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The Big Bang Firewall and the Emergence of Spacetime

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Abstract.
We propose that the Big Bang can be understood as a cosmic-scale entanglement transition occurring in a pre-geometric quantum state. Motivated by the black hole information paradox and the AMPS argument, we interpret the pre-Bang phase as an over-constrained entanglement structure producing a monogamy tension, rather than a fundamental violation of quantum mechanics. The resulting cosmic firewall is not a localized destructive barrier, but a global reorganization of quantum correlations that preserves fine-grained unitarity while allowing the emergence of semiclassical spacetime. We model the pre-Bang substrate as a quantum graph whose highly connected phase encodes dense pre-geometric correlations. Within a semiclassical approximation, the replica trick applied to the gravitational path integral leads to an entanglement–cosmology scaling relation linking variations of entanglement entropy to variations of the effective cosmological constant through the normalized spacetime volume of the emergent background. This scaling is consistent with the known dependence of de Sitter entropy on the cosmological constant. The framework provides a unitary information-theoretic mechanism for spacetime emergence, connects the thermodynamic arrow of time to post-transition entanglement growth, and extends the firewall paradigm from black hole horizons to cosmological initial conditions. It also suggests possible observational windows in primordial non-Gaussianities, stochastic gravitational-wave backgrounds, and ultra-slow variations of effective couplings.

Keywords: Cosmic Firewall; Big Bang; Quantum Entanglement; Unitarity Preservation.

Contents

1 Introduction

The black hole information paradox has long exposed a fundamental tension between quantum mechanics and general relativity. Hawking showed that black holes radiate thermally [1,2], suggesting information loss and violation of unitarity [3]. Page later argued that unitarity requires the entanglement entropy of Hawking radiation to follow the Page curve [4], while the AMPS argument [5] sharpened the paradox: late radiation must be entangled both with early radiation and with interior modes, violating monogamy of entanglement [6]. Resolving this requires either a firewall [7] or nonlocality via ER=EPR wormholes [8].

We extend this logic to cosmology. The Planck epoch following the Big Bang represents a regime where quantum gravitational effects dominate and similar information-theoretic tensions arise. Connections between black hole physics and cosmology have long been noted [9–11], with the holographic principle suggesting that the universe can be described by boundary data [10,12] and ER=EPR implying entanglement as the fabric of spacetime [8,11]. Yet no mechanism has been identified that simultaneously preserves unitarity, generates spacetime, and explains the arrow of time at cosmic origins.

We propose that the Big Bang was a cosmic firewall transition: **a global entanglement-restructuring event that resolves an over-constrained correlation pattern** in a pre-geometric quantum substrate. Unlike black hole firewalls, this process is not a destructive barrier but a unitary phase transition in entanglement structure. It yields two key outcomes: spacetime topology emerges through stable ER=EPR connections [8,11], and the coarse-grained irreversible restructuring of correlations establishes the thermodynamic arrow of time [13]. Unlike prior approaches that treat the Big Bang singularity as a classical boundary condition [14,15] or embed cosmological firewalls in an already-existing spacetime, our proposal identifies the firewall as the origin event that generates spacetime itself. The present model diverges from other proposals in three key respects: our firewall precedes spacetime and creates it; we avoid topological surgery on existing geometry; and spacetime emerges from the ER=EPR equivalence applied to the post-firewall consistent entanglement network.

To formalize this idea, we derive an entanglement–cosmology relation which links variations in entanglement entropy to the cosmological constant through the gravitational path integral [16–18]. This relation suggests a possible link between the firewall transition and the effective macroscopic parameters of the emergent universe. It also motivates possible observational windows in CMB anisotropies, primordial gravitational waves, and possible variations of fundamental constants. Thus, the Big Bang may be reframed as a firewall transition, generalizing the AMPS paradox to cosmology and providing an information-theoretic mechanism for the emergence of spacetime.

2 Theoretical Framework

2.1 Pre-Bang State: Entanglement Network

We model the pre-Bang universe as a dense network of interacting quantum degrees of freedom with no classical geometry. In this regime:

- quantum correlations form and reorganize at Planckian scales;
- high connectivity can generate over-constrained entanglement configurations;
- these configurations produce a monogamy tension in the AMPS sense, without implying a fundamental violation of quantum mechanics.

2.2 Firewall Transition

When the entanglement structure reaches a critical threshold, the system undergoes a unitary phase transition — the cosmic firewall — which:

- suppresses over-constrained correlations;
- reorganizes the entanglement network into a globally consistent configuration;
- supports the emergence of semiclassical spacetime through ER=EPR-type connectivity.

3 Mathematical Framework for the Cosmic Firewall

3.1 Pre-Bang Quantum State

The assumption that spacetime emerges from a more fundamental quantum substrate is strongly motivated by several modern approaches to quantum gravity. In holographic constructions, spacetime connectivity has been argued to emerge from quantum entanglement itself [8,11]. Tensor-network toy models such as MERA and HaPPY codes explicitly reconstruct bulk geometry from a Hilbert space of entangled qubits [19–21]. Similarly, pregeometric approaches, including 't Hooft's cellular automaton interpretation, replace continuum spacetime with discrete microscopic degrees of freedom [22]. Motivated by these developments, we model the pre-Bang substrate as a Hilbert space of interacting quantum degrees of freedom governed by a Hamiltonian $\mathcal{H}_{\text{pre}}$, without assuming a specific microscopic completion.

The entanglement entropy of a subsystem A is

$$S_{\text{ent}}(A) = -\operatorname{Tr}(\rho_A \log \rho_A), \tag{3.1}$$

with reduced density matrix ρ_A. For a tripartite pure state ABC, monogamy of entanglement requires

$$S_{\text{ent}}(A:B) + S_{\text{ent}}(A:C) \leq S_{\text{ent}}(A)\,, \tag{3.2}$$

consistent with the mutual information bound [6]. To make this statement more precise, we introduce the following diagnostic of monogamy tension,

$$\mathcal{M}_i = \sum_{j\neq i} E(i:j) - E_{\max}(i), \tag{3.3}$$

where $E(i:j)$ denotes an effective bipartite entanglement measure between the degrees of freedom i and j, and $E_{\max}(i)$ is the maximal entanglement capacity of subsystem i. The regime $\mathcal{M}_i \gtrsim 0$ signals an over-constrained correlation pattern, or monogamy tension, in the AMPS sense. It should not be interpreted as a fundamental violation of quantum mechanics.

Strictly speaking, quantum monogamy is not fundamentally violated. Rather, the AMPS paradox arises because the simultaneous requirements of unitarity, effective field theory, and smooth horizons lead to an over-constrained entanglement structure.

It is commonly known that, during black hole evaporation, late Hawking radiation B must be entangled both with early radiation C (to preserve unitarity) and with interior modes A (to maintain a smooth horizon). This leads to

$$S_{\text{ent}}(A:B) + S_{\text{ent}}(A:C) \gtrsim S_{\text{ent}}(A), \tag{3.4}$$

which signals an apparent tension with entanglement monogamy underlying the AMPS firewall paradox [5,23].

Resolution of this tension requires suppressing the A–B correlations,

$$S_{\text{ent}}(A:B) \to 0, \tag{3.5}$$

thereby restoring consistency of the entanglement structure through a high-energy firewall transition.

By analogy with the black hole framework, we interpret the Big Bang as a **cosmic firewall event**, in which proliferating over-constrained entanglement configurations in the pre-Bang state,

$$S_{\text{ent}}^{\text{pre}}(a:b) + S_{\text{ent}}^{\text{pre}}(a:c) \gtrsim S_{\text{ent}}^{\text{pre}}(a), \tag{3.6}$$

were dynamically restructured during the transition, resetting the entanglement network to

$$S_{\text{ent}}^{\text{post}}(a:b) + S_{\text{ent}}^{\text{post}}(a:c) \leq S_{\text{ent}}^{\text{post}}(a). \tag{3.7}$$

Here, a, b, c denote triplets of pre-geometric quantum degrees of freedom rather than localized spacetime subsystems. In this sense, the cosmic firewall plays a role analogous to the AMPS firewall for old black holes, enforcing consistency of the global entanglement structure through a large-scale entanglement transition [8]. The post-transition state is then interpreted as a stable entanglement configuration capable of supporting an emergent semiclassical spacetime geometry.

3.2 Firewall Transition Condition

We posit that the firewall transition is triggered when the entanglement entropy reaches a critical threshold,

$$S_{\text{ent}}^{\text{critical}} = \alpha \log N, \tag{3.8}$$

where N denotes the number of fundamental pre-geometric quantum degrees of freedom and α is an $\mathcal{O}(1)$ constant. The logarithmic scaling reflects the fact that the critical configuration corresponds to a maximally scrambled quantum state, analogous to the Page-saturated regime of highly entangled black holes [4,24].

Beyond this threshold, the entanglement structure becomes effectively over-constrained, motivating the firewall transition as a mechanism restoring global consistency of the quantum state.

3.3 Derivation of the Entanglement–Cosmology Relation

To connect the microscopic entanglement structure with macroscopic cosmology, we derive a semiclassical relation between variations of entanglement entropy and the cosmological constant. Our starting point is the Euclidean gravitational partition function

$$Z = \int \mathcal{D}g \, e^{-I[g]}, \tag{3.9}$$

where $I[g]$ is the Euclidean Einstein–Hilbert action.

The entanglement entropy is computed using the replica trick [25],

$$S_{\text{ent}} = -\frac{\partial}{\partial n} \log Z_n \bigg|_{n=1}, \tag{3.10}$$

where Z_n denotes the partition function on the n-sheeted replica manifold.

Varying with respect to the cosmological constant gives

$$\frac{\partial S_{\rm ent}}{\partial \Lambda} = -\frac{\partial}{\partial n}\left[\frac{1}{Z_n}\frac{\partial Z_n}{\partial \Lambda}\right]_{n=1}. \tag{3.11}$$

Using

$$\frac{\partial I}{\partial \Lambda} = -\frac{1}{8\pi G}\int d^d x\,\sqrt{g}, \tag{3.12}$$

the partition function variation becomes

$$\frac{\partial Z_n}{\partial \Lambda} = \int \mathcal{D}g\left(\frac{1}{8\pi G}\int d^d x\,\sqrt{g}\right)e^{-I[g]}. \tag{3.13}$$

This naturally identifies the spacetime volume operator

$$V[g] = \frac{1}{8\pi G}\int d^d x\,\sqrt{g}, \tag{3.14}$$

so that

$$\frac{1}{Z_n}\frac{\partial Z_n}{\partial \Lambda} = \langle V[g]\rangle_n \equiv V_n. \tag{3.15}$$

Substituting into Eq. (3.11) yields

$$\frac{\partial S_{\rm ent}}{\partial \Lambda} = -\frac{\partial V_n}{\partial n}\bigg|_{n=1}. \tag{3.16}$$

In the semiclassical saddle-point limit,

$$V_n = nV_d, \qquad V_d = \frac{1}{8\pi G}\int d^d x\,\sqrt{g_0}. \tag{3.17}$$

Therefore,

$$\frac{\partial S_{\rm ent}}{\partial \Lambda} = -V_d. \tag{3.18}$$

Integrating for small controlled variations gives

$$\Delta S_{\rm ent} = -V_d\,\Delta\Lambda. \tag{3.19}$$

Equivalently, independently of sign conventions and ensemble choices, the robust semiclassical scaling is

$$|\Delta S_{\rm ent}| \sim V_d\,|\Delta\Lambda|. \tag{3.20}$$

This result should be interpreted as a semiclassical scaling relation linking variations of entanglement entropy to the effective cosmological constant through the spacetime volume of the emergent geometry.

3.4 Interpretation and Implications of the Entanglement–Cosmology Relation

The relation derived in Eq. (3.20) should be understood as a semiclassical scaling relation rather than as an exact non-perturbative identity. It expresses how variations of the entanglement entropy are controlled, at leading semiclassical order, by variations of the effective cosmological constant and by the spacetime volume of the emergent background. In this sense, it provides a dictionary between microscopic quantum-information data and macroscopic gravitational parameters.

Independent validation from de Sitter entropy. As a consistency check, let us apply Eq. (3.20) to a de Sitter-like semiclassical background. The Gibbons–Hawking entropy is

$$S_{\rm dS} = \frac{\pi}{G\Lambda}. \tag{3.21}$$

Differentiating with respect to the cosmological constant gives

$$\frac{dS_{\rm dS}}{d\Lambda} = -\frac{\pi}{G\Lambda^2}. \tag{3.22}$$

On the other hand, Eq. (3.20) gives, at the level of scaling,

$$\frac{\partial S_{\rm ent}}{\partial \Lambda} \sim V_d. \tag{3.23}$$

For a four-dimensional de Sitter background, the characteristic spacetime volume scales as

$$V_d \sim \ell_{\rm dS}^4 \sim \Lambda^{-2}. \tag{3.24}$$

Thus, the scaling behavior of Eq. (3.20) is consistent with the known de Sitter entropy dependence on Λ, up to numerical factors and sign conventions associated with the Euclidean action and the choice of thermodynamic ensemble. This provides a useful semiclassical self-consistency check of the entanglement–cosmology relation.

The relation Eq. (3.20) admits two complementary interpretations:

- **Spacetime generation:** during the cosmic firewall transition, the reorganization of the pre-geometric entanglement structure fixes the effective semiclassical background that emerges after the transition.
- **Cosmological constant as information imprint:** the effective value of Λ can be viewed as an imprint of the entanglement restructuring that occurred during the transition, rather than as a completely arbitrary parameter.

Clarification: two distinct entropy quantities. A crucial point is that two different entropy variations must not be conflated:

1. **Firewall entropy jump.** The quantity

$$\Delta S_{\rm ent}^{\rm firewall} = S_{\rm ent}^{\rm post} - S_{\rm ent}^{\rm pre} < 0 \tag{3.25}$$

denotes the one-time coarse-grained entropy drop associated with the firewall transition. It corresponds to the suppression of over-constrained entanglement configurations in the pre-geometric phase. This does not imply a loss of fine-grained quantum information; the transition remains globally unitary.

2. **Post-transition entropy growth.** The quantity $S_{\rm ent}(t)$ denotes the subsequent thermodynamic growth of entanglement entropy in the post-Bang universe,

$$\frac{dS_{\rm ent}}{dt} \geq 0. \tag{3.26}$$

This post-transition evolution is responsible for the thermodynamic arrow of time and is distinct from the initial firewall entropy jump.

With this distinction, the apparent tension between entropy reduction at the transition and entropy growth after the Big Bang is removed. The firewall transition reorganizes the entanglement structure at the coarse-grained level, while the global fine-grained entropy remains conserved.

The corresponding coarse-grained entropy evolution across the firewall transition is shown schematically in Fig. 1.

The cosmic firewall process can then be summarized in three stages:

- **Pre-Bang: Entanglement saturation.** A dense web of quantum correlations develops in the pre-geometric substrate. Rather than assuming an actual violation of quantum monogamy, we interpret the configuration as an over-constrained entanglement structure, producing a monogamy tension in the AMPS sense. As the entanglement entropy approaches the critical threshold $S_{\text{ent}}^{\text{critical}}$, the pre-geometric phase becomes unstable.

- **Firewall transition.** At criticality, the system undergoes a unitary entanglement-restructuring transition,

$$U_{\text{firewall}}\,|\Psi_{\text{pre}}\rangle = |\Psi_{\text{post}}\rangle, \tag{3.27}$$

  with probability conservation

$$\sum_i \left|{}_{\text{post}}\langle\psi_i|U_{\text{firewall}}|\Psi_{\text{pre}}\rangle\right|^2 = 1. \tag{3.28}$$

  This transition suppresses over-constrained correlations and reorganizes the quantum state into a configuration compatible with global unitarity.

- **Post-Firewall: Spacetime emergence.** After the transition, the remaining consistent entanglement patterns can be interpreted as stable ER=EPR-type connections. Schematically, the Hilbert-space structure reorganizes as

$$\mathcal{H}_{\text{pre}} \xrightarrow{\text{Firewall}} \bigoplus_j \left(\mathcal{H}_{\text{ER}_j} \otimes \mathcal{H}_{\text{EPR}_j}\right). \tag{3.29}$$

  The resulting entanglement network supports an emergent semiclassical geometry, which at large scales can be modeled by an FRW-type spacetime,

$$\frac{\dot{R}^2}{R^2} = \frac{8\pi G}{3}\tilde{\rho} - \frac{k}{R^2} + \frac{\Lambda}{3}, \tag{3.30}$$

  where $\tilde{\rho}$ encodes the effective energy density associated with residual entanglement degrees of freedom.

Unlike the AMPS firewall, which appears as a high-energy obstruction at an already existing black-hole horizon, the cosmic firewall proposed here is not a localized destructive barrier. It is instead a global phase transition in the entanglement structure of a pre-geometric quantum state. Its role is to restore consistency of the quantum correlations and to select a post-transition sector capable of supporting semiclassical spacetime.

This reformulation highlights several physical implications:

- **Unitarity preservation.** The firewall transition is described by a unitary map U_{firewall} and therefore conserves fine-grained quantum information. The apparent reduction of entanglement entropy is a coarse-grained effect associated with the removal of over-constrained correlations.

- **Entanglement restructuring.** The change in correlation patterns may be modeled, at an effective level, by a spin-network-like quantity

$$\Delta\mathcal{E}_t = \frac{1}{2}\sum_{i,j} J_{ij}\left(\langle\sigma_i\sigma_j\rangle_{\text{post}} - \langle\sigma_i\sigma_j\rangle_{\text{pre}}\right), \tag{3.31}$$

where J_{ij} denotes an effective coupling between microscopic degrees of freedom. This emphasizes the phase-transition character of the cosmic firewall.

- **Arrow of time.** The thermodynamic arrow does not originate from the entropy drop itself, but from the subsequent monotonic growth of post-transition entanglement entropy, Eq. (3.26).

  Thus, the firewall transition prepares a low coarse-grained entropy state from which ordinary thermodynamic evolution can proceed.

- **Quantum gravitational memory.** If the emergent spacetime retains traces of the pre-geometric entanglement restructuring, such information may be encoded in large-scale cosmological observables, for example in primordial correlations or stochastic gravitational-wave backgrounds.

- **Cosmological constant as an effective information imprint.** Using Eq. (3.20), the effective change in the cosmological constant is controlled by the firewall entropy jump according to the scaling

$$|\Delta\Lambda_{\text{eff}}| \sim \frac{|\Delta S_{\text{ent}}^{\text{firewall}}|}{V_d}. \tag{3.32}$$

This should not be interpreted as a complete solution to the cosmological constant problem. Rather, it suggests that the value of the effective cosmological constant in the emergent spacetime may carry information about the entanglement restructuring that occurred at the cosmic firewall transition.

4 A Quantum Graph as Quantum Substrate

4.1 Quantum Graph Model

Quantum graphity [26,27] provides a compelling framework for pre-spacetime entanglement networks. Spacetime emerges from a dynamical graph of qubits evolving from a complete graph K_N to a sparse graph:

$$K_N \xrightarrow{\text{Phase Transition}} \text{Emergent spacetime (sparse graph).} \tag{4.1}$$

The maximum entanglement entropy of a geometric region is expected to scale with its boundary area [10],

$$S_{\text{ent}}^{\max} = \frac{\text{Area}}{4G} \sim N^{2/3}, \tag{4.2}$$

where N denotes the number of fundamental microscopic degrees of freedom.

In contrast, a pre-geometric complete graph contains a number of possible pairwise correlations scaling as $\mathcal{O}(N^2)$. Such a highly connected phase should not be interpreted as an ordinary geometric spacetime entropy, but rather as a graph-theoretic measure of microscopic entanglement capacity before the emergence of locality.

We therefore parametrize the pre-Bang entanglement structure by a super-holographic scaling

$$S_{\mathrm{ent}}^{\mathrm{pre}} \sim N^{\beta}, \qquad \beta > \frac{2}{3}, \tag{4.3}$$

where $\beta > 2/3$ indicates that the pre-geometric phase carries more correlations than allowed by the holographic area law of an emergent geometric spacetime. We call such a highly connected pre-geometric phase a *super-holographic graph*. This terminology refers to the connectivity and correlation capacity of the graph, not to a violation of holography within an already formed spacetime.

The transition to a geometric phase is then interpreted as a reduction of the effective entanglement connectivity from a super-holographic regime to a holographic, area-law-compatible regime,

$$K_N \text{ (super-holographicgraph)} \xrightarrow{\text{Firewall transition}} \text{Emergentspacetime (ER=EPR network)}. \tag{4.4}$$

The role of the cosmic firewall is thus not to destroy quantum information, but to reorganize an over-constrained entanglement structure into a sector compatible with global unitarity and emergent locality.

This transition from a highly connected pre-geometric quantum graph to a stable ER=EPR-type geometric network is illustrated schematically in Fig. 2.

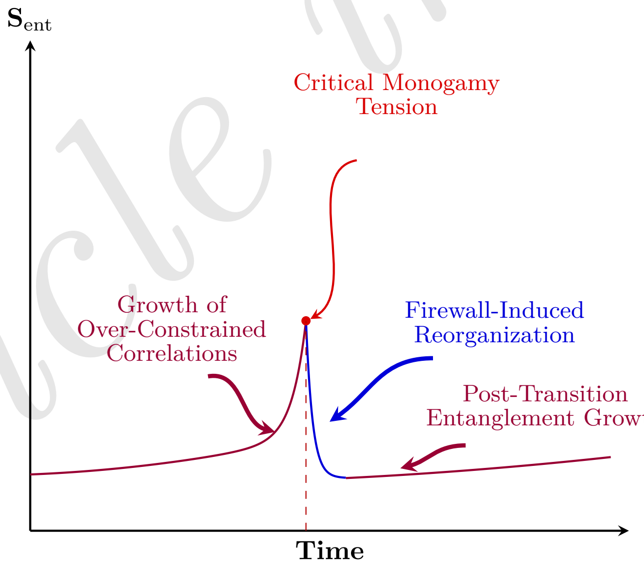

Figure 1: Schematic evolution of coarse-grained entanglement entropy across the cosmic firewall transition. The pre-transition phase exhibits growth toward an over-constrained entanglement regime. The transition reaches a critical point associated with maximal monogamy tension, followed by a rapid coarse-grained entropy drop induced by the firewall while preserving fine-grained unitarity. After the transition, the entanglement entropy grows monotonically, providing an effective thermodynamic arrow of time. The figure is schematic and not to scale.

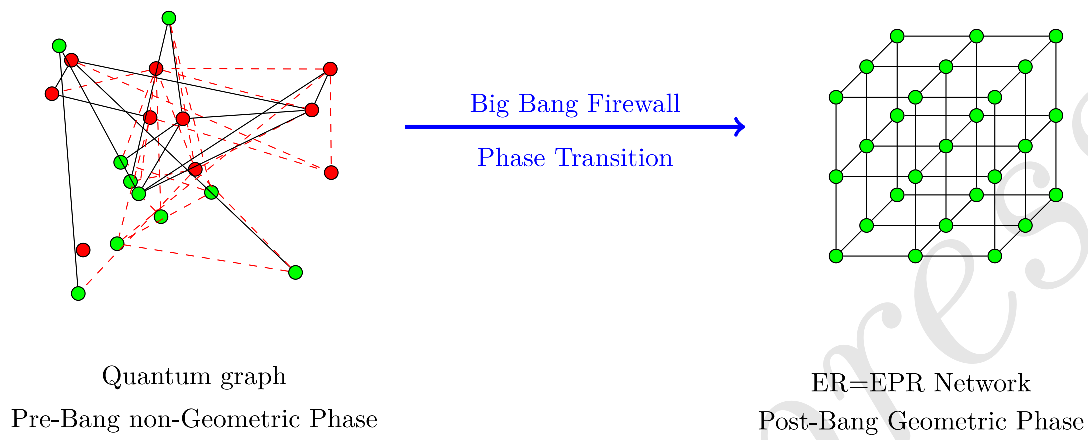

Figure 2: Schematic representation of the cosmic firewall transition. The pre-Bang phase is modeled as a highly connected quantum graph containing over-constrained entanglement configurations, represented by red dashed links. The firewall transition reorganizes these correlations through a unitary phase transition. The post-Bang phase is represented as a stable ER=EPR-type network supporting an emergent geometric spacetime. The subsequent post-transition growth of entanglement entropy is associated with the emergence of a thermodynamic arrow of time.

4.2 Entanglement Network Hamiltonian

To make the previous discussion concrete, we introduce an effective quantum-graph Hamiltonian inspired by quantum graphity models [26,28],

$$\hat{H} = -\frac{1}{2!}\sum_{ij} J_{ij}\,\sigma_i^z\sigma_j^z - \Gamma\sum_i \sigma_i^x + \frac{\lambda}{3!}\sum_{ijk}\sigma_i^z\sigma_j^z\sigma_k^z. \tag{4.5}$$

Here J_{ij} denotes the effective coupling between nodes i and j, Γ controls local quantum fluctuations, and λ weights higher-order correlations among triples of degrees of freedom.

The Pauli matrices are

$$\sigma^x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad \sigma^y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \qquad \sigma^z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \tag{4.6}$$

The three terms have distinct physical meanings:

- The Ising-like term $-\sum_{ij} J_{ij}\sigma_i^z\sigma_j^z$ encodes pairwise correlations between graph nodes.
- The transverse-field term $-\Gamma\sum_i \sigma_i^x$ introduces quantum fluctuations and allows the graph state to explore superpositions of connectivity patterns.
- The three-body term $\lambda\sum_{ijk}\sigma_i^z\sigma_j^z\sigma_k^z$ generates higher-order multipartite correlations. In a highly connected graph, such correlations may lead to an over-constrained entanglement structure, producing a monogamy tension analogous to that appearing in the AMPS argument. Moreover, in the highly connected regime, the three-body interaction proportional to λ enhances multipartite correlations and can drive the diagnostic $\mathcal{M}_i$ toward the over-constrained regime $\mathcal{M}_i \gtrsim 0$. In this sense, the Hamiltonian provides an effective microscopic mechanism for the emergence of monogamy tension, rather than merely assuming it.

In the super-holographic regime, where the graph is highly connected and higher-order correlations are non-negligible, the expectation values $\langle \sigma_i^z \sigma_j^z \rangle$ and $\langle \sigma_i^z \sigma_j^z \sigma_k^z \rangle$ can become collectively significant. This provides a concrete microscopic setting in which an effective monogamy tension can arise, without assuming any fundamental violation of quantum mechanics.

4.3 Entanglement Monogamy Tension

The entanglement structure undergoes a sharp reorganization at the firewall transition. In the pre-Bang phase, the high connectivity of the quantum graph produces an over-constrained correlation pattern that may be schematically represented as

$$S_{\rm ent}^{\rm pre}(a:b) + S_{\rm ent}^{\rm pre}(a:c) \gtrsim S_{\rm ent}^{\rm pre}(a). \tag{4.7}$$

This expression should not be read as a fundamental violation of entanglement monogamy. Rather, it represents an effective monogamy tension: the simultaneous correlation requirements imposed by the highly connected pre-geometric graph cannot all be realized within a smooth semiclassical geometry.

After the firewall transition, the entanglement structure is reorganized into a sector compatible with monogamy and holographic scaling,

$$S_{\rm ent}^{\rm post}(a:b) + S_{\rm ent}^{\rm post}(a:c) \leq S_{\rm ent}^{\rm post}(a), \qquad S_{\rm ent}^{\rm post} \sim \frac{\rm Area}{4G} \sim N^{2/3}. \tag{4.8}$$

Thus, the firewall transition acts as an entanglement filter: it suppresses over-constrained correlations and leaves behind a consistent ER=EPR-type network capable of supporting emergent semiclassical geometry.

Equivalently, in terms of the diagnostic introduced in Eq. (3.3), the pre-Bang highly connected regime corresponds schematically to $\mathcal{M}_a^{\rm pre} \gtrsim 0$, whereas the post-transition consistent entanglement sector satisfies $\mathcal{M}_a^{\rm post} \leq 0$.

Further, one may ask how a gravitational path integral can be used if spacetime itself is supposed to emerge from the quantum graph. The point is that the path integral is not assumed to be fundamental. It is an effective, semiclassical description valid after the transition, once a coarse-grained geometric phase has emerged. The fundamental description is the quantum graph and its entanglement structure, while the gravitational path integral provides the effective geometric language seen by observers inside the emergent spacetime.

In this sense, the entanglement–cosmology relation should be understood as a dictionary between two descriptions: a microscopic graph-theoretic description based on quantum correlations, and a macroscopic geometric description based on semiclassical gravity. This is analogous to the relation between microscopic statistical mechanics and macroscopic thermodynamics.

5 Effective Energy Density from the Graph Hamiltonian

An effective energy density associated with the emergent cosmological phase can be obtained from the expectation value of the graph Hamiltonian,

$$\tilde{\rho} = \frac{1}{V_{\rm eff}} \langle \Psi | \hat{H} | \Psi \rangle, \tag{5.1}$$

where $V_{\rm eff}$ denotes the effective coarse-grained volume of the emergent spacetime region.

For a general graph with adjacency matrix A_{ij} and three-body connectivity tensor B_{ijk}, one may write schematically

$$\tilde{\rho} = -\frac{J_0}{N}\sum_{i<j} A_{ij}\langle\sigma_i^z\sigma_j^z\rangle - \Gamma\langle\sigma^x\rangle + \frac{\lambda}{N}\sum_{i<j<k} B_{ijk}\langle\sigma_i^z\sigma_j^z\sigma_k^z\rangle. \tag{5.2}$$

The change in this effective energy density across the firewall transition,

$$\Delta\tilde{\rho} = \tilde{\rho}_{\rm post} - \tilde{\rho}_{\rm pre}, \tag{5.3}$$

provides an effective source term for the post-transition cosmological dynamics. At large scales, it can be decomposed phenomenologically as

$$\Delta\tilde{\rho} = \tilde{\rho}_m + \tilde{\rho}_r + \tilde{\rho}_\Lambda. \tag{5.4}$$

This decomposition should be understood as an effective late-time description, not as a microscopic derivation of the standard cosmological fluids.

6 First Effective Calculation: Isotropic, Homogeneous, Flat Universe

As a first illustrative calculation, we consider the simplest effective post-transition regime of the quantum graph. This calculation is not intended to describe the full microscopic triggering mechanism of the firewall, which requires higher-order correlations, but rather to estimate the leading contribution of the reorganized graph to the emergent Friedmann dynamics.

We model the universe as a quantum graph $\mathcal{G}$ with N nodes. For simplicity, we take homogeneous pairwise couplings $J_{ij} = J_0$ and neglect transverse and three-body corrections in this first estimate, setting $\Gamma = 0$ and $\lambda = 0$ after the transition. The effective Hamiltonian then reduces to

$$\hat{H}_{\rm eff} = -\frac{J_0}{2!}\sum_{ij}\sigma_i^z\sigma_j^z. \tag{6.1}$$

The pre-transition phase is characterized by a super-holographic number of effective links scaling as N^β, whereas the post-transition sparse graph has only Nl effective links, with $l \ll N$ the average valency of the emergent local graph.

Thus,

$$E_{\rm pre} \sim -\frac{J_0 N^\beta}{2}, \qquad \tilde{\rho}_{\rm pre} \sim -\frac{J_0 N^{\beta-1}}{2}, \tag{6.2}$$

and

$$E_{\rm post} \sim -\frac{J_0 N l}{2}, \qquad \tilde{\rho}_{\rm post} \sim -\frac{J_0 l}{2}. \tag{6.3}$$

The effective energy density released or reorganized during the transition is therefore

$$\Delta\tilde{\rho} = \tilde{\rho}_{\rm post} - \tilde{\rho}_{\rm pre} = -\frac{J_0 l}{2} + \frac{J_0 N^{\beta-1}}{2} \simeq \frac{J_0 N^{\beta-1}}{2}, \tag{6.4}$$

in the regime $N^{\beta-1} \gg l$[1].

[1] For a positive released effective energy density in this simplified normalization, one must restrict to the strongly super-holographic regime $\beta > 1$, or more generally assume $N^{\beta-1} \gg l$. In the present calculation we therefore interpret Eq. (6.4) as an illustrative estimate valid in this strongly connected regime.

Similarly, the coarse-grained entanglement entropy changes from a super-holographic pre-geometric scaling to an area-law-compatible post-geometric scaling,

$$S_{\text{ent}}^{\text{pre}} \sim N^{\beta}, \qquad S_{\text{ent}}^{\text{post}} \sim N^{2/3}. \tag{6.5}$$

Hence,

$$\Delta S_{\text{ent}}^{\text{firewall}} = S_{\text{ent}}^{\text{post}} - S_{\text{ent}}^{\text{pre}} \sim -N^{\beta}, \qquad \beta > \frac{2}{3}. \tag{6.6}$$

This negative jump is a coarse-grained entropy reduction associated with the suppression of over-constrained correlations. It does not imply loss of fine-grained quantum information, since the transition is described by a unitary map.

Using the semiclassical entanglement–cosmology scaling relation, the magnitude of the corresponding change in the effective cosmological constant scales as

$$|\Delta\Lambda_{\text{eff}}| \sim \frac{|\Delta S_{\text{ent}}^{\text{firewall}}|}{V_d}. \tag{6.7}$$

This relation should be interpreted as a scaling estimate within the present effective framework. It does not constitute a complete solution of the cosmological constant problem, since a full treatment would require vacuum-energy renormalization and a complete dynamical background analysis.

In a flat, isotropic, homogeneous universe ($k = 0$), the effective Friedmann equation becomes

$$\begin{aligned} H_b^2 \equiv \frac{\dot{R}^2}{R^2} &= \frac{8\pi G}{3}\Delta\tilde{\rho} + \frac{\Lambda_{\text{eff}}}{3} \\ &\simeq \frac{4\pi G J_0}{3} N^{\beta-1} + \frac{\Lambda_{\text{eff}}}{3}. \end{aligned} \tag{6.8}$$

This equation provides a first illustrative bridge between microscopic graph parameters (J_0, N, β) and the macroscopic expansion rate of the emergent universe.

We emphasize that this calculation is only a minimal homogeneous estimate. In particular, possible implications for dynamical dark energy, the Hubble tension, or the cosmic coincidence problem require a dedicated cosmological analysis and are left for future work.

7 Experimental Signatures and Predictions

The framework developed above is primarily theoretical. Nevertheless, it suggests a set of possible observational windows through which the entanglement-restructuring scenario could, in principle, be constrained. The estimates below should be understood as phenomenological order-of-magnitude signatures rather than precision predictions. A complete computation of the perturbation spectrum, bispectrum, and gravitational-wave transfer functions is left for future work.

7.1 CMB Non-Gaussianities

A rapid entanglement-restructuring event at the onset of the semiclassical phase may leave residual imprints in primordial correlations. We parametrize the corresponding fractional CMB temperature perturbation by

$$\frac{\Delta T}{T} \sim \varepsilon_{\text{fw}} \equiv \gamma_{\text{fw}} \frac{|\Delta S_{\text{ent}}^{\text{firewall}}|}{S_{\text{ent}}^{\text{dS}}}, \tag{7.1}$$

where $S_{\rm ent}^{\rm dS}$ denotes the de Sitter entropy of the emergent background and $\gamma_{\rm fw}$ is an efficiency factor encoding the fraction of the firewall entropy jump transferred to curvature perturbations.

Since the observed CMB temperature anisotropy is of order 10^{-5}, the framework is constrained by

$$\epsilon_{\rm fw} = \gamma_{\rm fw} \frac{|\Delta S_{\rm ent}^{\rm firewall}|}{S_{\rm ent}^{\rm dS}} \lesssim 10^{-5}. \tag{7.2}$$

Thus, versions of the model in which an $\mathcal{O}(1)$ fraction of the firewall entropy jump is converted into curvature perturbations would be observationally excluded. This provides a simple falsifiability condition for the entanglement-restructuring scenario.

If the transition induces non-linear correlations in the primordial curvature perturbation, one may expect a contribution to the local non-Gaussianity parameter of the schematic form

$$f_{\rm NL}^{\rm local} \sim \mathcal{C}_{\rm NG}\, \varepsilon_{\rm fw}, \tag{7.3}$$

where $\mathcal{C}_{\rm NG}$ depends on the effective sound speed, the duration of the transition, and the details of the conversion from entanglement perturbations to curvature perturbations.

Current Planck constraints are consistent with very small primordial non-Gaussianity, with $f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$ at 68% confidence level [29]. Therefore, the model is viable only if

$$|\mathcal{C}_{\rm NG}\, \varepsilon_{\rm fw}| \lesssim \mathcal{O}(1-10). \tag{7.4}$$

A distinctive signature would not simply be a large amplitude, but rather a specific bispectrum shape correlated with polarization or large-scale anomalies produced by the entanglement-restructuring process.

7.2 Stochastic Gravitational-Wave Background

A violent but global transition in the pre-geometric entanglement structure may also source a primordial stochastic gravitational-wave background. Instead of assigning a fixed amplitude, we parametrize the spectrum as

$$\Omega_{\rm GW}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_T} \mathcal{T}^2(f), \tag{7.5}$$

where Ω_* is the amplitude at a reference frequency f_*, n_T is the effective spectral tilt, and $\mathcal{T}(f)$ denotes the transfer function from the firewall epoch to today.

The characteristic frequency associated with a Planck-scale transition is expected to be very high after redshift, typically far above the most sensitive bands of current interferometers. However, depending on the transfer function and the duration of the transition, residual power may extend toward lower frequencies. Pulsar timing arrays, including NANOGrav, currently probe the nanohertz band and have reported evidence for a stochastic gravitational-wave background [30]. We do not identify this signal with the cosmic firewall contribution, but note that PTA data can constrain the low-frequency tail of Eq. (7.5).

A potentially falsifiable feature of the model would be a spectral tilt or running distinguishable from standard inflationary backgrounds, cosmic strings, or astrophysical supermassive black-hole binary populations. A robust prediction of n_T requires solving the perturbation dynamics of the entanglement transition, which we leave for future work.

7.3 Possible Drift of Effective Couplings

If the effective cosmological constant carries an imprint of entanglement restructuring, then slow post-transition evolution of the entanglement sector could induce tiny variations in effective dimensionless couplings. We parametrize such a drift phenomenologically as

$$\frac{\dot{\alpha}_{\rm eff}}{\alpha_{\rm eff}} = \kappa_\alpha \frac{\dot{\Lambda}_{\rm eff}}{\Lambda_{\rm eff}}, \tag{7.6}$$

where κ_α is a model-dependent sensitivity coefficient.

Existing atomic-clock and astrophysical constraints already require any present-day variation of the fine-structure constant to be extremely small, typically at or below the level of $\mathcal{O}(10^{-17})\,\mathrm{yr}^{-1}$ [31,32]. Hence the framework is observationally viable only if

$$\left| \kappa_\alpha \frac{\dot{\Lambda}_{\rm eff}}{\Lambda_{\rm eff}} \right| \lesssim 10^{-17}\,\mathrm{yr}^{-1}. \tag{7.7}$$

Future optical-clock comparisons could further constrain this possibility and thereby provide an indirect test of residual entanglement dynamics in the late universe.

Table 1: Phenomenological observational windows suggested by the cosmic firewall framework. The listed quantities should be understood as targets for future detailed calculations rather than precision predictions of the present model.

Observable	Model parameter	Current status	Future test
CMB anisotropy / non-Gaussianity	$\epsilon_{\rm fw}$, $\mathcal{C}_{\rm NG}\epsilon_{\rm fw}$	$\epsilon_{\rm fw} \lesssim 10^{-5}$, $\lvert f_{\rm NL}^{\rm local}\rvert \lesssim \mathcal{O}(10)$	CMB-S4, Simons Obs.
Stochastic GW background	$\Omega_*, n_T, \mathcal{T}(f)$	PTA constraints in nHz band	SKA, PTA, LISA
Coupling drift	$\kappa_\alpha \dot{\Lambda}_{\rm eff}/\Lambda_{\rm eff}$	$\lesssim 10^{-17}\,\mathrm{yr}^{-1}$	Next-generation clocks

In summary, the cosmic firewall framework does not yet provide precision cosmological predictions.
It does, however, identify three observational channels—primordial non-Gaussianity, stochastic gravitational waves, and possible ultra-slow drifts of effective couplings—where the entanglement-restructuring scenario can be constrained. These signatures provide a roadmap for future quantitative work connecting the microscopic quantum graph description to cosmological perturbation theory.

8 Discussion and Conclusion

We have proposed a framework in which the Big Bang is interpreted as a unitary-preserving firewall event: an over-constrained entanglement structure in a pre-geometric quantum graph is dynamically reorganized into a consistent ER=EPR-type network, thereby supporting the emergence of a semiclassical spacetime.

This perspective addresses three foundational issues:

- **Origin of Spacetime**: emergent from entanglement restructuring,
- **Arrow of Time**: associated with the subsequent monotonic growth of post-transition entanglement entropy,
- **Unitarity**: preserved through a globally information-conserving entanglement transition.

The key point is that the cosmic firewall should not be understood as a localized destructive barrier, but as a global phase transition in the entanglement structure of a pre-geometric quantum state. In this sense, our proposal provides a cosmological analogue of the AMPS logic: instead of resolving an inconsistency at an already existing black-hole horizon, the transition selects a consistent post-Bang entanglement sector capable of supporting semi-classical geometry.

To make this picture more concrete, we introduced a quantum-graph description of the pre-Bang substrate and an effective Hamiltonian encoding pairwise and higher-order correlations. This provides a microscopic setting in which a monogamy tension, in the AMPS sense, may arise without assuming any fundamental violation of quantum mechanics. Within a semiclassical approximation, the corresponding entanglement–cosmology relation links the firewall entropy jump to the effective cosmological background of the emergent spacetime.

The framework also clarifies the thermodynamic interpretation of the transition. The abrupt entropy change at the firewall is a coarse-grained reorganization of correlations, while the fine-grained quantum evolution remains unitary. The thermodynamic arrow of time is then associated with the subsequent growth of post-transition entanglement entropy, rather than with information loss.

Finally, we identified several possible observational windows through which this scenario may be constrained, including primordial non-Gaussian correlations, stochastic gravitational-wave backgrounds, and ultra-slow variations of effective couplings. At the present stage, these should be regarded as phenomenological signatures rather than precision predictions. A complete treatment will require deriving the perturbation spectrum, bispectrum, and gravitational-wave transfer functions from the underlying quantum-graph dynamics.

Future work will aim to develop this program in three directions: first, by studying the thermodynamic limit of the quantum-graph Hamiltonian; second, by deriving the effective cosmological perturbations generated by the firewall transition; and third, by exploring whether the entanglement–cosmology relation can be embedded in a broader holographic or quantum-gravity framework.

Authors' Contributions

All authors contributed equally to this work.

Data Availability

The manuscript has no associated data or the data will not be deposited.

Conflicts of Interest

The authors declare that there is no conflict of interest.

Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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