Searching for quantum gravity

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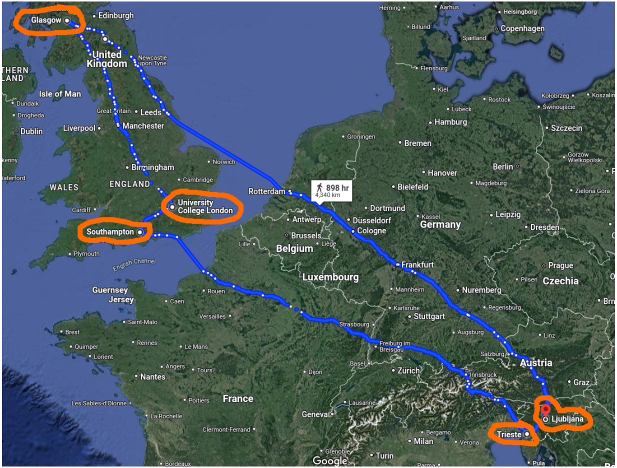
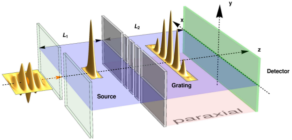
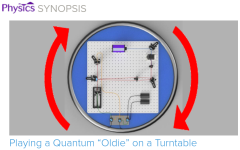
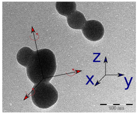
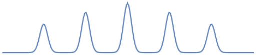


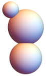
Physical systems and interesting ideas











Matterwave interferometry (*quantum to classical transition*)

Quantum optics (*rotationally induced quantum nonlocality*)

Levitated optomechanics (*exploiting rotranslational motion*)

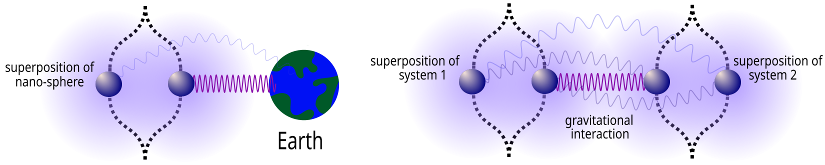
Toroš et al. Generating quantum non-local entanglement with mechanical rotations arXiv:2407.14276 (2024)

Slovenia – University of Ljubljana

Testing ideas about quantum gravity

- Quantum gravity entanglement of masses (QGEM)
  - *Can gravity entangle two systems?*
- Post-Newtonian QGEM
  - *What is the entangling power of gravity?*
- Quantized gravitational waves
  - *When can a physical system emit gravitons?*
- Quantum light bending
  - *Can we test the spin of gravity at the quantum level?*

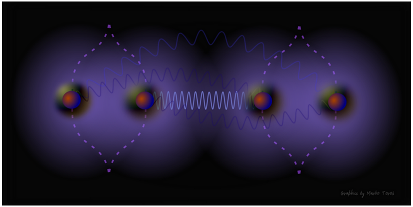
How to test quantum gravity?



Source and probe of the gravitational interaction.

Bose et al. Spin entanglement witness for quantum gravity. Phys. Rev. Lett. 119, 240401 (2017)

Gravitationally induced entanglement



Bose et al. Spin entanglement witness for quantum gravity. Phys. Rev. Lett. 119, 240401 (2017)

QGEM mechanism Static case $-\hat{T}_{00}$

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

$$\Delta \hat{H}_g = -\frac{16\pi G}{c^2} \int d\boldsymbol{k} \frac{\hat{T}^{\dagger}_{00}(\boldsymbol{k})\,\hat{T}_{00}(\boldsymbol{k})}{8c^2\boldsymbol{k}^2}$$

$$\Delta \hat{H}_g = -\frac{Gm^2}{|\hat{\boldsymbol{r}}_A - \hat{\boldsymbol{r}}_B|}$$

$$\hat{H}_{\text{AB}} \equiv \frac{2Gm^2}{d^3}\delta\hat{x}_A\delta\hat{x}_B$$

Bose et al. Mechanism for the quantum natured gravitons to entangle masses. Phys. Rev. D 105, 106028 (2022)

Non-static case – $\hat{T}_{00}, \hat{T}_{01}, \hat{T}_{11}$

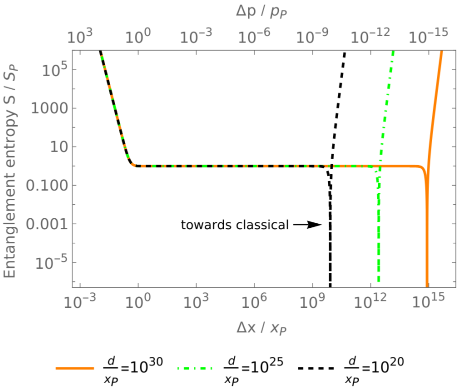
$$\Delta \hat{H}_g \equiv \int d\boldsymbol{k} \frac{\langle 0|\hat{H}_{\text{int}}|\boldsymbol{k}\rangle\langle \boldsymbol{k}|\hat{H}_{\text{int}}|0\rangle}{E_0 - E_{\boldsymbol{k}}}$$

$$\hat{H}_{\text{AB}} = \frac{Gm^2}{d^3}\hat{x}_A\hat{x}_B + \frac{G\hat{p}_A\hat{p}_B}{c^2 d} - \frac{G\hat{p}_A^2\hat{p}_B^2}{c^4 m^2 d} + \dots$$

- Entangling power?
  - $\frac{Gm^2}{d^3}\hat{x}_A\hat{x}_B,\ \frac{G\hat{p}_A^2\hat{p}_B^2}{c^4 m^2 d}$ --→"U shape"
  - $\frac{Gm^2}{d^3}\hat{x}_A\hat{x}_B + \frac{G\hat{p}_A\hat{p}_B}{c^2 d} = \hbar g_-(\underbrace{\hat{a}\hat{b} + \hat{a}^\dagger\hat{b}^\dagger}_{\text{TMS}}) + \hbar g_+(\underbrace{\hat{a}\hat{b}^\dagger + \hat{a}^\dagger\hat{b}}_{\text{BS}})$

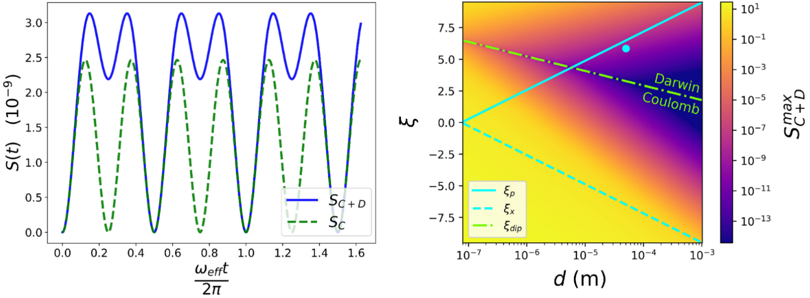
    $g_- = \frac{Gm}{d^3\omega_{\mathrm{m}}} - \frac{2Gm\omega_{\mathrm{m}}}{c^2 d}$,--→"Dips"

Relativistic dips in the entangling power of gravity



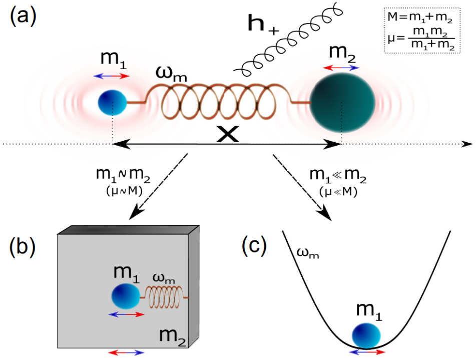
Toroš et al. Relativistic Dips in Entangling Power of Gravity. arXiv:2405.04661(2024); (2024)

Relativistic dips in the entangling power of electromagnetism



Toroš et al. Relativistic effects on entangled single-electron traps Phys. Rev. D 110, 056031 (2024)

Classical emission from a linear quadrupole



Center-of-mass decoupled from GWs, while *relative motion* coupled to GWs.

Quantized gravitational waves

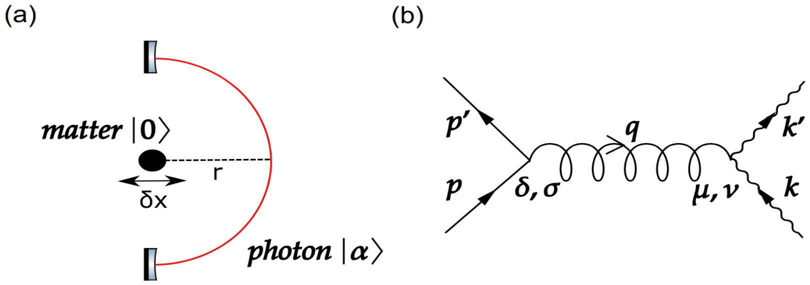
Master equation for graviton emission

$$\frac{d}{dt}\hat{\rho}_t = \gamma_{\rm grav}\left(\hat{b}^2\hat{\rho}_t\hat{b}^{\dagger 2} - \frac{1}{2}\{\hat{b}^{\dagger 2}\hat{b}^2, \hat{\rho}_t\}\right), \qquad \gamma_{\rm grav} = \frac{32}{15} t_{\rm Pl}^2 \omega_{\rm m}^3$$

- classical quadrupole radiation is recovered exactly for $|\alpha\rangle$ with $|\alpha|^2 \gg 1$
  - $\dot{E} = -\frac{16 G I^2 \omega_{\rm m}^6}{15 c^2}$,
- relative motion is only allowed transtions by two energy levels
  - $|n\rangle \to |n-2\rangle$
- coherence protection for special relative motion states
  - $\frac{|0\rangle + |1\rangle}{\sqrt{2}}$ is a steady state
- complete coherence protection for the center of mass
  - set $\omega_{\rm m} = 0$ to find $\gamma_{\rm grav} = 0$

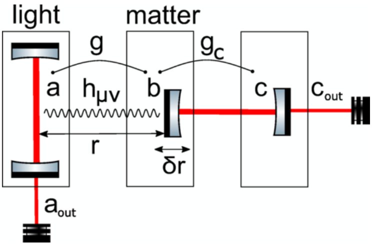
Toroš et al. Loss of coherence and coherence protection from a graviton bath Phys. Rev. D 109, 084050 (2024)

Quantum light bending effect



Testing the spin of the gravitational interaction at the quantum level.

Quantum light bending effect



Gravitational optomechanical interaction

$$\hat{V} = -\hbar g_0 (\hat{b} + \hat{b}^\dagger) \hat{a}^\dagger \hat{a}, \qquad g_0 = \frac{4Gm\omega}{r^2 c^2} \sqrt{\frac{\hbar}{2m\omega_m}}$$

- entanglement entropy and light-enhanced optomechanical coupling
  - $S = 2g^2\tau^2, \qquad g = g_0 |\alpha|$

Biswas et al Gravitational optomechanics: Photon-matter entanglement via graviton exchange
Phys. Rev. D 108, 064023 (2023)

Summary

Main message

Gravitationally induced entanglement as a test of quantum gravity

- PostNewtian effects
  - dips in entangling power
- quantized GWs
  - coherence protection $\sim |0\rangle + |1\rangle$
- quantum light bending
  - testing the spin of the interaction

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