QUANTUM SYSTEMS AS GRAVITATIONAL SOURCES: NONCLASSICAL SPACETIME AND THE LOW-ENERGY NATURE OF GRAVITY

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ETH Zürich

Image credits: J. Palomino

SIGRAV School "Applied Quantum Gravity"
Vietri, 13-17 February 2023

WHERE SHALL WE LOOK FOR QUANTUM EFFECTS IN GRAVITY?

HIGH ENERGIES:
PLANCK-SCALE
PHYSICS

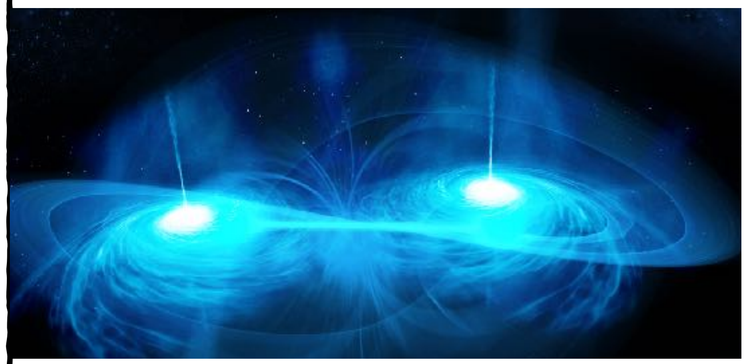
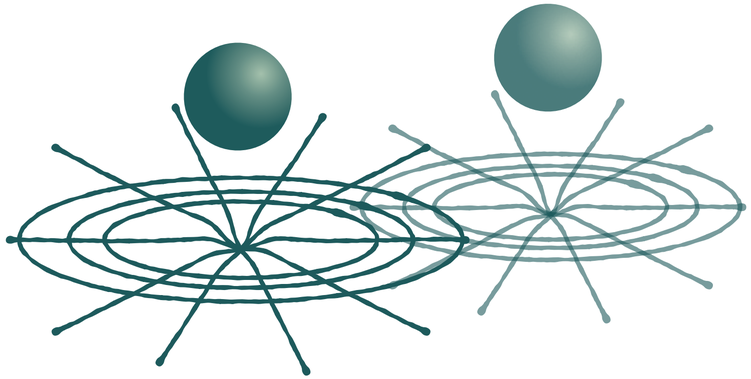


Image credits: Perimeter Institute

QUANTUM SPACETIME "FUZZINESS"

- Black Holes, spin foams, LQG
- String Theory
- Modified dispersion relations
- (…)

LOW ENERGIES:
PERTURBATIVE GRAVITY
QUANTUM PARTICLES



NONCLASSICAL SPACETIME

THIS TALK!

- Quantum Time and quantum clocks
- Indefinite causal structures
- Lack of classical reference frames
- (…)

Concrete scenarios with immediate physical meaning

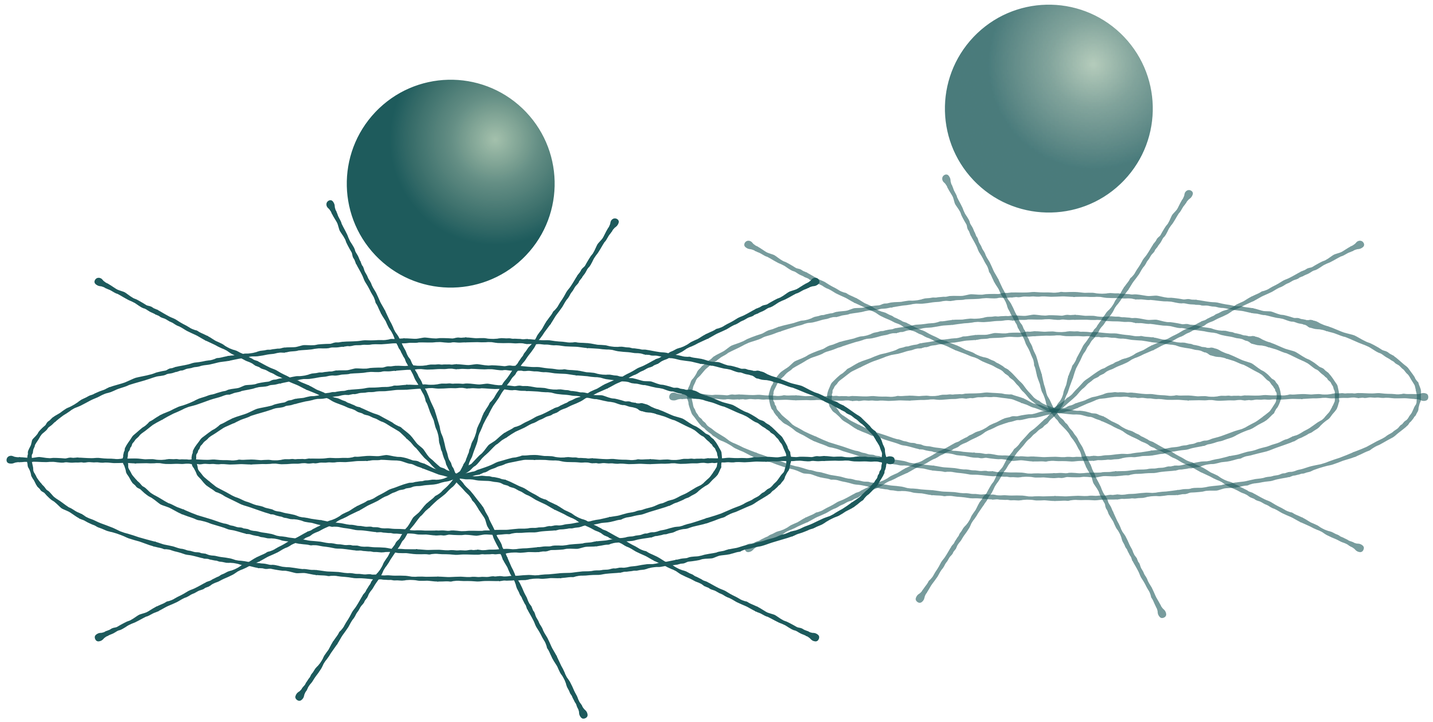
NONCLASSICAL SPACETIME FROM A QUANTUM SOURCE

GENERAL RELATIVITY

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

QUANTUM THEORY

$$T_{\mu\nu} \rightarrow \hat{T}_{\mu\nu}$$



WHAT IS THE ROLE OF (QUANTUM) PERTURBATIONS?

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{\mu\nu} \to \hat{h}_{\mu\nu}$$

Why is this not just classical spacetime?

The perturbation contributes to spacetime too!

CLASSICAL EXAMPLE 1

"Lower is slower"

$$\tau_2 = \int_{t_0}^{t} dt' \sqrt{1 + h_{00}(z_2)}$$

z_2

$$\tau_1 = \int_{t_0}^{t} dt' \sqrt{1 + h_{00}(z_1)}$$

z_1

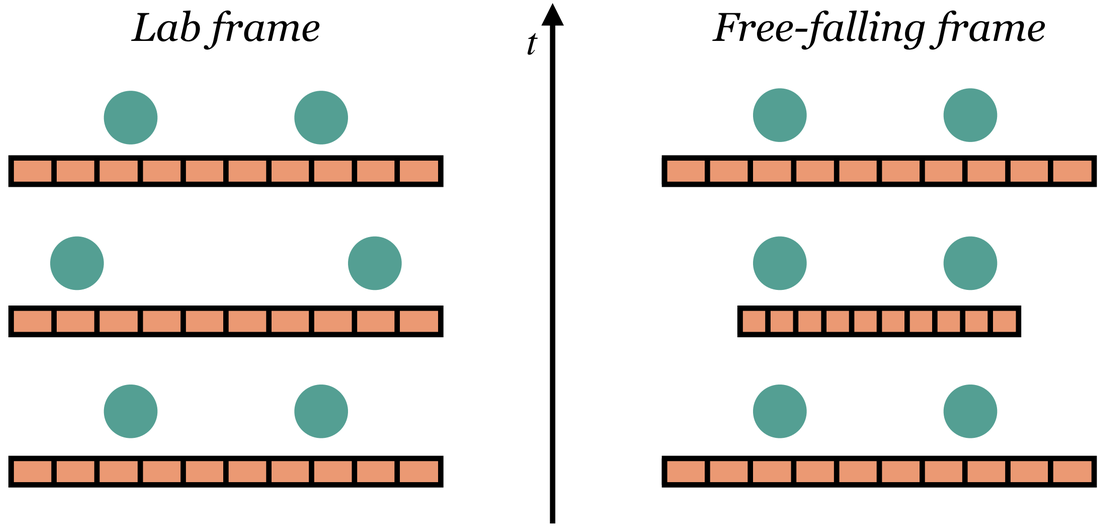
Article | Published: 16 February 2022

Resolving the gravitational redshift across a millimetre-scale atomic sample

Tobias Bothwell, Colin J. Kennedy, Alexander Aeppli, Dhruv Kedar, John M. Robinson, Eric Oelker, Alexander Staron & Jun Ye

Nature **602**, 420–424 (2022) | Cite this article

CLASSICAL EXAMPLE 2



$$s(t) = \int_{x_1}^{x_2} dx \sqrt{1 + h_{+}(x - ct)}$$

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. **119**, 161101 – Published 16 October 2017

NONCLASSICAL SPACETIME FROM A QUANTUM SOURCE

Article | Published: 10 March 2021 **LIGHTEST GRAVITY SOURCE:** $90\,mg$

Measurement of gravitational coupling between millimetre-sized masses

Tobias Westphal ✉, Hans Hepach, Jeremias Pfaff & Markus Aspelmeyer ✉

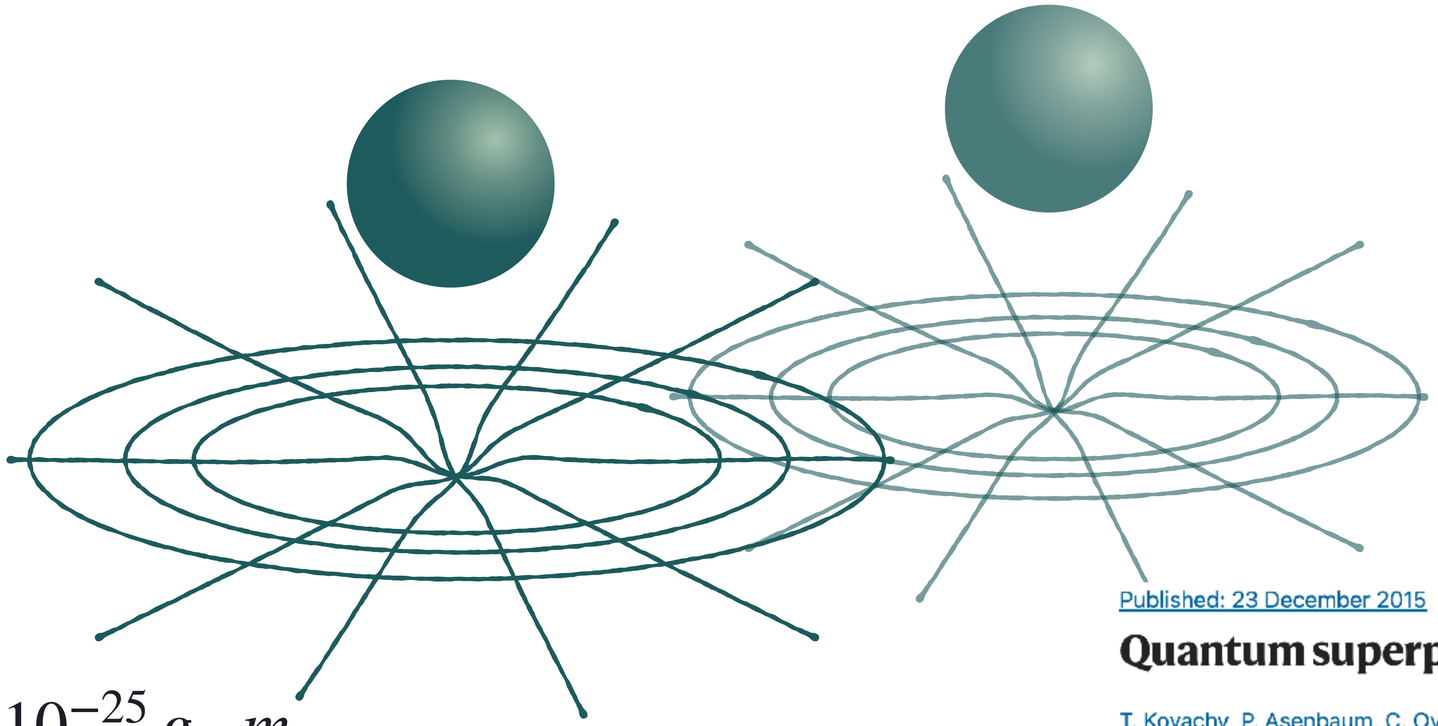
Nature **591**, 225–228 (2021) | Cite this article

Letter | Published: 23 September 2019 **SUPERPOSED MASS:** $10^{-20}g$

Quantum superposition of molecules beyond 25 kDa

Yaakov Y. Fein, Philipp Geyer, Patrick Zwick, Filip Kiałka, Sebastian Pedalino, Marcel Mayor, Stefan Gerlich & Markus Arndt ✉

Nature Physics **15**, 1242–1245 (2019) | Cite this article



$$m \cdot \Delta x \approx 10^{-25}\, g \cdot m$$

M. Aspelmeyer, 2203.05587 (2022)

Published: 23 December 2015 **LARGEST SUPERPOSITION:** $0.5\,m$

Quantum superposition at the half-metre scale

T. Kovachy, P. Asenbaum, C. Overstreet, C. A. Donnelly, S. M. Dickerson, A. Sugarbaker, J. M. Hogan & M. A. Kasevich ✉

Nature **528**, 530–533 (2015) | Cite this article

WHY IS THIS INTERESTING?

LEVEL 1: We do NOT know which observation would prove in a compelling way that gravity has quantum features.

Good news: There will be experimental guidance!

LEVEL 2: Open questions in quantum gravity show up in this regime
(e.g. lack of a classical spacetime, quantum time, indefinite causality, relationalism, partition of Hilbert space into local algebras/subsystems, etc)

LEVEL 3: First-principle approach:
How do we reconcile the principles of GR and QT?
Internal consistency of GR and QT can be tested in thought experiments

NB: quantum information is not tied to a specific regime

TOPICS IN THIS LECTURE

QUANTUM CLOCKS

- *Clocks as probes of spacetime*
- *Limitations to the measurability of spacetime from operational considerations*

GRAVITATIONALLY INDUCED ENTANGLEMENT

- *The basic protocol*
- *What does it mean that gravity is quantum?*
- *Another protocol and further considerations*

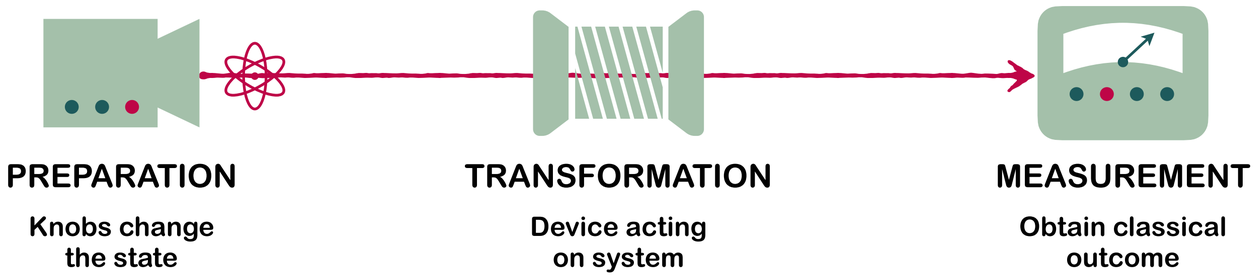
GRAVITY IN A QUANTUM SUPERPOSITION STATE?

- *The quantum state of the Newtonian field*
- *Nonclassical spacetime requires nonclassical reference frames*
- *Example: the Gravitational Aharonov-Bohm experiment*

SIDE REMARK: OPERATIONAL APPROACH AND DEVICE INDEPENDENCE

WHAT DOES IT MEAN TO BE QUANTUM?

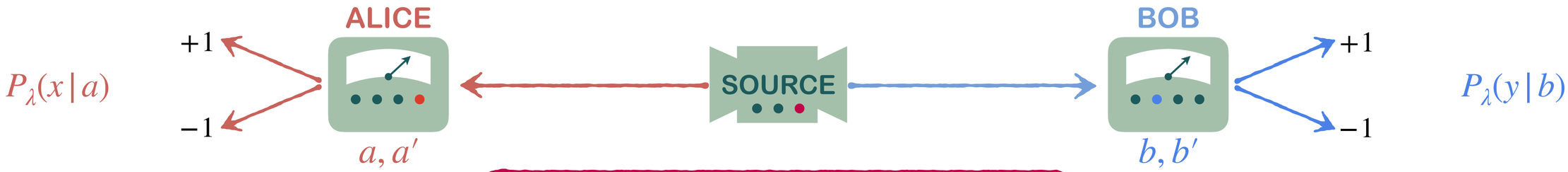
1) Quantum superposition or entanglement
2) Action in path integral
3) Expectation values in Heisenberg picture
4) Emission of quantised radiation
5) Measurements do not commute



A theory is characterised by its probabilities.
No ontological commitment.

L. Hardy, arXiv:0101012 (2001)
M. Müller, arXiv:2011.01286 (2020)

BELL'S THEOREM



LOCAL CAUSALITY/LOCAL REALISM

$$P(x,y\,|\,a,b) = \int d\lambda Q(\lambda)\, P_\lambda(x\,|\,a)\, P_\lambda(y\,|\,b)$$

V. Scarani, Bell Nonlocality (book)

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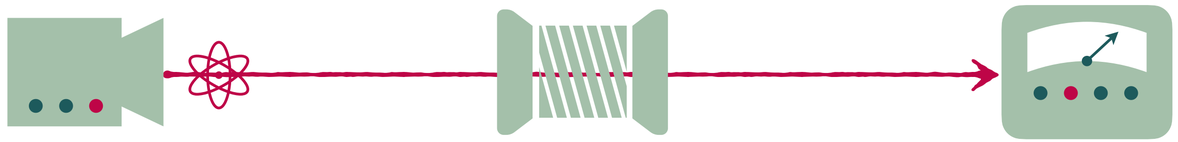


PREPARATION
Knobs change the state

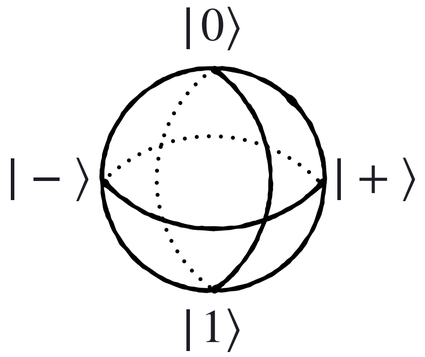
TRANSFORMATION
Device acting on system

MEASUREMENT
Obtain classical outcome

A theory is characterised by its probabilities.
No ontological commitment.

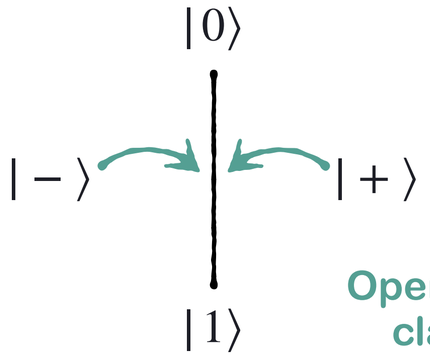
How to cheat without the full set of measurements...

QUBIT



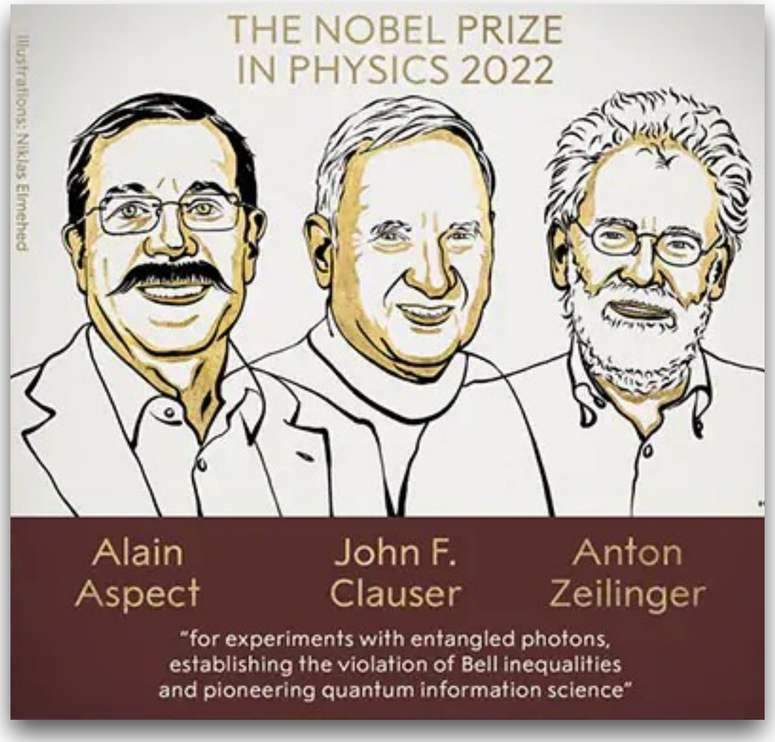
Only allow Z measurements

CLASSICAL BIT



Operationally classical

$$p\,|0\rangle\langle 0| + (1-p)\,|1\rangle\langle 1|$$



TAKE-HOME MESSAGE

FULLY THEORY INDEPENDENT ARGUMENTS ARE VERY HARD

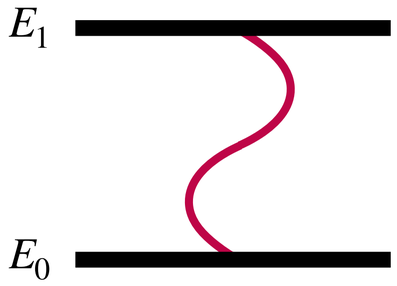
for gravitational quantum systems!

1) Consider concrete scenario using both QT and GR
2) Identify relevant operational/observable features
3) Map them onto a mathematical/Hilbert space description
4) Test internal consistency/foundational principles of the model

QUANTUM CLOCKS AS PROBES OF SPACETIME

A SIMPLE CLOCK MODEL

=



$$|\psi_0\rangle = \frac{1}{\sqrt{2}}(|E_0\rangle + |E_1\rangle)$$

$$H_C = E_0\,|E_0\rangle\langle E_0| + E_1\,|E_1\rangle\langle E_1|$$

$$|\psi_t\rangle = \frac{1}{\sqrt{2}}(|E_0\rangle + e^{\frac{i}{\hbar}(E_1-E_0)t}|E_1\rangle)$$

-1

$$\langle\psi_{t_\perp}|\psi_0\rangle = 0$$

ORTHOGONALISATION TIME

$$t_\perp = \frac{\pi\hbar}{(E_1 - E_0)}$$

$$E = mc^2$$

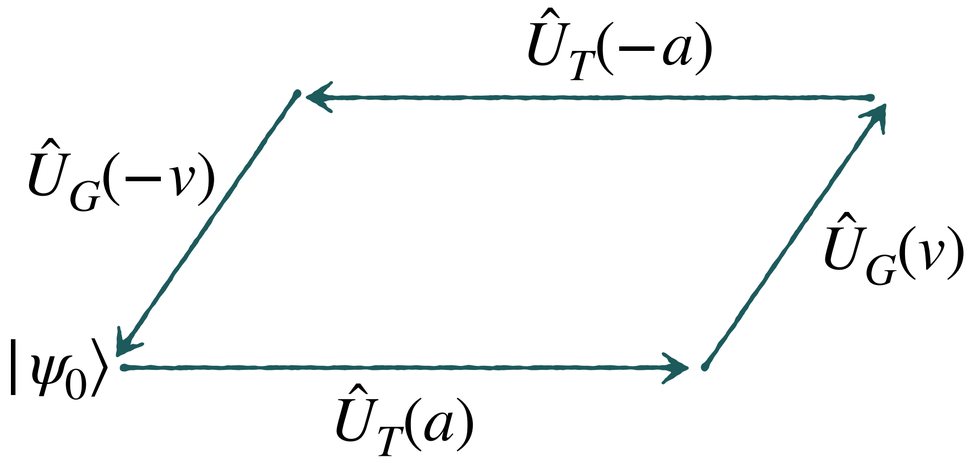
MASS AND PROPER TIME

$$g_{\mu\nu}p^\mu p^\nu = c^{-2}E_{rest}$$

$$E_{rest} = mc^2 + H_C$$

Total rest energy
(internal + external degrees of freedom)

SUPERPOSITION OF MASSES?



$$|\psi_0\rangle \rightarrow e^{\frac{i}{\hbar}mav}|\psi_0\rangle$$

Bargmann: mass superselection rule

$$e^{\frac{i}{\hbar}mav} = e^{\frac{i}{\hbar}\Delta\tau c^2\Delta m}$$

Greenberger, PRL 87 (2001)

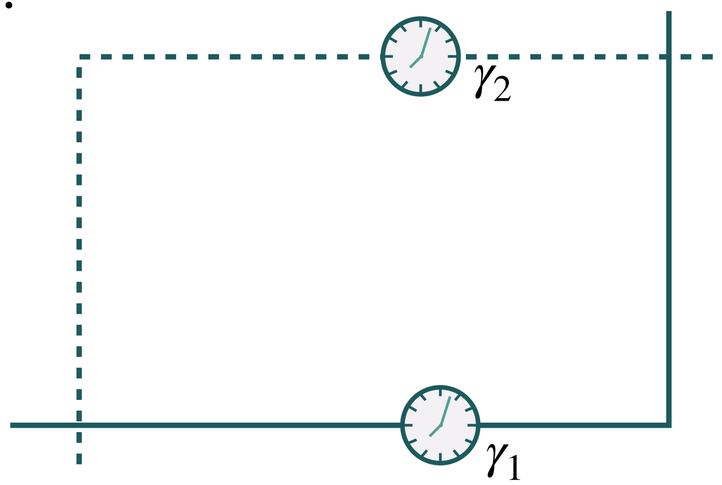
QUANTUM SUPERPOSITIONS OF MASSES

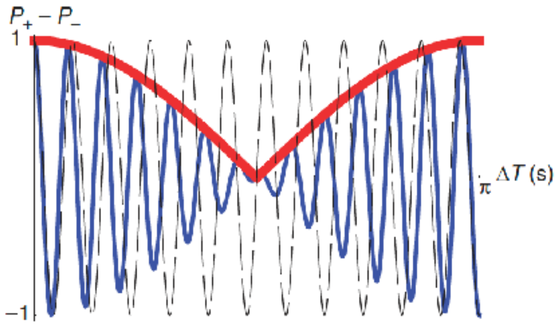
Quantum clocks test the principle of linear superposition and gravitational time dilation together.

“LOWER IS SLOWER”

$$|\tau_0\rangle = \frac{1}{\sqrt{2}}\left(|E_0\rangle + |E_1\rangle\right)$$

$$\frac{1}{\sqrt{2}}\left(|\gamma_1\rangle|\tau_1\rangle + e^{i\Delta\phi}|\gamma_2\rangle|\tau_2\rangle\right)$$





$$\mathscr{V} = |\langle\tau_1|\tau_2\rangle|^2$$ **Visibility (interference)**

$$\mathscr{D} = 1 - |\langle\tau_1|\tau_2\rangle|^2$$ **Distinguishability (which-way information)**

The clock carries “which-way” information in its proper time.

Zych, Costa, Pikovski, Brukner, Nat. Commun. (2011)

ENTANGLEMENT OF QUANTUM CLOCKS THROUGH GRAVITY

$$H = H_A + H_B - \frac{G}{c^4 x} H_A H_B$$

Precision of clock A

$$t_\perp = \frac{\pi\hbar}{(E_1 - E_0)}$$

Disturbance to clock B due to clock A

$$\Delta t = \frac{G(E_1 - E_0)}{c^4 x} t$$

$$t_\perp \Delta t = \frac{\pi\hbar G t}{c^4 x}$$

Limitation to the measurability of time for nearby clocks

Castro Ruiz, Giacomini, Brukner, PNAS (2017)

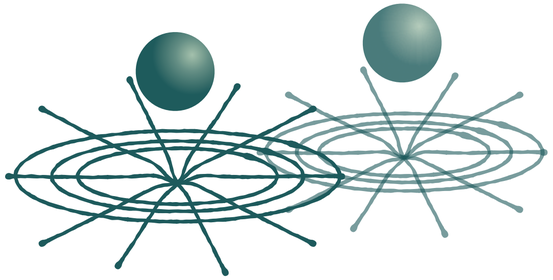
QUESTIONS?

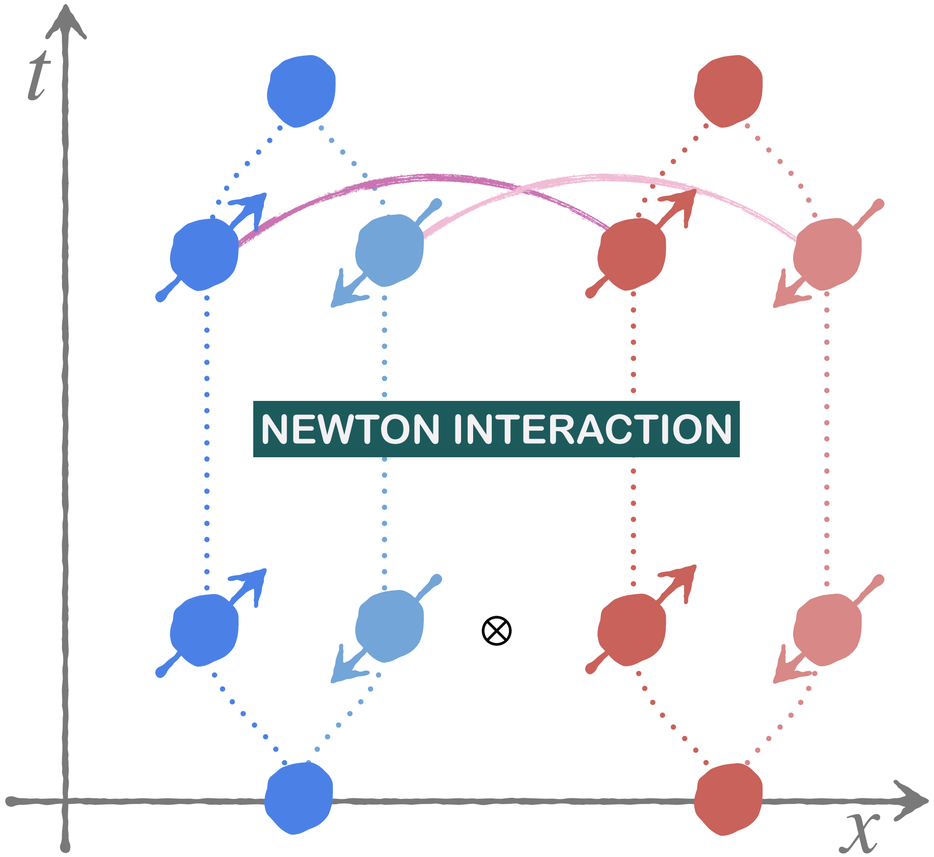
GRAVITATIONALLY INDUCED ENTANGLEMENT

GRAVITATIONALLY INDUCED ENTANGLEMENT

"If you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

R. Feynman, Chapel Hill Conference (1957)





ENTANGLED STATE

Nonclassical channel (LOCC theorem)

PRODUCT STATE

$$\frac{1}{2}\sum_{i,j=1,2} e^{i\phi_{ij}}|x_i\rangle_A|x_j+L\rangle_B$$

$$\hat{H}_{int} = -G\frac{m_A m_B}{|\hat{x}_A-\hat{x}_B|}$$

$$\frac{1}{\sqrt{2}}(|x_1\rangle_A+|x_2\rangle_A)\otimes\frac{1}{\sqrt{2}}(|x_1+L\rangle_B+|x_2+L\rangle_B)$$

Bose et al. PRL (2017)
Marletto, Vedral PRL (2017)

LOCC: Bennett et al. PRA (1995)

FREQUENTLY ASKED QUESTIONS AND OBJECTIONS

1. **Newton potential is "just gauge"**
   (no physical/dynamical degrees of freedom)

   → *Split is arbitrary*

2. **This is a "graviton effect"**

   → *Not enough to detect gravitons*

3. **Can be explained via "interaction at a distance"**

   → *True, however see next and Christodoulou et al., arXiv 2202.03368*

4. **Alternative explanations to standard quantum theory**

   → *No-go theorem: Galley, Giacomini, Selby, Quantum 6 (2022) + arXiv 2301.10261*
   (see also Marletto, Vedral PRD 2020, npj Quantum Inf. 2017)

5. **This is not the correct regime**

   → *cfr. quantum optics experiments*

SIDE REMARK: WHAT PROVES THAT ELECTROMAGNETISM IS QUANTUM?

1905: photoelectric effect (Einstein)

1923: photoelectric effect does not require quantum (Millikan)

1923: Compton effect

1960s: semiclassical theory of radiation (Jaynes)

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

$$\tau = 0 \qquad g^{(2)}(0) = \frac{\langle I^2(t)\rangle}{\langle I(t)\rangle^2} \geq 1$$

For a single photon source

$$g^{(2)}(0) = 0 \ngeq 1$$

Signature of nonclassicality

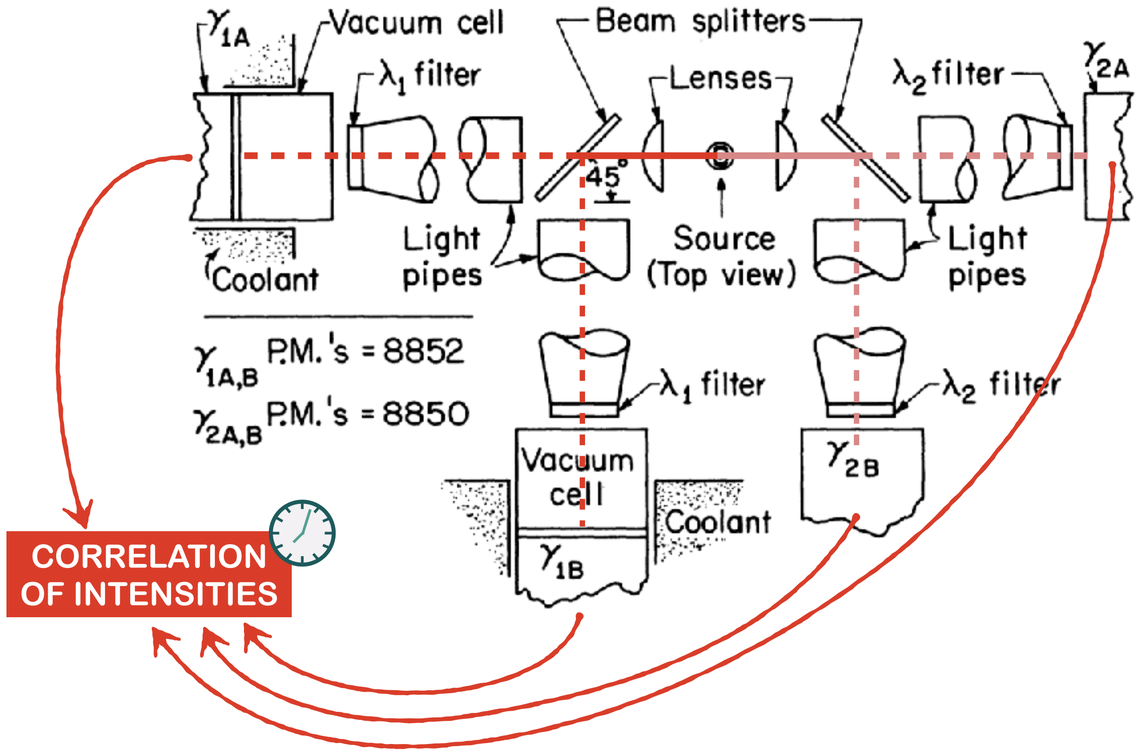
PHYSICAL REVIEW D VOLUME 9, NUMBER 4 15 FEBRUARY 1974

Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect*

John F. Clauser

Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 30 October 1973)



LET’S ANSWER SOME QUESTIONS!

1) IS THE NEWTON POTENTIAL ALWAYS HARMLESS?

2) IS THE RELATIVE PHASE LOCAL OR GLOBAL?

3) DOES THE NEWTON POTENTIAL HAVE A QUANTUM STATE?

4) IS THE SUPERPOSITION OF GRAVITATIONAL FIELDS A RELATIVE CONCEPT?

NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

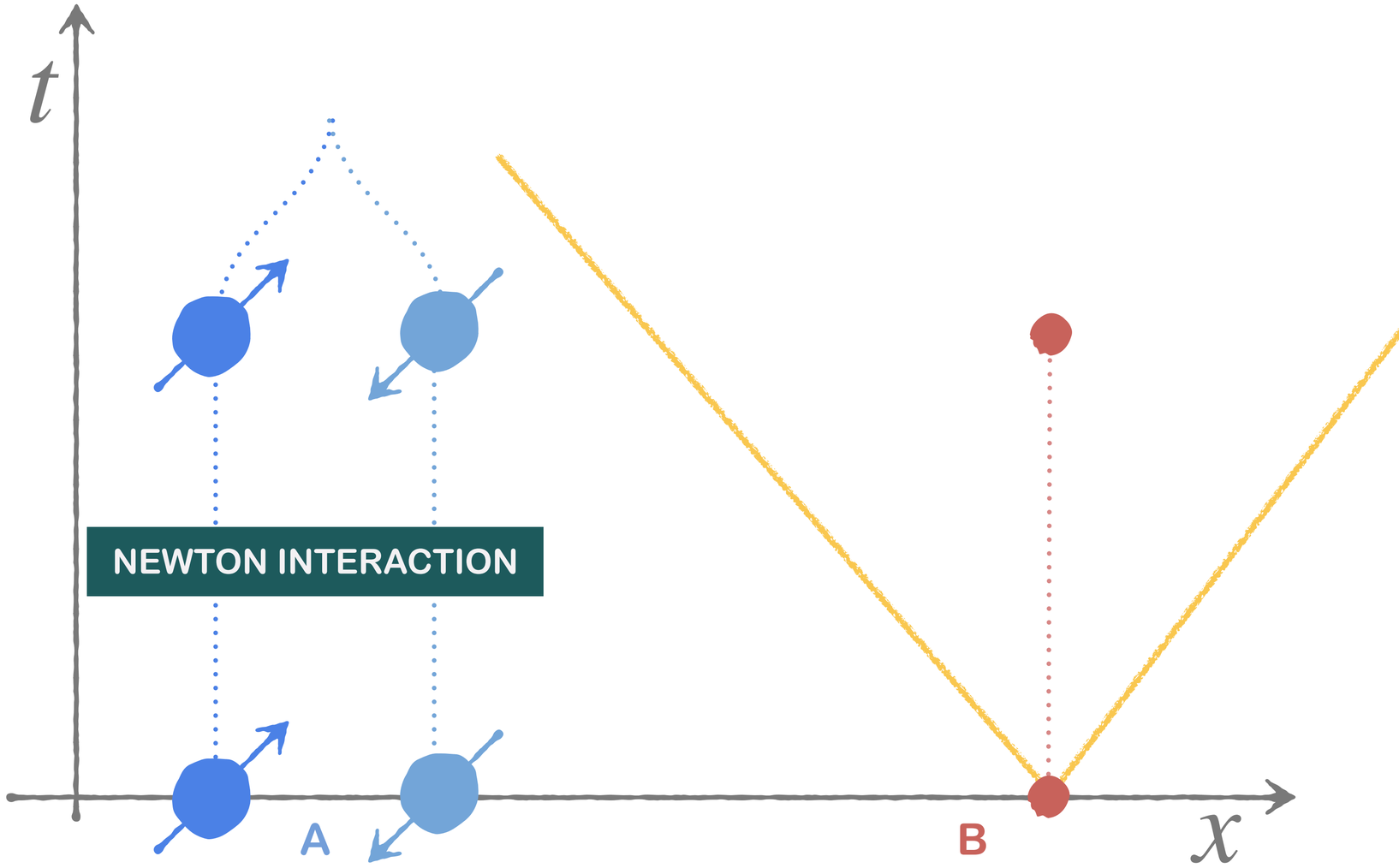
Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)

Along the lines of Baym, Ozawa (2009)
and Mari, De Palma, Giovannetti (2016)

G is a field (GR)
No interaction at a distance
Linearized quantum gravity

B does not release the trap

$$\frac{1}{\sqrt{2}}\left(|L\rangle_A|\alpha_L\rangle_G + |R\rangle_A|\alpha_R\rangle_G\right)|\psi_0\rangle_B$$



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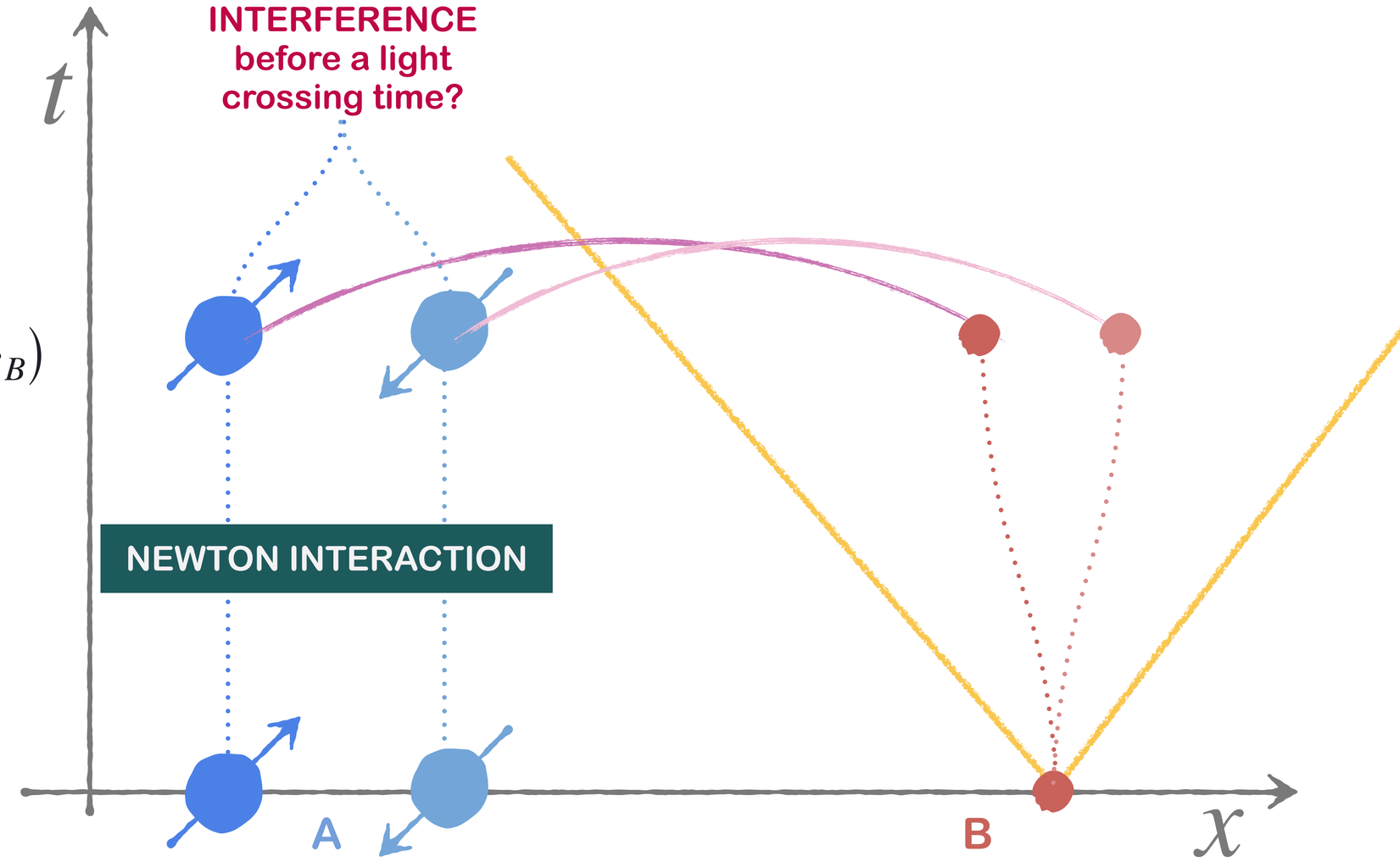
G is a field (GR)
No interaction at a distance
Linearized quantum gravity

$$\frac{1}{\sqrt{2}}\left(|L\rangle_A|\alpha_L\rangle_G|L\rangle_B+|R\rangle_A|\alpha_R\rangle_G|R\rangle_B\right)$$

B releases the trap

$$\frac{1}{\sqrt{2}}\left(|L\rangle_A|\alpha_L\rangle_G+|R\rangle_A|\alpha_R\rangle_G\right)|\psi_0\rangle_B$$



NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)

TAKE-HOME MESSAGE

Quantum properties of the gravitational field

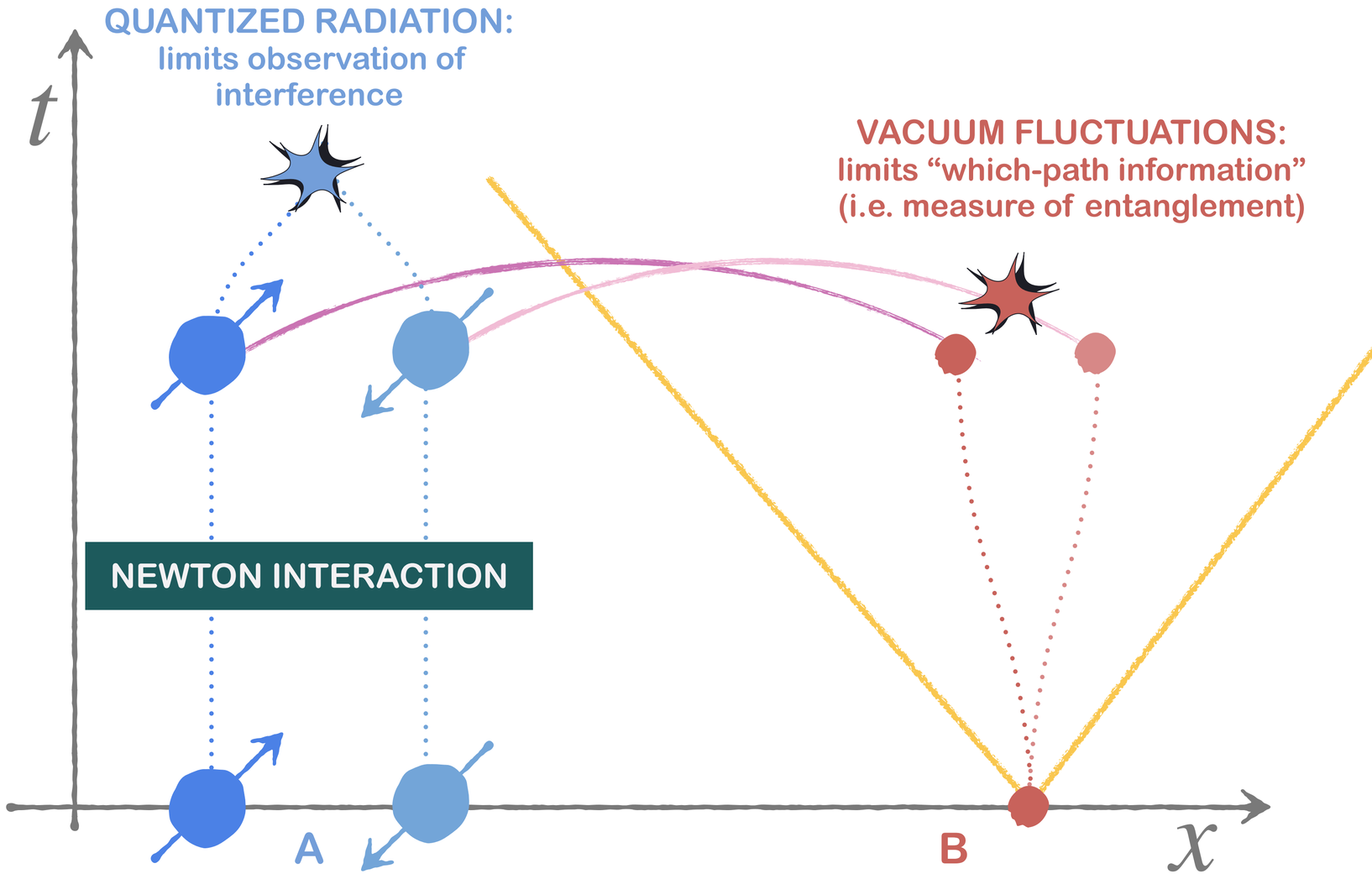
QUANTIZED RADIATION
VACUUM FLUCTUATIONS

are essential to obtain a consistent description of the experiment

ARGUMENT:
Newtonian potential has a quantum information content, has its own quantum state and should be considered entangled with the source of the gravitational field

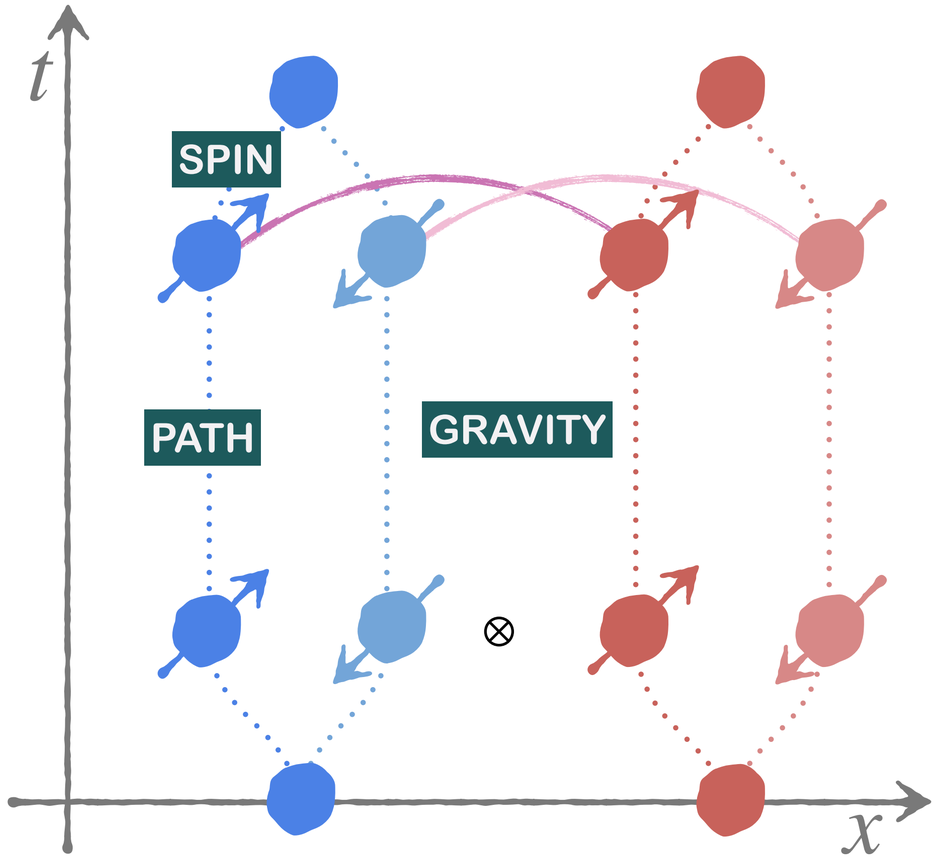
If instead we want to keep a classical description of gravity, we need to drastically modify our basic principles.

See also Danielson, Satishchandran, Wald PRD (2022)



IS THE RELATIVE NEWTONIAN PHASE LOCAL?

Christodoulou, Di Biagio, Aspelmeyer, Brukner, Rovelli, Howl, 2202.03368 (2022)



$$\int \mathcal{D}f'\mathcal{D}x' \exp\left(\frac{iS}{\hbar}\right) |\psi^f\rangle\langle\psi^i|$$

Paths + Gravity + Spins

- Masses follow a “superposition of trajectories”
- Saddle point approximation for gravity

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

$$U^\sigma_{i\to f} \propto \exp\left(\frac{iS^\sigma\left[x_a^{s_a}, \mathcal{F}[x_a^{s_a}]\right]}{\hbar}\right) |\psi^f\rangle\langle\psi^i|$$

On-shell action for the total system

Entanglement is mediated by the field
Relative phase is local, gauge-invariant

Bose et al. PRL (2017)
Marletto, Vedral PRL (2017)

DOES THE NEWTONIAN FIELD HAVE A QUANTUM STATE?

SHORT ANSWER: YES!

Chen, Giacomini, Rovelli 2207.10592 (2022)

Stationary quantum source $|\Psi_S\rangle$ **is in a quantum superposition of charge density eigenstates:** $\hat{J}_0(\vec{x})\,|\Phi_i\rangle = \rho_i(\vec{x})\,|\Phi_i\rangle$

$$|\Psi_S\rangle = \sum_i \alpha_i\,|\Phi_i\rangle$$

Linearised regime
3+1 decomposition

$$N = 1 + n \qquad N_i = 0 + n_i \qquad g_{ij} = \delta_{ij} + h_{ij}$$

$$H_{G+M} = H_G(h_{ij}) + n\mathscr{C} + n_i\mathscr{C}^i$$

QUANTISATION IN THE FIELD BASIS
(Schrödinger representation)

$$\mathscr{C}(\vec{x}) = -\Delta h_T - \rho = 0 \longrightarrow -(\Delta h_T + \rho)\Psi[h_{kl}] = 0$$

$$\mathscr{C}^i(\vec{x}) = \partial_j \pi^{ij} = 0 \longrightarrow \partial_j \frac{\delta}{\delta h_{ij}}\Psi[h_{kl}] = 0$$

$$\hat{h}_{ij}(x)\,|h\rangle = h_{ij}(x)\,|h\rangle$$

$$[\hat{h}_{ij}(\vec{x}), \pi^{kl}(\vec{x}')] = i\{\delta_i^k\delta_j^l\}\delta^{(3)}(\vec{x} - \vec{x}')$$

Constraint on the trace of the transverse mode

The physical states are independent of the longitudinal mode

DOES THE NEWTONIAN FIELD HAVE A QUANTUM STATE?

SHORT ANSWER: YES!

Chen, Giacomini, Rovelli 2207.10592 (2022)

Then the quantum state of the Newtonian field is the ground state $|h_i^0\rangle_G$ of the Hamiltonian with the charge in the quantum state $|\Phi_i\rangle$

	Electromagnetism	**Linearized Gravity**
Temporal gauge	$A_0 = 0$	$h_{0\mu} = 0$
Canonical variables	$\{A_i(\vec{x}), E_j(\vec{x}')\}$	$\{h_{ij}(\vec{x}), \pi^{kl}(\vec{x}')\}$
No. of constraints	1	4
Similar constraints (without matter)	Gauss law in A basis $\partial_j \frac{\delta}{\delta A_j(\vec{x})} \Psi[A] = 0$	Vector constraint in h basis $\partial_i \frac{\delta}{\delta h_{ij}(\vec{x})} \Psi[h_{ij}] = 0$
Similar constraints (with matter)	Gauss law in E basis with charge $\nabla \cdot E = \Delta\phi = \rho$	Scalar constraints $\Delta h^T = -\rho$
Vaccum state	Gaussian of transverse mode	Gaussian of transverse mode with zero trace
The d.o.f activated with a static source	Longitudinal mode A_L	Trace of transverse mode h_T

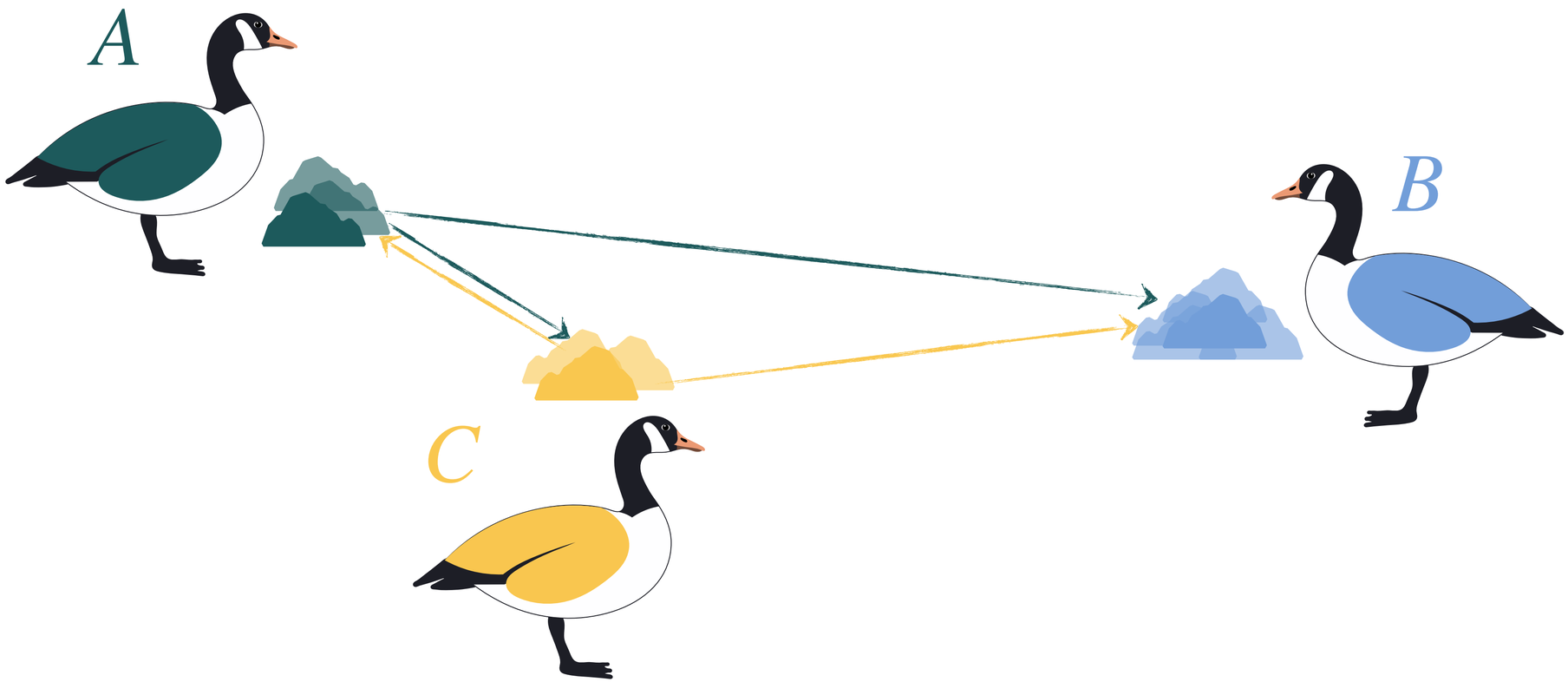
$$|\Psi\rangle_{G+M} = \sum_i \alpha_i |h_i^0\rangle_G |\Phi_i\rangle_M$$

ELECTROMAGNETISM IS ANALOGOUS!

IS THE SUPERPOSITION OF GRAVITATIONAL FIELDS A RELATIVE CONCEPT?

QUANTUM REFERENCE FRAMES (QRFs)

Giacomini, Castro-Ruiz, Brukner, Nat. Commun. (2019)

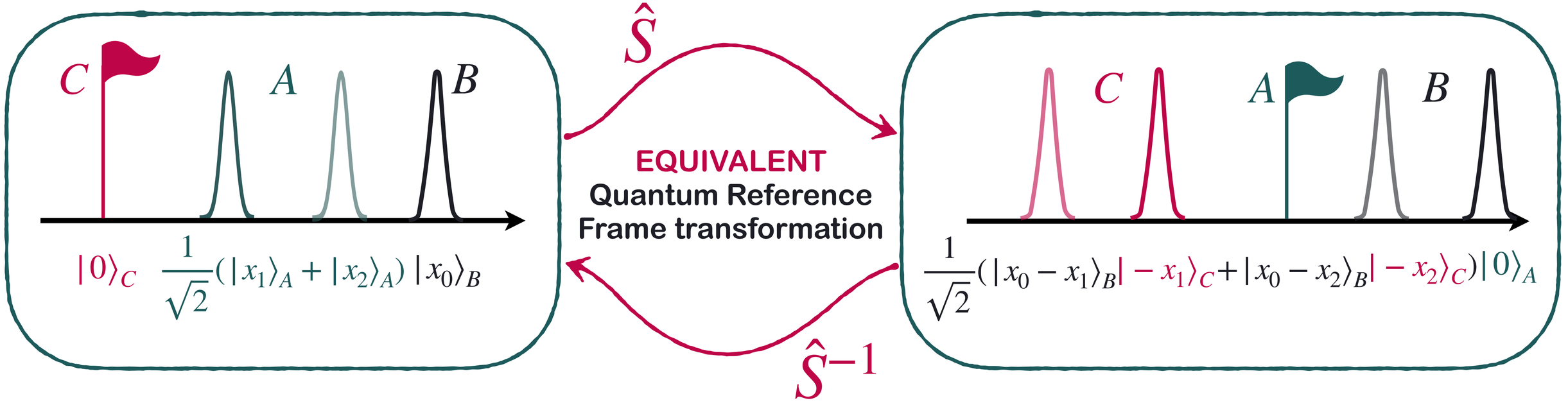


QUANTUM REFERENCE FRAME TRANSFORMATIONS

The simplest case: spatial translations in 1D

Giacomini, Castro-Ruiz, Brukner, Nat. Commun. (2019)

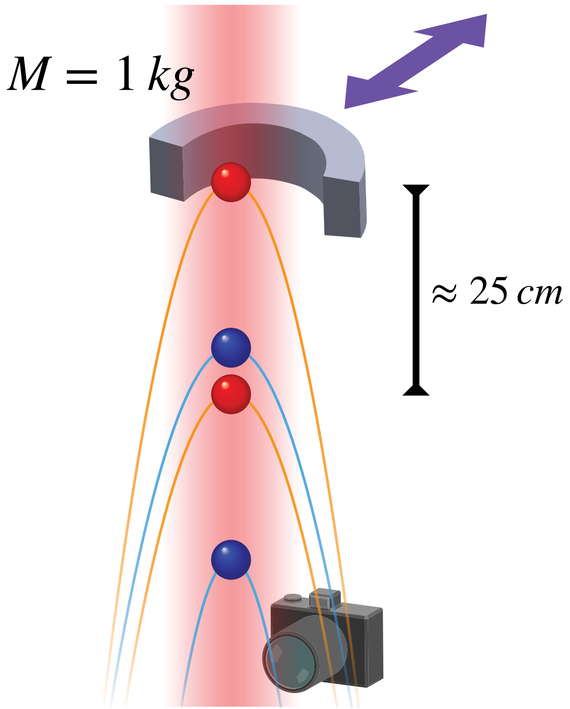
$$\hat{S} = \mathscr{P}_{AC}\, e^{\frac{i}{\hbar}\hat{x}_A \hat{p}_B}$$

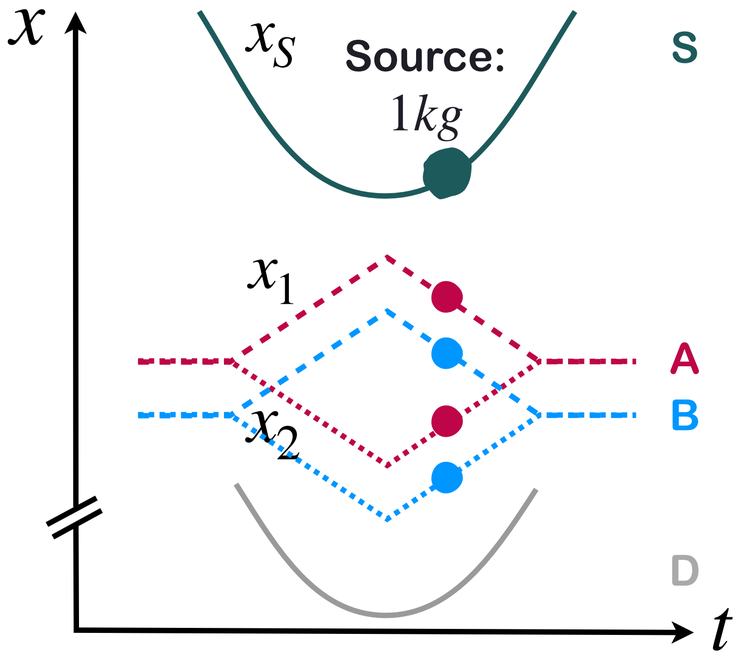


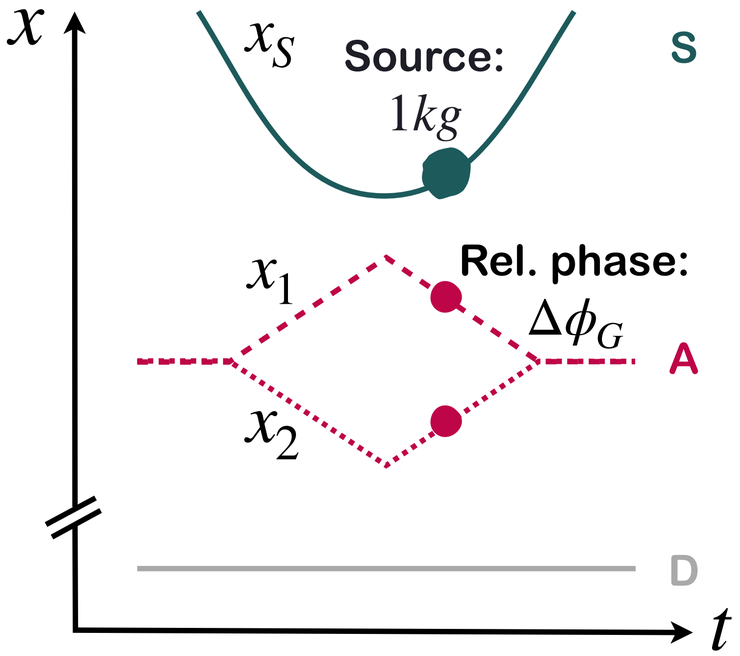
1. Quantum-controlled translation on state of A
2. QRF has a Hilbert space assigned to it

GRAVITATIONAL AHARONOV-BOHM EXPERIMENT

Overstreet, Asenbaum, Curti, Kim, Kasevich, Science (2022)







Gravitational action difference: $\Delta\phi_G = \frac{1}{\hbar}\int_0^T dt[V(x_2 - x_S) - V(x_1 - x_S)]$

Phase shift beyond linear regime

NB: Earth factors out from the description

WHAT WE KNOW FROM CURRENT EXPERIMENTS

- **Localised masses as light as $90\,mg$ source a gravitational field**

  Westphal, Hepach, Pfaff, Aspelmeyer, Nature (2021)

- **Equivalence Principle is valid up to experimental resolution (10^{-15})**

  MICROSCOPE mission, PRL (2022)

- **Existence of gravitational waves**

  B. Abbott et al., PRL (2016)

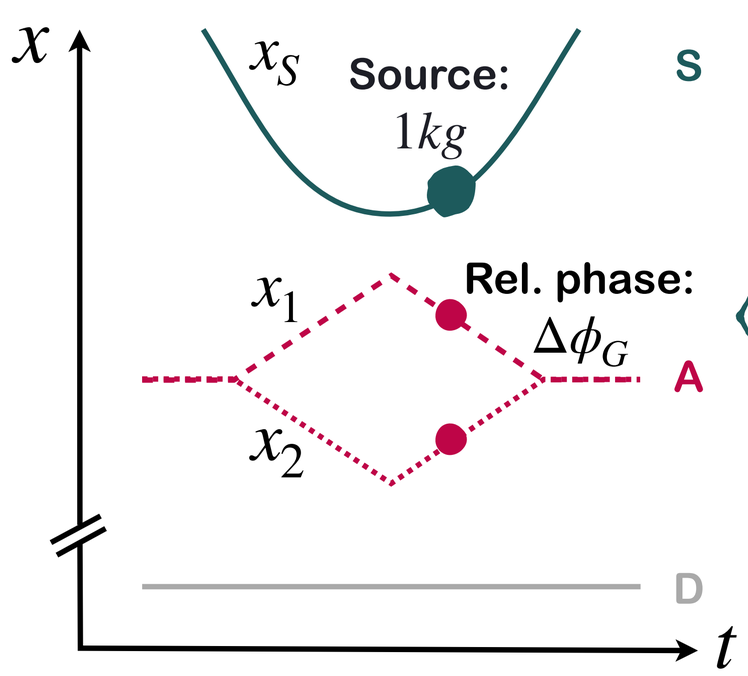
- **Gravitational phase shift between different paths**

- **Classical gravity (tungsten) and Quantum Theory (atom) are compatible beyond the linear regime**

What are we missing to have a superposition of gravitational fields?

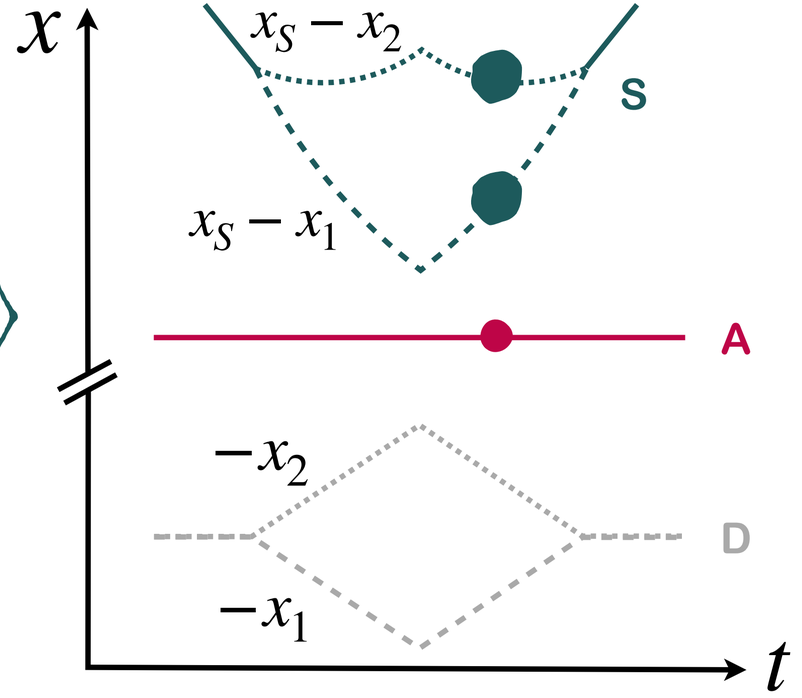
QRF DESCRIPTION OF THE EXPERIMENT

CLASSICAL GRAVITATIONAL FIELD



EQUIVALENT VIA QRF TRANSFORMATION

SUPERPOSITION OF GRAVITATIONAL FIELDS



1. **EXISTENCE OF GRAVITATIONAL FIELDS**
2. **QUANTUM RELATIVITY PRINCIPLE**

Overstreet, Asenbaum, Curti, Kim, Kasevich, Giacomini 2209.02214 (2022)

CONCLUSIONS

FROM AN EXPERIMENTAL PERSPECTIVE:

We do NOT know which observation would prove in a compelling way that gravity has quantum features.

FROM A THEORETICAL PERSPECTIVE:

We do NOT know how to reconcile the fundamental principles of GR and QT.

We can solve, in this regime, some open questions that will help us make progress towards combining QT and GR.

Swiss National Science Foundation

ETH zürich