13/07/2026 Queen Mary

Laboratory-based tests of quantum effects in the gravitational field

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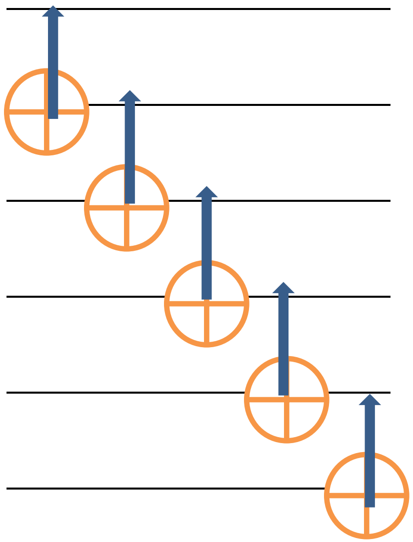
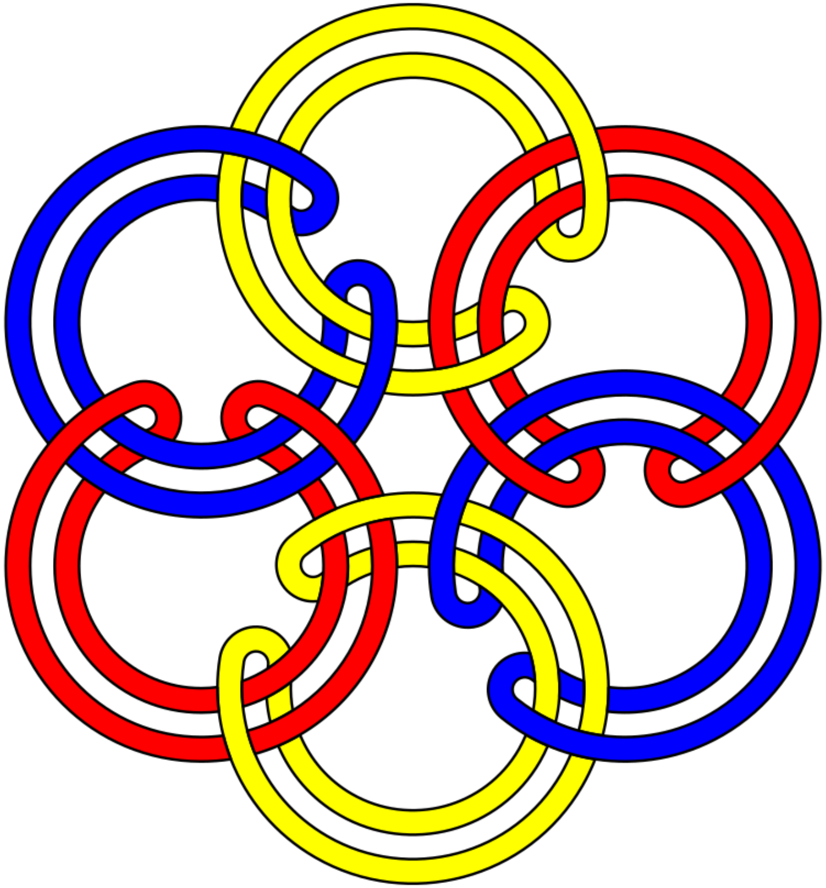
Universal quantum

- Measurement is just creation of entanglement between an observer and the system
- Observer is just another physical system with no other special properties
- There are no collapses, no quantum jumps, no discontinuities, no spooky actions at a distance
- Fundamental elements of reality are q-numbers

Classicality arises because of entanglement





"United we are entangled, divided we become classical!"

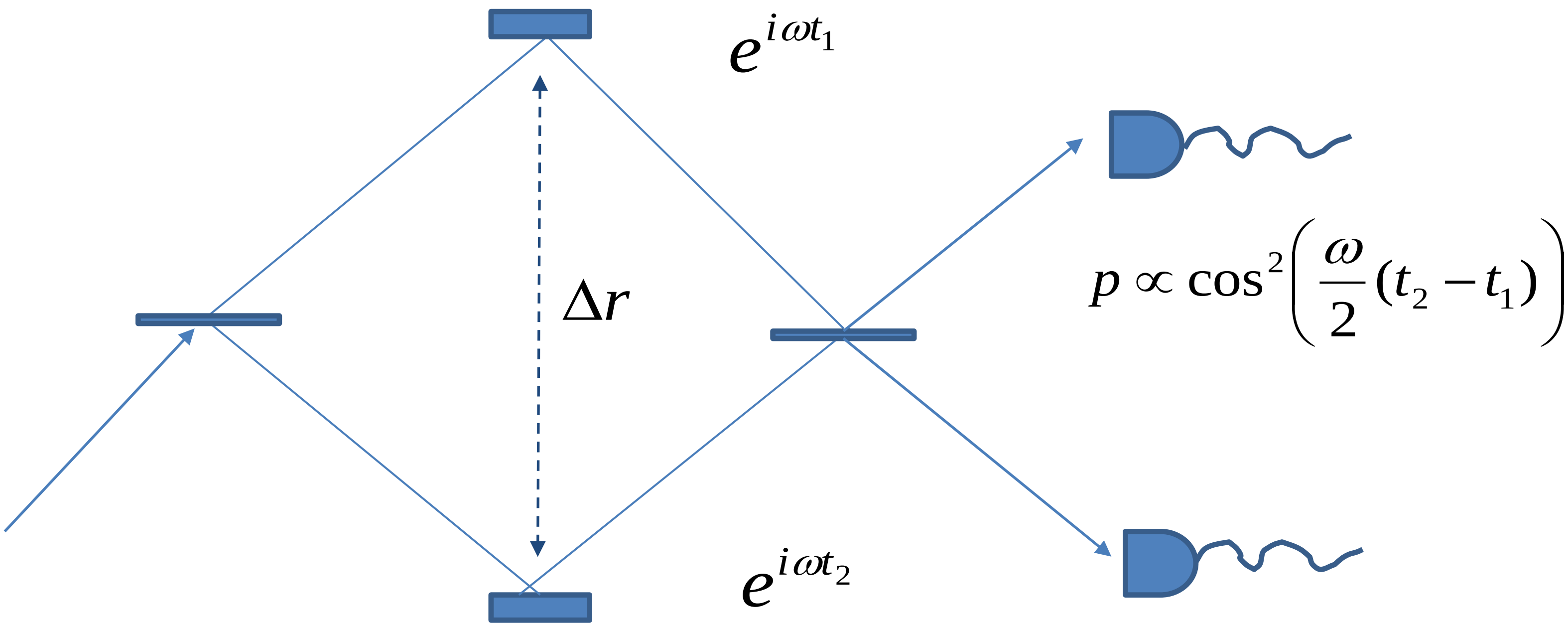
Time Dilation in GR

- Gravity is the “flow of time from space to space”
- A clock closer to a massive object runs slower than a clock further away.

The difference dt/t is 1 part in 10 to the power of 16 per meter
In Earth’s gravitational field. Certainly accessible to atomic clocks

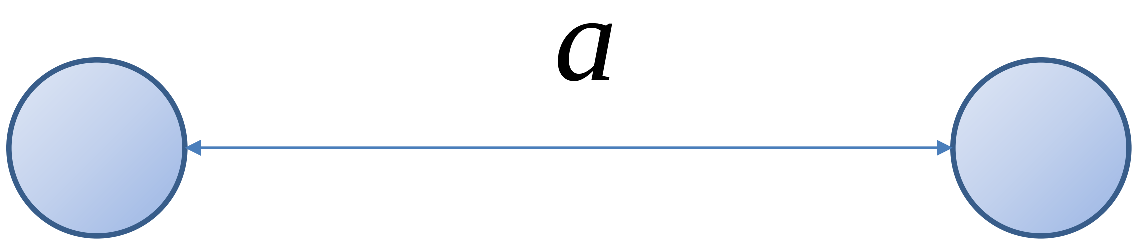
Quantum clock in two gravities

But can this difference affect superpositions of one clock at two different heights?



$$\Delta\varphi = \omega\Delta t = \frac{mc^2}{\hbar}\Delta t = \frac{mg\Delta r\,\tau}{\hbar} + \frac{mg^2(\Delta r)^2\tau}{c^2\hbar} + \dots$$

Classical vs quantum – "collapse" doesn't tell us much!



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

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

And neither does a successful interference…

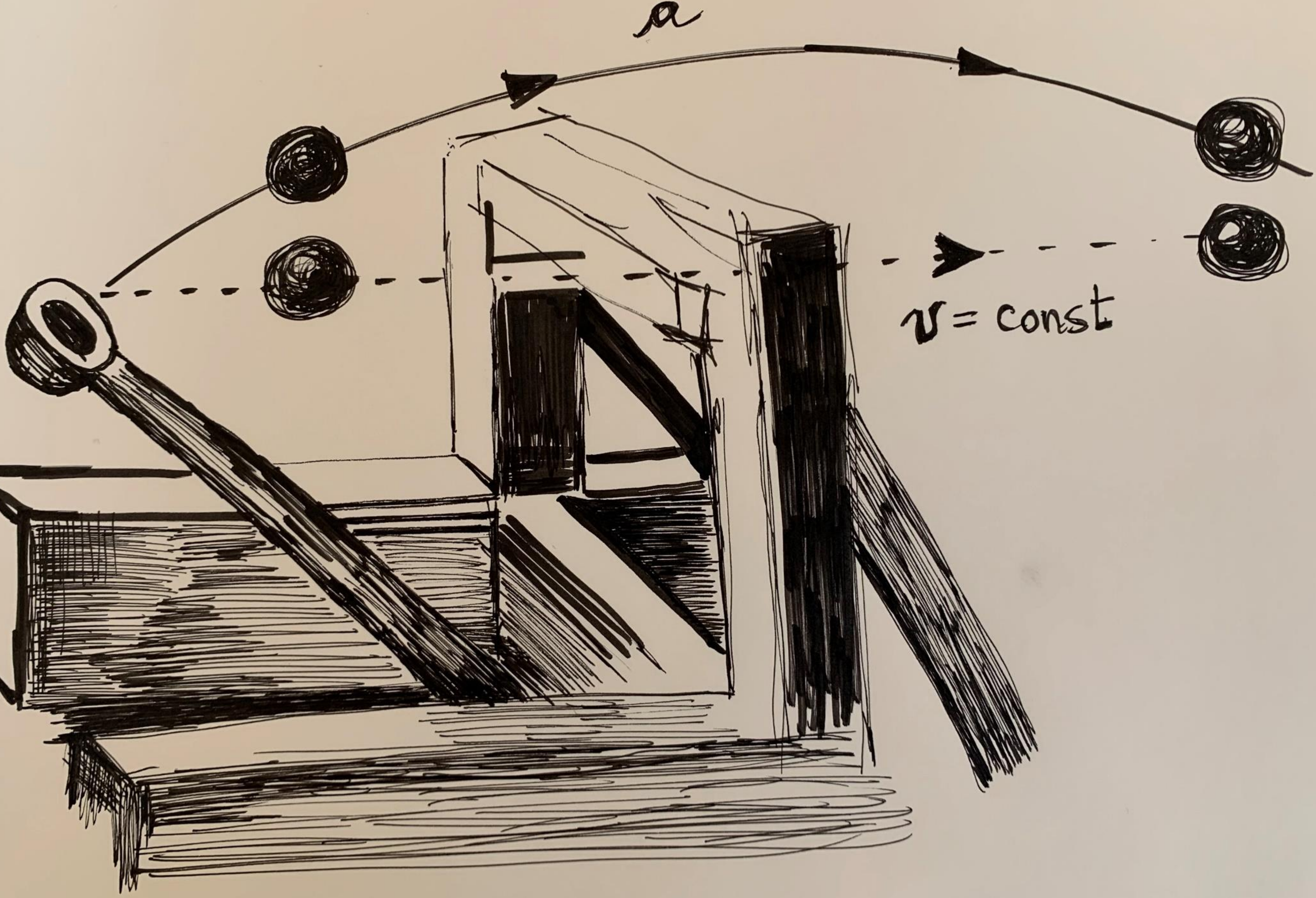
Quantum Equivalence principle I

- A mass in a spatial superposition of two different gravitational accelerations. How is the equivalence principle upheld?

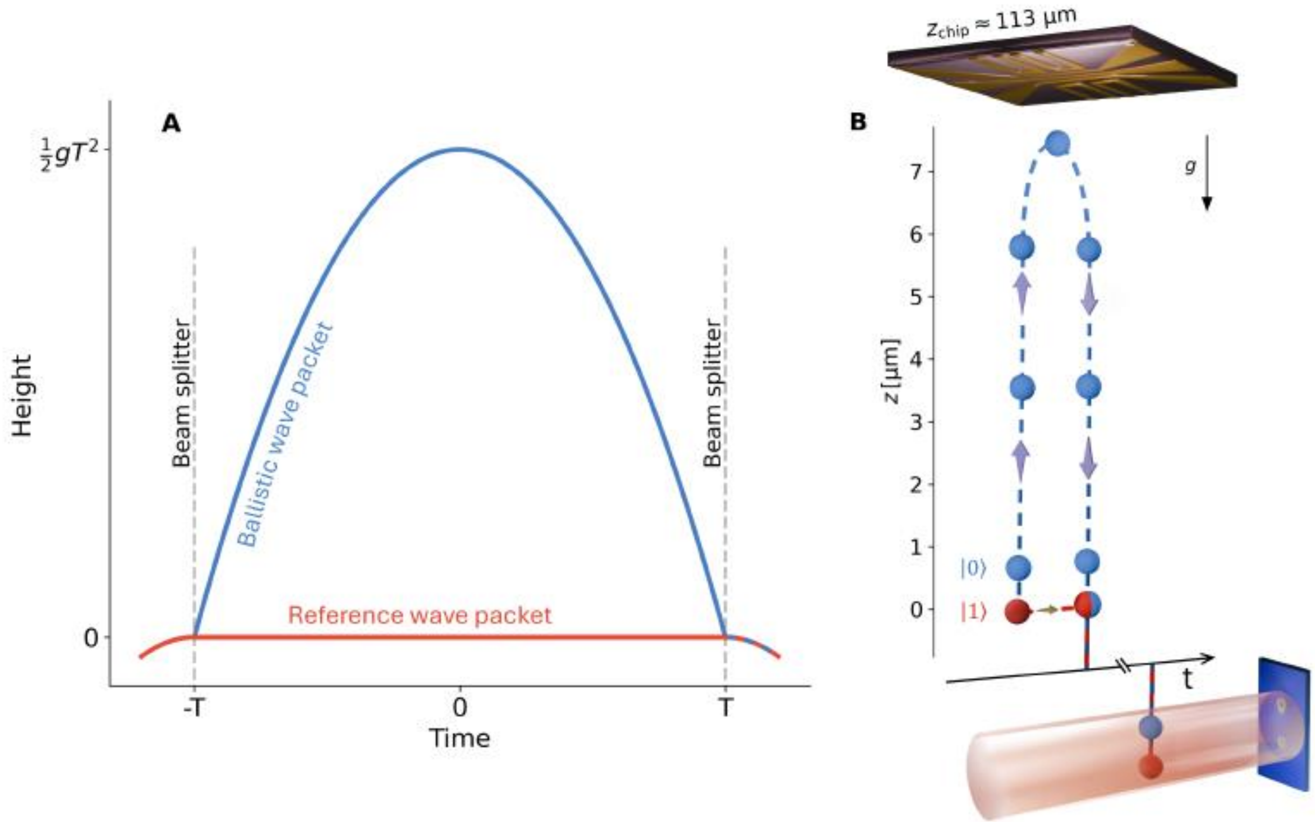
- In a branch-by-branch way

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

An interference test



Folman’s experiment

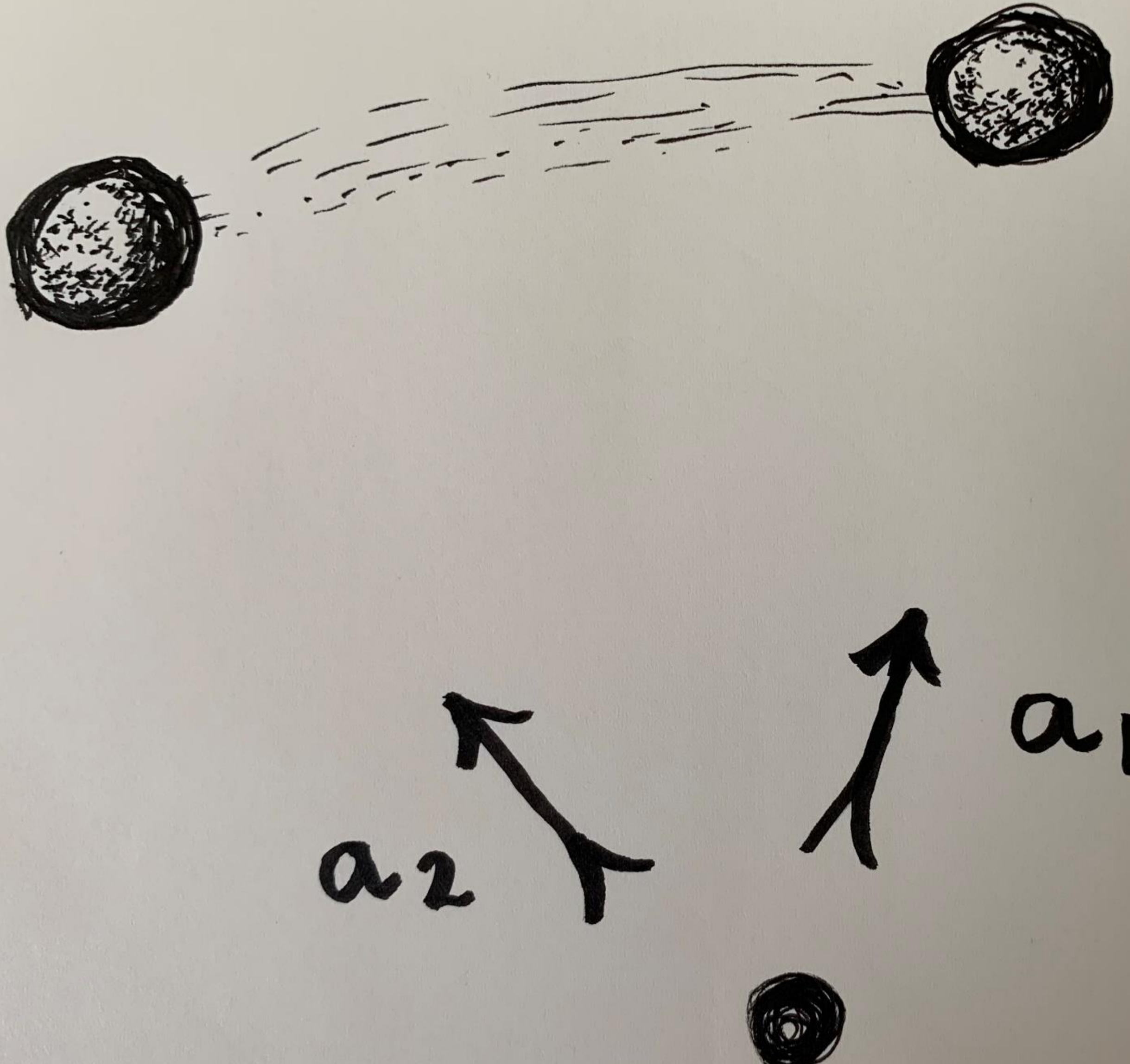


- Or Dobkowski, Barak Trok, Peter Skakunenko, Yonathan Japha, David Groswasser, Maxim Efremov, Chiara Marletto, Ivette Fuentes, Roger Penrose, Vlatko Vedral, Wolfgang P. Schleich, Ron Folman, arxiv 2025.

Quantum Equivalence Principle II

Acceleration and gravity are locally indistinguishable.

If a massive object is in a superposition of two locations, how does another test mass respond to it?


a1
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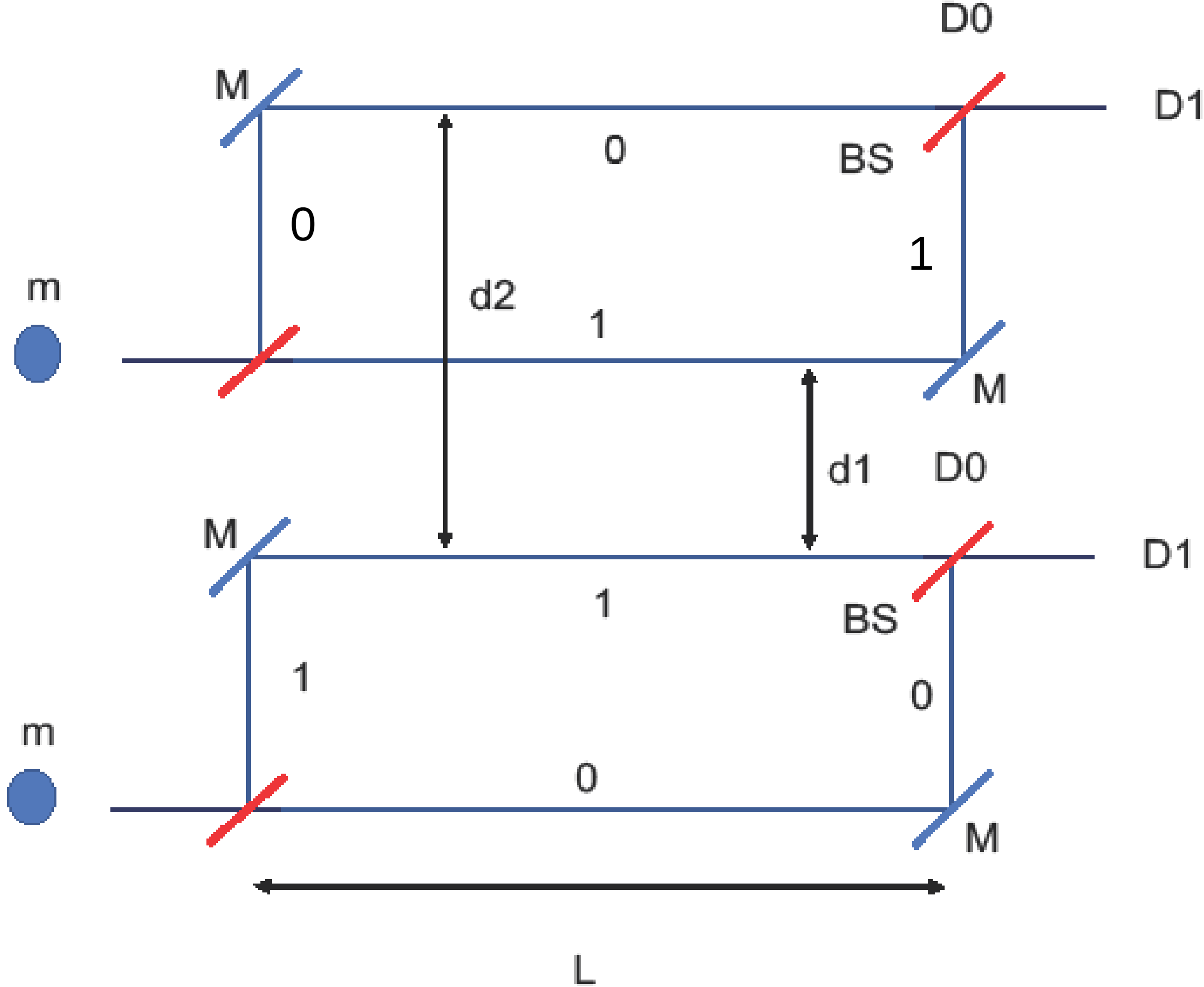
Totalitarianism

- Anything that couples to a quantum superposition becomes entangled to it.

- Schrödinger’s cat.

C. Marletto and V. Vedral, Rev. Mod. Phys. (2025).

Testing Quantum Gravity



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.

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

$$\varphi = \pi$$

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

Some numbers leading to max ent

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

$$d \approx \mu m;$$

$$t \approx \mu s$$

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

Linear quantum gravity and EM

Which GR degrees of freedom do not commute?

- g is like A
- Γ is like F

Peres and Rosen 1960

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.

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

All canonical approaches should agree in this regime…

$$H = mc^2(b_1^{+}b_1 + b_2^{+}b_2) + \sum_k \hbar\omega_k a_k^{+} a_k +$$

$$\sum_k \hbar g_k^1 b_1^{+} b_1 (a_k + a_k^{+}) + \hbar g_k^2 b_2^{+} b_2 (a_k + a_k^{+})$$

$$|1\rangle_{r_1}|1\rangle_{r_2}|0\rangle \rightarrow e^{i\int \frac{\left(g_k^1 e^{ikr_1} + g_k^2 e^{ikr_2}\right)^2 dk}{\omega_k} t} |1\rangle_{r_1}|1\rangle_{r_2} \prod_k \left| \frac{g_k}{\omega_k}\left(1 - e^{-i\omega_k t}\right) \right\rangle$$

$$\int \frac{\left(g_k^1 e^{ikr_1} + g_k^2 e^{ikr_2}\right)^2 dk}{\omega_k} = \frac{Gm^2}{\hbar |r_1 - r_2|}$$

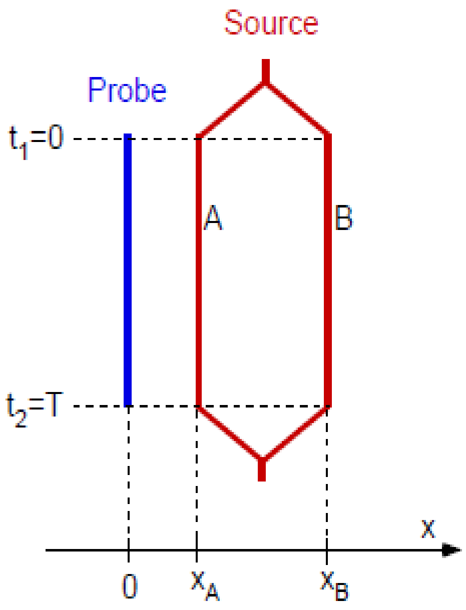
Marletto, Vedral, Rev. Mod. Phys. (2025).

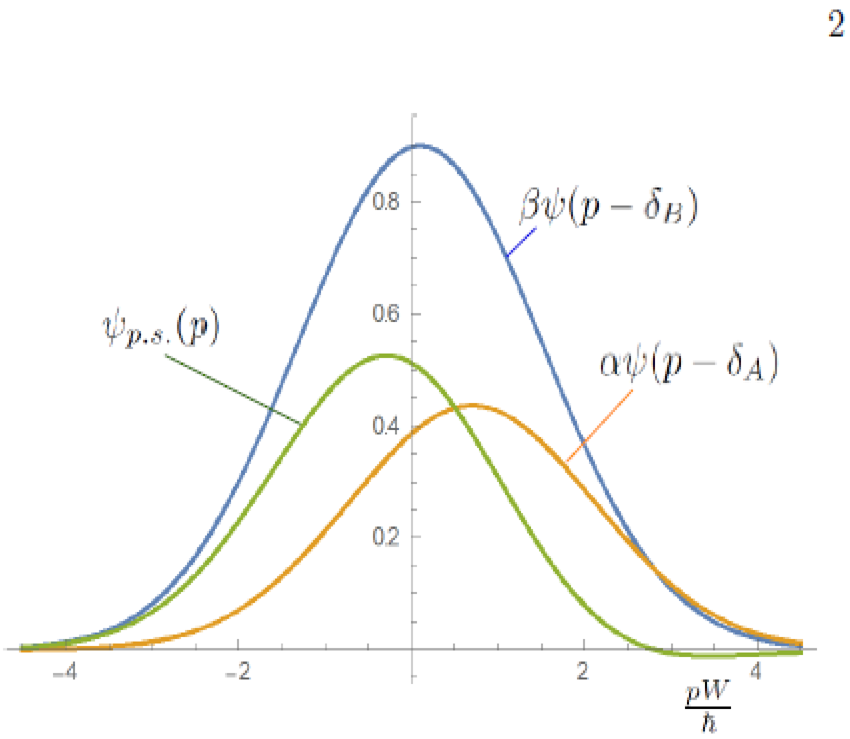
…But collapse and QFT in curved space ought to disagree

- 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!

Anti-gravity as a Witness?





Saldanha, Marletto, V.V., arxiv 2026

Final Thoughts

- 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 present technology and appear in the lowest Newtonian order;
- The non-linear quantum effects are so small that non-renormalizability could well be irrelevant.
- We desperately need experimental tests.