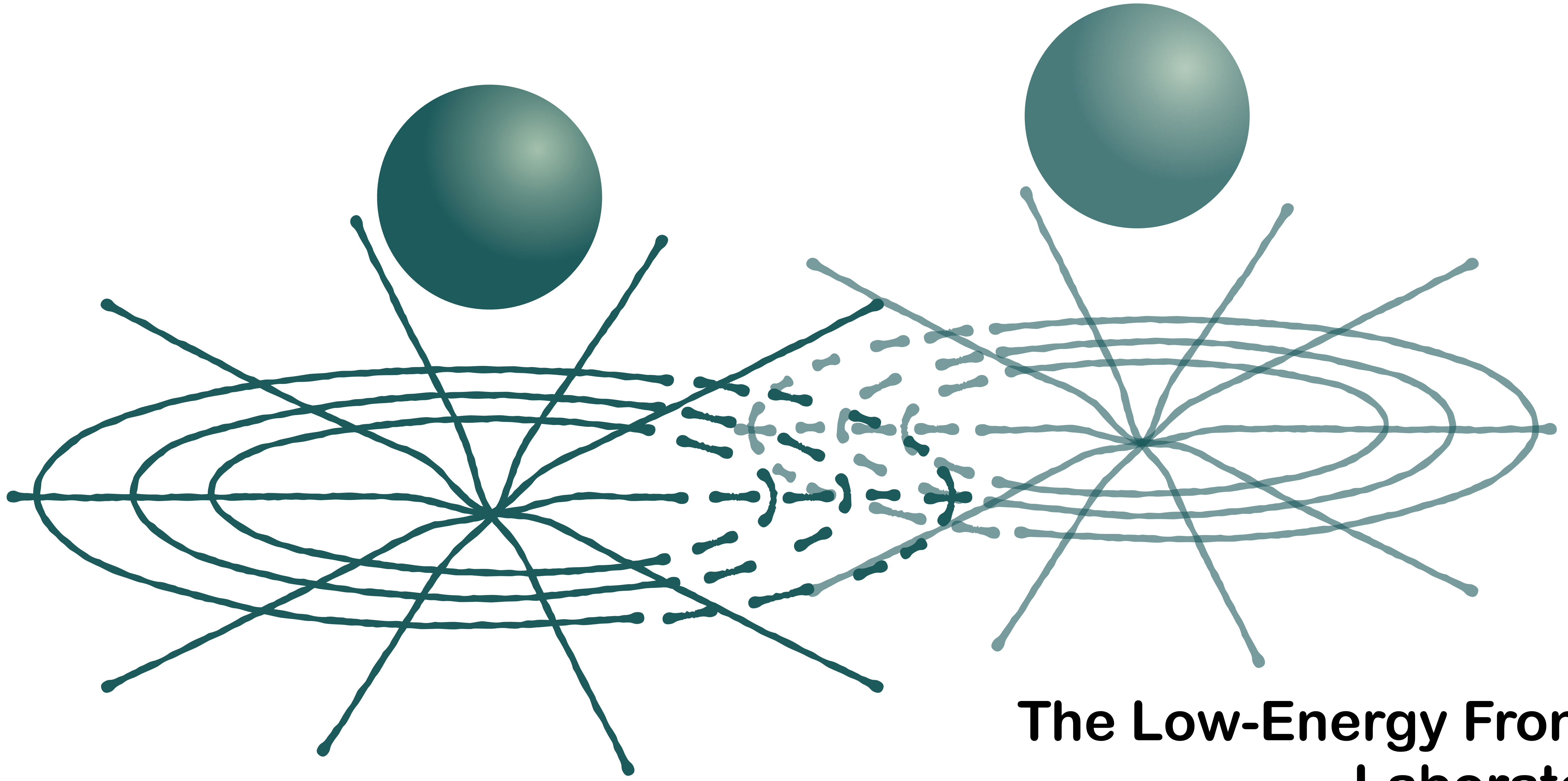
QUANTUM EFFECTS IN GRAVITY FOM A DELOCALISED QUANTUM SOURCE

Flaminia Giacomini

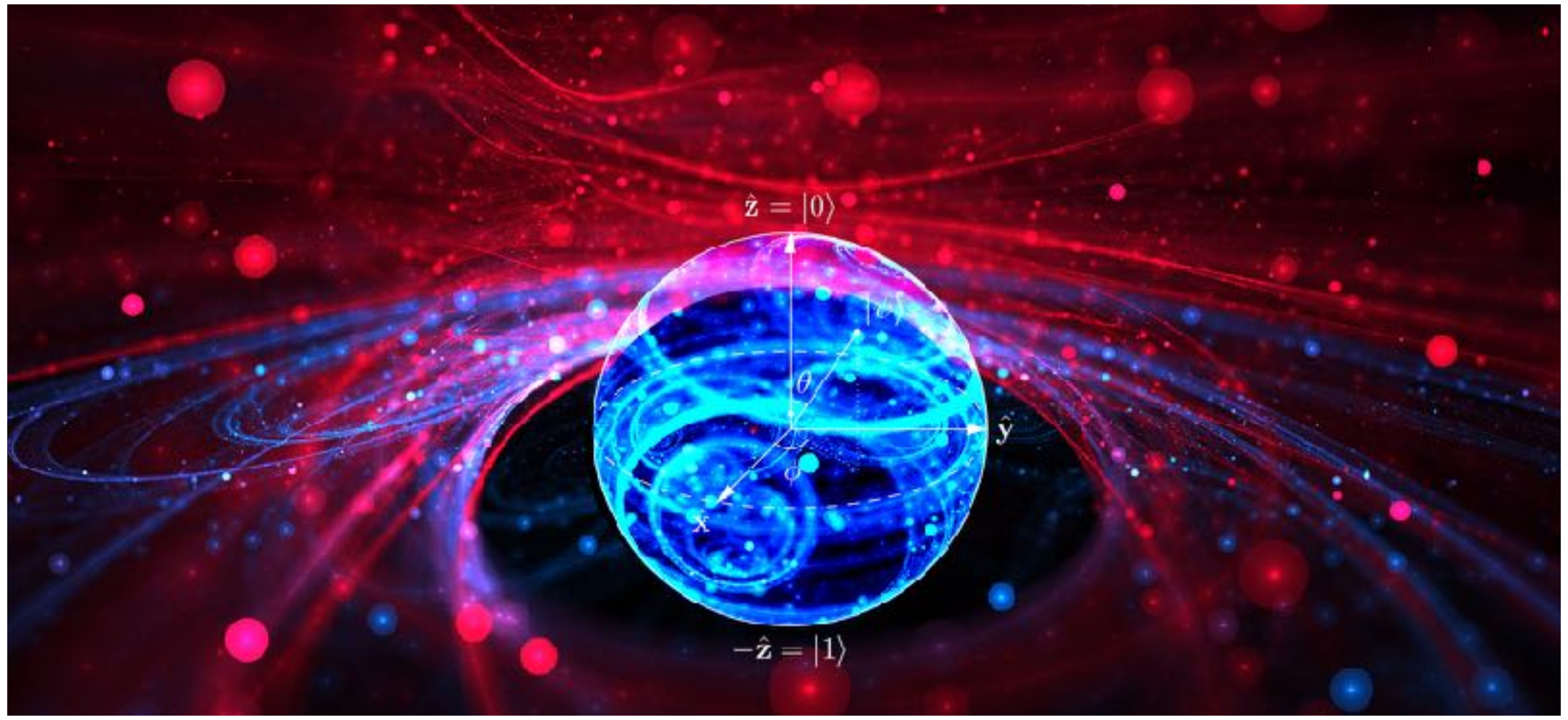
SNSF Ambizione Fellow, ETH Zürich



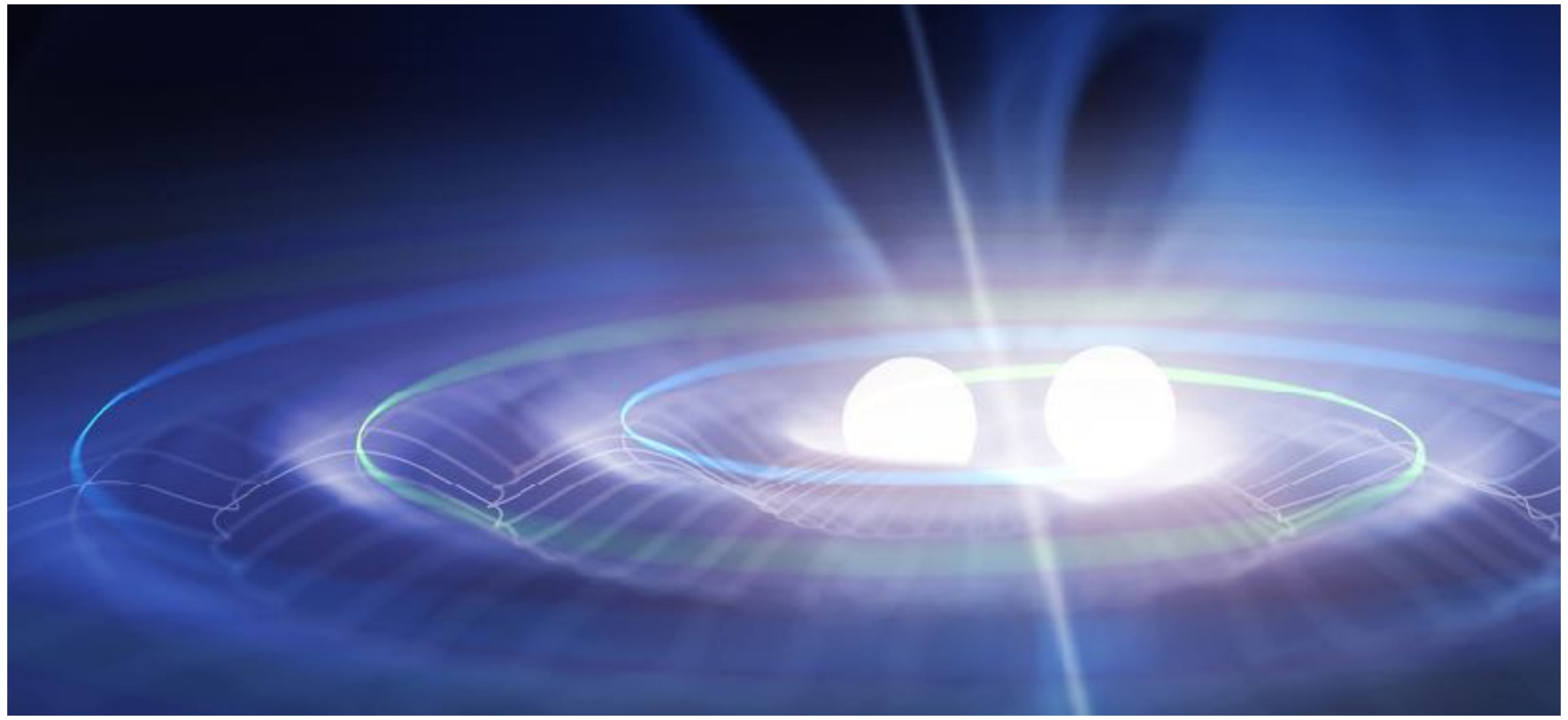
The Low-Energy Frontier of Particle Physics
Laboratori Nazionali di Frascati
10-12 February 2025

TWO SUCCESSFUL THEORIES, DIFFERENT PRINCIPLES

QUANTUM THEORY



GENERAL RELATIVITY



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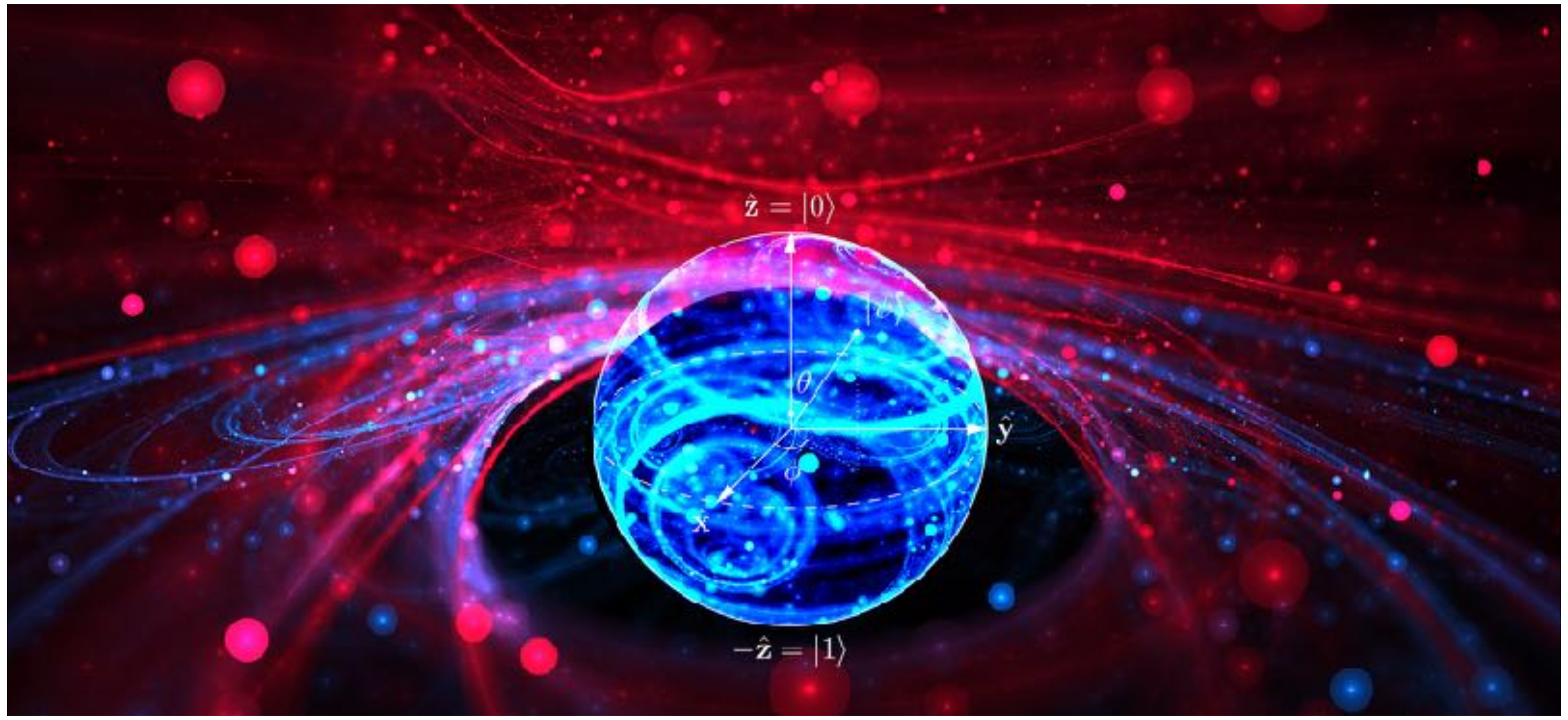

Entanglement, superposition…

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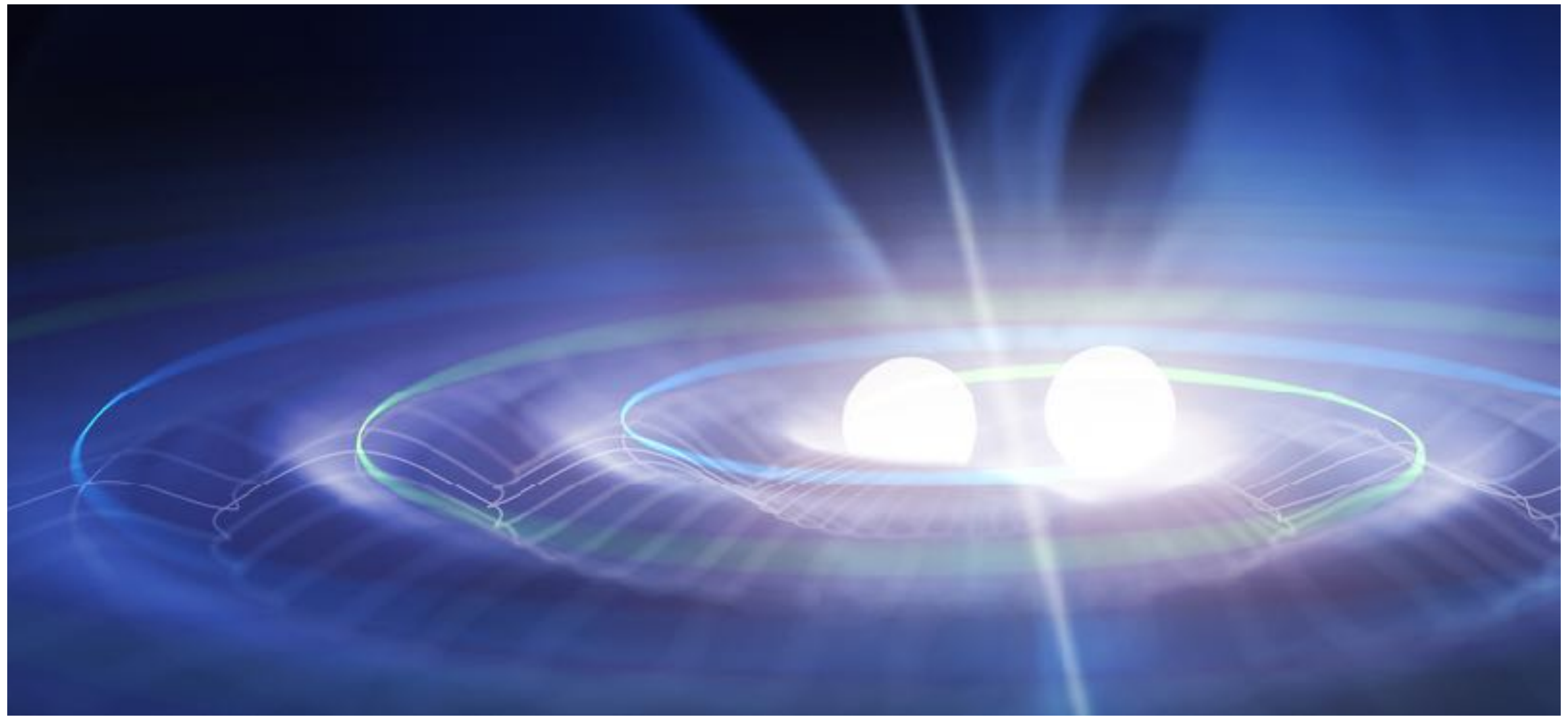

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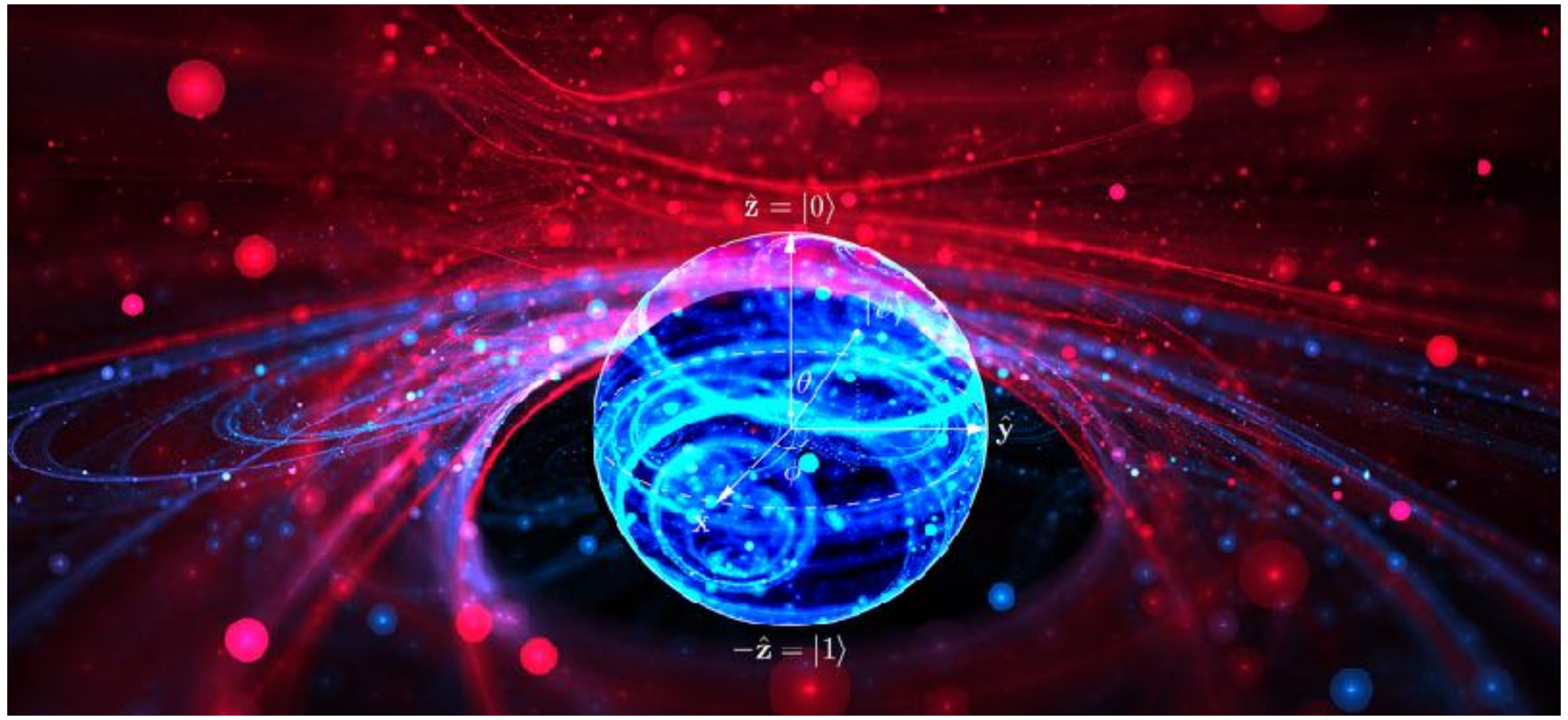

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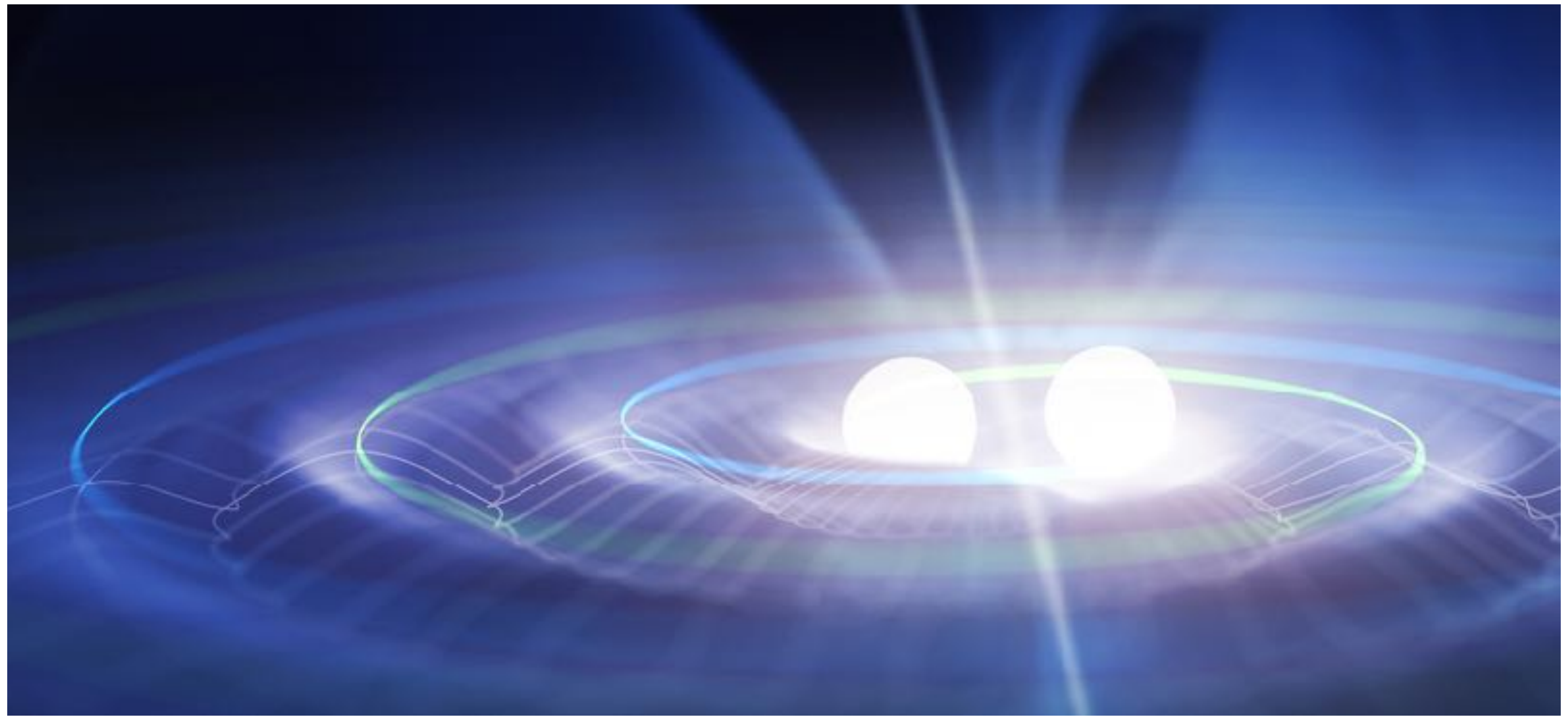

Relation between gravity and matter

Matter tells spacetime how to curve;
spacetime tells matter how to move.

Image credits: Perimeter Institute

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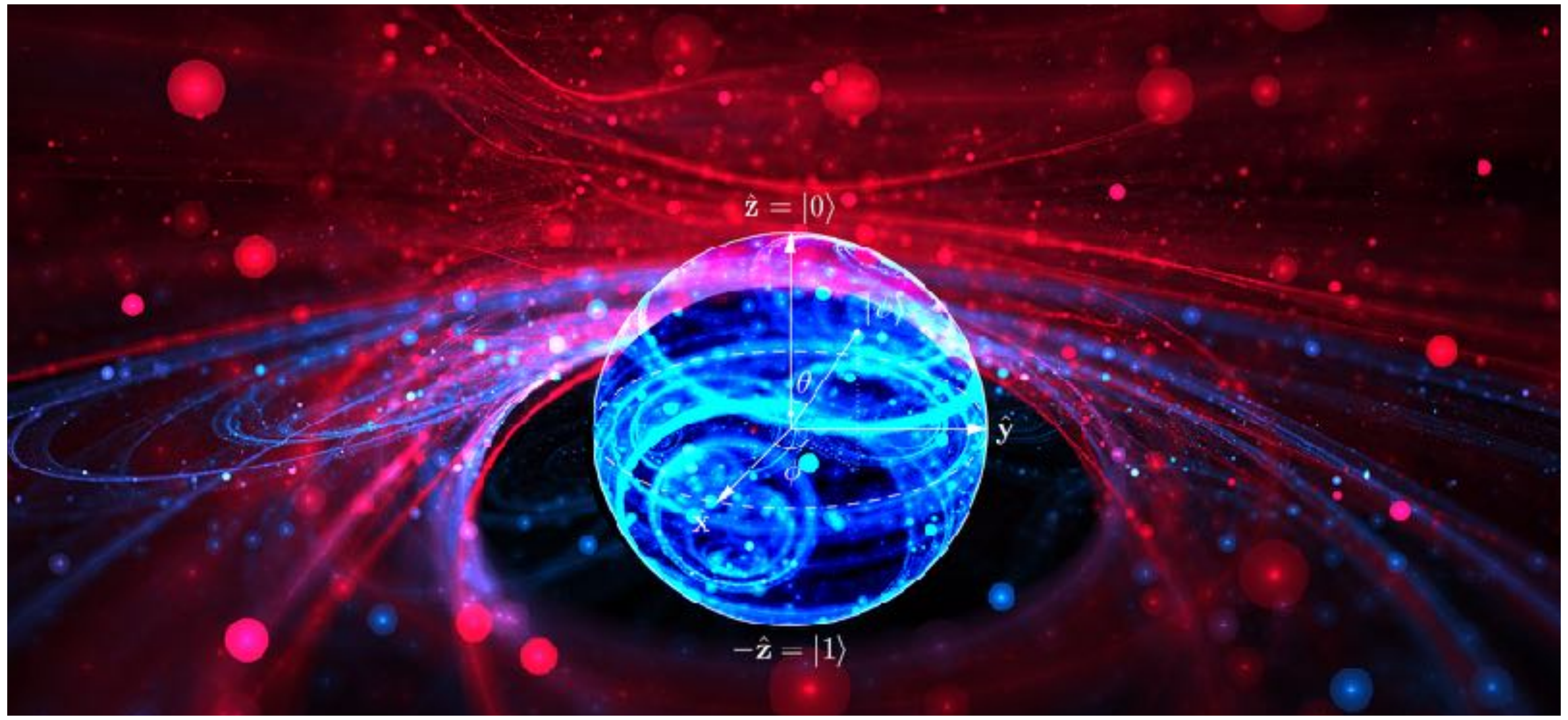

Entanglement, superposition…

Spacetime is the stage

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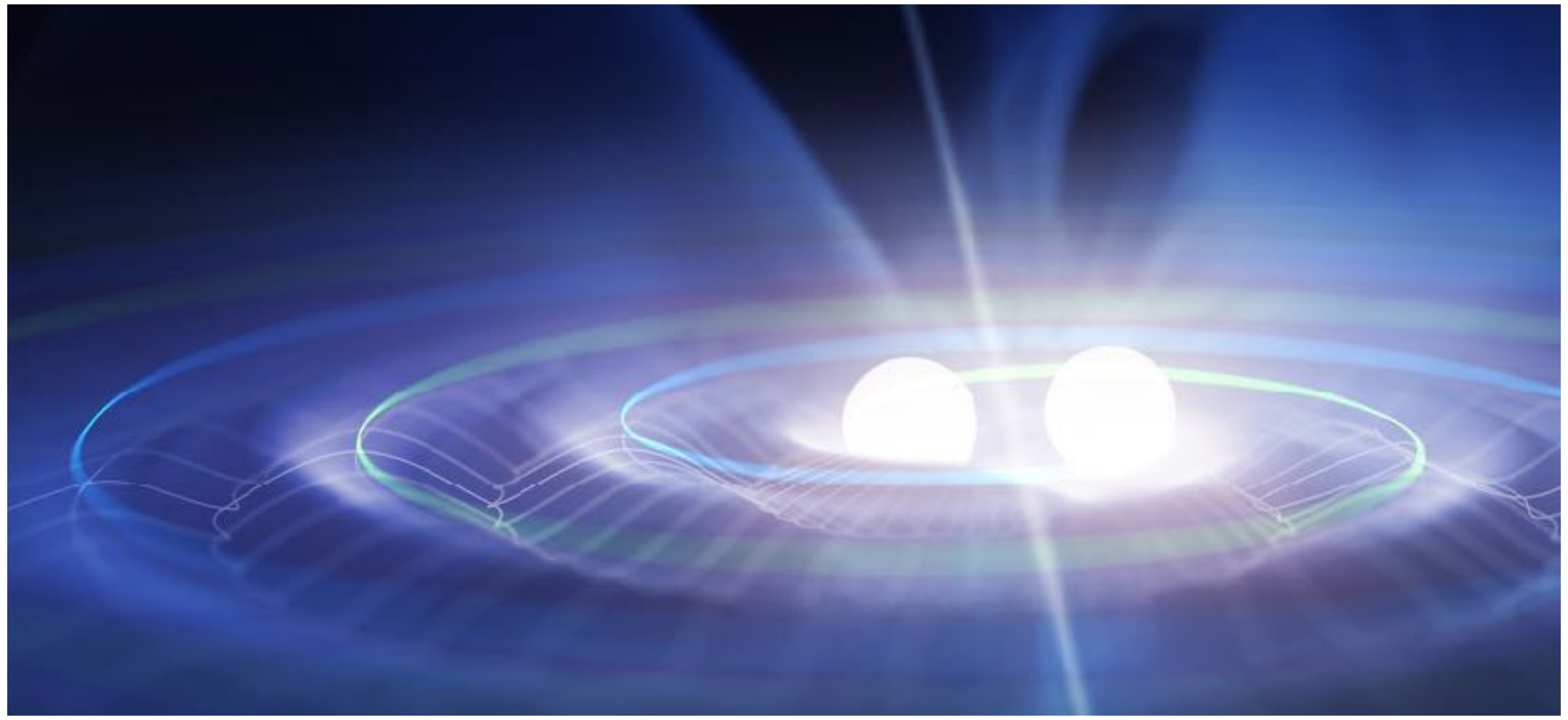

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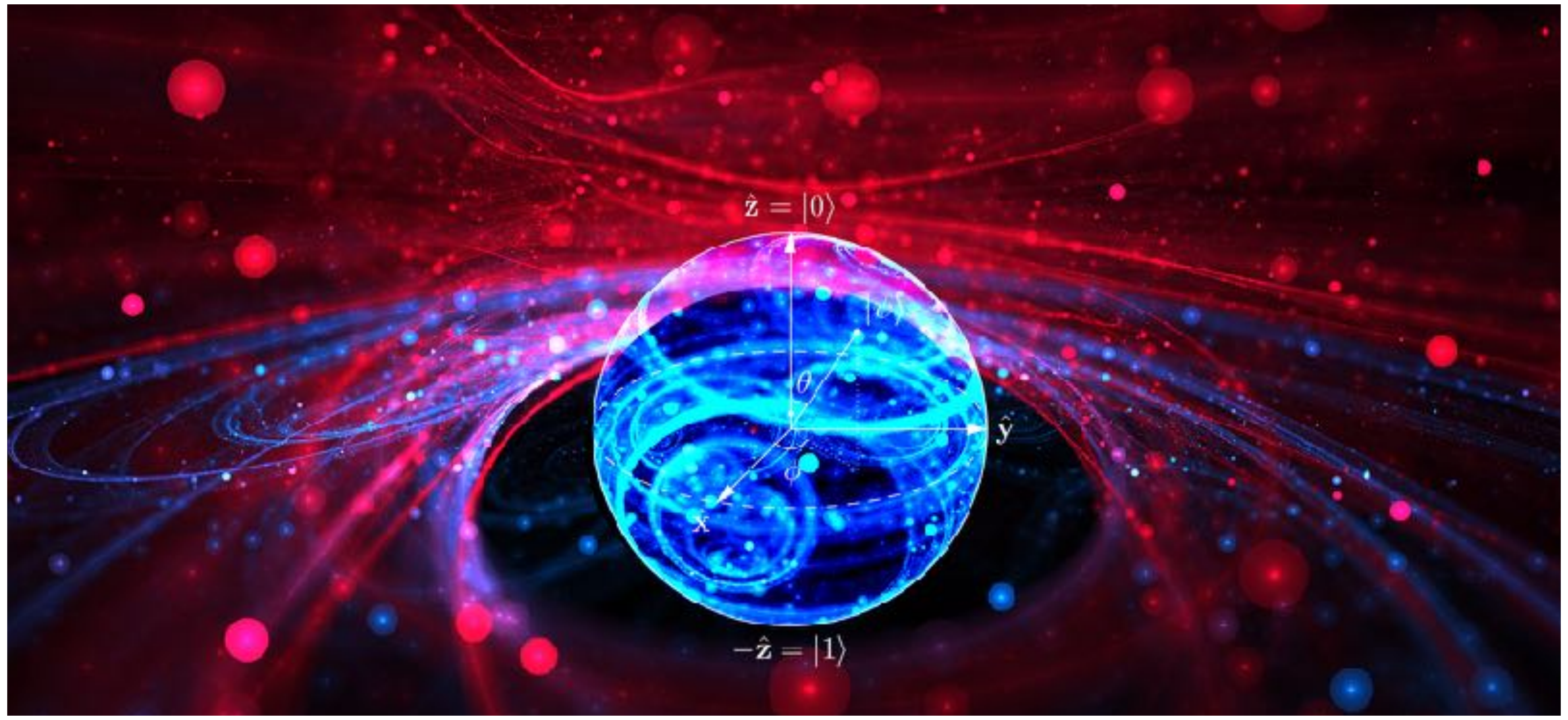

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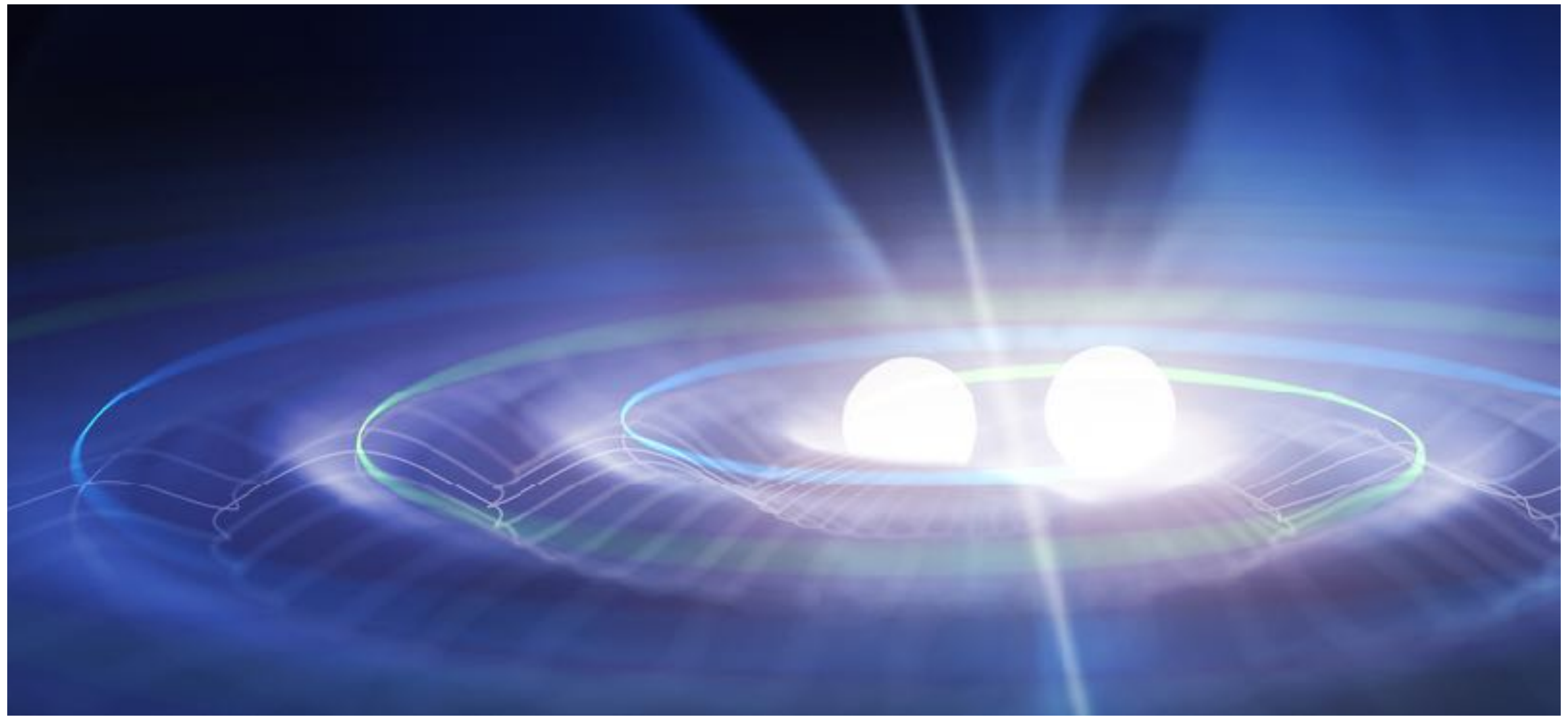

Relation between gravity and matter

Matter tells spacetime how to curve;
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Spacetime is the actor

All experiments are compatible with these theories.

Image credits: Perimeter Institute

WHERE SHALL WE LOOK FOR QUANTUM EFFECTS IN GRAVITY?

HIGH ENERGIES: STRONG GRAVITATIONAL AND QUANTUM EFFECTS

Image credits: Perimeter Institute

QUANTUM GRAVITY

$$\ell_P \approx 10^{-35} m$$

WHERE SHALL WE LOOK FOR QUANTUM EFFECTS IN GRAVITY?

HIGH ENERGIES:
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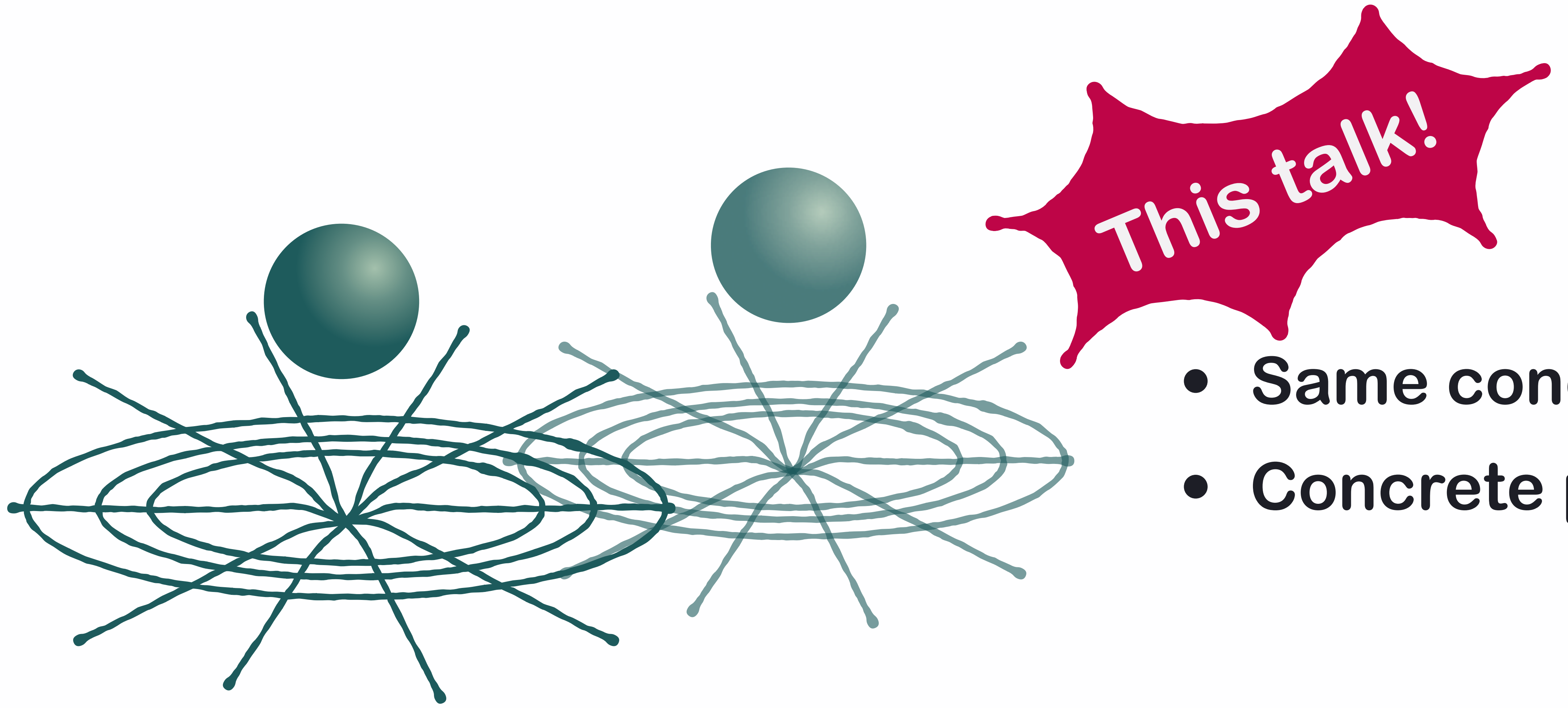
QUANTUM GRAVITY

$$\ell_P \approx 10^{-35}\, m$$

LOW ENERGIES:
WEAK-FIELD GRAVITY
QUANTUM PARTICLES



- Same conceptual questions as in QG
- Concrete physical situations

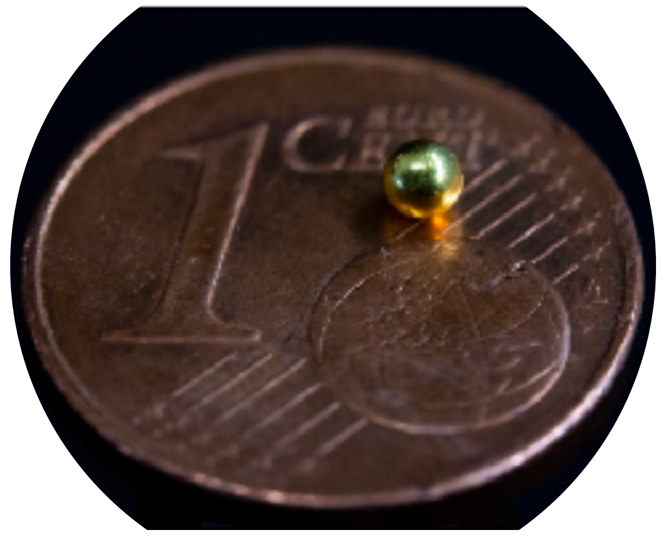
NONCLASSICAL SPACETIME FROM A QUANTUM SOURCE

Article | Published: 10 March 2021 **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

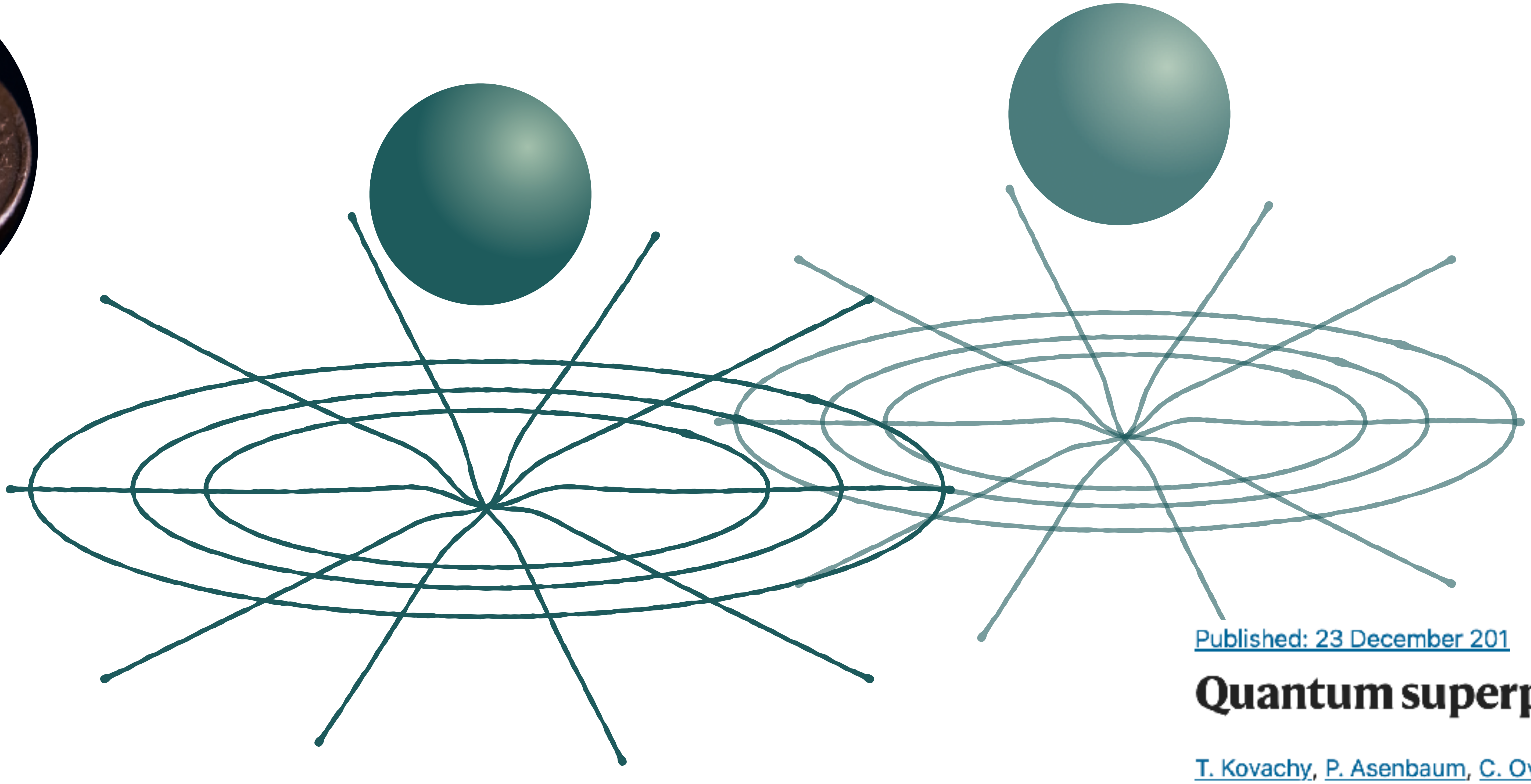


Schrödinger cat states of a 16-microgram mechanical oscillator

SUPERPOSED MASS: $10^{-5}g$

MARIUS BILD, MATTEO FADEL, YU YANG, UWE VON LÜPKE, PHILLIP MARTIN, ALESSANDRO BRUNO, AND YIWEN CHU Authors Info & Affiliations

SCIENCE • 20 Apr 2023 • Vol 380, Issue 6642 • pp. 274-278 • DOI: 10.1126/science.adf7553



Published: 23 December 201 **QUANTUM SUPERPOSITION:** $0.5\,m$

Quantum superposition at the half-metre scale

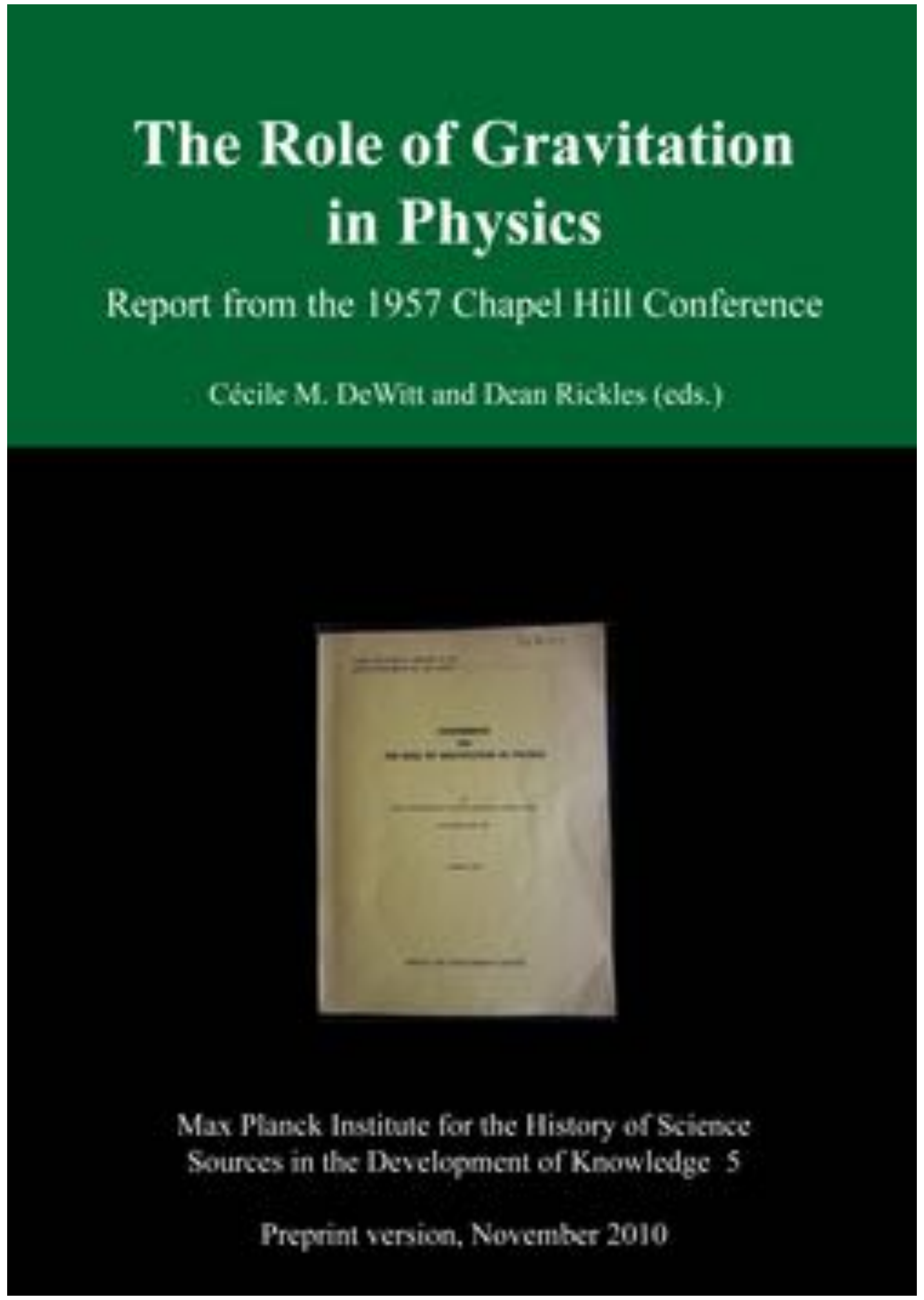
T. Kovachy, P. Asenbaum, C. Overstreet, C. A. Donnelly, S. M. Dickerson, A. Sugarbaker, J. M. Hogan & M. A. Kasevich

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

DO WE REQUIRE A QUANTUM DESCRIPTION OF GRAVITY?

"... it seems to me that we are in trouble if we believe in quantum mechanics but do not quantize gravitational theory"

R. Feynman, Chapel Hill Conference (1957)



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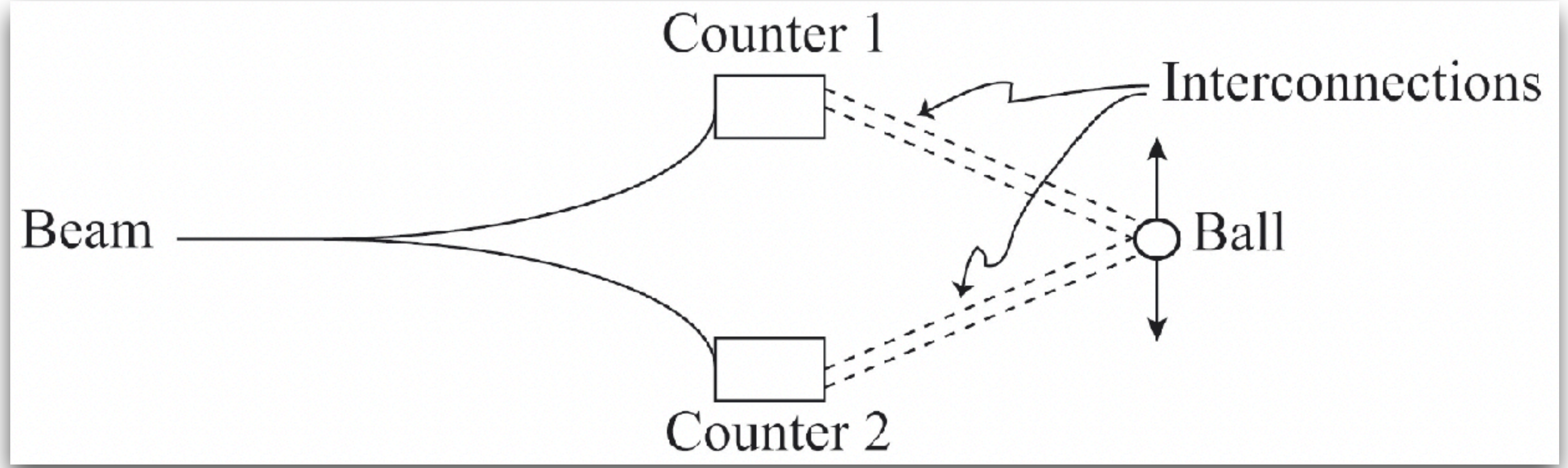

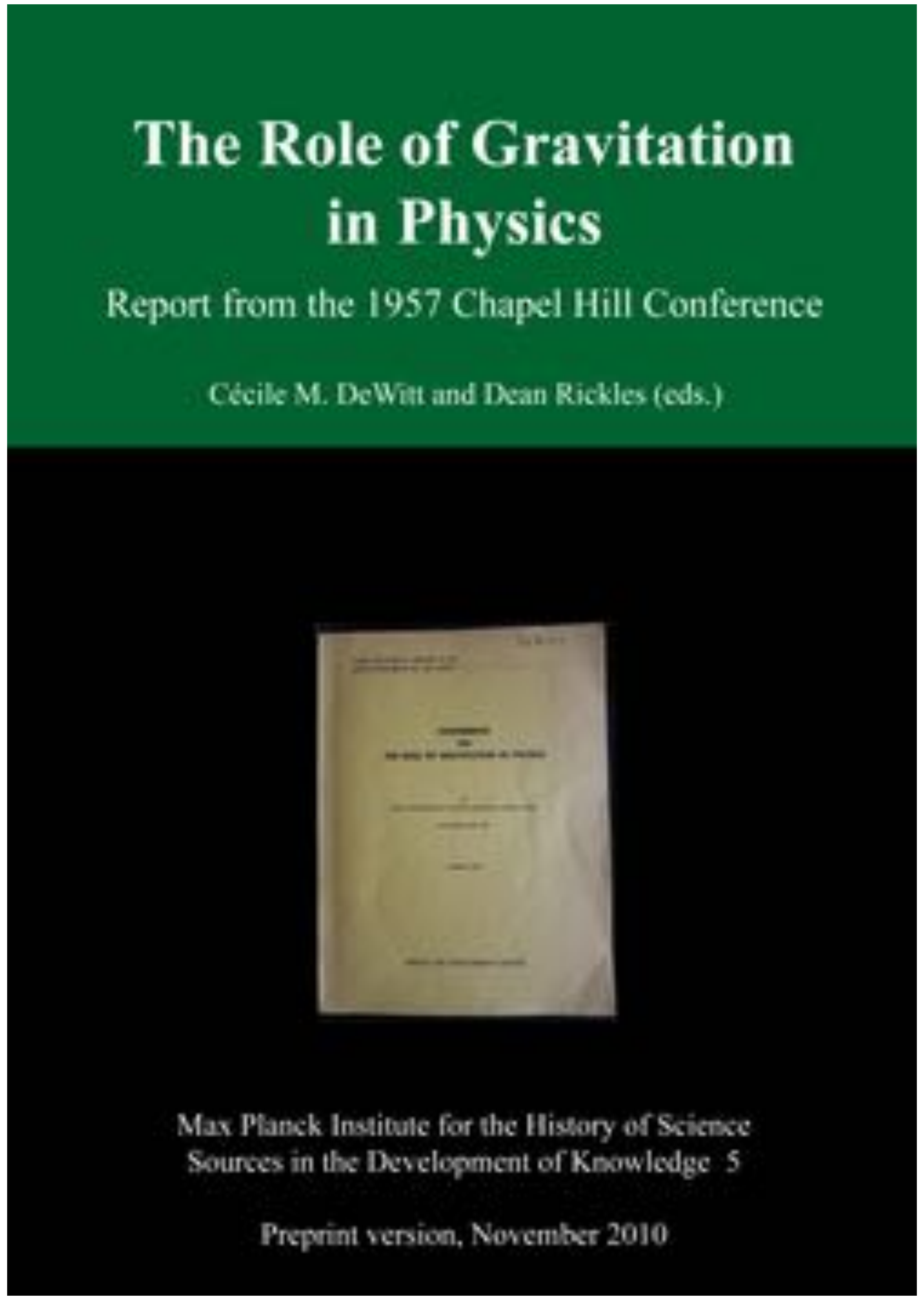

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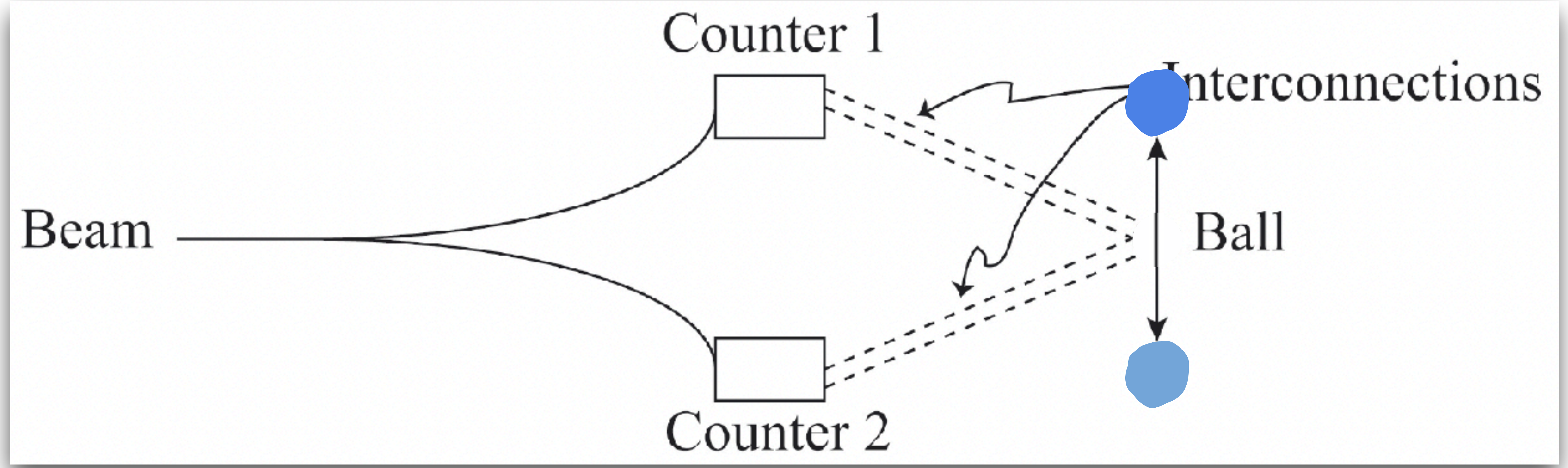

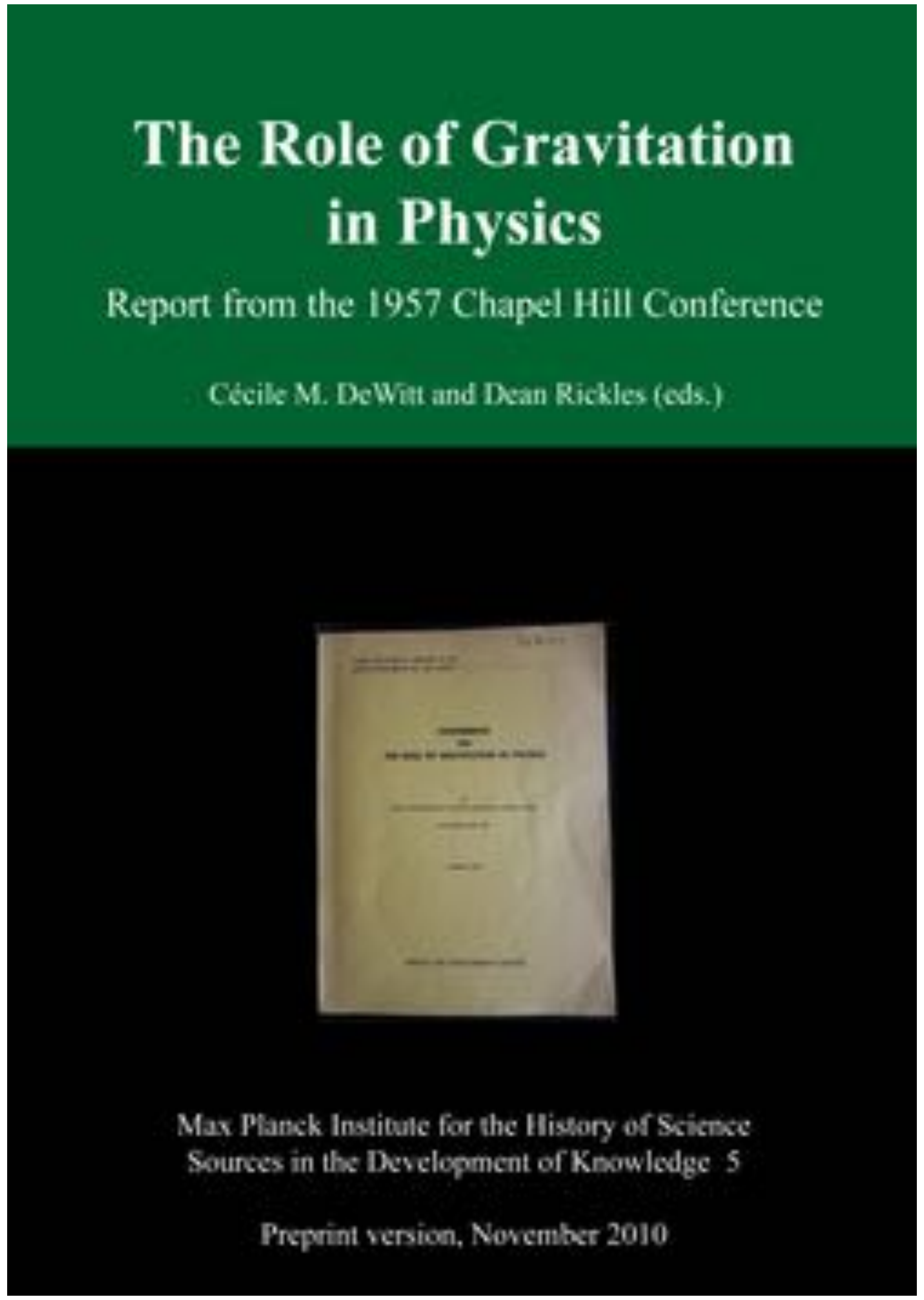

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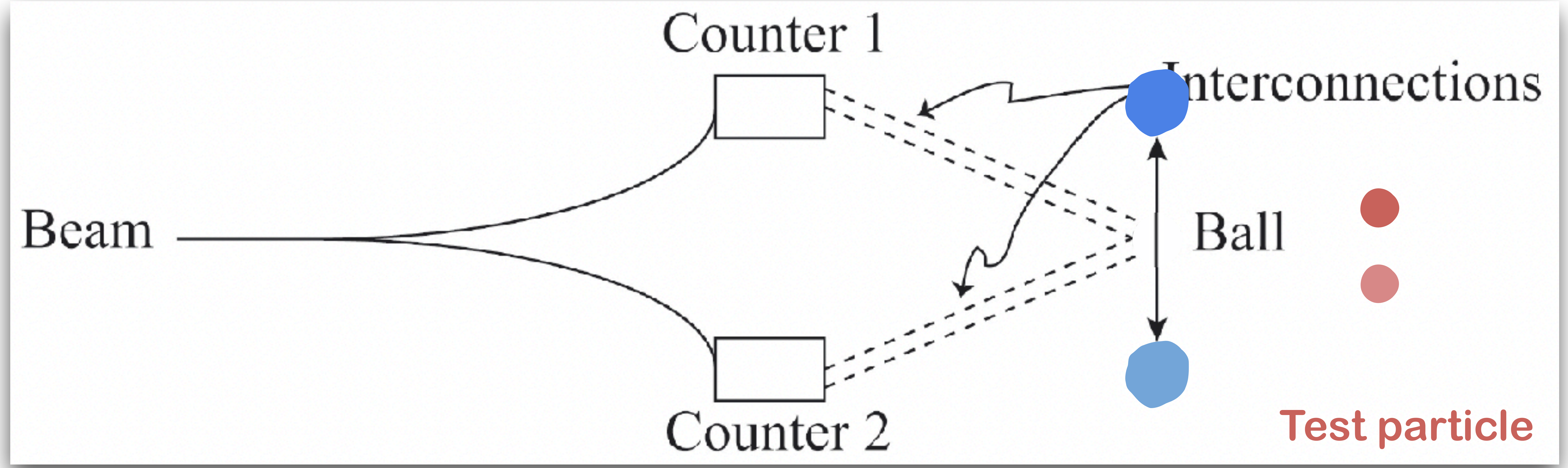

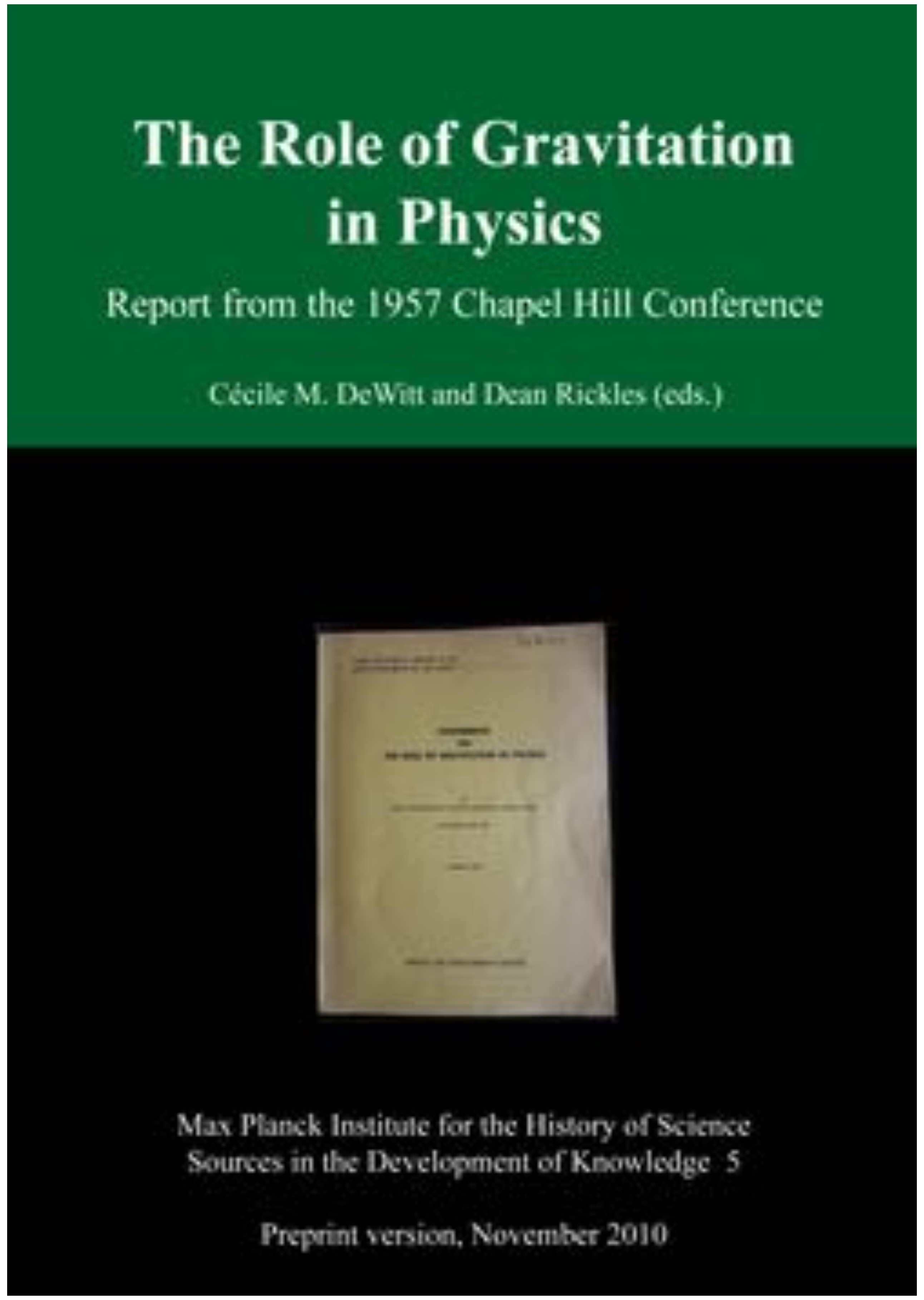

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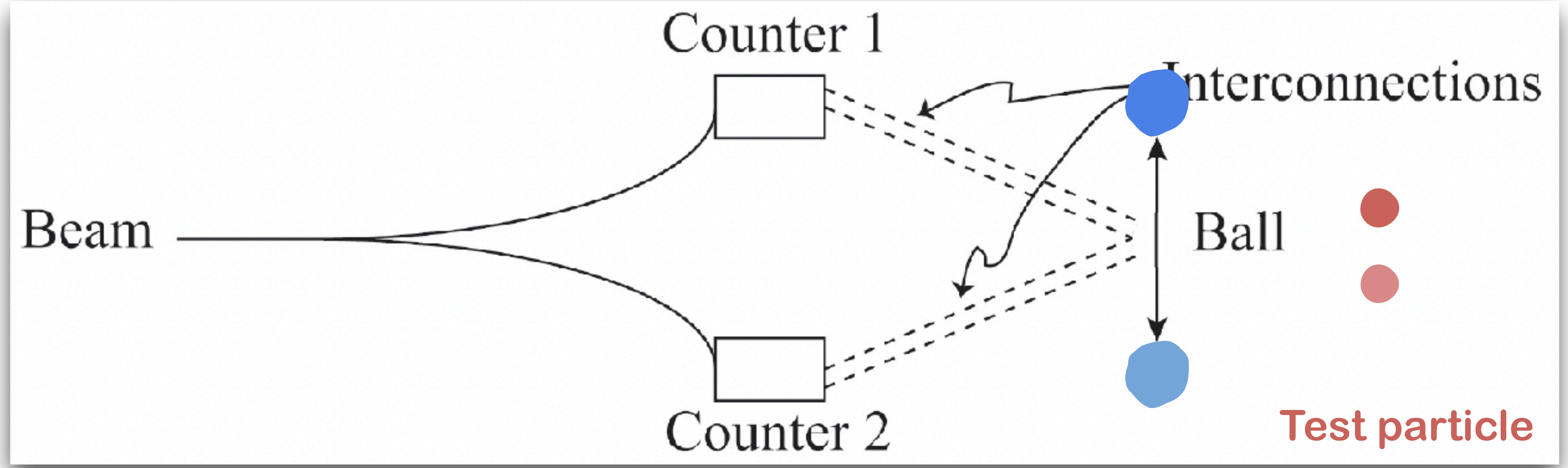
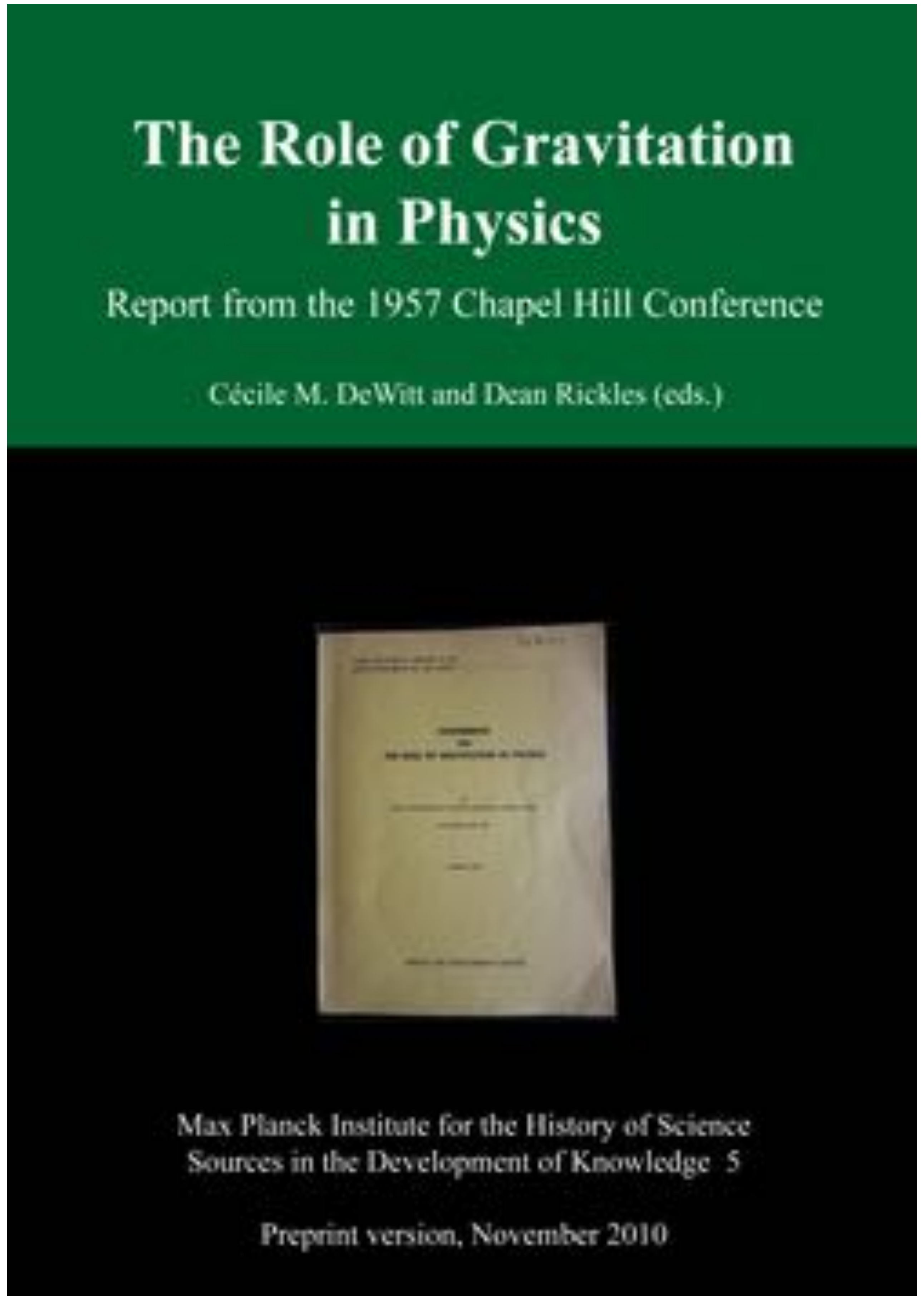




"If you believe in quantum mechanics up to any level then you have to believe in gravitational quantization in order to describe this experiment."

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)

PHYSICAL REVIEW D VOLUME 9, NUMBER 4 15 FEBRUARY 1974

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

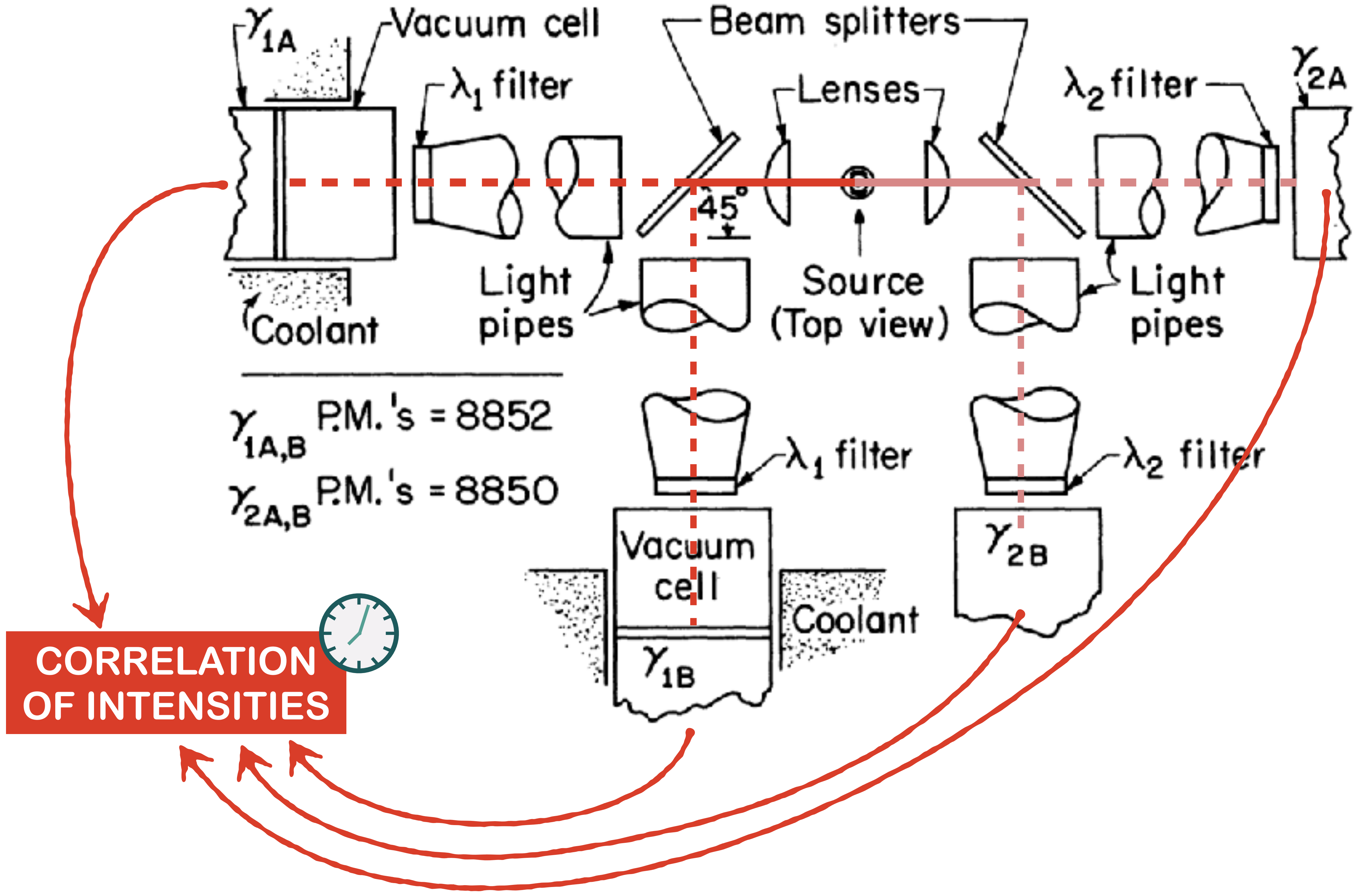
John F. Clauser

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

(Received 30 October 1973)

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

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



For a single photon source

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

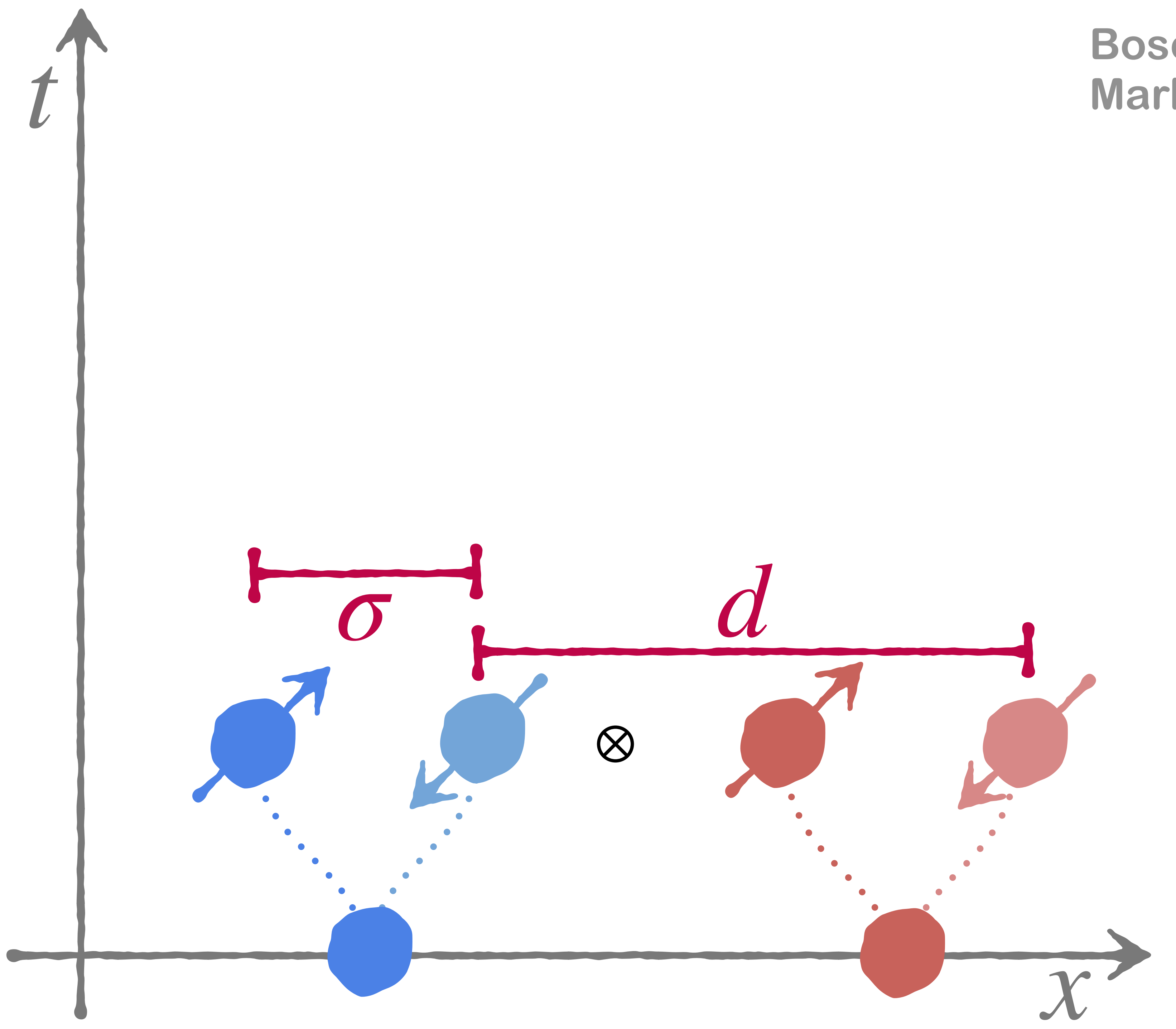
Signature of nonclassicality

GRAVITATIONALLY INDUCED ENTANGLEMENT

LOCC: Bennett et al. PRA (1995)

GRAVITATIONALLY INDUCED ENTANGLEMENT

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



PRODUCT STATE $\sim (|x_1\rangle_A + |x_2\rangle_A) \otimes (|x_1 + d\rangle_B + |x_2 + d\rangle_B)$

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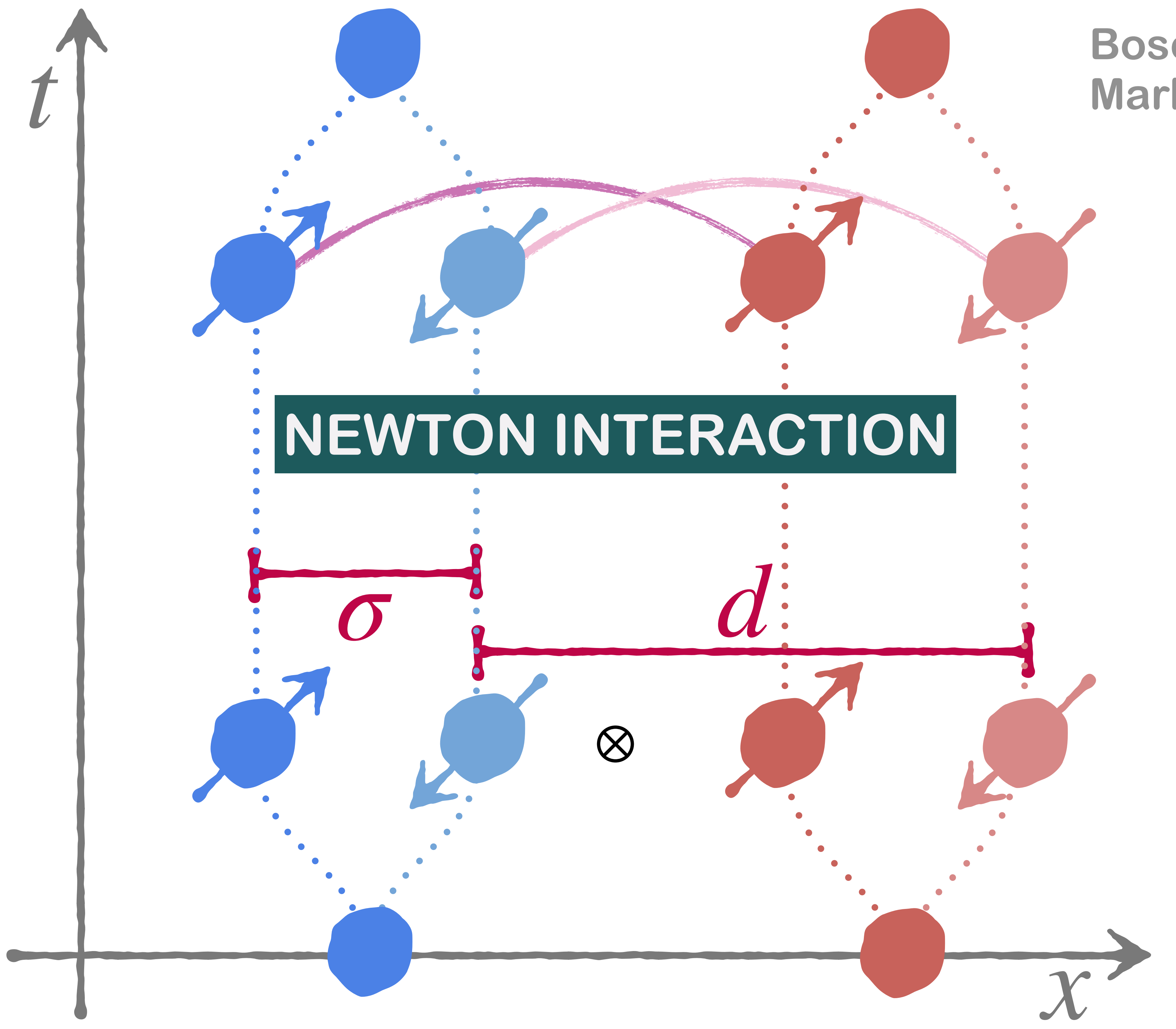

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$$\hat{H}_I = \hat{V}_N = -G\frac{m_A m_B}{|\hat{x}_A - \hat{x}_B|}$$

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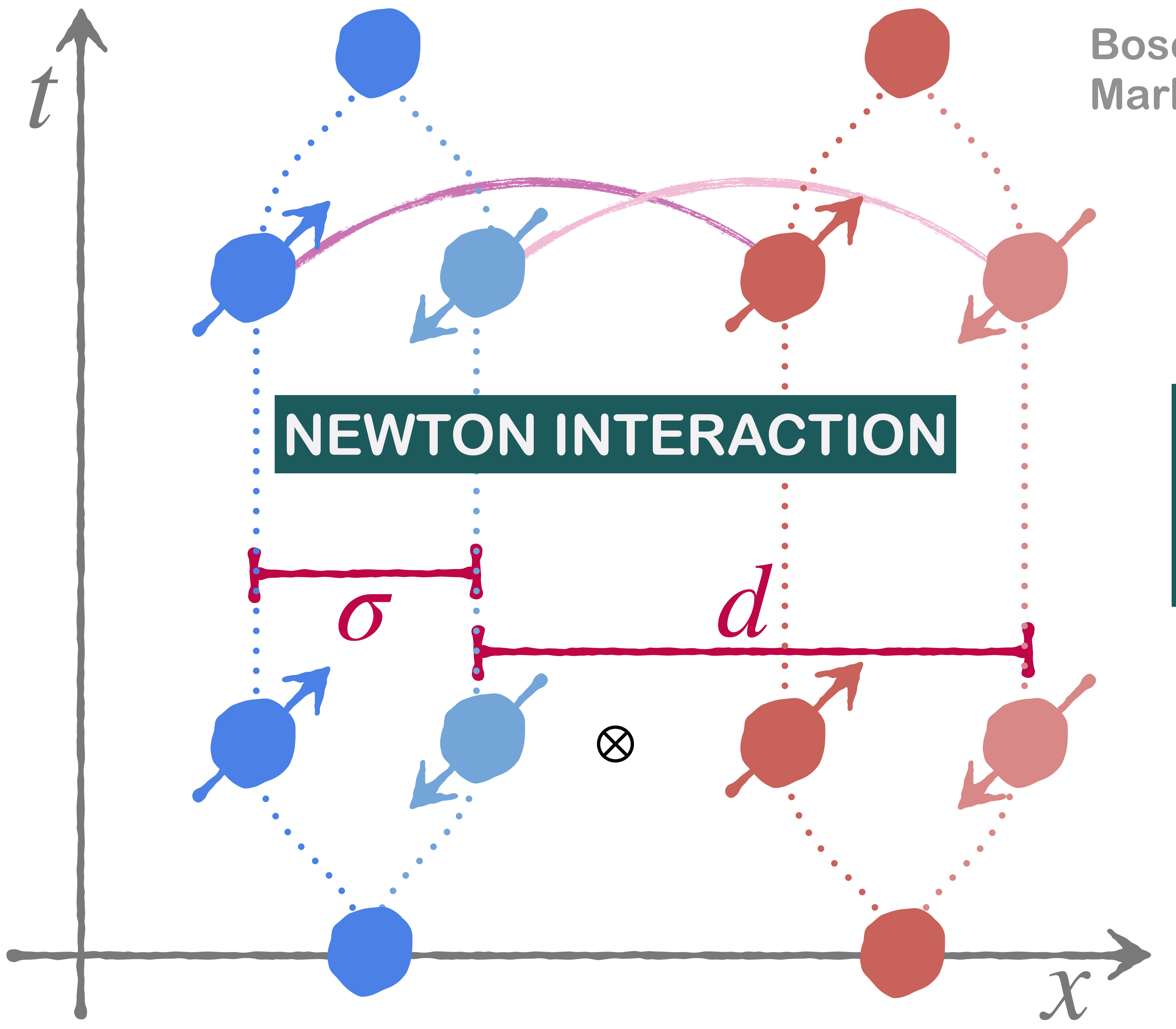

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ENTANGLED STATE $\sim \sum_{i,j=1,2} e^{i\phi_{ij}} |x_i\rangle_A |x_j + d\rangle_B$

Nonclassical channel (LOCC theorem)

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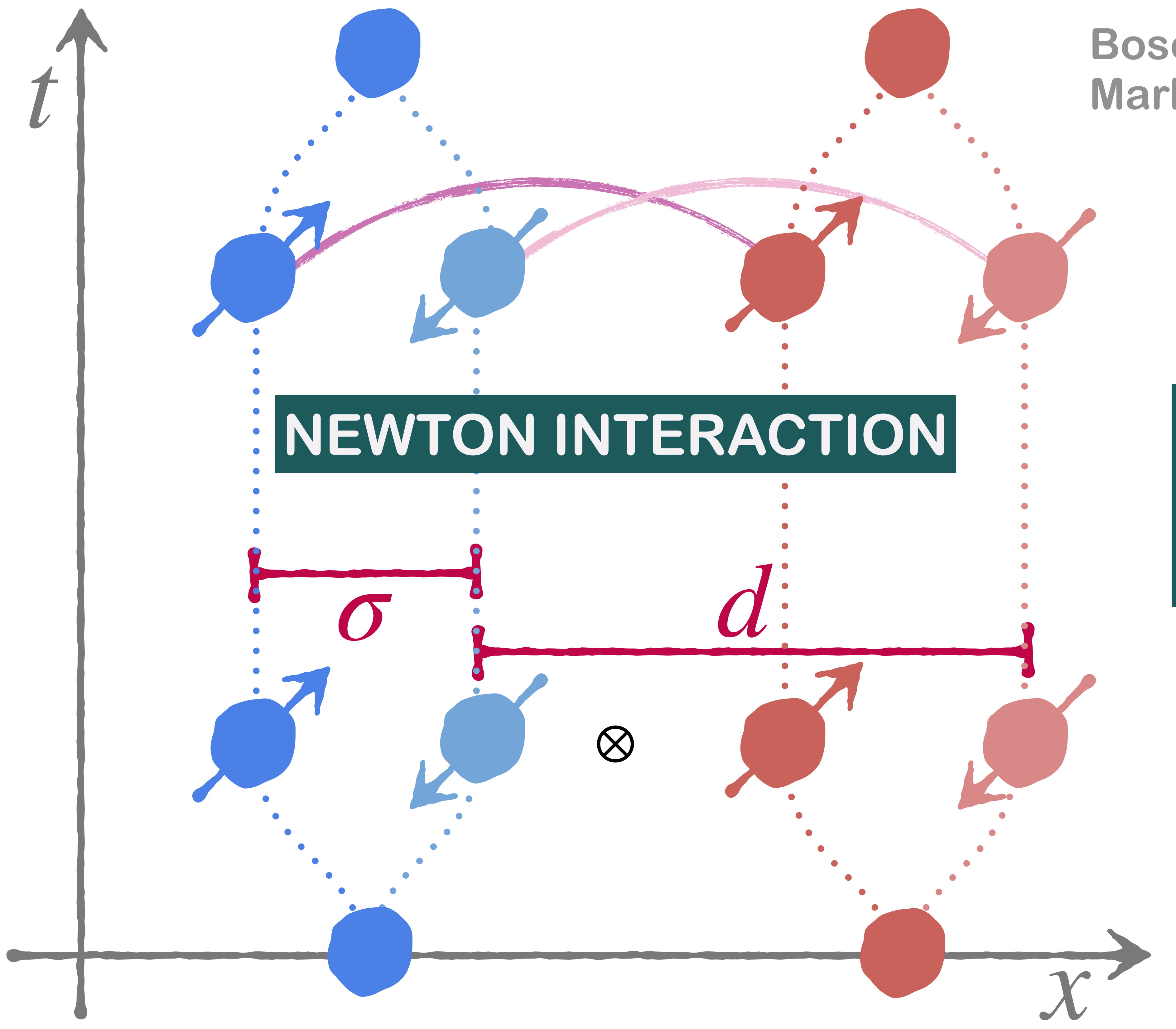

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Many people contributed! *E.g. Anastopoulos, Aspelmeyer, Barker, Belenchia, Bengyat, Bhatar, Blencowe, Bose, Brukner, Carney, Castro-Ruiz, Chen, Christodoulou, Cooper, Di Biagio, Galley, Geraci, Hackermüller, Howl, Hu, Huggett, Iyer, Kent, Kim, Krisnanda, Lami, Linneman, Liu, Mahesh, Marletto, Marshman, Martín-Martínez, Mazumdar, Milburn, Morley, Müller, Mummery, Naik, Pal, Paterek, Paternostro, Pedernales, Perche, Pitalúa-García, Plenio, Quarfort, Rovelli, Schneider, Schut, Selby, Serafini, Sillanpää, Tam, Taylor, Toros, Ulbricht, Vedral, Wald, Yant…*

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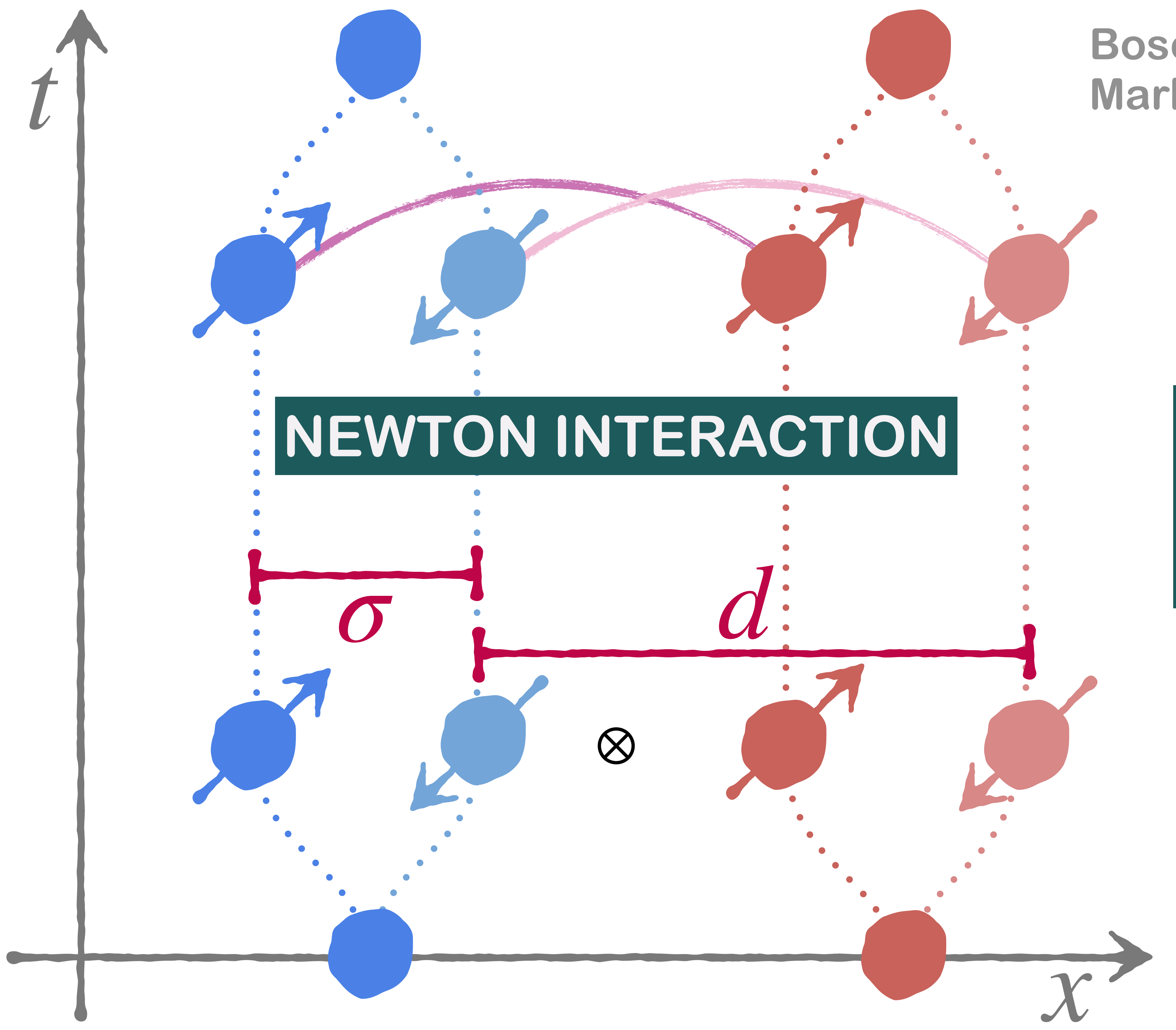

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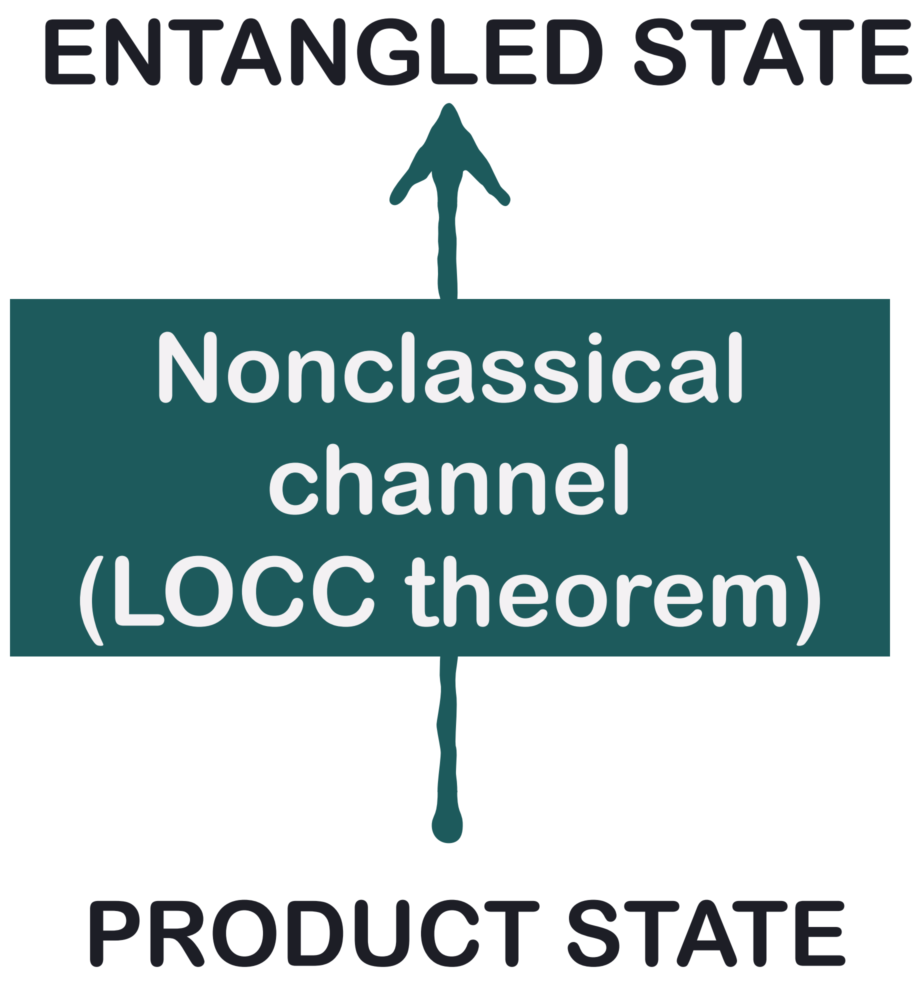

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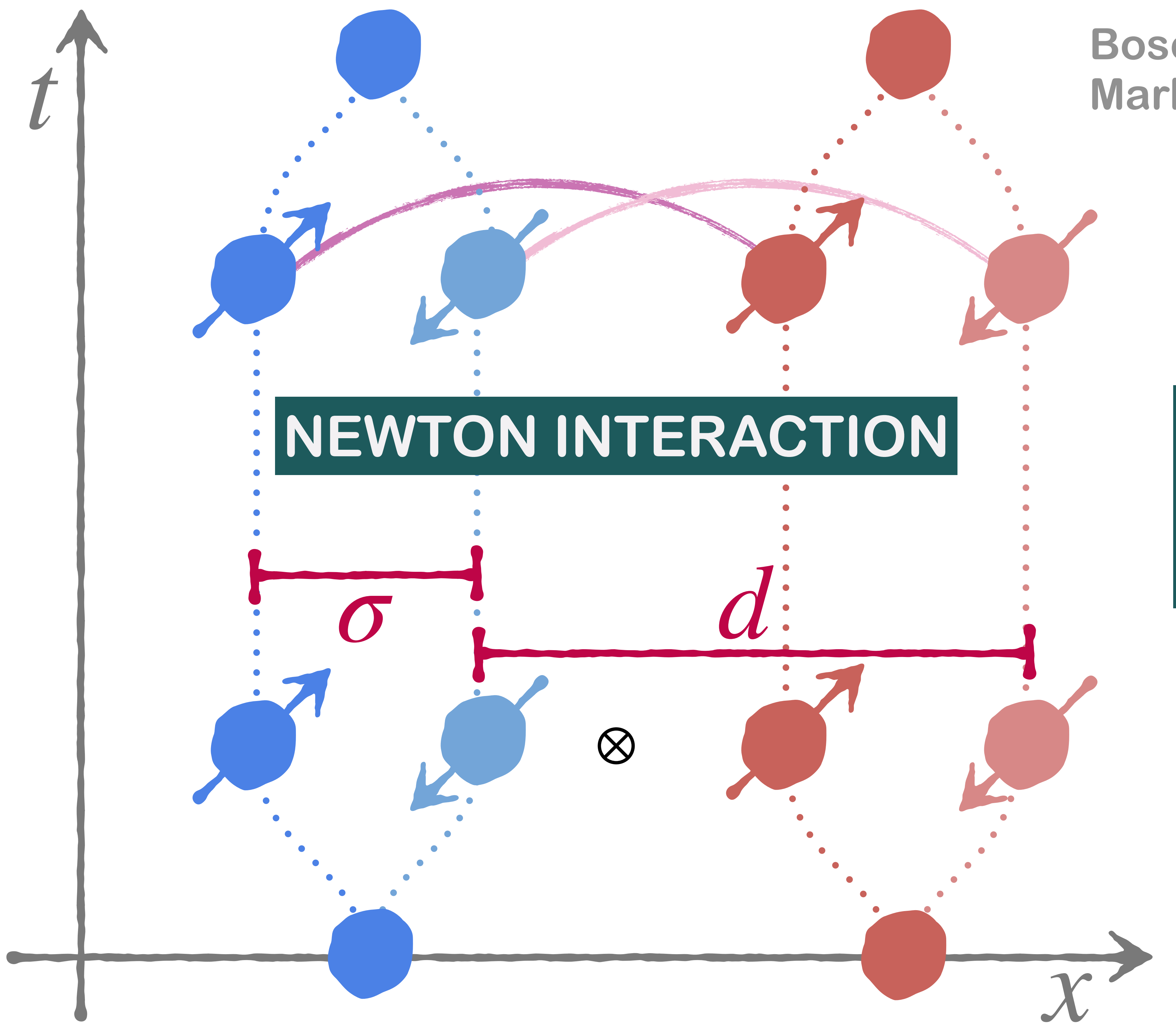

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ENTANGLED STATE

Nonclassical channel (LOCC theorem)

PRODUCT STATE

ENTANGLEMENT RATE

$$\Gamma_{ent} = \frac{d}{dt}\Delta\phi = \frac{G}{\hbar}\frac{m^2\sigma^2}{d^3}$$

$$m \approx 10^{-5}\, g$$
$$d \approx 100\, \mu m$$
$$\sigma \approx 1\, nm$$

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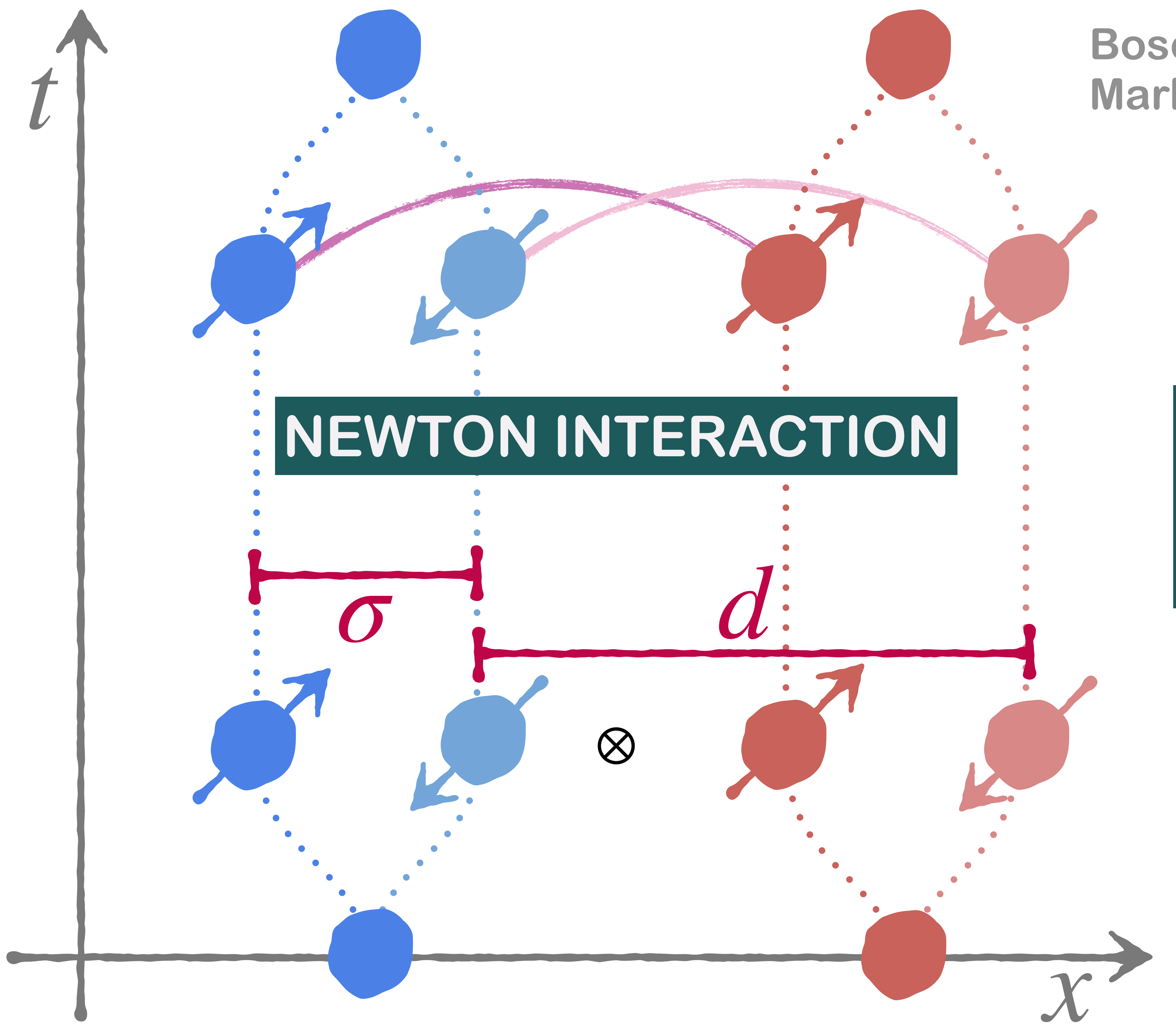

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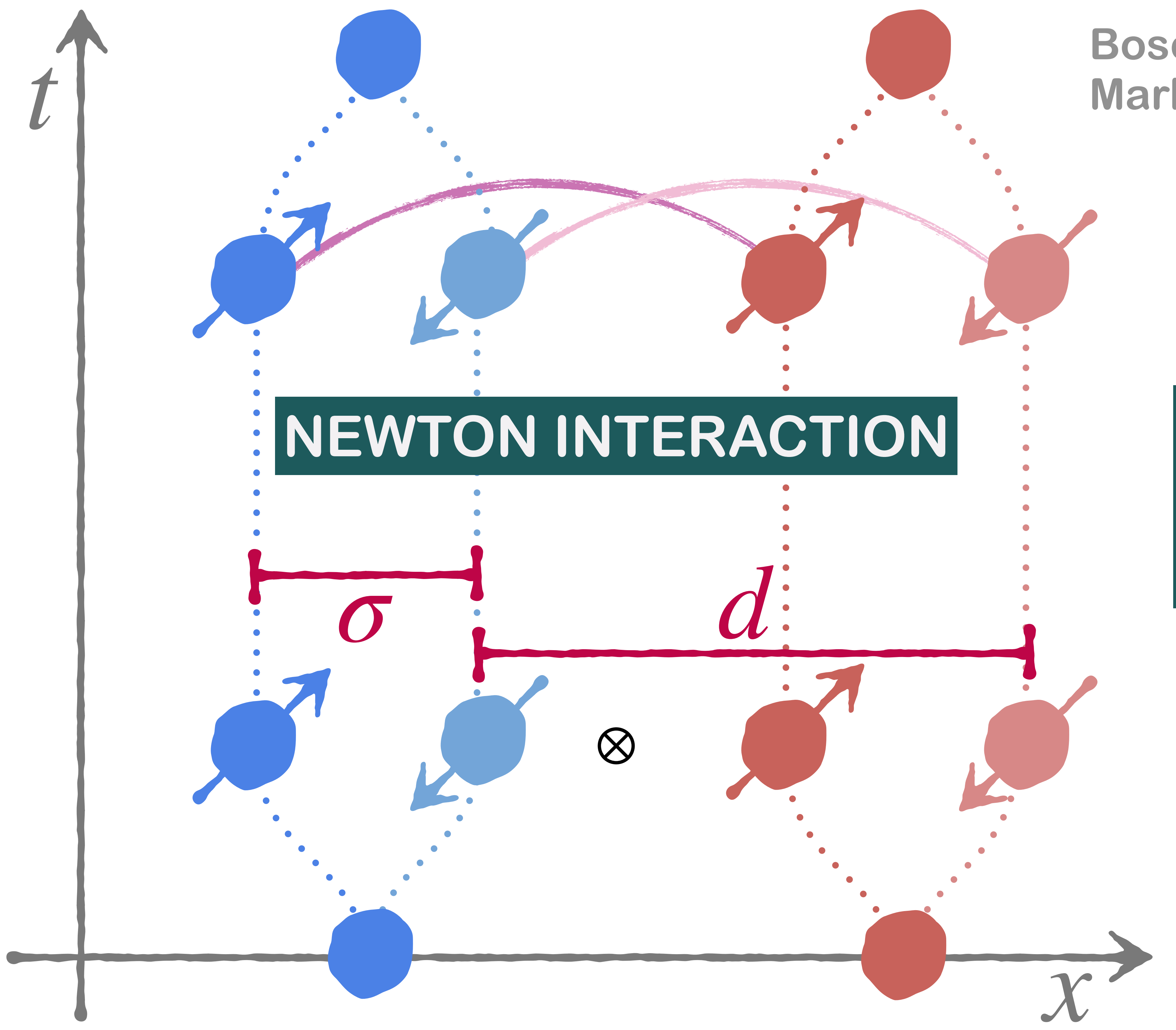

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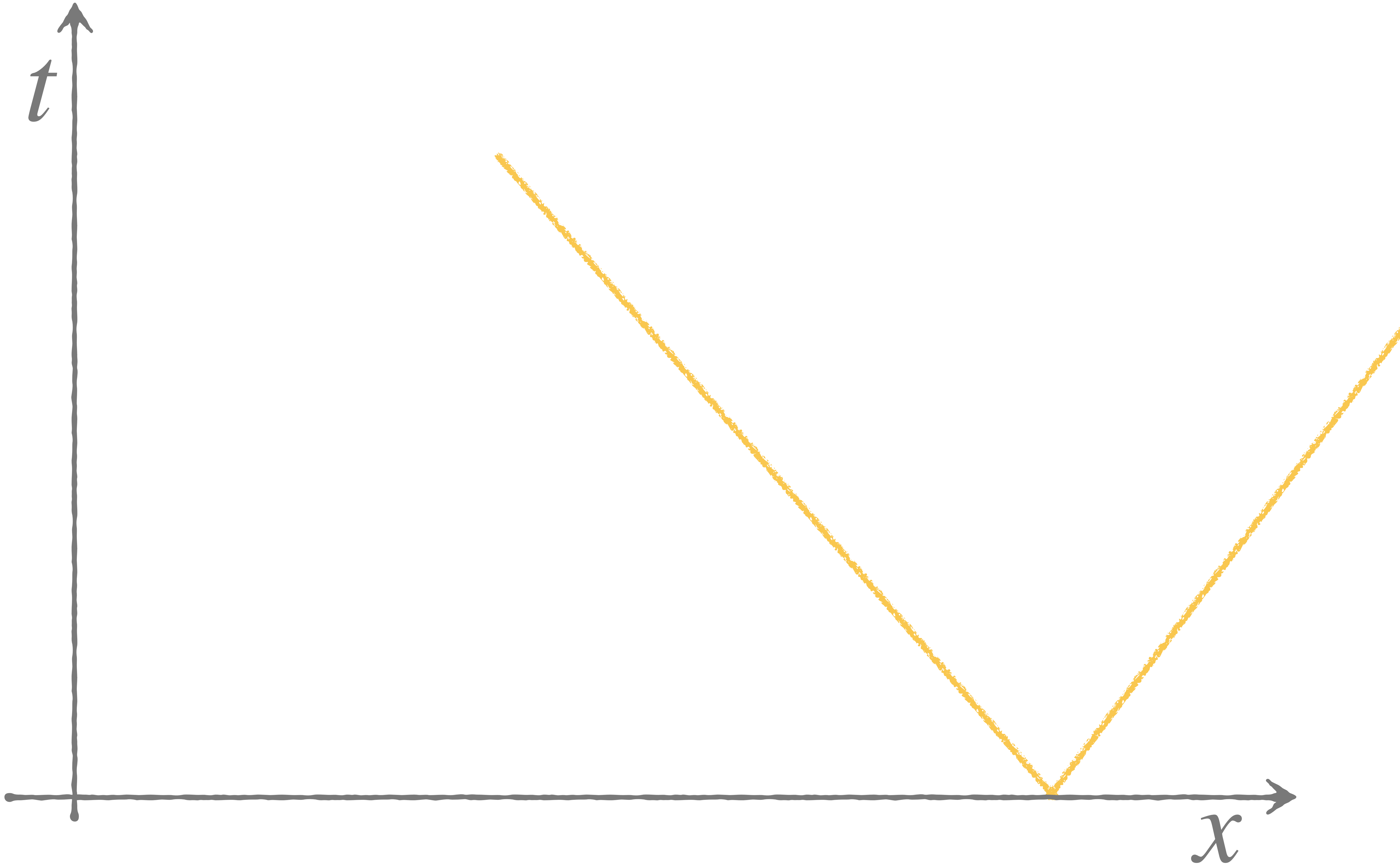
QUESTION/OBJECTION:
You only used the Newton potential to generate entanglement!

NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

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

Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)
2019 **First prize Essay** of the Gravity Research Foundation



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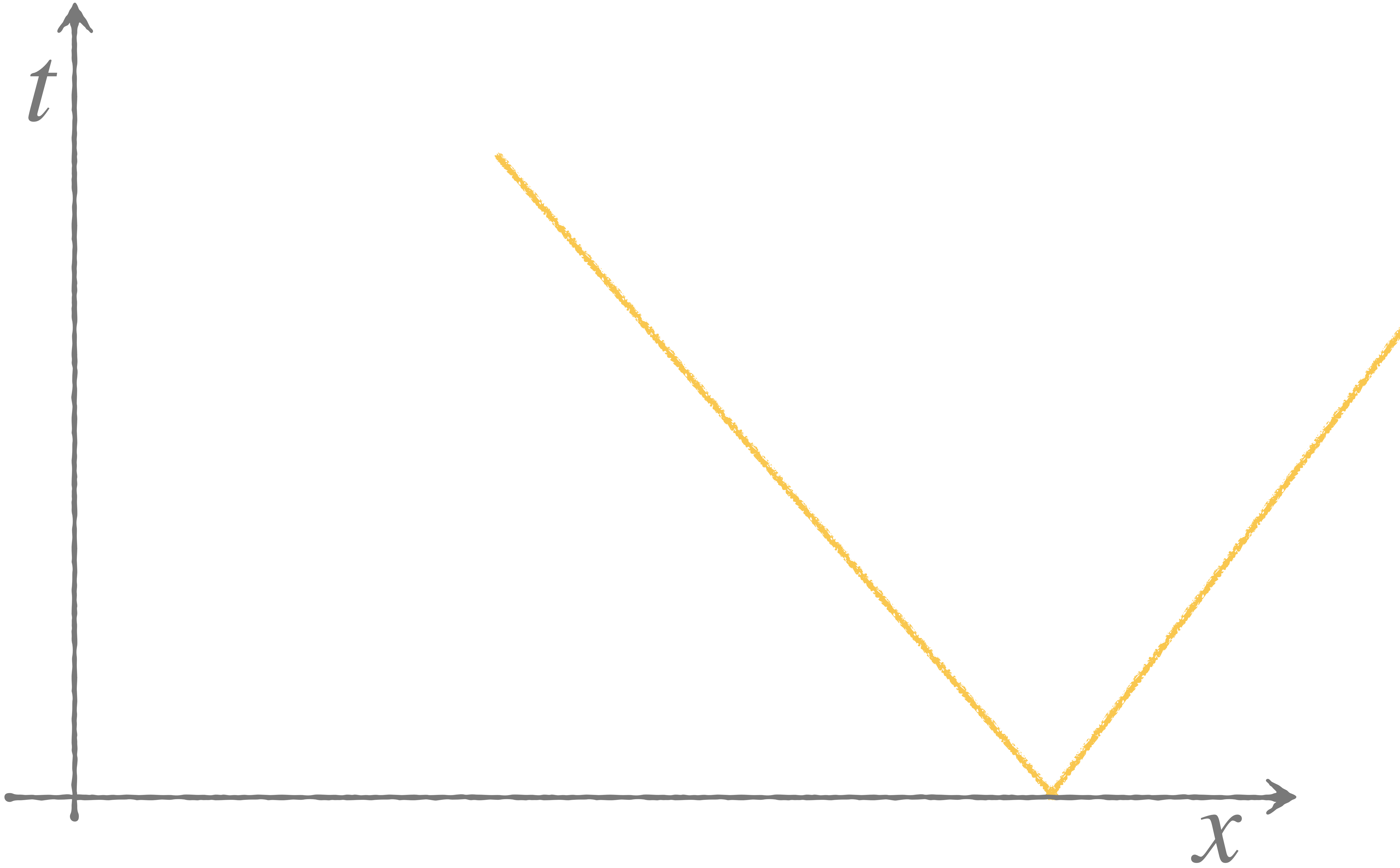
G is a field (GR)
No interaction at a distance
Linearized quantum gravity



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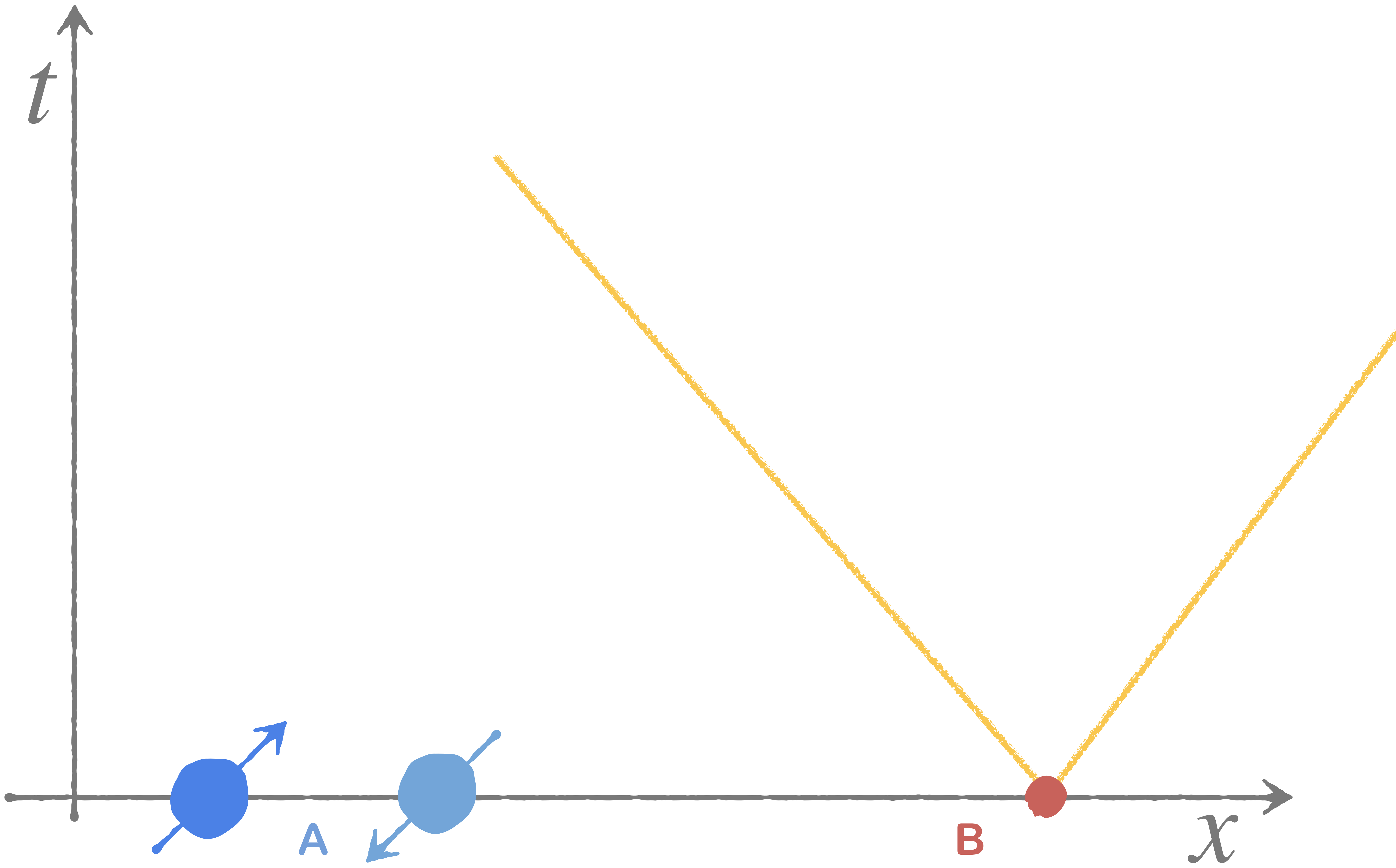
$$\frac{1}{\sqrt{2}}\left(|L\rangle_A|\alpha_L\rangle_G + |R\rangle_A|\alpha_R\rangle_G\right)|\psi_0\rangle_B$$



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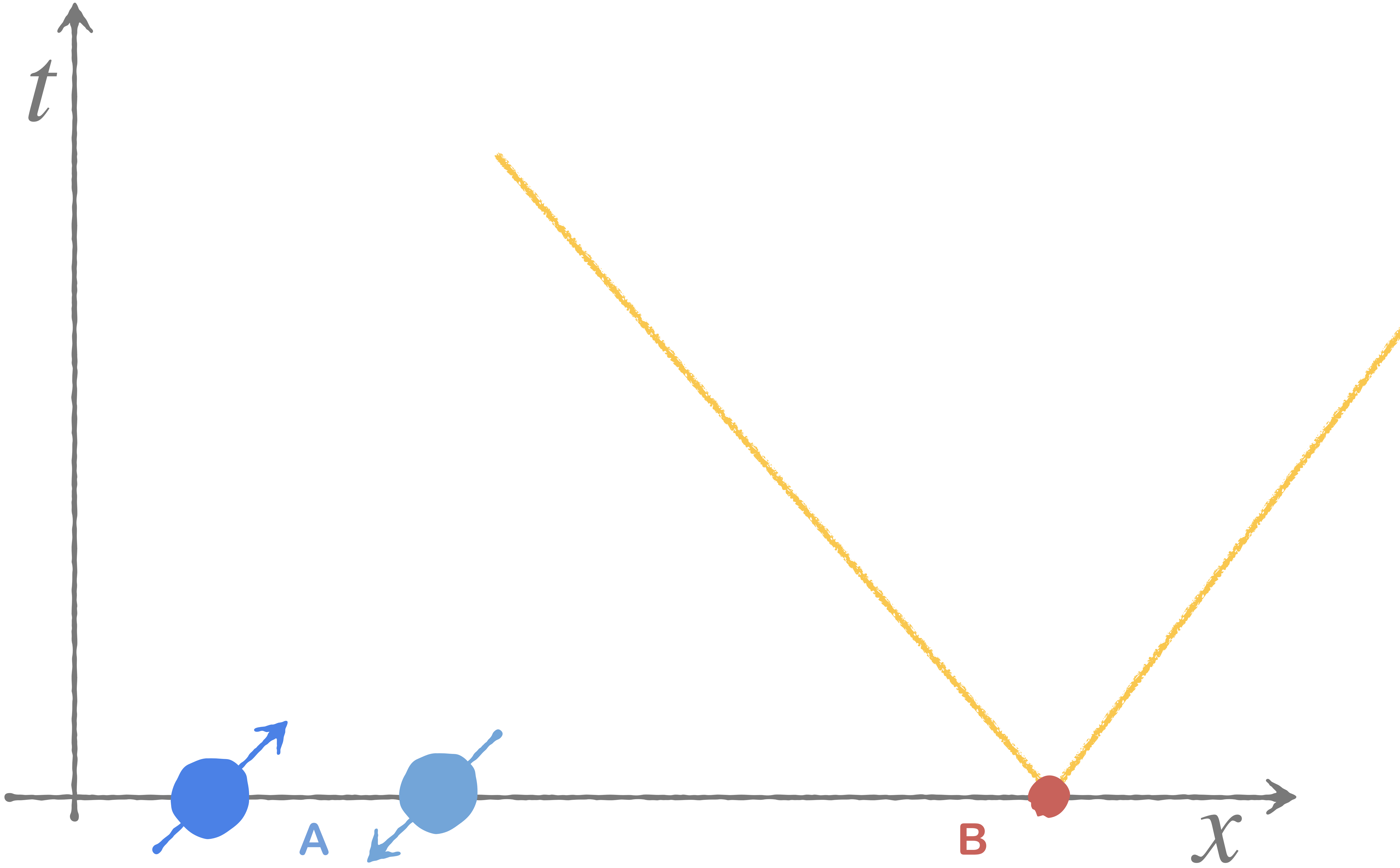

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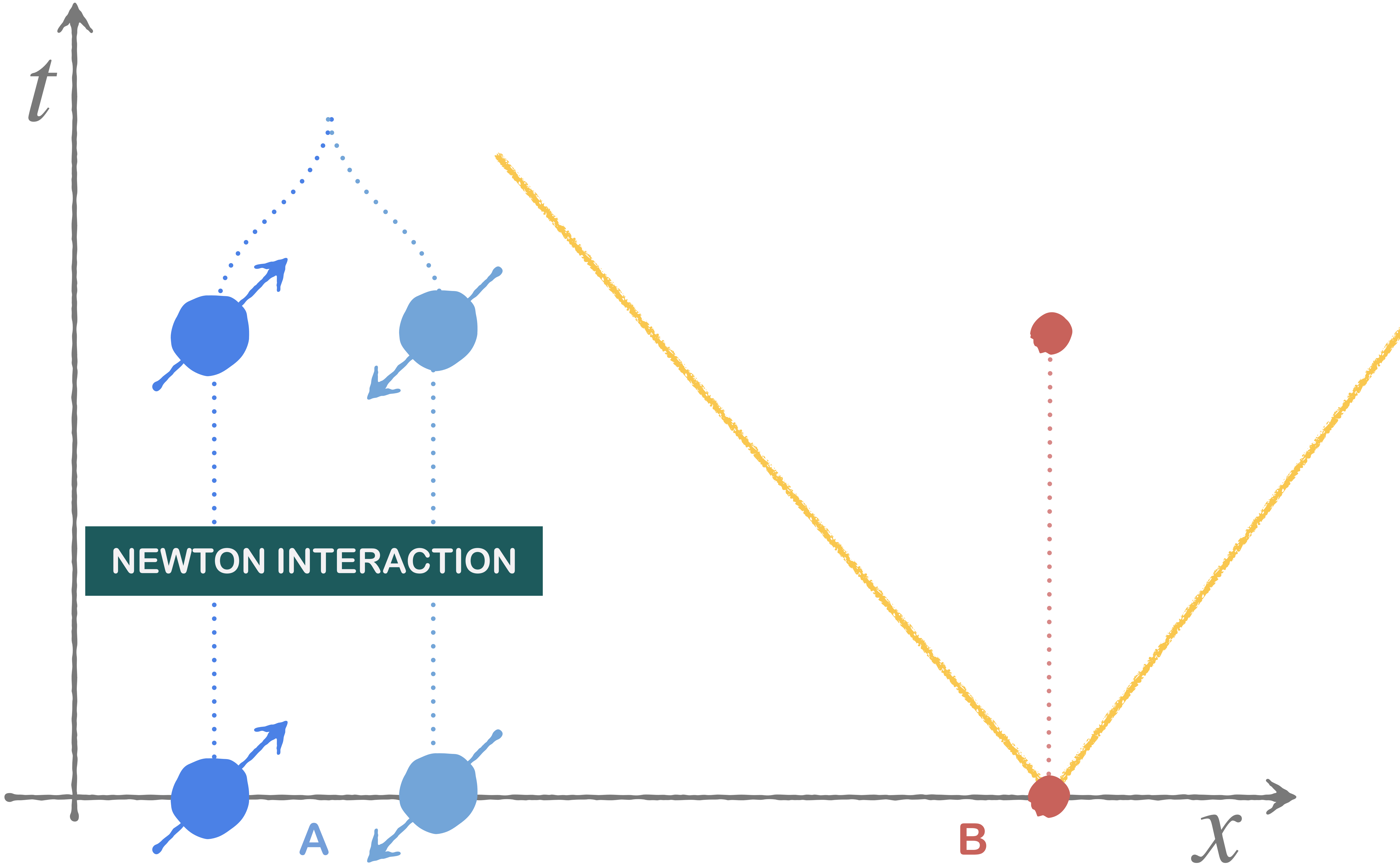

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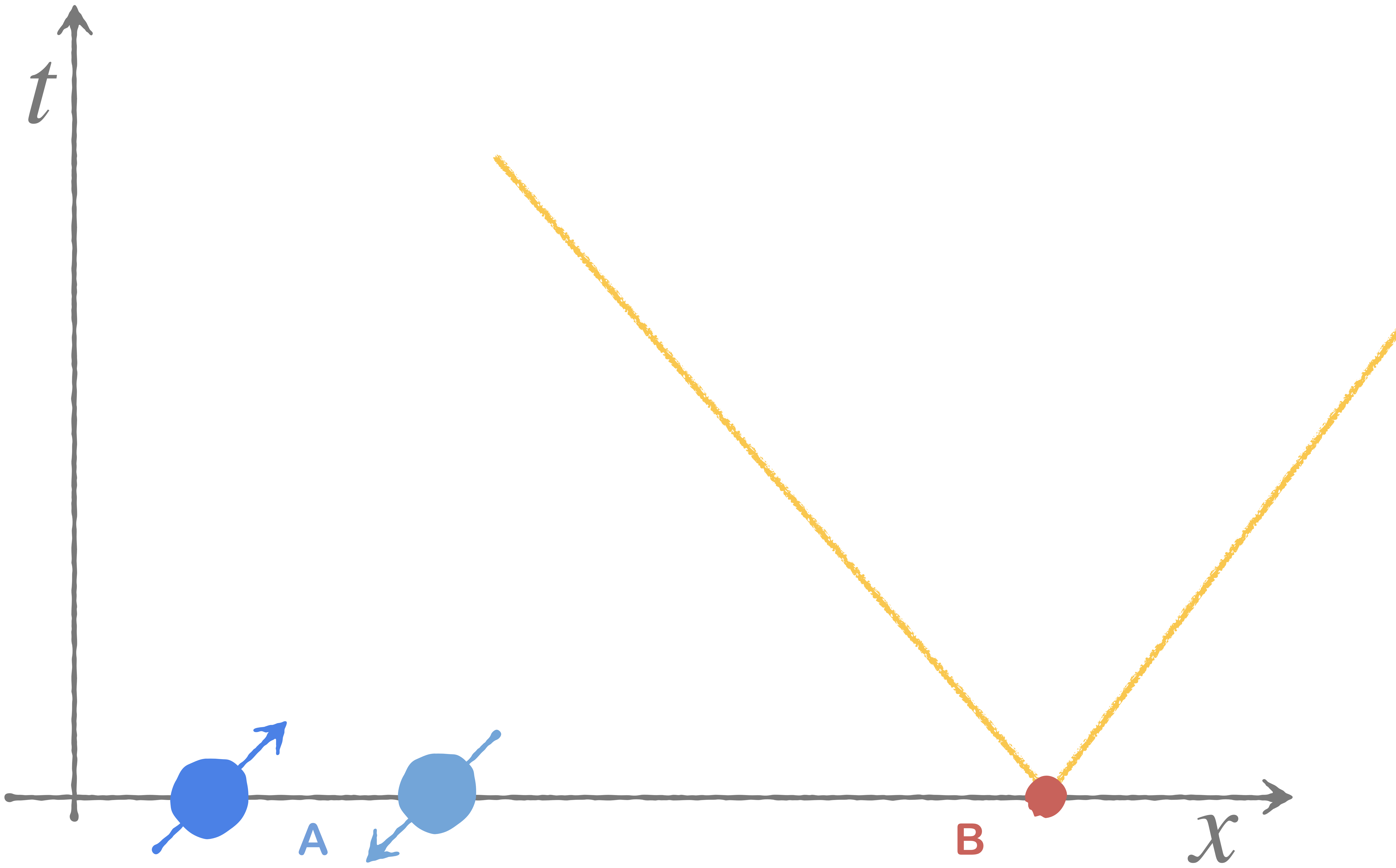

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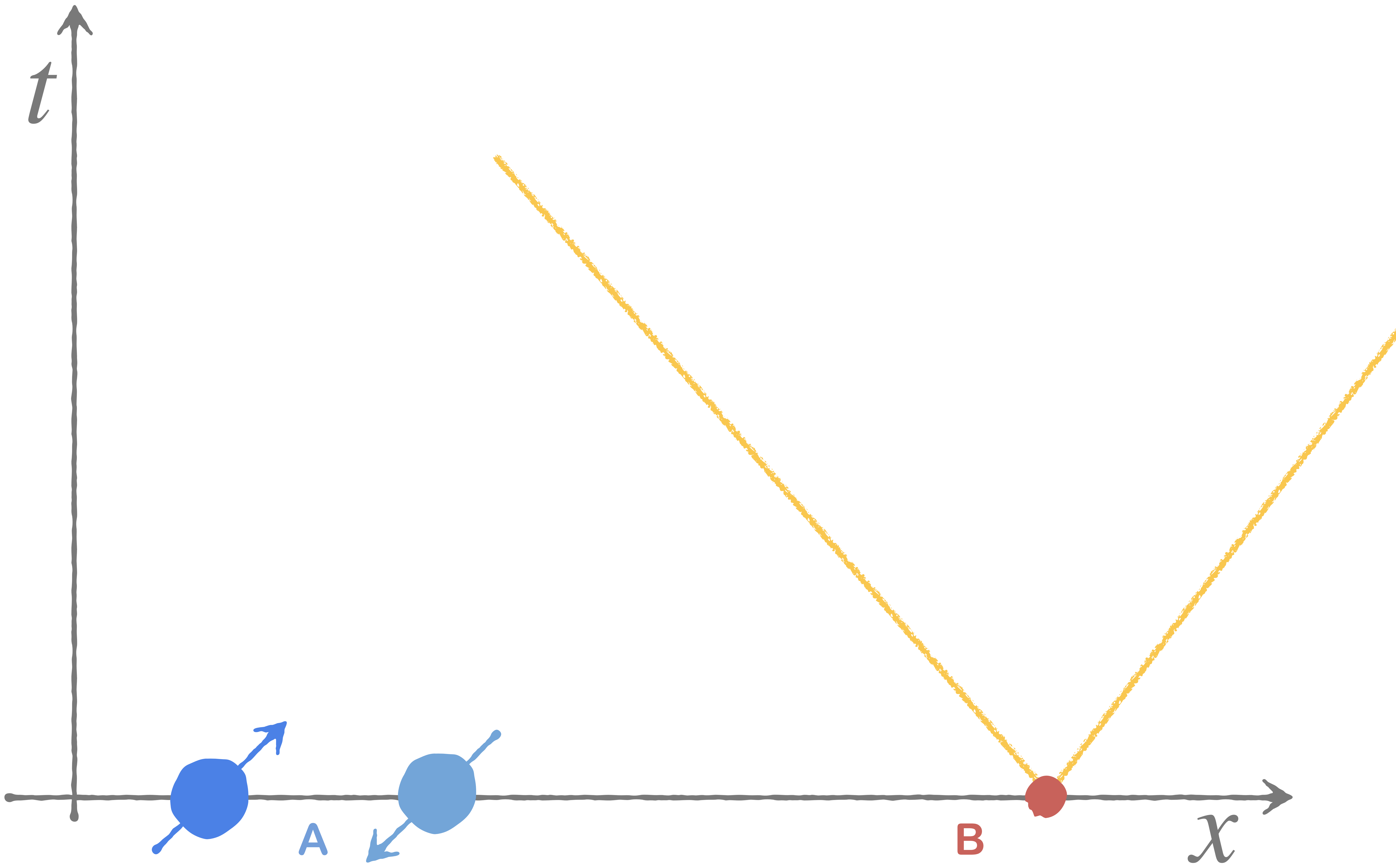

NEWTON POTENTIAL AS QUANTUM INFORMATION CARRIER

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

Belenchia, Wald, Giacomini, Castro-Ruiz, Brukner, Aspelmeyer, PRD (2018)
2019 **First prize Essay** of the Gravity Research Foundation

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

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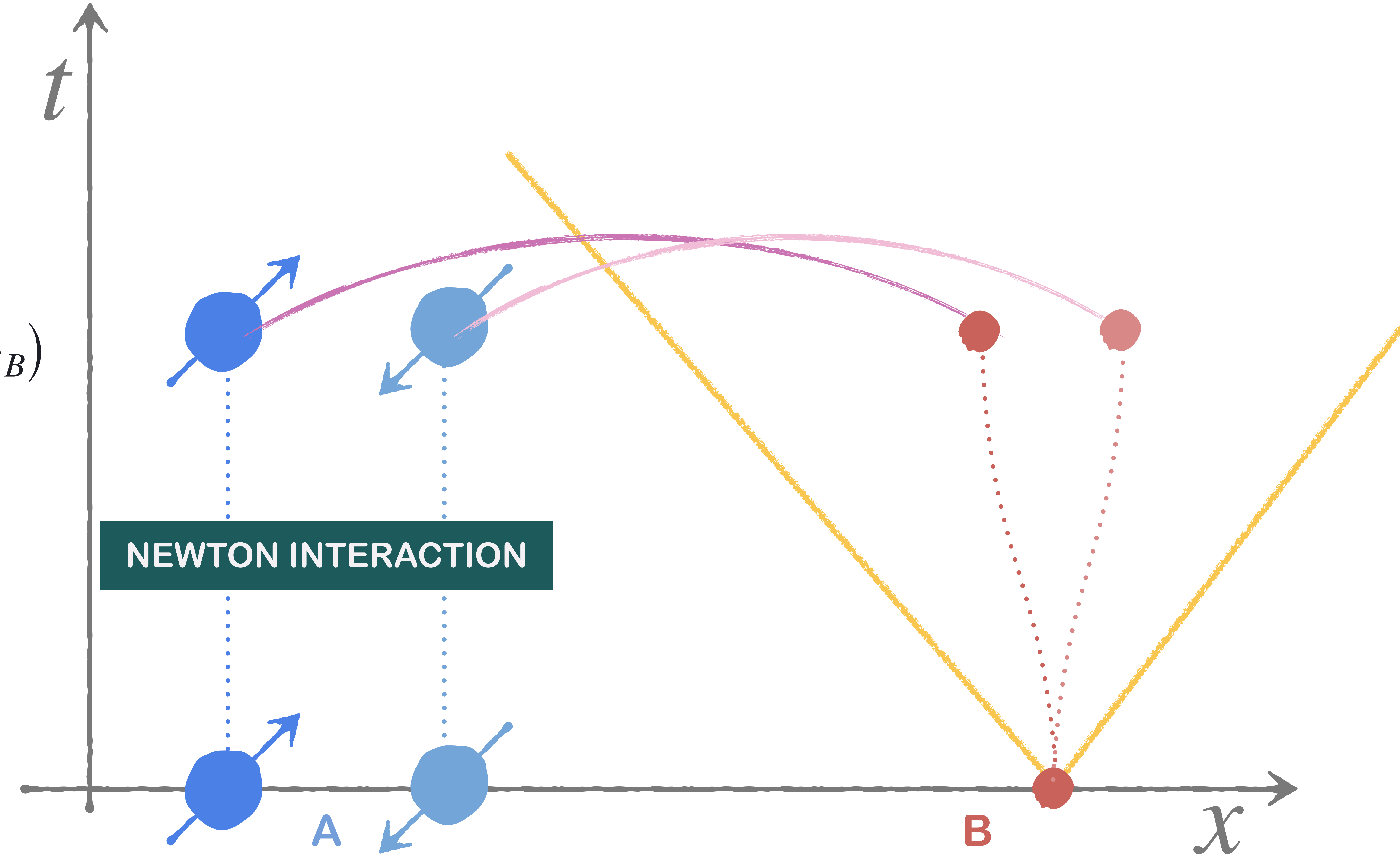

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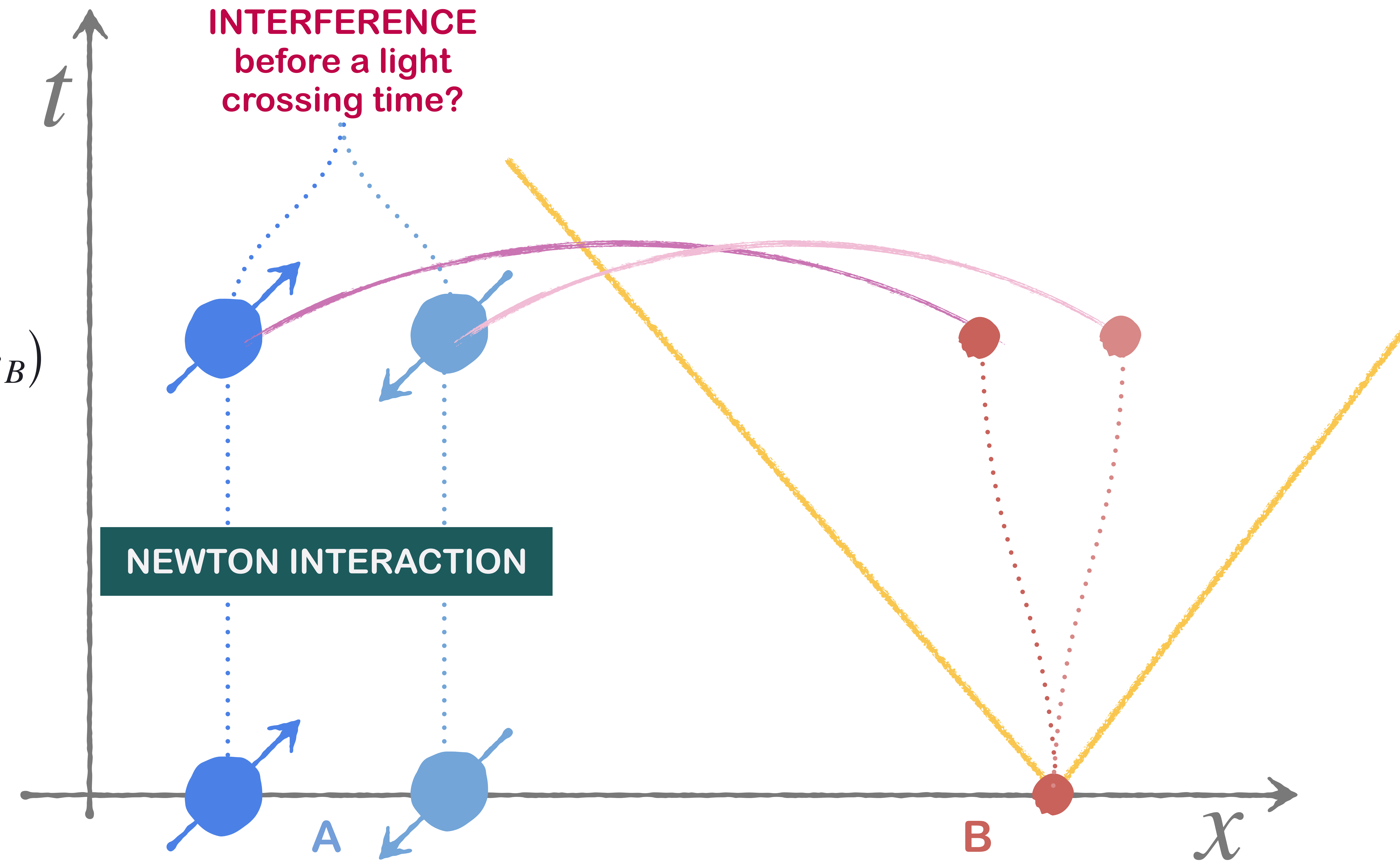

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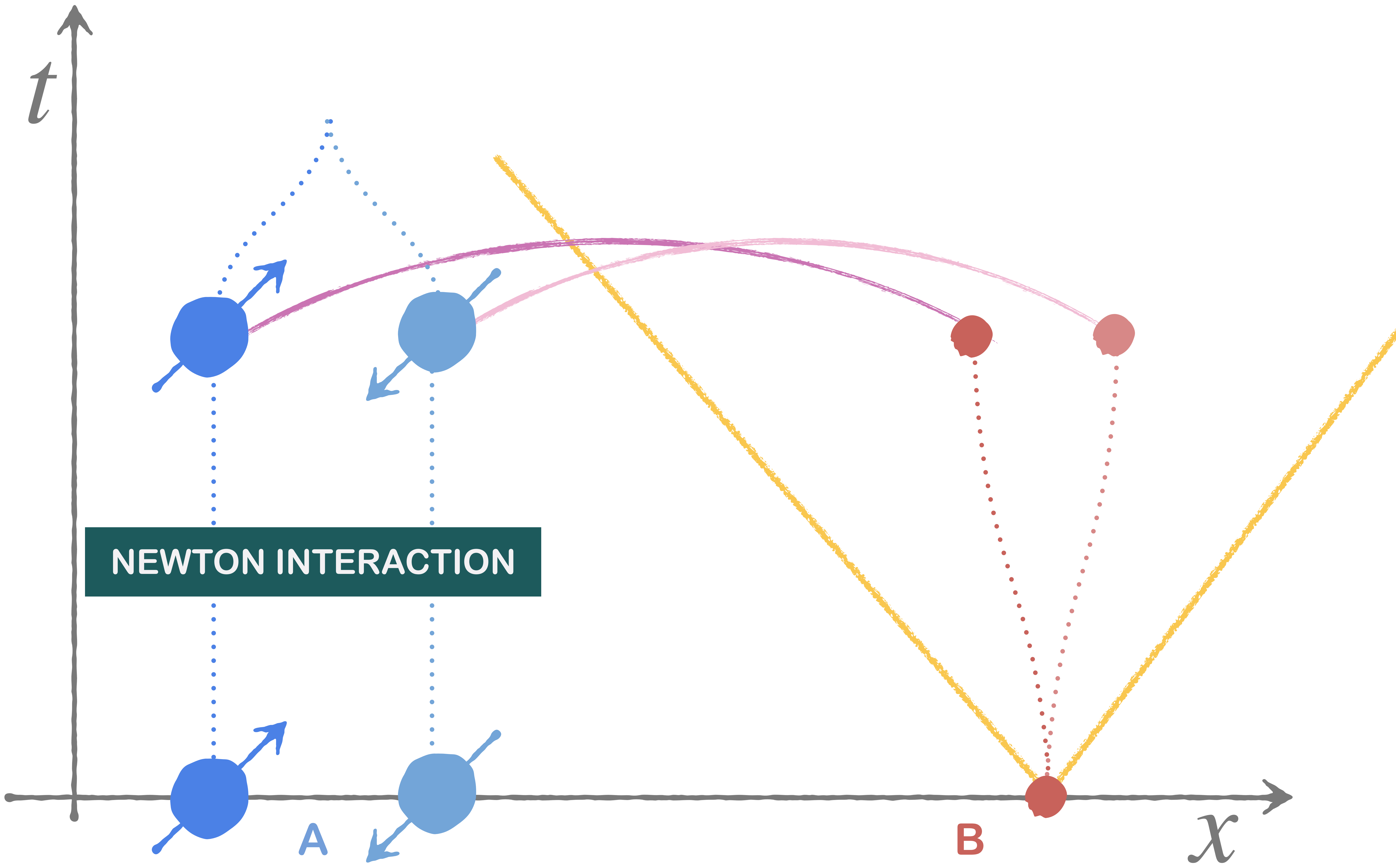

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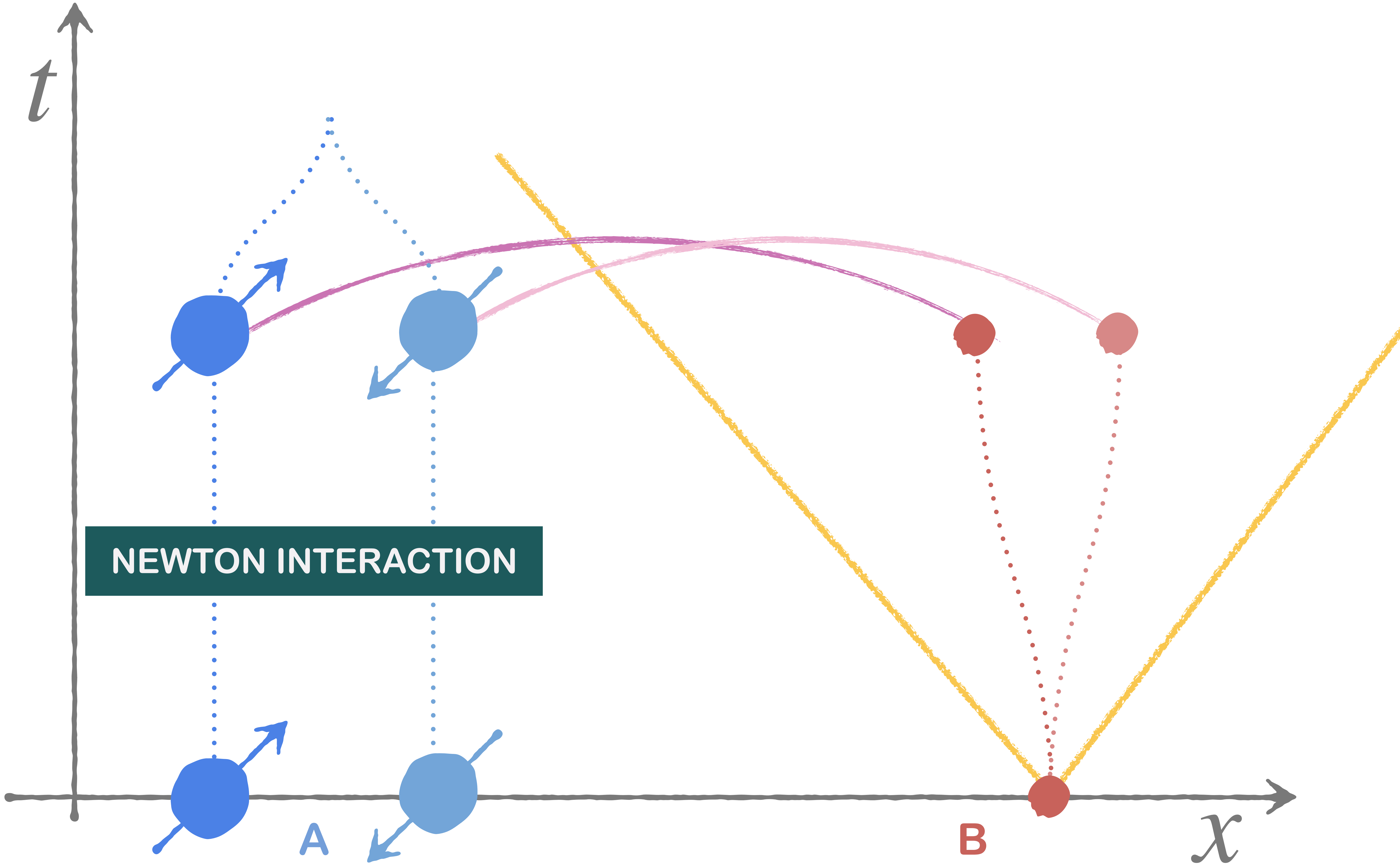
TAKE-HOME MESSAGE



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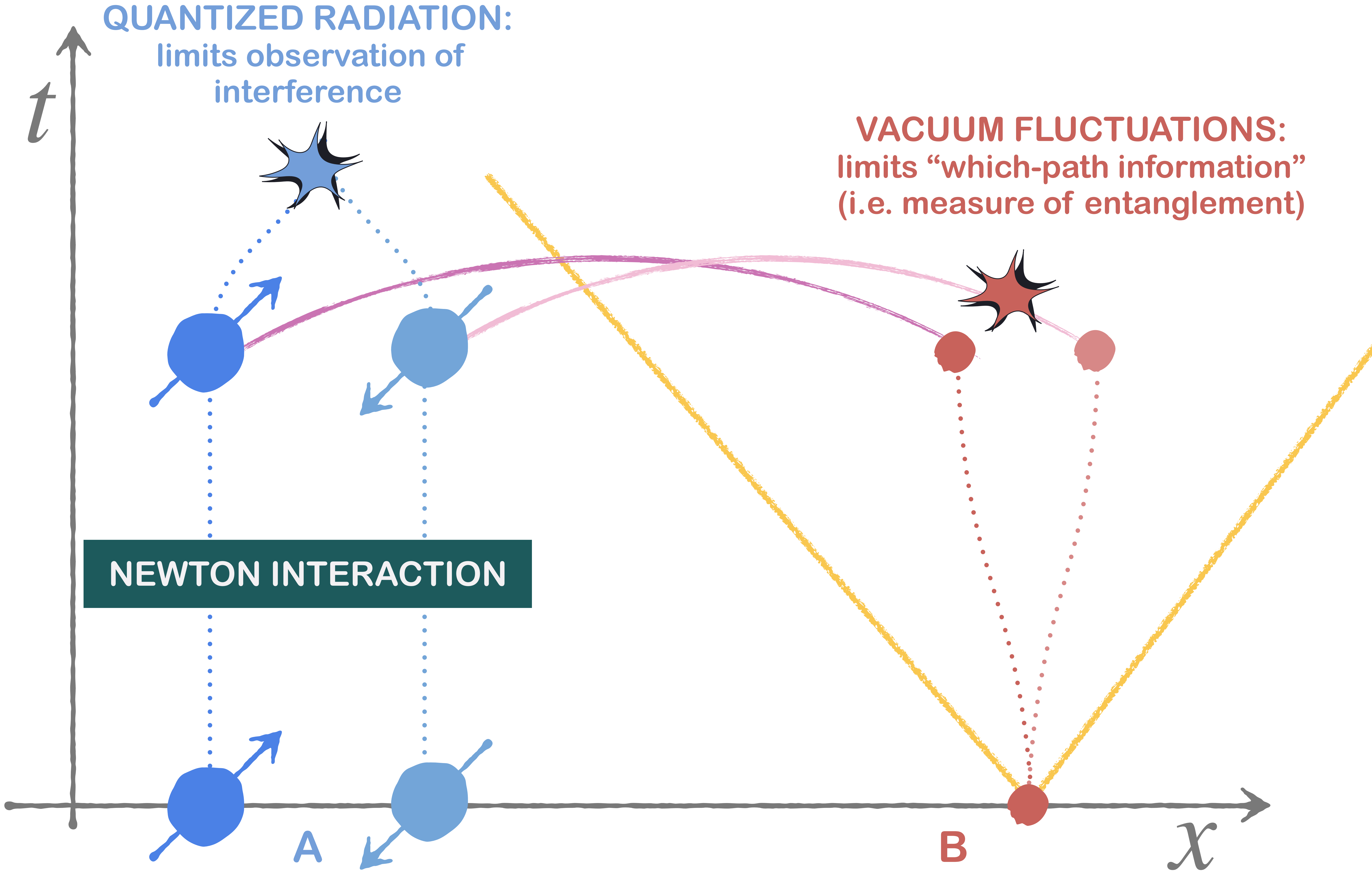
TAKE-HOME MESSAGE

Quantum properties of the gravitational field

QUANTIZED RADIATION
VACUUM FLUCTUATIONS

are essential to obtain a consistent description of the experiment



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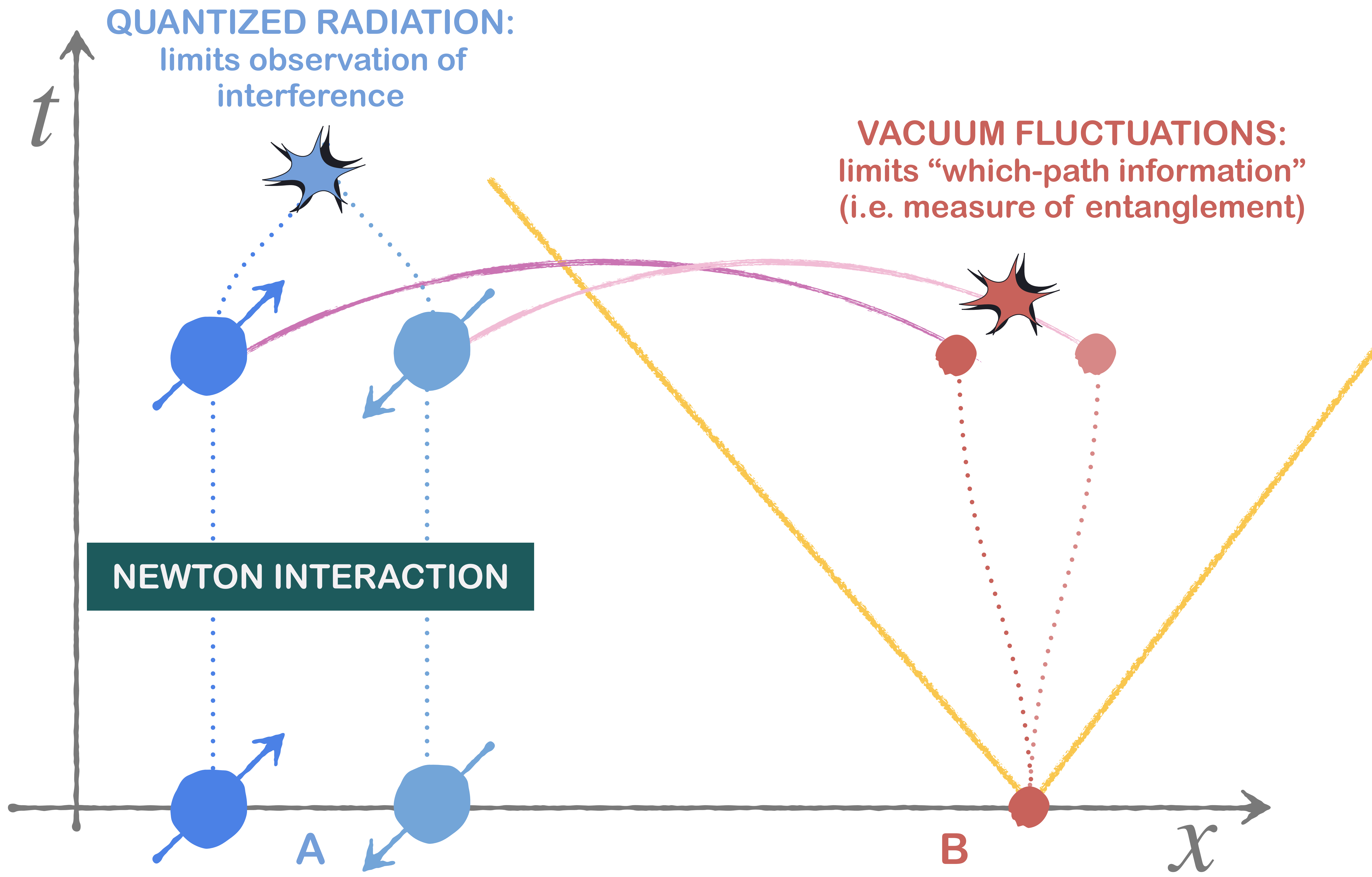
ARGUMENT:
Newtonian potential has a quantum information content



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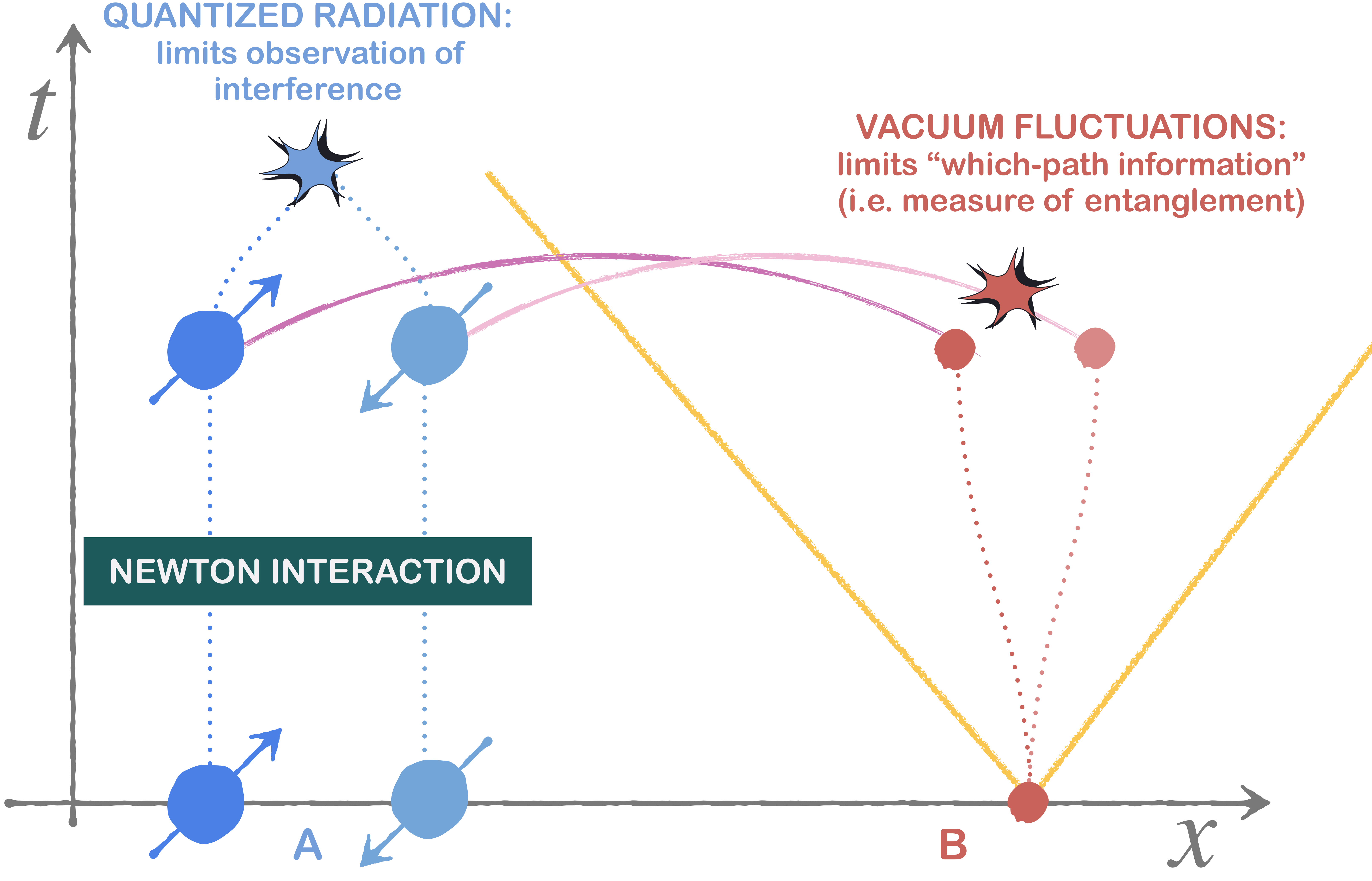
If instead we want to keep a classical description of gravity, we need to drastically modify our basic principles.

See also Danielson, Satishchandran, Wald PRD (2022)



IMPLICATIONS OF ENTANGLEMENT VIA THE NEWTON POTENTIAL

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EMBEDDING INTO GR

GENERAL RELATIVITY + QUANTUM MECHANICS

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EMBEDDING INTO GR

GENERAL RELATIVITY + QUANTUM MECHANICS

1. Classical GR + QM does not generate entanglement ✓

THEORY-INDEPENDENT NO-GO THEOREM

Galley, F.G., Selby Quantum (2022)

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limit to

EXPERIMENT

NEWTON POTENTIAL + QUANTUM MECHANICS

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Newton potential is compatible with the weak-field, non relativistic limit of GR ✗

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EMBEDDING INTO GR

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NEW RESULT: MORE GENERAL EFFECT THAN NEWTON POTENTIAL IN TABLE-TOP EXPERIMENTS ✓

Chen, **F.G.**, 2402.10288 (2024)

THE INTUITIVE IDEA: GENERAL QUANTUM STATES OF THE SOURCE

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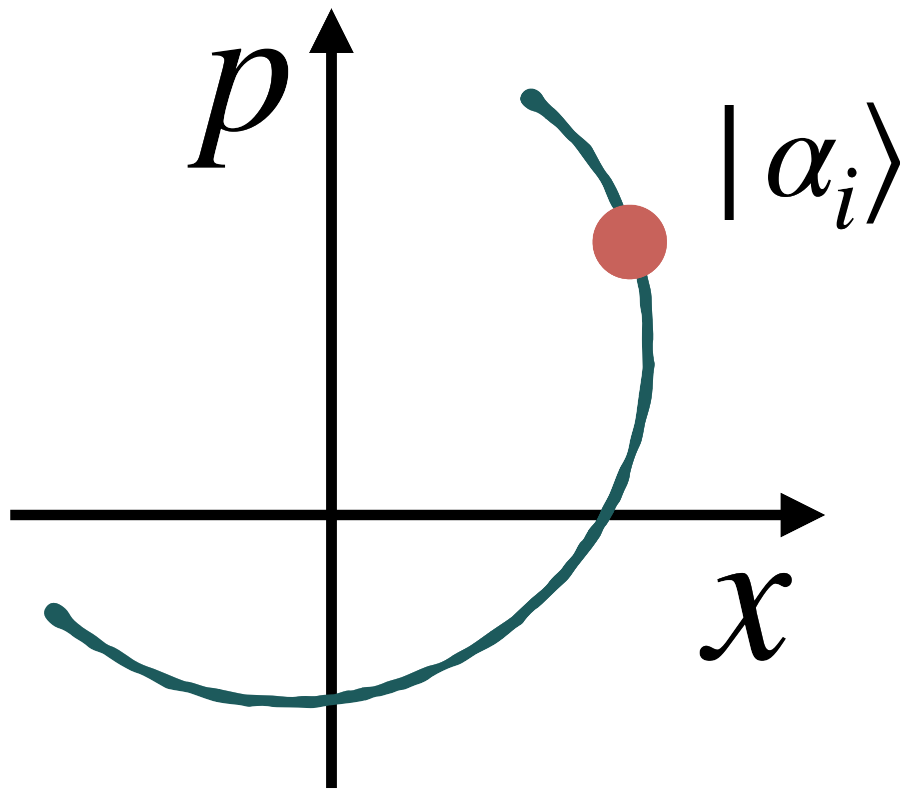
SUPERPOSITION OF LOCALISED GAUSSIANS

$$\frac{1}{\sqrt{2}}\left(|\alpha_1\rangle + |\alpha_2\rangle\right)$$



Arbitrary localisation
in x and p

SUPERPOSITION OF LOCALISED GAUSSIANS

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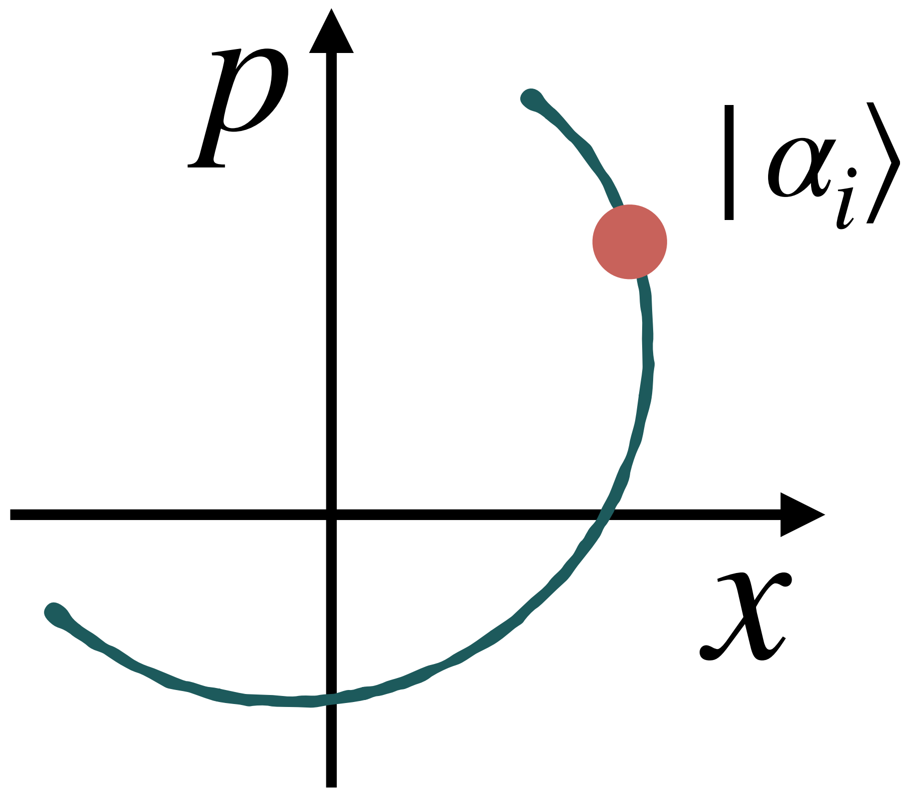

Arbitrary localisation
in x and p

Effectively a classical source

THE INTUITIVE IDEA: GENERAL QUANTUM STATES OF THE SOURCE

SUPERPOSITION OF LOCALISED GAUSSIANS

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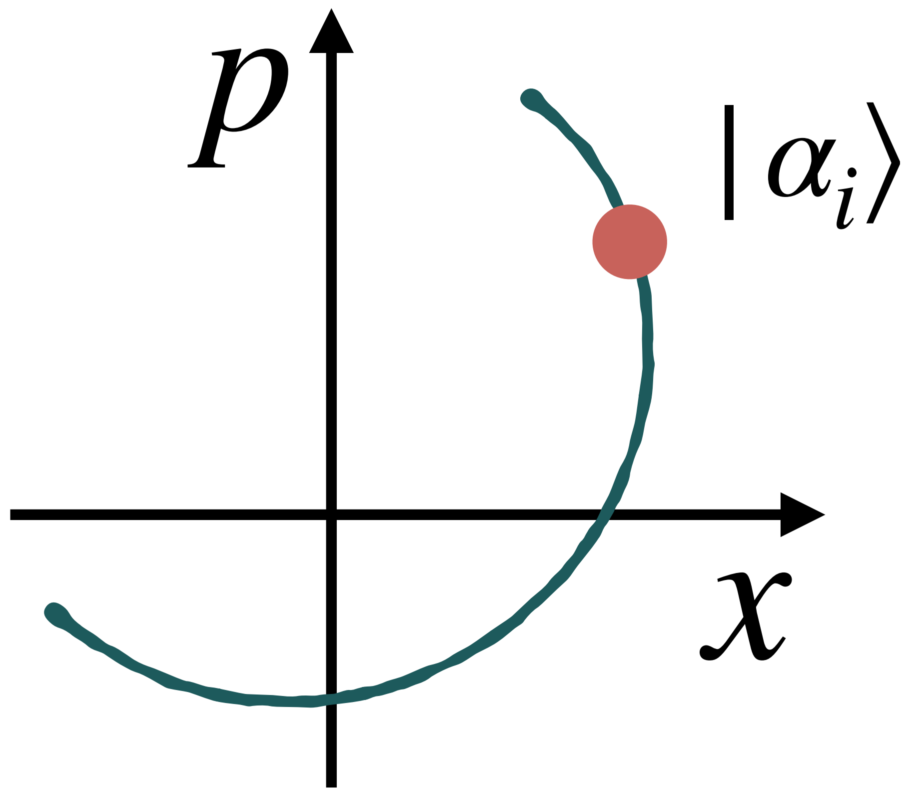

Arbitrary localisation
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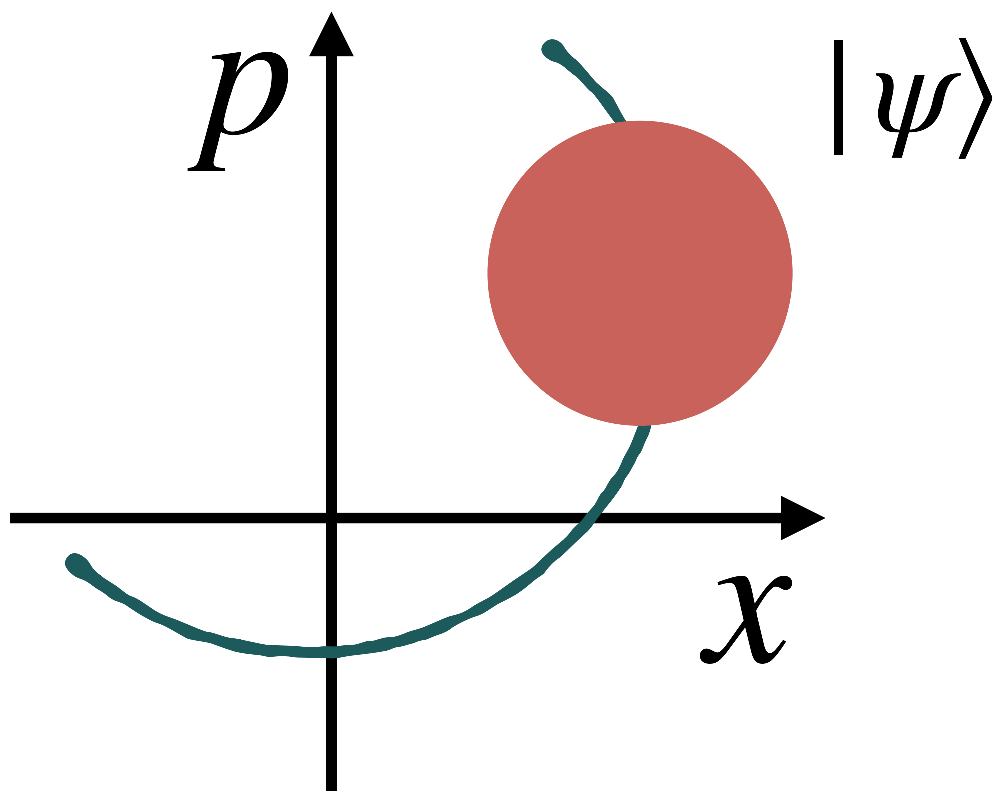
Effectively a classical source

GENERAL QUANTUM STATE



Delocalisation can be measured

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

THE INTUITIVE IDEA: GENERAL QUANTUM STATES OF THE SOURCE

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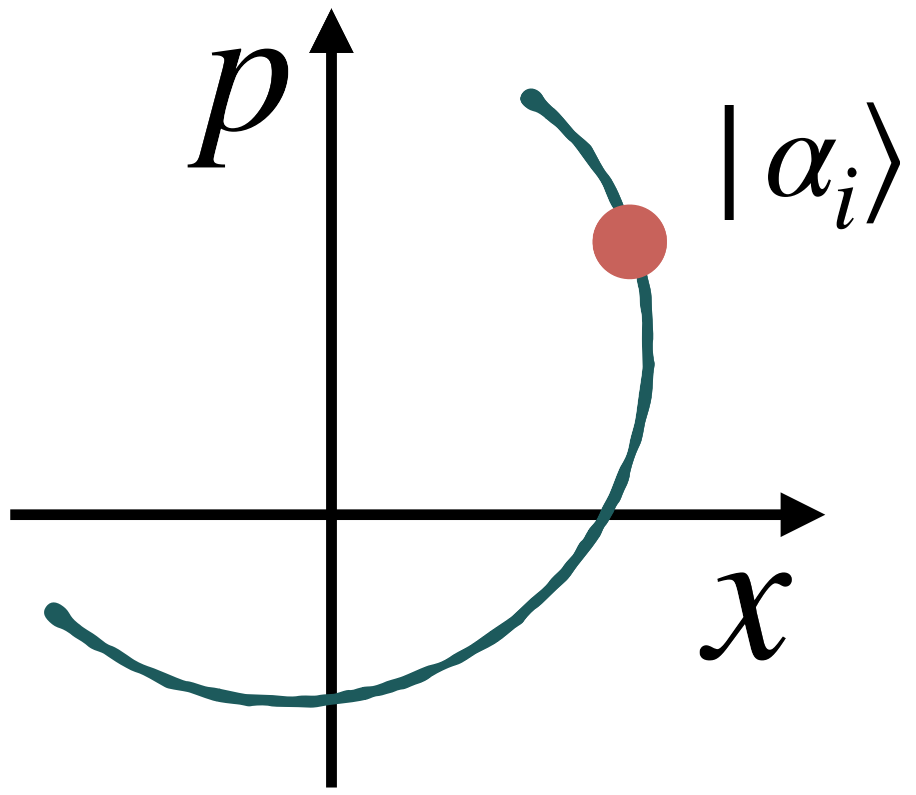
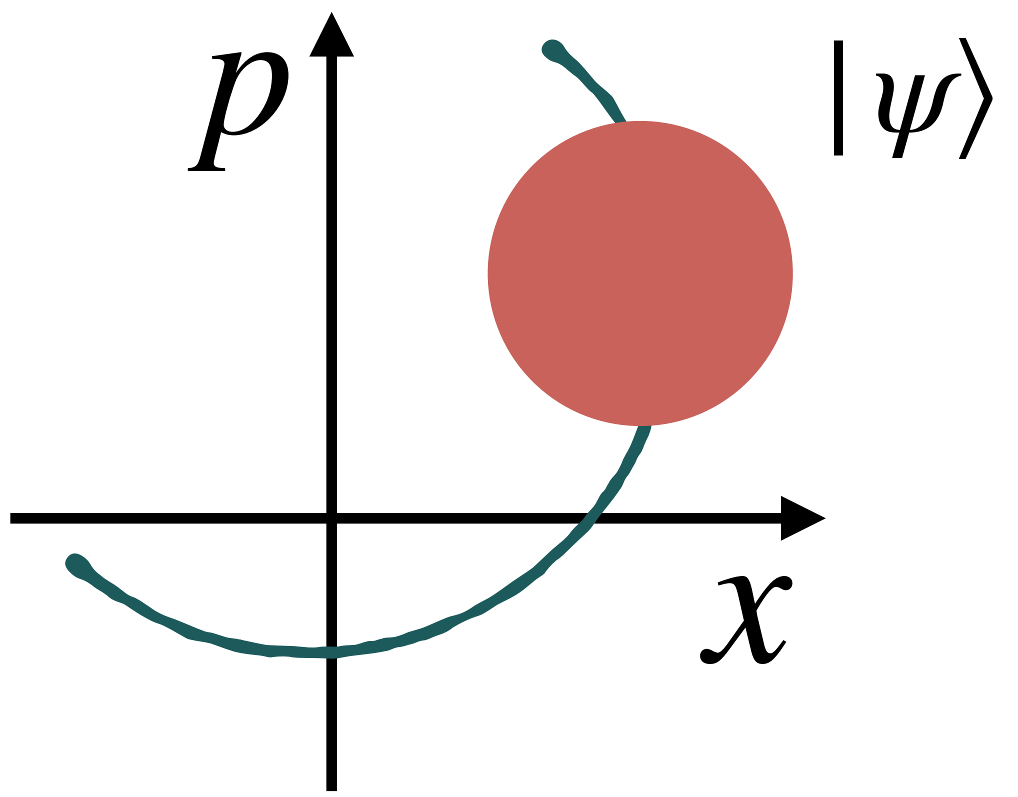


Arbitrary localisation
in x and p

Effectively a classical source

⇒

GENERAL QUANTUM STATE



Delocalisation can be
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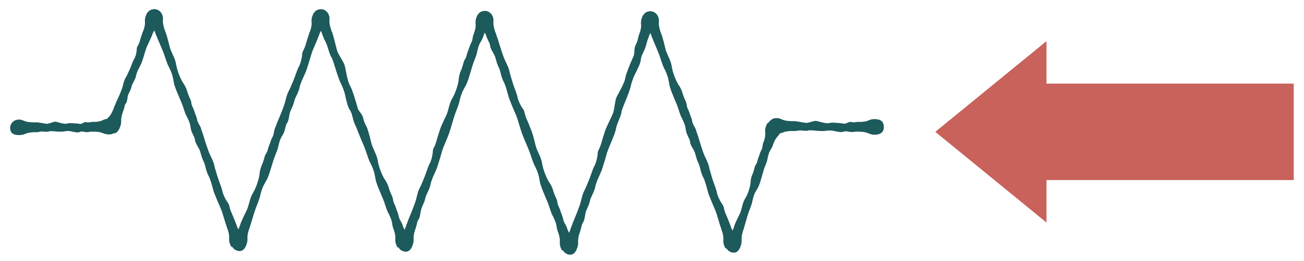
Not a classical source!

Chen, Giacomini, Rovelli Quantum (2023)



$\vec{F}_i$

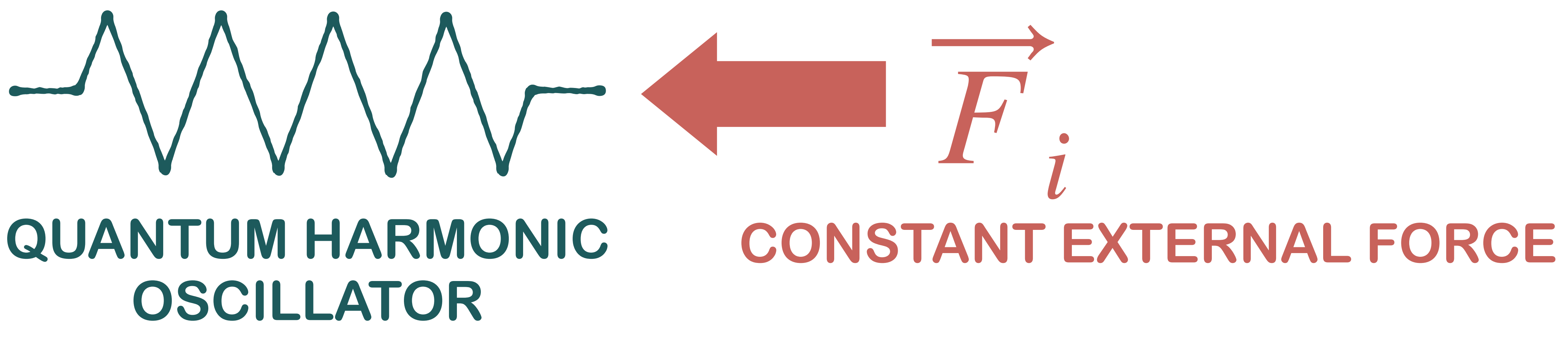
QUANTUM HARMONIC OSCILLATOR

CONSTANT EXTERNAL FORCE

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{m\omega^2}{2}\hat{x}^2 - m\gamma\hat{x}$$

METHODOLOGY: ANALOGY WITH THE HARMONIC OSCILLATOR

Chen, Giacomini, Rovelli Quantum (2023)



$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{m\omega^2}{2}\hat{x}^2 - m\gamma\hat{x}$$

Particular solution of classical EoM

$$x_\gamma = \frac{\gamma}{\omega^2}$$

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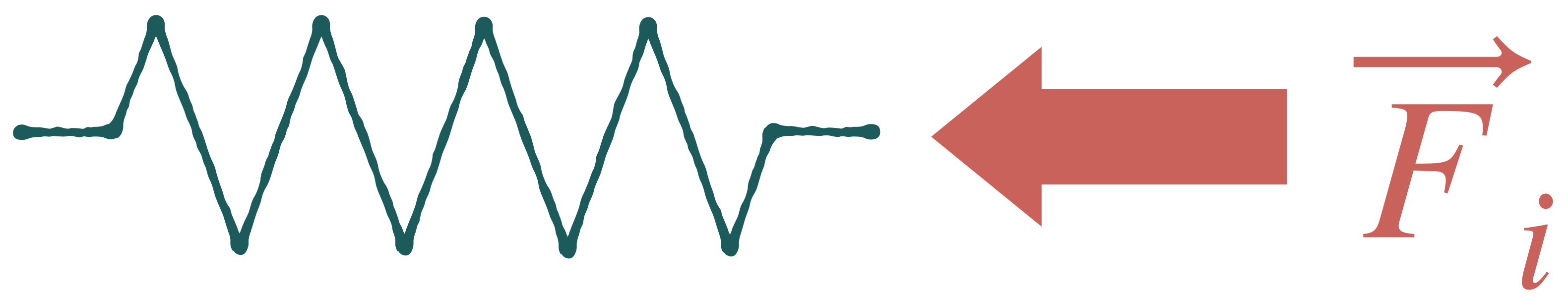
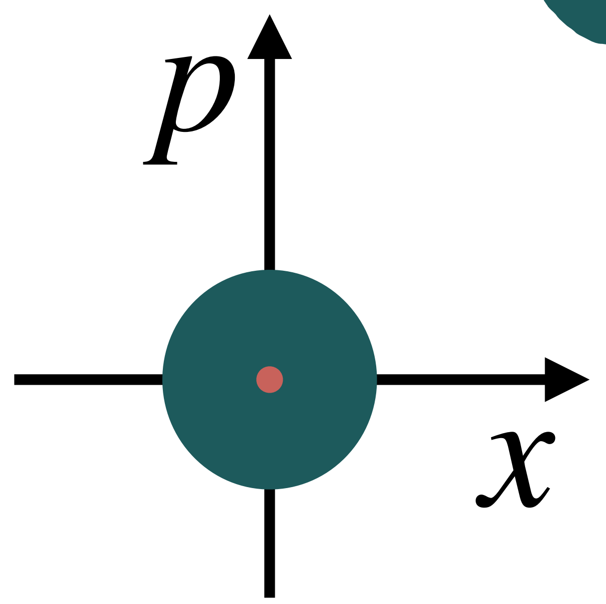


NO FORCE



GROUND STATE:
coherent state

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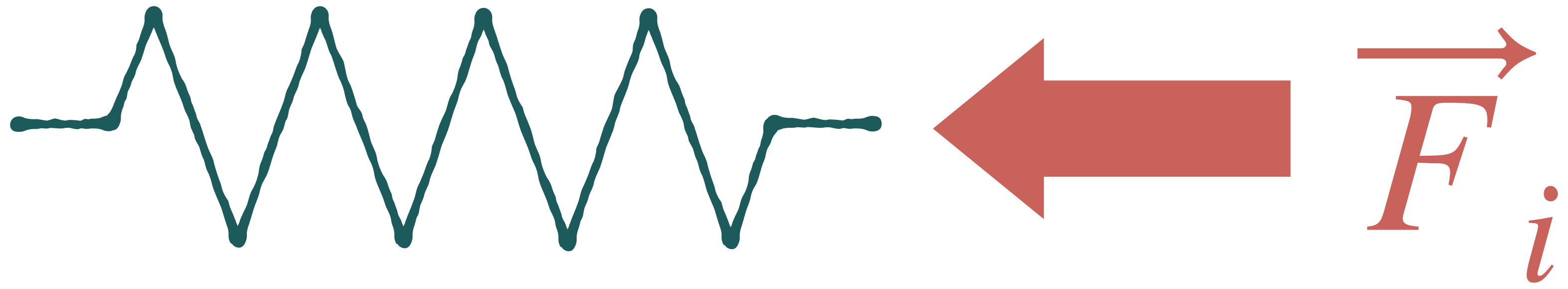
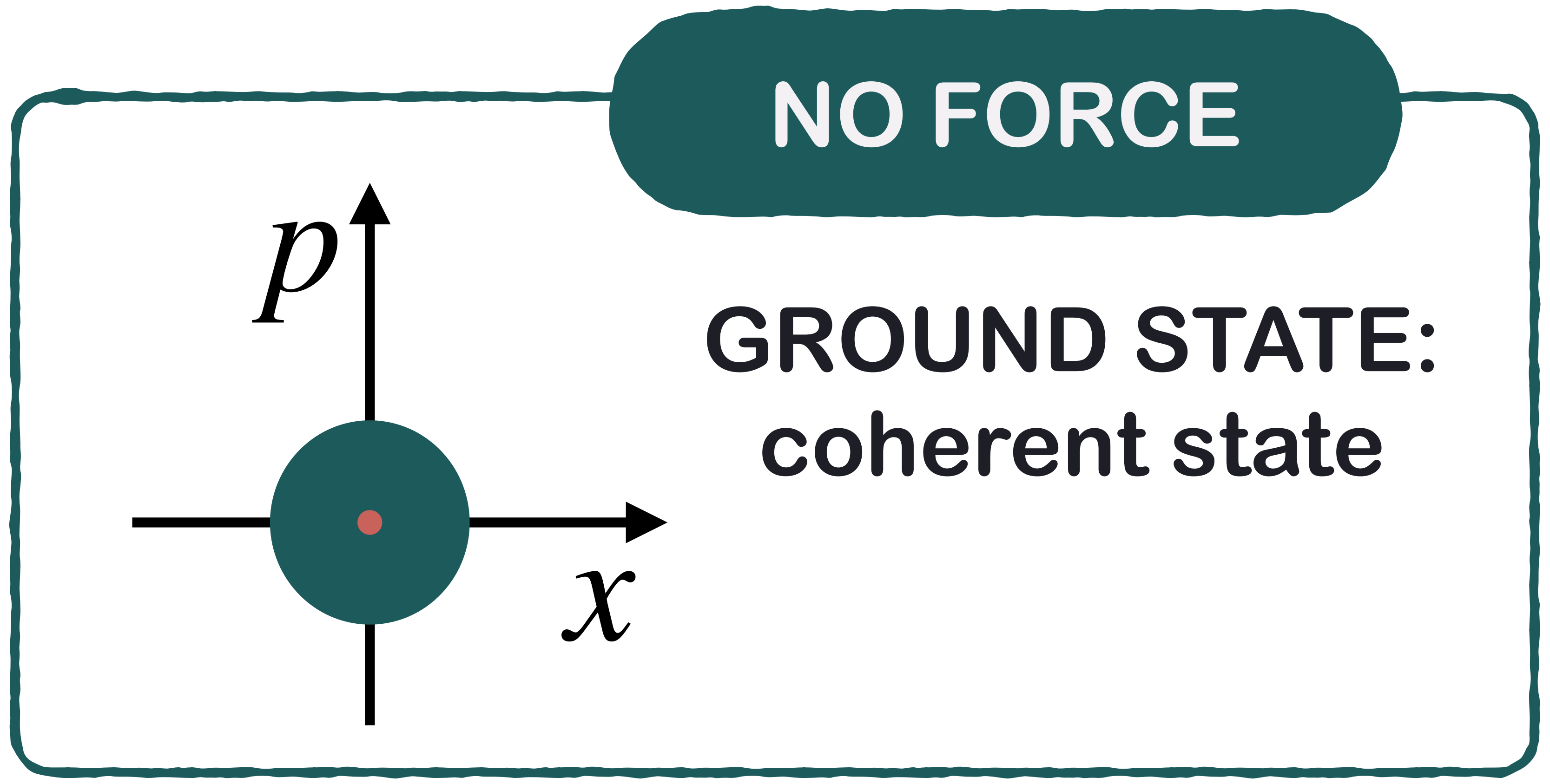


QUANTUM HARMONIC OSCILLATOR

CONSTANT EXTERNAL FORCE



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Particular solution of classical EoM

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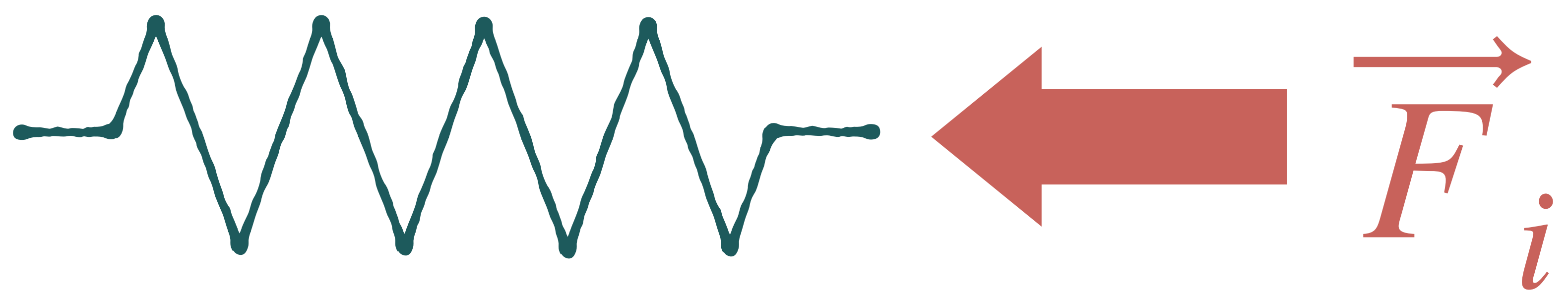
Change of coordinates $\hat{x}' = \hat{x} - x_\gamma$

$$\hat{H}' = \frac{\hat{p}'^2}{2m} + \frac{m\omega^2}{2}\hat{x}'^2 - \frac{m\gamma^2}{2\omega^2}$$

METHODOLOGY: ANALOGY WITH THE HARMONIC OSCILLATOR

Chen, Giacomini, Rovelli Quantum (2023)



QUANTUM HARMONIC OSCILLATOR

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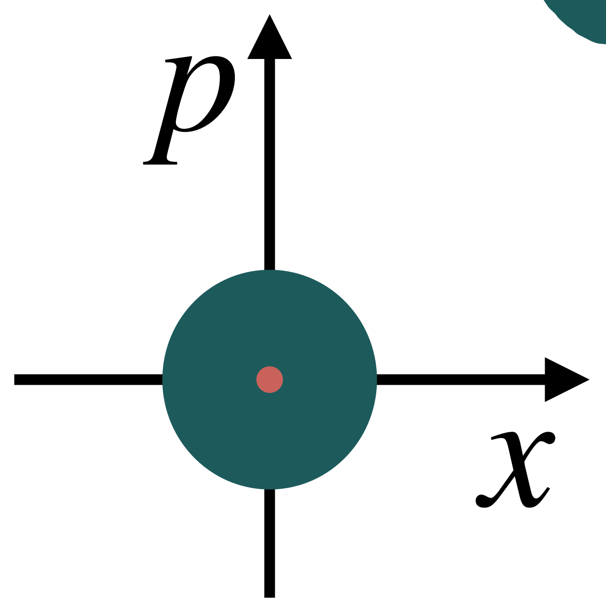
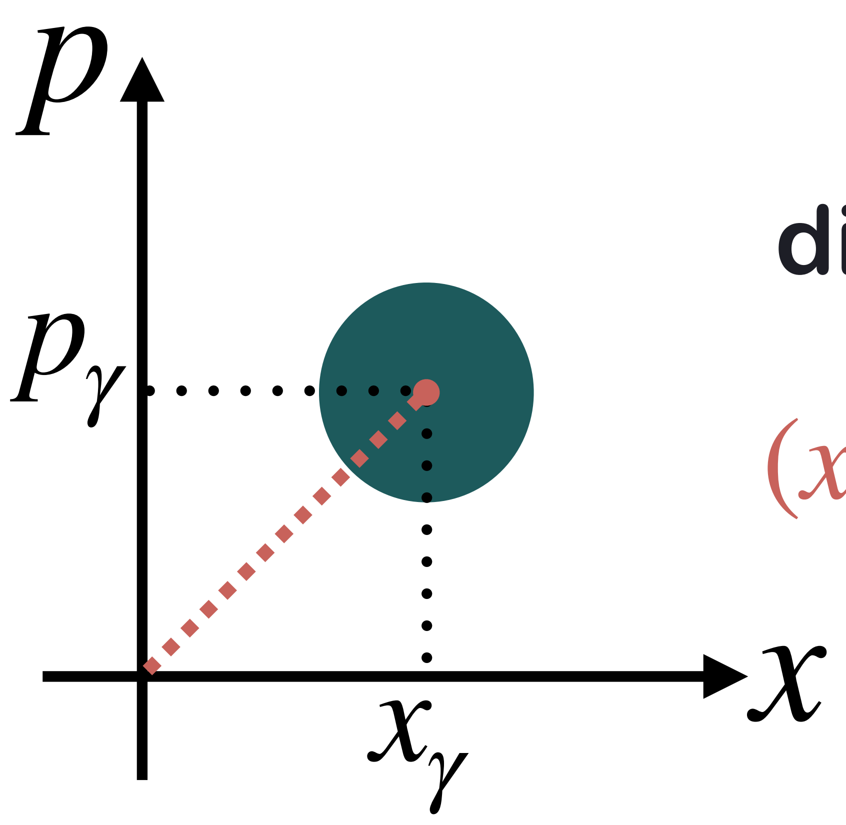


GROUND STATE: coherent state

WITH FORCE

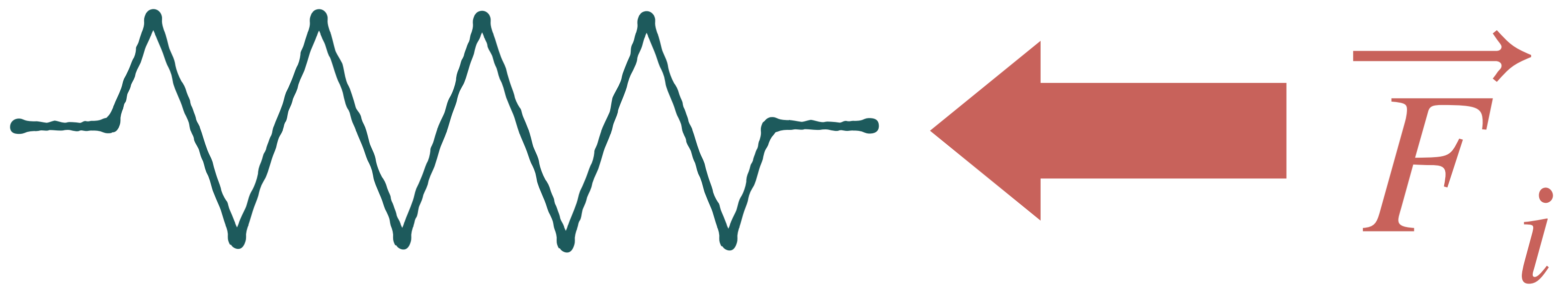


GROUND STATE: coherent state displaced due to the classical force

$(x_\gamma, p_\gamma = 0)$: solution of the classical Newton's equation with $\vec{F}_i$

METHODOLOGY: ANALOGY WITH THE HARMONIC OSCILLATOR

Chen, Giacomini, Rovelli Quantum (2023)



QUANTUM HARMONIC OSCILLATOR

(gravity)

CONSTANT EXTERNAL FORCE

eigenvalue of $T_{00}(x - x_i)$

$$\hat{x} \to \hat{h}_{ij}; \quad \hat{p} \to \hat{\pi}_{ij}$$

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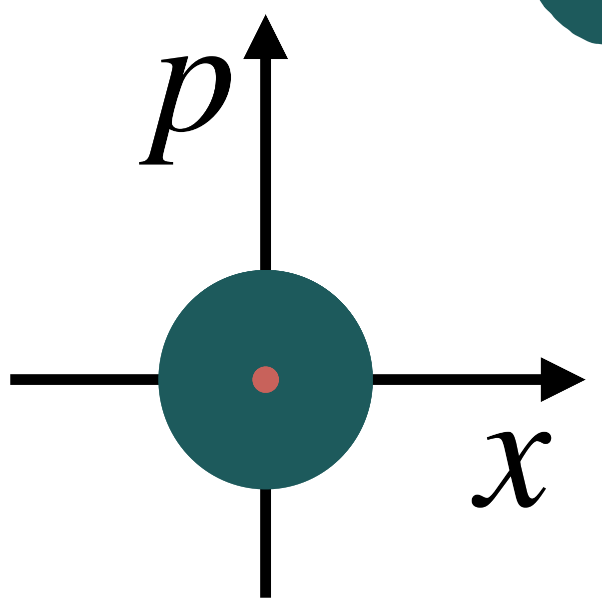

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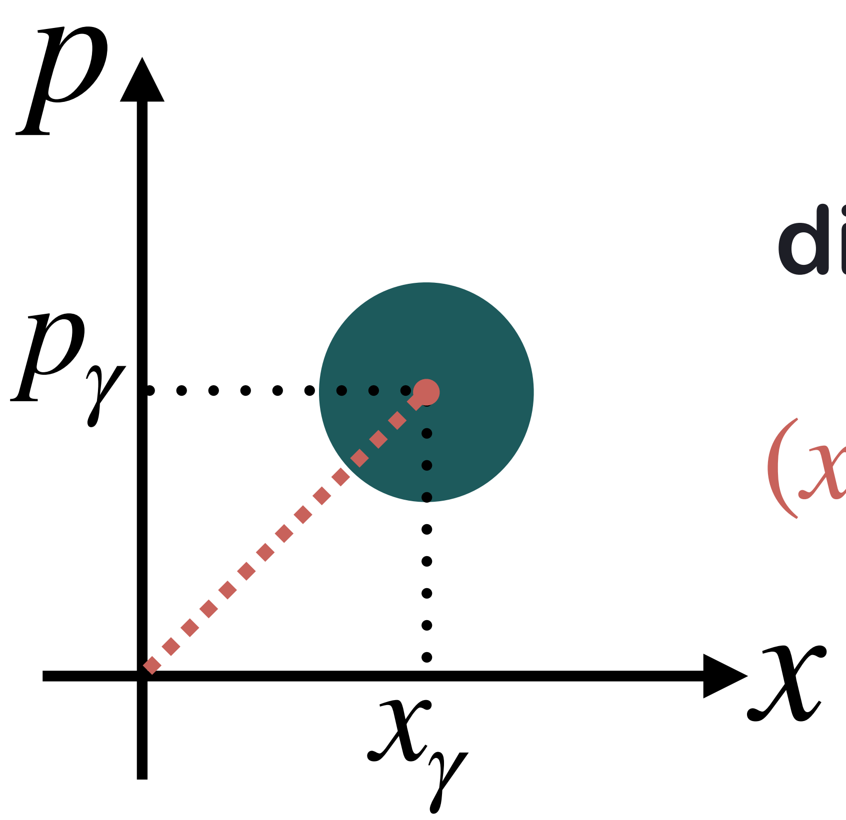

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METHODOLOGY - GRAVITY AS A (PERTURBATIVE) QUANTUM FIELD

Chen, **F.G.**, 2402.10288 (2024)

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Chen, **F.G.**, 2402.10288 (2024)

linearized quantum gravity

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

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

METHODOLOGY - GRAVITY AS A (PERTURBATIVE) QUANTUM FIELD

Chen, F.G., 2402.10288 (2024)

$$\hat{H}_G(\hat{h}_{ij}, \hat{\pi}_{ij}) \,|\, \Psi\rangle_{G+S} = E_0(x) \,|\, \Psi\rangle_{G+S}$$

(ground state)

Free gravity Hamiltonian

linearized quantum gravity

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

$$[\partial_i \partial^i \hat{h}^T(x) + \hat{T}_{00}(x)] \,|\, \Psi \rangle_{G+S} = 0$$

Scalar constraint: Gauss law

$$\partial_j \hat{\pi}^{ij}(x) \,|\, \Psi \rangle_{G+S} = 0$$

GAUGE

Vector constraint: transversality condition

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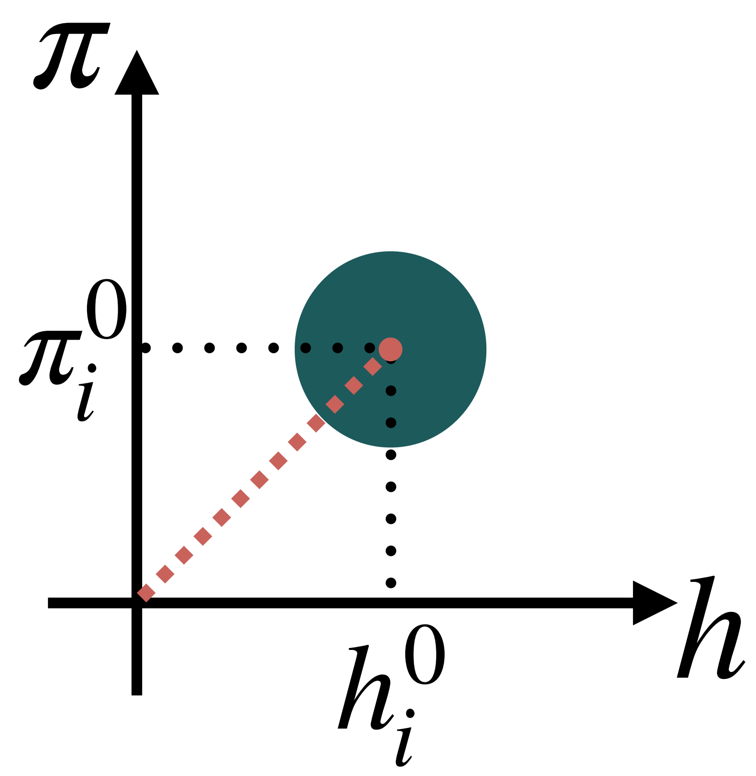

GROUND STATE: coherent state displaced by the eigenvalue solution

- **Localised source: Newton potential**
- **Delocalised source: general function**

THE QUANTUM STATE OF GRAVITY OF A GENERAL QUANTUM SOURCE

Chen, Giacomini, 2402.10288 (2024)

Interaction Hamiltonian

$$\hat{H}_I = -\frac{1}{2}\int d^3x \hat{h}_{\mu\nu}(\vec{x})[\hat{T}^{\mu\nu}_A(\vec{x}) + \hat{T}^{\mu\nu}_B(\vec{x})]$$

… zero in the temporal gauge ($h^{0\mu} = 0$)!

Constraint changes the gravitational energy

$$\hat{C} = \partial_i \partial^i \hat{h}^T(x) + \hat{T}^A_{00}(x) + \hat{T}^B_{00}(x)$$

Chen, Giacomini, 2402.10288 (2024)

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Entangling phase:

$$\Delta\phi = -\frac{G}{c^4\hbar}\int d^3x d^3y \frac{E_A(\vec{x})E_B(\vec{y})}{|\vec{x}-\vec{y}|}$$

Chen, Giacomini, 2402.10288 (2024)

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depend on the matter distribution

COMPARISON TO CLASSICAL GRAVITY

Chen, Giacomini, 2402.10288 (2024)

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COMPARISON TO CLASSICAL GRAVITY

Chen, Giacomini, 2402.10288 (2024)

$$\Delta\phi = -\frac{G}{c^4\hbar}\int d^3x d^3y \frac{E_A(\vec{x})E_B(\vec{y})}{|\vec{x}-\vec{y}|}$$

LIMIT TO THE NEWTON POTENTIAL

Quantum state: coherent semiclassical state

$$|\psi\rangle \approx |\alpha(x_i, p_i)\rangle$$

Classical mass density

$$E^Z(\vec{x}) = m_Z c^2 \delta(\vec{x}-\vec{x}_i)$$

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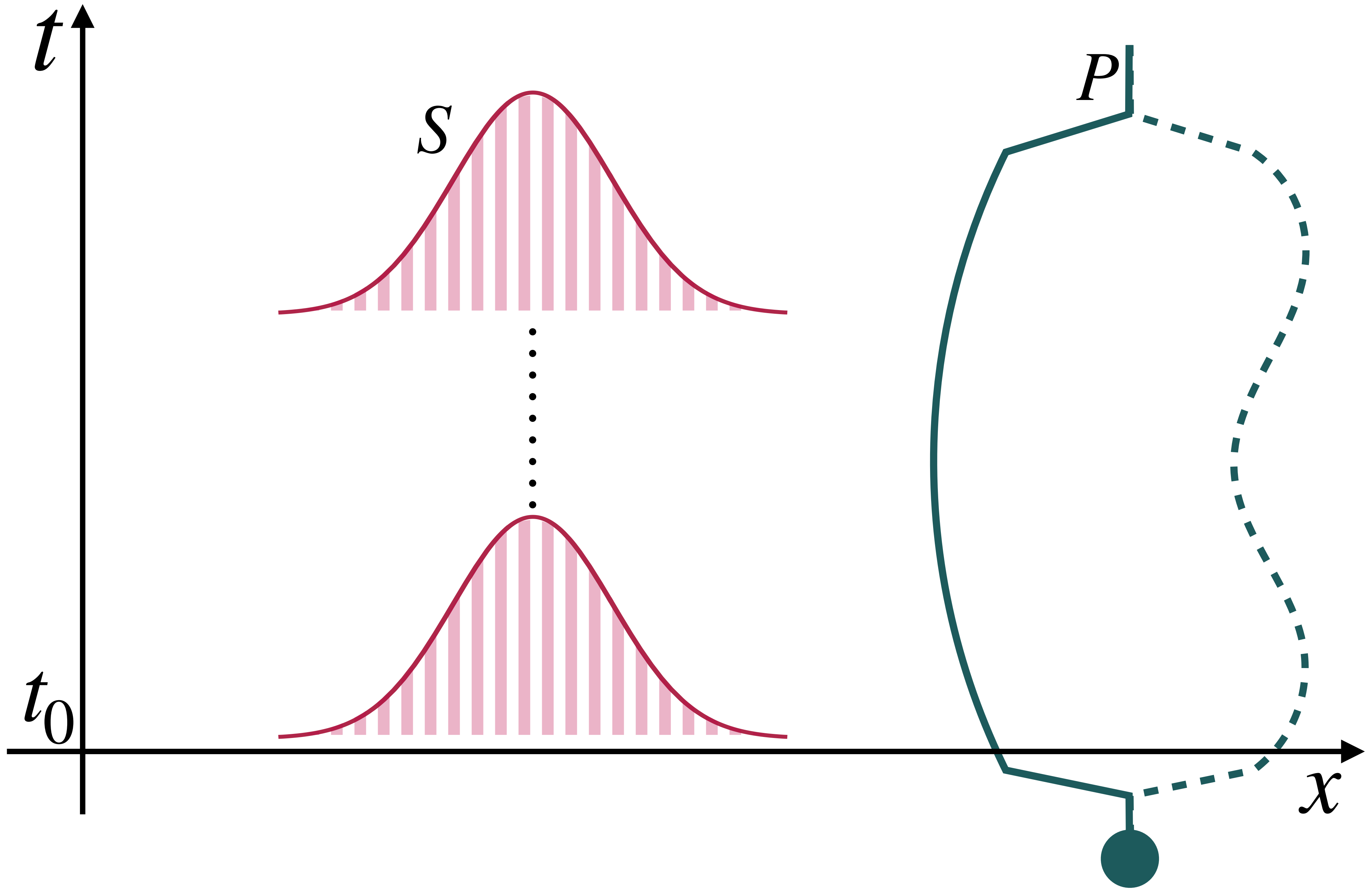
CANNOT BE REPRODUCED WITH:

1. Newton potential
2. Schrödinger-Newton equation
3. Classical-quantum coupling (Semiclassical gravity)

QUANTUM COMMUTATOR OF THE GRAVITATIONAL FIELD

Chen, Giacomini, 2402.10288 (2024)



Total Hamiltonian

$$\hat{H}_{tot} = \hat{H}_S + \hat{H}_P + \hat{H}_G + \hat{H}_I$$

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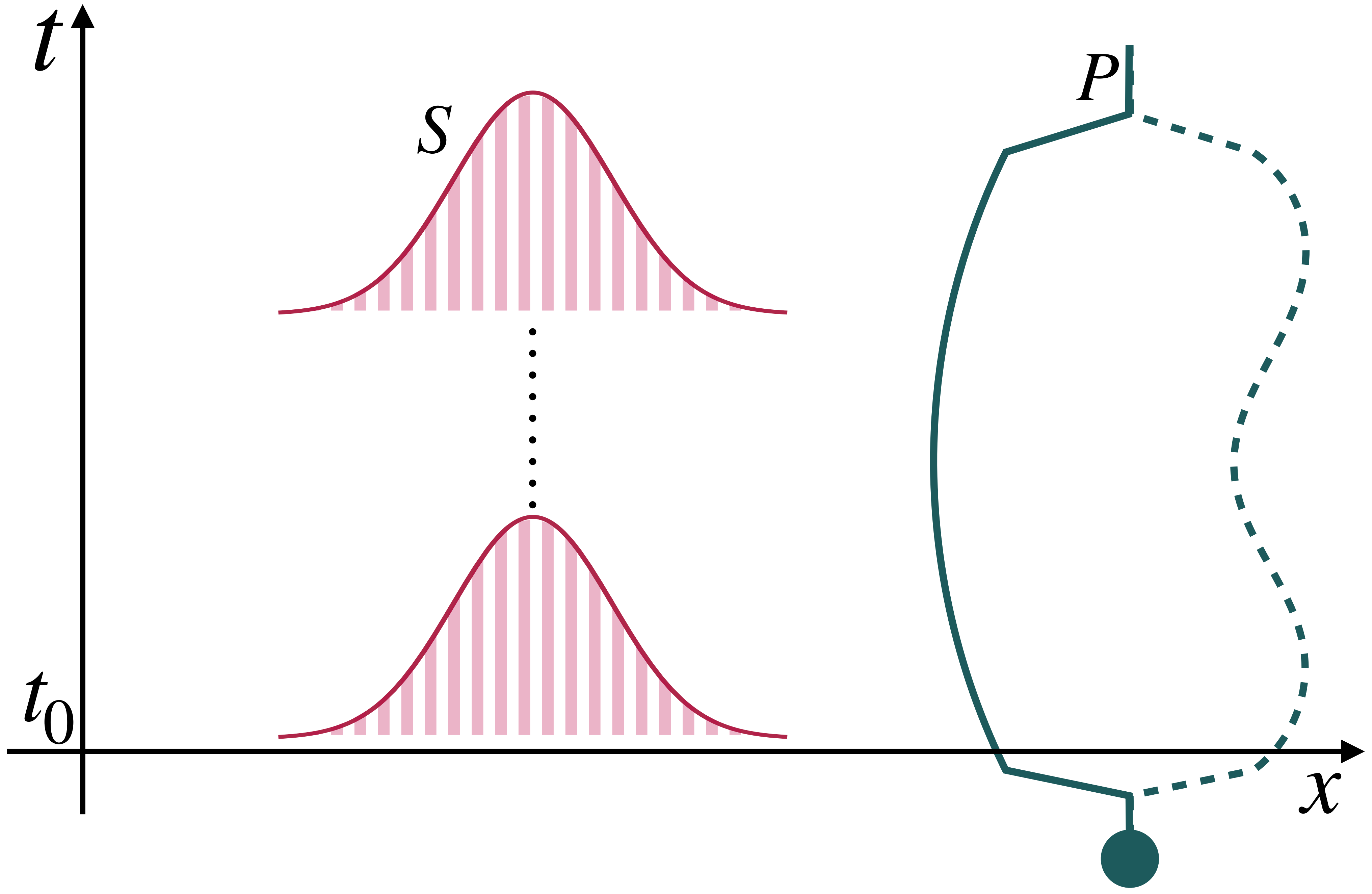

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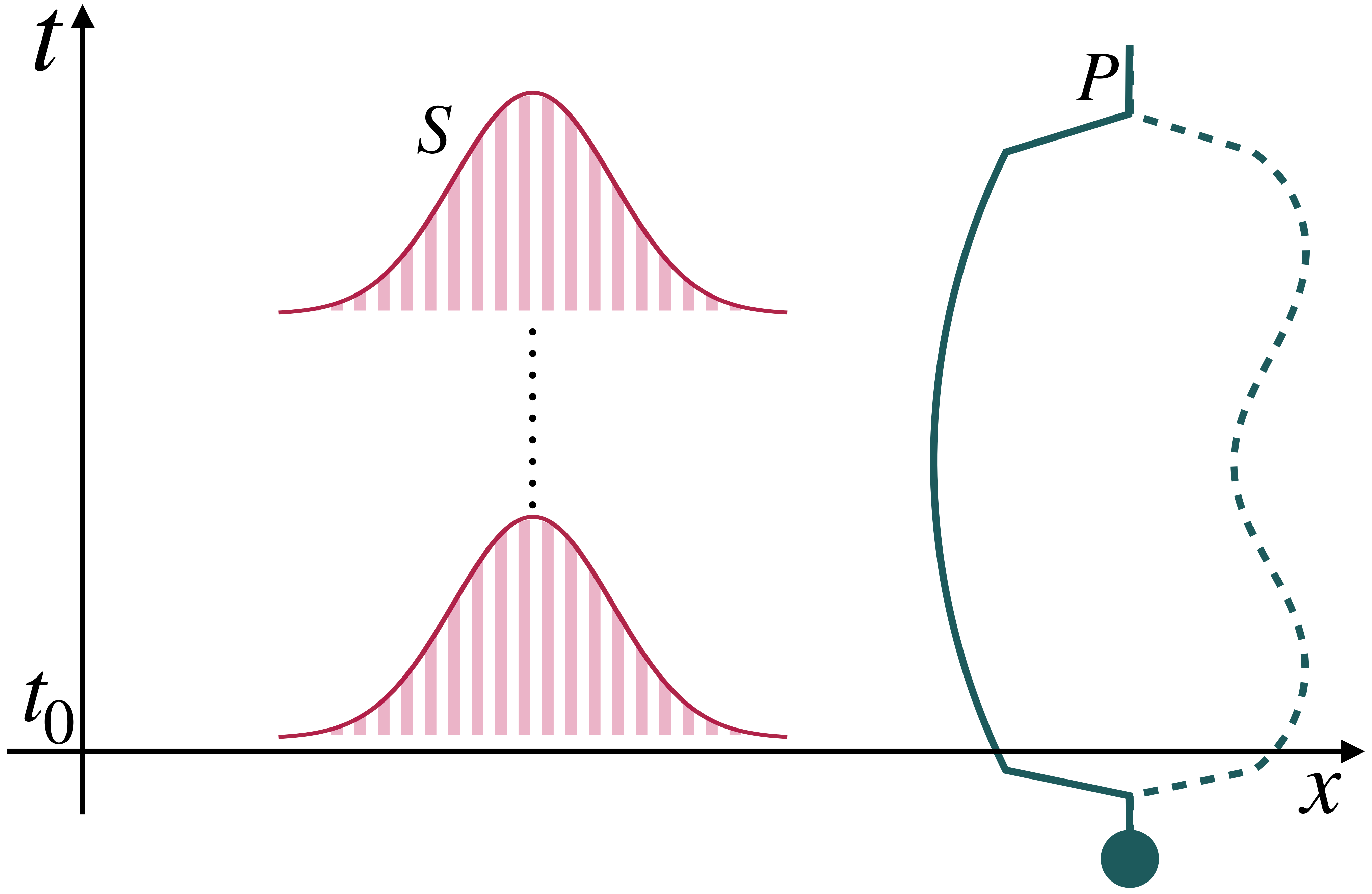

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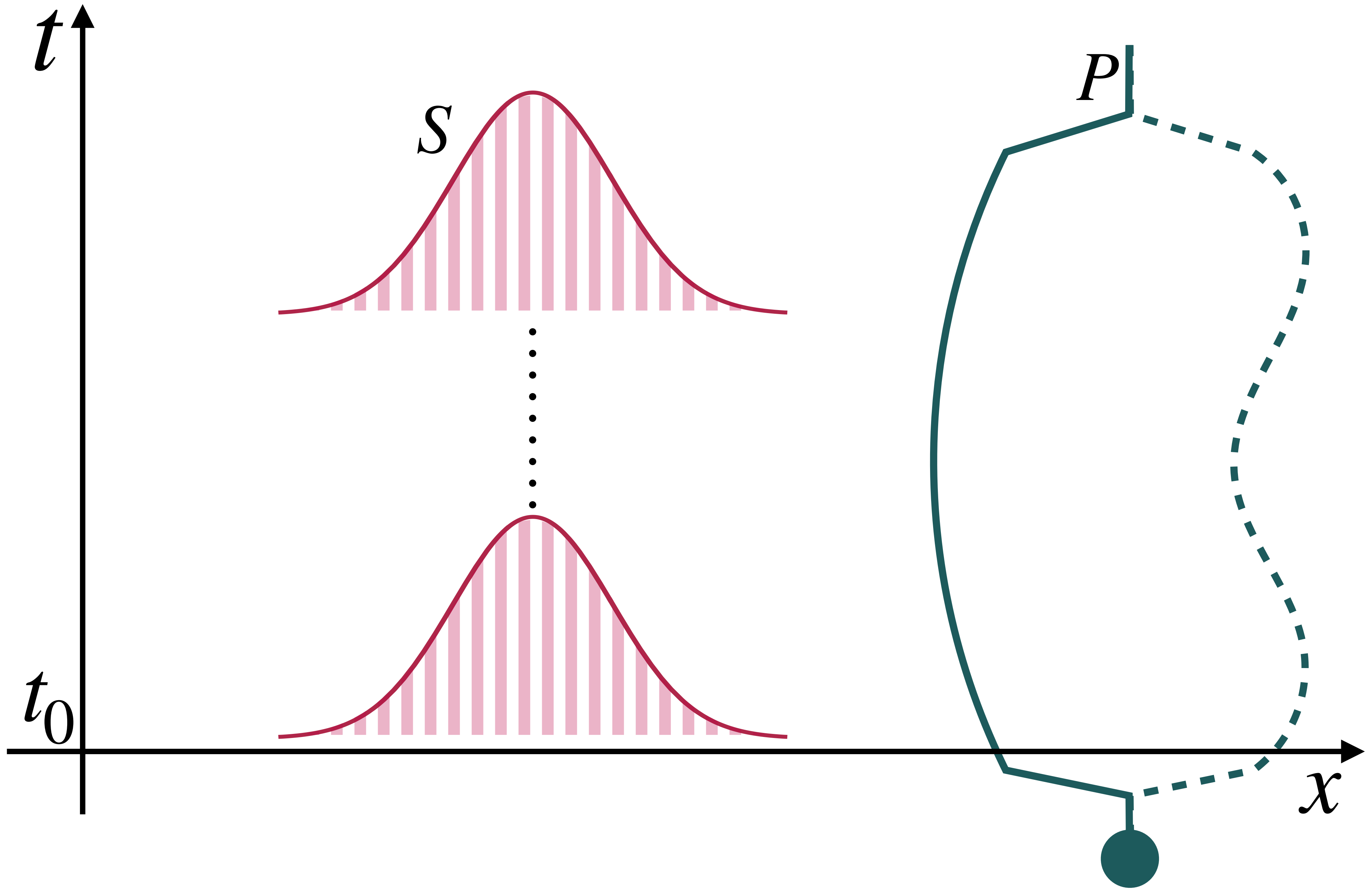

Correction terms to relative phase

$$\Delta\phi \sim \frac{Gt}{c^4\hbar} t^2 [\alpha f_1(T_P^{ij}) + \alpha^2 f_2(T_P^{ij})]$$

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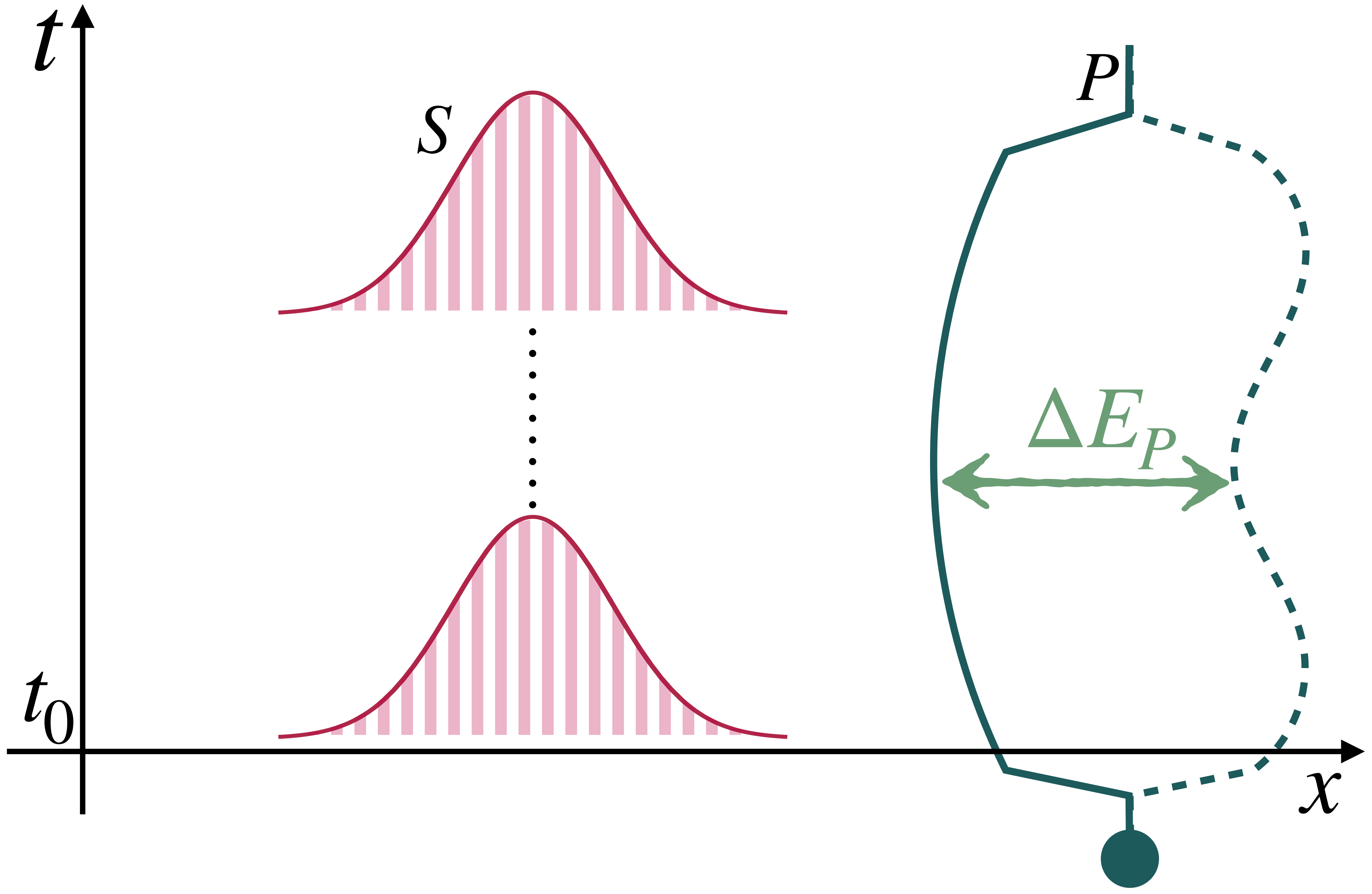

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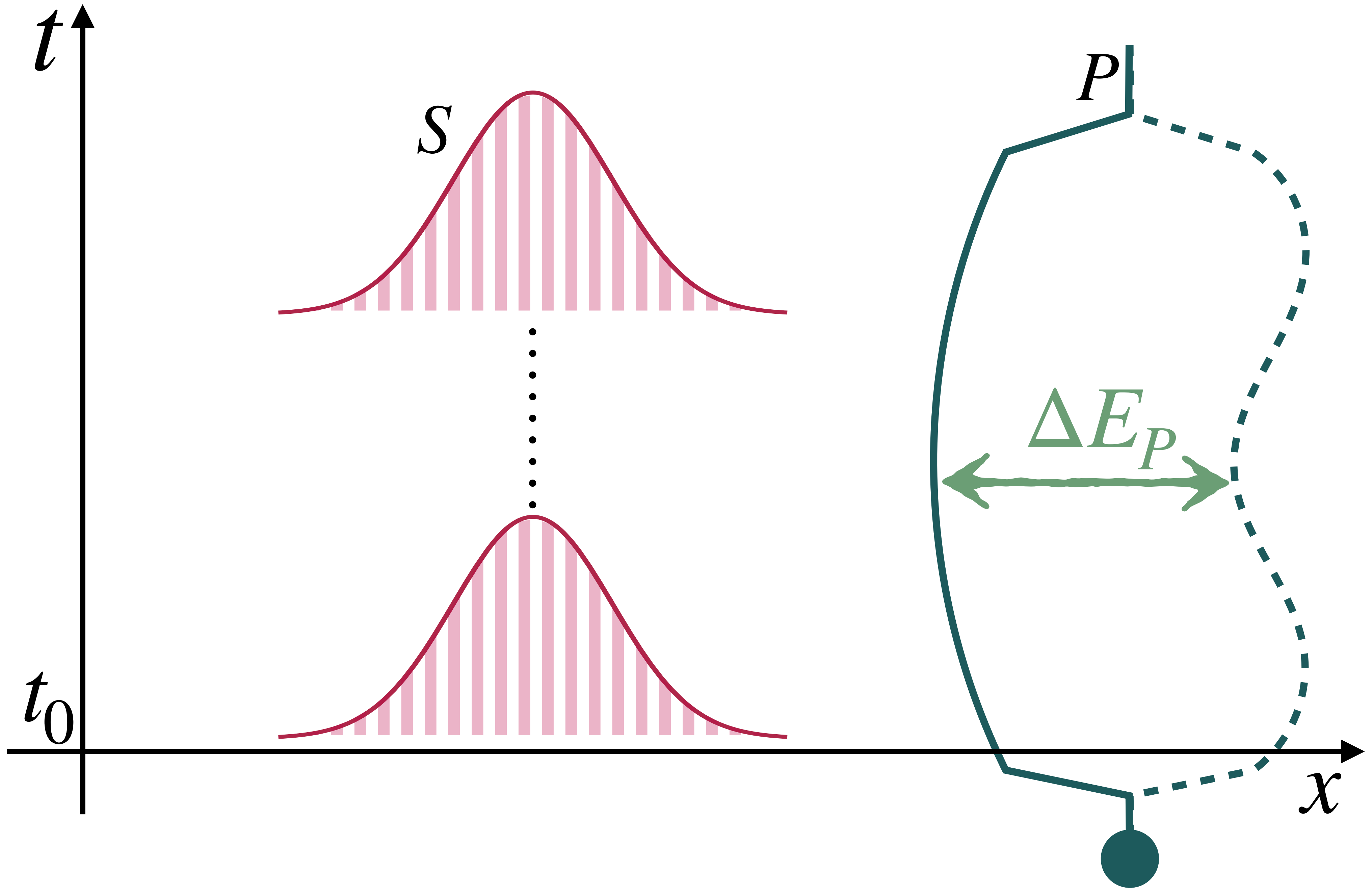

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Stronger indication that gravity is a quantum field

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Gravitationally-induced entanglement via Newton potential

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OPEN QUESTIONS: concrete implementation and estimates

BACK-UP SLIDES

WHAT IS THE QUANTUM STATE OF GRAVITY ASSOCIATED TO A QUANTUM SOURCE?

Chen, Giacomini, Rovelli Quantum (2023)

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

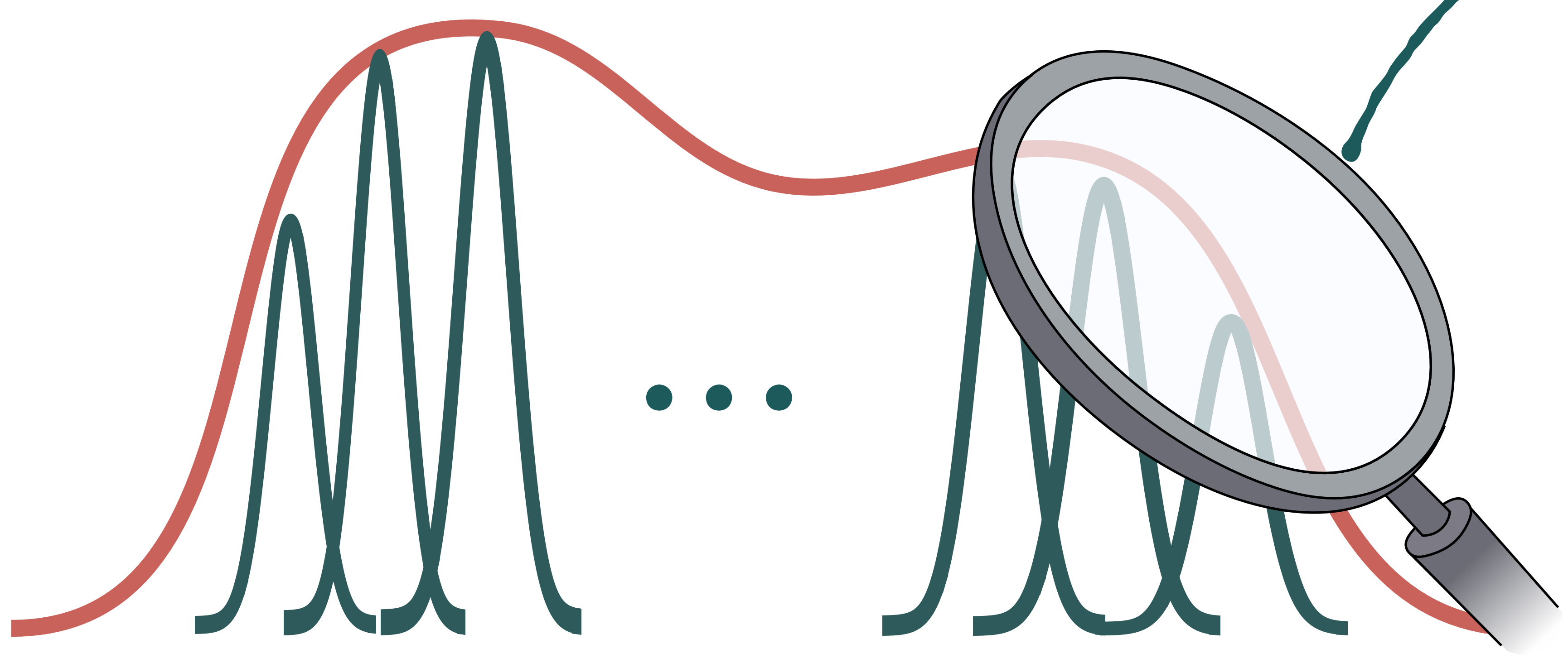
	Electromagnetism	Linearized Gravity
Temporal gauge	$A_0 = 0$	$h_{0\mu} = 0$
Canonical variables	$\{A_i(\vec{x}), E_j(\vec{x}')\}$	$\{h_{ij}(\vec{x}), \pi^{kl}(\vec{x}')\}$
No. of constraints	1	4
Similar constraints (without matter)	Gauss law in A basis $\partial_j \frac{\delta}{\delta A_j(\vec{x})}\Psi[A] = 0$	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 $\Delta h^T = -\rho$
Vacuum 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

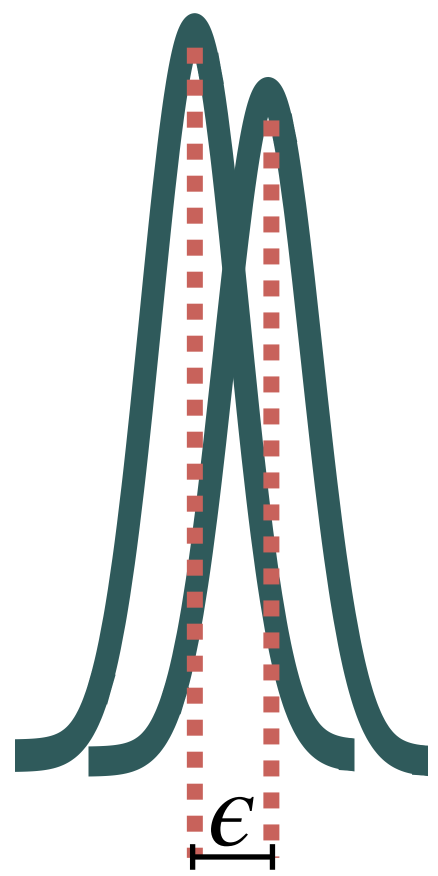
$$|\Psi\rangle_{G+M} = \sum_i \alpha_i |\Phi_i, h_i^0\rangle_{MG}$$

THE QUANTUM STATE OF GRAVITY OF A GENERAL QUANTUM SOURCE

Chen, Giacomini, 2402.10288 (2024)

The first naive attempt...





$$\langle \alpha_x | \alpha_{x+\epsilon} \rangle \neq 0$$

$$\langle \alpha_x, h_\alpha | \alpha_{x+\epsilon}, h_\alpha \rangle = 0$$ ✗

The shift by the classical solution makes the states perfectly distinguishable

$$|\psi\rangle = \int d\mu(\alpha)\, \psi(\alpha)\, |\alpha\rangle$$

$$\langle \Delta x \rangle_\alpha \ll \mathrm{Exp\,.\,resol\,.}$$

$$\langle \Delta p \rangle_\alpha \ll \mathrm{Exp\,.\,resol\,.}$$

...still the Newton potential!

$$|\psi\rangle = \int d\mu(E)\, \psi(E)\, |E\rangle$$

$$\hat{T}_{00}(x)\, |E\rangle = E(\vec{x})\, |E\rangle \qquad E(\vec{x}) \neq mc^2 \delta(\vec{x} - \vec{x}_i)$$

$$\langle \psi, h_\psi | \phi, h_\phi \rangle = \langle \psi | \phi \rangle$$ ✓