Title: Witnessing Quantum gravity via Entanglement of Masses

Speakers: Anupam Mazumdar

Series: Quantum Gravity

Date: October 15, 2020 - 2:30 PM

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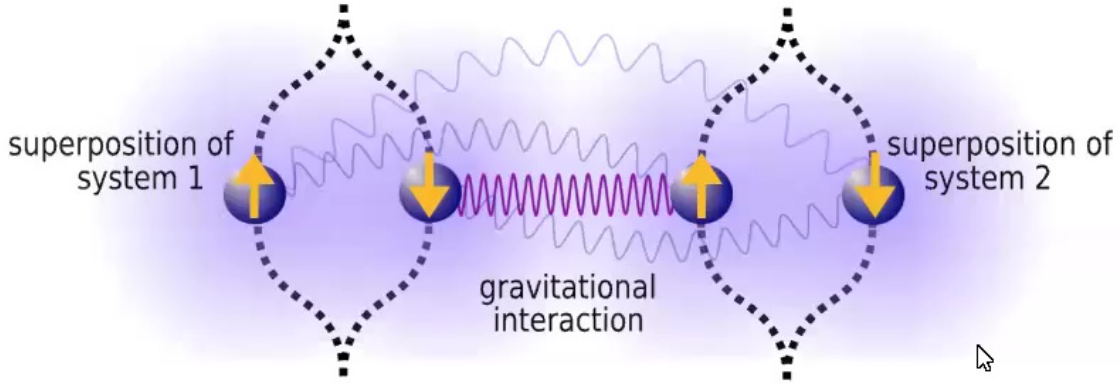
Abstract: Understanding gravity in the framework of quantum mechanics is one of the great challenges in modern physics. Along this line, a prime question is to find whether gravity is a quantum entity subject to the rules of quantum mechanics. It is fair to say that there are no feasible ideas yet to test the quantum coherent behaviour of gravity directly in a laboratory experiment. Here, 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.

Quantum Gravity witness via Entanglement of Masses: QGEM protocol

Anupam Mazumdar



Quantum Superpositions of Geometries

Bose + Mazumdar + Morley + Ulbricht + Toros + Paternostro + Geraci + Barker + Kim + Milburn, Phy. Rev. Lett. [ArXiv: 1707.06050]

Marshman +Mazumdar+Bose, [ArXiv: 1907.01568] Phys. Rev. A.
Van de Kamp+Marshman +Bose+Mazumdar [2006.06931 [quant-ph]
Toros + Van de Kamp + Marshman + Kim + Mazumdar + Bose [arXiv:2007.15029 [gr-qc]
Toros + Mazumdar + Bose 2008.08609 [gr-qc]

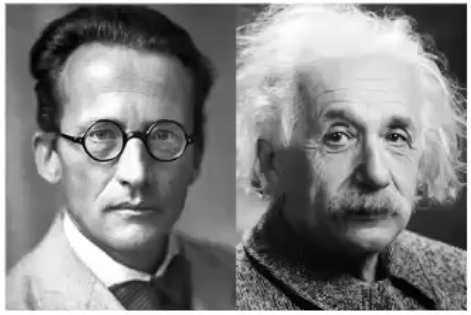
rijksuniversiteit
groningen

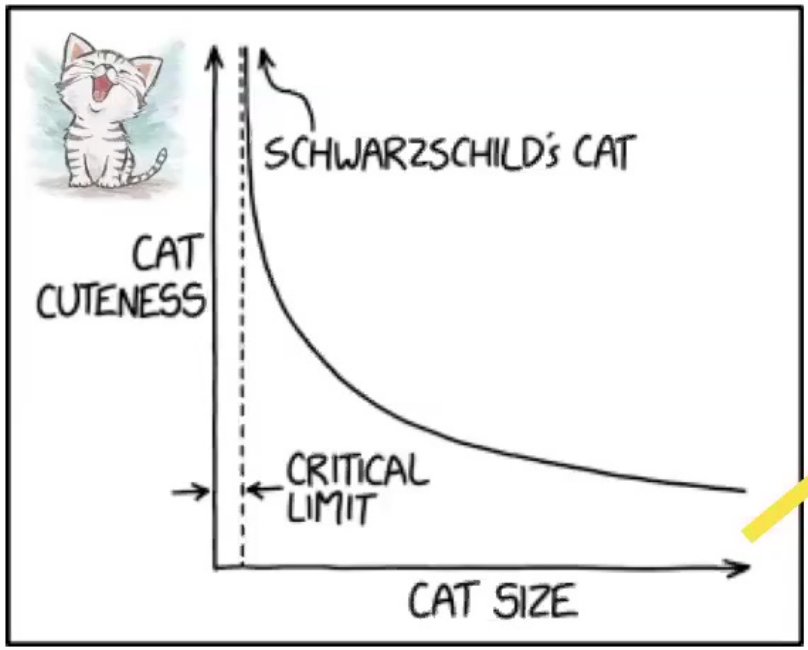
See Also: Marletto and Vedral appeared on the same day [1707.06036]

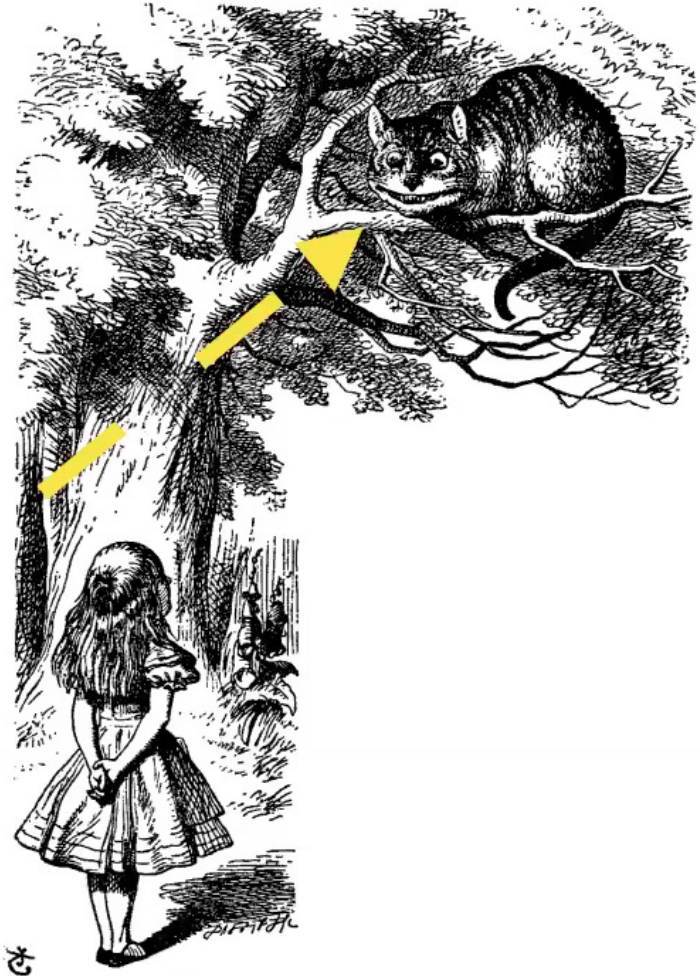
Is Gravity Classical or Quantum?

A very simple question, but extremely hard to answer !

Gravity's Cheshire Cat?







Today's Science Fiction is Tomorrow's Reality

- Can we put a graviton in a quantum superposition in lab? No !
- Can we study coalescing atoms, and study the loss of gravitons ? No!

- **Can we witness Quantum Entanglement due to Quantum Nature of a Graviton ?**

Yes!

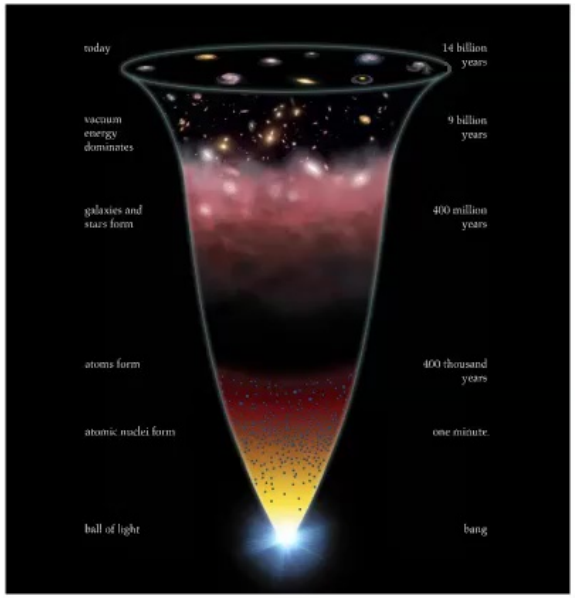
Lively discussions with

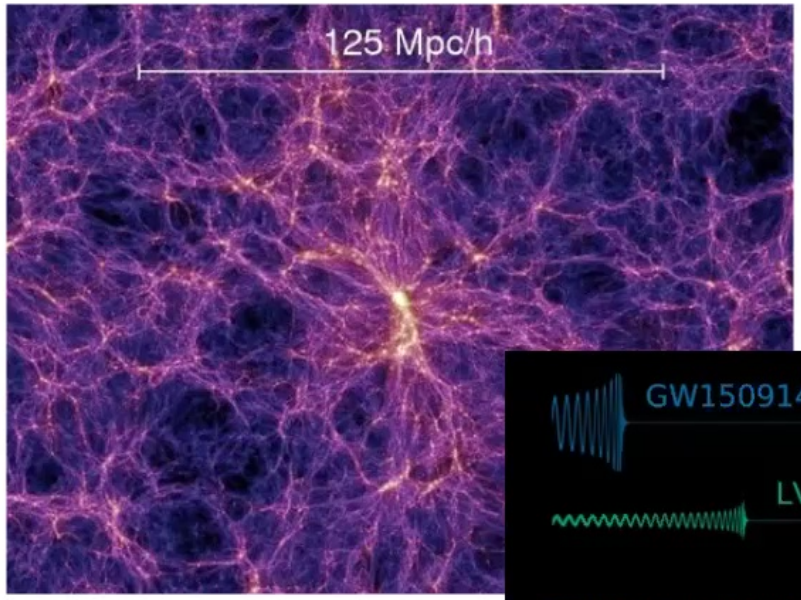
Sougato Bose, Jan Ambjorn, Abhay Ashtekar, Markus Aspelmeyers, Markus Arndt, Valeri Frolov, Gary Horowitz, Rob Myers, Don Page, Roger Penrose, Carlo Rovelli, Ashoke Sen, Gabriele Veneziano, Bob Wald, ...

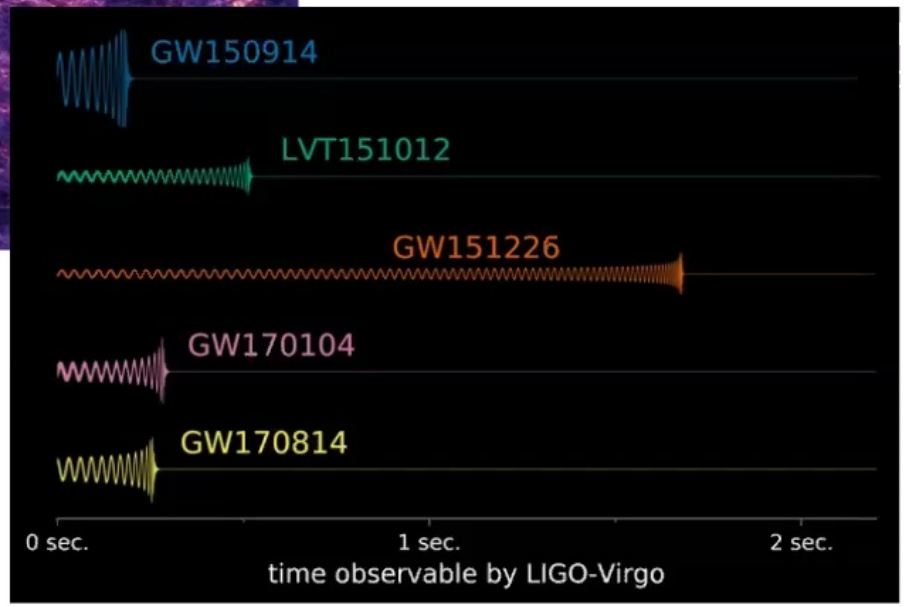
Things should be made as simple as possible, but no simpler! — Albert Einstein


◉ QG-Witness protocol for Quantum Gravity
◉ Reading the Witness
◉ Associated Challenges & Future Program
◉ Quantum Gravity

Gravity is Universal & Successful



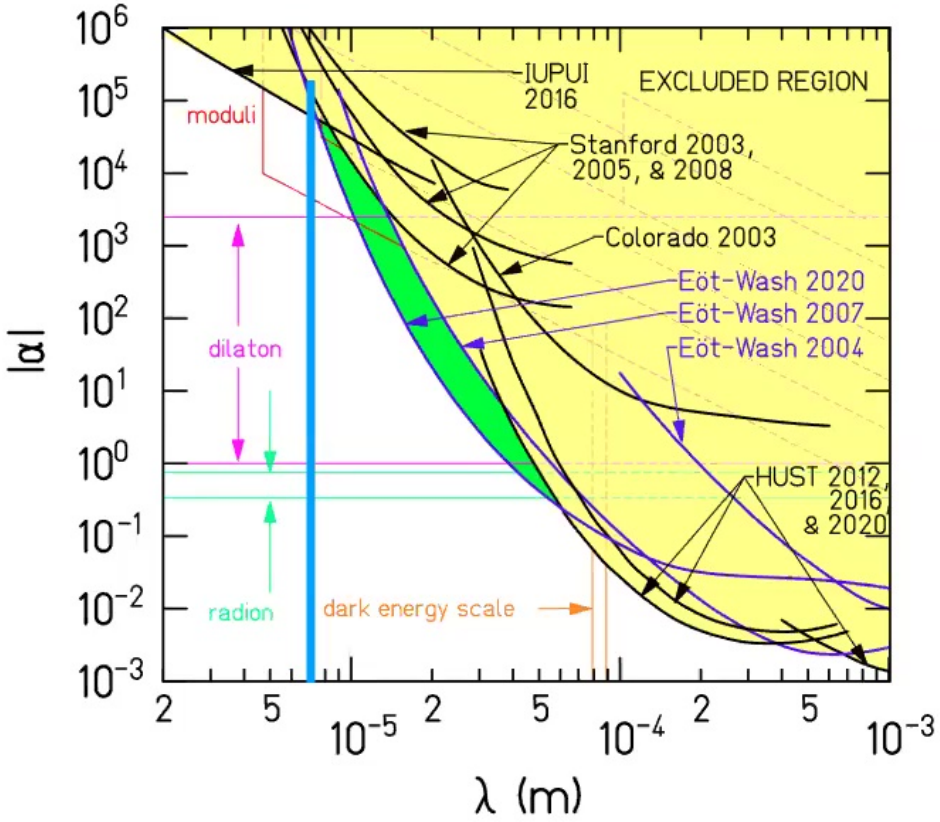




In the simplest case: Minimal Coupling with matter

$$\kappa h^{\mu\nu} T_{\mu\nu}$$

Constraints on Gravity, Newton's potential



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

$(10^{27}\ \mathrm{eV})^4$

?

$(10^{-2}\ \mathrm{eV})^4$

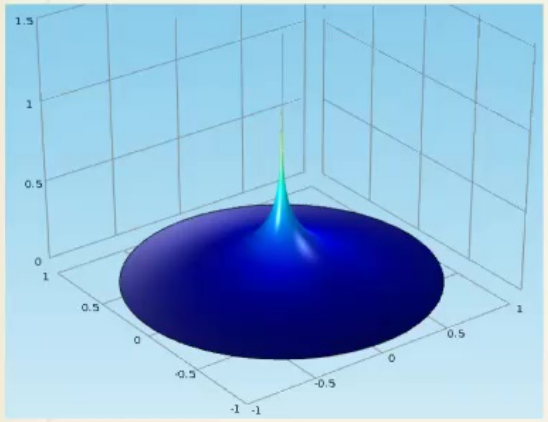
$(10^{-3}\ \mathrm{eV})^4$

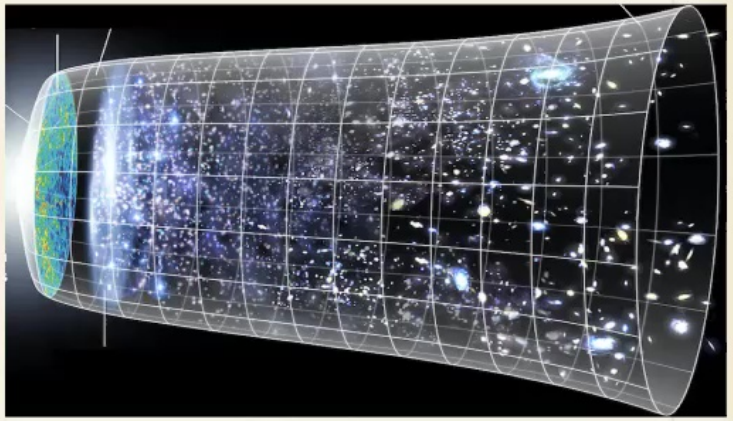
Dark Energy

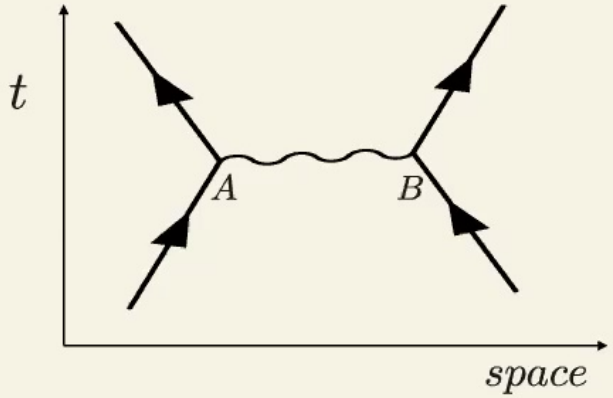
J. G. Lee, E. G. Adelberger, T. S. Cook, S. M. Fleischer, B. R Heckel 2002.11761 [hep-ex]

New effects in gravity could be around the corner !

Cosmological & Black hole Singularities







$$V \sim \frac{1}{r}$$

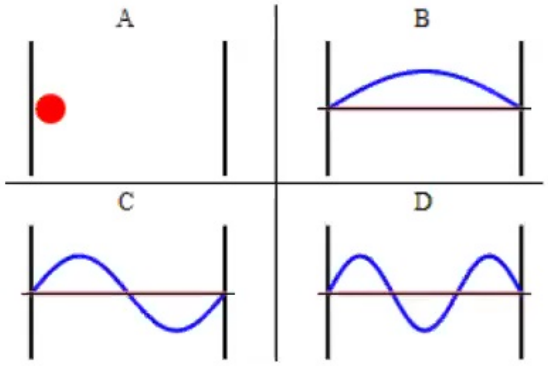
Graviton or Photon (mediator is massless)

Conservation of Probability will not allow singularities to develop,

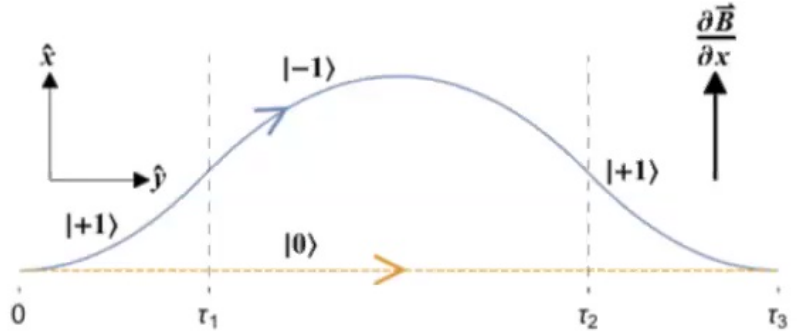
Non-local effects will forbid singularities to form

Classical Gravity Induced Quantum Phase

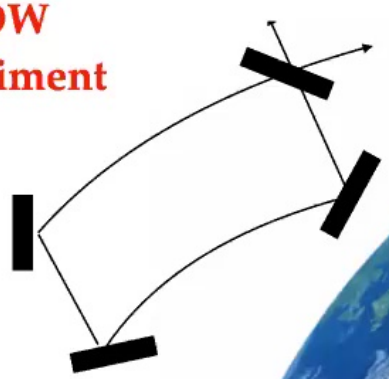
$$\Delta\phi \sim i\frac{S(G, G^2, G^2\hbar\cdots)}{\hbar}$$

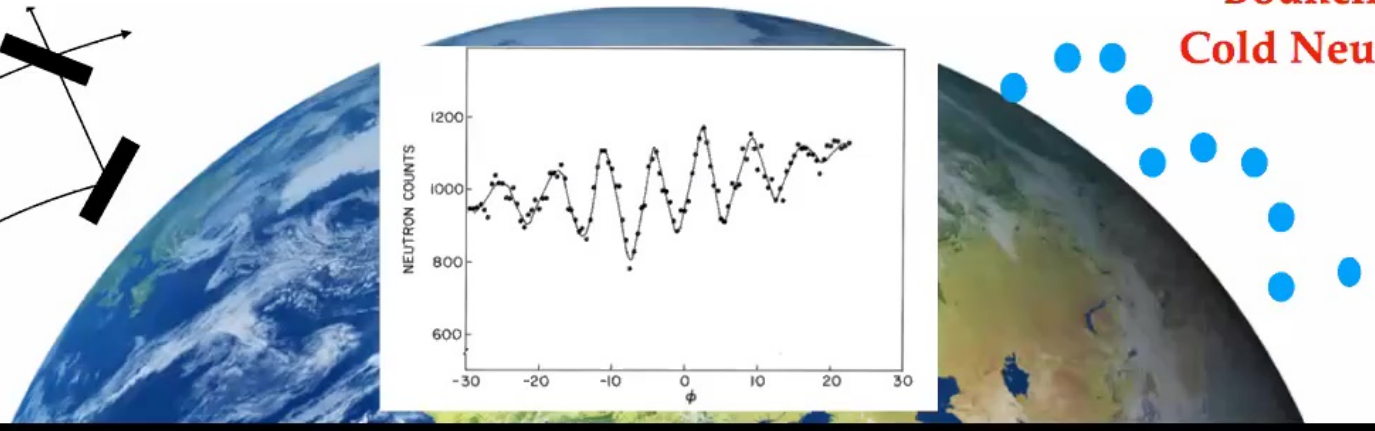


MIMAC. Mesoscopic Interferometer for Metric and Curvature



COW Experiment





Bouncing Cold Neutron

Initial Initiatives against Semi-Classical Gravity

VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

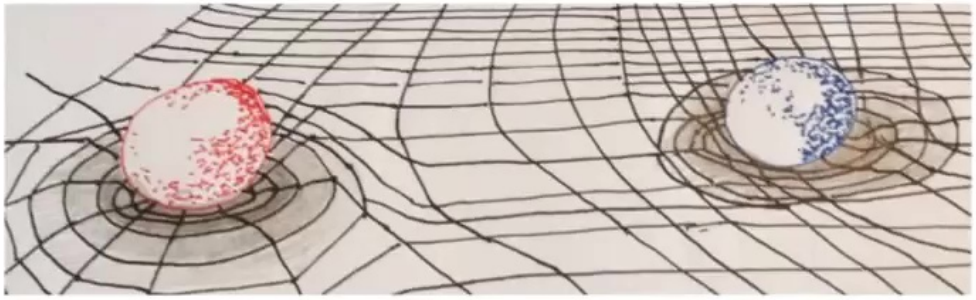
Indirect Evidence for Quantum Gravity

Don N. Page
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802

and

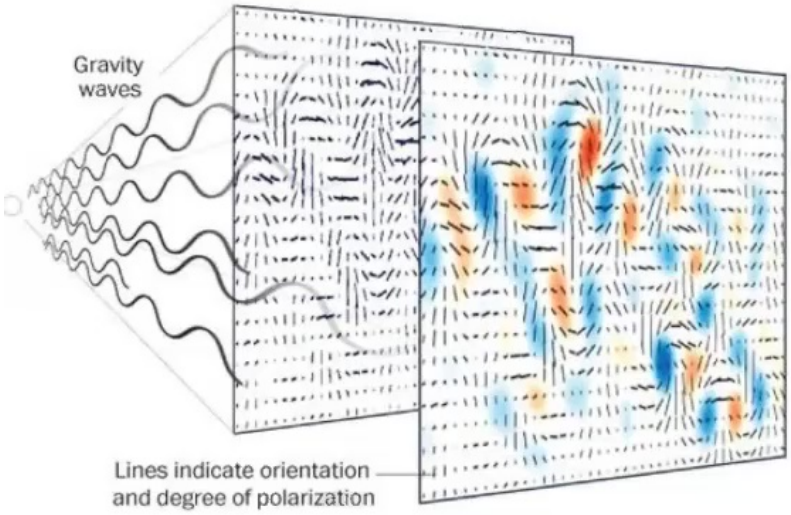
C. D. Geilker
Department of Physics, William Jewell College, Liberty, Missouri 64068
(Received 9 June 1981)

An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.



$$G_{\mu\nu} = \kappa^2 \langle T_{\mu\nu} \rangle$$

Primordial Gravitational Waves: is it a signature of QG?



Caution!

Positive Detection of a B-mode polarization by BICEP (2013)

But the origin was not found to be primordial in nature.

$$\mathcal{P}_g = \frac{64[\,|\alpha_k|^2 + |\beta_k|^2]\hbar^2 H^2}{M_p^2}$$

Bunch-Davies quantum vacuum: $\alpha_k = -\frac{\sqrt{\pi}}{2}, \beta_k = 0$

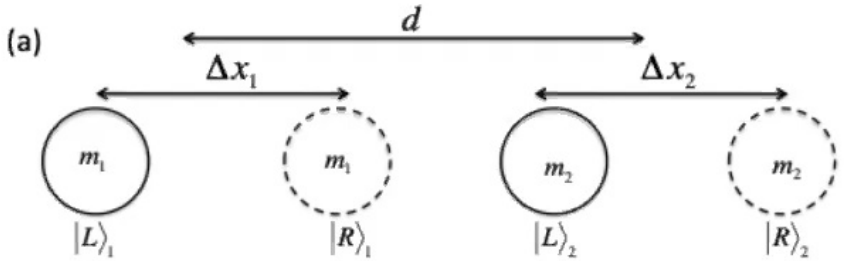
Initial Conditions: Classical or Quantum?

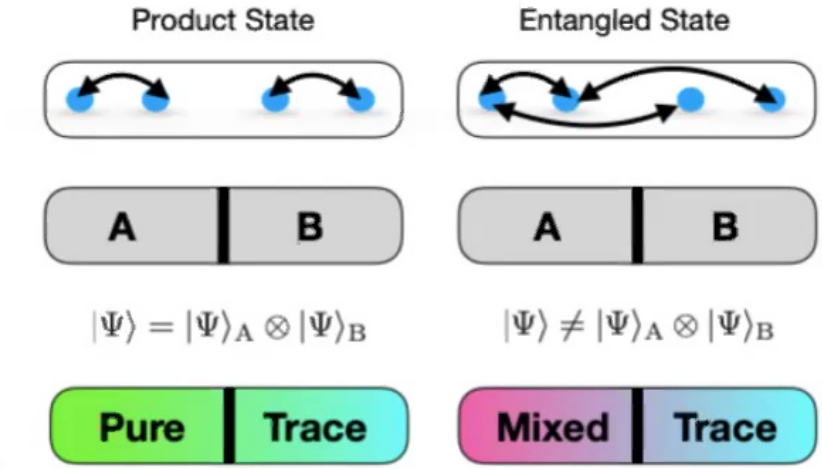
Mere presence of $\hbar$ is not sufficient to say that gravity is quantum !

L. M. Krauss and F. Wilczek,
``Using Cosmology to Establish the Quantization of Gravity,"
[arXiv:1309.5343 [hep-th]].

A. Ashoorioon, P. S. Bhupal Dev and AM,
``Implications of purely classical gravity for inflationary tensor modes,"
[arXiv:1211.4678 [hep-th]].

Key Ingredients





◉ Macroscopic Quantum Superposition of Localised Objects

Curvatures are Localised

10^{-21}Kg **[Markus Arndt's Lab, University of Vienna]**

◉ Quantum Entanglement

$$e^+e^- + e^-e^+$$

$$\uparrow\downarrow - \downarrow\uparrow$$

Bose+AM+Morley+Ulbricht+Toros+Paternostro+Geraci+Barker+Kim+Milburn, PRL (2017) [1707.06050]

What is the QGEM Protocol ?

Razor Sharp Argument

- If the Witness is Positive then Gravity is Quantum
- If the Witness is Negative: Inconclusive !

Only Entropy is Entanglement Entropy

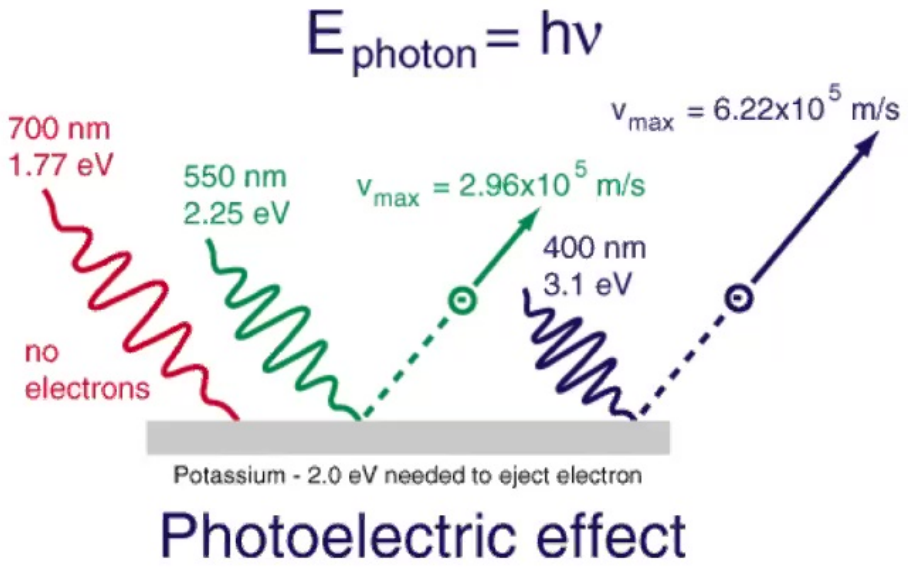
$$|\Psi\rangle = \sum_{i=1}^{N} C_i \psi_i^A \otimes \psi_i^B$$

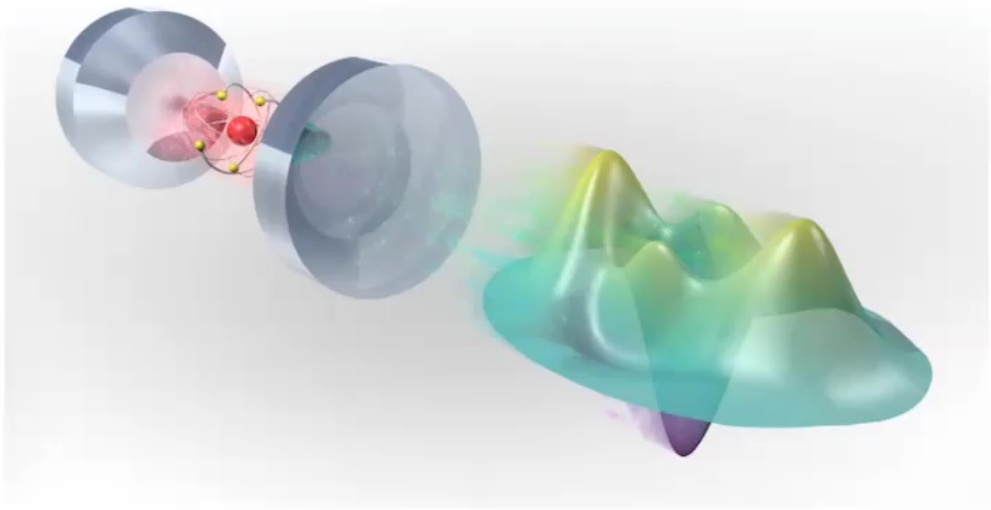
We can trace out the degrees of freedom of 'B' to get a reduced density matrix describing 'A'

$$\rho_A = \sum_{i=1}^{N} |C_i|^2 \psi_i^A \langle \psi_i^A| \qquad S(A) = -Tr[\rho_A \ln \rho_A] = \sum_{i=1}^{N} |C_i|^2 \ln |C_i|^2$$

$$S(A) + S(B) = 0$$

From Photoelectric Effect to Schrödinger Cat States of Photon



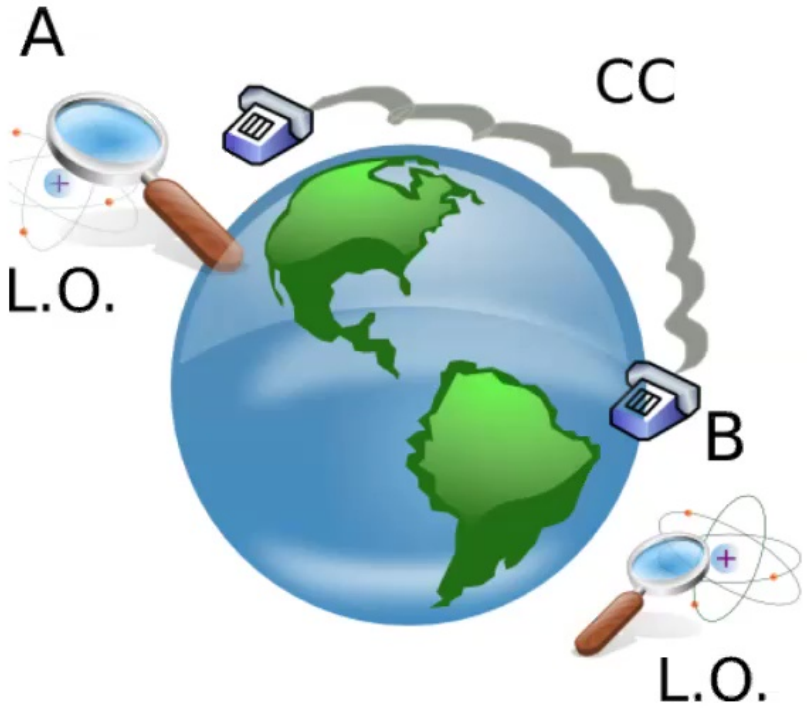


M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, S. Haroche,
Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity, Physical Review Letters, 76 (1996) 1800-1803.

Creating Schrödinger cat (kitten) states with photons and observing their decoherence:
M. Brune, E. Hagley, J. Dreyer, X. Maitre, A. Maali, C. Wunderlich, J.M. Raimond, S. Haroche,
Observing the progressive decoherence of the "meter" in a quantum measurement, Physical Review Letters, 77 (1996) 4887-4890.

Gerhard Rempe's group, Max Planck Institute of Quantum Optics

Local Operations & Classical Communication (LOCC)



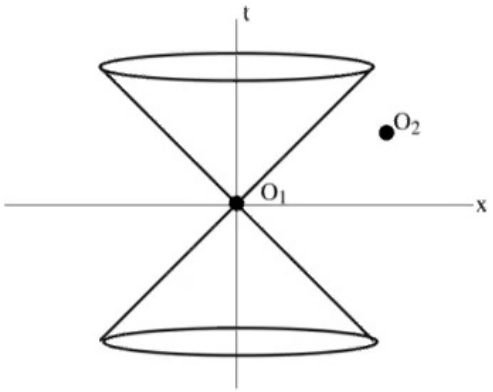
- It is impossible to generate/increase entanglement between A and B by local operations and classical communications

Bennett, et.al, (1996)
Review by Plenio+Virmani (2006)

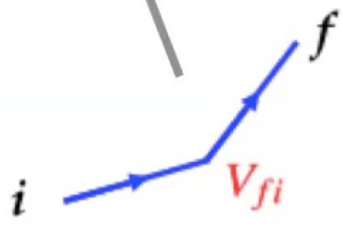
LOCC keeps Separable state remains Separable (Cannot Create Entanglement)

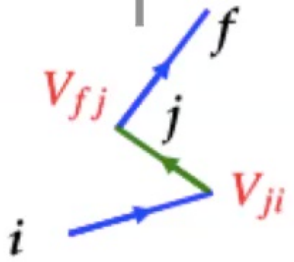
Quantum origin of V(r)

- "Classical picture" – particles act as sources for fields which give rise a potential in which other particles scatter – "action at a distance"
- "Quantum Field Theory picture" – forces arise due to the exchange of virtual particles. No action at a distance + forces between particles now due to particles



$$T_{fi} = \langle f|V|i\rangle + \sum_{j\neq i} \frac{\langle f|V|j\rangle\langle j|V|i\rangle}{E_i - E_j} + \ldots$$



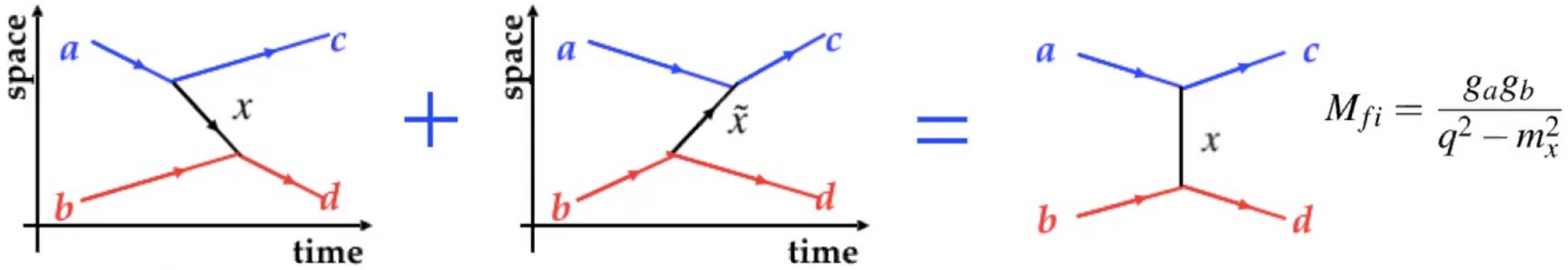


Violates Special Relativity

There are papers by Bei-lok Hu and company, who believe that tree level scattering is classical & not quantum! And these papers are incorrect !

Quantum Mechanics to Quantum Field Theory

- The sum over all possible time-orderings is represented by a FEYNMAN diagram



$$M_{fi} = \frac{g_a g_b}{q^2 - m_x^2}$$

- Momentum conserved at vertices
- Energy not conserved at vertices
- Exchanged particle "on mass shell"

$$E_x^2 - |\vec{p}_x|^2 = m_x^2$$

- Momentum AND energy conserved at interaction vertices
- Exchanged particle "off mass shell"

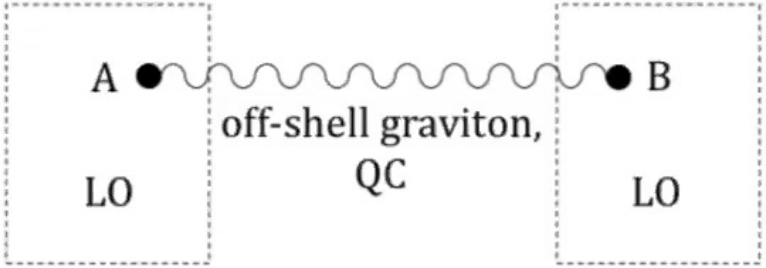
$$E_x^2 - |\vec{p}_x|^2 = q^2 \neq m_x^2$$

VIRTUAL PARTICLE

$$\Delta x \Delta p_x \geq \hbar$$

- On-shell (Follows Classical Equations of Motion): $E^2 = (pc)^2 + (mc^2)^2$
- Off-shell does not follow Classical Equations of Motion

LOQC: Local operation & Quantum Communication



$$S_{EH} = \frac{1}{4}\int d^4x\, h_{\mu\nu}\, \mathcal{O}^{\mu\nu\rho\sigma}\, h_{\rho\sigma} + \mathcal{O}(\kappa h^3)$$

$$\mathcal{O}^{\mu\nu\rho\sigma} := \frac{1}{4}\left(\eta^{\mu\rho}\eta^{\nu\sigma} + \eta^{\mu\sigma}\eta^{\nu\rho}\right)\Box - \frac{1}{2}\eta^{\mu\nu}\eta^{\rho\sigma}\Box + \frac{1}{2}\left(\eta^{\mu\nu}\partial^\rho\partial^\sigma + \eta^{\rho\sigma}\partial^\mu\partial^\nu - \eta^{\mu\rho}\partial^\nu\partial^\sigma - \eta^{\mu\sigma}\partial^\nu\partial^\rho\right)$$

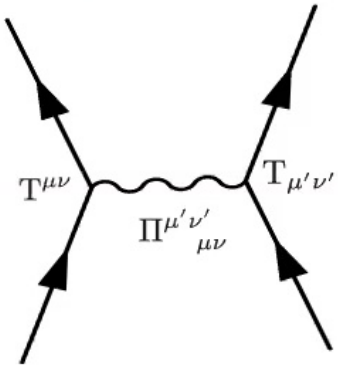
$$\Pi_{\mu\nu\rho\sigma}(k) = \left(\frac{\mathcal{P}^2_{\mu\nu\rho\sigma}}{k^2} - \frac{\mathcal{P}^0_{s,\,\mu\nu\rho\sigma}}{2k^2}\right)$$

Gauge invariant part of the propagator

$$g_{\mu\nu} = \eta_{\mu\nu} + \kappa h_{\mu\nu}$$

Minimal Coupling : $\kappa h_{\mu\nu} T^{\mu\nu}$

Local Interaction

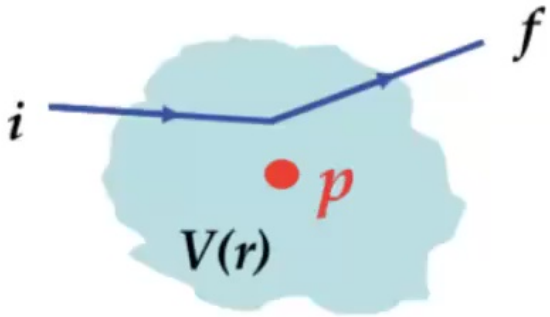


Unitary Local Operation, Measurement

$$\Phi(r) = -\kappa^2 \int \frac{d^3|\vec{k}|}{(2\pi)^3} T_1^{00}(k)\Pi_{0000}(k)T_2^{00}(-k)e^{i\vec{k}\cdot(\vec{r}} = -\frac{\kappa^2 m}{2}\int \frac{d^3|\vec{k}|}{(2\pi)^3}\frac{1}{\vec{k}^2}e^{i\vec{k}\cdot(\vec{r})} = -\frac{Gm}{r},$$

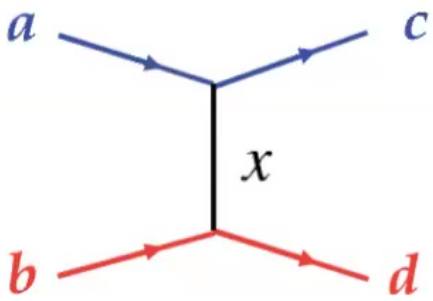
Marshman +Mazumdar+Bose, [ArXiv: 1907.01568] Phys. Rev. A. (2020)

What Aspects of Quantum Gravity Can We test in the Lab ?



$\Delta\phi \sim G/\hbar$

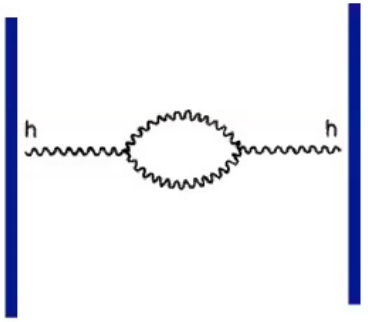
Classical



$\Delta\phi \sim G/\hbar$

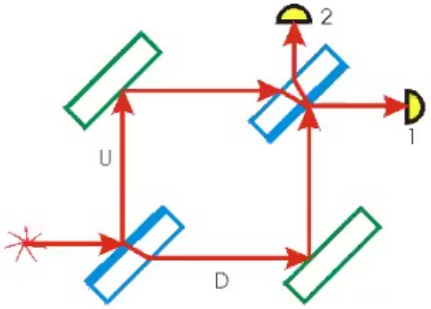
Quantum

2nd order in perturbation



$\Delta\phi \sim G^2\hbar/\hbar$

Quantum Loop Effect



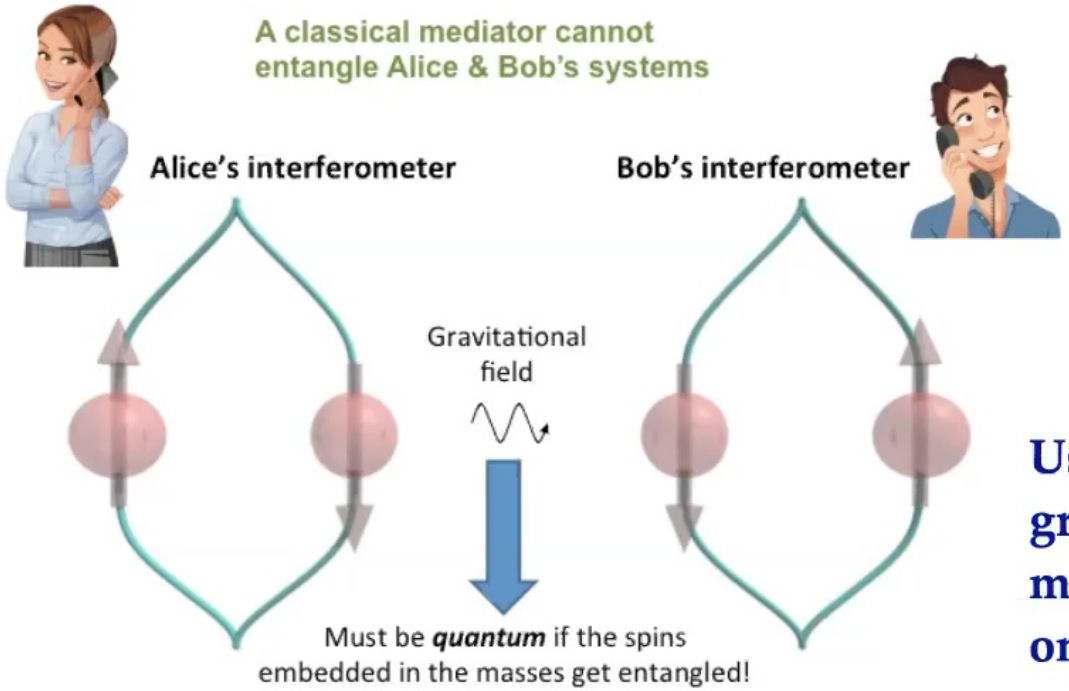
Fine Print

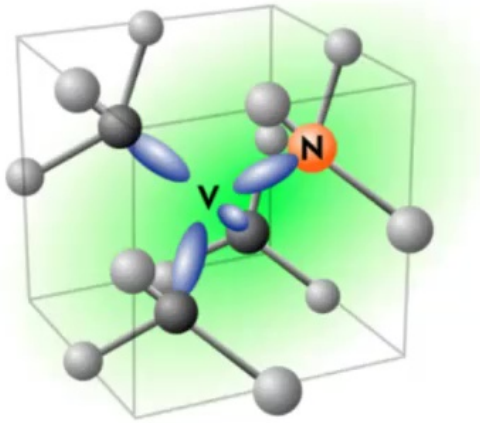
Quantum experiments are full of Off-shell processes

Beam splitter

QGEM protocol: 2 Freely Falling Superposed masses

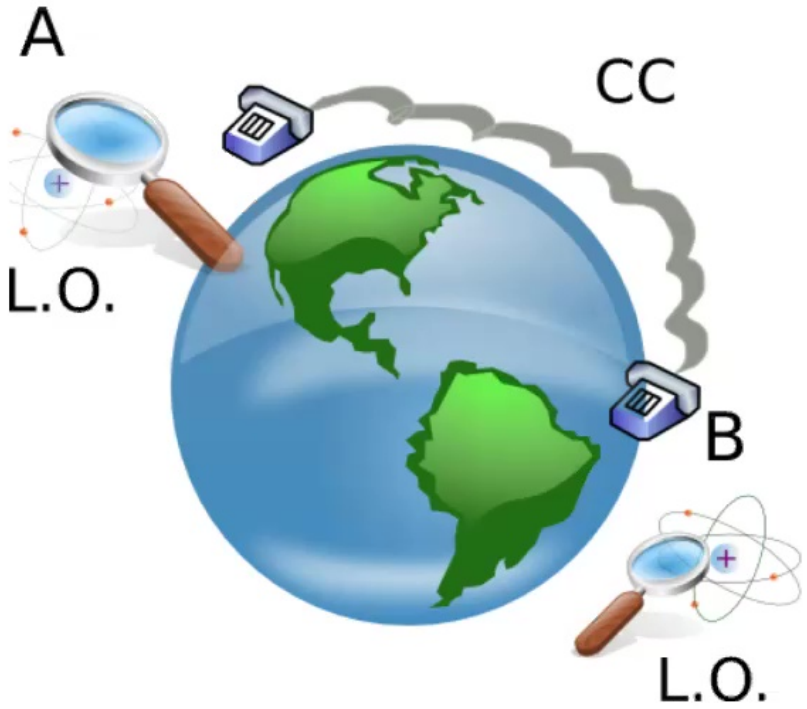
Macroscopic superposition with Spin Embedded Inside





Use very strong atom chip gradients to push and split massive objects using just one spin!

Local Operations & Classical Communication (LOCC)



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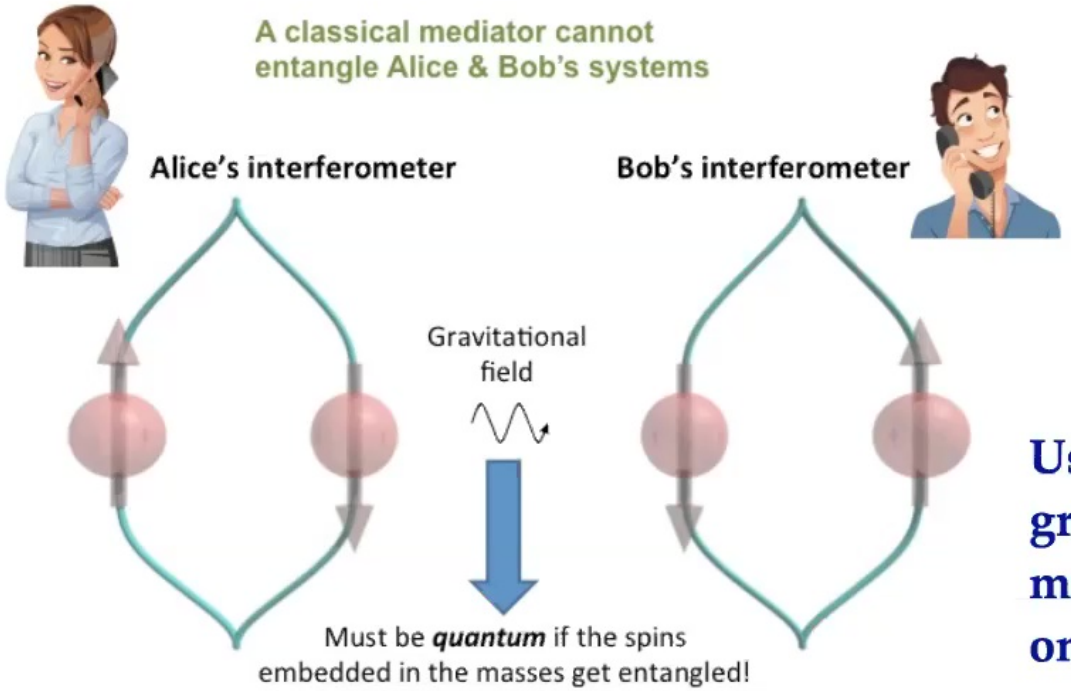
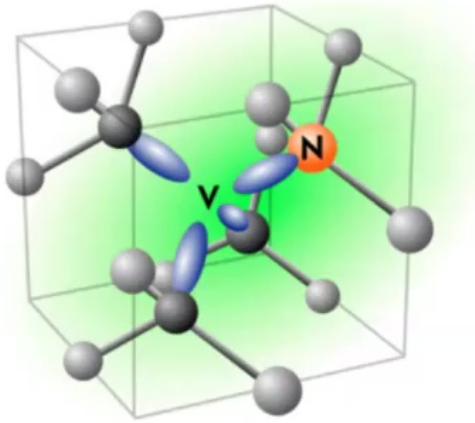
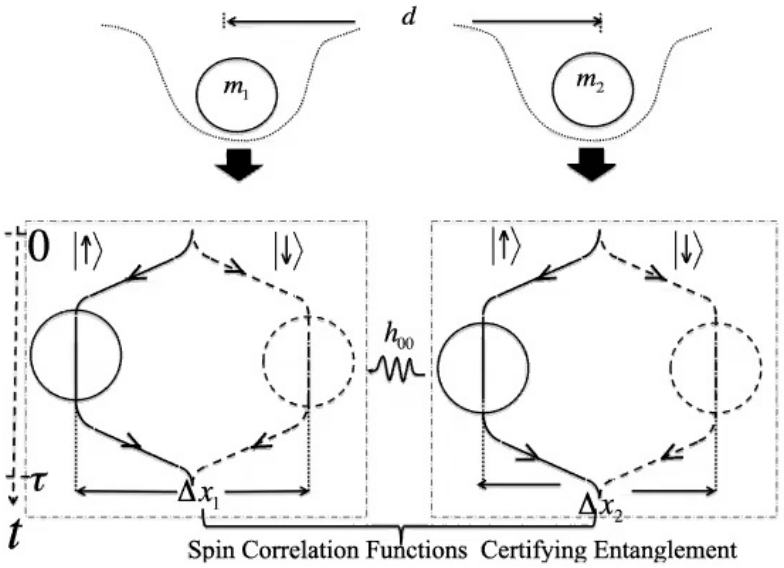
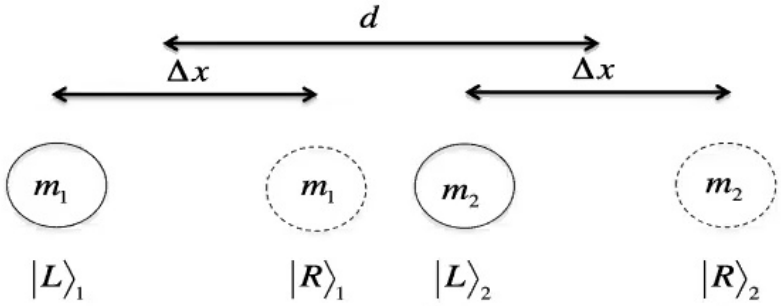




Use very strong atom chip gradients to push and split massive objects using just one spin!

QGEM protocol: 2 Freely Falling Superposed masses





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

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

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

Maximum Entanglement Phase

Step 4: Witness spin entangled state:

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

through the correlations:

$$\mathcal{W} = |\langle\sigma_x^{(1)} \otimes \sigma_z^{(2)}\rangle - \langle\sigma_y^{(1)} \otimes \sigma_z^{(2)}\rangle|$$

If $\mathcal{W} > 1 \implies$ *Graviton is quantum*

$$\Delta\phi_{LR} + \Delta\phi_{RL} \sim \mathcal{O}(1)$$

we have

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

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

Planck's Constant fights Newton's Constant!

Maximum Entanglement Phase

Step 4: Witness spin entangled state:

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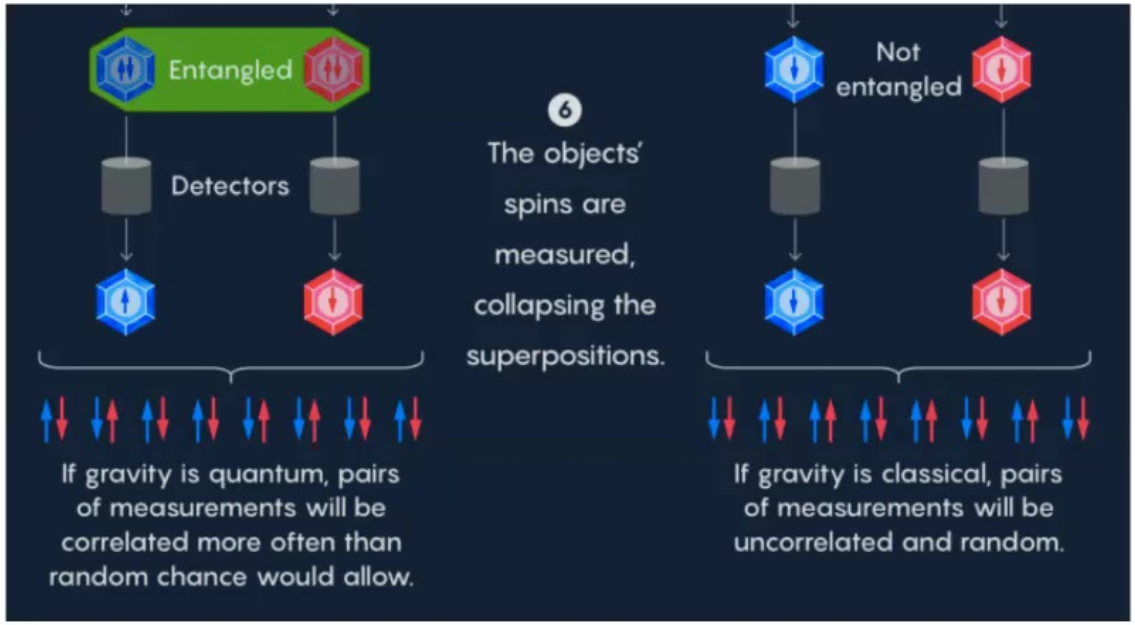
Planck's Constant fights Newton's Constant!

Entanglement Witness: Spin Correlation



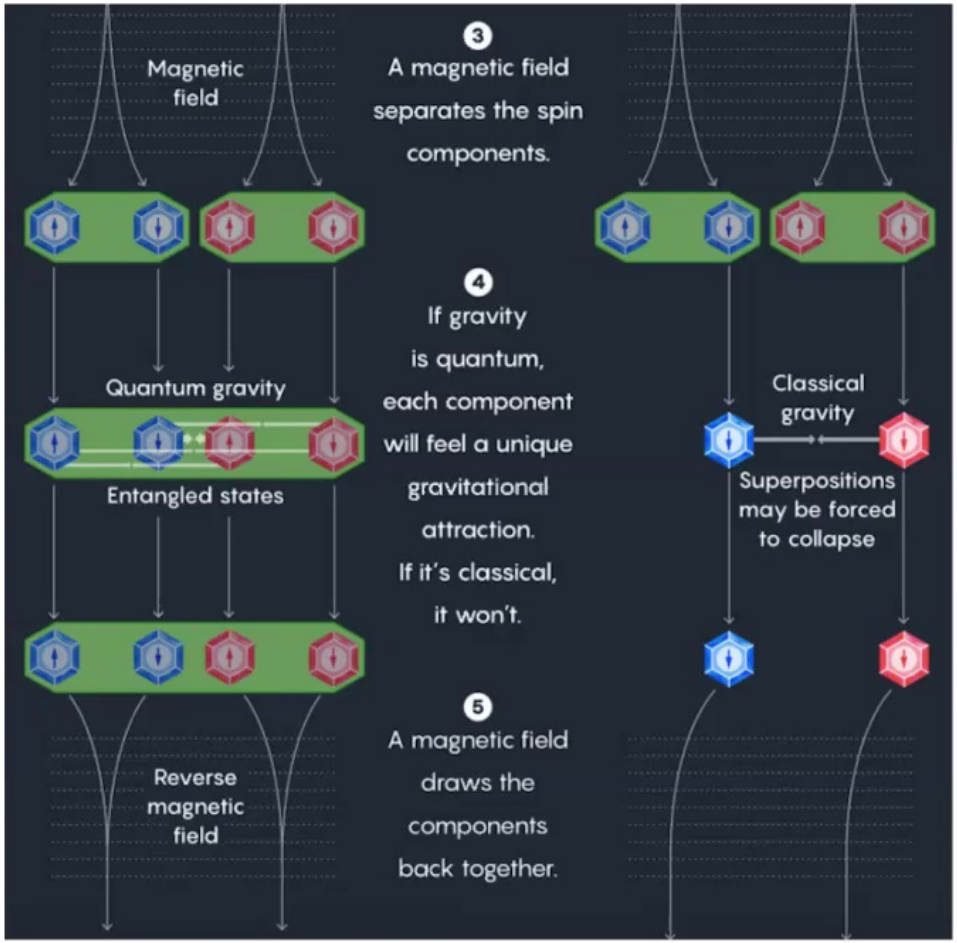
Basis Dependent Witness, similar to Bell's

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

H. Chevalier, A. Paige, and M. Kim arXiv:2005.13922 [quant-ph].

Basis Independent Witness: $S_{\mathrm{A}} = -\mathrm{Tr}_{\mathrm{A}}\rho_{\mathrm{A}}\log\rho_{\mathrm{A}} = S_{\mathrm{B}}$

Challenges for QGEM



M. Frimmer, K.Luszcz, S. Ferreiro, V. Jain, E.Hebestreit, and L.Novotny, Phys. Rev. A95, 061801 (2017).

$10^{-14} Kg$ Radius : 100nm

Neutralising e.m. charges

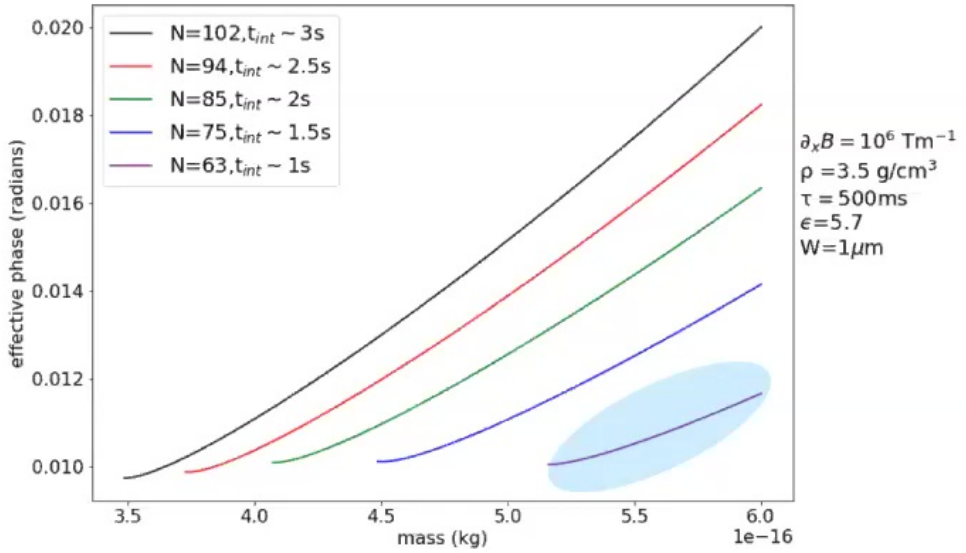
A magnetic field gradient of ~ 10^6 T/m and a time $\tau_{acc} \sim 500$ m/s^2, $\Delta x \sim 250\mu m$, $d - \Delta x \sim 200\mu m$

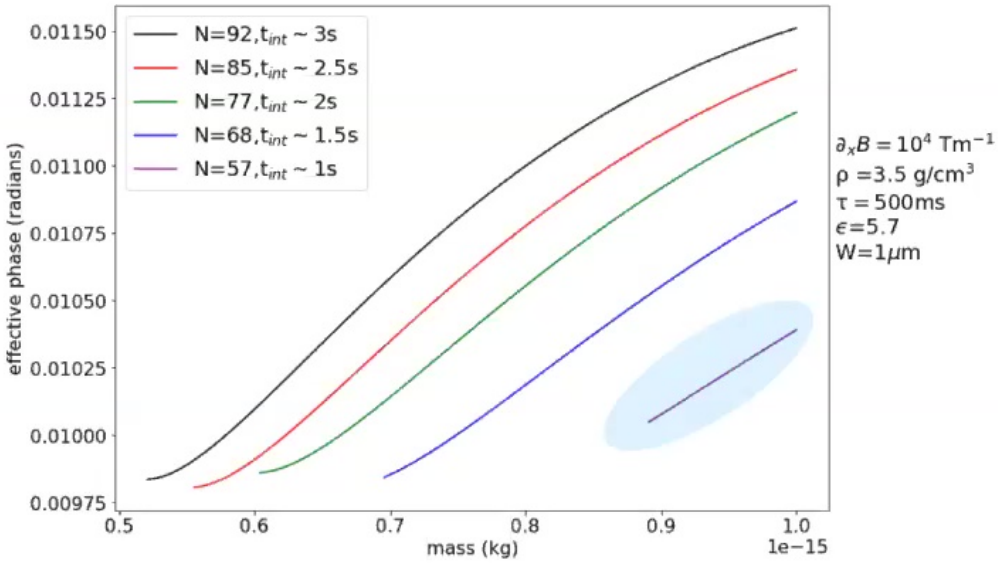
Electronic spins coherent for 1s, which should be possible for macro-diamond below 77 K

To estimate collisional and thermal decoherence times of the orbital degree of freedom we consider the pressure P = $10^{-15} Pa$ and the temperature 0.15 K. the collisional decoherence time for a superposition size of $\Delta x \sim 250\mu m$ is the same order of magnitude as the total microsphere's fall time $\tau + 2\tau_{acc} \sim 3.5$ s

T. Krisnanda, M. Zuppardo, M. Paternostro, T. Paterek, arXiv:1607.01140.
C. Wan, M. Scala, G. W. Morley, ATM. A. Rahman, H. Ulbricht, J. Bateman, P. F. Barker, S. Bose, and M. S. Kim, Phys. Rev. Lett. 117, 143003 (2016);
H. Pino, J. Prat-Camps, K. Sinha, B. P. Venkatesh, and O. Romero-Isart, arXiv:1603.01553v2
N. Bar-Gill, L.M. Pham, A. Jarmola, D. Budker, R. L. Walsworth, Nature Comm, 4, 1743 (2013),
S. Knowles, D. M. Kara and M. Atatu¨re, Nature Materials 13, 21 (2014),
Kaltenbaek, Aspelmeyer, (2015)

QGEM Protocol (Phase vs Mass)





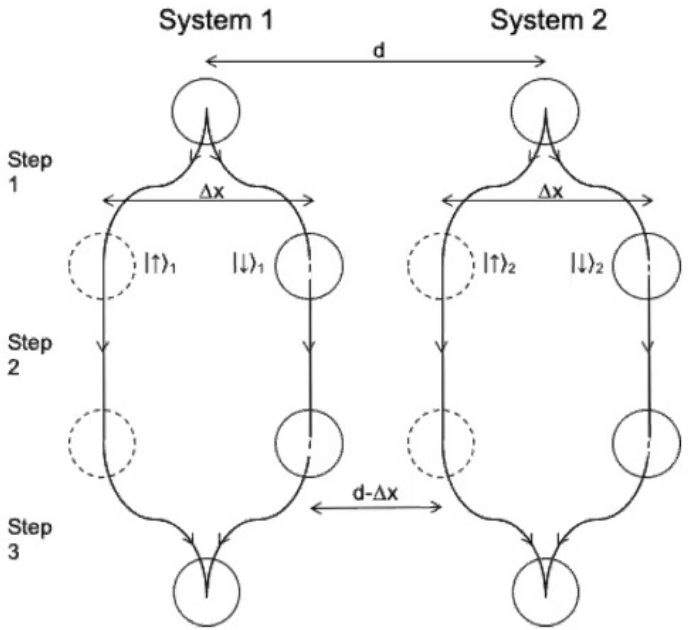
$$10^{-14}\text{Kg} \Longrightarrow 10^{-16} - 10^{-15}\text{Kg}$$

$$\Delta x \sim 200\mu m \Longrightarrow 20\mu m$$

$$P \sim 10^{-16} \Longrightarrow 10^{-15} Pa$$

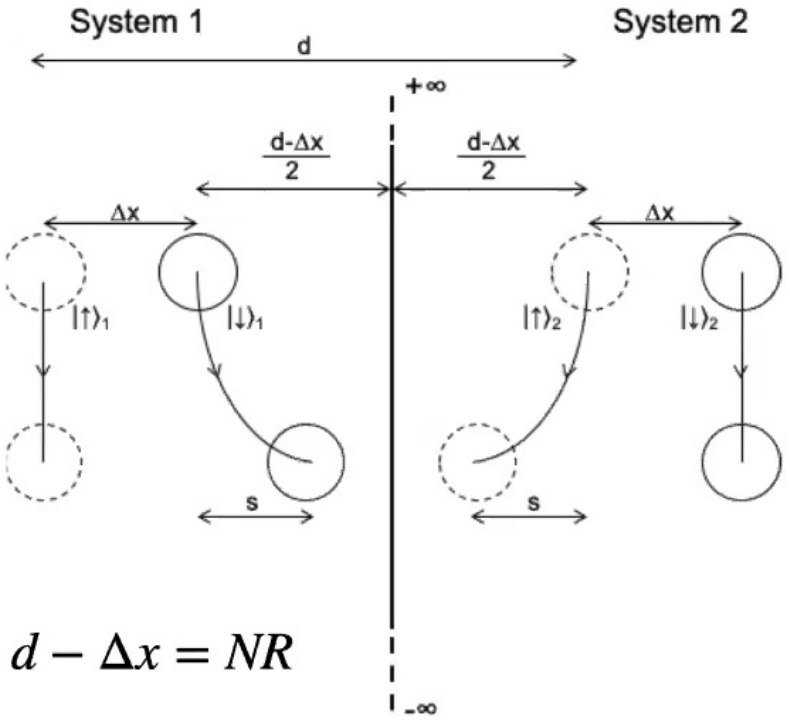
Van de Kamp+Marshman +Bose+Mazumdar [2006.06931 [quant-ph]]

QGEM Protocol : Improved Design



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

$$F_{\rm ca} = -\frac{3\hbar c}{2\pi}\left(\frac{\epsilon-1}{\epsilon+2}\right)\frac{R^3}{x^5}$$

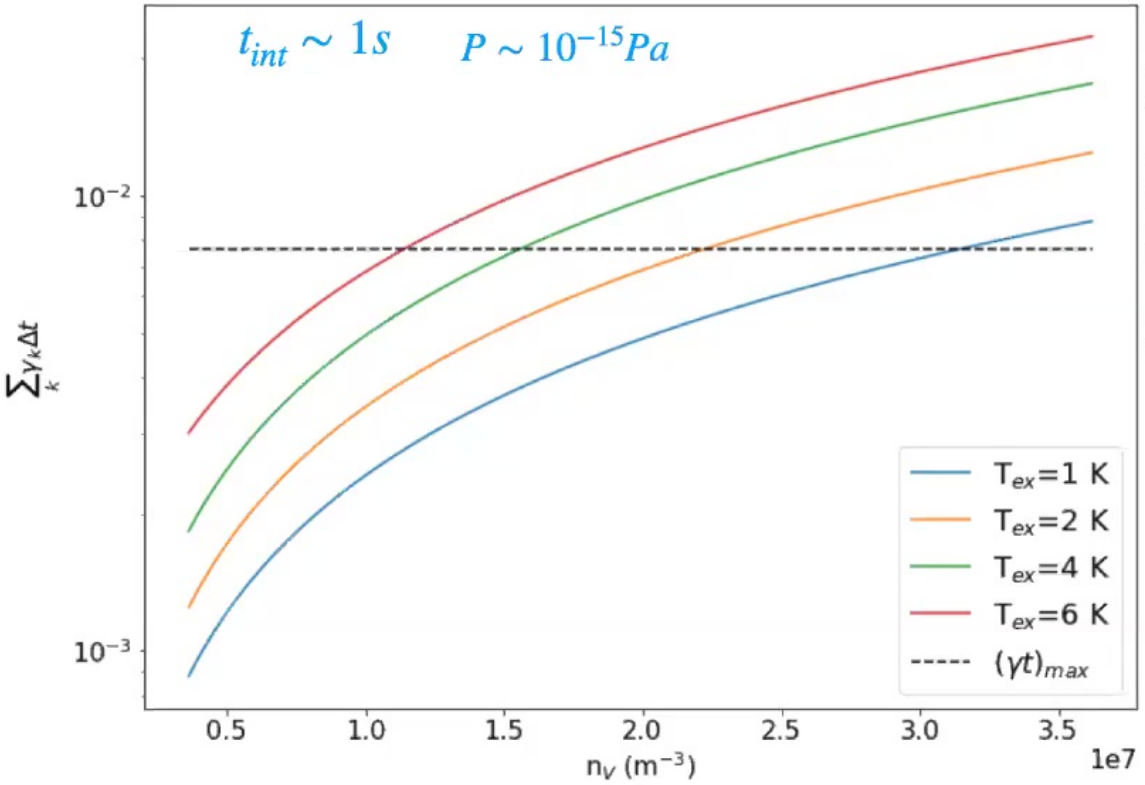


$$d - \Delta x = NR$$

Van de Kamp+Marshman +Bose+Mazumdar [2006.06931 [quant-ph]]

Sources of Dephasing/Decoherence

$$\mathcal{W} = I^{(1)}I^{(2)} - \sigma_x^{(1)}\sigma_x^{(2)} - \sigma_y^{(1)}\sigma_z^{(2)} - \sigma_x^{(1)}\sigma_z^{(2)} \qquad \mathrm{Tr}(\mathcal{W}\rho) < 0 \qquad \Rightarrow \gamma_{dec} t_{int} < \Phi/2 \sim 0.0075$$



ρ =3.5 g/cm^3
T_{int}=0.15K
m_{air}=28.97 amu
ϵ=5.68 + 1.1·10^{-4}i
$\partial_x B = 10^4$ Tm^{-1}
τ=500 ms
m=10^{-15} kg
N=57

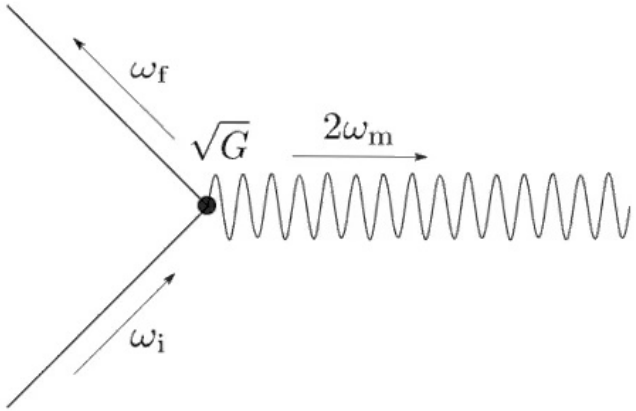
Main Sources of Decoherence

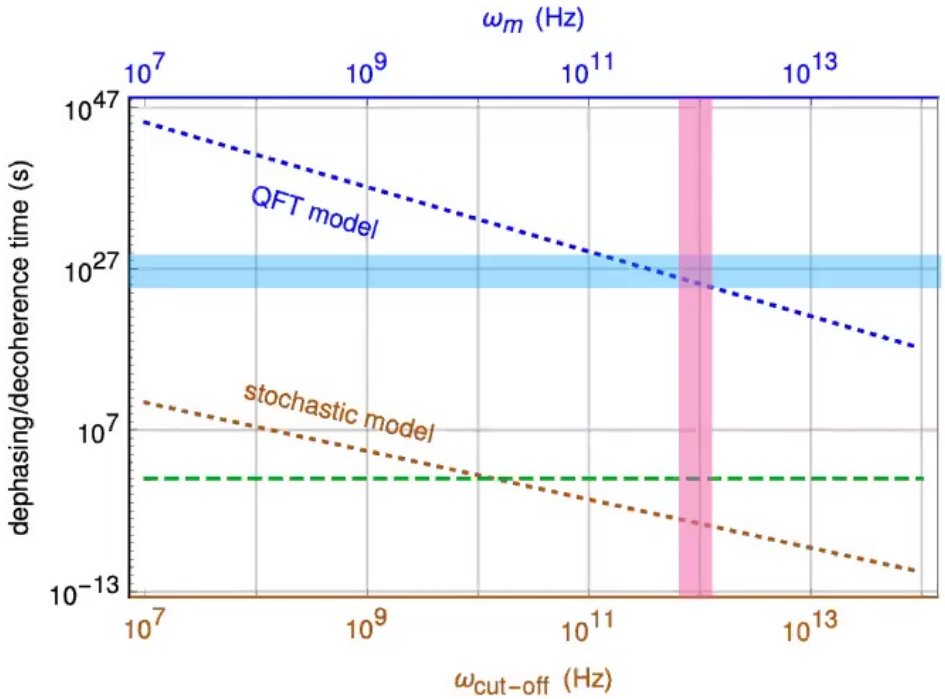
- **Collisional**
- **Black body emission, absorption**
- **Photon scattering**

- **At temperatures below 4k phonon vibration is not a problem for dephasing**

H. Van Kamp, R. Marshman, S. Bose, and A. Mazumdar. arXiv:2006.06931 [quant-ph].

Dephasing due to Graviton is extremely tiny

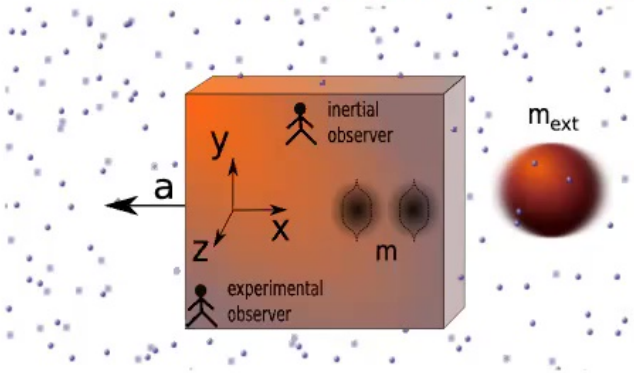




$$\gamma_{grav} = \frac{32G\hbar\omega_m^3}{15c^5} = \frac{32}{15}t_{pl}^2\omega_m^3$$

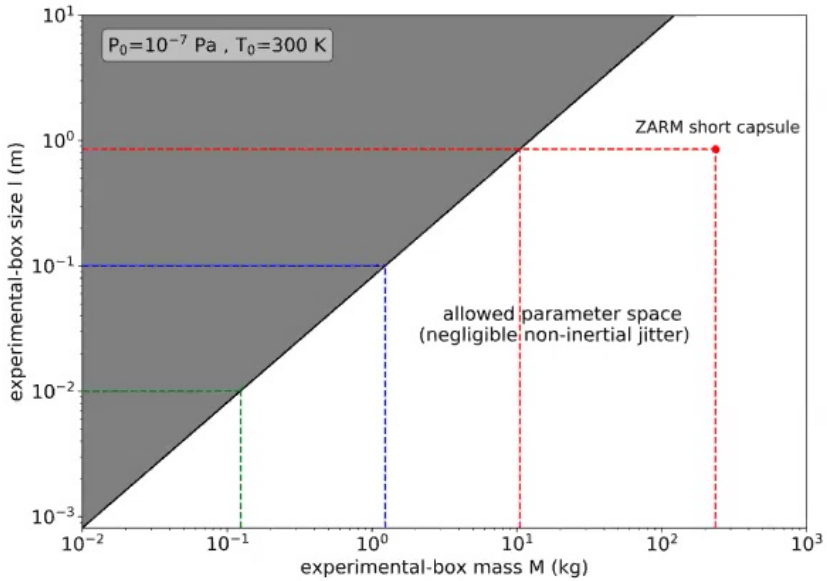
Toros + Bose + Mazumdar [2008.08609 gr-qc]

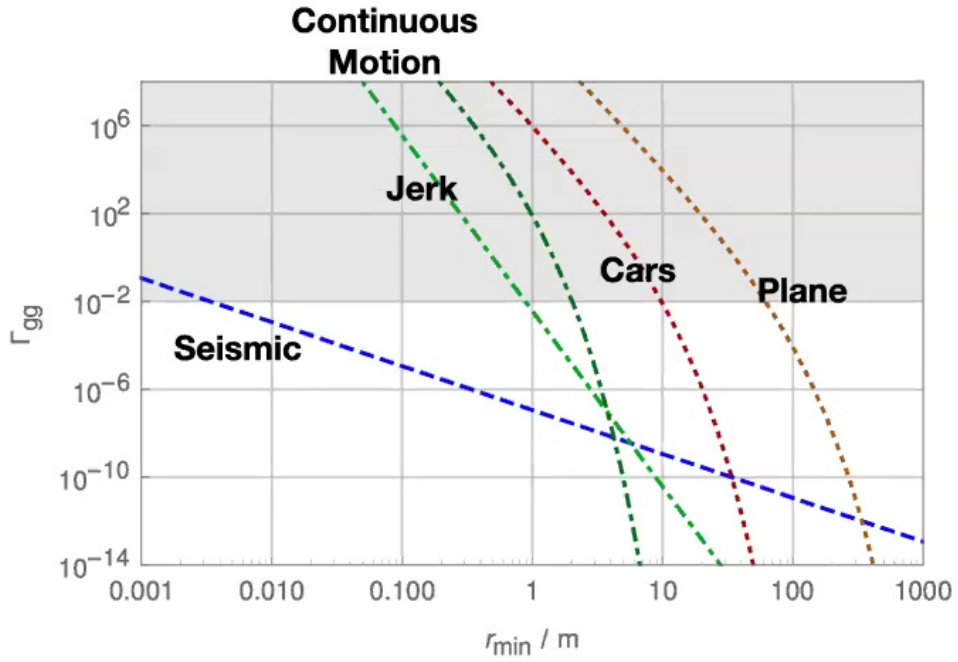
Relative Acceleration+Gravity Gradient Noise



$$\Phi_{eff} > \Gamma_d + \Gamma_{non-inertial} + \Gamma_{jitter} + \Gamma_{ggn}$$

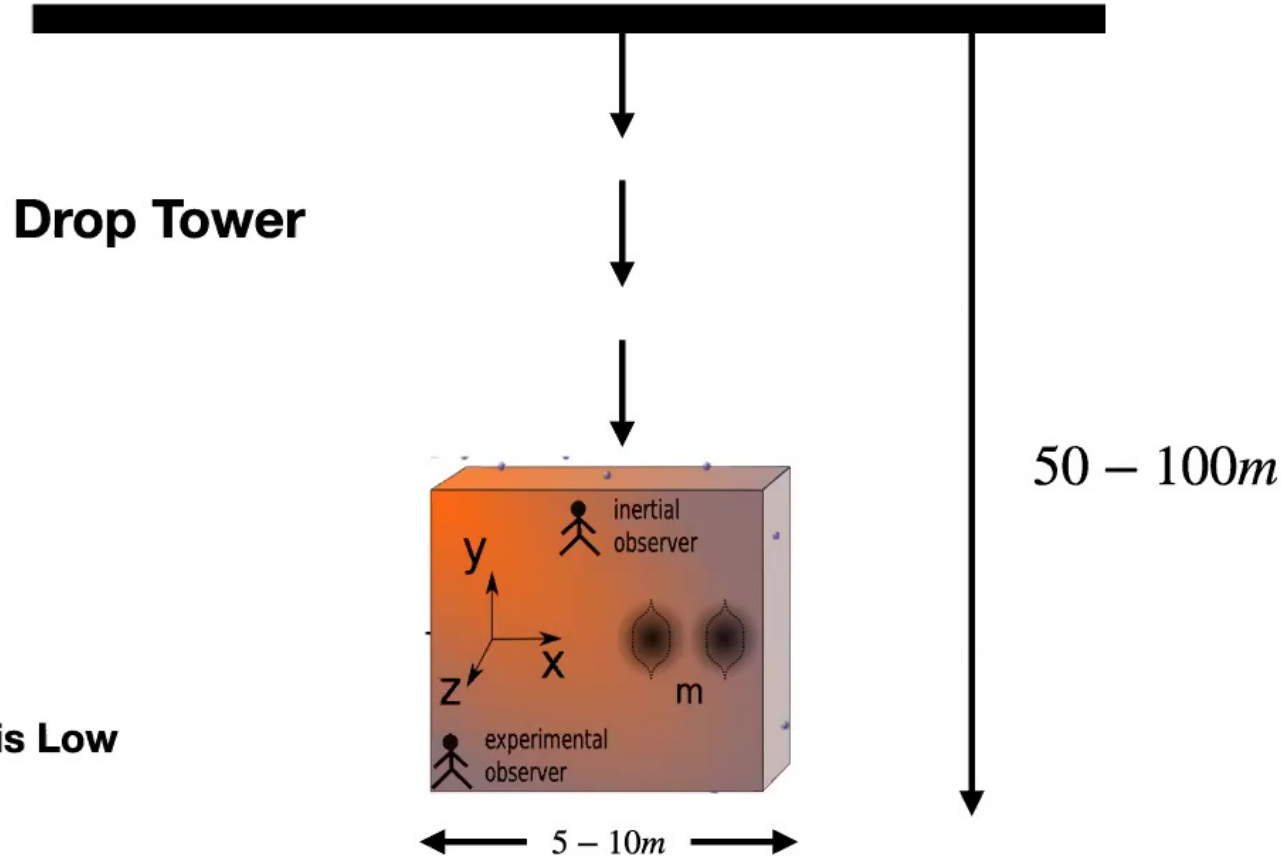
Non-inertial, GGN (Atmospheric+Seismic+ Constant movement+ Jerks+Cars+Planes)





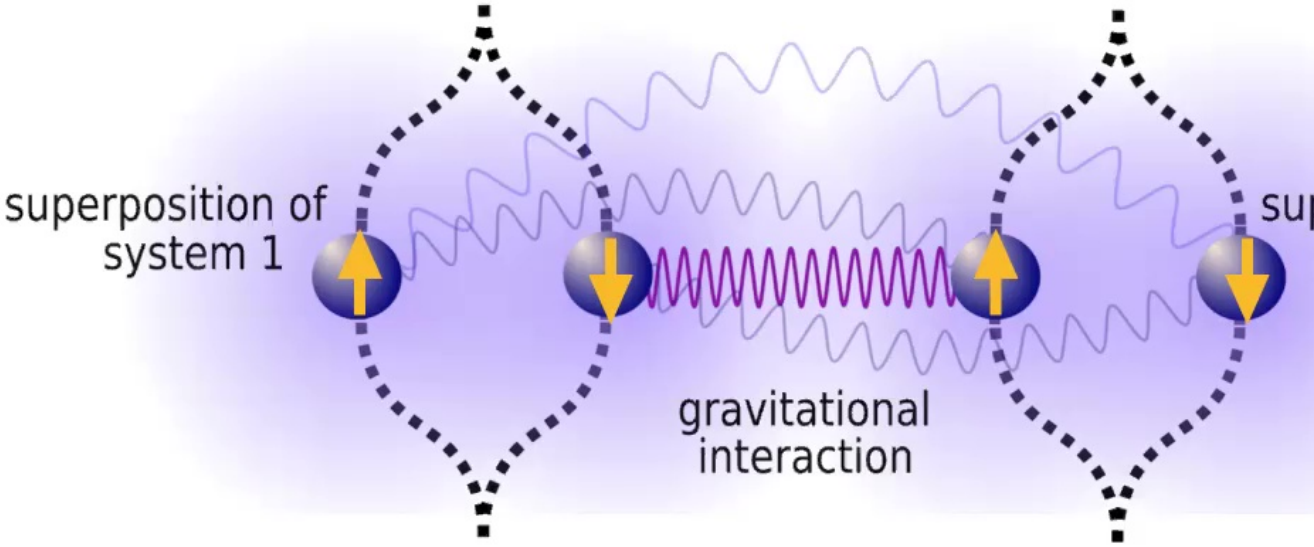
Toros+Van de Kamp+Kim+Mazumdar+ Bose, 2007.15029 [gr-qc]

Underground Laboratory



Seismic Noise is Low

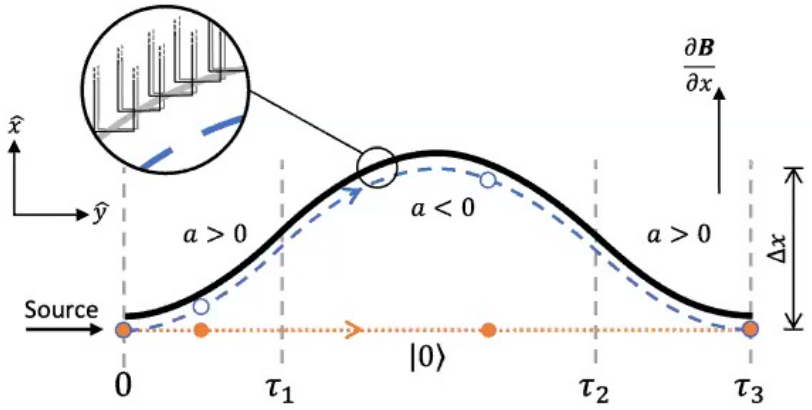
Formidable Challenges



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

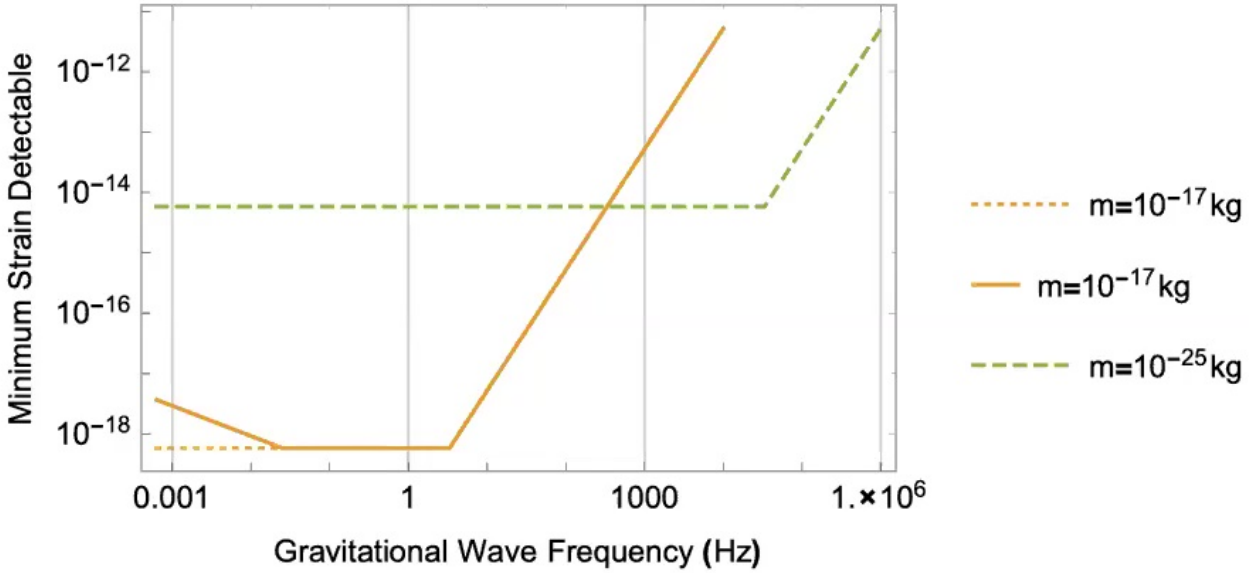
Zero-field Splitting **Diamagnetic part** **NV-part**

MIMAC: Mesoscopic Interferometer for Metric and Curvature



Sub-Hz Gravitational Wave Detector

We need to Improve upon the Strain Sensitivity



Theoretical Aspects

Alice, Bob and Eve

We are all Entangled : If Gravity is QUANTUM !

We can test it !

Probing UV Gravity

(1) GR: $\lim_{k^2\to 0} \Pi = (\mathcal{P}^2/k^2) - (\mathcal{P}_s^0/2k^2) \equiv \Pi_{GR}$

(2) F(R) Gravity:

$$\mathcal{L}(R) = \mathcal{L}(0) + \mathcal{L}'(0)R + \frac{1}{2}\mathcal{L}''(0)R^2 + \cdots$$

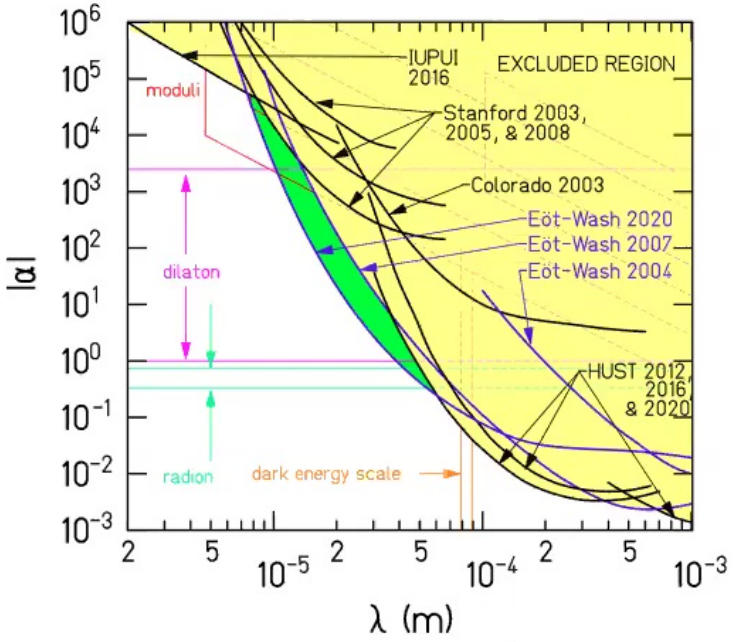
$$\Pi = \Pi_{GR} + \frac{1}{2}\frac{\mathcal{P}_s^0}{k^2+m^2}, \quad m^2 = \frac{1}{3\mathcal{L}''(0)}$$

(3) Weyl Gravity: $\mathcal{L} = R - \frac{1}{m^2}C^2$

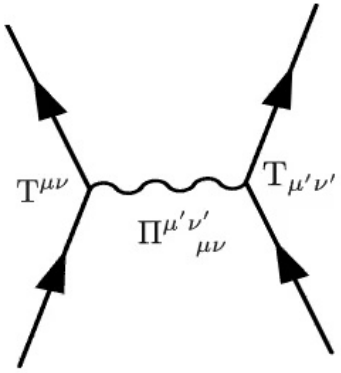
$$C^2 = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 2R_{\mu\nu}R^{\mu\nu} + \frac{1}{3}R^2$$

$$\Pi = \frac{\mathcal{P}^2}{k^2\left(1-(k/m)^2\right)} - \frac{\mathcal{P}_s^0}{2k^2} = \Pi_{GR} - \frac{\mathcal{P}^2}{k^2+m^2}$$

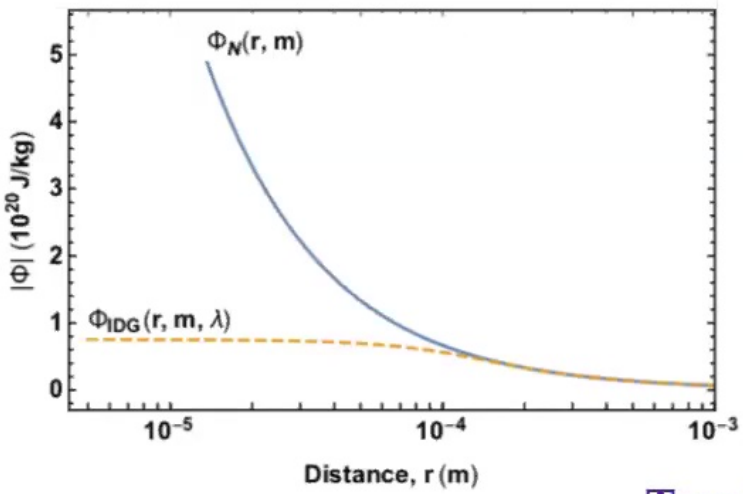
P. Van Nieuwenhuizen, Nucl. Phys. B60, 478-492 (1973)
T. Biswas, T. Koivisto and A. Mazumdar,
``Nonlocal theories of gravity: the flat space propagator,''
arXiv:1302.0532 [gr-qc]

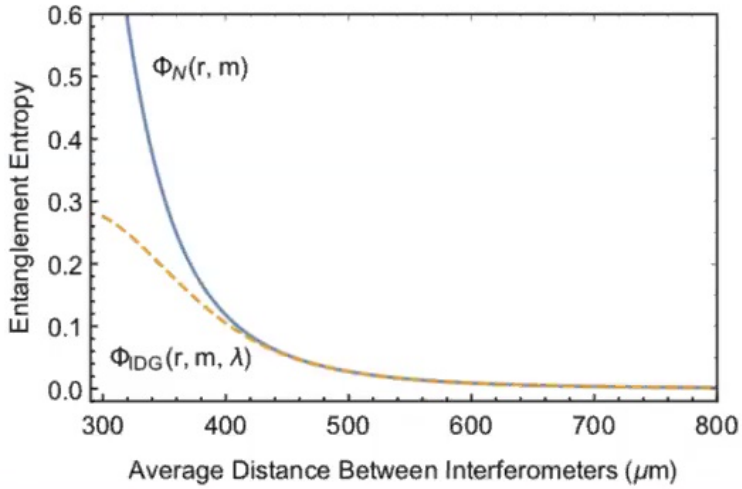


$$V \sim \frac{1}{r}e^{-mr} + \cdots$$

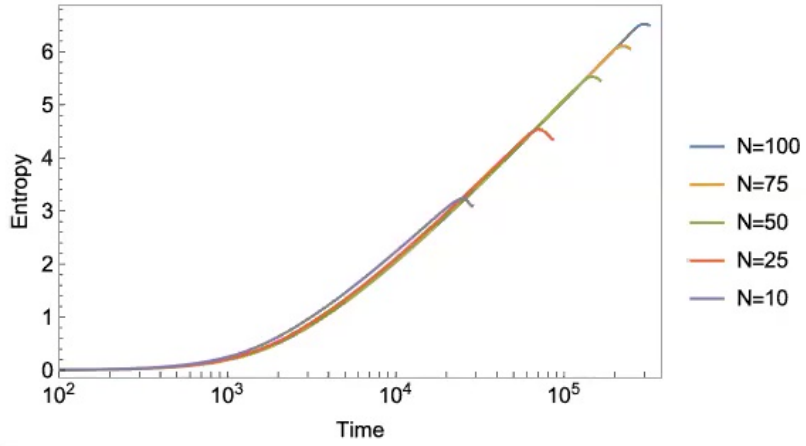


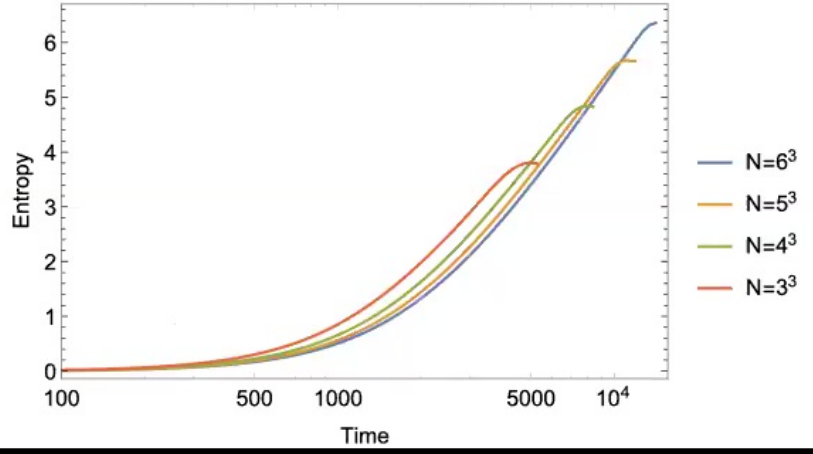
Entanglement Entropy & it's Universal Growth



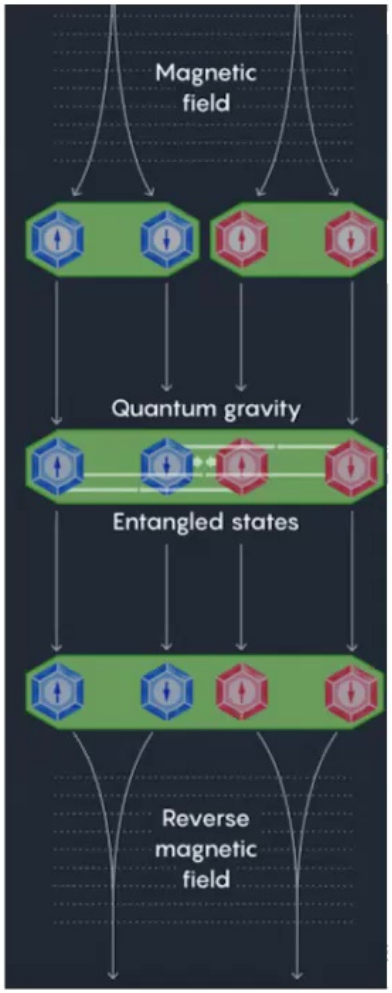


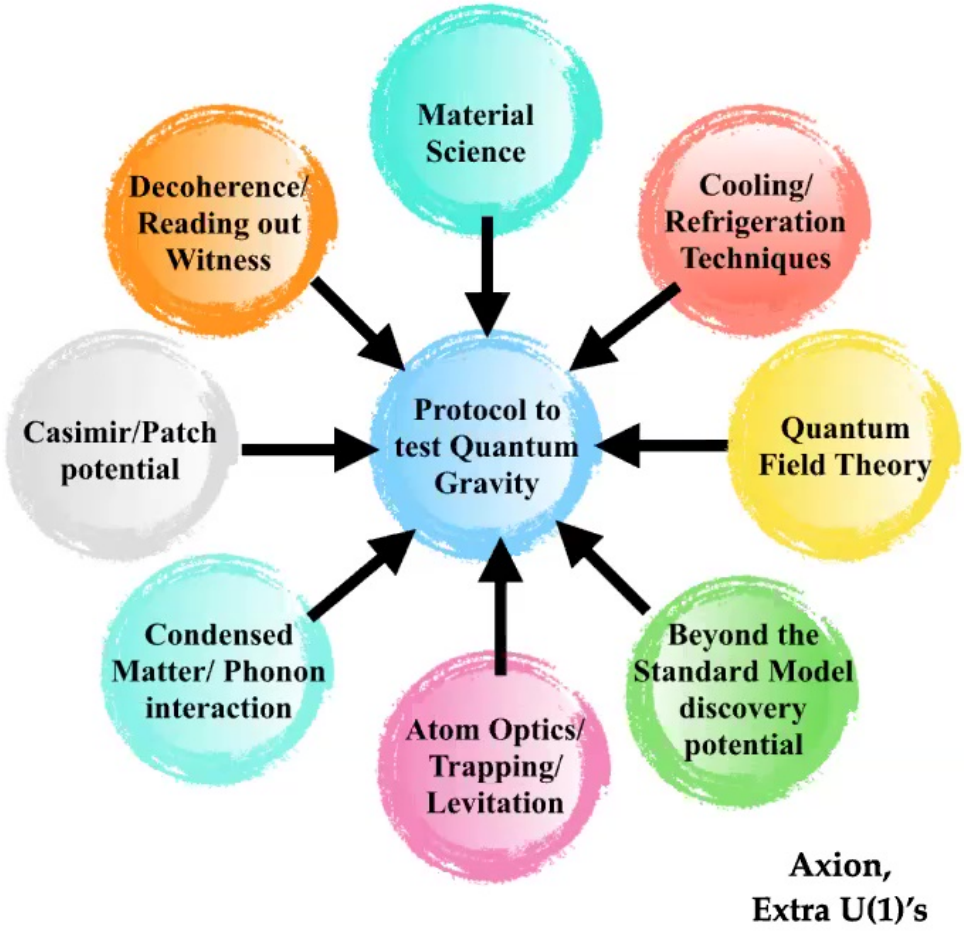
Two Self-Gravitating systems



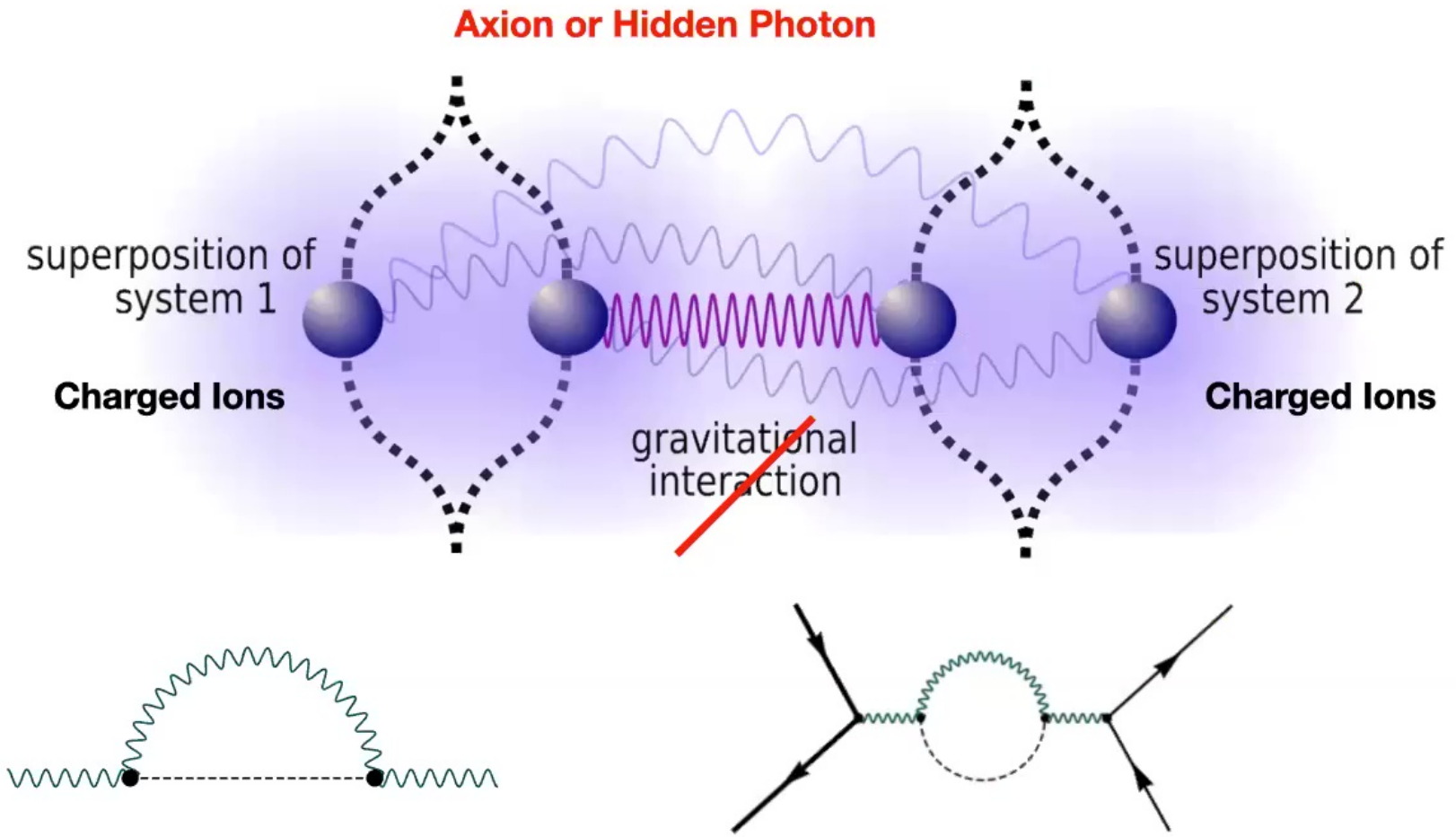


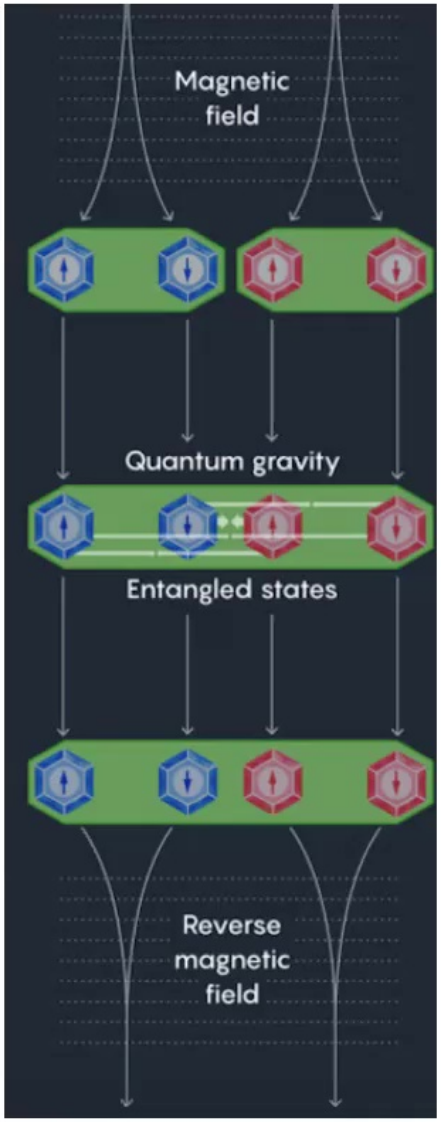
QGEM Protocol Unites All





Probing Beyond the Standard Model Physics





Conclusion

Test Quantum Gravity

The Final Frontier !

One Protocol to rule them all,
One Protocol to find them,
One Protocol to bring them all,
and Quantum Gravity which binds them.

We can test QGEM Protocol

Bose+AM+Morley+Ulbricht+Toros+Paternostro+Geraci+Barker+Kim+Milburn, PRL (2017) [1707.06050]

Marshman+AM+Bose, PRA (2020) [1907.01568]