QUANTUM INFORMATION TOOLS AT THE INTERFACE BETWEEN QUANTUM THEORY AND GRAVITY

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Image credits: J. Palomino

Basics of Quantum Gravity
22-25 May 2023

ETH zürich

Swiss National Science Foundation

LECTURE 2: GRAVITATIONAL QUANTUM PHYSICS

- Superposition of massive objects
- Gravitationally-induced entanglement
- The debate
- The quantum state of the gravitational field
- No-go theorems

Basics of Quantum Gravity
22-25 May 2023

QUANTUM SOURCES FOR THE GRAVITATIONAL FIELD

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

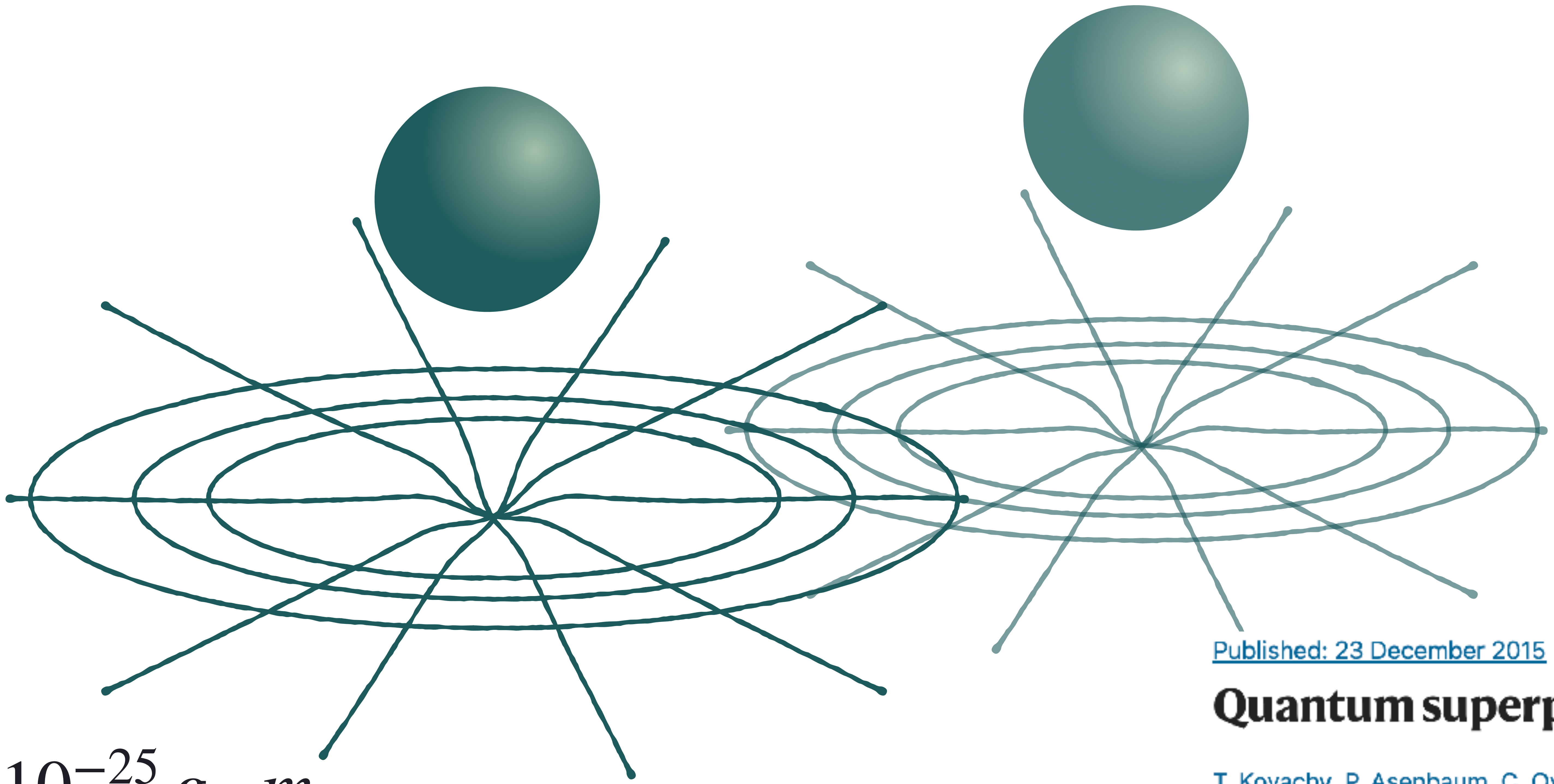
Nature **591**, 225–228 (2021) | Cite this article

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:** $0.5\,m$

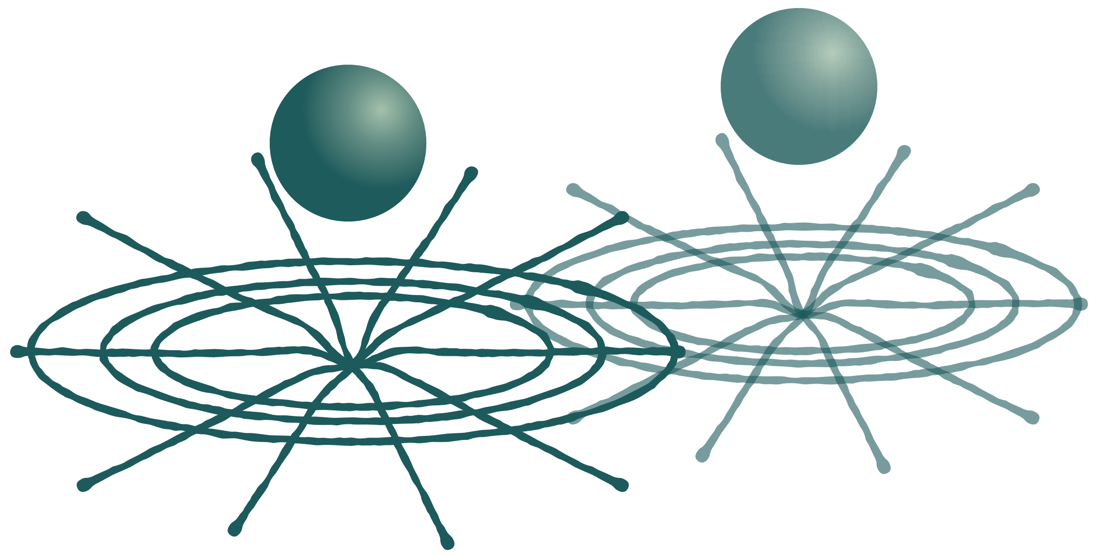
Quantum superposition at the half-metre scale

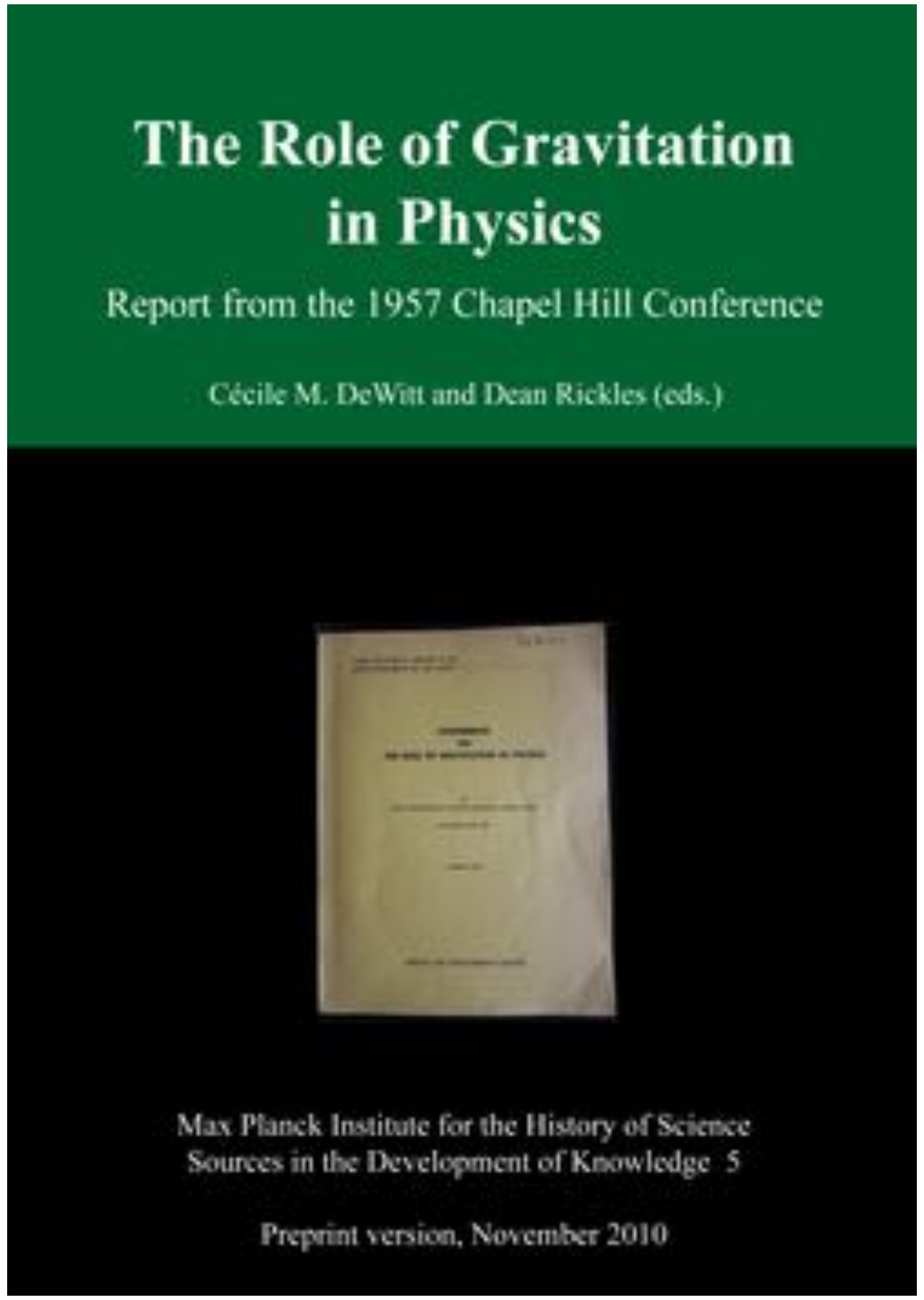
T. Kovachy, P. Asenbaum, C. Overstreet, C. A. Donnelly, S. M. Dickerson, A. Sugarbaker, J. M. Hogan & M. A. Kasevich

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

QUANTUM SOURCES FOR THE GRAVITATIONAL FIELD

CHAPEL HILL CONFERENCE (1957)





*“**Salecker** then raised again the question why the gravitational field needs to be quantized at all. In his opinion, charged quantized particles already serve as sources or a Coulomb field which is not quantized.”*

***Feynman**: “[…] it seems clear to me that we’re in trouble if we believe in quantum mechanics but don’t quantize gravitational theory.”*

***Feynman:** “If you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment.”*

QUANTUM SOURCES FOR THE GRAVITATIONAL FIELD

Eppley-Hannah
"The necessity of quantizing the gravitational field" (1977)

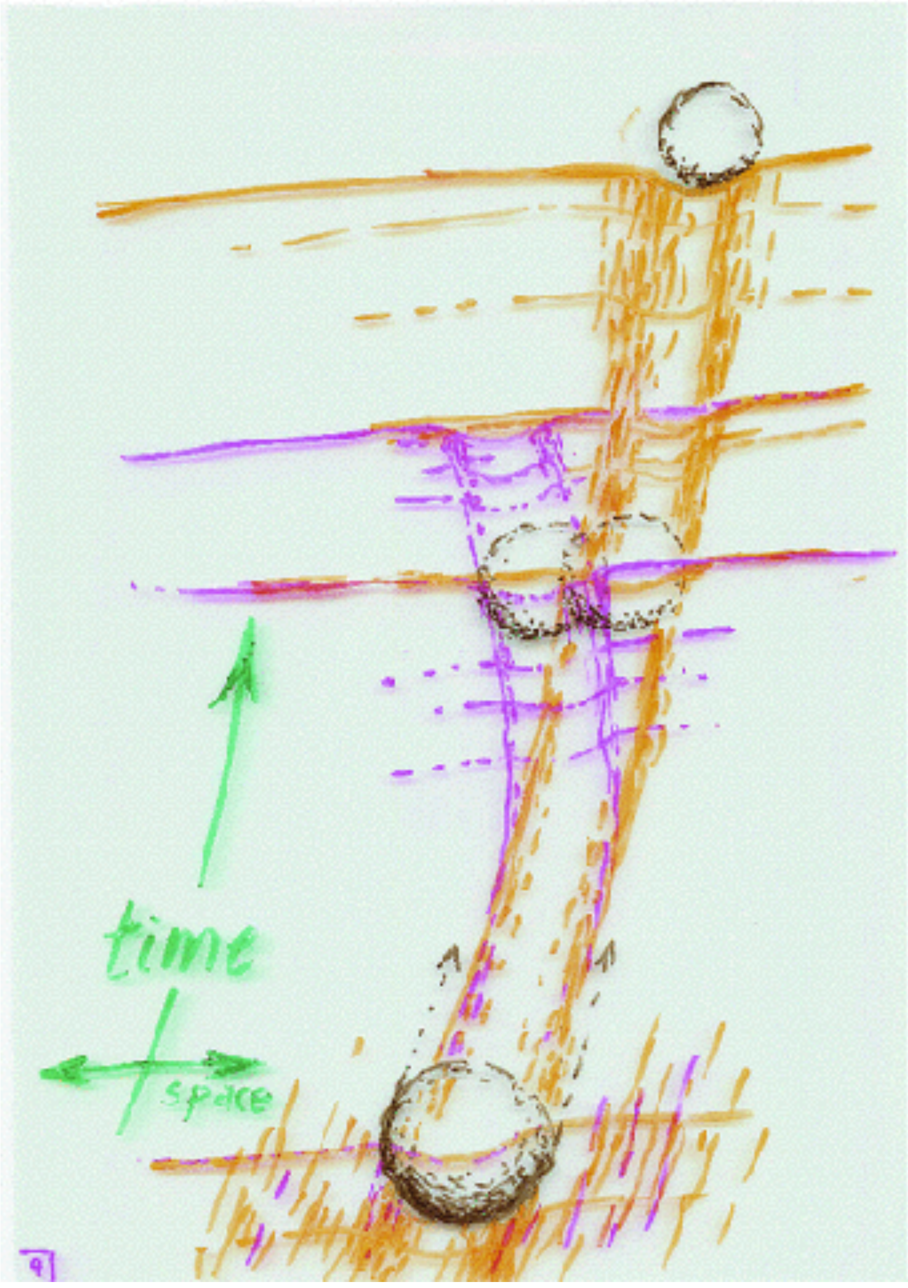
Page-Geilker
"Indirect Evidence for Quantum Gravity" (1981)

Penrose
"On gravity's role in quantum state reduction" (1996)

Lindner-Peres
"Testing quantum superpositions of the gravitational field with Bose-Einstein condensates" (2004)

Anastopoulos -Hu
"Probing a gravitational cat state" (2015)

(…)



R. Penrose, Found. Phys. (2014)

When matter sourcing gravity is quantum, gravity is:

QUANTUM: most approaches

CLASSICAL: alternative models (Schrödinger-Newton, Collapse Models, Gravitational Decoherence, stochastic models) →

$$G_{\mu\nu} = \kappa \langle \hat{T}_{\mu\nu} \rangle$$

quantum-classical coupling is not trivial!

SOMETHING ELSE!

EVIDENCE FOR A QUANTUM NATURE OF GRAVITY?

What does it mean that gravity is quantum?

1. Superposition of spacetimes
2. Generates entanglement (LOCC)
3. There is (and we measure) quantised radiation
4. Post-quantum

Should we look for a quantum field description of gravity?

Not necessarily

What is evidence that gravity is quantum?

~~DIRECT EVIDENCE: measure gravitational degrees of freedom~~

Too hard for now

INDIRECT EVIDENCE: measure effects induced by gravity on matter

This lecture

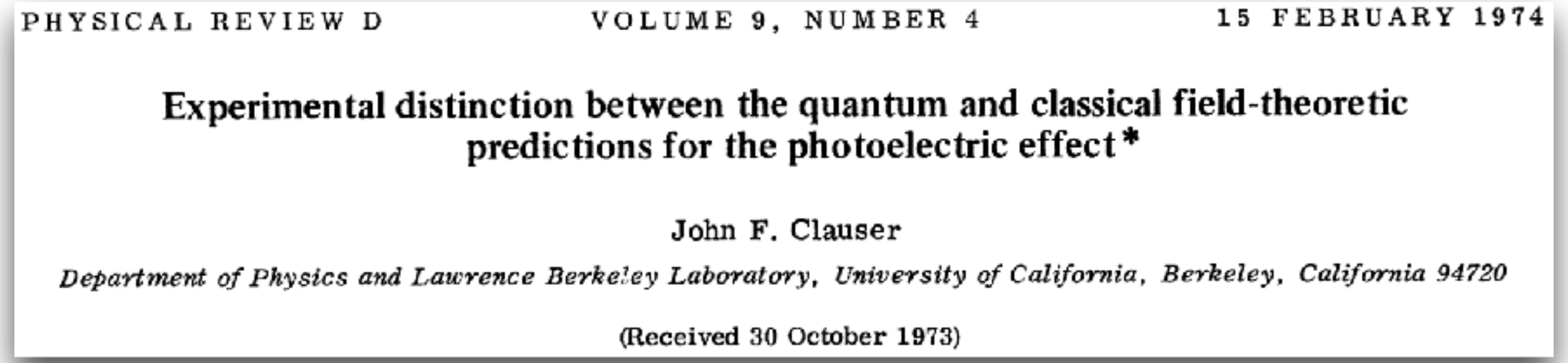
NB: Similar to Stern-Gerlach!

1905: photoelectric effect (Einstein)

1923: photoelectric effect does not require quantum (Millikan)

1923: Compton effect

1960s: semiclassical theory of radiation (Jaynes)


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)

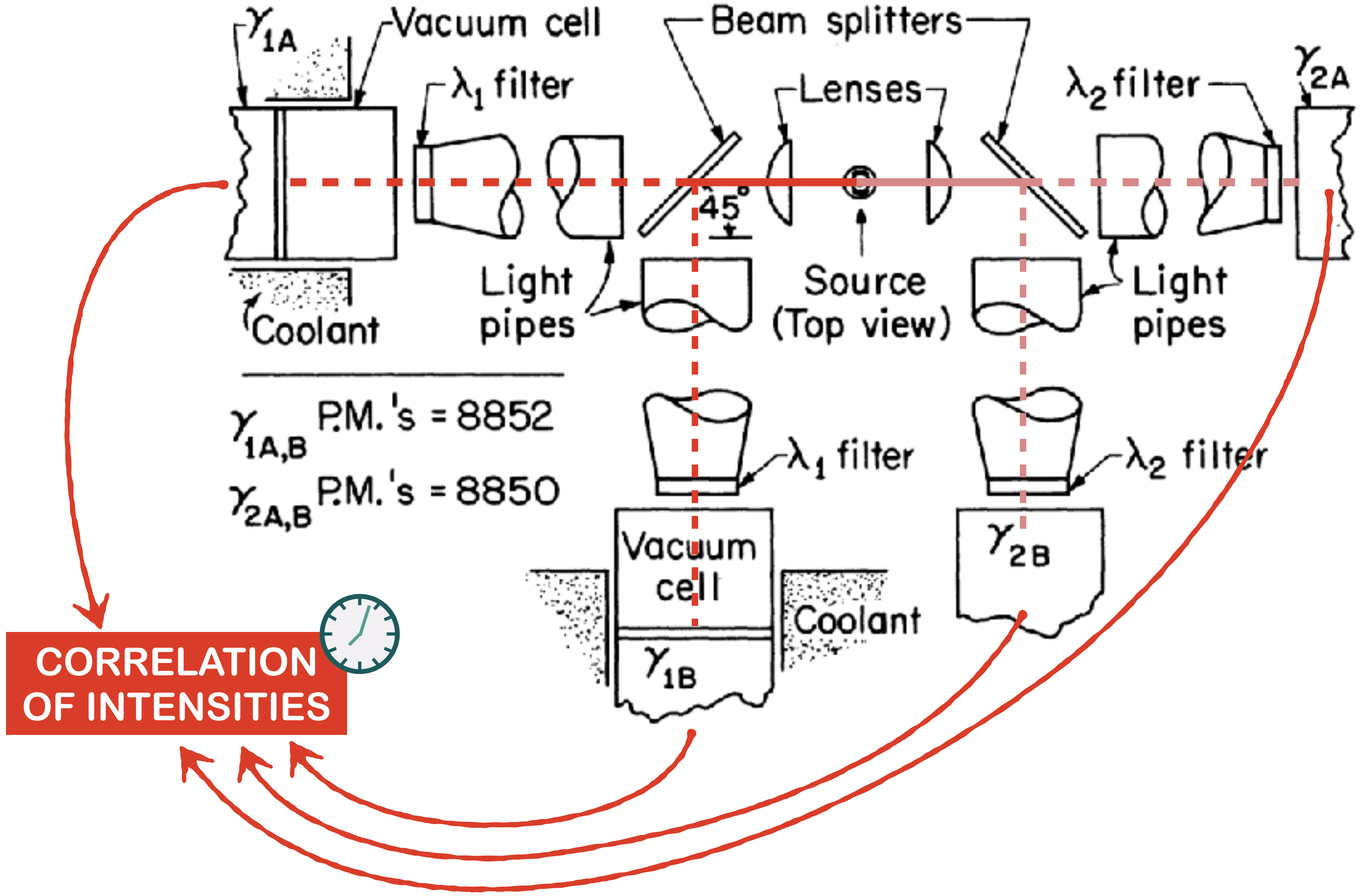
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

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

For a single photon source

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

Signature of nonclassicality

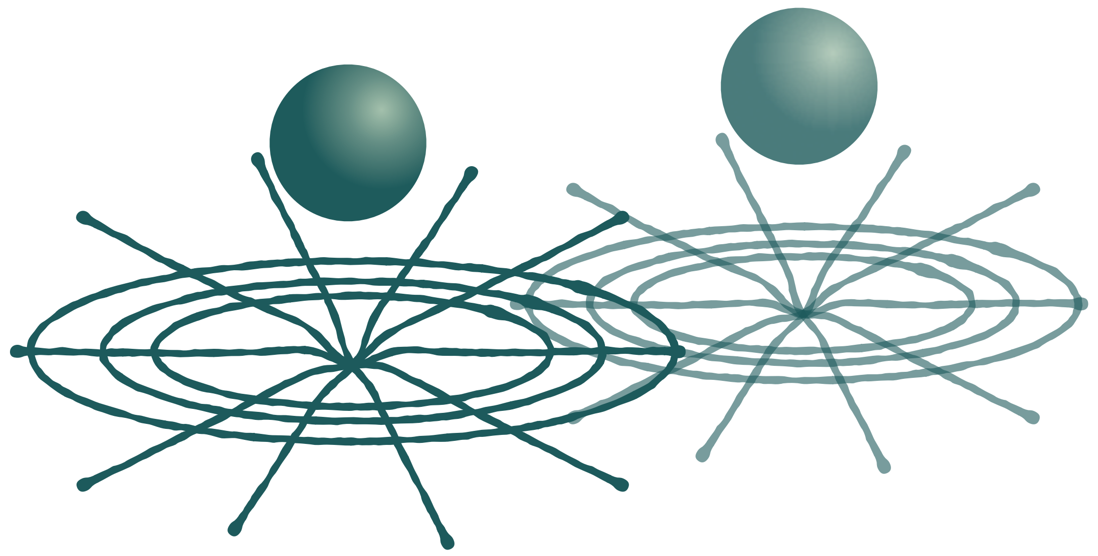


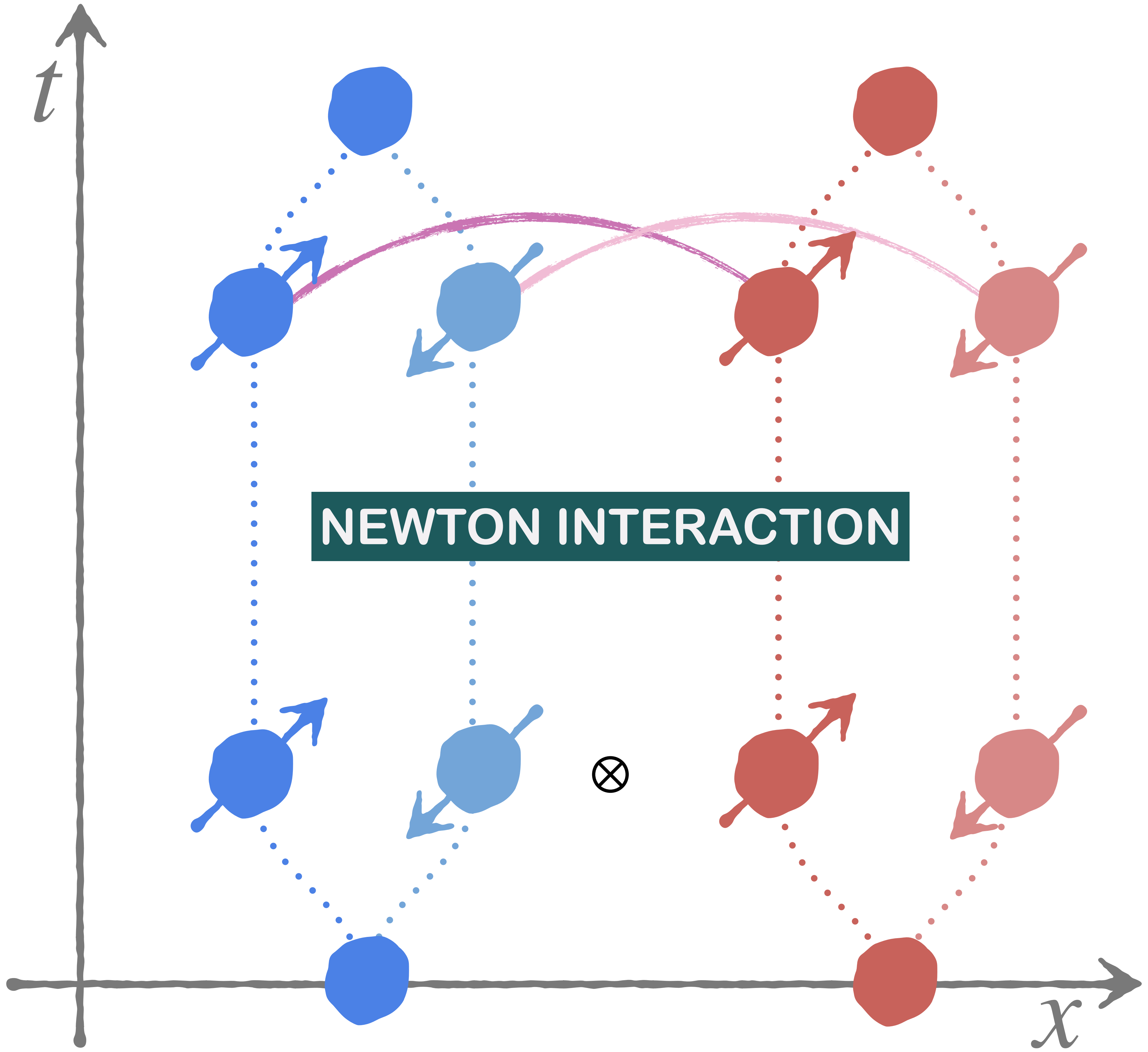
GRAVITATIONALLY INDUCED ENTANGLEMENT

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., PRL (2023)*

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*

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) CAN WE TEST THE INTERNAL CONSISTENCY OF THE THEORY WITH THEORY-INDEPENDENT ARGUMENTS?

NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

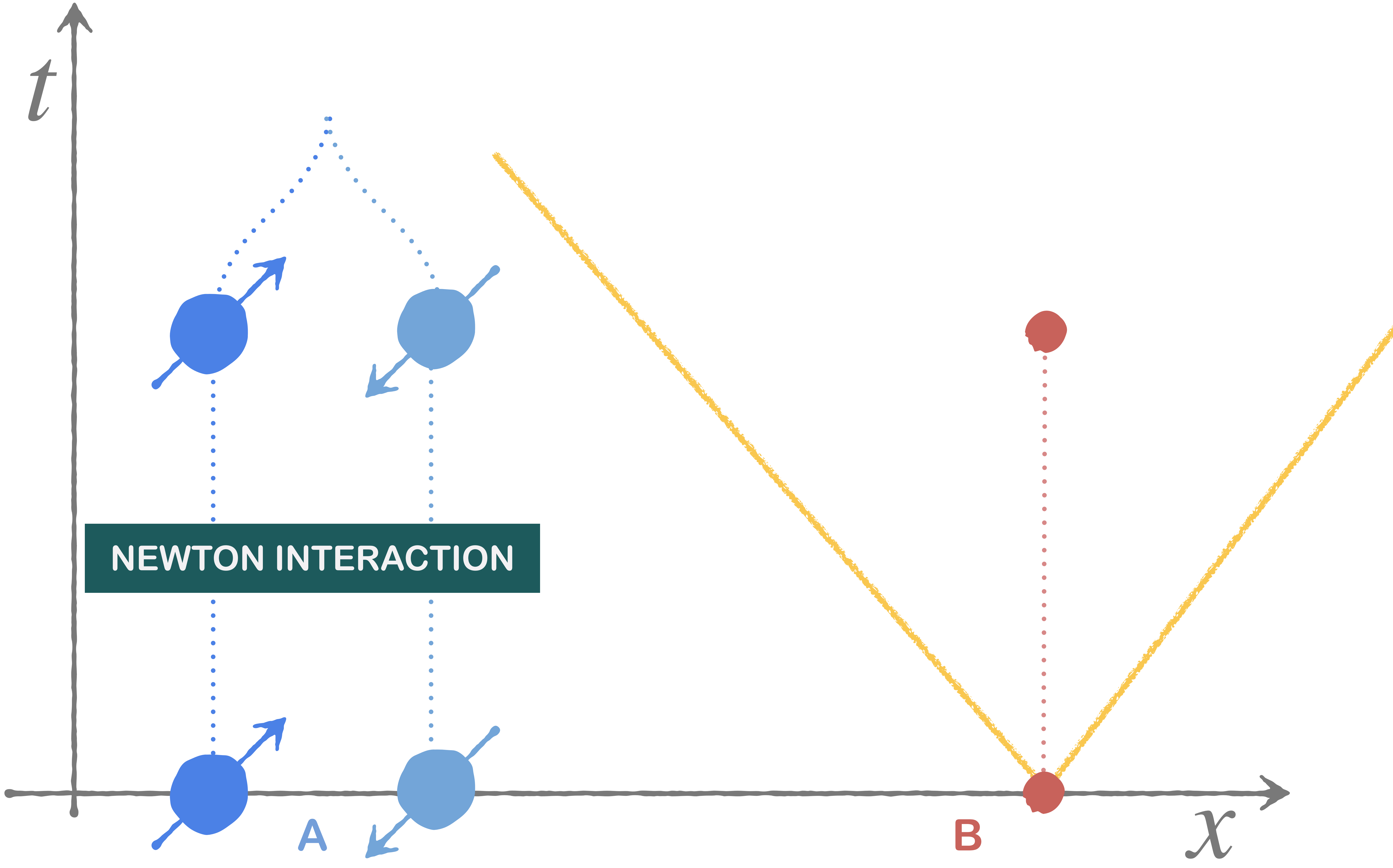
Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)

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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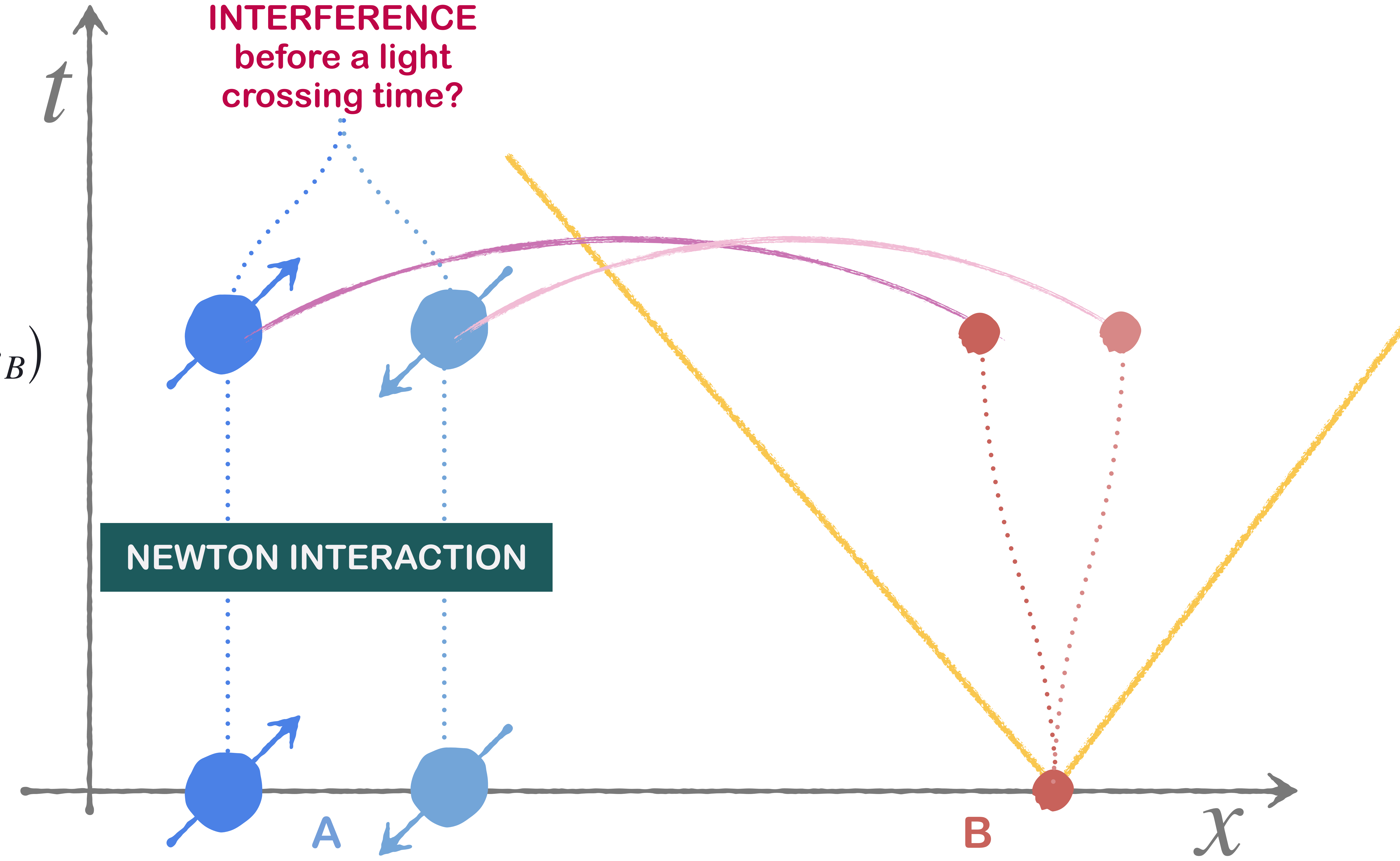


NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

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

TAKE-HOME MESSAGE

Quantum properties of the gravitational field

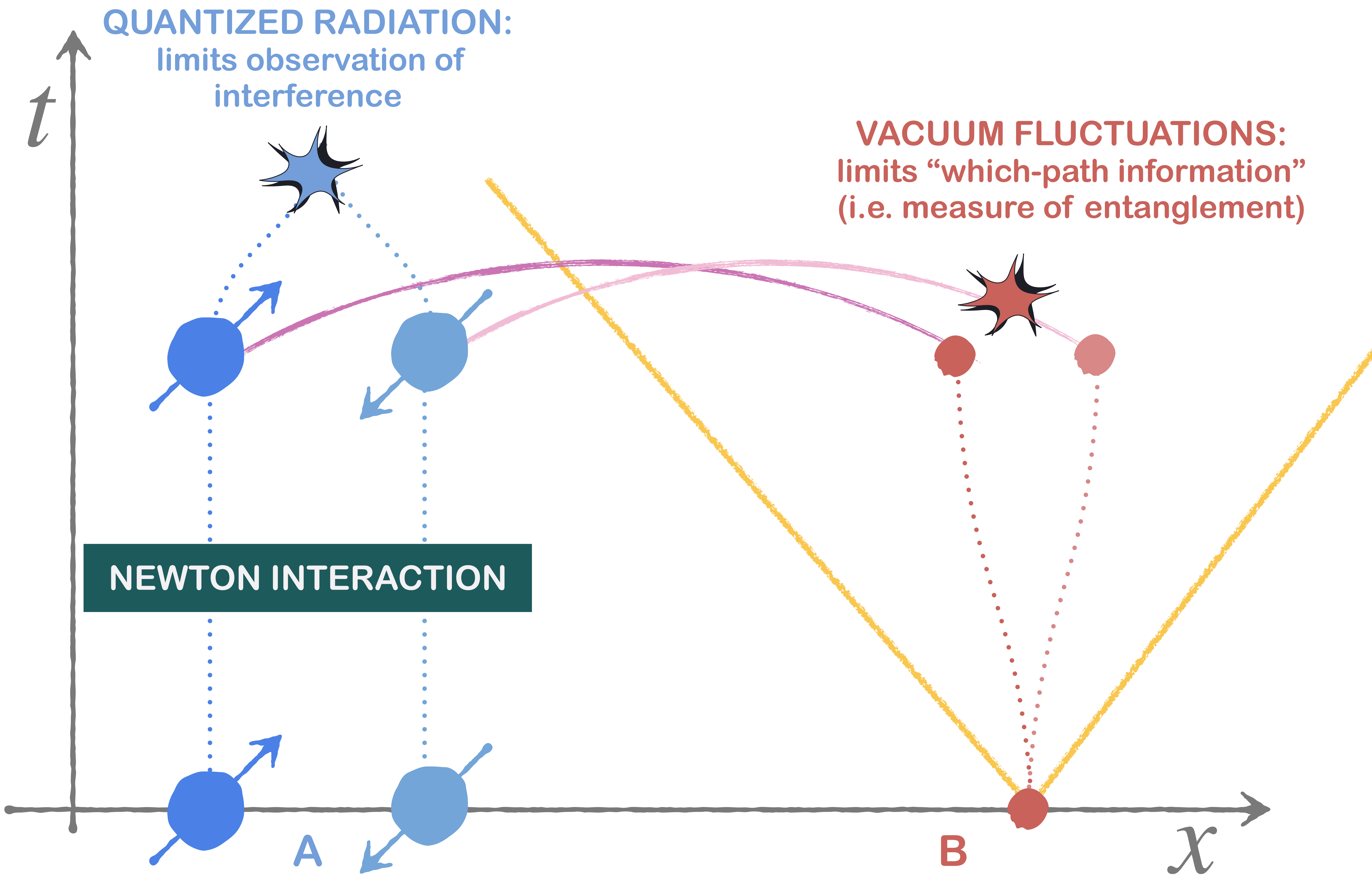
QUANTIZED RADIATION
VACUUM FLUCTUATIONS

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

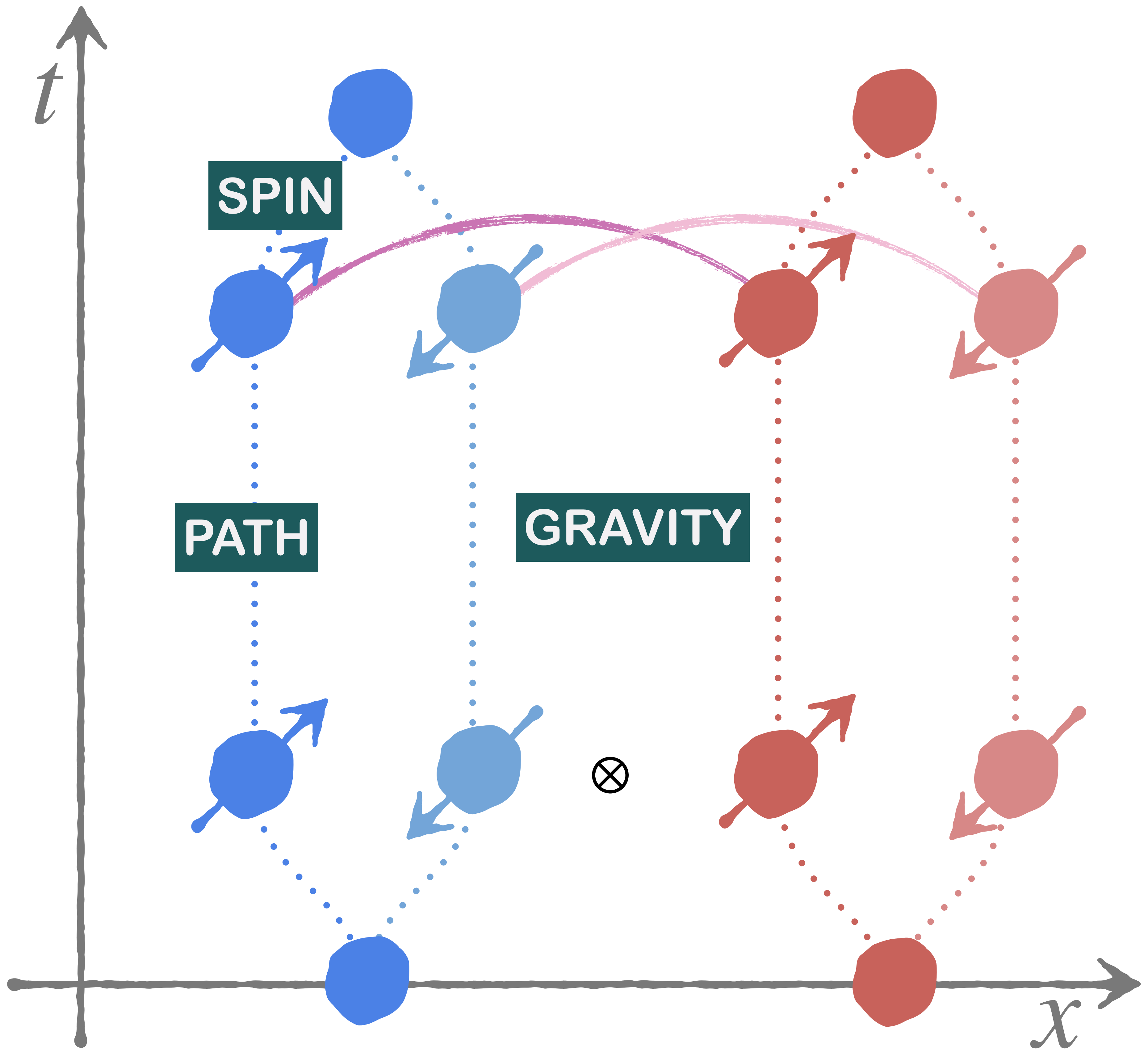
If instead we want to keep a classical description of gravity, we need to drastically modify our basic principles.

See also Danielson, Satishchandran, Wald PRD (2022)



IS THE RELATIVE NEWTONIAN PHASE LOCAL?

Christodoulou, Di Biagio, Aspelmeyer, Brukner, Rovelli, Howl, PRL (2023)



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

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

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

DOES THE NEWTONIAN FIELD HAVE A QUANTUM STATE?

SHORT ANSWER: YES!

Chen, Giacomini, Rovelli Quantum (2023)

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)

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

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

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

Constraint on the trace of the transverse mode

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

The physical states are independent of the longitudinal mode

DOES THE NEWTONIAN FIELD HAVE A QUANTUM STATE?

Chen, Giacomini, Rovelli 2207.10592 (2022)

SHORT ANSWER: YES!

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

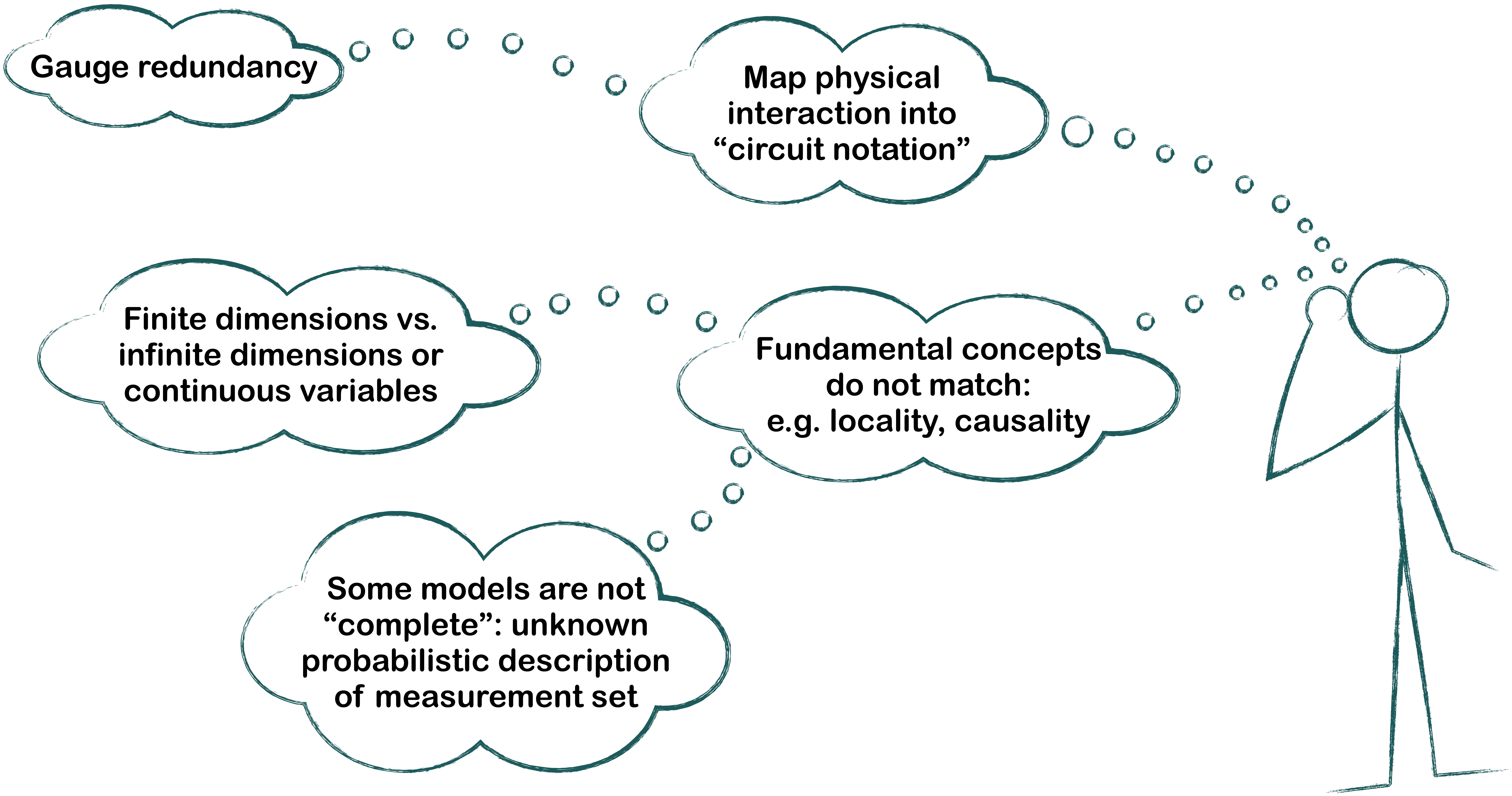
$$|\Psi\rangle_{G+M} = \sum_i \alpha_i |h_i^0\rangle_G |\Phi_i\rangle_M$$

ELECTROMAGNETISM IS ANALOGOUS!

THEORY-INDEPENDENT APPROACH

Provided that we observe gravitationally-induced entanglement in the laboratory, which conclusions can we draw on the nature of the gravitational field?

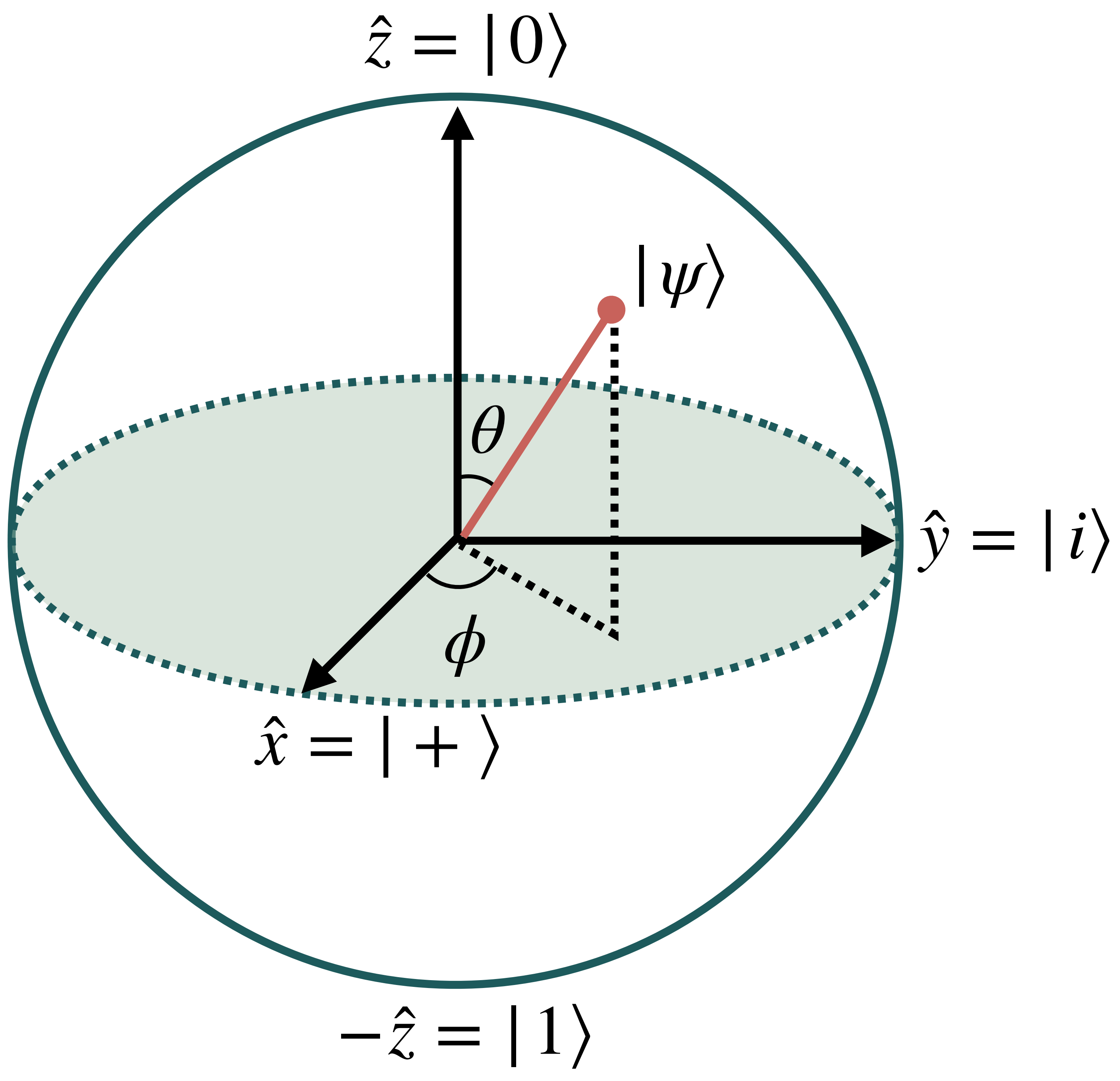
CHALLENGES OF THIS APPROACH



MAPPING COMPLICATED PHYSICS ONTO QUBITS

QUBIT: fundamental unit of quantum information

$$|\psi\rangle = \cos\theta|0\rangle + e^{i\phi}\sin\theta|1\rangle$$



BLOCH SPHERE

QUBIT REPRESENTATION

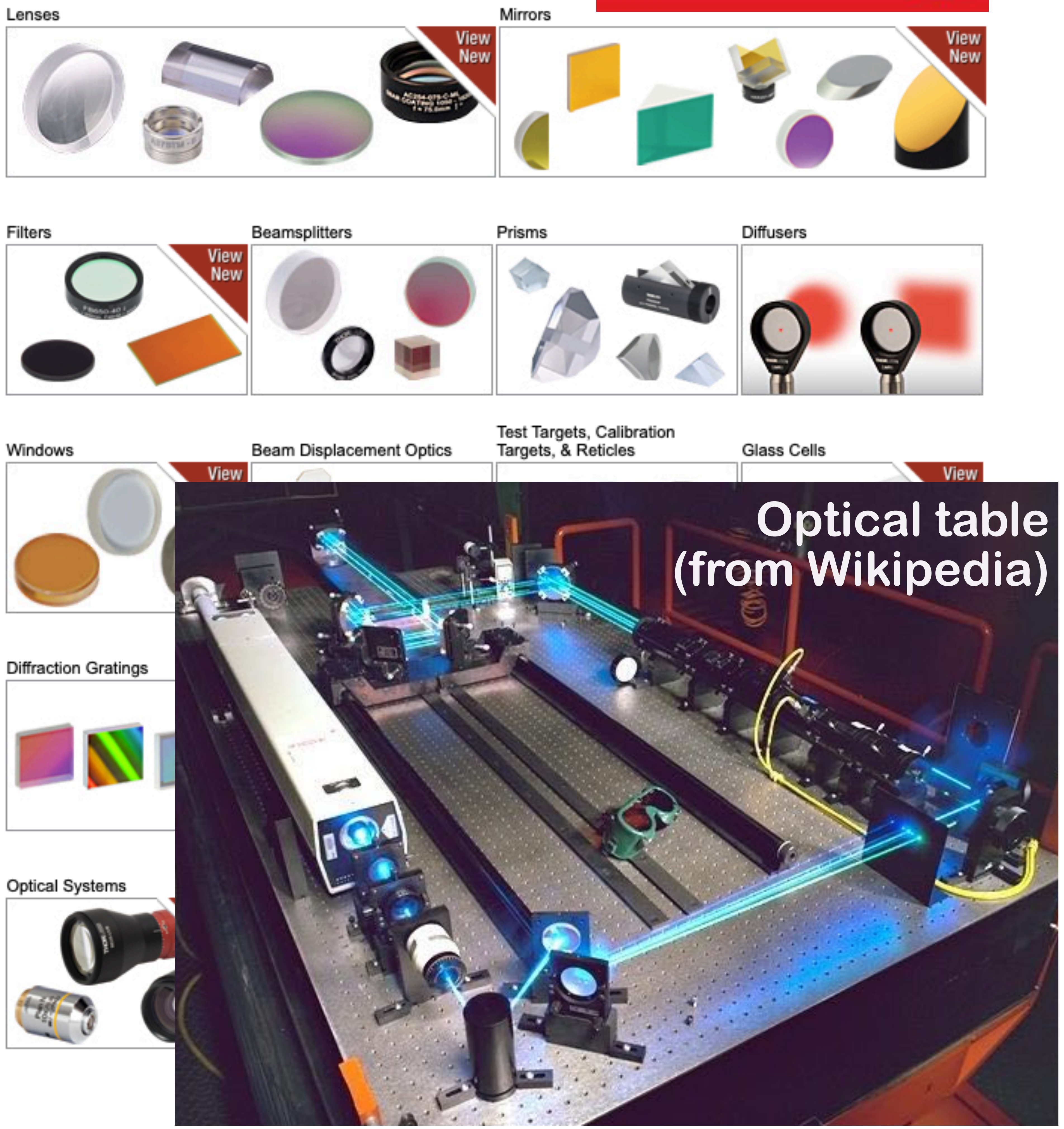
Only a subset of states is relevant

Sometimes mix different d.o.f.

Qubit behaviour

NB: a qubit is not a specific physical system

Optical components from THORLABS



Optical table (from Wikipedia)

Galley, Giacomini, Selby, Quantum (2022)

Theorem: We consider two nonclassical* systems A and B, initially in a separable state,

and the gravitational field G in a product state.

We assume that the systems A and B only interact gravitationally.

Then the following statements are incompatible:

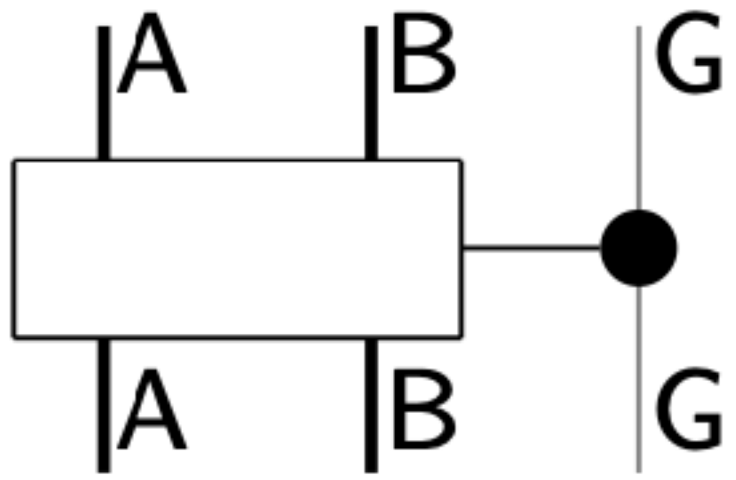
1. The gravitational field G is able to generate entanglement;
2. A and B interact via the mediator G;
3. G is classical.

*also valid for classical A and B

MEDIATION OF INTERACTION (QUANTUM INFORMATION NOTION)

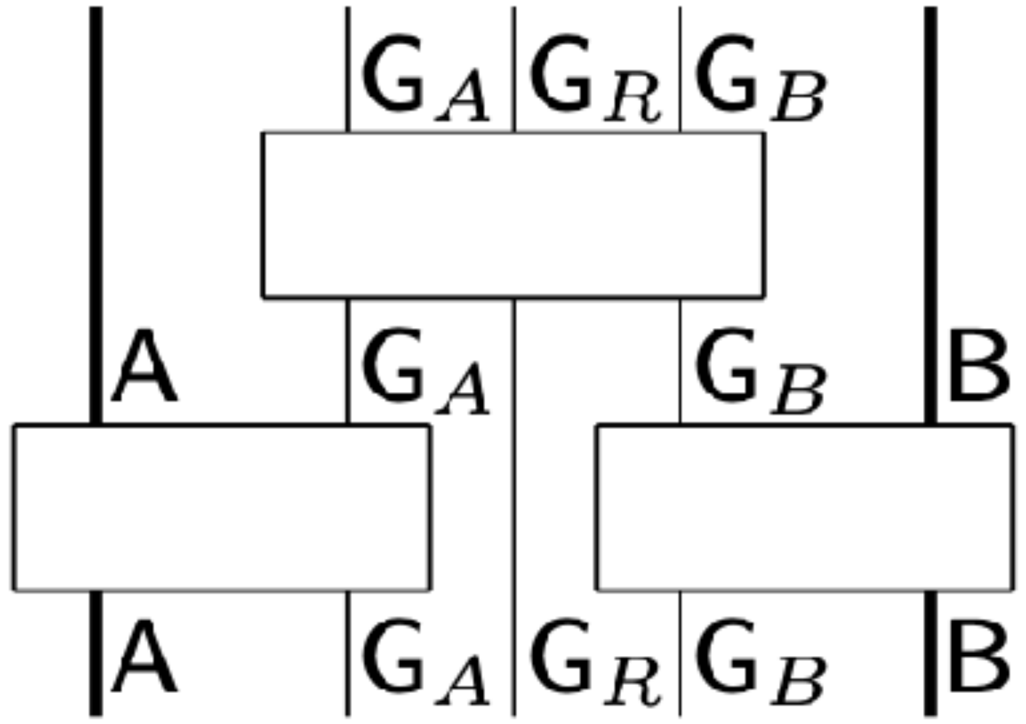
Galley, Giacomini, Selby, Quantum (2022)

G is not a mediator



A and B interact directly, and the interaction is conditioned on the state of G

G is a mediator



A and B interact “locally” via G

G cannot be measured, but we infer its operational nature by observing how it acts on other systems.

CLASSICALITY CONDITION

Galley, Giacomini, Selby, Quantum (2022)

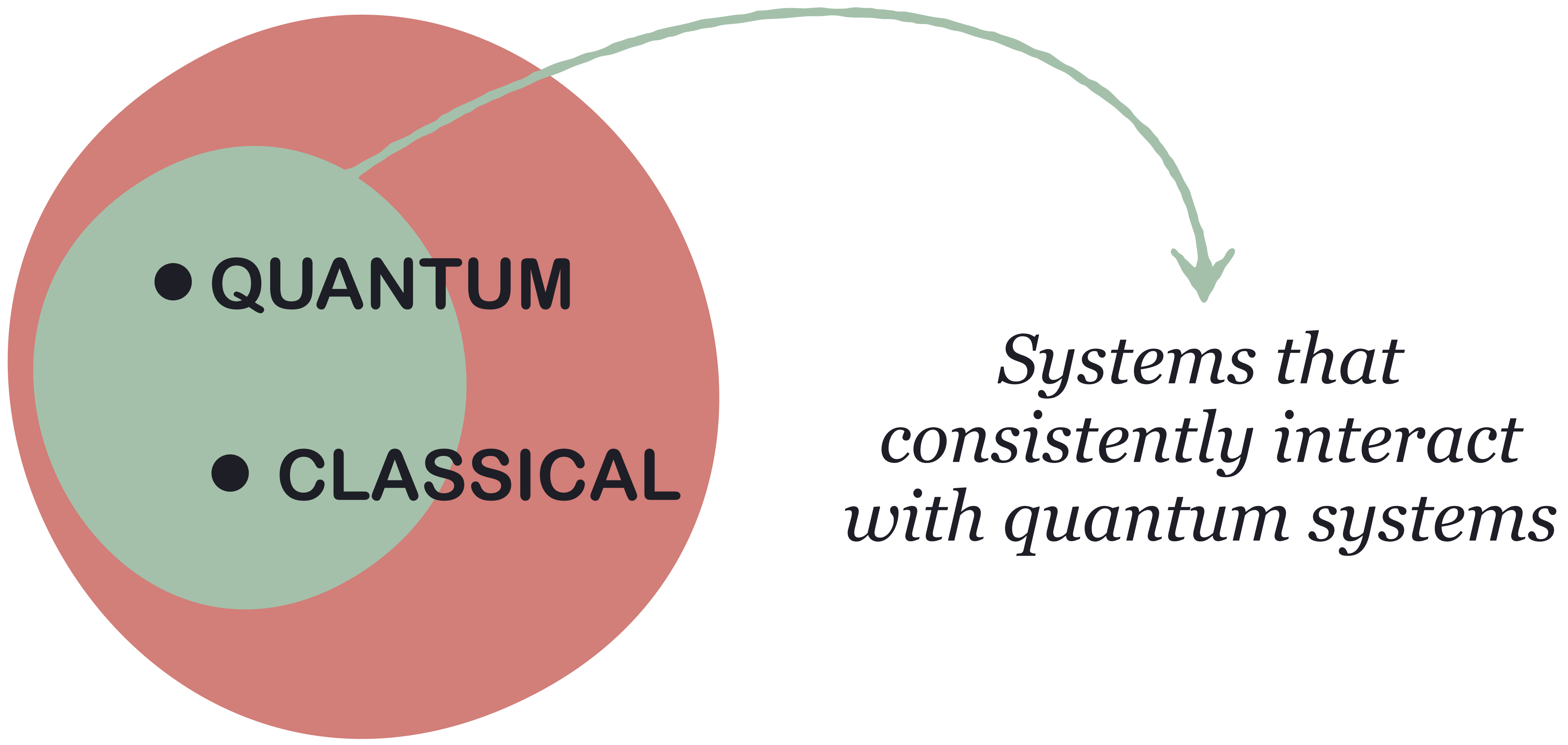
A classical system is

Kinematically classical: any two pair of states can be perfectly distinguished;

Compositionally classical: it composes with the standard tensor product rule with other systems (whether classical or non-classical)

Not Classical $\nRightarrow$ Quantum

- QUANTUM
- CLASSICAL



Galley, Giacomini, Selby, arXiv:2301.10261 (2023)

Theorem: Given two GPT systems S and G which interact via some interaction I then at least one of the following conditions must be violated:

(i) The system S is fully non-classical

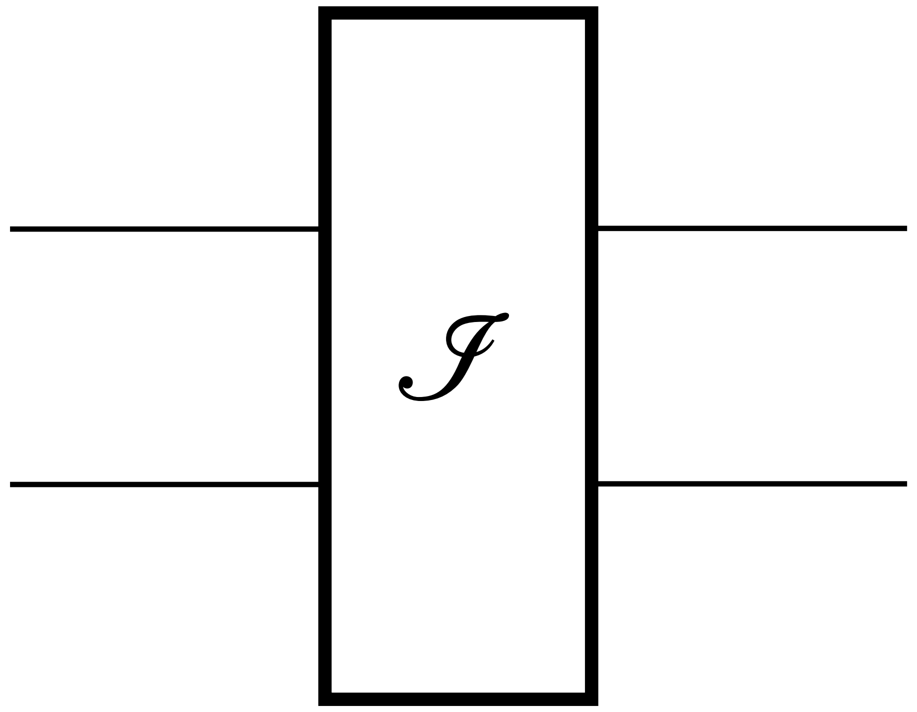
Note for experts:
"fully" means irreducible
(i.e. not super-selected)

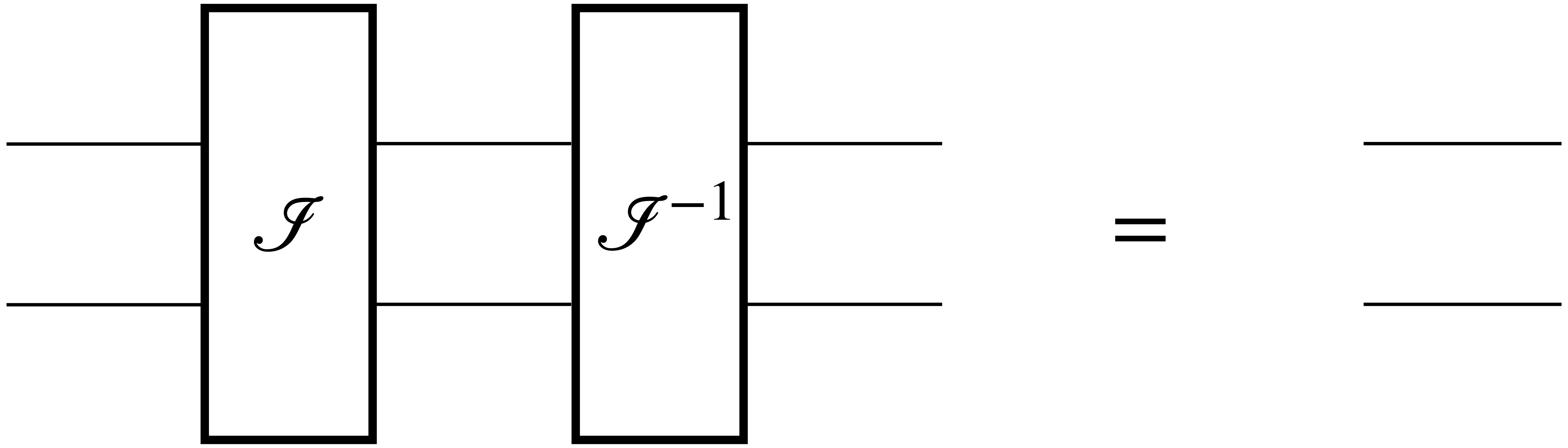
(ii) The interaction I is reversible

(iii) There is information flow from system S to system G

(iv) G is classical

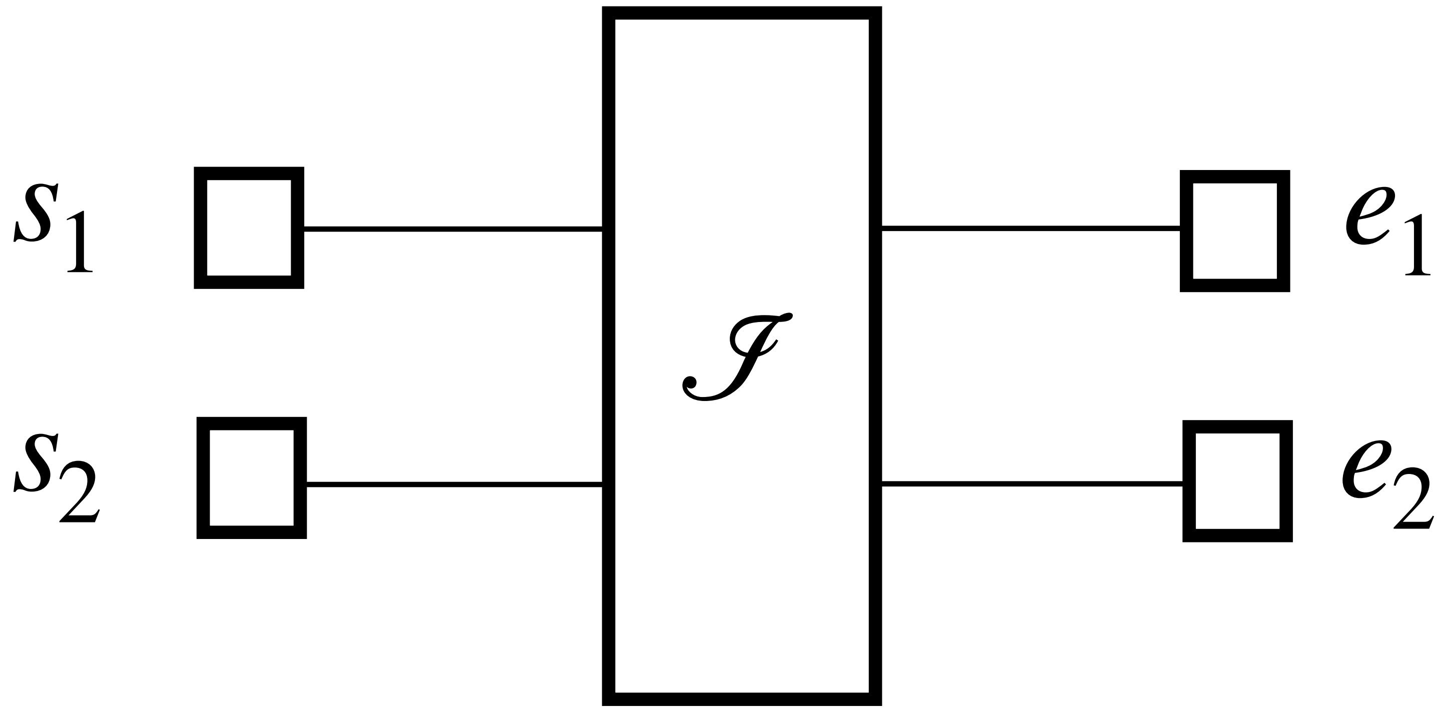
Galley, Giacomini, Selby, arXiv:2301.10261 (2023)





INFORMATION FLOW FROM SYSTEM 1 TO SYSTEM 2

Galley, Giacomini, Selby, arXiv:2301.10261 (2023)



$p(e_2 \mid s_1, s_2, \mathscr{I})$ **depends non trivially on** s_1

Signalling from 1 to 2

ARGUMENT FOR NONCLASSICALITY OF G

Galley, Giacomini, Selby, arXiv:2301.10261 (2023)

Theorem: Given two GPT systems S and G which interact via some interaction I then at least one of the following conditions must be violated:

(i) The system S is fully non-classical

(ii) The interaction I is reversible

(iii) There is information flow from system S to system G

(iv) G is classical ✗

S: position degree of freedom of a quantum system — (i) is satisfied ✓

G: gravitational field — In classical gravity matter back-reacts on G — (iii) is satisfied ✓

Interactions are reversible — (ii) is satisfied ✓

WHAT IS G IS CLASSICAL NONETHELESS?

Theorem: Given two GPT systems S and G which interact via some interaction I then at least one of the following conditions must be violated:

(i) The system S is fully non-classical

(ii) The interaction I is reversible ✗

(iii) There is information flow from system S to system G

(iv) G is classical

S: position degree of freedom of a quantum system

G: gravitational field

In classical gravity matter back-reacts on G

G is classical (assumption)

(i) is satisfied ✓

(iii) is satisfied ✓

(iv) is satisfied ✓

SUMMARY

Galley, Giacomini, Selby, arXiv:2301.10261 (2023)

If gravity is classical:

Reject condition	
i)	*Reject QT*
ii)	*Reject reversibility*
iii)	*Reject GR*

There is no coupling between classical gravity and quantum theory which preserves all the main features of the two theories

EXAMPLE: Oppenheim model

Consistent

No-faster than light signalling

Has back-reaction

Not reversible (stochastic dynamical flow)

SUMMARY

MESSAGE 1: Two approaches:

1. Specific description of (thought) experiments
2. Theory-independent description

Each has advantages and disadvantages: we need both!

MESSAGE 2: Gravitationally induced entanglement is hard.

Which other tests can we realise before?

Study of the fundamental principles can help us to lay out the basis of the theory and move forward.

Task: devise experiments which do not require additional assumptions, but test the superposition of gravitational fields

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