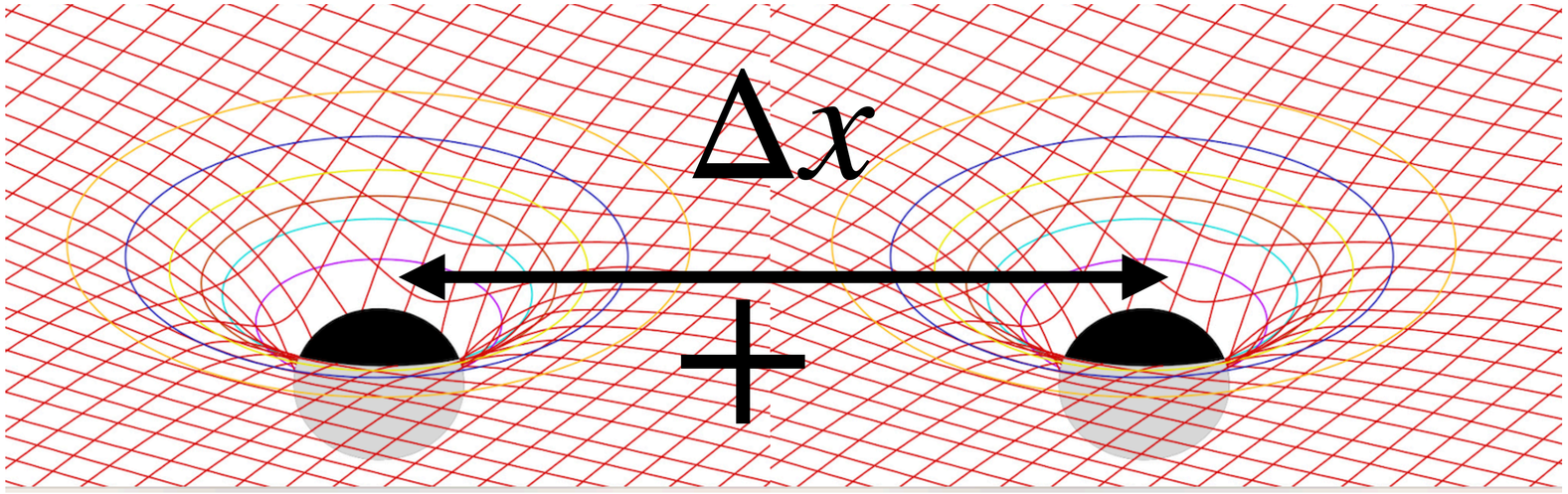
Spin Entanglement Witness to Test Spacetime being quantum in a Lab

Anupam Mazumdar

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

GORDON AND BETTY MOORE FOUNDATION

ALFRED P. SLOAN FOUNDATION



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

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

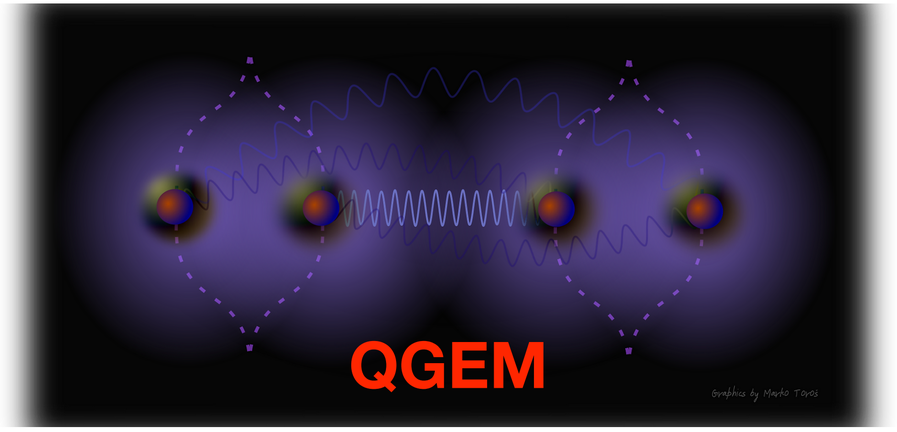
CITA ICAT
Canadian Institute for Theoretical Astrophysics
L'institut Canadien d'astrophysique théorique

Plan of my talk

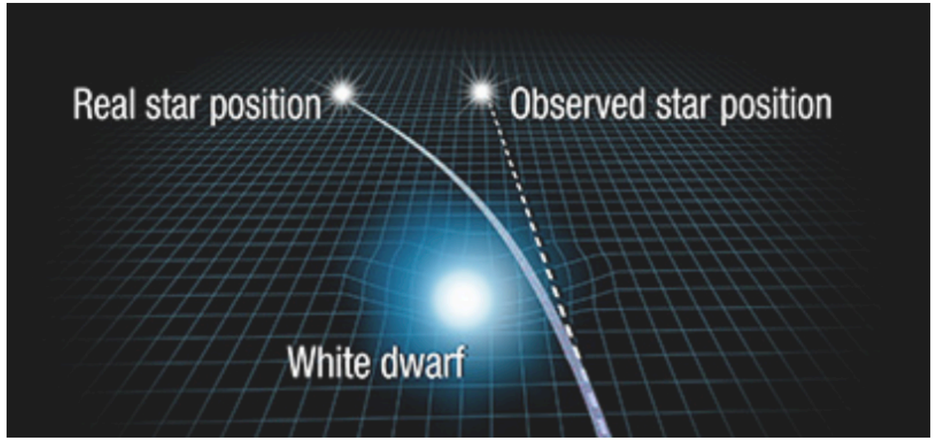
Foundations: Quantum mechanics, Macroscopic quantum superposition

Fundamental Implications:

Matter-Matter Entanglement



Matter-Photon Entanglement



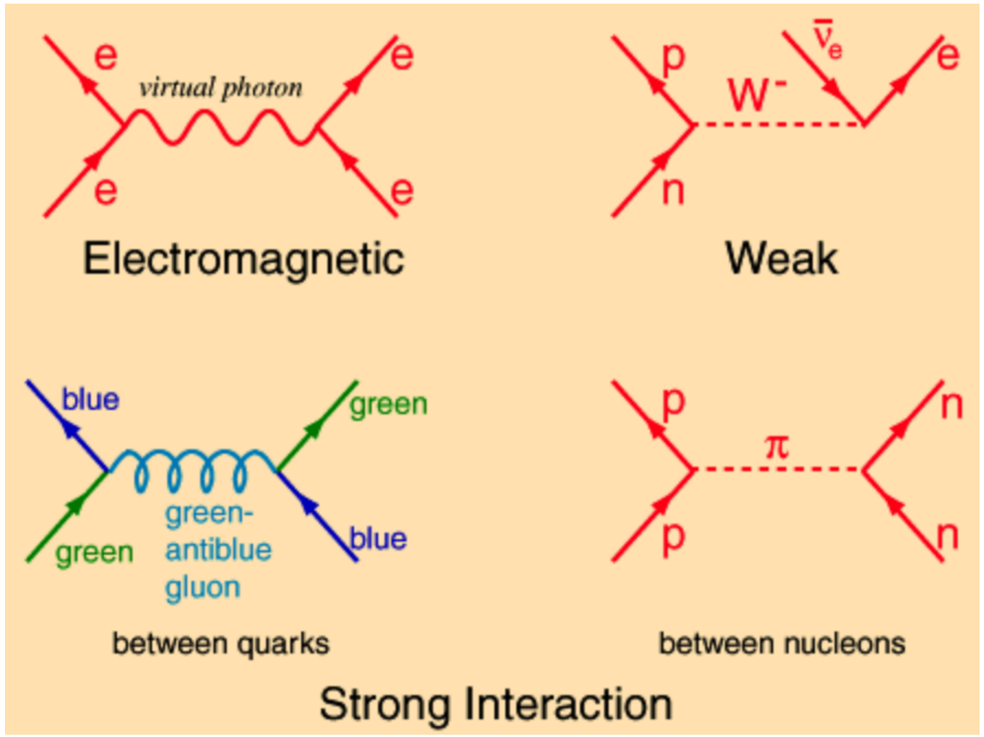
Future Outlook: Experimental challenges & future planning

Future Applications: Electromagnetic levitation & extreme quantum sensors

Dedicated Groups: Austria, Germany, Switzerland, Israel, Japan, Netherlands, United Kingdom, USA

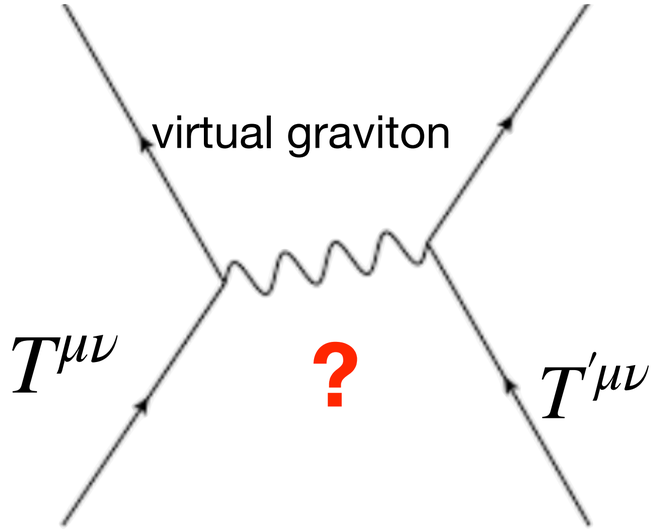
Quantum Gravity-Induced Entanglement of Masses (QGEM)

400 years of Spacetime & Gravity



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

- **Standard quantum mechanics**
- **General relativity**
- **Quantum field theory**
- **Local interactions**



Who mediates the force?

Entanglement generation

$$H = \hat{H}_A + \hat{H}_B \quad |\psi_i\rangle = |0\rangle_A |0\rangle_B \qquad H = \hat{H}_A + \hat{H}_B + \lambda \hat{H}_{AB} \quad |\psi_f\rangle \equiv \frac{1}{\sqrt{\mathcal{N}}} \sum_{n,N} C_{nN} |n\rangle |N\rangle$$



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

Product State

Non-Product State

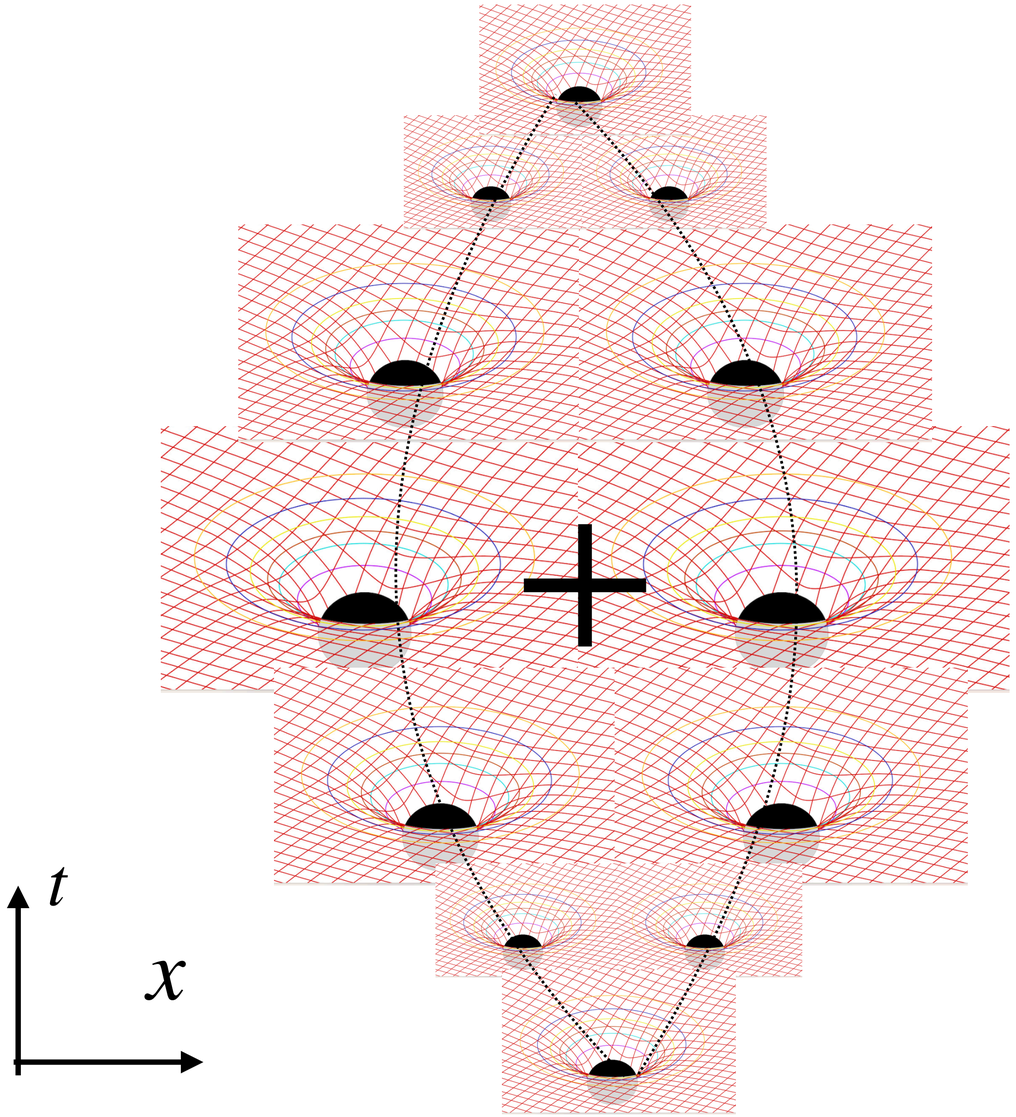
$$C_{nN} = \lambda \frac{\langle n | \langle N | \hat{H}_{AB} | 0 \rangle | 0 \rangle}{2E_0 - E_n - E_N} \neq 0$$

Condition for an Entanglement

$\hat{H}_{AB}$: QED, QCD, Weak, phonon, gravity, or any other quantum Interaction

Bose, Mazumdar, Schut, Toros, 2201.03583

Matter wave Interferometer: Toy model for quantum gravity



$$L = -mc^2\sqrt{-g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu},$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| \ll 1$$

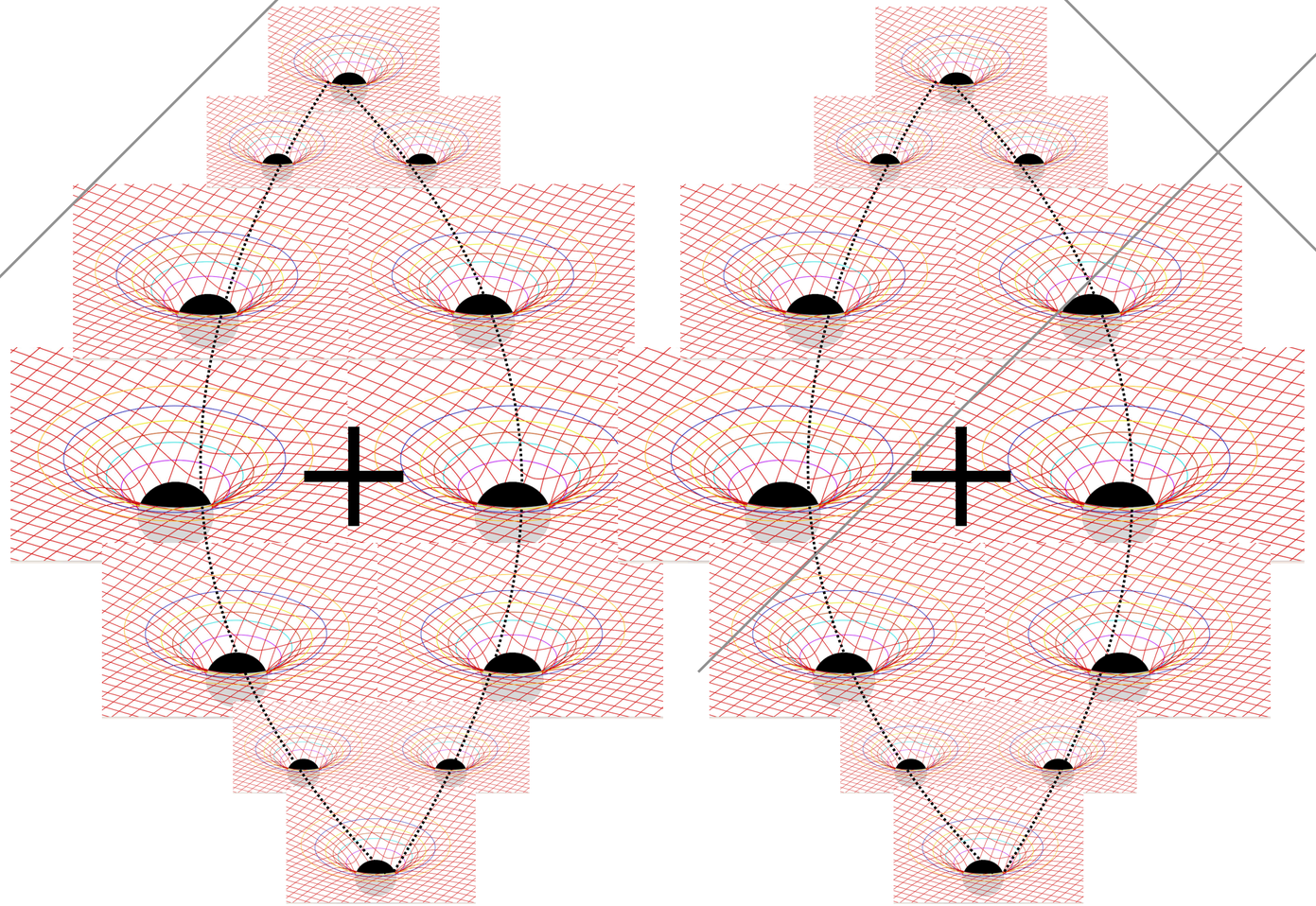
$$\hat{H}_{int} \sim m\,\hat{R}_{0101}\,\hat{x}^2$$

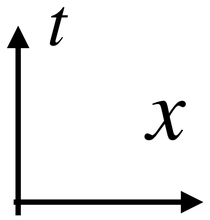
Curvature Harmonic Oscillator

Genuine tripartite entanglement between curvature & matter

Carmona Rufo, Mazumdar, Sabin 2411.03293

QGEM protocol



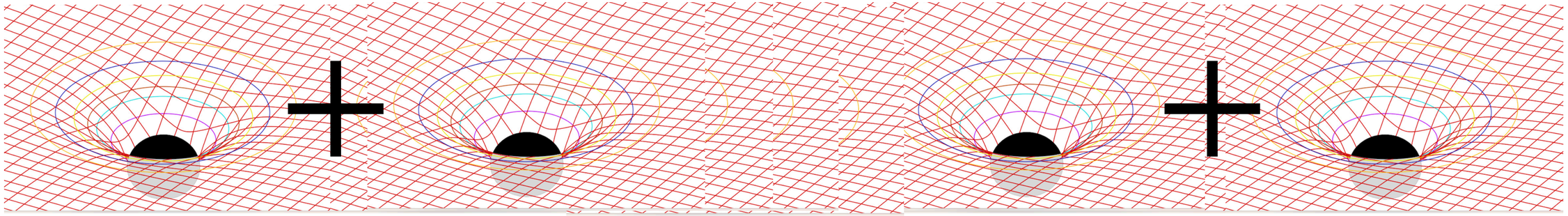


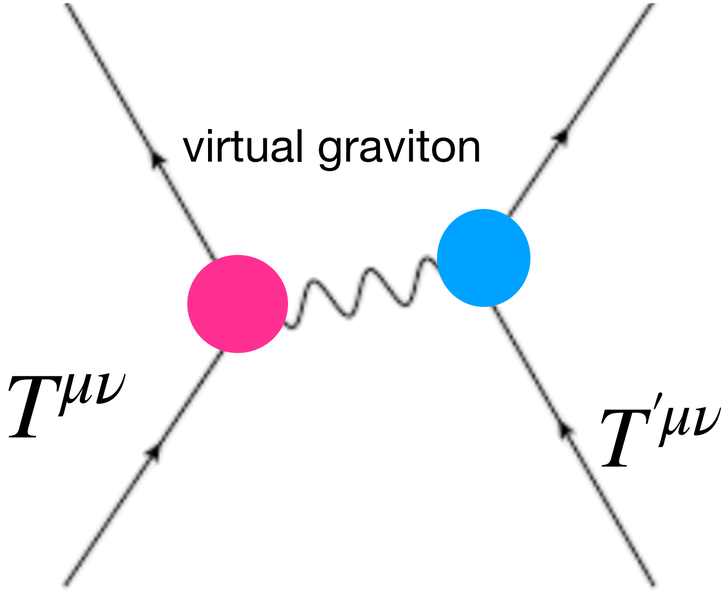
Two matter-wave interferometers next to each other within the light cone

QGEM protocol

Alice

Bob





Integrate the curvature (graviton propagator):
Alice and Bob are entangled

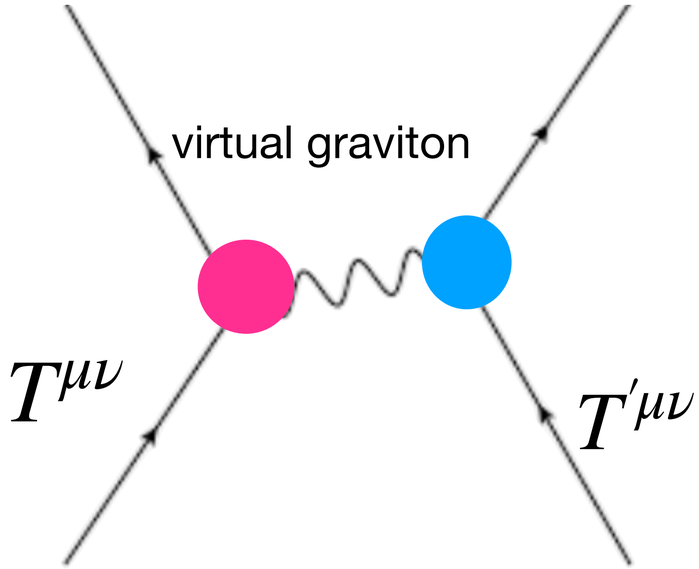
S-matrix:

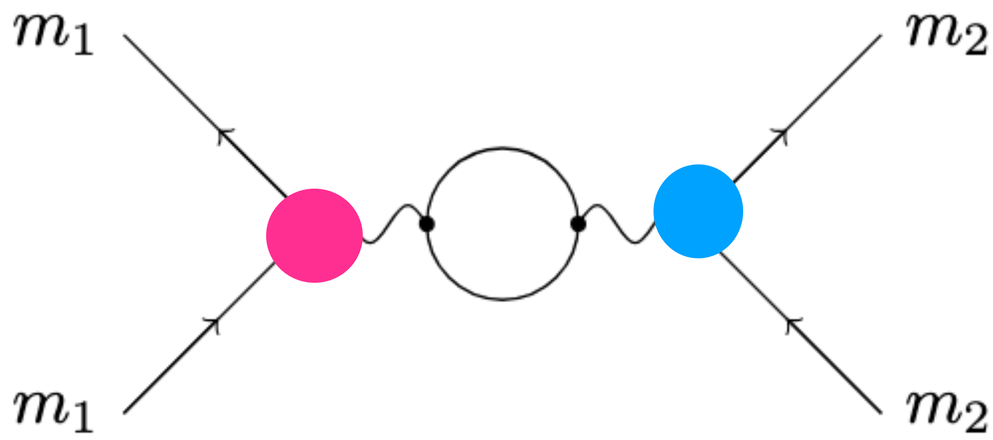
$$\langle f|\, S\, |i\rangle = \langle f|i\rangle - \frac{i\kappa^2}{4}\int \mathrm{d}^4x\mathrm{d}^4x'\, \langle f|\, T^{\mu\nu}(x)G_{\mu\nu\alpha\beta}(x,x')T^{\alpha\beta}(x')\, |i\rangle$$

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

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

Entanglement due to Post-Newtonian expansion





$$\widehat{H}_g \sim -\frac{Gm^2}{\hat{r}} - 7\frac{G\hat{p}^2}{c^2\hat{r}} - \frac{G\hat{p}^4}{c^4m^2\hat{r}} + 2\frac{G^2m^2}{c^2\hat{r}^2} + \frac{62G^2m\hbar}{15\pi c^2\hat{r}^3} + \cdots$$

Assuming masses and momenta are the same in C.O.M frame

LOCC vs. LOQC

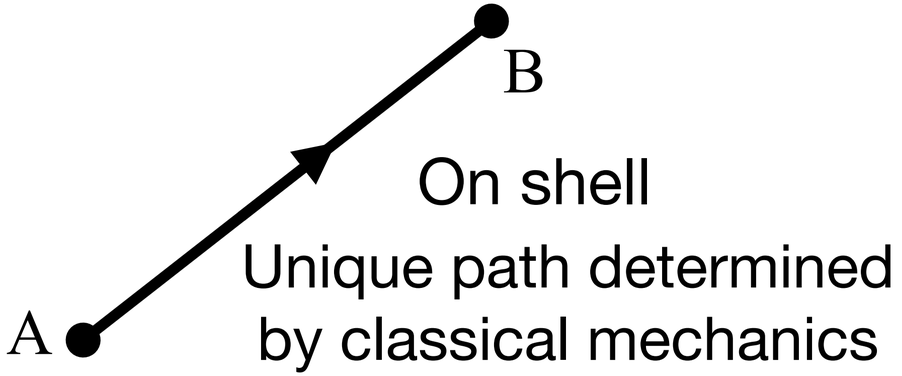
LOCC Theorem

It is *impossible* to generate/increase entanglement between A and B by local operations and classical communication (LOCC) if A & B were initially in product states. Bennett, et.al, (1996)

LOQC Theorem

***LOQC* (local operations and quantum communications) theorem: We need a quantum mediator, e.g. the virtual excitations of a graviton.**

Marshman, Mazumdar, Bose, arXiv:1907.01568

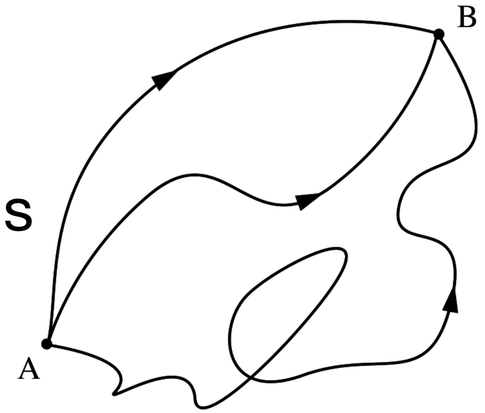


On shell

Unique path determined by classical mechanics

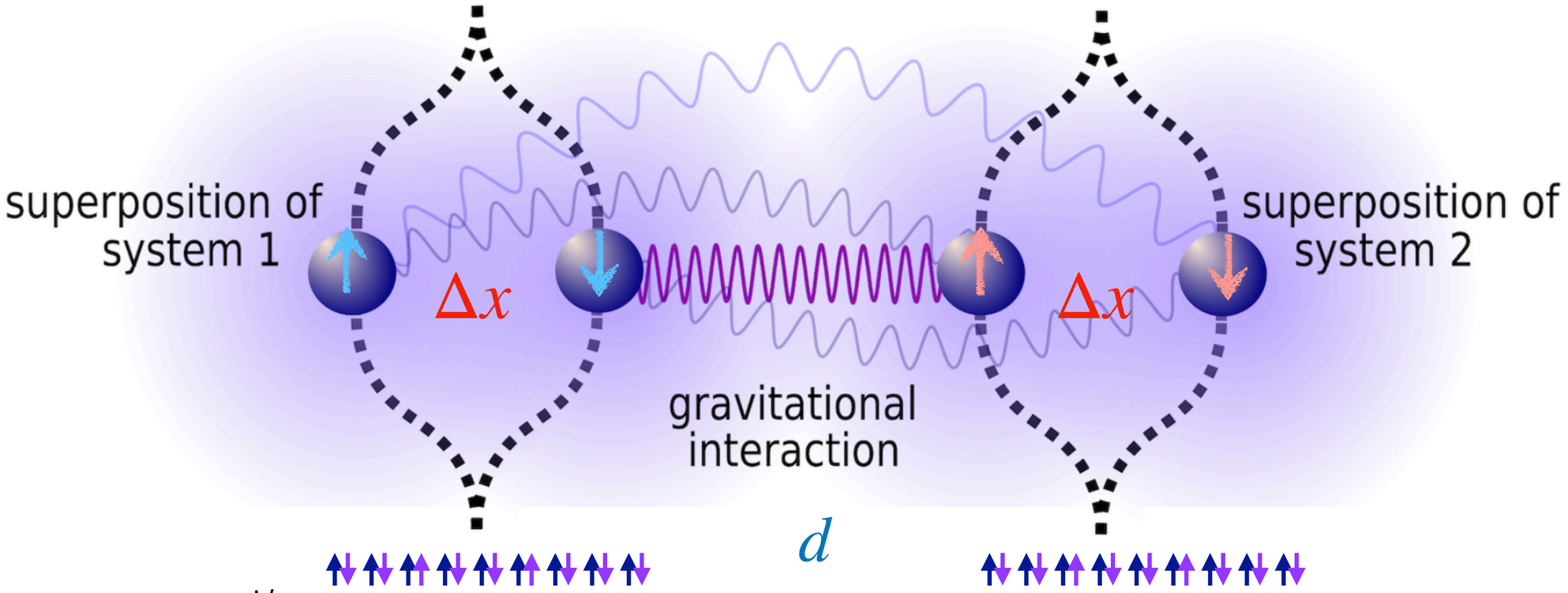
Off shell

Sum over all the paths



Entanglement happens due to off-shell gravitational fluctuations

Spin embedded nanodiamonds & Stern-Gerlach



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

Order Parameter: **Entanglement phase:** $\Delta\phi_{ent} = \phi_1 + \phi_2 \sim \frac{Gm^2}{\hbar d}\tau\left(\frac{\Delta x}{d}\right)^2$

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

Spin readout or Position/momentum readout

Spin readout

Positive Partial Transpose Witness

$$W = I^{(1)} \otimes I^{(2)} - \sigma_x^{(1)} \otimes \sigma_x^{(2)} - \sigma_y^{(1)} \otimes \sigma_z^{(2)} - \sigma_z^{(1)} \otimes \sigma_y^{(2)},$$

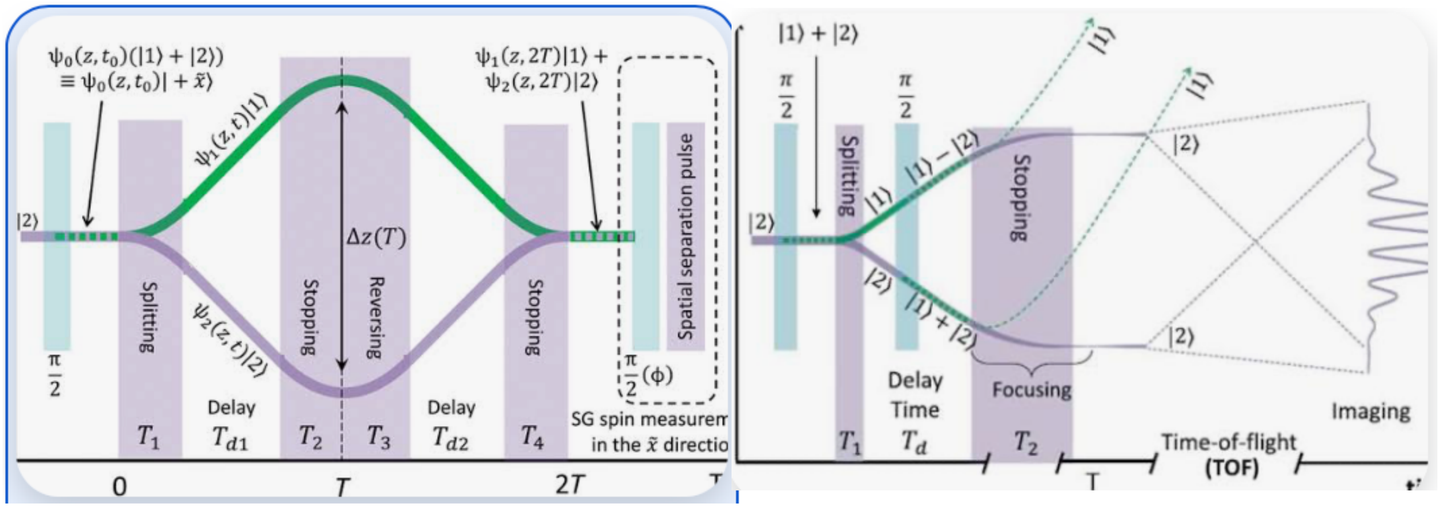
Entanglement criteria

$$\mathrm{Tr}(W\rho) < 0$$

$$\langle \mathscr{W} \rangle = \mathrm{Tr}(\mathscr{W}\rho) = 2\gamma t - \Delta\phi_{ent} < 0$$

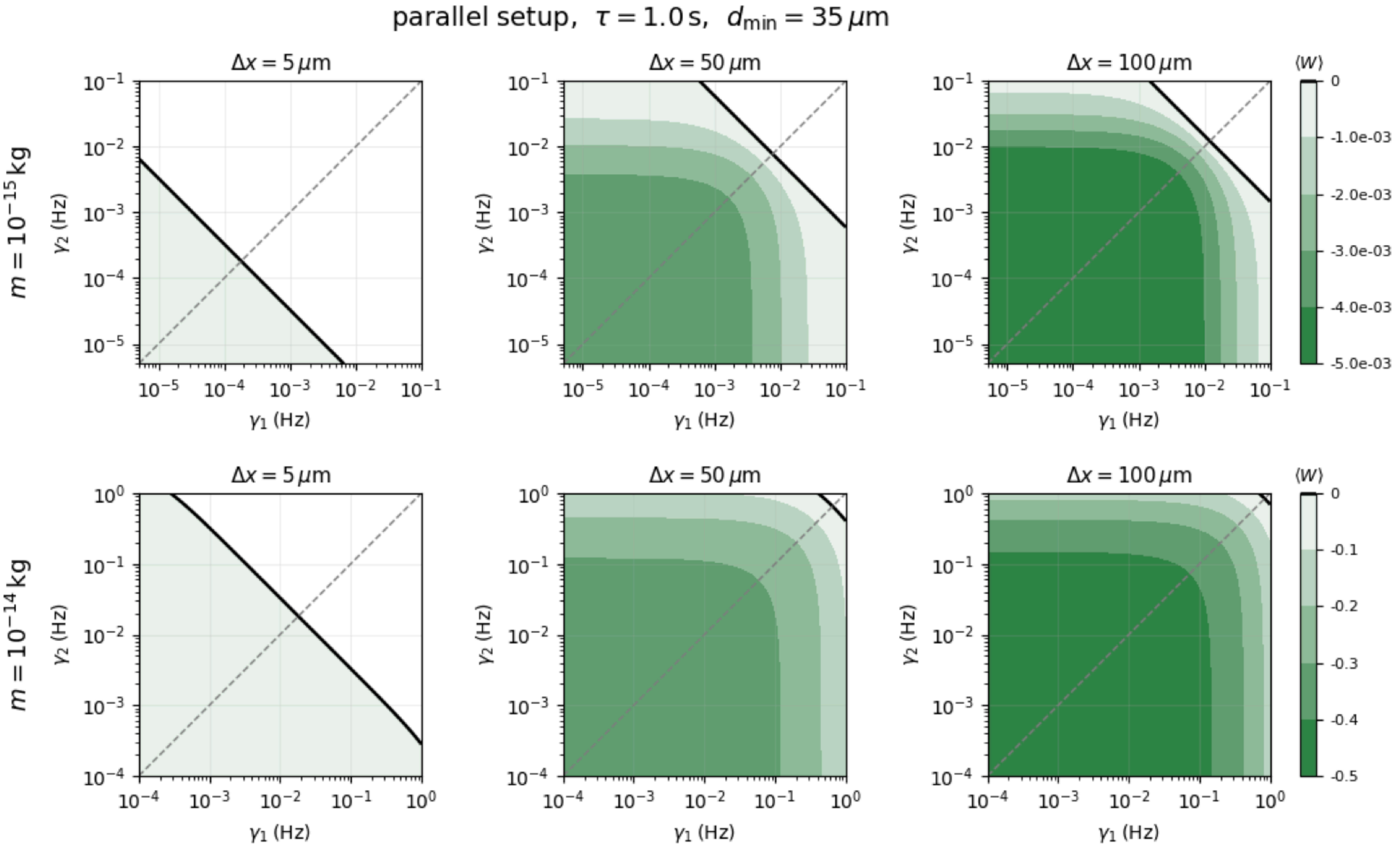
Chevalier, Paige, Kim, Phys. Rev. A. 102, 022428 (2020)

Position-momentum readout

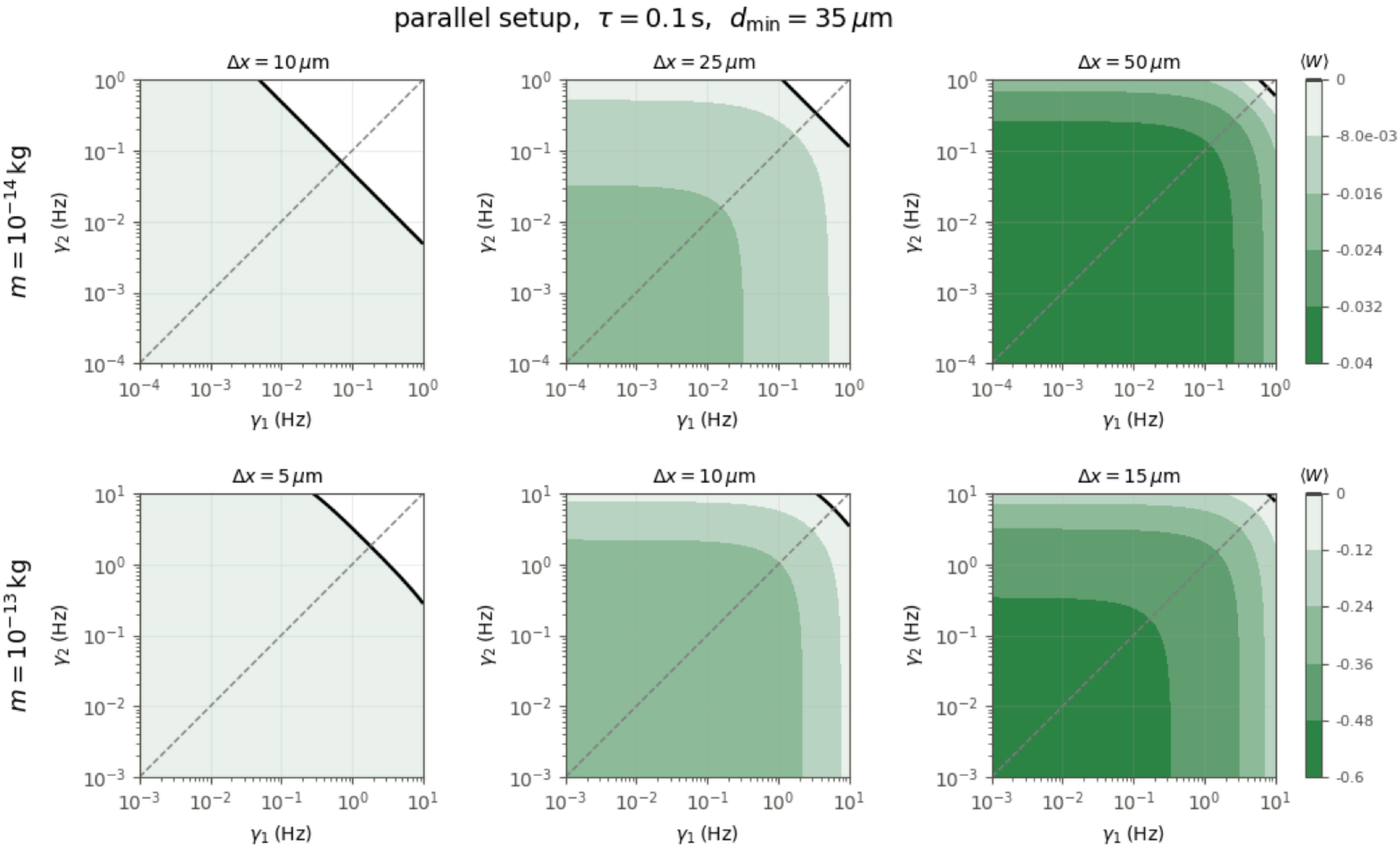


Half-loop Stern-Gerlach

Witness & decoherence



Witness & decoherence



QGEM: fun (love & hate) challenges

Material aspect: embedding spin qubit, purity of the material, coherence time of qubit, qubit manipulation, surface cleaning

Releasing & trapping: neutralising in a vacuum, diamagnetic trapping for neutral nanoparticles, microchip design for trapping

Cooling (motional/internal): motional, rotational, biasing the spin qubit, initiating superposition of the qubit

Creating superposition: motional, rotational, humpty-dumpty effect, spin coherence/constrast

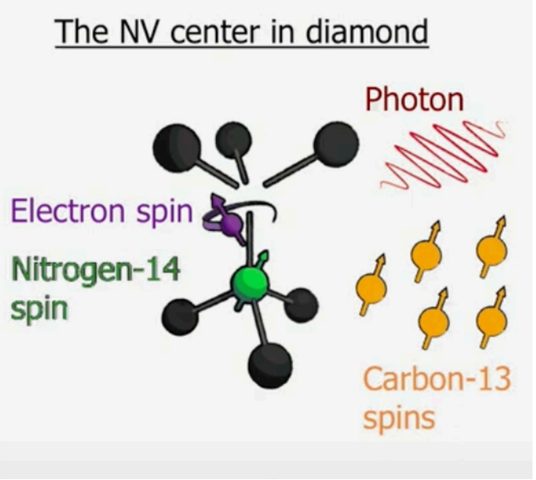
Dephasing/decoherence: electromagnetic screening, current fluctuations, superconducting magnetic flux, excellent vacuum

Gravitational/relative acceleration/seismic noise: 1 Hz or maybe 10 Hz experiment requires unprecedented challenge for noise mitigation

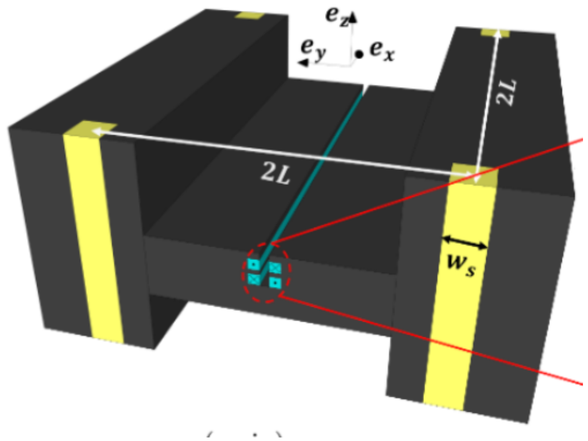
Material aspects & Trapping platforms

Material aspect

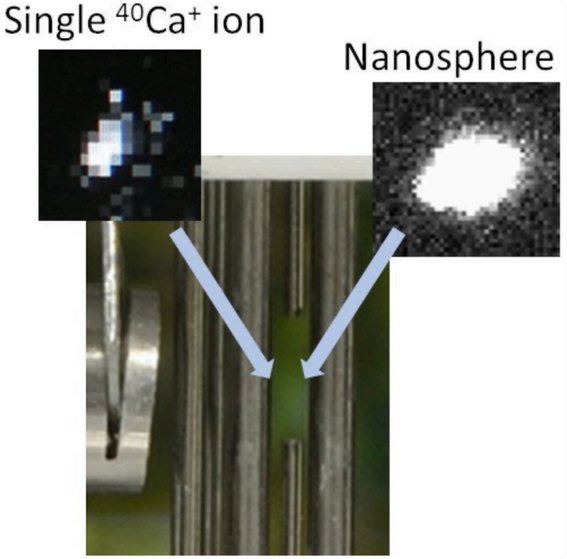
Trapping, Cooling, Superposition



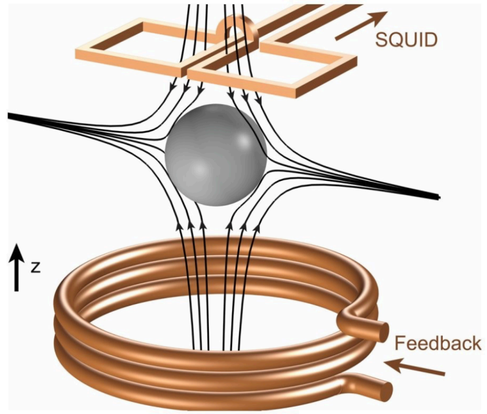
Nanodiamond



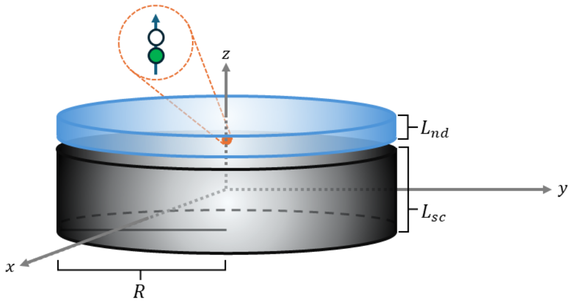
Diamagnetic trap
Chip
(MAST-QG)



Ion trap
(Innsbruck)



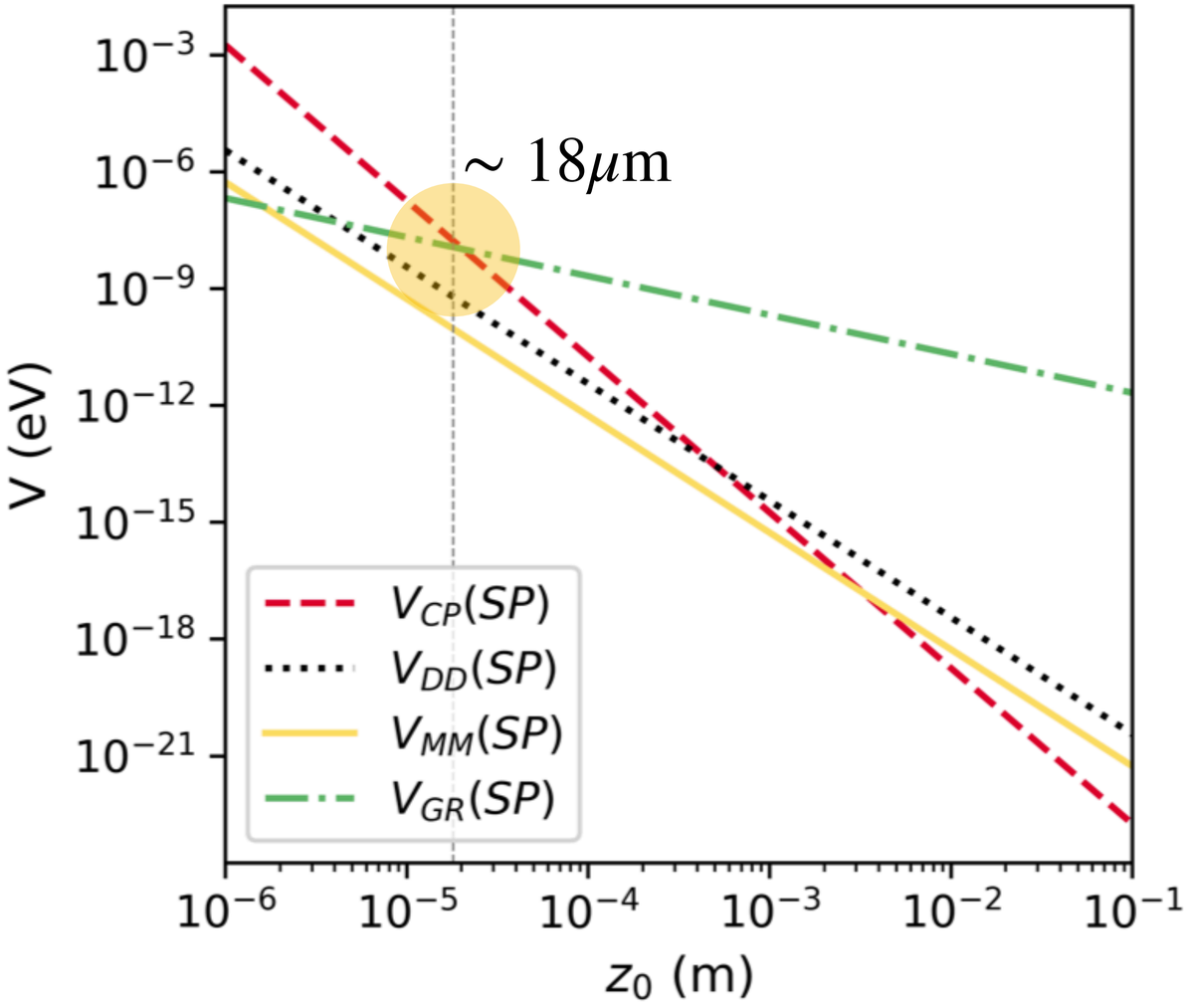
Superconducting trap
(Leiden, Vienna)

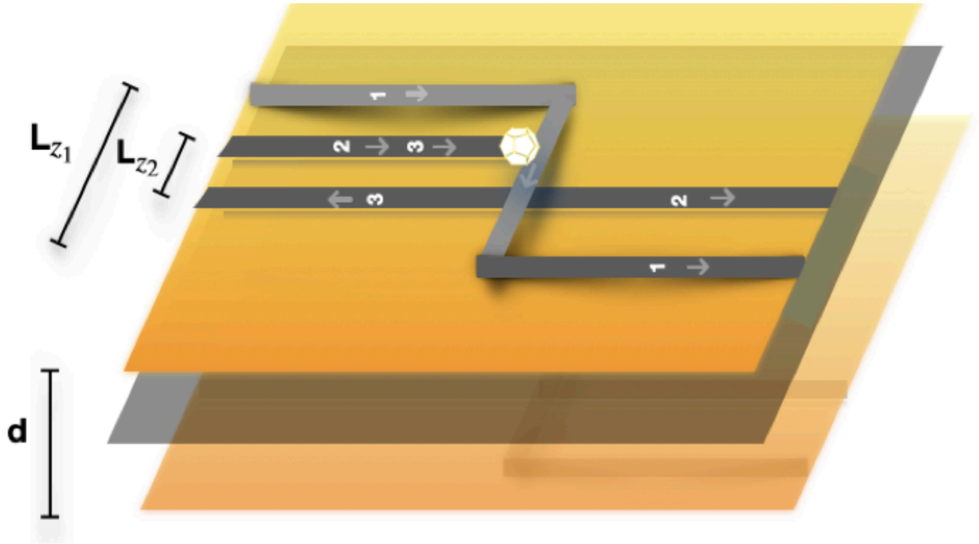


Hybrid material

Hybrid trap?

Electromagnetic Shielding





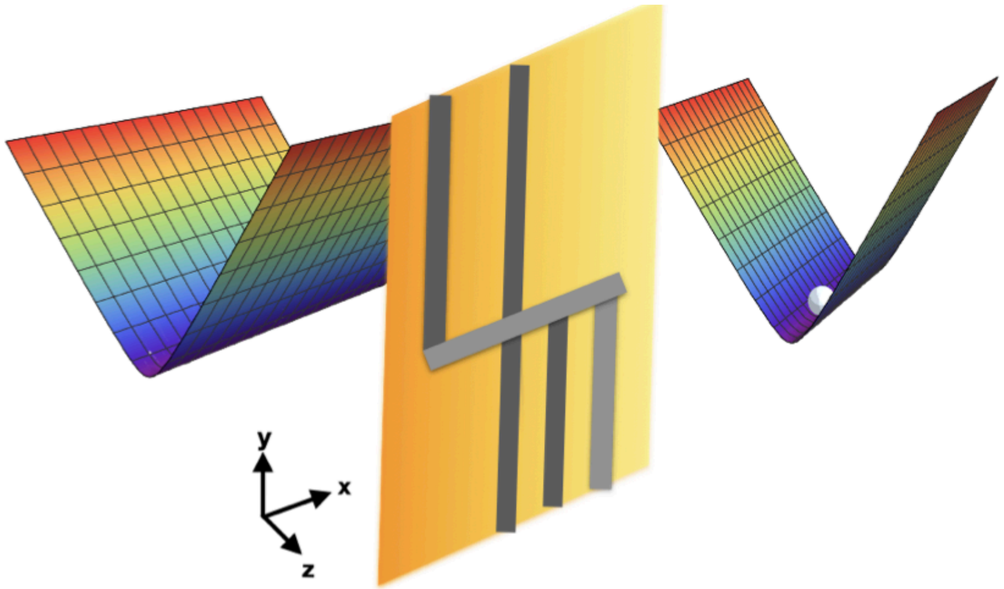
$$V_{\mathrm{DD}}^{\mathrm{S\text{-}P}} = -\frac{1}{4\pi\varepsilon_0}\frac{|\mathbf{d}|^2}{8z_0^3}\left[1+\cos^2(\theta_e)\right]$$

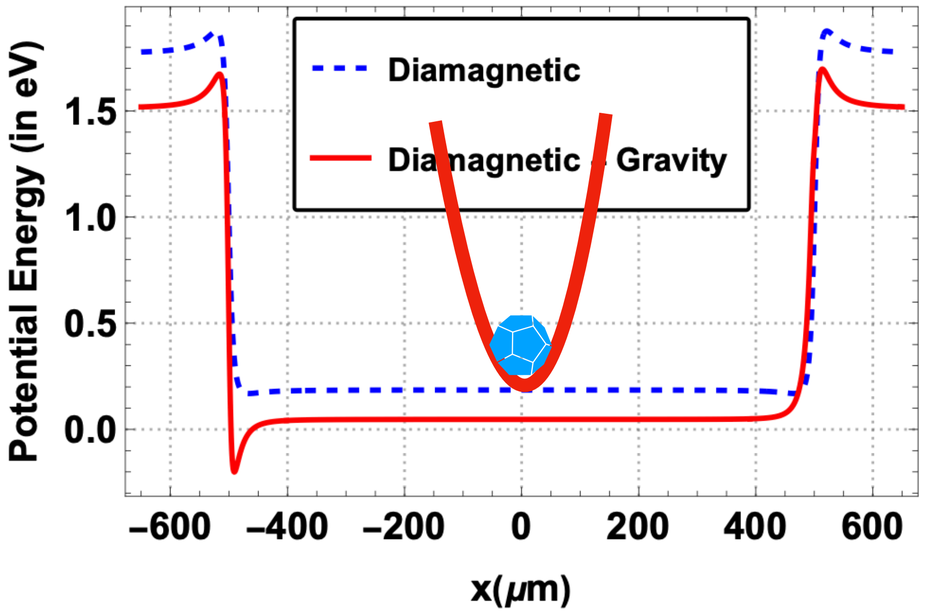
$$V_{\mathrm{CP}}^{\mathrm{S\text{-}P}} = -\frac{3\hbar c}{8\pi}\frac{\varepsilon-1}{\varepsilon+2}\frac{R^3}{z_0^4},$$

$$V_{\mathrm{MM}}^{\mathrm{S\text{-}P}} = \frac{\mu_0|\mathbf{m}|^2}{4\pi}\frac{1}{z_0^3}[1+\cos^2(\theta_m)]$$

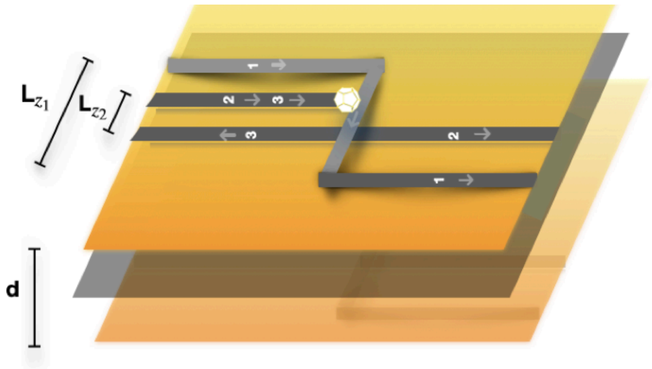
Schut, Geraci, Bose, Mazumdar 2307.15743
Elahi, Schut, Dana, Grinin, Bose, Mazumdar, Geraci, 2411.02325

Levitating Setup with a Long Diamagnetic Trap



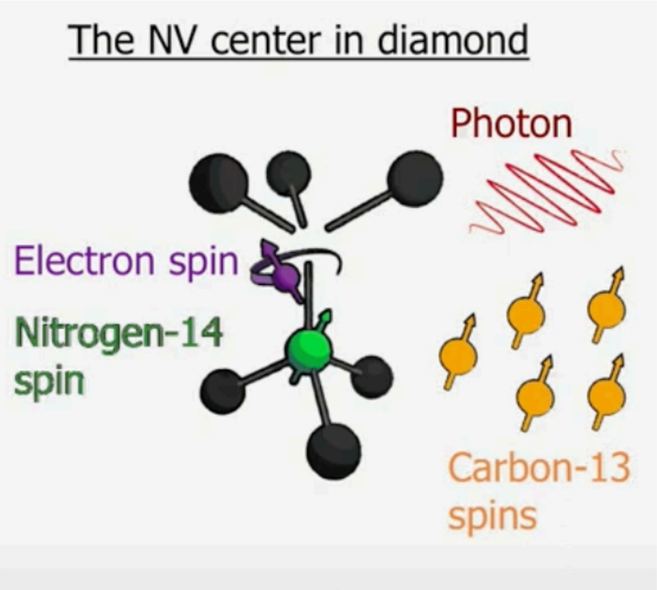


Trap	Orientation	$(\omega_x, \omega_y, \omega_z)/2\pi$ (Hz)	z_0(μm)
Short trap	B_{bias}= 0.2 T		
30 μm u-wire	(H)	(121.5,507, 585)	16.2
	(V)	(62, 380.7, 336)	18.6
30 μm z-wire	(H)	(191, 550, 785)	16.4
	(V)	(159, 351, 331)	18.3
Long trap	B_{bias}= 0.25 T		
1mm Z-wire	(H)	(0.1*, 553, 685)	16.4
	(V)	(0.01*,491.5, 521)	16.7



Horizontal

Qubit (NV Spin) Manipulation & Long Coherence

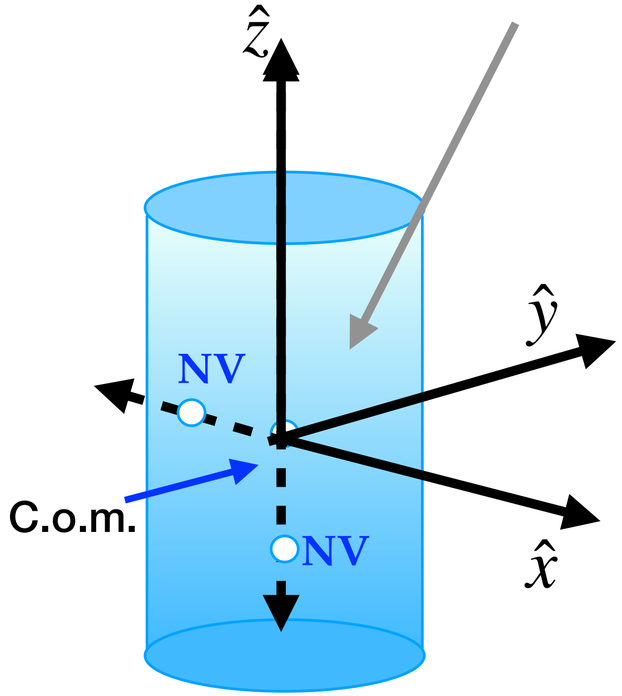


Dynamical decoupling or Mapping to Nuclear spin (~1 sec coherence)
(Taminiau Group, Delft, (arXiv: 1801.01196)

$$H = \frac{1}{2m}\vec{p}^2 + \hbar D(\mathbf{S}\,.\,\mathbf{n_s})^2 - \frac{\chi_\rho m}{2\mu_0}|B|^2 - g_s\frac{e\hbar}{2m_e}\vec{S}\cdot\overrightarrow{B}$$

$D = (2\pi) \times 2.87$ GHz $\qquad \chi_\rho \sim 6.9 \times 10^{-9}\mathrm{m}^3/\mathrm{Kg}$

Long Coherence Time Scale. (Gavin Morley's Group, Warwick) : T_2 : 780 micro seconds, and T_1 : 4.3 milli seconds (arXiv: 2301.10188)



Preferably single NV, close to the Centre of Mass
As pure a sample as possible

Other alternatives, e.g. Noble solids, etc.

Matter wave Interferometer

$$x^\mu = (-ct, x, y, z)$$



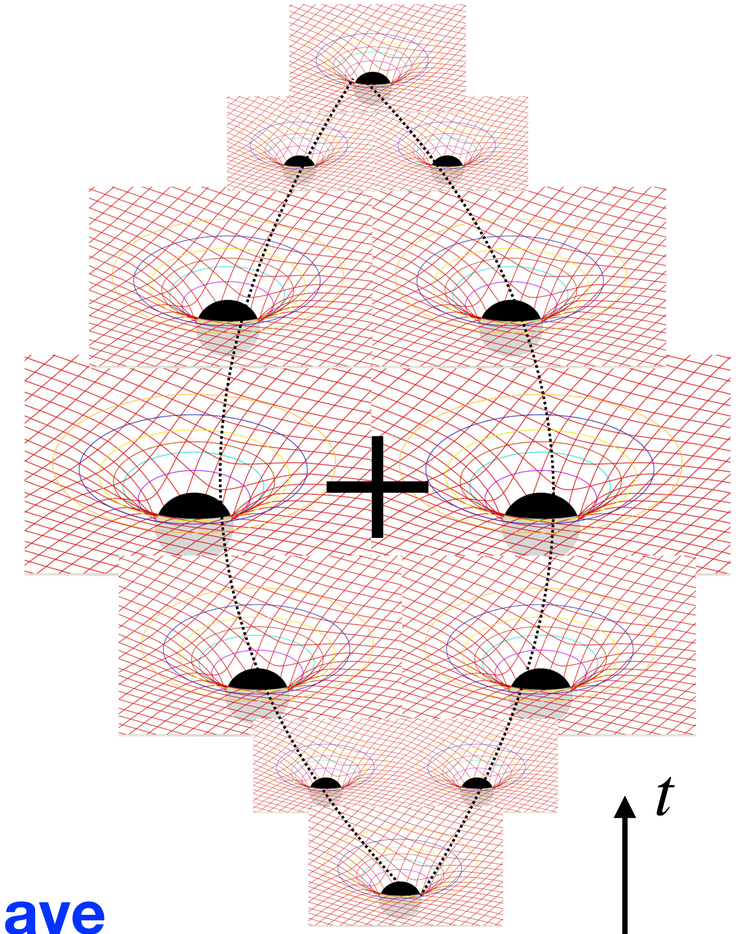
Fermi Normal Coordinates

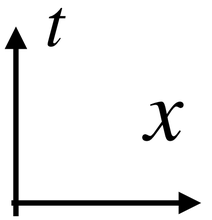
$$L = -mc^2\sqrt{-g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu},$$

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

$$g_{00} = -(1 + \frac{1}{2c^2}\frac{\partial h_{11}^2}{\partial t^2}|_{t=0}x^2)$$

$$\ddot{h}_{11} = 2c^2 R_{0101}$$





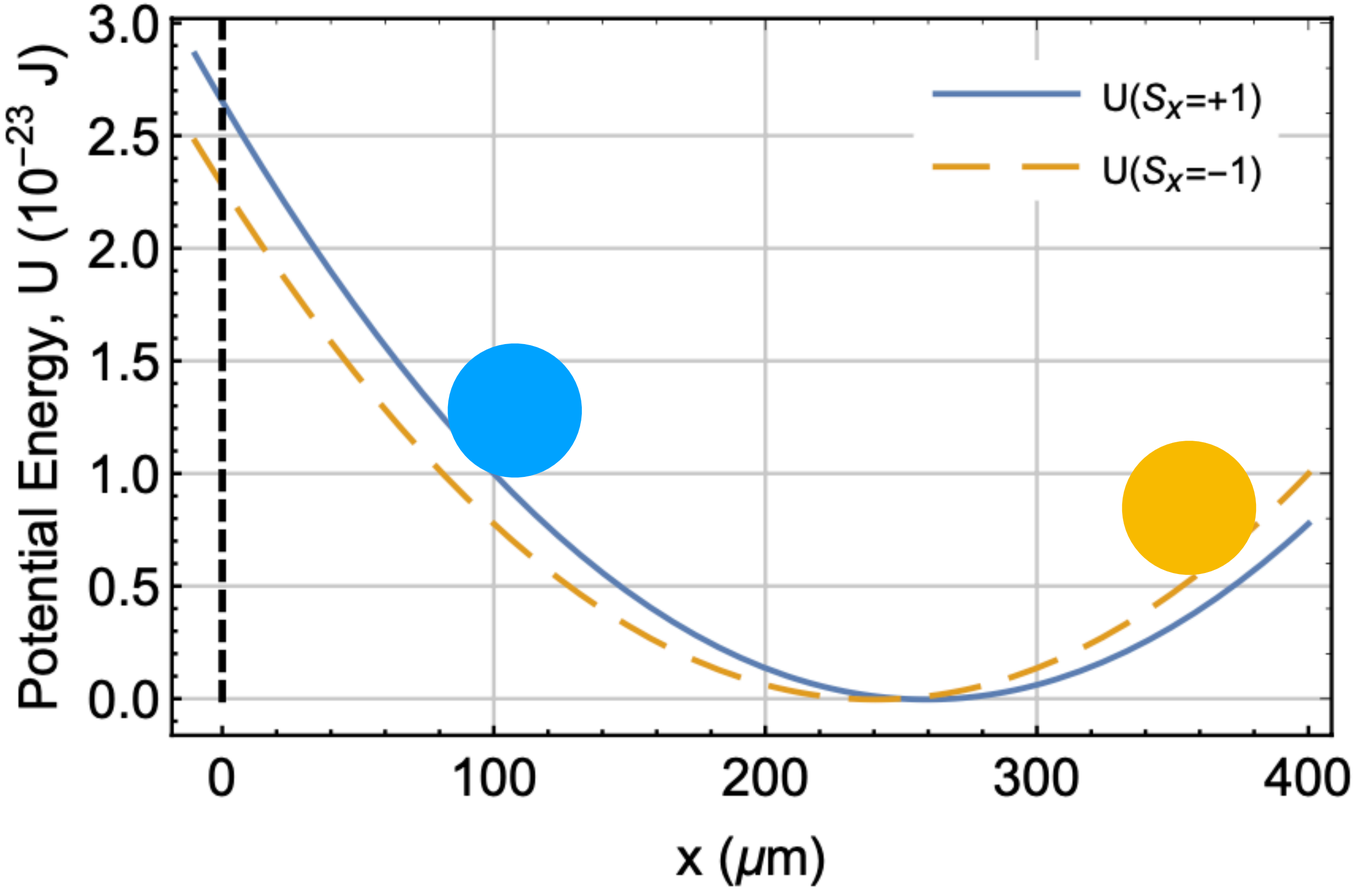
A freely falling observer would set in the vicinity all along the geodesic

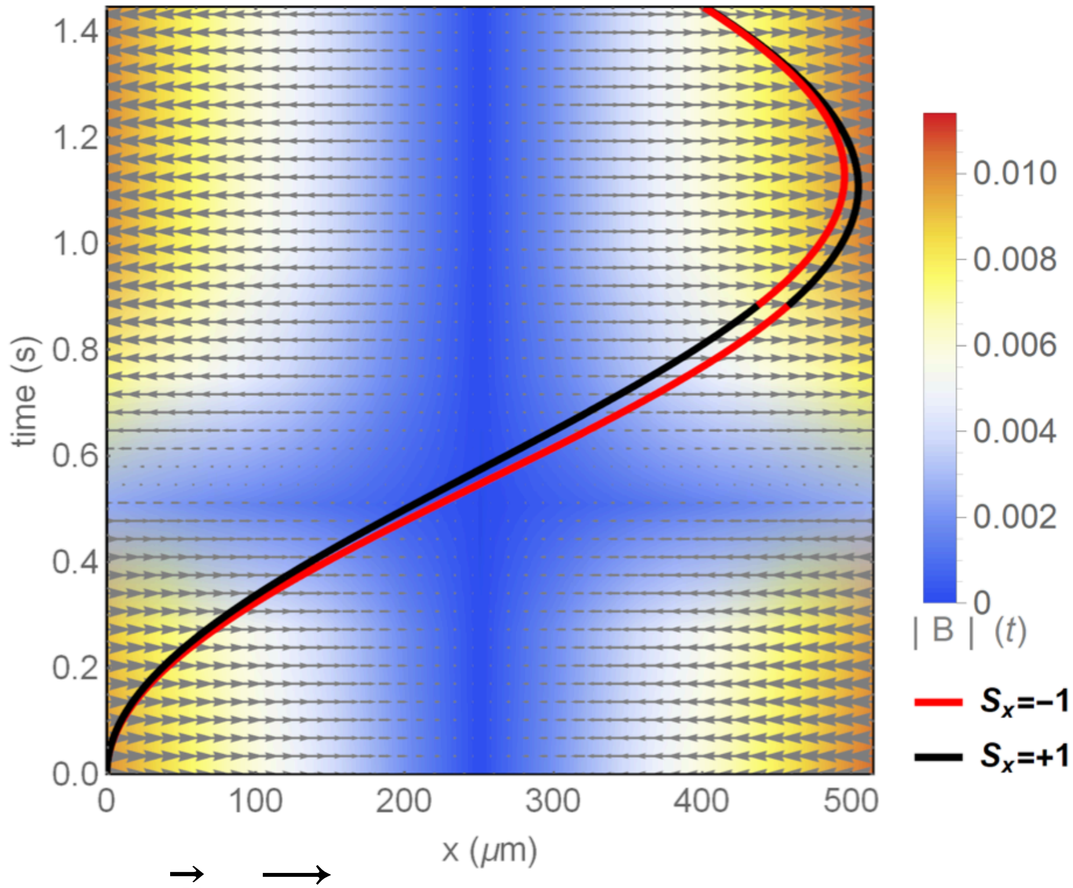
If matter is quantum, then we have operator valued $\hat{x}$, but it enforces

$\hat{g}_{\mu\nu}$, & $\hat{h}_{\mu\nu}$

Splitting the C.O.M motion in Stern Gerlach setup

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





To create superposition, we need entanglement $\sim \vec{S} \cdot \overrightarrow{B}$

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

One-loop Stern-Gerlach with Rb atoms

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

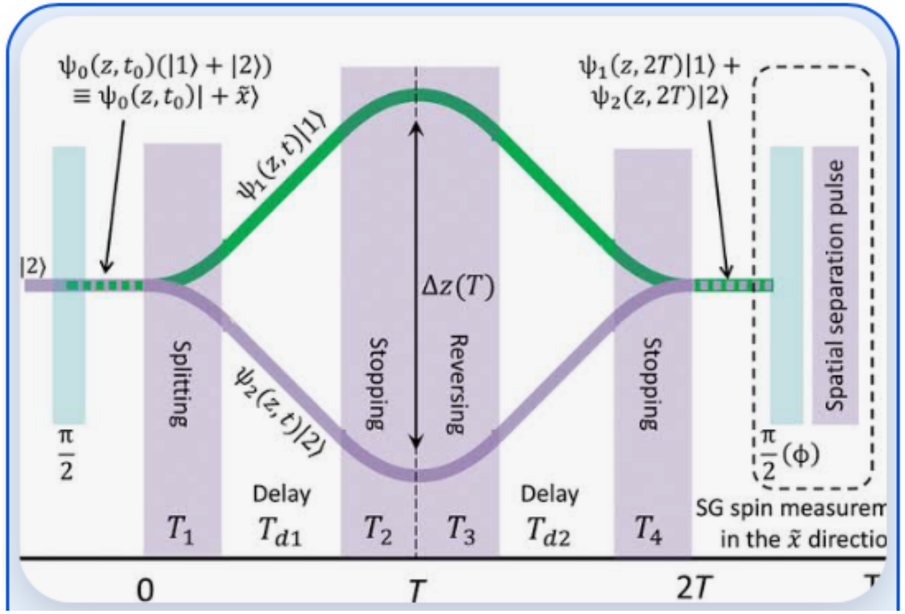
YAIR MARGALIT, OR DOBKOWSKI, ZHIFAN ZHOU, OMER AMIT, YONATHAN JAPHA, SAMUEL MOUKOURI, DANIEL ROHRLICH, ANUPAM MAZUMDAR, SOUGATO BOSE, [...], AND RON FOLMAN +1 authors Authors Info & Affiliations

SCIENCE ADVANCES • 28 May 2021 • Vol 7, Issue 22 • DOI: 10.1126/sciadv.abg2879

13,005 105

Abstract

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.



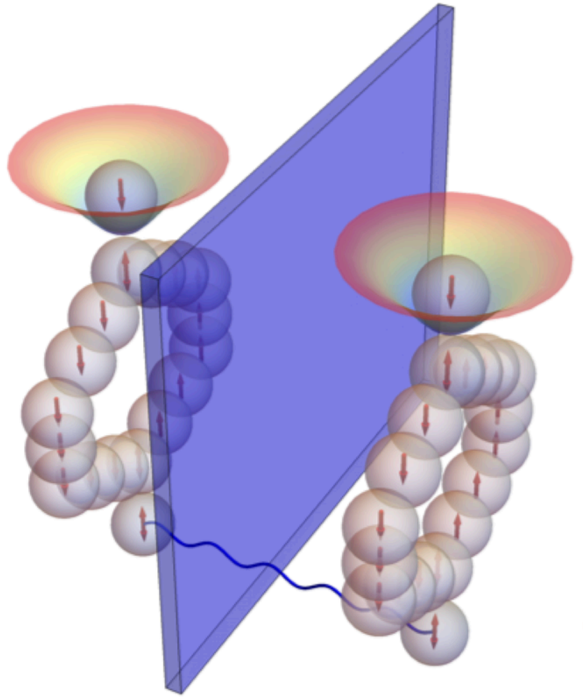
Technological development phase

- Vacuum requirements

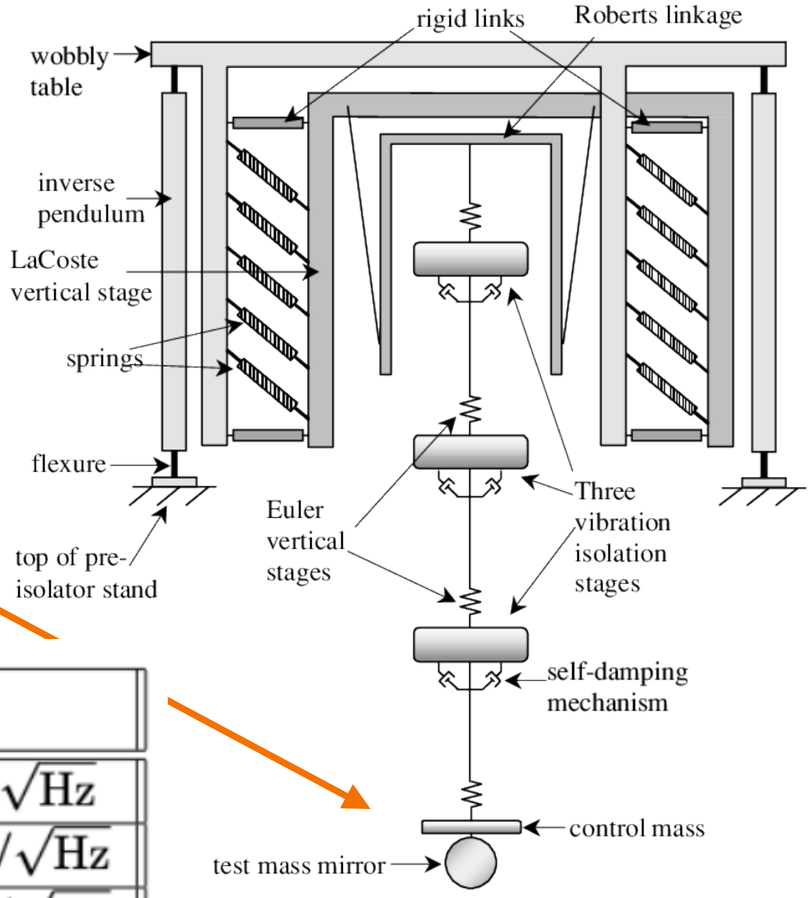
$P_{ext} \sim 10^{-13}\text{Pa}, \quad T_{ext} \sim 4\text{k}$

- Electromagnetic shielding

- Controlling decoherence



- Vibrational Isolation

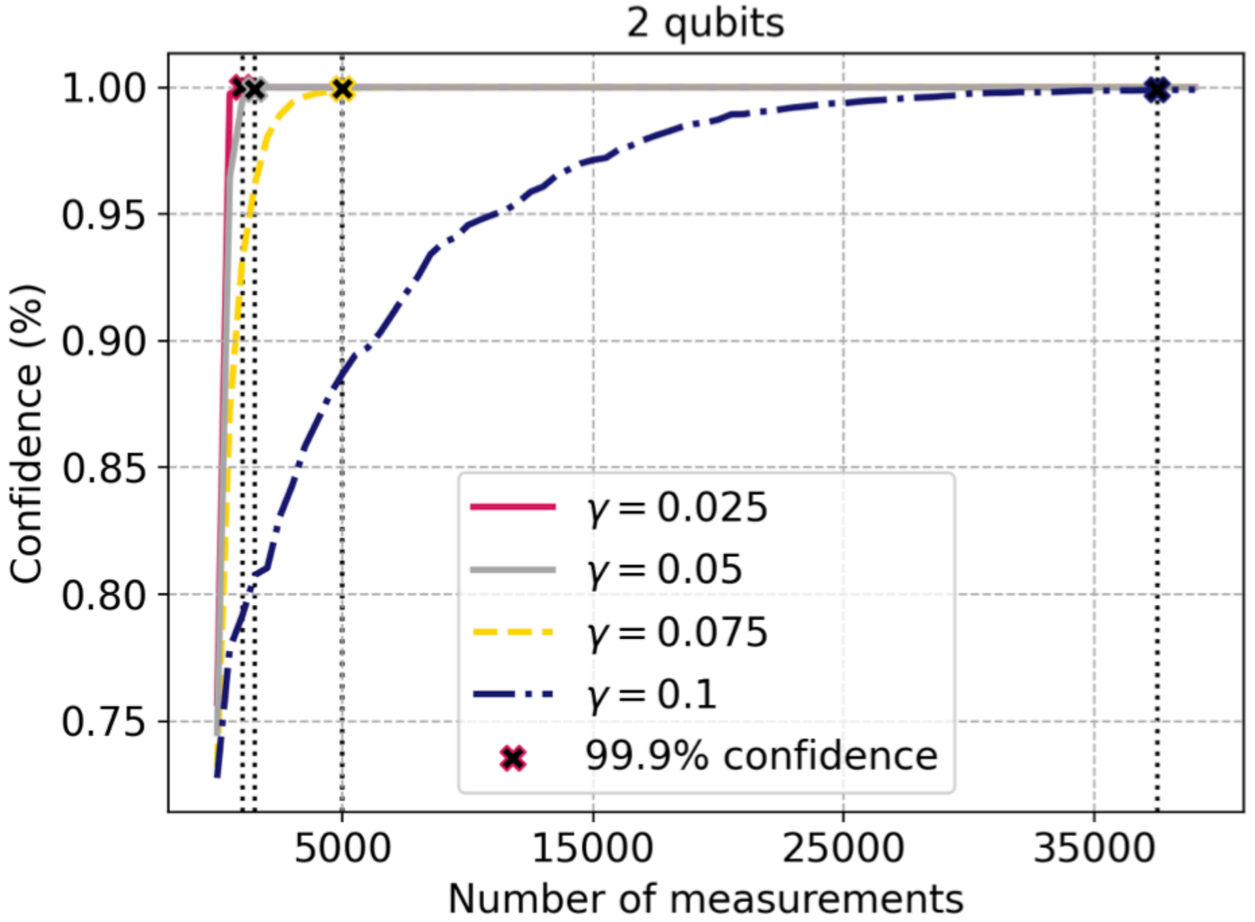


Δx	$\tau \geq 1/\Gamma$	p	$S_{aa}^{1/2}$	$S_{II}^{1/2}$	$S_{\eta\eta}^{1/2}$
10 fm	10μs	10^{-5}Pa	10^{-4} ms$^{-2}/\sqrt{\text{Hz}}$	$\text{A}/\sqrt{Hz}$	$10^{4}\text{Tm}^{-1}/\sqrt{\text{Hz}}$
10 pm	1 ms	10^{-8}Pa	10^{-7} ms$^{-2}/\sqrt{\text{Hz}}$	$10^{-2}\text{A}/\sqrt{Hz}$	$10^{-1}\text{Tm}^{-1}/\sqrt{\text{Hz}}$
10 nm	0.1 s	10^{-12}Pa	10^{-10} ms$^{-2}/\sqrt{\text{Hz}}$	$10^{-5}\text{A}/\sqrt{Hz}$	$10^{-4}\text{Tm}^{-1}/\sqrt{\text{Hz}}$
10 μm*	0.1-1 s	10^{-13}Pa	10^{-15}ms$^{-2}/\sqrt{\text{Hz}}$	$10^{-10}\text{A}/\sqrt{Hz}$	$10^{-9}\text{Tm}^{-1}/\sqrt{\text{Hz}}$

Extreme protection/isolation from the environment

QGEM: Decoherence & Statistical Inference

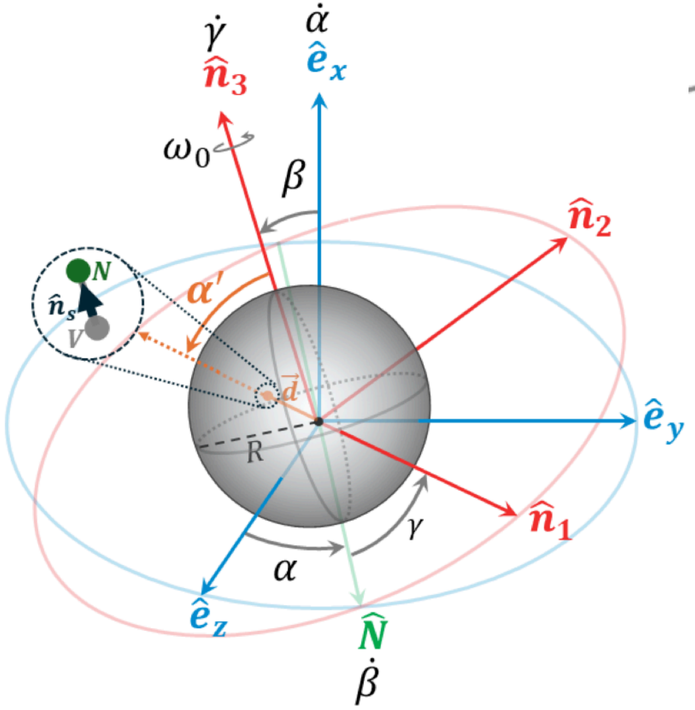
Γ	T	Δx	$n_v\ (\mathrm{m}^{-3})$	$P\ (\mathrm{Pa})$
0.01 Hz	1 mK	10 fm	$3 * 10^{21}$	$3.9 * 10^{-5}$
		10 pm	$3 * 10^{15}$	$3.9 * 10^{-11}$
		10 nm	$2 * 10^{10}$	$3.2 * 10^{-16}$
		10 µm	$2 * 10^{10}$	$3.1 * 10^{-16}$
0.05 Hz	1 K	10 fm	$4 * 10^{17}$	$6.1 * 10^{-6}$
		10 pm	$4 * 10^{11}$	$6.1 * 10^{-12}$
		10 nm	$4 * 10^{9}$	$4.9 * 10^{-14}$
		10 µm	$4 * 10^{9}$	$4.9 * 10^{-14}$
0.1 Hz	1 mK	10 fm	$3 * 10^{22}$	$3.9 * 10^{-4}$
		10 pm	$3 * 10^{16}$	$3.9 * 10^{-10}$
		10 nm	$2 * 10^{11}$	$3.2 * 10^{-15}$
		10 µm	$2 * 10^{11}$	$3.1 * 10^{-15}$
	1 K	10 fm	$9 * 10^{17}$	$1.2 * 10^{-5}$
		10 pm	$9 * 10^{11}$	$1.2 * 10^{-11}$
		10 nm	$7 * 10^{9}$	$9.7 * 10^{-14}$
		10 µm	$7 * 10^{9}$	$9.7 * 10^{-14}$
	4 K	10 fm	$1 * 10^{17}$	$6.1 * 10^{-6}$
		10 pm	$1 * 10^{11}$	$6.2 * 10^{-12}$
		10 nm	$4 * 10^{9}$	$1.9 * 10^{-13}$
		10 µm	$4 * 10^{9}$	$1.9 * 10^{-13}$

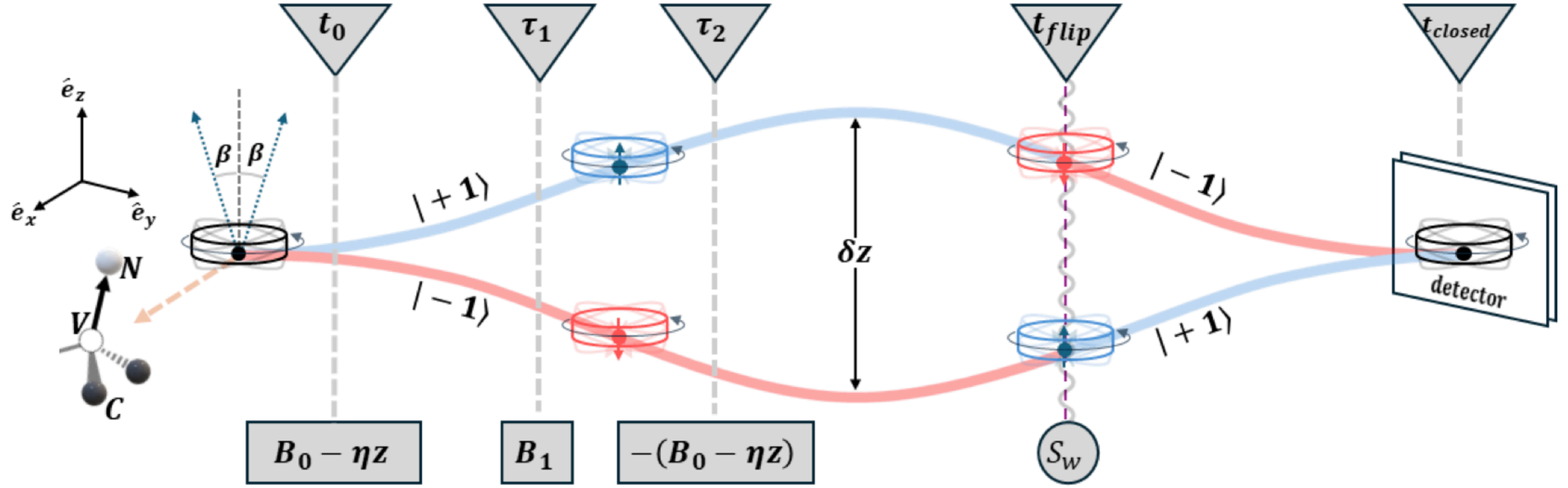


$$\langle \mathscr{W} \rangle = \mathrm{Tr}(\mathscr{W}\rho) = 2\gamma t - \Delta\phi_{ent} < 0$$

Schut, Andriolo, Toros, Bose, Mazumdar, 2410.20910 [quant-ph]

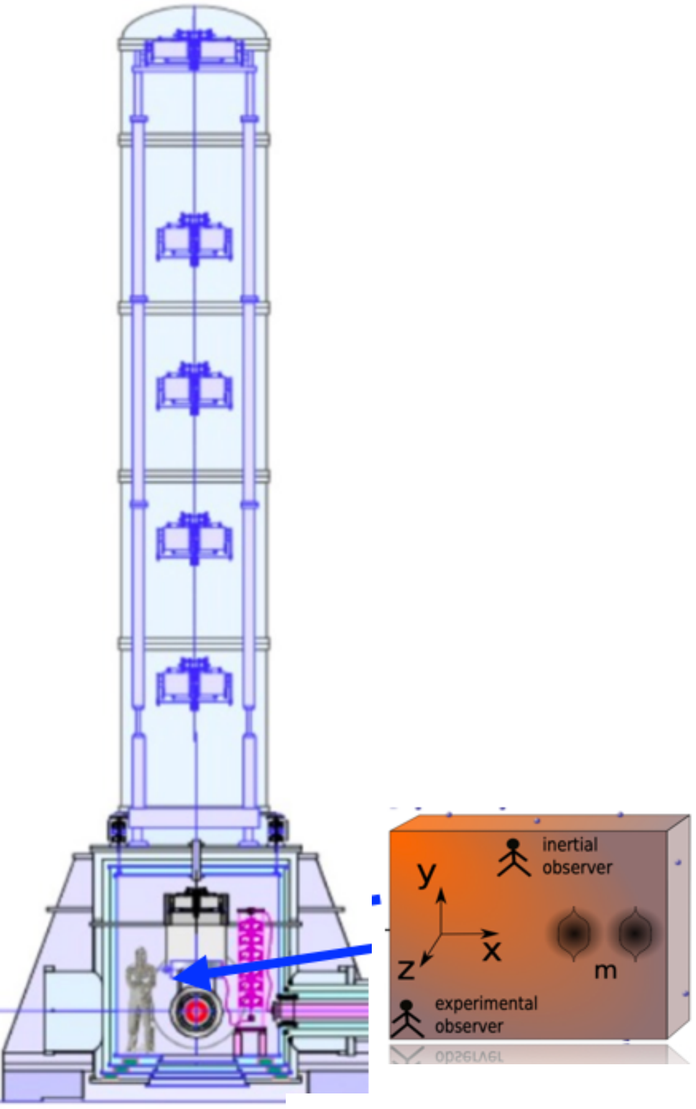
Gyroscopic Stability & Stern-Gerlach Sequence

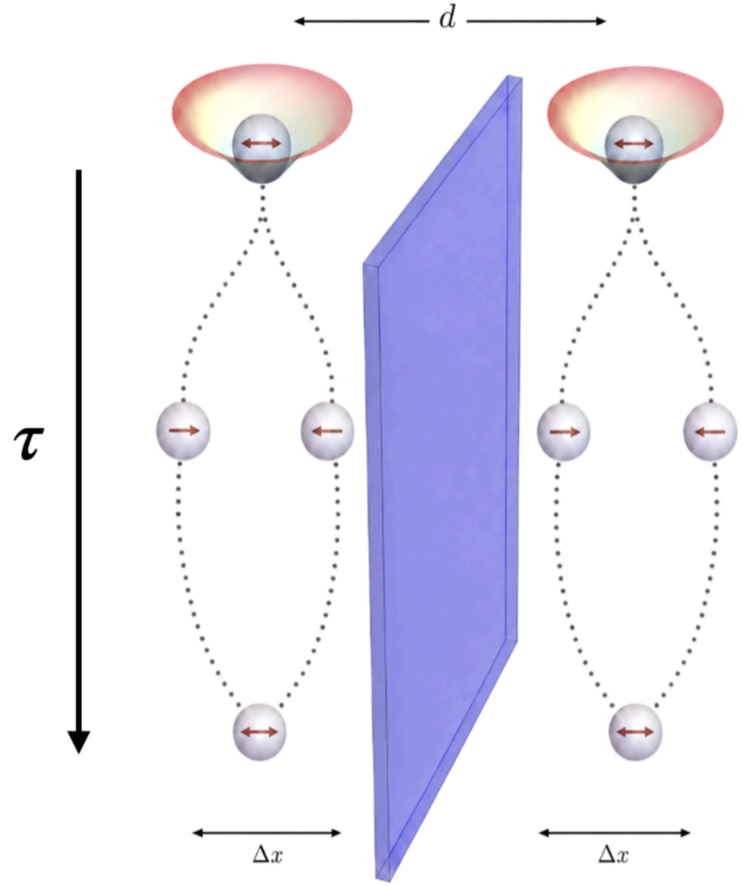




- Rizaldy, Mishra, Mazumdar 2603.05595 [quant-ph]
- Rizaldy, Zhou, Bose, Mazumdar, 2412.15335 [quant-ph]
- Zhou, Bose, Mazumdar, 2407.15813 [quant-ph]

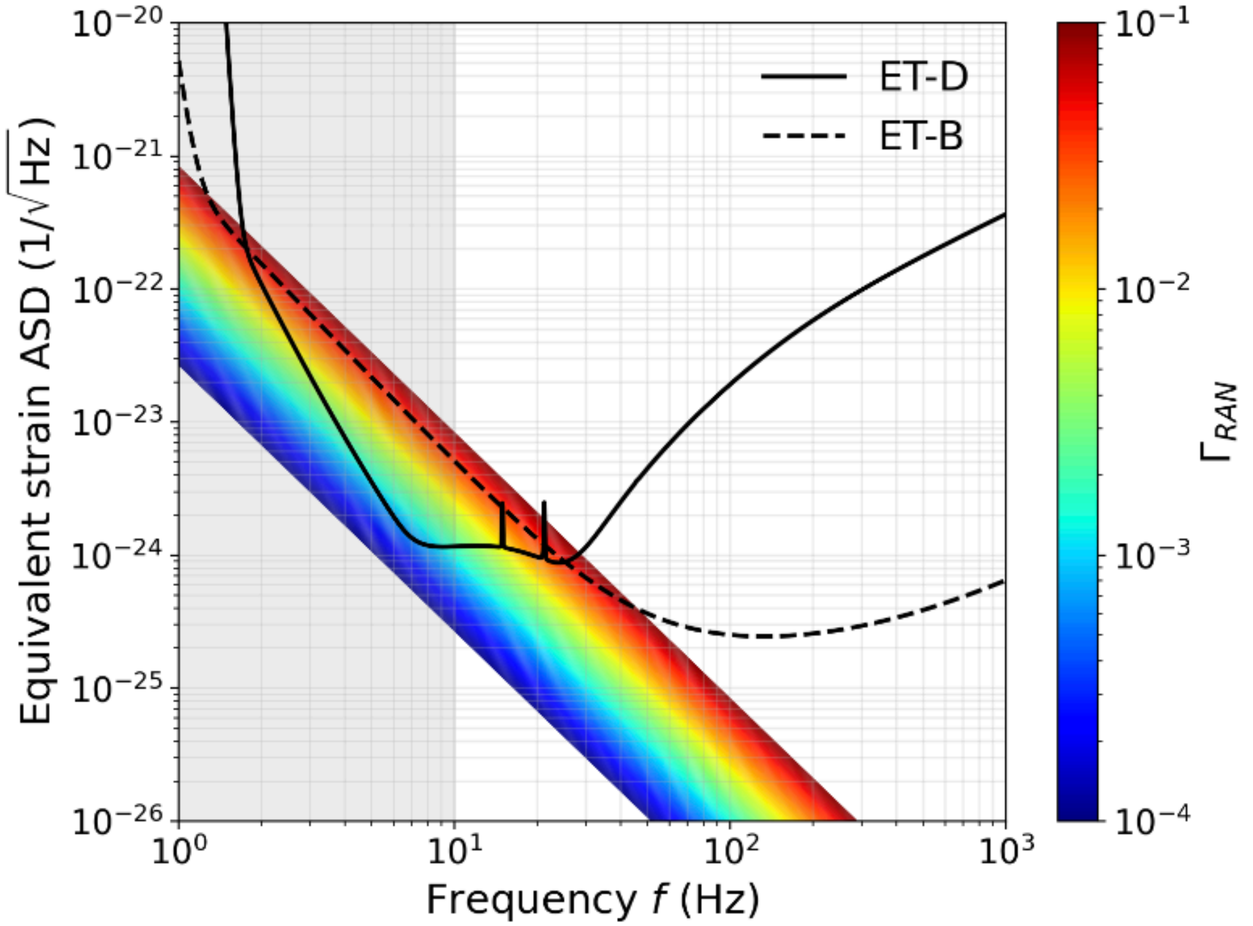
QGEM: Gravitational Wave Facility

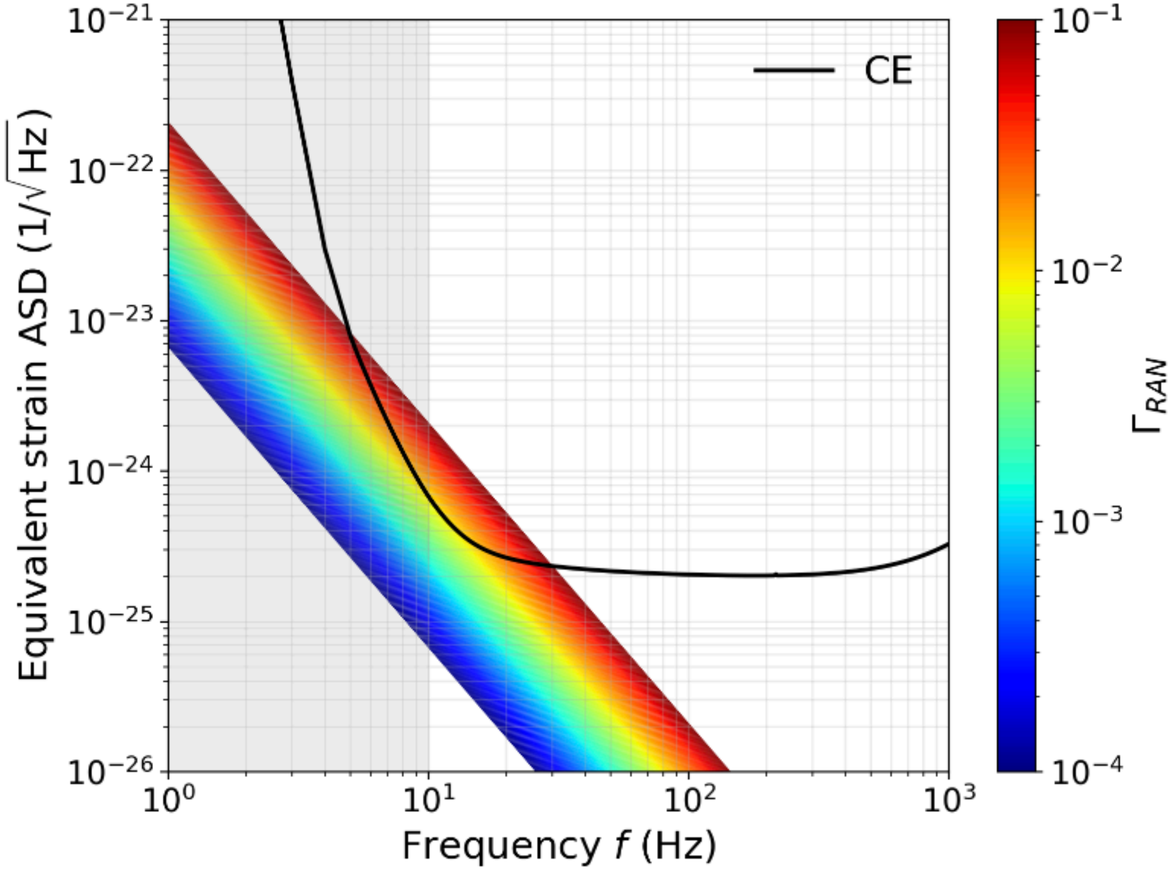




$$(S_{aa})^{1/2}_{\max} \approx 1.8 \times 10^{-16} \left(\frac{10^{-14}\mathrm{kg}}{m}\right) \left(\frac{10\mu\mathrm{m}}{\Delta x}\right) \left(\frac{1\mathrm{s}}{\tau}\right)^{1/2} \left(\frac{\Gamma_{\max}}{3.0 \times 10^{-2}}\right)^{1/2} \mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$$

QGEM: Gravitational Wave Facility





$$S_h^{1/2} = \frac{S_{aa}^{1/2}}{(2\pi f)^2 L} \approx \left(\frac{2.7\times10^{-22}}{\sqrt{\text{Hz}}}\right)\left(\frac{\Gamma_{RAN}}{0.01}\right)^{\frac{1}{2}}\left(\frac{10^{-14}\text{kg}}{m}\right)\left(\frac{10\mu\text{m}}{\Delta x}\right)\left(\frac{1\text{s}}{\tau}\right)^{\frac{1}{2}}\left(\frac{10\text{km}}{L}\right)\left(\frac{1\text{Hz}}{f}\right)^2$$

White paper: 1-10 Hz matter-wave interferometer to test the spin entanglement witness for quantum gravity

Sougato Bose[1], Anupam Mazumdar[2,3,*] Marko Toroš[4], Tian Zhou[2], Agya Sewara Alam[2], Peter F. Barker[1], Angelo Bassi[5], Ettore Bernardi[6], Guri K. Buza[4], Yanbei Chen[7], Ralph Jason Costales[1], Álvaro de la Cruz-Dombriz[8], Catalina Curceanu[9], Debarshi Das[10], Saurya Das[11], Pratika Dayal[3], Subhadeep De[12], Brian D'Urso[13], Ema Dimastrogiovanni[2], Or Dobkowski[14], Kemal Doener[15], Gurudev Dutt[16], Shafaq Gulzar Elahi[17], Omer Feldman[14], Fabiano Feleppa[18,19], Ron Folman[14], Giulio Gasbarri[20], Marco Genovese[21], Andrew Geraci[17], Menachem Givon[14], Jonathan M.H. Gosling[1], David Groswasser[14], Bas Hensen[22], Dipankar Home[23], Yonathan Japha[14], Eva Kilian-Rademacher[1], Adrian Kent[24], Myungshik S. Kim[25], Timothy Kovachy[17], Gaetano Lambiase[18], Naor Levi[14], Adrian Lupascu[26], Aaron G. Markowitz[27], Chiara Marletto[28], J. D. D. Martin[26], Gavin W. Morley[29], Maria Muretova[14], Robin Oberfrank[26,30], Matteo G. A. Paris[31], Mauro Paternostro[32], Fabrizio Piacentini[21], Tanmay Kumar Poddar[33], Sofia Qvarfort[34,35], Markus Rademacher[1], Anna Chiara Rescigno[18,19], Ryan Rizaldy[2], Carlos Sabín[36], Barry C. Sanders[37], Martine Schut[38], Helen M Sheehy[2], Peter Skakunenko[14], Hendrik Ulbricht[39], Vlatko Vedral[40], Giuseppe Filiberto Vitale[18], Qian Xiang[2], and Magdalena Zych[35]

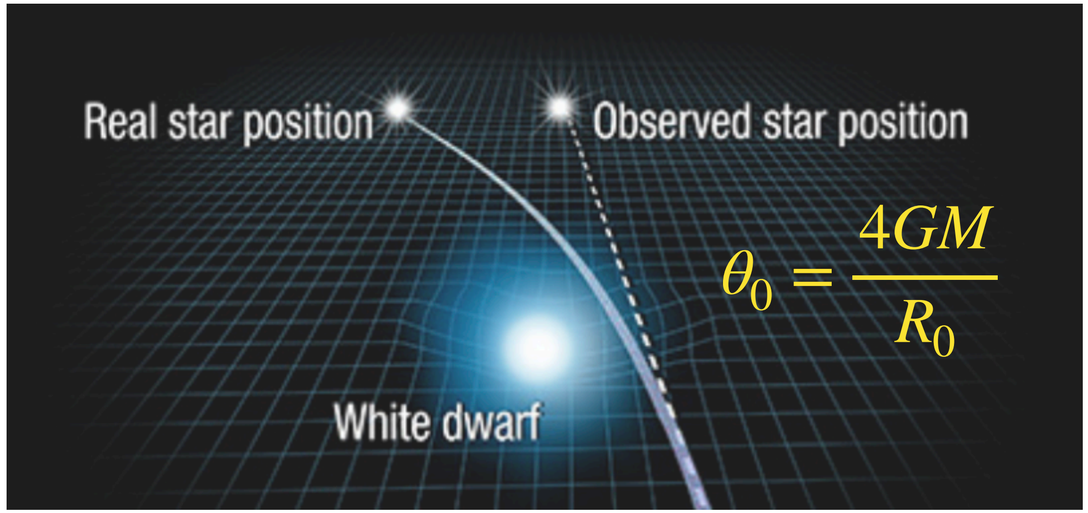
[1] *Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*

[2] *Van Swinderen Institute, University of Groningen, Nijenborg 3, 9747 AG Groningen, The Netherlands*

[3] *Canadian Institute for Theoretical Astrophysics, 60 St George St, University of Toronto,*

Matter-photon entanglement via graviton

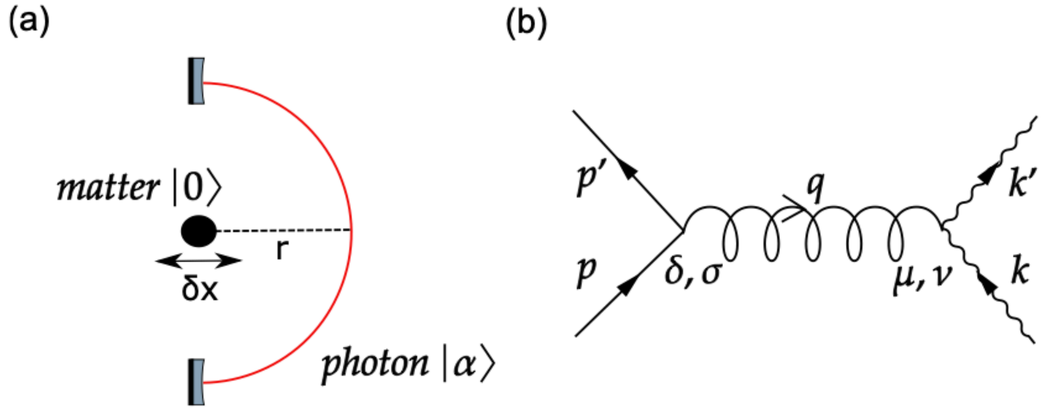
Gravitational Lensing: Only GR produces the right light bending



$$\hat{V} = -\frac{2Gm\omega}{r}\varepsilon^*(k')\cdot\varepsilon(k)$$

$$\hat{V} = -g_0(\hat{b}+\hat{b}^\dagger)\hat{a}^\dagger\hat{a} \qquad g_0 = \frac{4Gm\omega}{r^2(2m\omega_{\rm m})^{1/2}}$$

Opto-mechanical coupling



Biswas, Bose, Mazumdar, Toros, 2209.09273 [gr-qc]
Biswas, Bose, Mazumdar, Toros, 2606.09991 [quant-ph]

Peta-Watt Laser

10 Kg mass in a ground state $\Delta x \sim \mathcal{O}(\text{cm})$

$\omega_m\tau \sim \pi \qquad \tau \sim \text{ms} \qquad r \sim \mathcal{O}(10)\text{cm}$

$$S_{\rm max} = \frac{4g_0^2|\alpha|^2}{\omega_m^2}$$

Quantum Gravity & BSM Tests

- You can test the quantum entanglement and the equivalence principle,
  See: 2203.11628 [gr-qc], 2310.06899 [gr-qc]

- You can test the massive graviton hypothesis in an AdS extra dimension, and the string scale $\sim 10^7 \mathrm{GeV}$,
  See: 2303.07371 [gr-qc]

- The most decisive test for quantum gravity comes from the entanglement between matter and a photon due to the graviton exchange
  See: 2209.09273 [gr-qc]

- Beyond the Standard Model Discovery, see: Barker, Bose, Marshman, Mazumdar, PRD (2022)

QGEM White paper

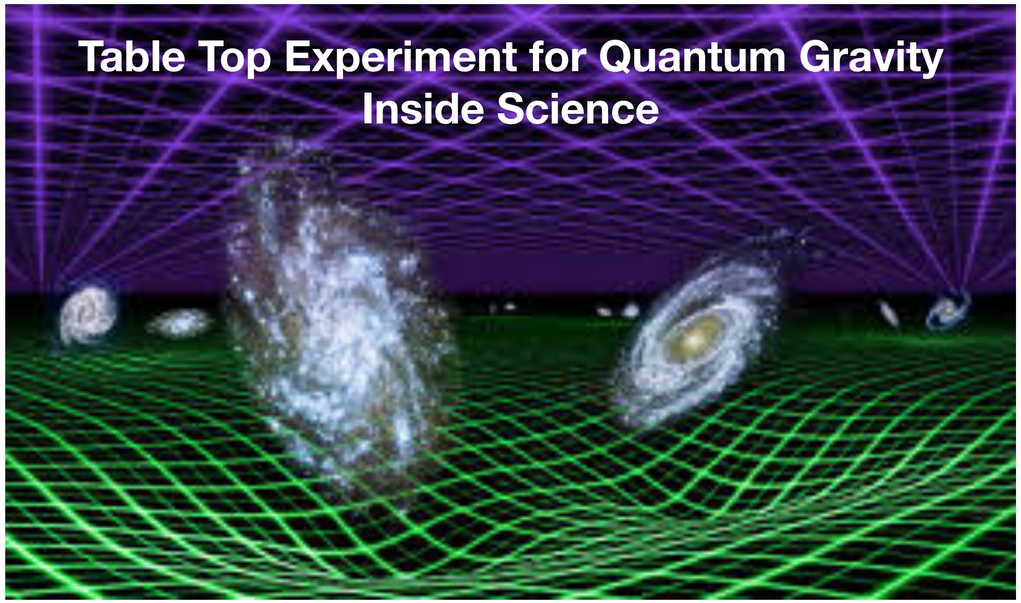
A Spin-Based Pathway to Testing the Quantum Nature of Gravity

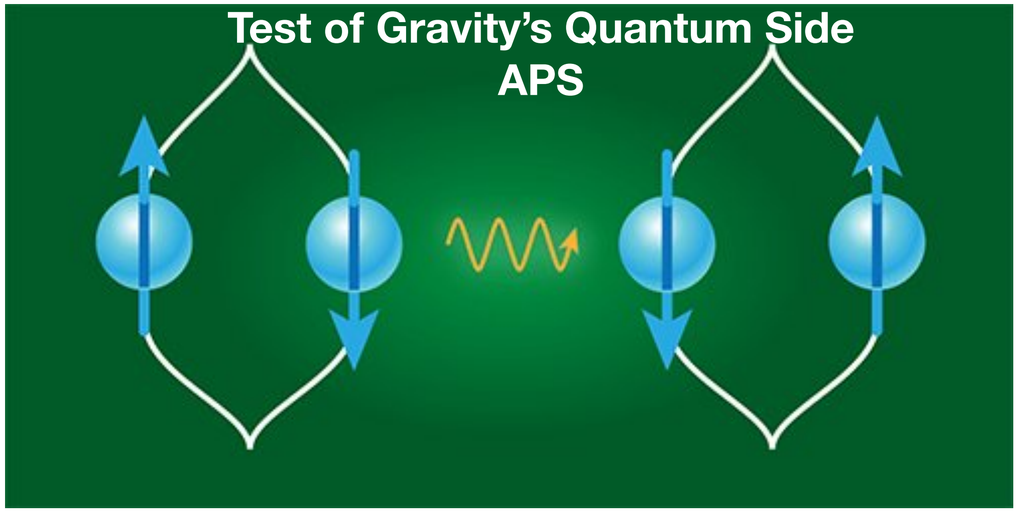
Sougato Bose*[1], Anupam Mazumdar[2], Roger Penrose[3], Ivette Fuentes[4,5], Marko Toroš[6], Ron Folman[7], Gerard J. Milburn[8], Myungshik Kim[9], Adrian Kent[10,11], A. T. M. Anishur Rahman[12], Cyril Laplane[13], Aaron Markowitz[14], Debarshi Das[1,15], Ethan Campos-Méndez[4], Eva Kilian[1], David Groswasser[7], Menachem Givon[7], Or Dobkowski[7], Peter Skakunenko[7], Maria Muretova[7], Yonathan Japha[7], Naor Levi[7], Omer Feldman[7], Damián Pitalúa-García[10], Jonathan M.H. Gosling[1], Ka-Di Zhu[16], Marco Genovese[17], Kia Romero-Hojjati[4], Ryan J. Marshman[1], Markus Rademacher[1], Martine Schut[18], Melanie Bautista-Cruz[19], Qian Xiang[2], Stuart M. Graham[12], James E. March[12], William J. Fairbairn[12], Karishma S. Gokani[12], Joseph Aziz[20], Richard Howl[20], Run Zhou[2], Ryan Rizaldy[2], Thiago Guerreiro[21], Tian Zhou[2], Jason Twamley[22], Chiara Marletto[19], Vlatko Vedral[19], Jonathan Oppenheim[1], Mauro Paternostro[23], Hendrik Ulbricht[4], Peter F. Barker[1], Thomas P. Purdy[24], M. V. Gurudev Dutt[24], Andrew A. Geraci[25], David C. Moore[14,26], and Gavin W. Morley†[12]

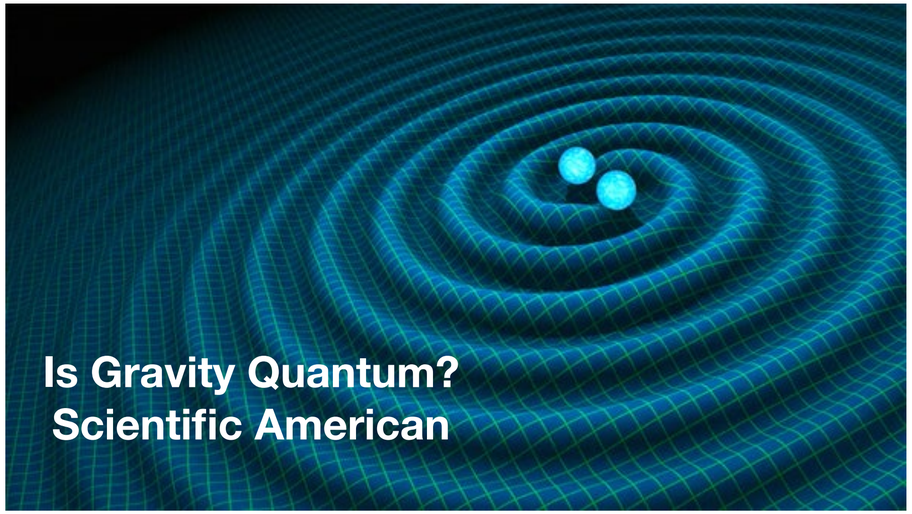
[1] *Department of Physics and Astronomy, University College London, Gower Street, WC1E 6BT London, UK*
[2] *Van Swinderen Institute, University of Groningen, 9747 AG, The Netherlands*
[3] *Mathematical Institute, Andrew Wiles Building, University of Oxford, Radcliffe Observatory Quarter, Woodstock Road, Oxford, OX2 6GG, UK*
[4] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK*
[5] *Keble College, University of Oxford, Oxford OX1 3PG, UK*
[6] *Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, SI-1000 Ljubljana, Slovenia*
[7] *Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

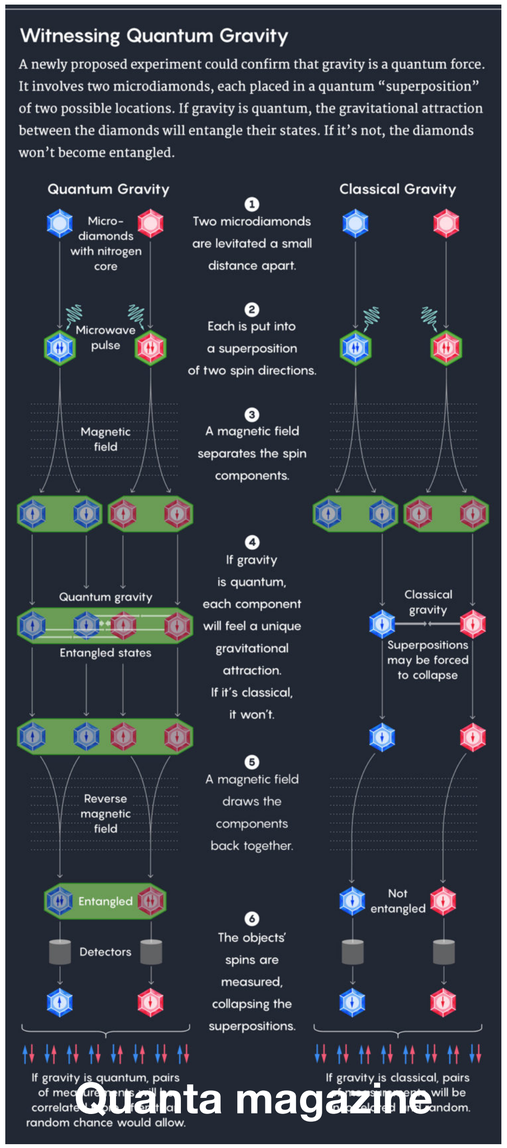
[quant-ph] 1 Sep 2025









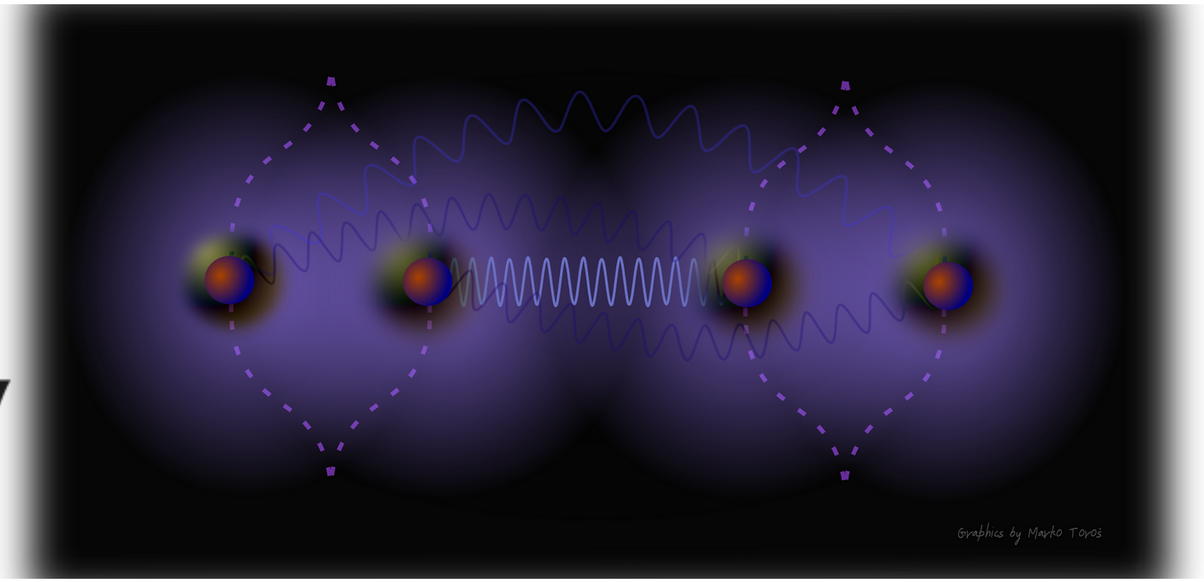


Quantum Gravity meets Quantum Information/Technologies,
Particle Physics, Condensed Matter, Material Science, Laser Physics,
Cosmic Ray Physics, … , essentially connect every branch of physics

nature › research highlights › article

RESEARCH HIGHLIGHT | 11 November 2024

Two places at once: superposed crystal could test whether gravity obeys quantum laws



Method could probe whether a key tenet of quantum mechanics applies to gravity, which has so far resisted quantum theory.

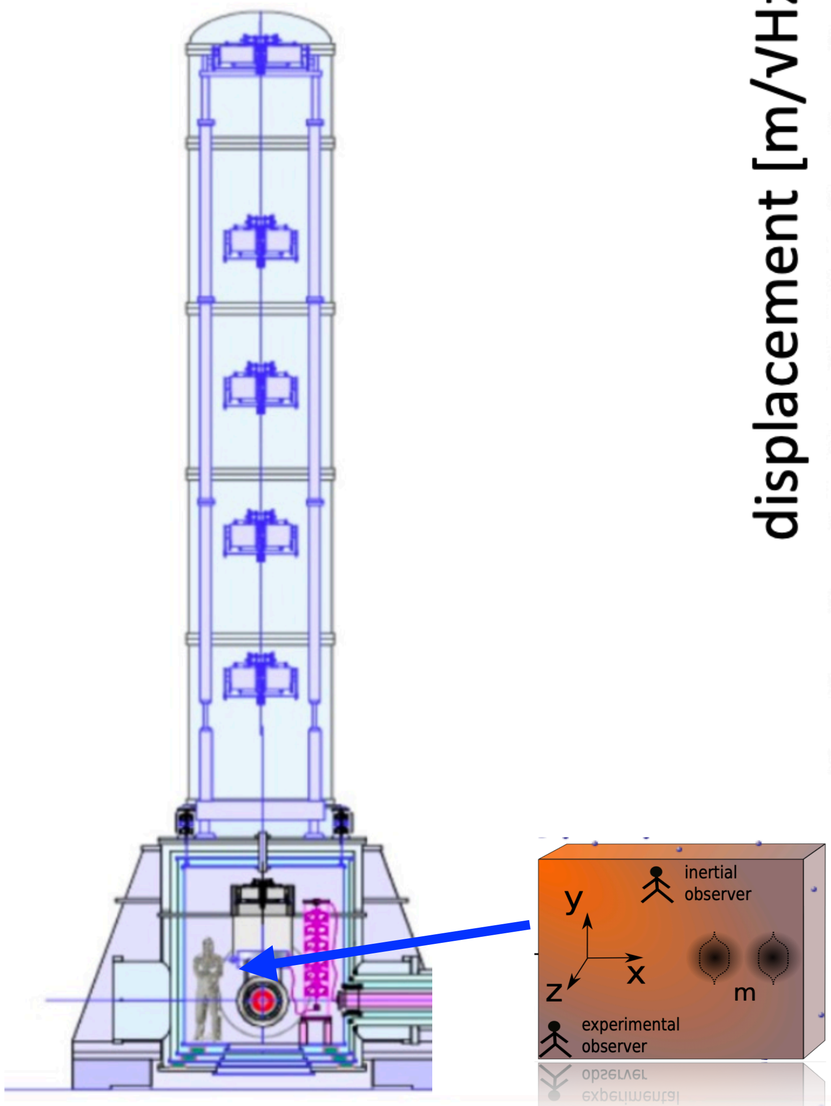
Community effort: join us in this highly disruptive, ambitious technology to understand spacetime

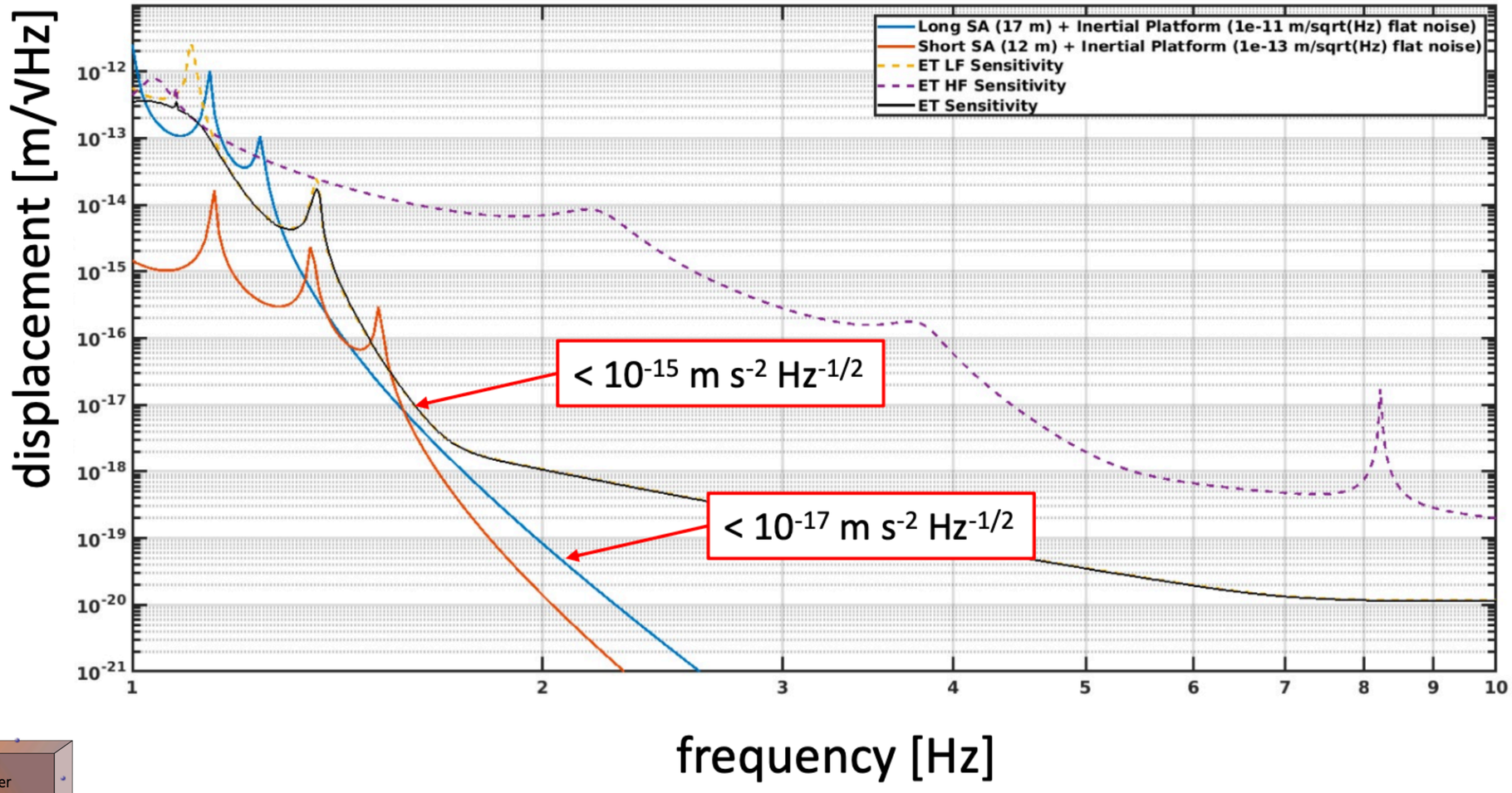
mazumdar@cita.utoronto.ca, anupam.mazumdar@utoronto.ca



Extra Slides

QGEM: Gravitational Wave Facility





1-10 Hz sensitivity is extremely hard to achieve:
We are working towards this goal

Quantum gravity from experimental perspective

- At low energies, a massless **spin-2 graviton** can be quantised canonically (e.g. **Bernstein**, **Gupta, Feynman, Kibble, Weinberg**, **Donoghue, Bern,** and many others). Any feasible experiment takes place around such a **weak background**.

- Quadratic curvature gravity in (1+3)d is renormalisable; it has other problems related to ghosts, but it is power-counting renormalisable. See **Stelle's gravity**.

- String theory (the most consistent theory of quantum gravity) has presumably no UV divergences, and at low energies it reproduces the results of the effective field theory of quantum gravity in 4d

- Non-perturbative quantum gravity aims to understand the UV, with no divergences, but at low energies, there is no satisfactory understanding, in my opinion

Experimental verifications are lacking; even spin-2 graviton as a quantum entity has not been verified in any experiment

Some of the Team Members

Helen Sheheey, Martine Schut, Tian Zhou, Qian Xiang, Agya Alam, Ryan Ryzaldy

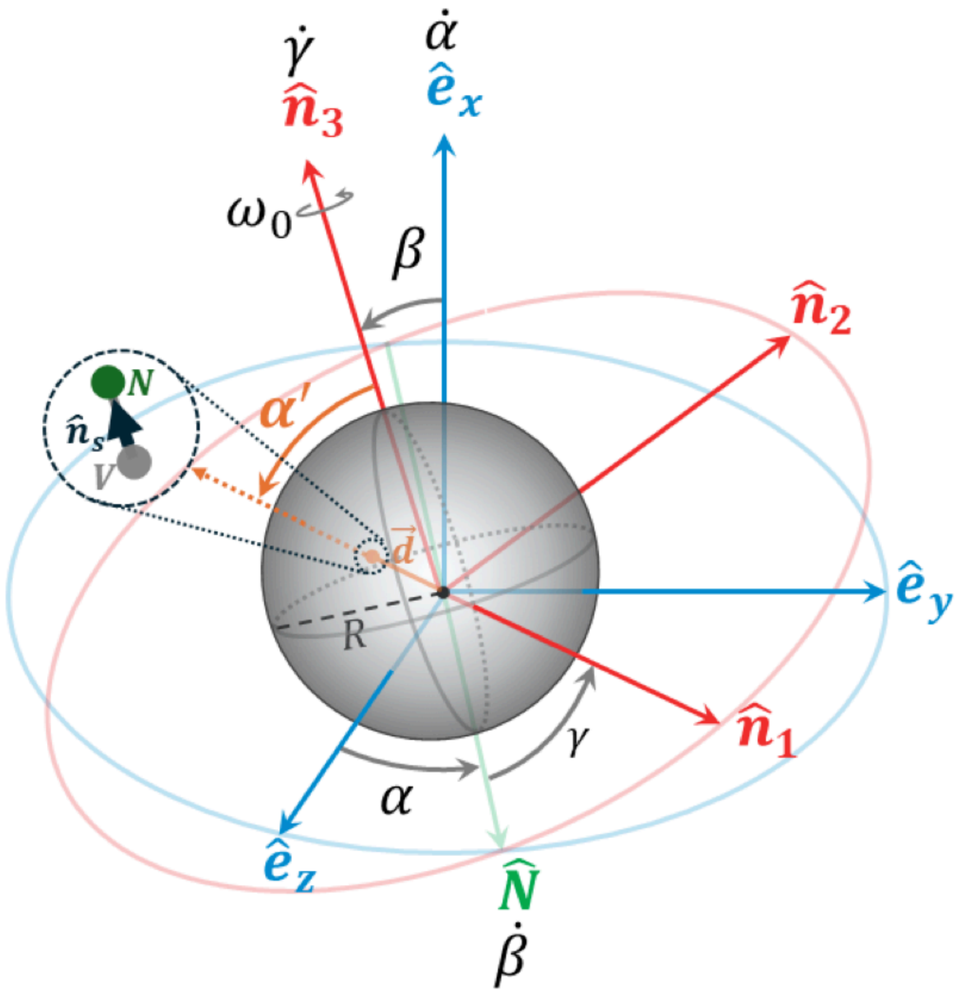


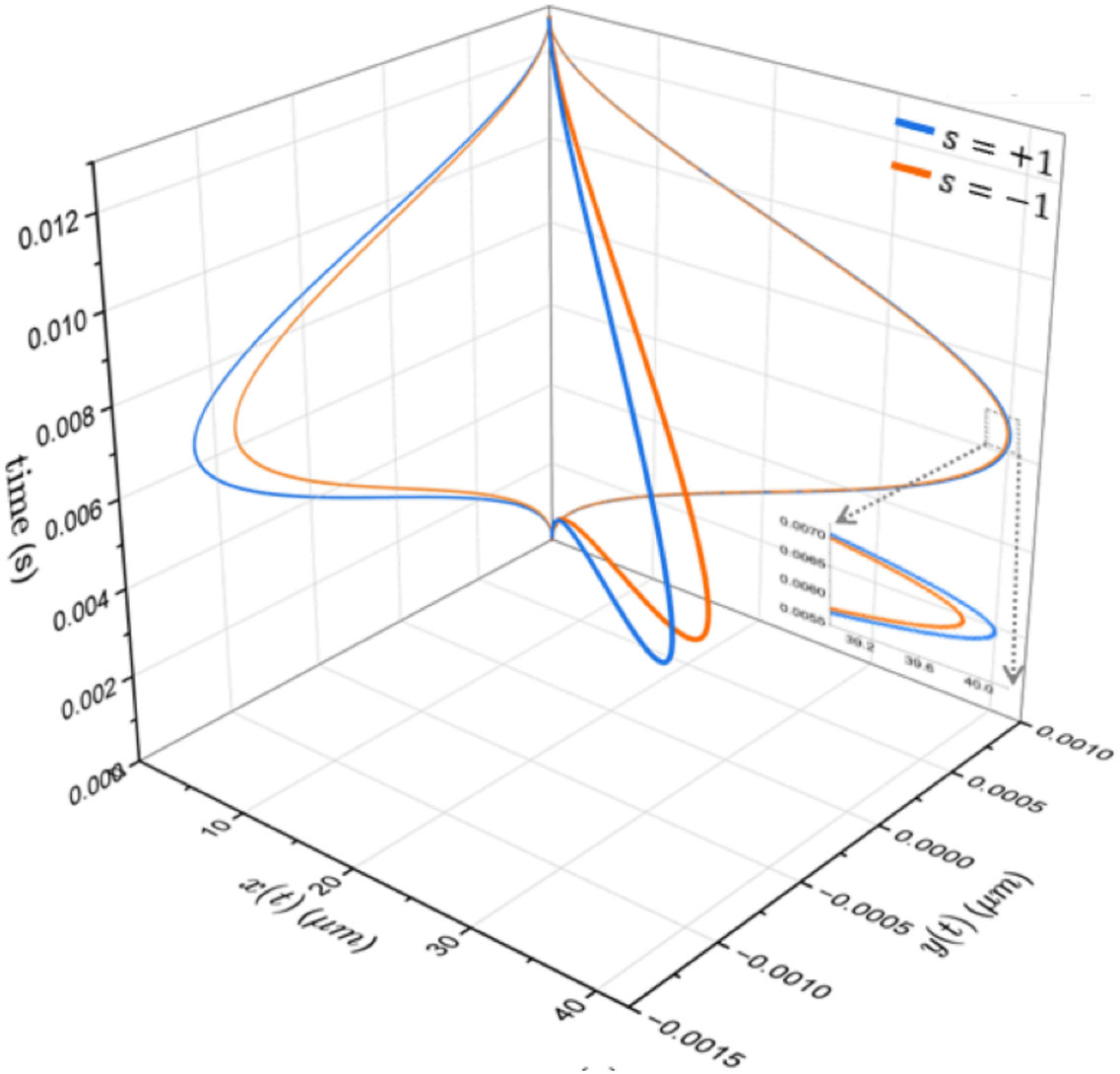
MAST-QG (PI’s)



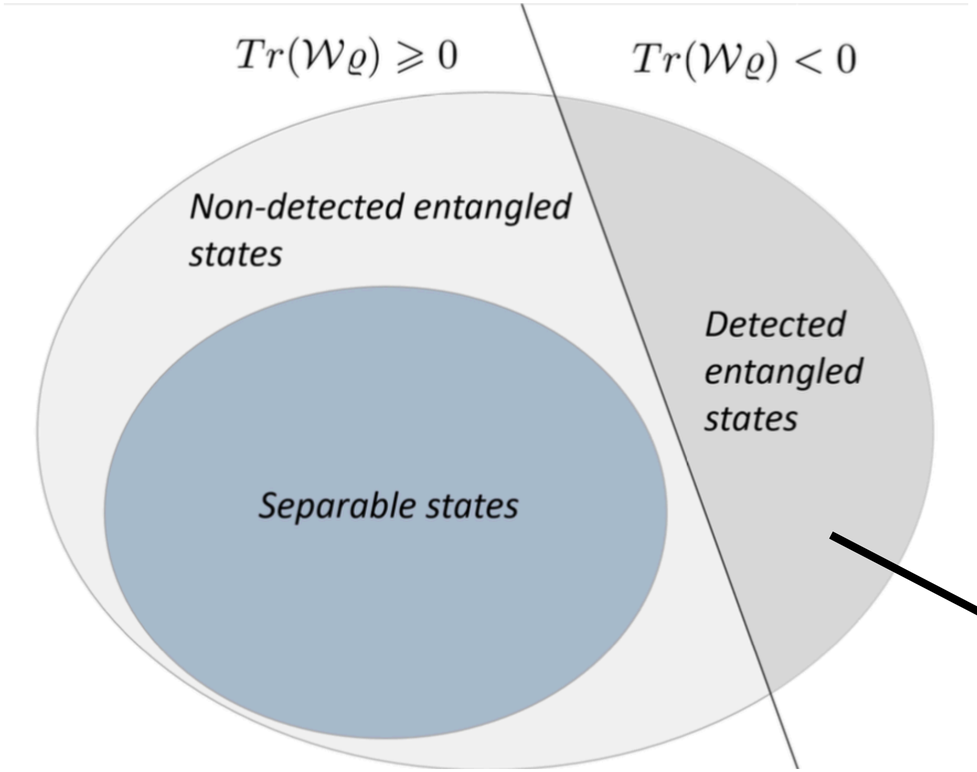
Andy Geraci (Northwestern), Sougato Bose (UCL), Dave Moore (Yale), Gavin Morley (Warwick)

Gyroscopic Stability & 2-dim Superposition





Entanglement Witness: Spin Correlation



System-1



System-2



Positive Partial Transpose Witness

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

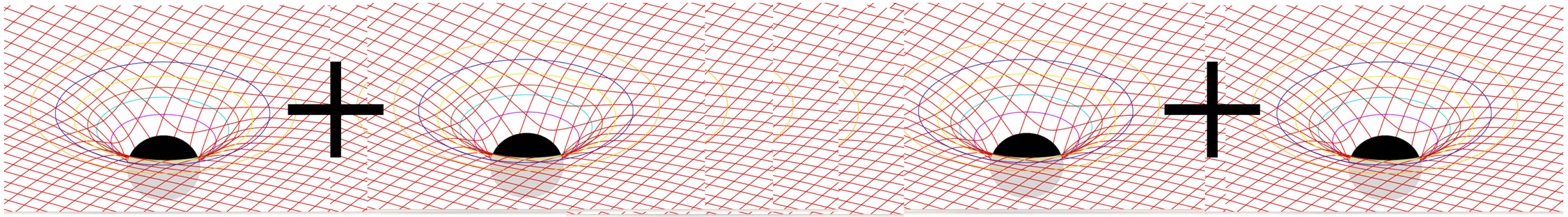
$$\langle \mathscr{W} \rangle = \mathrm{Tr}(\mathscr{W}\rho) = 2\gamma t - \Delta\phi_{ent} < 0$$

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

QGEM protocol

Alice

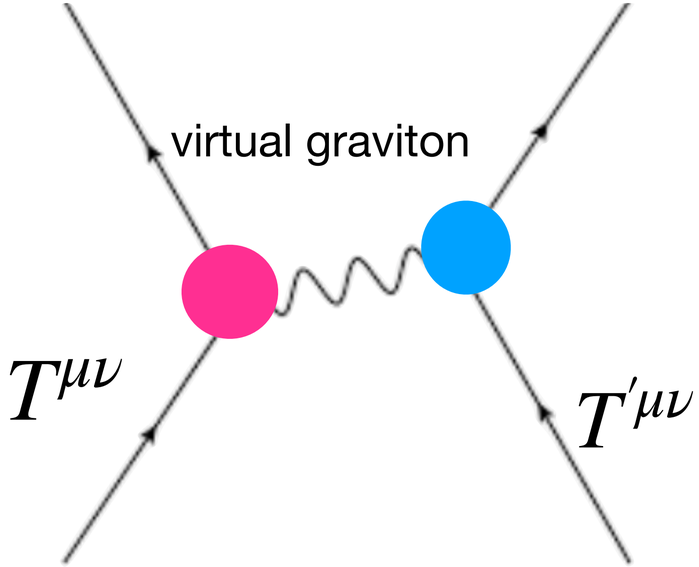
Bob



Curvature and matter are entangled in Alice's experiment

Curvature and matter are entangled in Bob's experiment

Integrate the curvature (graviton propagator): Alice and Bob are entangled



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

$$G_{\mu\nu\alpha\beta} = \left[\frac{P^2_{\mu\nu\alpha\beta}}{k^2} - \frac{P^0_{\mu\nu\alpha\beta}}{2k^2}\right] = \frac{1}{2k^2}\left[\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha} - \eta_{\mu\nu}\eta_{\alpha\beta}\right]$$

Matter wave Interferometer

$$x^\mu = (-ct, x, y, z)$$



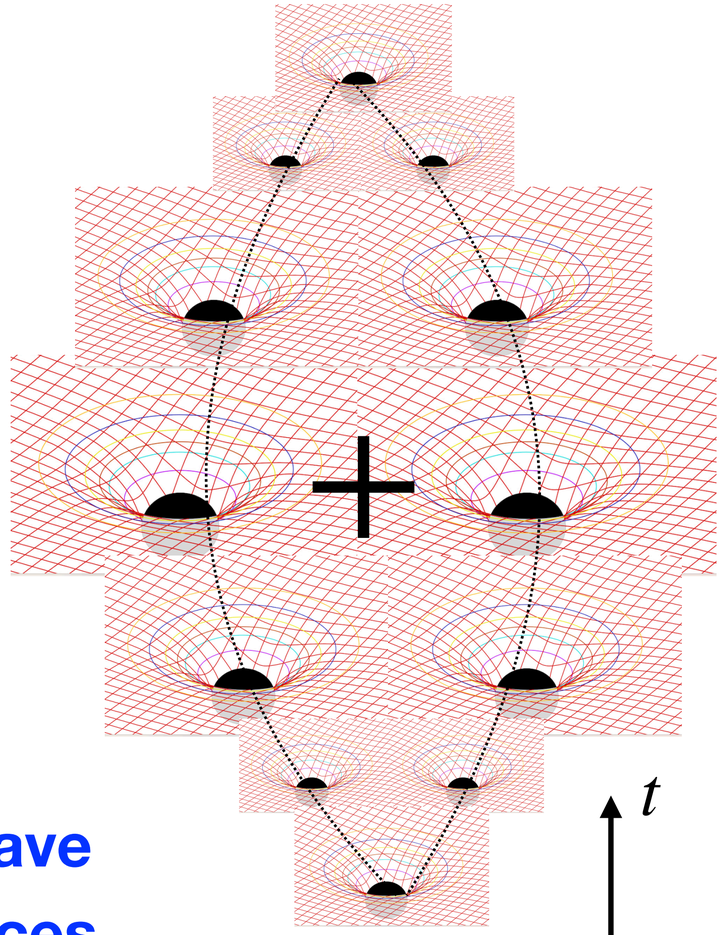
Fermi Normal Coordinates

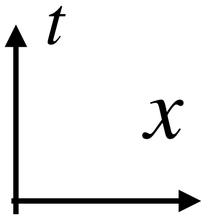
$$L = -mc^2\sqrt{-g_{\mu\nu}\dot{x}^\mu\dot{x}^\nu},$$

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

$$g_{00} = -(1 + \frac{1}{2c^2}\frac{\partial h_{11}^2}{\partial t^2}|_{t=0}x^2)$$

$$\ddot{h}_{11} = 2c^2 R_{0101}$$





A freely falling observer would set in the vicinity all along the geodesic

If matter is quantum, then we have operator valued $\hat{x}$, but it enforces $\hat{g}_{\mu\nu}$, & $\hat{h}_{\mu\nu}$

Semi-classical vs. Quantum Gravity

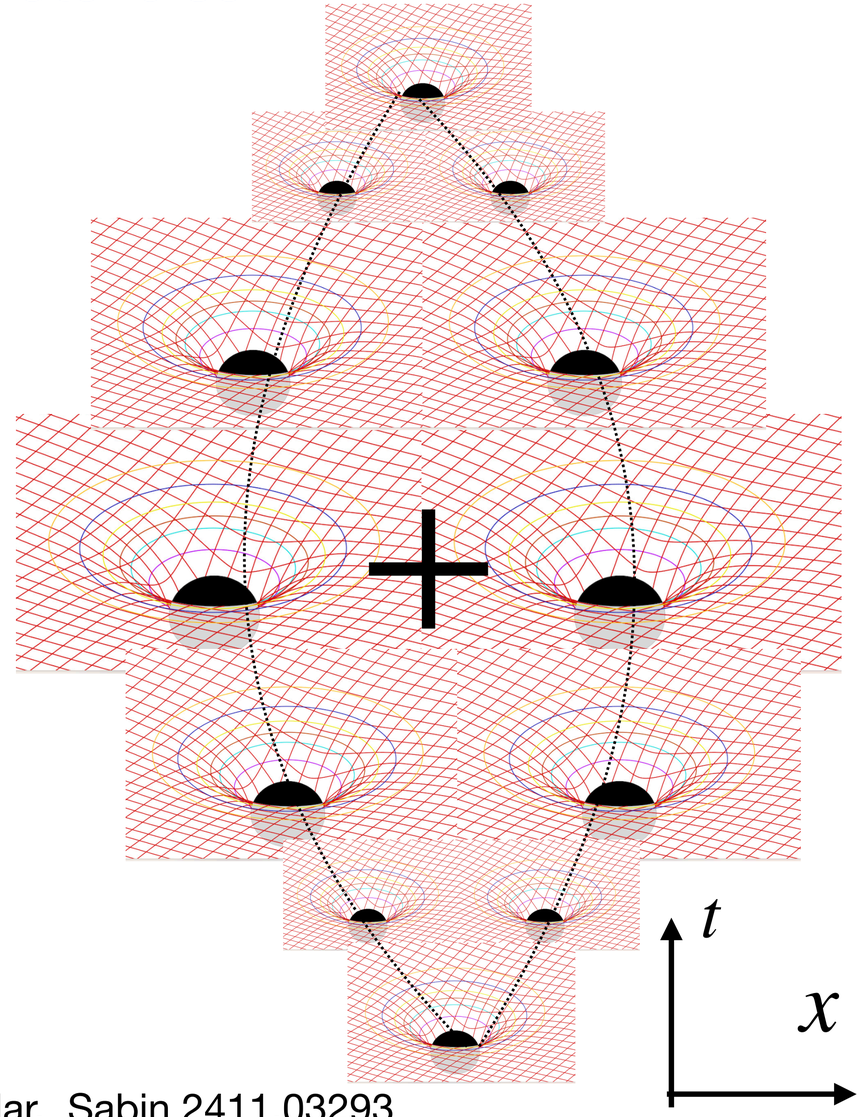
If position is an operator, then metric is an operator also

$$\hat{H}_{int} = \frac{m}{4}\frac{\partial \hat{h}_{11}^2}{\partial t^2}\hat{x}^2 = \frac{mc^2}{4}R_{0101}\,\underbrace{\hat{x}^2}$$

In a semiclassical theory, there is no entanglement between matter and gravity

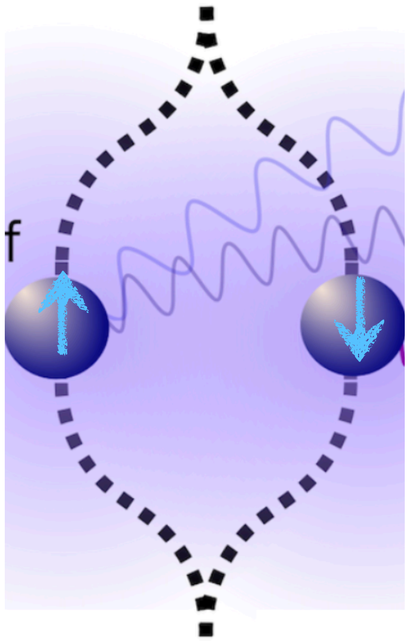
$$\hat{H}_{int} = \frac{m}{4}\frac{\partial \hat{h}_{11}^2}{\partial t^2}\hat{x}^2 = \frac{mc^2}{4}\underbrace{\hat{R}_{0101}\hat{x}^2}$$

Genuine Tripartite Entanglement between matter and gravity



Carmona Rufo, Mazumdar, Sabin 2411.03293

Quantum Decoherence, Witness, Superposition Size



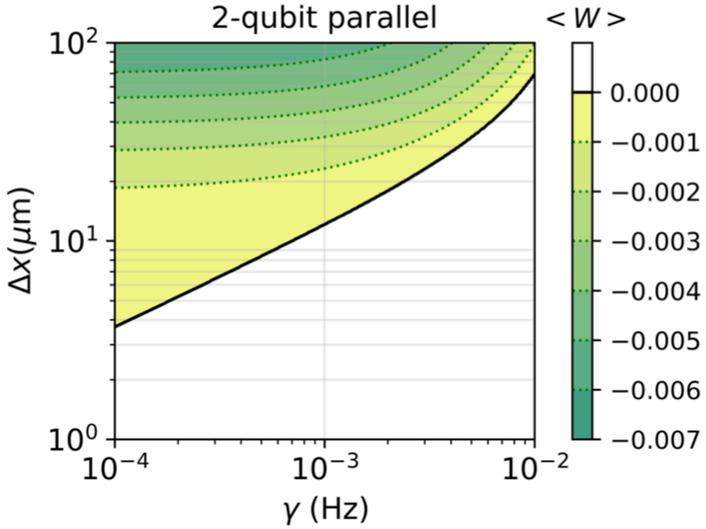
Unknown/unpredictable Noise/fluctuations

Density matrix:

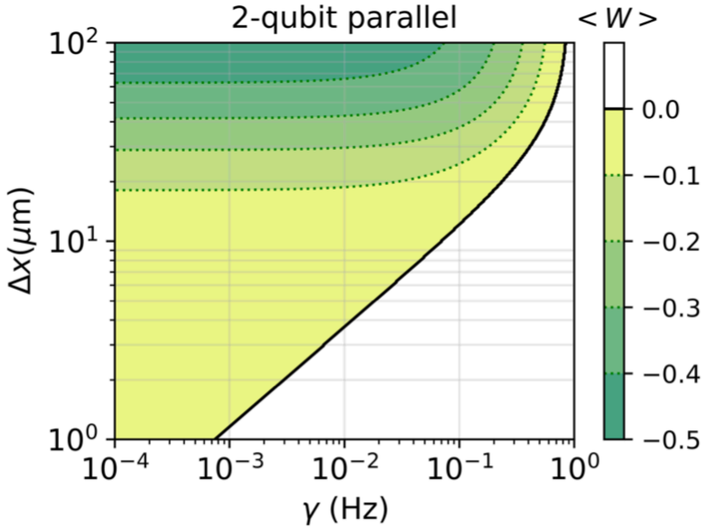
$$\rho = |\psi\rangle\langle\psi| = \frac{1}{4}\begin{pmatrix} 1 & e^{-i\Delta\phi}e^{-\gamma t} \\ e^{i\Delta\phi}e^{-\gamma t} & 1 \end{pmatrix}$$

Decoherence rate

Witness: $\langle \mathscr{W} \rangle = \mathrm{Tr}(\mathscr{W}\rho) = 2\gamma t - \Delta\phi_{ent} < 0$



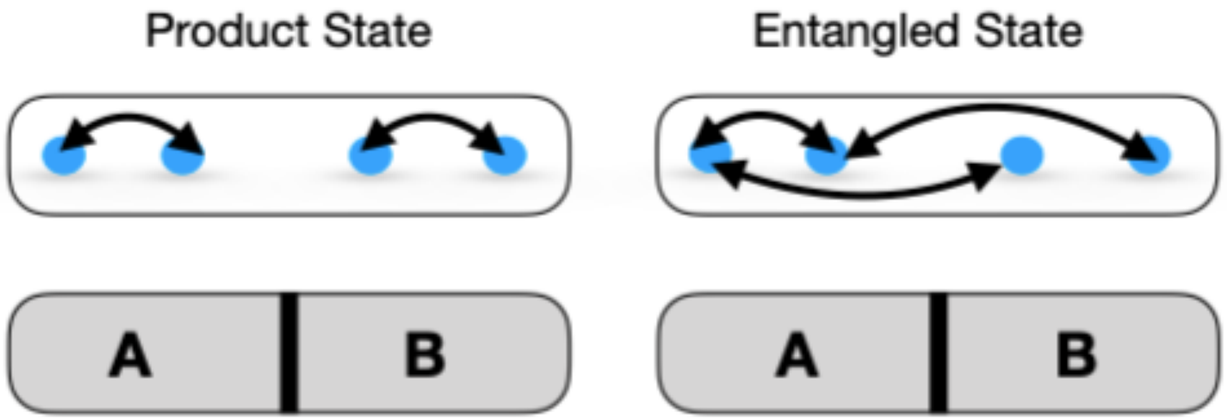
(a) For $m = 10^{-15}$ kg



(b) For $m = 10^{-14}$ kg

Van-Kamp, Marshman, Toros, Bose, Mazumdar, 2006.06931
Schut, Tilly, Marshman, Bose, Mazumdar, 2110.4695
Schut, Grinin, Dana, Bise, Geraci, Mazumdar, 2307.07536 [quant-ph]
Schut, Mazumdar, 2502.12474

Quantum experiment requires quantum measurement/witness: “Entanglement”



Entanglement Entropy

- If A is entangled with B, then B is entangled with A
- If A+B is a closed system, then the total entropy is zero

$$S_{A+B} = 0$$

Entanglement & Entanglement Entropy is a bonafide quantum entity which has no classical analogy

QGEM: Change in Gravitational Energy due to H.O's

$$\hat{g}_{\mu\nu} = \hat{\eta}_{\mu\nu} + \hat{h}_{\mu\nu} \qquad \hat{h}_{\mu\nu} = \hat{\gamma}_{\mu\nu} - \frac{1}{2}\hat{\eta}_{\mu\nu}\hat{h}$$

$$\hat{\gamma}_{\mu\nu} = \mathcal{A}\int d\boldsymbol{k}\sqrt{\frac{\hbar}{2\omega_{\boldsymbol{k}}(2\pi)^3}}(\hat{P}^{\dagger}_{\mu\nu}(\boldsymbol{k})e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} + \text{H.c}),$$

$$\hat{\gamma} = 2\mathcal{A}\int d\boldsymbol{k}\sqrt{\frac{\hbar}{2\omega_{\boldsymbol{k}}(2\pi)^3}}(\hat{P}^{\dagger}(\boldsymbol{k})e^{-i\boldsymbol{k}\cdot\boldsymbol{r}} + \text{H.c})$$

$$\mathcal{A} = \sqrt{16\pi G/c^2}$$

$$\left[\hat{P}_{\mu\nu}(\boldsymbol{k}),\ \hat{P}^{\dagger}_{\lambda\rho}(\boldsymbol{k}')\right] = [\delta_{\mu\lambda}\delta_{\nu\rho} + \delta_{\mu\rho}\delta_{\nu\lambda}]\delta(\boldsymbol{k}-\boldsymbol{k}')$$

$$\left[\hat{P}(\boldsymbol{k}),\ \hat{P}^{\dagger}(\boldsymbol{k}')\right] = -\delta(\boldsymbol{k}-\boldsymbol{k}').$$

$$\hat{H}_g = \int d\boldsymbol{k}\hbar\omega_{\boldsymbol{k}}\left(\frac{1}{2}\hat{P}^{\dagger}_{\mu\nu}(\boldsymbol{k})\hat{P}^{\mu\nu}(\boldsymbol{k}) - \hat{P}^{\dagger}(\boldsymbol{k})\hat{P}(\boldsymbol{k})\right)$$

$$|\boldsymbol{k}\rangle = (\hat{P}^{\dagger}_{00}(\boldsymbol{k}) + \hat{P}^{\dagger}(\boldsymbol{k}))|0\rangle$$

$$\hat{P}_{00}(\boldsymbol{k})|0\rangle = \hat{P}(\boldsymbol{k})|0\rangle = 0$$

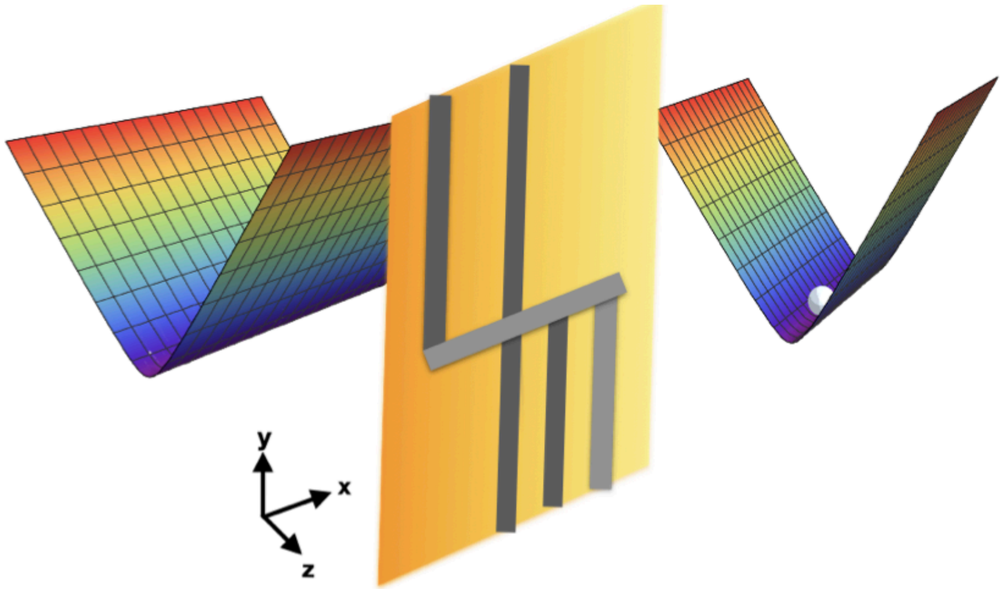
$$\Delta\hat{H}_g \equiv \sum\int d\boldsymbol{k}\frac{\langle 0|\hat{H}_{\text{int}}|\boldsymbol{k}\rangle\langle\boldsymbol{k}|\hat{H}_{\text{int}}|\boldsymbol{0}\rangle}{E_0 - E_{\boldsymbol{k}}}$$

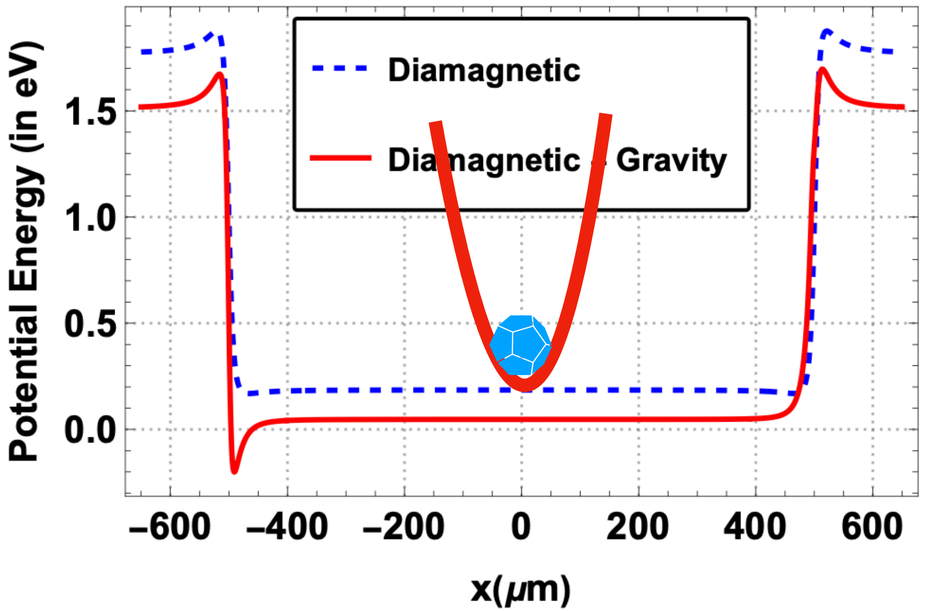
$$\Delta\hat{H}_g = -\frac{Gm^2}{|\hat{x}_A - \hat{x}_B|} - \frac{G(3\hat{p}_A^2 - 8\hat{p}_A\hat{p}_B + 3\hat{p}_B^2)}{2c^2|\hat{x}_A - \hat{x}_B|} - \frac{G(5\hat{p}_A^2 - 18\hat{p}_A^2\hat{p}_B^2 + 5\hat{p}_B^2)}{8c^4m^2|\hat{x}_A - \hat{x}_B|}$$

$$p \equiv p_A = -p_B$$

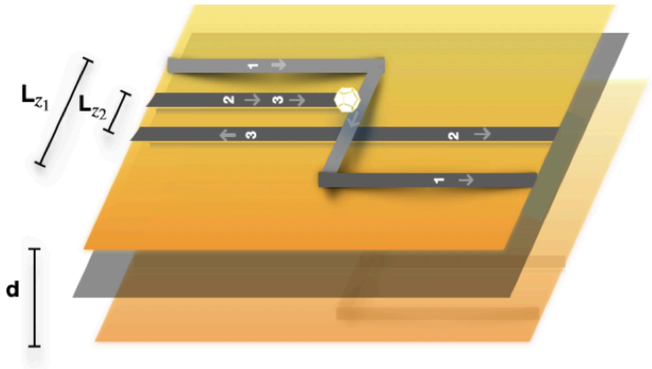
$$\Delta H_g = -\frac{Gm^2}{r} - 7\frac{Gp^2}{c^2r} - \frac{Gp^4}{c^4m^2r}$$

Levitating Setup with a Long Trap



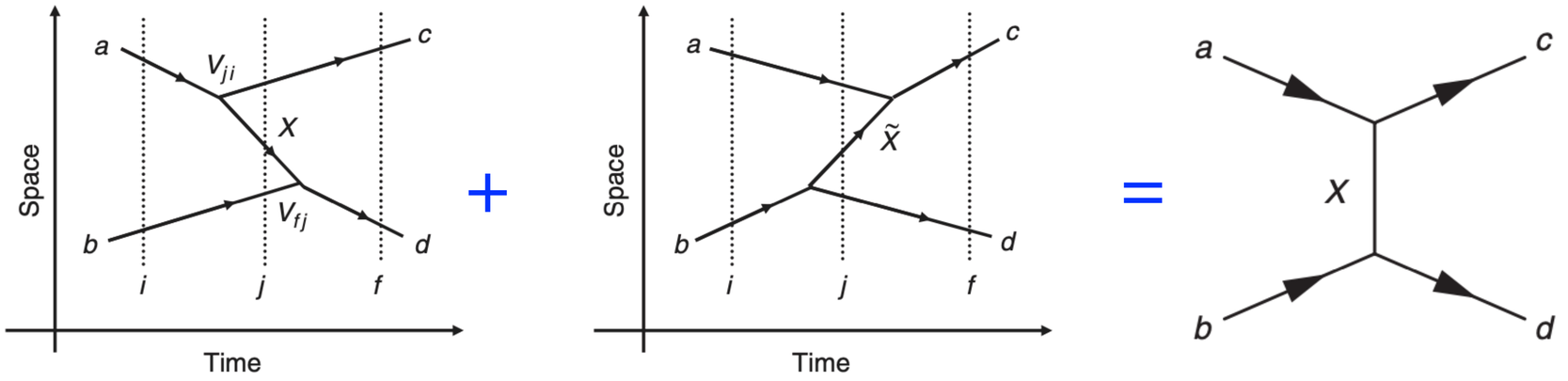


Trap	Orientation	$(\omega_x, \omega_y, \omega_z)/2\pi$ (Hz)	z_0(μm)
Short trap	B_{bias}= 0.2 T		
30 μm u-wire	(H)	(121.5,507, 585)	16.2
	(V)	(62, 380.7, 336)	18.6
30 μm z-wire	(H)	(191, 550, 785)	16.4
	(V)	(159, 351, 331)	18.3
Long trap	B_{bias}= 0.25 T		
1mm Z-wire	(H)	(0.1*, 553, 685)	16.4
	(V)	(0.01*,491.5, 521)	16.7



Horizontal

Non-Relativistic Potential from Scattering



- **Standard quantum mechanics**
- **General relativity**
- **Local interaction**

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

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

$$G_{\mu\nu\alpha\beta} = \left[\frac{P^2_{\mu\nu\alpha\beta}}{k^2} - \frac{P^0_{\mu\nu\alpha\beta}}{2k^2}\right] = \frac{1}{2k^2}\left[\eta_{\mu\alpha}\eta_{\nu\beta} + \eta_{\mu\beta}\eta_{\nu\alpha} - \eta_{\mu\nu}\eta_{\alpha\beta}\right]$$

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

Off-shell exchange is a quantum process that works within the energy-time uncertainty relationship

Effective Field Theory of Quantum Gravity

- At low energies, a massless spin-2 graviton can be quantised canonically (e.g. Gupta, Feynman, Kibble, Weinberg, and many others). Very similar to quantising a photon around a Minkowski background. Any feasible experiment takes place around such a weak background. Hence, we can apply Effective Field theory of quantum gravity. See Donoghue, Bern, etc,

  See: Bose, Mazumdar, Schut, Toros, 2201.03583 [gr-qc]
  Beckering Vinckers, Dombriz, Mazumdar, 2303.17640 [gr-qc] (see Appendix)
  Marshman, Mazumdar, Bose, 1907.01568 [quant-ph]

- Quadratic curvature gravity in 4d is renormalizable; it has other problems related to ghosts, but it is power-counting renormalizable. See Stelle's gravity. A well-known paper!

- String theory (the most consistent theory of quantum gravity) has presumably no UV divergences, and at low energies it reproduces the results of the effective field theory of quantum gravity in 4d

- Non-perturbative quantum gravity aims to understand the UV, with no divergences, but at low energies, there is no satisfactory understanding, in my opinion

Experimental verifications are lacking; even spin-2 graviton as a quantum entity has not been verified in any experiment