Decoherence caused by DM in Macro-superposition of Harmonic Oscillator

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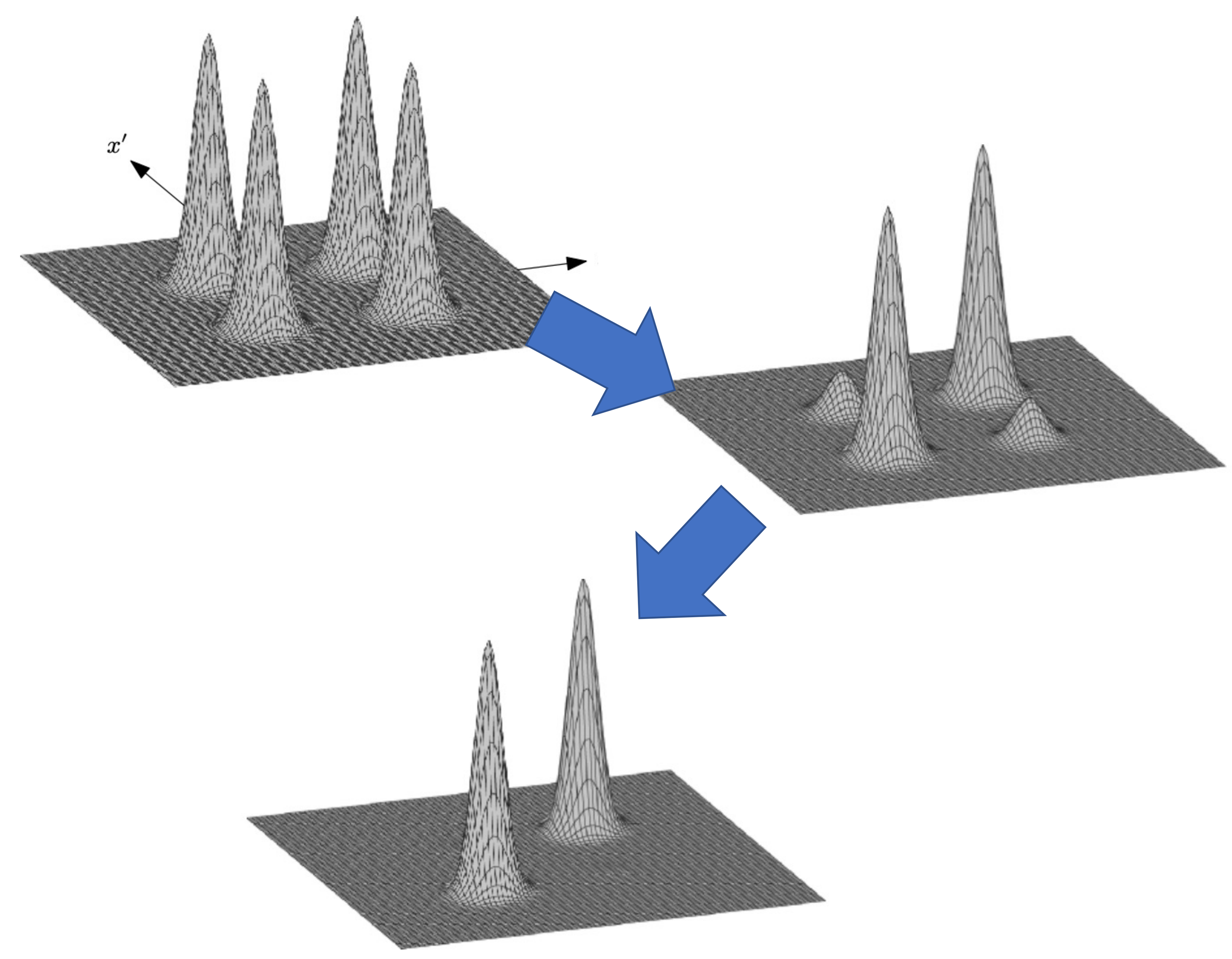


Fig. 3.11. Time evolution of the density matrix $\rho_S(x, x', t)$ for the superposition (3.96) of two Gaussian wave packets. Interference terms along the off-diagonal $x = -x'$ become progressively damped by the scattering of environmental particles.

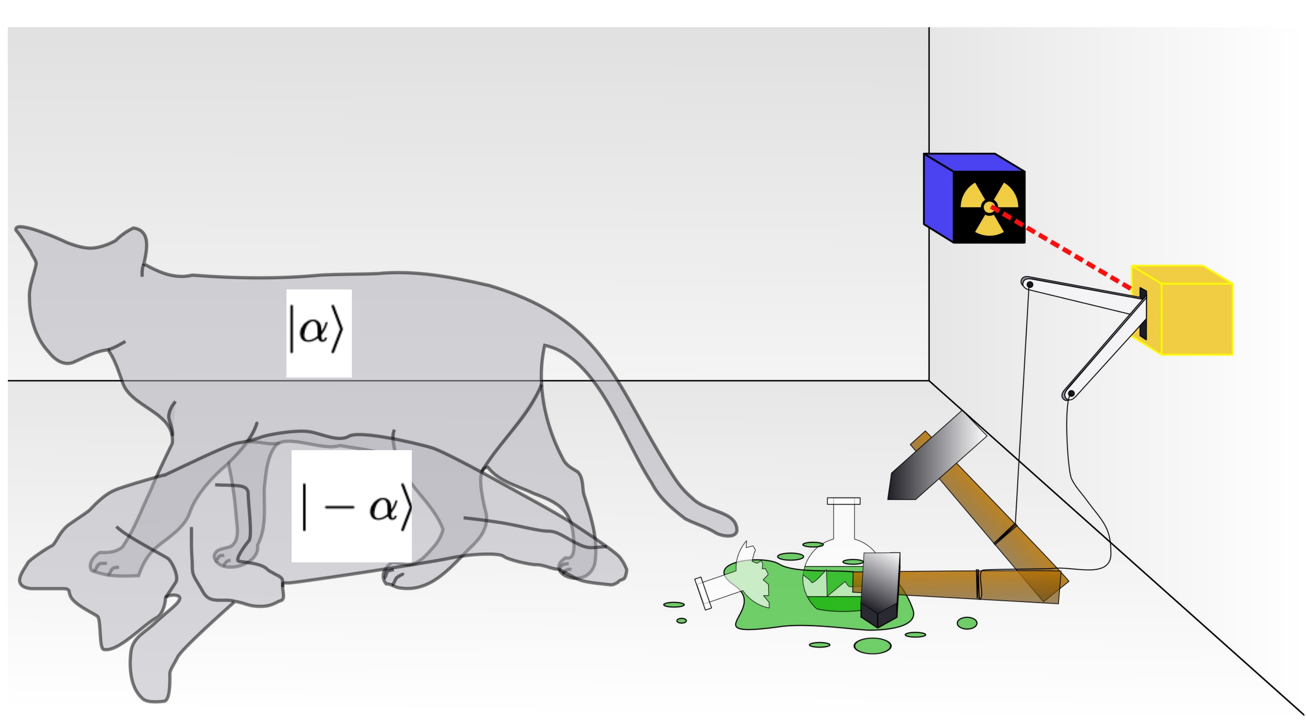
A illustrate figure from 《Decoherence and the Quantum-To-Classical Transition》 describing how reduced density matrix evolves over time.

Quantum decoherence means when system coupling with external field (mostly background or apparatus), even the total system is under unitary time evolution, the subsystem after tracing out the background field is undergoing a "**seemingly**" non-unitary process where the nondiagonal component shrink to 0 due to some information of the system been "taken out" or "measured" by the environment. The process of losing of quantum coherence is a pure quantum effect which we **can't** find any correspondence in classical mechanics and usually much faster than energy dissipation and that even exists if the system merely has energy dissipation. Those very delicate properties gives us a very good chance to monitor if DM really acts as a **quantum background**

In our work we verified how dark matter deduce the decoherence for a superposition harmonic oscillator via local interaction (also meaning bosonic quantum field acting on the number(charge) density).

$$H = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2 + \int d^3y[\frac{1}{2}\pi^2 + \frac{1}{2}(\nabla_y\phi)^2 + \frac{1}{2}m_D^2\phi^2] + H_I$$

Where
$$H_I = g_0\int d^3x\phi(x)\frac{J(x)}{m_N} = g\int d^3y\phi(y)\frac{m\delta(y-\hat{x})}{m_N}$$
$$= Ng_0\phi(\hat{x})$$
$$= g\phi(\hat{x})$$



We have used the superposition state performed by coherent state of harmonic oscillator

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}(|\alpha\rangle + |-\alpha\rangle)$$

where $|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}}e^{\alpha a^\dagger}|0\rangle$ and $|\langle\alpha|-\alpha\rangle| \ll 1$

And the background DM field is also described by a collection of coherent state

$$|\beta\rangle = \prod_k |\beta_k\rangle$$

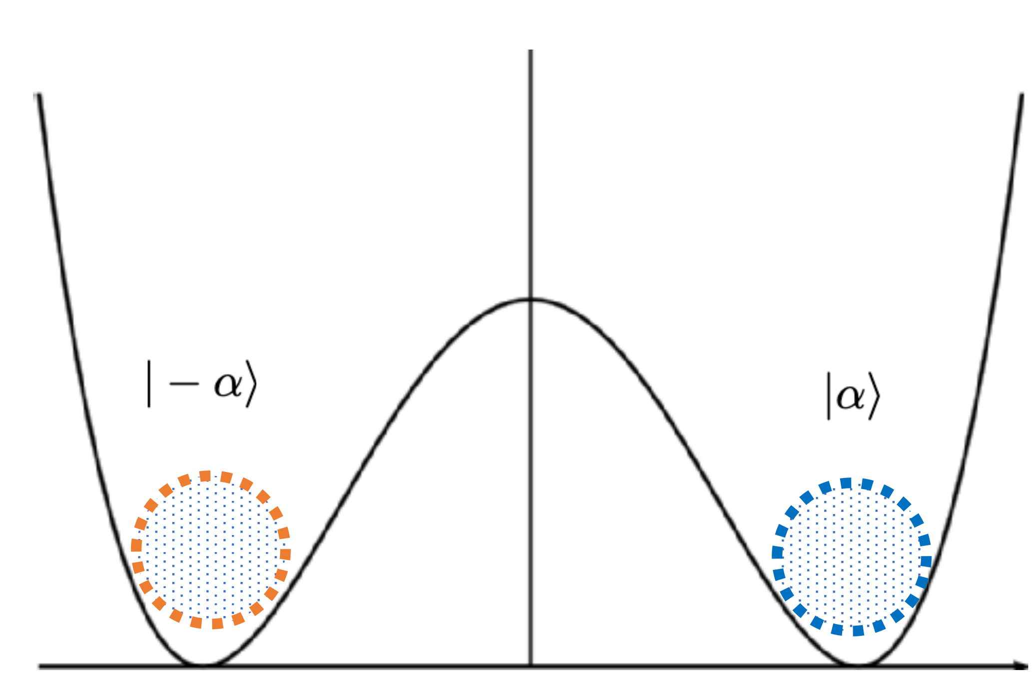
We can then write down the total density matrix and unitary time evolution and also reduced density matrix.

$$U^I(t_1, t_2) = \mathrm{T}\, e^{-i\int_{t_1}^{t_2} dt H_I}$$
$$\hat{\rho}^I(t)_M = \mathrm{tr_B}\, U^I\hat{\rho}^I_{M0} \otimes \hat{\rho}^I_{DM}(t)U^{I\dagger}$$

which can be explicitly evaluated by perturbation expansion (or in other words, by Born approximation)

$$\hat{\rho}_M(t) = \rho_{M0} + \rho_M^{(g)}(t) + \rho_M^{(g^2)}(t) + \ldots\ldots$$

Practically, the superposition state can be performed in a **Quantum Optical** system by adiabatically fine-tuning a double well potential from a ground state of single well potential.



As a result, for a given coupling constant we can evaluate if the superposition state can completely decohere or not in a given time.
2 tensive results are given for the limit of coupling that we can observe decoherence in 1s with mass of the harmonic oscillator (mirror object in quantum optics) = 10^-3 mg and 1 mg.
And the curve "bound" comes from mechanical sensing .(arXiv:2306.16468),Δx_0 means 0-point quantum fluctuation of harmonic oscillator.