General Relativistic Decoherence with Applications to Dark Matter

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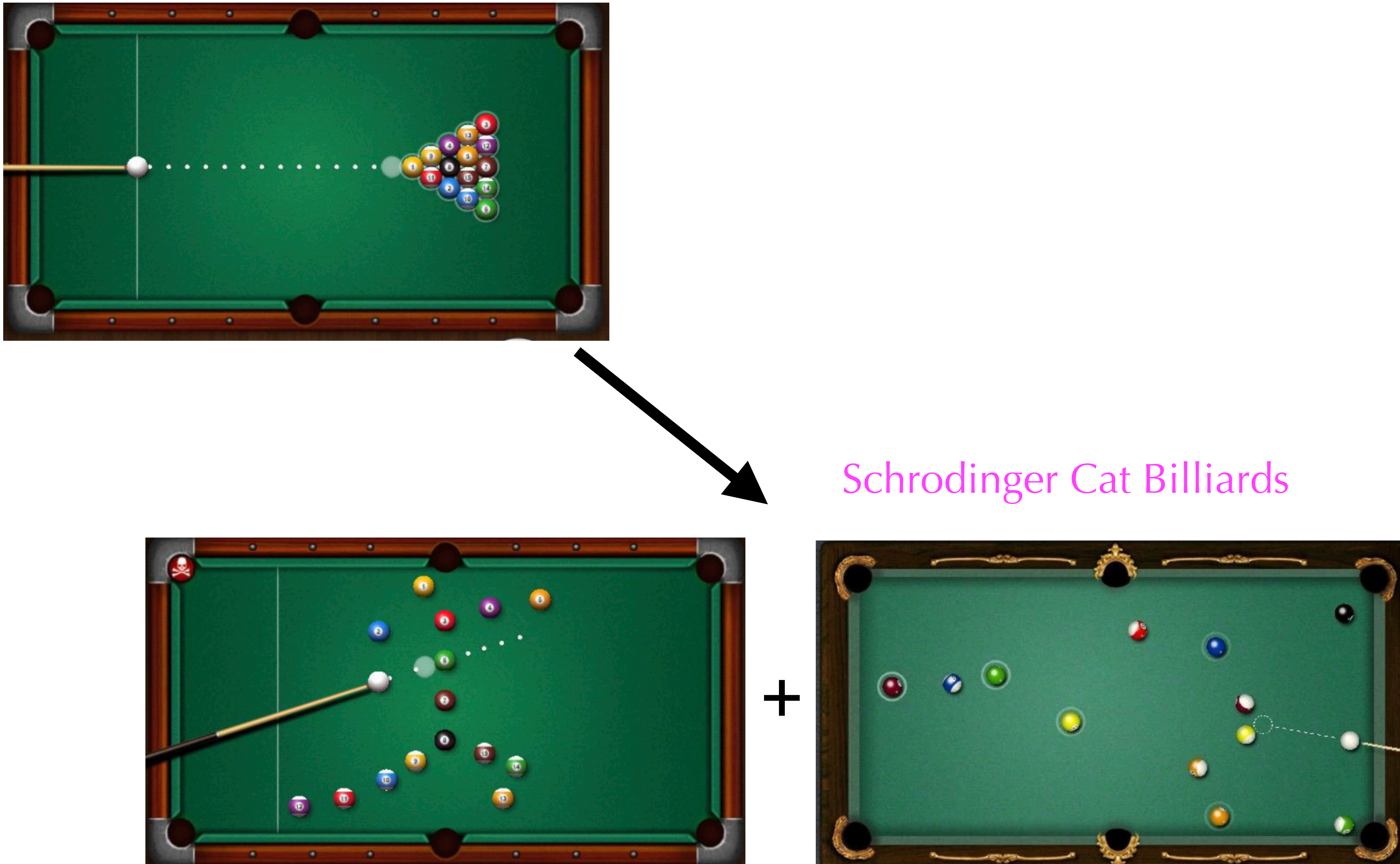
Based on work with Itamar Allali

Allali, Hertzberg 2005.12287 (JCAP), 2012.12903 (PRD), 2103.15892 (PRL)

Dynamics can launch states into Schrodinger cat-like states



Albrecht, Phillips 2012

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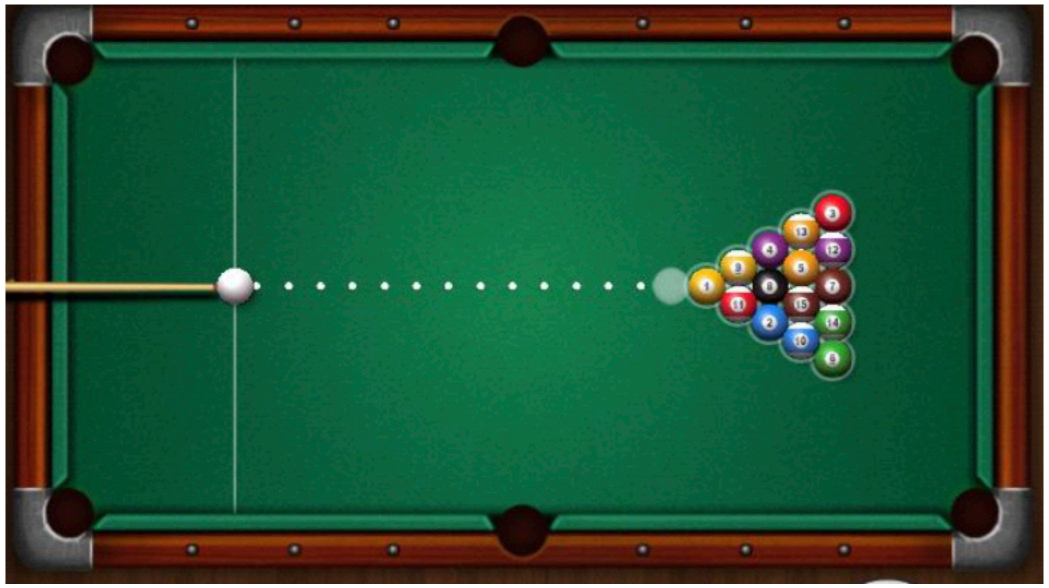
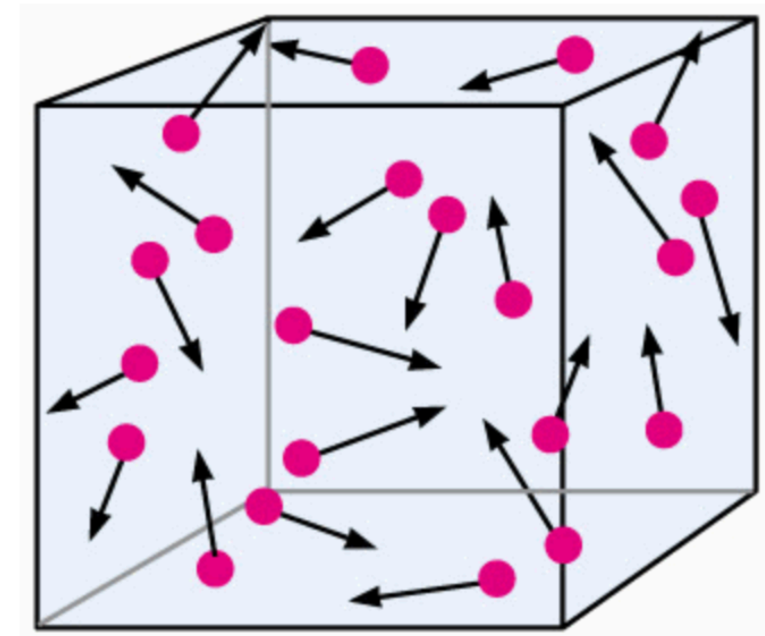
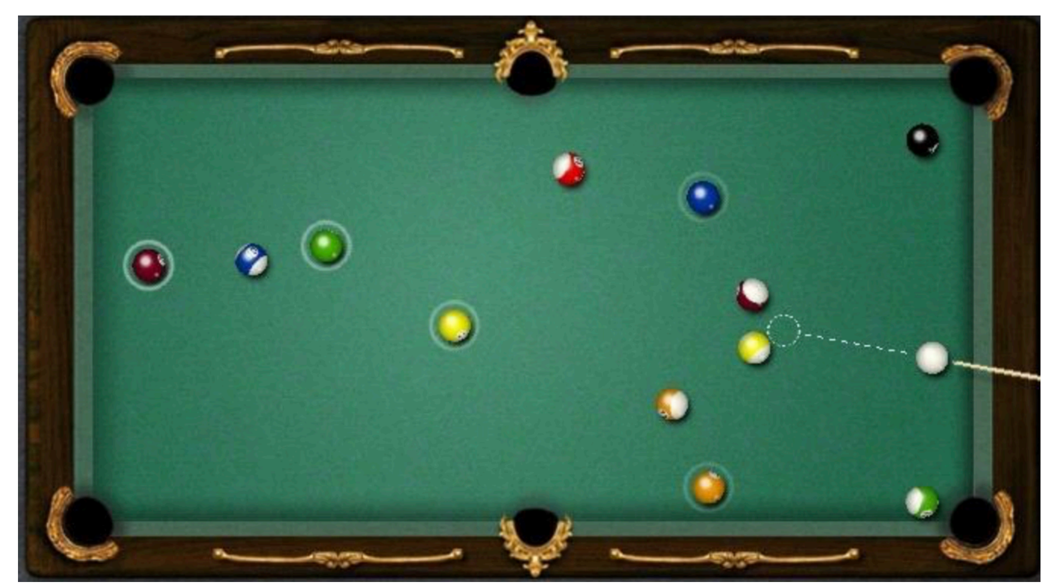




Quantumness destroyed due to DECOHERENCE

Schrodinger Cat Billiards

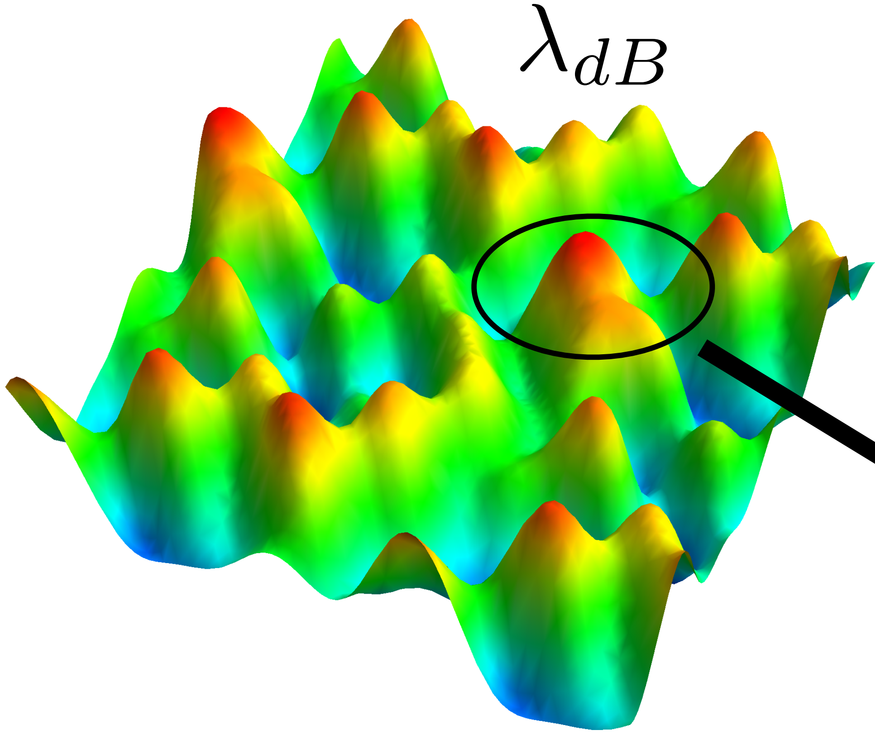
+

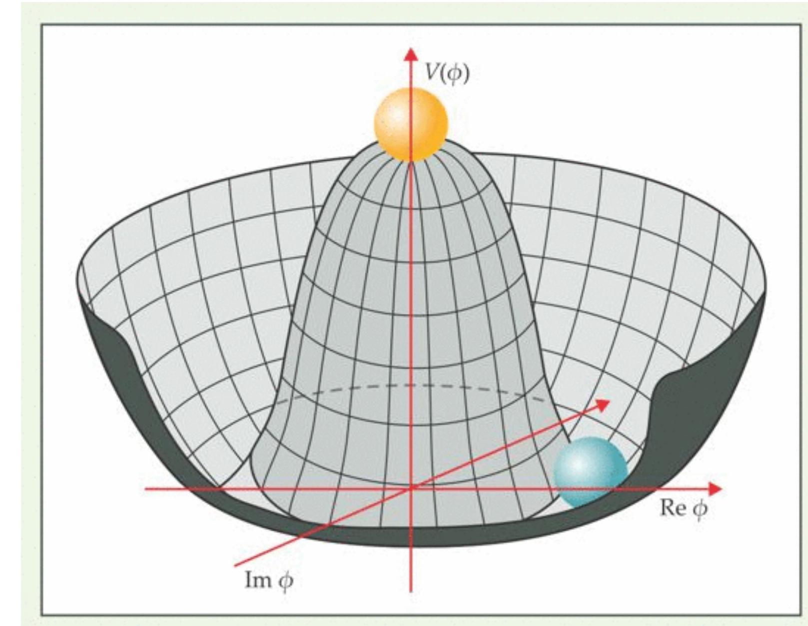


Albrecht, Phillips 2012

What about Dark Matter?
Conceivably in Schrodinger cat-like states too

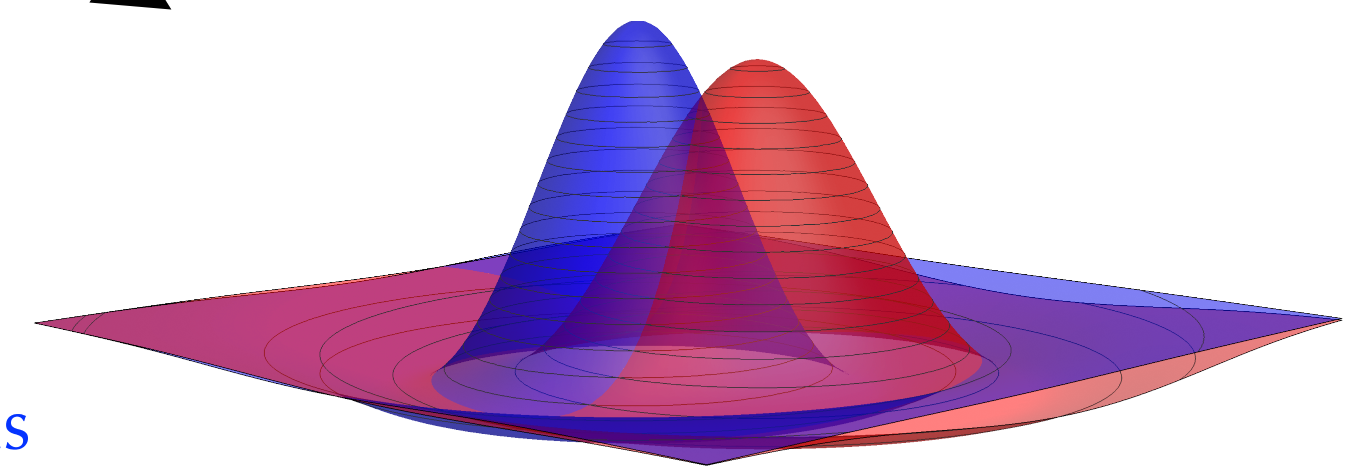
Claims: 0901.1106, 1111.1157, 1607.00949, 1710.02195, 1712.08219





Dark Matter Schrodinger Cat (Axions)

$$|\mathrm{DM}_1\rangle + |\mathrm{DM}_2\rangle$$



Quantumness destroyed due to DECOHERENCE???

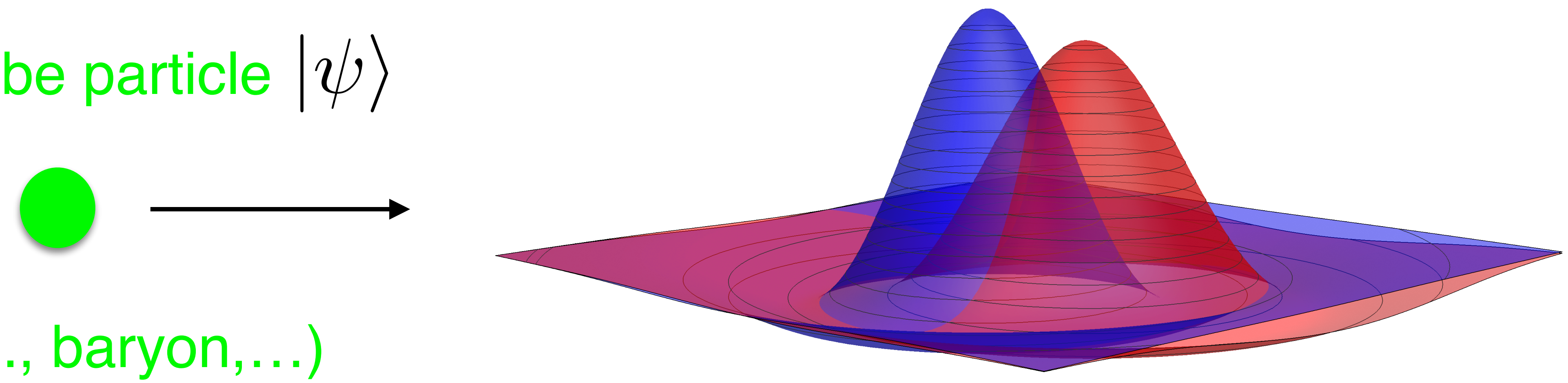
Less clear because dark matter has tiny (non-gravitational) interactions

Claim it affect axion experiments: 2211.13602 Marsh

Environmental Entanglement from Gravitational Scattering

$|\mathrm{DM}_1\rangle + |\mathrm{DM}_2\rangle$

Probe particle $|\psi\rangle$

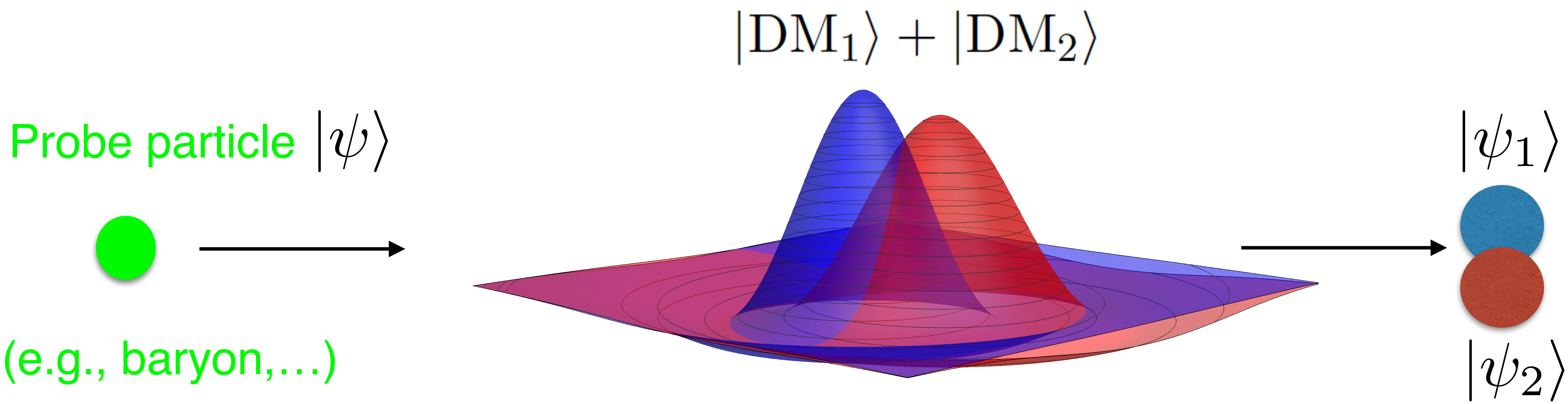


(e.g., baryon,…)

$$|\Psi_{\mathrm{ini}}\rangle = \left(|\mathrm{DM}_1\rangle + |\mathrm{DM}_2\rangle\right)|\psi\rangle$$

Product State with probe particle

Environmental Entanglement from Gravitational Scattering



$$|\Psi_{\text{ini}}\rangle = (|\text{DM}_1\rangle + |\text{DM}_2\rangle)\,|\psi\rangle$$

Product State with probe particle

$$|\Psi_{\text{fin}}\rangle = |\text{DM}_1\rangle\,|\psi_1\rangle + |\text{DM}_2\rangle\,|\psi_2\rangle$$

Entangled State

Trace Out Environmental Probe Particles

$$\hat{\rho} \equiv |\Psi\rangle\langle\Psi|$$ Full Density Matrix

$$\hat{\rho}_{\rm red} = {\rm Tr}_{|\psi\rangle}[\hat{\rho}]$$ Reduced Density Matrix

$$= |{\rm DM}_1\rangle\langle{\rm DM}_1| + \langle\psi_2|\psi_1\rangle|{\rm DM}_1\rangle\langle{\rm DM}_2| + \langle\psi_1|\psi_2\rangle|{\rm DM}_2\rangle\langle{\rm DM}_1| + |{\rm DM}_2\rangle\langle{\rm DM}_2|$$

Off diagonal elements; controlling true quantum effects

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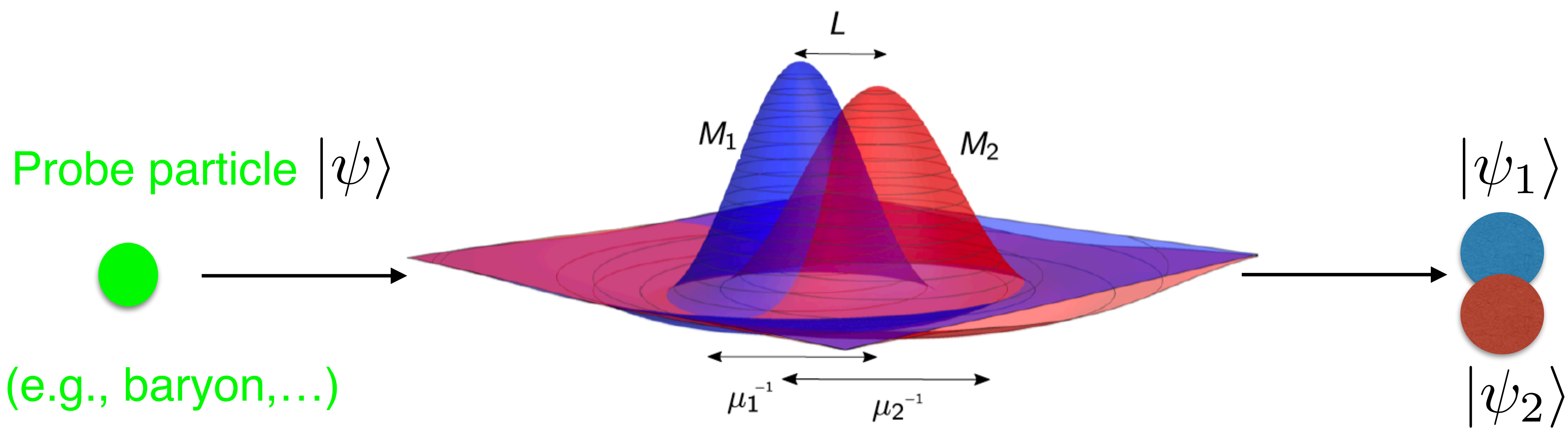
$$= |\mathrm{DM}_1\rangle \langle \mathrm{DM}_1| + \boxed{\langle\psi_2|\psi_1\rangle} |\mathrm{DM}_1\rangle \langle \mathrm{DM}_2| + \boxed{\langle\psi_1|\psi_2\rangle} |\mathrm{DM}_2\rangle \langle \mathrm{DM}_1| + |\mathrm{DM}_2\rangle \langle \mathrm{DM}_2|$$

Off diagonal elements; controlling true quantum effects

N-particles
$$\prod_{n=1}^{N} |\langle\psi_1|\psi_2\rangle|_n = \prod_{n=1}^{N} (1 - \Delta_b) \sim e^{-\sum_{n=1}^{N} \Delta_b}$$

Decoherence rate
$$\boxed{\Gamma_{\mathrm{dec}} = n\, v \int d^2 b\, \Delta_b}$$

Decoherence Rate from Generalized Cross-sections



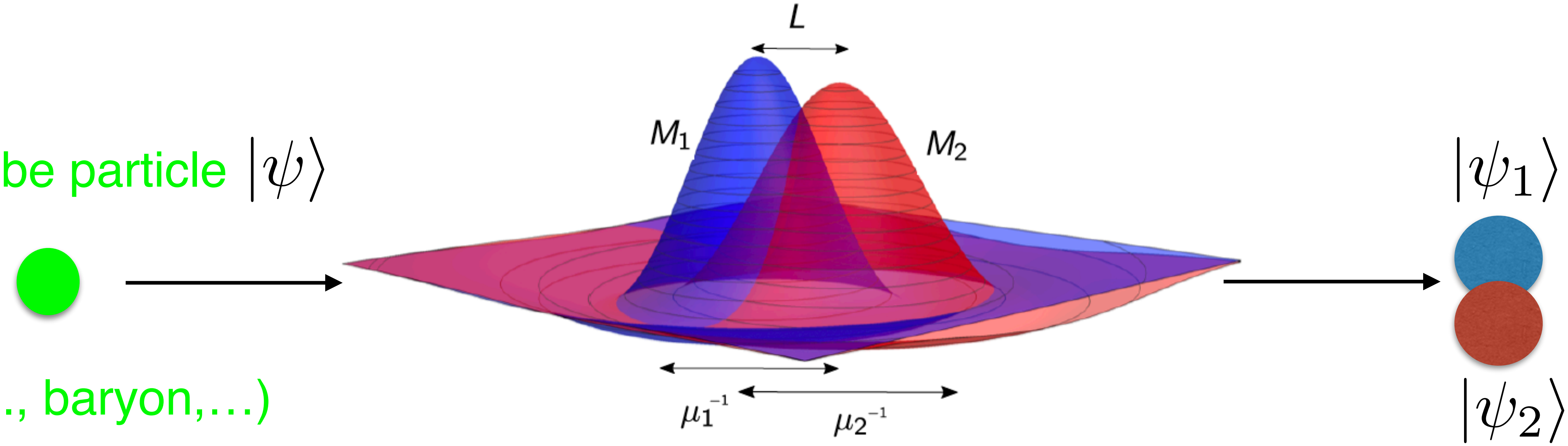
Scattering Amplitude $$f(\vec{q}', \vec{q}) \equiv -\frac{1}{2\pi}\int d^3x' e^{i(\vec{q}-\vec{q}')\cdot\vec{x}'}\Phi(\vec{x}')m^2$$

Cross-section $$\tilde{\sigma}_{ij}(q) \equiv \int d^2\Omega\, f_i^*(\vec{q}', \vec{q}) f_j(\vec{q}', \vec{q}) j_0(2qL_{ij}\sin\theta/2)$$

Allali, Hertzberg 2005.12287 (JCAP)

Decoherence Rate from Generalized Cross-sections

Probe particle $|\psi\rangle$



$|\psi_1\rangle$

$|\psi_2\rangle$

(e.g., baryon,…)

Decoherence Rate

$$\Gamma_{\text{dec}} \approx nv(\tilde{\sigma}_{1,1} + \tilde{\sigma}_{2,2} - 2\Re[\tilde{\sigma}_{1,2}])/2$$

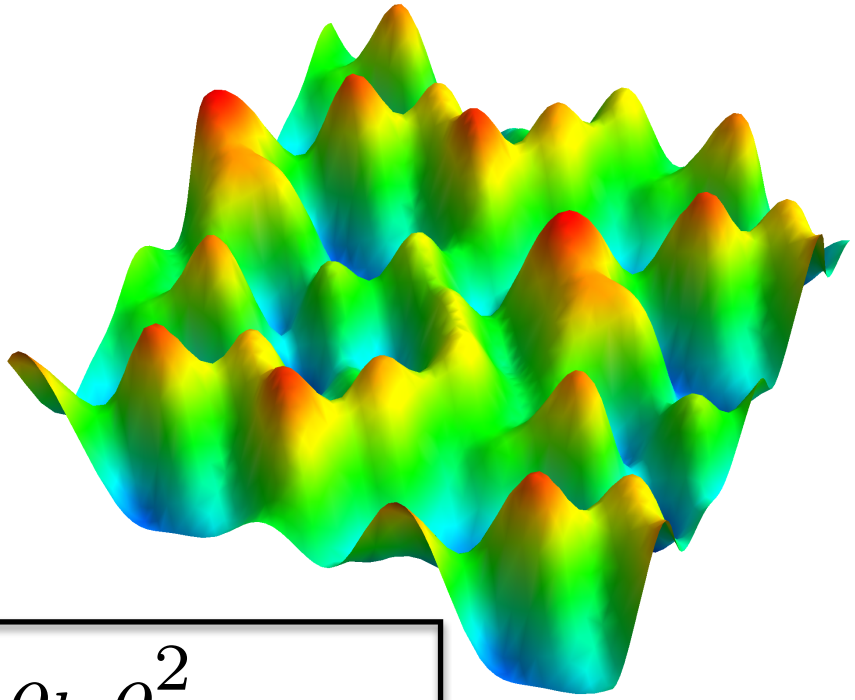
$$\Gamma_{\text{dec}} = \frac{4\pi G^2 m^4 n\, v}{k^2}\left[\frac{M_1^2}{\mu_1^2}\chi_{11} + \frac{M_2^2}{\mu_2^2}\chi_{22} - 2\frac{M_1 M_2}{\mu_1\mu_2}\chi_{12}\right]$$

Allali, Hertzberg 2005.12287 (JCAP)

Application to Light Diffuse scalar DM (axions)

Diffuse scalars (axions)

$$\mu_i \sim \frac{1}{\lambda_{dB,a}} \sim \frac{m_a v_{vir}}{2\pi} \qquad M_i \sim \frac{4\pi}{3}\rho_{DM}\lambda_{dB,a}^3$$



Probe: Diffuse baryons

$$k_p \sim m_p\, v_{vir}$$

Decoherence Rate

$$\Gamma_{dec} \sim \frac{G^2\, m_p\, \rho_b\, \rho_{DM}^2}{m_a^8\, v_{vir}^9}$$

Decoherence Time

$$t_{dec} = 1/\Gamma_{dec} \propto m_a^8$$

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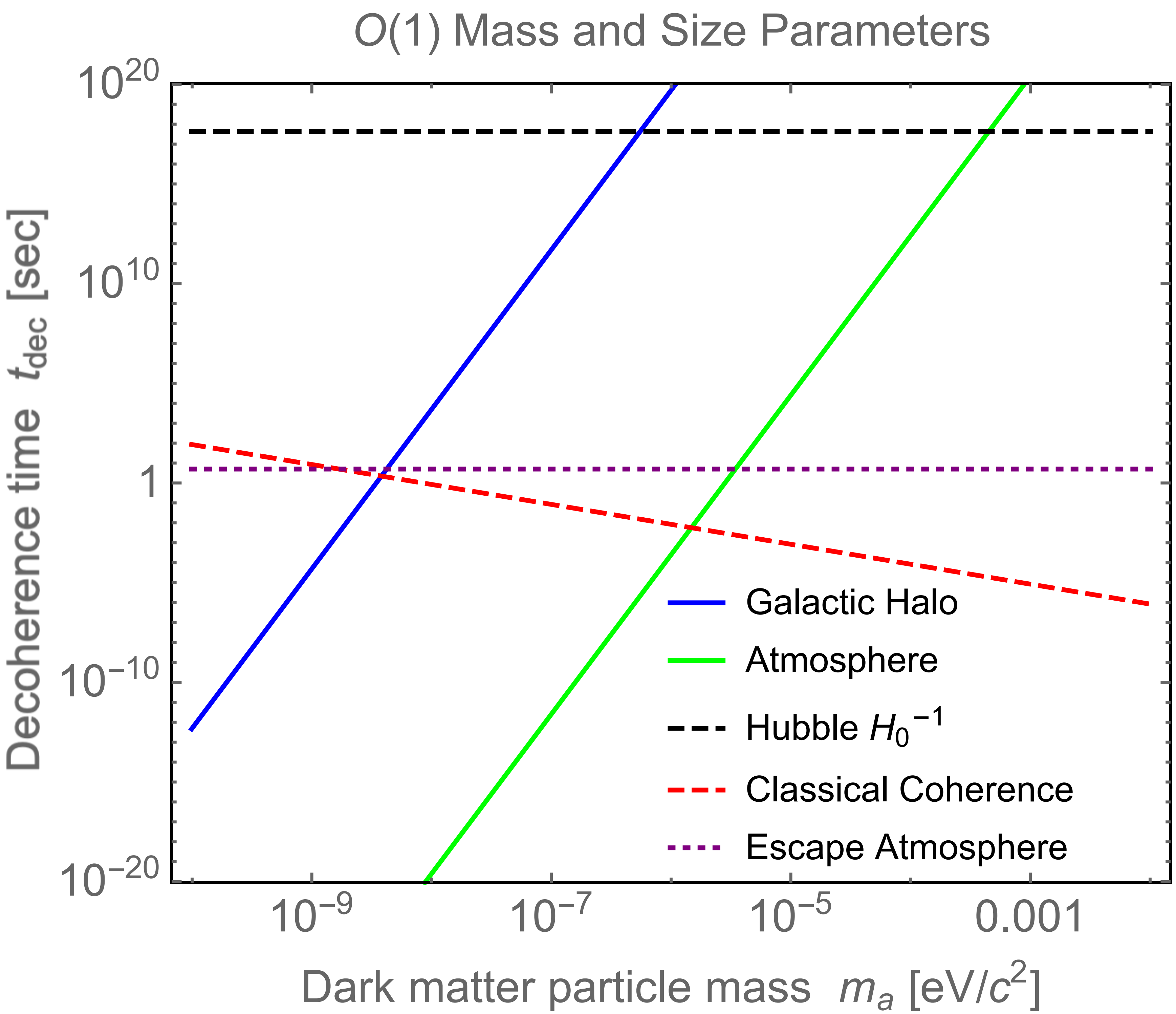
Application to Light Diffuse scalar DM (axions)



$$\Omega_{QCD,a} \sim 0.25 \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)^{1.2}$$

$$\lambda_{dB,a} \sim \mathrm{km} \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)$$

$$M \sim \mathrm{ng} \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)^{3}$$

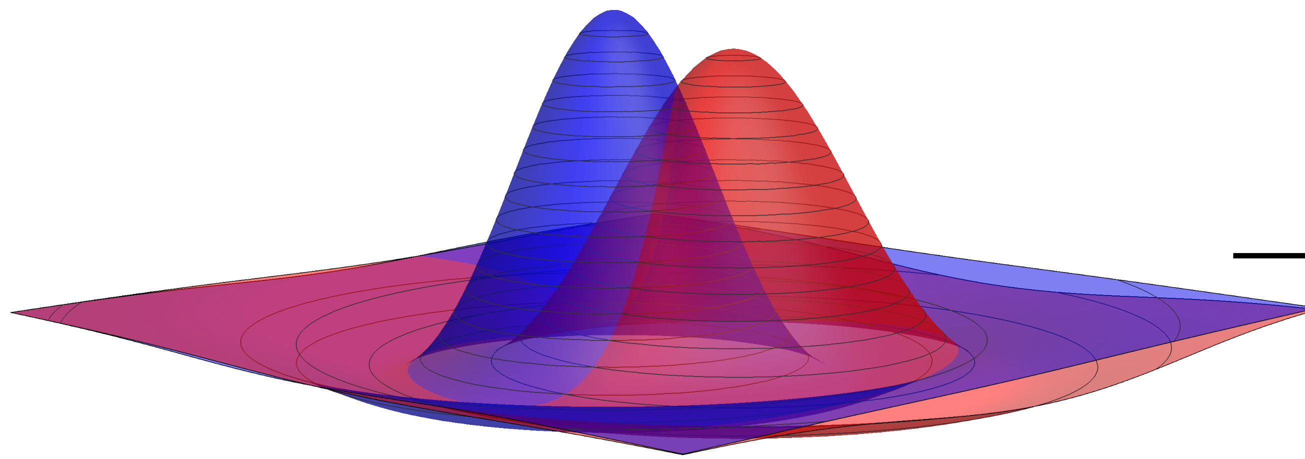
Allali, Hertzberg 2005.12287 (JCAP)

Application to Boson Stars

Boson star

Probe particle $|\psi\rangle$

(e.g., baryon,…)



$|\psi_1\rangle$

$|\psi_2\rangle$

Boson stars are much denser

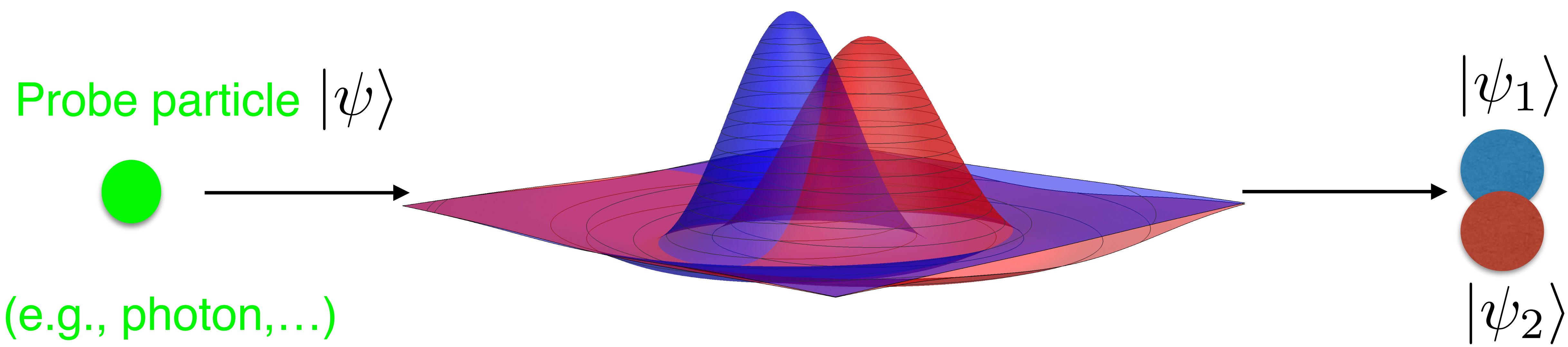
Decoherence Rate

$$\Gamma_{\rm dec} \gtrsim \frac{\hbar^2 m_p \rho_p}{v_p m_a^4} \sim 10^{21}\,{\rm sec}^{-1}\left(\frac{1\,{\rm eV}}{m_a\,c^2}\right)^4$$

Extremely rapid decoherence —> Very classical

Allali, Hertzberg 2005.12287 (JCAP)

General Relativistic Extension



Robust quantum gravity calculation;
General Relativity treated as quantum effective theory

Allali, Hertzberg 2012.12903 (PRD), 2103.15892 (PRL)

Decoherence Rate for Static Source

Metric - Newton gauge $$g_{\mu\nu} = \text{diag}[(1+2\Phi), -(1-2\Psi), -(1-2\Psi), -(1-2\Psi)]$$

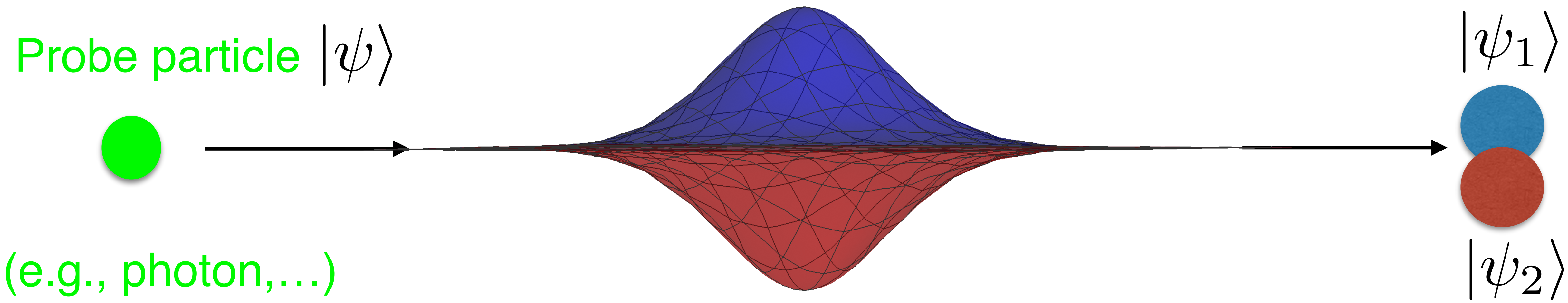
Amplitude $$f(\vec{q}', \vec{q}) \equiv -\frac{1}{2\pi} \int d^3x' e^{i(\vec{q}-\vec{q}')\cdot\vec{x}'} \left[\Phi(\vec{x}')E_q^2 + \Psi(\vec{x}')q^2\right]$$

Rate $$\Gamma_{\rm dec} \approx 4\pi G_N^2 n_p v_p \frac{(m_p^2+2k^2)^2}{k^2} \left(\frac{M_1^2}{\mu_1^2}\chi_{11} + \frac{M_2^2}{\mu_2^2}\chi_{22} - \frac{2M_1M_2}{\mu_1\mu_2}\chi_{12}\right)$$

In galaxy, the baryons provide a bigger environment than photons/neutrinos

Allali, Hertzberg 2012.12903 (PRD), 2103.15892 (PRL)

Decoherence Rate for Oscillating Source



To "learn" about phase; inelastic scattering

$$E_p \to E_p \pm \omega_a$$

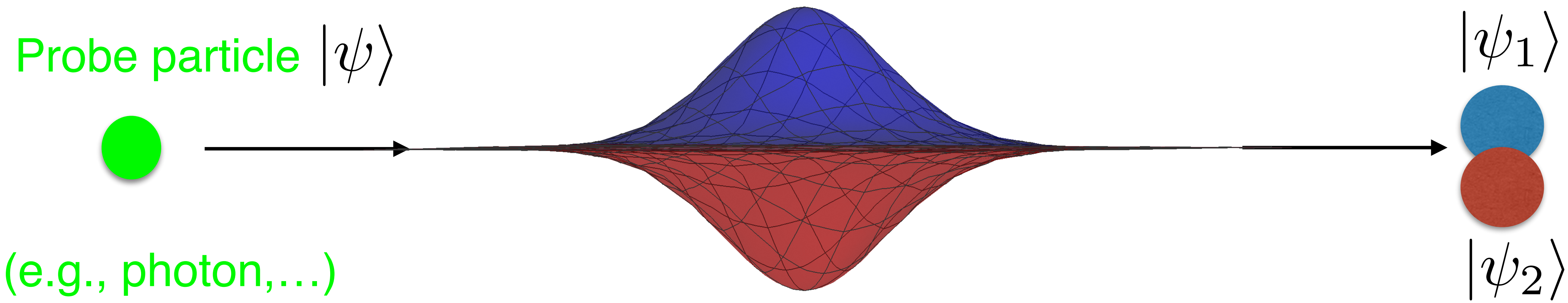
Kinematic mismatch

$$\delta p_T \sim \frac{E_p}{p_p}\omega_a \gg p_a$$

Decoherence of phase is suppressed (unless all states are relativistic)

Allali, Hertzberg 2012.12903 (PRD), 2103.15892 (PRL)

Decoherence Rate for Oscillating Source



Conceivably, relevant to direct detection, which is sensitive to axion phase

$$|\mathrm{DM}\rangle \sim \sum_i c_i |\cos(\omega t - \mathbf{k}_a \cdot \mathbf{x} + \varphi_i)\rangle$$

Open question: are there observables related to this?

Allali, Hertzberg 2012.12903 (PRD), 2103.15892 (PRL)

Conclusions

- Macroscopic quantum states (Schrodinger cats) of light scalar dark matter might exist, and could potentially have slow decoherence

- We studied the decoherence of such states due to gravitational scattering from probe particles; a robust quantum gravity calculation

- We found that superpositions of spatial profiles decohere rapidly for very light DM (axions), and boson stars decohere extremely rapidly

- We found that superpositions of phases live much longer, may launch detectors into superpositions (non-grav interactions can be considered in future work).

- Relativistic states (near black holes) decohere quickly

Allali, Hertzberg 2005.12287 (JCAP), 2012.12903 (PRD), 2103.15892 (PRL)