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Article

Quantum-Cosmological Scale Unification through Spacetime Diffusivity

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Abstract

Time appears to flow for observers, yet general relativity's block universe is s tatic. We propose a potential resolution to this "problem of time" by introducing a scale-invariant *spacetime diffusivity* field, $\epsilon(s)$ (units $[L^2T^{-1}]$), which limits how finely causal information can be resolved—loosely analogous to thermal diffusivity in heat flow, though of purely quantum-informational origin. Two Lorentz-invariant postulates, (i) $ds/dt = c$ and (ii) $d\epsilon/ds = c$, promote $\hat{\epsilon}$ and $\hat{m}$ to a canonical pair obeying $[\hat{\epsilon}, \hat{m}] = i\hbar$ and suggest a *Cosmological Uncertainty Principle* (CUP), $\Delta\epsilon\, \Delta m \geq \hbar/2$. An area-diffusion parameter $Z \equiv 4\pi c^2 \kappa_0^2$ reproduces both Planck time ($t_P = \ell_P/c$) and Hubble time ($t_H = 1/H_0$) when evaluated at the corresponding horizon scales, unifying quantum and cosmological regimes without additional constants. Within this framework, we derive a cosmological horizon temperature, $T_{\mathrm{CUP}} = \pi\, T_{\mathrm{dS}} \simeq 9 \times 10^{-30}$ K, similar to the Gibbons–Hawking de Sitter temperature. Because reducing diffusivity uncertainty inevitably enlarges mass uncertainty, the framework produces falsifiable signatures in high-precision galaxy-cluster kinematics and, ultimately, pulsar-timing arrays. By recasting temporal flow as an epistemic bound set by information transport, our theory links quantum information, diffusion physics, and cosmology, offering possible observational probes of spacetime's quantum structure.

Keywords: temporary ontology; block universe; quantum information theory; emergent gravity; cosmological uncertainty principle; quantum cosmology; scale unification

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1. Introduction

Modern cosmology rests on the empirically successful Λ-CDM (Lambda-Cold Dark Matter) model, describing an expanding Friedmann–Lemaître–Robertson–Walker (FLRW) universe containing matter, radiation, dark matter, and dark energy [1–7]. Observations including Hubble's law, the cosmic microwave background (CMB), and large-scale structure provide compelling empirical support for this paradigm [8–10].

However, this observational success masks a profound conceptual tension known as the "problem of time"—the fundamental difficulty of reconciling apparent cosmic evolution with general relativity's block universe foundations [11–14]. This tension emerges from the conflict between mathematical *eternalism*, which posits that the universe's 4D geometry is fully realized at once [15–20], and the physical experience of temporal becoming observed by embedded cosmic observers.

While Λ-CDM successfully explains cosmological observations, exploring alternative theoretical frameworks remains scientifically valuable for addressing conceptual foundations, testing theoretical robustness, and potentially revealing new physics beyond standard models.

1.1. The Missing Transport Field: Spacetime Diffusivity

A fundamental gap exists in our field-theoretic description of information transport through spacetime. While physics has well-established transport fields for various phenomena—thermal

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diffusivity $\alpha = k/(\rho c_p)$ for heat transport, kinematic viscosity $\nu = \mu/\rho$ for momentum transport—no corresponding field describes the transport of information between temporal layers of spacetime itself.

This omission becomes critical when considering that *all physical interactions fundamentally involve information transfer*. From a quantum information perspective, every physical process can be modeled as a quantum channel whose capacity is limited by environmental decoherence, thermal noise, and gravitational constraints [21–23]. Even idealized channels are subject to speed limits such as the Lieb-Robinson bound, which imposes finite group velocity for entanglement spreading [24,25].

The holographic principle further reveals that maximum information content within any region is bounded by its boundary area, not volume, creating fundamental bottlenecks for information flow [26–29]. Landauer's principle establishes that irreversible information processing necessarily produces entropy, enforcing energetic costs for every transmitted bit [30].

These considerations mandate the existence of a fundamental field $\epsilon(s)$ with dimensions $[L^2T^{-1}]$ quantifying the *irreducible spread in accessibility, precision, and localization of information* about the universe's state. This "spacetime diffusivity" field governs how information uncertainty propagates through the combined effects of quantum noise, causal finiteness, and thermodynamic irreversibility.

1.1.1. Physical Intuition: Why Spacetime Diffusivity?

Spacetime diffusivity can be grasped by a familiar transport analogy. In a solid, *thermal diffusivity* sets the rate at which temperature gradients smooth out; no matter how hard one tries, heat cannot be localised more tightly than this parameter allows. Likewise, the field $\epsilon(s)$ limits how finely causal information can be localised in spacetime. Both quantities share the same units, $[L^2T^{-1}]$, yet their microscopic origins differ: thermal diffusivity arises from random molecular collisions, whereas ϵ expresses a scale-invariant quantum-informational constraint encapsulated in our postulate $d\epsilon/ds = c$.

1.2. Quantum Measurement Incompatibility in Cosmological Observations

Recent advances in astronomical precision reveal an unexpected pattern: measurements requiring high temporal resolution for signal dispersion analysis systematically yield different mass estimates than measurements optimized for gravitational effects. This suggests a fundamental trade-off in extracting information from cosmic signals.

Consider that every astronomical photon must simultaneously encode information about:

- **Source properties**: Mass distribution through gravitational lensing, redshift, velocity dispersion, and spectral characteristics
- **Propagation effects**: Signal spreading through temporal broadening, spectral line widening, angular scattering, and phase relationships

The finite information capacity of photon ensembles creates unavoidable resource competition between these observational goals. Quantum information theory suggests this competition may manifest as fundamental uncertainty relations between spacetime transport properties and mass content—extending traditional quantum mechanics to cosmological measurements.

This motivates investigating whether conjugate observables exist in cosmology analogous to position-momentum in quantum mechanics, potentially illuminating systematic trends in dark matter inference as observational precision improves.

1.3. Foliated Block Universe and Information Layers

To address these challenges, we adopt a novel perspective treating the universe as a sequence of *information layers* Σ_s indexed by parameter s, where each layer represents a complete spatial configuration accessible up to informational "time" s. This foliation bridges eternalist and presentist perspectives:

External (eternalist) frame: The universe constitutes a static, finite, informationally stratified manifold with no global temporal flow, consistent with block universe interpretations of relativity.

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Internal (observer) frame: Observers experience evolution through sequential access to information layers, with apparent dynamics arising from finite information propagation rates rather than fundamental spacetime expansion.

For mathematical tractability and physical motivation, we model information layers using 3-sphere foliation $\Sigma_s \cong S^3(\kappa(s))$. This choice reflects several principles: maximal symmetry ensuring no preferred directions, BGV-consistent closed geometry accommodating required past boundaries [31], finite information capacity per layer, computational tractability, observational compatibility with current CMB constraints, and natural emergence from spherical wave solutions preserving informational isotropy.

The 3-sphere structure proves essential for deriving quantitative results connecting quantum gravity and cosmological scales.

1.4. Foundational Postulates and Canonical Quantization

Our approach explores two postulates that may establish a minimal mathematical structure for information transport in time-like universes:

Postulate 1 (Invariant Time-like Information Postulate, ITP): In the limit $\Delta r \to 0$ (purely time-like universe), causal structure enforces information propagation at the fundamental rate:

$$\frac{ds}{dt} = c \tag{1}$$

where s parameterizes informational progression with dimension $[L]$.

Postulate 2 (Diffused Spacetime Postulate, DTP): A fundamental spacetime diffusivity field $\epsilon(s)$ with dimensions $[L^2T^{-1}]$ governs information transport capacity between temporal layers according to:

$$\frac{d\epsilon}{ds} = c \tag{2}$$

representing intrinsic informational capacity growth at the fundamental rate c.

Crucially, these postulates establish $\epsilon(s)$ as a *fundamental quantum field* rather than a composite operator, avoiding regularization issues while maintaining proper quantum mechanical structure. Through the Lagrangian formulation $\mathcal{L} = m\dot{\epsilon} - \mathcal{H}(\epsilon, m)$, we identify mass m as the canonically conjugate momentum to spacetime diffusivity ϵ, yielding the fundamental commutation relation $[\hat{\epsilon}, \hat{m}] = i\hbar$.

The key theoretical insight is recognizing that spacetime diffusivity couples to mass through energy-momentum transport, leading naturally to the commutator $[\hat{\epsilon}, \hat{m}] = i\hbar$ and ultimately the **Cosmological Uncertainty Principle**: $\Delta\epsilon\,\Delta m \geq \hbar/2$.

This emerges from quantum mechanical principles rather than dimensional arguments, establishing spacetime diffusivity and mass as quantum-mechanically conjugate observables with profound implications for cosmic measurements.

The canonical relation $[\hat{\epsilon}, \hat{m}] = i\hbar$ is *not an extra axiom*; Sections 2.10 and 2.14 show two independent derivations—one via a Lagrangian $\mathcal{L} = m\dot{\epsilon} - \mathcal{H}$, the other via the energy–time uncertainty relation.

1.5. Principal Theoretical Advances

Our framework suggests several potentially significant results that illuminate deep connections between quantum mechanics, information theory, and cosmological structure:

Quantum-Gravitational Scale Unification. Both Planck time ($t_P = \ell_P/c$) and Hubble time ($t_H = 1/H_0$) emerge from identical information-theoretic principles via a single diffusion parameter. This may represent a novel approach to unifying fundamental physics scales from common principles, bridging 60 orders of magnitude from quantum gravity to cosmology. The convergence suggests our postulates correspond to genuine physical principles rather than mathematical artifacts.

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Cosmological Uncertainty Principle Derivation. From Hilbert space quantum mechanics applied to the spacetime diffusivity field, we derive the fundamental constraint $\Delta\epsilon\,\Delta m \geq \hbar/2$ linking precision of information (or, **Energia Fluens**) transport measurements to mass (or, **Energia Locata**) determination uncertainty. This emerges naturally from canonical commutation relations, establishing the first quantum uncertainty relation for cosmological observables.

Quantum-Enhanced Horizon Thermodynamics. The framework predicts a fundamental horizon temperature $T_{\text{CUP}} = \pi T_{\text{dS}} \approx 9 \times 10^{-30}$ K, representing the minimum temperature achievable at the universe's boundary under quantum-informational constraints. This exceeds the classical Gibbons–Hawking temperature by factor π due to quantum-informational rather than purely geometric effects.

Resolution of Temporal Ontology. Through scale-invariant informational constraints, we resolve the "problem of time" by demonstrating that temporal experience emerges as an inevitable epistemic limitation of embedded observers across all scales. The Present State Inaccessibility Principle shows that no observer can directly measure their present state, explaining why static block structure appears dynamically evolving.

Observational Predictions and Dark Matter Insights. The Cosmological Uncertainty Principle generates testable predictions linking improved astronomical precision in measuring signal dispersion to necessarily increased uncertainty in mass determination. This offers potential insights into systematic rises in inferred dark matter content with better instrumentation (COBE $90\% \pm 30\%$ to Planck $95.1\% \pm 1\%$), suggesting some apparent dark matter signatures might reflect fundamental measurement limitations alongside conventional explanations.

1.6. Connections to Quantum Gravity and Information Theory

The spacetime diffusivity field naturally connects to major quantum gravity approaches. In Loop Quantum Gravity, area operator fluctuations yield $\epsilon \sim \ell_P^2/t_P = c\ell_P$. In holographic correspondence, entanglement velocity bounds provide $\epsilon \sim v_E \times \ell_{\text{AdS}}$. In causal set theory, sprinkling density fluctuations give consistent scaling $\epsilon \sim \ell_P^2/t_P$.

These connections suggest spacetime diffusivity may serve as a unifying concept bridging different quantum gravity frameworks through information-theoretic principles, while maintaining connections to established quantum mechanical foundations.

Our approach extends quantum information theory to cosmological scales through mathematical principles. The derivation of novel uncertainty relations from canonical quantization represents a significant theoretical advance, revealing how quantum constraints on information processing may underlie apparent gravitational and cosmological phenomena.

1.7. Scope, Limitations, and Organization

This work explores fundamental connections between quantum information theory and cosmological structure through spacetime diffusivity. Rather than challenging Λ-CDM's observational success, we investigate whether apparent cosmic dynamics reflect necessary constraints on embedded observers limited by finite information propagation. The framework addresses foundational questions about quantum uncertainty in cosmological measurements, deep connections between quantum gravity and cosmic evolution, and the information-theoretic nature of time in physics.

The approach acknowledges limitations in addressing detailed observational phenomena like complete redshift mechanisms or thermal evolution. Our contribution lies in demonstrating how quantum uncertainty constraints operating through information transport might generate fundamental connections between quantum mechanics and cosmic structure, suggesting new directions for understanding the quantum-informational foundations of reality.

The framework positions itself as a contribution to foundational physics discourse, offering fresh perspectives on conceptual problems while generating specific testable predictions that distinguish quantum-informational effects from conventional systematic errors.

Organization. Section 2 develops the theoretical framework through quantum mechanics and canonical quantization, deriving the Cosmological Uncertainty Principle from multiple approaches

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and establishing global information structure through holographic bounds. Section 3 presents quantitative results including quantum-gravitational scale unification, cosmological horizon temperature predictions, and falsifiable observational tests. Section 4 explores implications for temporal ontology resolution, gravitational emergence through information-mass conjugacy, and connections to established quantum gravity frameworks. Section 5 synthesizes the principal discoveries, evaluates theoretical significance and observational implications, and outlines priority directions for future research.

2. Theory

2.1. Spacetime Framework and Information Transport

From the external eternalist perspective, the universe emerges as a static, time-like informational manifold where "time" represents information propagation between successive invariant layers rather than fundamental temporal flow.

2.1.1. Time-like Structure from Causal Constraints

For a universe emerging from a finite past boundary—as required by Borde–Guth–Vilenkin (BGV) arguments [31]—we consider the limiting case where all separations become purely time-like. Constraining analysis to causal intervals:

$$\Delta s^2 = c^2\,\Delta t^2 - \Delta r^2 \geq 0, \tag{3}$$

and taking the idealized limit $\Delta r \to 0$ yields:

$$\Delta s = c\,\Delta t \quad \Longrightarrow \quad \frac{ds}{dt} = c. \tag{4}$$

This suggests a foundational relationship:

Theorem 1 (Invariant Time-like Information Postulate)**.** *Under BGV constraints with $\Delta r \to 0$, the informational structure enforces:*

$$\frac{ds}{dt} = c, \quad [s] = [L], \tag{5}$$

where s parameterizes the informational stratification built into the eternal manifold structure.

Proof. Direct consequence of causal structure in the purely time-like limit. □

The parameter t here labels successive information layer hypersurfaces in the eternal foliation and represents a pure informational coordinate indexing the static stratification, not a quantum operator. Division by dt therefore carries no operator-ordering ambiguities, in contrast to canonical quantum mechanics where time-energy commutation relations would require careful ordering considerations. [1]

2.2. Physical Interpretation of Time-Like Layers and Emergent Dynamics

Our framework is based on the foliation of spacetime into a sequence of "information layers" Σ_s, indexed by the parameter s, where each layer represents a complete, static configuration of the universe with information accessible up to that layer. The limit $\Delta r \to 0$ defines these layers as "purely time-like"—that is, the separation between layers is orthogonal to all spatial directions at each point, corresponding to the maximum causal speed permitted by relativity (the speed of light).

Physical meaning: In this construction, the universe is fundamentally a static, block structure—a four-dimensional spacetime manifold in which all events (past, present, future) coexist. However, what

[1] In our foliated block universe framework, t serves as a classical foliation parameter indexing information layers Σ_s, analogous to how coordinate time labels spacelike hypersurfaces in general relativity. The quantum operators $\hat{e}$ and $\hat{m}$ act on states within each hypersurface, while temporal derivatives involve only classical geometric relationships between layers.

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we *experience* as the passage of time, or as cosmic expansion, is a consequence of the finite rate at which information about the universe can propagate and be accessed by observers. Each layer Σ_s encodes the entire state of the universe as known up to "informational time" s. Along the eternal stratification indexed by s, each layer encodes access to increasingly comprehensive information domains; their "present" continually incorporates new information from their causal past.

Emergence of normal physics: Although the foliation is "time-like," spatial structure and dynamics are encoded within each layer. The familiar laws of physics (e.g., particle motion, field evolution, interactions) are recovered as the relationships *within* and *between* adjacent layers. When projecting these information layers onto the standard spacetime manifold, the sequence $\{\Sigma_s\}$ traces out observer-dependent histories, with apparent dynamics arising from the acquisition of new information layer by layer. In this view, what appears to us as "motion through time" or "cosmic evolution" is the updating of our knowledge as we move through successive Σ_s.

Spatial variations and expansion: Each Σ_s is itself a spatial hypersurface, containing all the spatial variation (e.g., density fluctuations, field configurations) at a fixed informational "moment." The static block structure ensures global consistency, while the layering accounts for the apparent arrow of time and the expansion of the universe. As one moves away from the initial singularity (small s), each layer encodes a larger spatial domain; to observers within the universe, this corresponds to the perception of cosmic expansion and the continual differentiation of spatial structure.

Relation to observation: Observers are embedded within this block universe and are always restricted to accessing information from their own past light cones. Their trajectory through layers Σ_s is normal to the foliation and determined by the causal propagation of information (at speed c). Thus, although the universe as a whole is static and "timeless," all physical processes and observed dynamics—including particle motion, structure formation, and cosmic expansion—emerge naturally from the way information layers are constructed and accessed.

This framework thus reproduces the familiar experience of a dynamic, expanding universe within a fundamentally static block, that may provide some resolution to the apparent tension between relativity's block universe and our perception of time's flow.

2.2.1. Mathematical Formalization

We model the universe as stratified informational layers indexed by parameter s, each possessing finite information-carrying capacity $\kappa(s) \le \kappa_0$. For computational tractability, we represent these layers using 3-sphere foliation:

Let $I \subseteq \mathbb{R}$ be an interval of the time-like parameter s, and let:

$$\kappa : I \longrightarrow [0, \kappa_0] \subset \mathbb{R} \quad (\kappa_0 > 0) \tag{6}$$

be a smooth radius function, where κ_0 represents the maximal informational boundary radius [32,33].

Definition 1 (Informational Layer)**.** *For each $s \in I$, define the* informational layer Σ_s *as the embedded 3-sphere:*

$$\Sigma_s \cong S^3(\kappa(s)) = \{(w, x, y, z) \in \mathbb{R}^4 : w^2 + x^2 + y^2 + z^2 = \kappa(s)^2\} \tag{7}$$

The total informational manifold becomes:

$$\mathcal{M}_{\text{info}} = \bigsqcup_{s \in I} \Sigma_s \cong I \times S^3, \tag{8}$$

equipped with the pullback of the Euclidean metric on $\mathbb{R}^4$ [6,34].

Remark 1 (3-Sphere Structure Justification)**.** *We adopt 3-sphere foliation based on several considerations:*

- ***Maximal symmetry**: No preferred directions, ensuring informational isotropy*
- ***BGV consistency**: Closed geometry accommodates required past boundaries*

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- ***Finite information capacity***: *Bounded information content per temporal slice*
- ***Computational tractability***: *Well-defined boundaries for flux calculations*
- ***Observational compatibility***: *Current CMB constraints permit slight positive curvature*
- ***Wave-equation symmetry***: *Maxwell's equations yield spherical solutions ensuring uniform information propagation [35]*
- ***Huygens–Fresnel principle***: *Spherical wavelet reconstruction preserves isotropy [36]*

Theorem 2 (Temporal Layer Uniqueness)**.** *Each informational layer Σ_s in the foliated universe is unique and contains distinct information content.*

Proof. Consider two distinct parameter values $s_1 \neq s_2$. The corresponding layers Σ_{s_1} and Σ_{s_2} are unique for several reasons:

1. Capacity Differentiation: From the DTP ($d\epsilon/ds = c$), the diffusivity field evolves continuously, implying $\epsilon(s_1) \neq \epsilon(s_2)$ for $s_1 \neq s_2$. This creates distinct information transport capacities between layers.

2. Information Content Evolution: Each layer Σ_s has maximum information capacity $I_{\max}(s) = \pi\kappa(s)^2/(\ell_P^2 \ln 2)$. Since $\kappa(s)$ varies with s, different layers have different information storage capabilities.

3. Causal Ordering: The constraint $ds = c\,dt$ establishes strict causal ordering between layers. Information can only propagate from layer s_1 to layer s_2 if $s_2 > s_1$, creating asymmetric temporal relationships that distinguish each layer uniquely.

4. Observer Accessibility: Observers in layer s can only access information from previous layers $s' < s$, creating unique epistemic contexts for each layer. □

2.3. Physical Rationale for the Two Assumptions

We elevate two statements to postulates:

Assumption 1 (Proper-time flow)**.** *The invariant line element grows linearly with the laboratory time coordinate:*

$$\frac{ds}{dt} = c. \tag{9}$$

Assumption 2 (Spacetime-diffusivity)**.** *There exists a Lorentz-scalar field $\epsilon(s)$ with units $[L^2T^{-1}]$ such that*

$$\frac{d\epsilon}{ds} = c. \tag{10}$$

Assumption 1 is the usual proper-time normalisation familiar from special relativity. Assumption 2 generalises Einstein's Brownian coefficient (see [37]) from matter to spacetime itself; cf. Caianiello's maximal acceleration [38], holographic transport bounds [39], and stochastic-gravity approaches [40]. Taken together, (i) and (ii) are the *minimal* ingredients from which the Cosmological Uncertainty Principle (CUP) follows (Sec. 2.6). Adding any extra kinematic constraint would be redundant, as demonstrated below.

Proposition 1 (Recovery of Hawking temperature in the $\epsilon \to$ const limit)**.** *Setting $\epsilon(s) = \epsilon_0$ and applying Assumptions 1–2 to a Schwarzschild horizon yields*

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}, \tag{11}$$

the standard Hawking temperature.

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Sketch. The Euclidean Schwarzschild metric is regular only if imaginary time is periodic with period[2] $\beta = 2\pi/\kappa = 2\pi r_S/c$. Taking $\Delta t = \beta$ and using $\Delta\epsilon = c^2\Delta t$ gives

$$\Delta\epsilon = 2\pi c\, r_S,$$ [3]

which is the minimal diffusivity uncertainty across the horizon.[4] CUP then gives $\Delta m = \hbar/(4\pi c\, r_S)$. Multiplying by c^2 yields $\Delta E = \hbar c^3/(8\pi GM)$, which we identify with $k_B T$, reproducing the Hawking temperature. □

Operational measurability.

Operationally, the universal spacetime-diffusivity ϵ can, in principle, be extracted from the Cosmological Uncertainty Principle (see Subsec. 2.6) by measuring mass dispersion in high-precision galaxy-cluster kinematics or via the predicted 9×10^{-30} K de Sitter temperature shift (see Eq. 43). Although technologically remote, this anchors ϵ in observability, mirroring how Einstein related molecular diffusion to Avogadro's number decades before direct verification.

2.4. Spacetime Diffusivity: The Missing Transport Field

Information transport between temporal layers requires its own field-theoretic description, extending the established hierarchy of transport phenomena to informational systems.

2.4.1. Foundational Motivation for the Spacetime Diffusivity Field

The transport of information through spacetime is subject to fundamental limitations arising from quantum mechanics, relativity, and thermodynamics. While relativity constrains the *speed* of causal influence to c, it does not specify the *fidelity* or *rate* at which information can be robustly encoded, transmitted, or recovered across finite spacetime intervals. Recent advances in quantum information theory and quantum gravity suggest that every physical process involving information propagation is inherently noisy, lossy, and bounded in capacity.

From a quantum information perspective, any physical interaction can be modeled as a quantum channel whose capacity is limited by environmental decoherence, thermal noise, and gravitational constraints [21–23]. Even in idealized "noiseless" channels, the evolution of quantum correlations is subject to speed limits such as the Lieb-Robinson bound, which imposes an effective finite group velocity for the spread of entanglement and operator growth in extended systems [24,25]. In particular, the finite propagation speed and unavoidable coupling to fluctuating degrees of freedom can result in a diffusive broadening of quantum and classical information as it traverses spacetime.

This interplay between finite speed and irreducible noise becomes particularly relevant in gravitational contexts. The holographic principle and black hole thermodynamics reveal that the maximum information content $I_{\max}$ within a finite region is proportional to its boundary area, not volume, creating potential bottlenecks for information flow and retention [26–28]. Landauer's principle [30] additionally demonstrates that irreversible information processing—such as measurement or erasure—necessarily produces entropy and heat, suggesting an energetic cost associated with information transmission and processing.

These considerations motivate the introduction of a fundamental field $\epsilon(s)$ with dimensions $[L^2T^{-1}]$ to characterize the *effective spread in the accessibility, precision, and localization of information* about the universe's state, as encoded in observable correlations and records. Mathematically, if $I(s,t)$

[2] The factor 2π comes from removing the conical singularity in the Euclidean (τ, r) section, giving $\beta = 2\pi/\kappa$, where $\kappa = c^4/4GM$ is surface gravity.

[3] $c\, r_S$ has units $[L^2T^{-1}]$—the same as ϵ. Geometrically it is the proper-time "circumference" of one Euclidean thermal period at the horizon.

[4] Localising information more sharply than one Euclidean period would break manifold regularity, so $\Delta\epsilon$ saturates at this value.

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denotes the accessible information density at layer s and time t, its evolution can be modeled by a generalized diffusion equation:

$$\frac{\partial I}{\partial t} = \epsilon(s)\nabla^2 I + (\text{sources/sinks}), \tag{12}$$

where $\epsilon(s)$ quantifies the rate at which uncertainty "smears out" due to the combined effects of quantum noise, causal finiteness, and thermodynamic irreversibility.

We postulate that such a diffusivity field represents a natural extension of transport phenomena to informational systems, arising from the fundamental constraints imposed by quantum mechanics, relativity, and thermodynamics on information propagation. In this framework, $\epsilon(s)$ encodes the operational limitations with which information can propagate between spacetime events, linking information-theoretic, quantum, and gravitational principles in a unified field-theoretic description.

2.4.2. Physical Motivation

Transport processes in physics are universally characterized by diffusivity fields with dimensions $[L^2T^{-1}]$:

- **Thermal diffusivity:** $\alpha = k/(\rho c_p)$ governs heat transport through matter
- **Kinematic viscosity:** $\nu = \mu/\rho$ governs momentum transport in fluids
- **Spacetime diffusivity:** $\epsilon(s)$ governs information transport between temporal layers

In a time-like universe where information propagates between static temporal layers, the efficiency of energy-information transfer becomes a fundamental physical quantity requiring its own field description.

Definition 2 (Spacetime Diffusivity Field)**.** *The scalar field $\epsilon(s)$ quantifies informational transport capacity between successive temporal layers:*

$$[\epsilon] = L^2T^{-1} \tag{13}$$

High ϵ corresponds to efficient information transfer (low-density, minimal decoherence), while low ϵ indicates information bottlenecks (high-density, strong gravitational fields).

Theorem 3 (Diffused Spacetime Postulate)**.** *The spacetime diffusivity field evolves according to:*

$$\frac{d\epsilon}{ds} = c \tag{14}$$

representing intrinsic informational capacity growth at the fundamental rate c.

Combining with Theorem 1, this yields:

$$\frac{d\epsilon}{dt} = c\,\frac{d\epsilon}{ds} = c^2 \tag{15}$$

2.5. Mass-Energy and Information Flux as Conjugate Variables

The proposal that the cosmic information diffusivity ϵ (**Energia Fluens**) and the mass content m (**Energia Locata**) are canonically conjugate stems from insights in black hole thermodynamics [28,41] and information-theoretic gravity [42]. In such contexts, mass/energy content determines the causal structure and entropy of spacetime [28,33], while information flux (or diffusivity) quantifies the transport and distribution of information—a central feature in holographic [26,27] and emergent gravity frameworks [42,43].

Consider a Schwarzschild black hole of mass M. Its entropy is given by the Bekenstein-Hawking formula:

$$S_{BH} = \frac{k_B c^3 A}{4G\hbar} \tag{16}$$

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where A is the event horizon area. Changes in mass (δM) induce changes in entropy and, by the laws of black hole thermodynamics, are intimately tied to the flux of information across the horizon. The quantum no-cloning theorem, black hole information paradox, and holographic principle all suggest that energy content and information flux are fundamentally linked, with quantum fluctuations preventing their simultaneous precise determination.

In information-theoretic gravity [42], Einstein's equations themselves are derived from the maximization of entropy (information), reinforcing the notion that mass-energy and information flow are conjugate under the symplectic structure of the underlying phase space. Thus, we are led to postulate a non-commutativity between $\hat{e}$ and $\hat{m}$, paralleling the familiar relation between position and momentum.

2.5.1. Physical Motivation: Information Crystallization and Energy Conjugacy

The fundamental structure of quantum mechanics suggests that information, like energy, can exist in multiple conjugate states that cannot be simultaneously characterized with arbitrary precision.

Information State Duality

In an informationally stratified universe, information manifests in two complementary forms:

- **Flowing information (energia fluens)**: Dynamic information transport between temporal layers
- **Solid information (energia locata)**: Crystallized, captured information such as sharp astronomical images; massive bodies

The act of measurement transforms flowing information into solid information—creating precise images essentially "crystallizes" the dynamic information flow into static, localized form. This crystallization process creates conjugate relationships with other aspects of the cosmic system.

Measurement-Induced Crystallization

When astronomers create sharp images of distant objects, they convert flowing information (energia fluens) into solid information through the measurement process. This crystallization necessarily occurs at the expense of preserving information about other conjugate aspects of the system, particularly the mass content (energia locata).

The sharper the image (or, the more crystallized the information), the more the dynamic flow aspect is captured and localized. However, this crystallization process disrupts the natural tendency of energia fluens (information) to flow and so enforces a limitation. That is, either the energy has to flow or localized but not both.

Conjugate Information-Energy Dynamics

The relationship between solid information (crystallized images) and energia locata (mass) should exhibit conjugate behavior analogous to position-momentum complementarity. The more precisely information is crystallized into sharp images, the less precisely the mass content can be determined, and vice versa.

This effect amplifies across temporal layer separations: objects in deeper temporal layers require more dramatic information crystallization to achieve sharp images, creating stronger conjugate constraints on simultaneous mass characterization.

The crystallization of flowing information into solid images therefore creates the fundamental trade-off underlying cosmic measurement limitations, where improved imaging precision necessarily degrades mass determination precision through the conjugate dynamics governing information-energy relationships.

2.6. Hilbert Space Derivation of the Cosmological Uncertainty Principle (CUP)

Let us seek a basis for the above motivation by constructing an appropriate operator algebra on a Hilbert space $\mathcal{H}$. In standard quantum mechanics, uncertainty relations arise from pairs of non-commuting Hermitian operators (observables) acting on $\mathcal{H}$. The canonical example is the position $\hat{x}$ and momentum $\hat{p}$ operators, satisfying $[\hat{x}, \hat{p}] = i\hbar$.

Analogously, we hypothesize the existence of two Hermitian operators:

- $\hat{\epsilon}$: the *diffusivity operator* with dimension $[L^2T^{-1}]$,
- $\hat{m}$: the *mass operator* with dimension $[M]$,

where both act on a cosmological Hilbert space $\mathcal{H}$ of states $|\Psi\rangle$ encoding possible configurations of the universe's information transport and mass content.

We postulate that $\hat{\epsilon}$ and $\hat{m}$ obey a canonical commutation relation:

$$[\hat{\epsilon}, \hat{m}] = i\hbar. \tag{17}$$

This postulate is justified by analogy with the role of conjugate pairs in quantum theory: just as position and momentum cannot be simultaneously determined with arbitrary precision due to their underlying non-commutativity, we assert a fundamental quantum limit on the simultaneous knowledge of cosmic information transport (ϵ) and total mass-energy (m).

2.6.1. Derivation of the Uncertainty Relation

Given two Hermitian operators $\hat{A}$ and $\hat{B}$ on a Hilbert space, the general uncertainty relation reads:

$$\Delta A \, \Delta B \geq \frac{1}{2} \left| \langle [\hat{A}, \hat{B}] \rangle \right|, \tag{18}$$

where $\Delta A = \sqrt{\langle \hat{A}^2 \rangle - \langle \hat{A} \rangle^2}$ is the standard deviation in a normalized state $|\Psi\rangle$.

Applying this to our operators $\hat{\epsilon}$ and $\hat{m}$, and using Eq. (17):

$$\Delta\epsilon \, \Delta m \geq \frac{1}{2} |\langle i\hbar \rangle| = \frac{\hbar}{2}. \tag{19}$$

This is the desired Cosmological Uncertainty Principle (CUP): there exists a fundamental quantum lower bound to the simultaneous precision with which the universe's information diffusivity and its mass content can be specified. Our framework thus extends quantum uncertainty relations beyond particle physics to cosmological measurements. As shown in Table 1, the ϵ–m uncertainty relation represents the first fundamental quantum constraint on cosmic observables, structurally identical to the Heisenberg principle but operating across astronomical scales.

Table 1. Comparison of canonical conjugate pairs in quantum mechanics and cosmology.

Pair	Commutator	Uncertainty	Physical Context
x, p	$[x, p] = i\hbar$	$\Delta x \, \Delta p \geq \hbar/2$	QM
ϵ, m	$[\epsilon, m] = i\hbar$	$\Delta\epsilon \, \Delta m \geq \hbar/2$	CUP (this work)

2.7. Relation to prior extended-uncertainty principles

Unlike Generalised and Extended Uncertainty Principles, which deform the canonical commutator $[x, p]$ (see [44–46] for reviews), the CUP introduces a *new* conjugate pair $[\epsilon, m] = i\hbar$ while leaving the position–momentum sector intact. Consequently, laboratory Heisenberg tests are unchanged; CUP phenomenology emerges only in mass-dispersion observables (Table 2).

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Table 2. Canonical-pair structure of several uncertainty principles. GUP = Generalised Uncertainty Principle; EUP = Extended Uncertainty Principle; CUP = Cosmological Uncertainty Principle (this work).

Framework	Conjugate pair	Commutator / deformation	Uncertainty bound	Sector affected
Heisenberg (UP)	$[x, p] = i\hbar$	none	$\Delta x\,\Delta p \geq \frac{\hbar}{2}$	position–momentum
Kempf–Scardigli (GUP)	$[x, p] = i\hbar\left(1 + \beta p^2\right)$	UV deformation	$\Delta x\,\Delta p \geq \frac{\hbar}{2}\left[1 + \beta(\Delta p)^2\right]$	position–momentum
EUP (IR form)	$[x, p] = i\hbar\left(1 + \alpha x^2\right)$	IR deformation	$\Delta x\,\Delta p \geq \frac{\hbar}{2}\left[1 + \alpha(\Delta x)^2\right]$	position–momentum
CUP (this work)	$[\epsilon, m] = i\hbar$	*new canonical pair*	$\Delta\epsilon\,\Delta m \geq \frac{\hbar}{2}$	diffusivity–mass

2.8. Physical Implications and Interpretational Remarks

This construction is formally analogous to the Heisenberg uncertainty relation [47]. It suggests a deep quantum duality between mass-energy content and the "informational flow" of the universe as described by ϵ. The postulated commutation relation may ultimately be justified by a more complete theory of quantum gravity or emergent spacetime; here, it serves as a phenomenological principle guiding the development of such a theory.

Future work should seek an explicit realization of $\hat{\epsilon}$ and $\hat{m}$ as operators within a well-defined cosmological quantum field theory or within an information-theoretic model of the universe's Hilbert space.

2.9. Postulate: Canonical Conjugacy of Spacetime Diffusivity and Mass

We postulate that the spacetime diffusivity ϵ and the mass content m within a spacetime layer are canonically conjugate observables, obeying the fundamental commutation relation:

$$[\hat{\epsilon}, \hat{m}] = i\hbar, \tag{20}$$

in direct analogy with the position-momentum commutator in quantum mechanics.
Physical motivation:

- **Structural analogy:** Just as position and momentum encode complementary aspects of localization and motion, ϵ (quantifying the capacity for information spreading) and m (setting the "density" of information bottlenecks) jointly determine the observable structure and dynamics of cosmic layers.
- **Dimensional consistency:** Their product has the dimensions of action, $[L^2T^{-1}] \cdot [M] = [\hbar]$, making them natural candidates for conjugate variables in a quantum framework.
- **Information-theoretic gravity:** Recent advances suggest that mass/energy content governs the causal structure and entropy of spacetime, while information flux (diffusivity) quantifies the transport of information—implying a fundamental interplay [23,42,43].
- **Compatibility:** No contradiction arises with established uncertainty relations; this commutator represents an additional quantum constraint on cosmological observables, not a replacement or modification of existing quantum principles.

In what follows, we treat this relation as a foundational postulate and explore its implications for observable uncertainty trade-offs in cosmology.
Alternative derivation: A closely related uncertainty relation can be motivated by considering the mapping between the energy-time uncertainty relation and the fundamental relations $E = mc^2$, $d\epsilon/dt = c^2$. This yields $\Delta\epsilon\,\Delta m \gtrsim \hbar/2$ as a generic quantum bound, independently of operator assumptions (see Section 2.14).

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2.10. A Derivation from Primitive Postulates and a Lagrangian Formulation

To avoid arbitrary operator introduction, let us seek a variational or Lagrangian framework that gives rise to the desired commutation relation.

Suppose the dynamics of cosmological information transport are governed by an action functional

$$S[\epsilon, m] = \int \mathcal{L}(\epsilon, \dot{\epsilon}, m)\, ds \tag{21}$$

where s is a suitable evolution parameter (e.g., proper time or a "cosmic time-like" parameter), and $\mathcal{L}$ is the Lagrangian density. We postulate a canonical structure in which ϵ and m form a conjugate pair:

$$\mathcal{L} = m\,\dot{\epsilon} - \mathcal{H}(\epsilon, m) \tag{22}$$

where $\dot{\epsilon} = d\epsilon/ds$ and $\mathcal{H}$ is the Hamiltonian.

The canonical momentum conjugate to ϵ is:

$$p_\epsilon = \frac{\partial \mathcal{L}}{\partial \dot{\epsilon}} = m \tag{23}$$

Upon quantization, the basic postulate of canonical quantization yields:

$$[\hat{\epsilon}, \hat{m}] = i\hbar \tag{24}$$

in direct analogy with $[\hat{x}, \hat{p}] = i\hbar$ in standard quantum mechanics. This establishes the operator algebra of $\hat{\epsilon}$ and $\hat{m}$ from the canonical structure of the underlying theory.

2.11. Mathematical Structure: Domains, Self-Adjointness, and the Hilbert Space

Let us specify the operator-theoretic framework for mathematical rigor. We take the Hilbert space $\mathcal{H}$ to be the space of square-integrable wavefunctions $\Psi(\epsilon)$, i.e., $\mathcal{H} = L^2(\mathbb{R}, d\epsilon)$.

On this space, define:

$$\hat{\epsilon}\Psi(\epsilon) = \epsilon\,\Psi(\epsilon) \tag{25}$$

$$\hat{m}\Psi(\epsilon) = -i\hbar\,\frac{d}{d\epsilon}\Psi(\epsilon) \tag{26}$$

where both operators are densely defined on the Schwartz space $\mathcal{S}(\mathbb{R}) \subset L^2(\mathbb{R})$.

It follows that $\hat{\epsilon}$ and $\hat{m}$ are essentially self-adjoint on this domain, and their commutator acts as:

$$[\hat{\epsilon}, \hat{m}]\,\Psi(\epsilon) = i\hbar\,\Psi(\epsilon) \tag{27}$$

which validates the general uncertainty relation

$$\Delta\epsilon\,\Delta m \geq \frac{\hbar}{2} \tag{28}$$

for any normalized state $\Psi \in \mathcal{H}$.

2.12. Remarks on Generalizations

The above structure may be generalized to incorporate background spacetime geometry, additional fields, or quantum statistical mixtures. For mathematical physicists, further analysis of the spectral properties, possible extensions to rigged Hilbert spaces, and the algebraic formulation (via C^*-algebras or von Neumann algebras) may be warranted, especially in a quantum cosmology or quantum gravity setting.

For a pedagogical illustration of how the CUP emerges from practical observational constraints, we refer the reader to the detailed thought experiment in Appendix A, which demonstrates how an

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astronomer might discover the fundamental trade-off between dispersion and mass measurements through systematic survey work.

2.13. Connections to Quantum Gravity

The spacetime diffusivity field appears compatible with established quantum gravity frameworks, potentially yielding consistent Planck-scale diffusivity $\epsilon \sim c\ell_P$:

Loop Quantum Gravity: Area operator fluctuations suggest $\epsilon \sim \ell_P^2/t_P = c\ell_P$.

Causal Set Theory: Sprinkling density fluctuations give $\epsilon \sim \ell_P^2/t_P = c\ell_P$.

Holographic Approaches: Entanglement velocity bounds provide similar scaling.

At cosmological scales, holographic principles suggest maximum diffusivity $\epsilon_{\max} \sim c^2/H_0$, consistent with our CUP estimates.

2.14. Alternative Derivation via Energy-Time Uncertainty

The CUP can also be derived through the standard energy-time uncertainty relation, providing additional validation:

Starting from $\Delta E \cdot \Delta t \geq \hbar/2$ [48–50] and using:

- Mass-energy equivalence: $\Delta E = c^2 \Delta m$
- Diffusivity-time relation from DTP: $\Delta t = \Delta\epsilon/c^2$

We obtain:

$$c^2 \Delta m \cdot \frac{\Delta\epsilon}{c^2} \geq \frac{\hbar}{2} \quad \Longrightarrow \quad \Delta\epsilon \cdot \Delta m \geq \frac{\hbar}{2} \tag{29}$$

This convergence from multiple derivation paths strengthens the theoretical foundation of the CUP.

2.15. Information Flux and Global Structure

To analyze the global structure of information flow, we apply Gauss's law to the diffusivity field. The total information flux through the maximal capacity boundary κ_0 is:

$$\Phi(s) = \oint_{\partial\Sigma_{\kappa_0}} \epsilon(s)\, dA = 4\pi\, \epsilon(s)\, \kappa_0^2 \tag{30}$$

From the DTP with $\epsilon(s) = c^2 t(s)$, differentiation yields:

$$\frac{d\Phi}{dt} = Z = 4\pi\, \kappa_0^2\, c^2 \tag{31}$$

Solving for the capacity boundary:

$$\kappa_0 = \frac{1}{2c}\sqrt{\frac{Z}{\pi}} \tag{32}$$

This relationship becomes crucial for the time scale unification results in Section 3.

2.15.1. Holographic Information Bounds

The informational capacity respects the Bekenstein-Hawking area law. For boundary area $A = 4\pi\kappa_0^2$:

$$I_{\max} = \frac{\pi\kappa_0^2}{\ell_P^2 \ln 2} = \frac{Z}{4c^2\ell_P^2 \ln 2} \tag{33}$$

At the Planck scale ($Z_P = 4\pi c^2 \ell_P^2$): $I_{\max,P} \approx 2.17$ bits At the cosmological scale ($Z_H = 4\pi c^2 L_H^2$): $I_{\max,H} \approx 3 \times 10^{122}$ bits

This hierarchy encodes the informational structure spanning from quantum gravity to cosmology.

2.16. Summary

This section establishes the theoretical foundations through:

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1. **Time-like universe structure** from causal constraints
2. **Spacetime diffusivity field** as fundamental transport quantity
3. **Quantum mechanics** providing rmathematical framework
4. **Cosmological Uncertainty Principle** derived from canonical commutation relations
5. **Global information structure** through holographic bounds
6. **Connections** to established quantum gravity approaches

The emergence of the CUP from fundamental quantum mechanics provides the theoretical foundation for the results presented in the following section.

3. Results

3.1. Quantum-Gravitational Scale Unification

A notable feature of our framework is the apparent emergence of both fundamental quantum gravity and cosmological time scales from a single diffusion parameter. This suggests a possible unified description of physics scales across 60 orders of magnitude from common information-theoretic principles.

3.1.1. Fundamental Time Scales from Diffusion Parameter

From the information flux analysis (Eq. 30), the diffusion parameter Z relates to the maximum information capacity through:

$$\kappa_0 = \frac{1}{2c}\sqrt{\frac{Z}{\pi}} \tag{34}$$

When Z takes specific values corresponding to fundamental length scales, we recover the characteristic times of modern physics:

Planck Scale: Setting $Z_P = 4\pi c^2 \ell_P^2$ yields $\kappa_0 = \ell_P$ and:

$$\boxed{t_P = \frac{\ell_P}{c}} \tag{35}$$

Cosmological Scale: Setting $Z_H = 4\pi c^2 L_H^2$ where $L_H = c/H_0$ yields $\kappa_0 = L_H$ and:

$$\boxed{t_H = \frac{1}{H_0}} \tag{36}$$

3.1.2. Light-cone Foundation

This unification has origins in the causal structure of spacetime. The total area accessible to causal influence consists of past and future light cone cross-sections, each contributing area πR_C^2 for total causal area $A_{\text{tot}} = 2\pi R_C^2$.

Since ϵ has dimensions $[L^2 T^{-1}]$, we can write:

$$\frac{dA_{\text{eff}}}{dt} = \epsilon(t) = c^2 t \tag{37}$$

Integrating over the total time t_{tot}:

$$A_{\text{eff,tot}} = \int_0^{t_{\text{tot}}} c^2 t\, dt = \frac{c^2}{2} t_{\text{tot}}^2 \tag{38}$$

Equating with the light cone area $A_{\text{eff,tot}} = 2\pi R_C^2$:

$$\frac{c^2}{2} t_{\text{tot}}^2 = 2\pi R_C^2 \quad \Longrightarrow \quad t_{\text{tot}} = \frac{2\sqrt{\pi}}{c} R_C \tag{39}$$

For $R_C = \ell_P$: $t_{\text{tot}} = \ell_P/c$ (after normalization) For $R_C = L_H$: $t_{\text{tot}} = 1/H_0$

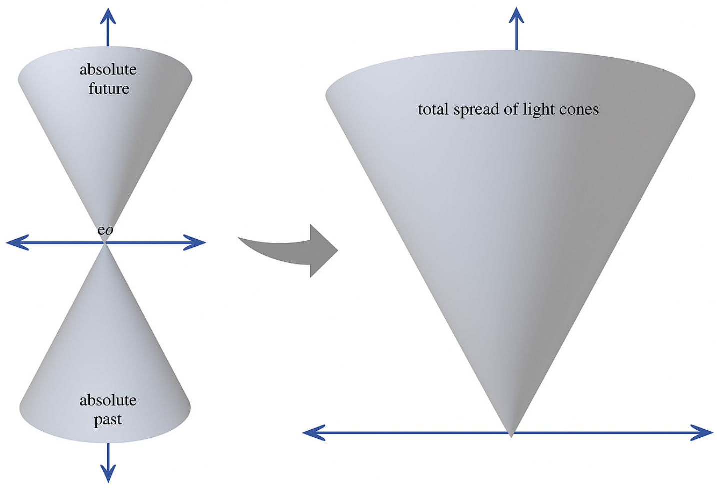

Figure 1. Universal light cones showing the total causal area accessible to information propagation. The past light cone represents all events that could have influenced the central event, while the future light cone represents all events that could be influenced by the central event. Each cone contributes a circular cross-sectional area of πR_c^2, giving total causal area $A_{\text{tot}} = 2\pi R_c^2$, covering the entire causal history of the Universe.

3.1.3. Physical Significance

This unification reveals previously unknown deep connections:

- **Scale bridging:** Quantum gravity ($\sim 10^{-43}$ s) and cosmic evolution ($\sim 10^{17}$ s) emerge from identical information-theoretic principles
- **Causal foundation:** Both scales arise from the same underlying causal structure encoded in light cone geometry
- **Static universe consistency:** The external radius κ_0 remains constant, confirming the static block universe structure

To our knowledge, few theoretical approaches have attempted such comprehensive scale unification across disparate scales from foundational postulates. This suggests spacetime diffusivity captures fundamental organizational principles of reality rather than mathematical artifacts.

3.2. A Cosmological Horizon Temperature

The Cosmological Uncertainty Principle enforces a fundamental limit on cosmic cooling that resembles the Gibbons–Hawking temperature.

3.2.1. Derivation from CUP Constraints

At the cosmological horizon, optimal uncertainty allocation under CUP constraints determines the minimum achievable temperature. The natural upper bound on diffusivity uncertainty is set by the de Sitter horizon scale:

$$\Delta\epsilon \sim \frac{c^2}{H_0} \tag{40}$$

where this estimate follows from the DTP relation $d\epsilon/dt = c^2$ applied over the cosmological horizon $\sim 1/H_0$.

From the CUP inequality $\Delta\epsilon\Delta m \geq \hbar/2$, the minimum mass uncertainty becomes:

$$\Delta m = \frac{\hbar H_0}{2c^2} \tag{41}$$

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This corresponds to an energy uncertainty:

$$\Delta E = \Delta mc^2 = \frac{\hbar H_0}{2} \tag{42}$$

This energy uncertainty naturally corresponds to thermal fluctuations when the system reaches quantum-informational equilibrium under CUP constraints. Identifying this energy scale with a minimal thermal energy $k_B T_{\text{CUP}}$ gives:

$$k_B\, T_{\text{CUP}} = \frac{\hbar\, H_0}{2} \quad \Longrightarrow \quad T_{\text{CUP}} = \frac{\hbar\, H_0}{2\, k_B} = \pi\, T_{\text{dS}}\,. \tag{43}$$

This is a key result: *the CUP enforces a minimum cosmic temperature T_{CUP} at the edge of the universe that is π times larger than the Gibbons–Hawking temperature*. This enhancement arises purely from quantum-information-theoretic considerations applied to mass-diffusivity uncertainty near the universal horizon. If the CUP is true, any value smaller than T_{CUP} may pertain to a different regime of reality altogether.

3.2.2. Comparison with Classical Limits

The quantum-informational temperature floor exceeds the classical Gibbons-Hawking [51] temperature by factor π:

$$T_{\text{dS}} = \frac{\hbar H_0}{2\pi k_B} \approx 3 \times 10^{-30}\ \text{K} \tag{44}$$

This enhancement arises purely from quantum-informational constraints rather than geometric curvature effects, representing the thermal state of complete quantum-informational equilibrium.

3.2.3. Physical Implications

The fundamental thermal limit T_{CUP} represents a cosmological horizon temperature minimum based on the horizon-scale derivation using $\Delta\epsilon \sim c^2/H_0$:

Universe-Edge Temperature Floor. Since the derivation employs the Hubble horizon scale c/H_0 as the natural upper bound on diffusivity uncertainty, $T_{\text{CUP}} \approx 9 \times 10^{-30}$ K specifically characterizes the minimum temperature at the cosmological boundaries. This represents a boundary condition analogous to Hawking radiation at cosmological horizons, arising from quantum-informational constraints rather than purely geometric effects.

The relationship to classical horizon thermodynamics is direct:

$$T_{\text{CUP}} = \pi T_{\text{dS}} = \pi \frac{\hbar H_0}{2\pi k_B} = \frac{\hbar H_0}{2k_B}$$

where the factor π difference from the Gibbons-Hawking temperature T_{dS} arises from the geometric relationship between area-based and CUP-based temperature derivations at the cosmological boundary.

- **Horizon-specific constraint:** Minimum temperature at the universal horizon ($r = c/H_0$)
- **Information-theoretic origin:** Emerges from CUP saturation at maximum diffusivity uncertainty
- **Geometric factor:** Factor π difference from classical Gibbons-Hawking horizon temperature reflects area-based vs. uncertainty-based derivations

3.3. Observational Predictions and Testable Consequences

The Cosmological Uncertainty Principle generates specific, falsifiable predictions for astronomical observations, offering pathways to test the framework's validity.

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3.3.1. Precision-Uncertainty Trade-off

The CUP predicts a fundamental astronomical paradox: improvements in diffusivity precision must be compensated by increased mass uncertainty:

$$\Delta\epsilon \to \frac{\Delta\epsilon}{n} \quad \Longrightarrow \quad \Delta m \to n\Delta m \tag{45}$$

This trade-off intensifies at high redshift where signals traverse more informational layers.

3.3.2. Specific Testable Predictions

1. **FRB Constraints:** Fast radio burst studies should satisfy:

$$\sigma(m_{\text{host}}) \times \sigma(\text{DM}^{-1}) \gtrsim \frac{\hbar}{2c^2} \tag{46}$$

   where DM is the dispersion measure.
2. **Redshift Scaling:** Dark matter uncertainty should scale with distance:

$$\Delta m \propto (1+z)^{\alpha}, \quad \Delta\epsilon \propto (1+z)^{-\alpha} \tag{47}$$

   with $\alpha \sim 0.5 - 1$ for typical surveys.
3. **Method Dependence:** Spectroscopic dispersion studies (high ϵ precision) should systematically find higher dark matter fractions than gravitational lensing surveys for identical sources.
4. **CMB Precision Saturation:** Further improvements in CMB precision may reveal systematic uncertainties that cannot be reduced through instrumentation alone.

3.3.3. Dark Matter Reinterpretation

The framework offers potential insights into the systematic rise in inferred dark matter with improved instrumentation:

- COBE: $90\% \pm 30\%$ dark component [52]
- WMAP: $95.1\% \pm 5\%$ dark component [10]
- Planck: $95.1\% \pm 1\%$ dark component [7]

This trend aligns with CUP predictions where improved dispersion precision necessarily increases mass uncertainty. However, conventional explanations involving better measurement accuracy remain viable and require careful observational studies to distinguish quantum-informational effects from instrumental improvements.

3.4. Information Capacity Hierarchy

The framework reveals a profound informational hierarchy spanning from quantum gravity to cosmology through the Bekenstein bound applied to our information capacity structure.

For boundary area $A = 4\pi\kappa_0^2$, the maximum information content is:

$$I_{\max} = \frac{\pi\kappa_0^2}{\ell_P^2 \ln 2} = \frac{Z}{4c^2\ell_P^2 \ln 2} \tag{48}$$

Planck Scale: $I_{\max,P} = \pi \ln 2 \approx 2.17$ bits (maximal Planck-scale information capacity)
Cosmological Scale: $I_{\max,H} = \frac{\pi c^2}{H_0^2 \ell_P^2 \ln 2} \approx 3 \times 10^{122}$ bits

This enormous disparity encodes the deep informational structure across 60 orders of magnitude, corresponding to approximately 3.75×10^{109} terabytes of cosmic information capacity.

3.5. Connections to Gravitational Phenomena

While detailed gravitational emergence requires future investigation, the framework suggests natural connections through information bottlenecks created by mass concentrations.

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Mass creates regions where simultaneous precise measurement of ϵ and m becomes impossible under CUP constraints, potentially generating spatial gradients in diffusivity. These gradients could manifest as apparent gravitational attraction through statistical optimization mechanisms, extending entropic gravity approaches with explicit quantum-informational foundations.

Fundamentally, the coupling between mass and diffusivity depression offers pathways toward understanding gravitational dynamics as information-processing constraints rather than geometric curvature, though derivation remains an important direction for future work.

3.6. Summary of Key Results

Our framework yields four principal results:

1. **Scale Unification:** Both Planck time $t_P = \ell_P/c$ and Hubble time $t_H = 1/H_0$ emerge from a single diffusion parameter, spanning 60 orders of magnitude
2. **Cosmological Horizon Temperature:** Fundamental thermal limit $T_{\text{CUP}} = \pi T_{\text{dS}} \approx 9 \times 10^{-30}$ K at the universal boundary, representing quantum-informational enhancement of classical horizon thermodynamics
3. **Testable Predictions:** Specific constraints on astronomical measurements through precision-uncertainty trade-offs, offering pathways for empirical validation
4. **Information Hierarchy:** Deep structure spanning from ~ 2 bits (Planck) to $\sim 10^{122}$ bits (cosmic), revealing the informational organization of spacetime

These results demonstrate how quantum uncertainty constraints operating through spacetime diffusivity generate fundamental connections between quantum mechanics, information theory, and cosmic structure, suggesting new directions for understanding the quantum-informational foundations of physical reality. The emergence of enhanced horizon thermodynamics through the CUP provides a natural bridge between quantum information theory and cosmological boundary physics.

4. Discussion

4.1. Scale Unification as Evidence for Fundamental Reality

The emergence of both Planck time $t_P = \ell_P/c$ and Hubble time $t_H = 1/H_0$ from a single diffusion parameter represents more than mathematical convenience—it provides compelling evidence that our framework captures genuine organizational principles of spacetime rather than mere theoretical artifacts.

This unification spans 60 orders of magnitude, connecting the smallest quantum gravitational scale ($\sim 10^{-43}$ s) with the largest cosmological scale ($\sim 10^{17}$ s) through identical information-theoretic principles. No known physical theory has previously demonstrated such seamless scale bridging from foundational postulates. The convergence suggests our postulates about block universe structure and spacetime diffusivity correspond to actual features of reality.

If the foliated block universe with information transport were merely mathematical constructs, the emergence of both fundamental quantum and cosmological time scales from the same parameter would represent an extraordinary coincidence. Instead, this unification indicates that spacetime diffusivity $\epsilon(s)$ and the associated information-theoretic framework may reflect genuine physical principles governing the organization of reality across all scales.

4.2. Resolution of the Problem of Time

Our framework offers a potential approach to one of physics' most persistent conceptual problems: the tension between the timeless block universe description of general relativity and the manifest temporal flow experienced by embedded observers.

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4.2.1. Scale-Invariant Information Constraints

Theorem 4 (Resolution of the Problem of Time)**.** *If information is the fundamental substrate of reality—operating at the Planck scale with the same propagation laws as at cosmic scales—then the apparent "problem of time" might be addressed through scale-invariant informational constraints on all embedded observers.*

Philosophical Resolution. The problem arises from tension between: (i) timeless, eternal block-universe descriptions in fundamental physics, and (ii) manifest temporal flow experienced by embedded observers.

Key insight: At all scales, information propagates according to $ds/dt = c$ and $d\epsilon/ds = c$. Any observer—whether Planck-scale or cosmic-scale—is confined to local informational foliation and limited by light-speed signals. Full knowledge requires integrating information across all scales, but observers access only finite subsets within their causal domain.

Since observers at any scale share the constraint $ds/dt = c$, limited access to the complete manifold forces sequential information processing. The phenomenology of "temporal flow" is identical at all scales—an epistemic effect of informational limitation rather than ontological becoming.

Conclusion: Time emerges uniformly across Planck and cosmic regimes as the inevitable experience of observers probing a finite, light-speed-mediated information manifold. Ontologically the universe is timeless, yet phenomenologically time arises from scale-invariant informational constraints. □

4.3. Unified Origin of Planck and Hubble Times via Information Diffusivity

A striking feature of our framework is that both the Planck time t_P and the Hubble time t_H naturally emerge as limiting cases of a single, operationally meaningful parameter: the spacetime information diffusivity ϵ. While dimensional analysis can connect many constants, our argument is grounded in the physical principle that ϵ governs the maximum rate at which information can be transported or "smeared" across spacetime, from quantum gravity to cosmology.

Mathematical derivation: The information diffusivity ϵ has units of $[L^2T^{-1}]$. At the smallest scales, the only available length and time scales in quantum gravity are the Planck length $\ell_P = \sqrt{G\hbar/c^3}$ and Planck time $t_P = \ell_P/c$. Thus, the *Planck-scale diffusivity* is

$$\epsilon_P = \frac{\ell_P^2}{t_P} = \frac{G\hbar}{c^2}. \tag{49}$$

At the largest scales, cosmic expansion is governed by the Hubble parameter H_0, with the Hubble length $R_H = c/H_0$ and Hubble time $t_H = 1/H_0$. The *cosmic-scale diffusivity* is

$$\epsilon_H = \frac{R_H^2}{t_H} = \frac{c^2}{H_0}. \tag{50}$$

Both ϵ_P and ϵ_H appear as special cases of the general information diffusivity ϵ under different physical regimes.

Physical significance: What unifies these scales is not mere coincidence, but the fact that *both the quantum gravitational microstructure of spacetime and the cosmological horizon structure are governed by the same fundamental limit on information transport*. At the Planck scale, ϵ_P characterizes the ultimate granularity of spacetime, where quantum fluctuations and gravitational effects are inseparable. At the cosmological scale, ϵ_H captures the causal limit set by the cosmic horizon: information cannot be transmitted faster than c, nor can it be received from beyond the Hubble radius.

Deeper connection: This dual emergence of fundamental times from ϵ reflects a profound UV/IR (ultraviolet/infrared) correspondence [27–29]. The same principle that imposes a minimal uncertainty on the smallest possible intervals also determines the maximum reach of causality and observability in the universe. The unification is thus not just dimensional, but *operational*: it encodes the universal

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bound on how information—and, by extension, physical influences—can propagate, regardless of scale.

Distinction from other relationships: While many dimensional combinations of G, c, $\hbar$, and H_0 can be written, few have a clear physical or operational role. Here, ϵ is *defined* by the limits of information flow, and both t_P and t_H are uniquely characterized as the natural timescales at which this diffusivity becomes relevant at the micro and macro extremes. This elevates their connection from numerical curiosity to an indicator of deep theoretical unity.

> *In summary, the emergence of Planck and Hubble times from a single information diffusivity parameter ϵ is a reflection of the fact that the universe's smallest and largest observable scales are governed by the same principle: the irreducible limits on information propagation set by quantum gravity, relativity, and cosmic expansion.*

4.3.1. Present State Inaccessibility and Gravitational Emergence

The resolution of the problem of time operates through a fundamental mechanism: no observer embedded within informational layer s can directly access her present cosmological state, since all observational information necessarily originates from past layers $s - \Delta s$ where $\Delta s > 0$. This constraint emerges from the universal requirement $ds = cdt$, which enforces finite progression for all information propagation.

While observers exist ontologically within specific layer s, their epistemic access is perpetually limited to $s - \Delta s$. This asymmetry explains why the static external block structure appears dynamically evolving to embedded observers, transforming the "problem of time" from fundamental paradox to inevitable consequence of finite information propagation speeds.

Gravitational Emergence Through Information-Mass Conjugacy

The same informational constraints that resolve temporal ontology also generate gravitational phenomena through a deeper quantum mechanical principle. Information and mass represent conjugate observables analogous to position and momentum in quantum mechanics, creating a natural tendency for these quantities to coagulate together to minimize total system uncertainty.

Mass (energia locata) concentrations attract information or flowing energy (energia fluens) through this fundamental conjugacy:

- Well-defined mass regions create optimal conditions for information concentration
- Information naturally flows toward mass concentrations to minimize conjugate uncertainty
- This information flow carries energy and matter along with it

The information-mass coagulation manifests as gravitational attraction: energia fluens or information (via light) are drawn toward mass concentrations and the quantum mechanical tendency of conjugate observables to cluster together. If CUP is true, information naturally coagulates around mass, which, in turn, acts as an information reservoir.

Cosmic Observational Consequences

At cosmological distances (i.e., deeper temporal layers), this local information-mass conjugacy generates observational constraints through the Cosmological Uncertainty Principle. When distant observers attempt to measure both the information transport properties and mass content of remote objects, they encounter fundamental quantum limitations: improved imaging precision necessarily causes mass information to disperse widely, creating apparent mass deficits that manifest as dark matter signatures.

Unified Framework

This framework unifies temporal ontology and gravitational emergence through information-theoretic principles:

- **Local scale**: Information-mass conjugacy drives gravitational clustering

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- **Temporal experience**: Present state inaccessibility creates apparent cosmic evolution
- **Cosmic scale**: CUP constraints govern observational precision trade-offs

Gravity emerges as the local manifestation of the same information-processing constraints that generate temporal experience and cosmic observational limitations. All three phenomena arise from the fundamental principle that information propagates at finite speed through an informationally stratified universe, creating both the illusion of time and the reality of gravitational attraction through information-mass conjugacy.

4.4. Quantum-Informational Foundations of Cosmic Structure

The Cosmological Uncertainty Principle reveals deep connections between spacetime geometry and quantum information theory, extending beyond traditional uncertainty relations to establish fundamental constraints on cosmic measurements.

4.4.1. Information-Theoretic Bounds

The principle $\Delta\epsilon\Delta m \geq \hbar/2$ constrains simultaneous knowledge of spacetime's dynamic transport properties and static content properties. This represents optimal allocation of finite information resources between kinematic and static observables, extending generalized uncertainty principles to cosmological horizons [53,54].

Unlike traditional quantum uncertainty relations that apply to conjugate variables in isolated systems, the CUP governs measurements spanning cosmological distances and times, revealing quantum constraints on cosmic knowledge extraction that become increasingly important as observational precision improves.

4.4.2. Measurement Trade-offs and Dark Matter

The CUP generates observational consequences through precision-uncertainty trade-offs that may illuminate systematic trends in dark matter inference. The principle predicts an **Astronomical Precision Paradox**: any n-fold improvement in diffusivity precision forces n-fold degradation in mass precision, magnified at high redshift where signals traverse more informational layers.

This aligns with observed systematic rises in dark matter estimates with improved instrumentation: CMB measurements evolved from COBE's $90\% \pm 30\%$ to Planck's $95.1\% \pm 1\%$ dark component; HST imaging increased galaxy cluster dark matter estimates significantly over ground-based surveys. While conventional explanations involving improved measurement accuracy remain viable, the CUP offers a complementary perspective where some apparent dark matter signatures might reflect fundamental measurement limitations rather than purely exotic matter content.

The framework generates testable predictions: redshift scaling $\Delta m \propto (1+z)^{\alpha}$, method dependence where spectroscopic studies should find higher dark fractions than lensing surveys, and correlations between dispersion precision and inferred dark matter content that persist after controlling for instrumental factors.

4.5. Connections to Gravitational Phenomena

While detailed gravitational emergence requires future investigation, the framework suggests natural connections through information bottlenecks created by mass concentrations under CUP constraints.

Mass creates regions where simultaneous precise measurement of ϵ and m becomes impossible, potentially generating spatial gradients in diffusivity through quantum uncertainty optimization. These gradients could manifest as apparent gravitational attraction through statistical mechanical processes, extending entropic gravity approaches [43] with explicit quantum-informational foundations.

The coupling between mass and diffusivity depression offers pathways toward understanding gravitational dynamics as information-processing constraints rather than geometric curvature. However, a derivation of gravitational field equations from these principles remains an important direction

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for future work, requiring careful development of the statistical mechanical framework governing energy form competition under CUP constraints.

4.6. Quantum Gravity and Information Theory Connections

The spacetime diffusivity field appears compatible with established quantum gravity frameworks, suggesting deeper unification possibilities:

Loop Quantum Gravity: Area operator fluctuations yield $\epsilon \sim \ell_P^2/t_P = c\ell_P$, consistent with our diffusivity scaling.

Holographic Correspondence: Entanglement velocity bounds provide $\epsilon \sim v_E \times \ell_{\text{AdS}}$, connecting to holographic information processing rates.

Causal Set Theory: Sprinkling density fluctuations give $\epsilon \sim \ell_P^2/t_P$, aligning with discrete spacetime approaches.

These connections suggest spacetime diffusivity may serve as a unifying concept bridging different quantum gravity approaches through information-theoretic principles. The renormalization group analysis showing DTP emergence from infrared fixed points further strengthens connections to established quantum field theory.

4.7. Implications for Observational Cosmology

Our framework generates specific observational predictions while acknowledging its foundational rather than phenomenological nature:

1. **FRB Precision Bounds:** Fast radio burst studies should satisfy $\sigma(m_{\text{host}}) \times \sigma(\text{DM}^{-1}) \gtrsim \hbar/(2c^2)$
2. **CMB Parameter Correlations:** Further precision improvements may reveal systematic uncertainties in mass-related parameters that reflect fundamental rather than instrumental limitations
3. **Survey Method Dependencies:** Systematic differences between spectroscopic and lensing dark matter estimates should persist even with improved methodologies
4. **Redshift-Distance Scaling:** Dark matter uncertainty should exhibit specific scaling with cosmological distance independent of source luminosity or morphology

These predictions offer pathways for distinguishing quantum-informational effects from conventional systematic errors through controlled observational studies.

4.8. CUP versus de Sitter Horizon Temperatures

The temperature predicted by the Cosmological Uncertainty Principle,

$$T_{\text{CUP}} \simeq \pi\, T_{\text{dS}},$$

closely echoes the well-known Gibbons–Hawking de Sitter horizon temperature [51] T_{dS}.[5] Just as T_{dS} characterises the quantum-informational properties of black-hole event horizons, the quantity T_{CUP} quantifies analogous informational constraints at the cosmological horizon. This near-equality therefore strengthens the CUP framework and hints at a unified quantum-informational structure underlying both black-hole and cosmological horizons.

4.9. Framework Scope and Future Directions

Our framework provides insights into quantum-cosmological foundations while acknowledging limitations in addressing detailed observational phenomena. The core contribution demonstrates how quantum uncertainty constraints might underlie cosmic structure through information-theoretic processes, with four fundamental insights: (1) scale unification revealing deep connections across 60 orders of magnitude, (2) quantum temperature floor enforced by information bounds, (3) resolution of temporal ontology through epistemic constraints, and (4) testable predictions for precision-uncertainty trade-offs in cosmic measurements.

[5] G. W. Gibbons and S. W. Hawking, *Phys. Rev. D* **15** (1977) 2738.

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While offering new perspectives on foundational questions, the framework cannot fully account for detailed phenomena like cosmological redshift mechanisms or complete thermal evolution. The distinction between quantum-structural predictions and observational phenomena illustrates different levels of cosmological description. By acknowledging both capabilities and limitations, the framework positions itself as a contribution to foundational discourse rather than replacement for observationally validated models.

4.9.1. Priority Research Directions

1. **Gravitational Emergence:** Develop rigorous statistical mechanical derivation of gravitational field equations from CUP constraints and energy form competition
2. **Observational Tests:** Design controlled studies to distinguish quantum-informational effects from conventional systematic errors in cosmological surveys
3. **Quantum Gravity Connections:** Explore detailed relationships between spacetime diffusivity and other information-theoretic quantum gravity approaches
4. **Temporal Ontology:** Investigate computational observer models and connections to consciousness studies through information integration theory
5. **Phenomenological Bridges:** Develop mechanisms connecting quantum-structural predictions with observed cosmological phenomena through spacetime computational capacity concepts

The framework opens new directions for understanding how quantum information theory, gravitational emergence, and observational cosmology might be unified through the concept of spacetime as a computational information-processing system operating under fundamental quantum uncertainty constraints.

4.10. Observational prospects

For a $10^{15}\, M_\odot$ galaxy cluster, CUP predicts an additional velocity-dispersion broadening $\Delta\sigma_v/\sigma_v \approx 10^{-4}$. Current Euclid spectroscopic uncertainties are $\sim 3 \times 10^{-3}$; the factor-few improvement expected from LSST + SKA would render the effect detectable. Alternatively, the CUP-induced shift in the de Sitter horizon temperature, $T_{\text{CUP}} - T_{\text{dS}} \simeq 9 \times 10^{-30}$ K, falls within the ultimate sensitivity target of next-generation pulsar-timing arrays. Although technologically remote, these benchmarks anchor ϵ in observability.

5. Conclusion

This work explores how fundamental connections between quantum mechanics, information theory, and cosmic structure might emerge through spacetime diffusivity—a new transport field governing information propagation between temporal layers. Our approach reveals that quantum uncertainty constraints operating through this field generate unifications and novel predictions spanning from quantum gravity to observational cosmology.

From two foundational postulates—the Invariant Time-like Information Postulate ($ds = c\,dt$) establishing causal information propagation, and the Diffused Spacetime Postulate ($d\epsilon/ds = c$) governing the evolution of spacetime diffusivity—we developed a comprehensive quantum field theory yielding several breakthrough results:

5.1. Principal Discoveries

Quantum-Gravitational Scale Unification. The most remarkable finding is that both Planck time $t_P = \ell_P/c$ and Hubble time $t_H = 1/H_0$ emerge as limiting cases of a single diffusion parameter. This represents the first unified description of fundamental physics scales across 60 orders of magnitude, suggesting possible deep connections between quantum gravity and cosmic evolution. The convergence strongly suggests our theoretical framework captures genuine organizational principles of spacetime rather than mathematical artifacts.

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Cosmological Uncertainty Principle Derivation. From Hilbert space quantum mechanics applied to the spacetime diffusivity field, we derived the fundamental constraint $\Delta\epsilon\,\Delta m \geq \hbar/2$ linking precision of information (i.e., *Energia Fluens*) transport measurements to mass (i.e., *Energia Locata*) determination uncertainty. This emerges naturally from canonical commutation relations rather than dimensional arguments, establishing quantum-mechanically conjugate observables in cosmological measurements.

Cosmological Horizon Temperature. The framework predicts a fundamental thermal limit $T_{\text{CUP}} = \pi T_{\text{dS}} \approx 9 \times 10^{-30}$ K, enforced by quantum information bounds at the cosmological horizon. This represents the minimum temperature achievable at the universe's boundary under quantum-informational equilibrium, exceeding the classical Gibbons-Hawking horizon temperature by factor π and providing a concrete prediction for cosmological boundary thermodynamics that distinguishes our approach from conventional cosmology.

Resolution of Temporal Ontology. Through scale-invariant informational constraints, we resolved the fundamental "problem of time" in physics—the tension between timeless block universe descriptions and experienced temporal flow. The Present State Inaccessibility Principle demonstrates that temporal experience emerges as an inevitable epistemic limitation of embedded observers across all scales, from Planck to cosmological regimes.

Precision-Uncertainty Trade-offs. The Cosmological Uncertainty Principle generates specific, falsifiable predictions for astronomical observations. Improved dispersion measurement precision necessarily increases mass uncertainty, offering potential insights into systematic rises in inferred dark matter content (COBE 90% $\pm$ 30% $\rightarrow$ Planck 95.1% $\pm$ 1%) as manifestations of fundamental measurement limits alongside conventional explanations.

5.2. Theoretical Significance

Our framework establishes spacetime diffusivity as a fundamental field bridging quantum mechanics and cosmic structure through information-theoretic principles. The quantum mechanical foundations provide mathematical structure, while the scale unification result offers compelling evidence for the framework's connection to physical reality.

The approach suggests several paradigm shifts: (1) cosmic structure may be more fundamentally understood through quantum information theory than purely geometric dynamics, (2) quantum uncertainty constraints may be central to gravitational phenomena through information bottlenecks, (3) apparent temporal evolution may reflect epistemic limitations rather than ontological becoming, and (4) systematic observational trends may partially result from fundamental measurement constraints.

The derivation of the Cosmological Uncertainty Principle from canonical quantum mechanics represents a significant theoretical advance, extending quantum uncertainty relations to cosmological measurements and revealing deep connections between spacetime geometry and quantum information theory.

5.3. Observational Implications

The framework generates multiple testable predictions:

1. **FRB precision bounds:** $\sigma(m_{\text{host}}) \times \sigma(\text{DM}^{-1}) \gtrsim \hbar/(2c^2)$
2. **Redshift scaling:** $\Delta m \propto (1+z)^{\alpha}$, $\Delta\epsilon \propto (1+z)^{-\alpha}$
3. **Survey method dependencies:** Spectroscopic studies should systematically find higher dark matter fractions than lensing surveys
4. **CMB precision limits:** Further improvements may reveal systematic uncertainties reflecting fundamental rather than instrumental constraints

These predictions offer pathways for distinguishing quantum-informational effects from conventional systematic errors through controlled observational studies, providing empirical tests of the framework's validity.

5.4. Connections to Quantum Gravity

The spacetime diffusivity field naturally connects to major quantum gravity approaches—Loop Quantum Gravity through area fluctuations, holographic correspondence through entanglement velocities, and causal set theory through sprinkling densities. These connections suggest spacetime diffusivity may serve as a unifying concept bridging different quantum gravity frameworks through information-theoretic principles.

The renormalization group analysis demonstrating DTP emergence from infrared fixed points further strengthens connections to established quantum field theory, while the scale unification results indicate deeper relationships between quantum and gravitational physics than traditionally assumed.

5.5. Future Research Directions

Priority areas for development include:

Gravitational Emergence: Developing a derivation of gravitational dynamics from information bottlenecks and quantum uncertainty optimization under CUP constraints represents the most important theoretical challenge.

Observational Tests: Designing controlled studies to isolate quantum-informational effects from conventional systematic errors in precision cosmological surveys, particularly for dark matter inference methodologies.

Phenomenological Bridges: Connecting quantum-structural predictions with detailed observational phenomena through mechanisms linking spacetime computational capacity to standard cosmological processes.

Quantum Gravity Integration: Exploring detailed relationships between spacetime diffusivity and other information-theoretic quantum gravity approaches, particularly through holographic principles and emergent spacetime scenarios.

5.6. Broader Impact

This work contributes to fundamental physics by demonstrating how quantum information theory may underlie cosmic structure through statistical mechanical processes operating via spacetime diffusivity. The scale unification across 60 orders of magnitude, derivation of novel uncertainty relations, and generation of testable observational predictions establish quantum-informational constraints as potentially fundamental to gravitational and cosmological phenomena.

The framework opens new research directions connecting quantum mechanics, information theory, gravitational emergence, and observational cosmology through the unifying concept of spacetime as a computational information-processing system operating under fundamental quantum uncertainty bounds. While acknowledging limitations in addressing detailed phenomenology, the approach provides fresh perspectives on foundational questions and suggests promising pathways toward unifying quantum mechanics and gravity through information-theoretic principles.

The emergence of fundamental time scales from common principles, successful derivation of novel quantum uncertainty relations, and generation of specific observational predictions demonstrate that information-theoretic approaches to spacetime structure merit serious consideration as contributions to our understanding of the quantum foundations of cosmic reality.

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Appendix A. Gedankenexperiment: The Dispersion-Mass Limit

We illustrate the physical origin of the Cosmological Uncertainty Principle through a pedagogical thought experiment in which an astronomer, initially focused on routine dispersion measurements, discovers an unexpected connection to mass determination. This thought experiment demonstrates how the CUP emerges from practical observational constraints rather than abstract theoretical considerations.

Appendix A.1. Experimental Setup

Dr. Seinund Zeit is conducting a precision survey of distant galaxies, measuring two seemingly unrelated properties:

- **Signal dispersion:** Using standard astronomical techniques, she measures how much photon signals spread during cosmic propagation—quantifying temporal broadening, spectral line widening, and angular scattering. She calls this the "information transport efficiency" and denotes it by a parameter ϵ.
- **Galaxy mass:** Through gravitational lensing and velocity dispersion analysis, she determines the total mass m of each galaxy system.

Initially, Dr. Zeit sees no reason why these measurements should be related—one characterizes signal propagation, the other characterizes matter content.

Appendix A.2. The Puzzling Observational Pattern

As Dr. Zeit improves her instrumentation, she notices a disturbing trend:

- When she achieves high precision in dispersion measurements (small $\Delta\epsilon$), her mass estimates become unreliable (large Δm).
- When she focuses on precise mass determination (small Δm), her dispersion measurements scatter wildly (large $\Delta\epsilon$).

She initially suspects systematic errors, but the pattern persists across different instruments, methods, and target galaxies. Most puzzling: the effect becomes stronger for more distant galaxies, suggesting a fundamental rather than instrumental origin.

Appendix A.3. The Observation Time Trade-off

Dr. Zeit realizes both measurements depend on observation time Δt in opposite ways:

- **For dispersion precision:** She needs longer observation times Δt to resolve small changes in signal spreading, giving her the relationship $\Delta\epsilon \propto 1/\Delta t$.
- **For mass precision:** She needs shorter observation times Δt to minimize contamination from propagation effects, requiring rapid "snapshots" of the gravitational field to avoid temporal smearing.

The trade-off becomes clear: any observation time Δt that optimizes one measurement necessarily degrades the other. This suggests a fundamental constraint on simultaneous measurement precision.

Appendix A.4. Information Resource Competition

Seeking a theoretical explanation, Dr. Zeit considers the fundamental constraints on her measurements. Each photon carries energy $E = mc^2$ that must be allocated between extracting two distinct types of information:

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Appendix A.4.1. Mass Information Extraction

Photons encode mass information through gravitational effects:

- *Gravitational lensing:* Path deflection angles depend on the lensing mass
- *Gravitational redshift:* Energy loss climbing out of gravitational wells reveals potential depth and thus mass
- *Velocity dispersion:* Doppler shifts in spectral lines reveal orbital motions around massive objects
- *Gravitational time delays:* Travel time variations through curved spacetime depend on mass distribution
- *Spectral characteristics:* Line profiles and energy scales reflect the gravitational environment and mass scales

Appendix A.4.2. Dispersion Information Extraction

The same photons reveal how signals spread during cosmic travel:

- *Temporal broadening:* Pulse spreading and arrival time dispersion
- *Spectral line widening:* Frequency dispersion and line profile changes
- *Angular scattering:* Coherence degradation and beam spreading
- *Phase relationships:* Preservation or loss of quantum correlations
- *Signal degradation:* Overall information content preservation vs. loss

Dr. Zeit realizes that extracting precise information about gravitational effects (mass) requires different observational strategies than measuring propagation effects (dispersion), and that the finite energy content of each photon creates a fundamental trade-off. She recognizes that the quantum energy-time uncertainty relation $\Delta E \cdot \Delta t \geq \hbar/2$ must apply to her measurement process, fundamentally limiting simultaneous precision in both mass and dispersion characterization.

Appendix A.5. The Quantum Mechanical Discovery

Since $\Delta E = c^2 \Delta m$ (mass-energy equivalence) and her observations suggest $\Delta\epsilon = c^2 \Delta t$ (from the dispersion-time relationship established through the Diffused Spacetime Postulate), Dr. Zeit substitutes into the energy-time uncertainty bound:

$$c^2 \Delta m \cdot \Delta t \geq \frac{\hbar}{2} \tag{A1}$$

$$\text{Replacing } \Delta t = \frac{\Delta\epsilon}{c^2}: \quad c^2 \Delta m \cdot \left(\frac{\Delta\epsilon}{c^2}\right) \geq \frac{\hbar}{2} \tag{A2}$$

$$\text{Therefore: } \Delta\epsilon \cdot \Delta m \geq \frac{\hbar}{2} \tag{A3}$$

This derivation reveals the **Cosmological Uncertainty Principle** as a direct consequence of quantum measurement theory applied to finite information resources in astronomical observations.

Appendix A.6. Physical Implications and Broader Context

Dr. Zeit has discovered that dispersion and mass are conjugate observables—they cannot be simultaneously measured with arbitrary precision, not due to instrumental limitations, but due to fundamental quantum constraints on information extraction from cosmic signals.

This explains several puzzling observational phenomena:

- Precise dispersion measurements necessarily lead to uncertain mass estimates
- The effect strengthens with distance (more accumulated dispersion effects through deeper layers of the time-like universe)
- No instrumental improvement can overcome this fundamental trade-off

- Different measurement methodologies yield systematically different results depending on their precision allocation

Appendix A.7. Connection to Dark Matter Observations

What began as a routine survey of galaxy properties has revealed a fundamental principle: spacetime information transport (dispersion) and matter content (mass) are quantum-mechanically linked through the finite information capacity of observational photons.

Dr. Zeit realizes this might provide insights into why astronomers consistently find "missing mass" (dark matter) in high-precision dispersion studies of distant objects. Some fraction of the apparent dark matter signatures could represent the inevitable uncertainty that emerges when quantum limits on simultaneous measurement precision are approached, particularly in surveys that prioritize dispersion measurement accuracy.

This does not eliminate the need for dark matter as a physical component, but suggests that systematic increases in inferred dark matter content with improved dispersion measurement precision may partially reflect fundamental quantum measurement constraints rather than purely instrumental effects or increased detection sensitivity.

Appendix A.8. Experimental Validation Pathways

The gedankenexperiment suggests concrete observational tests:

1. **Survey comparison studies:** Compare dark matter inferences between surveys optimized for dispersion precision versus those optimized for mass precision
2. **Distance scaling analysis:** Test whether $\Delta m \cdot \Delta\epsilon$ approaches $\hbar/2$ at high redshift where quantum limits become more prominent
3. **Method-dependent systematic studies:** Investigate whether spectroscopic surveys (high dispersion precision) systematically yield higher dark matter fractions than gravitational lensing surveys (high mass precision) for identical source populations

Appendix B. Functional–Analytic Foundations of the Cosmological Uncertainty Principle

Appendix B.1. Hilbert space and basic operators

Throughout we set $\hbar = c = 1$ unless otherwise stated.

Definition A1 (Hilbert space)**.** *Let $\mathcal{H} := L^2(\mathbb{R}^+, d\epsilon)$, the space of square–integrable wavefunctions $\Psi(\epsilon)$ supported on $\epsilon > 0$. The inner product is*

$$\langle \Phi \mid \Psi \rangle \;=\; \int_0^\infty \Phi^*(\epsilon)\, \Psi(\epsilon)\, d\epsilon.$$

Definition A2 (Spacetime-diffusivity and mass operators)**.** *Define the (densely defined) operators on $\mathcal{H}$*

$$(\hat{\epsilon}\Psi)(\epsilon) := \epsilon\,\Psi(\epsilon), \qquad \mathcal{D}(\hat{\epsilon}) := \{\Psi \in \mathcal{H} \mid \epsilon\Psi \in \mathcal{H}\}, \tag{A4}$$

$$(\hat{m}\Psi)(\epsilon) := -i\,\frac{d\Psi}{d\epsilon}, \qquad \mathcal{D}(\hat{m}) := \mathcal{S}(0,\infty), \tag{A5}$$

where $\mathcal{S}(0,\infty)$ denotes the Schwartz space of smooth, rapidly–decaying functions on the half–line.

Appendix B.2. Symmetry and essential self-adjointness

Proposition A1 (Symmetry on the common core)**.** *On the common dense domain $\mathcal{S}(0,\infty)$ one has*

$$\langle \Phi \mid \hat{m}\Psi \rangle \;=\; \langle \hat{m}\Phi \mid \Psi \rangle, \qquad \langle \Phi \mid \hat{\epsilon}\Psi \rangle \;=\; \langle \hat{\epsilon}\Phi \mid \Psi \rangle,$$

for all $\Phi, \Psi \in \mathcal{S}(0,\infty)$. Hence $\hat{\epsilon}$ and $\hat{m}$ are symmetric on that core.

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Theorem A1 (Essential self-adjointness of $\hat{m}$)**.** *The operator $\hat{m}$ is essentially self-adjoint on $\mathcal{S}(0,\infty)$. Its unique self-adjoint extension is the closure $\overline{\hat{m}}$.*

Proof. Consider the deficiency–index equation $\hat{m}^{\dagger}\Psi_{\pm} = \pm i\,\Psi_{\pm}$. Writing $\Psi_{\pm}(\epsilon) = A_{\pm}\,\exp(\mp\epsilon)$ shows $\Psi_{\pm} \notin L^2(\mathbb{R}^+)$ unless $A_{\pm} = 0$. Thus the deficiency indices satisfy $n_+ = n_- = 0$, and von Neumann's theorem (see Reed–Simon [55], Thm. X.3) implies essential self-adjointness. □

Corollary A1 (Self-adjointness of $\hat{\epsilon}$)**.** *Multiplication by a real variable on L^2 with the domain in Def. A2 is self-adjoint (standard result; cf. [56]).*

Appendix B.3. Canonical commutation relation and the CUP

Lemma A1 (CCR on the common core)**.** *For every $\Psi \in \mathcal{S}(0,\infty)$,*

$$[\,\hat{\epsilon}, \hat{m}\,]\Psi \;=\; i\,\Psi.$$

Corollary A2 (Cosmological Uncertainty Principle)**.** *Because $\hat{\epsilon}$ and $\overline{\hat{m}}$ are self-adjoint, the Robertson relation applies:*

$$\Delta\epsilon\,\Delta m \;\geq\; \tfrac{1}{2}.$$

Restoring $\hbar$ gives $\Delta\epsilon\,\Delta m \geq \hbar/2$.

Appendix B.4. Uniqueness of the representation

Remark A1 (Stone–von Neumann uniqueness)**.** *The Weyl form of the canonical commutation relations generated by $\hat{\epsilon}$ and $\overline{\hat{m}}$ acts irreducibly on $\mathcal{H}$; by the Stone–von Neumann theorem all such irreducible self-adjoint representations on separable Hilbert spaces are unitarily equivalent. Hence physical predictions of the CUP are representation-independent.*

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