Probing the Quantum Nature of Gravity Through Classical Motion

University of Genova

13th March 2025

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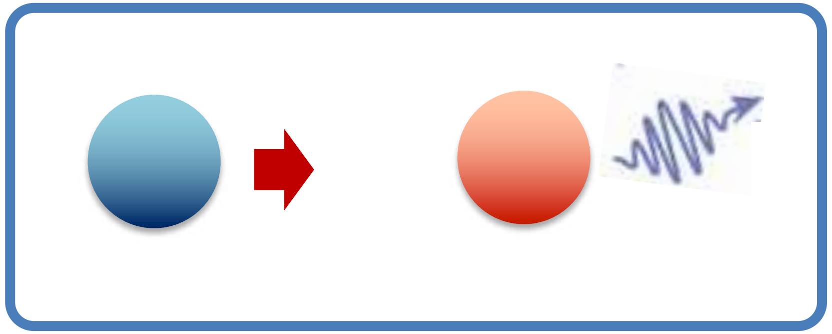
Is Gravity Quantum?

Very hard question: Does the graviton exist?



This is what high-energy people mean with quantum.
Roughly speaking, it requires reaching the Planck scale.

Detecting the graviton below the Planck scale?
J.D. Bekenstein, Phys. Rev. D 86, 124040 (2012)
D. Carney, P.C.E. Stamp, J.M. Taylor, Class. Quantum Grav. 36, 034001 (2019)
G. Tobar, S.K. Manikandan, T. Beitel, I. Pikovski, Nat. Comm. 7229 (2024)

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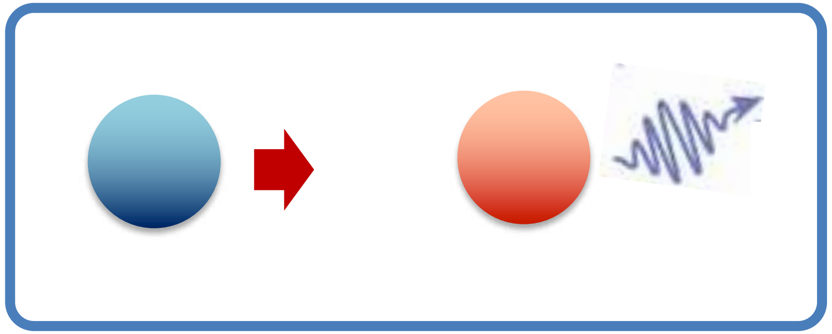

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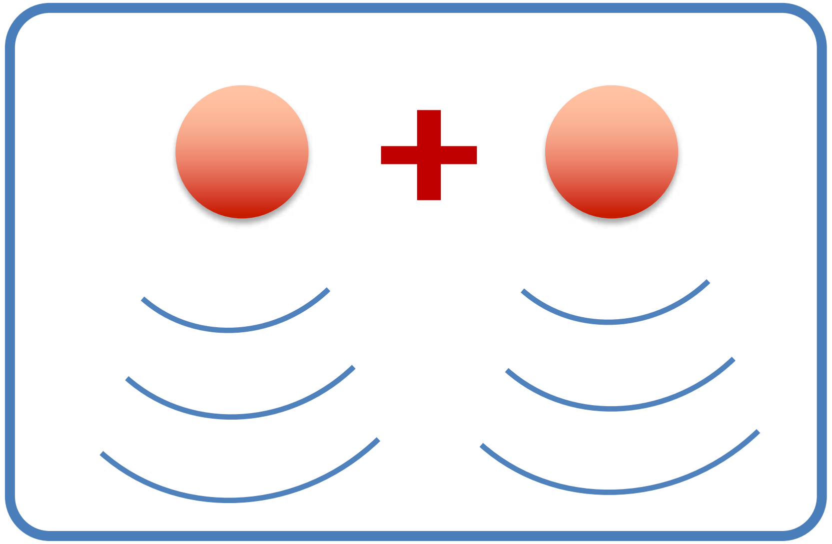
Less hard, but still hard question: Can the (static) gravitational field be in a superposition of states? Equivalently, does the Newtonian field enter the Schrödinger equation as the Coulomb field does?

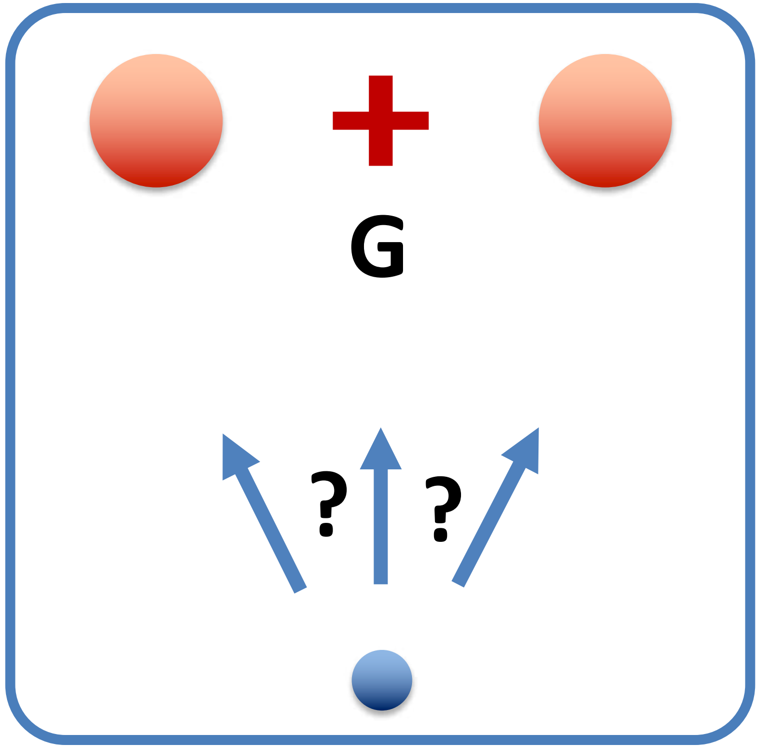


I will focus on this second question

Is Gravity Quantum (less hard question)?

Experimentally: we do not know.

We only now that **matter reacts** to an external classical gravitational potential as predicted by the **Schrödinger equation** (COW experiment, atom interferometry). We do not know what the gravitational field generated by a superposition is like.



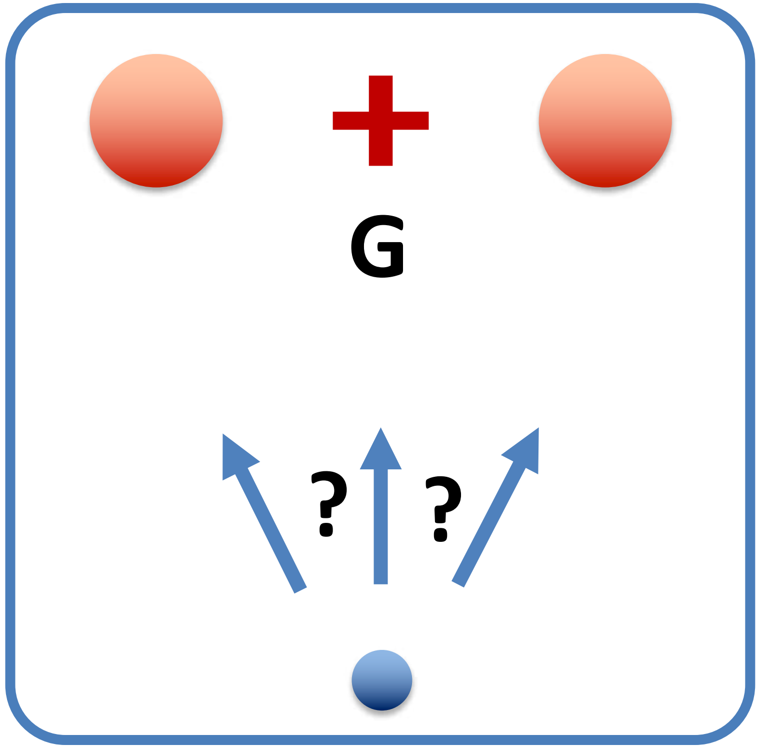
Is Gravity Quantum (less hard question)?

Experimentally: we do not know.

We only now that **matter reacts** to an external classical gravitational potential as predicted by the **Schrödinger equation** (COW experiment, atom interferometry). We do not know what the gravitational field generated by a superposition is like.

Theoretically: we do not know.

The general sentiment is that **gravity should be quantum**, like all other forces. Yet all attempts at quantizing gravity did not reach the expected results. Models of classical gravity exist (SN equation, LOCC models)



Schrödinger-Newton equation

L. Diosi. Physics Letters A 105, 199 (1984)

R. Penrose, Foundations of Physics 44 557 (2014)

LOCC models

D. Kafri, J.M. Taylor, and G.J. Milburn, NJP 16, 065020 (2014)

A. Tilloy, L. Diosi, Physical Review D 93, 024026 (2016)

B. J. Oppenheim, C. Sparaciari, B. Soda, Z. Weller-Davies. Nat. Comm. 14, 7910 (2023)

Testing the quantum nature of gravity

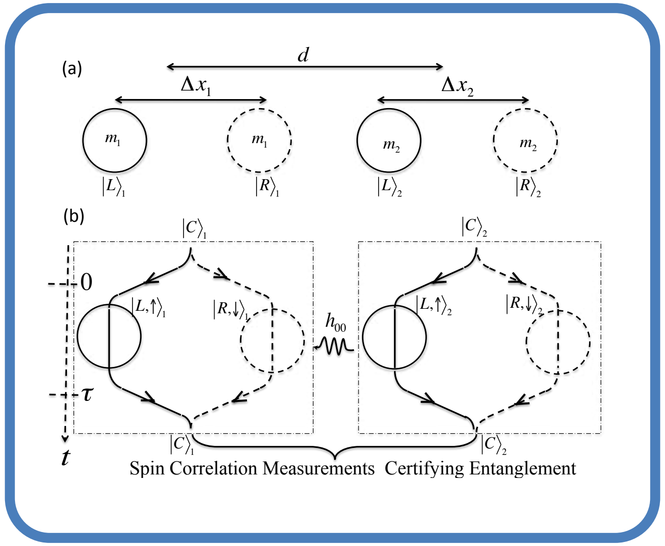
The main argument: a LOCC (local operation and classical communication) **cannot** generate entanglement.

Therefore, is entanglement is detected (and assuming locality), the interaction must be quantum.

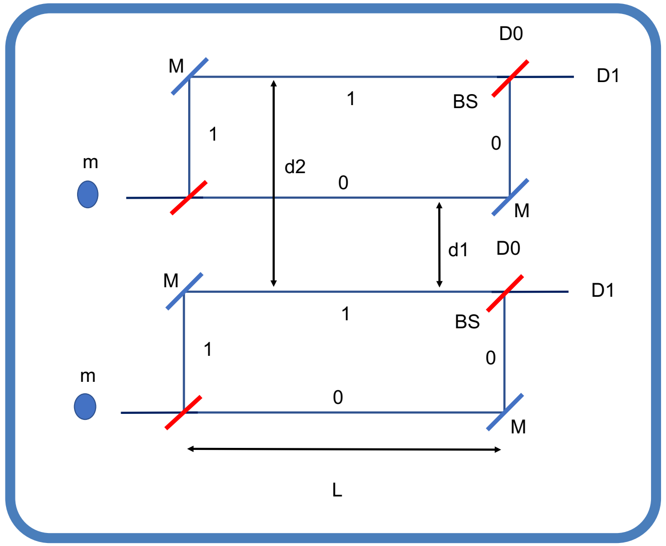
R. Horodecki, P. Horodecki, M. Horodecki, K. Horodecki, Reviews of Modern Physics 81, 865 (2009)

Quantum Gravity in the Lab 1

Idea: two adjacent interferometers to create superpositions and make them interact



S. Bose et al, PRL 119, 240401 (2017)



C. Marletto, V. Vedral, PRL 119, 240402 (2017)

$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2)$$

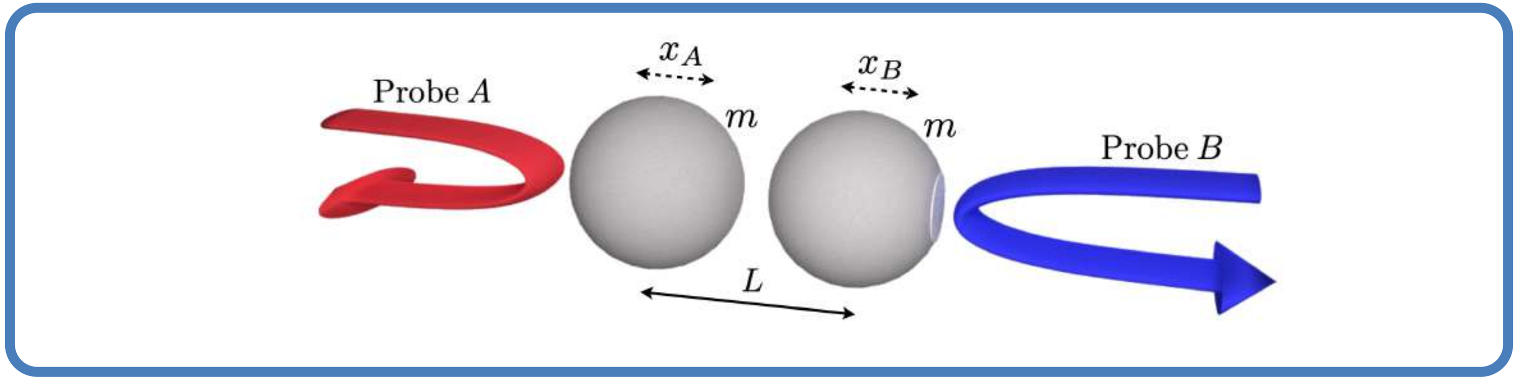
Factorized

$$|\Psi(t=\tau)\rangle_{12} = \frac{e^{i\phi}}{\sqrt{2}}\{|L\rangle_1 \frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2) + |R\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)\}$$

Entangled

Quantum Gravity in the Lab 2

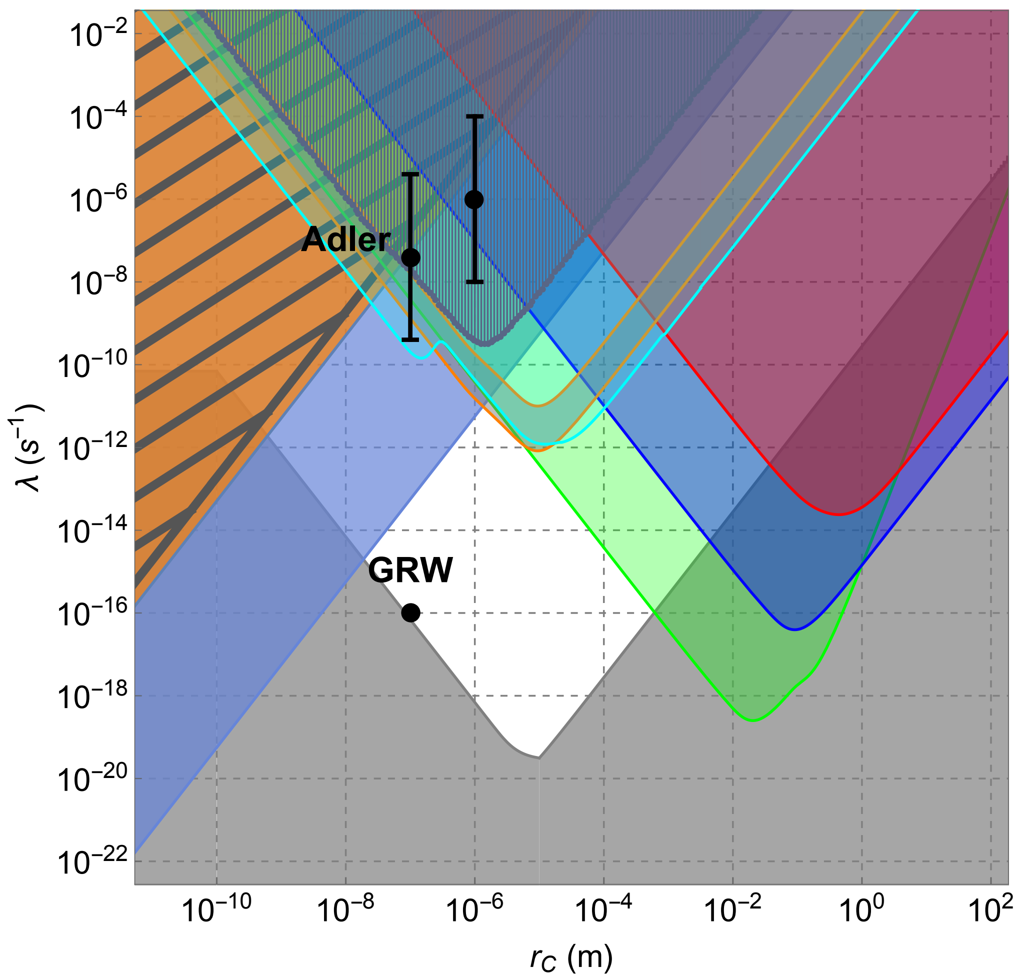
Idea: superpositions are not necessary to detect entanglement. Any quantum state will do.



T. Krisnanda, G. Yao Tham, M. Paternostro, T. Paterek, NPJ Quantum Information 6, 12 (2020)

Challenges

S. Rijavec, M. Carlesso, A. Bassi, V. Vedral, C. Marletto, NJP 23, 043040 (2021)



M. Carlesso, S. Donadi, L. Ferialdi, M. Paternostro, H. Ulbricht, A. Bassi, *Nature Physics 18, 243-250 (2022)*

Figure of merit

Performing these experiments would Improve tests of the CSL collapse model by **13 orders of magnitude** with respect to state of the art.

Tests not involving entanglement

L. Lami, J.S. Pedernales, M.B. Plenio, PRX 14, 021022 (2024)

How well can a LOCC simulate a unitary evolution?

Not perfectly. There is bound, which can be used to discriminate a unitary evolution from a LOCC.

Still, the protocol requires the preparation and control of the **quantum state** of a **massive system**.

Probing the Quantum Nature of Gravity through Diffusion

O. Angeli, S. Donadi, G. Di Bartolomeo, J.L. Gaona-Reyes, A.Vinante, A.Bassi, ArXiv 2501.13030

The main result: Any consistent coupling of classical gravity with quantum matter must induce **diffusion** on the system.

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The main result: Any consistent coupling of classical gravity with quantum matter must induce **diffusion** on the system.

Consequence: One does **not need to control the quantum state** of a system. It suffices to **monitor the classical motion** of the center of mass to check the presence of gravitational-induced diffusion.

Though challenging, this type of experiments is significantly **easier** to perform.

Probing the Quantum Nature of Gravity through Diffusion

O. Angeli, S. Donadi, G. Di Bartolomeo, J.L. Gaona-Reyes, A.Vinante, A.Bassi, ArXiv 2501.13030

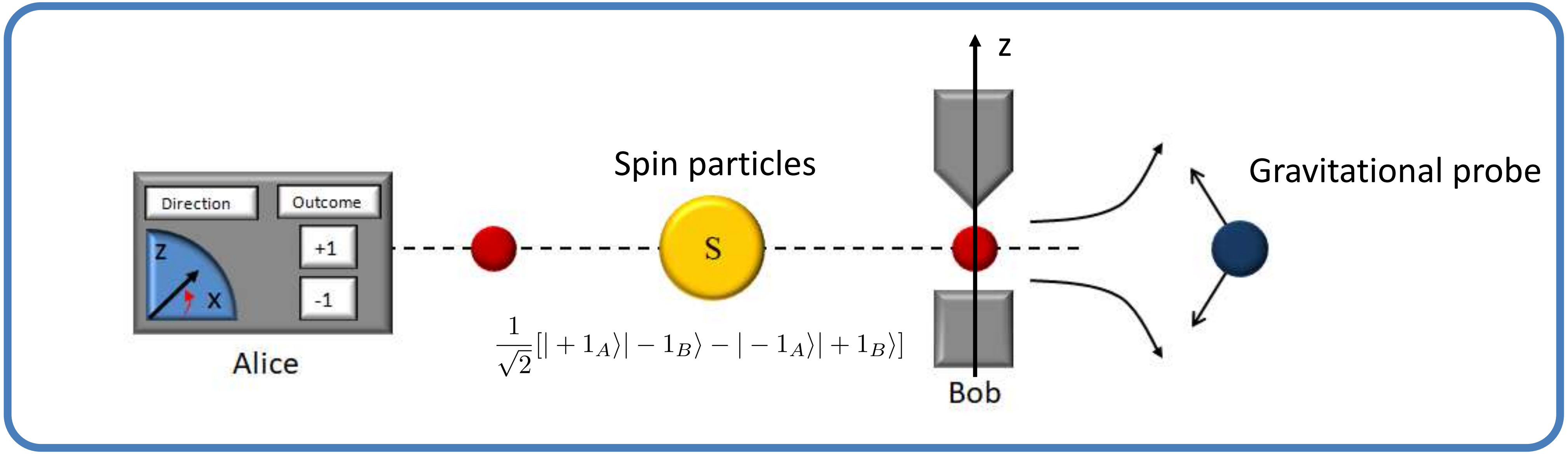
The **assumptions** are:

1. Matter is **quantum**
2. Gravity is **classical**
3. Gravity is **local**
4. Classical systems follow (almost) **Newton's law**

2+3 → Gravity is a LOCC → it cannot entangle
2 → no faster than light signaling

Quantum Gravity through Diffusion

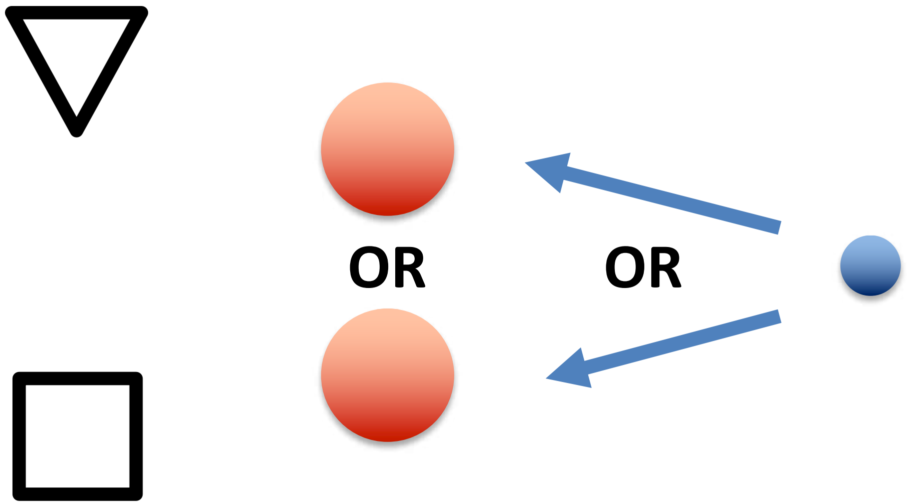
The setup: Alice and Bob sharing pairs of particles in the singlet spin state



Alice: she can perform spin measurements, along z or x.
Bob: his spin particles pass through a Stern-Gerlach (with magnetic filed aligned along z) after which a probe tests the gravitational field generated by the spin particle.

Quantum Gravity through Diffusion

Alice measures the spin along **z.**
At **Bob's side**, beyond the Stern-Gerlach:



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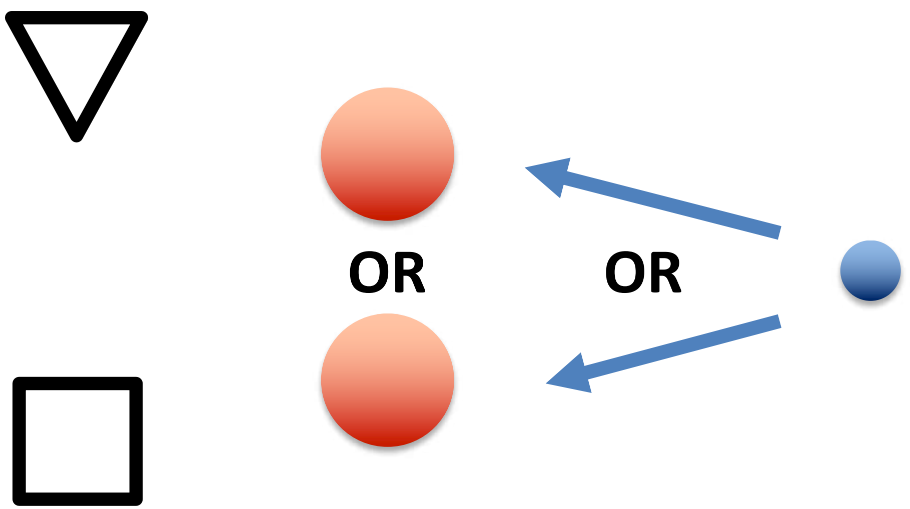
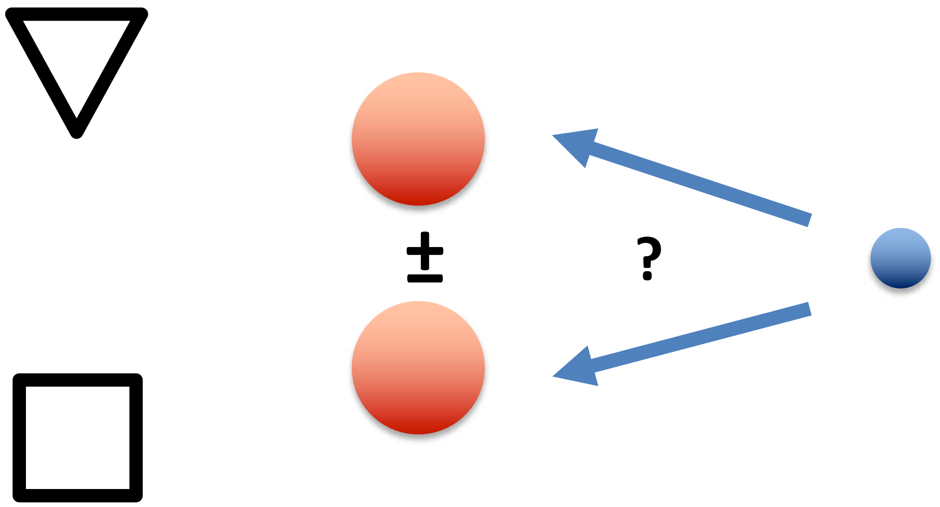


Alice measures the spin along **x.**
At **Bob's side**, beyond the Stern-Gerlach:



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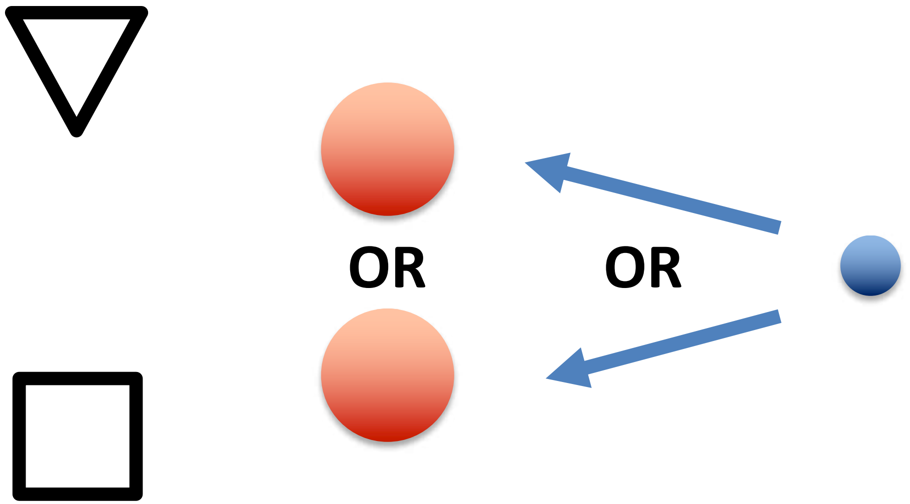

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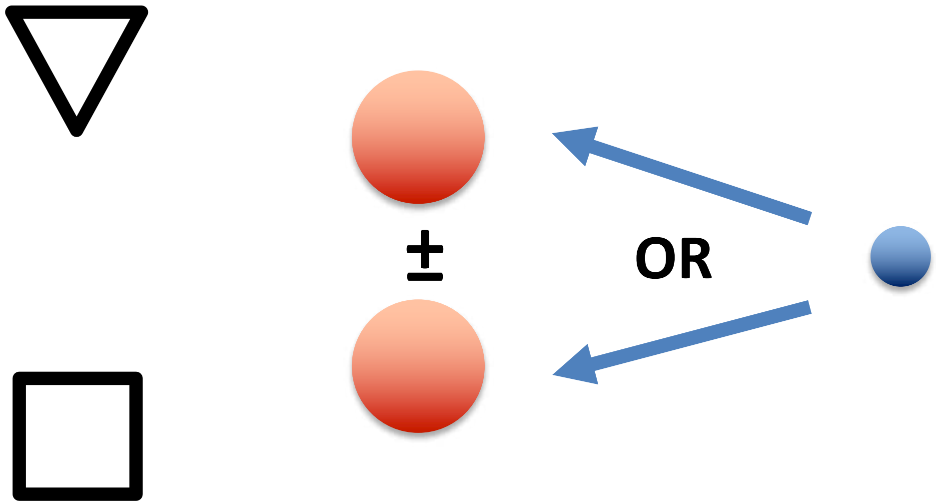
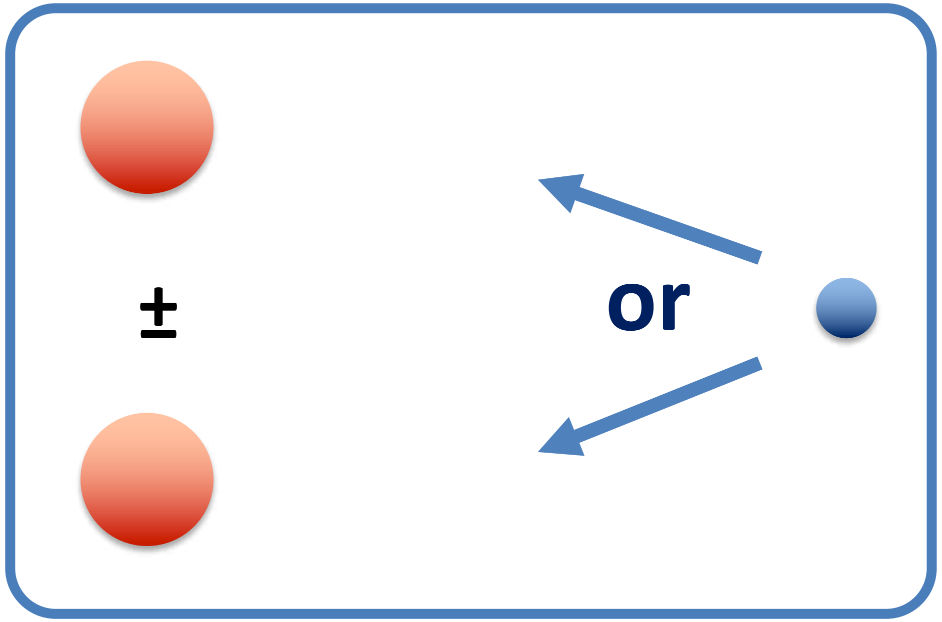


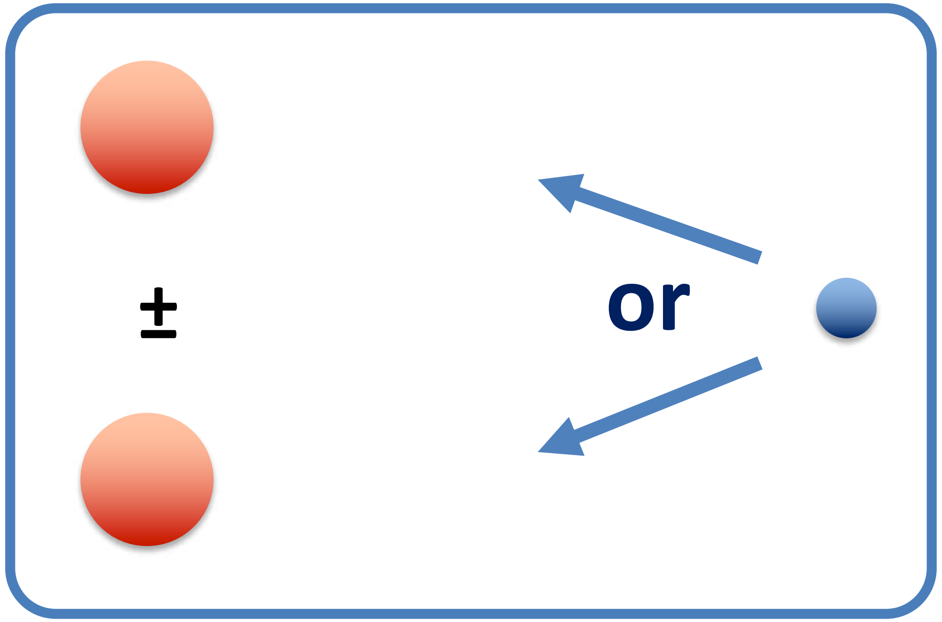
To avoid signaling, the probe **must react in the same way in both cases.**

Quantum Gravity through Diffusion



The superposition must collapse to the state towards which the probe is moving, otherwise Bob could further measure its position and there would be a 1/2 probability of finding it in the opposite state.

Quantum Gravity through Diffusion



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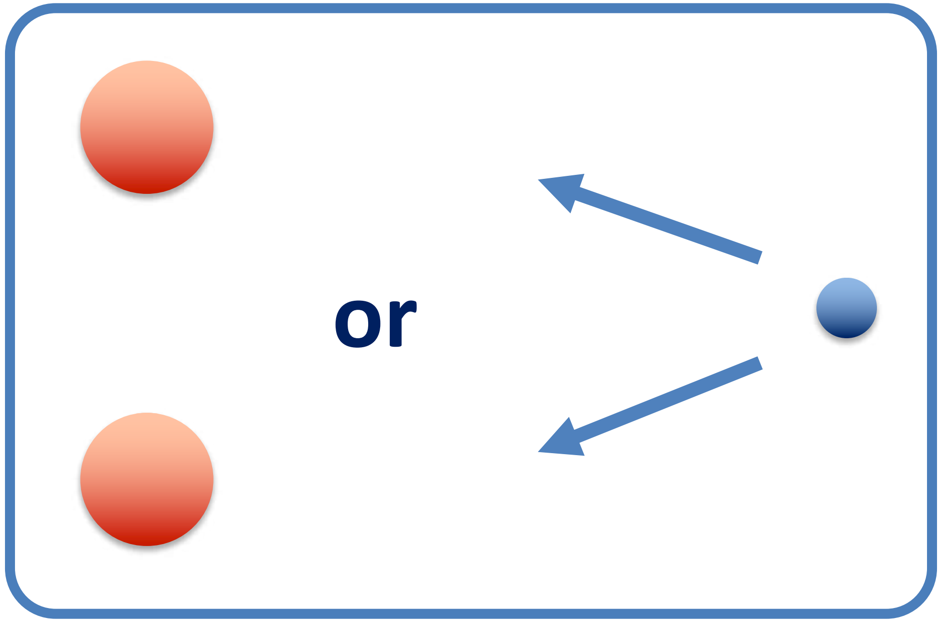


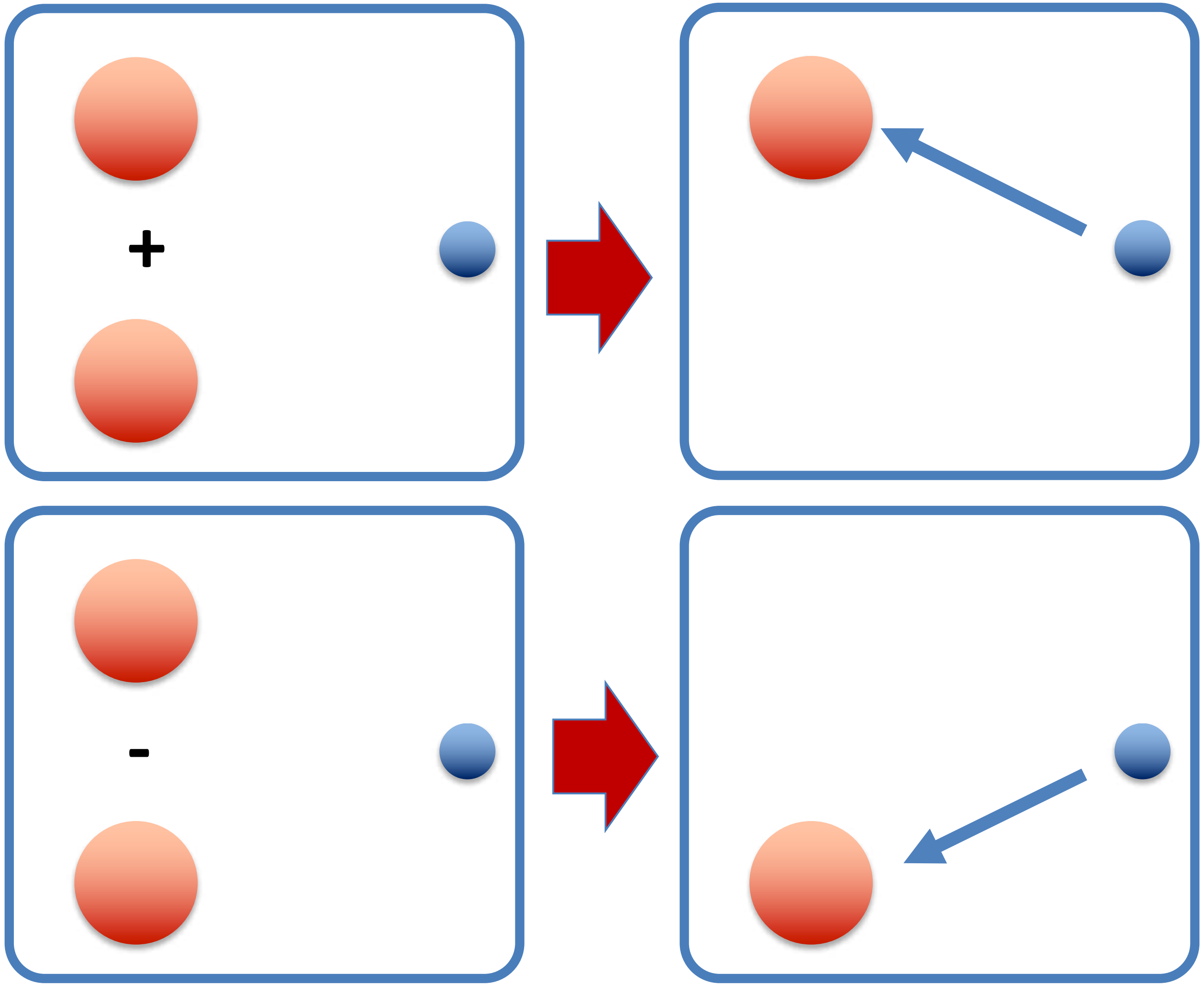
Quantum Gravity through Diffusion

The collapse must be random. Suppose it is not, so that we have for example:

$$\frac{1}{\sqrt{2}}\left[|+1_z^B\rangle|\mathrm{up}_z^B\rangle + |-1_z^B\rangle|\mathrm{down}_z^B\rangle\right]$$

State of the spin particle in the two cases, before the collapse

$$\frac{1}{\sqrt{2}}\left[|+1_z^B\rangle|\mathrm{up}_z^B\rangle - |-1_z^B\rangle|\mathrm{down}_z^B\rangle\right]$$



Quantum Gravity through Diffusion

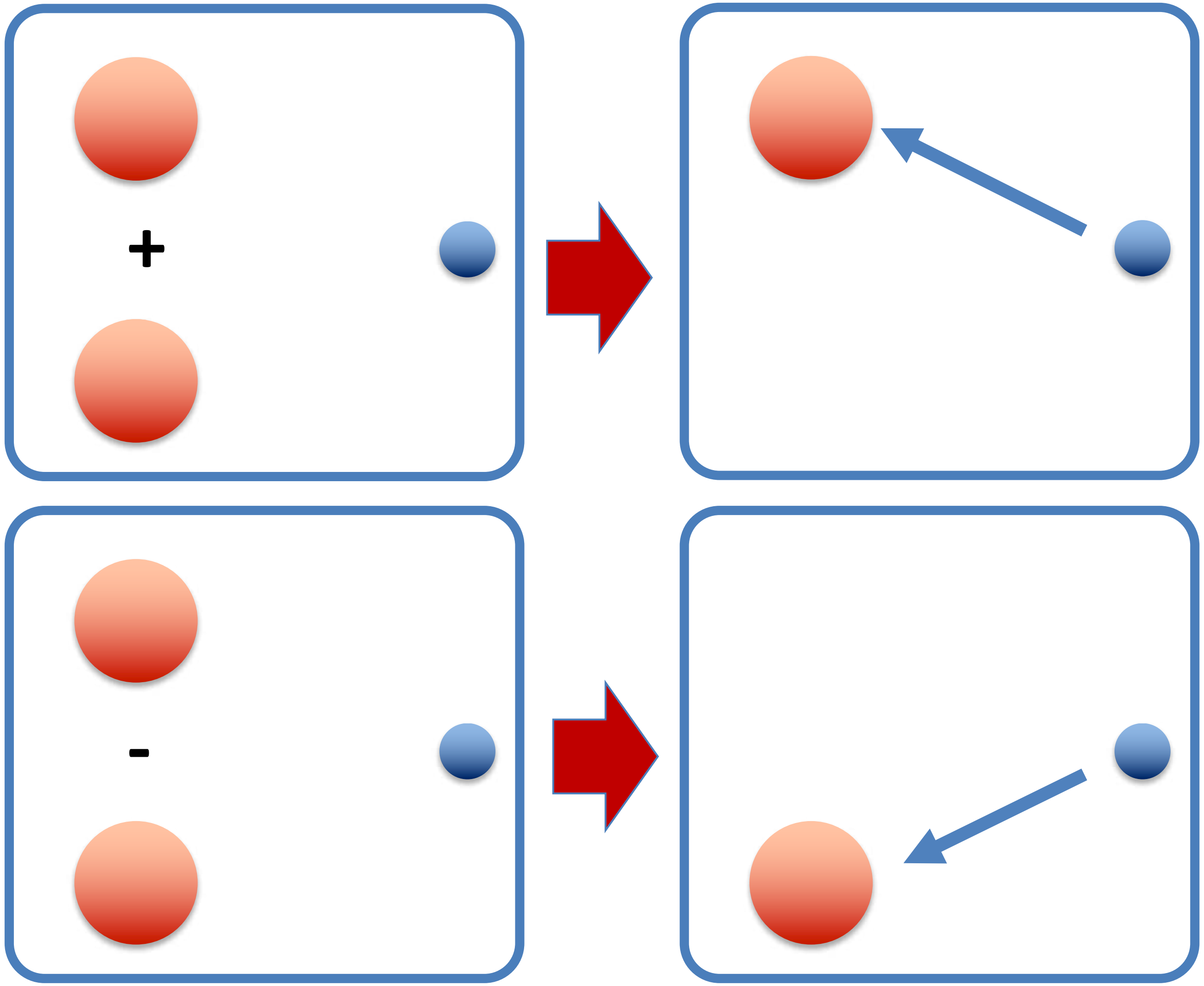
The + state is equivalent to:

$$\frac{1}{\sqrt{2}}\left[|+1_z^A\rangle|\mathrm{up}_z^B\rangle + |-1_z^A\rangle|\mathrm{down}_z^B\rangle\right]$$

where now the spin state belongs to Alice. By applying a Z gate to her spin, she can turn it into

$$\frac{1}{\sqrt{2}}\left[|+1_z^A\rangle|\mathrm{up}_z^B\rangle - |-1_z^A\rangle|\mathrm{down}_z^B\rangle\right]$$

Alice thus can decide from a distance the the reaction of Bob's gravitational probe.



Quantum Gravity through Diffusion

First Conclusion: Coupling quantum matter with classical gravity, avoiding superluminal signaling, must **collapse** quantum superpositions.

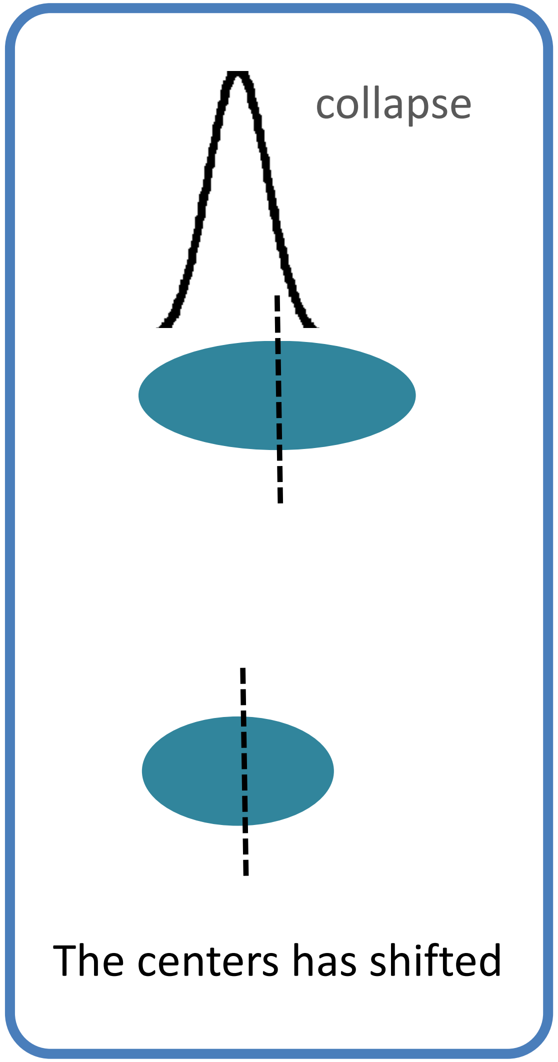
Quantum Gravity through Diffusion

First Conclusion: Coupling quantum matter with classical gravity, avoiding superluminal signaling, must **collapse** quantum superpositions.

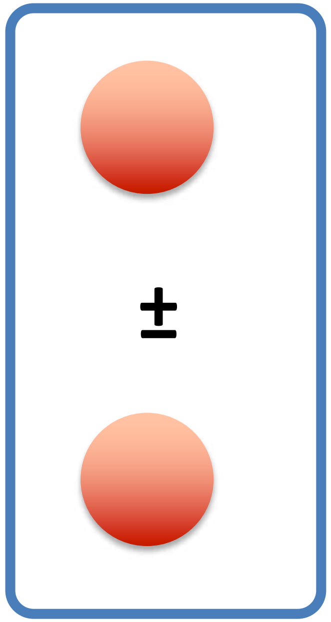
But any such dynamics is **diffusive.**

S. Donadi, L. Ferialdi, A. Bassi, PRL130, 230202 (2023)

Reason: to avoid signaling, the collapse must be blind to the state of the system (mathematically, a linear operator on the density matrix), and as such it changes it, in particular by randomly shifting it in space.



Quantum Gravity through Diffusion

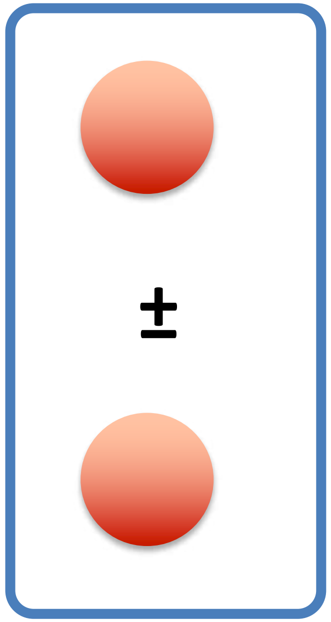


Because of the collapse, the superposition state changes

$$\rho \to \rho'$$

This change encodes also the shift of the center of mass

Quantum Gravity through Diffusion



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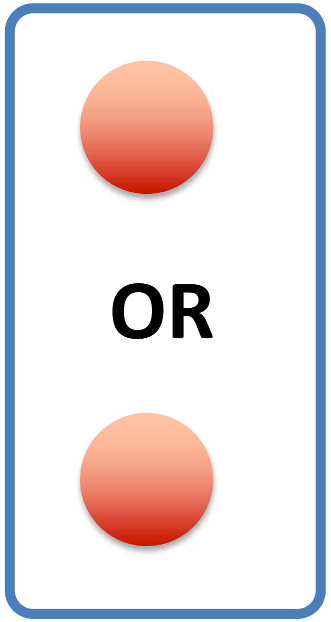

The same must happen for localized states, otherwise Alice and Bob can signal

Quantum Gravity through Diffusion

Second Conclusion: any consistent classical/quantum coupling must be random and diffusive

Quantum Gravity through Diffusion

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This conclusion **matches** with results in the literature

LOCC models
D. Kafri, J.M. Taylor, and G.J. Milburn, NJP 16, 065020 (2014)
A. Tilloy, L. Diosi, Physical Review D 93, 024026 (2016)
B. J. Oppenheim, C. Sparaciari, B. Soda, Z. Weller-Davies. Nat. Comm. 14, 7910 (2023)

Based on a continuous measurement + feedback scheme, which is diffusive

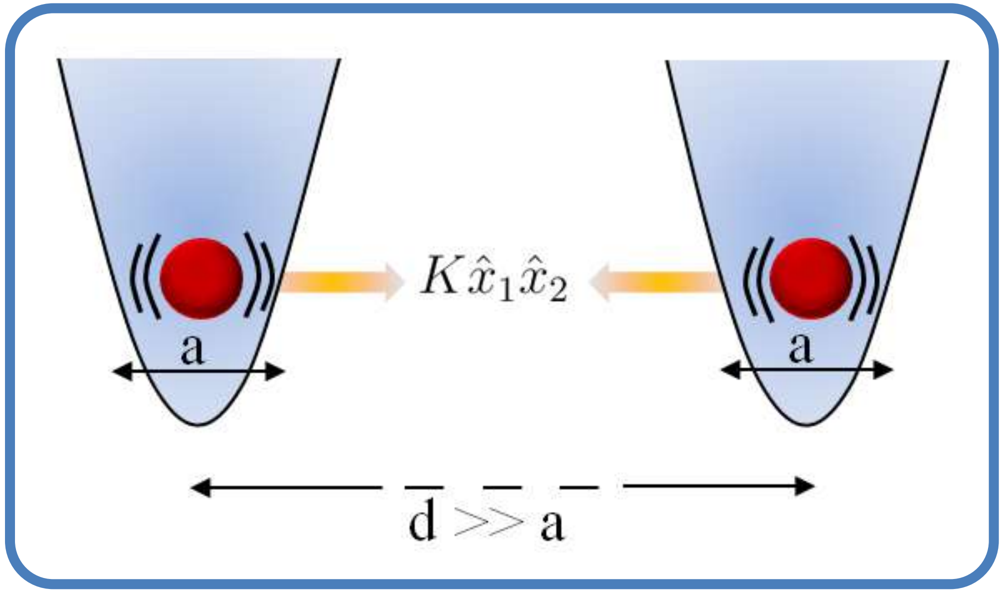
Schrödinger-Newton equation
L. Diosi. Physics Letters A 105, 199 (1984)
R. Penrose, Foundations of Physics 44 557 (2014)

Deterministic classical gravity, but allows for signaling

M. Bahrami, A. Großardt, S. Donadi, A. Bassi, NJP 16, 115007 (2014)

Application to a optomechanical setup

Under the previous assumptions (+ Markovianity and linearization), the general for the considered setup is



Generic diffusion

$$\frac{\mathrm{d}\hat{\rho}(t)}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}(t)] \boxed{-\frac{1}{2}\sum_{ij=1}^{4}\gamma_{ij}[\hat{c}_i,[\hat{c}_j,\hat{\rho}(t)]]}$$

$$\hat{c}^T = (\hat{x}_1,\hat{x}_2,\hat{p}_1,\hat{p}_2)$$

$$\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + \frac{1}{2}m\Omega^2\hat{x}_1^2 + \frac{1}{2}m\Omega^2\hat{x}_2^2 \boxed{+K\hat{x}_1\hat{x}_2}$$

Reproduces (linearized) Newtonian gravity for classical states

$$K := 2Gm^2/d^3 \qquad \Omega := \sqrt{\omega^2 - K/m}$$

Application to an optomechanical setup

$$\frac{\mathrm{d}\hat{\rho}(t)}{\mathrm{d}t} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}(t)] \boxed{- \frac{1}{2}\sum_{ij=1}^{4} \gamma_{ij}[\hat{c}_i, [\hat{c}_j, \hat{\rho}(t)]]}$$

It destroys entanglement

$$\hat{H} = \frac{\hat{p}_1^2}{2m} + \frac{\hat{p}_2^2}{2m} + \frac{1}{2}m\Omega^2\hat{x}_1^2 + \frac{1}{2}m\Omega^2\hat{x}_2^2 + \boxed{K\hat{x}_1\hat{x}_2}$$

It entangles

To avoid entanglement, **the Lindblad terms must be stronger than the Newtonian interaction**. For Gaussian states one finds

$$\boxed{\gamma_{11} + m^2\omega^2\gamma_{33} \geq \frac{Gm^2}{\hbar d^3}}$$

Measuring the extra diffusion

Consider the **density noise spectrum** of one of the two particles

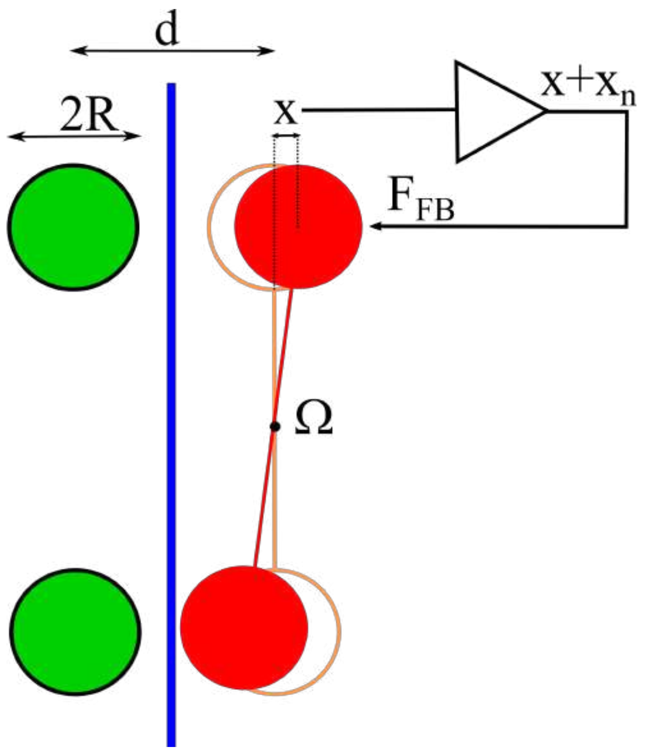
$$S_{xx}(\omega) = \frac{\hbar^2}{\left|m(\Omega^2 - \omega^2 - i\eta\omega) + K\right|^2}\left[\gamma_{11} + m^2\omega^2\gamma_{33} + \frac{\eta m\omega}{\hbar}\left(1 + \coth\left(\frac{\hbar\omega}{2k_bT}\right)\right) + m^2\eta^2\gamma_{33} - 2m\eta\gamma_{13}\right]$$

To see the extra diffusion, **the thermal noise should be lower than the gravity-induced noise**, giving (for high quality factors):

$$\frac{\eta m}{\hbar}\Omega\coth\left(\frac{\hbar\Omega}{2k_bT}\right) \leq \frac{Gm^2}{\hbar d^3}$$

Measuring the extra diffusion

Since gravitational interaction is easily overwhelmed by electromagnetic forces at the microscale, this clearly favors **macroscopic experiments.**



Parameters	Value
$\Omega/2\pi$	10^{-4} Hz
ρ	2.26×10^{4} Kg/m^3
R	3 cm
β	≈ 1
T	0.01 K
Q	2×10^{10}
N	≈ 1
r	0.01

Such parameters are achievable in **ground-based massive cryogenic torsion pendulums**, or in **space experiments similar to LISA Pathfinder** but performed in a cryogenic environment and vacuum

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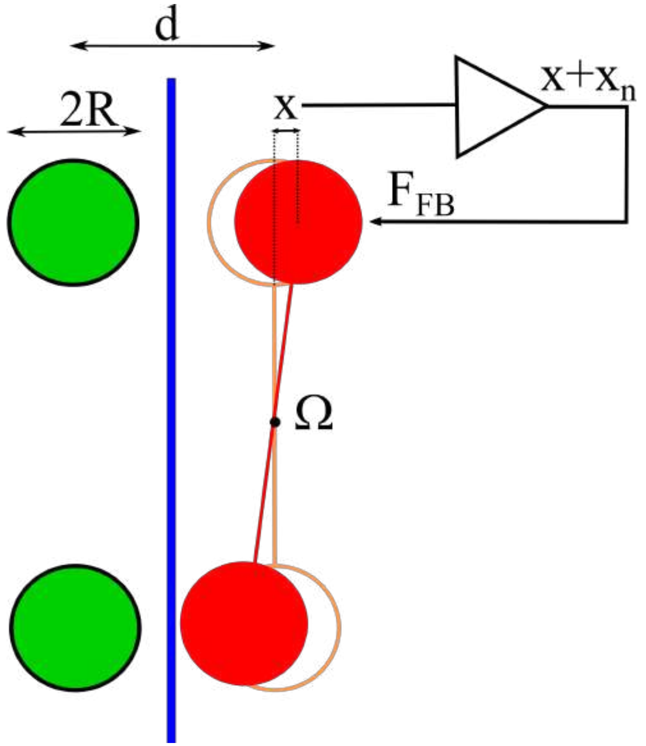

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Challenging, but within foreseeable technology

Acknowledgments

The Group (www.qmts.it)

- Postdocs: M. Carlesso, J.L. Gaona Reyes, A. Gundhi, M. Vischi, N. Piccione.
- Ph.D. students: A. Altamura, O. Angeli, F. Cesa, G. Crognaletti, T. Feri, L. Figurato, G. Di Bartolomeo