Information-Theoretic Bounds on Gravitational Decoherence Rates

Marc Sperzel*

Independent Researcher

MSci Physics, King's College London

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Abstract

Gravitational decoherence—the loss of quantum coherence due to gravitational effects—presents a sharp theoretical puzzle: the Diósi-Penrose mechanism predicts decoherence rates scaling as G^1, while perturbative quantum field theory predicts G^2, a difference of $\sim 10^{35}$ in predicted rates for laboratory-scale masses. We apply the Margolus-Levitin quantum speed limit to establish a fundamental rate scale for gravitational decoherence. For a mass M in spatial superposition of separation d, we show that the Margolus-Levitin theorem establishes a characteristic rate $\Gamma_{\mathrm{ML}} = 2GM^2/(\pi\hbar d)$, where the gravitational self-energy $E_G = GM^2/d$ sets the fundamental energy scale. The Diósi-Penrose rate $\Gamma_{\mathrm{DP}} = GM^2/(\hbar d)$ is of the same order as this scale, with $\Gamma_{\mathrm{DP}}/\Gamma_{\mathrm{ML}} = \pi/2 \approx 1.57$, while the perturbative QFT rate lies a factor of $(M/M_P)^2(\ell_P/d) \sim 10^{-35}$ below it for typical laboratory masses. This implies that if gravitational decoherence occurs at the Diósi-Penrose rate, gravity extracts information from quantum superpositions at rates characteristic of the fundamental quantum limit. Our results provide a new perspective on the G^1 versus G^2 debate: G^1 scaling represents operation at the fundamental information-theoretic scale, while G^2 represents perturbative physics far below this scale. Experimental discrimination between these scalings would reveal whether gravity operates at its fundamental information-theoretic limit.

Keywords: gravitational decoherence, quantum speed limits, Margolus-Levitin theorem, Diósi-Penrose mechanism, information theory

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*ORCID: 0009-0000-6252-3155. Email: `me@marcsperzel.com`

1 Introduction

Gravitational decoherence—the loss of quantum coherence due to gravitational effects on spatial superpositions of massive objects—presents a sharp theoretical puzzle.

1.1 The G^1 versus G^2 Puzzle

Two fundamentally different predictions exist for the rate of gravitational decoherence:

The Diósi-Penrose mechanism [1, 2] proposes that a mass M in spatial superposition of separation d decoheres at a rate

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

where G is Newton's constant. This scales as G^1.

Perturbative quantum field theory [3, 4], treating gravitational interactions via graviton exchange, predicts rates that scale as

$$\Gamma_{\mathrm{QFT}} \propto G^2 \tag{2}$$

one power of G smaller than the Diósi-Penrose rate.

For a laboratory-scale mass of $M \sim 10^{-9}$ kg (1 μg) and separation $d \sim 10^{-3}$ m (1 mm), these predictions differ by a factor of approximately 10^{35}—perhaps the largest discrepancy between competing theoretical predictions in physics.

1.2 The Theoretical Gap

Despite decades of work, neither prediction has been rigorously derived from first principles. The Diósi-Penrose rate emerges from dimensional analysis combined with the gravitational self-energy $E_{\mathrm{G}} = GM^2/d$, but the step from energy scale to decoherence rate remains unproven. Perturbative QFT calculations are rigorous within their domain but may miss non-perturbative effects.

This paper takes a different approach: rather than attempting to derive either rate, we ask what *fundamental limits* quantum mechanics places on gravitational decoherence rates.

1.3 Information-Theoretic Approach

Quantum mechanics imposes universal speed limits on dynamical evolution. The Margolus-Levitin theorem [5] states that a quantum system with energy E above its ground state requires time at least

$$\tau \geq \frac{\pi\hbar}{2E} \tag{3}$$

to evolve to an orthogonal state.

We apply this bound to gravitational decoherence by modeling decoherence as information transfer from the quantum system to the gravitational environment. Our key assumption is that the gravitational self-energy $E_{\mathrm{G}} = GM^2/d$ provides the energy scale driving this information transfer. This assumption is physically motivated but not rigorously derived; our results are conditional on its validity.

1.4 Summary of Results

We establish three main results:

Theorem 1.1 (Margolus-Levitin Rate Scale)**.** *For a mass M in spatial superposition of separation d, the Margolus-Levitin theorem establishes a characteristic rate scale:*

$$\Gamma_{\text{ML}} = \frac{2E_{\text{G}}}{\pi\hbar} = \frac{2GM^2}{\pi\hbar d} \tag{4}$$

This is the maximum rate at which the gravitational environment can evolve to completely distinguish the two branches.

Theorem 1.2 (Diósi-Penrose at the Fundamental Scale)**.** *The Diósi-Penrose rate is of the same order as the Margolus-Levitin scale:*

$$\Gamma_{\text{DP}} = \frac{\pi}{2} \times \Gamma_{\text{ML}} \approx 1.57 \times \Gamma_{\text{ML}} \tag{5}$$

where $\Gamma_{\text{ML}} = 2GM^2/(\pi\hbar d)$. The factor $\pi/2$ reflects the distinction between complete orthogonalization (ML timescale) and $1/e$ coherence decay (decoherence rate).

Theorem 1.3 (QFT Far Below the Scale)**.** *The perturbative QFT rate lies far below the Margolus-Levitin scale:*

$$\frac{\Gamma_{\text{QFT}}}{\Gamma_{\text{ML}}} \sim \left(\frac{M}{M_{\text{P}}}\right)^2 \frac{\ell_{\text{P}}}{d} \sim 10^{-35} \tag{6}$$

for laboratory masses ($M \sim 1$ μg, $d \sim 1$ mm).

These results provide a new perspective on the G^1 versus G^2 debate: G^1 scaling represents operation at the fundamental information-theoretic scale set by quantum mechanics, while G^2 represents perturbative physics far below this scale.

1.5 Outline

Section 2 reviews quantum speed limits, focusing on the Margolus-Levitin bound and its extensions to open systems. Section 3 defines the gravitational self-energy for spatial superpositions. Section 4 presents the main theorems and proofs. Section 5 discusses the physical interpretation, including the significance of operating at the fundamental information-theoretic scale. Section 6 addresses implications and limitations. Section 7 concludes.

Series context. This paper provides information-theoretic foundations for gravitational decoherence, complementing Paper A (mechanism and predictions), Paper B (holographic dark energy), and Paper C (axiomatic framework). Each paper is self-contained.

2 Quantum Speed Limits

Quantum mechanics imposes fundamental limits on how fast physical processes can occur. These quantum speed limits (QSLs) have deep connections to the energy-time uncertainty relation and place universal constraints on dynamical evolution.

2.1 The Mandelstam-Tamm Bound

The first rigorous quantum speed limit was derived by Mandelstam and Tamm [6]. For a quantum system evolving under Hamiltonian H, the time required to evolve from an initial state $|\psi_0\rangle$ to a state with fidelity $F = |\langle\psi_0\rangle\, \psi_\tau|^2$ satisfies

$$\tau \geq \frac{\hbar \arccos \sqrt{F}}{\Delta E} \tag{7}$$

where $\Delta E = \sqrt{\langle H^2\rangle - \langle H\rangle^2}$ is the energy uncertainty (standard deviation) in the initial state.

For evolution to an orthogonal state ($F = 0$), this becomes

$$\tau_{\mathrm{MT}} = \frac{\pi\hbar}{2\Delta E} \tag{8}$$

The Mandelstam-Tamm bound is tight: there exist systems that saturate it.

2.2 The Margolus-Levitin Bound

A complementary bound was derived by Margolus and Levitin [5]. For evolution to an orthogonal state, the minimum time is

$$\tau_{\mathrm{ML}} = \frac{\pi\hbar}{2E} \tag{9}$$

where $E = \langle H\rangle - E_0$ is the mean energy above the ground state energy E_0.

Unlike the Mandelstam-Tamm bound, which depends on energy *fluctuations*, the Margolus-Levitin bound depends on the *total* available energy.

Remark 2.1. The Margolus-Levitin bound implies a fundamental limit on computation: no physical system can perform more than $2E/(\pi\hbar) \approx 6 \times 10^{33}$ operations per second per joule of energy [7].

2.3 Unified Quantum Speed Limit

The two bounds are independent and complementary. The tightest constraint comes from taking the maximum:

$$\tau \geq \max\left(\frac{\pi\hbar}{2\Delta E}, \frac{\pi\hbar}{2E}\right) \tag{10}$$

For systems where $E \gg \Delta E$ (highly excited states with small relative fluctuations), the Margolus-Levitin bound dominates. For systems where $\Delta E \gg E$ (which requires negative energy contributions), the Mandelstam-Tamm bound dominates.

2.4 Extension to Open Systems

The original quantum speed limits were derived for isolated systems undergoing unitary evolution. Several authors have extended these limits to open systems, which undergo decoherence and dissipation.

Del Campo, Egusquiza, Plenio, and Huelga [8] derived a quantum speed limit for open systems:

$$\tau \geq \frac{\sin^2[\mathcal{L}(\rho_0, \rho_\tau)]}{\langle \dot{\mathcal{L}}^2\rangle} \tag{11}$$

where $\mathcal{L}(\rho_0, \rho_\tau) = \arccos \sqrt{F(\rho_0, \rho_\tau)}$ is the Bures angle between initial and final density matrices, and F is the quantum fidelity.

Deffner and Lutz [9] showed that for Markovian dynamics described by a Lindblad master equation, the speed limit can be expressed in terms of the generator of the non-unitary dynamics.

2.5 Application to Decoherence

We can view decoherence as the environment acquiring information about the system. Initially, the system state is unknown to the environment; after decoherence, the environment has measured the system.

For a system in superposition $|\psi\rangle = (|L\rangle + |R\rangle)/\sqrt{2}$ (e.g., a mass localized left or right), decoherence corresponds to the environment states $|E_L\rangle$ and $|E_R\rangle$ becoming distinguishable:

$$|\langle E_L\rangle\, E_R|^2 \to 0 \tag{12}$$

The time for the environment states to become orthogonal is bounded by quantum speed limits applied to the *environment* evolution. The relevant energy is the energy available to drive this distinguishing process.

2.6 Application to Gravitational Decoherence

For a spatial superposition, the energy driving environment evolution is the gravitational self-energy difference between the two branches:

$$E_{\mathrm{G}} = \frac{GM^2}{d} \tag{13}$$

Applying the Margolus-Levitin bound with this energy yields the central result of this paper.

3 Gravitational Self-Energy for Spatial Superpositions

The application of quantum speed limits to gravitational decoherence requires identifying the relevant energy scale. In this section, we define the gravitational self-energy for spatial superpositions and justify its role in the Margolus-Levitin bound.

3.1 Penrose's Gravitational Self-Energy

Consider a mass M in a spatial superposition

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \tag{14}$$

where $|L\rangle$ and $|R\rangle$ represent the mass localized at positions separated by distance d.

Penrose [2] argued that each branch of the superposition is associated with a distinct spacetime geometry. The "difference" between these geometries can be quantified by the gravitational self-energy

$$E_{\mathrm{G}} = \int d^3x \int d^3x' \frac{G[\rho_L(\mathbf{x}) - \rho_R(\mathbf{x})][\rho_L(\mathbf{x}') - \rho_R(\mathbf{x}')]}{|\mathbf{x} - \mathbf{x}'|} \tag{15}$$

where ρ_L and ρ_R are the mass density distributions in the two branches.

3.2 Point Mass Approximation

For a compact mass M with size $r_0 \ll d$, the self-energy simplifies to

$$E_{\mathrm{G}} = \frac{GM^2}{d} \tag{16}$$

This expression represents the gravitational interaction energy between two copies of the mass separated by distance d. The quantity E_{G} has dimensions of energy and is purely classical in origin, being independent of both $\hbar$ and c.

3.3 Physical Interpretation

From the Newtonian viewpoint, E_{G} represents the work required to separate two masses M from distance d to infinity:

$$E_{\mathrm{G}} = \int_d^\infty \frac{GM^2}{r^2}\, dr = \frac{GM^2}{d} \tag{17}$$

In the general relativistic picture, each branch creates a metric perturbation $h_{\mu\nu}^{(L,R)}$ in linearized gravity. The difference $\delta h_{\mu\nu} = h_{\mu\nu}^{(L)} - h_{\mu\nu}^{(R)}$ carries energy proportional to E_{G}.

From an information-theoretic perspective, the two branches carry different gravitational information. The energy required to "read" this information—to distinguish the branches gravitationally—is at least E_{G}.

3.4 Role in the Margolus-Levitin Bound

For the Margolus-Levitin bound $\tau \geq \pi\hbar/(2E)$, we must identify the energy E available to drive the relevant evolution.

In gravitational decoherence, the "relevant evolution" is the environment—comprising gravitational field modes, distant masses, or cosmological degrees of freedom—acquiring information about which branch the system occupies. This process is equivalent to the environment states $|E_L\rangle$ and $|E_R\rangle$ becoming orthogonal.

We *hypothesize* that the energy available to drive this orthogonalization is the gravitational self-energy E_{G}. This identification is the central assumption of our analysis; the main results follow if it is correct. Three considerations support this hypothesis. First, E_{G} is the only energy scale in the problem that depends on both M and d, the two parameters characterizing the superposition. Second, E_{G} characterizes the gravitational "signal" that distinguishes the branches—it quantifies how different the two gravitational field configurations are. Third, E_{G} represents the maximum energy extractable from the superposition by gravitational measurements.

A rigorous derivation would require specifying the gravitational environment's Hilbert space and Hamiltonian, then computing the energy above the ground state that drives distinguishability. In the absence of a complete theory of quantum gravity, such a derivation is not available. Our hypothesis is that E_{G} plays this role.

3.5 Comparison with Other Energy Scales

Several other energy scales appear in the problem, but none is appropriate for the Margolus-Levitin bound in this context.

The rest mass energy $E_{\text{rest}} = Mc^2$ is enormous but independent of the superposition—both branches have identical rest mass. The kinetic energy depends on the preparation but is typically much smaller than E_G for mesoscopic masses at rest. The Planck energy $E_P = \sqrt{\hbar c^5/G} \approx 10^9$ J is many orders of magnitude larger than E_G for all laboratory masses.

The gravitational self-energy E_G is the unique energy scale that depends on the superposition parameters (M and d), is gravitational in origin (proportional to G), and characterizes the distinguishability of the branches. This uniqueness motivates—though does not rigorously derive—its use in the Margolus-Levitin bound for gravitational decoherence.

4 Main Results

We now present and prove the main theorems establishing information-theoretic bounds on gravitational decoherence rates.

Notation: We use Γ for rates (dimension T^{-1}) throughout. The corresponding timescales are $\tau = 1/\Gamma$.

4.1 Setup and Definitions

Consider a mass M prepared in a spatial superposition:

$$|\Psi_0\rangle = \frac{1}{\sqrt{2}} (|L\rangle + |R\rangle) \otimes |E_0\rangle \tag{18}$$

where $|L\rangle$ and $|R\rangle$ are spatially localized states separated by distance d, and $|E_0\rangle$ is the initial state of the gravitational environment.

Definition 4.1 (Decoherence)**.** The system undergoes decoherence when the reduced density matrix evolves from pure to mixed:

$$\rho_S(0) = |\Psi_0\rangle \langle\Psi_0| \quad \rightarrow \quad \rho_S(\tau) = \frac{1}{2} (|L\rangle \langle L| + |R\rangle \langle R|) \tag{19}$$

The *decoherence time* τ_{dec} is the timescale for the off-diagonal elements to decay: $|\rho_{LR}(\tau_{\text{dec}})| \approx e^{-1}|\rho_{LR}(0)|$.

Definition 4.2 (Decoherence Rate)**.** The decoherence rate is $\Gamma_{\text{dec}} = 1/\tau_{\text{dec}}$.

Decoherence occurs because the environment states correlated with $|L\rangle$ and $|R\rangle$ become distinguishable:

$$|\Psi(\tau)\rangle = \frac{1}{\sqrt{2}} (|L\rangle \otimes |E_L(\tau)\rangle + |R\rangle \otimes |E_R(\tau)\rangle) \tag{20}$$

with $| \langle E_L(\tau)\rangle\, E_R(\tau)|^2 \to 0$ as $\tau \to \tau_{\text{dec}}$.

4.2 Central Assumption

The application of quantum speed limits to gravitational decoherence requires identifying the relevant energy scale. We make this explicit:

Assumption 4.3 (Gravitational Energy as Environment Driver)**.** The energy available to drive the gravitational environment toward distinguishing the two branches of a spatial superposition is the gravitational self-energy:

$$E_{\text{env}} = E_G = \frac{GM^2}{d} \tag{21}$$

where M is the mass and d is the superposition separation.

This assumption is physically motivated but not derived from first principles. The theorems that follow are conditional on its validity.

4.3 Physical Motivation for Assumption 4.3

Three arguments support identifying E_G as the relevant energy:

Energy difference: The gravitational field configurations in the two branches differ by energy $\sim E_G$. This energy is available to drive environmental degrees of freedom into distinguishable states.

Holographic considerations: In AdS/CFT, the energy cost of distinguishing geometric configurations is set by gravitational scales, not perturbative amplitudes.

Classical correspondence: Classically, the gravitational self-energy determines field dynamics. The assumption extends this to the quantum-classical interface.

These arguments are suggestive, not conclusive. Assumption 4.3 is a hypothesis whose consequences we explore. Experiment will determine its validity.

4.4 Theorem 1: Margolus-Levitin Rate Scale

Theorem 4.4 (Information-Theoretic Rate Scale)**.** ***Given*** *Assumption 4.3, the Margolus-Levitin theorem establishes a characteristic rate scale for gravitational decoherence:*

$$\boxed{\Gamma_{\text{ML}} = \frac{2E_{\text{G}}}{\pi\hbar} = \frac{2GM^2}{\pi\hbar d}} \tag{22}$$

This is the maximum rate at which the gravitational environment can evolve to completely distinguish the two branches.

Proof. Decoherence requires the environment states $|E_L\rangle$ and $|E_R\rangle$ to become distinguishable. Complete distinguishability corresponds to orthogonality: $\langle E_L\rangle\, E_R = 0$.

The Margolus-Levitin bound states that a quantum system with energy E above its ground state requires time at least $\tau \geq \pi\hbar/(2E)$ to evolve to an orthogonal state.

By Assumption 4.3, the energy driving this evolution is $E_{\text{G}} = GM^2/d$. Applying the Margolus-Levitin bound:

$$\tau_\perp \geq \frac{\pi\hbar}{2E_{\text{G}}} = \frac{\pi\hbar d}{2GM^2} \tag{23}$$

The corresponding maximum orthogonalization rate is:

$$\Gamma_{\text{ML}} = \frac{1}{\tau_\perp} = \frac{2E_{\text{G}}}{\pi\hbar} = \frac{2GM^2}{\pi\hbar d} \tag{24}$$

□

Remark 4.1 (Ground State Definition). The Margolus-Levitin bound uses energy above the ground state. We define the ground state of the gravitational environment as the vacuum configuration with no mass present. The energy E_G represents the energy added by the superposed mass. Vacuum fluctuation corrections are suppressed by $(\ell_P/d)^2 \sim 10^{-64}$ for laboratory scales and are neglected.

Remark 4.2. The rate $\Gamma_{\rm ML}$ depends only on the gravitational self-energy and fundamental constants. It represents the fastest rate at which the gravitational environment can acquire complete "which-path" information about the superposition. Actual decoherence rates (typically defined by $1/e$ decay of coherence) may differ from $\Gamma_{\rm ML}$ by order-unity factors depending on the specific dynamics, but $\Gamma_{\rm ML}$ sets the fundamental scale.

4.5 Theorem 2: Diósi-Penrose at the Fundamental Scale

Theorem 4.5 (Diósi-Penrose Rate at Order $\Gamma_{\rm ML}$)**.** *The Diósi-Penrose decoherence rate*

$$\Gamma_{\rm DP} = \frac{GM^2}{\hbar d} = \frac{E_{\rm G}}{\hbar} \tag{25}$$

is of the same order as the Margolus-Levitin rate scale:

$$\boxed{\Gamma_{\rm DP} = \frac{\pi}{2} \times \Gamma_{\rm ML} \approx 1.57 \times \Gamma_{\rm ML}} \tag{26}$$

Proof. Direct calculation:

$$\frac{\Gamma_{\rm DP}}{\Gamma_{\rm ML}} = \frac{GM^2/(\hbar d)}{2GM^2/(\pi \hbar d)} \tag{27}$$

$$= \frac{\pi}{2} \tag{28}$$

$$\approx 1.57 \tag{29}$$

□

Remark 4.3. The ratio $\pi/2 \approx 1.57$ reflects the distinction between two related but different timescales. The Margolus-Levitin bound gives the minimum time $\tau_\perp = \pi\hbar/(2E)$ for evolution to complete orthogonality. Decoherence rates are conventionally defined by $1/e$ decay of coherence, which occurs at a different time. For two-level dynamics with overlap $|\langle\psi(t)\rangle\,\psi(0)| = |\cos(Et/\hbar)|$, the orthogonality time is $t_\perp = \pi\hbar/(2E)$, while the $1/e$ decay time is $t_{1/e} = \hbar\,\mathrm{arccos}(1/e)/E \approx 1.19\hbar/E$. The Diósi-Penrose timescale $\tau_{\rm DP} = \hbar/E_{\rm G}$ lies between these values. The key physical content is that $\Gamma_{\rm DP}$ and $\Gamma_{\rm ML}$ differ by only a factor of order unity, not by orders of magnitude as with perturbative QFT.

4.6 Theorem 3: Perturbative QFT Far Below the Fundamental Scale

Theorem 4.6 (QFT Rate Far Below $\Gamma_{\rm ML}$)**.** *Perturbative QFT calculations give decoherence rates scaling as G^2. The ratio to the Margolus-Levitin scale is:*

$$\boxed{\frac{\Gamma_{\rm QFT}}{\Gamma_{\rm ML}} \sim \left(\frac{M}{M_{\rm P}}\right)^2 \frac{\ell_{\rm P}}{d} \sim 10^{-35} \quad \textit{for } M \sim 1\ \mu g, d \sim 1\ mm} \tag{30}$$

Prediction	**Scaling**	**Ratio to Γ_{ML}**
Margolus-Levitin scale	G^1	1 (by definition)
Diósi-Penrose	G^1	$\frac{\pi}{2} \approx 1.57$
Perturbative QFT	G^2	$\sim \left(\frac{M}{M_{\text{P}}}\right)^2 \frac{\ell_{\text{P}}}{d} \sim 10^{-35}$

Table 1. *Gravitational decoherence rate scalings compared to the Margolus-Levitin scale $\Gamma_{\text{ML}} = 2E_{\text{G}}/(\pi\hbar)$. Both Γ_{ML} and the Diósi-Penrose rate scale as G^1, differing by only an order-unity factor ($\pi/2$). Perturbative QFT scales as G^2, lying thirty-five orders of magnitude below for laboratory masses.*

Proof. Perturbative QFT calculations [3, 4] give rates $\Gamma_{\text{QFT}} \propto G^2$, one power of G below $\Gamma_{\text{ML}} \propto G^1$.

To form the dimensionless ratio $\Gamma_{\text{QFT}}/\Gamma_{\text{ML}}$ from the quantities G, M, d, $\hbar$, c, we need one power of G (since $\Gamma_{\text{QFT}}/\Gamma_{\text{ML}} \propto G^1$). The unique dimensionless combination linear in G is:

$$\frac{GM}{c^2 d} = \frac{M^2}{M_P^2} \cdot \frac{\ell_P}{d} = \left(\frac{M}{M_P}\right)^2 \frac{\ell_P}{d} \tag{31}$$

where we used $G = \ell_P^2 c^3/\hbar = c^2 \ell_P/M_P$.

For $M = 10^{-9}$ kg and $d = 10^{-3}$ m:

$$\left(\frac{10^{-9}}{2 \times 10^{-8}}\right)^2 \times \frac{1.6 \times 10^{-35}}{10^{-3}} \approx 2.5 \times 10^{-3} \times 1.6 \times 10^{-32} \approx 4 \times 10^{-35} \tag{32}$$

□

Remark 4.4. The perturbative QFT rate lies a factor of $\sim 10^{35}$ below the Margolus-Levitin scale. Perturbative physics operates far from the fundamental information-theoretic limit—achieving G^1 scaling requires non-perturbative effects.

4.7 Summary of Results

Table 1 summarizes the three rate scales and their relationships. The hierarchy

$$\Gamma_{\text{QFT}} \ll \Gamma_{\text{ML}} \sim \Gamma_{\text{DP}} \tag{33}$$

reveals a stark separation: the Diósi-Penrose rate is of the same order as the Margolus-Levitin scale (differing by a factor of $\pi/2$), while perturbative QFT lies approximately 10^{35} times below. This enormous gap provides a clear experimental discriminant between the two scenarios.

Remark 4.5. Once E_{G} is identified as the relevant energy in the Margolus-Levitin bound, the relation $\Gamma_{\text{DP}} \sim \Gamma_{\text{ML}}$ follows immediately from dimensional analysis since both are proportional to $E_{\text{G}}/\hbar$. The non-trivial content of our analysis is twofold: (i) arguing that E_{G} is the appropriate energy, and (ii) showing that perturbative QFT lies approximately 10^{35} times below this scale. The G^1 versus G^2 dichotomy, not the $\pi/2$ coefficient, is the physically significant result.

5 Physical Interpretation

This section explores the physical meaning of the mathematical results in Section 4: what it means for a physical process to operate at the fundamental information-theoretic scale.

5.1 The Significance of the Margolus-Levitin Scale

Quantum speed limits establish fundamental scales that characterize the maximum rate of dynamical evolution. When a physical process operates at or near this scale, it indicates that the system is extracting information or performing work at rates approaching the fundamental limit quantum mechanics allows.

Two notable examples illustrate this phenomenon. Black holes scramble quantum information at the maximum rate allowed by the chaos bound $\lambda_L \leq 2\pi k_B T/\hbar$, as shown by Maldacena, Shenker, and Stanford [10]. This saturation is intimately connected to the holographic nature of black hole physics. Similarly, optimal quantum algorithms approach the Margolus-Levitin limit of approximately 6×10^{33} operations per second per joule [7].

The Diósi-Penrose rate being of order the Margolus-Levitin scale, with $\Gamma_{\mathrm{DP}}/\Gamma_{\mathrm{ML}} = \pi/2 \approx 1.57$, suggests that gravitational decoherence—if it occurs at this rate—operates at the fundamental information-theoretic scale of quantum dynamics.

5.2 Why Might Gravity Operate at the Fundamental Scale?

Several distinctive features of gravity may explain why gravitational decoherence could operate at the information-theoretic scale.

Universal coupling. Gravity couples to all forms of energy-momentum through the stress-energy tensor. Unlike electromagnetic or nuclear forces, there is no gravitational "charge"—every quantum system gravitates. This universality means gravitational information about a superposition is maximally available to the environment.

No shielding. Gravitational fields cannot be screened or shielded. While electric fields can be blocked by conductors and nuclear forces are short-ranged, gravitational effects extend to infinity without attenuation. The gravitational "signal" of a spatial superposition reaches all environmental degrees of freedom simultaneously.

Holographic properties. In theories with holographic duality, gravitational dynamics at the boundary encodes bulk physics in a maximally efficient way. If some version of holography applies to flat spacetime, gravitational information transfer may be inherently optimal.

Non-perturbative nature. The G^1 scaling of Diósi-Penrose cannot arise from perturbative graviton exchange, which gives G^2. We use "non-perturbative" here as a descriptive label—meaning "not arising from perturbation theory"—rather than as an explanation.

A candidate mechanism: flat spectral density. A potential explanation for saturation emerges from Fourier analysis of the gravitational constraint. The Poisson equation $\nabla^2\Phi = 4\pi G\rho$ gives, in Fourier space, $\tilde{\Phi}_k = -4\pi G\tilde{\rho}_k/k^2$. For a spatial superposition of point masses at positions

$\pm d/2$, the source difference transforms as $\Delta\tilde{\rho}_k = 2iM\sin(kd/2) \approx iMkd$ for long wavelengths ($k \ll 1/d$). The gravitational field energy per unit k then scales as

$$\mathcal{E}(k) \propto k^2|\Delta\tilde{\Phi}_k|^2 \propto k^2 \times \frac{|Mkd|^2}{k^4} = (Md)^2 = \text{constant}. \tag{34}$$

This *flat spectral density* for $k < 1/d$ is unique to the $1/r$ potential. The $1/k^2$ of the gravitational Green's function exactly compensates the k^2 growth of the source transform, yielding scale-independent energy distribution. Other potentials—Yukawa ($1/k^2+\mu^2$), contact (constant)—lack this cancellation.

The flat spectrum implies that all long-wavelength gravitational modes carry equal energy from the superposition. When these modes serve as an environment, information about the superposition flows to all of them simultaneously with no single mode limiting the rate. This is precisely the condition for approaching quantum speed limits: no information bottleneck. A complete derivation of saturation would require specifying the quantum dynamics of these modes, but the flat spectrum provides a concrete physical reason why gravity might achieve maximum information transfer efficiency.

5.3 The G^1 versus G^2 Dichotomy

Our results cast the long-standing debate between G^1 and G^2 scaling in a new light. The G^1 scaling of Diósi-Penrose represents operation at the fundamental information-theoretic scale, extracting position information from superpositions at rates of order the Margolus-Levitin limit. The G^2 scaling of perturbative QFT represents physics operating far below this scale, suppressed by factors of $(M/M_{\mathrm{P}})^2 \sim 10^{-35}$ for laboratory masses.

This distinction is not merely quantitative but qualitative. The central question becomes: does gravitational decoherence involve physics that operates at the fundamental information-theoretic scale, or is it simply another perturbative interaction far from any fundamental limit?

5.4 Comparison with Other Systems at Fundamental Limits

Table 2 compares the relationship to fundamental bounds across different physical systems. A consistent pattern emerges: systems involving gravity and holography tend to operate at their fundamental limits, while perturbative processes do not. Black hole scrambling saturates the chaos bound through holographic dynamics. The Bekenstein entropy bound is saturated by black holes, again through holographic physics. Diósi-Penrose decoherence operates at order the Margolus-Levitin scale, with the flat spectral density providing a candidate mechanism. Perturbative graviton exchange lies far below this scale.

A crucial difference should be noted: black hole scrambling and Bekenstein entropy saturation have *rigorous theoretical explanations* rooted in holographic duality. For gravitational decoherence, the flat spectral density argument provides a *candidate mechanism* but not a complete derivation—we have identified a plausible physical reason for saturation, pending a full quantum treatment of the gravitational environment. The analogy to black holes is suggestive and may reflect deep connections through holography.

System	Bound/Scale	At limit?	Mechanism
Black hole scrambling	Chaos bound	Yes	Holography
Bekenstein entropy	Area bound	Yes	Holography
Diósi-Penrose	Margolus-Levitin	$O(1)$ $(\pi/2)$	Flat spectrum (candidate)
QFT graviton exchange	Margolus-Levitin	No (10^{-35})	Perturbative

Table 2. *Comparison across physical systems. Systems involving gravity and holography consistently operate at their fundamental limits, while perturbative processes do not.*

5.5 What Our Analysis Does Not Establish

We emphasize three limitations of our results. First, we do not prove that the Diósi-Penrose rate is correct—only that it is of the same order as the fundamental information-theoretic scale. Second, we do not derive the specific coefficient in the decoherence rate. The relationship between the orthogonalization timescale ($\tau_\perp = \pi\hbar/2E_\mathrm{G}$) and the decoherence timescale ($\tau_\mathrm{DP} = \hbar/E_\mathrm{G}$) involves dynamics-dependent factors. Third, while the flat spectral density provides a candidate mechanism for G^1 scaling, a complete derivation requires specifying the quantum Hilbert space of gravitational modes—which lies beyond current theory.

These questions require either a complete theory of quantum gravity or experimental resolution.

5.6 Experimental Implications

The Margolus-Levitin scale provides a clear experimental target. If experiments measure decoherence rates of order Γ_ML, this would support non-perturbative gravitational decoherence mechanisms such as Diósi-Penrose. Rates measured far below Γ_ML would support perturbative QFT predictions.

Current experiments have not yet reached the sensitivity required to discriminate between these scenarios. However, progress in optomechanics and matter-wave interferometry continues rapidly, with microgram-scale masses in superposition states becoming increasingly accessible. The coming decade may bring definitive experimental tests.

6 Discussion

6.1 Assumptions and Limitations

Our derivation rests on several assumptions.

Applicability of Margolus-Levitin to open systems. The original Margolus-Levitin bound was derived for isolated systems undergoing unitary evolution. We apply it to the environment's evolution, treating the system-environment composite as isolated. This approach is justified when the total system (mass plus gravitational environment) is closed, but may require modification if additional external influences are present. Del Campo et al. [8] and Deffner and Lutz [9] have extended quantum speed limits to open systems, providing a rigorous foundation for our application.

Identification of the relevant energy. We identify the gravitational self-energy $E_\mathrm{G} = GM^2/d$ as the energy driving decoherence. This identification is physically motivated but not derived from first principles. Alternative energy scales—involving the cosmological horizon, vacuum energy, or other gravitational degrees of freedom—might be relevant in a complete theory.

Nature of the gravitational environment. Our analysis treats the "gravitational environment" as a quantum system that becomes entangled with the mass in superposition. However, we do not specify what this environment consists of—gravitational field modes, distant masses, cosmological degrees of freedom, or something else entirely. In the absence of quantum gravity, the Hilbert space structure of such an environment is not well-defined. Our results should be understood as conditional: *if* gravity can be modeled as an environment acquiring information about the superposition, *then* the Margolus-Levitin scale applies.

Point mass approximation. We treat the mass as point-like with $E_\mathrm{G} = GM^2/d$. For extended objects, the self-energy involves an integral over the mass distribution as shown in equation (15). Our results remain valid with E_G interpreted as this integral.

Non-relativistic limit. We work in the non-relativistic limit where $v \ll c$ and $E_\mathrm{G} \ll Mc^2$. Relativistic corrections may modify both the bound and the Diósi-Penrose rate when the superposition separation approaches the Compton wavelength or when gravitational fields become strong.

6.2 Relation to Prior Work

Diósi [1] and Penrose [2] proposed the rate $\Gamma = E_\mathrm{G}/\hbar$ based on different physical arguments. Diósi derived a master equation from stochastic modifications to the Schrödinger equation, while Penrose argued from the requirement of general covariance applied to superposed spacetime geometries. Our work reveals that this rate has deeper significance: it is of the same order as the fundamental Margolus-Levitin scale.

Anastopoulos and Hu [3] derived a master equation for gravitational decoherence from quantum field theory, finding rates scaling as G^2. Blencowe [4] obtained similar results using effective field theory methods. Our analysis is consistent with their findings: perturbative QFT lies far below the information-theoretic scale, exactly as expected for a process that does not operate at fundamental limits.

Deffner and Campbell [11] provided a comprehensive review of quantum speed limits, including extensions to open systems and various applications. Our application to gravitational decoherence appears to be novel, connecting two previously separate research areas.

6.3 The Order-Unity Coefficient

The Diósi-Penrose rate $\Gamma_\mathrm{DP} = E_\mathrm{G}/\hbar$ differs from the Margolus-Levitin scale $\Gamma_\mathrm{ML} = 2E_\mathrm{G}/(\pi\hbar)$ by a factor of $\pi/2 \approx 1.57$. This does *not* constitute a violation of the Margolus-Levitin bound, because the two quantities measure different things.

The Margolus-Levitin theorem gives the minimum time $\tau_\perp = \pi\hbar/(2E)$ for evolution to an *orthogonal* state—complete distinguishability. Decoherence rates, however, are conventionally defined by the $1/e$ decay time of coherence, following $|\rho_{LR}(t)| = e^{-\Gamma t}|\rho_{LR}(0)|$, which occurs before orthogonality. For two-level dynamics where the overlap evolves as $|\langle\psi(t)\rangle\,\psi(0)| = |\cos(Et/\hbar)|$, the orthogonality time is $\tau_\perp = \pi\hbar/(2E)$, while the $1/e$ decay time is $\tau_{1/e} = \hbar\arccos(1/e)/E \approx 1.19\hbar/E$. The Diósi-Penrose timescale $\tau_{\rm DP} = \hbar/E_{\rm G}$ lies between these values, consistent with $1/e$ decay occurring before full orthogonalization.

The key physical content is that all three timescales—orthogonalization, $1/e$ decay, and Diósi-Penrose—scale identically with G, M, and d, differing only by $\mathcal{O}(1)$ coefficients. This stands in stark contrast to perturbative QFT, which differs by thirty-five orders of magnitude.

6.4 Implications for Quantum Gravity

If gravitational decoherence operates at the Margolus-Levitin scale, several implications follow for quantum gravity.

First, non-perturbative physics is essential. Perturbative graviton exchange cannot achieve G^1 scaling; any mechanism operating at this scale must be non-perturbative. This suggests that gravitational decoherence, if it occurs at the Diósi-Penrose rate, probes aspects of gravity that lie beyond perturbation theory.

Second, gravity may function as a quantum channel operating at near-maximum capacity. Operating at the information-theoretic scale suggests viewing gravity not merely as a force but as an efficient channel for information transfer between quantum systems and their gravitational environment.

Third, the pattern of gravitational systems operating at fundamental limits—black hole scrambling, Bekenstein entropy, and potentially decoherence—suggests deep connections to holographic principles. Whether a version of holography underlies gravitational decoherence remains an open question.

6.5 Open Questions

Can the order-unity coefficient relating $\Gamma_{\rm DP}$ to $\Gamma_{\rm ML}$ be derived from first principles? What physical mechanism is responsible for G^1 scaling? How does the Margolus-Levitin scale modify in curved spacetime or in the presence of horizons? Is there a connection to the holographic principle? Can analogous information-theoretic analyses be applied to other decoherence mechanisms?

7 Conclusions

We establish information-theoretic rate scales for gravitational decoherence using the Margolus-Levitin quantum speed limit. Our main results are:

1. Margolus-Levitin scale. For a mass M in spatial superposition of separation d, the Margolus-Levitin theorem establishes a characteristic rate scale:

$$\Gamma_{\rm ML} = \frac{2GM^2}{\pi\hbar d} \tag{35}$$

This scale follows from fundamental quantum mechanics, conditional on the assumption that the gravitational self-energy $E_{\rm G} = GM^2/d$ is the energy available to drive the environment toward distinguishing the superposition branches. This assumption is physically motivated but not rigorously derived.

2. Diósi-Penrose at the fundamental scale. The Diósi-Penrose rate $\Gamma_{\mathrm{DP}} = GM^2/(\hbar d)$ is of the same order as the Margolus-Levitin scale, with $\Gamma_{\mathrm{DP}}/\Gamma_{\mathrm{ML}} = \pi/2 \approx 1.57$. This suggests that if gravitational decoherence occurs at the Diósi-Penrose rate, gravity extracts information from superpositions at rates characteristic of the fundamental quantum limit.

3. Perturbative QFT far below the scale. The perturbative QFT rate from graviton exchange lies a factor of $(M/M_{\mathrm{P}})^2(\ell_{\mathrm{P}}/d) \sim 10^{-35}$ below the Margolus-Levitin scale for laboratory masses. Perturbative physics operates far from fundamental information-theoretic limits.

These results provide a new perspective on the long-standing G^1 versus G^2 debate in gravitational decoherence. The G^1 scaling of Diósi-Penrose represents operation at the fundamental information-theoretic scale; the G^2 scaling of perturbative QFT represents physics far below this scale. Experimental discrimination between these scalings would reveal whether gravity operates at its fundamental information-theoretic limit.

Our analysis does not prove that the Diósi-Penrose rate is correct. It establishes that this rate is of the same order as a fundamental quantum scale, conditional on our central assumption. The ultimate arbiter is experiment. Experimental confirmation of G^1 scaling would validate both the Diósi-Penrose mechanism and our assumption that E_G is the relevant energy scale. Current technology has not yet reached the regime where G^1 and G^2 predictions can be distinguished, but continued progress in optomechanics and matter-wave interferometry may enable such tests within the coming decades.

If gravitational decoherence is experimentally confirmed to occur at rates of order Γ_{ML}, it would join black hole scrambling and the Bekenstein bound as cases where gravity operates at fundamental information-theoretic limits. This raises the question of whether such saturation is generic to gravitational physics.

Appendices

A Derivation of the Margolus-Levitin Bound

For completeness, we provide a derivation of the Margolus-Levitin bound following the original argument [5].

A.1 Setup

Consider a quantum system with Hamiltonian H having ground state energy E_0. Let $|\psi_0\rangle$ be the initial state and $|\psi_\tau\rangle = e^{-iH\tau/\hbar} |\psi_0\rangle$ the state at time τ.

We seek the minimum time for the system to evolve to an orthogonal state, $\langle\psi_0\rangle\, \psi_\tau = 0$.

A.2 Energy Representation

Expand the initial state in the energy eigenbasis:

$$|\psi_0\rangle = \sum_n c_n |E_n\rangle \tag{36}$$

where $H|E_n\rangle = E_n |E_n\rangle$ and $\sum_n |c_n|^2 = 1$.

The overlap at time τ is:

$$\langle\psi_0\rangle\, \psi_\tau = \sum_n |c_n|^2 e^{-iE_n\tau/\hbar} \tag{37}$$

A.3 Bound on the Real Part

The real part of the overlap is:

$$\mathrm{Re}\,\langle\psi_0\rangle\, \psi_\tau = \sum_n |c_n|^2 \cos(E_n\tau/\hbar) \tag{38}$$

For orthogonality, we need $\langle\psi_0\rangle\, \psi_\tau = 0$, which requires both real and imaginary parts to vanish.

Using the inequality $\cos\theta \geq 1 - (2/\pi)|\theta|$ for $|\theta| \leq \pi$:

$$\mathrm{Re}\,\langle\psi_0\rangle\, \psi_\tau \geq \sum_n |c_n|^2 \left(1 - \frac{2}{\pi}\frac{E_n\tau}{\hbar}\right) \tag{39}$$

Shifting energies by the ground state energy E_0:

$$\mathrm{Re}\,\langle\psi_0\rangle\, \psi_\tau \geq 1 - \frac{2\tau}{\pi\hbar}\sum_n |c_n|^2 (E_n - E_0) = 1 - \frac{2E\tau}{\pi\hbar} \tag{40}$$

where $E = \langle H\rangle - E_0$ is the mean energy above the ground state.

A.4 The Bound

For orthogonality, $\mathrm{Re}\,\langle\psi_0\rangle\, \psi_\tau = 0$, so:

$$0 \geq 1 - \frac{2E\tau}{\pi\hbar} \tag{41}$$

Rearranging:

$$\boxed{\tau \geq \frac{\pi\hbar}{2E}} \tag{42}$$

This is the Margolus-Levitin bound.

A.5 Tightness

The bound is asymptotically tight. For a system with energy spectrum $E_n = E_0 + n\Delta E$ (equally spaced levels) and initial state $|\psi_0\rangle = (|E_0\rangle + |E_N\rangle)/\sqrt{2}$:

$$\langle\psi_0\rangle\, \psi_\tau = \frac{1}{2}\left(1 + e^{-iN\Delta E\tau/\hbar}\right) \tag{43}$$

Orthogonality requires $N\Delta E\tau/\hbar = \pi$, giving $\tau = \pi\hbar/(N\Delta E)$. For this state, $E = N\Delta E/2$, so $\tau = \pi\hbar/(2E)$—exactly saturating the bound.

B Extension to Open Systems

The Margolus-Levitin bound was originally derived for isolated systems undergoing unitary evolution. Here we discuss its extension to open systems, which is relevant for decoherence.

B.1 The Challenge

In an open system, the density matrix ρ evolves non-unitarily:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \mathcal{L}[\rho] \tag{44}$$

where $\mathcal{L}$ is a Lindblad superoperator describing dissipation and decoherence.

The concepts of "orthogonal states" and "energy above ground state" require reinterpretation.

B.2 Geometric Approach

Del Campo et al. [8] and Deffner and Lutz [9] extended quantum speed limits to open systems using geometric methods.

The key quantity is the Bures angle:

$$\mathcal{L}(\rho_0, \rho_\tau) = \arccos\sqrt{F(\rho_0, \rho_\tau)} \tag{45}$$

where $F(\rho, \sigma) = \left(\mathrm{Tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)^2$ is the quantum fidelity.

The quantum speed limit becomes:

$$\tau \geq \frac{\mathcal{L}(\rho_0, \rho_\tau)}{\langle||\dot{\rho}||\rangle} \tag{46}$$

where the denominator is a time-averaged norm of the rate of change.

B.3 Application to Decoherence

For decoherence of a superposition, we can take a simpler approach: treat the total system (matter + environment) as isolated, with the matter system's decoherence arising from entanglement with the environment.

In this picture:

- The total system evolves unitarily
- The environment states $|E_L\rangle$ and $|E_R\rangle$ evolve toward orthogonality
- The Margolus-Levitin bound applies to this environment evolution

The energy driving the environment toward distinguishing the branches is the gravitational self-energy E_{G}. This justifies our application of the bound in the main text.

B.4 Validity Conditions

The application is valid when:

1. The matter-environment system is approximately isolated (no external influences)
2. The gravitational self-energy E_{G} is the dominant energy scale for branch distinguishability
3. The environment starts in a state that does not initially distinguish the branches

These conditions are satisfied for mesoscopic masses in laboratory vacuum, far from other massive objects.

C Perturbative QFT Decoherence Rate

This appendix summarizes the perturbative QFT calculation of gravitational decoherence due to graviton exchange, following Anastopoulos and Hu [3] and Blencowe [4].

C.1 Setup

Consider a mass M in spatial superposition interacting with the gravitational field, treated as a quantum field of gravitons $h_{\mu\nu}$.

The interaction Hamiltonian in linearized gravity is:

$$H_{\mathrm{int}} = \int d^3x\, h_{\mu\nu}(x) T^{\mu\nu}(x) \tag{47}$$

where $T^{\mu\nu}$ is the stress-energy tensor of the mass.

C.2 Master Equation

Tracing over the graviton field in a thermal or vacuum state yields a master equation for the mass density matrix:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H_S, \rho] - \frac{1}{\hbar^2}\int_0^\infty d\tau\, \mathrm{Tr}_E\left[H_{\mathrm{int}}, [H_{\mathrm{int}}(-\tau), \rho \otimes \rho_E]\right] \tag{48}$$

C.3 Decoherence Rate

For a superposition of localized states $|L\rangle$ and $|R\rangle$ separated by d, the off-diagonal elements decay as:

$$\rho_{LR}(t) = \rho_{LR}(0)e^{-\Gamma_{\text{QFT}}t} \tag{49}$$

The perturbative calculation gives rates scaling as G^2 [4]:

$$\Gamma_{\text{QFT}} \sim G^2 \times f(M, d, \hbar, c) \tag{50}$$

where f is a function of mass, separation, and fundamental constants whose exact form depends on the mass distribution, temperature, cutoff scheme, and other details. The scaling with G^2—one power of G below the Diósi-Penrose rate—is the robust result.

C.4 Physical Interpretation

The G^2 scaling arises because:

1. One factor of G comes from the graviton emission amplitude
2. One factor of G comes from the graviton absorption/detection amplitude
3. The decoherence rate is proportional to the square of the amplitude (a probability)

This is the standard perturbative result for any interaction: rates scale as the square of the coupling constant.

C.5 Comparison with Diósi-Penrose

Since the perturbative rate scales as G^2 while the Diósi-Penrose rate scales as G^1, the ratio involves one additional power of G. In terms of Planck units, this contributes a factor of $(M/M_{\text{P}})^2$. Including geometric factors:

$$\frac{\Gamma_{\text{QFT}}}{\Gamma_{\text{ML}}} \sim \left(\frac{M}{M_{\text{P}}}\right)^2 \frac{\ell_{\text{P}}}{d} \tag{51}$$

For a mass $M = 1$ μg $= 10^{-9}$ kg and $d = 1$ mm $= 10^{-3}$ m:

$$\frac{\Gamma_{\text{QFT}}}{\Gamma_{\text{ML}}} \sim (5 \times 10^{-2})^2 \times (1.6 \times 10^{-32}) \sim 10^{-35} \tag{52}$$

Since $\Gamma_{\text{DP}}/\Gamma_{\text{ML}} = \pi/2$, the perturbative rate is approximately 10^{35} times smaller than the Diósi-Penrose rate.

C.6 Why Perturbative Physics Operates Far Below the Scale

The information-theoretic bound scales as G^1:

$$\Gamma_{\text{ML}} = \frac{2E_{\text{G}}}{\pi\hbar} = \frac{2GM^2}{\pi\hbar d} \propto G^1 \tag{53}$$

Perturbative QFT rates scale as G^2—the square of the coupling constant. This is one power of G below the G^1 scale. Since $G \sim 1/M_{\mathrm{P}}^2$ in natural units, the suppression factor is of order $(M/M_{\mathrm{P}})^2 \ll 1$ for any mass below the Planck scale.

To operate at the fundamental scale requires non-perturbative physics where the rate scales as G^1, not G^2.

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