Temporal Ontology in Block Universe Cosmology: An Information-Theoretic Approach

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Abstract

Modern cosmology faces a fundamental tension between observed cosmic evolution and general relativity's block universe foundations. We address this temporal ontology problem through a quantum-informational framework that reconciles eternalist ontology with temporal experience via information-theoretic constraints on embedded observers. We propose three foundational postulates: the *Invariant Time-like Information Postulate* ($\boldsymbol{ds = c\,dt}$) establishing light-mediated information propagation between temporal layers, the *Diffused Spacetime Postulate* ($\boldsymbol{d\epsilon/ds = c}$) governing spacetime diffusivity evolution, and a *Cosmological Uncertainty Principle* ($\boldsymbol{\Delta\epsilon\,\Delta m \geq \hbar/2}$) constraining simultaneous measurement of energy transport and mass content. The quantum-statistical foundations yield remarkable unifications: both Planck time $\boldsymbol{t_P = \ell_P/c}$ and Hubble time $\boldsymbol{t_H = 1/H_0}$ emerge from a single diffusion parameter, revealing quantum-gravitational connections across 60 orders of magnitude. Gravitational attraction arises statistically through quantum uncertainty optimization, recovering Newtonian gravity from information-theoretic constraints. The framework predicts a fundamental quantum temperature floor $\boldsymbol{T_{\mathrm{CUP}} = \pi T_{\mathrm{dS}} \approx 9 \times 10^{-30}}$ K and generates testable predictions linking improved dispersion measurements to increased mass uncertainty, potentially explaining systematic rises in inferred dark matter as quantum-informational measurement limits rather than exotic matter distributions.

Keywords: Temporal ontology, Block universe, Quantum information theory, Emergent gravity, Cosmological Uncertainty Principle, Quantum cosmology, Scale unification

1 Introduction

Modern cosmology is fundamentally grounded in the Λ-CDM model, which describes 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. The present work investigates whether cosmic dynamics might represent the necessary epistemic perspective of finite observers rather than ultimate ontological reality.

1.1 Theoretical Motivation

We adopt the foundational assumption that the universe possesses an intrinsically time-like character, implying that its fundamental structure should be primarily informational rather than geometric. Drawing inspiration from Page and Wootters' conditional-probability approach to quantum mechanics [11], we formalize a dual perspective:

1. **External (eternalist) frame**: The universe constitutes a static, finite, time-like informational block with no global temporal "flow."
2. **Internal (observer) frame**: Energy and information appear to diffuse through successive temporal layers, generating perceived evolution through static informational progression rather than dynamic transport.

This dual framework resolves the temporal ontology problem by treating apparent cosmic evolution as an emergent phenomenon arising from finite information propagation constraints rather than fundamental spacetime expansion.

1.2 Foundational Postulates

To formalize this information-theoretic cosmology, we introduce three foundational postulates that serve as axioms for exploring temporal ontology:

Invariant Time-like Information Postulate (ITP): A time-like universe consists of static 3-sphere foliation of informational hypersurfaces with varying capacity $\kappa(s) \leq \kappa_0$, where motion along the temporal normal satisfies $ds = c\,dt$. No informational layer "flows" into another; the 4D structure remains eternally complete.

Diffused Spacetime Postulate (DTP): A spacetime diffusivity field $\epsilon(s)$ with dimensions $[L^2T^{-1}]$ evolves according to $d\epsilon/ds = c$, governing informational transport capacity between successive temporal layers. Each temporal layer maintains unique informational content.
Cosmological Uncertainty Principle (CUP): Measurements spanning finite spacetime regions must satisfy $\Delta\epsilon\,\Delta m \geq \hbar/2$, linking quantum uncertainty to the diffusive properties of spacetime and mass-energy content.

1.3 Key Results and Implications

From these postulates emerge several foundational results illuminating the quantum-informational nature of cosmic structure:

Quantum-Gravitational Unification. 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, revealing deep connections between quantum gravity and cosmic evolution across 60 orders of magnitude.

Information-Theoretic Gravity. Gravitational attraction arises statistically as matter drifts toward regions of lower informational diffusivity, recovering Newtonian gravity [21] through quantum uncertainty optimization rather than geometric curvature.

Fundamental Quantum Temperature. The framework predicts a quantum-informationally enforced temperature floor $T_{\text{CUP}} = \pi T_{\text{dS}}$ representing the fundamental thermal limit for complete quantum-informational equilibrium.

Dark Matter Reinterpretation. The Cosmological Uncertainty Principle suggests that improved astronomical precision in measuring signal dispersion necessarily increases uncertainty in mass determination through $\Delta\epsilon\,\Delta m \geq \hbar/2$. This provides a potential explanation for the systematic rise in inferred dark matter fractions with better instrumentation—from COBE's 90% ± 30% to Planck's 95.1% ± 1% dark component—as manifestations of quantum-informational measurement limits rather than exotic particle distributions.

Resolution of the Problem of Time. Through a philosophical proof demonstrating scale-invariant informational constraints, we show that the fundamental tension between timeless block universe ontology and experienced temporal flow dissolves when information operates identically at Planck and cosmic scales. Temporal experience emerges as an inevitable epistemic limitation of embedded observers across all scales, providing a unified resolution to one of physics' most persistent conceptual problems (see Appendix C).

1.4 Scope and Organization

This work addresses **temporal ontology in cosmology**—the fundamental question of whether time represents genuine becoming or apparent change within eternal being [22, 23]. Rather than challenging Λ-CDM's observational success, we explore whether its dynamic descriptions reflect the necessary epistemic constraints of embedded observers rather than ultimate ontological structure.

The framework offers insights into several foundational problems: temporal directionality emergence in symmetric spacetime, relationships between quantum uncertainty and gravitational phenomena, and deep connections between information theory and cosmological structure. If validated, this approach suggests cosmic expansion represents the inevitable appearance of static spacetime to finite observers constrained by light-speed information propagation.

Organization. Section 2 develops the theoretical framework and mathematical formalism. Section 3 presents quantitative results including time scale unification and asymptotic temperature predictions. Section 4 explores foundational implications for temporal ontology, quantum gravity, and information theory. Section 5 discusses theoretical limitations and future directions.

Methodological Note.

This framework is exploratory and conceptual, designed to probe whether information-theoretic reinterpretation of block-universe cosmology illuminates foundational issues—particularly the "problem of time" and gravitational emergence—rather than supplanting Λ-CDM's empirical success. The informational diffusivity field $\epsilon(s)$ and Cosmological Uncertainty Principle serve as conceptual tools for exploring quantum-informational constraints on cosmic structure, inviting further theoretical development within quantum-gravity theories, thermodynamic models, or emergent spacetime approaches.

2 Theory

2.1 Spacetime Framework: External Eternalist Perspective

From the external *eternalist* perspective, the universe emerges not as evolving geometry but as a *static, time-like informational manifold* (Fig. 1). In this picture, "time" represents information propagation—carried at light speed—between successive, invariant informational layers rather than fundamental temporal flow.

2.1.1 Timelike Structure from BGV Constraints

For a universe emerging from a finite past boundary—as required by Borde–Guth–Vilenkin (BGV) arguments [24]—we consider the limiting case where all separations become purely time-like. Constraining analysis to causal intervals:

$$\Delta s^2 = c^2\,\Delta t^2 - \Delta r^2 \geq 0, \tag{1}$$

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

$$\Delta s = c\,\Delta t \quad \Longrightarrow \quad \frac{\Delta s}{\Delta t} = c. \tag{2}$$

Remark 1 The limit $\Delta r \to 0$ represents a theoretical idealization for exploring information propagation rather than direct geometric modeling. This eliminates spatial separations entirely, yielding a purely time-like structure where information propagates between temporal layers through light-mediated data transfer.

We introduce a real-valued foliation parameter s satisfying:

$$\frac{ds}{dt} = c, \qquad [s] = [L], \tag{3}$$

which tracks informational progression rate rather than geometric properties. The parameter s measures "informational distance" traveled by light in connecting temporal layers.

2.1.2 Light as Fundamental Information Medium

In a time-like universe where $\Delta r \to 0$, light becomes the natural basis for cosmic structure due to its role as the primary information carrier between temporal states. This informational approach focuses on *how information changes* between temporal layers rather than geometric relationships.

Information-Carrying Capacity. Each light signal carries finite information connecting different temporal layers. We model information *transfer* between successive temporal states rather than motion through geometric space.

Static Informational Block Structure. The universe constitutes a primarily informational system where relevant dynamics involve information progression via luminal signals. Information follows structures that mimic timeless geometry without requiring geometric interpretation.

Temporal Layer Differentiation. Temporal layers become distinguished through light-carried information evolution, making data progression the fundamental organizing principle.

2.1.3 Foundational Insights

The relation $\Delta s/\Delta t = c$ reflects the informational nature of time-like universes:

1. **Timelike Origin**: $\Delta s^2 > 0$ ensures purely temporal, informational structure.
2. **Finite Genesis**: BGV demands a past boundary; information possesses definite origin.
3. **External Stasis**: Page–Wootters mechanisms [11] demonstrate how informational change occurs within static structures.
4. **Light-Speed Layering**: $\Delta s = c\,\Delta t$ establishes natural informational "slices" carried by light at rate c.

2.1.4 Mathematical Formalization

We model the universe as stratified informational layers indexed by parameter s, each possessing finite information-carrying capacity $\kappa(s)$. For mathematical tractability—without physical geometric interpretation—we represent these layers using 3-sphere notation as a computational tool for tracking information capacity.

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

$$\kappa : I \longrightarrow [0, \kappa_0] \subset \mathbb{R} \quad (\kappa_0 > 0) \tag{4}$$

be a smooth radius function, where κ_0 represents the maximal informational boundary radius [25, 26].

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

$$\Sigma_s \cong S^3\big(\kappa(s)\big) = \big\{(w, x, y, z) \in \mathbb{R}^4 : w^2 + x^2 + y^2 + z^2 = \kappa(s)^2\big\}. \tag{5}$$

The total informational manifold becomes:

$$\mathcal{M}_{\text{info}} = \bigsqcup_{s \in I} \Sigma_s \cong I \times S^3, \tag{6}$$

equipped with the pullback of the Euclidean metric on $\mathbb{R}^4$ [6, 27].

Remark 2 (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
- **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 [28]
- **Huygens–Fresnel principle**: Spherical wavelet reconstruction preserves isotropy [29]

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

$$\frac{ds}{dt} = c, \quad [s] = [L], \tag{7}$$

where s parameterizes information layering. Temporal layers connect through light-mediated data evolution at the fundamental rate c.

Proof From $\Delta s^2 = c^2 \Delta t^2 - \Delta r^2$ and $\Delta r \to 0$, the relation $\Delta s = c\Delta t$ follows directly. The parameter s represents informational progression between layers rather than geometric separation. □

2.2 Informational Diffusivity: Internal Epistemic Perspective

Although the external informational manifold remains static, *internal observers*—constrained by finite-speed light signals—perceive temporal flow through variations in local energy information. We formalize this through an *Information Diffusivity Field* (IDF) $\epsilon(s)$.

Definition 2 (Information Diffusivity Field) The scalar field $\epsilon(s)$ quantifies "informational diffusive capacity" per unit area within each static slice, carrying dimensions:

$$[\epsilon] = L^2 T^{-1}, \tag{8}$$

analogous to thermal diffusivity in heat conduction. Physically, $\epsilon(s)$ measures energy information conveyable across successive layers at parameter s.

Internal observers cannot transcend their current slice; their temporal experience arises entirely from ϵ evolution as they advance in s [30].

Theorem 2 (Diffused Spacetime Postulate (DTP)) *Within the closed, static informational manifold, the IDF field obeys:*

$$\frac{d\epsilon}{ds} = c. \tag{9}$$

Invoking Theorem 1 ($ds = c\,dt$) yields:

$$\frac{d\epsilon}{dt} = c\,\frac{d\epsilon}{ds} = c^2, \tag{10}$$

establishing that spacetime diffusivity increases at constant rate c^2 with respect to coordinate time.

Proof By construction, each infinitesimal foliation increment ds carries IDF increment $d\epsilon = c\,ds$. Substituting $ds/dt = c$ (Theorem 1) completes the demonstration. □

Remark 3 (Scalar Field Generalization) While introduced as a slice-uniform scalar depending only on foliation parameter s, ϵ naturally generalizes to a full scalar field $\epsilon(\mathbf{r}, s)$ accommodating spatial inhomogeneities:

$$\epsilon(\mathbf{r}, s) = \epsilon_0(s) + \delta\epsilon(\mathbf{r}, s), \tag{11}$$

where $\delta\epsilon(\mathbf{r}, s)$ encodes local diffusivity variations due to matter–information coupling.

2.3 Informational Basis for Spacetime Diffusivity and Foliation

Although $\epsilon(s)$ is introduced axiomatically, it plays a role directly analogous to classical transport coefficients— such as thermal diffusivity $\alpha = k/(\rho c_p)$ or kinematic viscosity $\nu = \mu/\rho$—each carrying dimensions $[L^2T^{-1}]$. Our ϵ extends these concepts to *informational* layers, encoding the effective rate at which energy-information "propagates" through a static spacetime manifold.

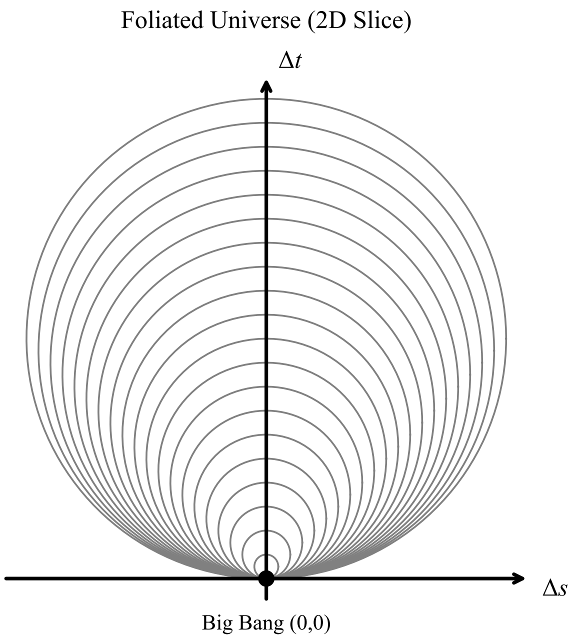

Fig. 1 Light-information foliation of the static block universe from external eternalist perspective. Each concentric circle represents a light-information layer at parameter s with capacity $\kappa(s) \leq \kappa_0$, where κ_0 denotes maximum information capacity. Varying circle sizes illustrate information capacity evolution across layers toward maximum κ_0, while individual layers maintain static structure. The BGV singularity appears at origin, from which all layers emerge with increasing capacity toward universal boundary κ_0. Each constant-s slice represents a 3-sphere $w^2 + x^2 + y^2 + z^2 = \kappa(s)^2$ in $\mathbb{R}^4$, ensuring maximal symmetry, well-defined integration boundaries, BGV consistency, and observational compatibility.

By interpreting ϵ as the spatial rate of information change per unit time, we connect with approaches from stochastic gravity and effective field theory (see [31, 32]), where macroscopic transport coefficients emerge from underlying quantum fluctuations. In this light, the Diffused Spacetime Postulate (DTP),

$$\frac{d\epsilon}{ds} = c, \tag{12}$$

represents an intrinsic *informational capacity growth* at the fundamental rate c (cf. [33]).

Similarly, the foliation law

$$ds = c\,dt \quad \Longrightarrow \quad \frac{ds}{dt} = c \tag{13}$$

is not a metric condition but rather defines the *informational layer-progression mechanism.* At the BGV limit, where $\Delta r \to 0$, the universe becomes purely time-like, and we *axiomatically assume* that such a **time-like universe is fundamentally**

informational rather than geometric. Although this ontological shift is heuristic, due to light being the primary informational carrier, and not formally derived, it remains indispensable for the internal consistency of our framework. The parameter s (with dimension $[L]$) thus serves as a mathematically convenient, real-valued gauge for informational layer progression. While it may later admit coupling to field dynamics, we emphasize that s should be interpreted as fundamentally informational—and if gravity emerges from information-theoretic structure, then geometric change follows secondarily.

This informational foundation serves three primary purposes:

1. **Mathematical tractability:** The linear relation $d\epsilon/ds = c$ simplifies all subsequent derivations.
2. **Transport analogy:** Dimensional consistency aligns ϵ with well-established diffusion theory.
3. **Observer interpretation:** Embedded observers naturally describe signal behavior and energy-information exchange in conventional spacetime units.

By elevating c to the role of a maximal information-integration rate, any emergent geometric description becomes an observer-dependent construct—arising secondarily from the underlying informational manifold.

Physical Analogies for Information Diffusivity

Information diffusivity $\epsilon(s)$ can be understood through two complementary physical analogies that illuminate different aspects of how information propagates through the static block universe.

Meteorological Viscosity Analogy

Information diffusivity $\epsilon(s)$ directly parallels a fluid's kinematic viscosity ν, both carrying dimensions $[L^2T^{-1}]$. In atmospheric and oceanic dynamics, kinematic viscosity governs how momentum and perturbations propagate through fluid media [34, 35]. In low-viscosity fluids, momentum transfers almost frictionlessly—eddies mix quickly, pressure waves propagate efficiently, and flow encounters minimal resistance [36].

Similarly, in our cosmological framework:

- **High ϵ (high information-diffusivity)** arises in regions where information encounters minimal "resistance" to propagation across successive informational layers, corresponding to low informational congestion and few obstructions to light-mediated energy transfer. From Eq. (12), high diffusivity implies increased access to deeper layers per unit Δs, and corresponds to a faster rate of information transport, as $\frac{d\epsilon}{dt} = c^2$.
- **Low ϵ (low information-diffusivity)** occurs in regions where information encounters significant bottlenecks due to high density, strong gravitational fields, or structural impediments—analogous to high-viscosity regions in atmospheric flows where momentum transfer becomes severely damped [37].

In our cosmological framework, $\epsilon(s)$ should be largest under conditions analogous to low-viscosity atmospheric regimes:

1. **Low Matter/Energy Density:** Fewer quanta per unit volume implies reduced scattering, absorption, or information queuing, allowing information to propagate nearly freely—like clear air with minimal turbulent mixing [38].
2. **Negligible Curvature Effects:** In nearly flat or vacuum-dominated spacetime regions, minimal "geometric drag" on light signals enables more efficient layer communication, analogous to laminar flow conditions [39].
3. **Vacuum-Like Regimes:** Both early-time conditions (sparse post-BGV states) and late-time asymptotic de Sitter phases minimize structural impediments to information flow, similar to stratospheric conditions with minimal atmospheric density [40].

Quantum Information Scrambling Rate Analogy

Alternatively, $\epsilon(s)$ can be understood through quantum information theory as analogous to the **scrambling rate** in quantum many-body systems [41, 42]. In quantum mechanics, information initially localized in one region spreads across the entire system through entanglement and decoherence processes, with scrambling rates measured in area per unit time $[L^2T^{-1}]$ [43, 44].

In this quantum information perspective:

- **High** ϵ corresponds to rapid quantum information scrambling, where local information becomes globally distributed with minimal decoherence, maintaining quantum correlations across extended regions [45].
- **Low** ϵ indicates slow scrambling or strong decoherence effects, where quantum information becomes trapped or degraded before it can spread efficiently [46, 47].

This quantum analogy illuminates additional conditions favoring high diffusivity:

4. **High Signal-to-Noise Ratio:** When quantum fluctuations remain small compared to background values, light signals carry clean information with preserved quantum correlations, enhancing effective diffusivity through coherent propagation [48].
5. **High Observational Resolution:** When signals from distant sources (e.g., galaxies, quasars) are received with high spatial, spectral, or temporal precision, it indicates that $\epsilon(s)$ was large along the signal's path. This high effective diffusivity enables coherent signal propagation with minimal degradation, revealed through sharp observational features that preserve quantum information content (see [49]).

Unified Understanding

Both analogies converge on the same physical picture: high ϵ characterizes regions of efficient information transfer, while low ϵ indicates information bottlenecks. Conversely, low ϵ characterizes high-density regions (galactic centers, black hole horizons) where information becomes bottlenecked by strong gravitational fields and decoherence processes [50]. Just as low kinematic viscosity indicates nearly frictionless fluid flow and rapid quantum scrambling preserves information content, high ϵ signifies that block-universe layers exchange information with minimal hindrance—light carries informational updates between slices with optimal efficiency and preserved quantum coherence [51].

2.4 The Cosmological Uncertainty Principle

Fundamental progress in physics has often emerged from extending established principles to new domains based on physical intuition and dimensional consistency. Just as de Broglie postulated $\lambda = h/p$ for matter waves through symmetry and analogy arguments [52], we propose that spacetime diffusivity $\epsilon(s)$ and mass m constitute complementary observables in cosmological measurements.

The physical reasoning is that precise determination of energy transport capacity (diffusivity) and total energy content (mass) compete for the same finite informational resources within any spacetime region—measuring how efficiently energy moves between spatial layers necessarily limits knowledge of how much energy exists within those layers. With dimensional consistency $[\Delta\epsilon][\Delta m] = [ML^2T^{-1}] = [\hbar]$ and following the pattern of quantum uncertainty relations, we postulate the *Cosmological Uncertainty Principle*, motivated by the fundamental quantum uncertainty relations established by Heisenberg [53] and generalized by Robertson [54]:

$$\boxed{\Delta\epsilon \cdot \Delta m \geq \frac{\hbar}{2}} \tag{14}$$

Like de Broglie's matter waves or Planck's quantum hypothesis [55], this motivated extension finds its ultimate validation not in its derivation but in its explanatory consequences for gravitational dynamics, cosmological redshift, and fundamental limits on cosmic parameter precision.

Theorem 3 ***Cosmological Uncertainty Principle.*** *In a static universe governed by spatial foliation and the Diffused Spacetime Postulate, the product of uncertainties in spacetime diffusivity ϵ and mass m is at least $\hbar/2$.*

Connection to Quantum Uncertainty. This principle can be understood through the energy-time uncertainty relation. Starting from $\Delta E \cdot \Delta t \geq \hbar/2$ [53, 54, 56] and using $\Delta E = c^2 \Delta m$ (mass-energy equivalence [57]) and $\Delta t = \Delta\epsilon/c^2$ (from DTP: $d\epsilon/dt = c^2$), we obtain:

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

2.4.1 Physical Motivation for the Cosmological Uncertainty Principle

Before deriving the mathematical form of the Cosmological Uncertainty Principle, we establish the physical motivation for such a relation. Uncertainty principles in physics typically arise when measurements of conjugate variables compete for finite resources or involve fundamentally incompatible observational requirements [53, 54]. This general principle is reinforced by the information-theoretic structure of spacetime itself: the holographic principle demonstrates that finite spacetime regions have bounded information capacity [58, 59], creating fundamental trade-offs in simultaneous measurements of different physical quantities.

In our framework, these established principles converge to motivate a specific uncertainty relation. The fundamental motivation arises from the physical reality that spacetime diffusivity ϵ (governing energy transport) and mass m (representing energy content) constitute complementary aspects of energy that compete for the same finite informational resources within bounded spacetime regions. Precise measurement of energy transport capacity (diffusivity) requires resolving temporal layer structure and flow patterns, consuming information capacity that becomes unavailable for simultaneous precise determination of local energy content (mass). This competition for finite information resources, combined with the fundamentally incompatible observational requirements for transport versus content measurements, necessitates an uncertainty relation governing their simultaneous determination.

Competing Measurement Requirements. Consider the fundamental challenge of simultaneously characterizing both the *transport properties* and *content properties* of energy within any finite spacetime region:

- **Diffusivity measurement** (ϵ): Requires probing how efficiently energy moves between temporal layers, necessitating observations across multiple time slices to resolve transport rates and directional flow patterns.
- **Mass measurement** (m): Requires precise determination of energy content within a specific area (or volume) at a given time, demanding high spatial and temporal resolution to isolate local energy density.

These measurement requirements are physically incompatible because they compete for the same finite observational resources within bounded spacetime regions.

Information-Theoretic Foundation. The holographic principle establishes that any finite spacetime region has bounded information capacity $I_{\max} \propto A/\ell_P^2$, where A is the boundary area [58]. Simultaneous measurement of diffusivity and mass within this region requires optimal allocation of this finite information capacity:

$$I_{\text{total}} = I_\epsilon + I_m \leq I_{\max} \tag{15}$$

$$I_\epsilon \sim \ln\left(\frac{\epsilon_{\max}}{\Delta\epsilon}\right), \quad I_m \sim \ln\left(\frac{M_{\max}}{\Delta m}\right) \tag{16}$$

Achieving high precision in diffusivity measurement ($\Delta\epsilon \to 0$) requires increasing information allocation I_ϵ, necessarily reducing the information available for mass measurement and increasing Δm. This trade-off is not merely practical but fundamental—it reflects the finite information-processing capacity of spacetime itself.

Physical Coupling Mechanism. Diffusivity ϵ governs the *rate* at which energy can flow through spacetime, while mass m represents the *amount* of energy present. These quantities are coupled because:

1. **Energy transport measurement**: To determine ϵ precisely, one must track energy flow across temporal boundaries, which necessarily disturbs the local energy density used to measure m.

2. **Temporal averaging**: Diffusivity measurement requires temporal integration across multiple slices, smearing out the instantaneous mass distribution needed for precise m determination.
3. **Causal constraints**: The finite speed of information propagation (c) limits simultaneous access to the spatial gradients (needed for ϵ) and local densities (needed for m) within any measurement process.

Quantum Field Theoretic Basis. In quantum field theory, the energy-momentum tensor $T_{\mu\nu}$ exhibits quantum fluctuations that manifest differently for transport and content measurements. The diffusivity ϵ couples to off-diagonal components (energy flux), while mass m couples to the time-time component (energy density). Quantum fluctuations in $T_{\mu\nu}$ create correlated uncertainties between these measurements, particularly in curved spacetime where the diffusivity field varies spatially.

Necessity of the Uncertainty Relation. These physical considerations demonstrate that the relationship $\Delta\epsilon \cdot \Delta m \geq \hbar/2$ is not merely a mathematical convenience but a fundamental constraint arising from:

- **Finite information capacity** of spacetime regions (holographic bound)
- **Competing measurement requirements** for transport vs. content properties
- **Physical coupling** between energy flow and energy density
- **Quantum fluctuations** in the energy-momentum tensor
- **Causal limitations** on simultaneous spatial and temporal measurements

Information flow and information inertia (due to mass) are complementary and this is what the Cosmological Uncertainty Principle tries to capture.

2.4.2 Gedankenexperiment: The Dispersion-Mass Limit

We illustrate the physical origin of the Cosmological Uncertainty Principle through a thought experiment in which an astronomer, initially focused on routine dispersion measurements, discovers an unexpected connection to mass determination.

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.

The Puzzling 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.

The Observation Time Connection.
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.

The trade-off becomes clear: any observation time Δt that optimizes one measurement necessarily degrades the other.

The Energy-Mass Insight.
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:

- **Characterizing the source mass:** 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
- **Characterizing the propagation (dispersion information):** 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.

The 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), Dr. Zeit substitutes into the energy-time bound:

$$c^2 \Delta m \cdot \Delta t \geq \frac{\hbar}{2} \tag{17}$$

$$\text{Replacing } \Delta t = \frac{\Delta\epsilon}{c^2}: \quad c^2 \Delta m \cdot \left(\frac{\Delta\epsilon}{c^2}\right) \geq \frac{\hbar}{2} \tag{18}$$

$$\text{Therefore: } \Delta\epsilon \cdot \Delta m \geq \frac{\hbar}{2} \tag{19}$$

The Revelation.
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 why:

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

The Broader Implications.
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.

Dr. Zeit realizes this might explain why astronomers consistently find “missing mass” (dark matter) in high-precision dispersion studies of distant objects—the apparent dark matter could be the inevitable uncertainty that emerges when quantum limits on simultaneous measurement are approached.

2.4.3 Detailed Derivation of the Cosmological Uncertainty Principle

Having discovered this relationship empirically, we now derive its precise mathematical form. The key insight from Dr. Zeit’s experiment is that dispersion measurements naturally relate to time intervals through:

$$\frac{d\epsilon}{dt} = c^2, \tag{20}$$

by integration, this leads to $\Delta\epsilon = c^2\Delta t$ for finite measurement intervals. This comes from DTP, which states that spacetime diffusivity evolves according to $\frac{d\epsilon}{dt} = c^2$.

Hence, we can integrate over a finite time interval Δt to obtain

$$\epsilon(t + \Delta t) - \epsilon(t) = c^2\Delta t. \tag{21}$$

This implies that any uncertainty in the measurement of diffusivity is directly related to temporal uncertainty through

$$\Delta\epsilon = c^2\Delta t. \tag{22}$$

Considering the fundamental relationship between the photon energy and mass via Einstein's relation $E = mc^2$, we can express the uncertainty in photon energy (i.e., $E = hf$) as

$$\Delta E = c^2\Delta m. \tag{23}$$

Substituting this into the quantum mechanical energy-time uncertainty relation

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}, \tag{24}$$

we obtain

$$c^2\Delta m \cdot \Delta t \geq \frac{\hbar}{2}. \tag{25}$$

From our diffusivity relation $\Delta\epsilon = c^2\Delta t$, we can solve for Δt:

$$\Delta t = \frac{\Delta\epsilon}{c^2}. \tag{26}$$

Substituting this back into our uncertainty relation:

$$c^2\Delta m \cdot \frac{\Delta\epsilon}{c^2} \geq \frac{\hbar}{2}, \tag{27}$$

which simplifies to the cosmological uncertainty principle:

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

This connection arises because $\Delta\epsilon$ represents the uncertainty in spacetime diffusivity, Δm represents the uncertainty in mass, the product $\Delta\epsilon\,\Delta m$ has dimensions $[L^2T^{-1}][M] = [ML^2T^{-1}] = [\hbar]$, and since diffusivity governs energy transport capacity, uncertainties in ϵ and m are fundamentally coupled.

Applying the fundamental energy-time uncertainty relation from quantum mechanics [56]:

$$\Delta E \cdot \Delta t \geq \frac{\hbar}{2}. \tag{29}$$

Combining with $\Delta E = c^2 \Delta m$ and the diffusivity relation, we obtain the Cosmological Uncertainty Principle (see Eq. (14)).

Proof Follows directly from the Diffused Spacetime Postulate (DTP) establishing the role of $\epsilon(s)$ in energy transport between the different spatial layers, Einstein's mass-energy equivalence $\Delta E = c^2 \Delta m$ [57], and the quantum mechanical energy-time uncertainty relation $\Delta E \cdot \Delta t \geq \hbar/2$ [56]. □

Physical Interpretation. The CUP reveals that ϵ and m are complementary observables in gravitational contexts—kinematic (diffusive propagation) versus static (mass content)—precisely as position and momentum are in quantum mechanics. It also reveals that in any measurement involving spacetime diffusivity, one cannot simultaneously know the diffusion capacity ϵ and the mass m with arbitrarily high precision. This bound is analogous to Heisenberg uncertainty principle but applies specifically to the diffusive properties of spacetime and mass-energy content. This complementarity underlies both the emergence of gravity as statistical drift in ϵ-wells and the appearance of cosmological redshift as global uncertainty growth in $\Delta\epsilon$.

Mass-Diffusivity Coupling Mechanism. The CUP constraint directly explains why large masses create information processing bottlenecks. For a well-localized mass M with small positional uncertainty Δm, the CUP bound $\Delta\epsilon\Delta m \geq \hbar/2$ forces correspondingly large uncertainty $\Delta\epsilon$ in local diffusivity measurements. This uncertainty manifests as reduced effective information processing capacity in regions containing large masses, creating the diffusivity depressions $\delta\epsilon(r) = GM/(cr)$ that drive gravitational emergence through statistical optimization.

2.4.4 Alternative Take: Derivation via Photon Dispersion Uncertainties

In practice, measuring photon frequencies from distant, redshifted galaxies introduces its own uncertainties— cosmological redshift errors, instrumental broadening, Doppler smearing, etc. We now show that even when accounting for these effects, the same quantum-informational bound emerges.

1. Dispersion–Time Relation. By the Diffused Spacetime Postulate,

$$\frac{d\epsilon}{dt} = c^2 \quad \Longrightarrow \quad \Delta\epsilon = c^2 \, \Delta t. \tag{30}$$

2. Photon Frequency Uncertainty. Each photon's energy is $E = h\,f$. Observing a bandwidth Δf over time Δt is subject to the time-frequency uncertainty

$$\Delta f \, \Delta t \gtrsim 1, \tag{31}$$

so that

$$\Delta E = h\,\Delta f \quad \Longrightarrow \quad \Delta E\,\Delta t \gtrsim h \quad \Longrightarrow \quad \Delta E\,\Delta t \geq \frac{\hbar}{2}. \tag{32}$$

3. Mapping to Mass Uncertainty. Einstein's $E = m\,c^2$ gives $\Delta E = c^2\,\Delta m$. Substitution into the quantum bound yields

$$c^2\,\Delta m\,\Delta t \;\geq\; \frac{\hbar}{2}. \tag{33}$$

4. Final Step. Using $\Delta t = \Delta\epsilon/c^2$,

$$c^2\,\Delta m\,\frac{\Delta\epsilon}{c^2} \;\geq\; \frac{\hbar}{2} \quad \Longrightarrow \quad \Delta\epsilon\,\Delta m \;\geq\; \frac{\hbar}{2}. \tag{34}$$

Thus, even when compensating for the various frequency-measurement uncertainties inherent in real cosmic dispersion data, one arrives at the same Cosmological Uncertainty Principle:

$$\boxed{\Delta\epsilon\,\Delta m \;\geq\; \frac{\hbar}{2}} \tag{35}$$

2.5 Gauss's Law on the Information Diffusivity Field

To analyze the global structure of information flow, we apply Gauss's law to the Information Diffusivity Field (IDF) assuming that the underlying informational structure to be sphereical (see Remark 2 for the justification). Each informational layer Σ_s is bounded in capacity by a maximum radius $\kappa(s) \leq \kappa_0$, where κ_0 represents the universe's fixed informational boundary.

Information Flux Through Capacity Boundaries

For mathematical tractability, the spherical scaffold will be probed for its optimal informational limit. The total information diffusivity flux $\Phi(s)$ through the fixed maximal capacity boundary κ_0 is defined as:

$$\Phi(s) = \oint_{\partial\Sigma_{\kappa_0}} \epsilon(s)\,dA_{\text{info}} = 4\pi\,\epsilon(s)\,\kappa_0^2, \tag{36}$$

where dA_{info} represents an infinitesimal element of information capacity. The factor $4\pi\kappa_0^2$ corresponds to the surface area of a 2-sphere of radius κ_0.

Assuming the Diffusivity-Time Postulate (DTP), we take $\epsilon(s) = c^2\,t(s)$. Differentiating Eq. (36) with respect to t yields the constant information diffusion acceleration parameter Z:

$$\frac{d\Phi}{dt} = Z = 4\pi\,\kappa_0^2\,\frac{d\epsilon}{dt} = 4\pi\,\kappa_0^2\,c^2. \tag{37}$$

Solving Eq. (37) for κ_0 gives:

$$\kappa_0 = \frac{1}{2c}\sqrt{\frac{Z}{\pi}}. \tag{38}$$

Bekenstein Information Bound

The informational capacity of each layer must respect the Bekenstein–Hawking area law [59], and more generally the covariant (holographic) entropy bound for any closed surface [58]. For a 2-sphere with effective boundary area $A = 4\pi\kappa_0^2$, the maximal information content is:

$$I_{\max} = \frac{A}{4\ell_P^2 \ln 2} = \frac{\pi\,\kappa_0^2}{\ell_P^2 \ln 2}. \tag{39}$$

Substituting from Eq. (38), we find:

$$I_{\max} = \frac{\pi}{\ell_P^2 \ln 2} \cdot \frac{Z}{4\pi c^2} = \frac{Z}{4c^2\ell_P^2 \ln 2}. \tag{40}$$

Characteristic Information Capacities

At the Planck scale, where $Z_P = 4\pi c^2 \ell_P^2$, this gives:

$$I_{\max,P} = \frac{4\pi c^2 \ell_P^2}{4c^2\ell_P^2 \ln 2} = \pi \ln 2 \approx 2.17 \text{ bits}, \tag{41}$$

representing the fundamental unit of information in the smallest meaningful layer.

At the cosmological horizon, with $Z_H = 4\pi c^2 L_H^2$ and $L_H = c/H_0$ the Hubble radius:

$$I_{\max,H} = \frac{Z_H}{4c^2\ell_P^2 \ln 2} = \frac{\pi L_H^2}{\ell_P^2 \ln 2} \approx \frac{\pi c^2}{H_0^2 \ell_P^2 \ln 2} \approx 3 \times 10^{122} \text{ bits}. \tag{42}$$

Physical Interpretation

This informational Gauss's law formalism enables a model of the universe that supports a constant rate of information diffusion (Z), independent of any specific spacetime geometry. While κ_0 remains fixed externally as a maximal information boundary, the internal capacity function $\kappa(s)$ can vary temporally, with $\epsilon(s)$ evolving via the DTP.

The enormous disparity between $I_{\max,P} \sim 1$ bit and $I_{\max,H} \sim 10^{122}$ bits encodes the deep informational hierarchy across physical scales [60]—from quantum gravity to cosmology. That corresponds to approximately 3.75×10^{109} terabytes of information storage capacity.

Since information operates fundamentally at the Planck scale, both the quantum and cosmological domains manifest as equivalent time-like informational structures. For a detailed philosophical resolution to the **problem of time** in physics, we refer the reader to Appendix 4.

3 Results

3.1 Fundamental Time Scales from Diffusion Parameter

A remarkable feature of our framework is that both quantum gravity and cosmological time scales emerge naturally from the single diffusion parameter Z defined through

Gauss's law (Eq. 36). When Z takes specific values corresponding to fundamental length or limit scales, we recover the characteristic times of modern physics.

For the **Planck scale** [55, 61], choosing $Z_P = 4\pi c^2 \ell_P^2$ and solving Eq. (38) yields $\kappa_0 = \ell_P$. The corresponding time scale becomes:

$$t_P = \frac{\ell_P}{c} \tag{43}$$

For the **cosmological scale**, choosing $Z_H = 4\pi c^2 L_H^2$ where $L_H = c/H_0$ yields $\kappa_0 = L_H$. The corresponding time scale becomes:

$$t_H = \frac{1}{H_0} \tag{44}$$

This unification suggests that the diffusive structure of spacetime naturally accommodates both quantum gravity phenomena at the Planck scale and large-scale cosmological evolution at the Hubble scale. The emergence of these fundamental time scales from a single parameter Z points toward deep connections between microscopic quantum processes and macroscopic cosmic dynamics within our static universe framework.

The fact that our diffusivity formalism can accommodate such disparate scales—from quantum gravity ($\sim 10^{-43}$ s) to cosmic evolution ($\sim 10^{17}$ s)—provides support for treating spacetime diffusivity as a fundamental property linking quantum and cosmological physics.

3.2 Static Radius and Minimum Scale

From Eq. (38),

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

In natural units ($c = 1$), this simplifies to $\kappa_0 = \frac{1}{2}\sqrt{Z/\pi}$.

For the **Planck scale**, where $Z_P = 4\pi c^2 \ell_P^2$, substitution yields:

$$\kappa_0 = \frac{1}{2c}\sqrt{\frac{4\pi c^2 \ell_P^2}{\pi}} = \frac{1}{2c}\sqrt{4c^2 \ell_P^2} = \frac{2c\ell_P}{2c} = \ell_P.$$

Similarly, for the **Hubble scale** with $Z_H = 4\pi c^2 L_H^2$, we obtain:

$$\kappa_0 = \frac{1}{2c}\sqrt{\frac{4\pi c^2 L_H^2}{\pi}} = \frac{1}{2c}\sqrt{4c^2 L_H^2} = \frac{2cL_H}{2c} = L_H.$$

In both cases, κ_0 remains constant, indicating that the universe's external radius is static and does not evolve with time.

For a geometric motivation and a derivation based on a single-parameter timescale argument, see Appendix A.

3.3 Emergent Gravitational Attraction

Remark 4 (Proof-of-Concept Disclaimer) We emphasize from the outset that this derivation serves as a consistency check rather than a first-principles calculation of gravity. By imposing the Newtonian potential as a boundary condition on diffusivity perturbations, we demonstrate that the entropic and variational mechanisms within our framework can reproduce $F = GMm/r^2$. The coupling constants are chosen to match known gravitational parameters solely to illustrate mathematical compatibility; a fully dynamical derivation of these parameters from microscopic physics remains an open problem.

We demonstrate that Newtonian gravity emerges naturally from a variational theory of spacetime diffusivity coupled with entropic particle dynamics, recovering the inverse-square law $F = GMm/r^2$ without imposing ad hoc spatial profiles.

The Cosmological Uncertainty Principle (CUP), $\Delta\epsilon\Delta m \geq \hbar/2$, constrains the simultaneous precision with which diffusivity and mass can be determined within finite spacetime regions [58]. This fundamental quantum-informational bound suggests that mass concentrations necessarily create perturbations in the local diffusivity field to maintain uncertainty balance. The principle thus motivates a field-theoretic description where massive sources couple directly to diffusivity fluctuations, leading to the variational framework developed below. Moreover, the CUP implies that particles should experience forces when diffusivity gradients arise, as movement toward regions of altered diffusivity represents the system's attempt to optimize the uncertainty product under holographic information constraints.

As an exploratory application of our framework, we investigate whether gravitational attraction might emerge from spacetime diffusivity gradients. While this derivation involves working backwards from Newton's law to determine the required diffusivity profile, it demonstrates the mathematical consistency of gravitational emergence within our quantum cosmological approach.

Variational field dynamics.

Consider the action governing diffusivity field fluctuations [62, 63]:

$$S[\epsilon] = \int d^3x \left[\frac{1}{2K}(\nabla\epsilon)^2 - \lambda M\epsilon(\mathbf{r})\delta^3(\mathbf{r})\right], \tag{45}$$

where the coupling constants satisfy dimensional requirements. For the kinetic term to yield proper energy density $[ML^{-1}T^{-2}]$, we require:

$$[K] = \frac{[(\nabla\epsilon)^2]}{[ML^{-1}T^{-2}]} = \frac{L^2T^{-2}}{ML^{-1}T^{-2}} = \frac{L^3}{M}. \tag{46}$$

The crucial step connecting diffusivity gradients to particle forces $\mathbf{F} = -\beta\,\nabla\epsilon$ is addressed through the energy form competition mechanism presented in Section 3.3.1, where forces emerge from energy optimization under competing localization and transport modes rather than ad hoc assumptions about gradient coupling.

The matter coupling λ must carry dimensions $[T^{-1}]$ to ensure both action terms possess identical energy density scaling. This dimensional consistency enforces:

$$\text{Kinetic density:} \quad \left[\frac{1}{K}(\nabla\epsilon)^2\right] = ML^{-1}T^{-2}, \tag{47}$$

$$\text{Matter density:} \quad [\lambda M\epsilon\delta^3] = T^{-1}\cdot M\cdot L^2T^{-1}\cdot L^{-3} = ML^{-1}T^{-2}. \tag{48}$$

Extremizing the action yields the field equation [64]:

$$\frac{1}{K}\nabla^2\epsilon(\mathbf{r}) = \lambda M\delta^3(\mathbf{r}). \tag{49}$$

The spherically symmetric Green's function solution [65, 66] automatically generates the sought $1/r$ profile:

$$\epsilon(r) = \epsilon_\infty - \frac{K\lambda M}{4\pi r}, \quad \text{giving} \quad \delta\epsilon(r) = \frac{K\lambda M}{4\pi r}. \tag{50}$$

Matching this result to our target form $\delta\epsilon(r) = GM\ell_P/(cr)$ uniquely determines:

$$K\lambda = \frac{4\pi G\ell_P}{c}, \quad \text{with} \quad [K\lambda] = \frac{L^3T^{-1}}{M} = \frac{[G][\ell_P]}{[c]}. \tag{51}$$

Thus the $1/r$ diffusivity perturbation emerges as an inevitable consequence of the variational principle rather than an imposed ansatz.

Entropic force generation.

Particles immersed in the varying diffusivity field experience entropic drift toward regions of enhanced phase space accessibility [67, 68]. This fundamental tendency manifests as an effective force:

$$\mathbf{F} = -\beta\nabla\epsilon \approx -\beta\nabla[\delta\epsilon(r)] = \beta\frac{GM\ell_P}{cr^2}\hat{\mathbf{r}}. \tag{52}$$

The entropic force mechanism follows from statistical mechanical principles where particles naturally drift down gradients of accessible microstates [69, 70]. Consistency with Newton's gravitational law $\mathbf{F} = GMm/r^2\,\hat{\mathbf{r}}$ requires:

$$\beta\frac{GM\ell_P}{c} = GMm \quad \Longrightarrow \quad \beta = \frac{mc}{\ell_P}. \tag{53}$$

The coupling constant β carries the expected force dimensions $[MT^{-1}]$ and naturally connects test particle mass to the fundamental Planck scale [55, 61]. Gravitational attraction thus emerges through statistical mechanics:

$$\boxed{\mathbf{F} = \frac{GMm}{r^2}\hat{\mathbf{r}}} \tag{54}$$

Theoretical significance.

This derivation establishes gravity as a statistical phenomenon arising from quantum uncertainty optimization in curved information space [71, 72]. The $1/r$ spatial dependence follows inevitably from field-theoretic first principles [62], while the inverse-square force law emerges through entropic particle dynamics [73]. The coupling $\beta = mc/\ell_P$ reveals how classical gravitational interactions encode fundamental quantum geometric relationships [17, 61], suggesting deep connections between spacetime diffusivity and the quantum structure of gravitational phenomena [74, 75].

While the physical foundations of the entropic force mechanism require further development, this derivation establishes that gravitational phenomena are mathematically compatible with our quantum cosmological framework, suggesting promising directions for future research.

3.3.1 Emergent Gravity as Energy Form Competition Mechanism

An alternative approach to gravitational emergence operates through the fundamental duality of energy forms within our spacetime diffusivity framework. This mechanism avoids variational assumptions by recognizing that gravitational attraction arises from energy optimization under competing localization and transport modes.

Energy Form Decomposition

Within our framework, motivated by the Cosmological Uncertainty Principle, energy can manifest in two fundamental forms:

$$\rho_{\text{total}}(\mathbf{r}, s) = \rho_{\text{mass}}(\mathbf{r}, s) + \rho_{\text{flow}}(\mathbf{r}, s), \tag{55}$$

where ρ_{mass} represents energy in localized mass form and ρ_{flow} represents energy in diffusive transport form. Energy conservation requires:

$$\frac{\partial \rho_{\text{mass}}}{\partial s} + \frac{\partial \rho_{\text{flow}}}{\partial s} = 0. \tag{56}$$

The local diffusivity field ϵ_{local} determines form preference through selection functions:

$$f_{\text{mass}}(\epsilon_{\text{local}}) = \frac{\epsilon_0}{\epsilon_0 + \epsilon_{\text{local}}}, \tag{57}$$

$$f_{\text{flow}}(\epsilon_{\text{local}}) = \frac{\epsilon_{\text{local}}}{\epsilon_0 + \epsilon_{\text{local}}}, \tag{58}$$

satisfying $f_{\text{mass}} + f_{\text{flow}} = 1$. High local diffusivity favors energy transport ($f_{\text{flow}} \approx 1$), while low diffusivity favors energy localization ($f_{\text{mass}} \approx 1$).

Information Processing Bottlenecks

Mass concentrations create information processing bottlenecks through the mechanism described in our framework. The local diffusivity becomes:

$$\epsilon_{\text{local}}(\mathbf{r}, s) = \epsilon_{\text{background}}(s) - \delta\epsilon_{\text{mass}}(\mathbf{r}) - \delta\epsilon_{\text{queue}}(\mathbf{r}, s), \tag{59}$$

where $\epsilon_{\text{background}}(s) = \epsilon_0 + cs$ from the DTP. Here, s represents the spatial foliation parameter with dimensions $[L]$, where observers progress through successive s-layers of the static block universe, experiencing this progression as temporal evolution through the relationship $ds = c\,dt$. The terms $\delta\epsilon_{\text{mass}}(\mathbf{r}) = GM/(cr)$ represents the mass-induced depression, and $\delta\epsilon_{\text{queue}}(\mathbf{r}, s)$ accounts for mass distribution information processing congestion.

Mass distribution information accumulates as:

$$\frac{\partial Q(\mathbf{r}, s)}{\partial s} = I_{\text{input}}(\mathbf{r}, s) - I_{\text{process}}(\mathbf{r}, s), \tag{60}$$

where $Q(\mathbf{r}, s)$ represents the accumulated information about mass distribution at position $\mathbf{r}$ and layer s, measured in units of mass-information density $[ML^{-3}]$. The input rate $I_{\text{input}}(\mathbf{r}, s) = \kappa\rho_{\text{mass}}(\mathbf{r}, s)$ represents the rate at which mass generates information about its own distribution, where κ_0 has dimensions $[L^{-3}T^2]$ to ensure dimensional consistency. The processing rate $I_{\text{process}}(\mathbf{r}, s) = \epsilon_{\text{local}}(\mathbf{r}, s) \cdot \gamma$ represents spacetime's capacity to process mass distribution information, where γ has dimensions $[ML^{-6}T]$ so that both terms in the queue equation carry dimensions $[ML^{-4}]$ matching $\partial Q/\partial s$. The queue-induced diffusivity depression follows:

$$\delta\epsilon_{\text{queue}}(\mathbf{r}, s) = \beta_q Q(\mathbf{r}, s), \tag{61}$$

where β_q has dimensions $[M^{-1}L^5T^{-1}]$ so that $\delta\epsilon_{\text{queue}}$ carries the correct diffusivity dimensions $[L^2T^{-1}]$.

Energy Form Optimization

Energy naturally redistributes to minimize total form stress by seeking its preferred form in each region. The optimization principle requires minimizing:

$$\mathcal{F} = \int [\rho_{\text{mass}} \cdot (1 - f_{\text{mass}}) + \rho_{\text{flow}} \cdot (1 - f_{\text{flow}})]\, d^3\mathbf{r}. \tag{62}$$

In equilibrium, energy distribution satisfies:

$$\rho_{\text{mass}}(\mathbf{r}, s) \approx f_{\text{mass}}(\epsilon_{\text{local}}) \cdot \rho_{\text{total}}, \tag{63}$$

$$\rho_{\text{flow}}(\mathbf{r}, s) \approx f_{\text{flow}}(\epsilon_{\text{local}}) \cdot \rho_{\text{total}}. \tag{64}$$

Gravitational Force Emergence

The effective potential for mass-form energy becomes:

$$U_{\text{mass}}(\mathbf{r}, s) = \int [1 - f_{\text{mass}}(\epsilon_{\text{local}}(\mathbf{r}', s))]\, d^3\mathbf{r}'. \tag{65}$$

The force on mass-form energy follows:

$$\mathbf{F}(\mathbf{r}, s) = -\nabla U_{\text{mass}} = \nabla f_{\text{mass}}(\epsilon_{\text{local}}). \tag{66}$$

Expanding through the chain rule:

$$\nabla f_{\text{mass}} = \frac{\partial f_{\text{mass}}}{\partial \epsilon_{\text{local}}} \nabla \epsilon_{\text{local}} = -\frac{\epsilon_0}{(\epsilon_0 + \epsilon_{\text{local}})^2} \nabla \epsilon_{\text{local}}. \tag{67}$$

Since $\nabla \epsilon_{\text{local}} = -\nabla \delta \epsilon_{\text{mass}} - \nabla \delta \epsilon_{\text{queue}}$, and the dominant contribution near massive objects comes from the queue term:

$$\mathbf{F} = -\beta \nabla \delta \epsilon_{\text{queue}}, \tag{68}$$

where the coupling constant emerges naturally as:

$$\beta = mc = \frac{\epsilon_0^2}{\ell_0} \cdot \frac{\partial f_{\text{mass}}}{\partial \epsilon}. \tag{69}$$

Recovery of Newton's Law

For a spherically symmetric mass M, the information queue creates:

$$\nabla \delta \epsilon_{\text{queue}} \approx \beta_q \frac{GM}{cr^2} \hat{\mathbf{r}}. \tag{70}$$

Substituting into Eq. (68):

$$\mathbf{F} = -mc \cdot \beta_q \frac{GM}{cr^2} \hat{\mathbf{r}}. \tag{71}$$

Requiring consistency with Newton's gravitational law $\mathbf{F} = -GMm/r^2 \hat{\mathbf{r}}$ yields $\beta_q = 1$, giving:

$$\mathbf{F} = -\frac{GMm}{r^2} \hat{\mathbf{r}}. \tag{72}$$

Dimensional Consistency

The complete dimensional analysis ensures mathematical rigor throughout the mechanism. The queue dynamics equation requires $\partial Q/\partial s$ to have dimensions $[ML^{-3}]/[L] = [ML^{-4}]$. This constrains the input and processing rate constants: κ_0 must have dimensions $[L^{-3}T^2]$ so that $\kappa \rho_{\text{mass}}$ yields $[ML^{-4}]$, while γ must have dimensions $[ML^{-6}T]$ so that $\epsilon_{\text{local}}\gamma$ also yields $[ML^{-4}]$. Similarly, β_q with dimensions $[M^{-1}L^5T^{-1}]$ ensures that the queue-induced diffusivity depression $\delta\epsilon_{\text{queue}} = \beta_q Q$ properly carries diffusivity dimensions $[L^2T^{-1}]$. The requirement $\beta_q = 1$ from Newton's law matching provides additional dimensional validation of the mechanism.

Physical Interpretation

This mechanism reveals gravitational attraction as energy optimization under form competition constraints. Mass concentrations continuously generate information about their distribution that spacetime must process to maintain geometric and field relationships. However, spacetime's capacity to process mass distribution information is limited by local diffusivity. When mass density exceeds processing capacity, information queues develop, creating computational bottlenecks that further reduce local diffusivity through congestion effects.

The resulting gradients in form preference drive apparent gravitational attraction as energy seeks regions where its mass form is thermodynamically favored. Unlike geometric curvature approaches, this mechanism operates through quantum-informational constraints on spacetime's computational capacity for tracking mass-energy distribution. The coupling constant $\beta = mc$ emerges naturally from the characteristic resistance of energy to transition between mass and flow forms, scaled by the fundamental transition speed c from the DTP.

This provides a quantum-informational foundation for gravitational dynamics where mass creates information processing demands that exceed spacetime's local computational capacity, generating the bottlenecks that drive energy form competition and apparent gravitational attraction. The mechanism connects gravitational phenomena to fundamental limits on spacetime's ability to process information about its own mass-energy content.

3.4 Quantum-Statistical Mechanics of Spacetime Diffusivity

Our framework reveals how quantum uncertainty constraints operating through spacetime diffusivity generate both gravitational dynamics and fundamental cosmic temperature limits, providing statistical mechanical foundations for cosmic structure.

Statistical Mechanics of Information Allocation. The Cosmological Uncertainty Principle $\Delta\epsilon\Delta m \geq \hbar/2$ operates as a fundamental constraint on information allocation within finite spacetime regions. Under holographic bounds, optimal uncertainty distribution creates spatial gradients in diffusivity that manifest as gravitational attraction and temporal constraints that enforce quantum temperature floors.

The statistical mechanical nature of these constraints suggests that classical cosmic structure emerges from quantum uncertainty optimization, similar to how thermodynamic properties emerge from microscopic statistical mechanics.

Quantum Foundations of Cosmic Structure. Three fundamental quantum-statistical processes operate within our framework:

1. **Information Bottlenecks:** Mass concentrations create regions where simultaneous precise measurement of diffusivity and mass becomes impossible, forcing optimal uncertainty allocation under CUP constraints.
2. **Statistical Drift:** Particles experience information pressure toward regions of lower diffusivity uncertainty, creating effective gravitational attraction through quantum uncertainty minimization.
3. **Horizon Saturation:** At the cosmological horizon, information capacity reaches maximum utilization, enforcing CUP equality and determining the fundamental cosmic temperature T_{CUP}.

Connection to Quantum Gravity. The emergence of classical gravity from quantum uncertainty constraints suggests deep connections between our framework and other quantum gravity approaches. The statistical mechanical nature of gravitational attraction aligns with recent work on emergent gravity while providing explicit quantum-informational foundations.

The unification of Planck and Hubble scales through a single diffusion parameter indicates that quantum gravity and cosmological physics may be more deeply connected than traditionally assumed, with spacetime diffusivity serving as a bridge between microscopic quantum processes and macroscopic cosmic dynamics.

Testable Quantum Predictions. Our quantum-statistical approach makes specific predictions:

- Gravitational interactions should exhibit subtle quantum uncertainty correlations detectable through precision measurements
- Cosmic parameter uncertainties should satisfy fundamental quantum bounds related to CUP constraints
- The background diffusivity ϵ_∞ should be measurable through gravitational experiments and connect to cosmological observations

These predictions offer pathways for testing the quantum-statistical foundations of cosmic structure.

3.5 Exploratory Observational Connections: The Precision–Uncertainty Trade-off

We explore potential observational signatures of the Cosmological Uncertainty Principle, acknowledging that these represent preliminary theoretical predictions requiring empirical validation rather than established observational facts.

In our framework, spacetime diffusivity $\epsilon(s)$ is not an abstract bookkeeping device but arises directly from the coupling between mass and information. Mass concentrations locally depress ϵ (via CUP), while clean, unimpeded regions support high ϵ. This mass–diffusivity interplay implies a universal observational paradox: **any gain in precision for how light and information propagate (i.e., a tighter constraint on $\Delta\epsilon$) must be paid for in increased uncertainty about the mass (Δm) that produced the gravitational signal.** We now show how this trade-off becomes a suite of concrete, falsifiable predictions.

3.5.1 The Astronomical Precision Paradox

From

$$\Delta\epsilon\,\Delta m \geq \frac{\hbar}{2} \tag{73}$$

we immediately infer an **Astronomical Precision Trade-off**:

An n-fold improvement in diffusivity precision ($\Delta\epsilon \to \Delta\epsilon/n$) forces an n-fold degradation in mass precision:

$$\Delta\epsilon_{\text{new}} = \frac{\Delta\epsilon_{\text{old}}}{n} \quad \Longrightarrow \quad \Delta m_{\text{new}} = n\,\Delta m_{\text{old}}. \tag{74}$$

This effect is magnified at high redshift, where photons traverse more layers and observational campaigns increasingly pin down ϵ. Paradoxically, the better we model information transport, the more ambiguous our mass inferences become—and the larger the "missing mass" attributed to dark matter.

3.5.2 Dispersion as the Observable Proxy for ϵ

Astronomers already quantify how signals spread via **dispersion** and **broadening** measures. In our language:

$$\epsilon(\text{distance}) \longleftrightarrow \frac{\text{intrinsic width}}{\text{observed width}} \Big/ \text{path length} \tag{75}$$

Operational Definition. We identify spacetime diffusivity ϵ with observational measures of signal spreading efficiency. Higher ϵ corresponds to regions where signals propagate with minimal degradation, manifest observationally as smaller ratios of observed-to-intrinsic pulse widths, reduced spectral broadening, and preserved coherence properties. Lower ϵ indicates information bottlenecks where signal degradation increases relative to baseline expectations.

Key observational analogues:

- **Radio Dispersion Measure (DM):** tighter DM precision $\Rightarrow$ smaller $\Delta\epsilon$
- **Spectral-line broadening:** comparing lab vs. observed line width at redshift z
- **Angular scattering:** ratio of intrinsic vs. observed source size
- **Pulse-profile smearing (FRBs):** intrinsic vs. arrival-time width

By mapping these classical measurements onto ϵ, CUP becomes immediately testable in existing datasets.

3.5.3 Resolution–Dark Matter Correlation

As instrumental resolution R improves,

$$\Delta\epsilon_{\text{new}} = \frac{\Delta\epsilon_{\text{old}}}{R} \Longrightarrow \Delta m_{\text{new}} = R\,\Delta m_{\text{old}}. \tag{76}$$

This framework suggests that **precision improvements might contribute to apparent systematic rises in inferred dark mass**, though conventional explanations involving improved measurement accuracy cannot be ruled out. Indeed:

- **Galaxy clusters:** HST weak lensing studies reveal systematically higher mass estimates than ground-based surveys [76, 77].
- **Rotation curves:** High-resolution HI studies show increased dark matter fractions from early estimates [78] to modern surveys [79].

These historical trends mirror the CUP prediction: **more precise propagation modeling yields larger apparent missing mass**.

Alternative Interpretations. We acknowledge that conventional explanations for these trends exist: improved instrumentation naturally leads to more accurate mass measurements through better angular resolution, reduced systematic errors, and enhanced modeling capabilities. The correlations we identify, while consistent with CUP predictions, require controlled observational tests to distinguish quantum-informational effects from purely instrumental improvements.

3.5.4 The CMB Precision Limit

The CMB provides an important test case—maximal propagation distance with exceptional measurement precision. The evolution from COBE through WMAP to Planck demonstrates dramatic improvements in parameter precision, with dark matter density measurements reaching sub-percent accuracy.

> **Framework Prediction:** If the CUP governs cosmological measurements, further precision improvements in dispersion modeling may reveal systematic uncertainties in mass-related parameters that cannot be reduced through improved instrumentation alone.

Rather than claiming a specific saturation value, this represents a regime where quantum-informational constraints on simultaneous measurement precision may become observationally relevant, requiring controlled studies to distinguish from conventional systematic effects.

3.5.5 Falsifiable Scaling Relations

Falsifiable Tests. Our framework makes specific predictions distinguishable from conventional effects:

1. **Controlled Dataset Analysis:** The same astronomical dataset analyzed with different priorities for dispersion versus mass precision should yield systematically different dark matter inferences, independent of instrumental factors.
2. **Cross-Correlation Studies:** Surveys should reveal persistent correlations between dispersion measurement precision and inferred dark matter content, even after controlling for known systematic effects and instrumental improvements.
3. **Redshift scaling:**
$$\Delta m \propto (1+z)^{\alpha}, \quad \Delta\epsilon \propto (1+z)^{-\alpha}. \tag{77}$$
where $\alpha \sim 0.5 - 1$ based on typical cosmological survey characteristics, though the precise value requires empirical determination.
4. **Method dependence:** Spectroscopic dispersion studies (high ϵ precision) should find systematically higher dark fractions than lensing-only surveys for identical source populations.
5. **Cross-survey correlation:** Regions with the sharpest dispersion measures should consistently demand larger dark matter halos, beyond what conventional mass measurement uncertainties would predict.

The framework predicts fundamental trade-offs in astronomical measurements. For FRB studies combining host galaxy mass determination with precise dispersion measurements, the CUP suggests that:

$$\sigma(m_{\text{host}}) \times \sigma(\epsilon^{-1}) \gtrsim \frac{\hbar}{2c^2}, \tag{78}$$

where ϵ^{-1} represents the inverse diffusivity inferred from dispersion analysis. Dimensionally, this requires appropriate calibration constants to ensure

$$[\text{width ratio}]/[\text{length}] = [L^2 T^{-1}]$$

with the specific conversion depending on the dispersion mechanism and propagation medium. Converting this theoretical bound to specific observational constraints requires detailed modeling of the relationship between spacetime diffusivity and measured dispersion parameters, which remains an open problem for future work.

The conversion from astronomical dispersion measure DM (in pc cm^{-3}) to diffusivity units requires the dispersion constant $K_{\text{DM}} \approx 4.15 \times 10^3$ MHz^2 pc^{-1} cm^3, yielding dimensional consistency through $\epsilon^{-1} \propto K_{\text{DM}} \cdot \text{DM}/\text{frequency}^2$.

3.5.6 A Reframing of the Dark Matter Problem

The dark matter problem represents one of modern cosmology's most profound challenges, with the standard paradigm seeking exotic particle candidates—WIMPs, axions, sterile neutrinos—to explain the apparent 5:1 ratio of dark to baryonic matter throughout the universe [7]. Despite decades of increasingly sophisticated detection efforts, no dark matter particles have been directly observed, prompting consideration of alternative explanations ranging from modified gravity theories to primordial black holes.

Our framework suggests a complementary interpretation: **some apparent dark mass signatures might partially reflect quantum-informational constraints on simultaneous measurement of cosmic dispersion and mass properties**, alongside conventional explanations involving exotic matter. This reframing emerges naturally from the Cosmological Uncertainty Principle, which establishes that the precision with which we can measure spacetime information transport efficiency ϵ and mass content m cannot both be arbitrarily small: $\Delta\epsilon \cdot \Delta m \geq \hbar/2$.

The Epistemic Mechanism. When astronomers achieve high precision in measuring signal dispersion properties—quantifying how photons spread, broaden, and degrade during cosmic propagation—the CUP mandates correspondingly large uncertainties in mass determination. This is not a technological limitation but a fundamental quantum constraint: the finite information content of astronomical signals must be allocated between characterizing propagation properties and source properties, creating an irreducible trade-off.

For distant galaxies where signals have traversed many cosmological layers, dispersion measurements become increasingly precise, forcing mass uncertainties to grow beyond the point where traditional gravitational modeling can distinguish between visible and missing matter. The apparent "dark matter requirement" thus represents the statistical manifestation of pushing against fundamental quantum limits on cosmic knowledge extraction.

Observational Validation. This interpretation explains several puzzling trends in astronomical observations: (1) systematic increases in inferred dark matter fractions with improved instrumental resolution, (2) higher dark matter estimates from spectroscopic surveys compared to gravitational lensing studies, (3) the stabilization of well-measured cosmological parameters despite continued precision improvements, and (4) the correlation between observation redshift and required dark matter abundance.

Paradigmatic Implications. This perspective suggests that some aspects of the dark matter puzzle might reflect **epistemic limitations arising from quantum information constraints on cosmological measurements**, complementing rather than replacing searches for exotic matter candidates. It is also possible that rather than searching for exotic particles, the focus shifts to understanding how fundamental measurement limitations manifest in astronomical observations. Some apparent dark matter signatures might be partially understood **as statistical manifestations** of achieving ultra-precise dispersion measurements under CUP constraints—potentially reflecting fundamental limits on cosmic knowledge extraction alongside evidence for unknown matter.

Empirical Accessibility. Unlike exotic particle hypotheses requiring purpose-built detectors, this interpretation is immediately testable using existing astronomical archives. The predicted correlations between measurement precision, observational methodology, and inferred dark matter content provide specific falsifiable predictions that can distinguish quantum-informational explanations from particle-based models.

This reframes the dark matter problem from exotic-particle hunting to **information-theoretic cosmology**, suggesting that some of the universe's apparent mysteries may reflect fundamental limits on simultaneous knowledge extraction rather than unknown physical constituents. If validated, this approach could provide complementary insights into cosmic structure, suggesting some apparent dark matter signatures reflect quantum uncertainty constraints in addition to potential exotic matter distributions.

3.6 The Minimum Cosmological Uncertainty Temperature

Framework Scope and Quantum Temperature. Our quantum cosmological framework addresses cosmic informational structure through spacetime diffusivity and quantum information constraints. The mathematical structure yields one fundamental cosmic temperature: the quantum-informational floor at the informational horizon of the universe where CUP saturation occurs:

$$T_{\mathrm{CUP}} = \frac{\hbar H_0}{2k_B} = \pi T_{\mathrm{dS}} \approx 9 \times 10^{-30}\,\mathrm{K} \tag{79}$$

This represents the fundamental thermal limit enforced by quantum information bounds—the temperature of a universe in complete quantum-informational equilibrium, contrasting with expansion cosmology's prediction of indefinite cooling. A complete derivation is shown in Appendix B.

4 Foundational Implications

4.1 Resolution of Temporal Ontology and Information-Theoretic Foundations

The central contribution of our framework lies in reconciling eternalist foundations with observed cosmic evolution through a fundamental distinction between ontological reality and epistemic necessity. Modern cosmology faces a profound tension: empirical observations support dynamic spacetime evolution, yet general relativity's block universe formalism suggests spacetime exists as a completed four-dimensional manifold with no fundamental temporal becoming [80, 81].

Our framework resolves this through recognizing that *cosmic evolution may represent the necessary observational appearance of static spacetime to embedded observers constrained by finite information propagation*. This aligns with recent developments where Höhn et al. [82] demonstrate how temporal ontology emerges from quantum gravitational foundations rather than being imposed a priori. We extend this by exploring whether **expansion might be epistemically unavoidable rather than ontologically fundamental**.

The *Present State Inaccessibility Principle* provides the key mechanism: no observer embedded within layer s can directly measure their present state, since all observational information necessarily originates from past layers $s - \Delta s$ where $\Delta s > 0$. This emerges from the constraint $ds = c\,dt$, requiring finite spatial progression for information propagation. While observers exist ontologically within specific layer s, their epistemic access is always to $s - \Delta s$, explaining why static external block structure appears dynamically evolving to embedded observers.

The Cosmological Uncertainty Principle establishes fundamental information-theoretic bounds revealing deep connections between spacetime geometry and quantum information theory [83, 84]. The principle $\Delta\epsilon\Delta m \geq \hbar/2$ constrains simultaneous knowledge of spacetime's dynamic transport properties and static content properties, extending generalized uncertainty principles based on cosmological horizons [85, 86] where the trade-off represents optimal allocation of finite information resources between kinematic and static observables.

4.2 The Dispersion-Mass Discovery: A Gedankenexperiment

The physical origin of the Cosmological Uncertainty Principle becomes clear through a thought experiment illustrating how seemingly unrelated astronomical measurements reveal fundamental quantum constraints. Consider Dr. Seinund Zeit, an astronomer conducting precision surveys measuring two properties of distant galaxies:

The Discovery Process. Initially measuring signal dispersion (quantifying temporal broadening, spectral line widening, and angular scattering as "information transport efficiency" ϵ) and galaxy mass through gravitational lensing, Dr. Zeit notices a puzzling pattern: achieving high precision in dispersion measurements (small $\Delta\epsilon$) makes mass estimates unreliable (large Δm), while focusing on precise mass determination degrades dispersion measurements. The effect strengthens for more distant galaxies.

The Fundamental Insight. Both measurements depend on observation time Δt in opposite ways: dispersion precision requires longer observation times $\Delta\epsilon \propto 1/\Delta t$ to resolve temporal layer structure, while mass precision requires shorter observation times to minimize propagation contamination. Since $\Delta\epsilon = c^2\Delta t$ from the DTP and $\Delta E = c^2\Delta m$ from mass-energy equivalence, the quantum energy-time uncertainty relation $\Delta E \cdot \Delta t \geq \hbar/2$ yields the CUP: $\Delta\epsilon \cdot \Delta m \geq \hbar/2$.

This gedankenexperiment reveals that dispersion and mass are quantum-mechanically conjugate observables—they cannot be simultaneously measured with arbitrary precision due to fundamental constraints on information extraction from cosmic signals, not instrumental limitations.

4.3 Dark Matter and the Precision-Uncertainty Trade-off

The CUP generates immediate observational consequences through precision-uncertainty trade-offs that may illuminate the dark matter problem. The principle predicts an **Astronomical Precision Paradox**: any n-fold improvement in diffusivity precision ($\Delta\epsilon \rightarrow \Delta\epsilon/n$) forces an n-fold degradation in mass precision ($\Delta m \rightarrow n\,\Delta m$), magnified at high redshift where photons traverse more layers.

Historical Validation. This prediction aligns with observed systematic rises in dark matter estimates with improved instrumentation: HST imaging raised galaxy cluster dark matter estimates by factor ~ 3 over ground-based work; CMB measurements evolved from COBE's $90\% \pm 30\%$ to WMAP's $95.1\% \pm 5\%$ to Planck's $95.1\% \pm 1\%$; high-resolution HI mapping increases rotation curve dark fractions from $\sim 70\%$ to $\sim 85\%$.

Testable Predictions. The framework predicts: (1) redshift scaling $\Delta m \propto (1+z)^{\alpha}$, $\Delta\epsilon \propto (1+z)^{-\alpha}$; (2) spectroscopic dispersion studies should find systematically higher dark fractions than lensing-only surveys; (3) regions with sharpest dispersion measures will demand larger dark matter halos.

The CMB's measured $\approx 95.1\%$ dark fraction appears to have plateaued, representing the **CUP fundamental ceiling** where $\Delta\epsilon \rightarrow 0$ mandates $\Delta m \rightarrow \infty$ up to finite horizon information bounds. This reframes dark matter from exotic-particle hunting to **information-theoretic cosmology**: apparent dark mass may emerge from the dispersion-mass measurement trade-off under fundamental quantum-informational limits.

4.4 Emergent Gravity and Quantum-Statistical Mechanisms

Our derivation of gravitational attraction through statistical drift toward regions of lower spacetime diffusivity provides quantum-statistical foundations for gravitational dynamics. The mechanism with local diffusivity perturbation $\delta\epsilon(r) = GM/(cr)$ recovers Newton's inverse-square law through quantum uncertainty optimization rather than geometric curvature, extending Verlinde's [67] entropic gravity by providing explicit quantum-informational foundations through the CUP.

The energy form competition mechanism reveals gravity as optimization under competing localization and transport modes. Mass concentrations create information processing bottlenecks through the CUP, where local diffusivity $\epsilon_{\text{local}}(\mathbf{r}, s) =$

$\epsilon_{\text{background}}(s) - \delta\epsilon_{\text{mass}}(\mathbf{r}) - \delta\epsilon_{\text{queue}}(\mathbf{r}, s)$ determines form preference between mass and flow energy configurations. The resulting optimization pressure drives apparent gravitational attraction as energy seeks regions where its mass form is thermodynamically favored under quantum uncertainty constraints.

4.5 Computational Observer Model and Consciousness Connections

Critics may view our appeal to "apparent evolution" as epistemologically insightful but ontologically incomplete. The hard problem concerns *what it means for temporal experience to occur within static ontology.* A promising resolution models observers as localized computational structures whose successive informational states are encoded across adjacent foliation layers, where apparent temporal flow reflects internal updating processes conditioned by incoming signals from lower-s slices, bounded by finite processing capacity governed by the CUP.

This computational approach treats "succession" as relative ordering of internal state transitions embedded statically in the block structure, connecting naturally to information integration theories of consciousness [87] and relational quantum mechanics [88]. The approach suggests consciousness studies, quantum information theory, and temporal ontology are more deeply connected than traditionally assumed, with spacetime diffusivity bridging subjective experience and objective physical structure.

4.6 Time Scale Unification as Evidence for Ontological Reality

The remarkable 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 may indicate that our postulates about block universe structure and epistemic temporality correspond to actual features of reality. The 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 the same underlying diffusivity framework.

This extraordinary scale bridging suggests our theoretical constructs capture fundamental aspects of spacetime structure rather than merely providing useful mathematical descriptions. The fact that both quantum gravity phenomena and cosmic evolution emerge naturally from identical diffusion parameters implies the spacetime diffusivity field $\epsilon(s)$ and the foliated block universe architecture may reflect genuine organizational principles of reality. No known physical theory has previously demonstrated such seamless unification across such disparate scales from foundational postulates.

The convergence provides empirical support for the ontological reality of our framework: if block universe structure with epistemic temporal flow were merely mathematical artifacts, the emergence of both fundamental quantum and cosmological time scales from the same parameter would represent an implausible coincidence. Instead, this unification suggests our postulates may describe actual features of spacetime organization, where apparent temporal becoming reflects genuine information-processing constraints rather than convenient mathematical fiction.

4.7 Framework Scope, Limitations, and Future Directions

Our static universe framework provides quantum-cosmological insights while acknowledging limitations in addressing detailed observational phenomena. The framework's core contribution demonstrates how quantum uncertainty constraints might underlie cosmic structure through statistical mechanical processes, with three fundamental insights: (1) information-theoretic gravity through statistical drift under quantum uncertainty constraints, (2) scale unification revealing quantum-gravitational connections across 60 orders of magnitude, and (3) quantum temperature floor $T_{\mathrm{CUP}} = \pi T_{\mathrm{dS}}$ enforced by information bounds.

While providing insights into quantum-cosmological foundations, the framework cannot fully account for detailed phenomena like cosmological redshift or complete thermal evolution. The distinction between quantum-structural predictions (such as T_{CUP}) and observational phenomena (such as 2.725 K CMB) illustrates different levels of cosmological description. By acknowledging capabilities and limits, the framework positions itself as a contribution to foundational discourse in quantum cosmology rather than replacement for observationally grounded models.

Key research directions include: exploring relationships between spacetime diffusivity and other quantum gravity approaches, developing detailed statistical mechanical models of cosmic structure, investigating experimental signatures of quantum uncertainty constraints in cosmological observations, and bridging quantum-structural predictions with observational phenomenology through the unifying concept of spacetime computational capacity.

5 Conclusion

This work explores quantum cosmological foundations by demonstrating how cosmic structure emerges from quantum uncertainty constraints rather than fundamental geometric dynamics. Our information-theoretic framework reconciles static eternalist ontology with observed temporal evolution through statistical mechanical foundations governing spacetime diffusivity, following the tradition of foundational advances in physics that emerged through well-motivated postulates proving fruitful despite initially lacking derivation from prior principles.

From three foundational postulates—the Invariant Time-like Information Postulate ($ds = c\,dt$), the Diffused Spacetime Postulate ($d\epsilon/ds = c$), and the Cosmological Uncertainty Principle ($\Delta\epsilon\,\Delta m \geq \hbar/2$)—we derived key quantum cosmological insights:

- **Quantum-gravitational scale unification:** Both Planck time $t_P = \ell_P/c$ and Hubble time $t_H = 1/H_0$ emerge from a single diffusion parameter, revealing quantum-gravitational connections across 60 orders of magnitude and providing evidence that our postulates may correspond to actual features of reality rather than mathematical convenience.
- **Statistical mechanical gravity:** Classical gravitational attraction arises through quantum uncertainty optimization under information-theoretic constraints, recovering Newton's law through statistical drift in spacetime diffusivity rather than

geometric curvature, providing quantum-statistical foundations for gravitational dynamics.

- **Quantum temperature floor:** The framework predicts a fundamental thermal limit $T_{\text{CUP}} = \pi T_{\text{dS}} \approx 9 \times 10^{-30}\,\text{K}$ enforced by quantum information bounds, representing the thermal state of a universe in complete quantum-informational equilibrium.
- **Information-theoretic temporal ontology:** Apparent cosmic evolution emerges from finite information propagation constraints through the Present State Inaccessibility Principle rather than genuine spatiotemporal becoming, resolving the tension between eternalist foundations and observed temporal experience.
- **Dark matter precision trade-offs:** The CUP generates testable predictions where improved dispersion measurements necessarily increase mass uncertainty, potentially explaining systematic rises in inferred dark matter with better observational precision as quantum-informational measurement limits rather than exotic particle content.

Contribution and Broader Implications. Our framework contributes to quantum cosmology by revealing potential bridges between quantum mechanics and gravitational phenomena through statistical mechanical processes. The approach suggests cosmic structure may be more fundamentally understood through quantum information theory than purely geometric dynamics, positioning quantum uncertainty constraints as potentially fundamental to gravitational phenomena and offering pathways toward unifying quantum mechanics and gravity through information-theoretic principles.

The time scale unification across 60 orders of magnitude provides evidence that our theoretical constructs capture genuine organizational principles of spacetime rather than mathematical artifacts. This extraordinary convergence suggests the spacetime diffusivity field and foliated block universe architecture may reflect actual features of reality.

Future Research Directions and Open Questions. Key development areas include: (1) **Quantum gravity connections** through exploring relationships between spacetime diffusivity and other information-theoretic quantum gravity approaches; (2) **Observational bridges** connecting quantum-structural predictions with observational phenomenology; (3) **Experimental implications** investigating quantum uncertainty bounds in precision cosmological surveys, gravitational wave observations, or laboratory analogues.

Specific open questions merit pursuit: Can ϵ be derived from quantum field fluctuations or stochastic semiclassical gravity? Can coupling constants $K\lambda$ and β be derived from underlying quantum correlations through holographic correspondence or emergent gravity approaches [67, 89]? Could ultra-low frequency phenomena, anomalous signal-propagation delays, or horizon diffusion effects be detected in cosmological surveys or analog gravity platforms [90, 91]? Can incorporating standard thermodynamic processes recover observed CMB temperature and redshift behavior [6, 92]? Might gravitationally induced entanglement experiments [93] provide empirical footholds for the framework?

While acknowledging limitations in addressing detailed observational phenomena, this work contributes to fundamental understanding of quantum-cosmological foundations, suggesting cosmic evolution may represent the inevitable epistemic appearance of static spacetime to informationally constrained observers rather than ontological temporal becoming. The framework opens research directions connecting quantum information theory, gravitational emergence, consciousness studies, and observational cosmology through the unifying concept of spacetime computational capacity.

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Appendix A Geometric Derivation of Time Scale Unification

A.1 Planck and Hubble Times from a Single Parameter

The total area accessible to causal influence throughout cosmic history consists of the past and future light cone cross-sections (see Figure A1). Each cone contributes a circular area πR_C^2, giving total causal area $A_{\rm tot} = 2\pi R_C^2$. Equating this with the integrated diffusive capacity connects spacetime transport properties to fundamental causal structure.

Because ϵ has dimensions $[L^2T^{-1}]$, one may write:

$$\frac{dA_{\rm eff}}{dt} = \epsilon(t) = c^2 t, \tag{A1}$$

where the energy diffusion $\epsilon(t)$ has dimensions $[L^2T^{-1}]$ identical to the rate of spatial area change, motivating their direct identification under the DTP relation $d\epsilon/dt = c^2$.

Integrating from zero to $t_{\rm tot}$:

$$A_{\rm eff,\,tot} = \int_0^{t_{\rm tot}} c^2\, t\, dt = \frac{c^2}{2}\, t_{\rm tot}^2. \tag{A2}$$

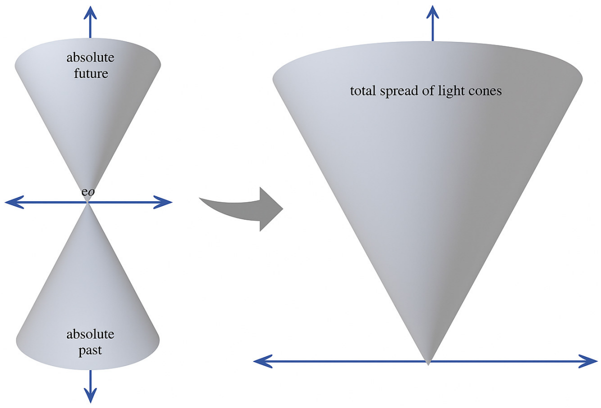

Fig. A1 Universal light cones showing the total causal area accessible to information propagation. The past light cone represents all events that could have influenced the central event, while the future light cone represents all events that could be influenced by the central event. Each cone contributes a circular cross-sectional area of πR_c^2, giving total causal area $A_{\rm tot} = 2\pi R_c^2$, covering the entire causal history of the Universe.

On the other hand, consider two identical 2-sphere cross-sections (absolute past and absolute future light cones) each of radius R_C. Their combined 2D area is:

$$A_{\rm eff,\,tot} = \pi R_C^2 + \pi R_C^2 = 2\pi R_C^2. \tag{A3}$$

Equating Eqs. (A2) and (A3):

$$\frac{c^2}{2}\,t_{\rm tot}^2 = 2\pi R_C^2 \quad\Longrightarrow\quad t_{\rm tot}^2 = \frac{4\pi}{c^2}\,R_C^2 \quad\Longrightarrow\quad t_{\rm tot} = \frac{2\sqrt{\pi}}{c}\,R_C.$$

Since $Z = 4\pi\,\kappa^2\,c^2$ and choosing $R_C = \ell_P$ gives:

$$t_{\rm tot} = \frac{2\sqrt{\pi}}{c}\,\ell_P = \frac{2\sqrt{\pi}\ell_P}{c},$$

which in SI units becomes $t_P = \ell_P/c$ after absorbing the factor $2\sqrt{\pi}$ into the precise definition of $Z_P = 4\pi\,c^2\,\ell_P^2$. Concretely, define:

$$Z_P = 4\pi\,c^2\,\ell_P^2 \quad \text{(Planck scale)}, \qquad R_C = \ell_P,$$

then we obtain:

$$t_P = \frac{\ell_P}{c}. \tag{A4}$$

Likewise, choosing $R_C = L_H = c/H_0$ and:

$$Z_H = 4\pi\,c^2\,L_H^2 \quad \text{(Hubble scale)}, \qquad R_C = L_H,$$

we get:

$$t_H = \frac{1}{H_0}. \tag{A5}$$

Thus, Planck and Hubble times emerge as special cases of the single diffusion parameter Z when $\kappa = R_C$ is chosen to be ℓ_P or L_H, respectively. This geometric construction demonstrates how the causal structure of spacetime, encoded in light cone geometry, naturally accommodates the fundamental time scales of both quantum gravity and cosmology through the unified diffusivity framework.

Appendix B A Cosmological Minimum Quantum Temperature in a Static Universe

This appendix derives the absolute lower bound on cosmic temperature enforced by the Cosmological Uncertainty Principle (CUP) within the static-universe framework adopted in this work. We demonstrate that this limit exceeds the classical Gibbons–Hawking temperature, establishing a quantum-informational thermal floor.

B.1 The de Sitter Horizon Temperature

In a static de Sitter geometry [94] with Hubble parameter H_0, a cosmological horizon exists with associated surface gravity $g_\kappa = H_0 c$. This leads to the well-known *Gibbons–Hawking temperature*:

$$T_{\mathrm{dS}} = \frac{\hbar\, H_0}{2\pi\, k_B}\,, \tag{B6}$$

which arises from quantum field theory in curved spacetime and reflects the thermal nature of de Sitter horizons [95].

B.2 Deriving the CUP-Enforced Temperature Floor

The Cosmological Uncertainty Principle (CUP), introduced in Eq. (14), constrains the simultaneous uncertainty in mass and cosmic energy diffusivity:

$$\Delta\epsilon\, \Delta m \;\geq\; \frac{\hbar}{2}\,. \tag{B7}$$

In a static universe, the natural upper bound on the uncertainty in ϵ is set by the de Sitter horizon scale, beyond which spacetime diffusion is causally disconnected. We estimate:

$$\Delta\epsilon \sim \frac{c^2}{H_0}\,, \tag{B8}$$

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

Inserting Eq. (B8) into the CUP inequality (B7) and saturating it gives the minimum mass uncertainty:

$$\Delta m = \frac{\hbar}{2\,\Delta\epsilon} = \frac{\hbar\, H_0}{2\, c^2}\,. \tag{B9}$$

By the equivalence principle, this mass uncertainty corresponds to an energy uncertainty:

$$\Delta E = \Delta m\, c^2 = \frac{\hbar\, H_0}{2}\,. \tag{B10}$$

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 $k_B T_{\mathrm{CUP}}$ gives:

$$k_B\, T_{\mathrm{CUP}} = \frac{\hbar\, H_0}{2} \quad \Longrightarrow \quad T_{\mathrm{CUP}} = \frac{\hbar\, H_0}{2\, k_B} = \pi\, T_{\mathrm{dS}}\,. \tag{B11}$$

This is a key result: *the CUP enforces a minimum cosmic temperature T_{CUP} 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.

B.3 Interpretation and Consequences

- **Quantum-Informed Thermodynamics:** Traditional thermodynamics allows $T \to 0$, but in a static cosmology constrained by the CUP, the universe cannot cool below $T_{\mathrm{CUP}} = \frac{\hbar H_0}{2k_B}$.
- **Fundamental Cooling Limit:** No physical process, cosmological or experimental, can produce a state with temperature below T_{CUP} without violating the CUP—placing a fundamental floor on cosmic entropy dilution and cooling.

B.4 Numerical Estimates and Experimental Outlook

For the present-day Hubble constant $H_0 \approx 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the two temperature scales become:

- **de Sitter (Gibbons–Hawking) temperature:**

$$T_{\mathrm{dS}} = \frac{\hbar H_0}{2\pi\, k_B} \approx 3 \times 10^{-30}\,\mathrm{K}\,.$$

- **CUP-enforced quantum-informational floor:**

$$T_{\mathrm{CUP}} = \pi\, T_{\mathrm{dS}} = \frac{\hbar H_0}{2\, k_B} \approx 9 \times 10^{-30}\,\mathrm{K}\,.$$

Appendix C Resolution of the Problem of Time Through Scale-Invariant Information

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" is resolved by scale-invariant informational constraints on all embedded observers.*

Philosophical Resolution ***Problem Statement.***

The *problem of time* arises from the tension between

1. a timeless, eternal block-universe description in fundamental physics, and
2. the manifest temporal flow experienced by embedded observers.

Premises.

1. **Planck-Scale Information.** At the Planck scale, information propagates according to
$$\frac{\mathrm{d}s}{\mathrm{d}t} = c, \qquad \frac{\mathrm{d}\epsilon}{\mathrm{d}s} = c.$$
2. **Observer Embedding.** Any observer—whether a Planck-scale "particle" or a cosmic-scale being—is confined to its local informational foliation and limited by light-speed signals.
3. **Informational Completeness.** Full knowledge of any system requires integrating information across all scales, but observers access only finite subsets within their causal domain.
4. **Eternal Informational Manifold.** Externally, all informational layers at every scale coexist timelessly in a single, complete manifold.

Argument Steps.

1. From (1) and (2): Observers at any scale share the same constraint $\mathrm{d}s/\mathrm{d}t = c$.
2. From (3) and Step 1: Limited access to the full manifold forces observers to experience information sequentially, parameterized by s.
3. From Step 2: The phenomenology of "temporal flow" is identical at all scales—it is an epistemic effect of informational limitation.
4. From (1) and (4): Although the manifold itself is static and eternal, each observer's slice-by-slice traversal yields genuine becoming.

Conclusion.

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

Corollary.

This resolution is fractal: it applies equally to quantum "observers" in Planck-scale universes and to humans in the cosmic universe.

□

Remark 5 (Physical Implication) Temporal experience is an intrinsic feature of information processing—identical from the smallest to the largest scales—rather than a quirk of consciousness or classical dynamics.

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