Quantized Linearized Gravity Does Not Supply the Diósi–Penrose Decoherence Rate

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Abstract

The Diósi–Penrose proposal assigns a mass superposition a decoherence rate $E_{\mathrm{G}}/\hbar$ of first order in Newton's constant. We ask whether quantized linearized gravity supplies that rate for a static, inertial source whose two branches carry equal mass. A rate of this kind has a sharp signature: at fixed geometry its exponent grows as GM^2t. We examine the two channels available at linearized order. For the field, the fluctuation–dissipation theorem ties a zero-frequency noise floor to an Ohmic dissipative response. Two-point functions of a free field are supported on the mass shell in any translation-invariant state, and equal branch masses make the source difference vanish as k^2. The field spectral density therefore rises as ω^3, and the floor vanishes at every temperature, including the modular temperature of a causal diamond. For relational clocks, the branch coherence depends on G, M and t only through the product GMt, for any number of clocks in any joint state. A canonical Page–Wootters readout yields a redshift phase at the E_{G} scale with constant visibility. Corrections of higher order in G cannot restore a first-order term. The exponent $E_{\mathrm{G}}t/\hbar$ is reproduced exactly by mass density coupled to white noise with correlation $\hbar G/|\mathbf{x}-\mathbf{y}|$, whose weight lies off the mass shell. Within this scope an observed first-order rate would indicate physics beyond quantized linearized gravity, such as an explicit collapse mechanism.

1 Introduction

Diósi [2, 3] and Penrose [4] proposed that a mass M in a superposition of two locations decoheres at the rate

$$\Gamma_{\mathrm{dec}} = \frac{E_{\mathrm{G}}}{\hbar}, \qquad E_{\mathrm{G}} = \frac{G}{2}\iint \frac{\Delta\rho(\mathbf{x})\,\Delta\rho(\mathbf{y})}{|\mathbf{x}-\mathbf{y}|}\, d^3x\, d^3y, \qquad \Delta\rho = \rho_L - \rho_R, \tag{1}$$

whose separation-dependent cross term is GM^2/d for well-separated bodies. The rate is first order in G. Perturbative treatments of the graviton field as an environment give rates of second order in G [5, 6]. For a 1 μg mass at 1 mm separation the two differ by a factor $(M_{\mathrm{P}}/M)^2(d/\ell_{\mathrm{P}}) \approx 3\times 10^{34}$, so the question of which order nature follows can be settled by experiment.

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A recurring hope is that the first-order rate is not new physics but a consequence of quantizing gravity correctly. One version of this idea imposes the Hamiltonian constraint on the initial state. Each branch then carries its own Newtonian dressing, and the two dressings are distinguishable at first order in G [1]. That distinguishability is static, however. Turning it into a rate needs a further dynamical step, and the proposed step is relational: time is read from a physical clock [9], or the diamond's modular flow [10, 11] is identified with physical time within a crossed-product algebra [12, 13].

This paper tests that step at linearized order. We ask whether any channel available in quantized linearized gravity turns the static first-order distinguishability into an irreversible rate that is first order in G. The answer is no, for a static inertial source with equal branch masses. Section 2 states the setting and a scaling test that any candidate rate must pass. Section 3 treats the field: it has no zero-frequency noise at any temperature. Section 4 treats clocks: their readout depends only on GMt. Section 5 identifies the structure that does reproduce Eq. (1), and shows that no free relativistic field supplies it. Section 6 lists the assumptions under which the conclusion holds and the routes that remain open.

The statement is scoped. It does not exclude a first-order rate from physics outside the stated assumptions, and it makes no claim about what experiments will find. It locates the rate: within quantized linearized gravity it is not produced, so a measured first-order rate would indicate a further ingredient.

2 Setting and the scaling test

Assumptions. A rigid body of mass M is prepared in a superposition of two static positions separated by d. Both branches carry the same mass. The source is inertial. Gravity is treated to linear order in G about flat space. The field state is translation-invariant, which includes the vacuum and thermal states. Couplings are linear. The branch coherence $z(t) = 2\rho_{LR}(t)$ is read by recombining the two paths, and its modulus is the fringe visibility.

What is already known. Solving the Newtonian constraint $\nabla^2\Phi = 4\pi G\rho$ branch by branch dresses each branch with its own field. The dressings are distinguishable by a static overlap exponent of order $GM^2/(\hbar c)$, up to a logarithm [1]. That exponent does not grow with time. The self-energy of a rigid body is the same in both branches, so the Newtonian action produces no relative phase either. The quantity E_G is not a difference of branch energies. It is the energy of the density *difference*: it pairs the mass of one branch with the field of the other.

The scaling test. Write $F(M,t) = -\ln|z(t)|$ at fixed geometry: fixed d, body shape, and positions of any probes. For Eq. (1) the exponent is $F = E_\mathrm{G}t/\hbar \propto GM^2t$. Define the mass- and time-doubling ratios

$$R_M = \frac{F(2M,t)}{F(M,t)}, \qquad R_t = \frac{F(M,2t)}{F(M,t)}. \tag{2}$$

A first-order rate of the form (1) has $R_M = 4$ and $R_t = 2$. We apply this test to each channel below.

3 The field channel

Noise, dissipation and the rate. Let the source couple linearly to a Gaussian environment through the operator $X = \int \Delta\rho\, \hat{\phi}\, d^3x$, where $\hat{\phi}$ is the field that carries the gravitational interaction. For pure dephasing the exponent is

$$F(t) = \int_0^\infty d\omega\ S(\omega)\, \frac{1 - \cos\omega t}{\omega^2}, \tag{3}$$

where $S(\omega)$ is the symmetrized noise spectrum of X, normalized so that F is dimensionless. Since $\int_0^\infty (1 - \cos\omega t)\, \omega^{-2} d\omega = \pi t/2$, the long-time slope is $\lim_{t\to\infty} F(t)/t = (\pi/2)S(0)$. A sustained rate therefore requires a nonzero zero-frequency floor. If instead $S(\omega) = \mathcal{O}(\omega^2)$ as $\omega \to 0$, the integrand stays bounded at small ω and $F(t)$ saturates. In a state that is thermal at inverse temperature β, the fluctuation–dissipation theorem gives $S(\omega) \propto J(\omega) \coth(\beta\hbar\omega/2)$, with J the dissipative (spectral) density of X. Hence

$$S(0)\ \propto\ \frac{2}{\beta\hbar} \lim_{\omega\to 0} \frac{J(\omega)}{\omega}. \tag{4}$$

A floor exists only if the response is *Ohmic*, $J \propto \omega$ at low frequency.

The modular temperature adds no noise. For a free field, the vacuum restricted to a Rindler wedge [10] or, for a conformal field, to a causal diamond [11] is a KMS state for its modular flow at modular inverse temperature 2π. The "modular bath" is therefore the vacuum itself, described in the modular time parameter. Identifying modular flow with physical time relabels this state; it does not add excitations. Equation (4) applies with whatever β describes the state, and the question reduces to the form of J.

On-shell support forces a super-Ohmic spectrum. A free massless field obeys $\Box\hat{\phi} = 0$ as an operator identity. Every two-point function therefore obeys the wave equation in each argument. In a translation-invariant state its Fourier transform is supported on $\omega = \pm c|\mathbf{k}|$. Weight at $\omega \to 0$ can then come only from $|\mathbf{k}| \to 0$. There the source difference is suppressed. For two spheres of equal mass with form factor $\tilde{\rho}(k)$, the angle average is

$$\langle |\Delta\tilde{\rho}_{\mathbf{k}}|^2 \rangle = 2\, \tilde{\rho}(k)^2 \Big(1 - \frac{\sin kd}{kd}\Big) \xrightarrow{kd\to 0} \tfrac{1}{3} M^2 k^2 d^2. \tag{5}$$

The monopole cancels because the two branches have the same mass. To make the statement quantitative, take the most favourable case: a propagating field whose coupling is normalized so that its reorganization energy equals E_G (Appendix A). Then

$$J(\omega) = \frac{G\omega}{c} \langle |\Delta\tilde{\rho}_{\omega/c}|^2 \rangle\ \simeq\ \frac{GM^2 d^2}{3c^3}\, \omega^3 \qquad (\omega d/c \ll 1). \tag{6}$$

If the recoil of the apparatus is included, so that the net mass dipole of source plus apparatus vanishes, the leading term becomes quadrupolar and $J \propto \omega^5$. Only a difference of branch *masses* would make J Ohmic.

The constrained sector is reactive. General relativity is less favourable than this model. At linear order the static mass density has no propagating scalar partner. Its Newtonian potential is fixed by the constraint, $\Phi(\mathbf{x}, t) = -G \int \rho(\mathbf{y}, t)/|\mathbf{x} - \mathbf{y}|\, d^3y$, an instantaneous kernel that is real at every frequency. That sector therefore contributes no dissipation. Its fluctuations are those of the matter that sources it, so its correlator is of order G^2. The transverse-traceless sector couples to static sources only through stresses, and it begins at the quadrupole.

Proposition 3.1 (Field channel)**.** *For a static inertial source with equal branch masses, in any translation-invariant state of a free linearized gravitational field, including states that are KMS for modular flow, the zero-frequency noise of the which-path coupling vanishes. The dephasing exponent saturates. It does not grow linearly in t.*

Perturbative master equations with a graviton environment decohere superpositions in the energy basis [5, 6]. That is the monopole channel of Eq. (5). For a spatial superposition of equal masses it is absent, in line with Eq. (6). Neither the choice of state nor the modular temperature restores it.

4 The clock channel

The remaining linearized coupling is the one relational proposals rely on: a physical clock whose rate depends on the branch through gravitational redshift.

One canonical clock. Let the clock have energy q with a spectrum bounded below, as for the observer adjoined in the crossed-product construction [12, 13]. Let it sit at $\mathbf{x}_{\text{obs}}$. With branch projectors Π_j and source Hamiltonian H_S (levels E_n), the Hamiltonian constraint reads

$$\hat{C} = H_S - \sum_{j=L,R} \Pi_j \, \nu_j \, q, \qquad \nu_j = 1 + \frac{\Phi_j(\mathbf{x}_{\text{obs}})}{c^2}, \tag{7}$$

where Φ_j is the source potential in branch j. The self-energy of the source and any common external potential are the same in both branches and are absorbed into H_S. Group averaging a seed with clock wavefunction $\chi(q)$ fixes $q = E_n/\nu_j$ in each branch and level. Conditioning on the covariant time states $|\tau\rangle = (2\pi\hbar)^{-1/2} \int dq\, e^{iq\tau/\hbar} |q\rangle$ of the semibounded clock [9] gives

$$\psi_{j,n}(\tau) \;\propto\; c_j \sqrt{p_n}\, \frac{\chi(E_n/\nu_j)}{\nu_j}\, e^{-iE_n\tau/(\hbar\nu_j)}, \tag{8}$$

so each branch evolves in clock time with the redshifted Hamiltonian H_S/ν_j. The clock energy is fixed by the constraint in each sector, so the clock is not an independent environment. For a structureless source, a single level $E = Mc^2$, the coherence has constant modulus and rotates at

$$\omega_{\text{rel}} = \frac{M\, |\Phi_L - \Phi_R|(\mathbf{x}_{\text{obs}})}{\hbar}, \tag{9}$$

to first order in Φ/c^2. On the separation axis at distance r from the midpoint, $\omega_{\text{rel}} = GM^2 d/[\hbar(r^2 - d^2/4)]$, which equals $(4/3)\, E_{\text{G}}/\hbar$ at $r = d$. The effect is first order in G and set by the E_{G} scale, but it shifts the fringes rather than reducing their contrast. An observer on the plane bisecting the separation measures $\Phi_L = \Phi_R$ and sees no branch dependence at all, although $E_{\text{G}} > 0$.

Two refinements do not change this conclusion. An internal energy spread of the source turns $|z|$ into the characteristic function of that spread at argument $\tau\,(1/\nu_L - 1/\nu_R)/\hbar$. This is time-dilation dephasing, the loss of visibility of an interfering clock [20, 14]. It is Gaussian at short times and revives for a discrete spectrum. For a spectrum bounded below it cannot be exponential at all times, by the Paley–Wiener theorem (Khalfin's argument; see [21]). A clock whose reading diffuses, with variance $D\tau$, gives an exponential $\exp(-\omega_{\mathrm{rel}}^2 D\tau/2)$. At fixed D its rate scales as G^2.

Any number of clocks. Now allow many clocks with Hamiltonians H_k at positions $\mathbf{x}_k$, in an arbitrary joint state, product or entangled. Whether they are traced out or conditioned on, the branch-relative evolution is generated by $\sum_k H_k\,\Delta\Phi(\mathbf{x}_k)/c^2$. At fixed geometry the potential difference is $\Delta\Phi(\mathbf{x}) = GM\,\varphi(\mathbf{x})$, with φ independent of G and M. Hence

$$z(t) = \Big\langle \exp\Big(\frac{i\,GMt}{\hbar c^2}\sum_k H_k\,\varphi(\mathbf{x}_k)\Big)\Big\rangle. \tag{10}$$

Proposition 4.1 (Clock channel)**.** *For redshift-coupled clocks with source-independent statistics, the branch coherence depends on G, M and t only through GMt. Consequently $R_M = R_t$ for every clock ensemble, whereas a first-order rate of the form* (1) *requires $R_M = 4$, $R_t = 2$.*

Two cases illustrate the proposition. If every clock energy has finite variance σ_k^2, the exponent is $F = (t^2/2\hbar^2c^4)\sum_k \sigma_k^2\,\Delta\Phi(\mathbf{x}_k)^2 \propto G^2M^2t^2$. If the clock energies are Cauchy distributed with widths γ_k, the decay is exponential with $F = (t/\hbar c^2)\sum_k \gamma_k|\Delta\Phi(\mathbf{x}_k)| \propto GMt$. The Cauchy case is also excluded exactly for semibounded spectra. The mass dependence M^2 arises only if the probe's own energy scales with M, that is, if the probe is a second massive body. This is the two-mass entanglement setting [15, 16], not a clock timing a fixed source.

5 What does produce the rate

Couple the mass density to a stationary, Gaussian potential noise that does not depend on the source, with correlation

$$\langle \delta\Phi(\mathbf{x},t)\,\delta\Phi(\mathbf{y},s)\rangle = \frac{\hbar G}{|\mathbf{x}-\mathbf{y}|}\,\delta(t-s). \tag{11}$$

The coupling $\int \rho\,\delta\Phi\,d^3x$ gives $-\ln|z| = (2\hbar^2)^{-1}\,\mathrm{Var}\!\int_0^t dt'\!\int \Delta\rho\,\delta\Phi\,d^3x = E_{\mathrm{G}}t/\hbar$, which is exactly Eq. (1). This is the noise underlying Diósi's master equation [2, 3]. It passes the scaling test: the mass enters once through each of the two couplings in the variance, G enters once through the noise strength, and the white spectrum makes the exponent linear in t, so $R_M = 4$ and $R_t = 2$. Evaluated in Fourier space, the exponent reproduces the closed-form energy of two uniform spheres both for separated and for overlapping configurations (Appendix A).

The structural difference from Sections 3–4 is where the correlation (11) lives in $(\mathbf{k},\omega)$ space. Its Fourier transform is $4\pi\hbar G/k^2$ at every frequency. It therefore carries finite weight at $\omega = 0$ with $\mathbf{k} \neq 0$, which is off the mass shell. By Section 3, such weight belongs to no two-point function of a free relativistic field in any translation-invariant state. The Newtonian sector does not fluctuate independently at order G. Equation (11) is therefore an additional ingredient, not a property of quantized linearized gravity.

Proposition 5.1 (Linearized no-go)**.** *Under the assumptions of Section 2, quantized linearized gravity yields a static first-order overlap and a first-order relational phase, but no irreversible decoherence rate of first order in G. Corrections of higher order in G cannot supply one. A rate of the form* (1) *requires a source-independent, off-shell noise with the structure* (11)*, or physics outside the stated assumptions.*

The reason can be stated without formulas. The field a probe samples is sourced by one factor of GM. The energy E_{G} pairs one branch's mass with the difference between the branches' fields. It is not an energy available within either branch, so within-branch unitary dynamics cannot convert it into a rate. A rule that compares the branches can. This matches Penrose's view that the rate reflects an ill-defined identification between two branch geometries [4].

6 Scope and open routes

Each assumption of Section 2 marks where the conclusion could fail. Table 1 lists them.

Table 1. *Routes outside the scope of Proposition 5.1.*

Route	Status	Would it give $E_{\mathrm{G}}/\hbar$?
Killing horizons	Real Ohmic mechanism [17, 18, 19]	Rates set by horizon data; absent for an inertial laboratory without a horizon
Accelerated or moving source	Violates the static, inertial premise	Same class as horizons
Interacting or non-invariant medium	Can place weight off shell	Requires an order-G gravitational medium; none is known
Non-perturbative gravity	Not constrained here	Open
Different branch masses	Monopole channel, Ohmic	Not a spatial superposition of one body
Explicit noise postulate	Eq. (11)	Yes, by construction

Consequences. If an experiment finds first-order decoherence for an isolated, inertial, equal-mass spatial superposition, Proposition 5.1 places its origin outside quantized linearized gravity. The explicit-noise route is the Diósi–Penrose collapse model in its dynamical form [7]. Mass-density noise of this kind heats matter and makes charged particles radiate, and an underground search has excluded the version without a smearing length [8]. A smearing length must therefore enter as a parameter constrained by such data. If an experiment instead finds coherence out to times set by the second-order rate, that result is what Proposition 5.1 predicts for quantized linearized gravity alone.

Relation to relational and modular proposals. Proposals that derive the first-order rate from the Hamiltonian constraint, from Page–Wootters time, or from identifying modular flow with physical time [1] meet the obstruction at a definite point. The constraint gives a static overlap. The relational clock gives a phase. The modular temperature is the vacuum's. Establishing an operator identity between the modular and physical generators would not, by itself, supply the missing dissipator. The framework of Ref. [1] accordingly treats the first-order rate as an explicit postulate.

Limitations. The analysis is linear in G, uses a flat background with a static inertial source, and treats probes whose statistics do not depend on the source. It does not address non-perturbative quantum gravity, and it makes no statement about the strength of any collapse mechanism.

A Normalization of the field model

In Fourier space, $\int d^3k\,(2\pi)^{-3}\,4\pi k^{-2} f(k) = (2/\pi)\int_0^\infty dk\,\langle f\rangle$ for any angle average $\langle f\rangle$. Equation (1) then reads

$$E_{\mathrm{G}} = \frac{G}{\pi}\int_0^\infty dk\,\langle|\Delta\tilde{\rho}_{\mathbf{k}}|^2\rangle, \tag{12}$$

with the angle average of Eq. (5). For a uniform sphere of radius R the form factor is $\tilde{\rho}(k) = 3M(\sin kR - kR\cos kR)/(kR)^3$. The spectral density of Eq. (6) has reorganization energy $\pi^{-1}\int_0^\infty J(\omega)\,\omega^{-1}d\omega$ equal to Eq. (12), which fixes its normalization. Its expansion at $\omega d/c \ll 1$ gives the ω^3 law of Eq. (6).

The white-noise exponent of Section 5 is $(Gt/2\hbar)\iint \Delta\rho\,\Delta\rho\,|\mathbf{x}-\mathbf{y}|^{-1} = E_{\mathrm{G}}t/\hbar$ by the same identity. Direct quadrature of Eq. (12) agrees with the closed-form energy of two uniform spheres to better than one part in 10^6. For separation $s = d/R \geq 2$ the closed form is $E_{\mathrm{G}} = (GM^2/R)(6/5 - 1/s)$. For $s < 2$ it is $E_{\mathrm{G}} = (GM^2/R)\,s^2(1/2 - 3s/16 + s^3/160)$. The agreement holds at $s = 0.3$, 1.2, 3 and 10. The same quadrature confirms the ω^3 coefficient of Eq. (6).

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