Gravitational Decoherence as a Fundamental Limit on Massive Quantum Technologies

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Abstract

The Diósi-Penrose hypothesis predicts that gravity causes irreducible decoherence of spatial superpositions at a rate $\Gamma_{\text{grav}} = GM^2/(\hbar d)$, where M is the superposed mass and d the separation. We analyze the implications of this gravitational decoherence floor for quantum computing platforms. While conventional qubits (superconducting, trapped ion, photonic) have gravitational decoherence times exceeding the age of the universe and are entirely unaffected, we show that emerging massive quantum technologies—optomechanical oscillators and electromechanical resonators—approach a regime where gravitational decoherence could become the dominant coherence-limiting mechanism. For a levitated nanosphere of mass 10^{-12} kg (nanogram scale) in a 10 μm superposition, the predicted decoherence time is $\tau_{\text{grav}} \approx$ 16 μs. We identify three experimental signatures that uniquely distinguish gravitational from environmental decoherence: M^2 scaling of the decoherence rate, material independence at fixed mass and separation, and temperature independence below a critical threshold. The G^1 (Diósi-Penrose) and G^2 (perturbative) scaling predictions differ by a factor of $\sim 10^{35}$ for microgram-scale masses, providing a stark experimental discriminant. These results establish optomechanical quantum systems as a concrete testing ground for gravitational decoherence within the coming decade.

1 Introduction

Quantum technologies rely on maintaining coherent superposition states for durations sufficient to perform useful operations. In practice, environmental decoherence—arising from electromagnetic noise, thermal fluctuations, and material defects—limits coherence times and constrains the performance of quantum processors, sensors, and communication devices. Decades of engineering effort have progressively reduced these environmental sources, pushing coherence times from nanoseconds to seconds across multiple platforms [9, 10, 11].

A qualitatively different question arises from gravitational physics: does gravity itself impose an irreducible decoherence floor that no amount of environmental shielding can eliminate? The Diósi-Penrose hypothesis [1, 2] proposes that a mass M in spatial superposition with separation d decoheres at rate

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

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where G is Newton's constant and $\hbar$ is the reduced Planck constant. This rate is first-order in G (the "G^1 scaling"). In contrast, perturbative quantum field theory calculations of graviton-mediated decoherence yield rates proportional to G^2 [3, 4], differing by many orders of magnitude for laboratory-scale masses.

If the Diósi-Penrose rate is correct, it establishes a *fundamental* coherence limit: no quantum technology using massive components can maintain superposition indefinitely, regardless of isolation quality. This limit is negligible for current quantum computing platforms but becomes relevant as the field advances toward larger, more massive quantum systems—particularly optomechanical and electromechanical devices.

In this paper, building on the theoretical framework and experimental signatures identified in Ref. [19], we systematically evaluate the gravitational decoherence floor for all major quantum computing platforms. We identify the mass-separation regime where gravitational decoherence transitions from negligible to dominant, quantify how gravitational signatures can be distinguished from environmental backgrounds in each platform, and discuss implications for the scaling of massive quantum technologies.

2 The Gravitational Decoherence Floor

2.1 Decoherence rate and scaling

The Diósi-Penrose gravitational decoherence rate for a point mass M in spatial superposition with separation d is

$$\Gamma_{\text{grav}} = \frac{GM^2}{\hbar d}, \qquad \tau_{\text{grav}} = \frac{\hbar d}{GM^2}. \tag{2}$$

The key scaling properties are:

- **Quadratic mass dependence**: $\tau_{\text{grav}} \propto M^{-2}$. Doubling the mass reduces coherence time by a factor of four.
- **Linear separation dependence**: $\tau_{\text{grav}} \propto d$. Larger superposition separations yield longer coherence times (the gravitational potential difference decreases with d for point masses at fixed center-of-mass distance).
- **No temperature dependence**: Unlike thermal decoherence, Γ_{grav} is independent of temperature.
- **No material dependence**: Γ_{grav} depends only on M and d, not on composition, crystal structure, or surface properties.

Numerically,

$$\tau_{\text{grav}} = 1.58 \times 10^{-24} \, \frac{d\,[\text{m}]}{(M\,[\text{kg}])^2} \text{ seconds.} \tag{3}$$

2.2 Extended mass distributions

For an extended object, the decoherence rate generalizes to the Diósi integral over the mass density difference $\delta\rho = \rho_L - \rho_R$ between superposition branches [1, 19]. For a rigid body displaced by $d \gg R$ (object radius), this reduces to Eq. (2). Finite-size corrections enter as $\tau_{\text{grav}}^{-1} \to \tau_{\text{grav}}^{-1}(1 + \frac{6}{5}R^2/d^2 + \cdots)$ and are negligible for the parameter regimes considered below.

2.3 G^1 versus G^2 scaling

The rate in Eq. (2) scales as the first power of Newton's constant (G^1); for a detailed discussion of the theoretical status and physical motivation, see Ref. [19]. Perturbative quantum field theory, treating gravitons as a bath and computing the decoherence rate via the Lindblad master equation, yields instead [3, 4]

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

where $f(d, c)$ encodes geometric factors. The ratio of rates is

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

which exceeds 10^{35} for microgram-scale masses. This enormous difference makes the two predictions experimentally distinguishable in principle, provided gravitational decoherence can be isolated from environmental backgrounds.

Key result: The G^1 and G^2 predictions for gravitational decoherence differ by a factor $\sim 10^{35}$ at the microgram scale. An experiment sensitive to decoherence at the G^1 level would either confirm the Diósi-Penrose hypothesis or rule it out decisively in favor of the perturbative G^2 rate.

3 Platform Analysis

We evaluate the gravitational decoherence time $\tau_{\text{grav}} = \hbar d/(GM^2)$ for each major quantum computing platform. The effective superposed mass M and spatial separation d are determined by the physical degrees of freedom encoding quantum information.

3.1 Conventional platforms

Superconducting qubits. Transmon and fluxonium qubits encode information in collective charge or flux states of a Josephson junction circuit. The effective superposed mass is that of the delocalized Cooper pairs, $M \sim 10^{-23}$ kg, with spatial separation $d \sim 1$ μm set by the junction geometry. This gives $\tau_{\text{grav}} \sim 10^{16}$ s, exceeding the age of the universe by six orders of magnitude. Gravitational decoherence is entirely negligible.

Trapped ions. Individual ions (e.g., $^{171}\text{Yb}^+$, mass $\sim 3 \times 10^{-25}$ kg) are confined in Paul traps with motional superpositions of order $d \sim 10$ μm. The resulting $\tau_{\text{grav}} \sim 10^{21}$ s is even more remote from measurability.

Neutral atoms. Cold atoms ($M \sim 10^{-25}$ kg) in optical lattices or tweezers achieve superposition separations $d \sim 1$ μm, yielding $\tau_{\text{grav}} \sim 10^{20}$ s. Gravitational decoherence plays no role.

Photonic qubits. Single photons have effective gravitational mass $M = E/c^2 \sim 10^{-36}$ kg for optical frequencies. Even with meter-scale path separations, $\tau_{\text{grav}} \sim 10^{48}$ s. This is the most gravitationally robust platform.

Nitrogen-vacancy centers. NV centers in diamond encode spin qubits with negligible spatial delocalization of mass ($M \sim 10^{-26}$ kg, $d \sim 1$ nm), giving $\tau_{\text{grav}} \sim 10^{19}$ s.

3.2 Massive quantum platforms

Optomechanical oscillators. Levitated dielectric nanospheres [5, 6] represent the most promising platform for gravitational decoherence tests. Current experiments achieve:

- Masses: $M = 10^{-18}$ to 10^{-12} kg (silica, silicon, diamond spheres)
- Superposition separations: $d = 1$ nm to 10 μm (proposed)
- Coherence times: $T_2 \sim 1$ ms to 1 s (projected)

For a nanogram (10^{-12} kg) nanosphere in a 10 μm superposition:

$$\tau_{\text{grav}} = \frac{1.055 \times 10^{-34} \times 10^{-5}}{6.674 \times 10^{-11} \times 10^{-24}} = \frac{1.055 \times 10^{-39}}{6.674 \times 10^{-35}} = 15.8\ \mu\text{s}. \tag{6}$$

This is comparable to current coherence times in state-of-the-art cryogenically levitated systems.

Electromechanical resonators. Piezoelectric nanobeams and membrane resonators coupled to superconducting circuits [7, 8] achieve:

- Masses: $M = 10^{-16}$ to 10^{-13} kg
- Phonon number state separations: $d \sim 10$ nm to 1 μm
- Coherence times: $T_2 \sim 10$ μs to 1 ms

For a 10^{-14} kg resonator with $d = 1$ μm phonon separation:

$$\tau_{\text{grav}} = \frac{1.055 \times 10^{-34} \times 10^{-6}}{6.674 \times 10^{-11} \times 10^{-28}} = \frac{1.055 \times 10^{-40}}{6.674 \times 10^{-39}} = 15.8\ \text{ms}. \tag{7}$$

For larger resonators ($M = 10^{-13}$ kg, $d = 100$ nm):

$$\tau_{\text{grav}} = \frac{1.055 \times 10^{-34} \times 10^{-7}}{6.674 \times 10^{-11} \times 10^{-26}} = \frac{1.055 \times 10^{-41}}{6.674 \times 10^{-37}} = 15.8\ \mu\text{s}. \tag{8}$$

This is comparable to current coherence times in state-of-the-art electromechanical systems.

3.3 Summary

Table 1 summarizes the gravitational decoherence time for each platform.

The table reveals a clear division: conventional qubit platforms have τ_{grav} exceeding the age of the universe by many orders of magnitude, while massive optomechanical and electromechanical systems can enter the regime where τ_{grav} is comparable to or shorter than achievable environmental coherence times.

4 Experimental Signatures

A central challenge in gravitational decoherence experiments is distinguishing the gravitational contribution from environmental decoherence backgrounds. Ref. [19] identified four qualitative signatures of the Diósi-Penrose mechanism: M^{-2} mass scaling, temperature independence, vacuum independence, and linear separation scaling. Here we provide a quantitative comparison of gravitational and environmental decoherence scaling laws relevant to quantum computing platforms, focusing on the three signatures most directly testable in optomechanical and electromechanical systems.

Table 1. *Gravitational decoherence times for quantum computing platforms. The effective mass M and superposition separation d represent typical or projected operating parameters. Platforms are ordered by decreasing τ_{grav}.*

Platform	M [kg]	d [m]	$\tau_{\rm grav}$ [s]	**Testable?**
Photonic	10^{-36}	1	1.6×10^{48}	No
Trapped ion	10^{-25}	10^{-5}	1.6×10^{21}	No
Neutral atom	10^{-25}	10^{-6}	1.6×10^{20}	No
NV center	10^{-26}	10^{-9}	1.6×10^{19}	No
Superconducting	10^{-23}	10^{-6}	1.6×10^{16}	No
Optomech. (small)	10^{-15}	10^{-6}	1.6	Future
Electromech. (small)	10^{-14}	10^{-6}	1.6×10^{-2}	Marginal
Electromech. (large)	10^{-13}	10^{-7}	1.6×10^{-5}	**Yes**
Optomech. (medium)	10^{-12}	10^{-5}	1.6×10^{-5}	**Yes**
Optomech. (large)	10^{-9}	10^{-4}	1.6×10^{-10}	**Yes**

4.1 M^2 scaling of the decoherence rate

The gravitational decoherence rate scales as $\Gamma_{\rm grav} \propto M^2/d$. Environmental decoherence mechanisms scale differently with mass:

- **Blackbody radiation**: $\Gamma_{\rm BB} \propto R^6T^9d^2/(c^6\hbar^4)$, where R is the particle radius. For a sphere of uniform density, $R \propto M^{1/3}$, so $\Gamma_{\rm BB} \propto M^2d^2T^9$.
- **Gas collisions**: $\Gamma_{\rm gas} \propto PR^2d^2/(\hbar k_BT)$, where P is the residual gas pressure. This gives $\Gamma_{\rm gas} \propto M^{2/3}d^2$.
- **Photon scattering**: $\Gamma_{\rm scat} \propto IR^6d^2/(\hbar c^4)$, giving $\Gamma_{\rm scat} \propto M^2d^2$ for fixed trapping intensity I.

Blackbody and photon scattering rates share the M^2 dependence with gravity but scale as d^2 rather than d^{-1}. A systematic measurement of the decoherence rate as a function of d at fixed M would distinguish gravitational ($\Gamma \propto d^{-1}$) from environmental ($\Gamma \propto d^2$) contributions.

Discriminating measurement: Vary the superposition separation d at fixed mass M. Gravitational decoherence predicts $\Gamma \propto 1/d$; all environmental mechanisms predict $\Gamma \propto d^2$. The opposite dependence on separation provides an unambiguous discriminant.

4.2 Material independence

Gravitational decoherence depends only on M and d, not on the material composition. Environmental decoherence depends on material properties:

- Blackbody: depends on dielectric constant $\epsilon(\omega)$
- Gas scattering: depends on surface cross-section and accommodation coefficient
- Photon scattering: depends on polarizability $\alpha(\omega)$

A definitive test: prepare identical mass superpositions (M, d fixed) using different materials—silica, silicon, and diamond nanospheres, or different-composition mechanical resonators. Gravitational decoherence predicts identical rates; environmental decoherence produces material-dependent rates.

4.3 Temperature independence

The gravitational rate $\Gamma_{\rm grav}$ is independent of temperature. Environmental decoherence from thermal sources scales strongly with temperature:

- Blackbody: $\Gamma_{\rm BB} \propto T^9$ (dominant at $T > 10$ K)
- Gas collisions: $\Gamma_{\rm gas} \propto P/\sqrt{T}$
- Phonon emission: $\Gamma_{\rm ph} \propto e^{-\Delta/k_B T}$ (activated process)

As the experimental temperature is lowered, environmental contributions decrease while the gravitational contribution remains constant. Below a critical temperature T_c where $\Gamma_{\rm env}(T_c) = \Gamma_{\rm grav}$, gravitational decoherence would dominate and the total decoherence rate would plateau:

$$\Gamma_{\rm total}(T) = \Gamma_{\rm grav} + \Gamma_{\rm env}(T) \xrightarrow{T \ll T_c} \Gamma_{\rm grav}. \tag{9}$$

Observation of such a temperature-independent decoherence plateau would constitute strong evidence for a gravitational origin.

5 Implications for Quantum Technology Scaling

5.1 Fundamental coherence limit

If the Diósi-Penrose rate is correct, the maximum coherence time for any massive quantum system is bounded by

$$T_2 \leq \tau_{\rm grav} = \frac{\hbar d}{G M^2}. \tag{10}$$

For quantum error correction, the physical error rate per gate must satisfy $\epsilon < \epsilon_{\rm th}$, where $\epsilon_{\rm th} \sim 10^{-2}$ to 10^{-4} depending on the code [12]. The gravitational contribution to the error rate is

$$\epsilon_{\rm grav} = \frac{t_{\rm gate}}{\tau_{\rm grav}} = \frac{G M^2 t_{\rm gate}}{\hbar d}, \tag{11}$$

where $t_{\rm gate}$ is the gate duration.

For the error rate to remain below threshold:

$$\frac{M^2}{d} < \frac{\hbar \epsilon_{\rm th}}{G\, t_{\rm gate}}. \tag{12}$$

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

$$\frac{M^2}{d} < 1.58 \times 10^{-21}\ \frac{\rm kg^2}{\rm m}. \tag{13}$$

Table 2 shows the maximum superposed mass for useful quantum computation at various separation distances.

These limits are well above the masses of conventional qubits but impose meaningful constraints on proposed massive quantum processors using optomechanical or electromechanical elements.

Table 2. *Maximum superposed mass for quantum error correction below threshold ($\epsilon_{th} = 10^{-3}$, $t_{gate} = 1\ \mu s$), assuming the Diósi-Penrose decoherence rate.*

Separation d	$M_{\max}$	Physical system
1 μm	4.0×10^{-14} kg	Nanomechanical resonator
10 μm	1.3×10^{-13} kg	Levitated nanoparticle
100 μm	4.0×10^{-13} kg	Optomechanical cavity
1 mm	1.3×10^{-12} kg	Large levitated sphere

5.2 Crossover mass

The crossover mass M_c at which gravitational decoherence equals the environmental coherence time τ_{env} is

$$M_c = \sqrt{\frac{\hbar d}{G\tau_{\text{env}}}}. \tag{14}$$

For a system with $d = 10\ \mu$m and $\tau_{\text{env}} = 1$ s:

$$M_c = \sqrt{\frac{1.055 \times 10^{-34} \times 10^{-5}}{6.674 \times 10^{-11}}} = 4.0 \times 10^{-15}\ \text{kg} \approx 4\ \text{femtograms}. \tag{15}$$

Above this mass, gravitational decoherence dominates over environmental decoherence. This places the crossover firmly in the regime of levitated nanoparticle experiments.

5.3 Self-limiting testability

An interesting feature of gravitational decoherence is that it limits the very superpositions needed to test it. Testing requires maintaining coherent superpositions of massive objects, but the more massive the object, the faster gravity decoheres it. The experimental window is therefore bounded:

- **Lower bound**: $M > M_c$ so that $\tau_{\text{grav}} < \tau_{\text{env}}$ (gravitational signal detectable above environmental noise)
- **Upper bound**: $\tau_{\text{grav}} > t_{\text{prep}}$, where t_{prep} is the time required to prepare the superposition

For typical state preparation times $t_{\text{prep}} \sim 1$ ms, the accessible mass range is

$$M_c \sim 10^{-15}\ \text{kg} \ < \ M \ < \ \sqrt{\frac{\hbar d}{G\, t_{\text{prep}}}} \sim 10^{-12}\ \text{kg}. \tag{16}$$

This three-decade window (10^{-15} to 10^{-12} kg) defines the "gravitational decoherence testing zone" for optomechanical experiments.

6 Discussion

6.1 Relation to existing proposals

Several proposals exist for testing gravitational decoherence using matter-wave interferometry [13, 14, 15]. Our analysis complements these by focusing on quantum computing platforms, where decoherence is routinely measured as part of device characterization. The key advantage of the quantum-technology perspective is that the infrastructure for high-precision decoherence measurements already exists and is continuously improving.

The MAQRO space mission proposal [16] aims to test collapse models including Diósi-Penrose in microgravity, using nanospheres of mass $\sim 10^{-17}$ to 10^{-14} kg. Our analysis shows that ground-based optomechanical systems with heavier masses ($\sim 10^{-12}$ kg) may provide comparable or superior sensitivity due to the M^2 scaling of the gravitational rate.

6.2 Comparison with collapse model bounds

Current experimental bounds on the collapse rate parameter λ from optomechanical [17], X-ray emission [18], and underground experiment [18] measurements constrain the Continuous Spontaneous Localization (CSL) model. The Diósi-Penrose model is more constrained: its single parameter (Newton's constant G) is fixed, leaving no freedom to adjust the predicted rate. This makes it maximally falsifiable—the predicted rate either matches observations or it does not.

6.3 Status of G^1 scaling

The Diósi-Penrose rate (Eq. 1) has been derived in linearized gravity by imposing the Wheeler-DeWitt constraint on the Feynman-Vernon influence functional [20]. The key insight is that the standard product initial state $|\psi\rangle \otimes |0\rangle$ violates the constraint; the physical entangled state produces decoherence through coherent-state overlap at G^1 rather than the noise-kernel mechanism at G^2 [3, 4]. Both scalings are correct for their respective initial conditions. Whether nature enforces the Wheeler-DeWitt constraint on the initial state is an experimentally decidable question.

If the G^2 rate is correct, gravitational decoherence is negligible for all foreseeable quantum technologies ($\tau_{\text{grav}} > 10^{35}$ times longer). The experiments proposed here would then set upper bounds on non-perturbative gravitational effects.

6.4 Recommended experimental program

Based on our analysis, we propose a phased experimental program:

1. **Near-term (1–5 years)**: Precision decoherence measurements on electromechanical resonators ($M \sim 10^{-13}$ kg). Demonstrate material-independence tests using different resonator compositions.

2. **Medium-term (5–10 years)**: Levitated nanosphere experiments with masses 10^{-15} to 10^{-12} kg. Systematic d-dependence and M-dependence measurements to test scaling predictions.

3. **Long-term (10–15 years)**: Space-based optomechanical experiments for extended coherence in microgravity. Definitive G^1 vs G^2 discrimination.

7 Conclusions

We have shown that the Diósi-Penrose gravitational decoherence hypothesis, if correct, imposes a fundamental coherence limit on massive quantum technologies. While conventional quantum computing platforms (superconducting, trapped ion, photonic, NV center) are entirely unaffected—their gravitational decoherence times exceed 10^{16} s—emerging optomechanical and electromechanical platforms operate in a regime where gravitational decoherence could become the dominant coherence-limiting mechanism.

Three experimental signatures uniquely identify gravitational decoherence: the inverse dependence on superposition separation ($\Gamma \propto 1/d$, versus d^2 for environmental mechanisms), material independence at fixed mass and separation, and temperature independence below a critical threshold. The G^1 versus G^2 discrimination is dramatic: the predicted rates differ by a factor of $\sim 10^{35}$ for microgram-scale masses.

The "gravitational decoherence testing zone" spans masses from $\sim 10^{-15}$ to 10^{-12} kg, coinciding with the parameter space targeted by next-generation optomechanical experiments. This establishes massive quantum technologies as a concrete testing ground for gravitational decoherence, complementing dedicated interferometric proposals.

A Numerical Estimates

We provide detailed numerical estimates for the gravitational decoherence time across the full range of relevant masses and separations.

A.1 Reference values

Using $G = 6.674 \times 10^{-11}$ m^3/(kg·s^2) and $\hbar = 1.055 \times 10^{-34}$ J·s:

Table 3. *Gravitational decoherence times for representative mass-separation combinations.*

Mass M	Separation d	τ_{grav}	Physical context
10^{-25} kg	10 μm	1.6×10^{21} s	Single atom
10^{-20} kg	1 nm	1.6×10^{7} s	Large molecule
10^{-18} kg	10 nm	1.6×10^{4} s	Virus-size particle
10^{-16} kg	100 nm	16 s	Small nanoparticle
10^{-15} kg	1 μm	1.6 s	Nanosphere
10^{-14} kg	1 μm	16 ms	Large nanoparticle
10^{-13} kg	1 μm	160 μs	Electromechanical
10^{-13} kg	100 nm	16 μs	Phonon state
10^{-12} kg	10 μm	16 μs	Levitated sphere
10^{-12} kg	1 μm	1.6 μs	Trapped microsphere
10^{-9} kg	100 μm	0.16 ns	Milligram crystal
10^{-6} kg	1 mm	1.6 fs	Microgram mass

A.2 Crossover masses

The crossover mass $M_c = \sqrt{\hbar d/(G\tau_{\text{env}})}$ at which gravitational and environmental decoherence rates are equal:

In all cases, the crossover mass lies in the femtogram-to-nanogram range (10^{-17} to 10^{-12} kg), squarely within the operating regime of optomechanical experiments.

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Table 4. *Crossover masses for various environmental coherence times and superposition separations.*

τ_{env}	$d = 100$ nm	$d = 1$ μm	$d = 10$ μm
10 μs	1.3×10^{-13} kg	4.0×10^{-13} kg	1.3×10^{-12} kg
1 ms	1.3×10^{-14} kg	4.0×10^{-14} kg	1.3×10^{-13} kg
1 s	4.0×10^{-16} kg	1.3×10^{-15} kg	4.0×10^{-15} kg
100 s	4.0×10^{-17} kg	1.3×10^{-16} kg	4.0×10^{-16} kg

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] C. Anastopoulos and B. L. Hu, "A master equation for gravitational decoherence: probing the textures of spacetime," Class. Quant. Grav. **30**, 165007 (2013).

[4] M. P. Blencowe, "Effective field theory approach to gravitationally induced decoherence," Phys. Rev. Lett. **111**, 021302 (2013).

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

[6] O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, "Large quantum superpositions and interference of massive nanometer-sized objects," Phys. Rev. Lett. **107**, 020405 (2011).

[7] A. D. O'Connell *et al.*, "Quantum ground state and single-phonon control of a mechanical resonator," Nature **464**, 697 (2010).

[8] Y. Chu, P. Kharel, W. H. Renninger, L. D. Burkhart, L. Frunzio, P. T. Rakich, and R. J. Schoelkopf, "Quantum acoustics with superconducting qubits," Science **358**, 199 (2017).

[9] M. H. Devoret and R. J. Schoelkopf, "Superconducting circuits for quantum information: an outlook," Science **339**, 1169 (2013).

[10] C. D. Bruzewicz, J. Chiaverini, R. McConnell, and J. M. Sage, "Trapped-ion quantum computing: progress and challenges," Appl. Phys. Rev. **6**, 021314 (2019).

[11] M. Kjaergaard *et al.*, "Superconducting qubits: current state of play," Annu. Rev. Cond. Matt. Phys. **11**, 369 (2020).

[12] A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, "Surface codes: towards practical large-scale quantum computation," Phys. Rev. A **86**, 032324 (2012).

[13] D. Bouwmeester, "A proposal to test quantum gravity using a particle in a superposition of locations," Phys. Rev. A **68**, 012301 (2003).

[14] W. Marshall, C. Simon, R. Penrose, and D. Bouwmeester, "Towards quantum superpositions of a mirror," Phys. Rev. Lett. **91**, 130401 (2003).

[15] I. Pikovski, M. R. Vanner, M. Aspelmeyer, M. S. Kim, and Č. Brukner, "Probing Planck-scale physics with quantum optics," Nature Phys. **8**, 393 (2012).

[16] R. Kaltenbaek *et al.*, "Macroscopic quantum resonators (MAQRO)," Exp. Astron. **34**, 123 (2012).

[17] A. Vinante *et al.*, "Improved noninterferometric test of collapse models using ultracold cantilevers," Phys. Rev. Lett. **119**, 110401 (2017).

[18] S. Donadi *et al.*, "Underground test of gravity-related wave function collapse," Nature Phys. **17**, 74 (2021).

[19] M. Sperzel, "Gravitational decoherence via entanglement-geometry: testing the Diósi-Penrose hypothesis," (2026), to appear on arXiv.

[20] M. Sperzel, "Gravitational decoherence at $O(G)$: the Wheeler-DeWitt constraint on the Feynman-Vernon influence functional," (2026), Paper K of the Quantum-Geometric Duality Series.