Title: Quantum Information-Inspired Tests of Quantum Gravity

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Collection/Series: Quantum Gravity

Subject: Quantum Gravity

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Abstract:

I plan to review several ways of testing if the gravitational field has quantum aspects in the low energy regime. I explain why the hybrid (half quantum/half classical) models are inadequate and how they could be ruled out. Furthermore, I maintain that there is no prima facie reason to expect problems when quantizing gravity in the linear regime; I summarise the main perceived difficulties only to dismiss them as irrelevant. Going beyond the linear regime is challenging in the lab, and one might have to look towards astrophysics and cosmology of the early universe instead. Finally, many interesting features of quantum field theory could be explored in the low-energy regime that may not necessarily be specific to gravity.

Quantum information-based tests of quantum gravity

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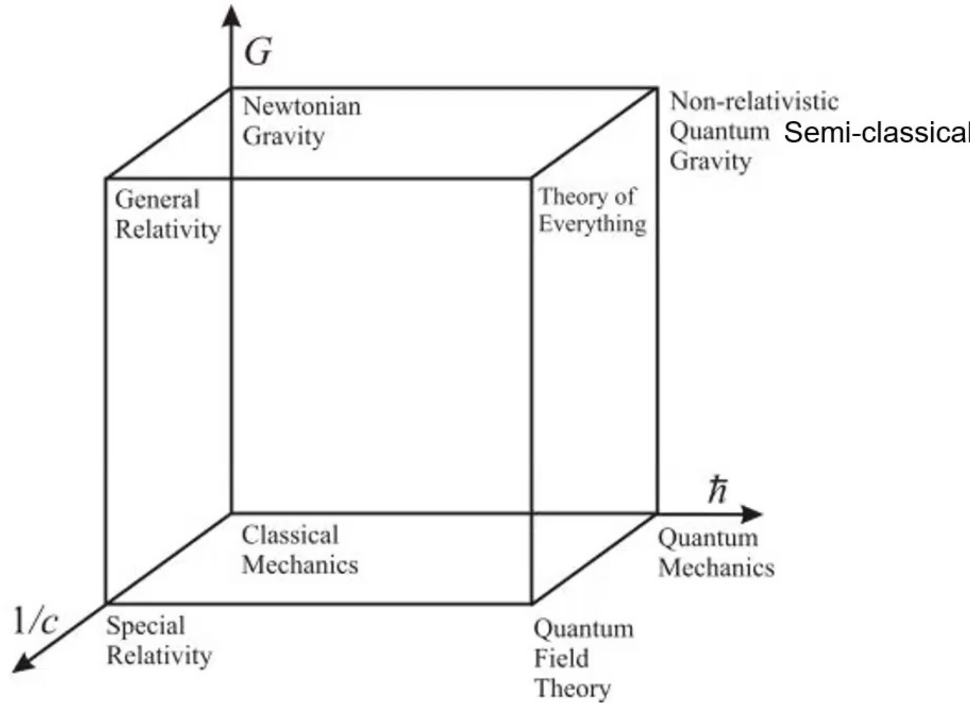
G, hbar and c

The main problem: we have barely tested some aspects of semiclassical regime (COW) but have no idea about others (Unruh, Hawking), let alone lowest order fully quantum



Why is it difficult to test quantum gravity?

Fine structure constant versus gravitational fine structure constant:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx 10^{-2}$$

$$\alpha_G = \frac{G m_{electron}^{\;2}}{\hbar c} = \left(\frac{m_{electron}}{m_{Planck}}\right)^2 \approx 10^{-45}$$

Spontaneous emission of gravitons (as opposed to photons) by atoms is unobservable (takes longer than the age of the Universe!)

Rates (Fermi's Golden Rule)

$$\Gamma_{em} = \frac{e^2 \omega^3 a^2}{\hbar c^3} = \alpha \frac{\omega^3 a^2}{c^2} \Rightarrow e \to \sqrt{G} m \,\&\, a \to a^2$$

$$\Gamma_g = \frac{G m^2 \omega^5 a^4}{\hbar c^5} = \left(\frac{m}{m_{pl}}\right)^2 \left(\frac{a}{l_{pl}}\right)^4 \omega^5 t^4{}_{pl} \propto \alpha_G$$

(NOTE: No more irreversible than EM induced decay.)

Heisenberg's Argument

- If charge couples to a classical electromagnetic field, there is a problem with the uncertainty principle

- Put a charge in a superposition of two places, what is the field at another point?

DeWitt’s Generalization

- Hybrid formulations always problematic. The classical system has to inherit the quantum uncertainty, however, there are issues with satisfying conservation laws (and other symmetries)

What are the problems?

- Entanglement is not a problem
- Equivalence principle is not a problem
- Time, measurement problems etc?…not really
- “A field on itself” problem? No.
- Non-local observables? Gauge/diffeomorphism. Not a problem.
- Nonlinearities (“gravity gravitates”) no different to other field theories

Entanglement is not Einstein non-local

Bell said: "lose locality or lose reality"

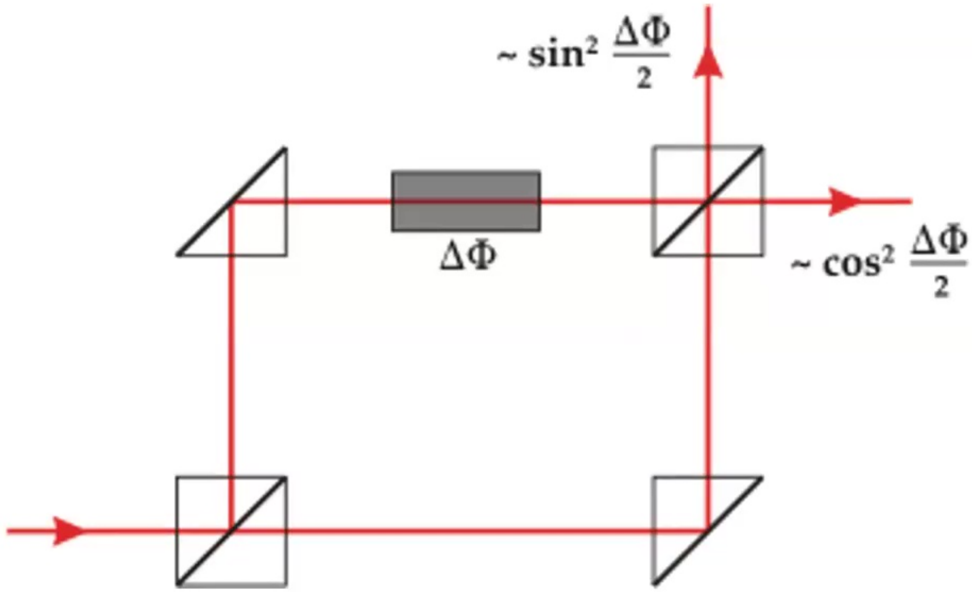
$$|\psi^-\rangle = |\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle$$

$$|\psi^-\rangle = |\rightarrow\rangle|\leftarrow\rangle - |\leftarrow\rangle|\rightarrow\rangle$$

Key conclusion: the value of spin does not exist before it is measured! Randomness and breakaway from classical reality and causality.
Or, the value of the spin (or anything else) is a q-number.

V.V., arXiv:2011.01039

Quantum Interference



$$|0\rangle\, e^{i\theta}|1\rangle + |1\rangle|0\rangle = e^{i\theta}|0\rangle|1\rangle + |1\rangle|0\rangle$$

$$|0\rangle|1\rangle + e^{-i\theta}\, |1\rangle|0\rangle = |0\rangle|1\rangle + |1\rangle\, e^{-i\theta}\, |0\rangle$$

Local description (Heisenberg)

Beables are quables. There are always there, independently of us.

$(a_L + a_L^+,\ a_R + a_R^+)$ after the first beam-splitter

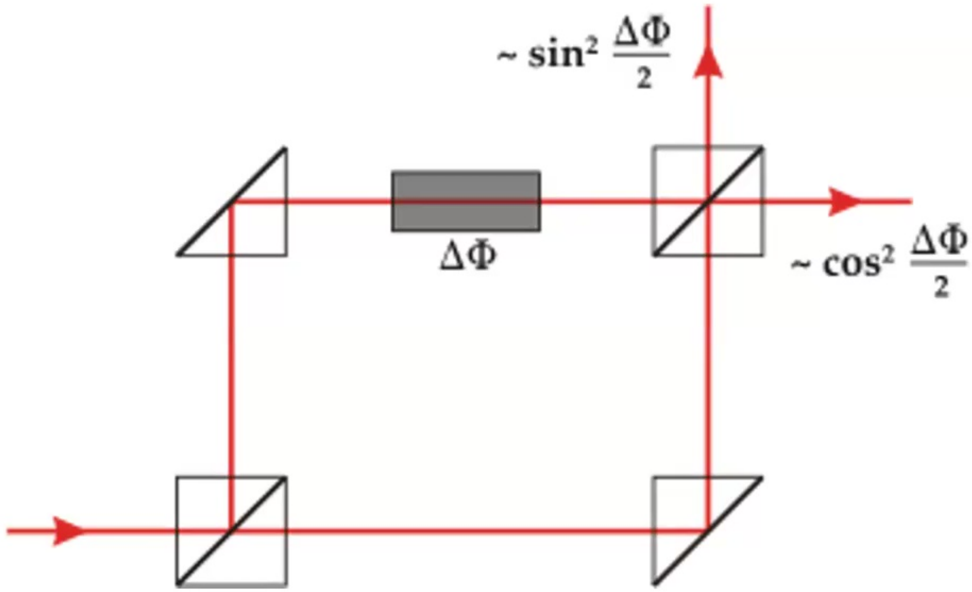
$(e^{i\theta} a_L + e^{-i\theta} a_L^+,\ a_R + a_R^+)$ after the phase kick in the left arm

$(e^{i\theta} a_L + e^{-i\theta} a_L^+ + a_R + a_R^+,\ e^{i\theta} a_L + e^{-i\theta} a_L^+ - a_R - a_R^+)$ end

Calculate the expected value of number in L (or R).

V.V., arxiv 2104.11333

Quantum Interference



$|0\rangle e^{i\theta}|1\rangle + |1\rangle|0\rangle = e^{i\theta}|0\rangle|1\rangle + |1\rangle|0\rangle$

$|0\rangle|1\rangle + e^{-i\theta} |1\rangle|0\rangle=|0\rangle|1\rangle + |1\rangle e^{-i\theta} |0\rangle$

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$(a_L + a_L^+, \; a_R + a_R^+)$ after the first beam-splitter

$(e^{i\theta} a_L + e^{-i\theta} a_L^+, \; a_R + a_R^+)$ after the phase kick in the left arm

$(e^{i\theta} a_L + e^{-i\theta} a_L^+ + a_R + a_R^+, \; e^{i\theta} a_L + e^{-i\theta} a_L^+ - a_R - a_R^+)$ end

Calculate the expected value of number in L (or R).

V.V., arxiv 2104.11333

Interference

$$<(e^{i\theta} a_L + e^{-i\theta} a_L^{+} + a_R + a_R^{+})^{+} (e^{i\theta} a_L + e^{-i\theta} a_L^{+} + a_R + a_R^{+})>$$

$$=< a_L^{+} a_L + a_R^{+} a_R + e^{-i\theta} a_L a_R + H.C.>$$

$$=(1+\cos(\theta))/2=\cos^2 \theta/2$$

The cross terms carry the phase information.

But it is only after the second beam-splitter that the phase “exists” in both arms!

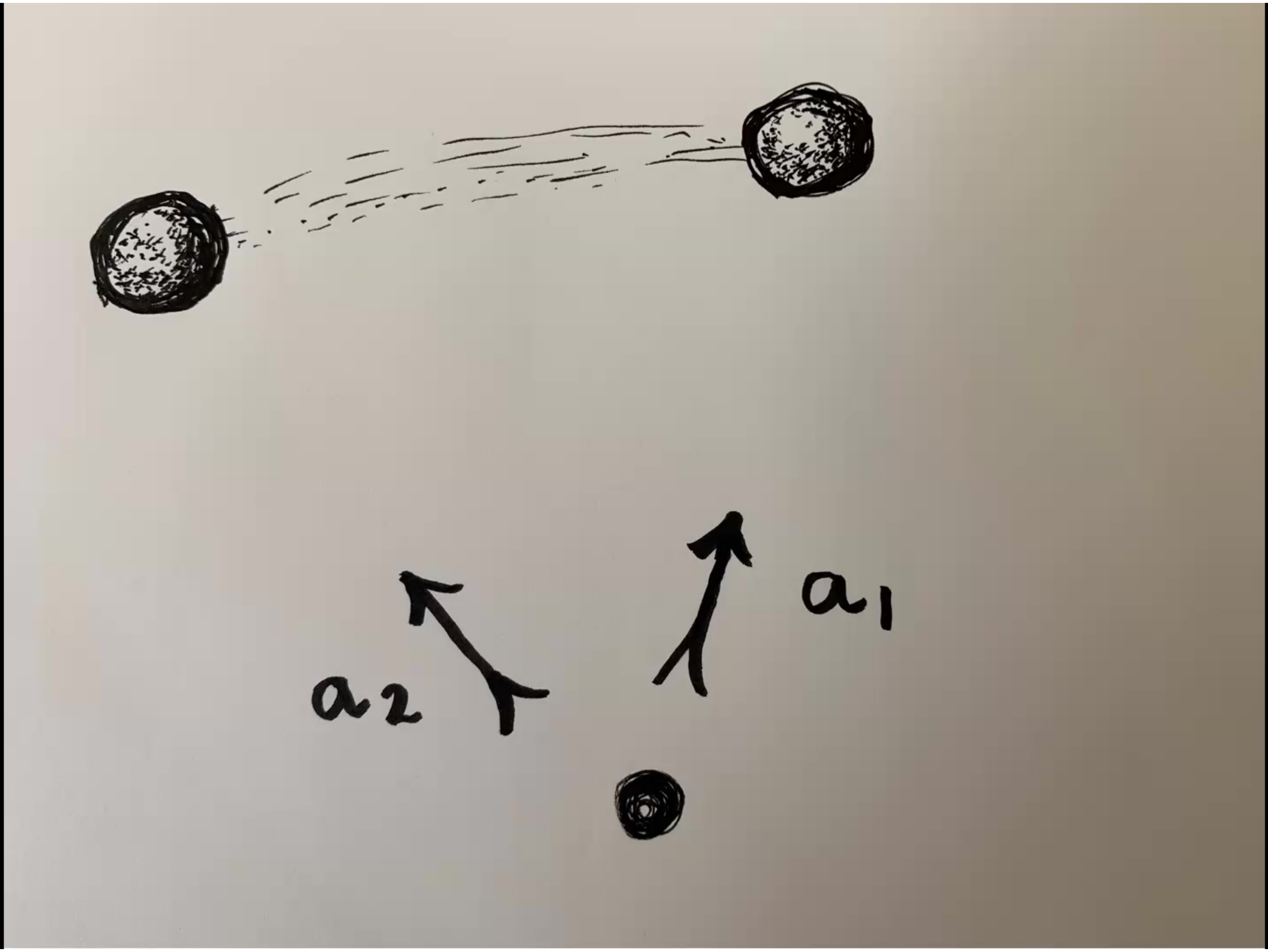
C. Marletto, A. Tibau Vidal, V. Vedral, arxiv 2020.

Equivalence principle

- A mass in a spatial superposition. How does a nearby point mass react to it?

“Totalitarianism” says it will become entangled to the first mass.

C. Marletto and V. V., Front. Phys., 28 May 2020


a1
a2

t cubed and all that

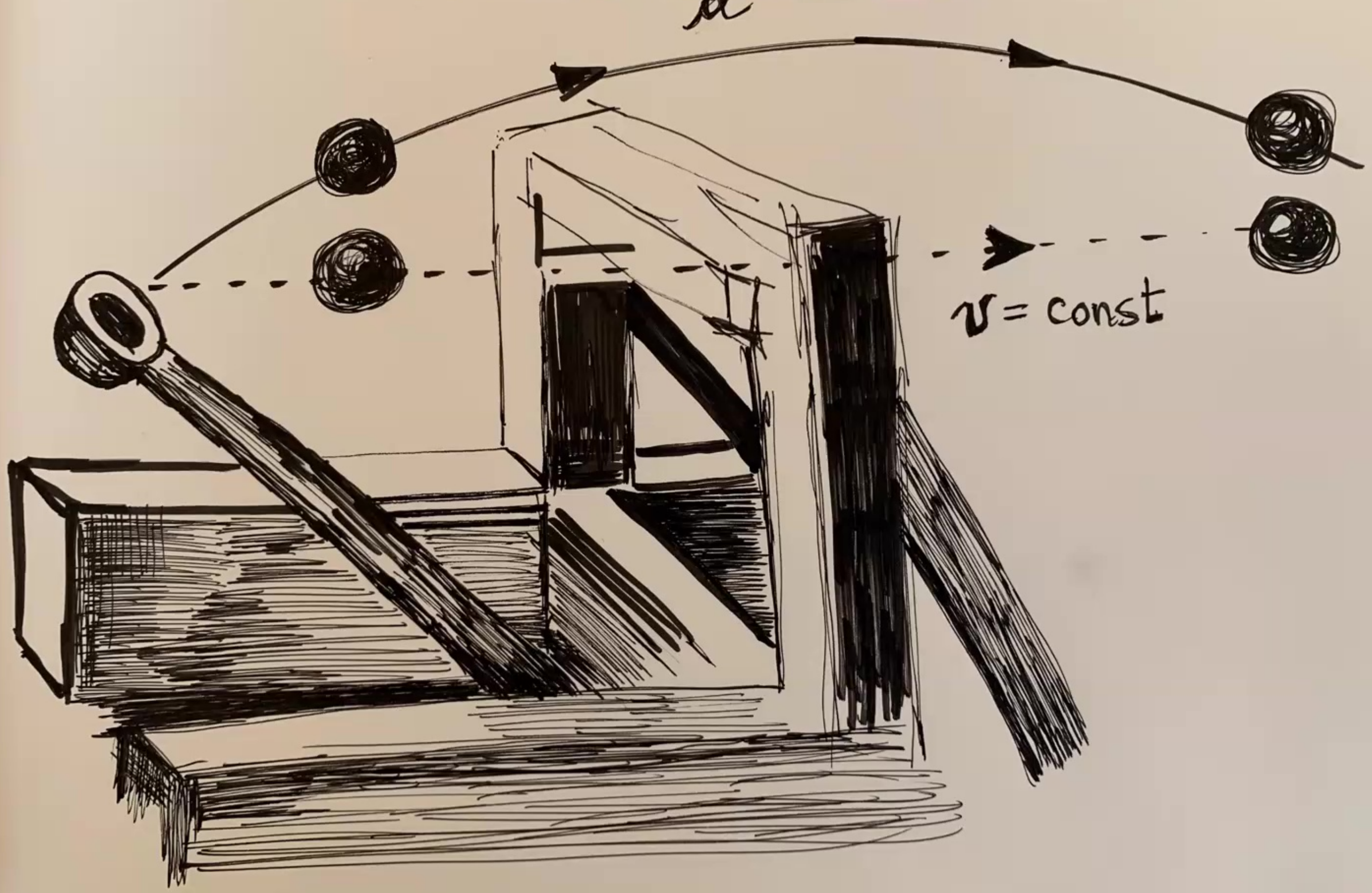
There is also no problem with superposition of inertial and non-inertial motions.

In addition to the m g h t term, there is a t^3 term.

<u>All this is still in the semiclassical regime.</u>

Marletto, Vedral, Frontiers in Physics (2020).

An interference test



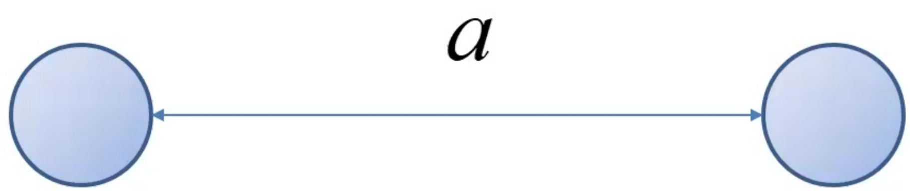
The problem of time?

This is an issue for any dynamical theory.

- Closed system can be described by a time independent equation from which time can arise in a relative way (e.g. Page-Wootters)
- Superposing different times is not a problem (but a consequence of quantum physics and relativity).
- Spacetime may well be a convenient fiction.

Marletto and Vedral, PRD (2017).

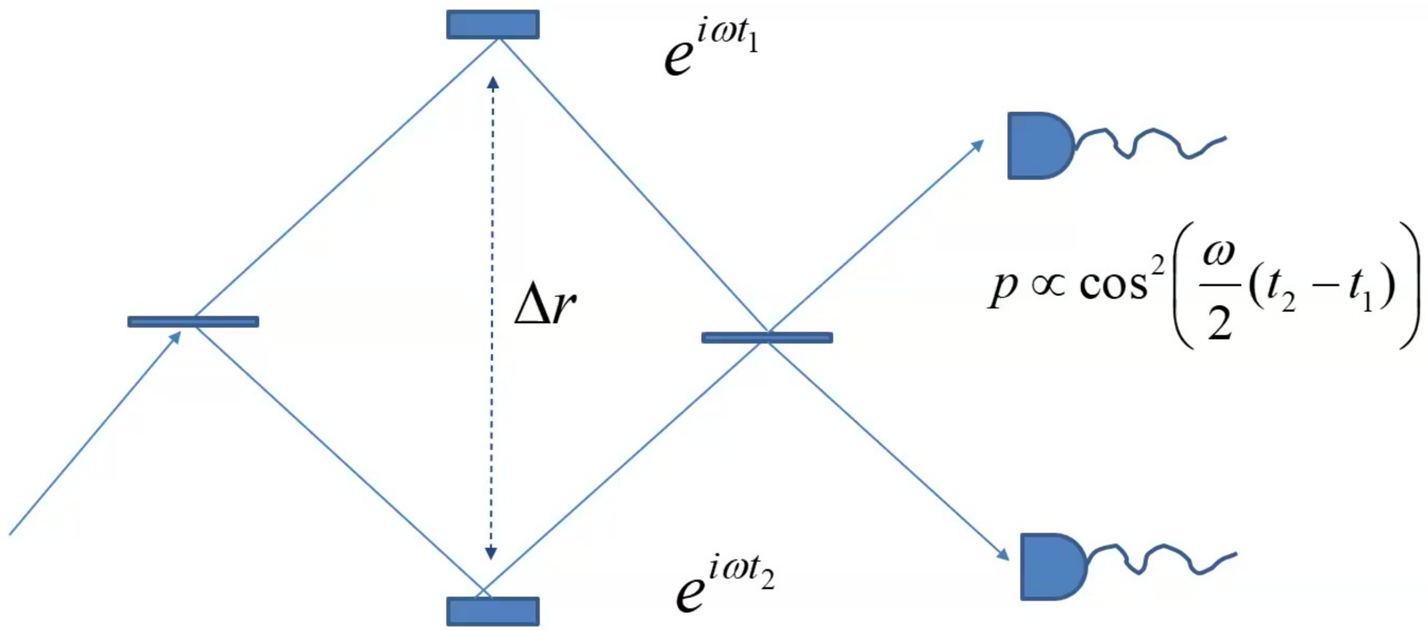
Classical vs quantum: a single superposition doesn't tell us much!



$$\left(|x\rangle + |x+a\rangle\right)_m \otimes |\alpha\rangle_g \xrightarrow{U?}$$

$$|x\rangle_m \otimes |\alpha\rangle_g + |x+a\rangle_m \otimes |\alpha'\rangle_g$$

Interferometers



Reversibility

- Classical gravitational noise –such as time dilation - can be undone by rotating the system (spin echo style)

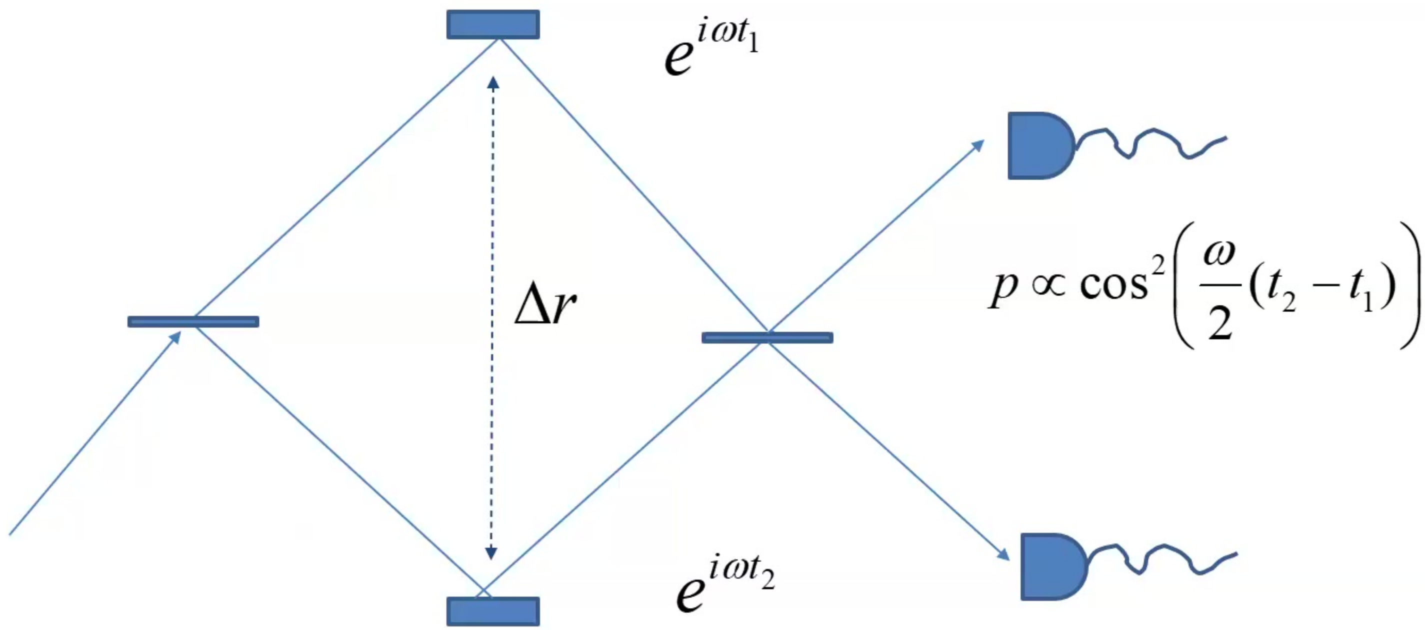
$$\left|x_1\right\rangle + \left|x_2\right\rangle \xrightarrow{\;U\;} e^{i\varphi_1}\left|x_1\right\rangle + e^{i\varphi_2}\left|x_2\right\rangle \xrightarrow{\;NOT\;}$$

$$e^{i\varphi_1}\left|x_2\right\rangle + e^{i\varphi_2}\left|x_1\right\rangle \xrightarrow{\;U\;}$$

$$e^{i(\varphi_1+\varphi_2)}\left|x_2\right\rangle + e^{i(\varphi_1+\varphi_2)}\left|x_1\right\rangle = e^{i(\varphi_1+\varphi_2)}\left(\left|x_1\right\rangle + \left|x_2\right\rangle\right)$$

- Quantum cannot unless we can act on the gravitational field too! (fake noise included)

Interferometers



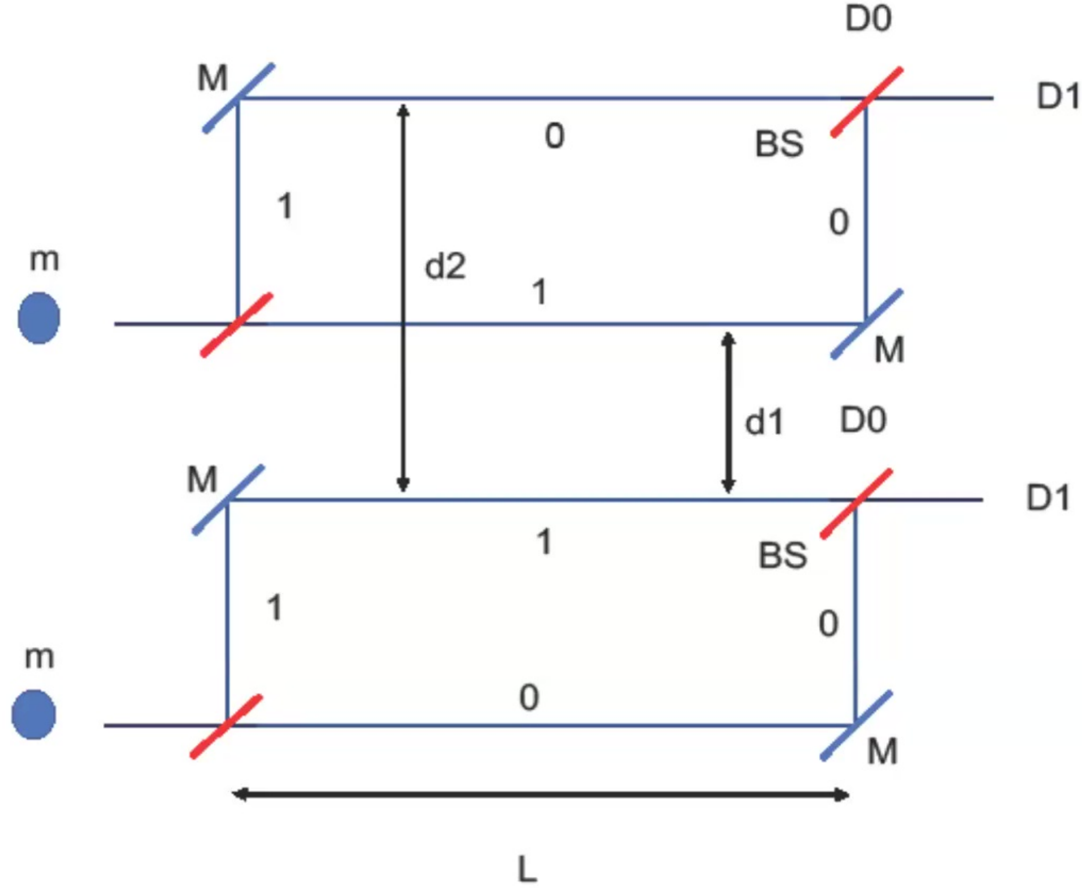
Gravity has to be quantum because of entanglement

- If a system can induce entanglement between two other systems by acting locally (with each), then that system has got to be quantum (i.e. it has to have complementary degrees of freedom).

Witness gravity's quantum side in the lab, Marletto & Vedral, Nature 2017.

Marletto and V.V. PRL 2017, Bose et al. PRL 2017.

An experiment with gravity



How the masses get entangled

$$|00\rangle + |01\rangle + |10\rangle + |11\rangle \Rightarrow$$

$$|00\rangle + |01\rangle + |10\rangle + e^{i\varphi}|11\rangle$$

$$\varphi = \frac{Gm^2}{\hbar d_1} t$$

For maximum entanglement

$$\varphi = \pi$$

$$|0\rangle(|0\rangle + |1\rangle) + |1\rangle(|0\rangle - |1\rangle)$$

Entanglement

- If we never allow any complementarity in the gravitational field, then the two masses can actually never get entangled.
- Hence, this experiment could probe if gravity is quantum and rule out all semi-classical and collapse models.
- The challenge would be to eliminate other possible sources of decoherence.
- Interestingly, there is entanglement between
  the field and the masses, though it is very small.

$$E_{mg} = 1 - \exp\left(-\frac{m^2}{m_P{}^2} \right)$$

Marletto, Vedral, Deutsch, J. Phys. Comm. (2018).

Some numbers

$$m \approx 10^{-12} kg;$$

$$d \approx \mu m;$$

$$t \approx \mu s$$

Could be a problem with many implementations since noise could be faster.

$$E_{mg} = 1 - \exp\left(-10^{-8}\right) \approx 0$$

…But collapse and QFT in curved space ought to disagree

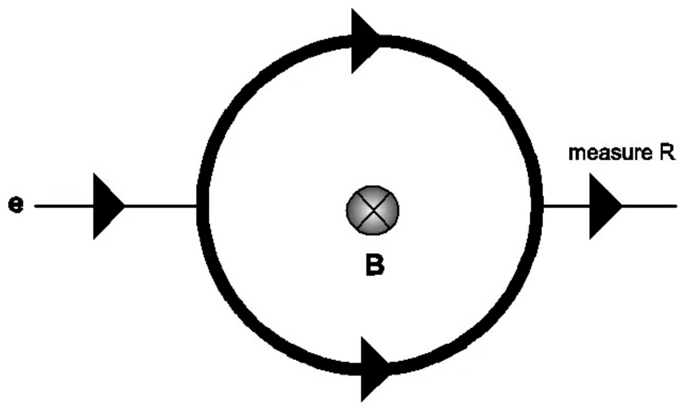
- Collapse implies that neither of the interferometers will show any interference (beyond some mass, of course);

- QFT in curved space would say that each mass experiences the average gravitational field of the other – so they can never become entangled!

- Induced gravity?

Non-local observables?

AB sometimes claimed to be non-local



Phase shift is the geometric phase

$$\Delta\phi = \frac{q}{\hbar}\oint \mathbf{A}.d\mathbf{r}$$

$$= \frac{q}{\hbar}\int_S \nabla \times \mathbf{A}.d\mathbf{S}$$

$$= \frac{q}{\hbar}\int_S \mathbf{B}.d\mathbf{S}$$

$$\Delta\phi = \frac{q\Phi_B}{\hbar}$$

Y. Aharonov & D. Bohm, Phys. Rev. **115** 485-491 (1959).

A perfectly local description given by: Marletto and Vedral, Phys. Rev. Lett. 125, 040401 (2020).

Conclusions

- General relativity is not apriori incompatible with quantum mechanics;
- Beables are q numbers and the locality in quantum physics is of the same type as in any field theory including GR;
- Quantum effects in the gravitational field can be tested with the preset technology and appear in the lowest Newtonian order;
- The non-linear quantum effects are so small that non-renormalizability could well be irrelevant. Although I don't know about the very early universe.
- We desperately need experimental tests.

Marletto, Vedral, Rev. Mod. Phys. To appear 2025