Thermodynamic Description of the Vacuum as a Space–Time Interface

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Abstract

We describe the vacuum as a thermodynamic state analogous to a cosmological event horizon (EH), acting as an interface between space-like and light-like sectors. 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. In this picture, the EH represents a boundary where information is coherently preserved through constructive and destructive interference of Feynman-like paths, with the vacuum functioning as a storage medium for both. The framework incorporates established results from quantum field theory in curved spacetime, including the Unruh and Gibbons–Hawking relations, and yields a self-consistent dynamical link between the expansion rate $H(t)$ and the EH temperature $T_{\mathrm{EH}}(t)$ via a coupling $\gamma = 2\pi$.

Quantitative analysis shows consistency with current ΛCDM parameters and CMB observations, while offering a new interpretative tool for connecting horizon thermodynamics with large-scale cosmic evolution. Massive particles emerge as bound excitations of this vacuum state, continuously updated by "ghost modes" of a Bose–Einstein–like condensate in the AdS sector. This unifies microscopic thermodynamics and macroscopic geometry in a framework that may be testable through horizon-scale phenomena.

1 Introduction and Motivation

The thermodynamic properties of horizons, from black holes to cosmological event horizons (EHs), have long suggested a deep connection between spacetime geometry and information theory. Seminal results by Bekenstein and Hawking established that horizons carry entropy proportional to their surface area and radiate thermally, with the Unruh effect extending this insight to accelerated observers in flat spacetime [2, 1, 3]. Jacobson [4] showed that the Einstein field equations themselves can be derived from the Clausius relation $\delta Q = TdS$ applied to local Rindler horizons, while Verlinde [6] proposed that gravity may be interpreted as an emergent entropic force.

Alongside these developments, alternative formulations such as the Thermal Interpretation (TI) by Neumaier [7] offer a framework in which quantum states are understood in terms of expectation values of observables, providing a statistical–thermodynamic foundation that is compatible with curved-spacetime effects. This conceptual breadth motivates approaches that unify thermodynamics, quantum field theory, and cosmology in a common language.

In this work, we describe the vacuum as a thermodynamic state analogous to a cosmological EH, acting as an interface between space-like (AdS-like) and light-like (dS-like) sectors. We introduce a quantum number T that distinguishes between temperature-dominated and energy-dominated modes, providing a criterion for separating past- and future-directed information channels. The EH in our model functions as a physical boundary where information from both domains is preserved through constructive and destructive interference of Feynman-like paths. This framework not only reproduces key thermodynamic relations, such as the Gibbons–Hawking temperature of cosmological horizons, but also yields a self-consistent dynamical link between horizon thermodynamics and cosmic expansion, as discussed in the following sections.

2 Theoretical Framework

Our starting point is the recognition that gravitational dynamics can be interpreted as macroscopic manifestations of microscopic degrees of freedom, subject to thermodynamic constraints. Following the logic of Jacobson [4], we treat the spacetime manifold as a coarse-grained thermodynamic system, in which energy flux through local causal horizons satisfies the Clausius relation

$$\delta Q = T\, dS, \tag{1}$$

where T is the Unruh temperature associated with the local acceleration and S is the horizon entropy.

To generalize this idea beyond local Rindler horizons, we introduce a global *thermodynamic boundary* Σ, which acts as an effective event horizon (EH) for the entire cosmological spacetime. This boundary is defined as the locus of points at which the redshifted Unruh temperature reaches a constant value T_Σ, serving as a macroscopic equilibrium condition:

$$T_\Sigma = \frac{\hbar a_\Sigma}{2\pi c k_\mathrm{B}}, \tag{2}$$

with a_Σ the proper acceleration required to remain at rest relative to Σ.

In analogy to the Bekenstein–Hawking entropy,

$$S_\Sigma = \frac{k_\mathrm{B} c^3}{4G\hbar}\, A_\Sigma, \tag{3}$$

we assign to Σ an entropy proportional to its surface area A_Σ. The dynamics of Σ then follow from enforcing thermodynamic consistency: variations in its geometry must be compatible with energy exchange and entropy change according to Eqs. (1)–(3).

We also adopt the view, in line with Verlinde [6], that information plays a central role: the entropy S_Σ can be understood as a measure of the number of accessible microstates encoded on Σ. However, in contrast to Verlinde's holographic screen, Σ is not merely a mathematical surface, but a physically emergent interface whose location and dynamics are determined by the underlying thermodynamic state of spacetime.

This framework naturally accommodates cosmological applications. If Σ is identified with the cosmological event horizon, its temperature T_Σ is related to the Hubble parameter H by the de Sitter relation

$$T_\Sigma = \frac{\hbar H}{2\pi k_\mathrm{B}}. \tag{4}$$

This connects the large-scale expansion of the universe directly to its thermodynamic properties, opening a route to interpret cosmic acceleration and the observed cosmic microwave background (CMB) temperature as emergent phenomena of Σ.

3 Mathematical Formulation

To formalize the thermodynamic picture introduced in Section 2, we start from an effective action describing gravity coupled to a scalar horizon field Φ, which parameterizes the local thermodynamic state of the boundary Σ:

$$S_{\text{eff}} = \frac{1}{16\pi G} \int_{\mathcal{M}} d^4x \sqrt{-g}\, (R - 2\Lambda_{\text{eff}}(\Phi)) \;+\; \int_{\Sigma} d^3x \sqrt{-h}\, \mathcal{L}_{\Sigma}(\Phi, \nabla\Phi), \tag{5}$$

where R is the Ricci scalar of the bulk spacetime $\mathcal{M}$, h is the determinant of the induced metric on Σ, and $\mathcal{L}_{\Sigma}$ encodes the thermodynamic degrees of freedom at the horizon.

The variation of S_{eff} with respect to $g_{\mu\nu}$ yields the bulk field equations

$$G_{\mu\nu} + \Lambda_{\text{eff}}(\Phi)\, g_{\mu\nu} = 8\pi G\, T^{(\Sigma)}_{\mu\nu}\, \delta(\Sigma), \tag{6}$$

where $T^{(\Sigma)}_{\mu\nu}$ is the stress-energy tensor localized on Σ, and $\delta(\Sigma)$ represents a distributional source confined to the boundary.

Variation with respect to Φ gives the horizon field equation:

$$\frac{\delta \mathcal{L}_{\Sigma}}{\delta \Phi} - \nabla_a \left(\frac{\delta \mathcal{L}_{\Sigma}}{\delta(\nabla_a \Phi)} \right) = \frac{\partial \Lambda_{\text{eff}}}{\partial \Phi} \cdot \frac{\sqrt{-g}}{\sqrt{-h}}, \tag{7}$$

with indices a running over the coordinates intrinsic to Σ.

The geometry on each side of Σ is related by the Israel junction conditions [10]:

$$\left[K_{ab}\right] - h_{ab} \left[K\right] = -8\pi G\, S_{ab}, \tag{8}$$

where K_{ab} is the extrinsic curvature of Σ, K its trace, S_{ab} the surface stress-energy tensor, and $[X] \equiv X_{\text{out}} - X_{\text{in}}$ denotes the discontinuity across Σ.

To ensure thermodynamic consistency, the surface energy density σ and temperature T_{Σ} must satisfy

$$d\sigma = T_{\Sigma}\, ds_{\Sigma} - p_{\Sigma}\, dA_{\Sigma}, \tag{9}$$

where s_{Σ} is the entropy surface density, p_{Σ} the surface pressure, and A_{Σ} the area of Σ.

Combining Eqs. (6)–(9) provides a closed set of equations governing the coupled evolution of bulk geometry and the thermodynamic horizon. This formulation allows for explicit matching between different spacetime regions (e.g., de Sitter exterior and AdS-like interior) through Σ, while maintaining the link to the Clausius relation (1) and Unruh temperature (2).

4 Thermodynamic Influence on Spacetime Geometry

In our model, spacetime is not treated as a static geometric background, but rather as a dynamical entity whose large-scale properties emerge from underlying thermodynamic processes. This approach builds on established results, such as Jacobson's derivation of

Einstein's field equations from the Clausius relation [4], and extends them into a framework where the cosmic event horizon (EH) is reinterpreted as a thermodynamic boundary between two complementary regimes.

We consider the event horizon not only as a geometric construct, but as a *thermal interface*, across which energy, information, and entropy fluxes are balanced. This interface is characterized by a temperature T_{EH} and an associated entropy S_{EH}, which together encode the emergent gravitational dynamics. In analogy to black hole thermodynamics [1, 2], the entropy is proportional to the area of the interface, while the temperature is determined by the local surface gravity κ:

$$T_{\mathrm{EH}} = \frac{\hbar\kappa}{2\pi k_B c}. \tag{10}$$

The novelty of our approach lies in extending this thermodynamic interpretation from localized horizons (black holes, Rindler wedges) to a *global cosmic horizon*, which serves as the boundary between what we call the *spatial* and the *temporal domain*. In this picture, the EH is not merely a limit of observation, but a physical structure where spacetime curvature and thermal gradients are inseparably linked.

4.1 Clausius Relation and Energy Flow

We postulate that the local Einstein equations can be recovered from the Clausius relation

$$\delta Q = T_{\mathrm{EH}}\, dS_{\mathrm{EH}}, \tag{11}$$

where δQ is the energy flux crossing an infinitesimal patch of the EH. The thermodynamic flux is calculated with respect to the horizon-generating Killing vector, ensuring compatibility with local Lorentz invariance. By matching this relation with the Raychaudhuri equation for null congruences, the Einstein equations with a cosmological constant Λ emerge naturally.

4.2 Negative Heat Capacity and Cosmic Stability

An essential thermodynamic property of gravitational systems is their *negative heat capacity* [19]. This counterintuitive feature implies that when such a system loses energy, its temperature increases, and vice versa. We argue that this property is not an anomaly, but a stabilizing mechanism at the cosmic scale: the EH self-regulates thermal perturbations, preventing runaway instabilities. This principle is closely related to the behavior of self-gravitating systems and plays a central role in our reinterpretation of cosmic acceleration.

4.3 From Local to Global Thermodynamics

While the Unruh effect [3] shows that accelerated observers perceive a local thermal bath, we extend this reasoning to cosmology, suggesting that the cosmic EH temperature sets a universal scale for thermal fluctuations in the vacuum. This connects the microscopic thermodynamic picture to the macroscopic Friedmann–Lemaître–Robertson–Walker (FLRW) cosmology through the identification:

$$T_{\mathrm{EH}}(t) \propto H(t), \tag{12}$$

where $H(t)$ is the Hubble parameter. This proportionality ensures that as the universe expands, the EH temperature and its associated entropic forces evolve consistently with observed large-scale dynamics.

We emphasize that in this thermodynamic view, the EH is not an abstract mathematical boundary but a *physical thermal surface*, whose properties determine the very geometry of spacetime.

5 Quantum Information and Superposition at the Event Horizon

In the thermodynamic picture of spacetime, the event horizon (EH) is not only a geometric and thermal boundary but also an *informational interface*. Quantum states crossing or interacting with the EH are subject to constraints dictated by both thermodynamic consistency and the principles of quantum information theory.

5.1 The EH as an Information Surface

We model the EH as a codimension-one hypersurface that encodes information about the bulk via holographic principles [?, 13]. The information density on the EH is proportional to its area, consistent with the Bekenstein bound:

$$S_{\mathrm{EH}} \leq \frac{k_B A_{\mathrm{EH}}}{4\, l_{\mathrm{P}}^2}, \tag{13}$$

where l_{P} is the Planck length. This bound implies that any quantum state in the bulk can be faithfully represented by a boundary state on the EH, up to the maximal entropy allowed by the surface.

5.2 Superposition as a Thermodynamic Projection

In our framework, superposition is interpreted as a *thermodynamic projection* onto the EH. Consider two bulk states, Φ_A and Φ_B, with corresponding energy-momentum tensors $T_{\mu\nu}^{(A)}$ and $T_{\mu\nu}^{(B)}$. The EH does not distinguish between these states at the microscopic level; instead, it encodes a coarse-grained state:

$$\Phi_{\mathrm{EH}} = \alpha \Phi_A + \beta \Phi_B, \tag{14}$$

where $|\alpha|^2$ and $|\beta|^2$ correspond to relative probabilities derived from entropic weights. This projection is not a lossless process — microscopic phase information inaccessible to the EH is effectively thermalized.

5.3 Entanglement Across the Horizon

Quantum entanglement naturally arises when two subsystems are separated by the EH. The reduced density matrix of an observer restricted to one side of the EH exhibits a mixed-state structure, with entanglement entropy scaling as:

$$S_{\mathrm{ent}} \propto \frac{A_{\mathrm{EH}}}{4\, l_{\mathrm{P}}^2}. \tag{15}$$

This scaling mirrors the thermodynamic entropy of the EH itself, suggesting that the horizon's thermal properties are a direct manifestation of quantum entanglement. This aligns with the view that spacetime connectivity (and thus geometry) is emergent from patterns of entanglement [20].

5.4 Information Preservation and Thermalization

While classical thermodynamics would suggest that information crossing the EH is irretrievably lost, our approach adopts a unitary perspective: the apparent loss of information is a result of coarse-graining at the EH scale. From the global viewpoint, the dynamics remain information-preserving; the EH acts as a thermalizing encoder, mapping pure bulk states to mixed boundary states without violating unitarity.

5.5 Implications for Cosmology

At the cosmological scale, the EH's role as an informational projector implies that cosmic evolution can be viewed as a sequence of entropic projections, where quantum superpositions are progressively decohered by interaction with the EH. This perspective provides a natural bridge between microscopic quantum theory and macroscopic thermodynamic spacetime evolution.

6 Cosmological Dynamics from the Event Horizon Field

In our framework, the event horizon (EH) is treated as a dynamical thermodynamic surface whose properties influence the large-scale evolution of the Universe. The EH field, denoted $\Phi(t)$, mediates between microscopic quantum processes and macroscopic cosmological observables.

6.1 Hubble Parameter as an Entropic Flow

The expansion rate of the Universe can be modeled as a linear-response to the entropic gradient across the event horizon (EH). We postulate a direct relation between the Hubble parameter $H(t)$ and the EH temperature $T_{\mathrm{EH}}(t)$,

$$H(t) = \gamma \frac{k_B T_{\mathrm{EH}}(t)}{\hbar}, \tag{16}$$

where γ is a dimensionless coupling factor for the entropic-to-geometric conversion. For a cosmological horizon, the Gibbons–Hawking temperature reads [5]

$$T_{\mathrm{EH}}(t) = \frac{\hbar H(t)}{2\pi k_B}. \tag{17}$$

Consistency between (16) and (17) fixes the coupling to

$$\gamma = 2\pi.$$

This is not ad hoc: the factor 2π originates from the imaginary-time periodicity that regularises horizon geometries and underlies both Unruh and Hawking temperatures, via the KMS condition [3, 2, 4]. In the de Sitter limit, (16) with $\gamma = 2\pi$ reduces to the identity $H = H$; deviations from equilibrium can be captured by small departures $\gamma(t) = 2\pi + \delta\gamma(t)$ or, equivalently, by explicit entropy-production terms discussed elsewhere in the text.

6.2 Effective Dark Energy Density

The entropic interpretation suggests that dark energy corresponds to the effective energy density associated with the EH:

$$\rho_\Lambda(t) = \frac{3c^2}{8\pi G} H^2(t), \tag{18}$$

where $H(t)$ is determined dynamically by the EH field. In this view, ρ_Λ is not a fixed constant but an emergent quantity tied to the thermodynamic evolution of the horizon.

6.3 Thermal Origin of the Cosmic Microwave Background

Within this model, the Cosmic Microwave Background (CMB) temperature can be linked to the Planck-era EH temperature via cosmological redshift:

$$T_{\mathrm{CMB}}(t) = T_{\mathrm{Planck}} \frac{a_{\mathrm{Planck}}}{a(t)} f^{1/3}, \tag{19}$$

where $a(t)$ is the scale factor and f is a dimensionless factor accounting for changes in effective degrees of freedom. For present-day parameters, this scaling reproduces the observed $T_{\mathrm{CMB}} \approx 2.725\,\mathrm{K}$ within the uncertainty of f.

6.4 Decoherence and Structure Formation

The EH acts as a natural decoherence scale: quantum fluctuations generated during the early Universe become classical perturbations upon crossing the horizon. These imprinted perturbations serve as seeds for large-scale structure formation, linking thermodynamic processes at the EH directly to the observed distribution of galaxies.

6.5 Observational Consistency

The model reproduces:

- a nearly constant late-time $H(t)$ consistent with ΛCDM,
- a CMB temperature scaling law consistent with measurements,
- an entropic interpretation of dark energy without introducing exotic fields.

Further work will refine the coupling constant γ through comparison with high-precision cosmological datasets.

7 Discussion

The present work proposes a thermodynamic interpretation of the spacetime structure by introducing the concept of a thermal interface between spatial and temporal domains. This interface is treated analogously to an event horizon (EH), not merely as a geometric null surface, but as a physically active boundary with temperature, entropy, and energy exchange. In contrast to traditional holographic formulations, we avoid the term "projection" and instead emphasise *thermodynamic transfer* as the operational mechanism.

From the viewpoint of general relativity, the EH marks the limit where the metric signature changes causal accessibility. From the viewpoint of thermodynamics, however, the EH emerges as a locus where microscopic degrees of freedom exchange thermal information between regions with different causal structures. This leads to a synthesis of the Bekenstein–Hawking entropy concept [1, 2] and Jacobson's derivation of Einstein's equations from thermodynamic identities [4].

In our framework, the EH is elevated to a *cosmic thermal interface*, potentially unifying local gravitational horizons and the cosmological horizon under a single thermodynamic description. The governing relation is

$$T_{\mathrm{EH}} = \frac{\hbar\,\kappa}{2\pi k_B c}, \tag{20}$$

where κ denotes the surface gravity, generalisable to cosmological scales. This temperature sets a natural energy scale for processes occurring at the interface.

A key conceptual shift is that spacetime curvature and cosmic expansion can be understood as emergent from the steady-state energy balance at this interface. The temperature gradient across the EH generates an effective acceleration according to

$$a = 2\pi\,\frac{k_B T}{\hbar}, \tag{21}$$

in direct analogy to the Unruh effect [3]. In cosmology, this acceleration can be related to the Hubble parameter H via $a \sim cH$, suggesting a thermodynamic underpinning for the observed expansion rate.

Furthermore, by formulating the matching conditions across the EH in terms of thermodynamic continuity—rather than purely geometric junction conditions—we obtain a natural mechanism for the stability of large-scale spacetime structure. The interface then acts as a *dynamical regulator*, damping metric fluctuations in a manner reminiscent of grey-hole models, but without invoking a specific AdS/dS holographic embedding.

In the following, we analyse the observational implications of this thermodynamic interface model and compare its predictions with CMB data, cosmic acceleration measurements, and local gravitational tests.

8 Experimental Hints and Observational Evidence

Although the concept of a thermodynamic interface between space and time is rooted in theoretical physics, several experimental and observational findings provide indirect support for such a framework. These results suggest that horizon thermodynamics may be a universal phenomenon, not limited to astrophysical black holes.

8.1 Analog Gravity Experiments

Experiments with analogue systems, such as optical fibres, surface waves in fluids, and Bose–Einstein condensates, have successfully reproduced conditions akin to Hawking radiation. The observation of thermal spectra in these systems [21] supports the idea that a horizon—even an effective one—is inherently associated with temperature and entropy.

8.2 Unruh-Like Effects in Accelerated Systems

Although a direct detection of the Unruh effect remains challenging, several studies using accelerated electrons in storage rings [25, 24] have reported thermal features compatible with the predicted Unruh temperature. Such results lend credence to the notion that acceleration and temperature are fundamentally linked, in line with the entropic interpretation of horizons.

8.3 Gravitational Wave Observations

The detection of gravitational waves by LIGO and Virgo [27] confirms the radiative nature of spacetime dynamics. From a thermodynamic perspective, these waves can be interpreted as a form of energy exchange across an evolving spacetime boundary, analogous to heat transfer across a horizon.

8.4 Cosmic Microwave Background

The cosmic microwave background (CMB) exhibits a nearly perfect blackbody spectrum at $T \approx 2.725$ K [26]. In the present context, this can be interpreted as a remnant of a primordial thermodynamic interface in the early universe. Small-scale anisotropies in the CMB encode information about perturbations at this boundary and thus may serve as an indirect probe of horizon thermodynamics on cosmological scales.

8.5 Mathematical Connection: Unruh Temperature and CMB

If the cosmic event horizon with radius R_{EH} is interpreted as an accelerated frame with surface gravity $a_H = c^2/R_{\mathrm{EH}}$, the associated Unruh temperature is

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

For a horizon radius of order the Hubble radius, $R_{\mathrm{EH}} \approx c/H_0$, this yields

$$T_{\mathrm{Unruh}} \approx \frac{\hbar H_0}{2\pi k_B} \sim 10^{-30}\ \mathrm{K}, \tag{23}$$

which is many orders of magnitude smaller than the observed CMB temperature. This discrepancy suggests that the CMB cannot be the direct Unruh radiation of the present-day cosmological horizon, but may instead be the cooled remnant of a much hotter primordial horizon. If we trace the CMB temperature T_{CMB} back to an early epoch with scale factor a_{early}, the scaling law

$$T_{\mathrm{CMB}}(a) = T_{\mathrm{Planck}} \cdot \frac{a_{\mathrm{Planck}}}{a} \tag{24}$$

connects the present 2.7 K with Planck-scale temperatures, consistent with the thermodynamic cooling of an expanding horizon.

8.6 Summary of Evidence

While none of these observations constitutes a direct measurement of the proposed space–time interface, they collectively suggest that thermodynamic aspects of horizons are physically real and may extend to the cosmological event horizon itself.

9 Experimental Signatures and Observational Relevance

A central challenge for any model that links thermodynamics to the structure of space–time lies in the identification of experimental or observational consequences that can be used to falsify or confirm its validity. In the present framework, the *thermal interface* between space and time — interpreted analogously to an event horizon — is not merely a mathematical abstraction but a surface with physically measurable consequences.

9.1 Laboratory-scale analogues

The concept of a thermal interface in space–time has parallels in analogue gravity experiments. For example, Bose–Einstein condensates (BECs) have been used to reproduce horizon-like behaviour [22]. In such setups, the propagation of phonons across a moving phase boundary mimics the redshift and mode-mixing seen in gravitational horizons. Applying our model to these systems suggests that temperature gradients at the interface should lead to a measurable frequency shift proportional to the *local surface gravity analogue*. This effect could be probed by high-resolution spectroscopy of BEC modes.

In optical analogue systems, such as slow-light media [23], the modulation of refractive index creates a controllable effective horizon. If the thermodynamic interface picture is correct, one expects that the observed *Hawking-like radiation* spectra will deviate subtly from a pure thermal distribution, encoding the finite heat capacity of the analogue horizon.

9.2 Astrophysical observations

On cosmological scales, the model predicts specific, testable signatures:

1. A correlation between the cosmic microwave background (CMB) temperature and the expansion rate $H(t)$ that deviates slightly from the standard ΛCDM scaling, due to the finite thermodynamic response time of the space–time interface.

2. A small but measurable phase shift in gravitational waves passing near massive structures, arising from temporary perturbations in the thermal interface. This could be detected in high-precision timing of binary pulsars or by next-generation interferometers such as LISA.

3. A predicted infrared cut-off in the spectrum of quantum fluctuations during inflation, reflecting the minimum thermal wavelength of the early-universe interface.

9.3 High-energy experiments

Although direct detection of horizon-scale effects in particle accelerators is beyond current technology, the model's thermodynamic basis suggests indirect avenues:

- Modifications to the Unruh effect at accelerations achievable in ultra-intense laser setups [24].
- Anisotropies in particle production at extremely high energies, interpretable as directional thermal gradients in the quantum vacuum.

9.4 Summary of observational strategy

The combination of laboratory analogues, cosmological surveys, and precision astrophysical measurements provides a multi-channel approach to test the model:

$$\text{Verification Path} \quad \Rightarrow \quad \{\text{Analogue Systems, CMB Analysis, GW Phase Shifts}\} \tag{25}$$

Each of these channels probes a different facet of the *thermal interface hypothesis*, enabling partial verification even in the absence of a direct measurement of the cosmic-scale horizon.

10 Conclusion

The thermodynamic interpretation of spacetime as a boundary system offers a unifying perspective on gravity, quantum theory, and cosmology. By modelling the large-scale universe as a dynamic event horizon (EH), we have shown that macroscopic gravitational phenomena can be understood as emergent, statistical effects of underlying microscopic degrees of freedom. This view aligns with the holographic principle, where the physics within a volume is encoded on its boundary, and extends it to a cosmological context.

The analysis suggests that temperature gradients across the EH generate accelerations that we perceive as gravitational forces, consistent with entropic gravity scenarios [4]. Furthermore, the scaling relations derived for the cosmic microwave background (CMB) temperature provide a potential observational anchor for the model, linking thermodynamic boundary conditions with measurable cosmological parameters.

Future research should refine the mathematical structure of the EH field, incorporate realistic matter-energy contents, and explore stability conditions for such thermodynamic boundaries. These steps are crucial for establishing the model as a predictive framework capable of confronting high-precision astrophysical data.

Appendix: Derivation of Field Equations (6)–(9)

The field equations (6)–(9) can be derived from the variation of the effective EH-field action

$$S_\Phi = \int d^4x\,\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{2}\nabla_\mu\Phi\nabla^\mu\Phi - V(\Phi) + \mathcal{L}_\mathrm{m}\right], \tag{26}$$

where R is the Ricci scalar, $V(\Phi)$ is the effective potential of the EH field, and $\mathcal{L}_\mathrm{m}$ denotes the matter Lagrangian density.

Varying S_Φ with respect to the metric $g_{\mu\nu}$ yields the modified Einstein equations,

$$G_{\mu\nu} = 8\pi G\left[T^{(\Phi)}_{\mu\nu} + T^{(\mathrm{m})}_{\mu\nu}\right], \tag{27}$$

with the EH-field stress–energy tensor

$$T^{(\Phi)}_{\mu\nu} = \nabla_\mu\Phi\nabla_\nu\Phi - g_{\mu\nu}\left(\frac{1}{2}\nabla_\alpha\Phi\nabla^\alpha\Phi + V(\Phi)\right). \tag{28}$$

Variation with respect to Φ gives the scalar field equation

$$\Box\Phi - \frac{dV}{d\Phi} = 0. \tag{29}$$

In a spatially flat FLRW background with metric

$$ds^2 = -dt^2 + a(t)^2\,\delta_{ij}dx^i dx^j,$$

the Einstein equations reduce to the Friedmann equations

$$H^2 = \frac{8\pi G}{3}\left[\rho_\Phi + \rho_{\rm m}\right], \tag{30}$$

$$\dot{H} = -4\pi G\left[\rho_\Phi + p_\Phi + \rho_{\rm m} + p_{\rm m}\right], \tag{31}$$

where the EH-field energy density and pressure are

$$\rho_\Phi = \frac{1}{2}\dot{\Phi}^2 + V(\Phi), \tag{32}$$

$$p_\Phi = \frac{1}{2}\dot{\Phi}^2 - V(\Phi). \tag{33}$$

These expressions correspond to equations (6)–(9) in the main text. The entropic coupling discussed in Section 7.1 can be incorporated by choosing $V(\Phi)$ such that its temperature dependence satisfies the thermodynamic–geometric matching conditions.

Derivation of the $H_{\rm EH}(z)$ Entries

Step 1: Entropic closure. Our closure uses the linear-response relation

$$H(t) \;=\; \gamma\,\frac{k_B\,T_{\rm EH}(t)}{\hbar}, \tag{34}$$

combined with the Gibbons–Hawking temperature of a cosmological horizon,

$$T_{\rm EH}(t) \;=\; \frac{\hbar\,H(t)}{2\pi\,k_B}. \tag{35}$$

Inserting (35) into (34) yields

$$H \;=\; \gamma\,\frac{k_B}{\hbar}\,\frac{\hbar H}{2\pi k_B} \;=\; \frac{\gamma}{2\pi}\,H,$$

which is satisfied nontrivially (i.e. for $H \neq 0$) only if

$$\gamma \;=\; 2\pi. \tag{36}$$

Equation (36) is the entropic fixed point (KMS/Unruh/Hawking 2π-factor). At this point the entropic closure does not introduce a new background equation; it is an identity that enforces consistency between thermodynamics and geometry. Hence, the *background* $H(z)$ is governed by the usual FLRW relation with Λ:

$$H_{\Lambda{\rm CDM}}(z) \;=\; H_0\,\sqrt{\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} + \Omega_{r,0}(1+z)^4}\,. \tag{37}$$

Since (36) makes (34)–(35) an identity, the entropic-horizon prediction coincides:

$$\boxed{H_{\rm EH}(z) \;=\; H_{\Lambda{\rm CDM}}(z) \quad \text{for } \gamma = 2\pi}. \tag{38}$$

Step 2: Numerical check at $z = 0, 1, 2$. Using the *Planck* 2018 values (flat universe, radiation negligible for $z \leq 2$) [**?**]:

$$H_0 = 67.4 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}, \qquad \Omega_{m,0} = 0.3153, \qquad \Omega_{\Lambda,0} = 0.6847,$$

we compute (37):

(i) $z = 0$:

$$H(0) \ = \ H_0 \ = \ 67.4 \ \mathrm{km\,s^{-1}\,Mpc^{-1}}.$$

(ii) $z = 1$: $(1+z)^3 = 8$.

$$H(1) \ = \ 67.4\sqrt{0.3153 \times 8 + 0.6847} \ = \ 67.4\sqrt{2.5224 + 0.6847} \ = \ 67.4{\times}1.7903 \ \approx \ 120.7\,\mathrm{km\,s^{-1}\,Mpc^{-}}$$

(iii) $z = 2$: $(1+z)^3 = 27$.

$$H(2) \ = \ 67.4\sqrt{0.3153 \times 27 + 0.6847} \ = \ 67.4\sqrt{8.5131 + 0.6847} \ = \ 67.4{\times}3.033 \ \approx \ 204.2\,\mathrm{km\,s^{-1}\,Mpc^{-}}$$

Step 3: Table entries. Within rounding, these reproduce the tabulated values. Any small mismatches ($\lesssim 0.2\%$) are due to rounding of $(\Omega_{m,0}, \Omega_{\Lambda,0})$, neglect of $\Omega_{r,0}$ at $z \lesssim 2$, and the displayed significant digits.

Remark on deviations. If the interface departs from the fixed point, we may parameterise $\gamma(t) = 2\pi + \delta\gamma(t)$ or allow a nonzero entropy production rate. Then (34) and (35) no longer collapse to an identity; instead they imply a small, testable modification of $H(z)$ that can be mapped to an effective $w_{\text{eff}}(z)$ via $w_{\text{eff}} = -1 - \frac{2}{3}\dot{H}/H^2$.

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