Title: Spin Entanglement Witness for Quantum Gravity

Speakers: Anupam Mazumdar

Series: Quantum Gravity

Date: January 24, 2023 - 11:00 AM

URL: https://pirsa.org/23010060

Abstract: Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. Along this line, a prime question is to find whether gravity is a quantum entity subject to the rules of quantum mechanics. It is fair to say that there are no feasible ideas yet to test the quantum coherent behaviour of gravity directly in a laboratory experiment. I will introduce an idea for such a test based on the principle that two objects cannot be entangled without a quantum mediator. I will show that despite the weakness of gravity, the phase evolution induced by the gravitational interaction of two micron size test masses in adjacent matter-wave interferometers can detectably entangle them even when they are placed far apart enough to keep Casimir-Polder forces at bay. I will provide a prescription for witnessing this entanglement, which certifies gravity as a quantum coherent mediator, through simple correlation measurements between two spins: one embedded in each test mass. Fundamentally, the above entanglement is shown to certify the presence of non-zero off-diagonal terms in the coherent state basis of the gravitational field modes.

Zoom link: https://pitp.zoom.us/j/99584743899?pwd=aHl1cVlpK29ZVDkrdFZyM01GemJJdz09

Witnessing Quantum Gravity via Entanglement

Quantum Gravity induced Entanglement of Masses (Q💎) protocol

Anupam Mazumdar

rijksuniversiteit groningen

Observing the Quantum nature of a system is NOT limited to evidencing $\mathcal{O}(\hbar)$ corrections to a Classical theory: Instead hinges upon verifying tasks that a Classical system CANNOT accomplish

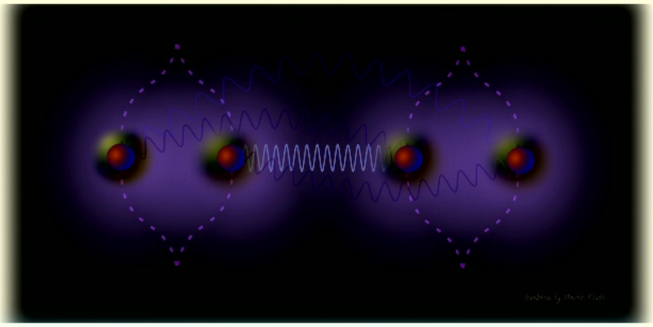
Bose + AM + Morley + Ulbricht + Toros + Paternostro + Geraci + Barker + Kim + Milburn, [ArXiv: 1707.06050]
(First reported in 2016 Workshop in ICTS Bangalore with all the authors)
Bose+AM+Schut+Toros [2201.03583, 2203.11628]
Biswas+Bose+AM+Toros [2209.09273] (Gravitational Optomechanics)

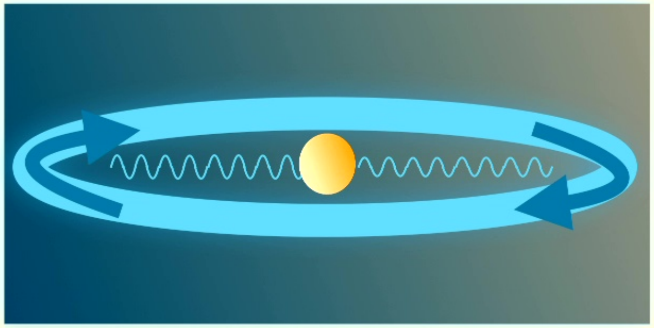
See Also: Marletto and Vedral appeared on the same day [1707.06036]

Fundamental limits on Gravitational Decoherence due to killing Horizon + Connection to Gravitational Memory:
Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, and Aspelmeyer (2018),
Danielson, Satishchandran, Wald (2021, 2022)

Plan: Unambiguous* test for the quantum nature of gravity in a lab

- QGEM Protocol (testing QM and GR)
- Quantum Gravity Optomechanical Experiment
- Experimental Challenges & Future outlook





Quantum Properties

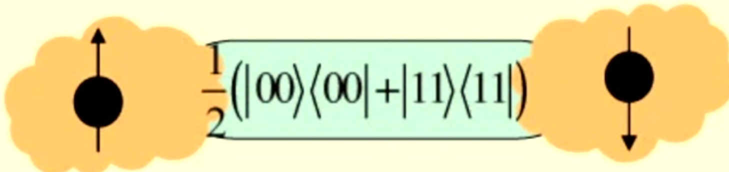
- Quantum Superposition
- Quantum Entanglement

No Classical counterpart

* a loop-hole free test

Classical vs Quantum Correlation

(a)

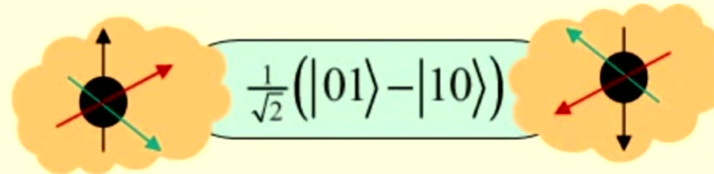


σ_z^a perfectly correlates with σ_z^b

σ_x^a does not correlate with σ_x^b

σ_y^a does not correlate with σ_y^b

(b)



σ_z^a perfectly correlates with σ_z^b

σ_x^a perfectly correlates with σ_x^b

σ_y^a perfectly correlates with σ_y^b

(a) A CLASSICAL correlation in a bipartite system involves the correlation of a certain sub-class of properties

(b) A QUANTUM correlation in a bipartite system also involves complementary correlations of incompatible properties. We have a freedom to select which one to extract.

Entanglement is a correlation which describes system (b)

Does Gravity follow the rules of QM?

There are various camps

(1) Spacetime is Classical: Gravitational interaction is Classical

$$V(r) \sim -\frac{Gm_1m_2}{r} - \frac{G^2\hbar m_1m_2}{r^3} - \cdots$$

(2) Classical
No Quantum Origin

(3) All the terms are Quantum in origin

Assumption & Observation

Type	Strength	Range	Mediator
strong	1	10^{-15} m	gluons (8)
electro-magnetic	10^{-2}	∞	photon
weak	10^{-5}	10^{-18} m	W^+, W^-, Z^0
gravity	10^{-38}	∞	graviton

Key assumption:
All the Interactions
are QUANTUM in Nature

Observation: In the limit when $\hbar \to 0$ Quantum Correlations DO not vanish, although it might become more challenging to detect, as shown for two entangled large spins.

Finite violation of a Bell inequality for arbitrarily large spin

Asher Peres*
Department of Physics, Technion–Israel Institute of Technology, 32 000 Haifa, Israel
(Received 20 August 1991)

A pair of spin-j particles, prepared in a singlet state, move away from each other and are examined by two distant observers. A simple experimental procedure can produce a 24% violation of a Bell inequality, for arbitrarily large j.

PACS number(s): 03.65.Bz

Maximal violation of Bell's inequality for arbitrarily large spin

N. Gisin
Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland

and

A. Peres
Department of Physics, Technion – Israel Institute of Technology, 32 000 Haifa, Israel

Received 4 November 1991; accepted for publication 2 December 1991
Communicated by J.P. Vigier

For any nonfactorable state of two quantum systems, it is possible to find pairs of observables whose correlations violate Bell's inequality. In the case of two particles of spin j prepared in a singlet state, the violation of Bell's inequality remains maximal for arbitrarily large j. It is thus seen that large quantum numbers are no guarantee of classical behaviour.

Key Challenges

Purity of the Quantum System → All the information about the ruler, e.g. Defect in the system → Cooling the c.o.m & Cooling the bulk / EM shielding / Finite box effect / Minimising noise → Observable/ Witness/ Measurement

Macroscopic Quantum System → $10^{-14} - 10\text{kg}, \quad t_{int} \leq 1\text{s}$

Macro molecules (Arndt's group)

$m \sim 10^{-22}\text{kg}, \ \Delta x \sim 0.25\mu\text{m}$

Large Spatial Superposition → $10^{-4} - 10^{-9}\text{m}$

Atom (Kasevich's group)

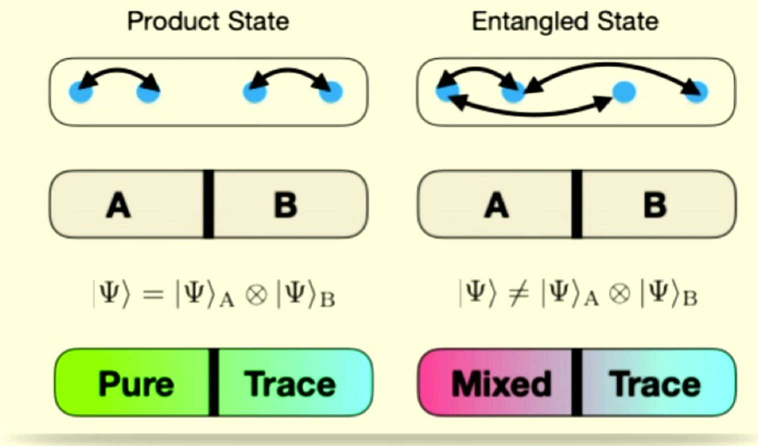
$m \sim 10^{-25}\text{kg}, \ \Delta x \sim 0.5\text{m}$

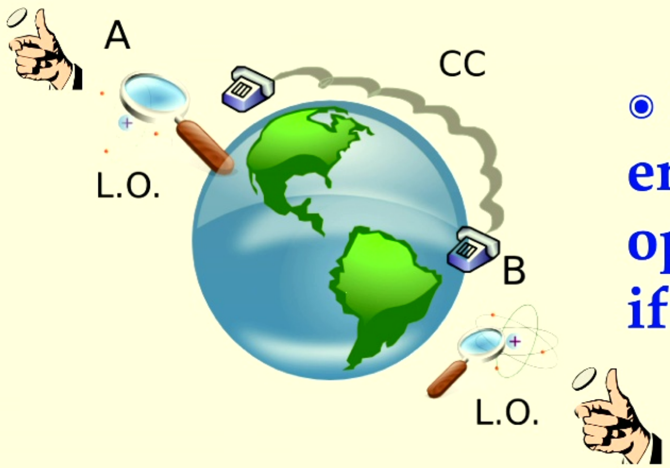
High Intensity Laser beam → Optical cavity with high intensity coherent photon, e.g. MegaWatt - PetaWatt

Biggest Challenge → Funding

No Entanglement via Classical Channel (field) !

Classical channel/field: No Hilbert space, classical probabilities, and not Operator valued entities





- It is impossible to generate/increase entanglement between A and B by local operations and classical communications (LOCC) if A & B were product states initially.

Bennett, et.al, (1996)

LOCC keeps Separable state Separable (Cannot Entangle)

Entanglement Non-Increasing Property

$$|\psi\rangle_A \otimes |\phi\rangle_B \longrightarrow \boxed{|0\rangle_A |\psi\rangle_A} \otimes \boxed{|\phi\rangle_B |0\rangle_B}$$

V_a $\quad$ U_B

Unitary evolution will maintain Separability

$\hat{A}_{i,j}(t)$

Classical Gravity

$\hat{B}_{j,k}(t)$

$$\rho(t) = \sum_i \sum_j \sum_k p(i)\, p(j)\, p(k)$$
$$\times\, \hat{A}_{i,j}(t)|\psi\rangle_A\langle\psi|_A \hat{A}^\dagger_{i,j}(t) \otimes \hat{B}_{j,k}(t)|\phi\rangle_B\langle\phi|_B \hat{B}^\dagger_{j,k}(t)$$

Arbitrary classical correlation will maintain the separability of the States

LOCC cannot entangle

Marshman, AM, Bose (2017)

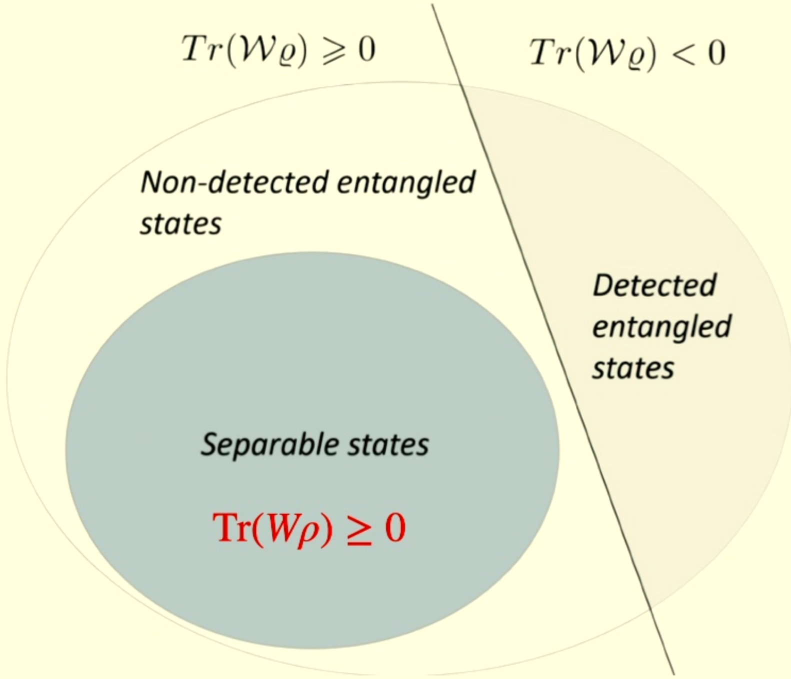
Entanglement Witness

An entanglement witness W is associated with a hyperplane such that the set of separable states are on one side.

For every entangled state ρ there exists W which can distinguish entanglement

Horodecki et al., 1996;

Terhal, 2000



$$\text{e.g. } W = I^{(1)} \otimes I^{(2)} - \sigma_x^{(1)} \otimes \sigma_x^{(2)} - \sigma_y^{(1)} \otimes \sigma_z^{(2)} - \sigma_z^{(1)} \otimes \sigma_y^{(2)}, \quad \mathrm{Tr}(W\rho) < 0$$

Genuine Quantum Correlation does not Vanish !

Basis independent Entanglement between systems exist, e.g.

$$C = \sqrt{2(1 - \mathrm{tr}(\rho_1^2))}, \qquad S_{en} = -\,\mathrm{Tr}\rho_1 \ln \rho_1 \neq 0$$

Entanglement in a Toy Model

$$H = \hat{H}_A + \hat{H}_B + \lambda \hat{H}_{AB}$$

$$|\psi_{\rm i}\rangle = |0\rangle_A |0\rangle_B \longrightarrow |\psi_{\rm f}\rangle \equiv \frac{1}{\sqrt{\mathcal{N}}} \sum_{n,N} C_{nN} |n\rangle |N\rangle$$

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

LOQC

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

Entanglement !

$\hat{H}_{AB}$ **: QED, Phonon mediated interaction, Gravity, or any Quantum Interaction**

Entanglement in a Toy Model

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

$$|\psi_f\rangle \sim \left(|0\rangle + \sum_{n>0} A_n |n\rangle \right) \cdot \left(|0\rangle + \sum_{N>0} B_N |N\rangle \right) + \sum_{n,N>0} \left(C_{nN} - A_n B_N \right) |n\rangle |N\rangle$$

LOQC

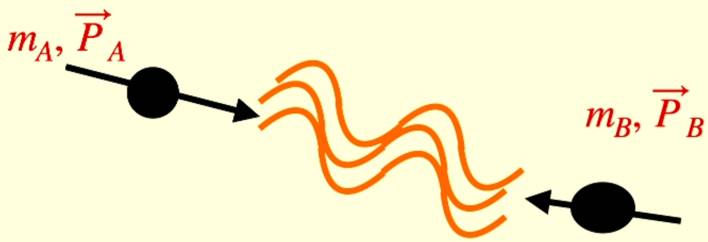
$$C_{nN} = \lambda \frac{\langle n | \langle N | \hat{H}_{AB} | 0 \rangle | 0 \rangle}{2E_0 - E_n - E_N} \neq 0$$

Entanglement !

$\hat{H}_{AB}$ **: QED, Phonon mediated interaction, Gravity, or any Quantum Interaction**

LOQC: Local Operation & Quantum Communication

$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h_{\mu\nu}| \ll 1$ If $\hat{h}_{\mu\nu}$ is an Operator, then what will be $\Delta\hat{H}_g$?



Quantum fluctuations
in the gravitational field

$$\Delta\hat{H}_g = -\frac{Gm^2}{|\hat{x}_A - \hat{x}_B|} - \frac{G(3\hat{p}_A^2 - 8\hat{p}_A\hat{p}_B + 3\hat{p}_B^2)}{2c^2|\hat{x}_A - \hat{x}_B|} - \frac{G(5\hat{p}_A^4 - 18\hat{p}_A^2\hat{p}_B^2 + 5\hat{p}_B^4)}{8c^4m^2|\hat{x}_A - \hat{x}_B|} - \cdots$$

If gravity is quantum, then the $\Delta\hat{H}_g$ (change in the gravitational energy) is an Operator-valued quantity. We will inevitably mix the position and the momentum operators of the two quantum systems

Entanglement in a Toy Model

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

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

LOQC

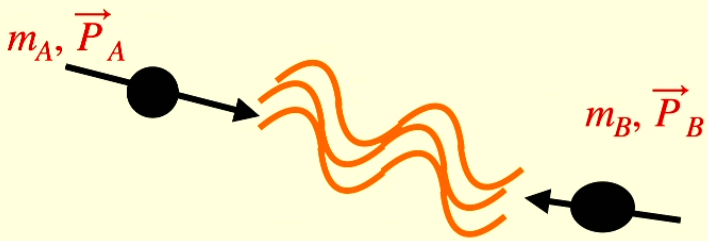
$$C_{nN} = \lambda\frac{\langle n|\langle N|\hat{H}_{AB}|0\rangle|0\rangle}{2E_0 - E_n - E_N} \neq 0$$

Entanglement !

$\hat{H}_{AB}$ **: QED, Phonon mediated interaction, Gravity, or any Quantum Interaction**

LOQC: Local Operation & Quantum Communication

$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad |h_{\mu\nu}| \ll 1$ If $\hat{h}_{\mu\nu}$ is an Operator, then what will be $\Delta\hat{H}_g$?



Quantum fluctuations
in the gravitational field

$$\Delta\hat{H}_g = -\frac{Gm^2}{|\hat{x}_A - \hat{x}_B|} - \frac{G(3\hat{p}_A^2 - 8\hat{p}_A\hat{p}_B + 3\hat{p}_B^2)}{2c^2|\hat{x}_A - \hat{x}_B|} - \frac{G(5\hat{p}_A^4 - 18\hat{p}_A^2\hat{p}_B^2 + 5\hat{p}_B^4)}{8c^4m^2|\hat{x}_A - \hat{x}_B|} - \cdots$$

If gravity is quantum, then the $\Delta\hat{H}_g$ (change in the gravitational energy) is an **Operator-valued** quantity. We will inevitably mix the position and the momentum operators of the two quantum systems

Two H-Os & perturbative Quantum Gravity

Perturbative Quantum Gravity

$$\hat{x}_A = -\frac{d}{2} + \delta\hat{x}_A, \qquad \hat{x}_B = \frac{d}{2} + \delta\hat{x}_B$$

$$\Delta\hat{H}_g = -\frac{Gm^2}{|\hat{x}_A - \hat{x}_B|} \qquad \Delta\hat{H}_g \approx -\frac{Gm^2}{d} + \frac{Gm^2}{d^2}(\delta\hat{x}_B - \delta\hat{x}_A) - \frac{Gm^2}{d^3}(\delta\hat{x}_B - \delta\hat{x}_A)^2$$

Entangle

Bose, AM, Schut and Toros 2201.03583

Position-Position Entanglement

$$\delta\hat{x}_A = \sqrt{\frac{\hbar}{2m\omega_\mathrm{m}}}(\hat{a}+\hat{a}^\dagger),\ \delta\hat{x}_B = \sqrt{\frac{\hbar}{2m\omega_\mathrm{m}}}(\hat{b}+\hat{b}^\dagger),$$

$$\hat{p}_A = i\sqrt{\frac{\hbar m\omega_\mathrm{m}}{2}}(\hat{a}^\dagger-\hat{a}),\ \hat{p}_B = i\sqrt{\frac{\hbar m\omega_\mathrm{m}}{2}}(\hat{b}^\dagger-\hat{b})$$

$$\hat{H}_\mathrm{AB} \approx \hbar\mathfrak{g}(\hat{a}\hat{b}+\hat{a}^\dagger\hat{b}+\hat{a}\hat{b}^\dagger+\hat{a}^\dagger\hat{b}^\dagger)$$

$$\mathfrak{g} \equiv \frac{Gm}{d^3\omega_\mathrm{m}}.$$

$$|\psi_\mathrm{i}\rangle = |0\rangle_A|0\rangle_B \longrightarrow |\psi_\mathrm{f}\rangle \equiv \frac{1}{\sqrt{1+(\mathfrak{g}/(2\omega_\mathrm{m}))^2}}\left[|0\rangle|0\rangle - \frac{\mathfrak{g}}{2\omega_\mathrm{m}}|1\rangle|1\rangle\right],$$

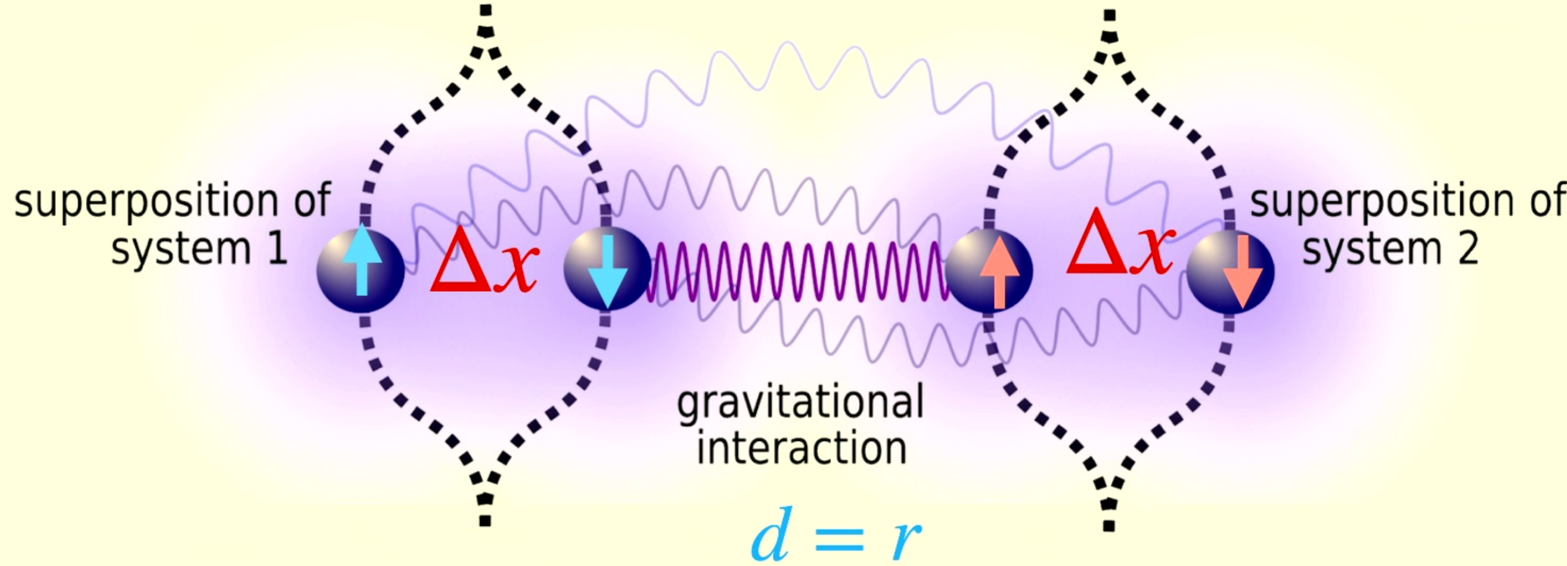
Concurrence (Entanglement): $C = \frac{\sqrt{2}Gm}{d^3\omega_\mathrm{m}^2} > 0$

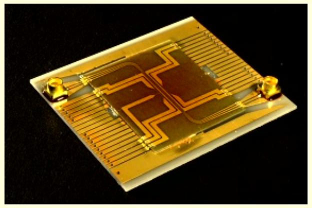
$$C = \sqrt{2(1-\mathrm{tr}(\hat{\rho}_\mathrm{A}^2))}$$

$$0 < C < \sqrt{2}$$

Entanglement Phase: $|\Delta\phi| = \frac{S}{\hbar} = \frac{E\tau}{\hbar} = \frac{2Gm^2\tau}{\hbar d}\left(\frac{\Delta x}{d}\right)^2$

Quantum Superposition of Non-Gaussian States



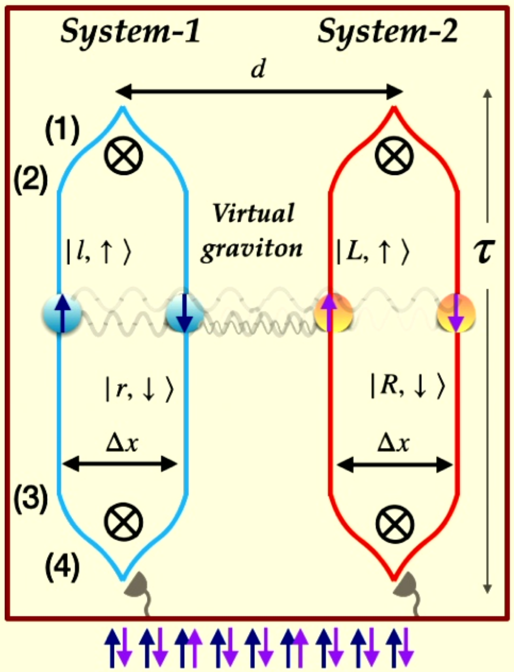


$$|\Psi(t_{int})\rangle = \frac{1}{2}e^{i\phi}[|\uparrow\rangle_1 \{|\uparrow\rangle_2 + e^{i\Delta\phi_{\uparrow\downarrow}}|\downarrow\rangle_2\} + e^{i\Delta\phi_{\downarrow\uparrow}}|\downarrow\rangle_1 \{|\uparrow\rangle_2 + e^{-i\Delta\phi_{\downarrow\uparrow}}|\downarrow\rangle_2\}]$$

$$\Delta\phi_{\uparrow\downarrow} = \phi_{\uparrow\downarrow} - \phi \text{ and } \Delta\phi_{\downarrow\uparrow} = \phi_{\downarrow\uparrow} - \phi$$

$$\Phi_{\text{eff}} = \Delta\phi_{\uparrow\downarrow} + \Delta\phi_{\downarrow\uparrow} = \phi_{\uparrow\downarrow} + \phi_{\downarrow\uparrow} - 2\phi = \frac{Gm^2}{\hbar}t_{int}\left(\frac{1}{d-\Delta x} + \frac{1}{d+\Delta x} - 2\frac{1}{d}\right)$$

Entanglement Witness in presence of Decoherence



Spin Correlation Measurement

Spin Entanglement Witness for Quantum Gravity

$$\rho = \frac{1}{4}\begin{pmatrix} 1 & e^{-i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & e^{-i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & e^{-2\gamma t} \\ e^{i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & 1 & (e^{i(\Delta\phi_{\uparrow\downarrow}-\Delta\phi_{\uparrow\downarrow})})e^{-2\gamma t} & e^{i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} \\ e^{i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & (e^{-i(\Delta\phi_{\uparrow\downarrow}-\Delta\phi_{\uparrow\downarrow})})e^{-2\gamma t} & 1 & e^{i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} \\ e^{-2\gamma t} & e^{-i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & e^{-i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & 1 \end{pmatrix}$$

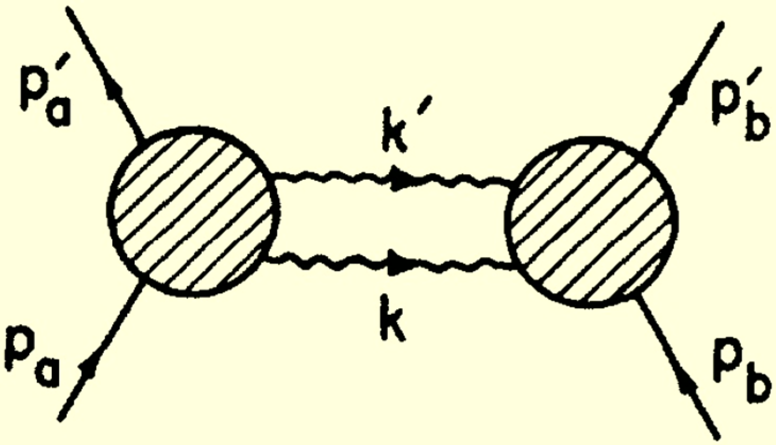
Witness for Quantum Gravity

$$\langle \mathcal{W} \rangle = \mathrm{Tr}(\mathcal{W}\rho) = 1 - e^{-\gamma t}(\sin\Delta\phi_{\uparrow\downarrow} + \sin\Delta\phi_{\downarrow\uparrow}) - \frac{e^{-2\gamma t}}{2}(1 + \cos(\Delta\phi_{\uparrow\downarrow} - \Delta\phi_{\downarrow\uparrow}))$$

$$\langle \mathcal{W} \rangle = \mathrm{Tr}(\mathcal{W}\rho) = 2\gamma t - \Phi_{\text{eff}} \qquad \mathrm{Tr}(\mathcal{W}\rho) < 0$$

$m \sim 10^{-14} - 10^{-15}\text{kg}, \;\; \Delta x \sim 100 - 10\mu\text{m}, \;\; d \sim 500\mu\text{m}, \;\; \tau \sim 1s \implies \Delta\phi_{ent} \sim \mathcal{O}(1)$

Casimir & Dipole Entanglement

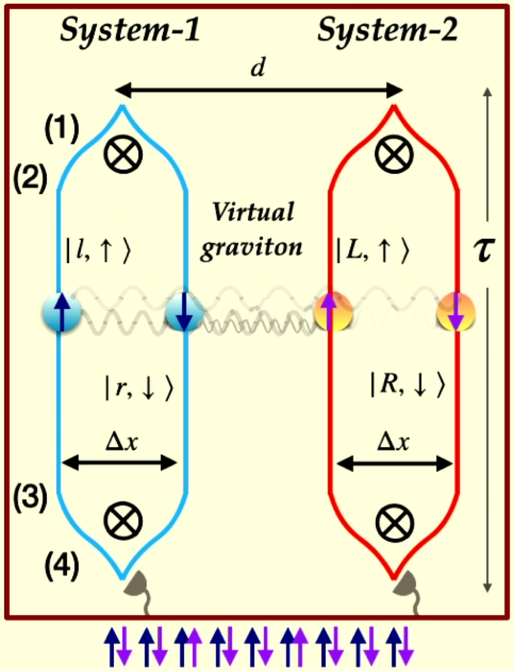


$$V_{CP} \sim -\frac{23\hbar c}{4\pi}\frac{R^6}{r^7}\left(\frac{\epsilon-1}{\epsilon+2}\right)^2$$

Casimir interaction will also entangle the two Diamonds

$$\Delta\phi_{gravity} > 10\Delta\phi_{CP}$$

Entanglement Witness in presence of Decoherence



Spin Correlation Measurement

Spin Entanglement Witness for Quantum Gravity

$$\rho = \frac{1}{4}\begin{pmatrix} 1 & e^{-i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & e^{-i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & e^{-2\gamma t} \\ e^{i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & 1 & (e^{i(\Delta\phi_{\uparrow\downarrow}-\Delta\phi_{\uparrow\downarrow})})e^{-2\gamma t} & e^{i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} \\ e^{i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & (e^{-i(\Delta\phi_{\uparrow\downarrow}-\Delta\phi_{\uparrow\downarrow})})e^{-2\gamma t} & 1 & e^{i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} \\ e^{-2\gamma t} & e^{-i\Delta\phi_{\uparrow\downarrow}}e^{-\gamma t} & e^{-i\Delta\phi_{\downarrow\uparrow}}e^{-\gamma t} & 1 \end{pmatrix}$$

Witness for Quantum Gravity

$$\langle \mathcal{W} \rangle = \mathrm{Tr}(\mathcal{W}\rho) = 1 - e^{-\gamma t}(\sin\Delta\phi_{\uparrow\downarrow} + \sin\Delta\phi_{\downarrow\uparrow}) - \frac{e^{-2\gamma t}}{2}(1 + \cos(\Delta\phi_{\uparrow\downarrow} - \Delta\phi_{\downarrow\uparrow}))$$

$$\langle \mathcal{W} \rangle = \mathrm{Tr}(\mathcal{W}\rho) = 2\gamma t - \Phi_{\mathrm{eff}} \qquad \mathrm{Tr}(\mathcal{W}\rho) < 0$$

$m \sim 10^{-14} - 10^{-15}\mathrm{kg}$, $\Delta x \sim 100 - 10\mu\mathrm{m}$, $d \sim 500\mu\mathrm{m}$, $\tau \sim 1s \implies \Delta\phi_{ent} \sim \mathcal{O}(1)$

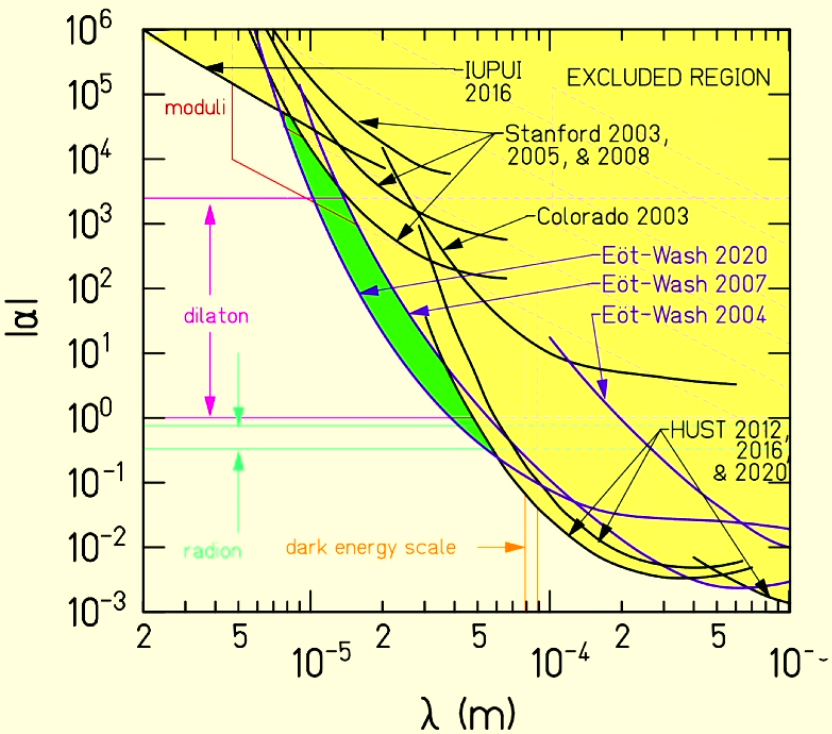
Many Applications

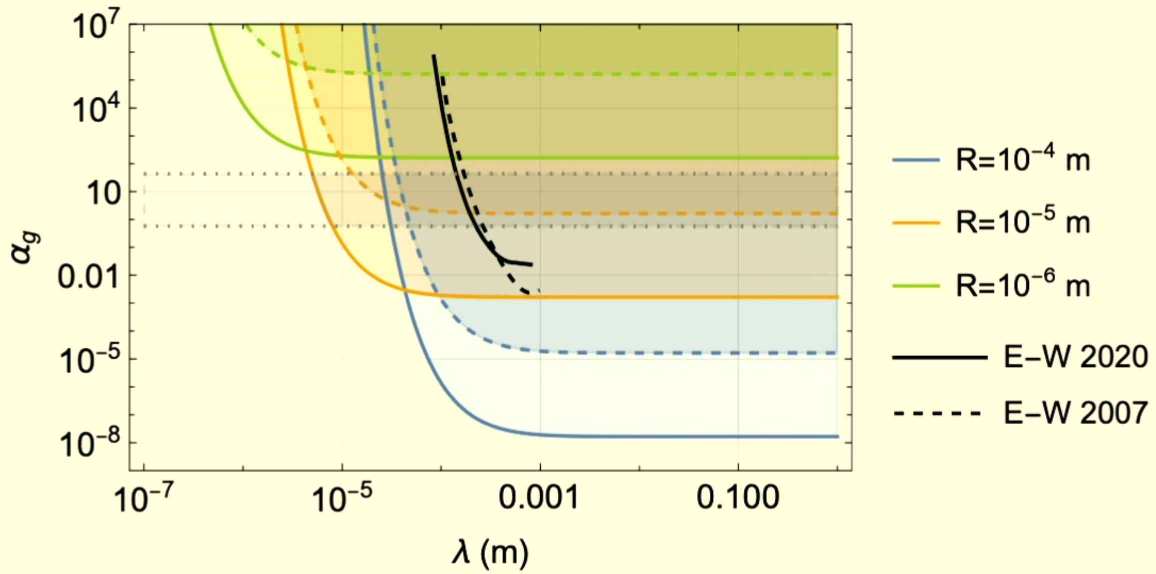
Weak Equivalence Principle via Entanglement

Probing beyond GR via Entanglement Tomography

Probing axion via Entanglement Tomography

Probing Gravity via Entanglement Tomography





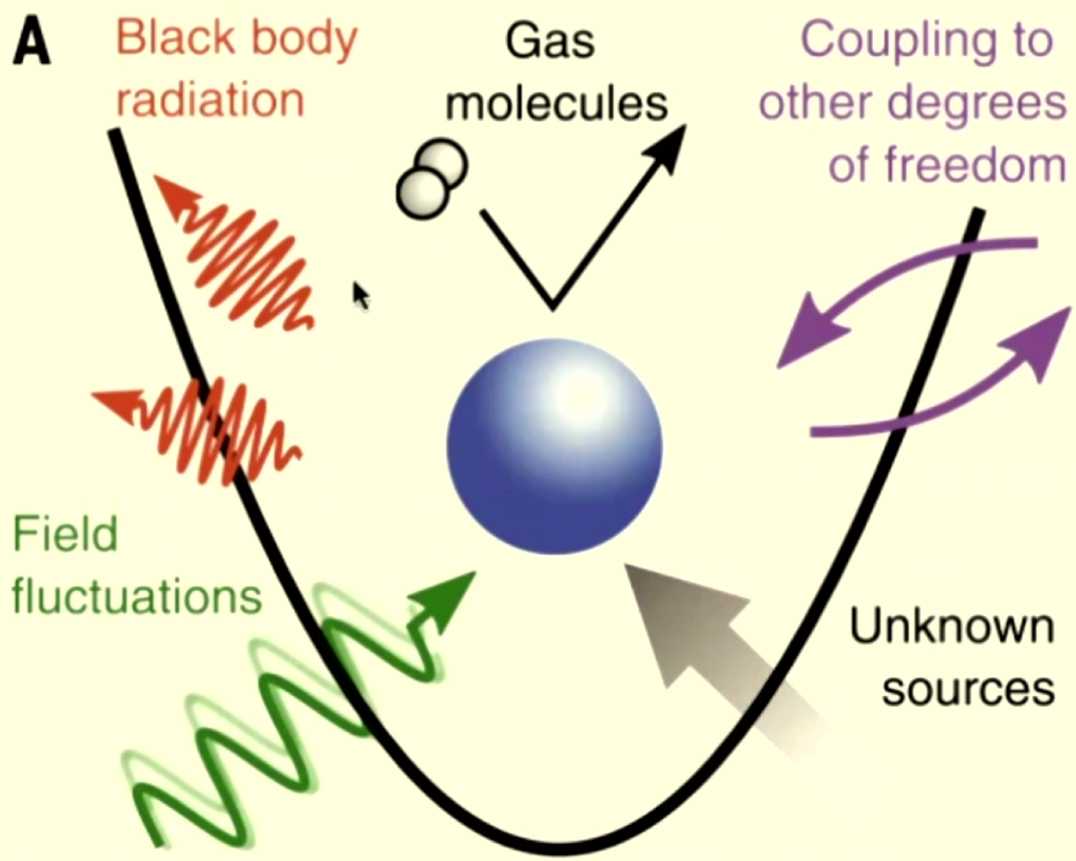
$$U_{Y_g} = \frac{Gm^2}{r}\left(1 + \alpha_g e^{-r/\lambda}\right)$$

Many beautiful challenges

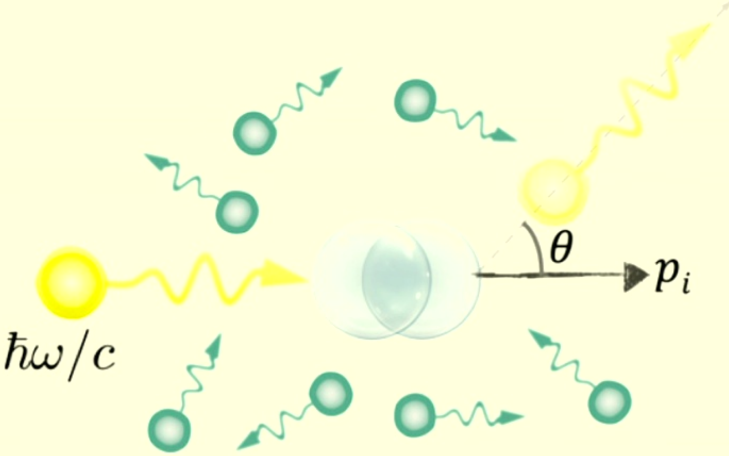
- Preparation of the initial wave packet
- Neutralising e.m. charges
- Cooling the diamond internally
- External cooling (minimising decoherence)
    - Avoiding black body radiation
    - Avoiding scattering
    - Avoiding collision with air molecule
- Levitating
- Creating superposition
- Closing one loop interferometer
    - Maintaining spin coherence
    - Controlling the current
    - Exciting internal phonons
    - Gravity Gradient Noise
    - Relative Acceleration Noise
- Humpty-Dumpty problem (stability)
- Reading Out
- Repeating to build statistics

There are still some unknown challenges from the BSM physics

Dephasing/Decoherence (Entanglement)



Creating the Ground State



Decoherence Rate = Interaction Rate

$$\gamma = \Gamma_{air} + \Lambda \Delta x^2$$

Phonon-dipole-photon interaction

$$\sigma(\omega) = \frac{8\pi}{3}\left(\frac{\omega}{c}\right)^4 |\alpha(\omega)|^2,$$

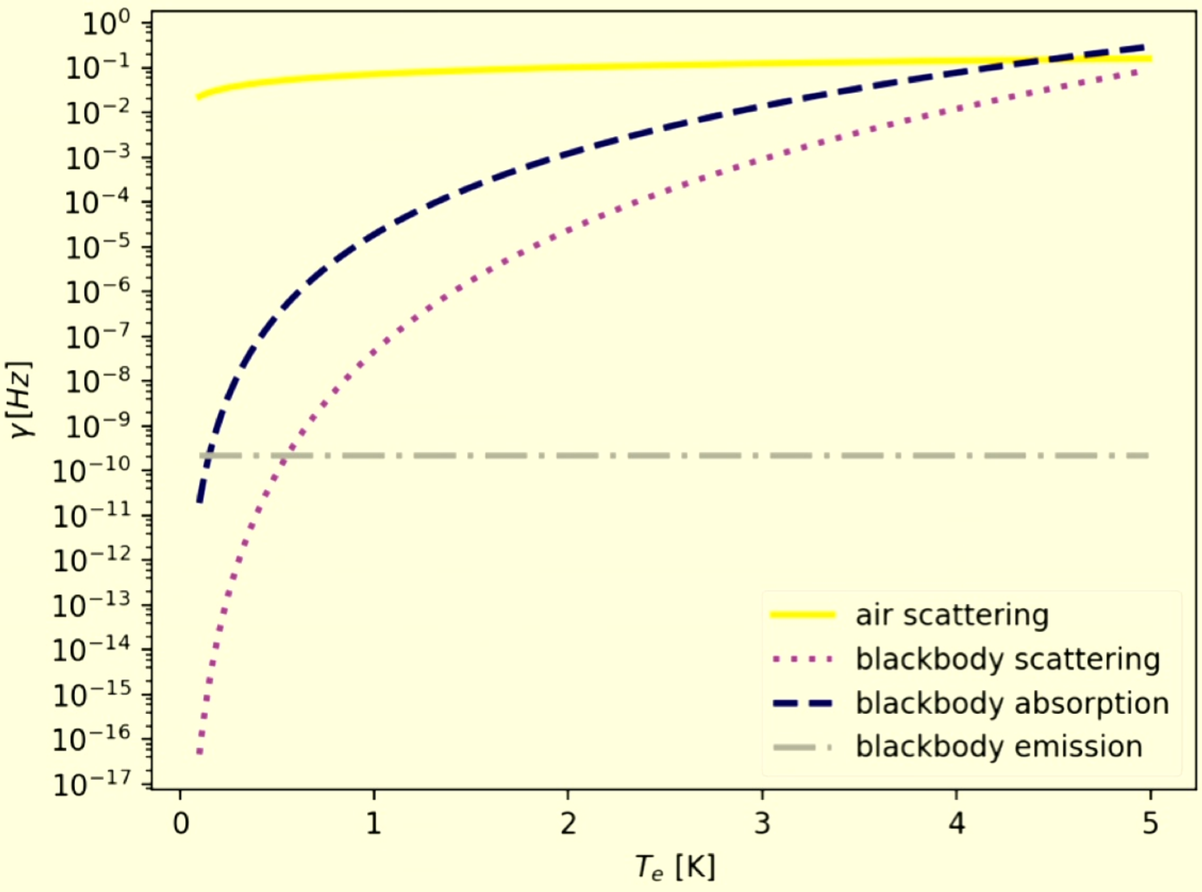
$$\Gamma_{air} = \frac{16\pi n R^2}{3}\sqrt{\frac{2\pi K_B T_{ex}}{m_{air}}}$$

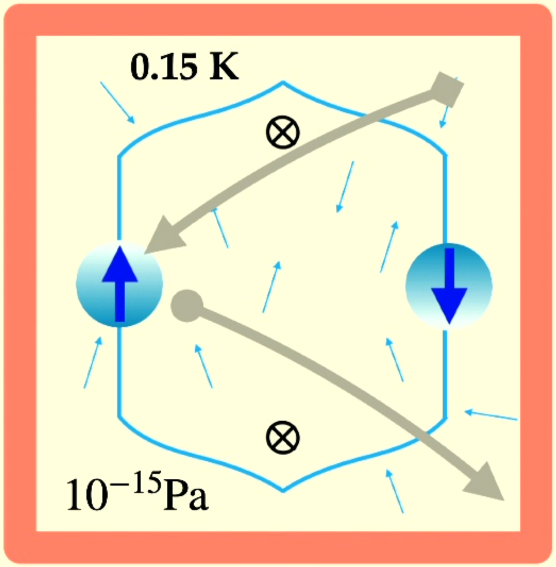
$$8!\frac{16}{9\pi}\zeta(9)a^6 c\left|\frac{\epsilon - 1}{\epsilon + 2}\right|^2\left(\frac{k_B T}{\hbar c}\right)^9 \equiv 2\Lambda,$$

External temperature

Joos, Zeh (1985)
Schlosshauer (2006, 2010), Adler (2006),
Hornberger, Spie (2003), Romero-Isart (2012)
Kanu, Milonni (2021)

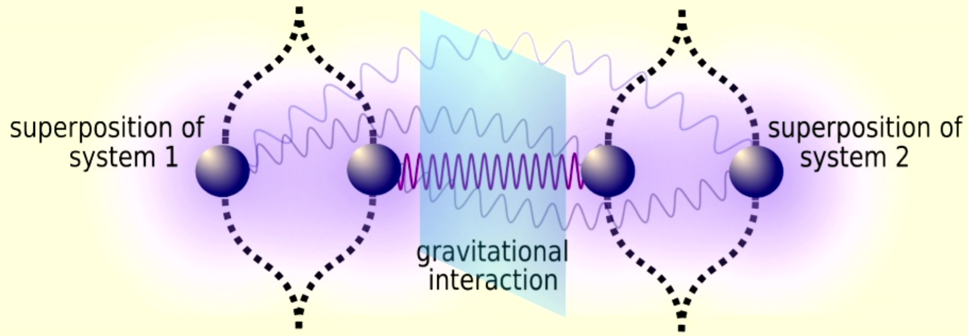
Cooling/Ground State (Decoherence)





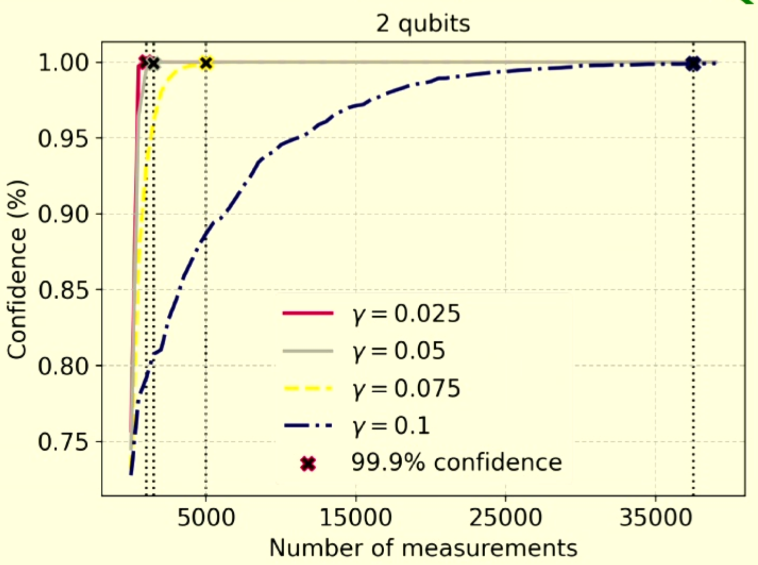
Van-Kamp, Marshman, Toros, Bose, AM, 2006.06931
Schut, Tilly, Marshman, Bose, AM, 2110.4695

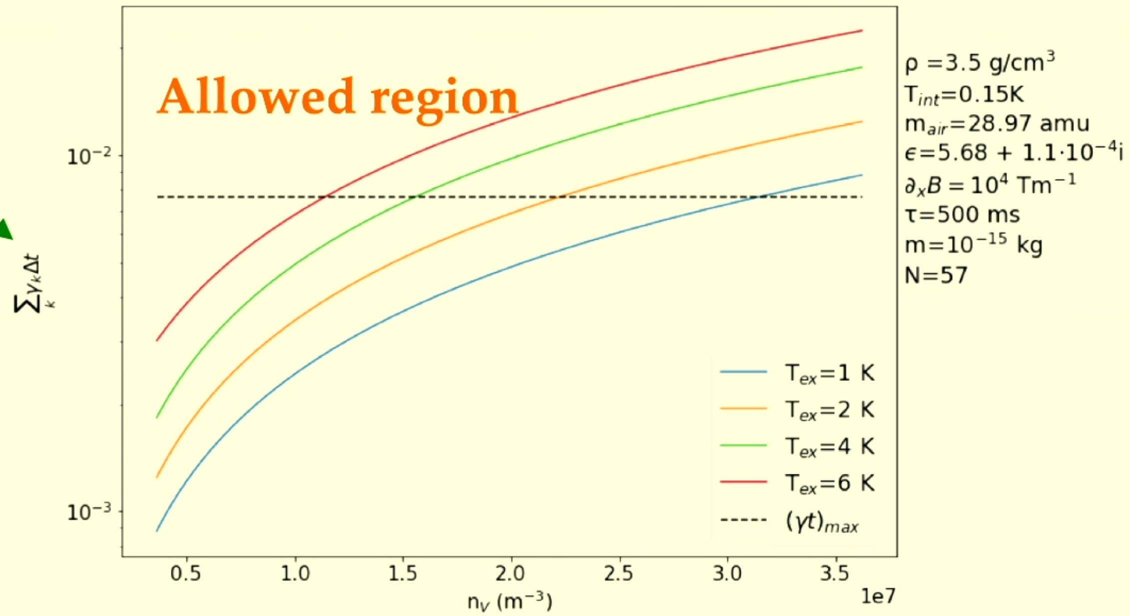
Entanglement Phase including Dephasing



$$\Phi_{\text{eff}} > \Gamma_{\text{jitter}} + \Gamma_{\text{gg}}$$

How many repetitions?





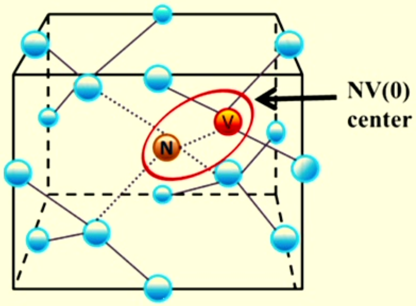
Hamiltonian for the NV centre

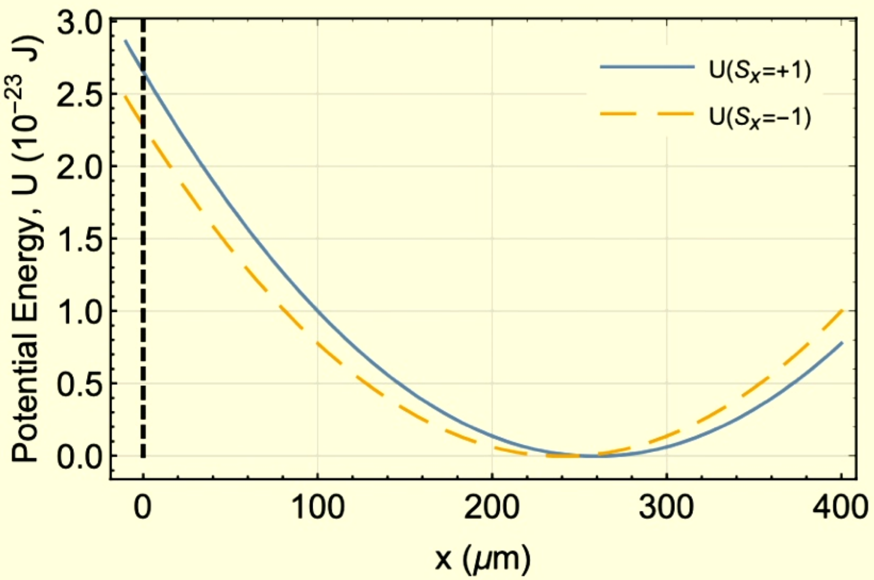
$$H = \frac{1}{2m}\vec{p}^2 + mg\hat{z} + \hbar D\hat{S}_z^2 - \frac{\chi_v V}{2\mu_0}\overrightarrow{B}^2 - \hbar\gamma_e\vec{S}\cdot\overrightarrow{B}$$

Zero-field Splitting

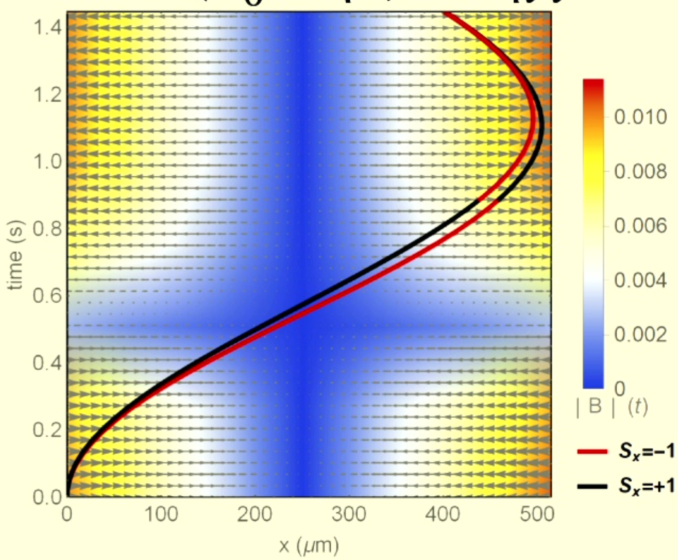
Diamagnetic part

NV- color centre part





$$B = (B_0 - \eta x)\hat{x} + \eta y\hat{y}$$



γe = (2π) 28 GHz/T the electronic **gyromagnetic ratio**

Marshman, AM, Folman, Bose. 2105.01094 [quant-ph]

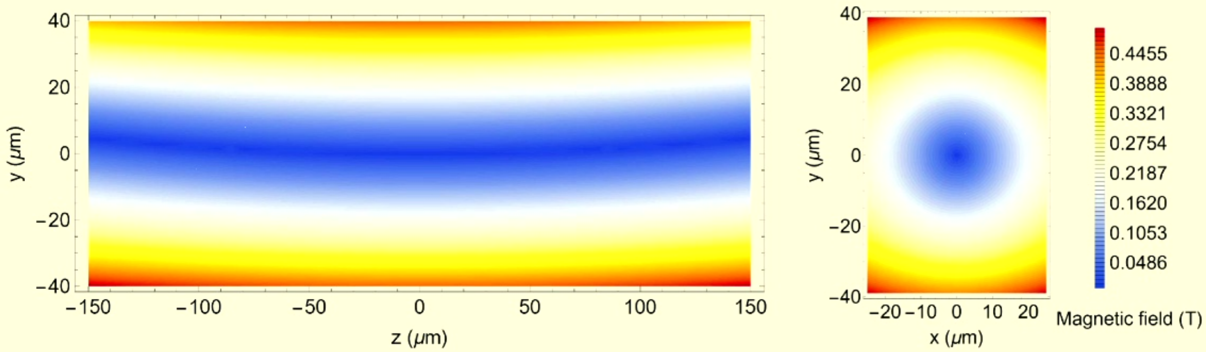
Levitating the Micro Crystal

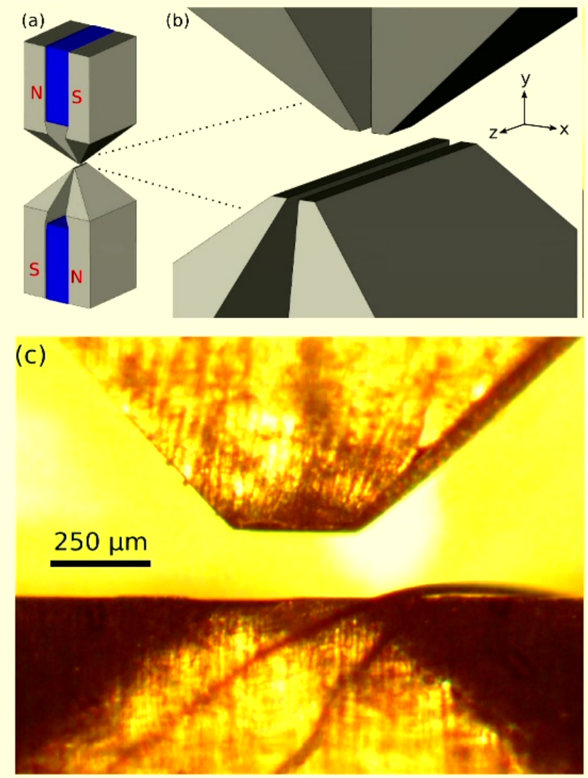
$$U = mg\hat{y} - \frac{\chi_m m}{2\mu_0} B^2$$

$B \sim \mathcal{O}(1)T \quad \omega_x \sim \omega_y \sim \omega_z \sim 2\pi \times \mathcal{O}(10 - 100)Hz$

Frequency range to trap the Motional Ground state

C.O.M via Active Feedback Mechanism by tuning the ambient magnetic field

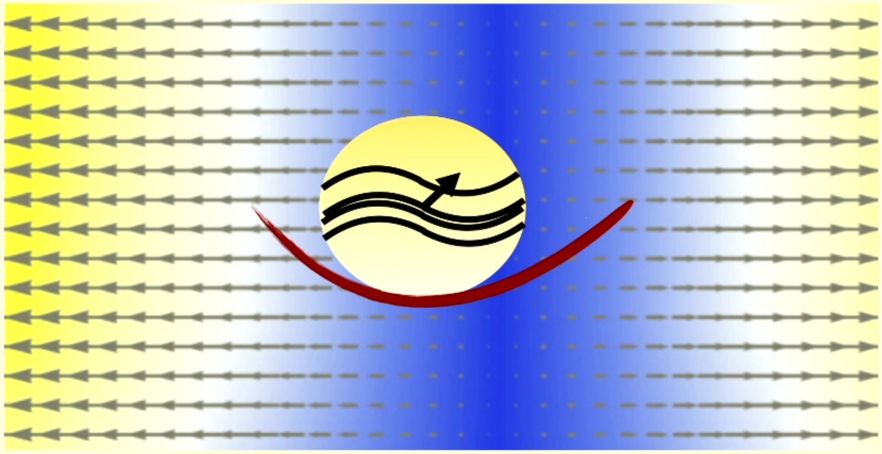




We will also need to cool the rotational degrees of freedom

Jen-Feng Hsu, Peng Ji, Charles W. Lewandowski & Brian D'Urso, Nature (2016)

Cooling the Phonons: Locating the Defect

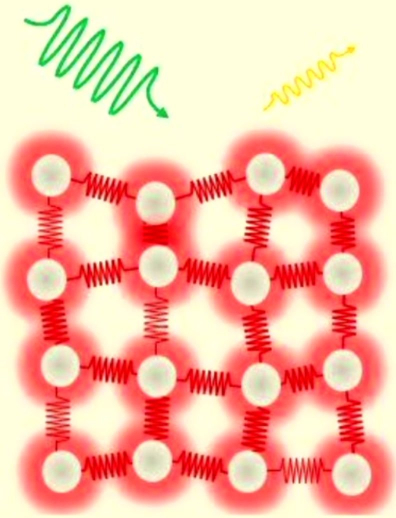


Levitating Magnetic field

$\omega_x \sim \omega_y \sim \omega_z \sim 2\pi \times \mathcal{O}(10 - 100)\text{Hz}$

Trapping C.O.M

$\omega_p \sim 10^{10}\text{Hz}$ (for micro diamond)

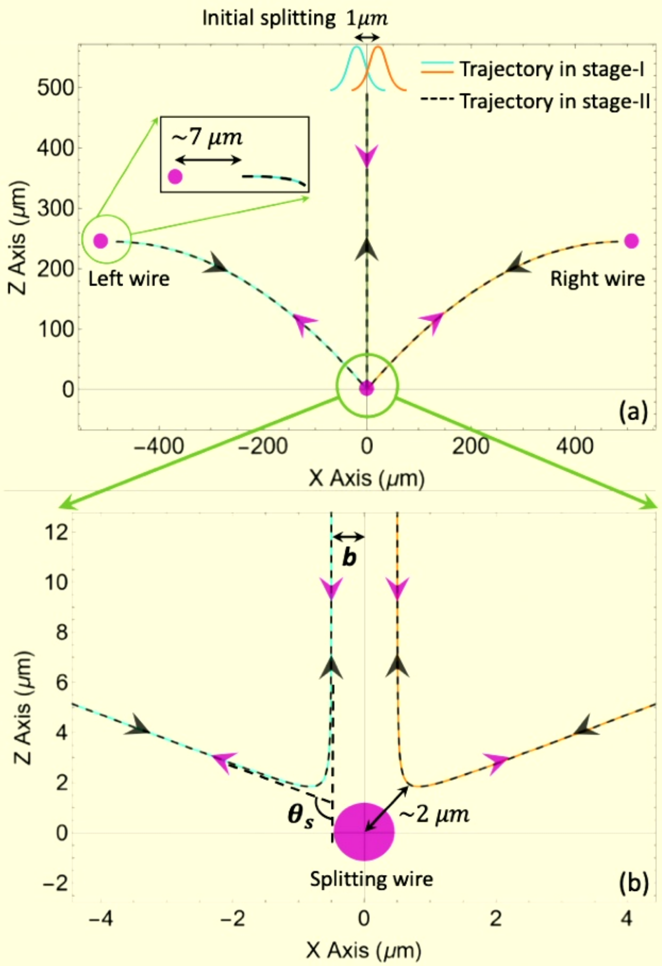


Phonon Cooling

Challenge: How would you take the phonon energy and cool the bulk?

$$n_p \sim e^{\hbar\omega_p/K_BT} \sim \mathcal{O}(1) \Longrightarrow T < 10^{-3}K$$

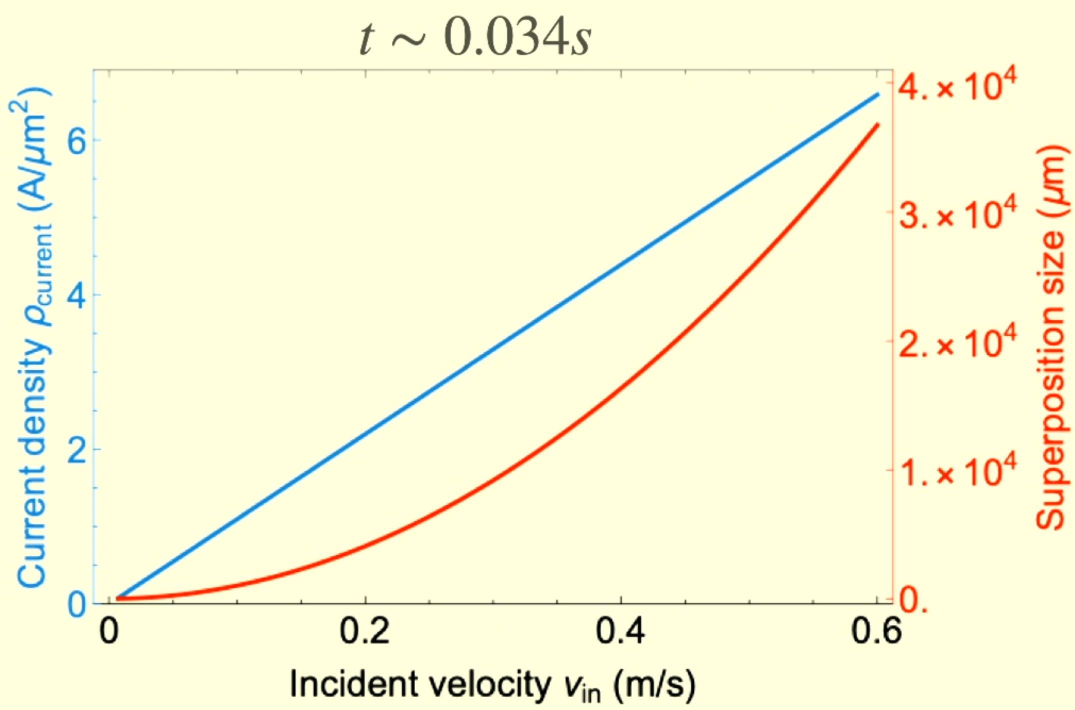
Enhancing the Superposition



Diamagnetic Repulsion :

Mapping the electronic Spin into the Nuclear Spin

Repulsive $1/r^3$ central potential



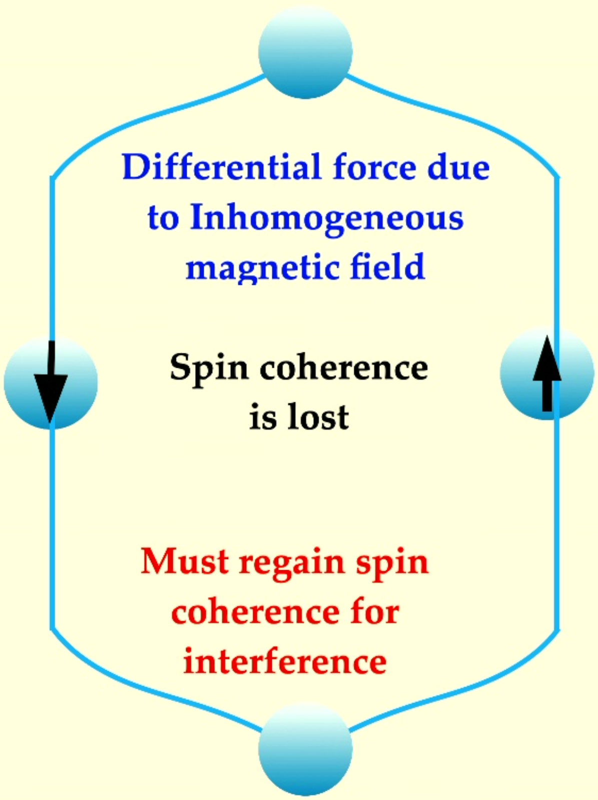
Spin Coherence

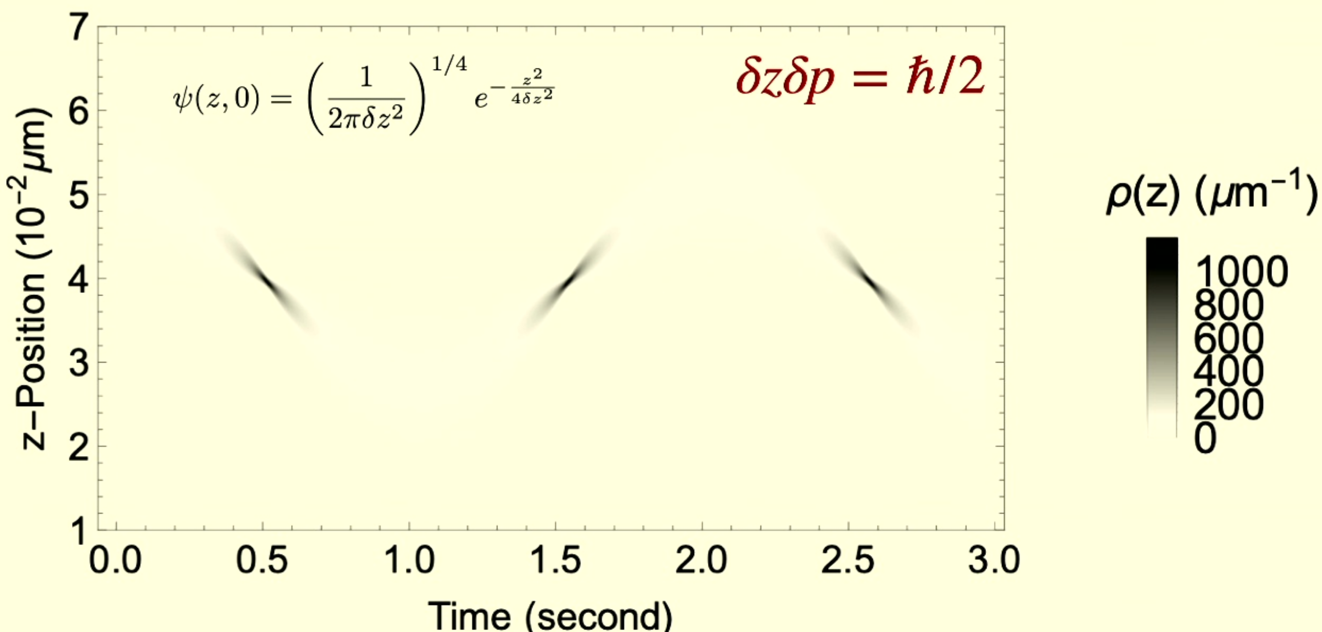
Humpty-Dumpty sat on a wall,
Humpty-Dumpty had a great fall;
All the King's horses and all the King's men
Couldn't put Humpty-Dumpty
together again.

$$i\hbar\frac{d\hat{A}_H(t)}{dt} = \left[\hat{A}_H(t), \hat{H}_H(t)\right]$$

$$\langle\hat{\sigma}_x(0)\rangle = 1,\ \langle\hat{\sigma}_y(0)\rangle = \langle\hat{\sigma}_z(0)\rangle = 0$$

$$\langle\hat{\sigma}_x(t)\rangle = \cos(\Phi(t))\exp\left(-\frac{1}{2}\left[\left(\frac{\Delta z}{\delta z}\right)^2 + \left(\frac{\Delta p}{\delta p}\right)^2\right]\right)$$





Englert, Scala, Schwinger

- 2206.04088

99% Spin Conherence

$$\boldsymbol{B} = (B_0 + \eta z^2 - \eta x^2)\hat{\boldsymbol{z}} - 2\eta z x \hat{\boldsymbol{x}}.$$

Mass	S_z	$\left(\frac{\Delta\eta}{\eta}\right)_z \lesssim$	$\left(\frac{\Delta\eta}{\eta}\right)_{p_z} \lesssim$
10^{-17}kg	1	9.3×10^{-6}	4.3×10^{-11}
	-1	9.3×10^{-6}	4.3×10^{-11}
10^{-16}kg	1	5.2×10^{-6}	1.4×10^{-11}
	-1	5.2×10^{-6}	1.4×10^{-11}
10^{-15}kg	1	2.9×10^{-6}	4.3×10^{-12}
	-1	2.9×10^{-6}	4.3×10^{-12}

- Zhou, Marshman, Bose, AM 2206.04088 [quant-ph]

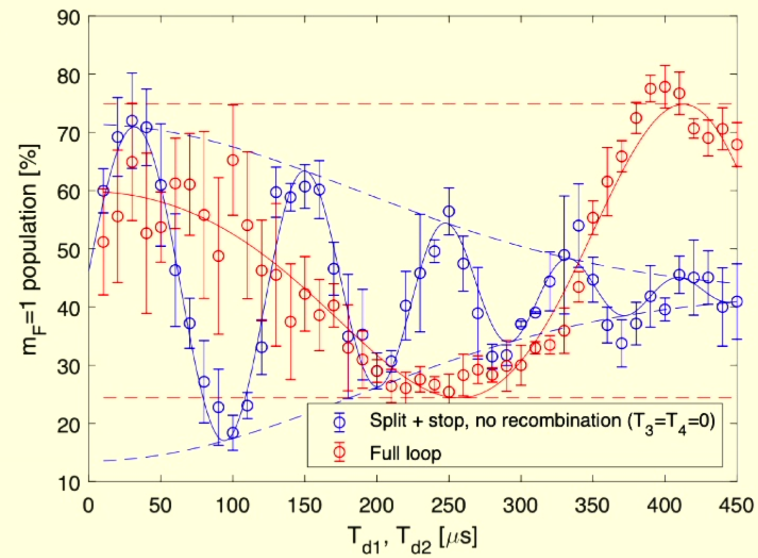
SCIENCE ADVANCES | RESEARCH ARTICLE

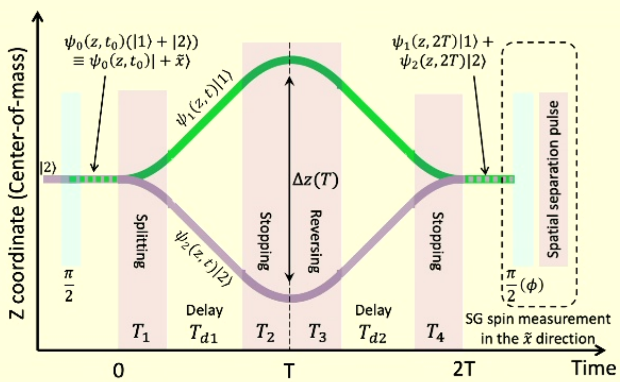
PHYSICS

Realization of a complete Stern-Gerlach interferometer: Toward a test of quantum gravity

Yair Margalit[1]*†, Or Dobkowski[1], Zhifan Zhou[1], Omer Amit[1], Yonathan Japha[1], Samuel Moukouri[1], Daniel Rohrlich[1], Anupam Mazumdar[2], Sougato Bose[3], Carsten Henkel[4], Ron Folman[1]

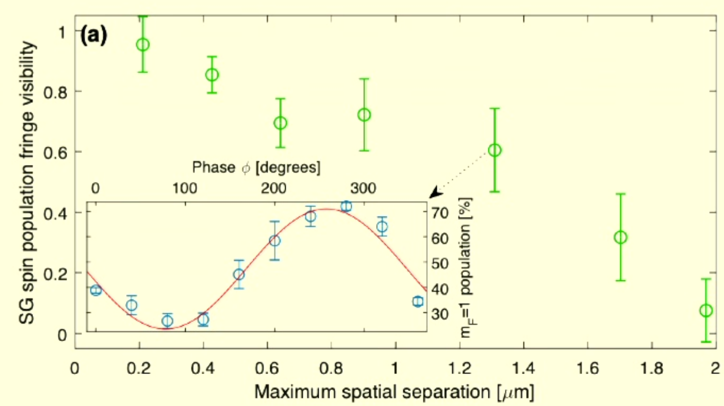
The Stern-Gerlach effect, found a century ago, has become a paradigm of quantum mechanics. Unexpectedly, until recently, there has been little evidence that the original scheme with freely propagating atoms exposed to gradients from macroscopic magnets is a fully coherent quantum process. Several theoretical studies have explained why a Stern-Gerlach interferometer is a formidable challenge. Here, we provide a detailed account of the realization of a full-loop Stern-Gerlach interferometer for single atoms and use the acquired understanding to show how this setup may be used to realize an interferometer for macroscopic objects doped with a single spin. Such a realization would open the door to a new era of fundamental probes, including the realization of previously inaccessible tests at the interface of quantum mechanics and gravity.





10^{-26}Kg

Rubidium atom



Today: Science Fiction, Tomorrow: Reality

Ground State Quantum System

Excellent Levitation Device (Motional Ground State Cooling)

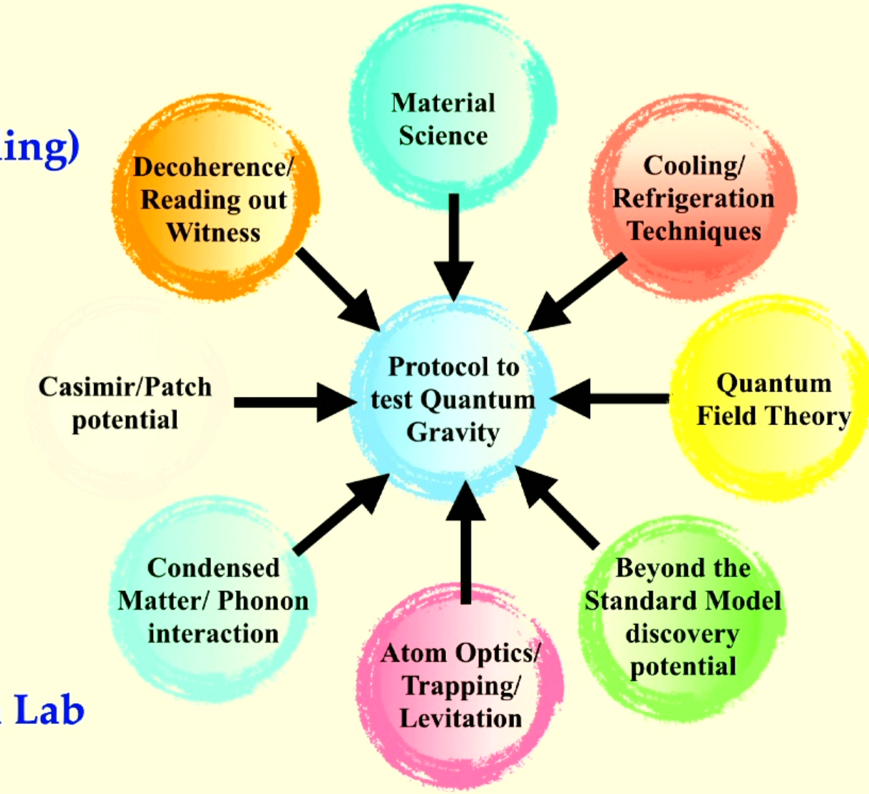
Best Vacuum

Quantum Manipulating of the Defect and Bulk Cooling

Unprecedented Control on Current

Innovative Material Science/Condensed Matter

Unambiguous test for the Quantum Nature of Gravity in a Lab




BEAM ME UP SCOTTY
COMMUNITY EFFORT : JOIN US
Graphics by