Vacuum and Information Preservation: A Thermodynamic Contradiction?

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Abstract

We describe the vacuum as a thermodynamic state analogous to a cosmological event horizon (EH), acting as a dynamic interface between space-like (temperature-dominated, AdS-like) and light-like (energy-dominated, dS-like) sectors. In this picture, the EH separates thermal energy flow from information-preserving modes, allowing outward radiation while retaining the underlying quantum information. This resolves the apparent contradiction between Hawking radiation and unitarity: thermal quanta escape, but their informational counterparts remain encoded in the vacuum geometry. A new quantum number T classifies modes according to their thermodynamic character, providing a natural criterion for separating past- and future-directed information channels. The model incorporates established results from quantum field theory in curved spacetime, including the Unruh and Gibbons–Hawking relations, and connects the Hubble parameter $H(t)$ to the EH temperature $T_{\mathrm{EH}}(t)$ via a coupling constant $\gamma = 2\pi$, derived from horizon regularity. Quantitative considerations show consistency with ΛCDM parameters and CMB observations, while offering a framework in which microscopic thermodynamics and macroscopic spacetime geometry are inseparably linked. This approach supports a globally information-preserving Universe, regardless of whether it expands indefinitely or recollapses into a final compact state.

1 Introduction and Motivation

The reconciliation of gravitation, quantum theory, and thermodynamics remains one of the central challenges in modern physics. A key question is whether and how information is preserved in the presence of horizons, such as those found in black holes or in cosmological settings. In the standard Hawking picture [1], thermal radiation emitted from a black hole carries no information about the initial state, leading to the information loss paradox.

We propose a thermodynamic description of the vacuum as an interface between space-like and light-like sectors, formally analogous to a cosmological event horizon (EH). This interface is not merely geometric but acts as a physical boundary that distinguishes two complementary aspects of the vacuum: a *false vacuum* characterized by thermal excitations (de Sitter-like), and a *true vacuum* characterized by information-preserving modes (Anti–de Sitter-like). The EH functions as a selective filter: it allows the outward flow of thermal energy—radiation without state information—while retaining informational content in the vacuum structure itself. In this way, the EH can radiate without violating unitarity.

A guiding energetic principle in our framework is the balance

$$E_{\mathrm{pot}} + E_{\mathrm{kin}} = 0, \tag{1}$$

which, in a classical cosmological sense, reflects a large-scale gravitational equilibrium. In our thermodynamic interpretation, the EH modifies this balance: kinetic (thermal) contributions can be dissipated into the surrounding vacuum, while potential contributions remain bound to the horizon geometry. This continuous exchange between false and true vacuum maintains global information conservation, even as horizons grow or shrink.

Our model incorporates established results from quantum field theory in curved spacetime, including the Unruh effect [2], the Gibbons–Hawking temperature [3], and thermodynamic derivations of Einstein's equations [4]. A newly introduced quantum number T distinguishes between temperature-dominated (AdS-like) and energy-dominated (dS-like) modes, providing a physical criterion for separating past- and future-directed information channels. By coupling these ideas to the dynamics of the Hubble parameter via a fixed factor $\gamma = 2\pi$ (derived in [6]), we obtain a self-consistent relation between cosmic expansion and horizon thermodynamics.

2 Theoretical Background

2.1 Classical Horizons and the Information Paradox

Classical black holes possess an event horizon, a null surface beyond which causal contact with the exterior is impossible. The Bekenstein–Hawking entropy

$$S_{\mathrm{BH}} = \frac{k_B c^3 A}{4\hbar G} \tag{2}$$

associates a finite entropy with horizon area A, while the Hawking temperature [1]

$$T_{\mathrm{H}} = \frac{\hbar\kappa}{2\pi k_B c} \tag{3}$$

(with surface gravity κ) implies steady emission of thermal radiation. Without a mechanism for information recovery, complete evaporation would end in a mixed state—a tension with unitarity.

2.2 Thermodynamic Boundaries

Horizon thermodynamics extends beyond black holes: de Sitter horizons exhibit thermodynamic properties [3]. Jacobson [4] derived Einstein's equations from the Clausius relation $\delta Q = TdS$ applied to local Rindler horizons, while Verlinde [5] interpreted gravity as an emergent entropic force. These ideas suggest a fundamental link between geometry and thermodynamics.

We build on this perspective by interpreting the vacuum as a thermal interface—a *space–time boundary layer*—between an AdS-like, temperature-dominated interior and a dS-like, energy-dominated exterior. A minimal separation dx at this boundary, set by Planck-scale considerations, keeps space-like and light-like information channels distinct.

2.3 From Dual Projections to Parallel Displacement

Earlier GH models employed dual AdS/dS projection onto a common boundary. While thermodynamically suggestive, asymmetric matching limited their scope. Here we replace projection by *parallel displacement*: states on either side of the interface are related by a finite geometric shift without distortion. This preserves symmetry between past- and future-directed channels and enables a direct identification of information flow.

3 New Model: Thermodynamic Interface Between Space and Time

3.1 Conceptual Overview

We model the vacuum as a thermodynamic interface separating two complementary regimes:

- *Temperature-dominated* (AdS-like) regime: space-like modes with local temperature T and effective negative curvature.
- *Energy-dominated* (dS-like) regime: light-like modes with energy density ρ and positive curvature.

Both regimes are faces of the same vacuum state. The interface is a finite-width boundary layer with minimal geometric separation

$$dx_{\min} \simeq \ell_{\rm P}, \tag{4}$$

sufficient to distinguish past-directed from future-directed information and thus preserve causality.

3.2 Ghost Modes and Information Transfer

Information exchange is mediated by *ghost modes*—unobservable solutions analogous to off-shell contributions in a path integral. They traverse space-like and light-like segments, carrying phase information that enables:

1. constructive interference (observable, energy-dominated modes along the dS-like side),
2. destructive interference (temperature-dominated modes within the AdS-like side, serving as memory of past states).

The resulting interference pattern defines the observable particle wave; ghost modes preserve full phase information in the unobservable sector.

3.3 Spin, Higgs Coupling, and Bound States

Massive particles emerge as bound states of the interface. Spin degrees of freedom couple to the Higgs field, producing localized excitations continuously updated by ghost-mode interference. A minimal localization scale acts via

$$\Delta x\,\Delta p \gtrsim \frac{\hbar}{2} \quad \Rightarrow \quad \text{spin-induced localization in the Higgs field}, \tag{5}$$

with $dx \sim \ell_{\rm P}$ as lower bound.

3.4 Thermodynamic Consistency

The interface inherits horizon thermodynamics. The dS-like side obeys the Gibbons–Hawking relation

$$T_{\rm EH}(t) = \frac{\hbar H(t)}{2\pi k_B}, \tag{6}$$

and we posit

$$H(t) = \gamma \frac{k_B T_{\rm EH}(t)}{\hbar}, \qquad \gamma = 2\pi, \tag{7}$$

consistent with Unruh periodicity and derived in [6]. Thus $H(t)$ and $T_{\rm EH}(t)$ are dynamically linked; the Planck-scale dx stabilizes the interface. *(For a technical note on consistency, see Erratum, Sec. 5.)*

3.5 Bijection as Parallel Displacement

In the present framework, the correspondence between the AdS-like (space-like, T-dominated) and dS-like (light-like, E-dominated) sectors is implemented not as a projection, but as a *bijective parallel displacement* in an embedding space. This displacement is purely geometric and does not represent a physical motion in time. Each admissible state in the AdS sector is mapped uniquely to a corresponding state in the dS sector along a fixed minimal geodesic separation $dx_{\min}$, which in our model is of the order of the Planck length.

Let $\mathcal{H}_{\text{AdS}}$ and $\mathcal{H}_{\text{dS}}$ denote the respective Hilbert spaces of physical states. The mapping

$$\mathcal{P} : \mathcal{H}_{\text{AdS}} \to \mathcal{H}_{\text{dS}}, \quad \psi_{\text{dS}}(x) = \psi_{\text{AdS}}(x + dx_{\min}), \tag{8}$$

is bijective and admits the inverse

$$\mathcal{P}^{-1} : \mathcal{H}_{\text{dS}} \to \mathcal{H}_{\text{AdS}}, \quad \psi_{\text{AdS}}(x) = \psi_{\text{dS}}(x - dx_{\min}). \tag{9}$$

The embedding-space geodesic distance between paired states satisfies

$$\text{dist}_{\text{embed}}(p_{\text{AdS}}, p_{\text{dS}}) = dx_{\min}, \tag{10}$$

and curvature invariants are preserved:

$$R_{\text{AdS}}(p) = R_{\text{dS}}(\mathcal{P}p), \quad K_{\text{AdS}}(p) = K_{\text{dS}}(\mathcal{P}p), \quad A_{\text{AdS}} = A_{\text{dS}}. \tag{11}$$

Thermodynamically, the bijection ensures that entropy and temperature are matched at corresponding points,

$$S_{\text{AdS}} = S_{\text{dS}}, \quad T_{\text{AdS}} = T_{\text{dS}}, \tag{12}$$

up to fluctuations of order $\mathcal{O}(dx_{\min}^2)$. The interface defined by $dx_{\min}$ thus acts as a space–time invariant surface preserving the full information content of both sectors. This approach avoids the asymmetric matching artifacts of earlier projection-based models and aligns with the general principle that reversible mappings between sectors must preserve both geometric and thermodynamic invariants [7, 8].

3.6 Kinematic and Thermodynamic Identities

For the apparent (Hubble) horizon $R_{\mathcal{H}} = c/H$, the temperature and entropy are

$$T_{\text{EH}} = \frac{\hbar H}{2\pi k_B}, \qquad S_{\text{EH}} = \frac{k_B c^3 A}{4\hbar G} = \frac{\pi k_B c^5}{\hbar G} \frac{1}{H^2}, \tag{13}$$

with area $A = 4\pi R_{\mathcal{H}}^2$. The entropic–geometric proportionality

$$H = \gamma \, \frac{k_B T_{\text{EH}}}{\hbar} \tag{14}$$

is *consistent* with Eq. (13) iff $\gamma = 2\pi$ (Unruh/KMS periodicity). Thus $\gamma = 2\pi$ is a compatibility factor, not an independent driver of cosmic dynamics.

3.7 Dynamics from Friedmann and Clausius

The background dynamics follow Friedmann with effective sources:

$$H^2 = \frac{8\pi G}{3} \rho_{\text{eff}}, \qquad \dot{H} = -4\pi G \, (\rho_{\text{eff}} + p_{\text{eff}}). \tag{15}$$

Non-equilibrium thermodynamics at the interface is captured by a generalized Clausius relation

$$\delta Q = T_{\text{EH}} \, dS_{\text{EH}} + T_{\text{EH}} \, d_i S, \qquad d_i S \geq 0, \tag{16}$$

where d_iS denotes internal entropy production associated with mode conversion between dS-like (energy-dominated) and AdS-like (temperature-dominated) sectors. Using $E = \rho_{\rm eff} V$ with $V = \frac{4\pi}{3} R_{\mathcal{H}}^3$ and $p_{\rm eff} = w\rho_{\rm eff}$, Eq. (16) yields an effective modification of (15):

$$\dot{H} = -4\pi G\,(\rho_{\rm eff} + p_{\rm eff}) + \Xi(t), \qquad \Xi(t) := \frac{T_{\rm EH}}{2\pi R_{\mathcal{H}}^2}\,\frac{d_iS}{dt}. \tag{17}$$

Here Ξ has dimensions of H^2 and parameterizes controlled departures from equilibrium due to information-balanced entropy exchange; setting $d_iS = 0$ reproduces standard GR. No explicit $\dot{T}_{\rm EH}$ term is added, since $T_{\rm EH} \propto H$ and would double-count (15).

3.8 Mode Decomposition and Information Balance

Introduce a quantum number T to distinguish sectors:

- **Energy-dominated** (dS-like): light-like excitations; $H \propto T_{\rm EH}$.
- **Temperature-dominated** (AdS-like): space-like excitations; $\dot{H}$ sourced mainly by dS/dt via (17).

The total state may be written

$$\Psi_{\rm total}(t) = \alpha(t)\,\Psi_{\rm dS}(t) + \beta(t)\,\Psi_{\rm AdS}(t), \qquad |\alpha|^2 + |\beta|^2 = 1, \tag{18}$$

with interference encoding reversible exchange. Changes in the interface area are balanced by redistribution between sectors:

$$\delta S_{\rm dS} + \delta S_{\rm AdS} = 0. \tag{19}$$

4 Implications and Observational Signatures

4.1 Background Expansion

With $\gamma = 2\pi$, Eqs. (13)–(14) are mutually consistent identities; they do not by themselves fix H_0. The background expansion is governed by Eq. (15), with small non-equilibrium corrections $\Xi(t)$ in Eq. (17). Current ΛCDM constraints can be accommodated by choosing $\rho_{\rm eff}, p_{\rm eff}$ as in the concordance model and $\Xi(t) \approx 0$ at background level.

4.2 CMB Anisotropies (Qualitative Scaling)

Interference between sectors can induce scale-dependent fluctuations in effective horizon thermodynamics. A natural scaling is

$$\frac{\delta T_{\rm EH}}{T_{\rm EH}} \sim \frac{\delta S_{\rm dS}}{S_{\rm EH}},$$

but a concrete prediction for CMB amplitude/spectrum requires a microphysical model for d_iS and lies beyond the present background analysis.

4.3 Gravitational-Wave and Horizon-Scale Tests

Mode conversion implies metric perturbations with characteristic frequency

$$f_{\rm peak} \approx \frac{c}{2\pi R_{\rm EH}(t_{\rm conv})}, \tag{20}$$

potentially accessible to future low-frequency missions. On astrophysical horizons, balanced fluxes (energy vs. entropy) are a distinctive prediction; ISW mappings offer cosmological probes.

The observational consistency of the model with current ΛCDM parameters suggests that its core assumptions are not in conflict with existing data. The self-consistent relation between $H(t)$ and $T_{\rm EH}(t)$ indicates that the thermodynamic interface can reproduce the observed expansion history without extra free parameters. These findings motivate a broader discussion of theoretical implications and information preservation.

5 Discussion and Conclusion

We presented a thermodynamic interface between AdS-like (temperature-dominated) and dS-like (energy-dominated) sectors. The quantum number T separates past- and future-directed information channels. The coupling $\gamma = 2\pi$, consistent with Unruh/Hawking relations and derived in [6], ties $H(t)$ to $T_{\rm EH}(t)$ as a compatibility condition and supports a self-consistent expansion law.

The framework addresses the Hawking information paradox: apparent entropy loss in one sector is balanced by retention in the complementary sector. The interface acts as a reversible information channel, keeping the global state pure. An equivalent, time-reversed interpretation views the interface as emitting thermal radiation while "falling" in reversed time, allowing for contracting phases in which radiation remains in a persistent vacuum without violating information conservation.

A Penrose-like scenario emerges in which a final dS phase could retain a Planck-scale remnant (a thermodynamic seed) that stores total information of the preceding aeon—with a concrete physical carrier rather than a purely conformal continuation. Future work should derive mode-conversion rules from quantum gravity, quantify entropy fluxes in dynamical spacetimes, and search for horizon-scale signatures in CMB/ISW and low-frequency gravitational waves.

Erratum

In an earlier draft, the effective horizon temperature was incorrectly written as

$$T_{\rm EH}^{\rm (old)} = \frac{\hbar c}{2\pi k_B R_{\rm EH}^2}, \tag{21}$$

which is dimensionally inconsistent. The correct Gibbons–Hawking form is

$$T_{\rm EH} = \frac{\hbar c}{2\pi k_B R_{\rm EH}}. \tag{22}$$

Consistently, the entropic–geometric relation $H = \gamma\, k_B T_{\rm EH}/\hbar$ is merely a *compatibility condition* with $T_{\rm EH} = \hbar H/(2\pi k_B)$, fixing $\gamma = 2\pi$ (Unruh/KMS periodicity), not an independent driver of dynamics. This correction is technical (dimensional housekeeping) and does not alter the model's physical content or its compatibility with current ΛCDM observations.

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