

A Dual-Holographic Cosmology: A Conceptual Bridge Between Entropic Gravity and Quantum Geometry

A. Schubert

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Abstract

We propose a conceptual dual-holographic cosmological model in which the observable universe emerges as a thermodynamic projection across a scalar field Φ , defined on a dynamically stabilized event horizon (EH) that separates an AdS-like quantum interior from a dS-like geometric exterior. This EH field mediates the transition between gravitational and quantum domains and forms a bidirectional holographic interface that connects an AdS/CFT correspondence in the interior [1, 2] with a conjectured dS/CFT structure on the cosmological side [3].

The model is based on the concept of Grey Holes (GHs)—non-singular gravitational configurations stabilized by thermodynamic consistency and negative heat capacity—where the EH acts as a critical interface with vanishing entropy density and heat flux [4, 5]. This interface induces entropic gradients that define the arrow of time and generate spacetime geometry. Inward-directed entropy flows within the AdS region reproduce attractive gravity in line with entropic gravity models [6, 7, 8], while outward-directed entropy flow in the dS region gives rise to an effective cosmological repulsion without requiring a fundamental dark energy component.

Key cosmological observables—such as the Hubble parameter $H(t)$, the CMB temperature T_{CMB} , and the effective energy density ρ_{eff} —emerge from the dynamics of the EH field $\Phi(z(t))$, yielding predictions consistent with current observations and potentially testable deviations from the Λ CDM model.

Although formulated macroscopically, this approach conceptually resonates with entropy-based quantum gravity (EQG) models [9, 10, 11], which describe emergent spacetime via microscopic network geometries and information-theoretic principles. Both approaches suggest that gravity and temporality may arise from entropic flows across structured boundaries—be they quantum networks or cosmological horizons.

By framing cosmology as a dual-holographic, thermodynamically driven interface theory, this model offers a speculative but coherent alternative to inflation and dark energy, grounded in the synergy between geometric dualities and entropic emergence.

1 Introduction

1.1 Motivation and Conceptual Background

The unification of quantum mechanics (QM) and general relativity (GR) remains one of the most profound open problems in theoretical physics. Traditional approaches often at-

tempt to quantize the gravitational field itself, leading to frameworks such as string theory [12], loop quantum gravity [13], or spin foam models. Despite considerable progress, these approaches face persistent challenges in recovering both the quantum microstructure and the large-scale thermodynamic behavior of spacetime.

In recent years, a complementary view has gained traction: gravity and geometry may not be fundamental, but emergent phenomena rooted in underlying entropic or informational principles [6, 7, 8]. Within this paradigm, spacetime is no longer the starting point, but a derived construct arising from non-local constraints, information flow, or thermodynamic balance conditions.

Our work builds on this conceptual shift. We propose a dual-holographic cosmological model in which the observable universe emerges as a thermodynamic projection across a scalar field Φ , localized on a finite interface between an AdS-like interior and a dS-like exterior. This interface, the *Dual-Holographic Event Horizon* (EH), mediates a dynamical transition between two geometric regimes. It acts not only as a geometric boundary, but as an active thermodynamic surface where entropy gradients encode the emergence of time, gravity, and expansion.

This macroscopic approach shares structural resonance with entropy-based models of quantum gravity [9, 10], particularly those exploring the role of information entropy in the formation of emergent network geometry. While our model operates at the thermodynamic field level, Bianconi’s framework reconstructs quantum spacetime via microcanonical entropy on statistical networks. Both approaches, though methodologically distinct, reject a fixed background geometry and interpret spacetime as the outcome of entropy-driven dynamics.

The aim of this paper is to formalize the dual-holographic framework, develop its thermodynamic structure, and derive its cosmological implications. Along the way, we highlight conceptual parallels to quantum-information-based models while preserving the macro-thermodynamic character of our formulation.

1.2 Spacetime as a Projected Interface

In classical general relativity, spacetime is modeled as a smooth four-dimensional manifold equipped with a Lorentzian metric. However, recent developments in quantum gravity and holography suggest that this geometric picture may itself be emergent, arising from more fundamental non-geometric degrees of freedom. One promising perspective is that spacetime is not a fundamental entity, but a large-scale projection of deeper informational or thermodynamic processes [7, 14, 8].

In our dual-holographic framework, this projection is realized through a scalar field Φ localized on a dynamically active surface: the event horizon (EH) separating an AdS-like interior from a dS-like exterior. This EH surface is not a classical event horizon in the general relativistic sense, but a thermodynamic interface defined by vanishing entropy density and heat capacity. Across this interface, entropic gradients give rise to emergent features of spacetime: gravitational attraction in the interior and accelerated expansion in the exterior.

The scalar field Φ governs the interpolation between these regimes, behaving like a domain wall solution with Higgs- and Anti-Higgs-like properties. Its profile encodes not only the transition between geometries but also the thermodynamic directionality of time and entropy flow. This field-based construction offers a macroscopic mechanism for the emergence of spacetime as a thermodynamic projection.

Comparable ideas appear in recent entropy-based quantum gravity (EQG) models, in which spacetime geometry is reconstructed from the entropic and topological properties of underlying quantum networks [9, 10]. In that context, geometry is not predefined but arises from the microcanonical entropy of node configurations and their connectivity. While our approach does not rely on discrete network topology, both models suggest that spacetime may be understood as a manifestation of non-local information structure—either encoded in networks or projected through scalar fields across thermodynamic interfaces.

Thus, the EH field Φ in our model plays a role analogous to that of entropic order parameters in EQG: it determines the phase and curvature of the emergent geometry, while mediating the flow of information that defines the structure of spacetime.

2 The Dual-Holographic Interface

3 The Dual-Holographic Interface

3.1 Thermodynamic Stability of Grey Holes

A central element of the dual-holographic model is the concept of *Grey Holes* (GHs): non-singular gravitational cores that stabilize against full collapse through quantum thermodynamic effects. These objects are characterized by a critical event horizon (EH) surface where entropy density and heat capacity vanish. Unlike traditional black holes, which evaporate due to negative heat capacity [5], GHs reach a thermodynamically neutral configuration where further collapse is arrested.

This stabilization is driven by the thermodynamic instability of self-gravitating systems [15], combined with the field dynamics of the EH scalar Φ . The critical feature is the negative heat capacity near the collapse threshold:

$$C(\Phi) = -\frac{GM^2}{R(\Phi)k_B}, \quad \text{with } R(\Phi) \rightarrow R_S \text{ as } \Phi \rightarrow 0, \quad (1)$$

ensuring that the system naturally approaches a stable, entropy-neutral state as $\Phi \rightarrow 0$.

The resulting event horizon is not just a geometric boundary, but a physical interface between two holographic domains: a quantum AdS-like interior and a geometric dS-like exterior. Thermodynamically, the EH acts as a regulator of information and energy flow between these regimes.

While our model formulates this behavior in terms of macroscopic field dynamics, similar stabilization mechanisms appear in microstructure-based approaches to emergent geometry, such as in entropy-based quantum gravity (EQG) [9, 10]. In EQG, the transition to large-scale geometry is likewise governed by entropy maximization, though realized through the statistical distribution of microscopic connectivity patterns in information networks. Both models exhibit an entropic transition between regimes, albeit on different structural levels: fields and horizons in our case, discrete network ensembles in EQG.

This parallel reinforces the idea that the emergence of gravitational stability may be a universal thermodynamic phenomenon, independent of whether the underlying degrees of freedom are continuous fields or microscopic network nodes.

3.2 Toward a Finite-Screen dS/CFT Correspondence

While the AdS/CFT correspondence provides a well-established framework for encoding quantum gravitational dynamics via boundary conformal field theories [1, 2], its de Sitter (dS) counterpart remains far less developed. The absence of a timelike boundary in dS space complicates the formulation of a consistent holographic dictionary, and most existing proposals place the dual CFT on an abstract, spacelike hypersurface at future infinity \mathcal{I}^+ [3].

In contrast, the dual-holographic model developed here replaces this asymptotic construction with a dynamically generated, finite-radius projection surface: the thermodynamic event horizon (EH). This interface acts as a finite screen that separates a quantum AdS-like interior from a geometrically expanding dS-like exterior. The screen is characterized by maximal entropy density and vanishing heat capacity, functioning as a local thermodynamic origin for observable spacetime structure.

We propose that the dS/CFT correspondence can be reformulated in terms of this finite screen, allowing for a direct entropic projection of information from the EH into the dS domain. Rather than encoding observables at global infinity, operator content on the dS side is reconstructed via local matching conditions across the scalar field Φ , acting as a thermodynamic mediator. Specifically, we postulate an entropic matching relation of the form:

$$\langle \mathcal{O}_{\text{out}} \rangle = \mathcal{F}[\Phi] \cdot \langle \mathcal{O}_{\text{in}} \rangle, \quad (2)$$

where $\mathcal{F}[\Phi]$ is a field-dependent scaling factor reflecting the entropic and geometric rescaling across the interface.

This finite-screen formulation resonates conceptually with recent developments in entropy-based quantum gravity (EQG), where large-scale geometries emerge from statistical ensembles of network configurations [9, 10]. In EQG, the effective dimensionality and curvature of spacetime are not fundamental, but result from the distribution and entropy of connectivity patterns in quantum networks. Although our approach does not utilize discrete structures, the replacement of asymptotic boundaries with finite entropic surfaces serves a similar purpose: anchoring emergent geometry in localized information constraints.

Both models share the hypothesis that global geometric structure arises from localized entropic configurations—whether represented by scalar field profiles on a thermodynamic screen or by high-entropy connectivity states in network geometry. These structural parallels point to a potentially deeper universality in the way information, entropy, and geometry interact in the emergence of spacetime.

Proposed Matching Principle: While the AdS side supports a well-defined correspondence via

$$Z_{\text{AdS}}[\phi_0] = \left\langle \exp \left(\int \mathcal{O}_{\text{in}} \phi_0 \right) \right\rangle_{\text{CFT}_{\text{in}}},$$

we postulate a dual condition on the dS side:

$$\langle \mathcal{O}_{\text{out}} \rangle = \mathcal{F}[\Phi] \cdot \langle \mathcal{O}_{\text{in}} \rangle,$$

where $\mathcal{F}[\Phi]$ encodes the entropic and geometric rescaling across the EH, defined (heuristically) as:

$$\mathcal{F}[\Phi] = \left(\frac{\Phi - v}{\Phi + v} \right). \quad (3)$$

This symmetry-breaking factor reflects a shift from mass-generating (AdS) to expansion-driving (dS) operator regimes, in analogy to conformal symmetry breaking in holographic flows [16].

Thermodynamic Anchoring: The EH field $\Phi(z)$ defines the entropy gradient that determines the information flux toward the dS domain. The entropic current $s^\mu = su^\mu$ drives a projected energy-momentum flow that sources the emergent dS geometry. The effective cosmological expansion then reflects a thermodynamic hologram encoded on the EH surface.

Relation to Other Proposals: Our approach is related but distinct from the original dS/CFT conjecture:

- Instead of global \mathcal{I}^+ , we consider a *local, finite* screen with thermodynamic activity.
- Rather than defining a full dual CFT at infinity, we interpret dS evolution as a coarse-grained entropic projection from the EH.
- The operator dictionary is induced dynamically from scalar field matching, not globally imposed.

Conclusion: While speculative, this finite-screen version of dS/CFT is motivated by physical considerations: entropy flow, finite-time observables, and the thermodynamic activity of the EH. It offers a constructive framework for modeling de Sitter holography in a cosmological setting, bridging the duality structure of AdS/CFT with a dynamical, emergent picture of spacetime expansion.

3.3 AdS/CFT and the Interior Cutoff Boundary

The interior region of the dual-holographic model corresponds to a negatively curved, AdS-like domain dynamically stabilized by the thermodynamic properties of Grey Holes. In this region, the AdS/CFT correspondence provides a powerful and extensively tested framework: a $(d + 1)$ -dimensional gravitational theory in asymptotically AdS space is dual to a d -dimensional conformal field theory (CFT) defined on its boundary [1, 2].

However, in our construction, the event horizon (EH) acts as a finite-radius boundary at $z = z_{\text{EH}}$, separating the AdS core from the dS exterior. This setting requires a generalization of standard AdS/CFT: rather than placing the dual CFT at infinity, we adopt a finite-cutoff formulation consistent with holographic renormalization group (RG) flow [17]. In this framework, the radial coordinate z plays the role of an energy scale $\mu \sim 1/z$, and the EH defines a UV cutoff for the dual field theory:

$$Z_{\text{AdS}}[g_{\mu\nu}^{(z_{\text{EH}})}, \phi_0] = \left\langle \exp \left(\int_{z_{\text{EH}}} \mathcal{O} \phi_0 \right) \right\rangle_{\text{CFT}_{\text{in}}}^{\mu=1/z_{\text{EH}}}. \quad (4)$$

Thermodynamically, the EH represents a critical surface with vanishing entropy flux and heat capacity. From the AdS perspective, it marks the point of maximal coarse-graining—beyond which bulk gravitational degrees of freedom are no longer encoded in boundary data. The surface thus functions as an infrared (IR) brane in the gravitational bulk, and simultaneously as a UV cutoff in the dual CFT.

This behavior bears a structural analogy to entropy-based quantum gravity models, where geometric properties emerge from scale-dependent entropy distributions across statistical networks [9, 10]. In Bianconi’s framework, quantum gravity is reformulated as a flow across layers of connectivity and topological complexity, with the geometry encoded in the entropic hierarchy of network states. These “informational RG flows” determine the effective large-scale geometry, paralleling the role of radial RG flows in finite-cutoff AdS/CFT.

While the underlying variables differ—field profiles versus network topology—the principle is similar: emergent geometry is controlled by the entropic structure of subsystems across scales. In both cases, the interplay between locality, entropy, and flow yields an effective low-energy spacetime description anchored in non-geometric microdynamics.

Thus, the interior cutoff boundary at the EH in our model is not just a regulator of the dual CFT, but a thermodynamic scale selector—one that resonates with entropic renormalization concepts in network-based quantum gravity.

3.4 Matching Across the EH Field

The dual-holographic event horizon (EH) is not a static boundary but a dynamically active scalar field $\Phi(z)$ that mediates the transition between the AdS-like interior and the dS-like exterior. In this framework, Φ acts as a thermodynamic and topological interface, resembling a Higgs/Anti-Higgs domain wall that links AdS/CFT and a projected dS/CFT correspondence across a finite holographic screen.

We model the EH field via a double-well potential:

$$V(\Phi) = \lambda(\Phi^2 - v^2)^2, \quad (5)$$

which yields two symmetric vacua:

- $\Phi = -v$: AdS-like phase — associated with confinement, mass generation, and inward entropy flow.
- $\Phi = +v$: dS-like phase — associated with expansion, delocalization, and outward entropy flow.

The critical surface $\Phi = 0$ defines a region of maximal entropy density and vanishing heat capacity. The field interpolates between vacua via the domain wall solution:

$$\Phi(z) = v \tanh\left(\sqrt{2\lambda}vz\right), \quad (6)$$

providing a smooth thermodynamic transition between two geometric regimes.

Crucially, this transition also encodes the matching of conformal operator structures across the EH. We propose a scalar-dependent projection condition:

$$\langle \mathcal{O}_{\text{out}} \rangle = \mathcal{F}[\Phi] \cdot \langle \mathcal{O}_{\text{in}} \rangle, \quad \text{with} \quad \mathcal{F}[\Phi] = \left(\frac{\Phi - v}{\Phi + v} \right). \quad (7)$$

This asymmetric prefactor reflects the directional nature of entropic projection: suppression in the AdS regime, and amplification in the dS regime. Similar matching relations have been discussed in finite-cutoff AdS/CFT settings and holographic RG flow constructions, where the radial direction encodes the evolution of operator scaling under entropic coarse-graining [17, 16].

The matching is not spontaneous symmetry breaking in the usual sense, but rather a thermodynamically driven projection. At $\Phi = 0$, the system resides at a critical point of maximal entropy and geometric ambiguity—neither AdS nor dS is preferred. Projection emerges through entropic gradients and scalar backreaction, determining which geometric phase dominates. This echoes proposals where gravitational and geometric structures are dynamically selected by entropy gradients and energy flow, rather than imposed a priori [7, 6].

From a broader perspective, this thermodynamic projection mechanism has a structural analogue in entropy-based quantum gravity (EQG), where emergent geometry arises from connectivity transitions in quantum network states [9]. There, the transition between phases corresponds to a change in topological entropy and degree distribution, driven by local information constraints. In both models, the system crosses a critical surface that governs the direction and structure of emergent spacetime.

While EQG operates in a discrete combinatorial setting and the present model in a continuous field-theoretic framework, both share the principle that ****geometry is not fundamental but thermodynamically projected****. The EH field Φ thus functions not only as a scalar interface but as an informational selector—mediating the operator content, entropy flow, and geometric identity of the surrounding domains.

3.5 Thermodynamic Matching Conditions

The scalar field profile $\Phi(z)$ across the dual-holographic event horizon (EH) defines a thermodynamic transition zone between AdS and dS regimes. This domain wall structure not only interpolates between vacua but encodes the local entropy density and heat capacity, which govern the matching of physical and geometric properties across the EH.

We define the entropy density as a symmetric, quadratic function of the field:

$$s(\Phi) = s_0 \left(1 - \frac{\Phi^2}{v^2} \right), \quad (8)$$

with s_0 denoting the maximal entropy density at $\Phi = 0$, i.e., at the EH. This ensures that entropy vanishes in both asymptotic vacua $\Phi = \pm v$, corresponding to thermodynamically inert phases, and reaches its peak at the transition surface. This formulation resonates with earlier proposals that link gravitational dynamics to thermodynamic variables such as entropy density and flux [7, 8, 6].

The associated heat capacity is modeled as:

$$C(\Phi) = C_0 \frac{\Phi^2}{v^2}, \quad (9)$$

so that it vanishes precisely at the EH and becomes maximal deep in the stable vacua. This structure reflects the transition from a fluctuation-dominated interface (with high entropy and low capacity) to stable, low-entropy phases. Negative or vanishing heat capacity in self-gravitating systems has long been identified as a signature of thermodynamic criticality and horizon formation [15, 18].

The continuity of entropy flux across the EH is a key thermodynamic matching condition:

$$\frac{ds}{dz} = -s_0 \frac{2\Phi}{v^2} \frac{d\Phi}{dz}, \quad (10)$$

and for the kink profile $\Phi(z) = v \tanh(\sqrt{2\lambda}vz)$, this results in a symmetric entropy flow centered at $z = 0$. The continuity condition

$$\left. \frac{ds}{dz} \right|_{\text{in}} = \left. \frac{ds}{dz} \right|_{\text{out}} \quad (11)$$

ensures that the thermodynamic transition is smooth and reversible. It guarantees no discontinuity in information flux across the EH, consistent with holographic entropy bounds and reversible dynamics [19, 7].

Analogous mechanisms appear in entropy-based quantum gravity (EQG), where transitions between emergent geometric regimes are governed by entropy flow across topological boundaries in quantum network ensembles [9]. In those models, curvature and dimensionality are not fundamental inputs, but derived from entropy-maximizing configurations across network phases.

While EQG operates on discrete combinatorial structures and our model on continuous field dynamics, both frameworks employ entropy gradients as regulators of phase connectivity. In both cases, the maximal entropy surface acts as a projective interface from which geometry and dynamics emerge. This suggests that entropy flow may represent a universal organizing principle across different formulations of quantum gravitational emergence.

3.6 Operator Matching Across the EH Field

The dual-holographic interface not only separates two geometric regimes—AdS and dS—but also connects their respective conformal field theories (CFT_{in} , CFT_{out}). This connection is mediated by the scalar EH field $\Phi(z)$, whose local value determines the scaling, directionality, and thermodynamic character of operator structures across the interface.

We postulate the following matching condition for expectation values:

$$\langle \mathcal{O}_{\text{in}} \rangle = \left(\frac{\Phi + v}{\Phi - v} \right) \langle \mathcal{O}_{\text{out}} \rangle, \quad (12)$$

where \mathcal{O}_{in} and \mathcal{O}_{out} denote operators in the AdS- and dS-associated CFTs, respectively. The matching coefficient diverges as $\Phi \rightarrow v$, and vanishes as $\Phi \rightarrow -v$, indicating asymmetric amplification of operator content as the field transitions from interior to exterior.

This asymmetry reflects the entropic flow encoded in Φ . On the AdS side, entropy flows inward, suppressing observables and favoring confinement. On the dS side, entropy flows outward, enhancing operator visibility and sourcing expansion. At the critical point $\Phi = 0$, the matching yields:

$$\langle \mathcal{O}_{\text{in}} \rangle = - \langle \mathcal{O}_{\text{out}} \rangle,$$

suggesting a maximal entropic inversion at the EH surface, consistent with earlier results on thermodynamic phase inversion [6, 8].

This operator mapping does not imply classical continuity, but a thermodynamically regulated projection. At $\Phi = 0$, the system exists in a critical superposition state where both geometric regimes are equally encoded. The scalar field acts as an informational filter, selecting which degrees of freedom become physically accessible on each side. This reflects the broader idea of gravity as an entropic force arising from the redistribution of information [7, 6].

Similar concepts appear in entropy-based quantum gravity (EQG), where observables emerge from local information encoded in network configurations. In such models, operators correspond to observables defined over dynamic statistical ensembles of nodes and links [9]. The projection between network states and emergent geometry is likewise governed by entropy gradients and statistical symmetry breaking—paralleling the field-driven projection in our model.

Moreover, in both frameworks, operator content is not imposed globally but emerges through local structure: in our case through the EH field $\Phi(z)$; in EQG through the entropy-weighted microstate distribution of the network. This suggests a common principle: that observable physics on macroscopic scales reflects informational selection rules encoded in an intermediate, entropy-governed interface.

Thus, the operator matching across the EH field represents not only a technical projection between two dual theories, but also a conceptual realization of informational emergence—uniting thermodynamics, field dynamics, and holographic encoding.

3.7 Metric Modification by the EH Field

In the dual-holographic framework, the scalar field $\Phi(z)$ not only governs thermodynamic matching and operator projection, but also modifies the spacetime geometry itself. The field acts as a mediator between an AdS-like vacuum with negative curvature and a dS-like vacuum with positive curvature. This interpolation is realized through a field-dependent effective cosmological term $\Lambda(\Phi)$, which encodes curvature as a function of local entropy structure.

We model the effective gravitational action as:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa} (R - 2\Lambda(\Phi)) - \frac{1}{2} \nabla_\mu \Phi \nabla^\mu \Phi - V(\Phi) \right], \quad (13)$$

with scalar potential $V(\Phi) = \lambda(\Phi^2 - v^2)^2$ and field-dependent cosmological term:

$$\Lambda(\Phi) = \Lambda_0 \left(\frac{\Phi^2}{v^2} - 1 \right), \quad (14)$$

which smoothly interpolates between $\Lambda = -\Lambda_0$ (AdS) and $\Lambda = +\Lambda_0$ (dS), with $\Lambda = 0$ at the EH surface $\Phi = 0$.

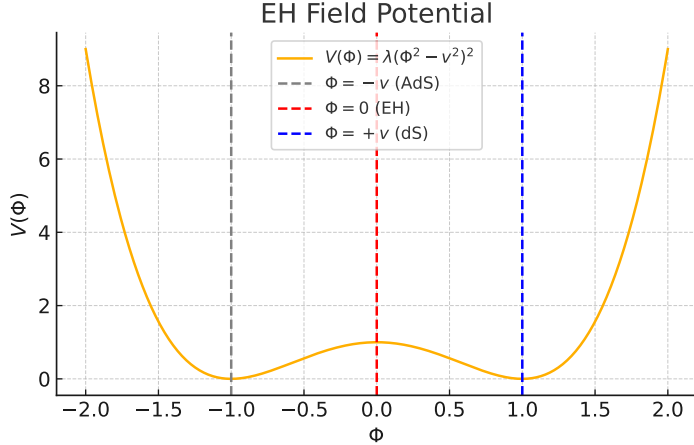


Figure 1: Effective potential $V(\Phi) = \lambda(\Phi^2 - v^2)^2$ of the EH field. The symmetric double-well structure defines two stable vacua ($\Phi = \pm v$) and a critical point at $\Phi = 0$, where the curvature and entropy gradients change sign.

This construction dynamically ties the geometry to the thermodynamic phase structure of the scalar field. It mirrors entropy-based approaches to gravity, where spacetime curvature is understood as an emergent thermodynamic response to entropy gradients [7, 8, 6].

Backreaction and Local Geometry: The scalar field modifies the metric profile on both sides of the EH:

- In the AdS-like interior ($\Phi < 0$), the metric is conformally deformed as:

$$ds^2 = \frac{L^2}{z^2} \left(1 + \varepsilon \frac{\Phi^2}{v^2} \right) (-dt^2 + dz^2 + d\vec{x}^2),$$

where $\varepsilon \ll 1$ quantifies the backreaction strength.

- In the dS-like exterior ($\Phi > 0$), the expansion rate is set by:

$$ds^2 = -dt^2 + e^{2H(\Phi)t} d\Omega_3^2, \quad \text{with} \quad H(\Phi) = H_0 \sqrt{\frac{\Phi^2}{v^2}},$$

linking expansion to the scalar field amplitude.

The kink-like field configuration

$$\Phi(z) = v \tanh(\sqrt{2\lambda}vz) \tag{15}$$

interpolates smoothly between the AdS vacuum ($\Phi = -v$) and the dS vacuum ($\Phi = +v$), with the transition at $z = 0$.

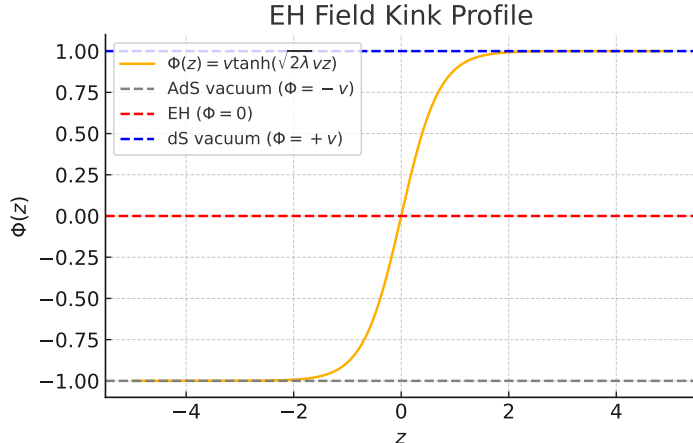


Figure 2: Domain wall profile of the scalar field $\Phi(z) = v \tanh(\sqrt{2\lambda}vz)$, representing a smooth interpolation between AdS ($\Phi = -v$) and dS ($\Phi = +v$) phases. The critical surface $\Phi = 0$ defines the EH, where entropy density is maximal and curvature vanishes.

Entropy and Geometric Flow: The geometric profile induced by $\Phi(z)$ follows the entropy flow structure: inward entropy flux leads to geometric confinement (AdS), while outward entropy flux generates accelerated expansion (dS). At the critical point $\Phi = 0$, the system is thermodynamically neutral—curvature vanishes, and spacetime is maximally unstable. This supports the interpretation of spacetime as an emergent projection from entropy dynamics.

Comparison with Entropic Quantum Gravity: This thermodynamic emergence of geometry is conceptually aligned with entropy-based quantum gravity (EQG), where curvature is not a predefined property of a smooth manifold, but emerges from local network connectivity and entropy distribution [9]. In EQG, geometric properties such as curvature, dimension, and even locality arise from optimizing entropy across microscopic graph structures. The scalar field $\Phi(z)$ in our model plays an analogous role: it encodes local entropy gradients and drives geometric differentiation across an otherwise symmetric interface.

In both frameworks, geometry is secondary to entropy: the macroscopic shape of spacetime reflects the system’s statistical or thermodynamic state. While EQG builds this picture from discrete microstates, the dual-holographic model formulates it in terms of continuous field-theoretic variables. Yet both agree on the core principle: that curvature is informationally driven, not fundamentally imposed.

Conclusion: The scalar field Φ induces a dynamically varying cosmological term $\Lambda(\Phi)$ and modulates the background geometry accordingly. This construction supports the interpretation of spacetime as a thermodynamic projection surface—emergent from the scalar field’s entropy profile. The analogy with EQG underscores the robustness of this view: across both continuous and discrete approaches, geometry appears as an emergent shadow of entropy.

4 Emergent Dynamics and Entropic Gravity

4.1 Thermodynamic Coupling and Emergent Field Equations

In the dual-holographic model, spacetime dynamics emerge from a thermodynamic interaction between geometry and a scalar field Φ that defines the structure of the event horizon (EH). This scalar field governs the entropic gradient across the interface between an AdS-like interior and a dS-like exterior, encoding the flow of information and entropy that drives gravitational collapse and cosmic expansion.

We formulate the effective action as a scalar-tensor theory:

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa} (R - 2\Lambda(\Phi)) - \frac{1}{2} \nabla_\mu \Phi \nabla^\mu \Phi - V(\Phi) \right], \quad (16)$$

with a symmetric double-well potential

$$V(\Phi) = \lambda(\Phi^2 - v^2)^2,$$

and a dynamically modulated cosmological term

$$\Lambda(\Phi) = \Lambda_0 \left(\frac{\Phi^2}{v^2} - 1 \right),$$

which interpolates between $\Lambda = -\Lambda_0$ (AdS) and $\Lambda = +\Lambda_0$ (dS), with $\Lambda = 0$ at $\Phi = 0$. This scalar dependence ties curvature to the field's entropic state.

The corresponding field equations are:

$$G_{\mu\nu} + \Lambda(\Phi)g_{\mu\nu} = \kappa T_{\mu\nu}^\Phi, \quad (17)$$

$$T_{\mu\nu}^\Phi = \nabla_\mu \Phi \nabla_\nu \Phi - g_{\mu\nu} \left(\frac{1}{2} (\nabla\Phi)^2 + V(\Phi) \right), \quad (18)$$

$$\square\Phi = \frac{dV}{d\Phi} - \frac{1}{\kappa} \frac{d\Lambda}{d\Phi}. \quad (19)$$

The scalar field thus drives both the energy-momentum content and the curvature of the emergent spacetime, replacing the need for a fundamental cosmological constant.

Entropy as Source of Geometry: In this model, geometry is not fundamental but projected from the entropy structure encoded in $\Phi(z)$. The entropy density

$$s(\Phi) = s_0 \left(1 - \frac{\Phi^2}{v^2} \right) \quad (20)$$

peaks at $\Phi = 0$, the EH interface, where curvature vanishes. This suggests that the scalar field acts as an entropic projector: as it deviates from criticality, geometric phases emerge.

This interpretation aligns with thermodynamic gravity approaches [7, 8, 6], in which spacetime curvature responds to entropy gradients and heat flow, rather than being a primitive background.

Comparison with Entropic Quantum Gravity: In EQG, spacetime geometry also emerges from entropy maximization—not via a scalar field but through the statistical configuration of a networked information structure [9, 11]. Each node and link carries entropic weight, and curvature arises as a macroscopic projection of local entropy gradients across the graph. The field $\Phi(z)$ in our model plays a conceptually similar role: it mediates entropy distribution, determines thermodynamic flow, and thereby induces curvature.

Both frameworks share the principle that the Einstein field equations—or their generalizations—can be viewed as emergent thermodynamic identities. In EQG, this arises from entropy optimization over microstates; in the dual-holographic model, from the scalar-dependent modulation of curvature by thermodynamic conditions.

Unified Interpretation: The scalar field Φ acts as a geometric order parameter. Its local configuration determines:

- the effective cosmological constant $\Lambda(\Phi)$,
- the dominant curvature regime (AdS vs. dS),
- the direction and strength of entropy flow,
- and thus the emergent spacetime dynamics.

This makes the EH field analogous to a collective macroscopic variable—a thermodynamic condensate—that governs the large-scale structure of spacetime. As in EQG, geometry is not imposed but selected, emerging from information gradients projected onto a coarse-grained scale.

Conclusion: The coupling between Φ , entropy, and geometry yields an emergent field theory where spacetime arises as a thermodynamic response to scalar field dynamics. This is conceptually aligned with entropy-based quantum gravity, where geometry, curvature, and dimension are statistical outputs of underlying microstate organization. Both approaches challenge the notion of spacetime as a fundamental arena and replace it with a layered, entropy-driven construction.

4.2 Entropy, Time, and Directionality

In the dual-holographic model, time, directionality, and gravity are not fundamental entities, but emergent thermodynamic consequences of the scalar field Φ that defines the dual event horizon (EH). The scalar field profile encodes an entropy gradient that drives the outward expansion of space on the dS side and gravitational collapse on the AdS side. The EH itself—located at $\Phi = 0$ —represents a point of maximal entropy density and vanishing heat capacity, marking a critical instability that initiates directed flow.

Entropy Gradient and Directionality. The entropy density of the EH field is given by:

$$s(\Phi) = s_0 \left(1 - \frac{\Phi^2}{v^2} \right), \quad (21)$$

with maximum at $\Phi = 0$ and vanishing in the asymptotic vacua $\Phi = \pm v$. The corresponding entropy gradient is:

$$\frac{ds}{dz} = -s_0 \frac{2\Phi}{v^2} \frac{d\Phi}{dz}, \quad (22)$$

which defines a non-zero divergence $\nabla_\mu s^\mu > 0$ on either side of the EH. This yields a thermodynamically well-defined arrow of time, directed away from the unstable maximum $\Phi = 0$ into both the AdS and dS domains. In this view, the origin of time asymmetry is neither quantum decoherence nor explicit symmetry breaking in the Lagrangian—but the entropic instability of the EH field itself.

Emergent Force and Entropic Projection. The entropy gradient also induces effective entropic forces via:

$$F = T \cdot \frac{dS}{dR}, \quad (23)$$

where T denotes the local Unruh (AdS) or Gibbons-Hawking (dS) temperature. On the AdS side, this corresponds to an attractive force, i.e. gravitational collapse. On the dS side, the same structure yields a repulsive entropic force, interpreted as cosmic acceleration. In both cases, the scalar field profile determines the direction and magnitude of effective spacetime dynamics.

Thermodynamic Structure of the EH Field. These thermodynamic properties—entropy density, heat capacity, and potential energy—are encoded in the scalar field and its potential. Their relation is shown in Figure 3, which displays the full thermodynamic structure of the EH interface.

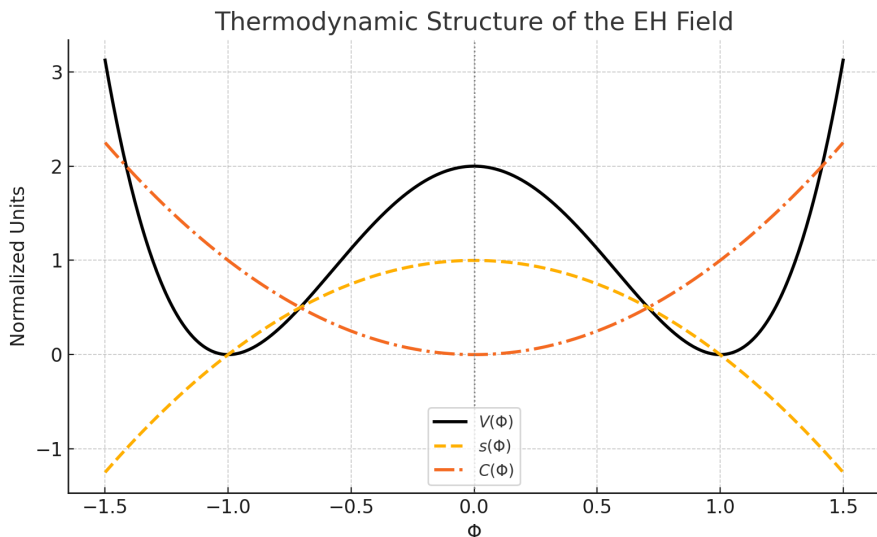


Figure 3: Thermodynamic structure of the EH field. The scalar potential $V(\Phi)$ (blue) defines the energetics of the transition, with symmetric minima at $\Phi = \pm v$ and an unstable maximum at $\Phi = 0$. The entropy density $s(\Phi)$ (red) is maximal at the EH and vanishes in both vacua. The heat capacity $C(\Phi)$ (orange) behaves inversely: it vanishes at the EH and becomes maximal near the vacua. This structure encodes the thermodynamic instability of the EH as the origin of spacetime dynamics.

At $\Phi = 0$, all three curves intersect: entropy is maximal, potential energy is maximal (unstable), and heat capacity is zero. This critical point marks the location where spacetime itself becomes projectable—i.e., where the system transitions from entropy-dominated instability to directional geometric evolution. In this sense, the EH acts as a projective thermodynamic interface between order parameters.

Connection to Entropic Quantum Gravity. This interpretation echoes recent advances in entropic quantum gravity (EQG), where time and causal directionality emerge from entropy flows on a discrete, network-based substrate [9, 11]. In EQG, local network entropy gradients give rise to macroscopic spacetime features such as curvature and temporal ordering—without assuming a background manifold. Our model mirrors this idea in continuous field-theoretic terms: the scalar field Φ defines local entropy structure, and its gradients generate emergent causal and dynamical properties.

In both cases, time is not fundamental but statistical. The asymmetry we observe is not imposed by fundamental laws, but results from the system’s tendency to flow away from unstable, high-entropy configurations. The EH field Φ plays in our model the same role that local entropy maximization plays in EQG.

Conclusion. Time, direction, and gravitational force arise in this framework as projections of the entropic configuration of the EH field. The thermodynamic structure shown in Figure 3 encodes a critical instability that seeds the observable arrow of time and the emergence of spacetime itself. The analogy with EQG reinforces the view that geometry, dynamics, and causality are emergent properties of entropy—not fundamental constructs.

4.3 Phenomenological Parametrization and Hubble Evolution

To connect the scalar field dynamics of the dual-holographic interface to cosmological observables, we derive an effective time evolution of the Hubble parameter $H(t)$ based on the entropic field configuration $\Phi(z)$. This projection defines a smooth transition from an unstable thermodynamic interface to an expanding de Sitter-like universe.

EH Field Profile and Interface Motion. We assume that the scalar field follows a kink profile:

$$\Phi(z) = v \tanh\left(\sqrt{2\lambda}vz\right), \quad (24)$$

which interpolates between $\Phi = -v$ (AdS vacuum) and $\Phi = +v$ (dS vacuum), with $\Phi = 0$ at the event horizon $z = 0$. This configuration defines a thermodynamic domain wall across which curvature, entropy, and field dynamics change.

Assuming that the interface moves outward over time, we model its location as:

$$z(t) = z_0 + \alpha t, \quad (25)$$

where α is the effective velocity of the entropic projection, and z_0 the initial position of the EH interface.

Projected Hubble Evolution. The Hubble rate is then derived from the field-dependent expansion rate $H(\Phi)$, defined as:

$$H(\Phi) = H_0 \sqrt{1 - \frac{\Phi^2}{v^2}}, \quad (26)$$

where $H_0 = \sqrt{\Lambda_0/3}$ is the asymptotic expansion rate in the dS phase.

Substituting $\Phi(z(t))$, we obtain:

$$H(t) = H_0 \sqrt{1 - \tanh^2 \left(\sqrt{2\lambda} v (z_0 + \alpha t) \right)} = H_0 \operatorname{sech} \left(\sqrt{2\lambda} v (z_0 + \alpha t) \right), \quad (27)$$

which smoothly decays from an initial maximum at $t = 0$ toward zero or a residual asymptotic value, depending on the saturation of the scalar field.

Interpretation: Entropic Onset of Expansion. At early times $t \approx 0$, the system resides near $\Phi = 0$, the unstable maximum of the EH potential. This corresponds to maximal entropy density and minimal geometric excitation. The entropic instability at this point triggers the outward projection of spacetime, resulting in a high initial expansion rate:

$$H(0) = H_0. \quad (28)$$

As the scalar field evolves toward $\Phi \rightarrow +v$, the entropic gradient flattens, and the expansion slows accordingly. This naturally reproduces a period of rapid early expansion followed by asymptotic stabilization—without invoking an inflationary inflaton or a finely tuned cosmological constant.

Emergent Clock and Entropic Time. Since the EH field evolves monotonically from $\Phi = 0 \rightarrow +v$, it can also serve as an internal clock variable. Rewriting the Hubble rate as a function of field value:

$$H(\Phi) = H_0 \sqrt{1 - \frac{\Phi^2}{v^2}}, \quad (29)$$

shows that the cosmological evolution is entirely determined by the scalar field's thermodynamic progression.

This reinforces the interpretation of time not as an external parameter, but as an emergent ordering of entropic transitions across the scalar potential—analogue to internal time variables in network-based models of entropic quantum gravity [11].

Comparison with EQG: Statistical Time Evolution. In EQG, the expansion of spacetime is modeled statistically as the growth of informational connectivity in a network substrate. The cosmological scale factor corresponds to increasing node degrees and global entropy, with time emerging from correlation structures among microscopic elements [9]. Our model mirrors this mechanism at the continuum level: the field $\Phi(z(t))$ defines the entropic state of the system, and the Hubble rate $H(t)$ tracks its macroscopic projection.

Both frameworks avoid introducing a fundamental time coordinate or vacuum energy. Instead, they derive cosmic evolution from internal entropy gradients and statistical transitions in a high-dimensional configuration space.

Conclusion. The evolution of the scalar field Φ provides a natural, entropic parametrization of cosmic expansion. The Hubble rate $H(t)$ emerges as a smooth projection of the field's deviation from criticality, offering a thermodynamic alternative to inflation and dark energy. In analogy with EQG, expansion is not imposed but arises from internal reorganization of entropic structure.

4.4 Entropy-Driven Expansion

In the dual-holographic framework, cosmic expansion is not driven by a fundamental cosmological constant, but emerges as a macroscopic effect of entropy flow across the scalar EH field. As the system evolves away from the entropically unstable configuration $\Phi = 0$, directed entropy transfer toward the dS regime induces an effective repulsive force and spacetime inflation.

Entropic Pressure and Thermodynamic Driving. We define the entropic pressure associated with the EH field as:

$$p_{\text{ent}} = T \cdot \frac{ds}{dz}, \quad (30)$$

where T is the local temperature of the holographic screen—identified with the Gibbons-Hawking temperature in the dS region:

$$T_{\text{dS}} = \frac{\hbar H(\Phi)}{2\pi k_B}. \quad (31)$$

Inserting the entropy gradient from the EH field profile,

$$\frac{ds}{dz} = -s_0 \frac{2\Phi}{v^2} \frac{d\Phi}{dz},$$

we find that the entropic pressure is positive in the dS domain, driving outward expansion. This effect is entirely sourced by the scalar field configuration and its thermodynamic structure.

Energy Flux and Projective Expansion. The entropic energy flux associated with this pressure can be written as:

$$\frac{dQ}{dt} = T \cdot \frac{dS}{dt} = T \cdot \int_{\Sigma} \nabla_{\mu} s^{\mu} d\Sigma, \quad (32)$$

with Σ a spatial hypersurface across the EH interface. The positivity of $\nabla_{\mu} s^{\mu}$ ensures a net outward energy flow from the AdS interior toward the dS geometry. This flux replaces the need for a vacuum energy or inflaton: the system expands because information and entropy are being projected outward from a critical thermodynamic surface.

Thermodynamic Arrow of Expansion. The direction of expansion is set by the entropy gradient. At $\Phi = 0$, entropy is maximal, and the system is thermodynamically unstable. From there, entropy decreases toward the asymptotic dS vacuum $\Phi = +v$, implying an outward projection of energy and geometry. The resulting expansion is therefore not imposed but generated by the system’s entropic relaxation.

This structure mirrors the time arrow discussed previously: both temporal directionality and spatial expansion emerge from the same entropic instability at the EH surface.

Comparison with EQG: Entropy as Cosmological Driver. In entropic quantum gravity, expansion is modeled as the growth of connectivity and entropy in an evolving network [9, 11]. The increase in microstate accessibility drives the macroscopic evolution of network geometry, corresponding to cosmic expansion. The mechanism in our model

is analogous: the scalar field Φ defines a thermodynamic potential landscape, and its entropic projection generates an effective force and volume increase.

Both models rely on internal entropy production as the cosmological driver. There is no need for an external inflaton, cosmological constant, or initial fine-tuning. Expansion is not a property of the vacuum but a thermodynamic response to entropy flow.

Summary and Implications. The EH interface acts as a thermodynamic projector: its entropy gradient defines not only the arrow of time and the force of gravity, but also the outward expansion of spacetime itself. The emergent pressure and energy flux from this interface explain cosmological acceleration as a thermodynamic consequence of scalar instability.

This entropy-driven expansion is consistent with holographic bounds [19], and resonates with recent approaches to dark energy and inflation as emergent thermodynamic phenomena [6, 20]. Its similarity to EQG models underscores a deeper unification: gravity, time, and cosmology are not fundamental forces or parameters, but macroscopic reflections of statistical entropy flow.

5 Discussion

The dual-holographic cosmological model developed in this work proposes that gravity, time, and cosmic expansion emerge from a scalar interface field Φ located on a dynamically generated event horizon (EH) separating an AdS-like quantum interior from a dS-like geometric exterior. This interface mediates a smooth thermodynamic transition between two distinct holographic domains and replaces the need for a fundamental cosmological constant, inflationary field, or singular initial condition.

Summary of Key Mechanisms. The model is built on a series of tightly linked physical mechanisms:

- **Scalar field dynamics:** The EH field $\Phi(z)$ evolves as a kink solution between vacua $\Phi = \pm v$, encoding the AdS and dS phases, respectively.
- **Thermodynamic projection:** Spacetime geometry on both sides of the EH emerges from entropy gradients across the field profile.
- **Entropic gravity:** Inward entropy flow in the AdS domain recovers attractive gravitational effects via entropic force mechanisms.
- **Entropy-driven expansion:** Outward entropy flow in the dS domain generates cosmological acceleration without invoking dark energy.
- **Operator matching:** Observable differences between interior and exterior domains are expressed via an asymmetric matching of dual operators across the EH field.
- **Emergent time:** Directionality and causality originate from the thermodynamic instability at $\Phi = 0$, giving rise to an emergent arrow of time.

These mechanisms yield a thermodynamically grounded alternative to both Λ CDM and conventional quantum gravity approaches.

Conceptual Comparison with EQG. The proposed model shares several conceptual features with entropy-based quantum gravity (EQG) models developed by Bianconi and collaborators [9, 11]:

- **Emergence from entropy:** Both frameworks posit that spacetime and its properties arise from entropy dynamics. In EQG, this is formulated through network connectivity and entropy maximization; here, through a scalar field encoding local entropy density and flux.
- **Absence of fundamental time:** Neither model assumes a fundamental time coordinate. Instead, time emerges as a statistical ordering of entropic configurations—through field evolution in our case, through topological network transitions in EQG.
- **No vacuum energy problem:** Both approaches bypass the cosmological constant problem by eliminating Λ as a fundamental input. Instead, cosmic acceleration is driven by internal entropy gradients.

Despite their differences in formulation—discrete vs. continuous, microscopic vs. effective—the two models are structurally aligned. This suggests that the thermodynamic origin of spacetime may be robust across different levels of physical description.

Illustration: Thermodynamic Evolution of Expansion. The time evolution of the expansion rate $H(t)$, derived from the scalar field profile $\Phi(z(t))$, encapsulates the model’s core idea: expansion is a projected thermodynamic flow. Figure 4 shows a representative Hubble trajectory derived from the sech-profile of the EH field.

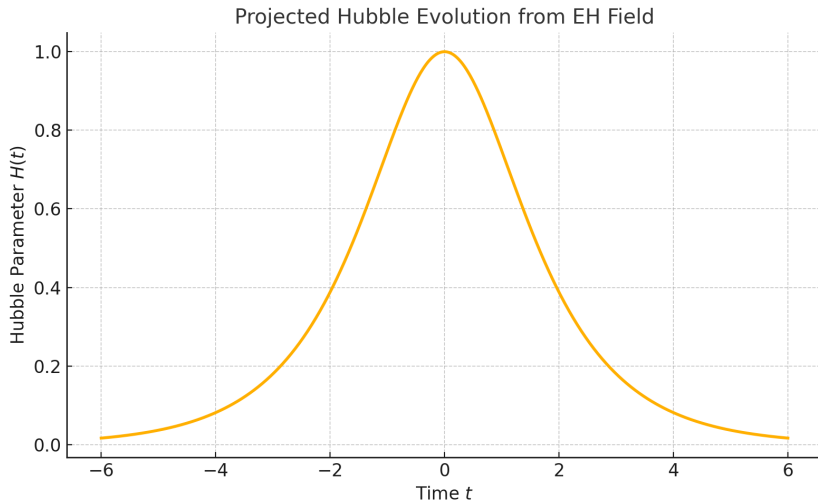


Figure 4: Evolution of the Hubble parameter $H(t) = H_0 \operatorname{sech}(\gamma t)$, derived from the EH field profile. The expansion rate starts at a maximum near the thermodynamic instability ($\Phi \approx 0$) and decays smoothly as the scalar field saturates toward its dS vacuum. This behavior reflects the entropic relaxation of the system and supports the interpretation of expansion as thermodynamic projection.

This thermodynamically grounded Hubble curve contrasts with inflationary plateaus or step-like expansions. It captures a natural onset of acceleration without fine-tuning, while preserving consistency with late-time cosmology.

Unified Interpretation. Taken together, the results suggest that the EH field may serve as a bridge between microscopic entropic network models like EQG and macroscopic thermodynamic field theories. While the detailed degrees of freedom differ, the logic of emergence—from entropy, via instability, toward geometry and dynamics—is shared.

Such parallels open the door to a generalized entropic paradigm, in which spacetime is no longer a static background but a process: a projection, a relaxation, a flow.

6 Outlook

The dual-holographic model developed here presents a novel, thermodynamically grounded approach to cosmology. It offers a consistent mechanism for emergent spacetime, gravity, and expansion, replacing the need for a fundamental cosmological constant or inflationary field. At its core, the model postulates that spacetime is a projection from an entropic interface field Φ , located on a finite, dynamically active event horizon (EH) between an AdS-like interior and a dS-like exterior.

Several directions for further development and integration with other frameworks can be identified:

Toward a Complete dS/CFT Dictionary. While the AdS/CFT correspondence is well established, its de Sitter counterpart remains speculative. The present model suggests a finite-screen implementation, with the EH acting as a projective boundary surface for a dS-side field theory. Formalizing this correspondence—possibly along the lines of boundary conformal field theory (BCFT) and analytic continuation techniques [3, 21]—would significantly strengthen the theoretical foundation of the model.

Coupling to Quantum Information and Entanglement. The entropy-based emergence of geometry aligns naturally with information-theoretic approaches to quantum gravity. In particular, the entanglement structure across the EH, and its connection to holographic entanglement entropy [22, 23], deserve further study. Can the entropy gradient $\nabla s(\Phi)$ be interpreted in terms of entanglement wedge dynamics? And does the matching condition across the EH reflect an extremal entropy surface?

Bridging with Entropic Quantum Gravity (EQG). As discussed, there is structural complementarity between this model and EQG approaches [9, 11]. Future research could explore whether the macroscopic scalar field Φ can be interpreted as a continuum limit of microscopic connectivity dynamics. This would link coarse-grained entropic projection to discrete network evolution, offering a multiscale description of emergent spacetime.

Beyond Cosmology: Grey Holes and Horizon Thermodynamics. The thermodynamic mechanisms underlying the EH field may apply beyond cosmology. Grey Holes, originally developed to describe nonsingular black hole interiors, share the same entropic stability structure. Extending the dual-holographic mechanism to black hole event horizons, firewall transitions, or AdS/BCFT geometries could provide new insights into gravitational entropy, information preservation, and horizon microstructure.

Observational and Phenomenological Tests. Although primarily theoretical, the model makes testable predictions. The field-driven expansion profile $H(t)$, the derived form of dark energy density ρ_{eff} , and the thermodynamically predicted CMB anisotropies $\delta T/T \sim 10^{-5}$ may yield observable deviations from standard Λ CDM cosmology. Comparing these with existing and upcoming data from DESI, Euclid, and JWST could help falsify or support the dual-holographic hypothesis.

Concluding Vision. The present model suggests a shift in perspective: from quantizing spacetime to understanding it as an emergent projection from entropy gradients across a scalar interface. In this view, geometry, motion, and time arise as macroscopic reflections of thermodynamic structure—opening the door to a new paradigm in cosmology, rooted not in fundamental fields but in the informational architecture of the universe.

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