Entanglement Decay from Gravitational Decoherence: A Unique Signature of Gravity's Quantum Role

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Abstract

Gravitational decoherence carries a signature no other decoherence mechanism shares: it degrades entanglement with a *distant* partner. When one member A (mass M) of an entangled pair is sent through a which-path interferometer of separation d, the pair's concurrence decays as $C(t) = C(0)\exp(-GM^2 t/\hbar d)$, at the Diósi–Penrose rate fixed by A's gravitational self-energy. Standard environmental decoherence scrambles only A's local coherence and leaves the entanglement with B intact; collapse models and ordinary scattering do not transfer which-path information into a field correlated with B. The entanglement-decay channel therefore isolates gravity's role in the quantum-to-classical transition. The decay rate equals the local-decoherence rate, both set by $GM^2/(\hbar d)$. For levitated optomechanics, proof-of-principle tests are achievable within two decades, contingent on space-based ultra-high vacuum or major advances in macroscopic quantum superposition. The underlying Diósi–Penrose rate is a hypothesis with strong physical motivation, not a theorem; observation of the entanglement-decoherence correlation would be direct evidence that gravity plays a fundamental role in the emergence of classicality.

1 Introduction

The Diósi-Penrose hypothesis [1, 2] holds that gravity decoheres spatial superpositions at a rate set by the gravitational self-energy,

$$\Gamma_{\text{grav}} = \frac{GM^2}{\hbar d} \tag{1}$$

for a mass M split by a separation d; a 1 μg particle separated by 1 mm decoheres in ≈1.6 ns. It is a hypothesis with strong physical motivation, not a theorem, and remains untested because the predicted times are short only for masses too large to place in superposition with current technology. This paper isolates a qualitatively distinct signature of the same mechanism, one that discriminates gravity from every other decoherence channel: gravitational decoherence

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degrades entanglement with a *distant* partner, whereas standard environmental decoherence does not.

The distinction is structural. Photon, gas, and phonon scattering entangle an *external* environment with A's position, destroying A's local coherence while leaving A's pre-existing entanglement with a distant B untouched. Gravitational decoherence has no external scatterer: the "environment" is the gravitational field, which is determined by A's own mass distribution and is therefore inseparable from A's spatial configuration. When A becomes entangled with that field, monogamy of entanglement forces its entanglement with B to fall. Gravity thus predicts correlated decay of local coherence and non-local entanglement at a common rate (1); ordinary environmental decoherence predicts local decay with A–B entanglement protected.

The Bose–Marletto–Vedral proposal [14, 15] uses gravitationally *generated* entanglement between levitated masses as a witness of quantum gravity. The signature here is complementary: gravity *destroying* pre-existing entanglement through the Diósi-Penrose mechanism.

Section 2 derives the entanglement-decay prediction. Section 3 contrasts it with competing frameworks. Section 4 sets out the experimental requirements. Section 5 treats interpretation, limitations, and outlook.

2 The Prediction

2.1 Setup: entangled pair plus which-path interferometer

Two particles A and B are prepared in a maximally entangled Bell state,

$$|\Psi^-\rangle_{AB} = \frac{1}{\sqrt{2}} \left(|0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B\right) \tag{2}$$

with $|0\rangle$, $|1\rangle$ internal states (e.g. spin up/down), B held at a fixed distant location. Particle A passes through a Stern–Gerlach interferometer coupling its internal state to its spatial path,

$$|0\rangle_A \to |0\rangle_A |L\rangle , \qquad |1\rangle_A \to |1\rangle_A |R\rangle , \tag{3}$$

where $|L\rangle$, $|R\rangle$ are positions separated by d. This which-path coupling, standard in the Bose–Marletto–Vedral and Stern–Gerlach proposals, makes A's position a faithful record of its internal state. Applied to (2), the matter-plus-field initial state is

$$|\Psi(0)\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_A |L\rangle |1\rangle_B - |1\rangle_A |R\rangle |0\rangle_B\right) \otimes |g_0\rangle_{\text{grav}} , \tag{4}$$

with $|g_0\rangle_{\text{grav}}$ the initial gravitational field configuration. A's which-path degree of freedom is now perfectly correlated with the internal qubit carrying its entanglement with B.

2.2 Matter–field entanglement and the overlap decay

Under the Diósi-Penrose mechanism the positions $|L\rangle$ and $|R\rangle$ source distinguishable gravitational field configurations, entangling the field with A's position,

$$|L\rangle |g_0\rangle \to |L\rangle |g_L\rangle , \quad |R\rangle |g_0\rangle \to |R\rangle |g_R\rangle , \tag{5}$$

where $|g_L\rangle$, $|g_R\rangle$ are the field states for A at L and R. Their overlap decays at the self-energy rate,

$$\langle g_L(t)\rangle\, g_R(t) = e^{-\Gamma_{\text{grav}} t}, \tag{6}$$

with $\Gamma_{\text{grav}} = GM^2/(\hbar d)$ from Eq. (1).

2.3 Entanglement decay of the reduced pair

The path lock (3) makes the gravitational which-path record act directly on the qubit carrying the A–B entanglement. Evolving (4) under the field coupling (6),

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_A |1\rangle_B |g_L(t)\rangle - |1\rangle_A |0\rangle_B |g_R(t)\rangle \right), \tag{7}$$

and tracing over the gravitational field,

$$\rho_{AB}(t) = \text{Tr}_{\text{grav}} \left[|\Psi(t)\rangle \langle \Psi(t)| \right], \tag{8}$$

multiplies the off-diagonal A–B coherence by the field overlap $\langle g_L(t)\rangle\, g_R(t) = e^{-\Gamma_{\text{grav}} t}$. The same conclusion follows from monogamy of entanglement [3]: as A entangles with the field, its entanglement with B must fall. In the basis $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ the off-diagonal elements decay exponentially,

$$\rho_{AB}(t) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2}e^{-\Gamma t} & 0 \\ 0 & -\frac{1}{2}e^{-\Gamma t} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{9}$$

2.4 Concurrence decay

The concurrence [4], a standard two-qubit entanglement measure, is

$$C = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4), \tag{10}$$

with λ_i the decreasing square roots of the eigenvalues of $\rho_{AB}(\sigma_y \otimes \sigma_y)\rho^*_{AB}(\sigma_y \otimes \sigma_y)$. Evaluated on (9), the off-diagonal $\frac{1}{2}e^{-\Gamma t}$ gives $C(t) = e^{-\Gamma_{\text{grav}} t}$.

$$\boxed{C(t) = C(0) \cdot e^{-\Gamma_{\text{grav}} t} = e^{-GM^2 t/(\hbar d)}} \tag{11}$$

The entanglement decays at the gravitational decoherence rate.

2.5 Bell inequality violation

The decay is directly observable through the CHSH parameter [5],

$$S = E(a, b) + E(a, b') + E(a', b) - E(a', b'), \tag{12}$$

with $E(a, b) = \langle \sigma_a \otimes \sigma_b \rangle$ the correlation functions for settings a, a', b, b'.

The state (9) is a pure-dephasing state, for which the exact CHSH maximum is

$$S_{\max}^{\text{deph}}(t) = 2\sqrt{1 + e^{-2\Gamma_{\text{grav}} t}}, \tag{13}$$

which exceeds 2 for all finite t and approaches 2 only asymptotically, so the dephasing violation persists indefinitely. The Werner approximation $\rho_W = p\,|\Psi^-\rangle\langle\Psi^-| + (1-p)\mathbb{I}/4$ with $p = e^{-\Gamma t}$ gives a depolarizing channel and replaces (13) with

$$S_{\max}^{\text{Werner}}(t) = 2\sqrt{2} \cdot e^{-\Gamma_{\text{grav}} t}, \tag{14}$$

which holds the threshold $S > 2$ until

$$t_{\text{Bell}} = \frac{\hbar d}{GM^2} \ln \sqrt{2} \approx 0.35 \cdot \tau_{\text{dec}}, \tag{15}$$

after which no Werner-state violation survives. The t_{Bell} column of Table 1 uses this Werner estimate; under the exact dephasing formula (13) the figure of merit is instead how far S exceeds the classical bound.

2.6 Numerical examples

Table 1 gives predicted decay times for experimentally relevant parameters.

Mass	**Separation**	τ_{dec}	t_{Bell}
1 fg	100 nm	1.6×10^5 s (≈44 h)	5.5×10^4 s (≈15 h)
10 fg	1 μm	1.6×10^4 s (≈4.4 h)	5.5×10^3 s (≈1.5 h)
100 fg	1 μm	158 s	55 s
1 pg	10 μm	15.8 s	5.5 s

Table 1. *Predicted entanglement decay times and Bell violation lifetimes for various masses and superposition separations, computed from $\tau_{\text{dec}} = \hbar d/(GM^2)$ and $t_{\text{Bell}} = \tau_{\text{dec}} \ln\sqrt{2} \approx 0.35\,\tau_{\text{dec}}$ (Werner approximation; see text). The target experimental regime is $M \sim 10$–100 pg, $d \sim 1$–100 μm (see Sec. 4).*

3 Comparison with Other Theories

The entanglement-decoherence correlation discriminates gravitational decoherence from competing mechanisms. The predictions of four frameworks differ on a single observable: whether local decoherence of A is accompanied by decay of its entanglement with distant B.

3.1 Standard quantum mechanics

Environmental interactions destroy local coherence while preserving entanglement with distant systems. Photon scattering off A entangles the photons with A's position,

$$|L\rangle|\gamma_0\rangle \to |L\rangle|\gamma_L\rangle, \quad |R\rangle|\gamma_0\rangle \to |R\rangle|\gamma_R\rangle, \tag{16}$$

but the photons carry information about A's position only, not the A–B correlations. Tracing over them destroys A's spatial coherence and leaves the A–B entanglement intact.

Prediction: local decoherence of A; entanglement C_{AB} preserved indefinitely (absent other interactions with B).

3.2 Diósi-Penrose gravitational decoherence

The "environment" is the gravitational field configuration, fixed by A's mass distribution rather than by external scatterers. The field does not learn A's position through scattering events; it *is* determined by it, so the position–gravity entanglement is intrinsic to having a mass in superposition.

Prediction: $C_{AB}(t) = C_{AB}(0)\, e^{-GM^2 t/(\hbar d)}$.

3.3 Continuous spontaneous localization

CSL [6, 7] postulates a universal collapse noise field with rate

$$\Gamma_{\text{CSL}} = \lambda \left(\frac{m}{m_0}\right)^2 \left(\frac{d}{r_C}\right)^2, \tag{17}$$

$\lambda \approx 10^{-16}$ s^{-1}, m_0 the nucleon mass, $r_C \approx 100$ nm the correlation length. The noise couples to A's position and has no direct effect on the A–B correlations.

Prediction: model-dependent; in the standard formulation entanglement decay is not tied to the local collapse rate.

3.4 Perturbative quantum gravity

Graviton exchange gives a decoherence rate scaling as G^2 (two graviton vertices),

$$\Gamma_{\text{QFT}} \sim \frac{G^2 M^4}{\hbar^3 d^3}. \tag{18}$$

For $M = 10$ fg, $d = 1$ μm, this gives $\tau_{\text{QFT}} \sim 10^{30}$ yr.

Prediction: no observable gravitational decoherence or entanglement decay.

3.5 Summary of predictions

Theory	**Local Decoherence**	**Entanglement Decay**
Standard QM	Environmental	Protected
Diósi-Penrose	$\Gamma = GM^2/(\hbar d)$	$\Gamma = GM^2/(\hbar d)$
CSL	Γ_{CSL}	Model-dependent
Perturbative QFT	$\Gamma \sim G^2$ (negligible)	Negligible

Table 2. *Comparison of predictions for local decoherence rate and entanglement decay rate across theoretical frameworks. Only Diósi-Penrose predicts correlated decay at the gravitational self-energy scale.*

The distinctive feature of the Diósi-Penrose prediction is the *equality* of the local-decoherence and entanglement-decay rates, both set by $GM^2/(\hbar d)$.

3.6 Falsifiability

The prediction fails under any of the following.

1. **No decay**: entanglement persists while local coherence decays ⇒ Diósi-Penrose gravitational decoherence is falsified.

2. **Wrong rate**: entanglement decays at a rate inconsistent with $GM^2/(\hbar d)$ ⇒ the specific Diósi-Penrose mechanism is falsified, though some gravitational effect may remain.

3. **Dependence on distance to** B: a decay rate that depends on the A–B separation ⇒ the mechanism is not purely local; the prediction is falsified.

4. **Temperature dependence**: a decay rate that varies with temperature ⇒ thermal effects dominate; the gravitational mechanism is not confirmed.

Observation of entanglement decay at $\Gamma = GM^2/(\hbar d)$, independent of temperature and A–B distance, supports the Diósi-Penrose hypothesis.

4 Experimental Implementation

4.1 Platform selection

Testing the entanglement-decoherence correlation requires four capabilities:

1. entanglement between two massive particles,

2. one particle in spatial superposition,

3. entanglement measured as a function of time,

4. environmental decoherence suppressed below the gravitational rate.

Levitated optomechanics is the most promising near-term platform: levitated nanoparticles reach femtogram-to-picogram masses with excellent thermal isolation and are under active development for both entanglement generation and spatial superposition [14, 15].

4.2 Proposed configuration

The prediction $\tau_{\text{grav}} = \hbar d/(GM^2)$ scales as $M^{-2}d$. Placing τ_{grav} in the accessible 1–1000 ms range requires $M \sim$ 10–100 pg and $d \sim$ 1–100 μm; smaller masses ($\sim$ fg or below) push τ_{grav} into the multi-minute regime, beyond optical coherence times. Two silica microparticles ($\rho = 2200$ kg/m^3) levitated in separate optical traps give:

Parameter	**Value**
Particle radius	1–3 μm
Particle mass	10–100 pg
Trap separation	100 μm − 1 mm
Superposition separation	1–100 μm
Vacuum pressure	$\leq 10^{-13}$ Pa (XHV)
Motional temperature	≤ 10 mK

For $M = 20$ pg and $d = 10$ μm,

$$\tau_{\text{grav}} = \frac{\hbar d}{GM^2} = \frac{(1.05 \times 10^{-34})(1 \times 10^{-5})}{(6.67 \times 10^{-11})(2 \times 10^{-14})^2} \approx 40 \text{ ms}, \tag{19}$$

long enough for preparation and measurement, short enough for observation within achievable coherence times.

Parameter accessibility. This mass and separation range sits beyond current quantum-superposition records. Levitated nanoparticles reach ~ 10 pg masses but only sub-nanometer superpositions; matter-wave interferometry reaches ~ 1 μm superpositions but at masses of order 10^{-22} kg. Reaching the target regime requires advances on both axes; Sec. 4.4 quantifies how the gas-decoherence floor constrains the window.

4.3 Experimental protocol

Phase 1: Preparation

1. Load particles A and B into separate optical traps
2. Cool both particles to motional ground state via feedback cooling
3. Verify ground state occupation $\bar{n} < 0.1$

Phase 2: Entanglement

4. Enable Coulomb coupling between charged particles
5. Apply entangling gate (Mølmer-Sørensen or equivalent)
6. Verify entanglement via partial tomography (subset of runs)

Phase 3: Superposition

7. Apply coherent displacement to particle A only
8. Create spatial superposition $|\psi_A\rangle = (|L\rangle + |R\rangle)/\sqrt{2}$
9. Particle B remains in ground state, undisturbed

Phase 4: Evolution

10. Allow free evolution for variable time τ
11. Vary τ from 0 to $5\tau_{\text{grav}}$

Phase 5: Measurement

12. Recombine A's superposition (interferometric readout)
13. Perform Bell-basis measurements on A and B
14. Repeat for statistical averaging (~ 1000 runs per time point)

4.4 Environmental decoherence control

The gravitational signal must exceed environmental backgrounds. The dominant channel for a levitated particle of radius R in dilute gas is the long-wavelength collisional rate [17],

$$\Gamma_{\text{gas}} = \pi R^2\, v_{\text{th}}\, n_{\text{gas}} = \frac{\pi R^2\, P}{k_B T}\sqrt{\frac{8k_B T}{\pi m_{\text{gas}}}}, \tag{20}$$

valid when the superposition separation exceeds the gas thermal de Broglie wavelength ($\lambda_{\text{dB}} \sim 1$ nm at 100 mK), as holds for all $d \geq 1\ \mu$m of interest here.

Table 3 compares Γ_{grav} with Γ_{gas} at standard ultra-high vacuum (UHV, $P = 10^{-8}$ Pa) and at extreme high vacuum (XHV, $P = 10^{-13}$ Pa) for the recommended ($M = 20$ pg, $d = 10\ \mu$m, $R = 1.29\ \mu$m) and larger ($M = 1\ \mu$g, $d = 100\ \mu$m, $R = 47.7\ \mu$m) configurations.

Configuration	Γ_{grav}	Γ_{gas} (UHV)	Γ_{gas} (XHV)
20 pg, 10 μm	25 Hz	3.3×10^5 Hz	3.3 Hz
1 μg, 100 μm	6.3×10^9 Hz	4.5×10^8 Hz	4.5×10^3 Hz

Table 3. *Gravitational decoherence rate $\Gamma_{grav} = GM^2/(\hbar d)$ versus collisional rate Γ_{gas} at $T = 100$ mK for two configurations and two pressures. UHV $= 10^{-8}$ Pa is the standard laboratory ultra-high vacuum; XHV $= 10^{-13}$ Pa is currently only projected for space-based experiments (e.g. MAQRO/DECIDE).*

Two regimes are relevant.

Modest mass at standard UHV. For the smallest practical configuration (20 pg, 10 μm, $R = 1.29\ \mu$m), $\Gamma_{\text{gas}} \gg \Gamma_{\text{grav}}$ at standard UHV by roughly 10^4. At XHV, $\Gamma_{\text{gas}} \approx 3.3$ Hz drops below $\Gamma_{\text{grav}} \approx 25$ Hz, so XHV suffices; such pressures are not yet achievable on the ground and require a space-based platform.

Larger mass at standard UHV. The ratio $\Gamma_{\text{grav}}/\Gamma_{\text{gas}}$ scales as $M^{4/3}\sqrt{T}/(d\,P)$, so a microgram mass brings Γ_{grav} above the collisional floor at standard UHV. Microgram superpositions of $\sim 100\ \mu$m are far beyond current capabilities, requiring roughly fifteen orders of magnitude of improvement.

A Bayesian forecast (supplementary material) maps discrimination feasibility across (M, d, P, T) space and the conditions for 5σ detection. First detection via the entanglement-decoherence correlation requires either (i) next-generation cryogenic XHV facilities (MAQRO/DECIDE class, projected for the mid-2030s), or (ii) major advances in macroscopic quantum superposition.

Photon recoil heating from the optical trap must also be suppressed during free evolution, by switching off the traps (ballistic trajectory) or using magnetic/electrostatic trapping with minimal photon scattering.

4.5 Control experiments

Four controls separate gravitational effects from systematic artifacts.

Control 1: No superposition. Skip Phase 3. If entanglement decay is observed without spatial superposition, systematic effects (not gravitational decoherence) are responsible.

Control 2: Mass scaling. Repeat with particles of different masses (10, 20, 50, 100 pg). Gravitational decoherence predicts $\tau \propto M^{-2}$; doubling mass should reduce decay time by factor of 4.

Control 3: Separation scaling. Create superpositions of different sizes (100 nm, 500 nm, 1 μm). Gravitational decoherence predicts $\tau \propto d$; doubling separation should double decay time.

Control 4: Temperature variation. Repeat at different temperatures (10 mK, 100 mK, 1 K). Gravitational decoherence is temperature-independent; thermal mechanisms would show strong T-dependence.

4.6 Technology readiness

Capability	**Current Status**	**Gap to target regime**
Nanoparticle levitation	Demonstrated for sub-pg masses	Scale to 10–100 pg
Ground-state cooling	Demonstrated	None
Spatial superposition	$\sim$ 100 fm achieved (10 pg)	10^7–$10^8\times$
Two-particle entanglement	In development	Major
Bell measurement	Demonstrated (photons)	Adaptation
XHV pressure ($P \leq 10^{-13}$ Pa)	Projected for space platforms	5 orders below ground UHV

The primary gaps are (1) micron-scale spatial superpositions of $\geq$ 10 pg masses, (2) entanglement between two such levitated particles, and (3) suppression of the collisional floor, either by reaching XHV pressures or by using much larger masses where the gravitational rate exceeds the collisional rate. Each is an active research area; their simultaneous achievement is significantly harder than any individual demonstration.

4.7 Timeline

From current technology trajectories and the constraints of Table 3:

Milestone	**Estimated Date**
$\sim$ 10 nm superposition, 10 pg particle	2030–2032
Two-particle Coulomb entanglement	2030–2035
Cryogenic XHV in space (MAQRO/DECIDE class)	mid-2030s
Proof-of-principle entanglement decay measurement	late 2030s
Mass and separation scaling verified	2040–2045
Definitive test of prediction	2045–2050

A proof-of-principle demonstration is feasible by the late 2030s contingent on space-based ultra-high vacuum, or by the early 2040s through advances in macroscopic ground-based superposition. Sub-2030 detection at the predicted rate is inconsistent with the gas-collision floor at any currently demonstrated platform parameters.

5 Discussion

5.1 Physical interpretation

The entanglement-decoherence correlation reflects the non-local character of gravitational decoherence. Environmental decoherence is local: scattering events occur at the particle's location and affect only its local state. Gravitational decoherence emerges from the mass configuration itself, which sets the gravitational field throughout spacetime.

Gravitational decoherence transfers information about A's position into the field's degrees of freedom. The transfer ignores the local-distant distinction: A's position becomes encoded in the global field configuration, which effectively measures A and so affects all of A's correlations, including those with distant B. The field acts as an information channel between matter and geometry, and $\Gamma = GM^2/(\hbar d)$ sets how fast it acquires which-path information.

5.2 Relation to ER=EPR

The Maldacena-Susskind ER=EPR conjecture [8] represents quantum entanglement geometrically by Einstein-Rosen bridges: the entangled state $|\Psi^-\rangle_{AB}$ corresponds to a geometric connection between A and B. In this reading, gravitational decoherence disrupts the geometry at A: the spatial superposition bifurcates the geometry incompatibly with a single coherent bridge, which degrades as A's position leaks into the gravitational environment.

This reading is speculative and extends ER=EPR beyond its established domain (asymptotically AdS spacetimes); it supplies intuition for why gravitational decoherence affects distant entanglement but is not required for the result. The prediction follows from standard quantum mechanics and the Diósi-Penrose rate alone.

5.3 Limitations and caveats

Theoretical uncertainty. The Diósi-Penrose rate $\Gamma = GM^2/(\hbar d)$ is derived in linearized gravity by imposing the Wheeler-DeWitt constraint on the Feynman-Vernon influence functional, a controlled-approximation result rather than a theorem [16]. Standard perturbative quantum field theory, using an unconstrained product initial state, gives G^2 scaling with rates $\sim 10^{35}$ times smaller. Both are correct for their respective initial conditions; experiment will decide which initial state nature realizes.

Coefficient ambiguity. The prediction takes the Diósi-Penrose coefficient to be of order unity. The canonical analysis [16] bounds it to $C \in [2/\pi, 1]$ (natural value $C = 1$; floor $2/\pi$ from the Margolus–Levitin quantum speed limit), a factor-$\pi/2$ ($\sim$57%) spread in the absolute rate that leaves the G^1 scaling untouched.

Extended objects and the point-mass convention. The rate $\Gamma = GM^2/(\hbar d)$ used throughout is the *point-mass* (cross-term) form of the Diósi–Penrose self-energy. For a spatially extended particle of radius R the self-energy is the full double integral over the mass distribution, which does *not* reduce to GM^2/d in the $d \gg R$ regime: for a uniform sphere split by $d \geq 2R$ it *saturates* at $E_G \to 1.2\,GM^2/R$, set by the particle size R rather than the separation d. At experimentally relevant parameters this is an $\mathcal{O}(10)$ effect, not a 1–10% form-factor correction (e.g. a 1 μg silica sphere at $d = 1$ mm has $d/2R \approx 10$ and a saturated rate $\sim$24$\times$ faster, d-independent). The point-mass rate should therefore be read as a benchmark convention; a precision comparison for finite-size particles must use the saturated self-energy, as developed for the orientation-dependent BMV/QGEM visibility in the companion BMV paper of this series. The finite-size correction rescales the absolute rate but leaves the paper's central signature—the *equality* of the local-decoherence and entanglement-decay rates—intact, since both channels are driven by the same self-energy.

Experimental systematics. The required environmental isolation, the superpositions, and the entanglement are each significant challenges, and systematic errors may initially limit sensitivity.

5.4 Implications of observation

Observation of the predicted entanglement decay would imply:

1. **Gravitational decoherence confirmed.** Gravity plays a fundamental role in the quantum-to-classical transition, beyond any known environmental mechanism.

2. **Quantum-gravity constraint.** The G^1 scaling would indicate non-perturbative gravitational physics at laboratory scales.

3. **Limit on quantum technology.** Gravitational decoherence would cap the coherence times of massive quantum systems regardless of environmental isolation.

5.5 Implications of non-observation

Entanglement persisting despite local decoherence would imply:

1. **Diósi-Penrose falsified.** The specific prediction $\Gamma = GM^2/(\hbar d)$ is ruled out.

2. **Standard QM confirmed** for the tested mass range, environmental decoherence without gravitational effects.

3. **Tighter collapse-model bounds.** The absence of decay constrains any model predicting correlated local-nonlocal decoherence.

Either outcome advances fundamental physics.

5.6 Conclusion

Gravitational decoherence carries a distinctive signature: the decay of entanglement between spatially separated particles when one is decohered. The decay rate $\Gamma = GM^2/(\hbar d)$ equals the local decoherence rate, a correlation that no environmental mechanism reproduces. The test requires entangled massive particles, one in spatial superposition, and Bell correlations measured over time. Levitated optomechanics is a feasible platform, with proof-of-principle within two decades, contingent on space-based ultra-high vacuum (MAQRO/DECIDE class, mid-2030s) or major advances in macroscopic superposition at the 10–100 pg scale. The outcome—whichever way it falls—bears directly on whether gravity has a special role in the emergence of classicality.

References

[1] L. Diósi, "A universal master equation for the gravitational violation of quantum mechanics," Phys. Lett. A **120**, 377 (1987).

[2] R. Penrose, "On gravity's role in quantum state reduction," Gen. Relativ. Gravit. **28**, 581 (1996).

[3] V. Coffman, J. Kundu, and W. K. Wootters, "Distributed entanglement," Phys. Rev. A **61**, 052306 (2000).

[4] W. K. Wootters, "Entanglement of formation of an arbitrary state of two qubits," Phys. Rev. Lett. **80**, 2245 (1998).

[5] J. F. Clauser, M. A. Horne, A. Shimony, and R. A. Holt, "Proposed experiment to test local hidden-variable theories," Phys. Rev. Lett. **23**, 880 (1969).

[6] G. C. Ghirardi, A. Rimini, and T. Weber, "Unified dynamics for microscopic and macroscopic systems," Phys. Rev. D **34**, 470 (1986).

[7] P. Pearle, "Combining stochastic dynamical state-vector reduction with spontaneous localization," Phys. Rev. A **39**, 2277 (1989).

[8] J. Maldacena and L. Susskind, "Cool horizons for entangled black holes," Fortsch. Phys. **61**, 781 (2013).

[9] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, "Cavity optomechanics," Rev. Mod. Phys. **86**, 1391 (2014).

[10] U. Delić *et al.*, "Cooling of a levitated nanoparticle to the motional quantum ground state," Science **367**, 892 (2020).

[11] R. Riedinger *et al.*, "Remote quantum entanglement between two micromechanical oscillators," Nature **556**, 473 (2018).

[12] I. Marinković *et al.*, "Optomechanical Bell test," Phys. Rev. Lett. **121**, 220404 (2018).

[13] A. Bassi, K. Lochan, S. Satin, T. P. Singh, and H. Ulbricht, "Models of wave-function collapse, underlying theories, and experimental tests," Rev. Mod. Phys. **85**, 471 (2013).

[14] S. Bose *et al.*, "Spin entanglement witness for quantum gravity," Phys. Rev. Lett. **119**, 240401 (2017).

[15] C. Marletto and V. Vedral, "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity," Phys. Rev. Lett. **119**, 240402 (2017).

[16] M. Sperzel, "The Quantum-Geometric Correspondence: Axioms, Gravitational Decoherence, and the Wheeler–DeWitt Rate," (2026), Quantum-Geometric Correspondence, canonical core paper.

[17] O. Romero-Isart, "Quantum superposition of massive objects and collapse models," Phys. Rev. A **84**, 052121 (2011).