The search for a table top quantum gravity signature

Marios Christodoulou
University of Vienna
Institute for Quantum Optics and Quantum Information

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1957

***The Role of Gravitation in Physics. Report from the 1957 Chapel Hill Conference*. D. Rickles and C. DeWitt. (Max Planck Institute for the History of Science eds.)**

Richard Feynman: “We’re in trouble if we believe in quantum mechanics but don’t quantize gravitational theory ”

Richard Feynman: “One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference”

Louis Witten: “What prevents this from becoming a practical experiment?”.

Richard Feynman: “You might argue this way: Somewhere in your apparatus this idea of [probability] amplitude has been lost. You don’t need it any more, so you drop it. The wave packet would be reduced (or something). Even though you don’t know where it’s reduced, it’s reduced. And then you can’t do an experiment which distinguishes interfering alternatives from just plain odds (like with dice).”

In modern parlance: Gravity mediated entanglement would seem to require a quantised gravitational field. The main trouble from realising such an experiment is decoherence to the environment which implies that the outcomes of measurements on the probe will be described by a probabilistic mixture. Sixty three years later, this is roughly still the state of affairs. Just that we may realistically hope to see this experiment done within a generation, which could not have been said in 1957.

***How to avoid the appearance of a classical world in gravity experiments*. M. Aspelmeyer (2203.05587)**

Macroscopic Quantum Mechanics in the lab

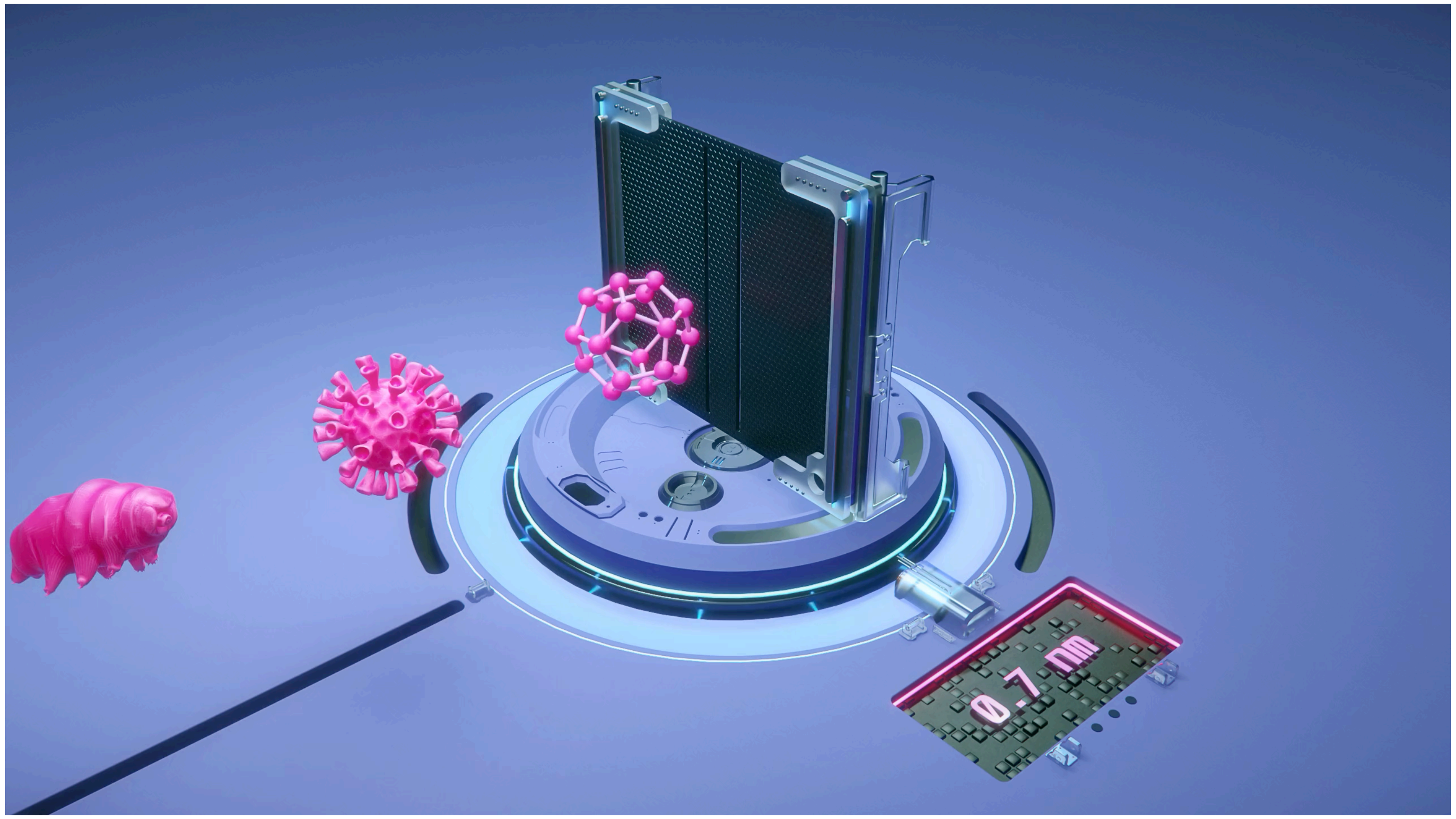


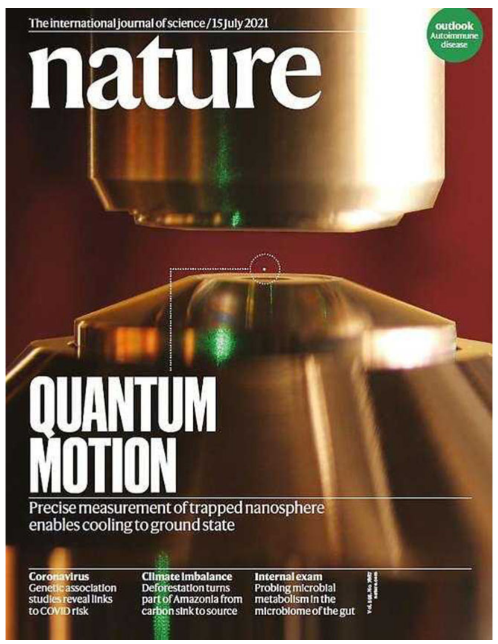
Image credit quanta magazine: How big can the quantum world be?

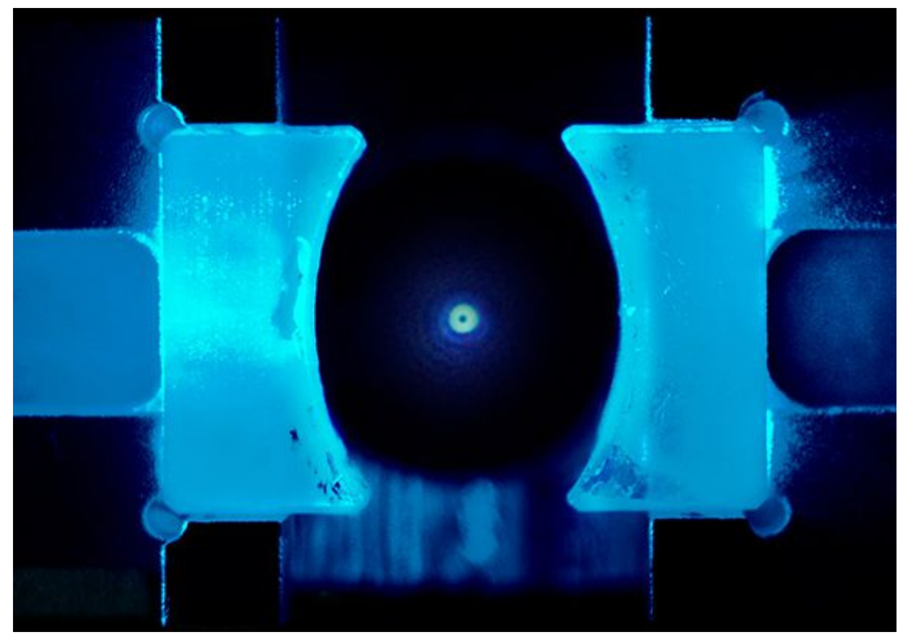
Quantum superposition of molecules beyond 25 kDa, Arndt et al, (Nature Physics 2019) 10^-20kg

Wave-particle duality of C60 molecules, M. Arndt, J. Vos-Andreae, C. Keller, G. Zouw, A. Zeilinger (Nature 1999) 10^-24kg

Macroscopic Quantum Mechanics in the lab

Using quantum levitation combined with optical cooling ground state preparation of particles at 10^-18kg (10^9 atoms) have been reported. Claims that several orders of magnitude improvement can happen within a couple of years, going up to 10^-12kg (10^15 atoms).



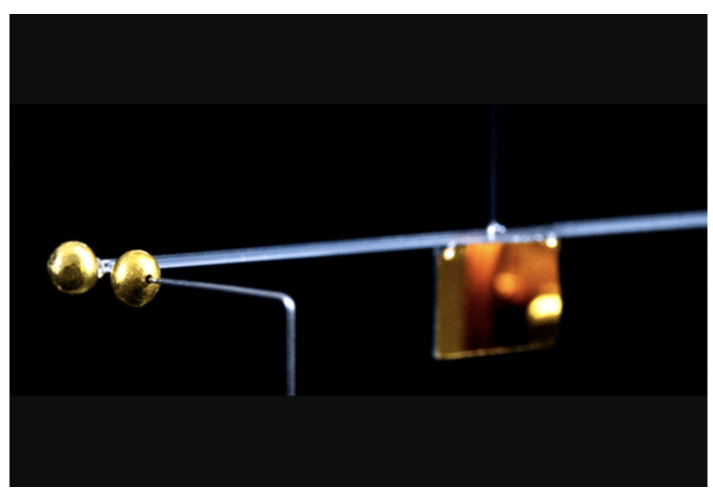


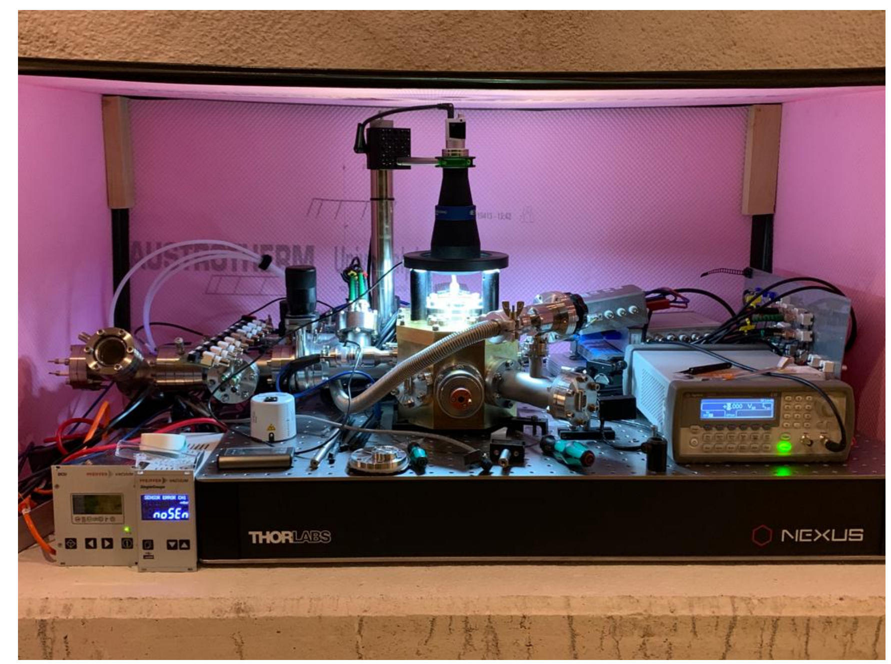
Real-time optimal quantum control of mechanical motion at room temperature, L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. Hofer, S. Hong, N. Kiesel, A. Kugi and Markus Aspelmeyer (Nature 2021)

Quantum control of a nanoparticle optically levitated in cryogenic free space, F. Tebben, M. Mattana, M. Rossi, M. Frimmer, and L. Novotny (Nature 2021)

Precision gravity measurements

Gravitational force between masses of 10^-5kg measured. Claimed that soon 10^-8kg (planck mass) or below.

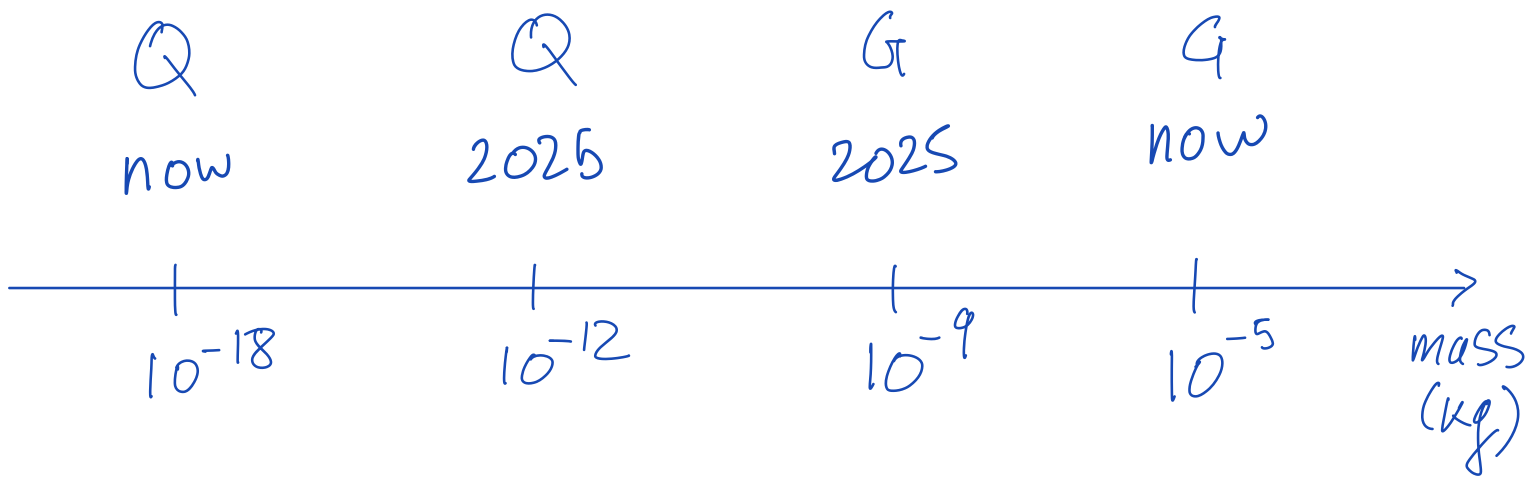




Measurement of gravitational coupling between millimetre sized masses, T. Westphal, H. Hepach, J. Pfaff, M. Aspelmeyer (Nature 2021)

Physicists Measure the Gravitational Force between the Smallest Masses Yet, SA

Summary of experimental news



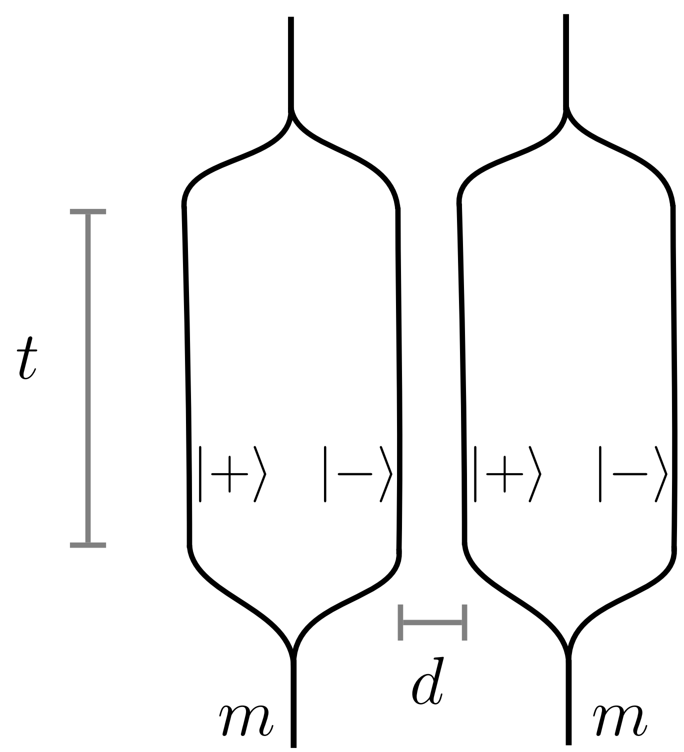
Overlap of mass scales should come soon, which will be an exciting moment. This overlap, however, in the <u>limited sense</u> that certain collective degrees of freedom of masses can be both set in their ground state and their gravitational field measured at the same scale.

Many great experimental challenges ahead:

- **Macroscopic superposition, not just ground state preparation.**
- **Keeping coherence long enough**
- **Biggest challenge, combine the two: Q+superposition and G, in one experiment.**
- **What setup? What measurements? What is the most feasible protocol?**

How to avoid the appearance of a classical world in gravity experiments. M. Aspelmeyer (2203.05587)

Conceptually simple setup for gravity induced entanglement



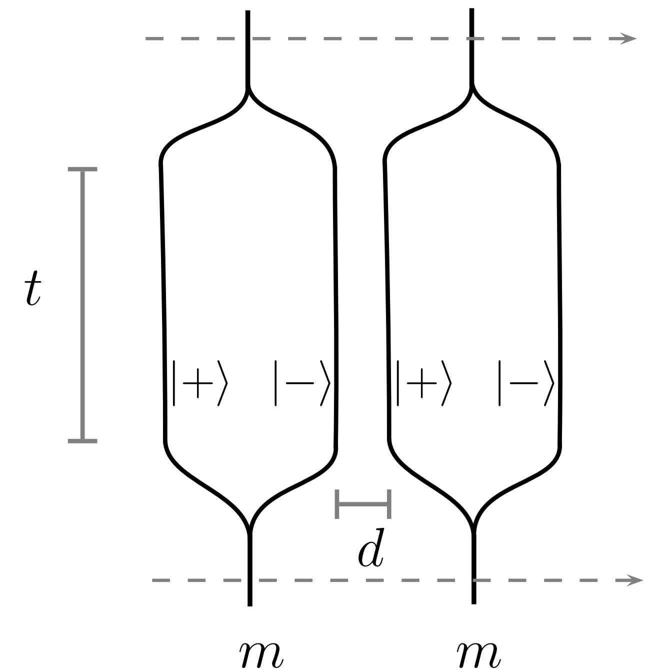
- Two masses set in path superposition by manipulating embedded spin through an external magnetic field.
- The spins are initially not entangled
- The branch of closest approach is at distance **d** and the free fall phase lasts **t**.
- Left to freefall, interacting gravitationally. The superposition is undone and measurements are performed on the spins.
- Original argument: If the spins become entangled, the mediator of the interaction must be able to carry quantum information. The mediator is the gravitational field, thus, it cannot be a classical field

Observable quantum entanglement due to gravity, T. Krisnanda, G. Y. Tham, M. Paternostro, T. Paterek (1906.08808)

Spin entanglement witness for quantum gravity. S. Bose, A. Mazumdar, G. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. Geraci, P. Barker, M. Kim, G. Milburn (1707.06050)

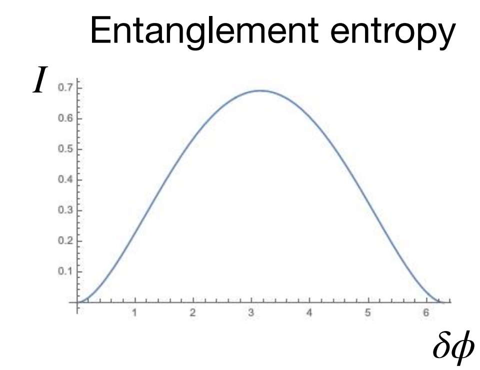
Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity, C. Marletto and V. Vedral (1707.06036)

Conceptually simple setup for gravity induced entanglement



$$|\Psi_f\rangle \propto \left(|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + e^{i\delta\phi(m,d,t)}\,|{-}{+}\rangle\right) \otimes |g\rangle$$

If the phase δϕ is not zero then there is entanglement production.

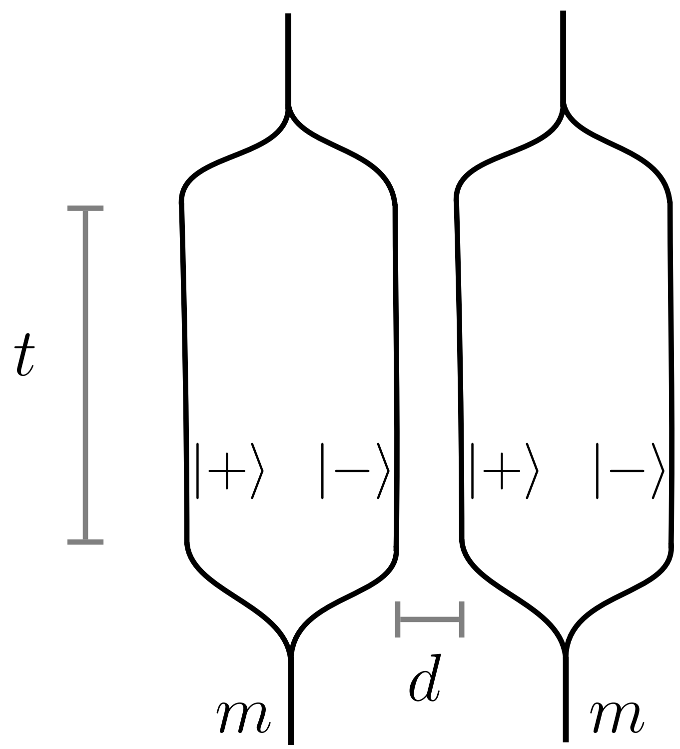


$$|\Psi_i\rangle = |\psi_A\rangle \otimes |\psi_B\rangle \otimes |g\rangle$$
$$\propto \left(|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + |{-}{+}\rangle\right) \otimes |g\rangle$$

- For simplicity, here we neglect gravitational interaction in all but the branch of closest approach.

- Each mass prepared initially in a separable state
$|\psi_{AB}\rangle = |\psi_A\rangle \otimes |\psi_B\rangle = (|+\rangle + |-\rangle) \otimes (|+\rangle + |-\rangle)$

Newtonian gravity suffices for numerical evaluation of entanglement



Newtonian potential energy

$$E_g = \frac{Gm^2}{d}$$

Free evolution

$$e^{i\delta\phi} = e^{i\frac{E_g t}{\hbar}}$$

Quantum phase

$$\delta\phi = \frac{Gm^2 t}{d\,\hbar}$$

These formulas are used to determine the parameters m,t,d so that entanglement is expected to be produced. If entanglement is detected, **assuming** a local interaction, then, the argument goes, we conclude that the gravitational field cannot be a classical field.

Essentially, the `trick' is to force one to either conclude this, or, abandon locality.

Overview of debate on relevance of GIE for QG

The two extremes

GIE nothing to do with QG

Comment on Bose et al and Marletto-Vedral papers. **C. Anastopoulos, B. Hu (1804.11315)**

We argue that gravity-induced entanglement by Newtonian forces is **agnostic to the quantum or classical nature** of the gravitational true degrees of freedom.

Gravitational effects in macroscopic quantum systems: a first principles analysis. **C. Anastopoulos, M. Lagouvardos, K. Savvidou (1804.11315)**

We analyze … recently proposed experiments on the generation of (Newtonian) gravitational forces from quantum distributions of matter, and phenomena like gravity-induced entanglement.. Our main results include: (i) The demonstration that these phenomena **do not involve true gravitational degrees of freedom**…

GIE implies detection of virtual gravitons

Locality & Entanglement in Table-Top Testing of the Quantum Nature of Linearized Gravity. **R. Marshman, A. Mazumdar, S. Bose (1907.01568)**

We explain the background concepts needed from quantum field theory and quantum information theory to fully appreciate the previously proposed table-top experiments: namely **forces arising through the exchange of virtual (off-shell) quanta**, as well as Local Operations and Classical Communication (LOCC) and entanglement witnesses

Mechanism for the quantum natured gravitons to entangle masses. **S. Bose, A. Mazumdar, M. Schut, M. Toros (2201.03583)**

We will use basic quantum mechanics and perturbation theory to show how the perturbed wave functions of **the matter systems become entangled solely by the virtue of the virtual exchange** of the quantum natured graviton.

Overview of debate on relevance of GIE for QG

Some middle grounds

GIE implies quantum information carried by `non radiative' part

Experiments testing macroscopic quantum superpositions must be slow. A. Mari, G. De Palma and V. Giovannetti. (1509.02408)

Quantum superposition of massive objects and the quantisation of gravity. A. Belenchia, B. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner, M. Aspelmeyer (1807.07015)

Information content of the gravitational field of a Quantum superposition. A. Belenchia, R. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner, M. Aspelmeyer (1905.04496)

Thus, a Newtonian-like gravitational field must be capable of carrying quantum information… Our analysis supports the view that table-top experiments testing entanglement of systems interacting via gravity do probe the quantum nature of gravity, even if no ``gravitons'' are emitted during the experiment… Since there is no radiation, **it clearly must be the "non-radiative part" of the electromagnetic/gravitational field that is responsible for the ultimate entanglemen**t of Alice's and Bob's particles.

GIE implies detection of on-shell gravitons

Newton, entanglement and the graviton. D. Carney. (2108.06320)

I demonstrate that this **"Newtonian entanglement" requires the existence of massless bosons**…

Gravitationally Mediated Entanglement: Newtonian Field vs. Gravitons, D. Danielson, G. Satishchandran and R. Wald. (2112.10798)

This suggests that Newtonian entanglement implies the existence of graviton entanglement and supports the view that the experimental discovery of **Newtonian entanglement may be viewed as implying the existence of the graviton**.

Overview of debate on relevance of GIE for QG

Our middle ground

GIE implies detection of macroscopic superposition of spacetimes

***On the possibility of laboratory evidence for quantum superposition of geometries*. M. Christodoulou, C. Rovelli (1804.11315)**

We point out that measurement of this effect would count as evidence for quantum superposition of spacetime geometries.

***Locally mediated entanglement from first principles*. M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

The physical picture arising from the analysis is that information travels in the quantum superposition of field wavefronts: the mechanism that propagates the quantum information with the speed of light is a quantum superposition of macroscopically distinct dynamical field configurations.

Entanglement is mediated locally

$$\int \mathscr{D}\mathscr{F}'\mathscr{D}x' \exp\left(\frac{iS}{\hbar}\right)$$ Partition function

$$S = S\left[x_a'(t), \mathscr{F}'(x,t); m_a, B_z, \sigma\right]$$ Action

$$|\psi^{i,f}\rangle = |F^{i,f}\rangle[x_a^{i,f}] \otimes |x_a^{i,f}\rangle$$ Boundary states

$$U_{i\to f} = \sum_\sigma |\sigma\rangle\langle\sigma| \otimes U^\sigma_{i\to f}$$ Evolution operator

$$U^\sigma_{i\to f} \propto \int \mathscr{D}x' \exp\left(\frac{iS\left[x_a', \mathscr{F}[x_a']\,\right]}{\hbar}\right)$$ Field on shell

$$U^\sigma_{i\to f} \propto \exp\left(\frac{iS^{os}\left[x_a^\sigma, \mathscr{F}[x_a^\sigma]\right]}{\hbar}\right)$$ Paths near orthogonal

Locally mediated entanglement from first principles. **M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

Entanglement is mediated locally

$$|\Psi^f\rangle \propto U_{i\to f}\left[\sum_\sigma A_\sigma|\sigma\rangle\right]\otimes|\psi^i\rangle$$

$$=\sum_\sigma A_\sigma|\sigma\rangle\otimes U^\sigma_{i\to f}|\psi^i\rangle$$

$$=\left[\sum_\sigma A_\sigma|\sigma\rangle \exp\left(\frac{iS^{os}\left[x^\sigma_a,\mathscr{F}[x^\sigma_a]\right]}{\hbar}\right)\right]\otimes|\psi^f\rangle$$

$$=|\Psi^f\rangle \propto \left[\sum_\sigma A_\sigma|\sigma\rangle e^{i\phi_\sigma}\right]\otimes|\psi^f\rangle$$

The quantum phases responsible for entanglement production are on-shell actions.

Locally mediated entanglement from first principles. **M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

Entanglement is mediated locally

$$S_{\mathcal{F}} = \frac{c^4}{64\pi G}\int d^4x\Big(-\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} + 2\partial_\rho h_{\mu\nu}\partial^\nu h^{\mu\rho} - 2\partial_\nu h^{\mu\nu}\partial_\mu h + \partial^\mu h\partial_\mu h\Big) + \frac{1}{2}\int d^4x\, h_{\mu\nu}T^{\mu\nu}$$

$$S_{\mathcal{F}} = \frac{c^4}{64\pi G}\int d^4x\Big(-\partial_\rho h_{\mu\nu}\partial^\rho h^{\mu\nu} + \frac{1}{2}\partial^\mu h\partial_\mu h\Big) + \frac{1}{2}\int d^4x h_{\mu\nu}T^{\mu\nu}$$ Lorentz gauge

$$\Box h_{\mu\nu} = -\frac{16\pi G}{c^4}\bar{T}_{\mu\nu}$$ Eoms

$$S_{\mathcal{F}}^{os} = \frac{1}{4}\int d^4x h_{\mu\nu}T^{\mu\nu}$$ On shell action

Locally mediated entanglement from first principles. **M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

Entanglement is mediated locally

Source point particles with arbitrary motion

$$T^{\mu\nu}(t,\mathbf{x}) = \sum_a m_a \delta^{(3)}(\mathbf{x}-\mathbf{x}_a(t))V_a^{\mu\nu}(t), \qquad V_a^{\mu\nu}(t) = \gamma_a(t) v_a^\mu(t) v_a^\nu(t), \quad v_a^\mu(t) = (c, d\mathbf{x}_a/dt) = (c, \mathbf{v}_a)$$

Field solution

$$h^{\mu\nu}(t,\mathbf{x}) = \frac{4G}{c^4}\sum_a \left[\frac{m_a \bar{V}_a^{\mu\nu}}{d_a - \mathbf{d}_a \cdot \mathbf{v}_a/c}\right]_{t=t_a}, \qquad \mathbf{d}_a(t,\mathbf{x}) = \mathbf{x}-\mathbf{x}_a(t), \qquad ct_a = ct - d_a(\mathbf{x}, t_a)$$

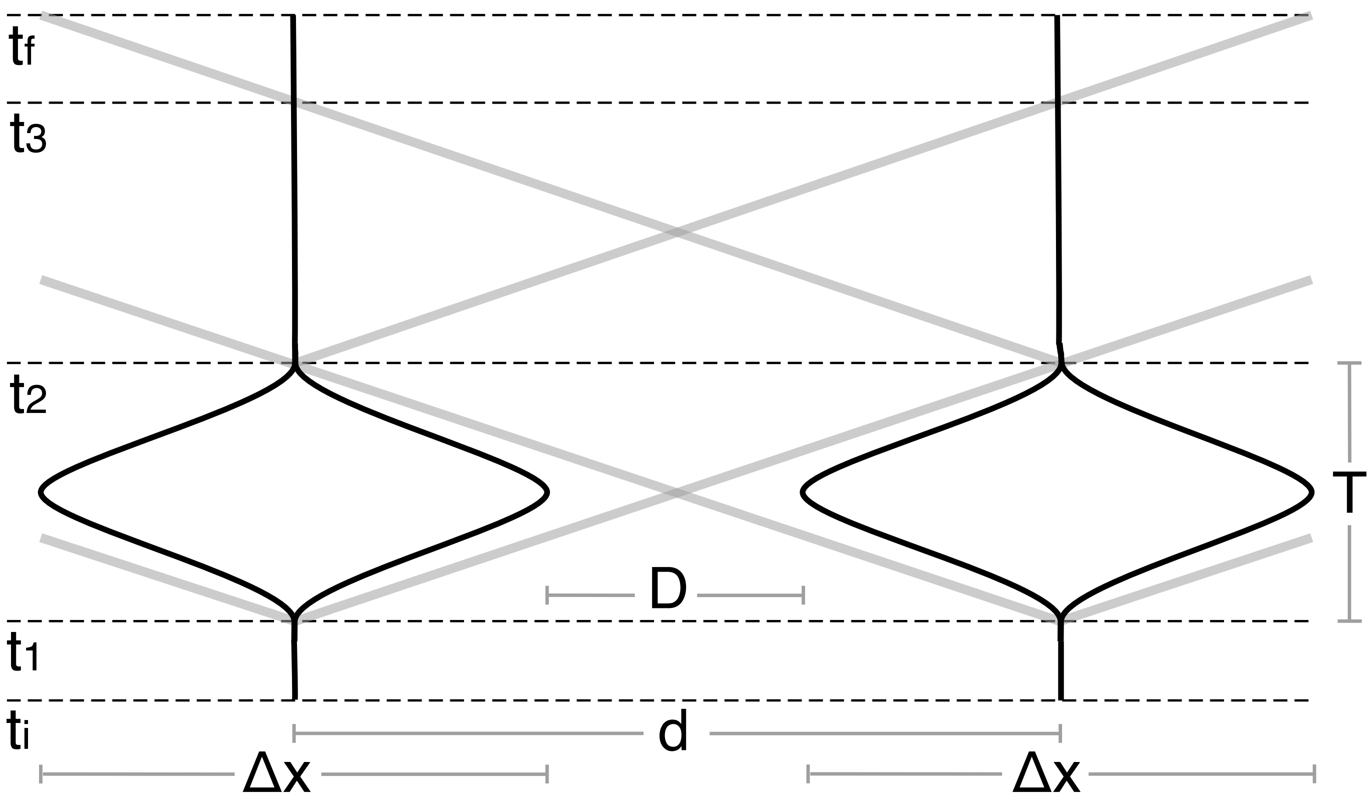
On shell action (quantum phases)

$$S_{\mathcal{F}}^{os} = \frac{G}{c^4}\sum_{a,b}^{a\neq b}\int dt \frac{m_a m_b \bar{V}_a^{\mu\nu}(t_{ab})V_{b\mu\nu}(t)}{d_{ab}(t_{ab},t) - \mathbf{d}_{ab}(t_{ab},t)\cdot \mathbf{v}_a(t_{ab})/c} \qquad ct_{ab} = ct - |\,\mathbf{d}_{ab}(t_{ab},t)\,|$$

We have the Lorentz invariant and gauge invariant expression for the observables measured in the experiment. Thus, we conclude that entanglement arises due to a local interaction mediated by physical degrees of freedom involved.

Locally mediated entanglement from first principles. **M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

Entanglement is mediated locally



Slow moving approximation

$$S_{\mathscr{F}}^{os} = \frac{1}{2} G \sum_{a,b}^{a \neq b} \int dt \frac{m_a m_b}{d_{ab}(t_{ab}, t)} .$$

Near-field approximation

$$t_{ab} \approx t$$

Newtonian limit

$$S_{\mathscr{F}}^{os} = G m^2 \int dt \frac{1}{d(t)} .$$

Static limit

$$S_{\mathscr{F}}^{os} = \frac{G m^2}{d} T$$

If d=cT, zero entanglement production

$$U_{i \to f} = \sum_{\sigma} |\sigma\rangle\langle\sigma| \otimes U_{i \to f}^{\sigma} = \sum_{s_a = \uparrow, \downarrow} \left[\left(\otimes_a |s_a\rangle\langle s_a| \right) \otimes U_{i \to f}^{s_a} \right]$$

Locally mediated entanglement from first principles. **M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)**

Discussion

- There have been claims that GIE and similar experiments can provide **theory independent empirical evidence** that the gravitational field is not classical. This heavily relies on the LOCC theorems of quantum information. This may be too strong a statement.

  A no-go theorem on the nature of the gravitational field beyond quantum theory. T. Galley, F. Giacomini, J. Selby (2012.01441)

  Vindication of entanglement based witness of non classicality of hybrid systems. E. Marconato, C. Marletto (2102.10615)

  It could be clarified by reformulating classical field theory in terms of subsystem local operations.

- The importance of the experiment is certainly more clear in the `theory fixed' setting: taking linearised quantum gravity, the effect witnesses that superpositions of semiclassical states exist in the state space.

- There remains confusion on what is the precise physics if we start the full QFT point of view (both for electromagnetism and gravity). This, in particular with respect to the role of radiation and the meaning of `true' degrees of freedom mediating the interaction.

- An experiment where also retardation is witnessed would be more powerful (locality need not be assumed). The protocol we suggest turns out near impossible for gravity. It is feasible for electromagnetism which would counter some of the criticisms (because they apply equally to electromagnetism). There is some hope of coming up with different protocols where the finite speed of propagation will be visible.

- Witnessing non-gaussianity production seems to not suffer from the above caveats and could a more powerful demonstration. Efforts underway to develop a solid state non-gaussianity protocol.

  Non-gaussianity as a signature of a quantum theory of gravity. **R. Howl, V. Vedral, D. Naik, M. Christodoulou, C. Rovelli and A. Iyer. (2004.01189)**

- Alternative protocols, techniques and smarter measurements to amplify the effect are continuously being devised.

- The role of the Planck mass scale in all these phenomena is intriguing, in particular to the possibility of testing for time discreteness.

  On the possibility of experimental detection of the discreteness of time. **M. Christodoulou and C. Rovelli (1812.01542)**

  An experiment to test the discreteness of time. M. Christodoulou, A. Di Biagio, P. Martin-Dussaud (2007.08431)