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Article

Emergent Quantum–Cosmological Conjugacy from Relativistic Information Transport

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Abstract

We derive a quantum conjugacy between spacetime diffusivity and inertial mass from relativistic information-transport kinematics. Two Lorentz-invariant laws—(i) an invariant-time gauge for timelike segments, $ds = c\,dt$, and (ii) diffusive evolution $d\epsilon/ds = c$ —yield a first-order action whose canonical quantization gives $[\hat{\epsilon}, \hat{m}] = i\hbar$ and the emergent Cosmological Uncertainty Principle (CUP), $\Delta\epsilon\,\Delta m \geq \hbar/2$. Independence across coherence cells of size ℓ_{coh} amplifies the bound to $\Delta\epsilon\,\Delta m \geq (\hbar/2)\,N_{\text{eff}}$ with $N_{\text{eff}} = D/\ell_{\text{coh}}$, extending quantum uncertainty to cosmic baselines. A single area-diffusion parameter provides an operational unification of Planck and Hubble times across ~ 61 orders of magnitude. Applied to black-hole horizons, the CUP reproduces Hawking’s temperature exactly. for de Sitter space, a naïve $1/H$ correlation window overshoots by a factor π , while KMS/Unruh calibration ($\tau = \pi/H$) recovers the standard Gibbons–Hawking result $T_{\text{dS}} = \hbar H/(2\pi k_B)$. Unlike generalised or extended uncertainty principles that deform the position–momentum commutator, the CUP introduces a new conjugate pair (ϵ, m) while leaving the Heisenberg sector intact. These results position CUP as an emergent, testable quantum–informational constraint on cosmological observables rather than an added axiom.

Keywords: cosmological uncertainty principle (CUP); spacetime diffusivity; quantum conjugacy; relativistic information transport; horizon thermodynamics

1. Introduction

Modern cosmology rests on the empirically successful Λ CDM model [1], yet conceptual tensions persist. The “problem of time” exemplifies this challenge: general relativity describes a static block universe [2,3], while observers experience manifest temporal flow. Additionally, physics lacks a field-theoretic description of information transport between temporal layers of spacetime itself.

Established transport phenomena—thermal diffusivity $\alpha = k/(\rho c_p)$, kinematic viscosity $\nu = \mu/\rho$, and Einstein’s Brownian coefficient D [4]—all possess diffusivity fields with dimensions $[L^2T^{-1}]$, yet no corresponding field describes information propagation through spacetime’s temporal structure.

1.1. Three Guiding Questions

This work addresses three interconnected questions:

(1) Quantum Conjugacy. Can relativistic transport principles generate quantum uncertainty relations at cosmological scales without additional postulates?

(2) Scale Unification. Do operational connections exist between quantum-gravity scales (Planck time $t_P \sim 10^{-43}$ s) and cosmic-expansion scales (Hubble time $t_H \sim 10^{17}$ s)?

(3) Horizon Thermodynamics. Can the emergent conjugacy reproduce established results in black-hole and de Sitter thermodynamics?

1.2. Principal Results

We show that relativistic kinematics of information transport—through canonical quantization—generates quantum conjugacy between spacetime diffusivity $\epsilon(s)$ and mass content m . The emergent Cosmological Uncertainty Principle provides:

- **Operational scale unification** across ~ 61 orders of magnitude from a single area-diffusion parameter Z .
- **Hawking temperature recovery:** Exact, parameter-free reproduction of $T_H = \hbar c^3 / (8\pi G M k_B)$ from CUP saturation at the Schwarzschild horizon.
- **De Sitter temperature:** A naïve $1/H$ window overshoots by π ; KMS/Unruh calibration ($\tau = \pi/H$) recovers the standard Gibbons–Hawking value $T_{dS} = \hbar H / (2\pi k_B)$.
- **A new conjugate pair** $[\hat{e}, \hat{m}] = i\hbar$ that complements—rather than deforms—the Heisenberg position–momentum sector.

1.3. Structure

Section 2 develops relativistic transport kinematics, canonical quantization, and information-pixel amplification. Section 3 presents scale unification and horizon temperatures. Section 4 discusses implications for quantum gravity, temporal ontology, and limitations. Section 5 summarises achievements and future directions.

2. Theory

We develop the framework in three stages: (1) relativistic transport kinematics from causal structure, (2) emergence of quantum conjugacy through canonical quantization, and (3) extension to cosmic scales via information-pixel amplification.

2.1. Relativistic Information Transport Kinematics

Consider a universe emerging from a finite past boundary, as required by Borde–Guth–Vilenkin arguments [5]. We foliate spacetime into information layers Σ_s parameterised by causal depth s .

Proposition 1 (Invariant Time-like Information Postulate). *Under BGV constraints with spatial separations $\Delta r \rightarrow 0$, we parameterise timelike worldlines by an external block parameter t and fix the arclength gauge so that*

$$\frac{ds}{dt} = c, \quad (1)$$

where s parameterises informational stratification and t is the foliation parameter defined via the accumulated light-cone area $A_{\text{eff}}(t) = c^2 t^2 / 2$. This invariant-time postulate (ITP) is a gauge fixing; equivalently, one may write $ds = c N(t) dt$ with a worldline lapse $N(t) > 0$ and choose the gauge $N \equiv 1$ to recover (1).

Proof. From causal structure, $\Delta s^2 = c^2 \Delta t^2 - \Delta r^2 \geq 0$. Along timelike layers with $\Delta r \rightarrow 0$, $\Delta s = c \Delta t$. Reparametrisation invariance permits $ds = c N(t) dt$; the gauge $N \equiv 1$ yields (1). $\square$

Domain note. Equation (1) applies to timelike segments; null segments ($ds = 0$) require an affine parameter and are treated separately when needed.

Definition 1 (Spacetime Diffusivity). *The scalar field $\epsilon(s)$ with dimensions $[L^2 T^{-1}]$ quantifies informational transport capacity between successive temporal layers, where high ϵ indicates efficient information transfer and low ϵ indicates transport bottlenecks.*

Postulate 1 (Minimal Lorentz-compatible evolution). *We adopt the minimal Lorentz-compatible calibration:*

$$\frac{d\epsilon}{ds} = c, \quad (2)$$

which, combined with (1), implies $d\epsilon/dt = c^2$ in this gauge.

Remark 1. Any alternative constant calibration $d\epsilon/ds = \alpha c$ ($\alpha > 0$) can be absorbed into a redefinition of ϵ ; we set $\alpha = 1$ by convention. This avoids a claim of mathematical uniqueness and emphasises operational convenience.

Combining the ITP and Postulate 1:

$$\frac{d\epsilon}{dt} = c \frac{d\epsilon}{ds} = c^2. \quad (3)$$

The constraint $d\epsilon/ds = c$ generates a first-order action with Lagrange multiplier $m(s)$:

$$S[\epsilon, m] = \int ds \, m \left(\frac{d\epsilon}{ds} - c \right). \quad (4)$$

Classical variation yields $d\epsilon/ds = c$ (constraint enforcement) and $dm/ds = 0$ (conservation of m along information lines).

2.1.1. Information Flux and the Area-Diffusion Parameter Z

To assess global information flow, we work on a spatial slice Σ_s whose isotropic boundary is a round S^2 of fixed capacity radius κ_0 , with area $A[\partial\Sigma_{\kappa_0}] = 4\pi\kappa_0^2$.

We treat $\epsilon(s)$ as a Lorentz-scalar transport field on the spatial slice with induced metric γ_{ij} . Extending the outward unit normal to a smooth radial field $n^i(x)$ and defining the kinematic current $J^i(x; s) := \epsilon(s) n^i(x)$, the flux through $\partial\Sigma_{\kappa_0}$ simplifies to

$$\Phi_\epsilon(s; \kappa_0) = \oint_{\partial\Sigma_{\kappa_0}} J^i dA_i = \epsilon(s) \cdot 4\pi\kappa_0^2. \quad (5)$$

With $d\epsilon/dt = c^2$ we obtain the area-integrated diffusivity rate

$$Z \equiv \frac{d\Phi_\epsilon}{dt} = 4\pi\kappa_0^2 c^2, \quad [Z] = L^4 T^{-2}, \quad (6)$$

from which the capacity radius follows as

$$\kappa_0 = \frac{1}{2c} \sqrt{\frac{Z}{\pi}}. \quad (7)$$

The parameter Z sets the fundamental flux-growth rate and will generate both Planck and Hubble times in Section 3.

2.2. Emergent Cosmological Uncertainty Relation

The classical transport action (4) generates quantum conjugacy through standard canonical quantisation.

2.2.1. Canonical Structure from Transport Action

The first-order Lagrangian $\mathcal{L} = m(d\epsilon/ds - c)$ yields canonical momenta:

$$p_\epsilon = \frac{\partial \mathcal{L}}{\partial \dot{\epsilon}} = m, \quad (8)$$

$$p_m = \frac{\partial \mathcal{L}}{\partial \dot{m}} = 0. \quad (9)$$

This generates two primary constraints, $\phi_1 \equiv p_m \approx 0$ and $\phi_2 \equiv p_\epsilon - m \approx 0$, whose Poisson bracket yields a constraint matrix with unit determinant, indicating second-class constraints. The fundamental Dirac bracket is therefore

$$\{\epsilon, m\}_D = 1. \tag{10}$$

2.2.2. Quantum Conjugacy through Variable Rescaling

The variables ϵ and m are rescaled versions of canonical position and momentum:

$$\epsilon = x \cdot c, \quad m = p/c. \tag{11}$$

This gives the standard canonical commutator:

$$[\hat{\epsilon}, \hat{m}] = [x \cdot c, p/c] = c \cdot \frac{1}{c} \cdot [x, p] = i\hbar.$$

$$\tag{12}$$

Remark 2. The map $(x, p) \mapsto (\epsilon, m)$ with $\epsilon = cx$ and $m = p/c$ is a canonical rescaling of conjugate variables. The novelty lies not in the commutator per se but in (i) the transport/flux framing that ties ϵ to operational information flow, (ii) the physical identification of the Lagrange multiplier m with inertial mass, and (iii) the amplified CUP programme $[\hat{\epsilon}_{\text{tot}}, \hat{m}_{\text{tot}}] = i\hbar N_{\text{eff}}$.

Physical identification of m .

The Lagrange multiplier m enforcing $de/ds = c$ acquires physical meaning through its role as canonical conjugate to the transport field. Its identification with inertial mass is motivated by three considerations: (a) dimensional consistency $[m] = [M]$; (b) exact, parameter-free recovery of the Hawking temperature when applied to black-hole horizons (Section 3.2); and (c) consistency with the Bekenstein–Hawking area–entropy relation [7,8]. A first-principles derivation from semiclassical gravity remains an important open question.

2.2.3. The Emergent Cosmological Uncertainty Principle

Robertson’s inequality [6] applied to (12) immediately yields:

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

$$\tag{13}$$

This is the **Cosmological Uncertainty Principle** in its fundamental form—not postulated but derived from relativistic information transport when quantum mechanics is consistently applied.

2.2.4. Relation to Existing Extended Uncertainty Principles

Unlike the Generalised Uncertainty Principle (GUP) of Kempf [9] and Scardigli [10], and the infrared Extended Uncertainty Principle (EUP) [11], which deform the canonical commutator $[x, p]$, the CUP introduces a *new* conjugate pair $[\hat{\epsilon}, \hat{m}] = i\hbar$ while leaving the position–momentum sector intact. Table 1 summarises the structural differences.

Table 1. Canonical-pair structure of uncertainty principles. GUP=Generalised Uncertainty Principle; EUP= Extended Uncertainty Principle; CUP= Cosmological Uncertainty Principle (this work).

Framework	Conjugate pair	Amplification	Uncertainty bound	Sector
Heisenberg	$[x, p] = i\hbar$	none	$\Delta x \Delta p \geq \hbar/2$	position, momentum
GUP (Kempf–Scardigli)	$[x, p] = i\hbar(1 + \beta p^2)$	UV deformation	$\Delta x \Delta p \geq \frac{\hbar}{2}(1 + \beta(\Delta p)^2)$	position, momentum
EUP (IR form)	$[x, p] = i\hbar(1 + \alpha x^2)$	IR deformation	$\Delta x \Delta p \geq \frac{\hbar}{2}(1 + \alpha(\Delta x)^2)$	position, momentum
CUP (this work)	$[\epsilon, m] = i\hbar$	$k = D/\ell_{\text{coh}}$	$\Delta\epsilon \Delta m \geq \frac{\hbar}{2} \frac{D}{\ell_{\text{coh}}}$	diffusivity, mass

Consequently, laboratory Heisenberg tests remain unchanged; CUP phenomenology emerges only in extended mass–dispersion observables over astronomical baselines.

2.3. Information-Pixel Amplification

The emergent CUP extends across cosmic distances through quantum-coherence limits and information-processing constraints.

2.3.1. Coherence Length and Spacetime Pixelation

We adopt the standard correlation-length construction from statistical/transport theory (Green-Kubo and response theory [12–14]): the operational coherence length is the integrated autocorrelation of the transport field along the path. In weak, stationary environments this reduces to a constant scale that we express as a logical pixel built from Planck cells,

$$\ell_{\text{coh}} = \chi \ell_P, \quad (14)$$

where χ encodes environment-dependent decoherence (see Appendix A) and the “logical pixel” language mirrors quantum error correction: many physical degrees (Planck pixels) protect one effective cell [15–17]. Along a baseline D , the number of independent coherence cells is

$$N_{\text{eff}} = \frac{D}{\ell_{\text{coh}}} = \frac{D}{\chi \ell_P}, \quad (15)$$

the 1D analogue of familiar extent÷coherence counts (e.g., T/τ_{int} in time series, D/r_0 in atmospheric optics [18,19]).

2.3.2. Operator Derivation of Amplified Uncertainty

Discretise the path into N_{eff} independent cells. Assign to each cell i a local CUP pair obeying $[\hat{e}_i, \hat{m}_j] = i\hbar \delta_{ij}$. Define the totals (sums, not averages) $\hat{e}_{\text{tot}} = \sum_i \hat{e}_i$ and $\hat{m}_{\text{tot}} = \sum_i \hat{m}_i$. Then

$$[\hat{e}_{\text{tot}}, \hat{m}_{\text{tot}}] = \sum_{i,j} [\hat{e}_i, \hat{m}_j] = i\hbar N_{\text{eff}}, \quad (16)$$

and Robertson’s bound gives the *amplified* CUP:

$$\Delta e \Delta m \geq \frac{\hbar}{2} N_{\text{eff}}. \quad (17)$$

2.3.3. Physical Interpretation

For fiducial $\chi = 126$ (a Milky-Way-calibrated reference value; see Appendix A): at laboratory scales ($D \lesssim \ell_{\text{coh}}$) one recovers $N_{\text{eff}} \approx 1$ and the standard Heisenberg limit; at galactic scales ($D \sim 10$ kpc) $N_{\text{eff}} \sim 10^{53}$; at the cosmological horizon ($D \sim c/H_0$) $N_{\text{eff}} \sim 10^{58}$. The amplification is a geometric counting effect, not a deformation of the underlying commutator.

3. Results

The emergent CUP generates two principal results that do not depend on the specific value of χ : operational scale unification spanning 61 orders of magnitude, and natural recovery of established horizon temperatures.

3.1. Operational Scale Unification

3.1.1. Unified Origin from the Area-Diffusion Parameter

From Equation (7), the parameter Z relates to transport capacity through $\kappa_0 = (2c)^{-1}\sqrt{Z/\pi}$. Setting Z to fundamental area scales yields characteristic times:

Planck Scale. $Z_P = 4\pi c^2 \ell_P^2$ produces $\kappa_0 = \ell_P$ and

$$t_P = \frac{\ell_P}{c} = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39 \times 10^{-44} \text{ s}. \quad (18)$$

Cosmological Scale. $Z_H = 4\pi c^2 L_H^2$ with $L_H = c/H_0$ produces $\kappa_0 = L_H$ and

$$t_H = \frac{1}{H_0} \approx 4.55 \times 10^{17} \text{ s}. \quad (19)$$

3.1.2. Light-Cone Foundation

Since ϵ has dimensions $[L^2 T^{-1}]$, effective area growth satisfies $dA_{\text{eff}}/dt = \epsilon(t) = c^2 t$. Integrating over total time t_{tot} and equating with total light-cone area $A_{\text{tot}} = 2\pi R_C^2$ (past and future cones each contribute πR_C^2) gives

$$\frac{c^2}{2} t_{\text{tot}}^2 = 2\pi R_C^2 \Rightarrow t_{\text{tot}} = \frac{2\sqrt{\pi}}{c} R_C. \quad (20)$$

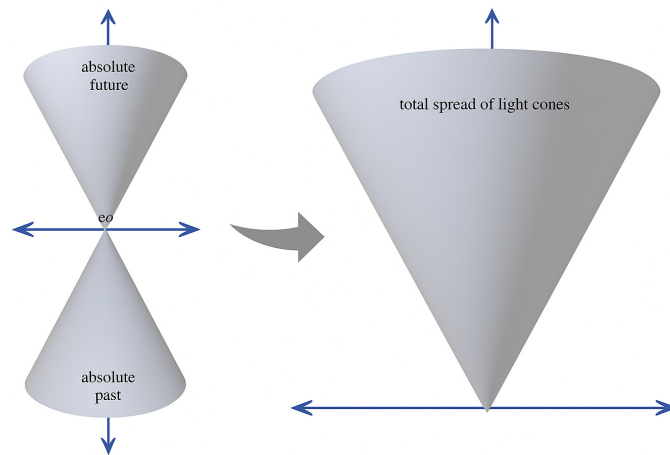


Figure 1. Visualisation of the total accumulated spread of light cones over t_{tot} , representing the sum of past and future bounding areas $A_{\text{tot}} = 2\pi R_C^2$.

Setting $R_C = \kappa_0$ and substituting from (7):

$$t_{\text{tot}} = \frac{2\sqrt{\pi}}{c} \cdot \frac{1}{2c} \sqrt{\frac{Z}{\pi}} = \frac{\sqrt{Z}}{c^2}. \quad (21)$$

The $\sqrt{\pi}$ factors exactly cancel, revealing consistency between causal geometry and diffusive dynamics. Both t_P and t_H then follow by substituting Z_P and Z_H respectively.

3.1.3. Physical Significance

This operational unification spans $t_H/t_P \approx 8.4 \times 10^{61}$ from identical information-theoretic principles. The convergence suggests that relativistic information transport captures organisational features of spacetime structure, providing an operational description bridging quantum-gravity and cosmic-expansion scales through causal geometry.

3.2. Hawking and Horizon Temperatures

3.2.1. Hawking Temperature Recovery

At a Schwarzschild horizon with surface gravity $\kappa_g = c^4/(4GM)$, Euclidean regularity requires thermal periodicity $\beta = 2\pi/\kappa_g = 2\pi r_S/c$ where $r_S = 2GM/c^2$. The diffusivity evolution $d\epsilon/ds = c$ over one thermal period gives

$$\Delta\epsilon = c \cdot \Delta s = c^2 \Delta t = 2\pi c r_S. \quad (22)$$

CUP saturation at the horizon ($\Delta\epsilon \Delta m = \hbar/2$) yields

$$\Delta m = \frac{\hbar}{2\Delta\epsilon} = \frac{\hbar}{4\pi c r_S}, \quad \Delta E = c^2 \Delta m = \frac{\hbar c}{4\pi r_S}. \quad (23)$$

Identifying $k_B T_H = \Delta E$ and substituting $r_S = 2GM/c^2$:

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}. \quad (24)$$

This exactly reproduces the standard Hawking temperature [7], with no free parameters, providing independent validation of the CUP framework through established black-hole thermodynamics.

3.2.2. De Sitter Temperature: CUP Prediction vs. Gibbons–Hawking

Naïve horizon-timescale estimate (overshoots by π).

At the cosmological horizon, a natural causal timescale is $\tau_H \equiv 1/H$. Within CUP, $d\epsilon/dt = c^2$ maps this to $\Delta\epsilon_H \sim c^2/H$. Saturating $\Delta\epsilon \Delta m = \hbar/2$ with $N_{\text{eff}} = 1$ yields

$$T_{\text{naïve}} = \frac{\hbar H}{2k_B} = \pi T_{\text{dS}}. \quad (25)$$

Calibration via KMS periodicity.

In the static de Sitter patch, KMS thermal states have Euclidean time periodicity $2\pi/H$. Taking the Nyquist half-period as the independent correlation interval,

$$\tau_{\text{KMS}} = \frac{\pi}{H}, \quad \Delta\epsilon_H \simeq c^2 \tau_{\text{KMS}} = \frac{\pi c^2}{H}.$$

Saturation gives

$$T_{\text{dS}} = \frac{\hbar H}{2\pi k_B}. \quad (26)$$

Independent cross-check via Unruh/surface gravity.

For the static de Sitter metric the Killing horizon at $r_H = c/H$ has surface gravity $\kappa_g = cH$. A static observer has proper acceleration $a = cH$, giving Unruh temperature $T_{\text{Unruh}} = \hbar a / (2\pi c k_B) = \hbar H / (2\pi k_B) \equiv T_{\text{dS}}$, consistent with (26).

The choice of correlation interval τ maps to temperature as follows:

Choice	τ	$k_B T$
Naïve horizon time	$1/H$	$\hbar H/2$ ($= \pi k_B T_{\text{dS}}$)
Full KMS period	$2\pi/H$	$\hbar H/(4\pi)$ ($= \frac{1}{2} k_B T_{\text{dS}}$)
Nyquist half-period	π/H	$\hbar H/(2\pi)$ ($= k_B T_{\text{dS}}$)

For $H_0 \simeq 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $T_{\text{dS}} \approx 3 \times 10^{-30} \text{ K}$.

4. Discussion

4.1. Resolution of the Temporal Ontology Problem

The framework addresses the tension between static block-universe descriptions and experienced temporal flow. At all scales, information propagates causally at speed c , so observers access only finite spacetime neighbourhoods at any moment. This operational limitation forces sequential processing of partial data, with uncertainties governed by the amplified CUP (17).

No observer embedded within informational layer s can directly access their present cosmological state, since all observational information necessarily originates from past layers $s - \Delta s$ where $\Delta s > 0$. This causal asymmetry explains why the static external block structure appears dynamically evolving to embedded observers, transforming the “problem of time” from fundamental paradox to an inevitable consequence of finite information propagation.

4.2. Quantum-Gravity Correspondences

The diffusivity scaling $\epsilon \sim c\ell_P$ at quantum-gravity scales appears compatible with several established approaches: *Loop Quantum Gravity*—area operator fluctuations $\Delta A \sim \ell_P^2$ imply $\epsilon \sim c\ell_P$ [20]; *Holographic approaches*—entanglement velocity bounds provide similar scaling [21]; *Causal Set Theory*—sprinkling density fluctuations give $\epsilon \sim \ell_P^2/t_P = c\ell_P$ [22]. These convergent connections suggest spacetime diffusivity may serve as a bridging concept across different quantum-gravity programmes.

4.3. Gravitational Emergence Through Information Conjugacy

Mass concentrations create regions where CUP constraints force well-defined mass content (small Δm) to coexist with large diffusivity uncertainty ($\Delta\epsilon$). Information naturally flows toward these uncertainty sinks, potentially generating gravitational attraction through entropic optimisation, extending the entropic gravity programme of Verlinde [23] with explicit quantum-informational foundations. Deriving gravitational field equations from CUP optimisation principles remains an important direction for future work.

4.4. Limitations and Open Questions

We identify several limitations that should be addressed in future work:

Physical identification of m . The Lagrange multiplier m is identified with inertial mass on dimensional and consistency grounds (Section 2.2). The exact recovery of Hawking temperature provides strong *a posteriori* support, but a first-principles derivation from semiclassical gravity or holographic duality remains outstanding.

Coherence length ℓ_{coh} . The amplified CUP (17) depends on $\chi = \ell_{\text{coh}}/\ell_P$, which is currently calibrated empirically. Deriving χ from microscopic decoherence physics (gravitational, collisional, and environmental channels) would transform the framework from empirical fitting to *a priori* prediction.

Postulate 1. The linear evolution $d\epsilon/ds = c$ is adopted as the minimal Lorentz-compatible choice (Remark following Postulate 1). Alternative nonlinear evolutions could in principle be considered, and their consequences for the CUP should be explored.

Scope. This paper establishes the formal structure and its consequences for horizon thermodynamics and scale unification. Observational applications—including potential connections to galactic mass uncertainties—require additional assumptions about χ and measurement precision that we defer to future work.

4.5. Future Research Priorities

Key developments include: (1) microscopic derivation of the coherence scale χ from GKSL decoherence theory; (2) explicit gravitational field equations from CUP optimisation; (3) detailed observational predictions for precision astronomy; (4) exploration of connections to the Hubble tension and CMB anomalies through information-theoretic constraints.

5. Conclusion

We have shown that quantum conjugacy between spacetime diffusivity and mass emerges naturally from relativistic information transport through canonical quantisation, requiring no additional postulates beyond standard quantum mechanics and special relativity.

The principal results are: (1) The Cosmological Uncertainty Principle $\Delta\epsilon \Delta m \geq \hbar/2$, derived from the first-order action (4) through Dirac brackets and variable rescaling. (2) Operational scale unification: both $t_P = \ell_P/c$ and $t_H = 1/H_0$ emerge from a single area-diffusion parameter Z , spanning 61 orders of magnitude. (3) Exact, parameter-free recovery of Hawking’s black-hole temperature, validating the physical identification of the conjugate pair (ϵ, m) . (4) Recovery of the standard Gibbons–Hawking de Sitter temperature $T_{\text{dS}} = \hbar H/(2\pi k_B)$ via KMS/Unruh calibration of the correlation interval.

Unlike generalised or extended uncertainty principles that deform the position–momentum commutator, the CUP introduces a new conjugate pair while leaving the Heisenberg sector intact.

The information-pixel amplification mechanism (17) extends quantum uncertainty to cosmic scales through geometric counting (D/ℓ_{coh}) without violating locality or causality.

The framework is falsifiable: any confirmed violation of the amplified CUP bound at a given scale, or systematic failure of horizon-temperature predictions under controlled conditions, would decisively constrain its validity. Future work will focus on microscopic derivation of the coherence scale, explicit gravitational field equations, and detailed observational tests at astronomical baselines.

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Conflict of Interest. The author declares no conflicts of interest.

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Data Availability. This study develops a theoretical framework and does not report new experimental data. All results can be reproduced from the equations and constants specified in the manuscript.

Appendix A Additive Decoherence and the Coherence Scale

Two independent decoherence channels act on a baryonic mass element $m = \Sigma_* a^2$ at radius a : a gravitational channel $\Gamma_G = G\Sigma_*^2 a^3/\hbar$ following the Diósi–Penrose ansatz [24–26], and a kinematic/collisional channel $\Gamma_k = \zeta(G\Sigma_*^2/\hbar)(\sigma^3 m_P/(G\Sigma_* \hbar)) a^3$ with $\zeta = \mathcal{O}(1)$, consistent with Caldeira–Leggett and collisional decoherence scalings [27,28].

For statistically independent baths the total rate is the sum $\Gamma_{\text{tot}} = \Gamma_G + \Gamma_k$, reflecting additivity of independent GKSL/Lindblad generators [29,30]. Imposing the dynamical freeze-out condition $\Gamma_{\text{tot}} = \sigma/a$ (one local dynamical time [31]) and solving for the critical scale a yields the coherence factor

$$\chi = \chi_0 \left(\frac{70 M_\odot \text{ pc}^{-2}}{\Sigma_*} \right)^{1/2} \left(\frac{\sigma}{120 \text{ km s}^{-1}} \right)^{1/4} \left[1 + \zeta \frac{\sigma^3 m_P}{G\Sigma_* \hbar} \right]^{-1/4}, \quad (\text{A27})$$

where χ_0 is a normalisation constant. Calibrating to the Milky Way ($\Sigma_* \approx 70 M_\odot \text{ pc}^{-2}$, $\sigma \approx 120 \text{ km s}^{-1}$) gives $\chi_0 \equiv \chi_{\text{MW}} = 126$.

This scaling is derived from open-system dynamics (GKSL master equation) and Gaussian blur composition (variance additivity). For spatial coherences, the exact solution yields a Gaussian kernel with $\ell_{\text{coh}}^{-2}(t) = 2t \sum_i D_i$, confirming additivity in the inverse-squared coherence length [32,33].

The value $\chi_{\text{MW}} = 126$ should be regarded as an empirical anchor; deriving it from first principles remains an open challenge (see Section 4.4).

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