Quantum Nature of Gravity in the Lab through Entanglement & Measurements

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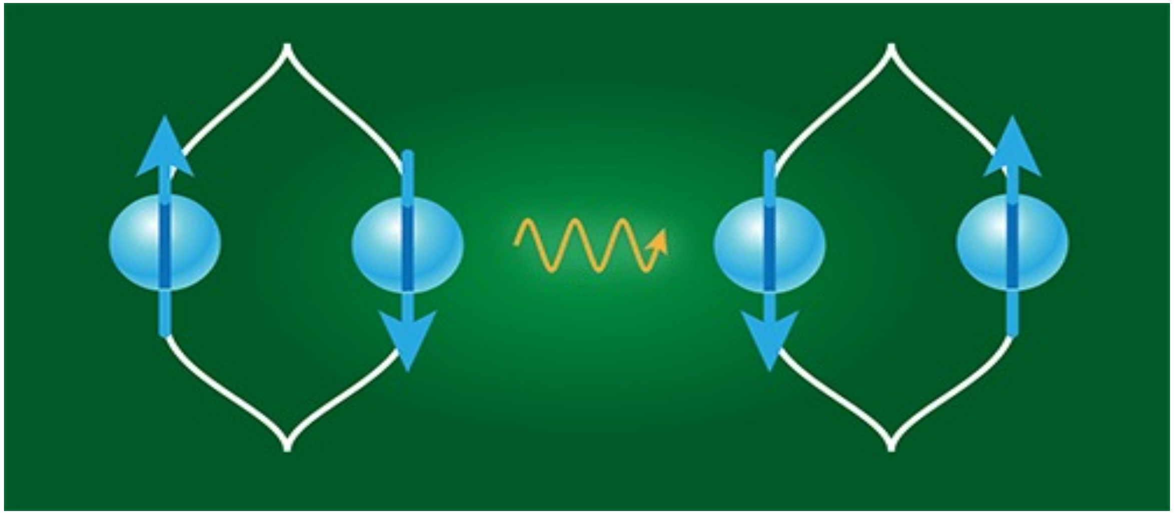
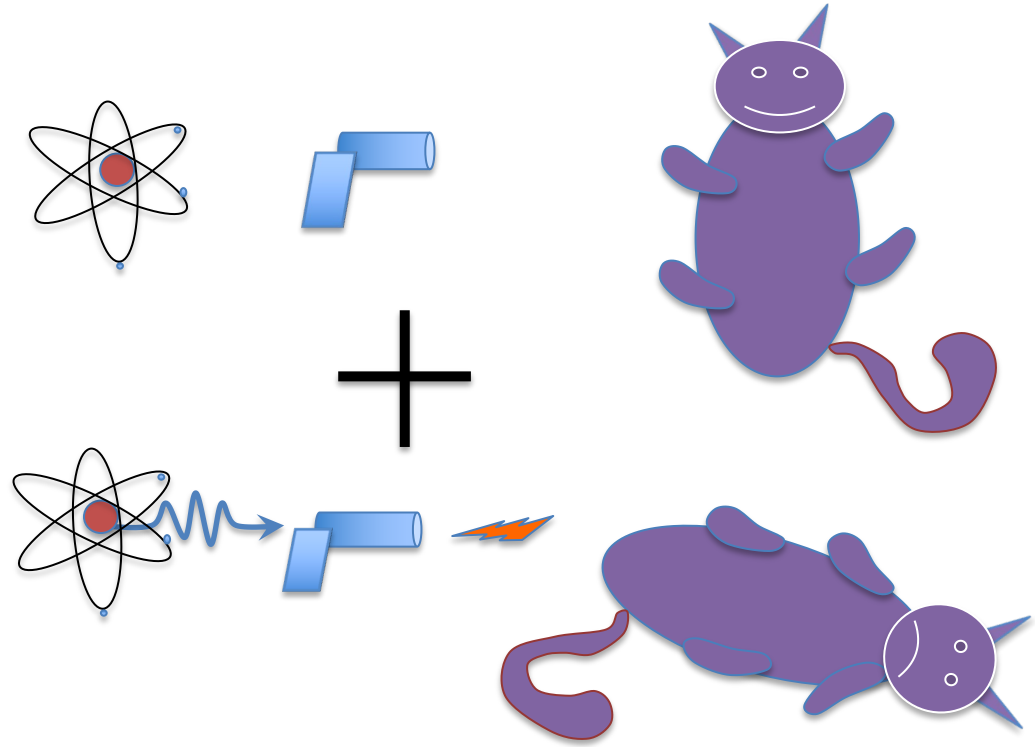
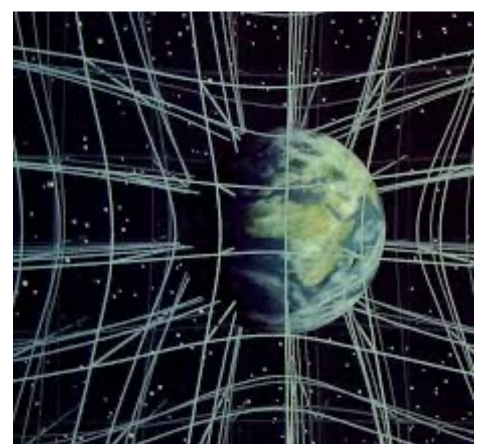


QTFP Community Meeting 2025

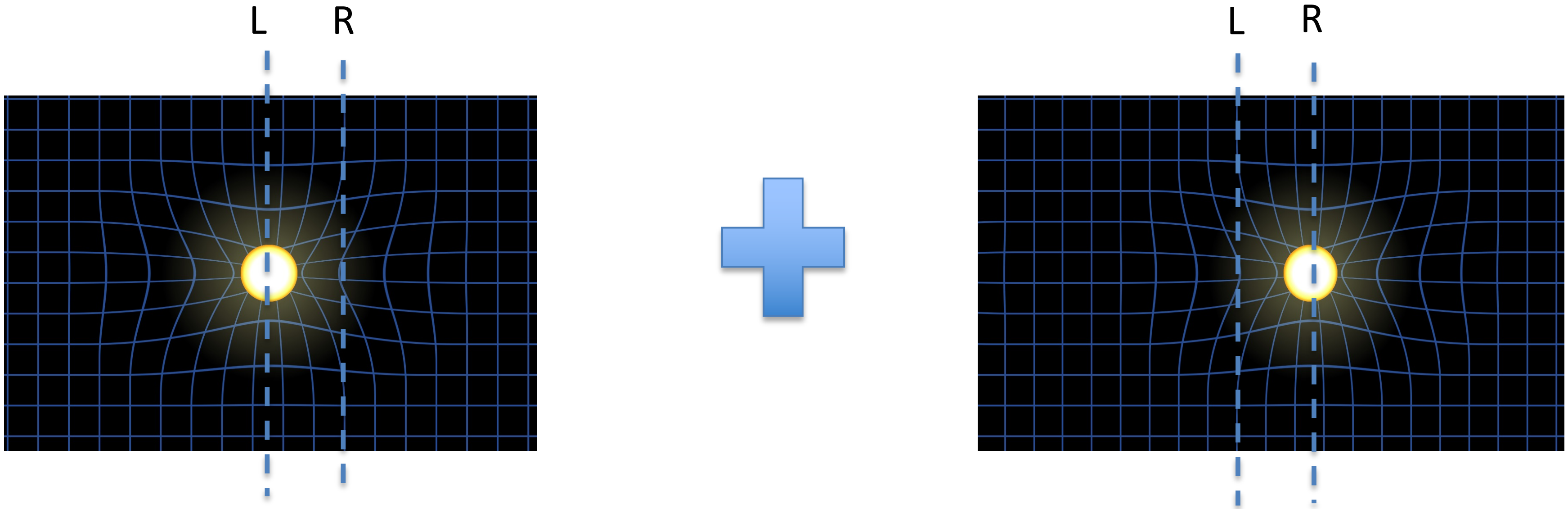
Quantum *Superposition*:



Gravity:



Can we Evidence Gravitational Field/Curvature To Exist in Quantum Superpositions?



- Need *another mass* to probe the gravity of the former.
- Need to show that it is a quantum superpositon instead of mixture (which has a classical statistical interpretation). → Entanglement

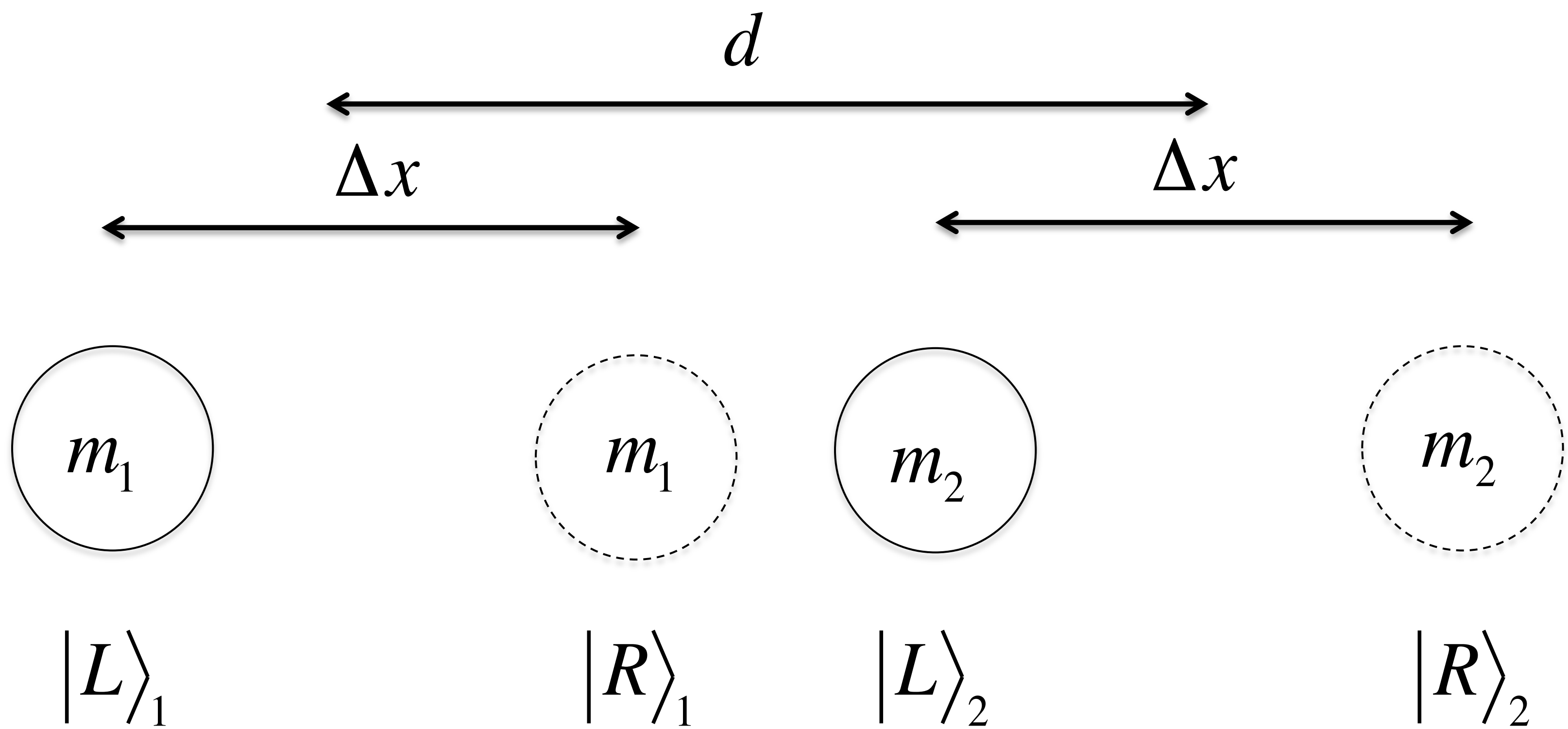
S. Bose, Matter wave ramsey interferometry & the quantum nature of gravity, Available at https://www.youtube.com/watch?v=0Fv-0k13s_k (2016), fundamental Problems of Quantum Physics, ICTS, Bangalore.

Spin Entanglement Witness for Quantum Gravity:
S. Bose, A. Mazumdar, G. W.Morley, H. Ulbricht, M. Toros, M. Paternostro, P. F. Barker, A. Geraci, M. S. Kim, G. J. Milburn, Phys. Rev. Lett. 119, 240401 (2017).

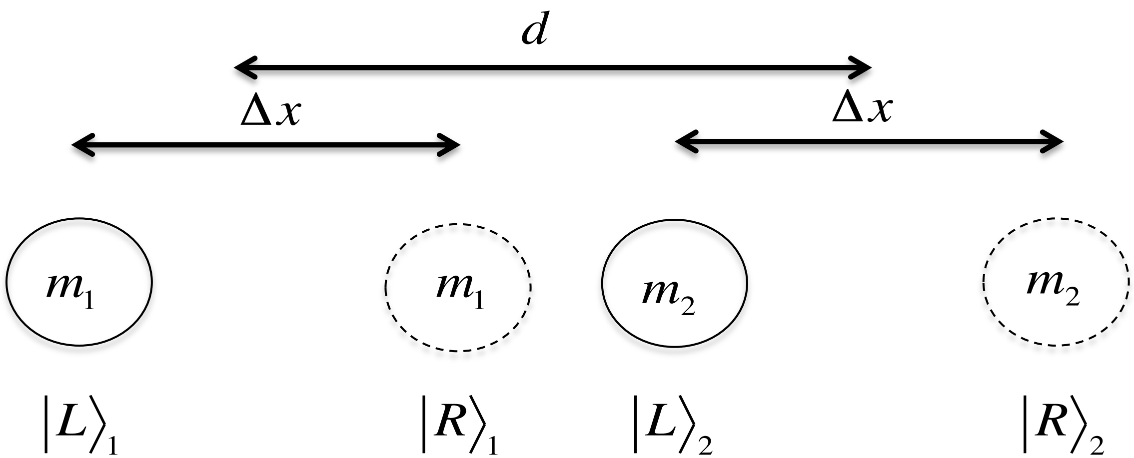
Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity: C. Marletto and V. Vedral, Phys. Rev. Lett. 119, 240402 (2017).

Two gravitationally interacting matter-wave interferometers

S. Bose, A. Mazumdar, G. W.Morley, H. Ulbricht, M. Toros, M. Paternostro, P. F. Barker, A. Geraci, M. S. Kim, G. J. Milburn, Phys. Rev. Lett. 119, 240401 (2017).



Consider two neutral test masses *held* in a superposition, each exactly as a spatial qubit (states |L> and |R>), near each other.



If they interact *only* through the gravitational force

$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2)$$

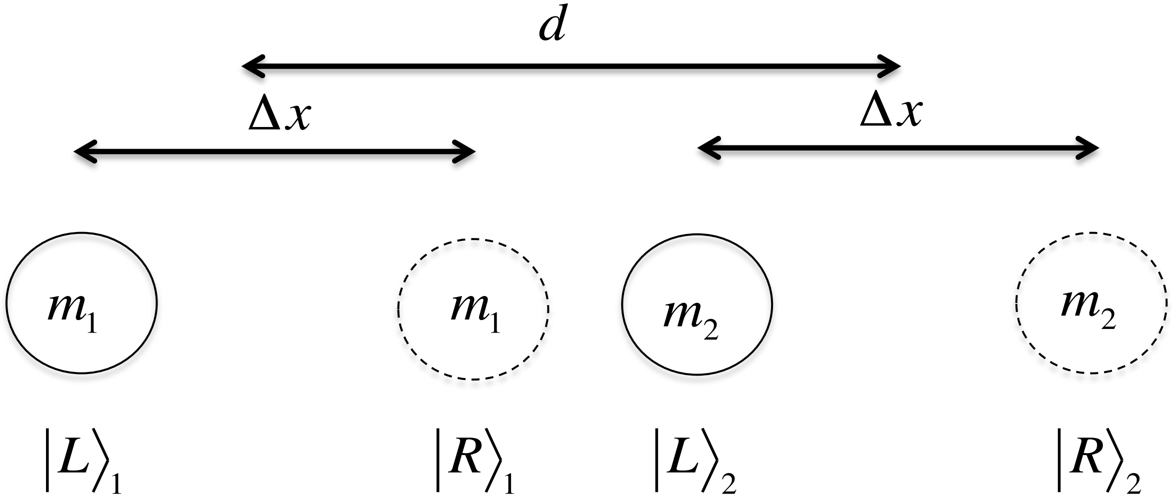
$$= \frac{1}{2}(|L\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2 + |R\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2)$$

$$\rightarrow |\Psi(t=\tau)\rangle_{12} = \frac{1}{2}(e^{i\phi_{LL}}|L\rangle_1|L\rangle_2 + e^{i\phi_{LR}}|L\rangle_1|R\rangle_2 + e^{i\phi_{RL}}|R\rangle_1|L\rangle_2 + e^{i\phi_{RR}}|R\rangle_1|R\rangle_2),$$

where

$$\phi_{RL} \sim \frac{Gm_1m_2\tau}{\hbar(d-\Delta x)}, \phi_{LR} \sim \frac{Gm_1m_2\tau}{\hbar(d+\Delta x)},$$

$$\phi_{LL} = \phi_{RR} \sim \frac{Gm_1m_2\tau}{\hbar d}$$

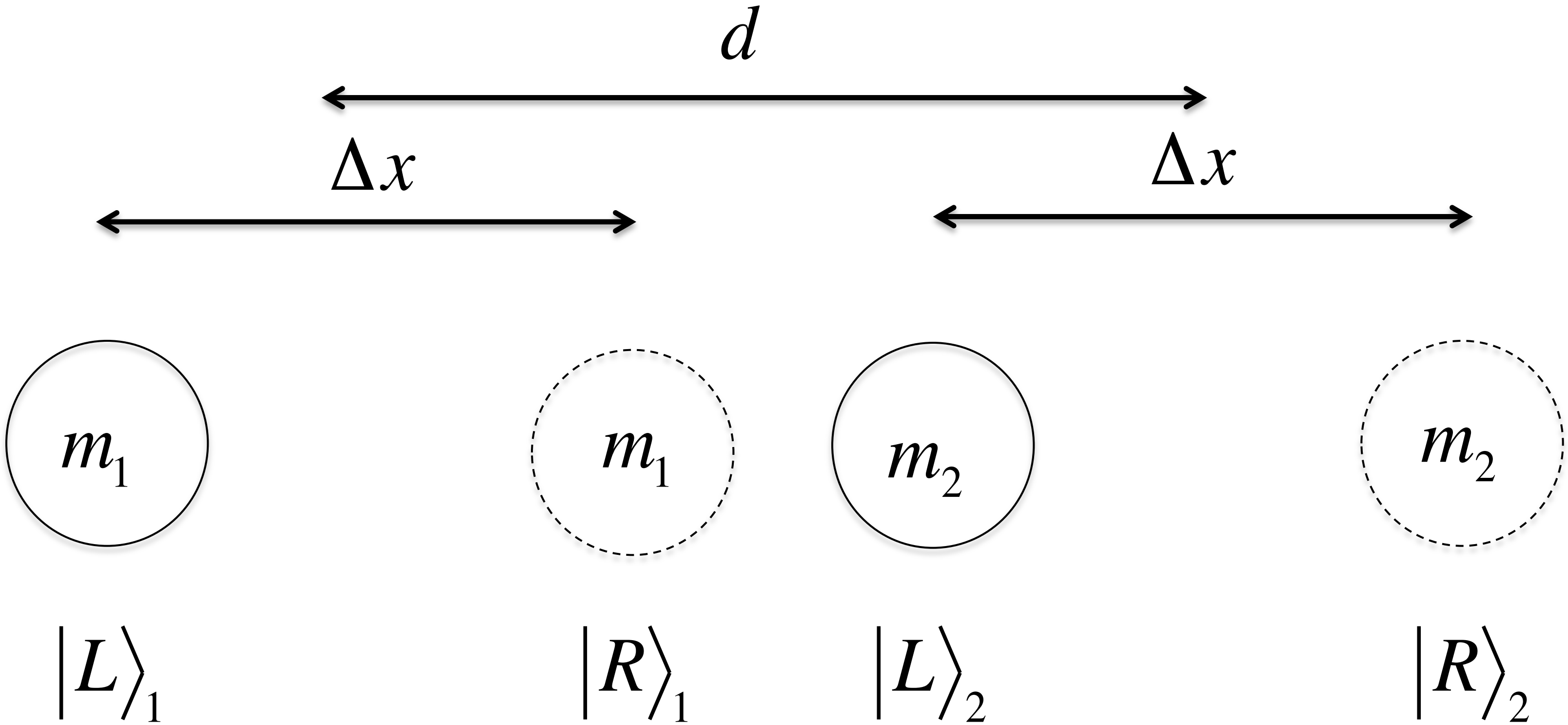


If they interact *only* through the gravitational force

$$|\Psi(t=\tau)\rangle_{12} = \frac{1}{2}(e^{i\phi_{LL}}|L\rangle_1|L\rangle_2 + e^{i\phi_{LR}}|L\rangle_1|R\rangle_2 + e^{i\phi_{RL}}|R\rangle_1|L\rangle_2 + e^{i\phi_{RR}}|R\rangle_1|R\rangle_2)$$

$$= \frac{e^{i\phi_{RR}}}{\sqrt{2}}\{|L\rangle_1 \frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2) + |R\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)\}$$

The above state is maximally entangled when $\Delta\phi_{LR} + \Delta\phi_{RL} \sim \pi$.



For

$$d - \Delta x << d, \Delta x,$$

An important limit in order to see the full strength of the effect.

we have

$$\Delta\phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar(d - \Delta x)} >> \Delta\phi_{LR}, \Delta\phi_{LL}, \Delta\phi_{RR}$$

Restrictions on *closest* approach:

$$\frac{U_{\text{Casimir}}}{U_{\text{Gravity}}} \sim \underbrace{\frac{23}{4\pi}\left(\frac{3}{4\pi}\right)^2\left(\frac{\epsilon-1}{\epsilon+2}\right)^2}_{0.03} \frac{m_p^2}{\rho^2(d-\Delta x)^6}$$

If you need gravity to dominate by a factor of 10, you have to go to 157 microns

[For experiments with screens you can bring this to ~ 20 microns; about 10 microns on each side of the screen]

For

$$d - \Delta x << d, \Delta x,$$

we have

$$\Delta\phi_{RL} \sim \frac{G m_1 m_2 \tau}{\hbar (d - \Delta x)} >> \Delta\phi_{LR}, \Delta\phi_{LL}, \Delta\phi_{RR}$$

Important limit to see the full strength

For mass ~ **10^(-14) kg (microspheres)**, separation at closest approach of the masses ~ 200 microns (Casimir interaction is safely smaller than gravity), **time ~ 1 seconds**, gives:
Scale of superposition ~ 100 microns, **Delta phi_{RL} ~ 1**

Planck's Constant fights Newton's Constant!

(Bose et. al. PRL 2017)

Verifies any quantum theory of gravity

$$\hat{G}_{\mu\nu} = \frac{8\pi G}{c^4}\hat{T}_{\mu\nu}$$

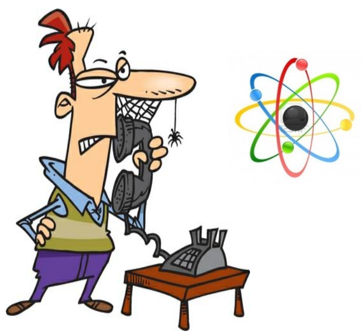
Falsifies hybrids: Quantum Source+Classical Gravity

$$P^{(j)}, \qquad G^{(j)}_{\mu\nu} = \frac{8\pi G}{c^4} T^{(j)}_{\mu\nu}(|\psi\rangle_{\text{Source}})$$

Including

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\langle\hat{T}_{\mu\nu}\rangle$$

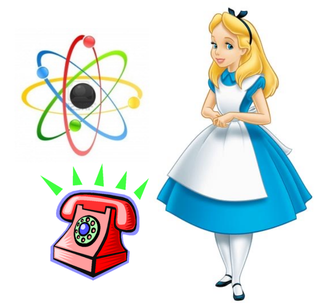
LOCC *Cannot* Entangle (Trivially proved)



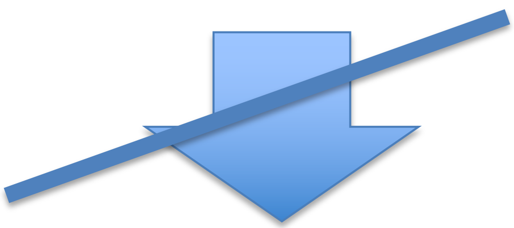
1. Unitary evolution

2. Measurements, Entangling , Tracing

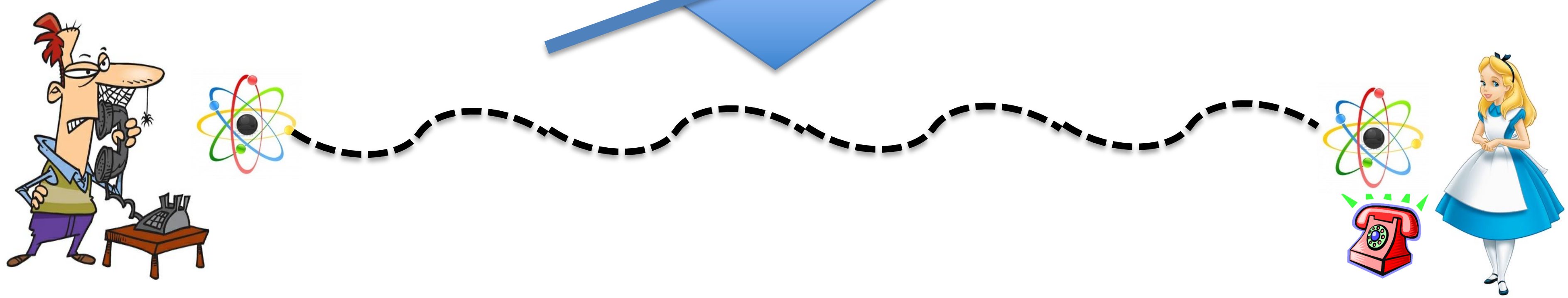
Informing the other party about the outcomes of measurements



Local Operations and Classical Communication (LOCC)



Not possible!



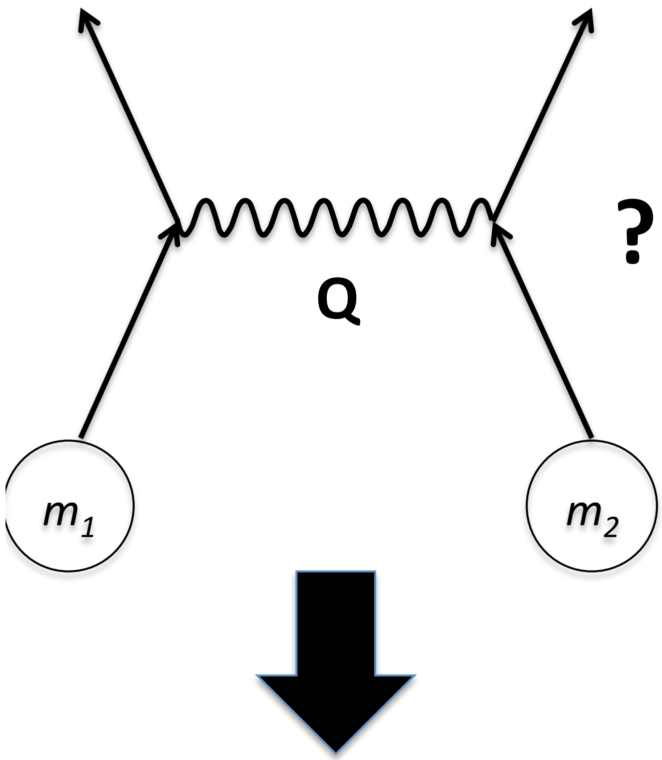
$$U_A \otimes U_B |\phi\rangle_A |\psi\rangle_B = |\phi'\rangle_A |\psi'\rangle_B$$

$$\sum_k P_k A_k \otimes B_k \left(\sum_i \Pi_i \rho_{iA} \otimes \rho_{iB}\right) A_k^+ \otimes B_k^+ \to \left(\sum_i P'_i \rho'_{iA} \otimes \rho'_{iB}\right)$$

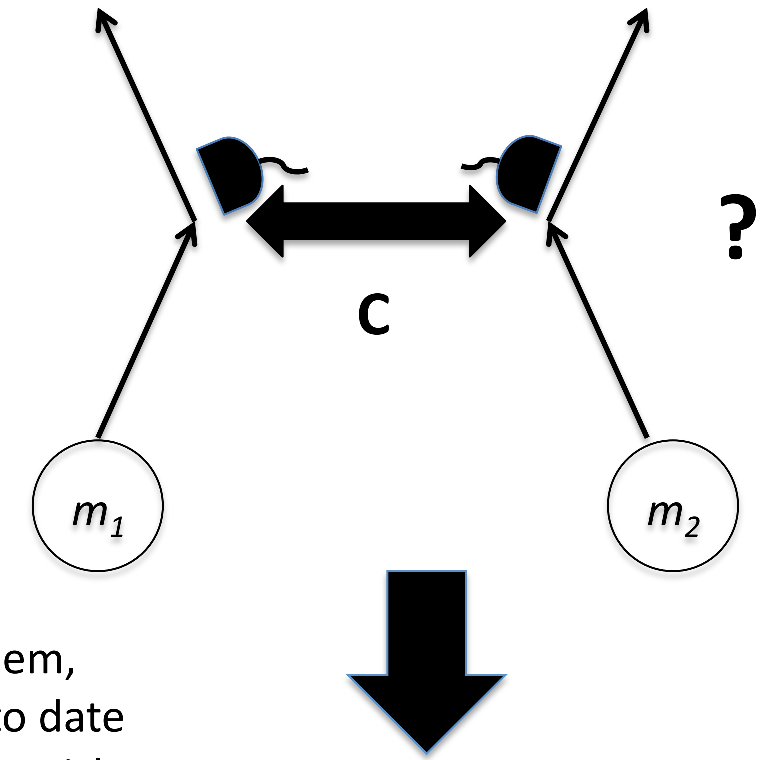
Thus equivalently, is gravitational force due to exchange of virtual quanta or not?

Is Gravity exactly like other forces in weak field limit? -- photons, W+/-, Z, gluons → **gravitons**

Or qualitatively different? **Is the Newtonian interaction actually quantum in origin?**



OR



Weird as
it may seem,
no expt to date
can distinguish
these alternatives!

m_1 and m_2 can entangle

m_1 and m_2 ***cannot*** entangle

Verification: An IR prediction of literally any theory of quantum gravity

Falsification: *All* semiclassical gravity (QS+CG): e.g. Oppenheim et al

PRL **117,** 143003 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Free Nano-Object Ramsey Interferometry for Large Quantum Superpositions

C. Wan,[1] M. Scala,[1] G. W. Morley,[2] ATM. A. Rahman,[2,3] H. Ulbricht,[4] J. Bateman,[5]
P. F. Barker,[3] S. Bose,[3,*] and M. S. Kim[1]

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

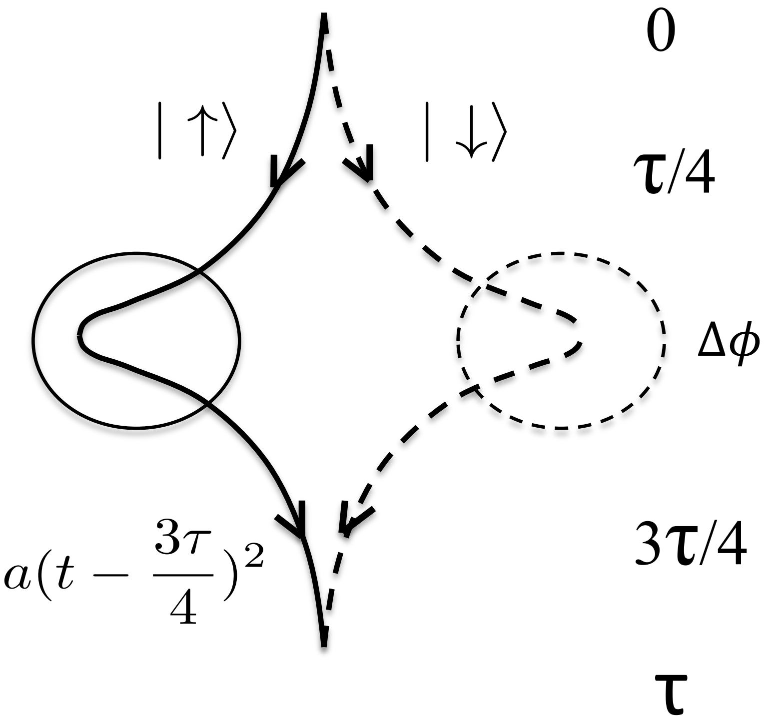
Realization of a complete Stern-Gerlach interferometer: Toward a test of quantum gravity

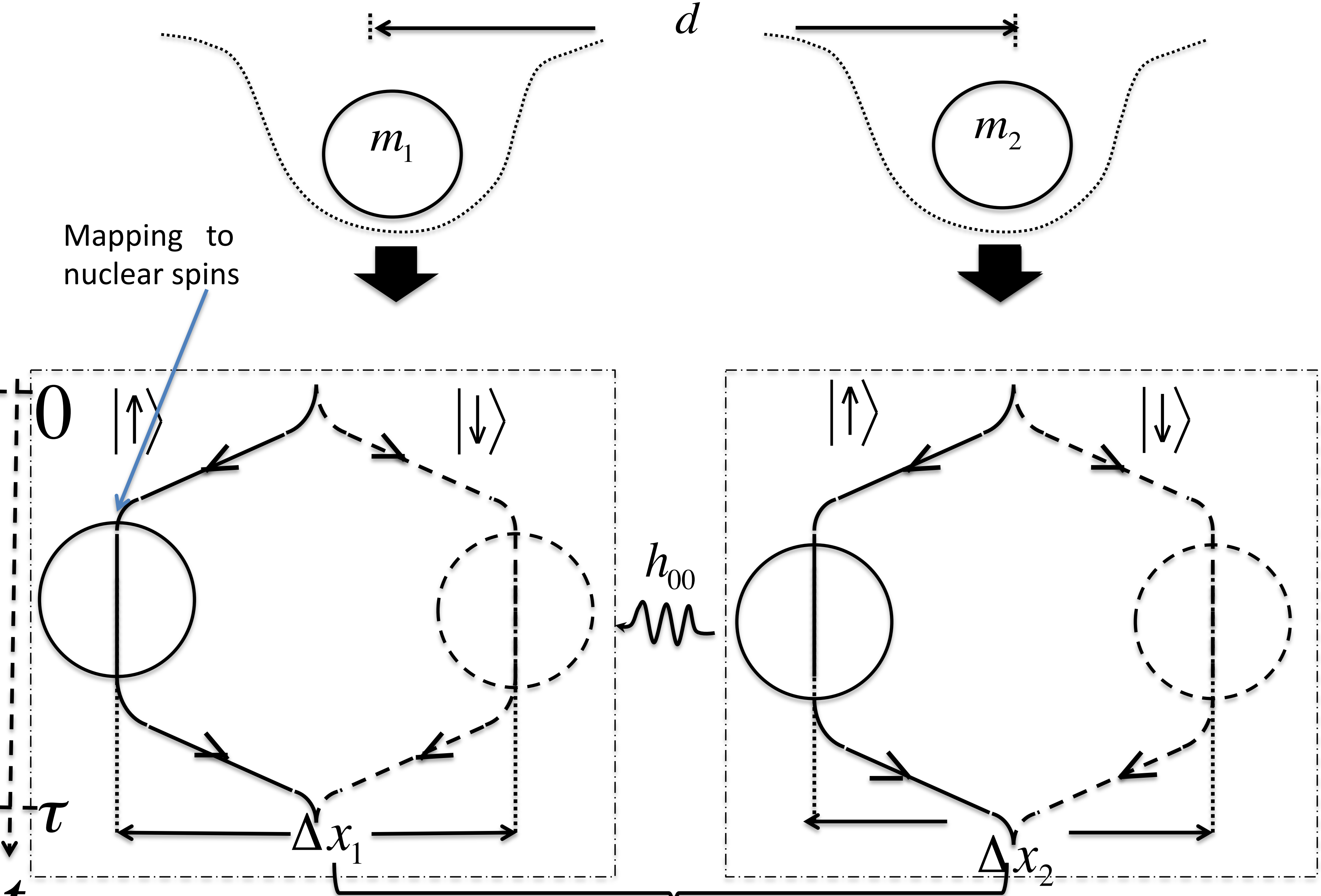
Yair Margalit[1*†], Or Dobkowski[1], Zhifan Zhou[1], Omer Amit[1], Yonathan Japha[1], Samuel Moukouri[1], Daniel Rohrlich[1], Anupam Mazumdar[2], Sougato Bose[3], Carsten Henkel[4], Ron Folman[1]

$$x_\sigma(t,j) = x_j(0) \pm \frac{1}{2}at^2$$

$$= \frac{a\tau}{4}(t-\frac{\tau}{4}) \mp \frac{1}{2}a(t-\frac{\tau}{4})^2$$

$$= \frac{1}{2}a(\frac{\tau}{4})^2 \mp \frac{a\tau}{4}(t-\frac{3\tau}{4}) \pm \frac{1}{2}a(t-\frac{3\tau}{4})^2$$





What happens to Ramsey signal when we have 2 interacting interferometers?

Spin Entanglement Witness:

Step 1: SG splitting:

$$|C\rangle_j \frac{1}{\sqrt{2}}(|\uparrow\rangle_j + |\downarrow\rangle_j) \rightarrow \frac{1}{\sqrt{2}}(|L,\uparrow\rangle_j + |R,\downarrow\rangle_j)$$

Step 2: Gravitational interaction induced phase accumulation on the joint states of masses 1 &2 (*mapped to nuclear spins*)

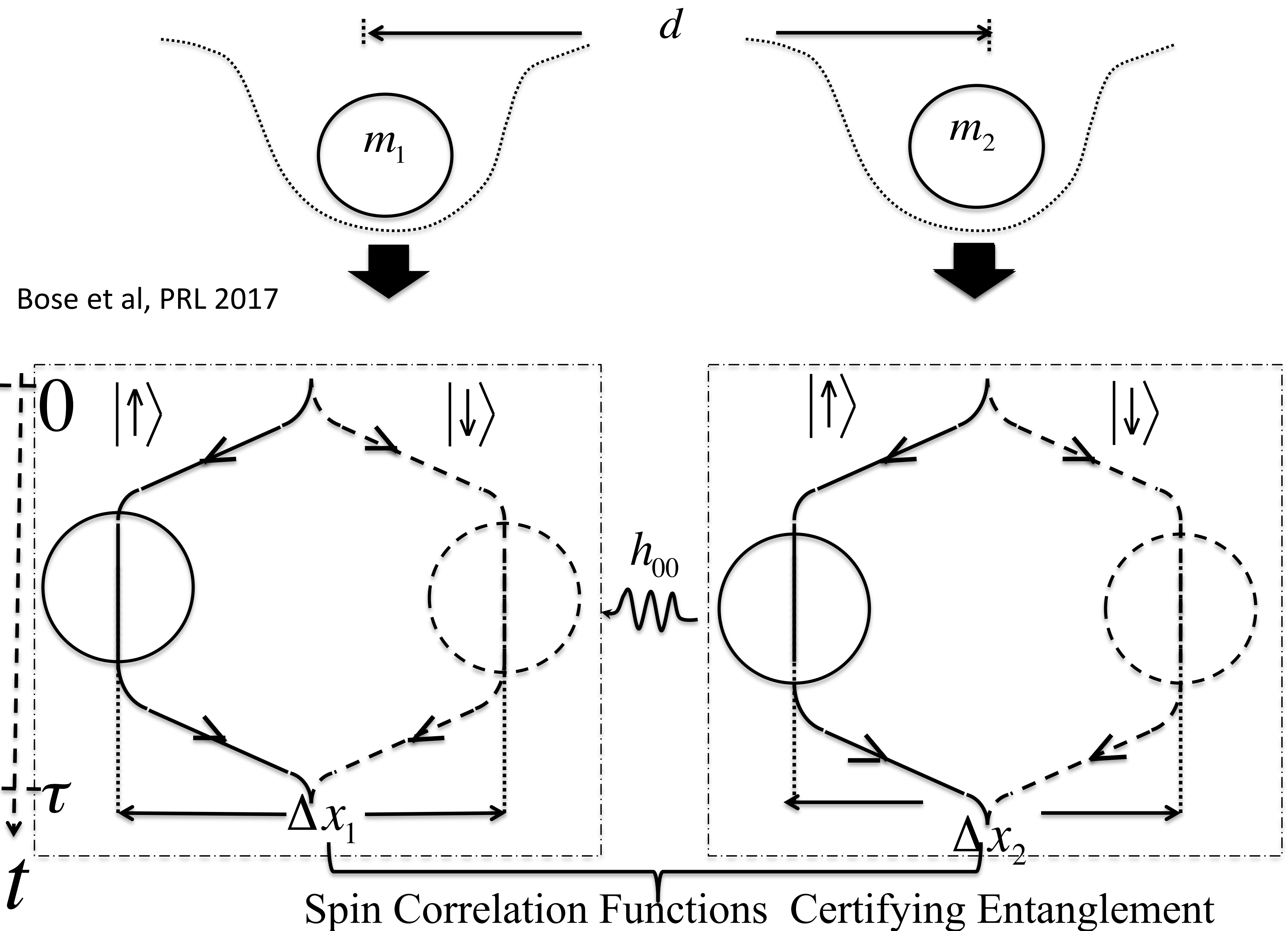
Step 3: SG recombination: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j, \; |R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$

Step 4: Witness spin entangled state:

$$|\Psi(t=t_{\mathrm{End}})\rangle_{12} = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1 \frac{1}{\sqrt{2}}(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}}|\downarrow\rangle_2) + |\downarrow\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|\uparrow\rangle_2 + |\downarrow\rangle_2)\}|C\rangle_1|C\rangle_2$$

through the correlations:

$$\mathcal{W} = \mathbb{I}\otimes\mathbb{I} - \sigma_x\otimes\sigma_x - \sigma_y\otimes\sigma_z - \sigma_x\otimes\sigma_z$$



d
m_1
m_2
Bose et al, PRL 2017
0
$|\uparrow\rangle$
$|\downarrow\rangle$
$|\uparrow\rangle$
$|\downarrow\rangle$
h_{00}
τ
Δx_1
Δx_2
t
Spin Correlation Functions Certifying Entanglement

$$\mathcal{W} = \mathbb{I} \otimes \mathbb{I} - \sigma_x \otimes \sigma_x - \sigma_y \otimes \sigma_z - \sigma_x \otimes \sigma_z$$

Full expression for an *open* system

Decoherence Rate

$$W = \frac{1}{2}(\Gamma t - |\phi|/2\,)$$

Entanglement phase

$$\Gamma_{\mathrm{n}} + \Gamma_{\mathrm{d}}$$

$$+\Gamma_{s} + \Gamma_{HD}$$

Acceleration & Relative Acceleration Noise.

Systematic (fluctuations from apparatus)

$\propto R^3 T^6$

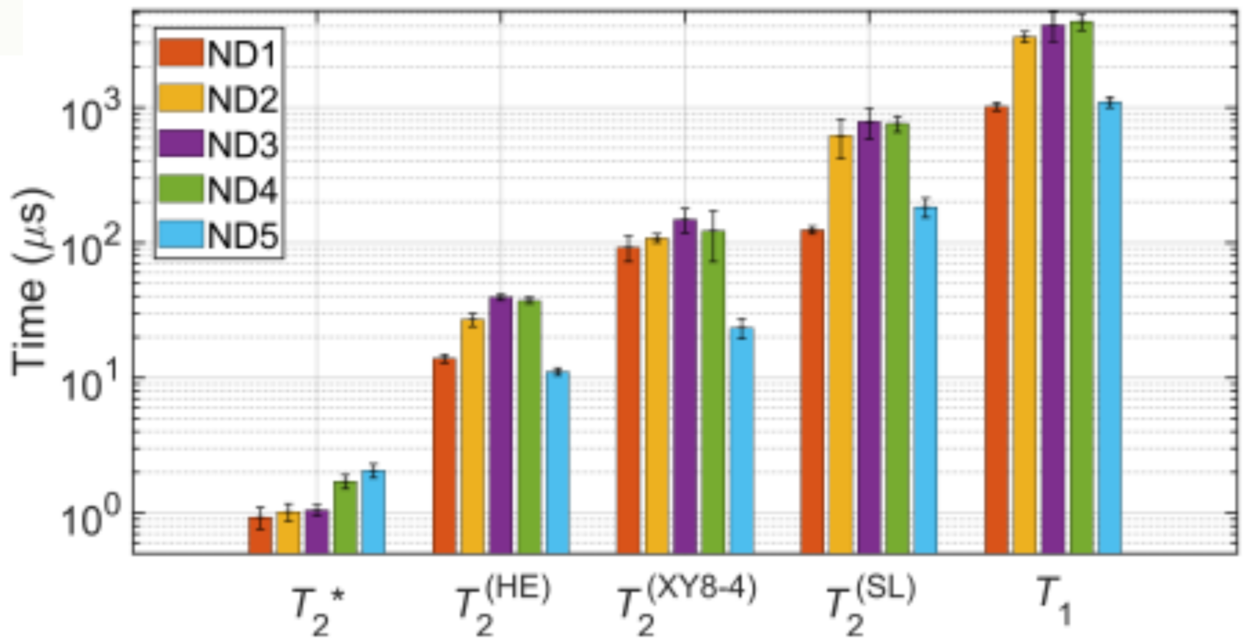
$\propto R^2 P$

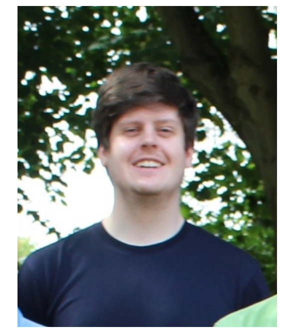
Black-Body Radiation + Atom Scattering (laboratory, T~1 K, P ~ 5*10^{-16} Pa, nano-object internal T ~ 150 mK)

Bose et al PRL 2017; van de Kamp et al PRA 2020

QTFP Project: Levitated Quantum Nanodiamonds (LQD); Warwick (Morley) & UCL (Bose)

Expt Side: Longest spin coherence in nanodiamonds





James March

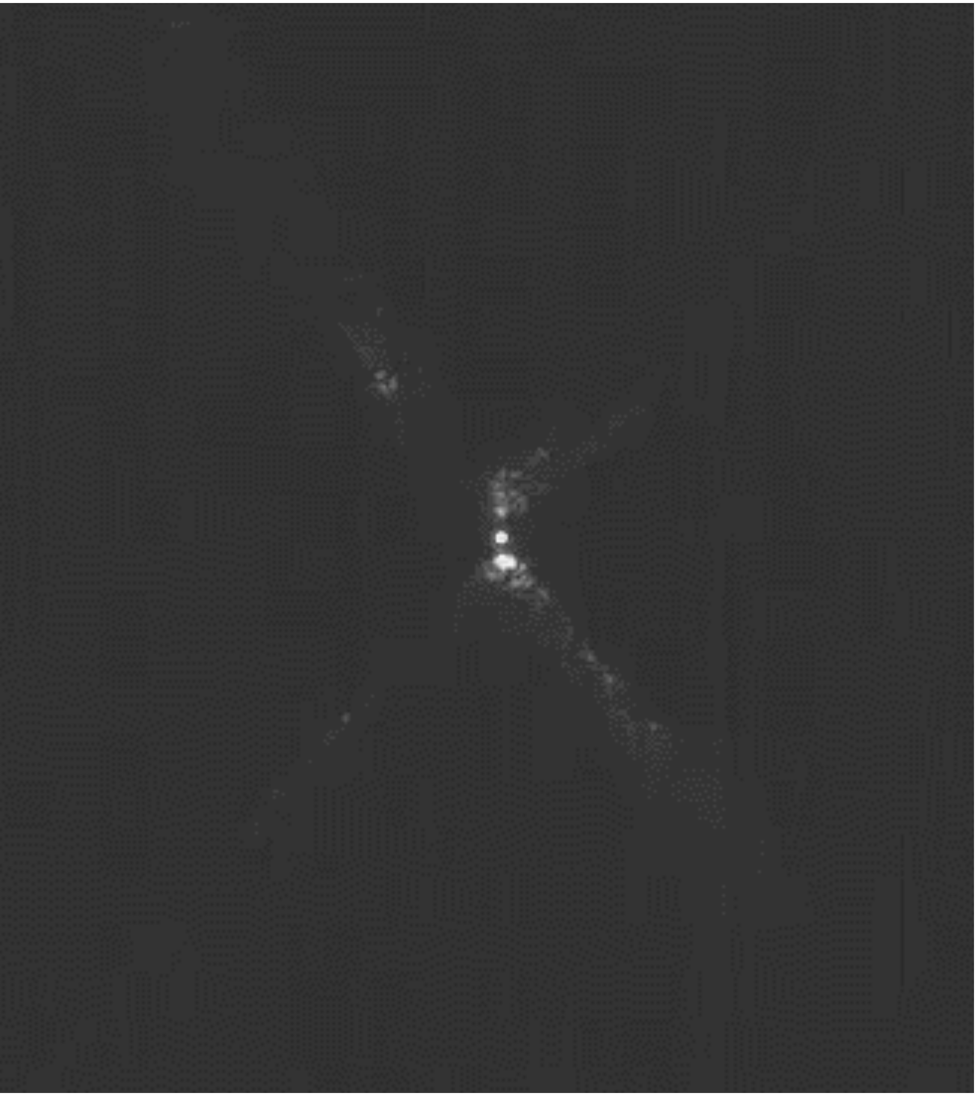
ND4: 50 nm x 80 nm
T_1 = 4.3 ms
T_2^* = 1.7 μs
$T_{1\rho}$ = 760 μs

James E March, Benjamin D Wood, Colin J Stephen, Soumen Mandal, Andrew M Edmonds, Daniel J Twitchen, Matthew L Markham, Oliver A Williams & GW Morley, Physical Review Applied 20, 044045 (2023)

WARWICK
THE UNIVERSITY OF WARWICK

See James March poster

QTFP Project: Levitated Quantum Nanodiamonds (LQD); Warwick (Morley) & UCL (Bose)



Magnetic trap for nanodiamonds at Warwick

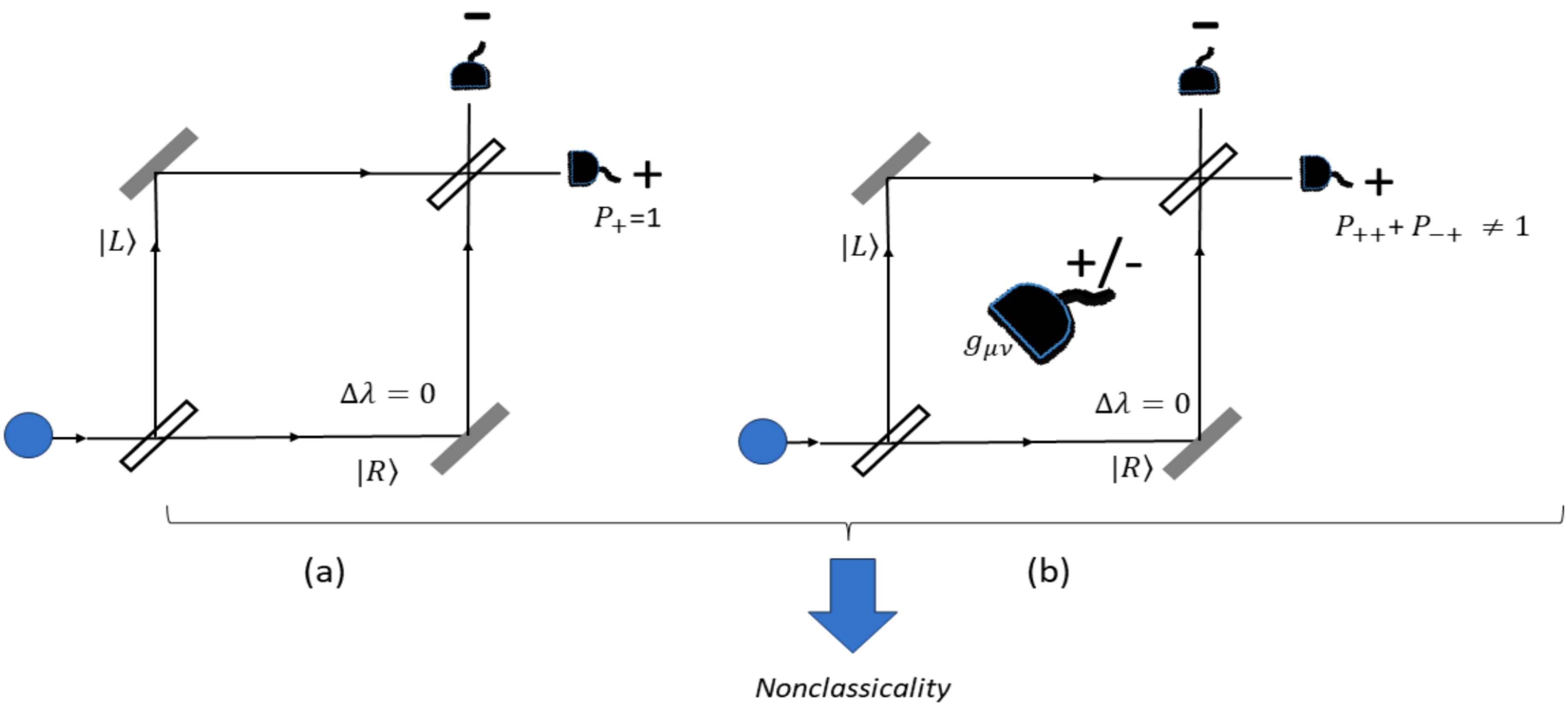
James March & Ben Wood

See James March poster

Follow-on Grants: 1. **MAST-QG (Sloane Foundation & Moore Foundation, USA; Warwick, UCL, Yale, Northwestern, Groningen) 2. STFC on Diamond Magnetometer.**

QTFP Project: Levitated Quantum Nanodiamonds (LQD); Warwick (Morley) & UCL (Bose)

On theory side: *How to test that gravity satisfies the quantum measurement postulate?*



Farhan Hanif, Debarshi Das, Jonathan Halliwell, Dipankar Home, Anupam Mazumdar, Hendrik Ulbricht, Sougato Bose, *Physical Review Letters* 133, 180201 (2024).

See poster by Debarshi Das