Gravity mediated entanglement

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i. Why gravity mediated entanglement in the lab are interesting

ii. What can the teach us

iii. Long term perspective

Quantum matter in a gravitational field $\neq$ quantum properties of gravity itself

Can we observe a genuine quantum gravitational phenomenon?

So far, none has been observed.

Observing one would a truly major scientific result

We have many good tentative theories of quantum gravity

Perturbative quantum general relativity

Loop Quantum Gravity

String theory

…

They all imply the same predictions regarding quantum gravity effects at the lab scale (as far as we can see). (But see point iii, later.)

No hope of distinguishing among these with lab experiments, for the moment, as far as I know.

There are also some (in my opinion not much credible) alternative speculations

Gravity is always classical

$$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi \langle T_{ab} \rangle$$

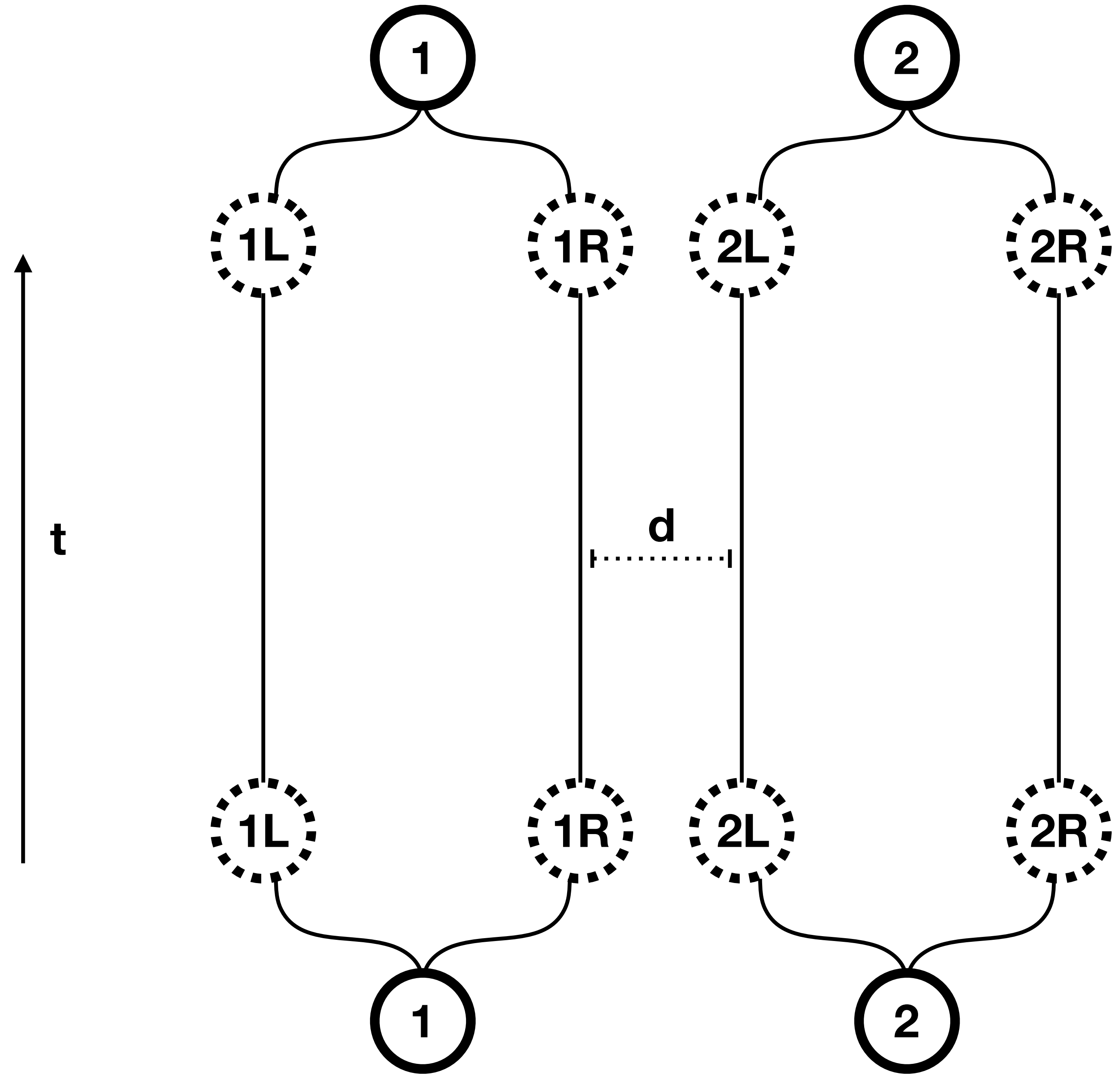
Gravity induced collapse models

Lab experiments count as strong negative confirmation against these

But the real scientific value is not so much to rule out implausible hypotheses

It is to actually witness a quantum gravitational phenomenon

Gravity mediated entanglement



$$|\psi\rangle = (|1x\rangle + |1x'\rangle) \otimes (|2y\rangle + |2y'\rangle)$$

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$$|\psi(t)\rangle = |1x\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y}t} + |1x'\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t} + |1x\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y'}t} + |1x'\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t}$$

$$\frac{Gm^2}{\hbar \Delta x} t \sim \pi$$

The two particles end up entangled

S Bose, A Mazumdar, GW Morley, H Ulbricht, M Toroš, M Paternostro, A Geraci, P Barker, MS Kim, G Milburn 2017.
C Marletto, V Vedral 2017.

The effect can be calculated assuming only

- Quantum particles
- Long-range instantaneous Newton interactions

But we know that there are no long-range instantaneous interactions.
These are only approximations of an actual **field** theory.

If we fold this knowledge in, we see that the field itself must be different in the different branches, in order for the effect to exit.

Hence the gravitational field must be in a quantum superposition of different configurations.

But we know that the gravitational field is the metric of spacetime

Hence spacetime metric must be in a quantum superposition of different configurations, for the effect to be real.

From:

- our knowledge about gravity that comes from relativity

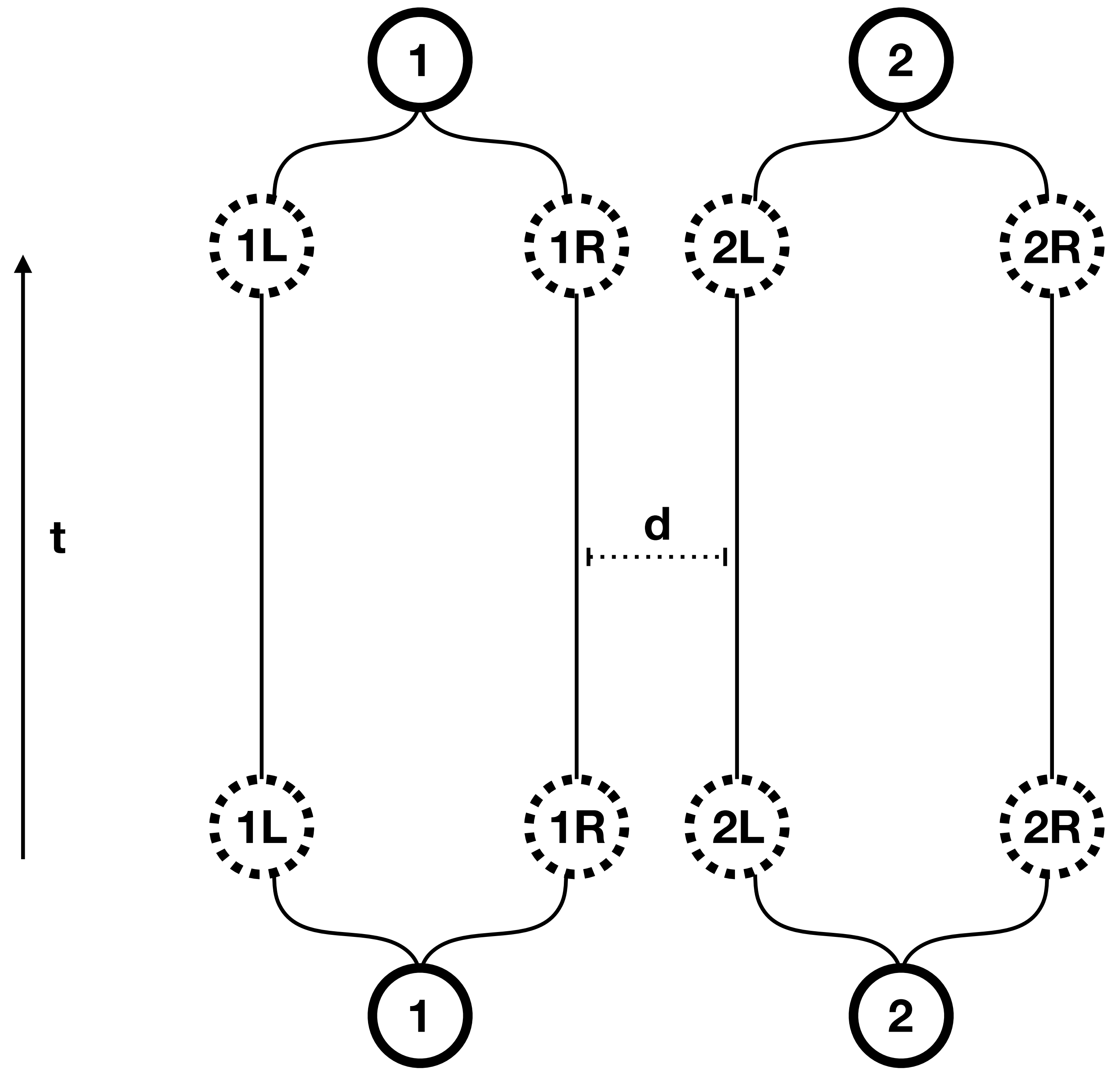
+

- a positive result of the GE experiment

It follows that :

- **spacetime geometries can be in quantum superposition**
- **namely a genuine quantum gravitational effect.**

Gravity mediated entanglement



$$|\psi(t)\rangle = |1x\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y}t} + |1x'\rangle \otimes |2y\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t} + |1x\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x-y'}t} + |1x'\rangle \otimes |2y'\rangle e^{\frac{i}{\hbar}\frac{Gm^2}{x'-y}t}$$

$$ds^2 = -\left(1 + \frac{2\Phi_1(x)}{c^2} + \frac{2\Phi_2(x)}{c^2}\right) dt^2 - d\vec{x}^2,$$

$$\frac{2\Phi_2(x)}{c^2} = -\frac{2Gm}{c^2 d}$$

$$\int \sqrt{-ds^2} = \int_0^T dt \sqrt{1 - \frac{2Gm}{c^2 d}}$$

$$\delta T = \frac{Gm}{c^2 d} T \qquad \delta\phi = \frac{mc^2 \delta T}{\hbar} = \frac{Gm^2 T}{d\hbar}. \qquad \delta\phi = \frac{m^2}{m_{Pl}^2} \frac{cT}{d}.$$

No action at a distance.

The entanglement is due to the proper-time difference between the branches: it is a genuine interference effect.

Christodoulou CR 2018

From:

- our knowledge about gravity that comes from relativity

+

- a positive result of the GE experiment

It follows that :

- spacetime geometries can be in quantum superposition
- namely **a genuine quantum gravitational effect**.

Newtonian gravity cannot be the static non relativistic limit of $$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi \langle T_{ab} \rangle$$

It is the static limit of a quantum field theory.

iii. Long term perspective

Can we hope along this direction to see genuine relativistic quantum gravity effects in the future?

Yes, is time is quantized at the Planck scale, pushing the experiments a few orders of magnitudes ahead in sensitivity, might give us access to the discreteness of time.

$$\delta\phi = \frac{mc^2\delta T}{\hbar}$$

$$\delta\phi = \frac{m}{m_{Pl}}\,\frac{\delta T}{t_{Pl}}$$

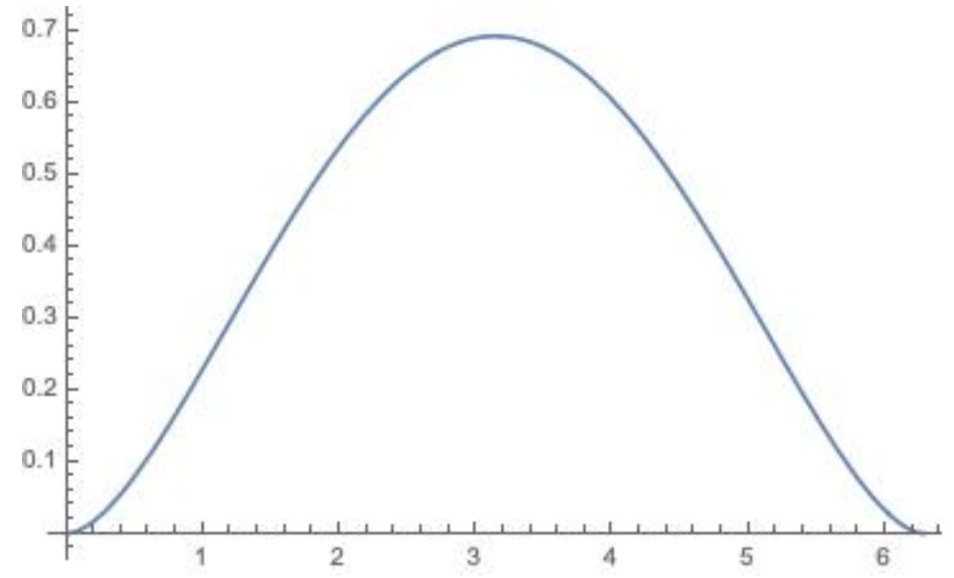


FIG. 1: The entanglement entropy for $\delta\phi \in \{0, 2\pi\}$.

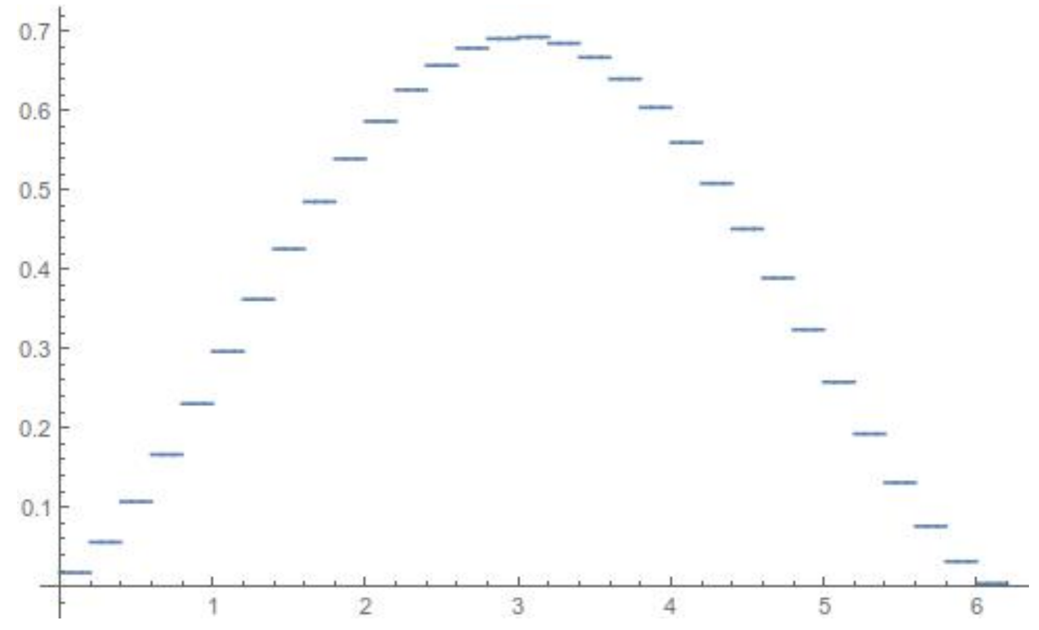


FIG. 2: The entanglement entropy for $\delta\phi \in \{0, 2\pi\}$ under the assumption that $\delta t/t_{Pl} \in \mathbb{N}^+$, for particles with mass one fifth of the Planck mass.

Christodoulou CR 2019

i. Why gravity mediated entanglement in the lab are interesting

- A genuine quantum gravitational effect:
  spacetime geometries can be in quantum superposition.

ii. What can the teach us

- That the basic ideas underpinning quantum gravity reproach are right
- That classical gravity or gravity induces entanglement are disfavoured

iii. Long term perspective

- Along this direction we could see the discreetness of time.