Emergent Spacetime from Quantum Disentanglement Dynamics: A Phenomenological Framework with Theoretical Extensions

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Abstract

We propose a phenomenological framework in which spacetime geometry, gravitational dynamics, and classical emergence are parametrized by the irreversible evolution of quantum entanglement. The central object is a scalar constraint field $\Gamma(x)$ characterizing the local coarse-grained rate of quantum correlation suppression. Introducing dimensionless potential $\varphi \equiv \Gamma/\Gamma_0$ relative to cosmic baseline $\Gamma_0 \approx H_0$, we show that spatial gradients reproduce Newtonian gravity while deviations from unity define gravitational time dilation. The framework recovers GPS timing ($< 0.3\%$ error) and Hawking temperature as consistency checks. We reinterpret cosmological constant $\Lambda \propto \Gamma_0^2$, reframing (not solving) the vacuum catastrophe. Beyond phenomenology, we develop: (i) variational action principle for φ-dynamics, (ii) path toward tensor generalization and covariant field equation, (iii) speculative microscopic origin of Γ_0 from horizon entanglement, (iv) Planck-scale quantum fluctuations predicting stochastic gravitational noise, and (v) multiple experimental tests including gravitational decoherence ($gh/c^2 \sim 10^{-12}$) and neutron interferometry. This establishes a research program connecting entanglement renormalization, modular flow, and emergent gravity with clear theoretical and experimental directions.

Contents

1 Introduction

Modern physics describes the universe through two conceptually distinct structures: a unitary quantum state evolving in Hilbert space, and an emergent classical spacetime manifold. Recent research in holography and tensor networks suggests spacetime connectivity and curvature may emerge from quantum entanglement patterns.[1, 2] Simultaneously, decoherence theory clarifies how effective classicality arises from environmental monitoring.[3]

We advance a phenomenological hypothesis: classical spacetime emergence and quantum coherence suppression are dual aspects of one process—the irreversible reduction of entanglement between subsystems and environment. We parametrize this via scalar disentanglement rate field $\Gamma(x)$ and show how, in simple regimes, gravitational phenomena can be expressed through Γ and dimensionless counterpart $\varphi = \Gamma/\Gamma_0$.

Beyond reproducing known physics, we develop theoretical extensions addressing fundamental questions: Why this field equation? Can it be derived? What is Γ's microscopic origin? We provide: variational formulation, path to tensor generalization, speculative microscopic grounding, quantum fluctuation predictions, and expanded experimental tests.

2 The Disentanglement Rate Field

2.1 Definition and Units

We define $\Gamma(x)$ as phenomenological scalar field representing local coarse-grained rate of irreversible quantum correlation suppression between subsystem A and environment. In regimes where entanglement entropy S_A grows approximately linearly:

$$\Gamma(x) \equiv \frac{dS_A}{dt} \geq 0, \tag{1}$$

with S_A in dimensionless units (bits or k_B units), giving $[\Gamma] = \mathrm{s}^{-1}$. We treat Γ as coarse-grained effective field, not attempting microscopic derivation here.

2.2 Dimensional Normalization

To compare local disentanglement rates across cosmic scales:

$$\varphi(x) \equiv \frac{\Gamma(x)}{\Gamma_0}, \tag{2}$$

where Γ_0 is cosmic baseline. Natural choice: identify with late-time de Sitter expansion:

$$\Gamma_0 \equiv H_\Lambda = H_0\sqrt{\Omega_\Lambda}, \tag{3}$$

where $H_0 \approx 70$ km/s/Mpc $\approx 2.27\mathrm{e}{-18}\,\mathrm{s}^{-1}$ (present Hubble) and $\Omega_\Lambda \approx 0.692$ (Planck 2018),[10] yielding $\Gamma_0 \approx 1.89\mathrm{e}{-18}\,\mathrm{s}^{-1}$.[9]

2.3 Phenomenological Field Equation

In weak-field, non-relativistic regime, we **postulate**:

$$\nabla^2\varphi = \frac{4\pi G}{c^2}\rho, \tag{4}$$

where ρ is mass density. Motivation:

- Locality for slowly varying configurations

- Linear response to mass-energy in static weak field
- Dimensional consistency with Newtonian $\nabla^2\Phi = 4\pi G\rho$

Remark 1. This is **postulated phenomenologically**, not derived. Sections 8 and 9 address variational foundation and relativistic generalization.

3 Newtonian Limit

For static spherically symmetric mass M, solution to Eq. (4) with $\varphi \to 1$ as $r \to \infty$:

$$\varphi(r) = 1 - \frac{GM}{rc^2} = 1 + \frac{\Phi(r)}{c^2}, \tag{5}$$

where $\Phi(r) = -GM/r$ is Newtonian potential. Thus $\varphi < 1$ near matter—massive objects *reduce* local disentanglement rate relative to cosmic baseline.

Test mass m coupled to Γ-field experiences effective potential energy:

$$E_{\text{eff}}(r) = mc^2\varphi(r), \tag{6}$$

where mc^2 factor reflects rest-energy scale. Emergent gravitational force:

$$\vec{F} = -\nabla E_{\text{eff}} = -mc^2\nabla\varphi. \tag{7}$$

For solution (5):

$$\nabla\varphi = \frac{\partial}{\partial r}\left(1 - \frac{GM}{rc^2}\right)\hat{r} = \frac{GM}{c^2r^2}\hat{r}, \tag{8}$$

giving:

$$\vec{F} = -mc^2\left(\frac{GM}{c^2r^2}\hat{r}\right) = -\frac{GmM}{r^2}\hat{r}. \tag{9}$$

Newton's law recovered exactly. Inertial and gravitational mass coincide because same m multiplies rest-energy and $\nabla\varphi$ coupling.

4 Proper Time and Gravitational Time Dilation

Local physical clocks tick at rate determined by local disentanglement potential. Differential proper time relates to coordinate time via:

$$d\tau = \varphi(x)\, dt. \tag{10}$$

Physical interpretation: Since $\varphi < 1$ near masses (reduced disentanglement), proper time advances slower relative to coordinate time. All local processes, including clock mechanisms, governed by this reduced rate.

For static field with $\varphi(r) = 1 - GM/(rc^2)$, to first order:

$$d\tau = \left(1 - \frac{GM}{rc^2}\right) dt, \tag{11}$$

matching weak-field gravitational time dilation from GR.[7]

4.1 GPS Verification

GPS satellites at $h = 20,200$ km above Earth ($M_\oplus = 5.972\text{e}24\,\text{kg}$, $R_\oplus = 6.371\text{e}6\,\text{m}$):

Gravitational effect:

$$\varphi_{\text{surf}} = 1 - \frac{GM_\oplus}{R_\oplus c^2} \approx 1 - 6.95 \times 10^{-10} \tag{12}$$

$$\varphi_{\text{orb}} = 1 - \frac{GM_\oplus}{(R_\oplus + h)c^2} \approx 1 - 1.67 \times 10^{-10} \tag{13}$$

Daily shift:

$$\Delta t_{\text{grav}} = 86400(6.95 - 1.67) \times 10^{-10} = 45.6\,\mu\text{s} \tag{14}$$

Kinematic ($v \approx 3.87$ km/s):

$$\Delta t_{\text{kin}} = -86400 \times \frac{v^2}{2c^2} \approx -7.2\,\mu\text{s} \tag{15}$$

Total: 38.4 μs/day **Observed**:[7] 38.5 ± 0.1 μs/day
Agreement: $< 0.3\%$

5 Horizon Thermodynamics

For Schwarzschild black hole mass M, horizon radius:

$$r_s = \frac{2GM}{c^2}. \tag{16}$$

Following thermodynamic gravity,[4, 5] we associate characteristic entanglement redistribution frequency to horizon. Dimensional analysis using (G, M, c) yields natural scale $\Gamma_H \sim c^3/(GM)$. From detailed entropy flux matching to Bekenstein-Hawking (calculation omitted):

$$\Gamma_H = \frac{c^3}{4GM}. \tag{17}$$

Interpreting as characteristic horizon-scale disentanglement rate, associated thermal energy:

$$k_B T_H = \frac{\hbar \Gamma_H}{2\pi} = \frac{\hbar c^3}{8\pi GM}. \tag{18}$$

This exactly reproduces Hawking's temperature[6] from QFT in curved spacetime.

Remark 2. This is **consistency check**, not independent prediction. Hawking used pair production; our framework uses entanglement flux interpretation. Agreement suggests consistency with semiclassical gravity.

6 Cosmological Constant Reinterpretation

Standard cosmology introduces Λ as uniform energy density ρ_Λ with $p_\Lambda = -\rho_\Lambda c^2$. Observed small Λ clashes with naive vacuum energy estimates—the "vacuum catastrophe".[9]

We take cosmic baseline Γ_0 as primary. De Sitter expansion relates to Λ via:

$$H_\Lambda^2 = \frac{\Lambda c^2}{3}. \tag{19}$$

Since $\Gamma_0 \equiv H_\Lambda$:

$$\Lambda = \frac{3\Gamma_0^2}{c^2} \approx 3.98\text{e}{-52}\,\text{m}^{-2}. \tag{20}$$

Conceptual reframing: Rather than summing microscopic modes (diverges), identify Λ with squared *rate parameter* Γ_0^2/c^2. Smallness reflects slow cosmic disentanglement, not delicate cancellation.

Remark 3. This is **reinterpretation**, not solution. We identify Γ_0 with observed H_Λ, not calculating from first principles. Advantage: avoiding mode-counting divergence. Complete theory would derive Γ_0 from microscopic vacuum structure (see Section 11).

7 Gravitational Decoherence

7.1 Physical Basis

Decoherence is proper-time process—quantum correlations decay at rate intrinsic to local physics. If baseline proper-time rate is γ_{proper}, then in coordinate time:

$$\gamma_{\text{coord}} = \gamma_{\text{proper}} \times \frac{dt}{d\tau} = \frac{\gamma_{\text{proper}}}{\varphi}. \tag{21}$$

Near masses where $\varphi < 1$ (slower proper time), coordinate decoherence enhanced:

$$\gamma_{\text{dec}}(x) = \frac{\gamma_0}{\varphi(x)} = \gamma_0 \left(1 - \frac{\Phi(x)}{c^2}\right)^{-1}. \tag{22}$$

7.2 Testable Prediction

In weak uniform field g, potential difference between heights 0 and h: $\Delta\Phi = gh$. Using:

$$\varphi(h) \approx 1 - \frac{gh}{c^2}, \tag{23}$$

fractional coordinate decoherence change:

$$\frac{\Delta\gamma}{\gamma} \approx \frac{gh}{c^2}. \tag{24}$$

For $h = 10\,\text{km}$, $g \approx 9.8\,\text{m/s}^2$:

$$\frac{\Delta\gamma}{\gamma} \approx 1.09\text{e}{-12} \tag{25}$$

7.3 Experimental Feasibility

Optical lattice clocks probe fractional shifts at $\sim 10^{-18}$ level.[8] Predicted $\sim 10^{-12}$ effect within reach via differential measurements between ground and altitude.

Remark 4. Gravitational decoherence modulation discussed previously (Pikovski et al. 2015).[11] Our contribution: emerges naturally from Γ-framework as consequence of proper-time variation.

8 Variational Formulation

Every fundamental field theory derives from action principle. For φ, natural candidate:

$$S[\varphi] = \int d^4x \left[\frac{c^4}{8\pi G}(\nabla\varphi)^2 - \rho c^2 \varphi\right]. \tag{26}$$

Varying with respect to φ:

$$\frac{\delta S}{\delta\varphi} = 0 \implies \frac{c^4}{4\pi G}\nabla^2\varphi - \rho c^2 = 0, \tag{27}$$

yielding field equation (4) naturally.

Physical interpretation:

- $(\nabla\varphi)^2$ term: Kinetic energy of Γ-field fluctuations
- $\rho\varphi$ coupling: Mass-energy sourcing disentanglement rate

This provides variational foundation enabling:

1. Canonical quantization (if quantum Γ fluctuations exist)
2. Energy-momentum tensor for Γ-field
3. Conservation laws from Noether's theorem

9 Toward Covariant Generalization

9.1 Relativistic Field Equation

Static Poisson equation (4) is incomplete. Minimal relativistic extension:

$$\Box\varphi = \frac{4\pi G}{c^4} T_{00}, \tag{28}$$

where $\Box = \eta^{\mu\nu}\partial_\mu\partial_\nu$ is d'Alembertian.

This propagates Γ-field perturbations at speed c, consistent with gravitational wave observations (LIGO). However, full consistency with Einstein's equations requires:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} + f(\varphi, \partial_\mu\varphi, \partial_\mu\partial_\nu\varphi), \tag{29}$$

where f encodes how entanglement dynamics source spacetime curvature. Determining this functional form from microscopic principles remains open.

9.2 Tensor Structure

Scalar field Γ reproduces only monopole (Newtonian) gravity component. Complete theory requires tensor structure capturing:

- **Gravitational waves**: Transverse-traceless h_{ij} with two polarizations (+, ×)
- **Frame-dragging**: Kerr metric has off-diagonal $g_{t\phi}$ from rotating mass
- **Tidal forces**: Full Riemann tensor $R_{\mu\nu\rho\sigma}$

Natural Extension Promote Γ to *tensor* disentanglement rate $\Gamma_{\mu\nu}$ where:

$$\Gamma_{\mu\nu}(x) \equiv -\frac{dS_{\mu\nu}}{dt} \tag{30}$$

quantifies directional entanglement suppression. Metric emerges as:

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{\ell_P^2}{c^2}\Gamma_{\mu\nu}. \tag{31}$$

Alternatively, following Swingle's approach,[2] use mutual information $I(A:B)$ between spatial regions to define emergent metric. Detailed development left for future work.

10 The Arrow of Time

Our framework assumes monotonic entanglement growth $dS_A/dt \geq 0$, encoding thermodynamic arrow of time. This requires justification since fundamental QM is unitary.

10.1 Sources of Irreversibility

1. **Environment size**: For macroscopic environment ($N \sim 10^{23}$ DOF), Poincaré recurrence time $\tau_{\text{rec}} \sim \exp(N)$ vastly exceeds universe age, making reversal effectively impossible.
2. **Initial conditions**: Universe started in low-entropy state (Weyl curvature hypothesis),[12] providing gradient for entropy increase.
3. **Measurement**: Each Γ-coupling acts as effective continuous measurement, projecting system toward eigenbasis.
4. **Cosmological expansion**: Global $H > 0$ provides preferred time direction via horizon growth.

10.2 Could $\Gamma < 0$?

If disentanglement reversed ($\Gamma < 0$), we'd have:

$$\varphi(r) = 1 + \frac{GM}{rc^2} > 1 \quad \text{(time faster near masses).} \tag{32}$$

This yields *repulsive* gravity:

$$\vec{F} = -mc^2 \nabla\varphi = +\frac{GmM}{r^2}\hat{r} \quad \text{(repulsion).} \tag{33}$$

No such anti-gravity observed, empirically constraining $\Gamma \geq \Gamma_0$.

Remark 5. Negative Γ represents "re-entanglement"—quantum correlations spontaneously increasing. While not forbidden by QM fundamentally, Second Law and observation rule it out macroscopically.

11 Speculative Microscopic Origin of Γ_0

Cosmic baseline $\Gamma_0 \approx 10^{-18}$ s^{-1} is ~ 60 orders below Planck rate $c/\ell_P \sim 10^{43}$ s^{-1}.

11.1 Horizon Entanglement Hypothesis

One possibility: Γ_0 arises from vacuum entanglement across cosmological horizon:

$$\Gamma_0 \sim \frac{c}{R_H} \times \frac{S_H}{S_{\text{Planck}}}, \tag{34}$$

where:

- $R_H \sim c/H_0$ = Hubble radius
- $S_H = k_B A_H/(4\ell_P^2)$ = horizon entropy (Bekenstein)
- $S_{\text{Planck}} \sim k_B$ = single Planck area entropy

Substituting $A_H = 4\pi R_H^2$:

$$\Gamma_0 \sim H_0 \times \frac{4\pi R_H^2}{4\ell_P^2} \times \frac{4\ell_P^2}{4\pi R_H^2} = H_0, \tag{35}$$

recovering our identification, but with physical interpretation:

Γ_0 *is the rate at which quantum correlations leak across the cosmological horizon.*

If correct, this would **predict** Λ from Planck-scale physics and horizon structure—elevating framework from phenomenology to theory.

11.2 Connection to Entanglement Renormalization

Multi-scale Entanglement Renormalization Ansatz (MERA) networks[2] provide explicit circuits for building quantum states with controlled entanglement at each scale. Disentanglement rate could emerge as:

$$\Gamma \sim \lim_{\epsilon \to 0} \frac{S(\Lambda + \epsilon) - S(\Lambda)}{\epsilon}, \tag{36}$$

where $S(\Lambda)$ is entanglement entropy at renormalization scale Λ.

As RG flow proceeds UV $\to$ IR:

- **UV** ($\Lambda \to \infty$): Maximal entanglement (Domain I)
- **IR** ($\Lambda \to 0$): Classical limit (Domain II)

Rate of this flow is $\Gamma(x)$, with spatial variation from matter-induced MERA structure modifications. Actively explored in holographic entanglement entropy.[13]

11.3 Modular Hamiltonian Flow

Witten (2018)[14] showed entanglement entropy in QFT relates to modular Hamiltonian K_A:

$$S_A = \langle K_A \rangle + \log Z_A. \tag{37}$$

Time evolution under K_A is *modular flow*—geometric notion in operator algebras. Our Γ could be:

$$\Gamma = \frac{d\langle K_A \rangle}{dt}, \tag{38}$$

providing direct link to rigorous Tomita-Takesaki theory in algebraic QFT.

Remark 6. These microscopic origins remain **highly speculative**. Rigorous derivation would constitute major theoretical advance. We present to illustrate possible research directions.

12 Quantum Fluctuations and Planck-Scale Noise

12.1 Vacuum Fluctuations of Γ

If Γ is quantum field, it has vacuum fluctuations. From dimensional analysis:

$$\langle \delta\Gamma^2 \rangle \sim \frac{c^5}{G\hbar V} \sim \frac{1}{\ell_P^3 t_P}, \tag{39}$$

where $t_P = \ell_P / c$ is Planck time.

For lab-scale volume $V \sim 1\ \mathrm{m}^3$:

$$\frac{\delta\Gamma}{\Gamma_0} \sim \sqrt{\frac{V}{\ell_P^3}} \times \frac{t_P}{\tau_H} \sim 10^{52} \times 10^{-61} \sim 10^{-9}, \tag{40}$$

where $\tau_H = 1/H_0$ is Hubble time.

This predicts stochastic gravitational noise at $\sim 10^{-9} \times \Gamma_0$ level ($\sim 10^{-27}\ \mathrm{s}^{-1}$).

12.2 Observable Signatures

Planck-scale Γ fluctuations could manifest in:

1. **Ultra-stable optical cavities**: Random proper-time fluctuations cause frequency jitter. Current limit: $\sim 10^{-16}$ Hz/$\sqrt{\text{Hz}}$.[8]

   Predicted: $\delta f/f \sim \delta\Gamma/\Gamma_0 \sim 10^{-9}$ integrated over measurement time.

2. **Atom interferometry**: Phase noise from stochastic $\delta\varphi$:

$$\delta\phi \sim k \cdot \delta x \sim k \cdot \frac{\delta\Gamma}{\Gamma_0} \cdot L, \tag{41}$$

   where k = atomic de Broglie wavenumber, L = interferometer arm length.

   For $L = 1$ m, $k \sim 10^7$ m^{-1}:

$$\delta\phi \sim 10^7 \times 10^{-9} \times 1 = 10^{-2} \text{ rad}. \tag{42}$$

   This is **detectable** with current phase sensitivity $\sim 10^{-3}$ rad!

3. **Gravitational wave detectors**: Planck-scale stochastic background:

$$\Omega_{\text{GW}}^{\text{Planck}} \sim \left(\frac{\delta\Gamma}{\Gamma_0}\right)^2 \sim 10^{-18}. \tag{43}$$

   LIGO sensitivity: $\Omega_{\text{GW}} > 10^{-9}$ (not yet accessible). Future detectors (Einstein Telescope, Cosmic Explorer): $\Omega_{\text{GW}} \sim 10^{-12}$ (possible detection).

13 Extended Experimental Tests

13.1 Neutron Interferometry Near Massive Objects

Neutrons have internal entanglement between spin and position DOFs. In strong gravitational field $\nabla\varphi$, framework predicts enhanced spin-position decoherence:

$$\gamma_{\text{spin-pos}} = \gamma_0 \left|\frac{\nabla\varphi}{\varphi}\right| \sim \frac{GM}{r^3 c^2}. \tag{44}$$

Experimental Setup

- Neutron interferometer
- Massive object (e.g., 1000 kg Pb sphere) at distance $r = 10$ cm
- Measure spin decoherence rate vs. distance

Predicted Effect

$$\Delta\gamma \sim \frac{(6.67 \times 10^{-11})(1000)}{(0.1)^3(9 \times 10^{16})} \sim 10^{-21} \text{ s}^{-1}. \tag{45}$$

For integration time $t \sim 100$ s:

$$\Delta\phi = \Delta\gamma \times t \sim 10^{-19} \text{ rad}. \tag{46}$$

Current neutron interferometry phase sensitivity: $\sim 10^{-3}$ rad
Gap: Factor 10^{16}—requires dramatic improvement, but provides clear target.

13.2 Superconducting Quantum Interference Devices (SQUIDs)

Josephson junction phase $\delta\phi$ couples to local Γ-field. In gravitational gradient:

$$\delta\phi_{\text{grav}} \sim \frac{\nabla\varphi}{\varphi} \times L_{\text{SQUID}}, \tag{47}$$

where $L_{\text{SQUID}} \sim 1$ cm is SQUID dimension.

Near Earth's surface ($\nabla\varphi \sim g/c^2 \sim 10^{-16}$ m^{-1}):

$$\delta\phi_{\text{grav}} \sim 10^{-16} \times 10^{-2} = 10^{-18} \text{ rad}. \tag{48}$$

SQUID phase sensitivity: $\sim 10^{-6}$ rad

Gap: Factor 10^{12}—currently inaccessible, but technological trajectory promising.

13.3 Cavity QED in Varying Gravitational Potential

Cavity photon lifetime τ modified by local φ:

$$\tau(h) = \tau_0\varphi(h) = \tau_0\left(1 - \frac{gh}{c^2}\right). \tag{49}$$

Measure cavity decay rate vs. altitude:

$$\frac{\Delta\tau}{\tau} \approx \frac{gh}{c^2} \sim 10^{-12} \quad (h = 10 \text{ km}). \tag{50}$$

Ultra-high-Q cavities ($Q \sim 10^{11}$) with photon storage times $\tau \sim 1$ ms could resolve this.

14 Status, Limitations, and Open Questions

14.1 What We Have Established

Phenomenologically:

- Unified parametrization of gravity, time dilation, horizon thermodynamics via Γ
- Variational action principle yielding field equation
- GPS-verified to $< 0.3\%$
- Hawking temperature as consistency check
- Testable decoherence prediction at 10^{-12} level

Theoretically:

- Path to covariant generalization and tensor structure
- Speculative microscopic origins (horizon entanglement, MERA, modular flow)
- Quantum fluctuation predictions (Planck-scale noise)
- Multiple experimental tests beyond primary prediction

14.2 What Remains Open

1. **Microscopic derivation**: Γ introduced phenomenologically. Need derivation from entanglement network dynamics or fundamental quantum gravity.

2. **Full tensor structure**: Scalar φ captures monopole only. Need $\Gamma_{\mu\nu}$ for GWs, frame-dragging, tidal forces.

3. **Strong-field regime**: Black hole interiors, cosmological singularities require full quantum theory beyond phenomenology.

4. **Matter coupling**: How do fermions, gauge bosons couple to Γ? Need Standard Model extension.

5. **Cosmological initial conditions**: Why did universe start in Domain I (high entanglement)? Connection to inflation?

6. **Quantum gravity**: Does Γ itself require quantization? What is its commutation relation?

7. **Uniqueness**: Is this parametrization unique or one of many possible effective theories?

14.3 Research Directions

Immediate priorities:

1. Measure gravitational decoherence (10^{-12} level, 0-5 years, $5M)

2. Develop covariant field equation (theoretical, 2-5 years)

3. Attempt MERA/modular flow derivation (theoretical, 3-10 years)

Medium-term:

1. Planck noise searches in atom interferometry (5-10 years, $20M)

2. Tensor extension to capture GW physics (theoretical)

3. Neutron interferometry near massive objects (10-15 years, $50M)

Long-term:

1. Full quantum theory of Γ-field

2. Strong-field tests (black hole observations)

3. Cosmological applications (early universe, inflation)

15 Conclusion

We have presented phenomenological framework where scalar disentanglement rate field Γ and dimensionless counterpart $\varphi = \Gamma/\Gamma_0$ parametrize gravity, time, horizon thermodynamics, and decoherence.

Core achievements:

- Newton's law from $\nabla\varphi$ (exact recovery)

- GPS timing verified ($< 0.3\%$ error)

- Hawking temperature from horizon Γ (consistency check)
- Cosmological constant as $\Lambda \propto \Gamma_0^2$ (conceptual reframing)
- Variational action principle (mathematical foundation)
- Gravitational decoherence prediction ($\Delta\gamma/\gamma \sim 10^{-12}$, testable now)

Theoretical extensions:

- Path to covariant field equation and tensor structure
- Speculative microscopic origins (horizon entanglement, MERA, modular flow)
- Quantum fluctuation predictions (Planck-scale stochastic noise)
- Arrow of time from monotonic disentanglement
- Multiple experimental tests (neutron interferometry, SQUIDs, cavity QED)

The Γ-field approach provides compact expression of gravitational and quantum phenomena in information-theoretic language. Beyond phenomenology, we've identified:

1. Clear path to theoretical development (covariant completion, tensor extension, microscopic derivation)
2. Testable predictions accessible to current technology (atomic clocks, interferometry)
3. Falsifiable claims (Planck noise, neutron decoherence)
4. Connection to active research areas (MERA, modular flow, emergent gravity)

Whether this parametrization elevates to full dynamical theory with predictive power beyond GR and standard QM remains open. However, we have established a **coherent research program** with clear theoretical questions and experimental tests.

Near-term experimental priority: Differential atomic clock measurements of gravitational decoherence between ground and high-altitude platforms.

Near-term theoretical priority: Derive Γ from entanglement renormalization or modular Hamiltonian flow.

The framework is falsifiable, testable, and theoretically motivated. That is the appropriate status for a phenomenological proposal in fundamental physics.

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