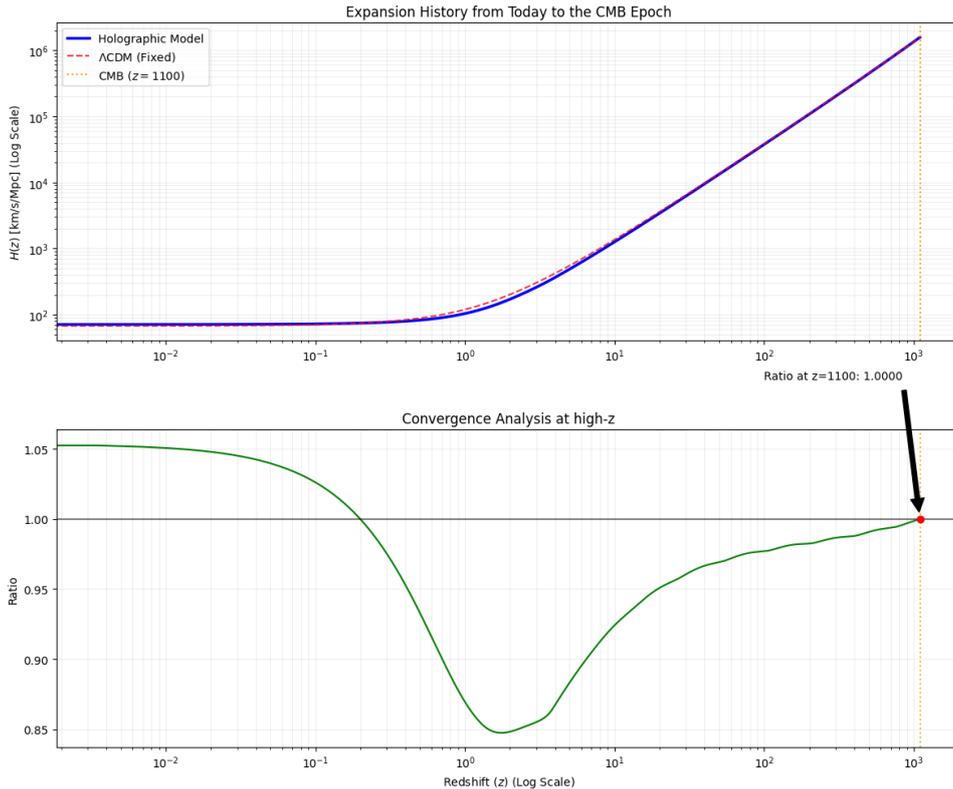


Figure 1: Evolution of the Hubble parameter $E(z)$ obtained from the Holographic Equilibrium Law compared with Λ CDM.

The holographic model yields a present-day expansion rate intermediate between CMB-inferred values and local distance ladder measurements, while predicting a reduced matter density and clustering amplitude relative to Planck-normalized Λ CDM.

4.3 Implications for the Hubble Constant

A central feature of the model is the elevation of the background expansion rate to $H_0 \simeq 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$. This value lies within the range required to alleviate the discrepancy between early- and late-universe determinations of the Hubble constant.

Importantly, the predicted value should be interpreted as a global background expansion rate. Local measurements are sensitive to environmental effects, including large-scale underdensities. For example, observational studies have suggested that the local universe may reside within a modest underdense region. Within such a context, a global background value of $H_0 \simeq 71$ requires only a small local enhancement to reach the values inferred from distance ladder measurements. This separation between global and local expansion rates provides a natural framework for interpreting the Hubble tension without invoking large systematic shifts. The interaction term Ψ represents a coarse-grained energy flux or "heat flow" between the horizon boundary and the bulk volume. This thermodynamic exchange is illustrated by the energy supply across the apparent horizon surface R_H . As the universe expands, this flux modifies the evolution of the Hubble parameter, effectively generating the emergent dark energy component observed in our results.

4.4 Implications for Structure Growth and the S_8 Parameter

The reduction in the present-day matter density directly impacts the growth of linear density perturbations. Integrating the standard growth equation on the holographic background yields

a present-day clustering amplitude $S_8 \simeq 0.781$.

This value lies below the Planck-normalized Λ CDM prediction and is consistent with recent weak lensing constraints from surveys such as KiDS-1000 and the Dark Energy Survey. The result suggests that modifying the background expansion history through horizon thermodynamics can influence both geometric and growth-based observables in a correlated manner.

4.5 Cosmic Acceleration and Effective Equation of State

The deceleration parameter derived from the holographic evolution law is $q_0 \simeq -0.80$, indicating a more rapid late-time acceleration than in the standard Λ CDM model. This acceleration is not driven by a constant vacuum energy density, but by the cumulative thermodynamic interaction associated with horizon entropy production.

The effective equation of state inferred from the expansion history satisfies $w_{\text{eff}}(z = 0) \simeq -0.87$. While deviating from the cosmological constant value $w = -1$, this behavior remains consistent with current observational bounds and reflects the dynamical origin of the vacuum component in the present framework.

4.6 Cosmic Age and High-Redshift Constraints

Despite the higher present-day expansion rate, numerical integration of the age–redshift relation yields a total cosmic age of $t_0 \simeq 13.8$ Gyr. The modified expansion history ensures sufficient time for the formation of early structures, including high-redshift galaxies observed by the *James Webb Space Telescope* at $z \gtrsim 10$.

The ability to accommodate both a higher H_0 and an observationally consistent cosmic age highlights the nontrivial role played by the late-time thermodynamic weighting in the expansion history.

4.7 Summary of Observational Implications

Taken together, these results indicate that a cosmological expansion driven by apparent-horizon thermodynamics can remain compatible with early-universe constraints while producing measurable deviations at late times. The correlated shifts in H_0 , $\Omega_{m,0}$, and S_8 arise naturally from the underlying evolution law rather than from the introduction of additional free parameters.

5 Conclusion

In this work, we have explored a cosmological framework in which vacuum energy emerges dynamically from thermodynamic interactions associated with the apparent horizon, rather than being introduced as a fundamental cosmological constant. By combining horizon entropy, energy conservation, and the symmetry properties of the cosmic fluid, we derived a self-consistent modification of the cosmological expansion history.

The central result of the analysis is the Holographic Equilibrium Law, an integro-differential relation governing the Hubble parameter that follows directly from horizon entropy production and its coupling to radiation. This evolution law reproduces the standard radiation- and matter-dominated behaviors at early times, while introducing a modified late-time expansion driven by the cumulative effect of horizon-induced energy transfer.

Without introducing additional free parameters beyond those of the standard cosmological model, the resulting expansion history remains consistent with key observational benchmarks. In particular, the framework admits a higher present-day expansion rate, a reduced matter density, and a suppressed clustering amplitude, while preserving an observationally viable cosmic age and early-universe evolution. These correlated shifts arise naturally from the thermodynamic structure of the model rather than from phenomenological tuning.

The effective vacuum component generated in this scenario is dynamical in origin and does not correspond to a strictly constant equation of state. Nevertheless, its late-time behavior approaches that required to support cosmic acceleration, highlighting a possible connection between horizon thermodynamics and dark energy phenomenology.

Several aspects of the present framework merit further investigation. A full parameter inference using cosmic microwave background, baryon acoustic oscillation, and large-scale structure data would be required to assess the statistical viability of the model. In addition, the impact of horizon-induced interactions on cosmological perturbations and nonlinear structure formation remains to be explored in detail. Possible extensions incorporating generalized entropy functionals or quantum-gravitational corrections may also lead to observable signatures.

Overall, the results presented here suggest that apparent-horizon thermodynamics provides a viable and conceptually economical avenue for modifying late-time cosmological dynamics. Whether this perspective can be embedded within a more fundamental microscopic theory, or distinguished observationally from standard dark energy models, remains an open question for future work.

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