Experimental Test of Local Gravitational Sourcing from Decoherence History

Paul D'Angelo[1, *]

[1] *PACES Research Group*

(Dated: February 23, 2026)

We propose an experimental protocol to test whether gravitational sourcing by a mesoscopic mass depends on its accumulated decoherence history, distinct from its stress-energy expectation value. The dual-bath design employs two levitated masses with independently controllable environmental coupling, enabling a decisive locality test: gravitational activation must be earned by each system's own entanglement history with its environment, not inherited from the classical background. The protocol discriminates semiclassical gravity—where mass-energy alone determines gravitational output—from dynamical activation models in which decoherence history is the activating variable. If activation is present, Phase 4 maps the full crossover curve. A consistent scalar-tensor extension demonstrates cosmological viability and early-universe testability. Required measurement sensitivity is within projected capability of near-term optomechanical platforms.

I. INTRODUCTION AND CONTEXT

Gravitational response of quantum systems has been extensively verified: neutrons, atoms, and molecules in interferometers respond to external gravitational fields exactly as semiclassical gravity predicts [1–3]. What has not been tested is the complementary question—whether a quantum system's own gravitational sourcing capacity depends on its quantum state history.

Semiclassical gravity assumes sourcing depends solely on the expectation value of the stress-energy tensor, written as $\langle \hat{T}_{\mu\nu} \rangle$, irrespective of whether the system is in a coherent superposition or a decohered classical mixture. We test an alternative motivated by quantum foundations: sourcing capacity may require accumulated decoherence, defined as the irreversible entanglement built up between a system and its environment over time. This distinction separates gravitational response (universal, already verified) from gravitational activation (history-dependent, untested).

A. Relation to Existing Frameworks

ER=EPR Correspondence: We extend the static entanglement-geometry equivalence of Maldacena and Susskind [4] to irreversible, dynamical accumulation, addressing the locality of sourcing explicitly rather than assuming it.

Objective Collapse Models: The proposal discriminates our framework from Penrose-Diósi dynamics [5, 6], in which gravity causes decoherence, via reversed causal structure—here, decoherence enables sourcing rather than the reverse. This is a testable causal distinction.

Emergent Gravity Programs: The proposal provides an operational criterion for when a classical gravitational description applies, complementary to thermodynamic derivations by Jacobson and Verlinde [7, 8].

II. THEORETICAL FRAMEWORK

A. Accumulated Decoherence

For a system S interacting with environment E, accumulated decoherence $\mathcal{D}_S(t)$ is defined as the monotone, irreversible integral of purity loss:

$$\mathcal{D}_S(t) = \int_0^t \max\left\{0, -\frac{1}{2}\frac{d}{dt'} \ln \mathrm{Tr}[\hat{\rho}_S(t')^2]\right\} dt' \tag{1}$$

This functional is monotone (never decreases), irreversible (consistent with thermodynamic directionality), and partition-dependent, meaning it tracks each system's own environmental entanglement history independently. Clipping enforces non-negativity. These are standard properties of decoherence functionals [9].

* correspondence@paces-research.org

B. Activation Hypothesis

Gravitational sourcing capacity is modeled by a Hill activation function—a smooth S-shaped curve that transitions from zero to full sourcing as accumulated decoherence crosses a threshold $\mathcal{D}_*$:

$$f_{\rm grav}(\mathcal{D}) = \frac{\mathcal{D}^n}{\mathcal{D}^n + \mathcal{D}_*^n} \tag{2}$$

The modified Poisson equation for the gravitational potential then becomes:

$$\nabla^2\Phi = 4\pi G_N \left[\rho_{\rm env} + f_{\rm grav}(\mathcal{D}_S)\rho_{S,\rm cl}\right] \tag{3}$$

Note the key asymmetry: the gravitational potential Φ couples universally to all test masses regardless of their decoherence state, but only $\mathcal{D}$-accumulated source densities contribute to generating Φ. A mass in ultra-high vacuum with minimal decoherence history sources less gravitational field, even if its mass-energy is identical to a fully decohered counterpart.

C. The Locality Test

A critical objection must be addressed directly: the present cosmic epoch has accumulated decoherence $\mathcal{D}_{\rm Universe} \gg \mathcal{D}_*$. Would not any laboratory mass automatically inherit full gravitational activation from the classical background?

The experiment tests this explicitly. Two masses occupy essentially the same spacetime location and share the same classical background, but accumulate different local decoherence histories through independent environmental coupling. If sourcing is local to each system's own $\mathcal{D}_S$, they must source differently despite identical backgrounds. If sourcing is inherited globally, they source identically regardless of local history. The dual-bath reversal test is designed to distinguish these cases decisively.

III. EXPERIMENTAL PROTOCOL

A. System Parameters

Two silica nanospheres, each with mass $m \sim 10^{-13}$ kg (approximately 10^{11} atomic mass units) and radius $R \sim 50$ nm, are suspended by optical or magnetic levitation in separate vacuum chambers. The chambers are separated by approximately 200 μm, electromagnetically shielded, and cryogenically baffled to suppress thermal and electromagnetic noise sources.

B. Decoherence Control

The primary decoherence control mechanism is collisional decoherence via residual gas pressure. The collisional decoherence rate scales as:

$$\Gamma_{\rm coll} \sim \eta \frac{P}{k_B T} v_{\rm th} \pi R^2 \tag{4}$$

where P is gas pressure, T is temperature, $v_{\rm th}$ is mean thermal velocity of gas molecules, and η is a sticking coefficient. For integration time t, accumulated decoherence $\mathcal{D} \sim \Gamma_{\rm coll} t$. Gas pressure is tunable from 10^{-10} to 10^{-3} mbar, giving $\mathcal{D}$ spanning many orders of magnitude relative to the activation threshold $\mathcal{D}_*$.

C. Gravitational Readout

Mutual gravitational force is measured via optomechanical displacement sensing or resonant force detection. Target signal: $F_N \sim 1.7 \times 10^{-26}$ N, corresponding to acceleration $a \sim 1.7 \times 10^{-13}$ m/s^2. State-of-the-art optomechanical accelerometers achieve $\sim 10^{-15}$ m/s$^2/\sqrt{\rm Hz}$, requiring approximately 10^3 seconds integration time for signal-to-noise ratio of 10.

D. Causal Ordering and Temporal Tracking

To establish causation rather than mere correlation between decoherence history and gravitational sourcing, the protocol includes temporal tracking of gravitational response as a function of $\mathcal{D}_S$ accumulation in real time during Phase 4. A genuine causal relationship predicts that the gravitational signal follows the $\mathcal{D}_S$ accumulation curve with consistent lag structure—the response tracks the cause forward in time from each environmental intervention point, not from the beginning of the experiment. This temporal ordering test distinguishes causal activation from coincidental correlation.

IV. INTERPRETATION OF OUTCOMES

Null result—gravitational force $F_A = F_B$ regardless of decoherence state: Confirms that semiclassical gravity is correct and sourcing depends only on stress-energy expectation value. This bounds the activation threshold $\mathcal{D}_* < \mathcal{D}_{\min}$ below the minimum $\mathcal{D}$ achieved in the experiment, and rules out local decoherence history as a sourcing variable.

Positive result—$F \propto f_{\text{grav}}(\mathcal{D})$, with suppression when $\mathcal{D} \ll \mathcal{D}_*$: Demonstrates that gravitational sourcing depends on local quantum correlation history. Gravitational activation is local to each system's own accumulated decoherence, not inherited from the classical background. Phase 4 then extracts the quantitative parameters $(\mathcal{D}_*, n)$ of the activation function.

Either outcome constitutes the first controlled measurement of gravitational sourcing in a regime where quantum state coherence is a variable. The experiment is scientifically decisive in both directions.

V. COSMOLOGICAL EXTENSION: SCALAR-TENSOR FORMULATION

While the non-relativistic framework above is operationally defined for mesoscopic laboratory systems, we construct a consistent scalar-tensor extension for cosmological testability. In this covariant formulation, the $\mathcal{D}$-field is treated as a fundamental field rather than derived from GKLS tracing. The two descriptions are complementary: one operational and laboratory-testable, the other covariant and cosmologically testable.

A. Action Principle

The Jordan-frame action couples the $\mathcal{D}$-field to spacetime curvature:

$$S = \int d^4x\sqrt{-g}\left[\frac{\Phi(\mathcal{D})}{16\pi G_N}R - \frac{\omega(\mathcal{D})}{2}(\nabla\mathcal{D})^2 - V(\mathcal{D}) + \mathcal{L}_{\text{matter}}\right] \tag{5}$$

with gravitational coupling function:

$$\Phi(\mathcal{D}) = \frac{1}{G_N f_{\text{grav}}(\mathcal{D})} = \frac{\mathcal{D}^n + \mathcal{D}_*^n}{G_N \mathcal{D}^n} \tag{6}$$

B. Field Equations

The modified Einstein equations are:

$$\Phi(\mathcal{D})G_{\mu\nu} = 8\pi T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\mathcal{D})} + \nabla_\mu\nabla_\nu\Phi - g_{\mu\nu}\Box\Phi \tag{7}$$

where the $\mathcal{D}$-field contributes stress-energy:

$$T_{\mu\nu}^{(\mathcal{D})} = \omega(\mathcal{D})\left[\nabla_\mu\mathcal{D}\nabla_\nu\mathcal{D} - \frac{1}{2}g_{\mu\nu}(\nabla\mathcal{D})^2\right] - g_{\mu\nu}V(\mathcal{D}) \tag{8}$$

C. Cosmological Viability

For a homogeneous, isotropic universe described by the FLRW metric with homogeneous $\mathcal{D}(t)$, the Friedmann equation becomes:

$$3H^2 = 8\pi G_N f_{\rm grav}(\mathcal{D})\rho + \frac{1}{2}\omega(\mathcal{D})\dot{\mathcal{D}}^2 + V(\mathcal{D}) \tag{9}$$

Early universe behavior: For $\mathcal{D} \ll \mathcal{D}_*$, $f_{\rm grav} \sim (\mathcal{D}/\mathcal{D}_*)^n \ll 1$. Effective gravitational coupling is suppressed relative to G_N; the early expansion rate is modified. This is physically consistent with the picture that gravitational activation builds as decoherence accumulates through the hot, rapidly interacting early universe.

BBN constraint: Helium-4 abundance requires effective gravitational coupling $G_{\rm eff}(t_{\rm BBN}) \approx G_N$ to approximately 20%. This is satisfied provided $\mathcal{D}_{\rm BBN} > 4^{1/n}\mathcal{D}_*$, meaning decoherence had accumulated past the activation threshold well before nucleosynthesis. This is a testable constraint on $\mathcal{D}_*$.

Late universe: As $\mathcal{D}$ approaches $\mathcal{D}_{\rm max}$, $f_{\rm grav} \to 1$ and standard ΛCDM cosmology is recovered with perturbative $\mathcal{D}$-field corrections. The framework reduces to general relativity in the fully decohered classical limit, as required.

D. Observable Signatures

TABLE I. Cosmological observables in D-activation framework

Probe	**Standard ΛCDM**	**D-Activation Prediction**
Growth index γ	$\gamma \approx 0.55$	$\gamma \neq 0.55$ due to $\mathcal{D}$-field perturbations to structure growth
σ_8 tension	Persistent—current data in tension	Modified growth rate may relieve or shift the tension
CMB H_0 inference	Tension with local distance ladder	Modified early expansion history shifts CMB-inferred H_0

VI. CONCLUSION

We have proposed a feasible, experimentally decisive test of whether gravitational sourcing is conditioned on accumulated local decoherence history. The dual-bath protocol with reversal test addresses the critical locality question directly, and Phase 4 maps the full activation curve if the effect is present. Temporal tracking of gravitational response during pressure sweeps provides a causal test beyond simple correlation.

A consistent scalar-tensor extension demonstrates cosmological viability across the full history of the universe, from early suppressed coupling through BBN to late-time ΛCDM recovery, with observable signatures in structure formation and the H_0 and σ_8 tensions.

The experiment is scientifically valuable regardless of outcome: a null result confirms semiclassical sourcing and bounds activation parameters with precision; a positive result demonstrates that gravity derives from local quantum correlation history, opening an entirely new information-theoretic sector of gravitational physics.

The framework is consistent with the irreversibility of classical records—decoherence runs strictly forward, gravity is its classical residue, and no mechanism returns classical states to the coherent ground. This thermodynamic consistency is a structural feature of the proposal, not an assumption.

ACKNOWLEDGMENTS

The author thanks the quantum gravity phenomenology community for discussions. This work was conducted independently by the PACES Research Group.

[1] R. Colella, A. W. Overhauser, and S. A. Werner, Phys. Rev. Lett. **34**, 1472 (1975).
[2] A. Peters, K. Y. Chung, and S. Chu, Nature **400**, 849 (1999).
[3] M. Arndt *et al.*, Nature **401**, 680 (1999).
[4] J. Maldacena and L. Susskind, Fortschr. Phys. **61**, 781 (2013).
[5] R. Penrose, Gen. Rel. Grav. **28**, 581 (1996).
[6] L. Diósi, Phys. Lett. A **120**, 377 (1987).
[7] T. Jacobson, Phys. Rev. Lett. **75**, 1260 (1995).
[8] E. Verlinde, JHEP **1104**, 029 (2011).
[9] E. Joos *et al.*, *Decoherence and the Appearance of a Classical World in Quantum Theory*, 2nd ed. (Springer, 2003).
[10] A. A. Geraci, S. B. Papp, and J. Kitching, Phys. Rev. Lett. **105**, 101101 (2010).
[11] J. Schmöle *et al.*, Classical Quantum Gravity **33**, 125031 (2016).
[12] S. Bose *et al.*, Phys. Rev. Lett. **119**, 240401 (2017).
[13] C. Marletto and V. Vedral, Phys. Rev. Lett. **119**, 240402 (2017).

Appendix A: Numerical Estimates for Experimental Parameters

1. Force and Acceleration Magnitudes

For two silica nanospheres with $m = 10^{-13}$ kg separated by $r = 200$ μm:

$$F_N = \frac{G_N m^2}{r^2} = \frac{(6.67 \times 10^{-11})(10^{-13})^2}{(2 \times 10^{-4})^2} \approx 1.7 \times 10^{-26} \text{ N} \tag{A1}$$

$$a = \frac{F_N}{m} \approx 1.7 \times 10^{-13} \text{ m/s}^2 \tag{A2}$$

State-of-the-art optomechanical accelerometers achieve $\sim 10^{-15}$ m/s$^2/\sqrt{\text{Hz}}$, requiring approximately 10^3 seconds integration for signal-to-noise ratio of 10.

2. Decoherence Rate Scaling

$$\Gamma_{\text{coll}} \sim \eta \frac{P}{k_B T} v_{\text{th}} \pi R^2 \tag{A3}$$

For $P = 10^{-6}$ mbar, $T = 300$ K, $R = 50$ nm, $\eta = 0.1$: $\Gamma_{\text{coll}} \sim 10^{-3}$ s^{-1}. For $t = 1$ s: $\mathcal{D} \sim 10^{-6} \ll \mathcal{D}_* \sim 1$ (ultra-low decoherence regime). For $P = 1$ mbar: $\Gamma_{\text{coll}} \sim 10^4$ s^{-1}, $\mathcal{D} \sim 10^4 \gg \mathcal{D}_*$ (fully activated regime).

3. Critical Pressure

$$P_* = \frac{\mathcal{D}_* k_B T}{\eta v_{\text{th}} \pi R^2 t} \tag{A4}$$

For $\mathcal{D}_* = 1$, $t = 1$ s: $P_* \sim 10^{-4}$ mbar. This is the crossover pressure at which accumulated decoherence equals the activation threshold, and is the operating point for Phase 4 sweep measurements.

Appendix B: Systematic Error Budget

TABLE II. Systematic noise sources and mitigation

Noise Source	**Magnitude**	**Mitigation Strategy**
Casimir force ($r > 100$ μm)	$< 10^{-30}$ N	Separation maintained above 100 μm; dielectric material choice
Electrostatic coupling	Variable	UV discharge neutralization; Faraday cage shielding; continuous charge monitoring
Seismic noise	$\sim 10^{-12}$ m/$\sqrt{\text{Hz}}$	Active vibration isolation platform; differential measurement cancels common-mode noise
Thermal radiation pressure	Photon recoil noise	Cryogenic shielding at $T < 4$ K
Residual gas composition	Pressure-dependent systematic	Mass spectrometry monitoring; identical gas species in both chambers