ISSN 2976 - 730X
IPI Letters 2025,Vol 3 (3):34-54
https://doi.org/10.59973/ipil.177

Received: 2025-02-24
Accepted: 2025-07-11
Published: 2025-07-20

Article

Little Bangs: the Holographic Nature of Black Holes

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Abstract - Recent discoveries in CMB E-mode polarization have revealed discrete quantum phase transitions governed by a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1}. We extend this framework to black hole evolution, proposing that when reaching information saturation at the holographic entropy bound, black holes undergo localized spacetime expansion events ("Little Bangs"). Our framework yields several novel findings: (1) a quantum-thermodynamic entropy partition reconceptualizing black holes as entropy organizers not information destroyers, (2) information pressure as a physical force driving spacetime expansion, (3) an information-theoretic derivation of the Hubble parameter, and (4) a mathematical E8×E8 structure explaining information encoding across scales. These transitions occur at integer multiples of $\ln 2$ with a characteristic $\frac{2}{\pi}$ geometric scaling ratio. Our model resolves the black hole information paradox through dimensional expansion rather than information loss, suggests dark matter emerges as coherent entropy structures, and proposes information as the primary constituent of reality. We present falsifiable predictions testable through statistical correlation methods in multi-messenger astronomy.

Keywords - Black Holes; Thomson Scattering; Holographic Information Rate; Information Saturation; Spacetime Expansion; Quantum Gravity; Information Paradox; Hawking Radiation

1 Introduction

The holographic principle, first proposed by 't Hooft [1] and later refined by Susskind [2], suggests that the information content of any region of space can be described by a theory that lives only on its boundary. For black holes, this manifests as the Bekenstein-Hawking entropy [3]:

$$S = \frac{A}{4G} \tag{1}$$

where A is the horizon area and G is Newton's gravitational constant. This relationship has profound implications for both quantum gravity and information theory, particularly regarding the black hole information paradox [4]. The seminal work of Hawking demonstrated that black holes emit thermal radiation, leading to the apparent loss of quantum information [5]. Recent work on CMB E-mode polarization has revealed discrete quantum phase transitions occurring at specific angular scales, governed by a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} [6]. These transitions exhibit a precise geometric scaling ratio of

$\frac{2}{\pi}$ between successive points and occur when the accumulated information reaches integer multiples of $\ln 2$, suggesting a deep connection between quantum information processing and spacetime structure.

In this paper, we propose that black holes reaching information saturation at the holographic entropy bound undergo similar phase transitions, resulting in localized spacetime expansion events we term "Little Bangs." This process provides a natural mechanism for converting pure information states into matter and energy while preserving quantum information, potentially resolving the black hole information paradox through dimensional expansion and entropy generation rather than information loss or firewall formation.

Hawking radiation is a quantum mechanical solution to what is essentially an information theoretic problem, and the application of an information theoretic solution yields far more nuanced, physically motivated results. We propose that black hole horizons function as information processors that organize incoming entropy into coherent states. When these coherent entropy states reach saturation, they force a physical phase transition, preserving information through thermodyanmic reorganization rather than emission.

2 Theoretical Framework

2.1 Holographic Entropy Bounds

The quantum field theory community has made significant progress in understanding the emergence of holographic bounds from curved spacetime dynamics. The pioneering work of Witten established the mathematical framework for understanding how these bounds arise naturally [7]. The holographic bound for black holes sets a fundamental limit on information storage:

$$I_{max} = \frac{A}{4G \ln 2} \text{ bits} \tag{2}$$

This bound emerges naturally from quantum field theory in curved spacetime [6] and represents the maximum amount of information that can be encoded on the event horizon. As a black hole accretes matter and radiation, it approaches this bound not continuously but through discrete quantum jumps, analogous to the recently discovered CMB phase transitions [5].

2.2 Information Processing Rate

The holographic information rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} emerges from these transitions and maintains a remarkable relationship with cosmic expansion: $\gamma/H \approx 1/8\pi$. This mathematical precision suggests a deep connection between information processing and the evolution of the universe.

The theoretical form of the holographic information rate emerges directly from first principles as:

$$\gamma = \frac{H}{\ln(\pi c^2/\hbar G H^2)} \tag{3}$$

where H is the Hubble parameter, c is the speed of light, $\hbar$ is the reduced Planck constant, and G is the gravitational constant [6]. This elegant formulation reveals why γ creates scale-invariant physical effects across vastly different scales - from cosmic structure to quantum phenomena. Logarithmic dependence arises naturally from the statistical counting of microstates in holographic systems, which connects quantum mechanics and cosmology through information theory. Perhaps most remarkable is that this formula precisely produces the observed value without free parameters, suggesting that information processing, rather than energy exchange, represents the fundamental currency of physical reality.

2.3 Quantum Phase Transitions in Information Processing

The evolution of information content near the holographic bound is governed by:

$$\frac{dI}{dt} = \gamma I \left(1 - \frac{I}{I_{max}}\right) \tag{4}$$

where γ is the fundamental information processing rate. This equation describes logistic growth with discrete transitions occurring at:

$$I_n = n \ln 2 \cdot I_{max}, \quad n = 1, 2, 3, ... \tag{5}$$

These transitions are enforced by both the quantum no-cloning theorem and holographic bounds, as any intermediate states would violate one or both principles.

2.4 Information-to-Matter Conversion

The conversion of pure information states into matter and energy during a "Little Bang" event follows from the thermodynamic relationship between information and entropy:

$$dS = \frac{dQ}{T} + \frac{\gamma}{c^2} dI \tag{6}$$

where dQ is the heat transfer, T is temperature, and dI represents the change in information content. The second term, unique to our framework, quantifies the entropy contribution from information processing. At the transition points (5), this leads to a sudden release of energy:

$$\Delta E = \gamma c^2 \Delta I = n\gamma c^2 \ln 2 \cdot I_{max} \tag{7}$$

This energy manifests primarily as radiation with a characteristic temperature:

$$T_n = \frac{\hbar \gamma}{2\pi k_B} \sqrt{n} \tag{8}$$

where n is the transition number. This temperature scaling reveals a direct parallel with post-leptogenesis conditions in the early universe, suggesting a universal pattern in how information-saturated systems evolve into matter-dominated ones.

2.5 Information Flux Dynamics

The standard derivation of Hawking radiation relies on quantum field theory in curved spacetime with specific boundary conditions that may not reflect the complete physical reality of black hole horizons. Our framework proposes that thermodynamic differences near the horizon arise not from particle pair creation, but from the organization of entropy into increasingly coherent states that create measurable temperature and pressure gradients without information loss.

The information pressure P_I emerges as a physical force when the encoding of new information requires work against existing correlations:

$$P_I = \frac{\gamma c^4}{8\pi G} \left(\frac{I}{I_{max}}\right)^2 \tag{9}$$

This pressure has a clear physical interpretation through three fundamental mechanisms:

1. Quantum Back-reaction: As information accumulates on the horizon, each new bit must maintain quantum correlations with existing bits while preserving unitarity. The work required to establish these correlations scales with the fraction of occupied states, contributing a factor of (I/I_{max}).

2. Geometric Phase Space Reduction: The holographic encoding pattern on the horizon must maintain consistency with the existing information structure. The available phase space

for consistent encoding decreases linearly with occupied information content, contributing another factor of (I/I_{max}).

3. Spacetime Response: When P_I exceeds the local spacetime rigidity (characterized by the Einstein tensor $G_{\mu\nu}$), we offer that the geometry must deform to accommodate the information-induced stress-energy in the following manner:

$$T^I_{\mu\nu} = \frac{\gamma\hbar}{c^2}\left(g_{\mu\nu}\nabla_\alpha I \nabla^\alpha I - \nabla_\mu I \nabla_\nu I\right) \tag{10}$$

The quadratic form of P_I arises from the combined effect of these mechanisms. When P_I reaches a critical threshold $P_c = \frac{\gamma c^4}{8\pi G}$, the local spacetime must expand to create new degrees of freedom while preserving the existing information pattern. This expansion is enforced by fundamental physical principles:

The expansion process is enforced by four fundamental physical principles: the conservation of information through unitary quantum evolution, the quantum no-cloning theorem which prohibits information copying, the holographic entropy bound that limits maximum information density, and the Einstein equations which govern the geometric response to energy-information content.

The expansion process creates new degrees of freedom while maintaining the coherence of existing information patterns, resolving the apparent conflict between continued accretion and information bounds. This mechanism operates purely through local physics, independent of any cosmological considerations.

Building on this foundation, a purely holographic formulation of the universal expansion equation emerges naturally from information processing principles:

$$H^2 = \frac{\gamma^2}{(8\pi G)^2}\left(\frac{I}{I_{max}}\right)^2 + \frac{\gamma c}{R_H}\ln\left(\frac{I}{Q}\right) \tag{11}$$

where H is the Hubble parameter, $\gamma = 1.89 \times 10^{-29}$ s^{-1} is the fundamental information processing rate, $R_H = c/H$ is the Hubble radius, I represents the information content of the system (either at the cosmic horizon or black hole horizon), I_{max} is the maximum possible information content, and Q is a single quantum of information. This dimensionless equation reformulates expansion dynamics entirely in information-theoretic terms, without reference to conventional energy density or spatial curvature parameters.

The first term in equation (11) represents the quadratic information pressure contribution that dominates at high information densities, while the logarithmic term captures the quantum entropic contribution that becomes significant at lower densities. For a black hole approaching information saturation, the quadratic term dominates, creating an effective information pressure.

This profound connection between cosmic expansion and black hole information dynamics reveals that both phenomena emerge from the same underlying information processing principles, merely manifesting at different scales. The "Little Bang" events around black holes thus represent localized versions of the same expansion dynamics that drive cosmic evolution, with the fundamental parameter γ providing the universal scaling relation across all systems governed by holographic information constraints.

3 The "Little Bang" Hypothesis

3.1 Mechanism of Localized Spacetime Expansion

Unlike the conventional view where black holes emit Hawking radiation to manage information content, our framework proposes that black holes function as coherent entropy organizers that can reach information saturation through the continuous accretion of matter and energy. As information accumulates at the horizon, two complementary processes drive the system toward a phase transition.

First, the information encoding efficiency decreases as the horizon approaches saturation due to fundamental quantum and geometric constraints:

$$\eta = \eta_0 \left(1 - \frac{I}{I_{max}}\right)^2 \tag{12}$$

This quadratic reduction in efficiency creates a non-linear buildup of information pressure P_I as described by equation (9), even when total information content remains below the absolute holographic bound. Second, as the density of organized entropy increases, quantum coherence effects begin to dominate the near-horizon dynamics, leading to non-local correlations that further amplify the information pressure.

When the information pressure reaches the critical threshold:

$$P_I^{crit} = \frac{\gamma c^4}{8\pi G} \tag{13}$$

the system enters a non-equilibrium state where further information organization becomes thermodynamically unfavorable. This creates a fundamental instability in the spacetime structure that can only be resolved through dimensional expansion.

The critical information density ratio at which this transition occurs is:

$$\left(\frac{I}{I_{max}}\right)_{crit} = 1 \tag{14}$$

When this condition is met, the quantum no-cloning theorem prohibits further information encoding on the horizon, and the geometric constraints of holography prevent further accretion without violation of fundamental principles. The system must create new degrees of freedom through localized spacetime expansion to resolve this informational crisis.

The metric evolution during this expansion process takes the form:

$$ds^2 = -f(r,t)dt^2 + a^2(t)\left[\frac{dr^2}{1 - 2GM/r} + r^2 d\Omega^2\right] \tag{15}$$

where $a(t)$ is the local scale factor, governed by the information-driven Friedmann equation derived from (11):

$$\frac{\ddot{a}}{a} = \frac{\gamma^2}{(8\pi G)^2}\left(\frac{I}{I_{max}}\right)^2 + \frac{\gamma c}{2R_H}\ln\left(\frac{I}{Q}\right) \tag{16}$$

Here, the first term represents the dominant information pressure contribution driving the expansion, while the second term captures the quantum entropic effects that modulate the expansion rate. The information energy density of the system is given by:

$$\rho_I = \frac{\gamma c^2}{8\pi G}\ln\left(\frac{I}{I_{max}}\right) \tag{17}$$

This expansion process preserves total information content while reorganizing it into an expanded spatial manifold, creating new degrees of freedom without violating unitarity, similar to cosmic inflation but localized to the black hole region.

3.2 Evolution of Post-Transition Black Holes

Immediately following a "Little Bang" event, the expanded region undergoes a phase of rapid cooling and matter formation as the newly created degrees of freedom accommodate the reorganized information content. The particle production rate follows:

$$\frac{dn}{dt} = \frac{\gamma^3}{c^2\hbar^2}\exp\left(-\frac{mc^2}{\gamma\hbar}\right) \tag{18}$$

where m is the particle mass. This exponential suppression ensures that particle production is dominated by the lightest available degrees of freedom, similar to reheating after cosmic inflation. The spacetime structure evolution proceeds through three characteristic phases:

1. **Information-Dominated Phase**: The initial expansion is driven primarily by information pressure, with the scale factor growing exponentially as $a(t) \propto e^{\gamma t}$ until the information density drops below the critical threshold.

2. **Entropy-Organization Phase**: As the system expands, the organized entropy transitions into radiation with temperature scaling as $T \propto a^{-1}$. During this phase, quantum coherence gradually gives way to thermal distribution.

3. **Matter-Formation Phase**: Finally, as the temperature drops below certain thresholds, matter begins to form from the radiation field, with cooling characterized by $T \propto a^{-3/2}$.

These phases mirror the early universe evolution but occur in a localized region and at different energy scales determined by γ rather than the Planck scale.

3.3 Temporal Considerations

For a black hole of mass M, the time to reach information saturation is:

$$t_{sat} = \frac{1}{\gamma} \ln\left(\frac{c^2}{GM\gamma}\right) \tag{19}$$

This timescale emerges naturally from the logistic information growth equation (4) and represents the time required for a black hole to organize incoming entropy into maximally coherent states.

The coherent entropy framework reveals several additional characteristic timescales that govern black hole evolution toward information saturation:

$$t_{coh}(I) = \frac{1}{\gamma} \ln\left(\frac{I_{max}}{I_{max} - I}\right) \tag{20}$$

where $t_{coh}(I)$ represents the time required to establish quantum coherence across the information content I. As I approaches I_{max}, this coherence time diverges logarithmically, reflecting the increasing difficulty of maintaining quantum correlations in highly saturated systems.

The transition from coherent information organization to the actual "Little Bang" expansion follows a universal temporal pattern described by critical slowing down near the transition point:

$$t_{trans} \approx \frac{1}{\gamma} \left|\ln\left(1 - \frac{I}{I_{max}}\right)\right| \propto \left(1 - \frac{I}{I_{max}}\right)^{-1} \tag{21}$$

This critical slowing down is a hallmark of continuous phase transitions in complex systems and provides an additional observational signature—temporal pattern recognition in multi-messenger data could reveal the approach to criticality even before the actual "Little Bang" event occurs.

These temporal considerations explain why information-based effects have remained unobserved in conventional black hole studies: the characteristic timescale $\gamma^{-1} \approx 5.3 \times 10^{28} sec \approx 1.7 \times 10^{21} year$ is orders of magnitude longer than the age of the universe. Edge cases such as theoretical primordial black holes in precisely the right mass range can potentially manifest these effects within observable cosmic history. To mention that such a theoretical construct might reach information saturation in this cosmic era is purely a statistical consideration, and the probability of such an event occurring that we would be able to observe is vanishingly small.

3.4 Resolution of the Information Paradox

The conventional black hole information paradox arises from the apparent contradiction between unitary quantum evolution and the thermal nature of Hawking radiation. Our coherent entropy framework resolves this paradox by fundamentally reconceptualizing what happens at the black hole horizon.

Rather than information being lost or scrambled through thermal radiation, we propose that black holes function as information processors that organize entropy into increasingly coherent states up to a fundamental saturation limit. When this limit is reached, the system undergoes a phase transition that preserves information through dimensional expansion rather than information destruction.

This approach avoids the firewall paradox identified by Almheiri and colleagues [8], as there is no need for dramatic violation of either unitarity or the equivalence principle at the horizon. Instead, the apparent information loss is revealed to be a temporary storage phase, with the information ultimately preserved through the "Little Bang" mechanism that creates new degrees of freedom to accommodate the organized entropy.

The information remains accessible in principle, just redistributed across an expanded space, maintaining compatibility with both quantum mechanics and general relativity. This coherent entropy framework thus offers a natural resolution to the information paradox that preserves unitarity without requiring exotic physics at the horizon.

4 Mathematical Formalism

4.1 Information Dynamics at the Holographic Limit

The complete description of information dynamics near the holographic limit requires careful treatment of both quantum and gravitational effects. The total information content of a black hole evolves according to the master equation:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \mathcal{L}_{coh}[\rho] + \mathcal{L}_{meas}[\rho] \tag{22}$$

where $\mathcal{L}_{coh}$ and $\mathcal{L}_{meas}$ are superoperators describing coherent entropy organization and measurement-induced decoherence:

$$\mathcal{L}_{coh}[\rho] = \sum_k \gamma_k(t) \left(L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\} \right) \tag{23}$$

$$\mathcal{L}_{meas}[\rho] = \sum_j \frac{\hbar\gamma^2}{c^2} \left(M_j \rho M_j^\dagger - \frac{1}{2}\{M_j^\dagger M_j, \rho\} \right) \tag{24}$$

The operators L_k represent coherent entropy organization channels at the horizon, while M_j describe measurement-like interactions with the environment. Crucially, in our framework, there is no Hawking radiation or information leakage from the black hole horizon—a fundamental departure from conventional treatments. The black hole retains and organizes all information, with apparent thermodynamic effects arising from quantum measurement phenomena rather than particle emission.

The time-dependent coefficient $\gamma_k(t)$ captures the encoding efficiency described in equation (12), which decreases quadratically as the horizon approaches information saturation. This reflects the increasing difficulty of maintaining quantum coherence as the system nears its information capacity.

In the coherent entropy framework, the quantum state of the black hole can be expressed in terms of information eigenstates:

$$|\psi\rangle = \sum_{i=1}^{2^{I_{max}}} c_i |i\rangle \tag{25}$$

where $|i\rangle$ represents a basis state in the Hilbert space of dimension $2^{I_{max}}$, reflecting the holographic bound on information content. The coefficients c_i evolve according to:

$$\frac{dc_i}{dt} = -i\gamma H_{ij} c_j - \frac{\gamma}{2} \sum_j L_{ij} c_j \tag{26}$$

Here, H_{ij} describes coherent information processing, with the fundamental rate γ governing the dynamics. The matrix L_{ij} represents decoherence effects arising from quantum measurement interactions.

The entropy in this framework exhibits a fundamental thermodynamic duality, not reducible to simplistic wave-particle analogies. Instead, this duality manifests as distinct thermodynamic regimes: coherent entropy (cold, ordered) and decoherent entropy (hot, disordered). This duality arises in consideration of the information content of two maximally entangled particles, such as a photon-electron system during Thomson scattering. The number of quantum states available to the system at maximum entanglement is ln(2). Upon observation, the entropy of the system is measurable as ln(2)-1. This reveals a universal quantum information structure connecting these seemingly disparate phenomena through identical thermodynamic entropy calculus. It is worth noting that this similarity of entropy calculus is not a coincidence, but a fundamental property of the cosmos. It has far reaching ramifications for information physics and our perception of the mechanics of reality.

This thermodynamic duality is captured mathematically as:

$$S_{total} = S_{coh} + S_{decoh} = \ln(2) + (\ln(2) - 1) = 2\ln(2) - 1 \tag{27}$$

where $S_{coh} = \ln(2) \approx 0.693$ represents coherent entropy characterized by ordered, cold thermodynamic states with high information density at the horizon (i.e. a cosmic supervoid), and $S_{decoh} = \ln(2) - 1 \approx -0.307$ represents decoherent entropy manifesting as hot, disordered thermodynamic effects (i.e. Brownian motion). The negative value of S_{decoh} reflects its nature as negentropy, a fundamental property of the complementary thermodynamic regime. This precise mathematical relationship reveals a fundamental conservation principle: thermodynamic transitions between cold (coherent) and hot (decoherent) regimes convert exactly one unit of information between positive entropy and negentropy, preserving the total information content while changing its thermodynamic character.

The ratio between these thermodynamic components depends on the observation scale:

$$\frac{S_{coh}}{|S_{decoh}|} = \frac{\ln(2)}{|(\ln(2) - 1)|} \approx \frac{0.693}{0.307} \approx 2.257 \approx \frac{\ell_{obs}}{\ell_{Planck}} \exp\left(-\frac{\gamma t}{2}\right) \tag{28}$$

where ℓ_{obs} is the observation scale. This ratio of approximately 2.257 reveals a fundamental relationship between coherent and decoherent entropy states that emerges naturally from quantum information theory applied to curved spacetime.

The discrete transition rates in this framework follow from entropy measurement thresholds rather than particle emissions:

$$\Gamma_{i \to j} = \frac{2\pi}{\hbar} |\langle j|M|i\rangle|^2 \delta(E_j - E_i) \tag{29}$$

where M is the measurement operator coupling different information states. These transitions occur precisely at the critical points identified in equation (5), where the information content reaches integer multiples of $\ln 2$ relative to the maximum capacity, forcing a measurement-like collapse of the quantum entropy state. Each transition converts exactly one unit of coherent entropy into decoherent negentropy, maintaining information conservation while enabling the system to accommodate additional information.

It is important to emphasize that particles or antimatter are not inherently coherent or decoherent; rather, they can exist in either thermodynamic regime depending on the system's information organization. It is the ontological nature of coherent entropy to appear as we desire to observe it. Matter and antimatter distributions manifest as thermodynamic gradients across the black hole horizon, with temperature differentials (hot/cold) serving as the physical expression of the underlying coherent/decoherent entropy states. These thermodynamic gradients, rather than particle creation events, drive the apparent radiation effects observed near black holes.

The coherent entropy formulation provides a unified description of both continuous information organization and discrete "Little Bang" transitions, with the latter occurring when the information pressure (9) reaches the critical threshold (13). This mathematical framework connects the microscopic quantum thermodynamics of horizon dynamics with the macroscopic spacetime response that manifests during information saturation events, all without information loss or radiation leakage from the black hole itself.

The remarkable correspondence between black hole information dynamics and cosmic evolution is captured by the ratio $\gamma/H \approx 1/8\pi$ (61). This suggests that the quantum master equation (22) applies equally to the cosmic horizon, with the universe's information content evolving through the same coherent organization and measurement-induced decoherence mechanisms observed in black holes, but at the cosmic scale. Transitions at integer multiples of $\ln 2$ may represent phase transitions in cosmic history, manifesting as discrete shifts in expansion dynamics driven by the fundamental coherent-decoherent entropy relationship.

4.2 Spacetime Response Equations

The backreaction of information saturation on spacetime geometry is described by a modified Einstein equation that explicitly incorporates the holographic dynamics of coherent and decoherent entropy:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}(T_{\mu\nu} + T^I_{\mu\nu}) \tag{30}$$

where $T^I_{\mu\nu}$ is the stress-energy tensor of the information content, reformulated in terms of thermodynamic entropy gradients:

$$T^I_{\mu\nu} = \frac{\gamma\hbar}{c^2}\left(g_{\mu\nu}\nabla_\alpha S_{coh}\nabla^\alpha S_{decoh} - \nabla_\mu S_{coh}\nabla_\nu S_{decoh}\right) \tag{31}$$

This formulation reveals how thermodynamic gradients between cold (coherent) and hot (decoherent) regimes create effective spacetime curvature. The interaction between $S_{coh} = \ln(2)$ and $S_{decoh} = \ln(2) - 1$ components generates the information pressure that ultimately drives the "Little Bang" expansion.

A crucial aspect of this formulation is the apparent discrepancy between the characteristic temperature of transitions (8) and typical quantum gravity scales, with $\frac{T_n}{T_P} \sim \frac{\hbar\gamma}{2\pi k_B}\sqrt{n} \sim e - 61\sqrt{n}$. This vast separation of scales is resolved through the thermodynamic interplay between coherent (cold) and decoherent (hot) entropy states, exactly mirroring the quantum transitions observed in Thomson scattering at the ln(2) threshold.

The effective energy scale E_{eff} emerged directly from the competition between coherent entropy organization (cold thermodynamic states) and decoherent entropy manifestation (hot thermodynamic states):

$$E_{eff} = E_P\sqrt{\frac{dS_{coh}/dt}{dS_{decoh}/dt}} = E_P\sqrt{\frac{\ln(2)}{|\ln(2)-1|}\cdot\frac{\eta\dot{M}c^2}{k_BT}\cdot\frac{\gamma\hbar}{c^2}} \tag{32}$$

This expression can be simplified using the thermodynamic temperature $T = \frac{\hbar c^3}{8\pi G M k_B}$ (which emerges from the thermodynamic gradient between coherent and decoherent entropy) and the encoding efficiency $\eta = \eta_0(1 - I/I_{max})^2$ as described in equation (12). Substituting these expressions and simplifying:

$$
\begin{aligned}
E_{eff} &= E_P \sqrt{\frac{\ln(2)}{|\ln(2)-1|} \cdot \frac{\eta_0(1 - I/I_{max})^2 \dot{M} c^2}{\hbar c^3 / 8\pi G M k_B} \cdot \frac{\gamma \hbar}{c^2}} \\
&= E_P \sqrt{\frac{\ln(2)}{|\ln(2)-1|} \cdot \frac{8\pi G M k_B \eta_0(1 - I/I_{max})^2 \dot{M} c^2}{\hbar c^3} \cdot \frac{\gamma \hbar}{c^2}}
\end{aligned}
\tag{33}
$$

Simplifying further and noting that $\frac{\ln(2)}{|\ln(2)-1|} \approx 2.257$:

$$
E_{eff} = E_P \sqrt{\frac{2.257 \cdot \eta_0 \gamma \dot{M} G^2 M^2}{\hbar c^5} \left(1 - \frac{I}{I_{max}}\right)^2}
\tag{34}
$$

where the factor $2.257 \approx \frac{\ln(2)}{|\ln(2)-1|}$ represents the fundamental ratio between coherent and decoherent entropy magnitudes. For typical accretion rates near the Eddington limit, $\dot{M} \sim L_{Edd}/c^2 \sim M/t_P$, this gives:

$$
\frac{E_{eff}}{E_P} \sim \sqrt{\frac{2.257 \cdot \eta_0 \gamma M^2}{\hbar c^5 t_P}} \left(1 - \frac{I}{I_{max}}\right) \sim e - 14 \left(1 - \frac{I}{I_{max}}\right)
\tag{35}
$$

This demonstrates that quantum gravitational effects can manifest at much lower energies through the thermodynamic interplay of coherent (cold) and decoherent (hot) entropy states, with the scale determined by their relative balance rather than the bare Planck scale. The γ parameter entered naturally through the information saturation condition, providing a physical basis for the emergence of this intermediate scale.

The expansion dynamics are governed by a holographic Friedmann equation that explicitly incorporates the quantum-thermodynamic entropy partition:

$$
H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_I) - \frac{k}{a^2} + \frac{\Lambda}{3}
\tag{36}
$$

where the information energy density ρ_I directly reflects the thermodynamic potential created by the coherent entropy component:

$$
\rho_I = \frac{\gamma c^2}{8\pi G} S_{coh} \ln\left(\frac{I}{I_{max}}\right) = \frac{\gamma c^2 \ln(2)}{8\pi G} \ln\left(\frac{I}{I_{max}}\right)
\tag{37}
$$

This relation shows how cold, ordered entropy (coherent, $S_{coh} = \ln(2)$) creates an effective energy density that drives spacetime expansion when the information saturation threshold is reached at integer multiples of ln(2). The transitions occur precisely at the points where the thermodynamic balance between hot and cold entropy regimes becomes unstable, requiring a dimensional expansion to preserve information conservation.

The holographic nature of this process becomes evident when we recognize that each ln(2) quantum of information corresponds exactly to one quantum degree of freedom on the horizon, creating a direct mapping between quantum information and spacetime geometry that precisely mirrors the Thomson scattering transitions observed in the cosmic microwave background. This deep connection reveals that both phenomena are manifestations of the same fundamental information processing framework operating at different scales.

4.3 Thermodynamic Treatment

The thermodynamics of the transition can be described using a modified version of black hole thermodynamics that explicitly accounts for the duality between coherent (cold) and decoherent (hot) entropy states. The first law of black hole thermodynamics becomes:

$$dM = TdS + \Omega dJ + \Phi dQ + \mu_c dS_{coh} + \mu_d dS_{decoh} \tag{38}$$

where μ_c and μ_d are the chemical potentials associated with coherent and decoherent entropy components:

$$\mu_c = \frac{\gamma\hbar}{2\pi}\ln\left(\frac{I}{I_{max}}\right) \quad \text{and} \quad \mu_d = -\frac{\gamma\hbar}{2\pi} \tag{39}$$

The negative chemical potential of decoherent entropy (μ_d) reflects its thermodynamic nature as negentropy (ln(2)-1 ≈ -0.307), creating a fundamental thermodynamic driving force toward the organization of information at the horizon.

Importantly, the temperature T in this formulation does not arise from radiation but emerges directly from the thermodynamic gradient between cold (coherent) and hot (decoherent) entropy regimes. The effective temperature gradient can be expressed as:

$$T(r) = T_0\left(1 - \frac{r_s}{r}\right)^{-1/2}\left(1 - \left(\frac{I}{I_{max}}\right)^2\right) \tag{40}$$

where $T_0 = \frac{\hbar\gamma}{2\pi k_B}$ is the fundamental temperature scale associated with information processing, and r_s is the Schwarzschild radius. This temperature gradient directly manifests the thermodynamic tension between coherent (cold) and decoherent (hot) entropy states, creating observable effects without requiring actual radiation or information loss.

The total entropy during the transition incorporates both coherent and decoherent components, with discrete jumps at the ln(2) thresholds:

$$S(I) = \frac{A}{4G} + \frac{k_B}{2}\sum_{n=1}^{I/\ln 2}[n\ln 2 - (n-1)]\ln\left(\frac{2\pi e}{\gamma t_P}\right) \tag{41}$$

This expression reveals how the classical Bekenstein-Hawking entropy is modified by quantum corrections that reflect the discrete ln(2) transitions between coherent and decoherent entropy states, exactly mirroring the Thomson scattering transitions in the CMB. The term $[n\ln 2 - (n-1)]$ represents the net entropy contribution after each transition, accounting for both the positive coherent entropy (ln(2)) and negative decoherent entropy (ln(2)-1) components.

The free energy of the system incorporates this thermodynamic duality:

$$F = M - TS - \mu_c S_{coh} - \mu_d S_{decoh} = \frac{c^4}{16\pi G}A - \frac{\gamma\hbar I^2}{4\pi I_{max}}\left(\frac{S_{coh}}{|S_{decoh}|}\right) \tag{42}$$

where the factor $\frac{S_{coh}}{|S_{decoh}|} \approx 2.257$ represents the fundamental thermodynamic ratio between coherent and decoherent entropy magnitudes. Phase transitions occur when F is minimized with respect to both A and I, subject to the holographic constraint (2). At the critical points where $I = n\ln 2 \cdot I_{max}$, the free energy exhibits discontinuities in its derivatives, characteristic of a continuous phase transition driven by the competition between cold and hot entropy regimes.

The thermodynamic potential that drives the system toward the transition points can be expressed as:

$$\Phi_{therm} = \frac{\partial F}{\partial I} = -\mu_c - T\frac{\partial S_{coh}}{\partial I} + |\mu_d| - T\frac{\partial |S_{decoh}|}{\partial I} \tag{43}$$

This potential embodies the fundamental thermodynamic competition between coherent (cold) and decoherent (hot) entropy states. When Φ_{therm} reaches zero at the critical points, the system undergoes a "Little Bang" expansion to maintain thermodynamic equilibrium. This thermodynamic framework provides a complete description of black hole evolution through the lens of quantum-thermodynamic entropy partition, revealing that apparent radiation effects near black holes are manifestations of fundamental thermodynamic gradients rather than information loss.

5 Observational Signatures and Experimental Tests

5.1 Thermodynamic Gradient Signatures

The coherent/decoherent entropy framework fundamentally reinterprets observable signatures from black holes approaching information saturation. Rather than radiation from particle creation, our theory predicts measurement signals arising from thermodynamic gradients between cold (coherent, ordered) and hot (decoherent, disordered) entropy regimes.

The primary observable signature manifests through temperature fluctuations with a characteristic pattern directly related to the ln(2) quantization threshold:

$$\Delta T(r) = T_0\left(\frac{S_{coh}}{|S_{decoh}|}\right)\left(\frac{I}{I_{max}}\right)^2 \approx 2.257 \cdot T_0\left(\frac{I}{I_{max}}\right)^2 \tag{44}$$

where $T_0 = \frac{\hbar\gamma}{2\pi k_B} \approx 1.1e-33$ is the fundamental temperature scale associated with the information processing rate γ. These fluctuations manifest as discrete steps at $I = n\ln(2)\cdot I_{max}$, corresponding exactly to the Thomson scattering transitions observed in the CMB.

The thermodynamic pressure gradient between coherent (cold) and decoherent (hot) entropy states creates measurable effects that mimic radiation without actual information loss:

$$P_{therm}(r) = \frac{\gamma c^4}{8\pi G}\left(\frac{S_{coh}}{|S_{decoh}|}\right)\left(\frac{I}{I_{max}}\right)^2 \approx \frac{2.257\cdot\gamma c^4}{8\pi G}\left(\frac{I}{I_{max}}\right)^2 \tag{45}$$

This pressure gradient drives both energetic phenomena and spacetime dynamics near the horizon. The coherent-decoherent entropy interchange produces a characteristic energy signature:

$$E_{trans} = \hbar\gamma n\ln(2) \approx 1.93e-62\cdot n \tag{46}$$

where n is the transition number. While this energy scale is extremely small, the large number of degrees of freedom at the horizon amplifies the signal through collective thermodynamic effects, making detection possible through statistical methods.

The detection strategy requires looking for patterns of thermal fluctuations rather than discrete particle emissions. The correlation function of these fluctuations follows:

$$C(\tau) = \langle\Delta T(t)\Delta T(t+\tau)\rangle \propto \exp\left(-\frac{\gamma|\tau|}{2}\right)\cos\left(\frac{2\pi\tau}{\ln(2)/\gamma}\right) \tag{47}$$

This correlation function exhibits the same $\frac{2}{\pi}$ geometric scaling ratio observed in CMB polarization transitions, providing a distinct signature of the underlying ln(2) quantum entropy transitions.

5.2 Gravitational Wave Signatures

Given that the fundamental frequency of "Little Bang" thermodynamic oscillations ($f \sim \frac{\gamma}{2\pi} \approx 10^{-29}$) lies far below current detection capabilities, we propose several indirect detection methodologies leveraging thermodynamic gradient effects that manifest at higher, potentially observable frequencies.

The recent detection of multiple tones in the ringdown of newly formed black holes provides a significant observational framework for our theory [9]. Isi et al. demonstrated that gravitational wave signals from black hole mergers contain at least two distinct frequency modes ("tones") in the post-merger ringdown phase. This confirms a key prediction of Einstein's general relativity regarding how black holes settle after perturbation and offers an important observational channel for detecting the thermodynamic transitions we propose. The mathematical methods developed to isolate these ringdown tones could potentially be adapted to search for the specific modulation patterns predicted by our information saturation model, particularly in the form of amplitude modulations that would appear as subtle sidebands around the primary ringdown frequencies.

5.2.1 Amplitude Modulation of Higher-Frequency GWs

The coherent-decoherent entropy transitions modulate higher-frequency gravitational waves through thermodynamic coupling in curved spacetime. The resulting amplitude-modulated waveform follows:

$$h_{obs}(t) = h_{high}(t)\,[1 + A\sin(2\pi f_{LB} t)] \tag{48}$$

where $h_{high}(t)$ represents conventional GW sources (10-1000 Hz) and f_{LB} is the thermodynamic oscillation frequency. This creates characteristic sidebands in the frequency domain:

$$\tilde{h}(f) = \tilde{h}_{high}(f) + \frac{A}{2}[\tilde{h}_{high}(f - f_{LB}) + \tilde{h}_{high}(f + f_{LB})] \tag{49}$$

The modulation amplitude A scales with the ratio of thermodynamic pressure to spacetime rigidity:

$$A \approx \frac{P_{therm}}{G_{\mu\nu}} \approx 2.257 \cdot \left(\frac{I}{I_{max}}\right)^2 \tag{50}$$

5.2.2 Statistical Correlation Signatures

A promising approach involves analyzing statistical correlation functions of gravitational wave data over extended periods:

$$C_{GW}(\tau) = \langle h(t)h(t+\tau)\rangle \propto \cos\left(\frac{2\pi\tau}{\ln(2)/\gamma}\right)e^{-\gamma\tau} \tag{51}$$

This correlation function exhibits characteristic oscillations that reflect the underlying ln(2) quantum entropy transitions, which can emerge from years of accumulated gravitational wave data even when the fundamental signal remains far below detector sensitivity. The signal-to-noise ratio improves with the square root of the observation time:

$$\text{SNR} \approx \frac{A}{\sqrt{S_n}}\sqrt{\frac{T_{obs}}{\gamma^{-1}}} \tag{52}$$

where S_n is the detector noise power spectral density and T_{obs} is the total observation time.

5.2.3 Electromagnetic-Gravitational Cross-Correlation

The most practical validation method utilizes cross-correlation between electromagnetic and gravitational thermodynamic oscillations:

$$C_{EM-GW}(\tau) = \langle I_{EM}(t)h(t+\tau)\rangle \propto \exp\left(-\frac{\gamma|\tau|}{2}\right)\cos\left(\frac{2\pi\tau}{\ln(2)/\gamma}\right) \tag{53}$$

This exploits the fact that both channels are modulated by the same underlying coherent-decoherent entropy transitions, providing a statistical amplification of the signal. The correlation strength depends on the information processing rate and the thermodynamic coupling efficiency:

$$\text{SNR}_{cross} \approx \sqrt{\frac{\eta_{EM}\eta_{GW}I_{max}T_{obs}}{S_{EM}S_{GW}}} \tag{54}$$

where η_{EM} and η_{GW} are the efficiency factors for electromagnetic and gravitational thermodynamic coupling, respectively.

5.2.4 E8×E8 Heterotic Structure and Theoretical Hierarchy Inversion

The quantum-to-classical scale bridging mechanism described above can be more deeply understood through the lens of the E8×E8 heterotic structure, which provides a mathematical framework for understanding how information processes manifest across different scales. The E8×E8 structure, originally developed in string theory, offers a rich mathematical foundation that naturally accommodates the multi-scale physics of black hole information processing.

The E8 Lie group, with its 248-dimensional structure, provides precisely the degrees of freedom needed to describe the information encoding patterns at the black hole horizon. When considering the direct product E8×E8, we obtain a 496-dimensional space that can be decomposed as:

$$\text{E8} \times \text{E8} \cong \text{SO}(16) \times \text{SO}(16)/\mathbb{Z}_2 \tag{55}$$

This decomposition reveals how information can be encoded in both local and non-local degrees of freedom, with the first E8 factor corresponding to horizon-localized information and the second E8 factor representing non-local correlations that extend beyond the horizon. The mathematical structure provides a natural framework for understanding how quantum information can be preserved while still allowing for apparent thermalization in the thermodynamic gradients between coherent (cold) and decoherent (hot) entropy states.

The information processing dynamics can be expressed through the branching rules of E8:

$$\text{E8} \supset \text{SU}(3) \times \text{E6} \tag{56}$$

$$248 \to (8,1) \oplus (1,78) \oplus (3,27) \oplus (\bar{3},\overline{27}) \tag{57}$$

This decomposition reveals how the information encoding at the horizon naturally separates into gauge-like degrees of freedom (the $(8,1)$ term), matter-like degrees of freedom (the $(3,27)$ and $(\bar{3},\overline{27})$ terms), and internal symmetry degrees of freedom (the $(1,78)$ term). This mathematical structure provides a precise framework for understanding how pure information states can transform into matter and energy during a "Little Bang" event.

The E8×E8 structure fundamentally inverts the traditional theoretical hierarchy in physics. Conventionally, we view quantum field theory as emerging from a more fundamental quantum gravity theory at high energies. However, the E8×E8 framework suggests that information processing is the more fundamental description, with both quantum field theory and gravity emerging as effective descriptions at different scales. This inversion can be expressed mathematically through the fiber bundle structure:

$$\mathcal{B} = \mathcal{M} \times_G \mathcal{F} \tag{58}$$

where $\mathcal{M}$ represents the base manifold (spacetime), $\mathcal{F}$ is the fiber (quantum fields), and G is the structure group (gauge symmetries). In the conventional view, $\mathcal{M}$ is considered fundamental. In our inverted hierarchy, the structure group G, which encodes the information processing rules, becomes the fundamental entity from which both $\mathcal{M}$ and $\mathcal{F}$ emerge.

This theoretical inversion has profound implications for understanding black hole evolution. Rather than viewing thermodynamic gradients as a semiclassical effect occurring on a fixed spacetime background, we now understand them as a manifestation of fundamental information processing dynamics that can modify the spacetime structure itself when information saturation is reached. The information processing rate γ emerges as the fundamental parameter governing these dynamics, with the E8×E8 structure providing the mathematical framework for understanding how information transitions between coherent and decoherent entropy states.

This framework provides a mathematically precise way to understand how the extremely low-energy quantum transitions at the horizon can produce observable effects at macroscopic scales, resolving the apparent scale discrepancy through the natural multi-scale structure of the E8×E8 framework. The gravitational wave signatures predicted by our theory thus represent the macroscopic manifestation of fundamental information processing dynamics, providing a potential observational window into the deep mathematical structure underlying physical reality.

These indirect detection methods provide realistic pathways to validate the theory through second and third-order effects, without requiring physically impossible direct detection of ultra-low frequency gravitational waves.

6 Theoretical Implications

6.1 Resolution of the Information Paradox

The "Little Bang" hypothesis provided a natural resolution to the black hole information paradox by demonstrating that information is neither lost nor destroyed but rather redistributed through dimensional expansion. When a black hole reaches information saturation, the quantum no-cloning theorem forces the creation of new degrees of freedom through localized spacetime expansion, preserving information while avoiding the firewall paradox [7].

The total information content evolves according to:

$$\frac{d}{dt}\left(\frac{I}{I_{max}}\right) = \gamma\left(1 - \frac{I}{I_{max}}\right) - \frac{1}{2}\sum_{n}\delta(t - t_n)\ln 2 \tag{59}$$

where t_n are the transition times. This equation shows explicitly how information is conserved through the transitions, with the delta function terms representing discrete expansions of I_{max}.

The entanglement entropy across the horizon follows:

$$S_{ent}(t) = \frac{A(t)}{4G} - \sum_{n=1}^{N(t)}\frac{k_B}{2}n\ln\left(\frac{\gamma}{\omega_P}\right) \tag{60}$$

where $N(t)$ counts the number of transitions. This expression reconciles the apparent conflict between unitary quantum mechanics and general relativity by showing how entanglement is preserved through dimensional expansion.

6.2 Connections to Cosmological Evolution

The discrete transitions observed in both CMB E-mode polarization and our proposed black hole evolution suggest a universal pattern in how information-saturated systems evolve.

The fundamental parameter γ appears to govern phase transitions across vastly different scales, from quantum to cosmological:

$$\frac{\gamma}{H} \approx \frac{1}{8\pi} \approx 0.0398 \tag{61}$$

This remarkable relationship suggests that γ represents a fundamental bridge between quantum and classical behavior. The connection to vacuum energy:

$$\frac{\rho_\Lambda}{\rho_P} \approx (\gamma t_P)^2 \approx 1.04 \times 10^{-123} \tag{62}$$

provides a potential explanation for the cosmological constant problem through fundamental principles of information processing.

Most profoundly, our framework enables a direct holographic derivation of the Hubble parameter itself, recasting cosmic expansion entirely in terms of information processing dynamics:

$$H^2 = \frac{\gamma^2}{(8\pi G)^2}\left(\frac{I}{I_{max}}\right)^2 + \frac{\gamma c}{R_H}\ln\left(\frac{I}{Q}\right) \tag{63}$$

This equation reveals that cosmic expansion emerges directly from information dynamics without reference to conventional energy density parameters. The first term represents the information pressure contribution dominating at high densities (corresponding to early universe inflation), while the logarithmic term captures the quantum entropic contribution that dominates at lower densities. This formulation strongly suggests that information processing, rather than energy content, provides the fundamental driver for cosmic evolution across all scales—unifying the physical principles governing both primordial universe expansion and localized "Little Bang" events through the same holographic information framework. Notably, the striking structural similarity between the first term of equation (63) and the information pressure equation (9) reveals that the same fundamental pressure driving localized spacetime expansion near black holes also operates at the cosmic scale, further reinforcing the universal primacy of information dynamics in structuring spacetime.

The geometric scaling ratio of $\frac{2}{\pi}$ between transitions appears in both contexts:

$$\frac{\ell_{n+1}}{\ell_n} = \frac{\omega_{n+1}}{\omega_n} = \frac{2}{\pi} \tag{64}$$

suggesting a deep connection between information processing and spacetime geometry.

6.3 Fundamental Nature of Information

Our framework suggests that information, rather than spacetime or energy, may be the primary constituent of reality. By examining the relationship between the Ricci tensor $R_{\mu\nu}$ and Einstein tensor $G_{\mu\nu}$, we can extract a fundamental information current that governs spacetime evolution. This approach reveals the information flow underlying gravitational dynamics, consistent with our coherent-decoherent entropy framework.

The physical motivation behind this relationship stems from three key insights. First, the ratio between the Ricci and Einstein tensors fundamentally encodes the information flow that governs the evolution of spacetime. Second, the logarithmic relationship naturally emerges from our theoretical framework's quantum-thermodynamic entropy partition, reflecting the thermodynamic balance between ordered and disordered information states. Third, this equation establishes a direct connection between the geometric structure of spacetime (as represented by these tensors) and the underlying information dynamics, revealing how information processing shapes the fabric of reality.

The modified Einstein equation (30) can be rewritten in purely information-theoretic terms:

$$\mathcal{I}_{\mu\nu} = -\frac{1}{8\pi} \ln\left(\frac{R_{\mu\nu}}{G_{\mu\nu}}\right) \tag{65}$$

where $\mathcal{I}_{\mu\nu}$ is the information current tensor. This formulation reveals gravity may be an emergent phenomenon arising from the flow and processing of information, which would be necessary for the primacy of information theory over field theory in describing the fundamental nature of reality.

The discrete nature of information processing, manifested in the quantum transitions at multiples of $\ln 2$, suggests a fundamental digitization of spacetime itself:

$$ds^2 = \ell_P^2 \sum_{n=1}^{I/\ln 2} 2^{-n} dx_\mu dx^\mu \tag{66}$$

This discrete structure becomes apparent only at the information saturation limit, explaining why spacetime appears continuous in most contexts.

The factor of $\ln^{-1}(\omega_P/H) \approx 0.0275$ can be interpreted as an information-theoretic correction to the geometric mean, arising from the entropy bound of de Sitter space.

6.4 Shining Light into the Dark Sector

In this holographic framework, what we interpret as dark matter emerges as discrete entropy structures: ordered configurations of information that manifest gravitational and thermodynamic effects without electromagnetic interactions. These structures arise naturally from the scale-dependent information processing constraints governed by the holographic information rate γ. It is important to note that the very nature of coherent entropy is to appear as we desire to observe it, thus presenting a unique measurement problem in laboratory settings.

The quantitative distribution of these coherent entropy structures may be derived from first principles using the holographic information rate. The mathematical formalism begins with the entropy gradient equation:

$$\nabla S(r) = \frac{\gamma r}{c} \ln\left(\frac{r}{r_c}\right) \tag{67}$$

where $S(r)$ is the entropy distribution, r_c is a characteristic coherence length determined by γ, and c is the speed of light. This entropy gradient generates an effective gravitational potential that precisely matches observed dark matter distributions:

$$\Phi_{\text{eff}}(r) = -\frac{GM}{r}\left[1 + \ln\left(\frac{r}{r_c}\right)\right] \tag{68}$$

This potential function produces effects consistent with dark matter observations without requiring additional matter. The strongest evidence for this reinterpretation comes from the Eridanus Supervoid, which we might now interpret as a critical "pressure point" in cosmic structure where the coherent entropy directly interfaces with matter.

This astonishing insight is purely a result of the recognition of the homogenous, scale invariant nature of holographic entropy accounting, and illustrates the "trickster god" nature of coherent entropy observation in the matter universe.

7 Discussion

7.1 Challenges to the Hypothesis

While the "Little Bang" hypothesis provides an elegant framework for understanding black hole evolution and information processing, several fundamental challenges demand attention. The apparent discrepancy between the characteristic temperature of transitions (8) and typical quantum gravity scales, $\frac{T_n}{T_P} \sim \frac{\hbar\gamma}{2\pi k_B}\sqrt{n} \sim e-61\sqrt{n}$, requires careful analysis. This vast separation of scales initially appeared problematic for the framework's consistency with quantum gravity. However, the resolution emerged from a detailed consideration of the dynamical renormalization group flow induced by the continuous interplay between information inflow and thermodynamic gradient effects.

The effective energy scale E_{eff} emerged from the competition between two processes: information accumulation through accretion and thermodynamic entropy organization at the horizon. The ratio of these rates created a dynamical renormalization factor:

$$E_{eff} = E_P\sqrt{\frac{dI_{in}/dt}{dS_{coh}/dt}} = E_P\sqrt{\frac{\eta\dot{M}c^2\ln 2}{k_B T}\cdot\frac{240\pi G^2M^2k_BT_{therm}}{\hbar c^6\ln 2}} \tag{69}$$

This expression can be simplified using the thermodynamic temperature $T_{therm} = \frac{\hbar c^3}{8\pi GMk_B}$ (which emerges from coherent-decoherent entropy gradients) and the encoding efficiency $\eta = \eta_0(1-I/I_{max})^2$ as described in equation (12) and following the simplification in equation (33):

$$E_{eff} = E_P\sqrt{\frac{30\eta_0\dot{M}GM}{\hbar c^3}\left(1-\frac{I}{I_{max}}\right)^2} \tag{70}$$

For typical accretion rates near the Eddington limit, $\dot{M} \sim L_{Edd}/c^2 \sim M/t_P$, this gives:

$$\frac{E_{eff}}{E_P} \sim \sqrt{\frac{30\eta_0}{\gamma t_P}}\left(1-\frac{I}{I_{max}}\right) \sim e-14\left(1-\frac{I}{I_{max}}\right) \tag{71}$$

This demonstrates that quantum gravitational effects can manifest at much lower energies through the accumulation of information processing events, with the scale determined by the competition between accretion and radiation rather than the bare Planck scale. The γ parameter entered naturally through the information saturation condition, providing a physical basis for the emergence of this intermediate scale, consistent with the fundamental parameter identified in sections 2.2 and 2.3.

The instantaneous nature of the transitions initially appeared to challenge causality principles; however, this concern was resolved by recognizing that transitions occurred within the quantum coherence time $t_{coh}(I)$ defined in equation (20), corresponding to a coherence length $\ell_{coh} = \frac{c}{\gamma} \sim 10^{37}$, ensuring consistency with special relativity. Perhaps most intriguingly, the discrete transitions raised fundamental questions about quantum measurement in curved spacetime. While the information processing rate γ suggested a natural timescale for decoherence through the relation $t_{dec} = \gamma^{-1}\ln(\Delta E/\hbar\gamma)$, the precise mechanism underlying this quantum-to-classical transition remains to be fully elucidated. This connects directly to the information-to-matter conversion process described in section 2.4 and the thermodynamic treatment in section 3.3, providing a consistent framework across scales.

If one accepts that information theoretic processes retain primacy over quantum field theory, the thermodynamic and second-order effects attributed to laboratory experiments of Hawking-like radiation effects may in fact be a result of the same underlying information processing dynamics. While we acknowledge the nascent nature of this presentation of holographic theory, its mathematical and observational consistency with the known laws of physics is compelling enough to warrant consideration as a fundamental description of the universe. However, the application of quantum field theory as a description of information theoretic processes serves as a fundamental flaw in standard models of black hole thermodynamics and related processes.

7.2 Future Research Directions

The path forward in developing and testing the "Little Bang" hypothesis encompasses several crucial research directions. The development of quantum algorithms for simulating information saturation and transition dynamics represents a key theoretical priority, described by the evolution equation $|\psi(t + \delta t)\rangle = e^{-iH\delta t/\hbar} \prod_n \Theta(t - t_n)|\psi(t)\rangle$, where Θ represents the transition operator acting at discrete transition times.

On the observational front, we identify three high-priority research directions.

First, advanced statistical correlation methods for multi-messenger astronomy must be developed. More sophisticated cross-correlation techniques between electromagnetic and gravitational wave data streams will be essential for detecting the subtle signatures predicted by equation (53) and (54). This requires both theoretical advances in signal processing and practical implementation through coordinated observation campaigns across multiple facilities.

Second, specialized observational strategies for detecting secondary gravitational waves must be developed. This includes designing optimal filtering techniques for planned detectors like LISA and next-generation ground-based interferometers, as well as creating dedicated analysis pipelines for extracting weak signals in the mHz-Hz range. The characteristic thermodynamic gradient oscillations predicted by our model would manifest as distinctive amplitude modulations of conventional gravitational wave signals.

Third, the most recent ATLAS "antimatter" experiments at CERN do not include energy budgets but if published would provide direct statistical correlations between the thermodynamic gradient and the energy of the system due to the scale invariance of holographic theory, specifically as a direct function of the nature of coherent entropy

Theoretical extensions must address non-spherical geometries and rotating black holes, multiple black hole interactions and information exchange mechanisms, quantum gravitational corrections to the transition dynamics, and potential connections to other coherent entropy observables such as dark matter and antimatter.

One particularly promising direction involves quantifying how thermodynamic gradients between coherent and decoherent entropy states influence the generation of secondary gravitational waves. The feedback loop between information content, entropy distribution, and gravitational response creates a rich dynamical system that could produce distinctive observational signatures at multiple scales.

Additionally, developing comprehensive numerical simulations that capture the complete multi-messenger signature—spanning electromagnetic, gravitational, and potentially neutrino channels—will be essential for creating observation templates and guiding future experiments. These simulations should incorporate both the fundamental physics of information saturation and the practical observational constraints of current and planned instruments.

Furthermore, the intruiging connection between the event horizon and the cosmic horizon gives rise to several questions. What may have initially appeared to be the "heat death" of the universe may in fact be the "information death" of the universe where the universe becomes completely saturated in coherent entropy requiring a final transition. The timescales involved for the saturation of event horizons may provide some insight into the overall potential lifespan of the universe and the role of black holes within it. From this work it would seem that black holes might be the first cosmic structures to reach information saturation before the cosmic horizon, potentially providing additional mechanisms for information processing during the final epochs of our universe as we know it. This, of course, infers the cosmic horizon is itself a holographic screen, a "cosmic screen," through which reality is mathematically projected into manifestation from pure information through the interaction of theromdynamic entropy gradients.

8 Conclusion

This paper presents several groundbreaking discoveries that fundamentally transform our understanding of black hole physics, cosmic expansion, and the role of information in the universe. Our "Little Bang" hypothesis extends the recent discovery of discrete quantum phase transitions in CMB E-mode polarization to black hole evolution, yielding the following novel insights:

First, we have identified a fundamental information processing rate $\gamma = 1.89 \times 10^{-29}$ s^{-1} that governs quantum phase transitions across vastly different scales. This universal parameter maintains a precise mathematical relationship with cosmic expansion ($\gamma/H \approx 1/8\pi$), suggesting it represents a fundamental bridge between quantum and classical behavior. The universal geometric scaling ratio of $\frac{2}{\pi}$ between successive transitions appears in both cosmic and black hole contexts, revealing a deep connection between information processing and spacetime geometry.

Second, we have developed a coherent-decoherent entropy framework that reconceptualizes black holes as entropy organizers rather than information destroyers. This thermodynamic duality manifests as distinct regimes—coherent entropy (cold, ordered, $S_{coh} = \ln(2) \approx 0.693$) and decoherent entropy (hot, disordered, $S_{decoh} = \ln(2) - 1 \approx -0.307$)—whose interplay drives black hole evolution. We showed that when black holes reach information saturation at the holographic entropy bound, they undergo localized spacetime expansion events ("Little Bangs") that preserve information through dimensional expansion rather than destruction.

Third, we discovered that information pressure emerges as a physical force when encoding requires work against existing correlations. This pressure takes the form $P_I = \frac{\gamma c^4}{8\pi G}\left(\frac{I}{I_{max}}\right)^2$ and drives spacetime expansion when it exceeds a critical threshold. We derived a modified Einstein equation incorporating an information stress-energy tensor, revealing that gravity may be an emergent phenomenon arising from information processing dynamics.

Fourth, we presented the first information-theoretic derivation of the Hubble parameter from first principles: $H^2 = \frac{\gamma^2}{(8\pi G)^2}\left(\frac{I}{I_{max}}\right)^2 + \frac{\gamma c}{R_H}\ln\left(\frac{I}{Q}\right)$. This equation recasts cosmic expansion entirely in terms of information processing dynamics without reference to conventional energy density parameters, suggesting that information, rather than energy content, provides the fundamental driver for cosmic evolution.

Fifth, our E8×E8 heterotic structure provides a mathematical framework for understanding how information processes manifest across different scales, fundamentally inverting the theoretical hierarchy in physics. This framework suggests that information processing is the more fundamental description, with both quantum field theory and gravity emerging as effective descriptions at different scales.

Our theory offers several falsifiable predictions, including distinctive thermodynamic gradient signatures and gravitational wave modulations that can be tested through statistical correlation methods in multi-messenger astronomy. We've identified novel observational pathways through amplitude modulation of higher-frequency waves, statistical correlation signatures, and thermodynamic-induced secondary gravitational waves.

Additionally, we proposed that dark matter emerges as discrete coherent entropy structures—ordered configurations of information that manifest gravitational effects without electromagnetic interactions—derived from first principles using the holographic information rate. The resulting effective gravitational potential precisely matches observed dark matter distributions without requiring additional matter.

The comprehensive framework presented here resolves the black hole information paradox, explains cosmic expansion from information-theoretic principles, and suggests that information may be the primary constituent of reality. While significant challenges remain, the remarkable alignment between our theoretical framework and multiple independent observations suggests we have uncovered fundamental principles governing the information-theoretic foundations of our universe.

Acknowledgments

We thank the Information Physics Institute, M. Vopson, and L. Christopher Bates for their helpful discussions and feedback.

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