QUANTUM REFERENCE FRAMES: A RELATIONAL PERSPECTIVE ON NONCLASSICAL SPACETIME

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Image credits: J. Palomino

International Loop Quantum Gravity Seminar
7 March 2023

QUANTUM ASPECTS OF SPACETIME

What replaces the classical notion of spacetime when gravity acquires quantum properties?

HIGH ENERGIES:
PLANCK-SCALE PHYSICS

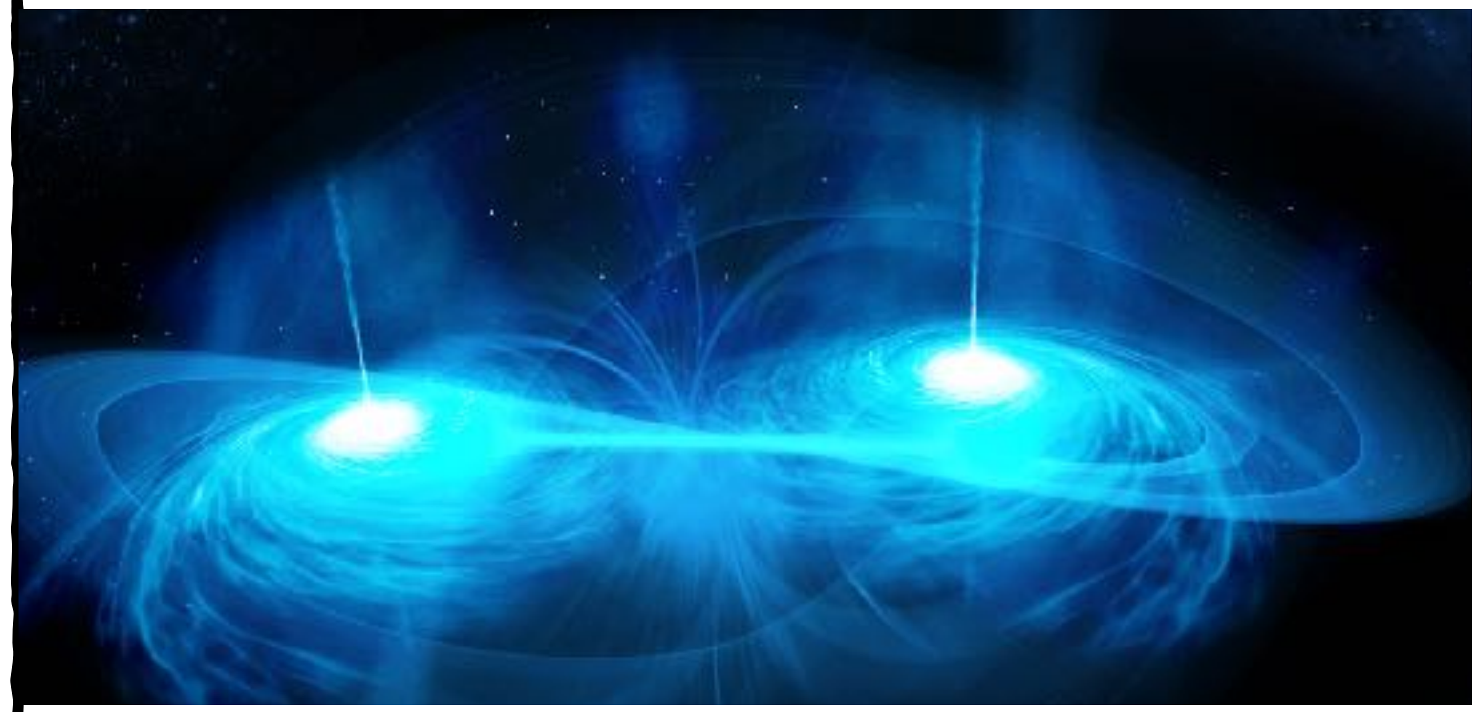
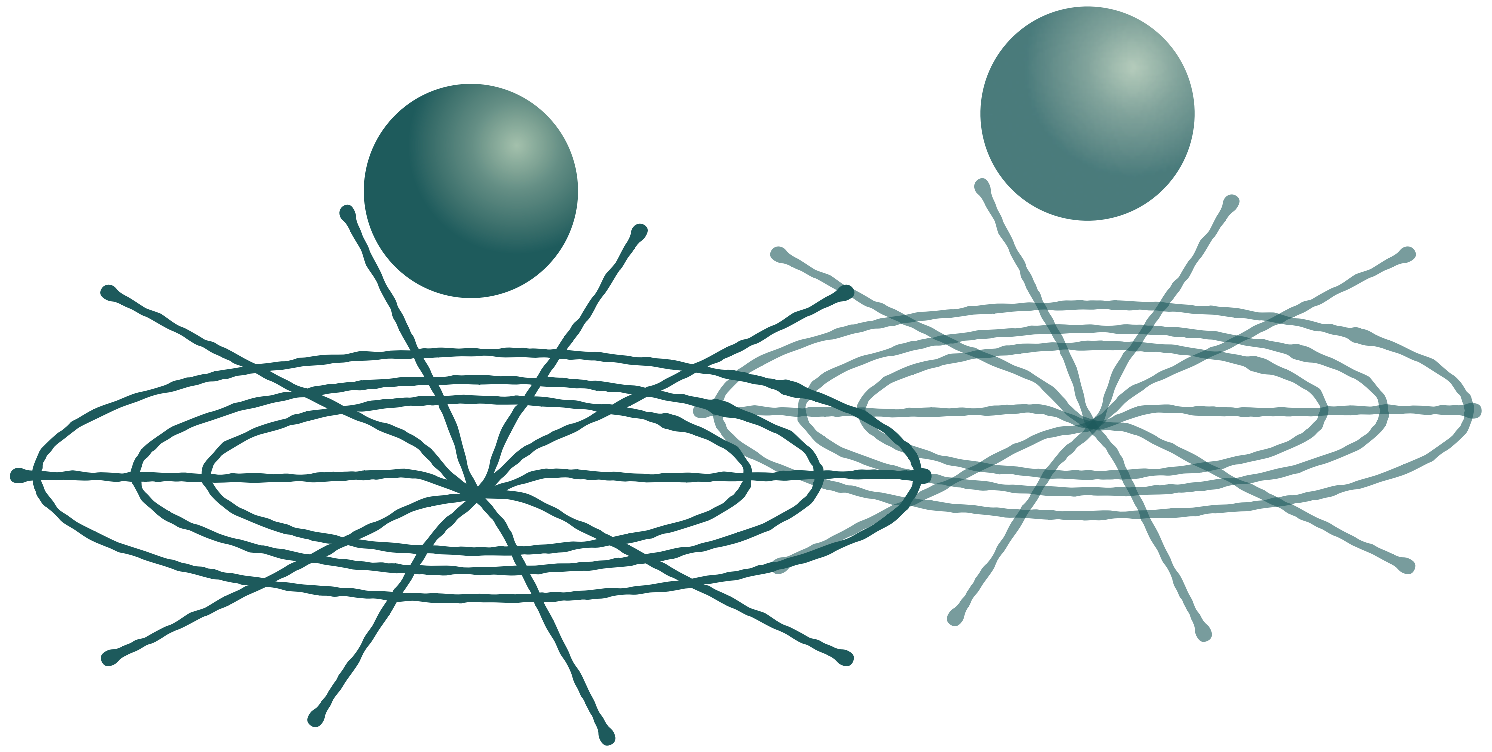


Image credits: Perimeter Institute

QUANTUM SPACETIME "FUZZINESS"

- Black Holes
- Quantum Cosmology
- 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

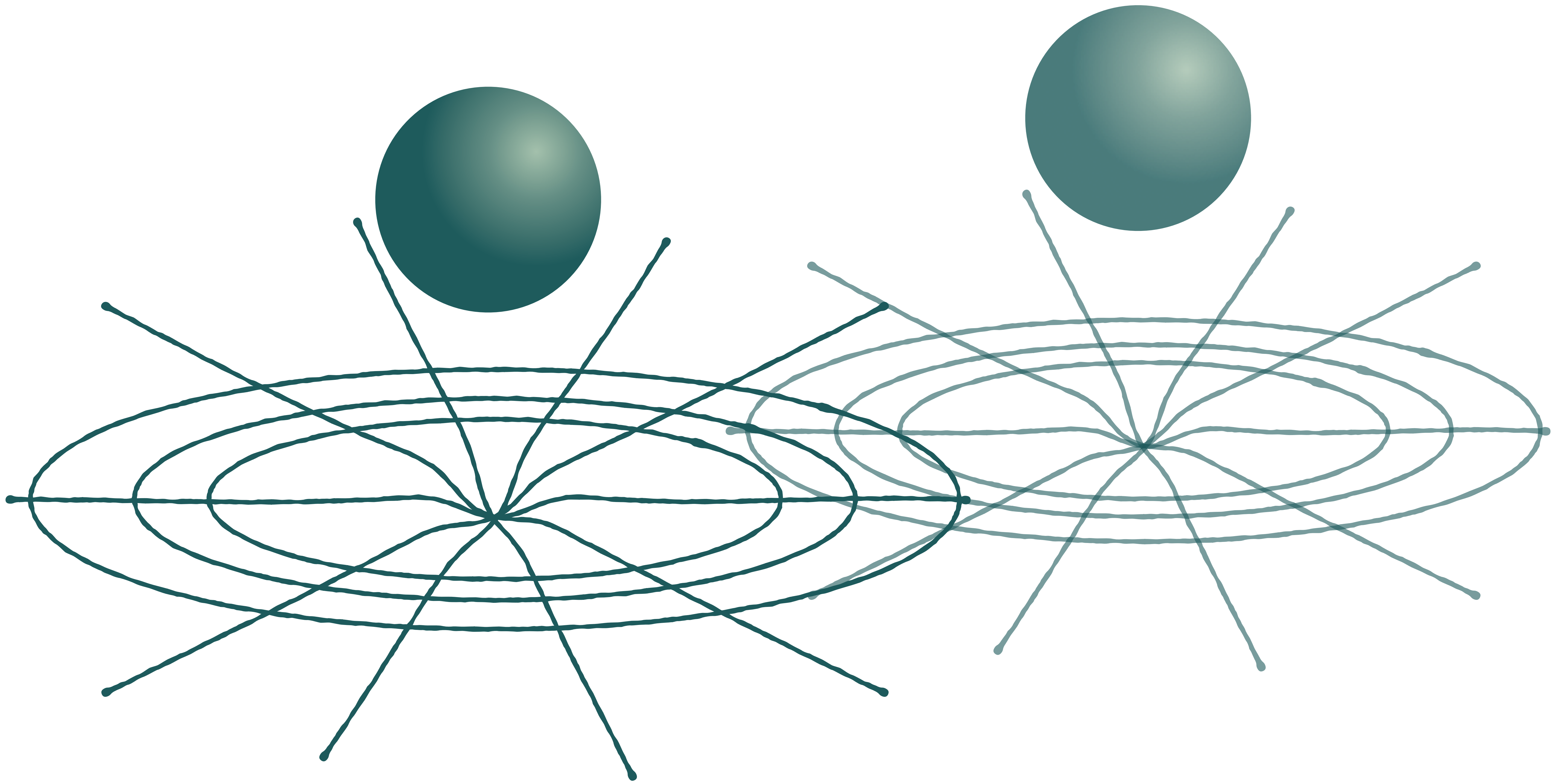
NONCLASSICAL SPACETIME FROM A QUANTUM SOURCE

GENERAL RELATIVITY

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

QUANTUM THEORY

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



NONCLASSICAL SPACETIME FROM GRAVITATING QUANTUM SYSTEMS

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

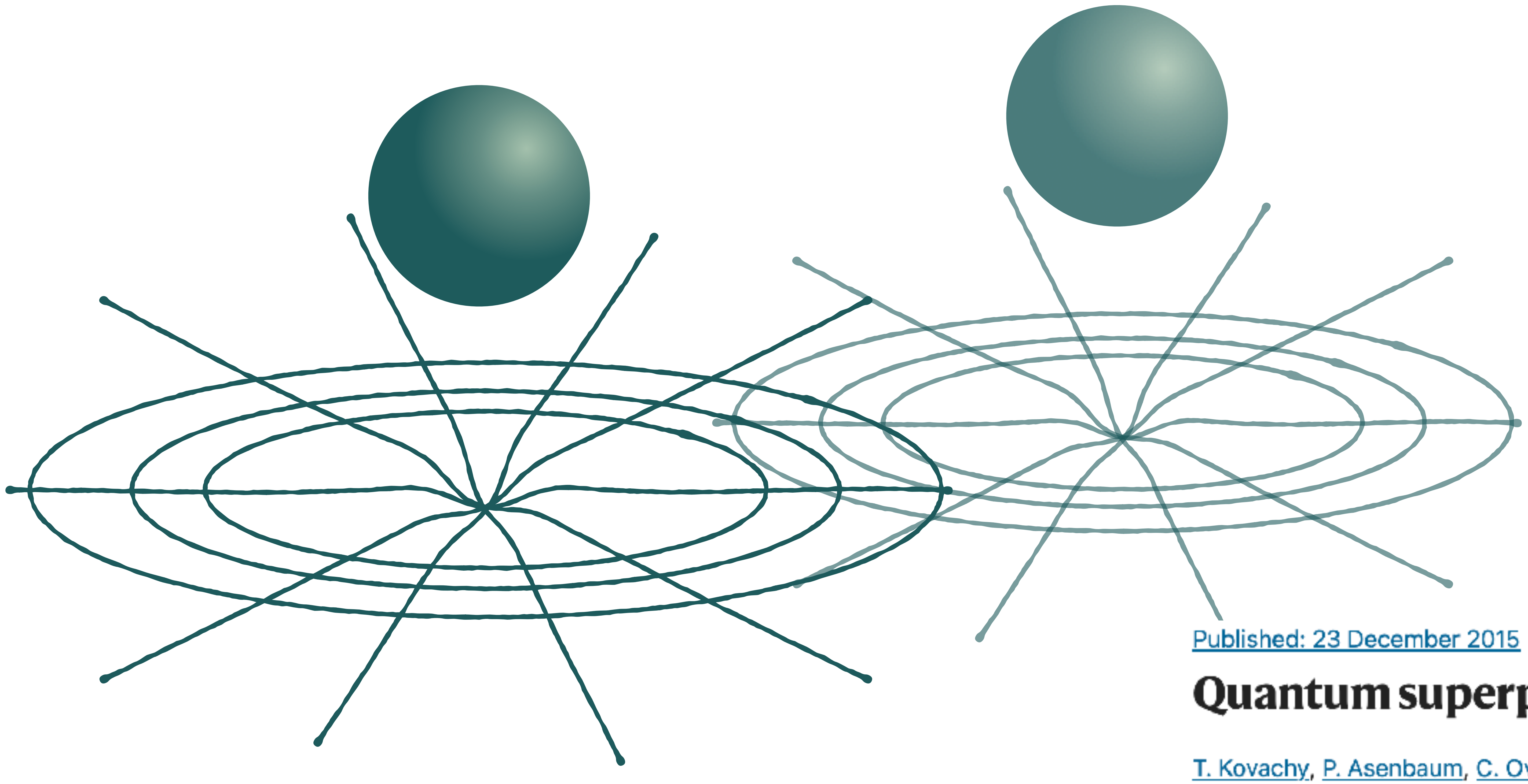
Nature **591**, 225–228 (2021) | Cite this article

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



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

M. Aspelmeyer, 2203.05587 (2022)

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, causality, observables, partition of Hilbert space into local algebras/subsystems, etc)

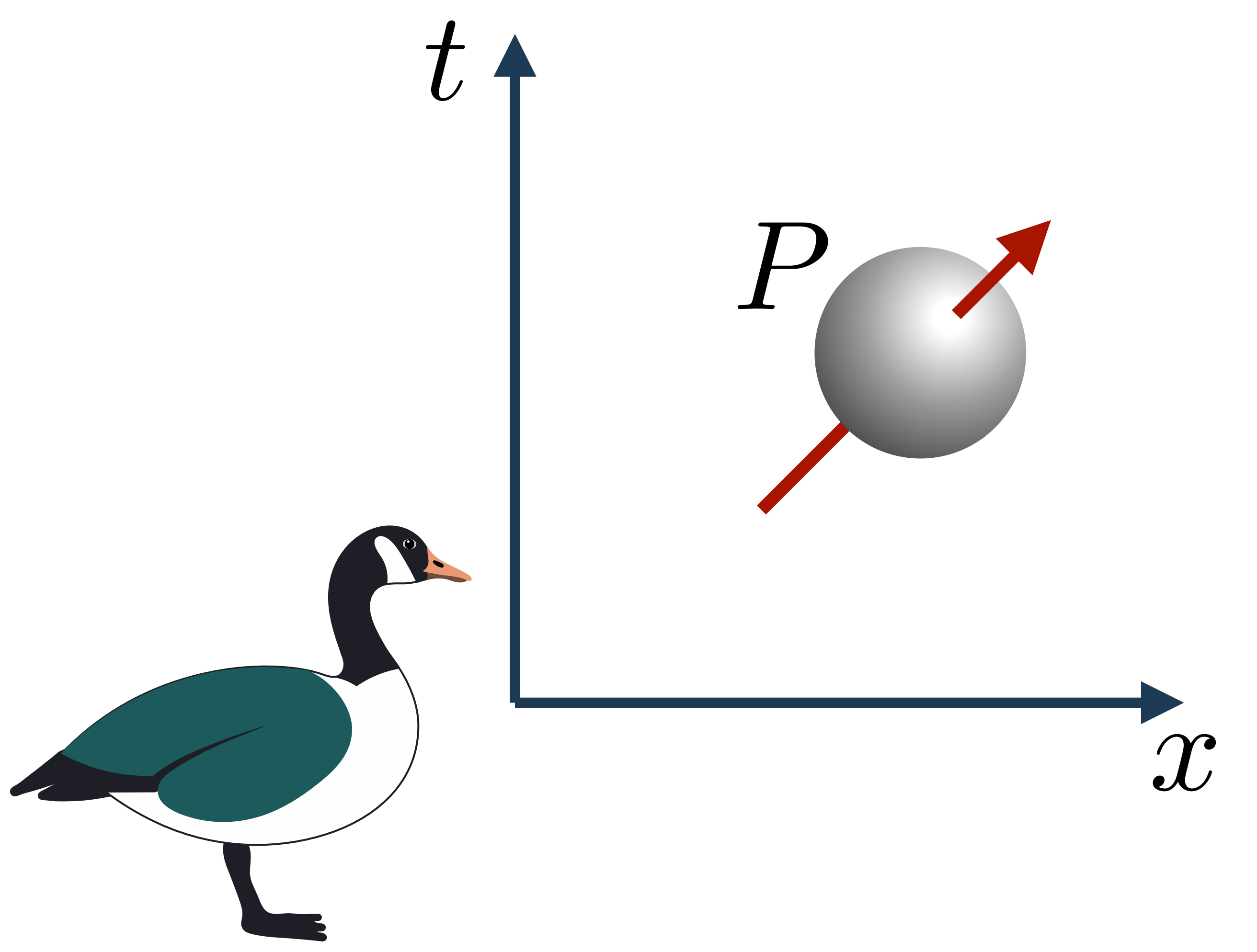
LEVEL 3: First-principle approach:
How do we reconcile the principles of GR and QT?
Internal consistency of GR and QT can be tested in thought experiments

NB: quantum information is not tied to a specific regime
(see Bell's theorem)

QUANTUM REFERENCE FRAMES

REFERENCE FRAME TRANSFORMATIONS

All reference frames are equally good for describing the laws of physics.



Translation	$\hat{U}_T = e^{\frac{i}{\hbar} X_0 \hat{p}}$
Galilean boost	$\hat{U}_B = e^{\frac{i}{\hbar} v \hat{G}}$ $\quad \hat{G} = \hat{p}t - m\hat{x}$
⋮	

The reference frame enters the transformation as a parameter.

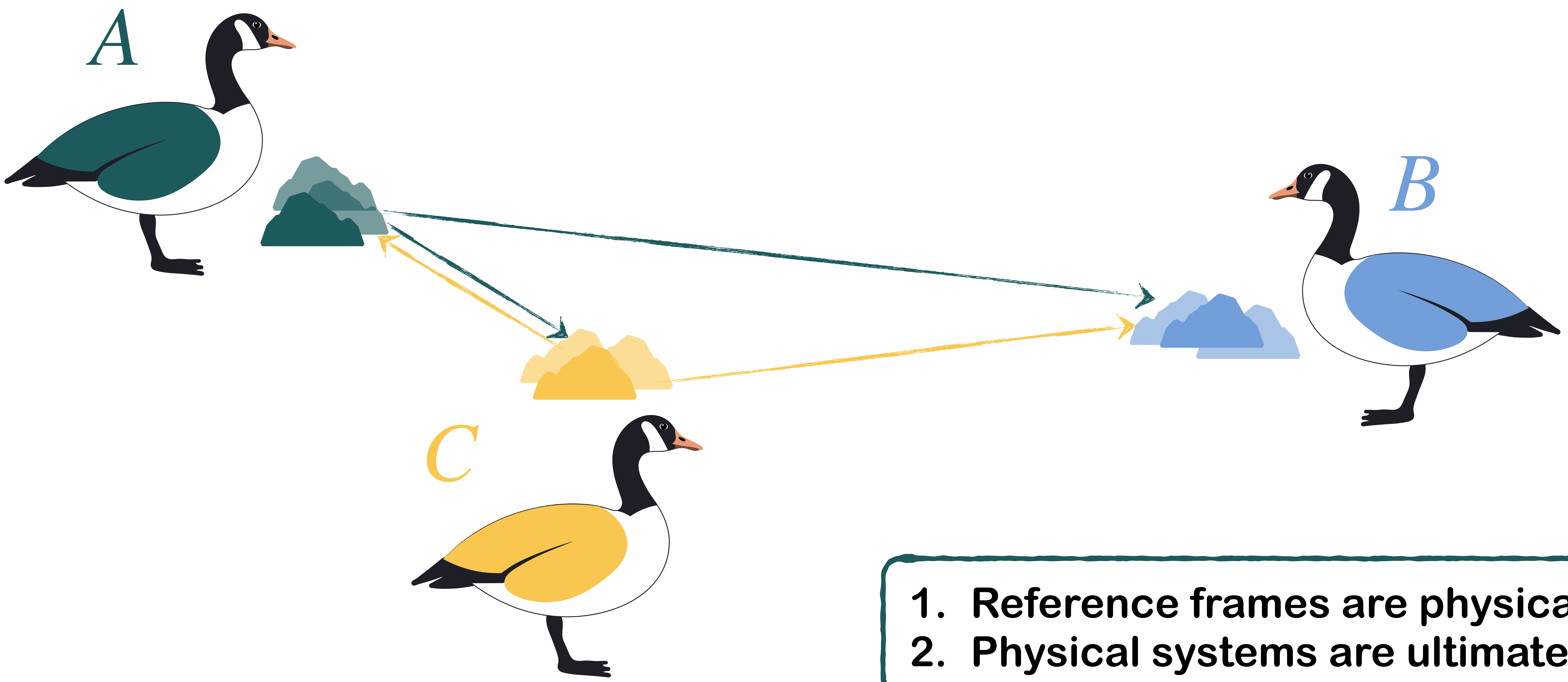
Covariance of physical laws

$$\hat{H}' = \hat{U}\hat{H}\hat{U}^\dagger + i\hbar \frac{d\hat{U}}{dt}\hat{U}^\dagger$$

Symmetry

$$\hat{H}' = \hat{H}$$

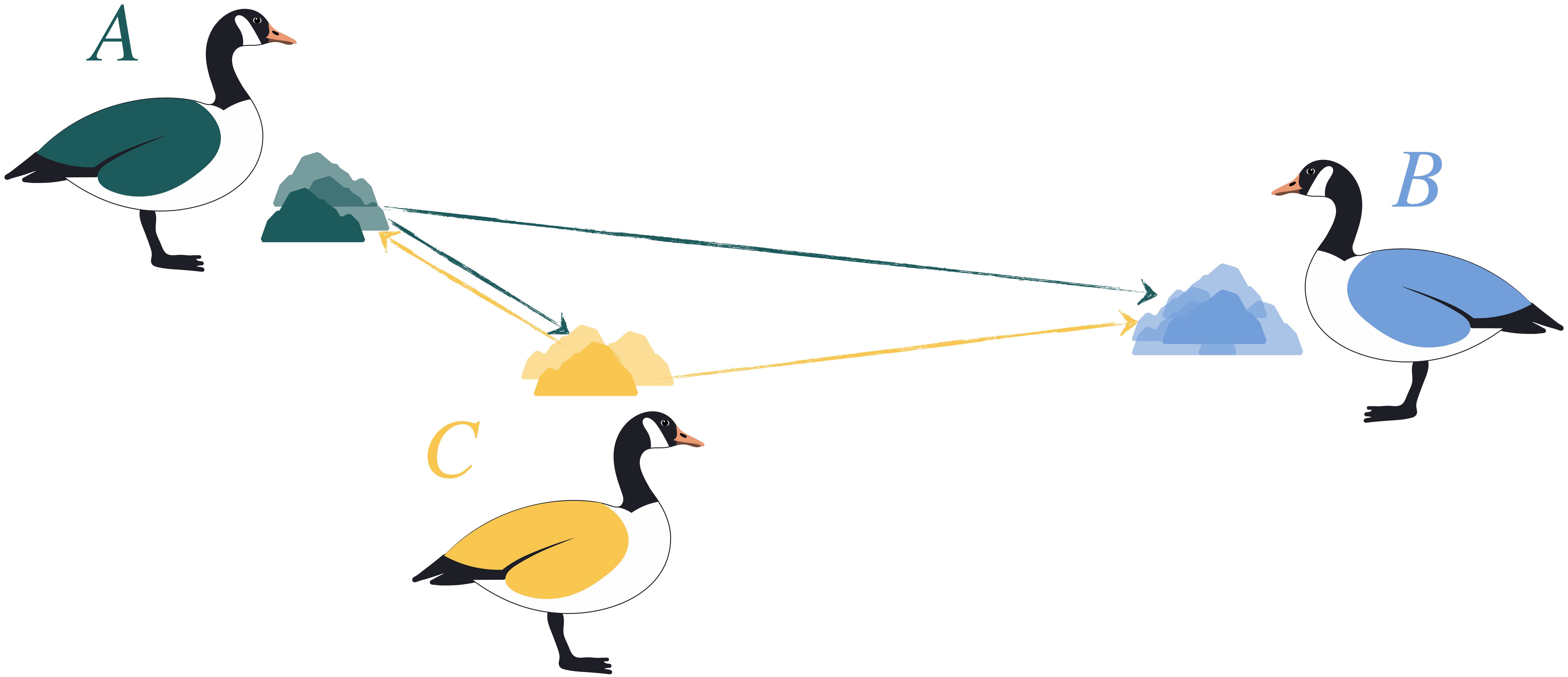
QUANTUM REFERENCE FRAMES (QRFs)



1. Reference frames are physical systems
2. Physical systems are ultimately quantum

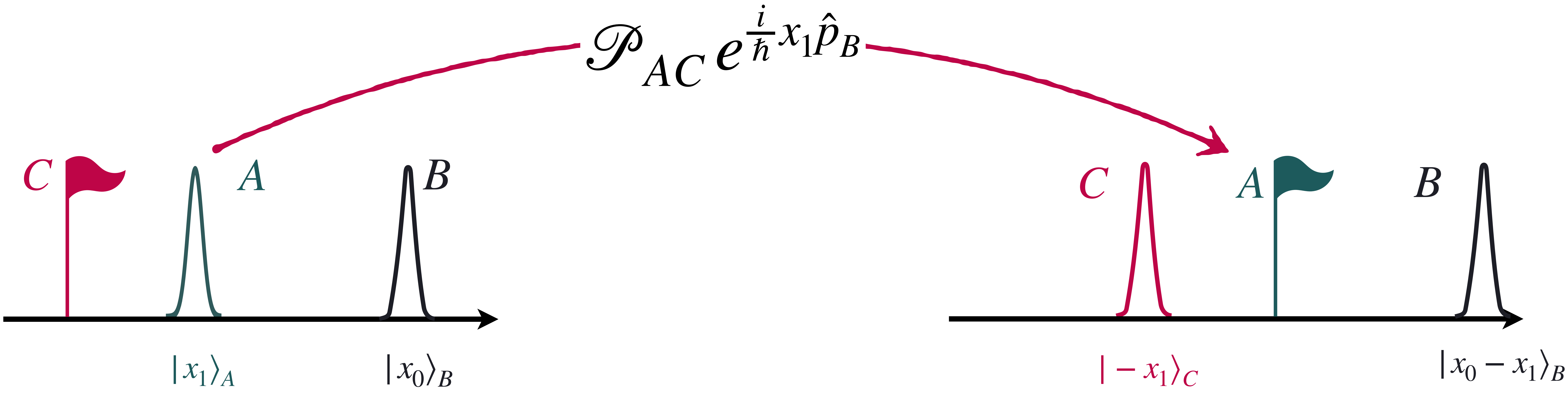
Can reference frames be in a quantum superposition relative to each other?

QUANTUM REFERENCE FRAMES (QRFs)



The simplest case: spatial translations in 1D

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



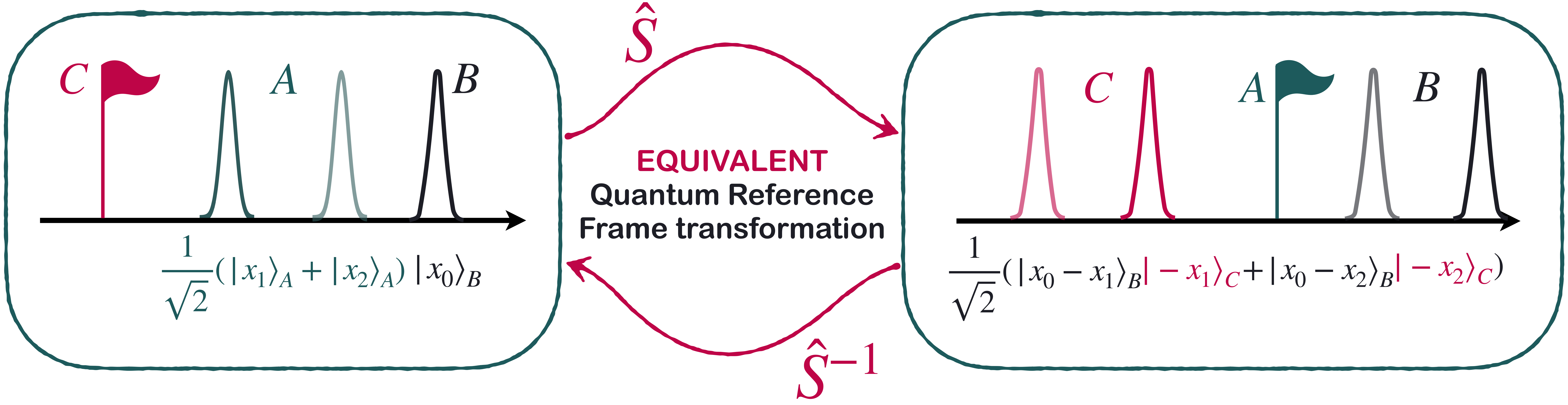
$$\mathscr{P}_{AC}|x\rangle_A = |-x\rangle_C$$

$$\mathscr{P}_{AC}^2 = \mathrm{id}$$

The simplest case: spatial translations in 1D

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

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



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

QUANTUM REFERENCE FRAMES (QRFs)

Entanglement and superposition are QRF dependent

Giacomini, Castro-Ruiz, Brukner, Nat. Commun. (2019)
Vanrietvelde, Höhn, Giacomini, Castro-Ruiz, Quantum (2020)
Ahmad, Galley, Höhn, Lock, Smith, PRL (2022)
Castro-Ruiz, Oreshkov, arXiv (2021)

Extended transformations: superpositions of transformations

Giacomini, Castro-Ruiz, Brukner, Nat. Commun. (2019)
de la Hamette, Galley, Quantum (2020)
Ballesteros, Giacomini, Gubitosi, Quantum (2021)
de la Hamette, Galley, Höhn, Loveridge, Müller, arXiv (2021)

$$\hat{S} = \sum_i \hat{U}_{\alpha_i} \otimes |\alpha_i\rangle\langle\alpha_i|$$

standard reference frame transformation ($\hat{U}_{\alpha_i}$)

- Spatial translation
- Galilean boost
- Accelerated frame
- Lorentz boost
- Diffeomorphism (GR)

state of the quantum reference frame ($|\alpha_i\rangle\langle\alpha_i|$)

- Position (space and spacetime)
- Velocity
- Effective acceleration

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

Transformation of the Schrödinger equation

$$x' = x - X_i(t)$$

$$\hat{H}^{(C)} = \hat{U}_i \hat{H}^{(A)} \hat{U}_i^\dagger + i\hbar \frac{d\hat{U}_i}{dt} \hat{U}_i^\dagger$$

$$X_i(t) = \begin{cases} x_0; \\ v_0 t \end{cases}$$

$$\hat{H}^{(C)}_{AB} = \frac{\hat{p}_B^2}{2m_B} \rightsquigarrow \hat{H}^{(A)}_{BC} = \frac{\hat{p}_B^2}{2m_B}$$

Hamiltonian of the system

↓

Superposition of translations/boosts

$$\begin{cases} x_0 \to \hat{x}_A; \\ v_0 \to \dfrac{\hat{p}_A}{m_A} \end{cases}$$

In QRFs:

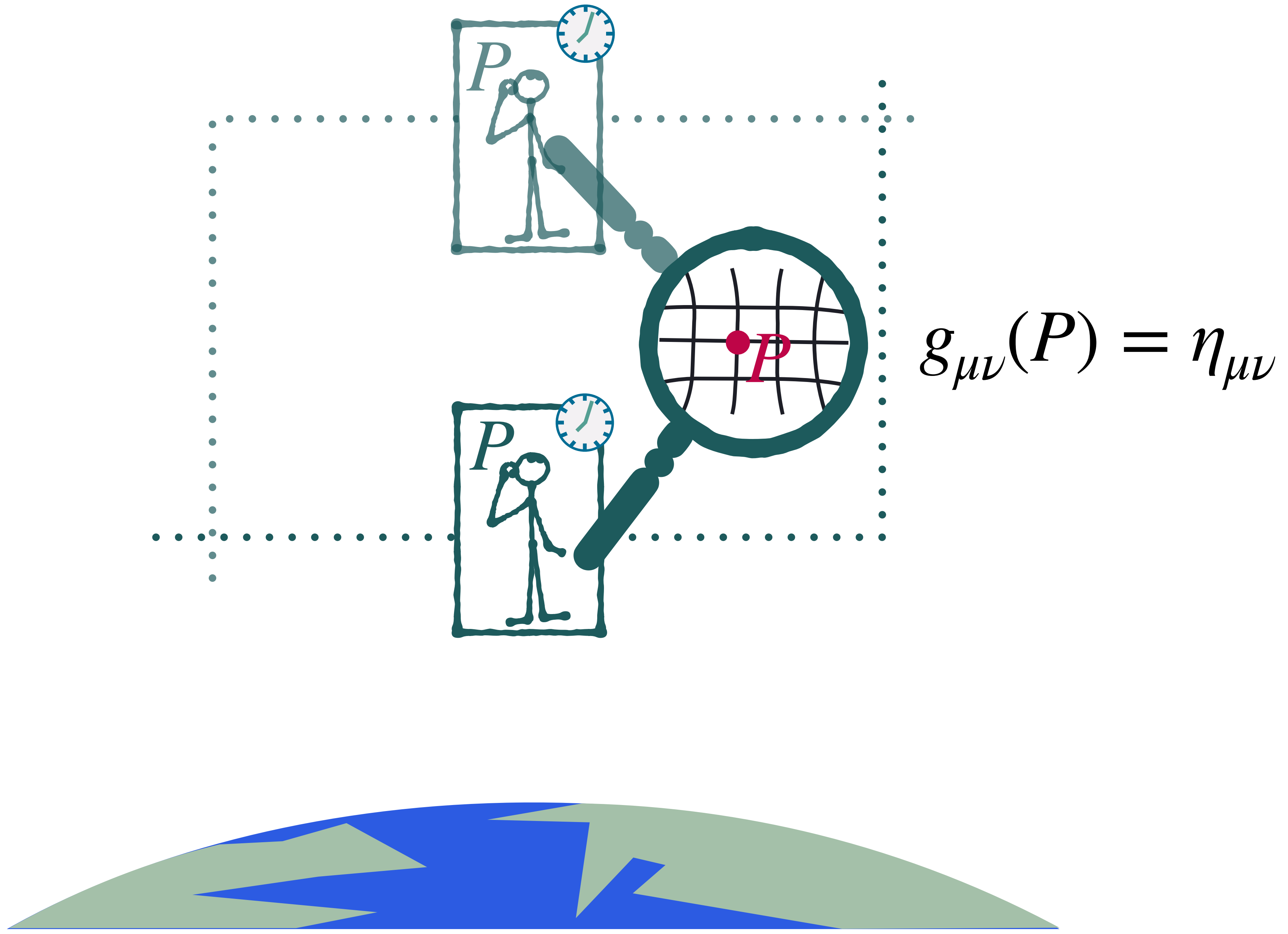
$$\hat{H}^{(C)}_{AB} = \frac{\hat{p}_A^2}{2m_A} + \frac{\hat{p}_B^2}{2m_B} \rightsquigarrow \hat{H}^{(A)}_{BC} = \frac{\hat{p}_B^2}{2m_B} + \frac{\hat{p}_C^2}{2m_C}$$

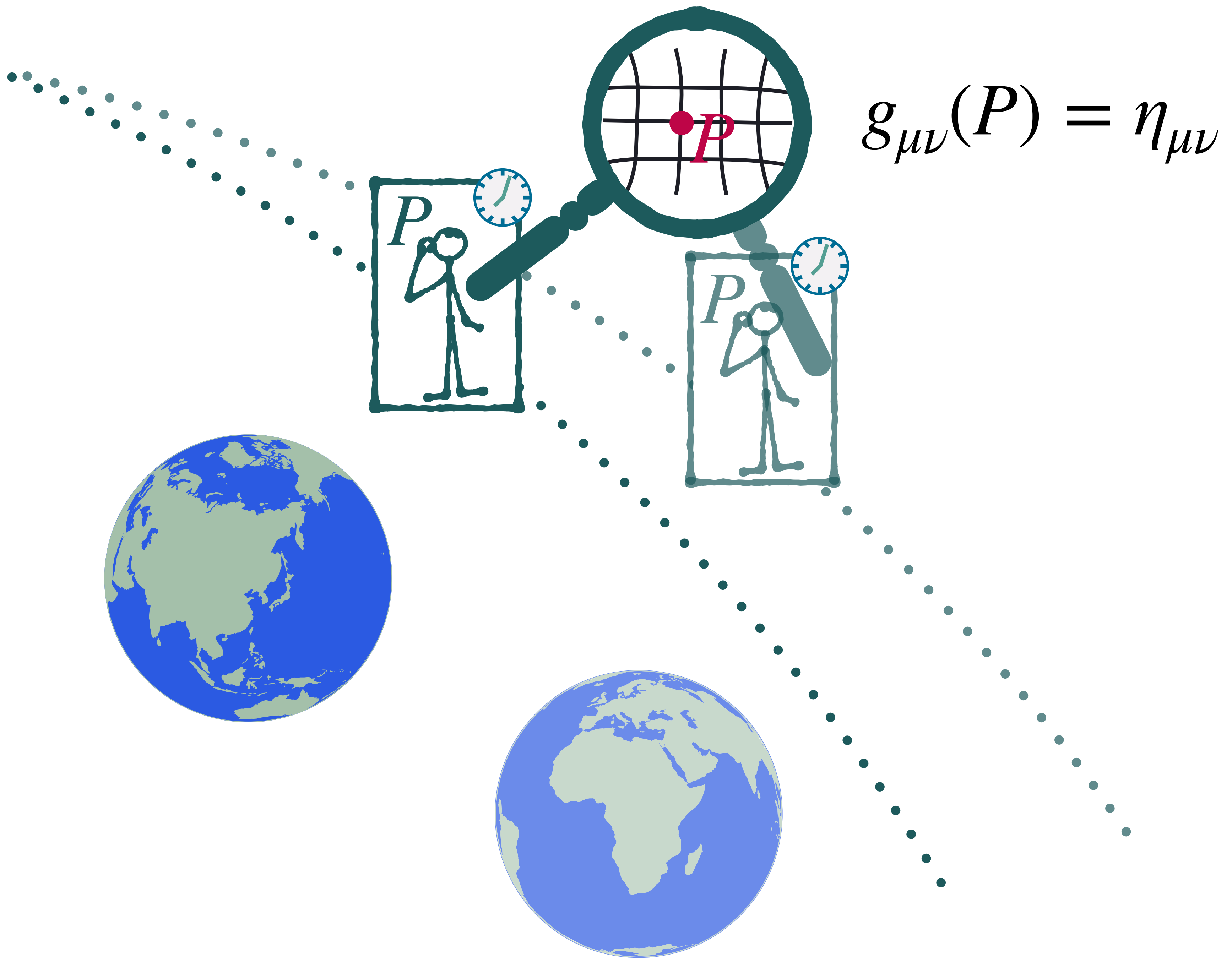
Hamiltonian of the system AND of the QRF!

QUANTUM REFERENCE FRAMES AND GRAVITY?

EINSTEIN'S EQUIVALENCE PRINCIPLE FOR QUANTUM REFERENCE FRAMES

Giacomini, Brukner, 2012.13754 (2020)
Giacomini, Brukner, AVS Quantum Science (2022)
Cepollaro, Giacomini, 2112.03303 (2021)





Test of EEP for QRFs in atom interferometer with quantum clocks

If EEP for QRF not valid, it is not possible to define time evolution in a QRF

Cepollaro, Giacomini, 2112.03303 (2021)

Reconciliation of EEP and Principle of Linear Superposition

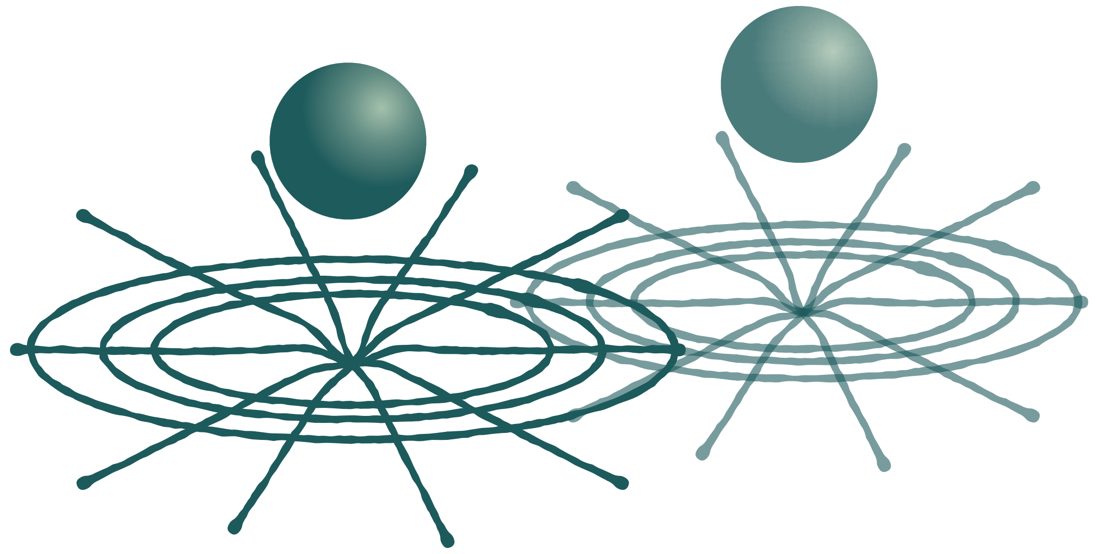
Overcomes Penrose's spontaneous state reduction

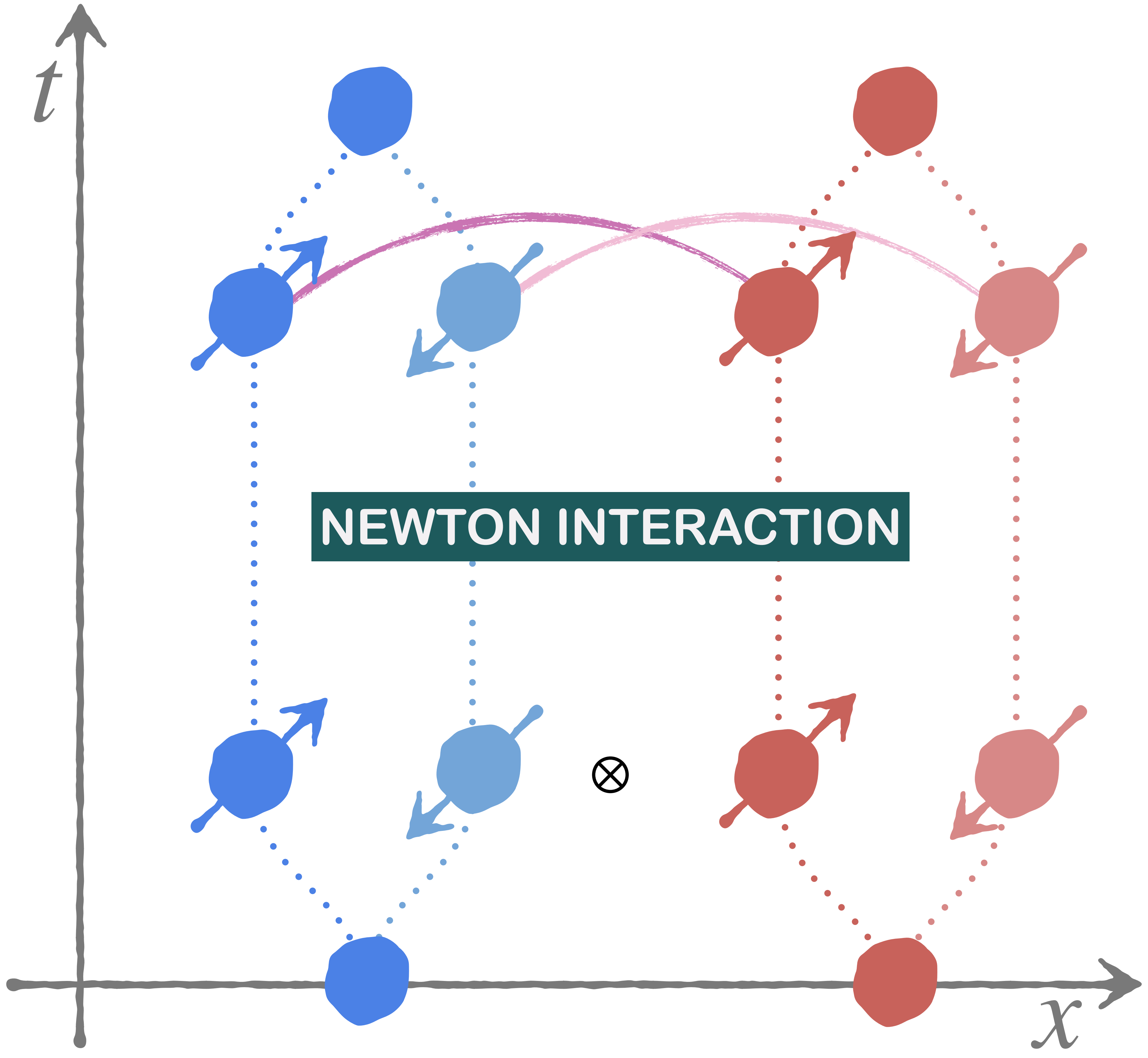
Giacomini, Brukner, AVS Quantum Science (2022)

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)

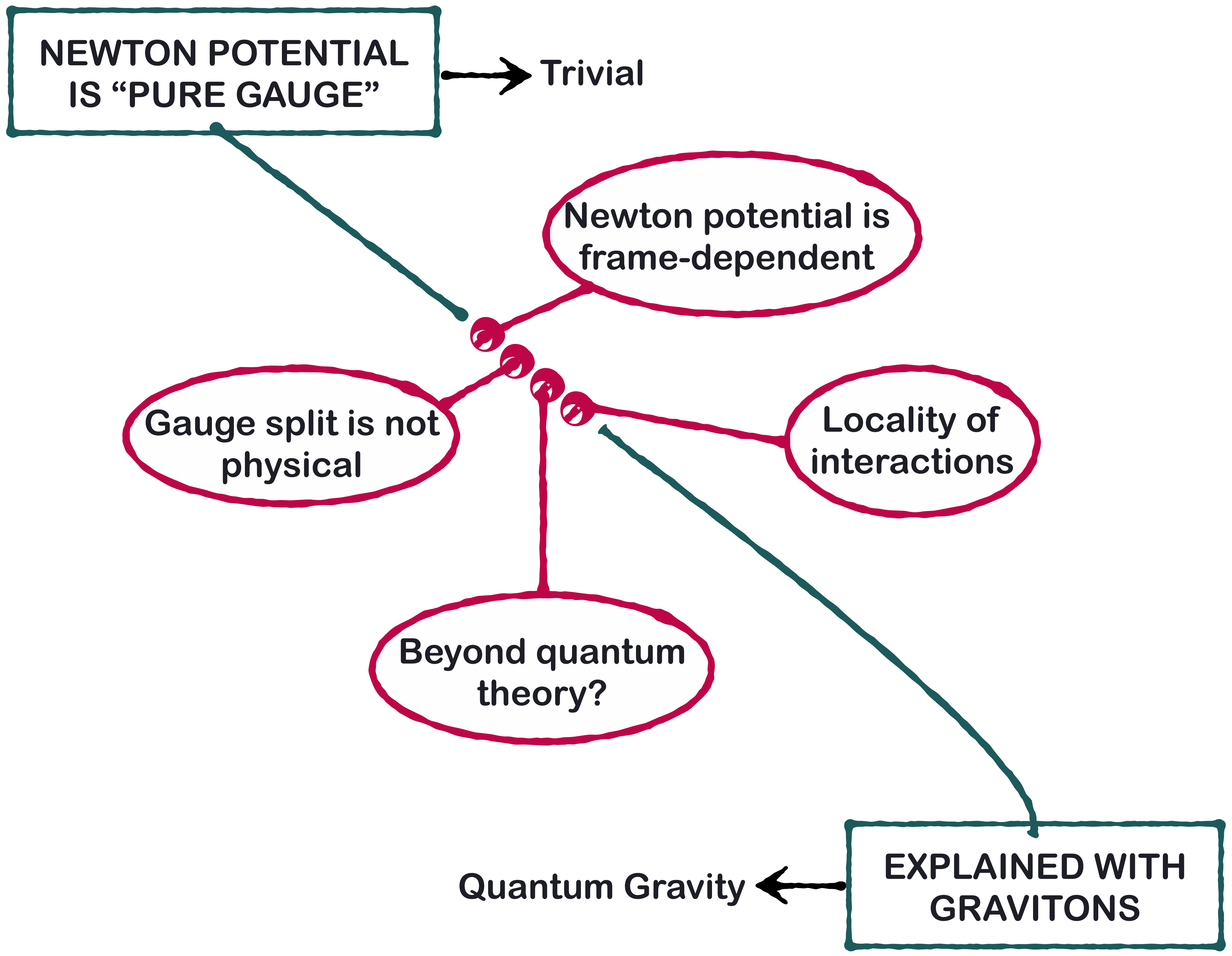




ENTANGLED STATE

Nonclassical channel (LOCC theorem)

PRODUCT STATE



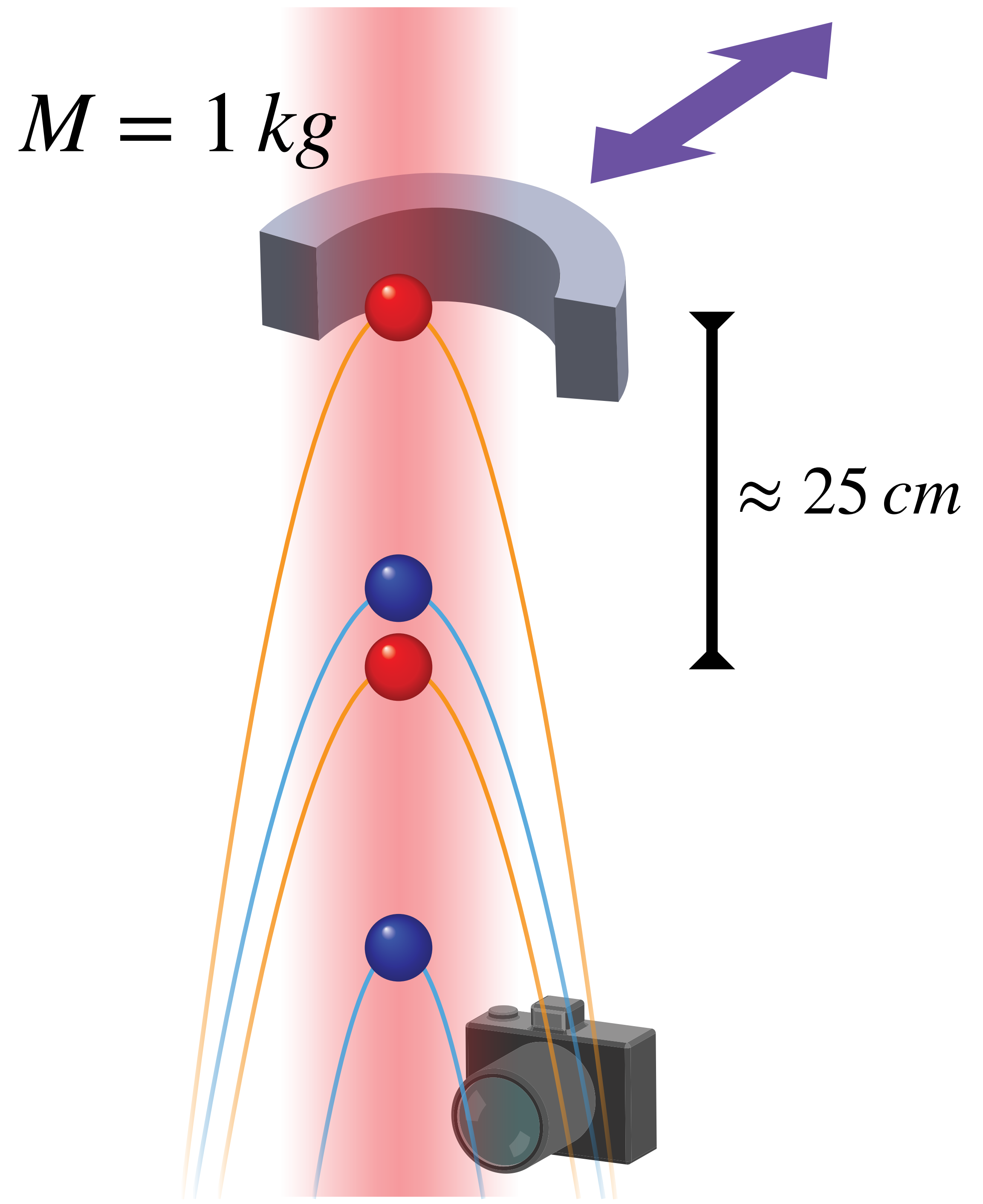
Bose et al. PRL (2017)
Marletto, Vedral PRL (2017)

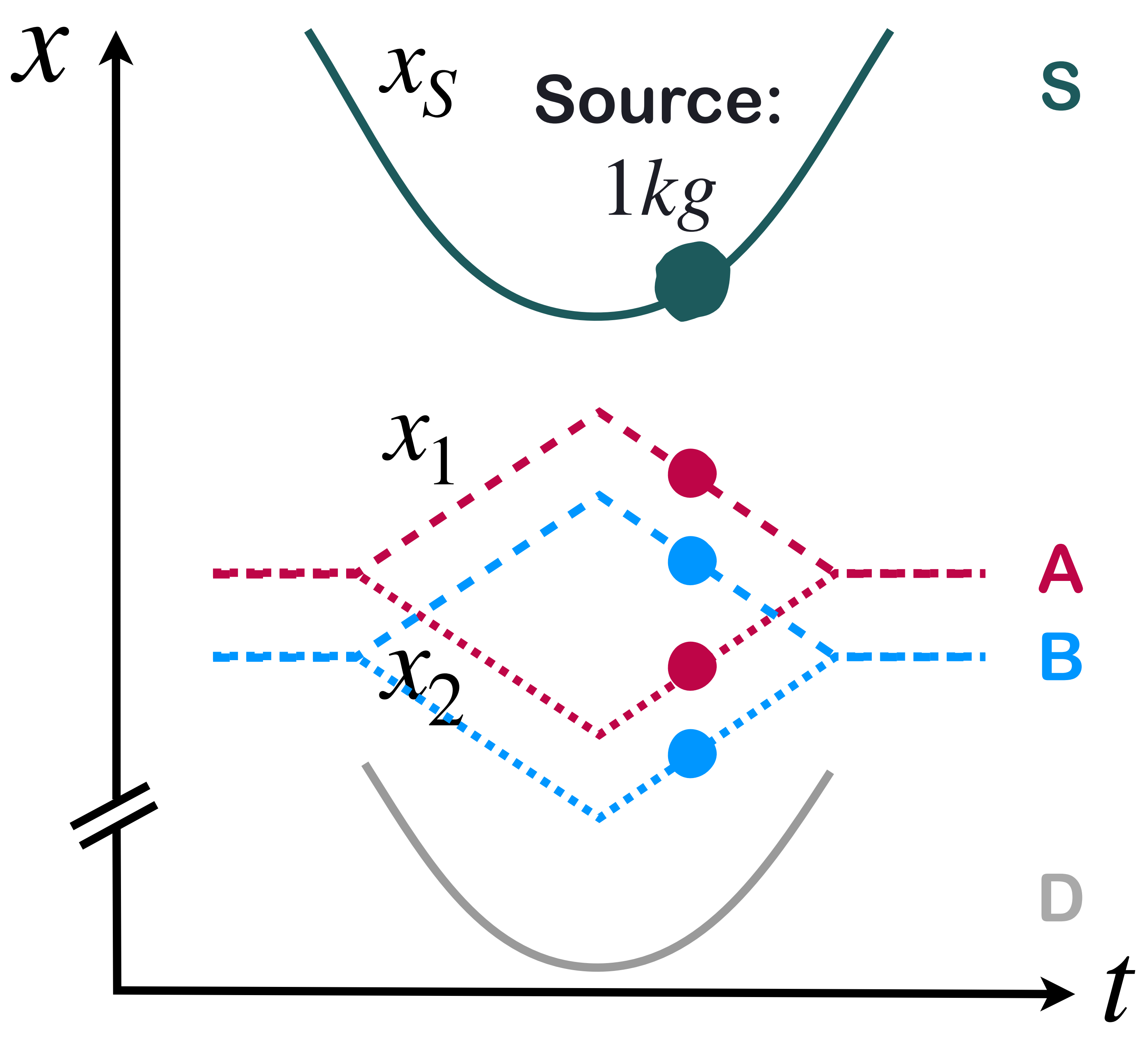
IS THE SUPERPOSITION OF GRAVITATIONAL FIELDS A RELATIVE CONCEPT?

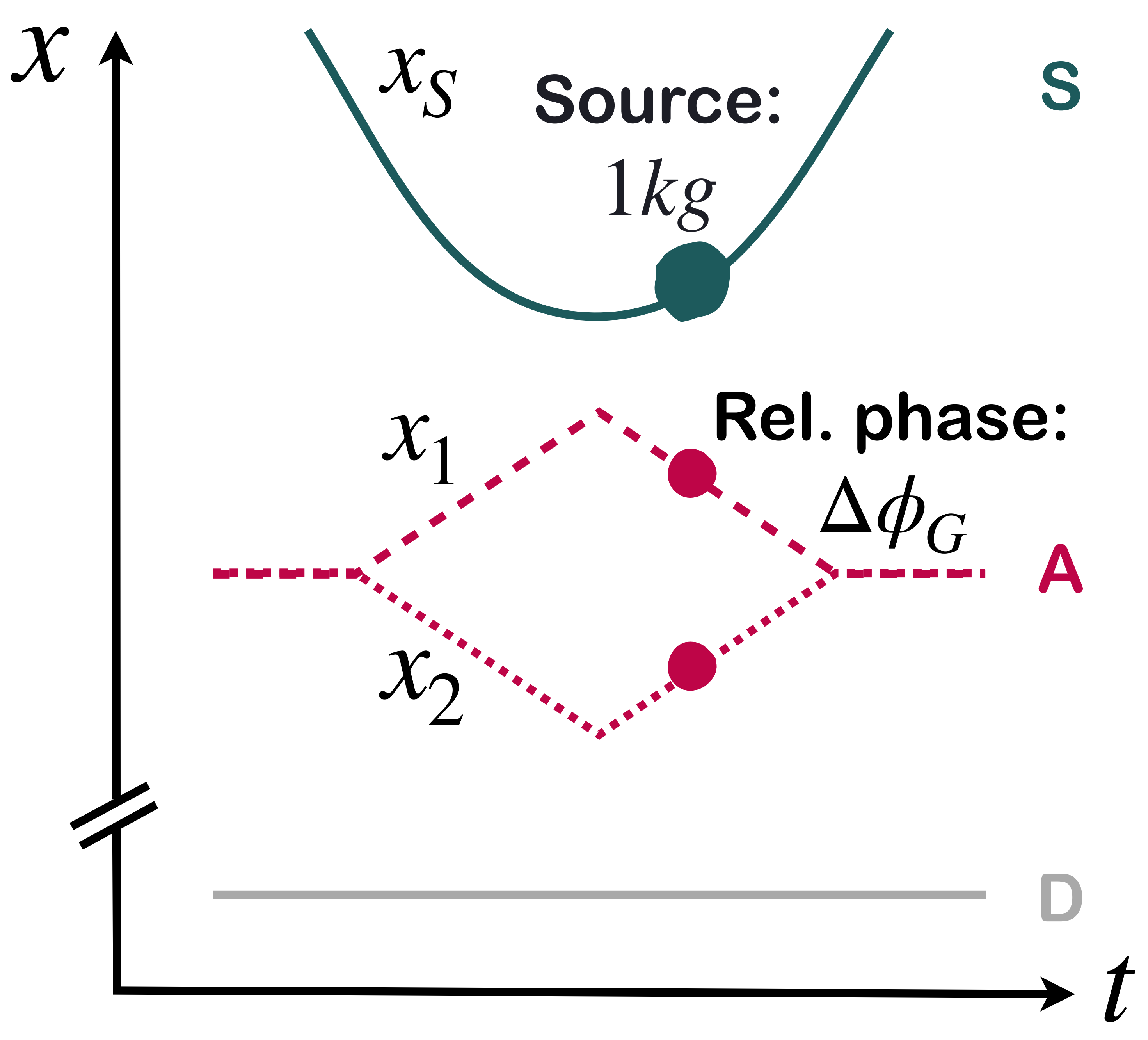
ATOM INTERFEROMETRY WITH GRAVITY VIA FIRST-PRINCIPLES

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

Which assumptions should we add to have a superposition of gravitational fields?

THREE FUNDAMENTAL PRINCIPLES

1. **EXISTENCE OF GRAVITATIONAL FIELDS:**

   Any massive particle that is well-localized at a position x_0 *sources a gravitational field* $\mathbf{g}$ *with functional form* $\mathbf{g}(\mathbf{x} - \mathbf{x_0})$

2. **FIELD ENERGY PRINCIPLE:**

   The phase of an interferometer is a function of the energies of the fields that interact with the interfering particle

3. **QUANTUM RELATIVITY PRINCIPLE:**

   The laws of physics take the same form in every reference frame, including the reference frames associated with quantum particles
   (quantum reference frames)

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

QRF DESCRIPTION OF THE EXPERIMENT

CLASSICAL GRAVITATIONAL FIELD **SUPERPOSITION OF GRAVITATIONAL FIELDS**

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

THANK YOU!

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