Thermodynamic Evolution of the Vacuum in the Rh = ct Universe: A Geometric Resolution of the Cosmological Constant Problem via Holography and Emergent Gravity

Stéphane Wojnow

Independent Researcher,

https://orcid.org/0000-0001-8851-3895

7 avenue Georges Dumas, 87000 Limoges, France

January 18, 2026

Mail : wojnow.stephane@gmail.com

Keywords: $R_h = ct$ Cosmology; Vacuum Catastrophe; Holographic Principle; Variable Cosmological Constant; Emergent Gravity; Planck Scale Thermodynamics.

Abstract

We explore the thermodynamic consistency of a universe evolving with a variable cosmological constant, linking the Planck scale to the current epoch. Starting from the observation that the Planck mass energy density equals the vacuum energy density of Quantum Field Theory (QFT) at the Planck time (t_{pl}), we demonstrate that in the $R_h = ct$ cosmological model (a "quasi-de Sitter" universe), the vacuum energy density scales inversely with the square of time (t^{-2}), mirroring the evolution of matter density. This scaling resolves the "vacuum catastrophe" and the coincidence problem naturally. We integrate the thermodynamic constraints derived by Haug and Tatum (2025), the holographic principle of Li, and the geometric interpretation of the cosmological constant (Λ) proposed by Özer, Taha, and Hu. Finally, we discuss how these relationships support an emergent gravity framework à la Verlinde, where Λ is identified as a geometric property of the de Sitter horizon rather than a distinct dark energy fluid.

1. Introduction

The "vacuum catastrophe"—the discrepancy of approximately 120 orders of magnitude between the observed value of the cosmological constant and the theoretical vacuum energy density predicted by Quantum Field Theory (QFT)—remains one of the most significant open problems in physics. Standard ΛCDM cosmology assumes a constant dark energy density, leading to the coincidence problem. However, alternative models proposing a dynamic vacuum energy density offer a resolution. This paper examines the thermodynamic evolution of the universe from the Planck epoch to the present, utilizing the $R_h = ct$ linear expansion model. By synthesizing recent works by Wojnow (2026) and Haug & Tatum (2025), alongside foundational concepts from Melia, Li, and Verlinde, we argue for a geometric and thermodynamic interpretation of Λ that remains consistent across cosmic history.

2. Discussion

The Planck Scale and the Vacuum Catastrophe

It is well-established that at the fundamental limit of measurement, the energy density is defined by the relation $m_{pl}\ c^2/V_{pl} = F_{pl} \cdot l_{pl}^{-2}\ J/m^3$, where l_{pl}^{-2} corresponds to the vacuum energy density in QFT. Consequently, the vacuum energy density in a primordial de Sitter universe is identical to the matter energy density at the Planck time (t_{pl}). As noted by Wojnow (2021), this suggests that Ω_Λ essentially quantifies the "vacuum catastrophe" within the $R_h = ct$ framework at the Planck epoch. By fixing the initial conditions at t_{pl} where these densities are unified, we establish a thermodynamic baseline for cosmic evolution that does not require fine-tuning, but rather results from the geometric boundary conditions of the early universe.

Density Scaling in the Rh=ct Universe

Following the work of Melia, the $R_h = ct$ universe describes a "quasi-de Sitter" expansion where the Hubble radius R_h coincides with the event horizon. A critical consequence of this model is that the total energy density scales as ρ is proportional to t^{-2}. We propose that in this framework, the vacuum energy density of QFT is not constant but coupled to the geometry of the horizon, thereby decaying proportionally to the inverse of t^2. This evolution implies that the vacuum energy density tracks the matter energy density exactly ($\rho_{vac} = \rho_m$), rendering them comparable at all epochs. This dynamic scaling mirrors the behavior of the Standard Model but imposes a strict thermodynamic equilibrium, allowing the Cosmic Microwave Background (CMB) temperature to be utilized directly within the $R_h = ct$ thermodynamic formalism.

Holography and the Geometric Cosmological Constant

This t^2 scaling exhibits a profound link to Li's holographic dark energy principle, which posits that the vacuum energy density is determined by the area of the future event horizon. This concept was effectively anticipated by Özer and Taha (e.g., 2011 revisit of their foundational work), who proposed a "variable cosmological constant" model. They explicitly posited the relation $\Lambda = 3H^2$, creating a scenario where the universe remains perpetually in a "quasi-de Sitter" state. In this view, the energy scale of the vacuum is not an arbitrary fluid parameter but is defined by the scale of the cosmic horizon itself.

The Effective Λ and Geometric Interpretation

Expanding on the geometric nature of the vacuum, Mu-Lin Yan et al. (2012) and Wojnow (2026) have formalized this relationship, indicating that the effective cosmological constant is given by:

$$\Lambda_{\text{eff}} = \frac{3}{(ct)^2} = \frac{3}{Rh^2} = \frac{3H^2}{c^2} \qquad (1)$$

more exactly, to correspond with ΛCDM:

$$\Lambda = \Lambda_{\text{eff}}\, \Omega_\Lambda = \frac{3H^2}{c^2}\, \Omega_\Lambda \tag{2}$$

Here, the radius of the de Sitter space is identified as $R = ct_0$. This formulation is crucial because it reidentifies Λ not as a mysterious "dark energy fluid" exerting negative pressure, but as an intrinsic geometric property of de Sitter space. This aligns with the $R_h = ct$ constraint, suggesting that what we perceive as accelerated expansion (or the source thereof) is a manifestation of the spacetime horizon's thermodynamics.

Thermodynamic Constraints Independent of de Sitter

The thermodynamic consistency of this approach is further bolstered by the recent analysis of Haug and Tatum (2025). Utilizing Friedmann-type equations expressed in thermodynamic form, they derived tighter constraints on the critical density of the universe. Notably, they arrive at the same "variable cosmological constant" behavior independently of the specific de Sitter assumptions used by Melia or Wojnow. Their work confirms that when the universe is treated as a thermodynamic system, the scaling of Λ naturally follows the evolution $H(t)^2 = t^{-2} = 1/t^2$, supporting the linear expansion hypothesis from a purely thermodynamic derivation.

Emergent Gravity and Entropic Force

Finally, this synthesis finds a natural theoretical home in Erik Verlinde’s theory of Emergent Gravity. If gravity is not a fundamental force but an entropic phenomenon arising from the information structure of spacetime, then the association of Λ with the horizon surface area (and temperature) is inevitable. In Verlinde’s view, the "dark energy" component is simply a result of the volume law contribution to the entropy of the de Sitter space. The $R_h = ct$ model, with its holographic scaling and thermodynamic definitions of density (where ρ_{vac} decays with the horizon surface gravity), essentially describes a universe driven by emergent gravity, unifying the Planck scale vacuum with the macroscopic Hubble flow.

3. Conclusion

We have presented a coherent picture where the "vacuum catastrophe" is resolved by treating the cosmological constant as a variable, geometric scalar proportional to H^2. From the equality of forces at the Planck scale ($m_{pl}\, c^2/V_{pl} = F_{pl} \cdot l_{pl}^{-2}\ J/m^3$) to the current epoch, the energy density of the vacuum in an $R_h = ct$ universe tracks the matter density as t^{-2}.This model is supported by the holographic principle, the geometric identification of Λ by Özer, Taha, and Hu, and the independent thermodynamic derivations of Haug and Tatum (2025). Ultimately, this suggests the universe is a holographic, emergent gravity system where Λ represents the curvature of the horizon rather than an exotic fluid.

References

1. Haug, E.G., & Tatum, E.T. (2025). Friedmann type equations in thermodynamic form lead to much tighter constraints on the critical density of the universe. *Discover Space*, 1, 129. https://doi.org/10.1007/s11038-025-09566-y
2. Wojnow, S. (2026). A Rh = ct Thermodynamic Cosmology Approach: Connecting the Effective Cosmological Constant and the Cosmic Microwave Background Temperature via the Haug–Tatum et al.–Wojnow Relation. *Preprint*. DOI: https://doi.org/ 10.13140/RG.2.2.35217.70245
3. Melia, F. (2012). The Cosmic Horizon. *Monthly Notices of the Royal Astronomical Society*. https://doi.org/10.1111/j.1365-2966.2011.19906.x
4. Li, M. (2004). A model of holographic dark energy. *Physics Letters B*, 603(1-2). https://doi.org/10.1016/j.physletb.2004.10.014.
5. Özer, M., & Taha, M. O. (1987/2011). A model of the universe with time-dependent cosmological constant. *Nuclear Physics B*. https://doi.org/10.1016/0550-3213(87)90128-3
6. Verlinde, E. (2011). On the Origin of Gravity and the Laws of Newton. *Journal of High Energy Physics*. https://doi.org/10.1007/JHEP04(2011)029
7. Mu-Lin Yan, Sen Hu, Wei Huang, Neng-Chao Xiao (2011), On determination of the geometric cosmological constant from the OPERA experiment of superluminal neutrinos. https://doi.org/10.48550/arXiv.1112.6217
8. Wojnow S. (2021) Interpretation and Solution of the Cosmological Constant Problem. https://vixra.org/pdf/2104.0179v3.pdf