The Gravitational Decoherence Floor: Platform Reach, Finite-Size Scaling Laws, and the Entanglement-Decay Signature

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Abstract

Gravity imposes a decoherence floor on massive quantum systems that no isolation can remove. We show that for a solid object this floor is not the point-mass rate $GM^2/(\hbar d)$: the Diósi–Penrose branch-pair self-energy of a uniform sphere of radius R displaced by d grows as d^2 below the crossover $d = 2R$ and *saturates*, separation-independent, above it. In the saturated regime the floor is $\Gamma_{\mathrm{sat}} = \frac{6}{5} GM^2/(\hbar R) = \frac{6}{5}(G/\hbar)(4\pi\rho/3)^{1/3}M^{5/3}$: at fixed density it depends on mass alone, $\Gamma_{\mathrm{sat}} = k\, M^{5/3}$ with $k = 1.59 \times 10^{25}$ SI for silica. A 1 pg silica sphere saturates in 0.63 s; the self-consistent testing zone, where the gravitational time falls between environmental and preparation timescales, is 0.8–48 pg for any $d \gtrsim 2R$. Conventional qubit platforms are untouched ($\tau_{\mathrm{grav}} \geq 10^{16}$ s); levitated spheres with $d \gtrsim 2R$ are the testing ground, while clamped and phonon-state resonators with sub-radius branch separations are protected by tidal suppression — reversing the naive point-mass verdict. The same self-energy drives a signature no environmental channel reproduces: entanglement with a distant partner decays at the local-decoherence rate, $\Gamma_{AB} = \Gamma_{\mathrm{loc}}$. Every prediction is conditional on the framework's first-order-in-G rate, established in expectation values and solvable models; the perturbative G^2 alternative is $\sim 3 \times 10^{34}$ slower. Observation would place gravity in the quantum-to-classical transition; a saturated law of the wrong shape, or a G^2-scale coherence lifetime, would falsify it.

1 Introduction

Environmental decoherence—electromagnetic noise, thermal fluctuations, material defects—limits coherence times and is reducible by isolation; gravity may impose a floor that isolation cannot remove. The Diósi–Penrose hypothesis [1, 2] sets that floor by the gravitational self-energy of a mass in spatial superposition. For a point mass M split by a separation d the rate is

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

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first order in G; a 1 μg mass at $d = 1$ mm decoheres in $\approx$1.6 ns in this convention. Perturbative quantum field theory for graviton-mediated decoherence instead gives rates $\propto G^2$ [3, 4], smaller by $\sim 3 \times 10^{34}$ at those parameters.

Equation (1) is the cross-term of the self-energy, valid for point masses. A real experiment uses a solid object, and the object's own extent changes the law. For a uniform sphere of radius R the branch-pair self-energy grows as d^2 while the branches overlap, crosses over at $d = 2R$, and *saturates* at $\frac{6}{5}GM^2/R$ once they separate—set by the particle size, not the separation. The point-mass rate is never the large-separation limit of a solid sphere. Two consequences follow: the floor for a levitated object is a mass-only law $\Gamma_{\text{sat}} = k\, M^{5/3}$ at fixed density, and clamped resonators with sub-radius branch separations are protected by tidal suppression rather than exposed. Both reverse conclusions drawn from Eq. (1) alone.

The same self-energy carries a signature that no environmental channel reproduces: gravitational decoherence degrades a particle's entanglement with a *distant* partner, at the rate at which it degrades local coherence. Photon, gas, and phonon scattering entangle an external environment with one particle's position and leave its pre-existing entanglement intact; gravity has no external scatterer, so the entanglement-decay rate equals the local rate. This is the one qualitative discriminant that a single-particle coherence measurement cannot deliver.

Every prediction below is conditional on the first-order-in-G rate. Within the framework this rate is obtained in linearized gravity by imposing the Wheeler–DeWitt constraint on the Feynman–Vernon influence functional [22]; the central modular identification is conjectured at the operator level and established in expectation values and solvable models. The prediction is falsifiable rather than open-ended: coherence surviving to the G^2 timescale would rule the G^1 rate out. This paper locates the mass regime where the floor is reachable, gives the finite-size scaling laws and the discriminants that separate them from environmental backgrounds, and derives the entanglement-decay channel. It supersedes and merges two earlier treatments of this series, correcting the point-mass floor to the finite-size law throughout.

2 The Finite-Size Decoherence Floor

2.1 The uniform-sphere self-energy

The decoherence rate is $\Gamma_{\text{self}} = E_{\text{G}}(d)/\hbar$, with $E_{\text{G}}(d)$ the Diósi–Penrose branch-pair self-energy: the gravitational interaction energy of the mass-density difference $\delta\rho = \rho_L - \rho_R$ between the two superposition branches. For a point mass this reduces to the cross-term GM^2/d of Eq. (1). For a uniform sphere of radius R and mass M rigidly displaced by d, the integral over $\delta\rho$ is exact.

Definition 2.1 (Uniform-sphere branch-pair self-energy)**.** For a uniform sphere of radius R displaced by d, write $s = d/R$. The branch-pair self-energy is

$$E_{\text{G}}(d) = \begin{cases} \dfrac{GM^2}{R}\left(\dfrac{s^2}{2} - \dfrac{3}{16}s^3 + \dfrac{1}{160}s^5\right), & s \le 2 \quad \text{(overlapping branches)}, \\[2ex] G\left(\dfrac{6M^2}{5R} - \dfrac{M^2}{d}\right), & s \ge 2 \quad \text{(separated branches)}. \end{cases} \tag{2}$$

The two branches join C^1-continuously at $s = 2$.

Equation (2) fixes three regimes.

- **Tidal** ($d \ll R$): expanding the overlapping branch, $E_G \approx \frac{1}{2}GM^2d^2/R^3$. The self-energy—and hence the rate—is suppressed as d^2; a sub-radius displacement barely distinguishes the two mass distributions.
- **Crossover** at $d = 2R$: the branches touch, and the growth in d stops.
- **Saturated** ($d \geq 2R$): the M^2/d cross-term is subdominant and $E_G \to \frac{6}{5}GM^2/R$, independent of d. The self-energy is set by the object's own size.

The point-mass rate GM^2/d is the cross-term convention, not the $d \gg R$ limit of a solid sphere. In the separated regime it is the small negative correction to the saturated value, and the saturated value dominates it by $\frac{6}{5}d/R$.

2.2 The saturated technology law

Proposition 2.2 (Mass-only floor at fixed density)**.** *In the saturated regime $d \geq 2R$, with R fixed by the density ρ through $M = \frac{4}{3}\pi\rho R^3$, the decoherence rate is*

$$\Gamma_{\text{sat}} = \frac{6}{5}\frac{GM^2}{\hbar R} = \frac{6}{5}\frac{G}{\hbar}\left(\frac{4\pi\rho}{3}\right)^{1/3} M^{5/3} \equiv k\, M^{5/3}. \tag{3}$$

At fixed density the floor depends on mass alone.

Proof. Substitute $R = (3M/4\pi\rho)^{1/3}$ into $\Gamma_{\text{sat}} = \frac{6}{5}GM^2/(\hbar R)$; the M^2 and $M^{-1/3}$ powers combine to $M^{5/3}$, and the density enters only through the prefactor $(4\pi\rho/3)^{1/3}$. $\square$

For silica, $\rho = 2200$ kg/m^3, the coefficient is

$$k = 1.59 \times 10^{25}\ \text{s}^{-1}\text{kg}^{-5/3}, \qquad \tau_{\text{sat}} = \frac{1}{k\, M^{5/3}}. \tag{4}$$

The saturated time is a single power law in mass. Table 1 lists it.

Table 1. *Saturated gravitational decoherence time $\tau_{\text{sat}} = (kM^{5/3})^{-1}$ for silica spheres ($\rho = 2200$ kg/m^3), from Eq. (3). Valid for any separation $d \geq 2R$.*

Mass M	Radius R	τ_{sat}
1 pg $= 10^{-15}$ kg	0.48 μm	0.63 s
10 pg $= 10^{-14}$ kg	1.03 μm	13.5 ms
100 pg $= 10^{-13}$ kg	2.21 μm	0.29 ms
1 ng $= 10^{-12}$ kg	4.77 μm	6.3 μs

2.3 G^1 versus G^2 scaling

The rate scales as G^1; its status is set out in Ref. [22]. Perturbative quantum field theory, treating gravitons as a bath and computing the rate via the Lindblad master equation, gives instead [3, 4]

$$\Gamma_{G^2} \sim \frac{G^2M^4}{\hbar^2c^5}\, f(d), \tag{5}$$

with $f(d)$ carrying the geometry and the dimensions required for an inverse time. In the point-mass convention the two timescales ratio as

$$\frac{\tau_{G^2}}{\tau_{G^1}} \sim \left(\frac{M_{\rm P}}{M}\right)^2 \frac{d}{\ell_{\rm P}}, \tag{6}$$

with $M_{\rm P} = \sqrt{\hbar c/G} \approx 2.18 \times 10^{-8}$ kg and $\ell_{\rm P} = \sqrt{\hbar G/c^3} \approx 1.62 \times 10^{-35}$ m. At $M = 1$ μg and $d = 1$ mm the ratio is $\sim 3 \times 10^{34}$.

The G^1 and G^2 predictions for gravitational decoherence differ by $\sim 3 \times 10^{34}$ for microgram masses at mm separation in the point-mass convention (scaling as $(M_{\rm P}/M)^2(d/\ell_{\rm P})$). Coherence surviving to the G^2 timescale would rule out G^1 decisively.

3 Platform Reach

The gravitational decoherence time follows from the effective superposed mass M, the spatial separation d of the branches, and—for a solid object—the ratio $d/2R$ that places the object among the three regimes of Eq. (2).

3.1 Conventional platforms

For conventional qubits the superposed mass is small enough that $\tau_{\rm grav}$ exceeds any experimental timescale in every convention; the finite-size correction changes nothing.

Superconducting qubits. Transmon and fluxonium qubits encode information in collective charge or flux states of a Josephson junction. The effective superposed mass is that of the delocalized Cooper pairs, $M \sim 10^{-23}$ kg, with $d \sim 1$ μm set by the junction geometry, giving $\tau_{\rm grav} \sim 10^{16}$ s—half a billion years.

Trapped ions. Individual ions ($^{171}{\rm Yb}^+$, $M \sim 3 \times 10^{-25}$ kg) in Paul traps reach motional separations $d \sim 10$ μm, with $\tau_{\rm grav} \sim 2 \times 10^{20}$ s.

Neutral atoms. Cold atoms ($M \sim 10^{-25}$ kg) in lattices or tweezers reach $d \sim 1$ μm, yielding $\tau_{\rm grav} \sim 10^{20}$ s.

Photonic qubits. Single optical photons have $M = E/c^2 \sim 10^{-36}$ kg; even at meter path separations $\tau_{\rm grav} \sim 10^{48}$ s, the most gravitationally robust platform.

Nitrogen-vacancy centers. NV spin qubits carry negligible mass delocalization ($M \sim 10^{-26}$ kg, $d \sim 1$ nm), giving $\tau_{\rm grav} \sim 10^{19}$ s.

Conventional qubit platforms have $\tau_{\rm grav} \geq 10^{16}$ s and are entirely unaffected.

3.2 Massive platforms and the point-mass reversal

Massive optomechanical and electromechanical devices reach the floor, and here the point-mass convention and the finite-size law diverge. Table 2 evaluates both for four representative configurations (silica density where applicable), with the regime fixed by $d/2R$.

Three of the four rows shift, and the last reverses the verdict.

- **Levitated nanosphere** (10^{-12} kg, 10 μm). Just separated, $d/2R = 1.05$: the sphere value 10.4 μs is close to the point-mass 15.8 μs. Exposed to the floor.

Table 2. *Gravitational decoherence time for massive platforms: point-mass convention ($\tau_{\text{grav}} = \hbar d/GM^2$) versus the finite-size sphere value from Eq. (2), with the regime fixed by $d/2R$. Silica density $\rho = 2200$ kg/m^3.*

Platform	M [kg]	d	R	$d/2R$	τ_{pm}	τ_{sphere}
Levitated nanosphere	10^{-12}	10 μm	4.77 μm	1.05 (separated)	15.8 μs	10.4 μs
Levitated sphere	10^{-15}	1 μm	0.48 μm	1.05 (separated)	1.6 s	1.04 s
Electromech. resonator	10^{-14}	1 μm	1.03 μm	0.49 (overlap)	16 ms	53 ms
Electromech. (phonon)	10^{-13}	100 nm	2.21 μm	0.023 (tidal)	16 μs	0.35 s

- **Levitated sphere** (10^{-15} kg, 1 μm). Also $d/2R = 1.05$: $\tau_{\text{sat}} \approx 1.04$ s, the canonical near-threshold target.
- **Electromechanical resonator** (10^{-14} kg, 1 μm). Overlapping branches, $d/2R = 0.49$: the sphere value 53 ms exceeds the point-mass 16 ms; the object is partly shielded by branch overlap.
- **Electromechanical phonon state** (10^{-13} kg, 100 nm). Deep tidal, $d/2R = 0.023$: $\tau_{\text{sat}} \approx 0.35$ s, not the 16 μs the point-mass formula suggests—a factor of 2.2×10^4. The verdict reverses.

The phonon row carries a modeling assumption the others do not: a phonon superposition of a clamped resonator is a collective internal-mode displacement, not a rigid centre-of-mass displacement of the whole body, and the row evaluates the rigid-sphere mass-density difference as a proxy. The tidal *regime* is the physically correct one for any small collective displacement, so the qualitative protection is robust; the precise reversal factor is model-dependent.

Clamped and electromechanical platforms with sub-radius branch separations ($d \ll 2R$) are *protected* by branch overlap: the tidal suppression $E_{\text{G}} \approx \frac{1}{2}GM^2d^2/R^3$ lengthens their gravitational time by orders of magnitude relative to the point-mass estimate. Levitated spheres with $d \gtrsim 2R$ are the testing ground; phonon-state resonators are shielded.

4 Experimental Signatures

Isolating the gravitational contribution from environmental backgrounds is the central experimental challenge. The finite-size self-energy of Eq. (2) sharpens the discriminants: each is a quantitative contrast of the gravitational and environmental scaling laws, and the finite-size law makes positive predictions where the point-mass convention made only null ones.

4.1 The separation knee

In the point-mass convention the gravitational rate falls as $\Gamma_{\text{grav}} \propto 1/d$, against d^2 for scattering-type environmental channels. For a solid sphere this is replaced by a sharper feature. From Eq. (2) the rate rises as d^2 in the tidal regime and *saturates* above $d = 2R$:

$$\Gamma_{\text{self}}(d) \propto d^2 \;\; (d \ll R), \qquad \Gamma_{\text{self}}(d) \to \Gamma_{\text{sat}} \;\; (d \geq 2R). \tag{7}$$

Vary the superposition separation d at fixed mass. Gravitational decoherence rises as d^2 and then saturates at a knee fixed at $d = 2R$—a geometry-set, material-blind location. Scattering-type environmental channels grow as d^2 without saturation. The knee, not a $1/d$ falloff, is the honest separation discriminant for finite-size objects.

4.2 Mass scaling in the saturated regime

In the saturated regime the rate is $\Gamma_{\text{sat}} = k\,M^{5/3}$ at fixed density (Proposition 2.2). The competing environmental channels carry distinct mass powers:

- Gas collisions: $\Gamma_{\text{gas}} \propto R^2 \propto M^{2/3}$, with a d^2 separation growth.
- Blackbody and photon scattering: $\Gamma \propto R^6 \propto M^2$, with a d^2 separation growth.

The gravitational $M^{5/3}$ sits between the gas $M^{2/3}$ and the radiative M^2, and—unlike either—carries no d^2 separation growth in the saturated regime. A joint scan in M and d separates all three.

4.3 Weak, specified material dependence

The point-mass rate is material-independent; the finite-size law is not, and its dependence is a positive prediction. From Eq. (3), $\Gamma_{\text{sat}} \propto \rho^{1/3}$ at fixed M: replacing silica ($\rho = 2200$ kg/m^3) by diamond ($\rho = 3510$ kg/m^3) raises the rate by $(3510/2200)^{1/3} \approx 1.17$, a factor of 1.17.

At fixed mass the saturated rate scales as $\Gamma_{\text{sat}} \propto \rho^{1/3}$: silica to diamond is a factor of 1.17, weak and specified. Dielectric and polarizability-driven environmental channels vary far more strongly with composition. The finite-size law replaces the point-mass "material independence" with a sharper positive prediction.

4.4 Temperature independence below the crossover

The gravitational rate carries no temperature; thermal environmental sources scale strongly with T:

- Blackbody: $\Gamma_{\text{BB}} \propto T^9$ (dominant above ~ 10 K);
- Gas collisions: $\Gamma_{\text{gas}} \propto P/\sqrt{T}$;
- Phonon emission: $\Gamma_{\text{ph}} \propto e^{-\Delta/k_{\text{B}}T}$ (activated).

Lowering T suppresses the environmental contributions while the gravitational one holds constant. Below the critical temperature T_c fixed by $\Gamma_{\text{env}}(T_c) = \Gamma_{\text{self}}$, the total rate plateaus:

$$\Gamma_{\text{total}}(T) = \Gamma_{\text{self}} + \Gamma_{\text{env}}(T) \xrightarrow{T \ll T_c} \Gamma_{\text{self}}. \tag{8}$$

A temperature-independent decoherence plateau is strong evidence for a gravitational origin.

5 Implications for Quantum Technology Scaling

5.1 The error-correction bound

Under the saturated law the coherence time of a massive quantum element is bounded by $T_2 \leq \tau_{\rm sat} = (kM^{5/3})^{-1}$. Quantum error correction requires a per-gate error rate $\epsilon < \epsilon_{\rm th}$, with threshold $\epsilon_{\rm th} \sim 10^{-2}$ to 10^{-4} depending on the code [7]. The gravitational error contribution over a gate of duration $t_{\rm gate}$ is

$$\epsilon_{\rm grav} = t_{\rm gate}\,\Gamma_{\rm sat} = t_{\rm gate}\,k\,M^{5/3}, \tag{9}$$

and below-threshold operation for separated branches requires

$$M < M_{\max} = \left(\frac{\epsilon_{\rm th}}{t_{\rm gate}\,k}\right)^{3/5}. \tag{10}$$

At $\epsilon_{\rm th} = 10^{-3}$ and $t_{\rm gate} = 1\ \mu$s,

$$M_{\max} = \left(\frac{10^{-3}}{10^{-6}\cdot 1.59\times 10^{25}}\right)^{3/5} = \left(6.3\times 10^{-23}\right)^{3/5} \approx 4.8\times 10^{-14}\ \text{kg} \approx 48\ \text{pg}. \tag{11}$$

For overlapping branches ($d \ll R$) the tidal suppression $E_{\rm G} \propto d^2$ relaxes the constraint by $(d/R)^2$, so a resonator operated below its own radius tolerates a proportionally larger mass.

5.2 The self-limiting testing window

Gravitational decoherence limits the very superpositions needed to test it. In the saturated regime the window is d-independent, bounded on both sides by timescales:

- **Lower edge**: $\tau_{\rm sat} < \tau_{\rm env}$, so the gravitational signal clears the environmental floor. At $\tau_{\rm env} = 1$ s, $\tau_{\rm sat} < 1$ s requires $M > (1/k)^{3/5} = 0.76$ pg.
- **Upper edge**: $\tau_{\rm sat} > t_{\rm prep}$, so the superposition survives its own preparation. Solving $\tau_{\rm sat} = t_{\rm prep}$ at $t_{\rm prep} = 1$ ms gives $M < (1/(k\,t_{\rm prep}))^{3/5} = 48$ pg.

The saturated testing zone is $M \approx 0.8$–48 pg for any $d \gtrsim 2R$, independent of separation. The lower edge $M > 0.76$ pg coincides with the framework's falsifiability threshold $M^* \approx 7.6\times 10^{-16}$ kg: the smallest mass whose gravitational time drops below a 1 s environmental coherence budget is the smallest mass that can test the prediction at all.

The upper edge coincides exactly with the error-correction ceiling of Eq. (11), because $\epsilon_{\rm th}/t_{\rm gate} = 10^3\ \text{s}^{-1} = 1/t_{\rm prep}$ at these parameters: the mass at which the floor first threatens fault-tolerant operation is the same mass at which the superposition can no longer be held long enough to test.

6 The Entanglement-Decay Channel

Every signature of Sec. 4 measures the loss of a single particle's local spatial coherence, and that signal is degenerate—photon scattering, gas collisions, and collapse noise all reproduce it. Gravitational decoherence carries one signature no other channel produces: it degrades a particle's entanglement with a *distant* partner, at the same rate at which it degrades local coherence.

6.1 Setup: entangled pair plus which-path interferometer

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

$$|\Psi^-\rangle_{AB} = \frac{1}{\sqrt{2}} \left(|0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B \right), \tag{12}$$

with $|0\rangle$, $|1\rangle$ internal states and B held at a fixed distant location. Particle A (mass M) passes through a Stern–Gerlach interferometer coupling its internal state to its spatial path,

$$|0\rangle_A \to |0\rangle_A |L\rangle, \qquad |1\rangle_A \to |1\rangle_A |R\rangle, \tag{13}$$

with $|L\rangle$, $|R\rangle$ positions separated by d. This which-path coupling makes A's position a faithful record of its internal state. Applied to (12), the matter-plus-field state is

$$|\Psi(0)\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_A |L\rangle |1\rangle_B - |1\rangle_A |R\rangle |0\rangle_B \right) \otimes |g_0\rangle_{\rm grav}, \tag{14}$$

with $|g_0\rangle_{\rm grav}$ the initial gravitational field configuration.

6.2 Matter–field entanglement and the overlap decay

The positions $|L\rangle$ and $|R\rangle$ source distinguishable gravitational field configurations, entangling the field with A's position,

$$|L\rangle |g_0\rangle \to |L\rangle |g_L\rangle, \qquad |R\rangle |g_0\rangle \to |R\rangle |g_R\rangle. \tag{15}$$

Their overlap decays at the self-energy rate $\Gamma_{\rm self} = E_{\rm G}(d)/\hbar$,

$$\langle g_L(t)\rangle\, g_R(t) = e^{-\Gamma_{\rm self} t}, \tag{16}$$

with $E_{\rm G}(d)$ the finite-size self-energy of Eq. (2).

6.3 Entanglement decay of the reduced pair

The path lock (13) makes the gravitational which-path record act directly on the qubit carrying the A–B entanglement. Evolving (14) under the field coupling,

$$|\Psi(t)\rangle = \frac{1}{\sqrt{2}} \left(|0\rangle_A |1\rangle_B |g_L(t)\rangle - |1\rangle_A |0\rangle_B |g_R(t)\rangle \right), \tag{17}$$

and tracing over the field multiplies the off-diagonal A–B coherence by the overlap $e^{-\Gamma_{\rm self} t}$. The same conclusion follows from monogamy of entanglement [13]: as A entangles with the field, its entanglement with B must fall. In the basis $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$,

$$\rho_{AB}(t) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2}e^{-\Gamma_{\text{self}}t} & 0 \\ 0 & -\frac{1}{2}e^{-\Gamma_{\text{self}}t} & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{18}$$

6.4 Concurrence decay

The concurrence [14] is $C = \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4)$, 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 (18), the off-diagonal $\frac{1}{2}e^{-\Gamma_{\text{self}}t}$ gives

$$C(t) = C(0)\, e^{-\Gamma_{\text{self}}t} = \exp[-E_{\text{G}}(d)\, t/\hbar]\,. \tag{19}$$

The entanglement decays at the gravitational decoherence rate, and the two rates are equal: $\Gamma_{AB} = \Gamma_{\text{loc}} = \Gamma_{\text{self}}$.

6.5 Bell inequality violation

The decay is observable through the CHSH parameter [15] $S = E(a,b) + E(a,b') + E(a',b) - E(a',b')$. The state (18) is a pure-dephasing state, for which the exact CHSH maximum is

$$S^{\text{deph}}_{\text{max}}(t) = 2\sqrt{1 + e^{-2\Gamma_{\text{self}}t}}, \tag{20}$$

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 $p = e^{-\Gamma_{\text{self}}t}$ gives a depolarizing channel and

$$S^{\text{Werner}}_{\text{max}}(t) = 2\sqrt{2}\, e^{-\Gamma_{\text{self}}t}, \tag{21}$$

which holds $S > 2$ until $t_{\text{Bell}} = \Gamma^{-1}_{\text{self}} \ln\sqrt{2} \approx 0.35\,\tau_{\text{dec}}$. The t_{Bell} column of Table 3 uses this Werner estimate; under the exact dephasing formula (20) the figure of merit is instead how far S exceeds the classical bound.

6.6 Numerical examples for finite-size spheres

The decay time is the finite-size $\tau_{\text{dec}} = \hbar/E_{\text{G}}(d)$ from Eq. (2), not the point-mass value. Table 3 gives both, with $t_{\text{Bell}} = \tau_{\text{dec}} \ln\sqrt{2}$ computed on the sphere value.

The point-mass 1 μg/1 mm benchmark, $\tau \approx 1.6$ ns, is the convention of the core paper [22]; for a solid silica sphere at those parameters the self-energy is saturated and the true rate is faster by roughly a factor 24 (the companion treatment in the core and BMV papers [22, 23]).

6.7 Comparison with other frameworks

The four frameworks below agree that A's local coherence decays; they disagree on the ratio of the entanglement-decay rate Γ_{AB} to the local rate Γ_{loc}.

Mass	**Separation**	τ_{dec} (point-mass)	τ_{dec} (sphere)	t_{Bell} (sphere)
1 fg	100 nm	1.6×10^5 s	1.04×10^5 s	3.6×10^4 s
10 fg	1 μm	1.6×10^4 s	1.5×10^3 s	5.1×10^2 s
100 fg	1 μm	158 s	36 s	12 s
1 pg	10 μm	15.8 s	0.65 s	0.23 s
20 pg	10 μm	40 ms	4.8 ms	1.7 ms

Table 3. *Entanglement decay times for silica spheres ($\rho = 2200$ kg/m^3): point-mass convention $\hbar d/(GM^2)$ versus the finite-size self-energy of Eq. (2). $t_{\mathrm{Bell}} = \tau_{\mathrm{dec}} \ln \sqrt{2} \approx 0.35\, \tau_{\mathrm{dec}}$ (Werner approximation) on the sphere value. The target regime is $M \sim 1$–20 pg, $d \sim 1$–100 μm (Sec. 7).*

Standard quantum mechanics. Photon scattering entangles the photons with A's position only, not with the A–B correlations. Tracing over them destroys A's spatial coherence and leaves the entanglement intact: $\Gamma_{AB} = 0$, $\Gamma_{\mathrm{loc}} \neq 0$.

Diósi–Penrose gravitational decoherence. The "environment" is the field configuration, fixed by A's mass distribution rather than by external scatterers. The field does not learn A's position through scattering; it *is* determined by it. Prediction: $\Gamma_{AB} = \Gamma_{\mathrm{loc}} = \Gamma_{\mathrm{self}}$.

Continuous spontaneous localization. CSL [16, 17, 18] postulates a universal collapse noise field coupling to A's position; it carries no information about the internal qubit, so $\Gamma_{AB} \approx 0$, decoupled from the local collapse rate.

Perturbative quantum gravity. Graviton exchange gives the G^2 rate of Sec. 2, slower than the G^1 rate by the factor $(M_P/M)^2(d/\ell_{\mathrm{P}})$; for $M = 10$ fg, $d = 1$ μm that factor is 3×10^{47} and $\tau_{\mathrm{QFT}} \sim 10^{44}$ yr—negligible in both channels.

Theory	**Local decoherence**	**Entanglement decay**
Standard QM	Environmental	Protected
Diósi–Penrose	$\Gamma_{\mathrm{self}} = E_{\mathrm{G}}(d)/\hbar$	$\Gamma_{\mathrm{self}} = E_{\mathrm{G}}(d)/\hbar$
CSL	Γ_{CSL}	≈ 0 (standard form)
Perturbative QFT	$\sim G^2$ (negligible)	Negligible

Table 4. *Predictions for the local-decoherence and entanglement-decay rates across frameworks. Only Diósi–Penrose predicts correlated decay at the gravitational self-energy scale, with the two rates equal.*

The distinctive feature is the *equality* of the two rates. It survives the finite-size correction unchanged: both channels are driven by the single self-energy $E_{\mathrm{G}}(d)$, so rescaling from the point-mass to the sphere value rescales both together.

6.8 Falsifiability

The prediction fails under any of the following.

1. **No decay**: entanglement persists while local coherence decays $\Rightarrow$ falsified.

2. **Wrong rate**: entanglement decays at a rate inconsistent with $E_{\mathrm{G}}(d)/\hbar \Rightarrow$ the specific mechanism is falsified.

3. **Dependence on distance to** B: a rate that varies with the A–B separation $\Rightarrow$ the mechanism is not purely local; falsified.

4. **Temperature dependence**: a rate that varies with temperature $\Rightarrow$ thermal effects dominate; not confirmed.

Observation of entanglement decay at $\Gamma_{AB} = \Gamma_{\rm loc} = E_{\rm G}(d)/\hbar$, independent of temperature and A–B distance, supports the hypothesis.

7 Experimental Program

7.1 Requirements and platform

Testing the floor and its entanglement signature requires four capabilities: a spatial superposition of a massive particle; where the entanglement channel is targeted, entanglement between two such particles; the decoherence or entanglement measured against time; and environmental decoherence suppressed below the gravitational rate. Levitated optomechanics [5, 6] 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 superposition and entanglement generation [19, 20, 21].

7.2 The gas-decoherence floor

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 [6],

$$\Gamma_{\rm gas} = \pi R^2\, v_{\rm th}\, n_{\rm gas} = \frac{\pi R^2\, P}{k_{\rm B}T}\sqrt{\frac{8k_{\rm B}T}{\pi m_{\rm gas}}}, \tag{22}$$

valid when the superposition separation exceeds the gas thermal de Broglie wavelength ($\lambda_{\rm dB} \sim$ 1 nm at 100 mK), as holds for all $d \geq 1$ μm of interest. Table 5 compares $\Gamma_{\rm self}$ with $\Gamma_{\rm gas}$ at standard ultra-high vacuum (UHV, $P = 10^{-8}$ Pa) and extreme high vacuum (XHV, $P = 10^{-13}$ Pa).

Configuration	$\Gamma_{\rm self}$	$\Gamma_{\rm gas}$ (UHV)	$\Gamma_{\rm gas}$ (XHV)
20 pg, 10 μm	2.1×10^2 Hz	3.3×10^5 Hz	3.3 Hz
1 pg, 10 μm	1.5 Hz	4.4×10^4 Hz	0.44 Hz

Table 5. *Gravitational rate $\Gamma_{\rm self} = E_{\rm G}(d)/\hbar$ (finite-size, silica) versus collisional rate $\Gamma_{\rm gas}$ at $T = 100$ mK for two configurations and two pressures. UHV $= 10^{-8}$ Pa is standard laboratory vacuum; XHV $= 10^{-13}$ Pa is currently projected only for space-based platforms (MAQRO/DECIDE class [10]).*

At standard UHV the collisional floor exceeds the gravitational rate by orders of magnitude; XHV brings $\Gamma_{\rm gas}$ below $\Gamma_{\rm self}$. Such pressures are not yet achievable on the ground and require a space-based platform. Photon recoil heating from the trap must also be suppressed during free evolution, by switching off the traps (ballistic trajectory) or by magnetic or electrostatic trapping with minimal photon scattering.

7.3 Protocol and controls

A single run proceeds in five phases: load and ground-state cool the particle(s) ($\bar{n} < 0.1$); where the entanglement channel is targeted, entangle A and B via Coulomb coupling and an entangling gate, verified by partial tomography; apply a coherent displacement to A to open the superposition d; evolve freely for a variable time $\tau \in [0, 5\tau_{\mathrm{dec}}]$; recombine and read out, by interferometry for the local channel or Bell-basis measurement for the entanglement channel, averaging $\sim 10^3$ runs per time point.

Four controls separate gravity from systematics.

- **No superposition**: skip the displacement; any decay signals a systematic, not gravity.
- **Mass scaling**: repeat across masses. In the saturated regime the rate follows $\Gamma_{\mathrm{sat}} \propto M^{5/3}$ (Sec. 4).
- **Separation scaling**: vary d across the knee at $d = 2R$; the rate rises as d^2 below it and saturates above.
- **Temperature variation**: repeat at 10 mK, 100 mK, 1 K; the gravitational rate is temperature-independent.

7.4 Phased timeline

1. **Near-term (1–5 yr)**: precision decoherence measurements on electromechanical resonators, with material-independence and separation-knee tests across compositions and superposition sizes.
2. **Medium-term (5–10 yr)**: levitated nanosphere experiments at $\sim$ 1–20 pg, with systematic M- and d-scans to test the saturated law and locate the knee.
3. **Long-term (10–20 yr)**: space-based optomechanics for XHV coherence and the entanglement-decay channel, contingent on MAQRO/DECIDE-class facilities (projected mid-2030s) or major advances in macroscopic superposition. Definitive G^1 versus G^2 discrimination.

8 Discussion

8.1 Status of the rate

Every prediction here is conditional on the first-order-in-G rate. Within the framework this rate is obtained in linearized gravity by imposing the Wheeler–DeWitt constraint on the Feynman–Vernon influence functional [22]: the product initial state $|\psi\rangle \otimes |0\rangle$ violates the constraint, and the physical constrained state decoheres through coherent-state overlap at G^1 rather than the noise-kernel mechanism at G^2 [3, 4]. The central modular identification is conjectured at the operator level and established in expectation values and solvable models. Because the constraint is not optional, the framework predicts the G^1 rate; the G^2 rate would obtain only if nature does not enforce the constraint on the initial state. The prediction is therefore falsifiable: coherence surviving to the G^2 timescale—longer by $(M_{\mathrm{P}}/M)^2(d/\ell_{\mathrm{P}}) \sim 3 \times 10^{34}$ at microgram mass and mm separation in the point-mass convention—would rule out G^1.

The overall coefficient is bounded, not uniquely pinned. The canonical analysis [22] places it in $C \in [2/\pi, 1]$ (natural value $C = 1$; floor $2/\pi$ from the Margolus–Levitin quantum speed limit), a factor-$\pi/2$ spread in the absolute rate that leaves the scaling laws of Secs. 2–4 untouched.

8.2 Relation to existing proposals

Matter-wave interferometry proposals [6, 8, 9] and the MAQRO space mission [10] target collapse models including Diósi–Penrose with nanospheres of mass $\sim 10^{-17}$ to 10^{-14} kg. The saturated law sharpens the mass reach: at fixed density $\Gamma_{\rm sat} \propto M^{5/3}$, so heavier ground-based spheres reach comparable sensitivity, but the floor also saturates—above $d = 2R$ no further separation gain is available, which fixes the testing zone rather than opening it indefinitely.

Current bounds on the CSL collapse parameter λ from optomechanical [11] and underground X-ray [12] measurements constrain a tunable rate; the gravitational floor has no tunable parameter, its single input G being fixed and its coefficient $O(1)$.

8.3 Companion predictions

Two companion papers of this series treat the same finite-size self-energy in different observables. The BMV/QGEM treatment [23] computes the two-mass entanglement-witness suppression driven by the identical saturated self-energy, predicting a square-law visibility with a weak $m^{-1/3}$ mass trend and a magic-angle phase null. The core paper [22] carries the frequency-domain modular-spectroscopy fingerprint and the derivation of the rate itself. The self-energy of Eq. (2) is the common object across all three.

8.4 Falsification routes

The framework is falsified by any of: coherence surviving to the G^2 timescale; a separation dependence without the $d = 2R$ knee; a saturated-regime mass scaling inconsistent with $M^{5/3}$ at fixed density; an entanglement-decay rate unequal to the local rate, or dependent on the A–B distance or on temperature. Each is accessible with the scans of Sec. 7, and each isolates a different structural feature of the prediction.

9 Conclusions

For a solid object the gravitational decoherence floor is not the point-mass rate $GM^2/(\hbar d)$ but a saturated, separation-independent law $\Gamma_{\rm sat} = \frac{6}{5}GM^2/(\hbar R) = k\, M^{5/3}$ at fixed density, with $k = 1.59 \times 10^{25}$ SI for silica. A 1 pg silica sphere saturates in 0.63 s; the self-consistent testing zone is 0.8–48 pg for any $d \gtrsim 2R$. Conventional qubit platforms are untouched; levitated spheres with $d \gtrsim 2R$ are the testing ground, while clamped and phonon-state resonators with sub-radius branch separations are protected by tidal suppression—reversing the naive point-mass verdict. The same self-energy drives the one channel no environmental mechanism reproduces: entanglement with a distant partner decays at the local rate, $\Gamma_{AB} = \Gamma_{\rm loc}$. The predictions are conditional on the framework's G^1 rate; observation would place gravity in the quantum-to-classical transition, and a floor of the wrong shape—or a G^2-scale coherence lifetime—would falsify it.

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