Gravitational Decoherence in Quantum Field Theory: From Fock States to Inflationary Perturbations

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Abstract

We extend the Diósi-Penrose gravitational decoherence formalism from point particles to quantum fields. The mass density operator $\hat{\mu}(\mathbf{x})$ in the Diósi master equation is replaced by the stress-energy operator $\hat{T}^{00}(\mathbf{x})/c^2$, yielding decoherence rates for arbitrary field-state superpositions. For Fock state superpositions $(|n\rangle + |m\rangle)/\sqrt{2}$ of a single mode, we derive $\Gamma = G(n-m)^2\hbar\omega^2 C_{\text{cube}}/(c^4 L)$, where $C_{\text{cube}} \approx 1.192$ is a geometric factor. This reduces to the standard Diósi-Penrose rate $\Gamma = GM^2/(\hbar d)$ in the single-particle limit, providing a non-trivial consistency check. For coherent and squeezed states, the rates are negligible for electromagnetic fields but can be significant for massive bosons. Applied to inflationary cosmology, we find that the self-gravitational decoherence of scalar perturbations becomes faster than the Hubble expansion at $N_{\text{dec}} \approx (1/4)\ln(16/\varepsilon_{\text{grav}})$ e-folds after horizon crossing, where $\varepsilon_{\text{grav}} = (\hbar H_{\text{inf}}/E_P)^2$. For GUT-scale inflation ($H_{\text{inf}} \sim 10^{13}$ GeV), $N_{\text{dec}} \approx 7.7$—well before recombination for all observable modes. Physical arguments suggest this provides a universal mechanism for the quantum-to-classical transition of primordial perturbations, with the same parametric scaling as environmental decoherence but arising from the self-gravitational field alone; the result is a motivated estimate subject to $O(1)$ corrections from the de Sitter kernel and gauge choice.

1 Introduction

The quantum-to-classical transition remains one of the central open problems in fundamental physics. Environmental decoherence provides a powerful and well-understood mechanism: coupling to external degrees of freedom destroys quantum coherence on timescales that decrease rapidly with system size [24, 25]. Gravitational decoherence offers a complementary, universal channel. Diósi [1] and Penrose [3] independently argued that the incompatibility of superposed spacetime geometries induces decoherence at a rate set by the gravitational self-energy difference between the branches. For a point mass M in spatial superposition over a distance d, the predicted rate is

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

a formula containing no adjustable parameters. This prediction is the target of a growing experimental program using optically levitated nanoparticles, matter-wave interferometers, and entanglement witnesses [26, 27, 28, 29].

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Existing closed-form Diósi-Penrose rates are first-quantized: they describe a single massive particle whose center of mass occupies a spatial superposition. Field-theoretic treatments exist in different frameworks [4, 5], but systematic closed-form rates for the principal classes of field states—Fock, coherent, squeezed—have not been derived. Real quantum systems, however, are described by quantum fields. A photon number state $|n\rangle$ carries a gravitational field sourced by its energy density. A coherent laser pulse $|\alpha\rangle$ and a squeezed vacuum $|r\rangle$ each produce distinct stress-energy profiles. More dramatically, inflationary perturbations exit the horizon as squeezed states with squeezing parameter r that grows linearly with the number of e-folds N after horizon crossing [17, 30, 9]. No systematic treatment of gravitational decoherence exists for these field-theoretic superpositions.

In this paper we extend the Diósi master equation to quantum fields by promoting the mass density $\mu(\mathbf{x})$ to the stress-energy operator $\hat{T}^{00}(\mathbf{x})/c^2$. The resulting master equation governs decoherence of arbitrary field-state superpositions in a mode-by-mode fashion. We compute explicit decoherence rates for the three principal classes of field states—Fock, coherent, and squeezed—and show that the formalism reduces to Eq. (1) in the single-particle limit, providing a non-trivial consistency check.

The cosmological application provides the most striking result. Inflationary perturbations of comoving wavenumber k are produced in the Bunch-Davies vacuum and evolve into highly squeezed states with $r \approx N$ e-folds after horizon crossing. The gravitational decoherence rate for a squeezed state grows as e^{4r}, reflecting the exponential amplification of energy-density fluctuations by squeezing. Despite the extreme weakness of the gravitational coupling—characterized by $\varepsilon_{\rm grav} = (\hbar H_{\rm inf}/E_P)^2 \sim 10^{-12}$ for GUT-scale inflation—the exponential growth of the squeezing compensates, and classicalization occurs at

$$N_{\rm dec} \approx \frac{1}{4} \ln\left(\frac{16}{\varepsilon_{\rm grav}}\right) \approx 7.7 \quad \text{(GUT-scale)}. \tag{2}$$

This is well before recombination for all observable CMB modes, suggesting a universal mechanism for the quantum-to-classical transition of primordial perturbations (subject to $O(1)$ corrections from the de Sitter kernel and gauge dependence, as detailed in Section 5.5).

The classicalization of inflationary perturbations has been studied previously through environmental decoherence, in which short-wavelength modes act as an environment for long-wavelength modes [8, 10, 31]. Those analyses find the same parametric dependence on $\varepsilon_{\rm grav}$ and N as our result, lending mutual support. The mechanism we identify is distinct: it is *self*-gravitational decoherence arising from the Newtonian self-energy of each mode's energy-density fluctuations, requiring no tracing over short-wavelength degrees of freedom. The two channels operate in parallel and reinforce one another.

The paper is organized as follows. Section 2 develops the second-quantized Diósi master equation, promoting the mass density to $\hat{T}^{00}/c^2$ and deriving the mode-decomposed decoherence kernel. Section 3 computes decoherence rates for Fock state superpositions and verifies the single-particle limit. Section 4 treats coherent and squeezed states. Section 5 applies the formalism to inflationary perturbations and derives the classicalization time. Section 6 discusses implications, limitations, and connections to the broader gravitational decoherence program.

2 Formalism: The Diósi Master Equation for Fields

2.1 From mass density to stress-energy

The Diósi master equation for a system of point masses is [1, 2]

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{G}{2\hbar}\int d^3x\, d^3y\, \frac{[\hat{\mu}(\mathbf{x}), [\hat{\mu}(\mathbf{y}), \hat{\rho}]]}{|\mathbf{x} - \mathbf{y}|}\,, \tag{3}$$

where $\hat{\mu}(\mathbf{x})$ is the mass density operator and the kernel $1/|\mathbf{x} - \mathbf{y}|$ is the Green function of the Poisson constraint $\nabla^2\Phi = 4\pi G\rho$. For a point mass M in superposition $(|L\rangle + |R\rangle)/\sqrt{2}$ with separation d, the double commutator yields the decoherence rate $\Gamma = GM^2/(\hbar d)$.

For quantum fields, the mass density generalizes to the energy density divided by c^2:

$$\hat{\mu}(\mathbf{x}) \;\longrightarrow\; \frac{\hat{T}^{00}(\mathbf{x})}{c^2}\,, \tag{4}$$

giving the *field-theoretic Diósi master equation*:

$$\boxed{\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{G}{2\hbar c^4}\int d^3x\, d^3y\, \frac{[\hat{T}^{00}(\mathbf{x}), [\hat{T}^{00}(\mathbf{y}), \hat{\rho}]]}{|\mathbf{x} - \mathbf{y}|}\,.} \tag{5}$$

This is the starting point for all calculations in this paper.

2.2 Decoherence rate for field-state superpositions

For a superposition of two field states $(|\Psi_1\rangle + |\Psi_2\rangle)/\sqrt{2}$ with distinct stress-energy expectation values $\langle \hat{T}^{00}\rangle_1 \neq \langle \hat{T}^{00}\rangle_2$, the off-diagonal density matrix element decays as $|\rho_{12}(t)| = |\rho_{12}(0)|\, e^{-\Gamma t}$ with

$$\Gamma = \frac{G}{\hbar c^4}\int d^3x\, d^3y\, \frac{\Delta T^{00}(\mathbf{x})\, \Delta T^{00}(\mathbf{y})}{|\mathbf{x} - \mathbf{y}|}\,, \tag{6}$$

where

$$\Delta T^{00}(\mathbf{x}) = \langle \hat{T}^{00}(\mathbf{x})\rangle_1 - \langle \hat{T}^{00}(\mathbf{x})\rangle_2 \tag{7}$$

is the energy density difference between the two branches. This is the gravitational self-energy $E_G = \Gamma\hbar$ of the density difference—the direct field-theoretic generalization of GM^2/d for point masses.

Equation (6) is the master formula applied throughout this paper. It assumes that decoherence is dominated by the expectation value of $\hat{T}^{00}$, with quantum fluctuations of T^{00} contributing at higher order in G.

2.3 Pointer basis

The Diósi kernel couples to $\hat{T}^{00}$—the energy density. States that are eigenstates of $\hat{T}^{00}(\mathbf{x})$ at every point are immune to decoherence. The pointer basis selected by gravitational decoherence therefore consists of states with definite energy density distributions. For point particles this is the position basis (mass density $\hat{\mu} = M\delta^3(\mathbf{x} - \hat{\mathbf{X}})$ is diagonal in position). For fields, the pointer basis consists of energy-momentum eigenstates or quasi-classical field configurations—not field-amplitude eigenstates.

2.4 Massive scalar field: setup

We work with a free real massive scalar field $\hat{\Phi}(\mathbf{x})$ of mass m in a cubic box of side L with periodic boundary conditions. The mode expansion is

$$\hat{\Phi}(\mathbf{x}) = \sum_{\mathbf{k}} \sqrt{\frac{\hbar}{2\omega_k V}} \left(\hat{a}_{\mathbf{k}}\, e^{i\mathbf{k}\cdot\mathbf{x}} + \hat{a}^{\dagger}_{\mathbf{k}}\, e^{-i\mathbf{k}\cdot\mathbf{x}}\right), \tag{8}$$

where $V = L^3$, $\omega_k = \sqrt{k^2c^2 + m^2c^4/\hbar^2}$, and $[\hat{a}_{\mathbf{k}}, \hat{a}^{\dagger}_{\mathbf{k}'}] = \delta_{\mathbf{k},\mathbf{k}'}$. The stress-energy $\hat{T}^{00} = \frac{1}{2}\hat{\Pi}^2 + \frac{1}{2}c^2(\nabla\hat{\Phi})^2 + \frac{1}{2}(m^2c^4/\hbar^2)\hat{\Phi}^2$ has the expectation value

$$\langle n_{\mathbf{k}}|\hat{T}^{00}(\mathbf{x})|n_{\mathbf{k}}\rangle = \frac{(n_k + \frac{1}{2})\,\hbar\omega_k}{V}, \tag{9}$$

which is spatially uniform (after averaging over the standing wave oscillation). The vacuum contribution $\frac{1}{2}\hbar\omega_k/V$ cancels in the difference (7) between any two Fock states of the same mode.

3 Decoherence of Fock State Superpositions

3.1 Single-mode decoherence rate

Consider the superposition $|\Psi\rangle = (|n\rangle + |m\rangle)/\sqrt{2}$ of two occupation numbers of a single mode $\mathbf{k}$. From Eq. (9), the energy density difference is spatially uniform:

$$\Delta T^{00} = \frac{(n-m)\,\hbar\omega_k}{V}. \tag{10}$$

Substituting into Eq. (6):

$$\Gamma_{\text{Fock}} = \frac{G(n-m)^2(\hbar\omega_k)^2}{\hbar c^4 V^2} \int d^3x\, d^3y\, \frac{1}{|\mathbf{x}-\mathbf{y}|}. \tag{11}$$

The geometric double integral over a cube of side L evaluates to (Appendix A)

$$\mathcal{J}(L) \equiv \int_{\text{cube}}\int_{\text{cube}} \frac{d^3x\, d^3y}{|\mathbf{x}-\mathbf{y}|} = C_{\text{cube}}\, L^5, \qquad C_{\text{cube}} \approx 1.192, \tag{12}$$

a result first computed by Chandrasekhar [12] and verified numerically by Ciftja and Wexler [13]. The integral is infrared-finite (no divergence as $|\mathbf{x}-\mathbf{y}| \to 0$ in 3D) and scales as $L^5 = V^{5/3}$.

With $V = L^3$, the Fock state decoherence rate is:

Fock state decoherence rate.

$$\Gamma_{\text{Fock}} = \frac{G\,(n-m)^2\,\hbar\omega_k^2\,C_{\text{cube}}}{c^4\,L}. \tag{13}$$

The rate scales as $(n-m)^2$, ω_k^2, and $1/L$.

3.2 Numerical estimates

The fundamental scale is $G\hbar/c^4 = 8.71 \times 10^{-79}\,\mathrm{m}^2\,\mathrm{s}$, an extraordinarily small number. Table 1 gives decoherence rates for representative systems.

Table 1: *Gravitational decoherence rates for Fock state superpositions* $(|n\rangle + |m\rangle)/\sqrt{2}$ *with* $|n - m| = 1$.

System	$\omega\,[\mathrm{s}^{-1}]$	$L\,[\mathrm{m}]$	$\Gamma\,[\mathrm{s}^{-1}]$	τ
Optical photon	3×10^{15}	1	9.3×10^{-48}	10^{40} yr
Microwave photon	10^{10}	0.1	1.0×10^{-57}	10^{50} yr
Phonon (1 GHz)	6×10^{9}	10^{-4}	3.7×10^{-55}	10^{47} yr

Gravitational decoherence of photon or phonon number states is negligible by any measure. The decoherence time exceeds the age of the universe by more than 36 orders of magnitude.

3.3 Consistency with the first-quantized limit

For a single massive particle ($n = 1$, $m = 0$) in a mode of wavelength $\lambda \sim d$ (the superposition separation), the frequency is $\omega_k = mc^2/\hbar$ and the mode size is $L \sim d$. Equation (13) gives

$$\Gamma = \frac{G\,\hbar\,(mc^2/\hbar)^2\,C_{\mathrm{cube}}}{c^4\,d} = \frac{G\,m^2\,C_{\mathrm{cube}}}{\hbar\,d}\,, \tag{14}$$

which reproduces the Diósi-Penrose rate $GM^2/(\hbar d)$ up to the geometric factor $C_{\mathrm{cube}} \approx 1.192$. The factor arises from treating the mass as uniformly distributed over the mode volume rather than as a point particle; in the limit of a localized wave packet ($\sigma \ll d$), the self-energy integral reduces to the point-particle result with $C_{\mathrm{cube}} \to 1$. This is a non-trivial consistency check of the formalism.

3.4 Multi-mode generalization

For a superposition involving multiple modes, $(|\{n_k\}\rangle + |\{m_k\}\rangle)/\sqrt{2}$, the total energy difference is $\Delta E = \sum_k (n_k - m_k)\hbar\omega_k$, and the energy density difference remains spatially uniform. The decoherence rate is

$$\Gamma = \frac{G\,(\Delta E)^2\,C_{\mathrm{cube}}}{\hbar\,c^4\,L}\,, \tag{15}$$

where ΔE is the *total* energy difference. Importantly, the rate depends on $(\Delta E)^2$, not on the sum of individual mode rates. This means constructive interference between modes enhances the decoherence, while modes that partially cancel each other's energy difference reduce it.

4 Coherent and Squeezed States

4.1 Coherent state superpositions

For a superposition of coherent states $(|\alpha\rangle + |\beta\rangle)/\sqrt{2}$, the energy density difference is

$$\Delta T^{00} = \frac{(|\alpha|^2 - |\beta|^2)\,\hbar\omega}{V}\,, \tag{16}$$

and the decoherence rate is

$$\Gamma_{\mathrm{coh}} = \frac{G\,(|\alpha|^2 - |\beta|^2)^2\,\hbar\omega^2\,C_{\mathrm{cube}}}{c^4\,L}\,. \tag{17}$$

This has the same form as the Fock state result (13) with $n \to |\alpha|^2$, $m \to |\beta|^2$.

Electromagnetic cat states. For a Schrödinger cat state of a laser field ($|\alpha|^2 = N \sim 10^{18}$, $|\beta|^2 = 0$):

$$\Gamma \sim N^2 \times 10^{-48}\,\mathrm{s}^{-1} \sim 10^{-12}\,\mathrm{s}^{-1} \qquad (N = 10^{18})\,. \tag{18}$$

Even macroscopic cat states of photons are immune to gravitational decoherence ($\tau \sim 10^4\,\mathrm{yr}$).

Massive boson condensates. For a Bose-Einstein condensate of N atoms of mass m in a trap of size L, a superposition of N and 0 atoms gives

$$\Gamma_{\mathrm{BEC}} = \frac{G\,N^2\,m^2\,C_{\mathrm{cube}}}{\hbar\,L}\,, \tag{19}$$

which reproduces the many-body scaling $\Gamma \propto N^2$ established in the first-quantized framework [1, 7]. For $N = 10^6$ rubidium atoms ($m = 1.44 \times 10^{-25}\,\mathrm{kg}$) in a $100\,\mu\mathrm{m}$ trap: $\Gamma \sim 10^{-10}\,\mathrm{s}^{-1}$ ($\tau \sim 300\,\mathrm{yr}$).

4.2 Squeezed state superpositions

A squeezed vacuum state $|r\rangle$ has mean occupation $\langle\hat{N}\rangle = \sinh^2 r$ and energy $E = \hbar\omega(\sinh^2 r + \frac{1}{2})$. For a superposition of squeezed vs. vacuum ($r_1 = r$, $r_2 = 0$):

$$\Gamma_{\mathrm{sq}} = \frac{G\,\hbar\omega^2\,\sinh^4(r)\,C_{\mathrm{cube}}}{c^4\,L}\,. \tag{20}$$

The rate grows as e^{4r} for large squeezing. Despite this exponential enhancement, the rates remain negligible for electromagnetic fields:

LIGO squeezed light. With $\lambda = 1064\,\mathrm{nm}$, $r \approx 1.7$ (15 dB), and $L = 4\,\mathrm{km}$:

$$\Gamma_{\mathrm{LIGO}} \approx 3.6 \times 10^{-50}\,\mathrm{s}^{-1}\,. \tag{21}$$

Gravitational decoherence does *not* limit the squeezing achievable in gravitational wave detectors.

Fundamental squeezing limit. For massive bosons ($\omega = mc^2/\hbar$), the maximum squeezing before gravitational decoherence dominates is

$$r_{\max} = \frac{1}{4}\ln\!\left(\frac{16\,\hbar\,L}{G\,m^2\,C_{\mathrm{cube}}\,\tau_{\mathrm{exp}}}\right), \tag{22}$$

where τ_{exp} is the experimental timescale. For atomic-mass bosons ($m = 1.66 \times 10^{-27}\,\mathrm{kg}$, $L = 1\,\mathrm{m}$, $\tau_{\mathrm{exp}} = 1\,\mathrm{s}$): $r_{\max} \approx 18$, corresponding to $\sim$155 dB—far beyond any achievable squeezing.

4.3 Summary of rates

Table 2 collects the key results.

Table 2: *Gravitational decoherence rates for different field states. All rates use* $C_{\text{cube}} = 1.192$.

State	Rate formula	Magnitude
Fock $\lvert n\rangle + \lvert m\rangle$ (photon)	$G(n-m)^2\hbar\omega^2/(c^4L)$	$\sim 10^{-48}\,\text{s}^{-1}$
Coherent cat (laser, $N = 10^{18}$)	$GN^2\hbar\omega^2/(c^4L)$	$\sim 10^{-12}\,\text{s}^{-1}$
Massive particle ($1\,\mu$g)	$Gm^2/(\hbar d)$	$6.3 \times 10^8\,\text{s}^{-1}$
LIGO squeezed ($r = 1.7$)	$G\hbar\omega^2 \sinh^4(r)/(c^4L)$	$\sim 10^{-50}\,\text{s}^{-1}$
Inflation ($N \sim 8$)	$\varepsilon_{\text{grav}}\, e^{4N}\, H/16$	$\sim H_{\text{inf}}$

The central conclusion: gravitational decoherence is entirely negligible for massless fields but becomes significant for massive particles (recovering the standard Diósi-Penrose prediction) and—remarkably—for inflationary perturbations, where exponential squeezing compensates for the weakness of gravity.

5 Inflationary Perturbations

We now apply the second-quantized Diósi-Penrose formalism to the quantum-to-classical transition of primordial perturbations during inflation. This is the central application of the paper: physical arguments suggest that inflation produces highly squeezed quantum states whose gravitational self-energy grows exponentially with the number of e-folds after horizon crossing, leading to rapid self-gravitational decoherence. The estimate involves several approximations (flat-space kernel, gauge-dependent T^{00}, unverified $O(1)$ coefficient) detailed in Section 5.5; the result should therefore be understood as a motivated order-of-magnitude estimate with the correct parametric dependence on $\varepsilon_{\text{grav}}$.

5.1 Inflationary perturbations as squeezed states

During slow-roll inflation, scalar perturbations are described by the Mukhanov-Sasaki variable v_k, which satisfies a parametric oscillator equation in conformal time η [16, 18]:

$$v_k'' + \left(k^2 - \frac{z''}{z}\right) v_k = 0, \tag{23}$$

where $z = a\dot{\phi}/H$ and primes denote derivatives with respect to conformal time. Deep inside the horizon ($k \gg aH$), each mode begins in the Bunch-Davies vacuum $\lvert 0_k\rangle$. After horizon crossing ($k \ll aH$), the time-dependent effective frequency in Eq. (23) acts as a parametric amplifier, squeezing the vacuum into a two-mode squeezed state [17, 30]:

$$\lvert \Psi_k\rangle = \hat{S}(r_k, \varphi_k)\,\lvert 0_k\rangle\,, \qquad r_k \approx N_k, \tag{24}$$

where $\hat{S}$ is the squeezing operator, r_k is the squeezing parameter, φ_k is the squeezing angle, and N_k is the number of e-folds elapsed since mode k crossed the horizon. The approximation $r_k \approx N_k$ holds to leading order in slow-roll parameters [9].

The mean occupation number of the squeezed state grows exponentially:

$$\bar{n}_k = \sinh^2(r_k) \approx \frac{1}{4} e^{2N_k} \qquad (N_k \gg 1). \tag{25}$$

The energy per mode is $E_k = \hbar\omega_k(\bar{n}_k + 1/2)$, where $\omega_k = kc/a$ is the physical frequency. At horizon crossing, $\omega_k \approx H_{\rm inf}$, and this frequency redshifts as a^{-1} thereafter. The enormous occupation numbers ($\bar{n}_k \sim 10^{40}$ for modes that crossed the horizon ~ 50 e-folds before the end of inflation) are what make inflationary perturbations effectively classical in terms of their power spectrum—but the quantum coherence of the squeezed state is a separate question that decoherence must address.

5.2 Gravitational self-energy of a perturbation mode

To compute the decoherence rate, we need the gravitational self-energy of a single perturbation mode. The energy density perturbation associated with mode k in a Hubble volume $V_H = (c/H_{\rm inf})^3$ is

$$\delta T^{00}_k \sim \frac{\hbar\omega_k\,\bar{n}_k}{V_H}, \tag{26}$$

where we use $\omega_k \approx H_{\rm inf}$ at horizon crossing. The gravitational self-energy of this perturbation, evaluated using the Diósi kernel over the Hubble volume with characteristic scale $L_H = c/H_{\rm inf}$, is

$$E_G(k) = \frac{G\,(\Delta E_k)^2}{c^4\,L_H}, \tag{27}$$

where $\Delta E_k = \hbar\omega_k\,\bar{n}_k$ is the energy fluctuation of the mode. The factor $c^4 L_H$ in the denominator ensures correct dimensions: $[G][E^2]/[c^4][L] = [\text{energy}]$.

Substituting $\omega_k = H_{\rm inf}$ and $\bar{n}_k \approx e^{2N_k}/4$ from Eq. (25):

$$E_G(k) \sim \frac{G\,\hbar^2 H_{\rm inf}^3}{c^5} \cdot \frac{e^{4N_k}}{16}. \tag{28}$$

The decoherence rate is then $\Gamma_k = E_G(k)/\hbar$, giving

$$\Gamma_k \sim \frac{G\,\hbar\,H_{\rm inf}^3}{c^5} \cdot \frac{e^{4N_k}}{16}. \tag{29}$$

5.3 Decoherence rate versus Hubble rate

The physically meaningful quantity is the ratio of the decoherence rate to the Hubble expansion rate. Classicalization occurs when $\Gamma_k > H_{\rm inf}$. From Eq. (29):

$$\frac{\Gamma_k}{H_{\rm inf}} \sim \varepsilon_{\rm grav} \cdot \frac{e^{4N_k}}{16}, \tag{30}$$

where we define the dimensionless gravitational coupling

$$\varepsilon_{\rm grav} \equiv \frac{G\,\hbar\,H_{\rm inf}^2}{c^5} = \left(\frac{\hbar H_{\rm inf}}{E_P}\right)^2 = \left(\frac{H_{\rm inf}}{M_P c^2/\hbar}\right)^2, \tag{31}$$

with $E_P = M_P c^2 = \sqrt{\hbar c^5/G}$ the Planck energy. When $H_{\rm inf}$ is quoted in energy units (i.e., as the energy $\hbar H_{\rm inf}$ in GeV), the formula $(\hbar H_{\rm inf}/E_P)^2$ uses $H_{\rm inf}$ as a rate (s^{-1}), so that $\hbar H_{\rm inf}$ has dimensions of energy. This parameter is directly related to the tensor-to-scalar ratio through $\varepsilon_{\rm grav} = r_{\rm tensor}/(128\pi)$ in single-field slow-roll inflation [19].

Setting $\Gamma_k = H_{\rm inf}$ in Eq. (30) and solving for N_k:

Key Result. A scalar perturbation mode undergoes self-gravitational decoherence at

$$\boxed{N_{\rm dec} = \frac{1}{4}\ln\left(\frac{16}{\varepsilon_{\rm grav}}\right)} \tag{32}$$

e-folds after horizon crossing, where $\varepsilon_{\rm grav} = (\hbar H_{\rm inf}/E_P)^2$. For GUT-scale inflation ($H_{\rm inf} \sim 10^{13}$ GeV), $\varepsilon_{\rm grav} \approx 6.7 \times 10^{-13}$ and $N_{\rm dec} \approx 7.7$.

Since all observable modes in the CMB cross the horizon between ~ 50 and ~ 60 e-folds before the end of inflation, they have $N_k \gg N_{\rm dec}$ by the end of inflation. The quantum coherence of primordial perturbations is destroyed by their own gravitational self-energy long before the modes re-enter the horizon.

5.4 Dependence on inflationary energy scale

The decoherence e-fold number $N_{\rm dec}$ depends logarithmically on the inflationary Hubble scale. Table 3 shows this dependence across the range of inflationary models.

$H_{\rm inf}$ (GeV)	$\varepsilon_{\rm grav}$	$N_{\rm dec}$	Comment
10^7	6.7×10^{-25}	14.6	Low-scale inflation
10^9	6.7×10^{-21}	12.3	Intermediate
10^{11}	6.7×10^{-17}	10.0	
10^{13}	6.7×10^{-13}	7.7	GUT scale
10^{15}	6.7×10^{-9}	5.4	Near Planck
10^{17}	6.7×10^{-5}	3.1	
10^{19}	6.7×10^{-1}	0.8	Planck scale

Table 3: *Decoherence e-fold number $N_{\rm dec}$ as a function of the inflationary Hubble scale. The column header $H_{\rm inf}$ (GeV) denotes the energy $\hbar H_{\rm inf}$ expressed in GeV, so that $\varepsilon_{\rm grav} = (\hbar H_{\rm inf}/E_P)^2 = (H_{\rm inf}[\text{GeV}]/1.22 \times 10^{19}\,\text{GeV})^2$. Values are computed from Eq. (32). For all scales above $H_{\rm inf} \sim 10^3$ GeV, the condition $N_{\rm dec} < 50$ is satisfied, meaning that all observable CMB modes undergo self-gravitational decoherence well before the end of inflation.*

Two features of Table 3 are noteworthy. First, the logarithmic dependence on $\varepsilon_{\rm grav}$ means that $N_{\rm dec}$ varies only by a factor of ~ 2 across twelve orders of magnitude in the inflationary scale. The mechanism is robust: for any inflationary model compatible with observational bounds, decoherence occurs within the first ~ 15 e-folds after horizon crossing. Second, for Planck-scale inflation, $N_{\rm dec} \approx 0.8$, meaning classicalization is nearly immediate—the perturbation decoheres within a single e-fold of leaving the horizon.

5.5 Caveats

Several approximations enter the calculation above, and we assess their impact on the result.

Flat-space kernel in de Sitter background. The Diósi kernel $|\mathbf{x}-\mathbf{y}|^{-1}$ is the Newtonian gravitational potential, not the de Sitter propagator. On sub-Hubble scales the two agree, but at separations $|\mathbf{x}-\mathbf{y}| \gtrsim c/H_{\rm inf}$ the de Sitter propagator differs. Since the dominant contribution to the self-energy integral comes from scales $\sim L_H$, this affects the $O(1)$ coefficient in Eq. (27) but not the parametric dependence on $\varepsilon_{\rm grav}$ or N_k.

Gauge dependence. The energy density T^{00} is gauge-dependent, while the comoving curvature perturbation ζ is gauge-invariant. A fully covariant formulation should express the decoherence rate in terms of ζ. In comoving gauge, ζ is directly related to the spatial metric perturbation, and our estimate for E_G corresponds to this gauge choice. The parametric scaling is gauge-invariant; only the $O(1)$ coefficient may shift under gauge transformations.

Backreaction. The perturbation contributes to the background energy density at order $\mathcal{P}_\zeta \sim 10^{-9}$, which is negligible. Self-consistently, the decoherence mechanism does not destabilize the inflationary background.

Mode-mode correlations. We have computed single-mode decoherence, neglecting cross-correlations between different k-modes. Since different Fourier modes are independent at the Gaussian level, cross-terms enter only through non-Gaussianities and are suppressed by $f_{\rm NL} \cdot \mathcal{P}_\zeta \ll 1$.

Markov approximation. The decoherence rate (29) is derived in the Markovian regime. For $N_k \lesssim 1$, the mode has not yet evolved significantly past the horizon and non-Markovian memory effects may be important. However, $N_{\rm dec} > 1$ for all sub-Planckian inflationary scales (Table 3), so the Markov approximation is self-consistently valid in the regime where the result applies.

5.6 Comparison with environmental decoherence

Our self-gravitational mechanism should be compared with the well-studied environmental decoherence of inflationary perturbations, in which short-wavelength modes serve as an environment that decoheres long-wavelength modes [8, 20, 21].

Kiefer, Polarski, and Starobinsky [8] found that environmental decoherence produces a rate

$$\frac{\Gamma_{\rm env}}{H_{\rm inf}} \sim \left(\frac{H_{\rm inf}}{M_P c^2/\hbar}\right)^2 = \varepsilon_{\rm grav}, \tag{33}$$

with a weaker N-dependence than our Eq. (30). The parametric scaling with $(H_{\rm inf}/M_P)^2$ is the *same* in both mechanisms. This agreement is suggestive: both the self-gravitational and environmental channels produce decoherence rates controlled by the single dimensionless parameter $\varepsilon_{\rm grav}$.

The mechanisms differ in their physical origin. Environmental decoherence requires mode-mode coupling: short-wavelength perturbations act as an effective environment for long-wavelength modes, and tracing over the short-wavelength sector generates a mixed state for the long-wavelength modes [21]. Our mechanism is self-contained: the gravitational self-energy of a *single* mode suffices to drive decoherence, with no mode coupling required. The shared parametric scaling may reflect the fact that both mechanisms ultimately originate from the same underlying gravitational physics—the Hamiltonian constraint of general relativity, which couples all gravitational degrees of freedom non-perturbatively.

5.7 Observable signatures

The decoherence of inflationary perturbations leaves specific imprints—and specific non-imprints—on observables.

Power spectrum. The primordial power spectrum $\mathcal{P}_\zeta(k)$ is determined by the diagonal elements of the density matrix, which are unaffected by decoherence. The observed spectrum is therefore unchanged: $\mathcal{P}_\zeta(k) = H_{\rm inf}^2/(8\pi^2 M_P^2 \epsilon)$ regardless of whether decoherence occurs. This explains why the standard inflationary predictions for the power spectrum are successful despite neglecting decoherence.

Non-Gaussianity. Quantum mechanical contributions to non-Gaussianity—specifically, those arising from interference between different field configurations—are suppressed by decoherence. Classical non-Gaussianity of order $f_{\rm NL} \sim \mathcal{O}(\epsilon, \eta)$ from the nonlinear evolution of ζ survives, as it is encoded in the diagonal density matrix elements. This provides a consistency check: if quantum contributions to $f_{\rm NL}$ were ever isolated, their suppression would test the classicalization mechanism.

Bell inequality violations. Quantum correlations between perturbation modes that would violate Bell-type inequalities [22, 23] are destroyed by decoherence well before any observation could detect them. The prediction is therefore that no Bell violation should be observable in the CMB, consistent with its manifestly classical statistical properties.

Classicalization timescale. The prediction $N_{\rm dec} \approx (1/4)\ln(16/\varepsilon_{\rm grav})$ is, in principle, testable through its effect on the suppression of quantum non-Gaussianity as a function of scale. Modes that crossed the horizon later (smaller N_k) have had less time to decohere; if N_k were comparable to $N_{\rm dec}$, residual quantum coherence could leave a scale-dependent signature. For realistic inflationary models, however, all observable modes satisfy $N_k \gg N_{\rm dec}$, and this signature is unobservably small.

6 Discussion and Conclusions

6.1 Summary of results

We have extended the Diósi-Penrose gravitational decoherence formalism from point particles to quantum fields. The field-theoretic master equation (5) replaces the mass density operator with $\hat{T}^{00}/c^2$ and yields decoherence rates for arbitrary field-state superpositions via the gravitational self-energy formula (6).

Three classes of field states were analyzed:

1. *Fock states*: $\Gamma \propto (n-m)^2\omega^2/L$, negligible for photons ($\sim 10^{-48}\,\mathrm{s}^{-1}$), reduces to $GM^2/(\hbar d)$ for massive particles.

2. *Coherent and squeezed states*: negligible for electromagnetic fields; squeezed states grow as e^{4r} but remain unobservable for photons.

3. *Inflationary perturbations*: the exponential squeezing $r \sim N$ compensates for gravitational weakness, giving classicalization at $N_{\rm dec} \approx 7$–8 e-folds after horizon crossing for GUT-scale inflation.

6.2 Relation to the constrained influence functional

The decoherence rates derived here use the Diósi master equation (5) as input. A companion paper [6] derives this master equation from the constrained Feynman-Vernon influence functional: imposing the linearized Wheeler-DeWitt constraint on the Schwinger-Keldysh path integral replaces the G^2 noise-kernel mechanism with a G^1 coherent-state-overlap mechanism. The present paper takes the G^1 rate as given and extends it to field configurations.

6.3 Limitations

Several limitations should be noted.

Newtonian kernel in curved spacetime. The Diósi kernel $1/|\mathbf{x}-\mathbf{y}|$ is the flat-space Newtonian Green function. For the inflationary application (Section 5), the relevant propagator is the de Sitter Green function, which differs significantly at super-Hubble separations. This affects the $O(1)$ coefficient in Γ/H but not the parametric scaling $\varepsilon_{\rm grav}\, e^{4N}$.

Gauge dependence. The stress-energy $\hat{T}^{00}$ is not gauge-invariant; the comoving curvature perturbation ζ is. A fully gauge-invariant formulation of the gravitational decoherence master equation in cosmology is an important open problem.

UV regularization. The kernel $1/|\mathbf{x}-\mathbf{y}|$ is singular at coincident points. For the box calculations (Sections 3–4), the integral is IR-finite in 3D, but the field-theoretic product $\hat{T}^{00}(\mathbf{x})\hat{T}^{00}(\mathbf{y})$ requires point-splitting or mode-cutoff regularization. We work with expectation values, which are finite, deferring the full operator treatment.

6.4 Comparison with prior work

The quantum-to-classical transition of inflationary perturbations has been studied extensively [8, 9, 10, 11]. Kiefer, Polarski, and Starobinsky [8] showed that tracing over short-wavelength modes as an environment decoheres long-wavelength perturbations at a rate $\Gamma_{\rm env}/H \sim (H/M_P)^2 = \varepsilon_{\rm grav}$—the *same parametric scaling* as our self-gravitational result. This agreement is suggestive: both mechanisms may represent different facets of the same constraint-enforced physics, viewed from the perturbative (mode-coupling) and non-perturbative (self-energy) perspectives respectively.

Our mechanism is distinguished by being *self-contained*: it requires only the gravitational self-energy of a single perturbation mode, not coupling to other modes or an external environment. Physical arguments suggest a classicalization timescale depending only on the inflationary Hubble rate $H_{\rm inf}$ through $\varepsilon_{\rm grav}$, with no free parameters beyond the approximations noted in Section 5.5.

6.5 Conclusions

Gravitational decoherence in the second-quantized setting is negligible for massless fields but significant for massive particles and—through the exponential amplification of squeezing—for inflationary perturbations. The self-gravitational classicalization of primordial perturbations at $N_{\rm dec} \sim \frac{1}{4}\ln(16/\varepsilon_{\rm grav})$ e-folds after horizon crossing provides a universal mechanism for the quantum-to-classical transition that involves no free parameters beyond the order-of-magnitude approximations detailed in Section 5.5, complementary to environmental decoherence. The consistency of the field-theoretic formalism with the established point-particle results (recovering $GM^2/(\hbar d)$ in the appropriate limit) validates the extension and suggests that the Diósi master equation captures the essential physics of gravitational decoherence across all energy scales from laboratory to cosmological.

Appendices

A The Geometric Double Integral

The gravitational self-energy of a uniform density distribution in a cube of side L requires the double integral

$$\mathcal{J}(L) = \int_0^L \int_0^L \int_0^L \int_0^L \int_0^L \int_0^L \frac{dx\, dy\, dz\, dx'\, dy'\, dz'}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} \,. \tag{34}$$

By dimensional analysis, $\mathcal{J}(L) = C_{\rm cube}\, L^5$ for some dimensionless constant $C_{\rm cube}$.

Convergence. The integrand $1/r$ is integrable in $\mathbb{R}^3$ because the volume element $d^3x\, d^3y$ scales as $r^5\, dr$ near the diagonal $\mathbf{x} = \mathbf{y}$, which overcomes the $1/r$ singularity. The integral is therefore finite without regularization.

Numerical value. The constant has been computed by Chandrasekhar [12] in the context of gravitational self-energy calculations and verified by Ciftja and Wexler [13] using Monte Carlo integration:

$$C_{\rm cube} = \frac{\mathcal{J}(L)}{L^5} \approx 1.19189 \,. \tag{35}$$

For comparison, a uniform sphere of radius R gives $\mathcal{J}_{\rm sphere} = \frac{6}{5}(4\pi/3)^{2/3}\, R^5 \times R^{-1} = (6/5) \times (4\pi R^3/3)^{5/3}/R$. More directly, for a sphere the self-energy integral $\int\int \rho^2/r\, d^3x\, d^3y = (3/5)M^2/(R)$, giving the Chandrasekhar coefficient $C_{\rm sphere} = 6/5 = 1.200$—very close to $C_{\rm cube}$, reflecting the approximate shape-independence of the gravitational self-energy for compact objects.

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