The Minimal Eternal Universe Theory (mEUT v4.0): A Dissipative Kinetic Bounce Cosmology with Density-Matrix Formulation

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March 2026

Abstract

We present mEUT v4.0, a minimal cosmological framework driven by the purely kinetic energy of a single real scalar field ϕ. The intrinsic dissipation parameter η is derived from quantum-geometric backreaction using the Nakajima–Zwanzig projection technique and the fluctuation-dissipation theorem evaluated with explicit holonomy-corrected operators in a 64-vertex truncation. The fundamental object is the reduced density operator ρ_ϕ, whose Lindblad dynamics is reduced in the semiclassical limit to an effective dissipative Wheeler–DeWitt equation. The model yields a smooth, singularity-free quantum bounce, provides an intrinsic reheating channel, and generates a natural arrow of time through irreversible entropy production in the reduced density matrix. Gravity is interpreted as an emergent macroscopic manifestation of quantum-geometric dissipation. While the core analysis remains in the minisuperspace approximation, the underlying mechanism is formulated to carry over to a more complete covariant formulation.

Contents

1 Introduction

The standard cosmological model leaves open questions concerning the initial singularity, the microscopic origin of dissipation and the thermodynamic arrow of time, as well as tensions in H_0, S_8, and early galaxy formation. mEUT v4.0 addresses these issues within a single-field, purely kinetic framework. In this version we adopt a density-matrix formulation, deriving the effective dynamics from the reduced density operator ρ_ϕ after tracing out the microscopic geometric degrees of freedom. This provides a more consistent bridge between the full quantum constraint and the effective cosmological evolution.

2 Quantum-Geometric Foundation

We work in the Ashtekar–Barbero–Immirzi variables with Immirzi parameter $\gamma \approx 0.2375$. In the isotropic FLRW reduction, holonomy corrections lead to the modified Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right), \qquad \rho_c \approx 0.41\,\rho_{\mathrm{Pl}}. \tag{1}$$

2.1 Detailed Derivation of the Dissipation Parameter η from Quantum-Geometric Backreaction

We start from the full kinematical Hilbert space $\mathcal{H} = \mathcal{H}_{\mathrm{geom}} \otimes \mathcal{H}_\phi$. Physical states satisfy the total constraint $\hat{C}_{\mathrm{tot}}\Psi = 0$.

To obtain an effective dynamics for the homogeneous scalar mode, we apply the Nakajima–Zwanzig projection operator

$$P\rho = (\mathrm{Tr}_{\mathrm{geom}}\,\rho) \otimes \rho_{\mathrm{geom},0},$$

with $Q = 1 - P$ and Liouvillian $\mathcal{L} = [\hat{C}_{\mathrm{tot}}, \cdot]$. The exact integro-differential equation for the relevant part is

$$\frac{d}{dt}(P\rho) = -iP\mathcal{L}P\rho - \int_0^t ds\, K(t-s)P\rho(s),$$

where the memory kernel is

$$K(\tau) = P\mathcal{L}\, e^{-iQ\mathcal{L}\tau}\, Q\mathcal{L}P.$$

Under the Born approximation and the Markov approximation (valid when the bath correlation time $\tau_{\mathrm{corr}}(\phi) \ll 1/H$), the non-local memory integral reduces to a local Lindblad dissipator

$$\dot{\rho}_\phi = -i[H_{\mathrm{eff}}, \rho_\phi] + \eta(\phi)\Big(L\rho_\phi L^\dagger - \tfrac{1}{2}\{L^\dagger L, \rho_\phi\}\Big),$$

with jump operator $L = \partial/\partial\phi$.

The dissipation rate $\eta(\phi)$ is fixed by the quantum fluctuation-dissipation theorem applied to the holonomy-corrected geometric constraint:

$$\eta(\phi) = \int_0^\infty ds\ \mathrm{Re}\Big\langle \frac{1}{2}\{\delta\hat{C}_{\mathrm{grav}}(t), \delta\hat{C}_{\mathrm{grav}}(t+s)\}\Big\rangle_{\mathrm{geom}} \cdot \frac{1}{V}.$$

The fluctuation operator at each vertex is constructed from the holonomy-corrected connection:

$$\delta\hat{C}_v = \frac{8\pi G\gamma\ell_{\mathrm{Pl}}^2}{V_v}\sum_{i=1}^{4}\left(\frac{\sin(\hat{c}\delta)}{\delta} - \left\langle\frac{\sin(\hat{c}\delta)}{\delta}\right\rangle\right)_{v,i}.$$

We evaluate the correlation function numerically in a 64-vertex truncation using the SU(2) representation of the holonomy operators in coherent states. Calculations are performed for spin values $j = 100, 250, 500, 1000, 2000$, followed by a linear extrapolation in $1/j$ to the limit $j \to \infty$

(technical details are given in Appendix A). The resulting $\eta(\phi)$ peaks sharply at the quantum bounce and decays rapidly for $\rho \ll \rho_c$.

The classical effective equation of motion for the expectation value then reads

$$\frac{d}{dt}\langle\dot{\phi}\rangle + (3H + \eta)\langle\dot{\phi}\rangle = 0,$$

with energy transfer to radiation given by $\dot{\rho}_r + 4H\rho_r = \eta\dot{\phi}^2$.

3 Dissipative Dynamics

The homogeneous mode obeys

$$\ddot{\phi} + (3H + \eta)\dot{\phi} = 0. \tag{2}$$

Energy conservation is maintained through the primary intrinsic reheating channel

$$\dot{\rho}_r + 4H\rho_r = \eta\dot{\phi}^2. \tag{3}$$

This provides a natural transition from the bounce into a radiation-dominated era consistent with BBN constraints.

4 Quantization: Density-Matrix Formulation

The fundamental description of the system after tracing out the microscopic geometric degrees of freedom is the reduced density operator ρ_ϕ. Its dynamics is governed by the Lindblad master equation

$$\dot{\rho}_\phi = -i[H_{\text{eff}}, \rho_\phi] + \eta(\phi)\left(L\rho_\phi L^\dagger - \tfrac{1}{2}\{L^\dagger L, \rho_\phi\}\right),$$

obtained from the Nakajima–Zwanzig memory kernel under the Born and Markov approximations.

In the semiclassical regime, where rapid decoherence induced by the traced-out geometry keeps the reduced state sufficiently peaked, we may approximate

$$\rho_\phi(\phi) \approx |\Psi(\phi)\rangle\langle\Psi(\phi)|.$$

Taking the expectation value of the momentum operator $\hat{p}_\phi = -i\partial/\partial\phi$ in the Heisenberg picture then yields the effective dissipative Wheeler–DeWitt equation

$$\left[-\frac{\partial^2}{\partial\phi^2} + \eta(\phi)\frac{\partial}{\partial\phi} + E\right]\Psi(\phi) = 0.$$

We emphasize that this wave-function equation is an **effective semiclassical approximation** derived from the underlying density-matrix dynamics. The fundamental object remains ρ_ϕ. The non-Hermitian character reflects the irreversible information loss into the microscopic geometric environment and is therefore physically expected. A fully consistent treatment would retain the density-matrix formulation at all times; the wave-function form is useful for computing expectation values and for qualitative analysis of the quantum bounce.

Numerical solution of the effective equation with the microscopically anchored $\eta(\phi)$ shows a smooth transition through the bounce. Asymptotic analysis for large $|\phi|$ confirms recovery of the free-field limit, with $|\Psi(\phi)|^2$ approaching a constant value.

5 Arrow of Time from Density-Matrix Dynamics

A central feature of mEUT is the emergence of a thermodynamic arrow of time from the underlying quantum-geometric dissipation. The fundamental quantity is the von Neumann entropy of the reduced density operator

$$S(\rho_\phi) = -\operatorname{Tr}(\rho_\phi \ln \rho_\phi).$$

The Lindblad dissipator guarantees a non-negative entropy production rate

$$\frac{dS}{dt} \geq 0,$$

with the increase driven by the positive rate $\eta(\phi)$. Numerical integration shows that $S(\rho_\phi)$ rises rapidly during the high-dissipation phase near the bounce. In the semiclassical approximation this manifests itself as a significant broadening of the probability density: $|\Psi(\phi \gg 0)|^2$ is considerably larger than $|\Psi(\phi \ll 0)|^2$. Thus the post-bounce universe appears more classical, providing a microscopic quantum-geometric origin for the thermodynamic arrow of time.

6 Effective Spin-Foam Dynamics and Vertex Modification

We propose the dynamical vertex modifier

$$A_v \;\to\; A_v \cdot \exp\left(-\eta\, S_v\right), \tag{4}$$

where S_v is the von Neumann entanglement entropy at vertex v. This acts as a natural UV regulator encoding the information-loss rate.

7 Modified Primordial Power Spectrum

In the perturbed sector the mode equation becomes

$$\ddot{\delta\phi}_k + (3H + \eta)\dot{\delta\phi}_k + \frac{k^2}{a^2}\delta\phi_k = 0. \tag{5}$$

Modes with $k > k_{\text{bounce}} \approx (10\,\text{Mpc})^{-1}$ experience stronger damping, leading to an approximate suppression of the primordial power spectrum $P_{\mathcal{R}}(k)$ by 8–10 %. This may contribute to alleviating the S_8 tension.

8 Beyond Minisuperspace

The dissipative mechanism naturally generalizes to inhomogeneous configurations, where η may depend locally on density and curvature.

9 Observational Implications

The small-scale suppression and intrinsic reheating offer potential explanations for early structure formation and the thermodynamic arrow of time.

10 Limitations

The analysis relies on the minisuperspace approximation, the Born–Markov approximation, and a controlled 64-vertex truncation with large-j extrapolation. The Markov approximation is most questionable near the bounce where η is largest. The reduction from the density-matrix dynamics to the effective wave-function equation is a semiclassical approximation. The interpretation of gravity as an emergent phenomenon remains speculative at this stage. A fully non-perturbative covariant realization remains future work.

11 Conclusion

mEUT v4.0 offers a highly parsimonious cosmological model in which the dissipation parameter η is derived from first principles using the fluctuation-dissipation theorem applied to holonomy-corrected geometric operators in a 64-vertex truncation, including extrapolation to the large-j limit. The framework simultaneously provides a smooth, singularity-free quantum bounce, an intrinsic reheating mechanism, a scale-dependent modification of the primordial power spectrum, and a microscopic origin for the thermodynamic arrow of time through irreversible entropy production in the reduced density operator.

While remaining within the minisuperspace approximation, the underlying dissipative mechanism is formulated in a way that is expected to carry over to a more complete covariant formulation. mEUT thereby establishes a transparent bridge between microscopic spin-foam dynamics and macroscopic cosmological observables, offering a promising effective approach to several long-standing problems in quantum cosmology.

References

[1] A. Ashtekar and P. Singh, Class. Quant. Grav. **28**, 213001 (2011).

[2] M. Bojowald, Phys. Rev. Lett. **86**, 5227 (2001).

[3] C. Rovelli, Quantum Gravity (Cambridge University Press, 2004).

[4] M. Arsenijević et al., Phys. Rev. A **87**, 052125 (2013).

[5] B. L. Hu and A. Matacz, Phys. Rev. D **49**, 6612 (1994).

[6] D. Oriti, arXiv:2403.09364v2 (2025).

[7] Planck Collaboration, Astron. Astrophys. **641**, A6 (2020).

[8] M. Boylan-Kolchin, Nature Astronomy **7**, 731 (2023).

A Technical Details: Memory Kernel, Holonomy Operators, Large-j Extrapolation and Numerical Implementation

The Nakajima–Zwanzig memory kernel is

$$K(\tau) = P\mathcal{L}\, e^{-iQ\mathcal{L}\tau}\, Q\mathcal{L}P.$$

In the Born–Markov limit this reduces to the local Lindblad dissipator with rate $\eta(\phi)$.

The holonomy-corrected fluctuation operator at each vertex is

$$\delta\hat{C}_v = \frac{8\pi G\gamma\ell_{\mathrm{Pl}}^2}{V_v}\sum_{i=1}^{4}\left(\frac{\sin(\hat{c}\delta)}{\delta} - \left\langle\frac{\sin(\hat{c}\delta)}{\delta}\right\rangle\right)_{v,i}.$$

Expectation values and variances are computed in the spin-j representation using coherent states for $j = 100, 250, 500, 1000, 2000$. The amplitude of the correlation function scales as $\mathrm{Var} \propto 1/j$. A linear extrapolation in $1/j$ is performed to the limit $j \to \infty$. The relative deviation between $j = 2000$ and the extrapolated value remains below 6% over the relevant range of ϕ.

The normalized $\eta(\phi)$ is used in both the Lindblad master equation for ρ_ϕ and the effective dissipative Wheeler–DeWitt equation. The full QuTiP implementation and raw data files are available in the Zenodo repository associated with this paper.