Gravitational Decoherence with Applications to Dark Matter Phenomenology

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I.J.A. and Mark P. Hertzberg

1. Motivation

2. Interaction with Environment

3. Decoherence Results

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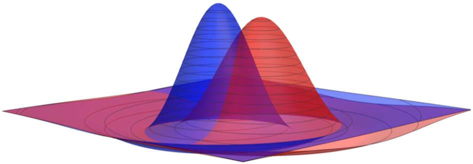
Motivation - Dark Matter Schrödinger Cat

- Gravity is the weakest fundamental interaction
- Matter that interacts only gravitationally may decohere slowly
- Consider a dark matter Schrödinger cat state



- Interested in Axion DM, light and diffuse scalar
- What is the rate of decoherence for this object?

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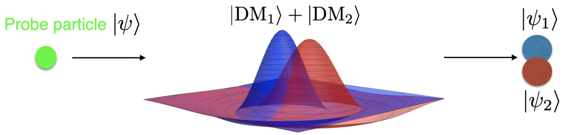
Scattering and Decoherence



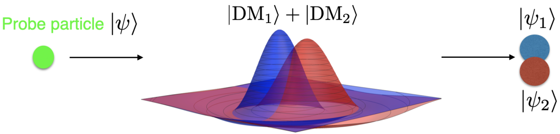
$$\begin{aligned} |\Psi\rangle &= (|\mathrm{DM}_1\rangle + |\mathrm{DM}_2\rangle) \otimes |\psi\rangle \\ &\rightarrow |\mathrm{DM}_1\rangle |\psi_1\rangle + |\mathrm{DM}_2\rangle |\psi_2\rangle \end{aligned} \tag{1}$$

$$\begin{aligned} \rho_{red} &= Tr(|\Psi\rangle \langle\Psi|)_\psi = |\mathrm{DM}_1\rangle \langle \mathrm{DM}_1| + |\mathrm{DM}_2\rangle \langle \mathrm{DM}_2| \\ &+ \langle\psi_2|\psi_1\rangle |\mathrm{DM}_1\rangle \langle\mathrm{DM}_2| + \langle\psi_1|\psi_2\rangle |\mathrm{DM}_2\rangle\langle\mathrm{DM}_1| \end{aligned} \tag{2}$$

$$|\psi_i\rangle = |\psi_u\rangle + |\psi_{s,i}\rangle \tag{3}$$

$$\Gamma_{\mathrm{dec}} \propto \frac{1}{2}(\langle\psi_{s,1}|\psi_{s,1}\rangle + \langle\psi_{s,2}|\psi_{s,2}\rangle - 2\Re[\langle\psi_{s,1}|\psi_{s,2}\rangle]) \tag{4}$$

Scattering and Decoherence



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$$|\psi_i\rangle = |\psi_u\rangle + |\psi_{s,i}\rangle \tag{3}$$

$$\Gamma_{\mathrm{dec}} \approx \frac{1}{2} nv(\tilde{\sigma}_{1,1} + \tilde{\sigma}_{2,2} - 2\Re\tilde{\sigma}_{1,2}) \tag{4}$$

(One-particle) Relativistic Schrödinger Equation

$$i\partial_t |\psi\rangle = \hat{H} |\psi\rangle \tag{5}$$

- Hamiltonian compatible with general relativity (ignoring spin)

$$S = \int d^4x \sqrt{-g} \left(g^{\mu\nu} \partial_\mu \chi^* \partial_\nu \chi - m^2 \chi^* \chi \right) \tag{6}$$

- Quantum gravity calculation, treated in effective field theory

$$g_{\mu\nu} = \mathrm{diag}[(1+2\Phi), -(1-2\Psi), -(1-2\Psi), -(1-2\Psi)] \tag{7}$$

- Ignore number changing processes (one-particle sub-space of Hilbert space)

$$H(\vec{x}, -\nabla^2) = \sqrt{-\nabla^2 + m^2} + \Phi\sqrt{-\nabla^2 + m^2} - \frac{\Psi \nabla^2}{\sqrt{-\nabla^2 + m^2}} \tag{8}$$

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Static Source

$$\psi_s^{(q)}(\vec{x}, t) = e^{-iE_q t} f(\vec{q}', \vec{q}) \frac{e^{iq|\vec{x}|}}{|\vec{x}|} \tag{9}$$

$$f(\vec{q}', \vec{q}) \equiv -\frac{1}{2\pi} \int d^3x' e^{i(\vec{q}-\vec{q}')\cdot\vec{x}'} \left[\Phi(\vec{x}')E_q^2 + \Psi(\vec{x}')q^2\right] \tag{10}$$

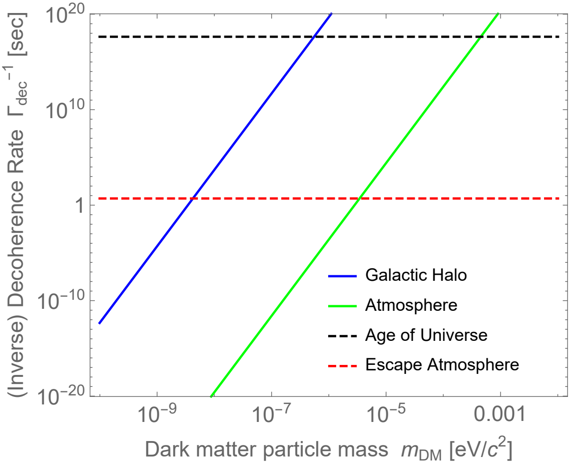
$$\tilde{\sigma}_{ij}(q) \equiv \int d^2\Omega \, f_i^*(\vec{q}', \vec{q}) f_j(\vec{q}', \vec{q}) \tag{11}$$

$$\Gamma_{\text{dec}} \approx \frac{1}{2} nv(\tilde{\sigma}_{1,1} + \tilde{\sigma}_{2,2} - 2\Re\tilde{\sigma}_{1,2}) \tag{12}$$

- Random Gaussian fluctuation in background DM density

$$f(\vec{q}', \vec{q}) \propto G \, e^{-\frac{(\vec{q}-\vec{q}')^2}{4\mu^2}}, \qquad \Gamma_{\text{dec}} \sim \frac{G^2 m_p \rho_{\text{DM}}^2 \rho_p}{m_{\text{DM}}^8 v_{\text{DM}}^8 v_p} \tag{13}$$

Spatial Superposition

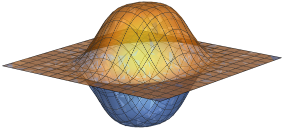


Scattering from Oscillating Scalar

- Typical populations are coherently oscillating scalar fields

$$\phi(r,t) = \sqrt{2}\,\phi_s(r)\cos(\omega t + \varphi) \tag{14}$$

$$\psi_s^{(q)}(\vec{x},t) = \sum_{\alpha=0,-1,+1} e^{-i(E_\alpha t + 2\alpha\varphi)} F_\alpha(\vec{q}'_\alpha, \vec{q}) \frac{e^{iq_\alpha r}}{r} \tag{15}$$



Decoherence of Phase Superposition

- Consider superposition of Axion phase φ_1 and φ_2

$$\Gamma_{\text{dec}} = \frac{1}{2} nv \Big(S_\varphi (\bar{\sigma}_{+1,+1} + \bar{\sigma}_{-1,-1}) - A_\varphi \Re[\bar{\sigma}_{-1,+1}] \Big) \tag{16}$$

$$S_\varphi = 2(1 - \cos(2(\varphi_1 - \varphi_2))) \tag{17}$$

$$A_\varphi = \cos(4\varphi_1) + \cos(4\varphi_2) - 2\cos(2(\varphi_1 + \varphi_2)) \tag{18}$$

- For a Gaussian $\phi_s \propto \exp(-r^2\mu^2/2)$, $\bar{\sigma} \propto \exp(-p_{tr}^2/4\mu^2)$

$$\frac{p_{tr}^2}{4\mu^2}\Big|_{\theta=0} = \frac{\omega^2 E^2}{\mu^2 q^2} \sim \frac{1}{v_a^2 v_p^2} \tag{19}$$

- Slowly-moving DM $\rightarrow$ exponentially suppressed
- Relativistic configurations $\rightarrow$ rapid decoherence

Relativistic Configurations

- Dense boson star (dilute have non-rel. bosons)

$$M \sim \frac{1}{G_N\, m_a}, \quad R \sim \frac{1}{m_a} \tag{20}$$

$$\Gamma_{\rm dec} \sim 10^6\,{\rm s}^{-1} \left(\frac{1\,{\rm eV}}{m_a}\right)^4 \tag{21}$$

- Near black hole horizon, high speeds/density
- Rapid decoherence → "most classical" state enters black hole

Conclusions

- DM interacts primarily gravitationally, prolongs coherence
- Non-relativistic DM in a spatial superposition undergoes decoherence from Newtonian Gravity
- Phase superpositions require General Relativistic treatment
- Typical slowly-moving DM is robust against decoherence of phase
- Possible implications for resonant-cavity haloscope experiments, sensitive to axion phase

$$|\text{axion}\rangle \sim \sum_i c_i |\cos(\omega t - \mathbf{k}_a \cdot \mathbf{x} + \varphi_i)\rangle \tag{22}$$