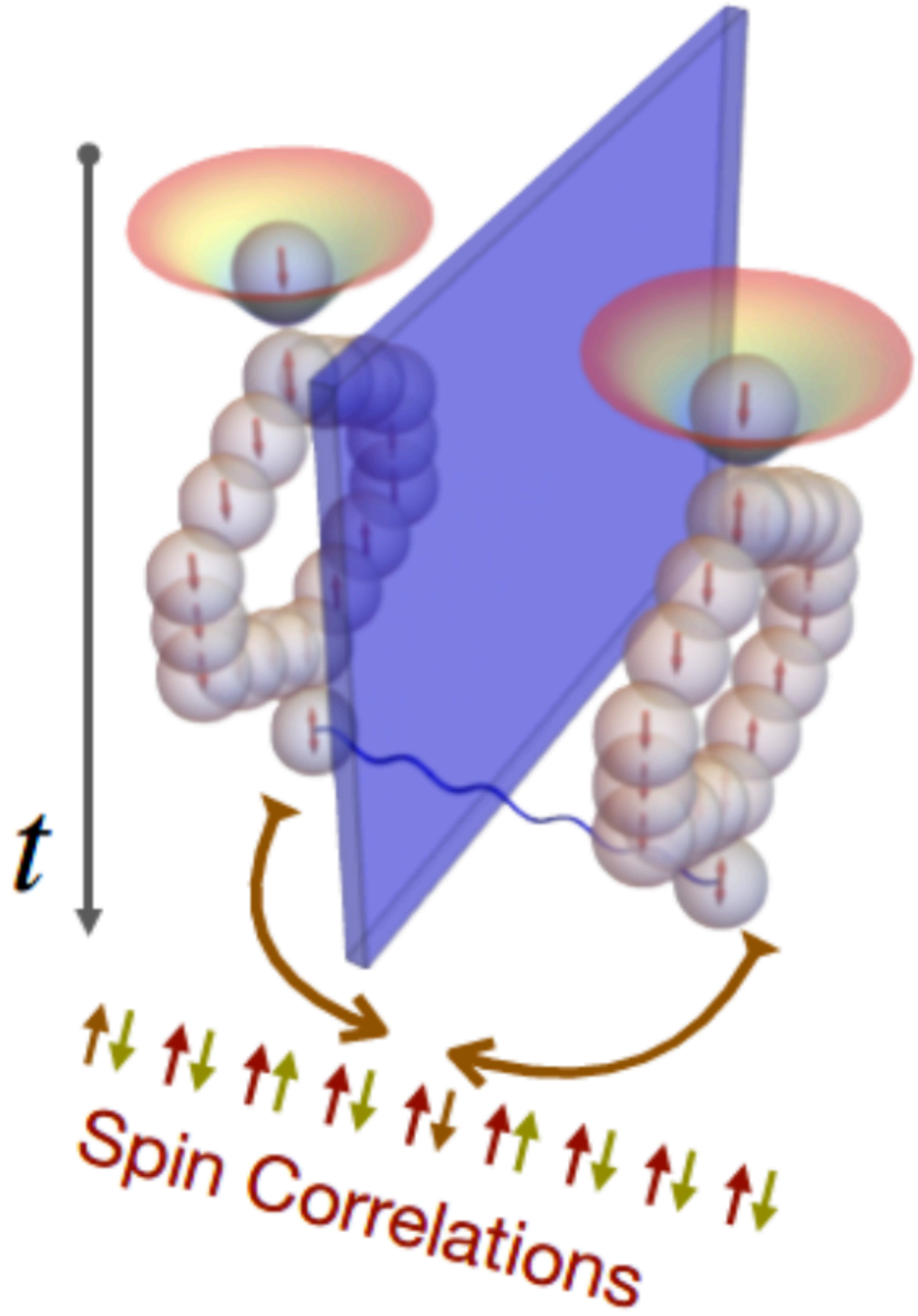
Entanglement Witnesses Mediated Via Axion-Like Particles



Anupam Mazumdar

rijksuniversiteit groningen

Based on:
Entanglement-based tomography to probe new macroscopic forces. 2203.00038 [hep-ph]

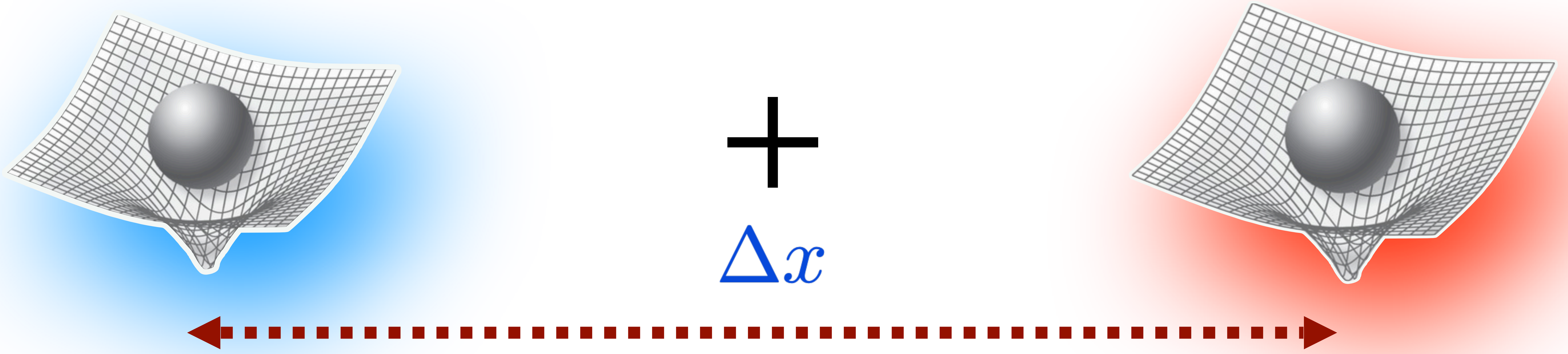
Entanglement witnesses mediated via axionlike particles. 2503.19072 [quant-ph]

GORDON AND BETTY MOORE FOUNDATION

ALFRED P. SLOAN FOUNDATION

MOTIVATION COMES FROM a Different Direction

Can space-time with matter be in two places at once?

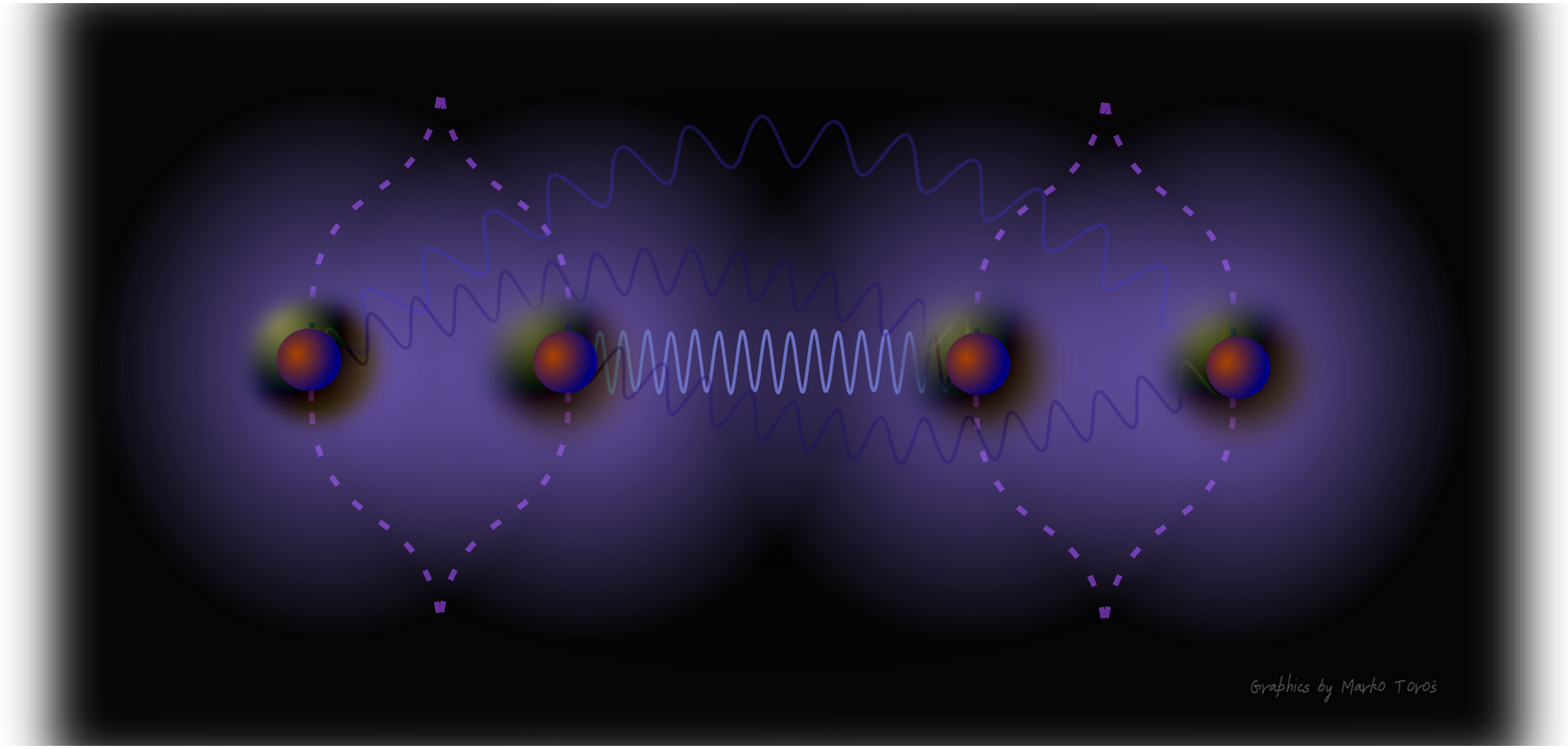


Bose, **Mazumdar,** Morley, Ulbricht, Toroš, Paternostro, Geraci, Barker, Kim & Milburn
PRL 119, 240401 (2017)

Biswas, Bose, **Mazumdar**, Toroš, PRD, 108, 064023 (2023)

The idea here is to test Quantum Gravity in a lab
To test the Graviton Hypothesis

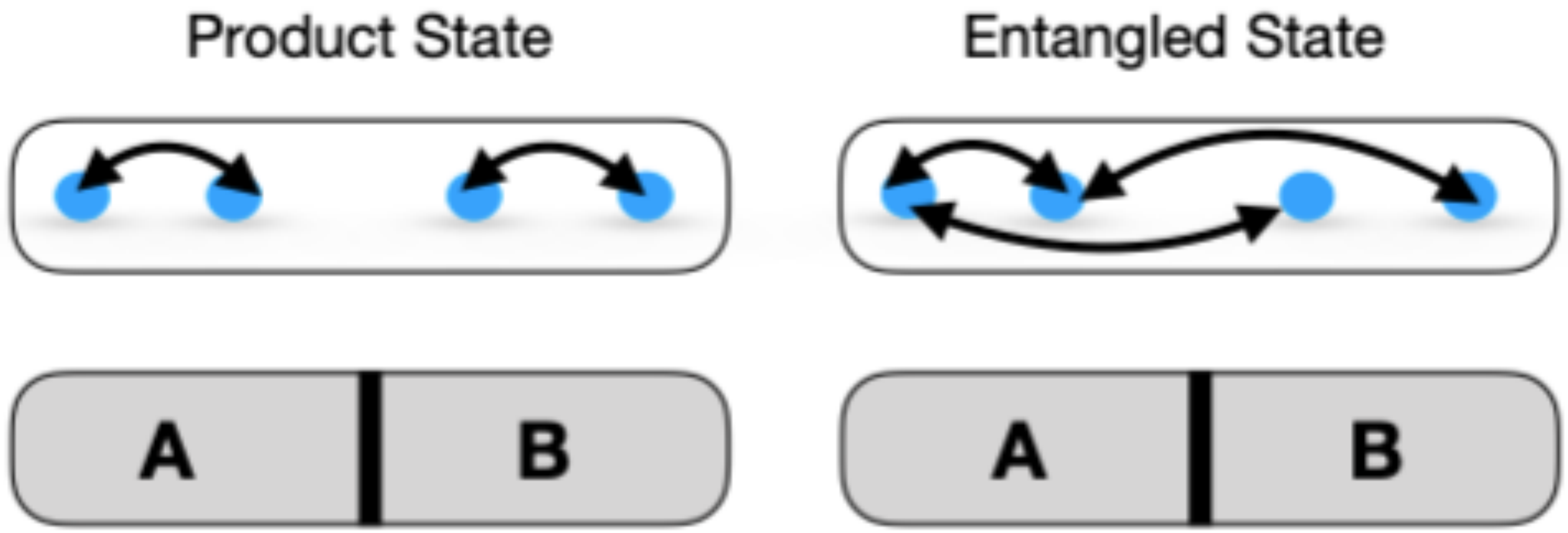
MOTIVATION & Added Advantage



Protocol is known as: Quantum Gravity Induced Entanglement of Matter (QGEM)

QGEM can test Beyond the Standard Model Physics

Quantum Interactions, Correlations & Entanglement



$|\Psi\rangle = |\Psi\rangle_A \otimes |\Psi\rangle_B$

$|\Psi\rangle \neq |\Psi\rangle_A \otimes |\Psi\rangle_B$

Entanglement is a bonafide quantum entity which has no classical analogy

Quantum Interactions —> Entanglement

$$H = \widehat{H}_A + \widehat{H}_B \quad |\psi_{\rm i}\rangle = |0\rangle_A|0\rangle_B \qquad\qquad H = \widehat{H}_A + \widehat{H}_B + \lambda\widehat{H}_{AB} \quad |\psi_{\rm f}\rangle \equiv \frac{1}{\sqrt{\mathcal{N}}}\sum_{n,N} C_{nN}|n\rangle|N\rangle$$

$$|\psi_{\rm f}\rangle \sim \left[|0\rangle + \sum_{n>0} A_n|n\rangle\right]\cdot\left[|0\rangle + \sum_{N>0} B_N|N\rangle\right] + \sum_{n,N>0}\left(C_{nN} - A_nB_N\right)|n\rangle|N\rangle$$

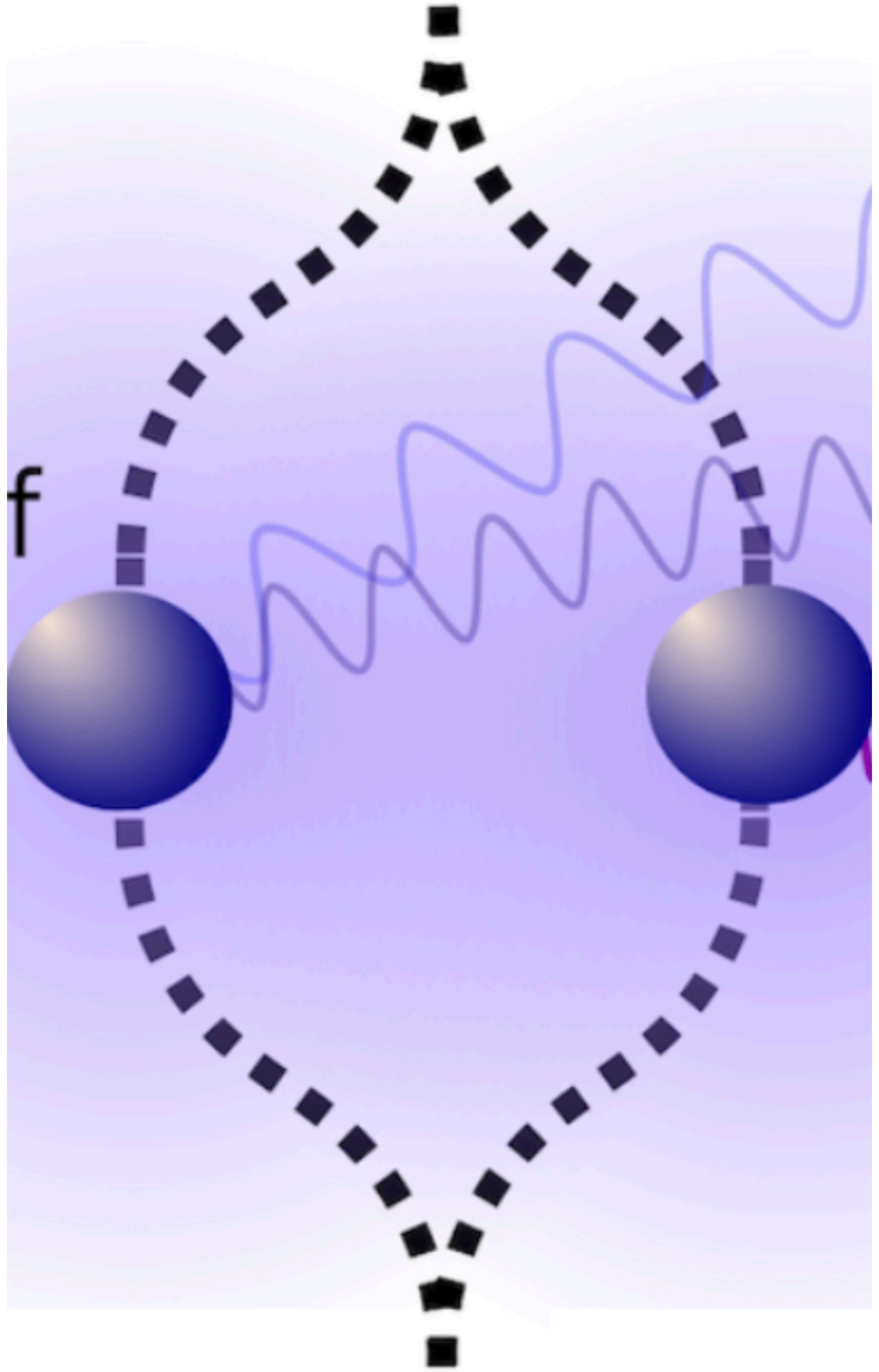
Product State   Non-Product State

$$C_{nN} = \lambda\frac{\langle n|\langle N|\widehat{H}_{AB}|0\rangle|0\rangle}{2E_0 - E_n - E_N} \neq 0$$ Entanglement

$\hat{H}_{AB}$: QED, QCD, Weak, phonon, gravity, or any other quantum Interaction such as Axion/Axion-Like Particle

Bose, Mazumdar, Schut, Toros, 2201.03583

Quantum Interaction Yields Entanglement



$$\mathscr{L} = \mathscr{L}_m + \mathscr{L}_{axion}$$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \sum_{j=1,2}\left[\bar{\psi}_j(i\gamma^\mu\partial_\mu - m_j)\psi_j - ig_{sj}\phi\bar{\psi}_j\psi_j\right]$$

Scalar

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \sum_{j=1,2}\left[\bar{\psi}_j(i\gamma^\mu\partial_\mu - m_j)\psi_j - ig_{pj}\phi\bar{\psi}_j\gamma_5\psi_j\right]$$

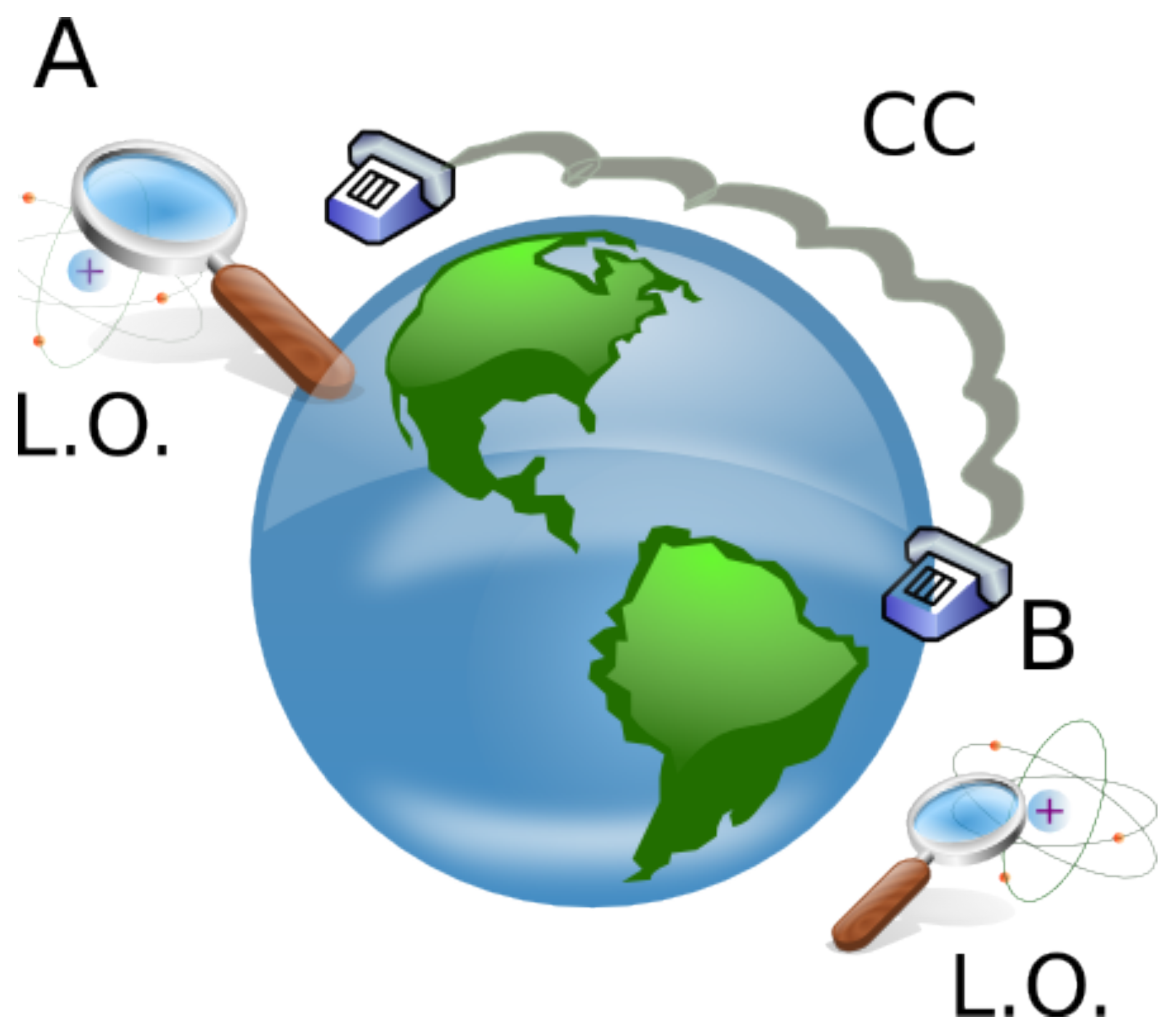
Pseudo Scalar

Macroscopic Spatial
Superposition of matter

Genuine Tripartite Entanglement

Carmona Rufo, Mazumdar, Sabin 2411.03293

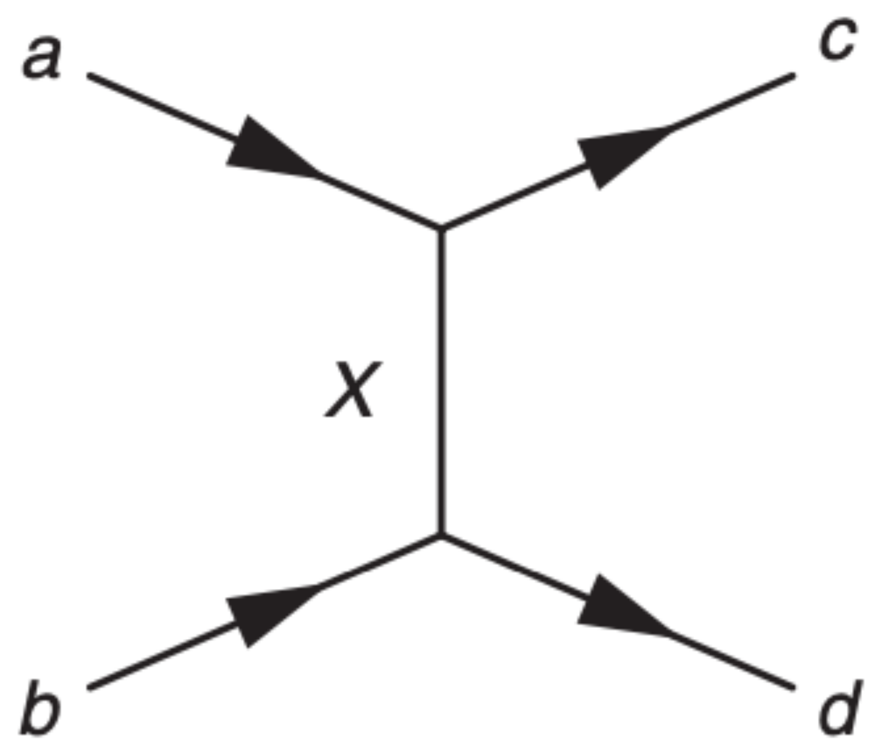
QGEM: No Entanglement via Classical Mediator



If A and B were initially product states, local operations and classical communications (LOCC) would not be able to generate/increase entanglement between them.

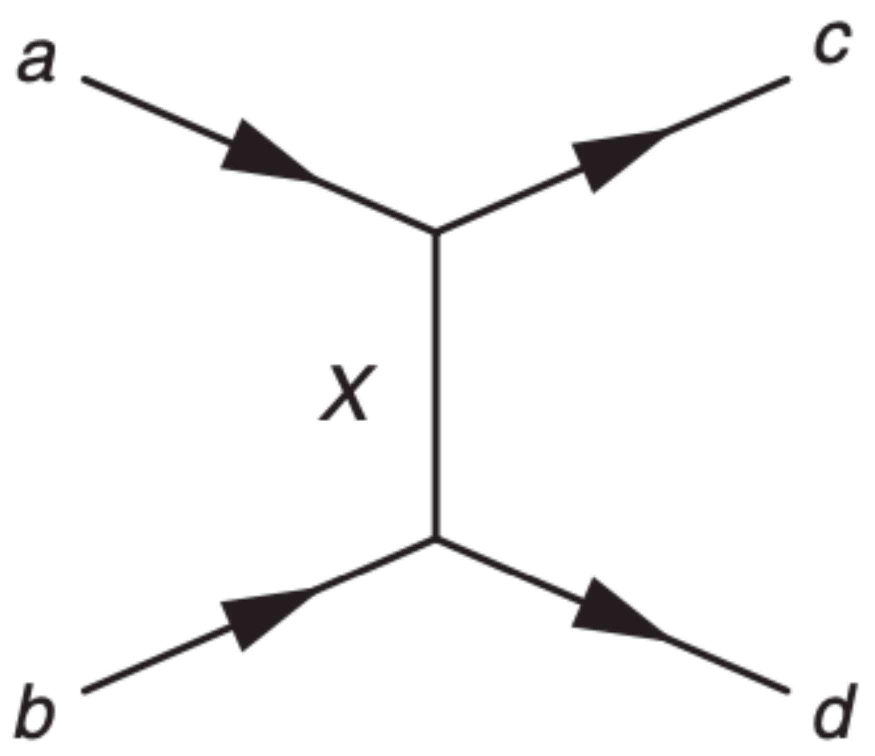
Bennett, et.al, (1996)

LOCC keeps separable states separable & cannot entangle states



LOQC: local operation & quantum communication can entangle

Non-Relativistic Quantum Field Theory



$$\langle f|\,S\,|i\rangle = \langle f|i\rangle - \frac{i\kappa^2}{4}\int \mathrm{d}^4x\mathrm{d}^4x'\,\langle f|\,T^{\mu\nu}(x)G_{\mu\nu\alpha\beta}(x,x')T^{\alpha\beta}(x')\,|i\rangle$$

$$\langle f|\,S-1\,|i\rangle = i\mathcal{A}(2\pi)^4\delta^{(4)}(P_{fi})$$

$$V(\boldsymbol{r}) = -\frac{1}{4E_pE_q}\int\frac{\mathrm{d}^3k}{(2\pi)^3}\mathrm{e}^{i\boldsymbol{k}\cdot\boldsymbol{r}}\mathcal{A}(\boldsymbol{k})$$

Entanglement via ALP exchange

Scalar Mediated

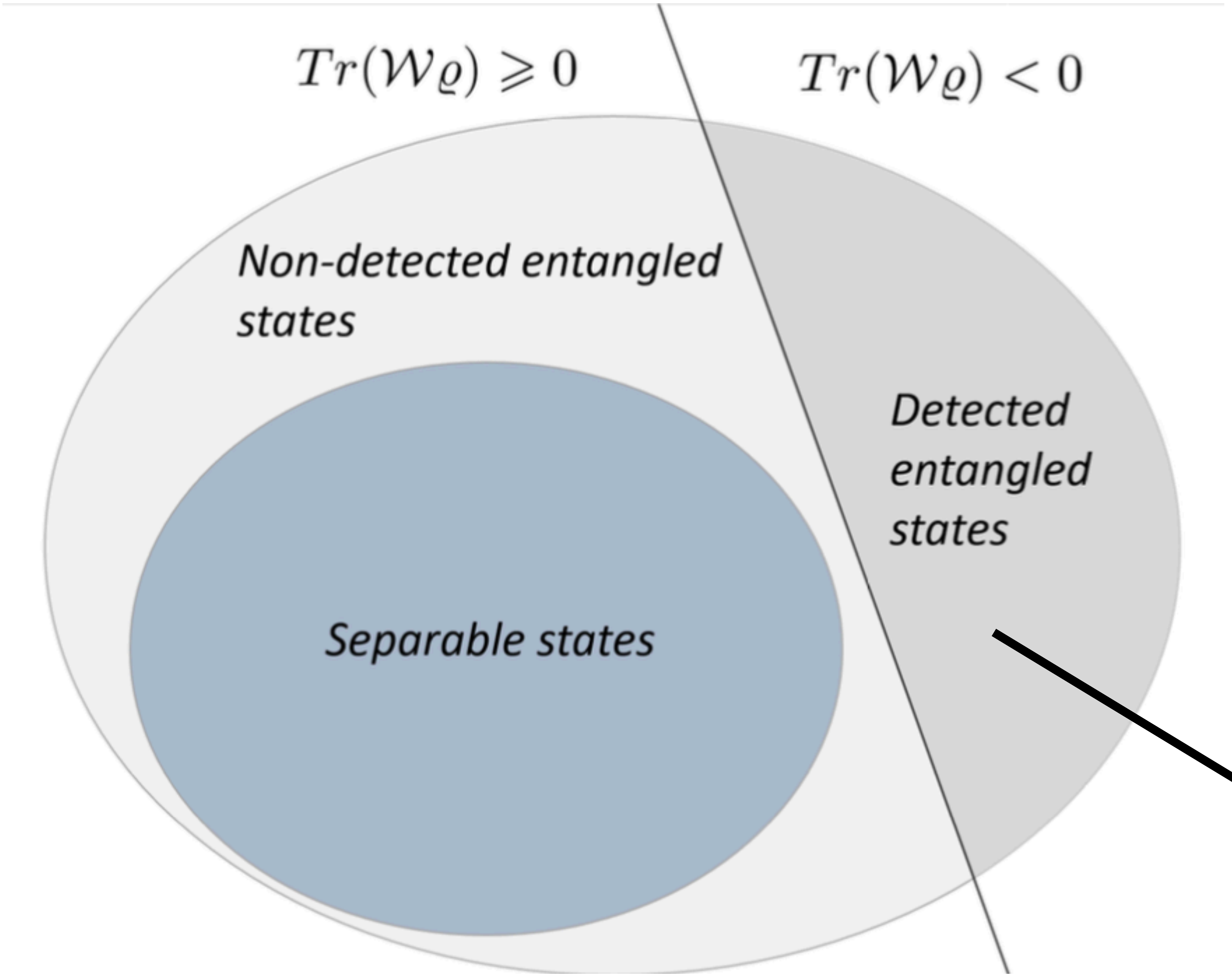
$$U(\vec{r}) = -\frac{g_S^2}{4\pi r}e^{-m_\phi r}$$

Pseudo Scalar Mediated

$$U(\vec{r}) = -\frac{g_P^2 e^{-m_\phi r}}{4\pi M_1 M_2}\left[(\vec{S}_1\cdot\vec{S}_2)\left(\frac{m_\phi}{r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right) - (\vec{S}_1\cdot\hat{r})(\vec{S}_2\cdot\hat{r})\left(\frac{m_\phi^2}{r}+\frac{3m_\phi}{r^2}+\frac{3}{r^3}\right)\right],$$

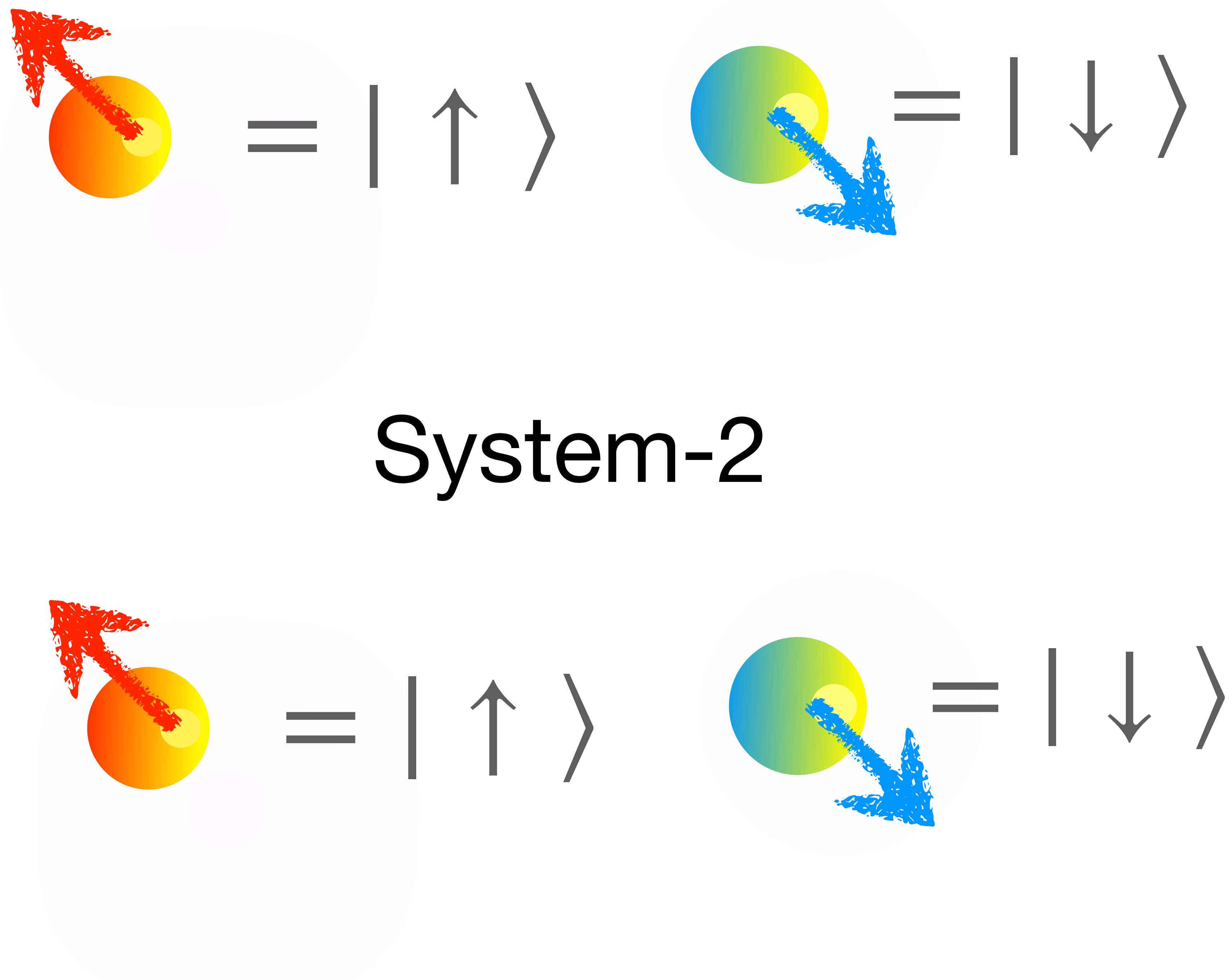
Moody & Wilczek (Phys. Rev. Lett. 1978), Daido & Takahashi (Phys. Lett. B, 2017)

Entanglement Witness: Spin Correlation



System-1

System-2

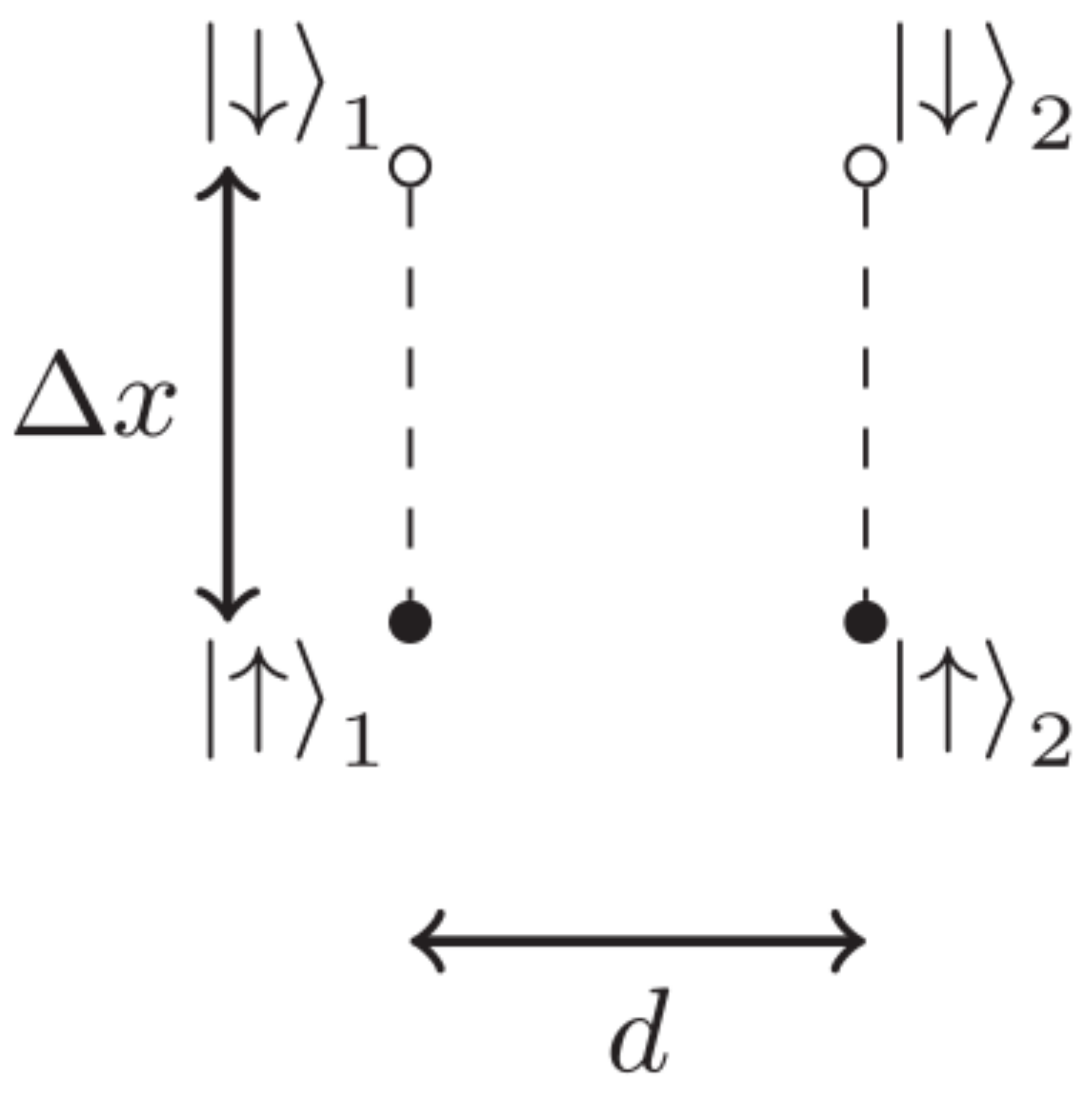


Entanglement

$$W = I^{(1)} \otimes I^{(2)} - \sigma_x^{(1)} \otimes \sigma_x^{(2)} - \sigma_y^{(1)} \otimes \sigma_z^{(2)} - \sigma_z^{(1)} \otimes \sigma_y^{(2)}, \qquad \mathrm{Tr}(W\rho) < 0$$

Chevalier, Paige, Kim, Phys. Rev. A. 102, 022428 (2020)

Entanglement Witness & Decoherence



$$\Psi(\tau=0)=\frac{1}{2}(|\uparrow\rangle+|\downarrow\rangle)_1\otimes(|\uparrow\rangle+|\downarrow\rangle)_2$$

$$\psi(\tau)=\frac{e^{i\phi}}{2}\left[\,|\uparrow\rangle_1|\uparrow\rangle_2+e^{i\phi_1}|\uparrow\rangle_1|\downarrow\rangle_2+e^{i\phi_2}|\downarrow\rangle_1|\uparrow\rangle_2+|\downarrow\rangle_1|\downarrow\rangle_2\,\right]$$

$$\phi^Y=\alpha\frac{e^{-\frac{d}{\lambda}}}{d}\frac{\tau}{\hbar}\qquad \phi_{1,2}=\alpha\frac{e^{-\frac{\sqrt{d^2+(\Delta x)^2}}{\lambda}}}{\sqrt{d^2+(\Delta x)^2}}\frac{\tau}{\hbar}-\phi^Y$$

Scalar-Exchange

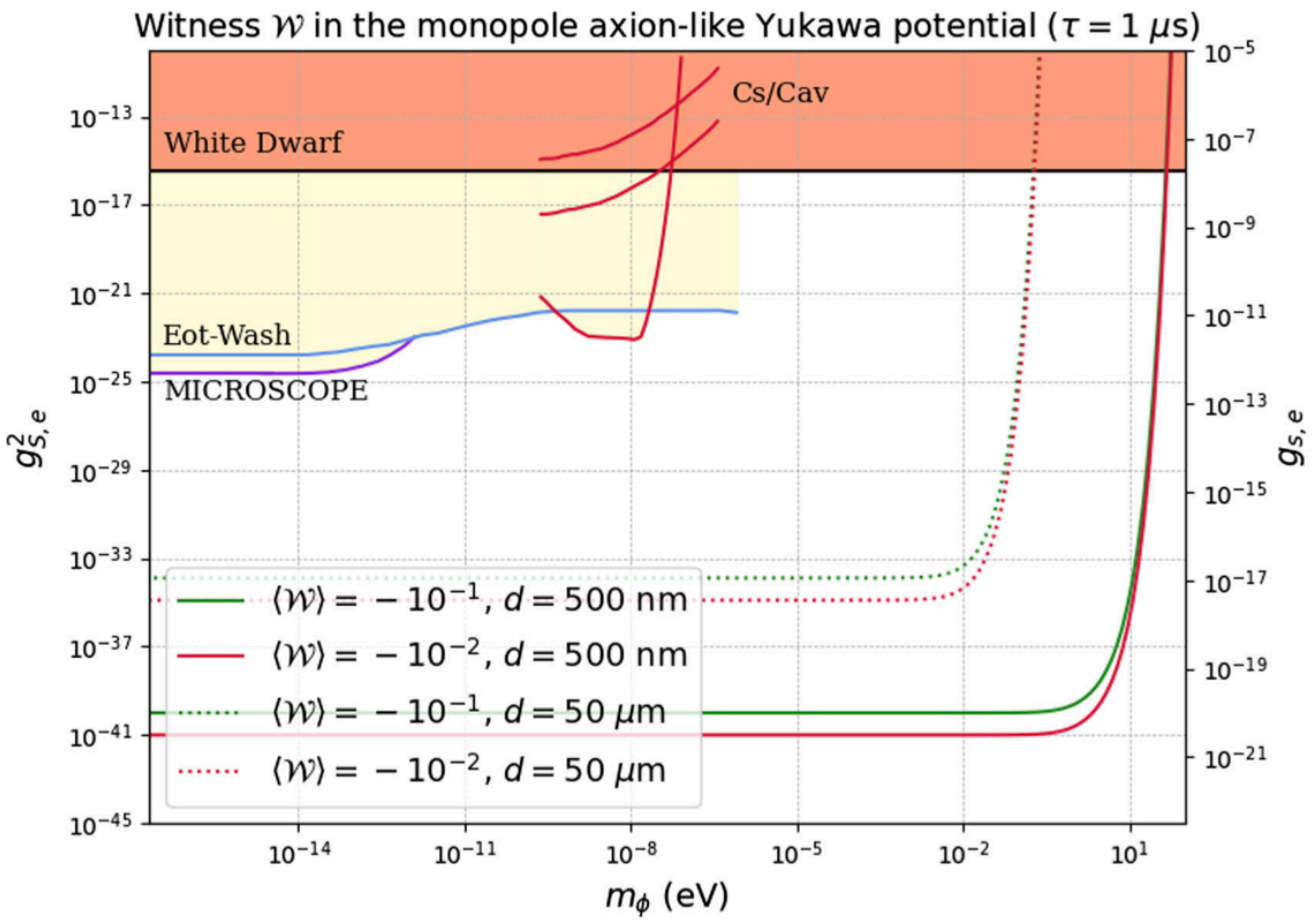
$$\langle\mathcal{W}\rangle(\tau)=\frac{1}{4}-\frac{1}{4}e^{-\gamma\tau}\left[e^{-\gamma\tau}-2\sin\left(\omega_{\text{ent}}\tau\right)\right]$$

γ = Decoherence rate

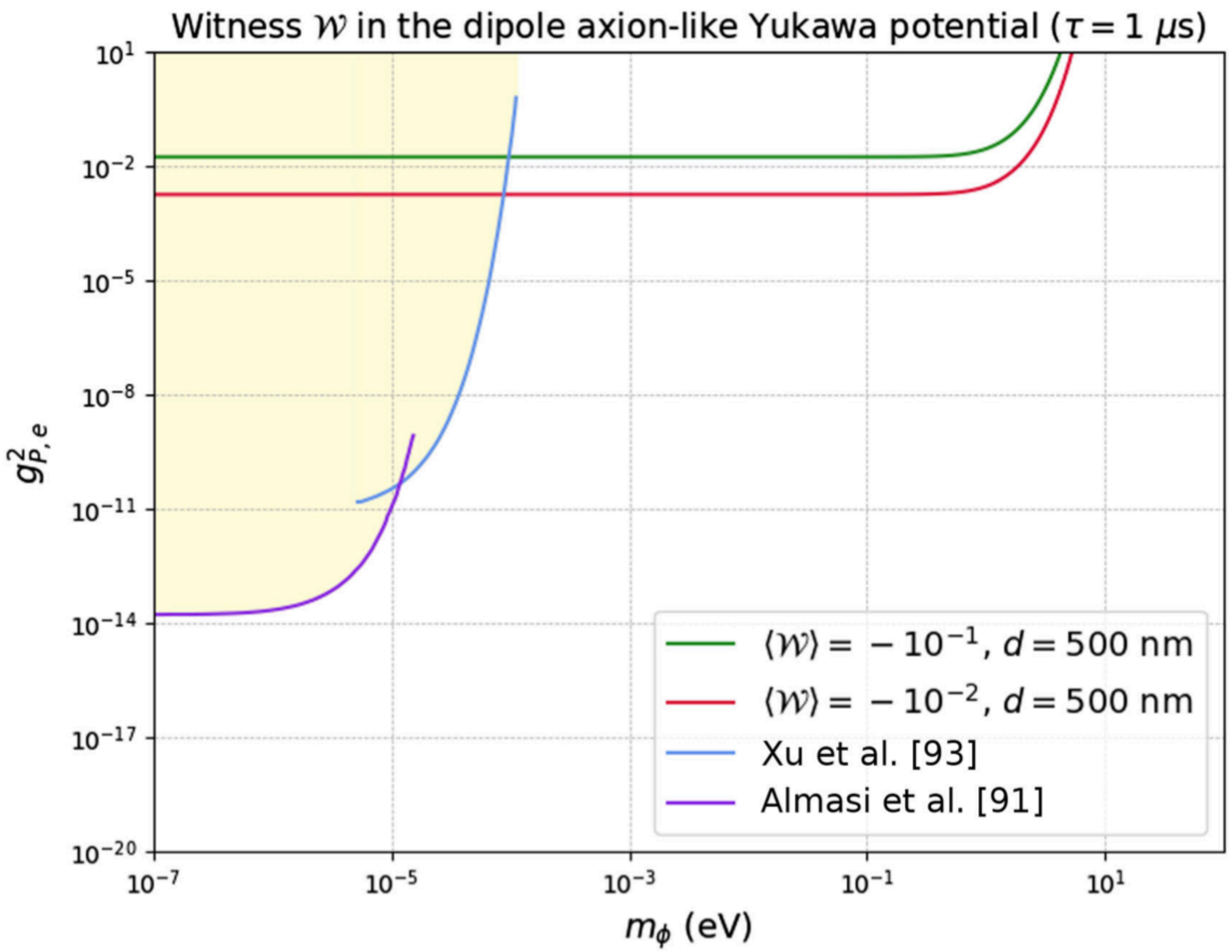
$$\omega_{int}\tau=\frac{\phi_1+\phi_2}{2}$$

ALP interaction in an Ion Trap

Scalar Mediated



Pseudo Scalar Mediated

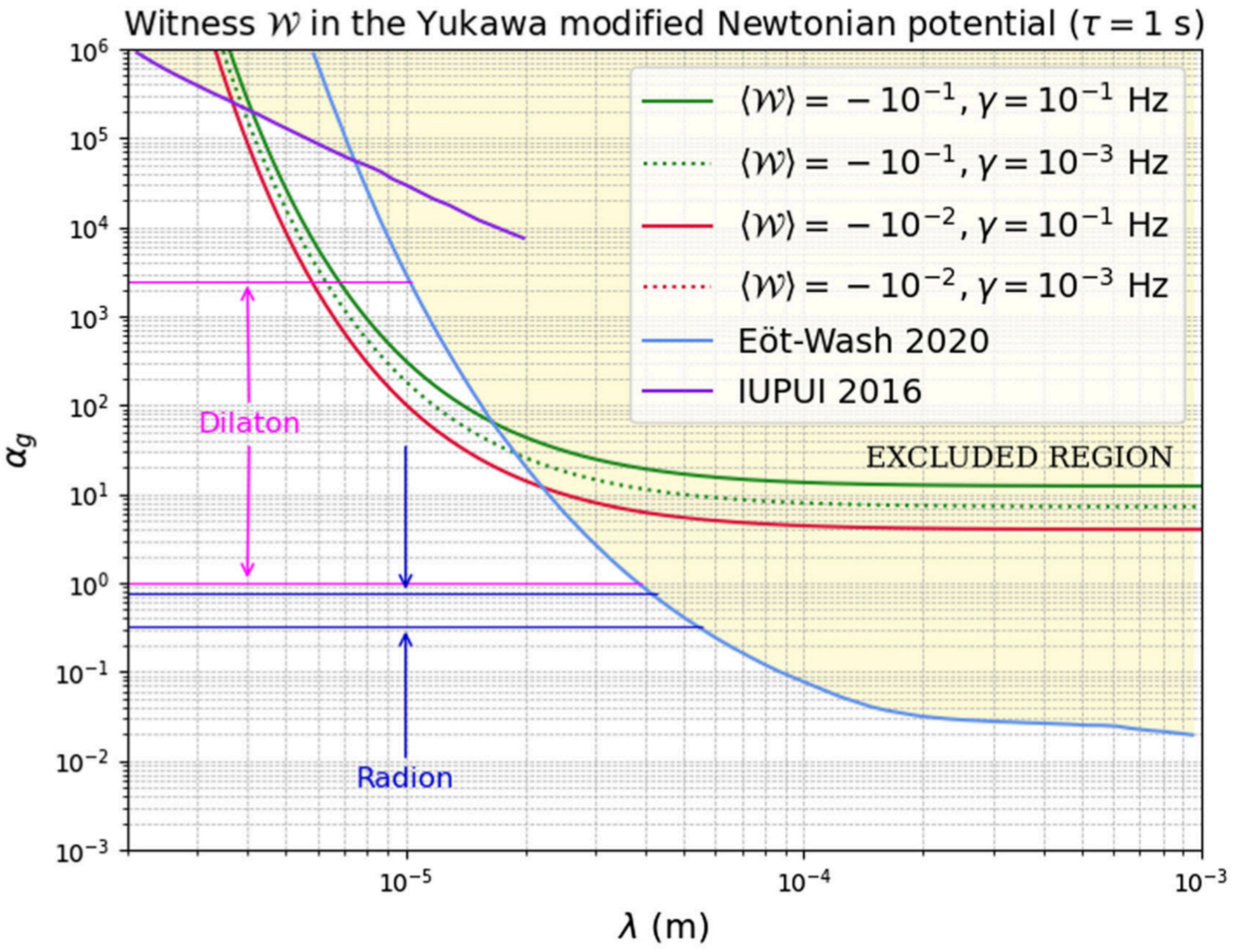


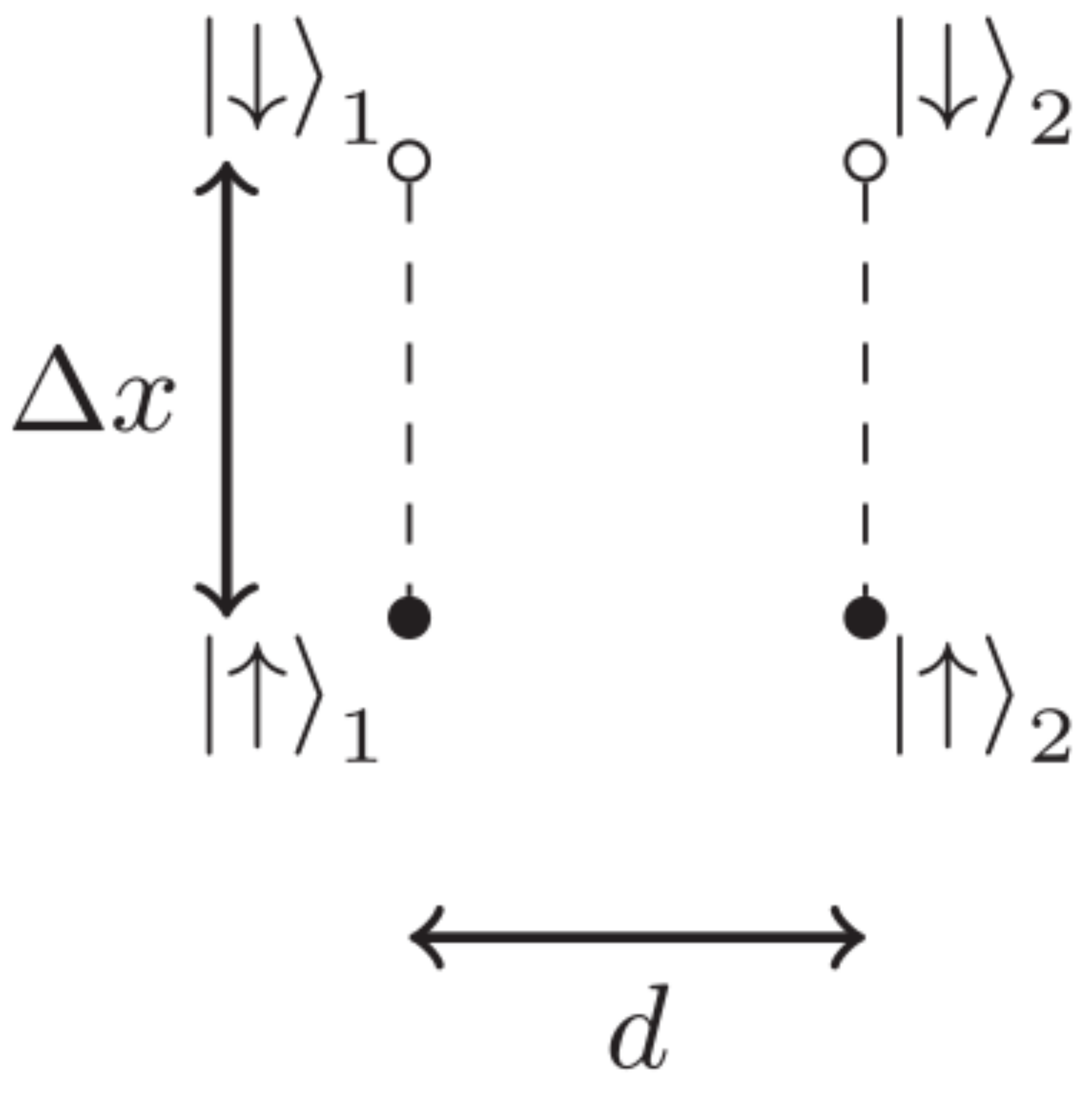
$q_1 = q_2 = e, \quad m = 10^{-27}$Kg (e.g. Rubium atom) $\quad \omega = 10^5$ Hz (Trapping frequency)

$\Delta x = \sqrt{\hbar/(2m\omega)} = 0.18\ \mu\text{m} \qquad \tau = 1\mu\text{s}, \ \ \gamma \sim 10^3$ Hz $\qquad M_1 = M_2 = m_e$

2503.19072 [quant-ph]

ALP interaction in Modifying Gravity

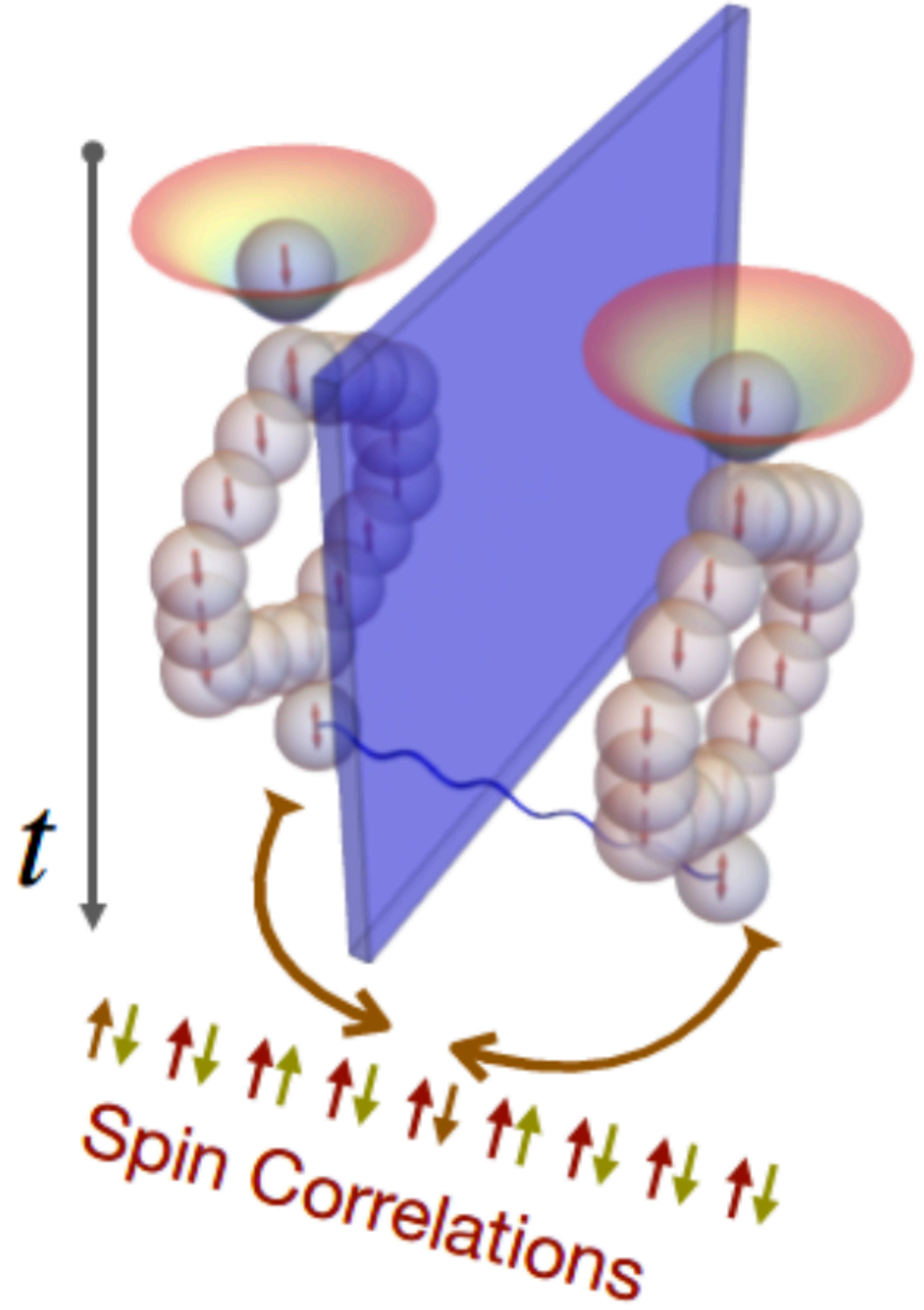


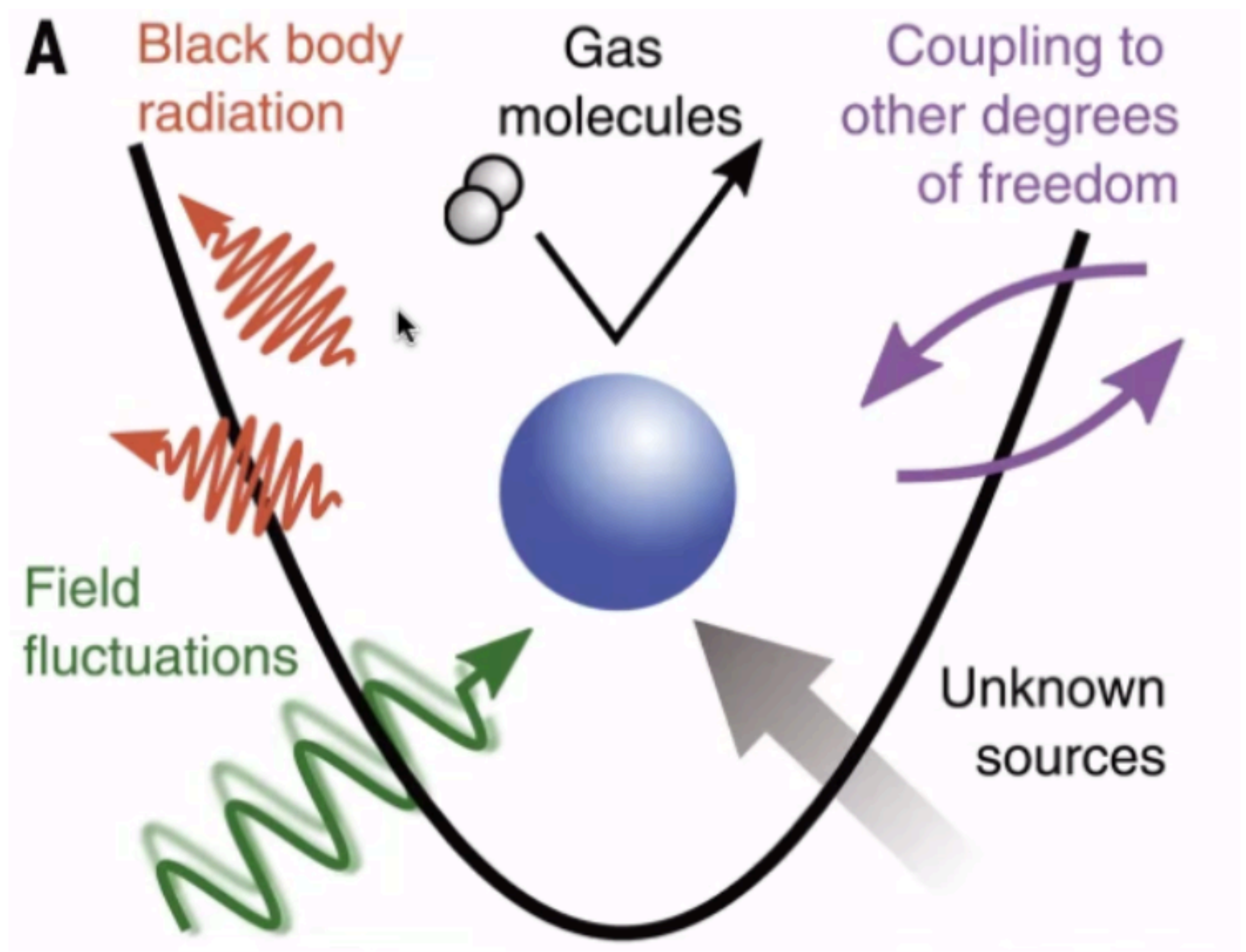


$\Delta x = 10\mu\text{m}, \quad d = 50\mu\text{m}, \quad m = 10^{-14}\text{Kg}$

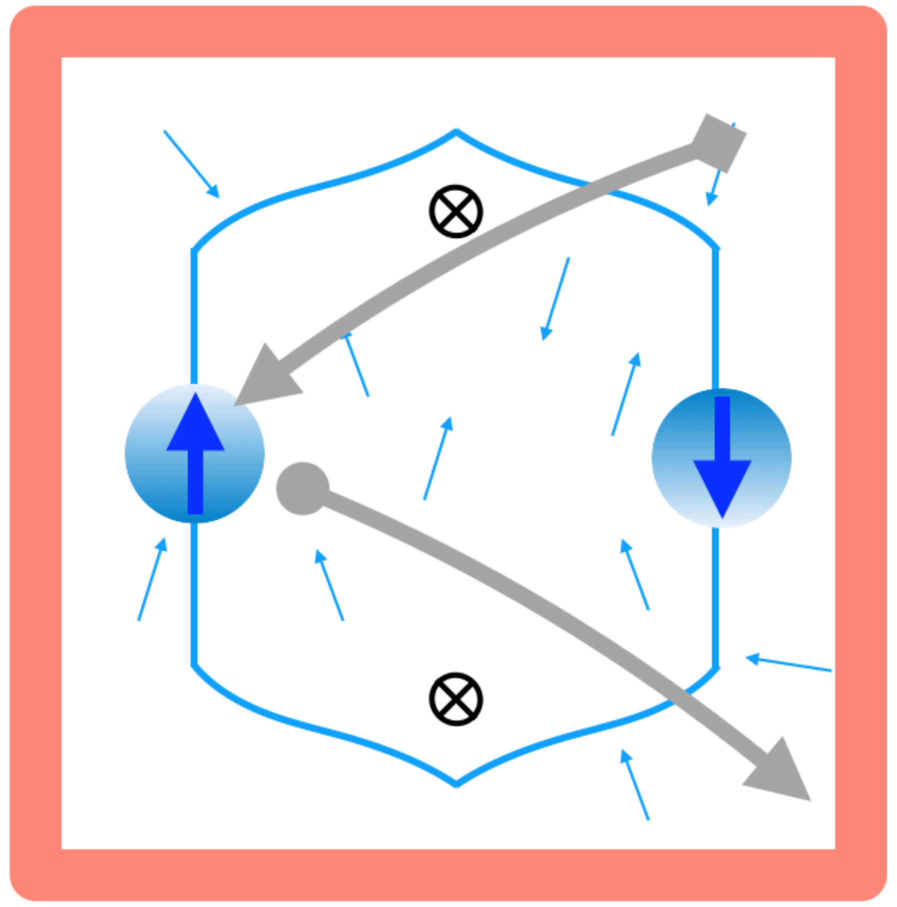
$$U_{Y_g}(\vec{r}) = \frac{Gm^2}{r}\left(1 + \alpha_g e^{-r/\lambda}\right)$$

Conclusion : Experimental Challenges





$P_{ext} \sim 10^{-13}\mathrm{Pa}, \quad \mathrm{T_{ext}} \sim 4\mathrm{k}$



- Quantum coherence

Despite all these Challenges, I believe this is the future of Axion Physics. An Entanglement Based Test to search for Physics Beyond the Standard Model