QUANTUM REFERENCE FRAMES: A RELATIONAL PERSPECTIVE ON NONCLASSICAL SPACETIME

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ETH Zurich

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A. Vanrietvelde, P. A. Höhn, F. Giacomini, E. Castro Ruiz, Quantum 4(225), 2020

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C. Cepollaro, F. Giacomini, arXiv:2112.03303 (2021)

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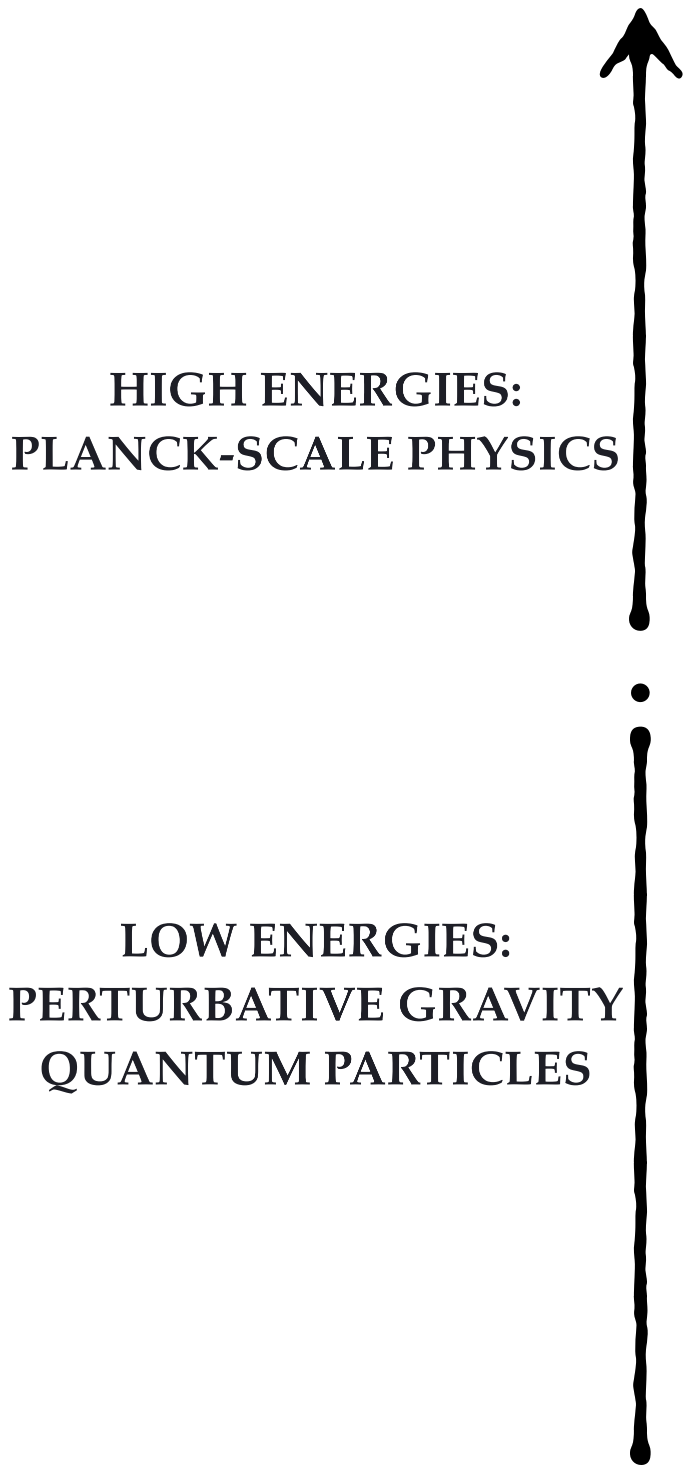
Quantum Gravity, Hydrodynamics and Emergent Cosmology

University of Munich, 9 December 2022

Quantum aspects of spacetime

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



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

HIGH ENERGIES: PLANCK-SCALE PHYSICS

Image credits: Perimeter Institute

QUANTUM SPACETIME "FUZZINESS"

- Spin foams
- Quantum Cosmology
- Modified dispersion relations
- (…)

LOW ENERGIES: PERTURBATIVE GRAVITY QUANTUM PARTICLES

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

HIGH ENERGIES:
PLANCK-SCALE PHYSICS

Image credits: Perimeter Institute

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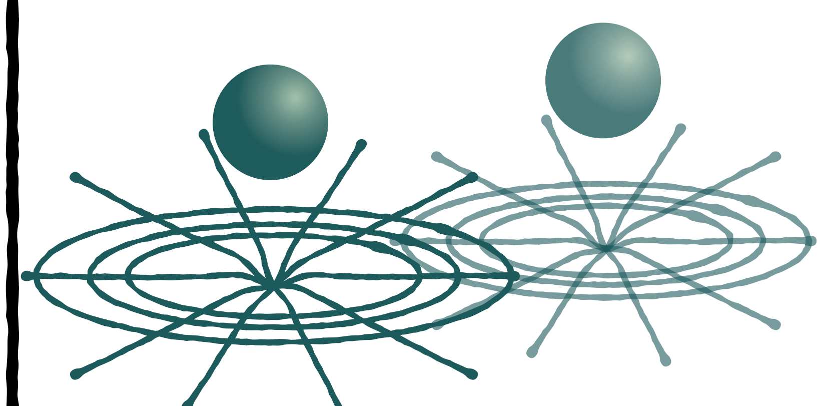
LOW ENERGIES:
PERTURBATIVE GRAVITY
QUANTUM PARTICLES



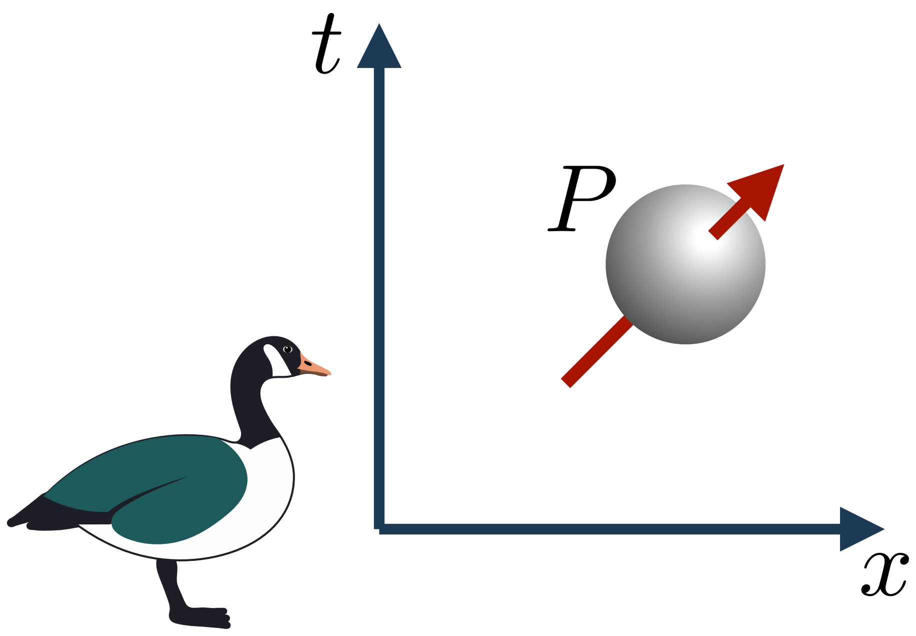
THIS TALK!

NONCLASSICAL SPACETIME

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

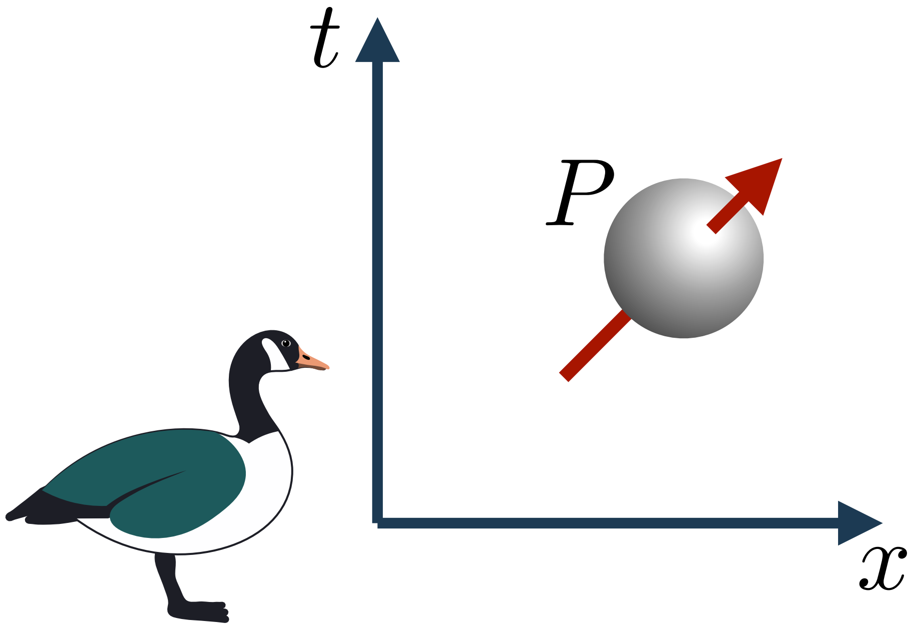
Concrete scenarios with immediate physical meaning

What are reference frames?



What are reference frames?

Reference frames are abstract entities, used to fix the point of view from which observations are carried out.



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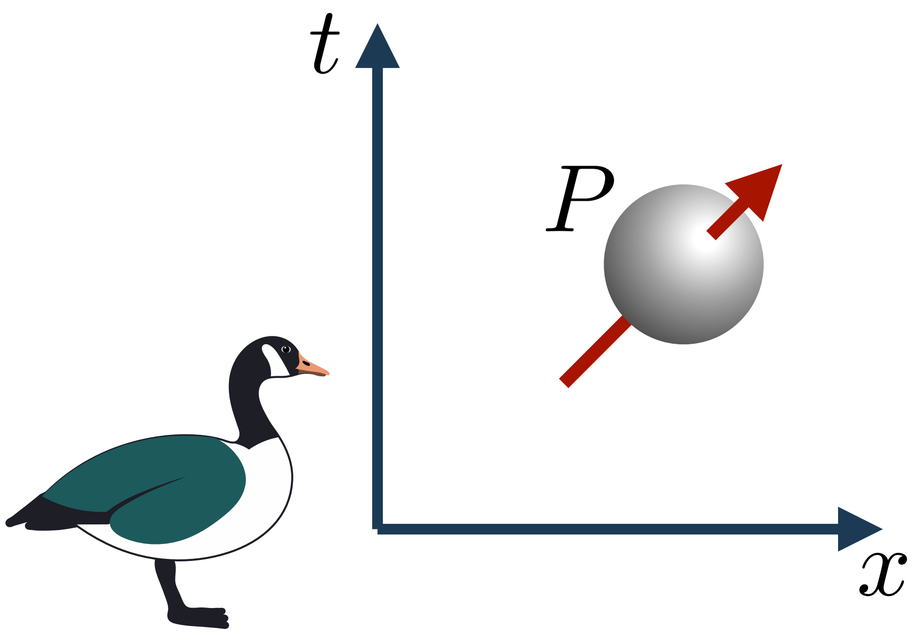
Reference frames are abstract entities, used to fix the point of view from which observations are carried out.

The laws of physics are the same regardless of the choice of the reference frame.
(**Principle of covariance**)



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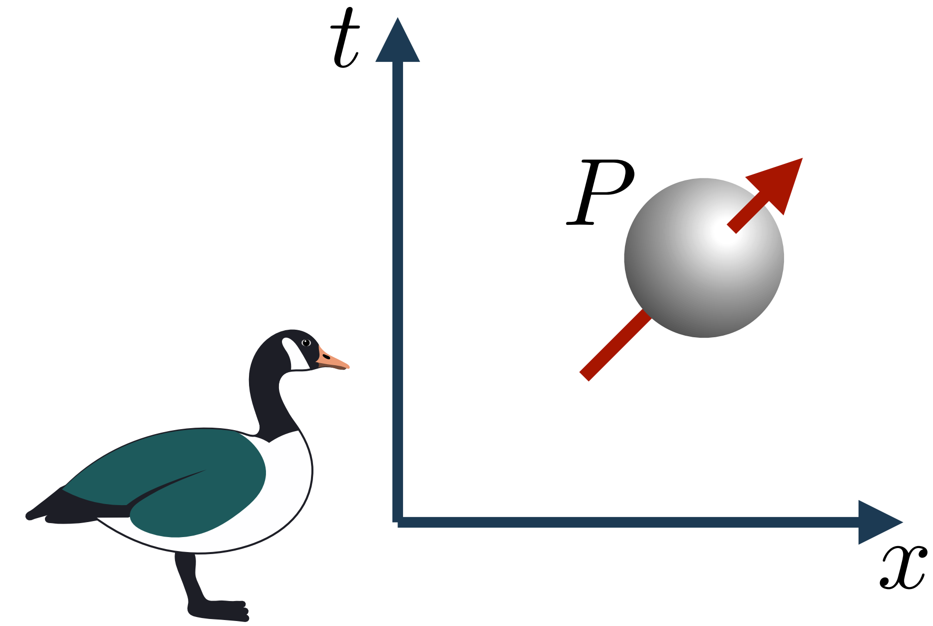

The laws of physics are the same regardless of the choice of the reference frame.
(**Principle of covariance**)

Translation $\hat{U}_T = e^{\frac{i}{\hbar} X_0 \hat{p}}$

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

⋮

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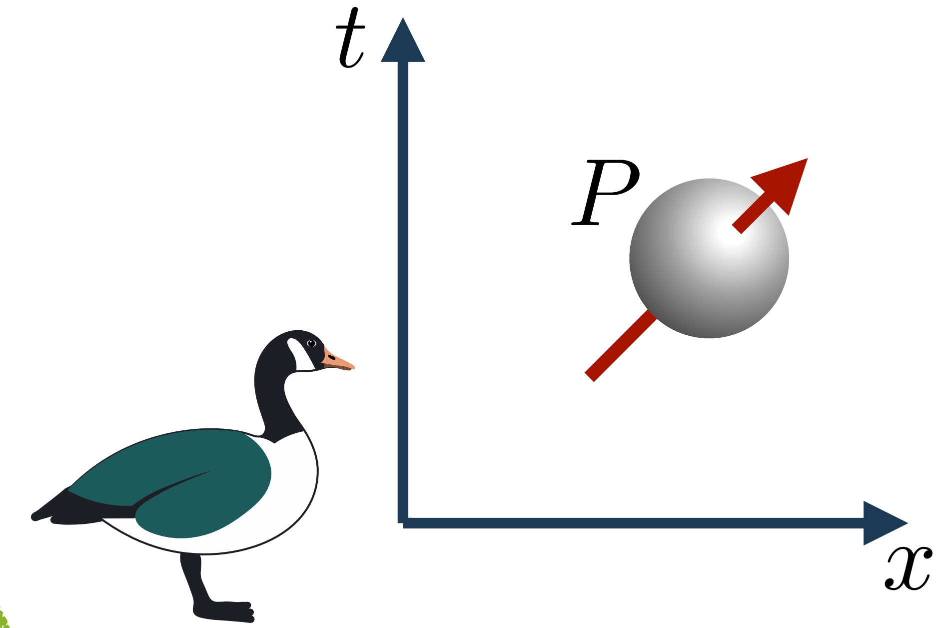

The reference frame enters the transformation as a **parameter**.

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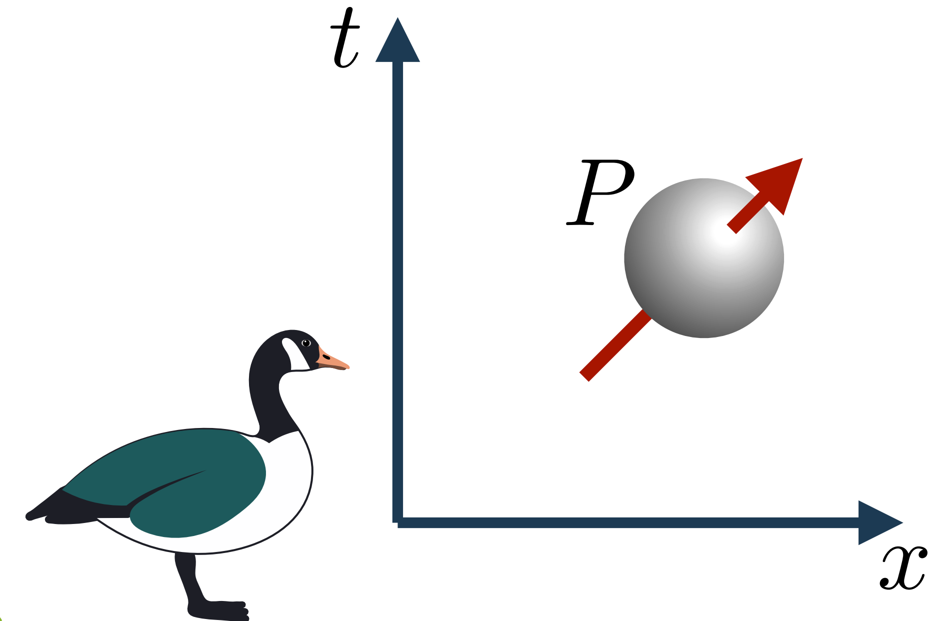

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Covariance of physical laws

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

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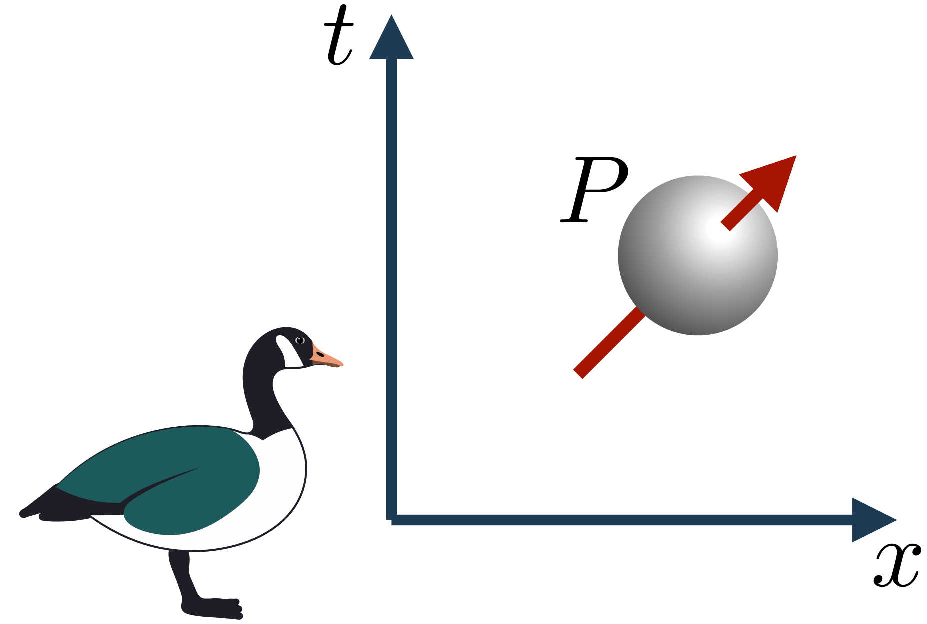

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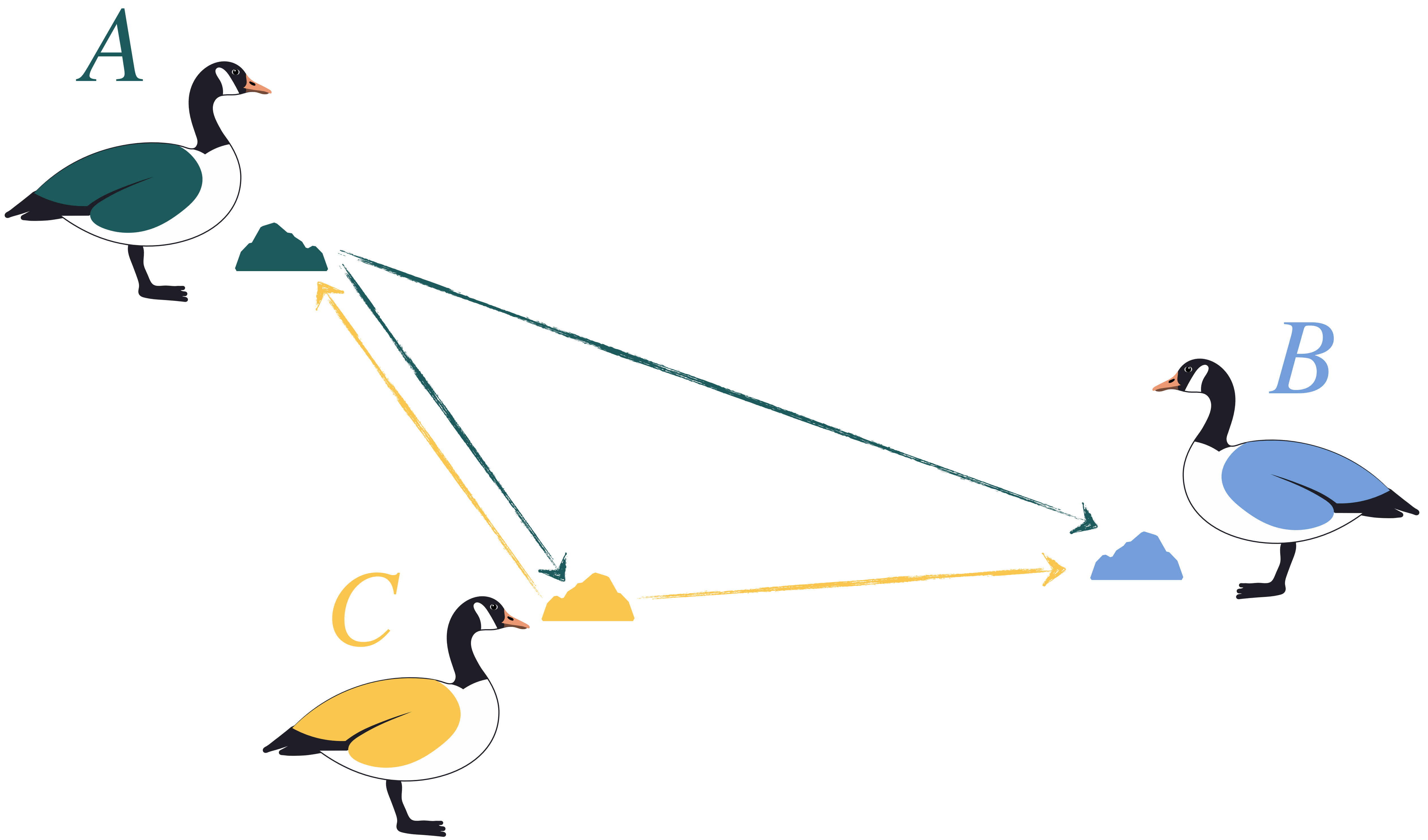
Covariance of physical laws

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

Symmetry

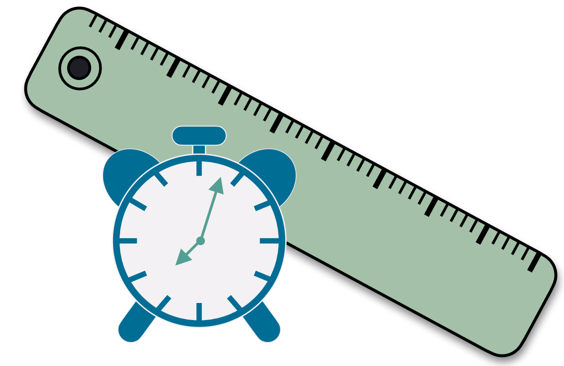
$$\hat{H}' = \hat{H}$$

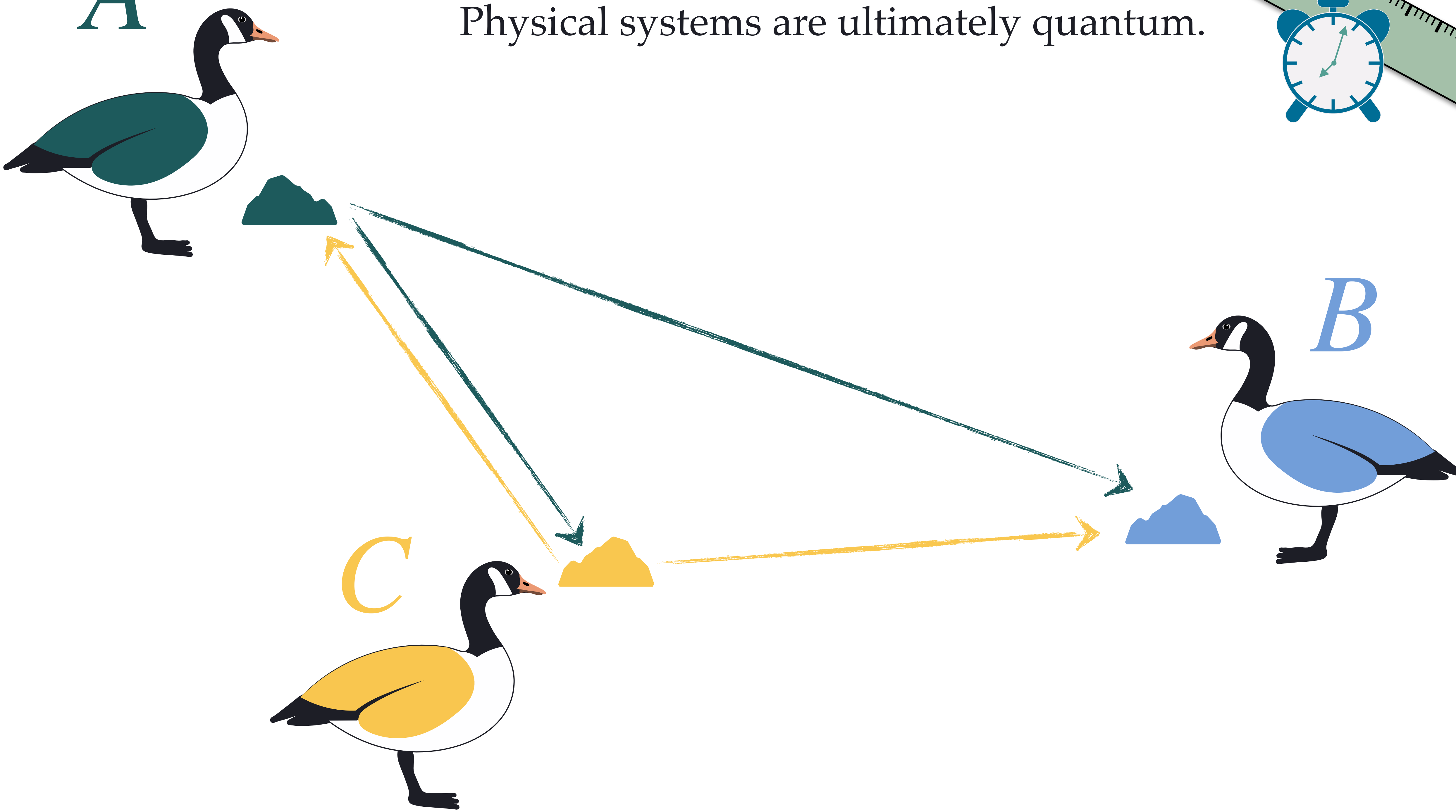
What are reference frames?



What are reference frames?

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





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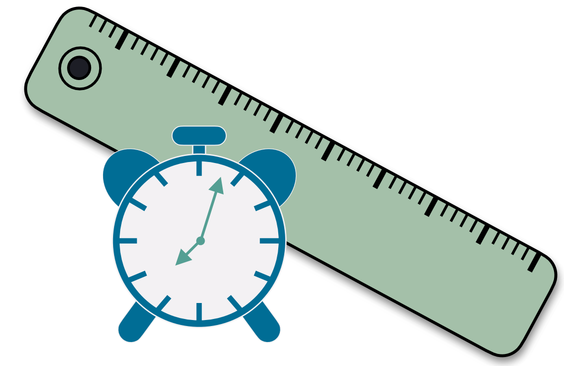
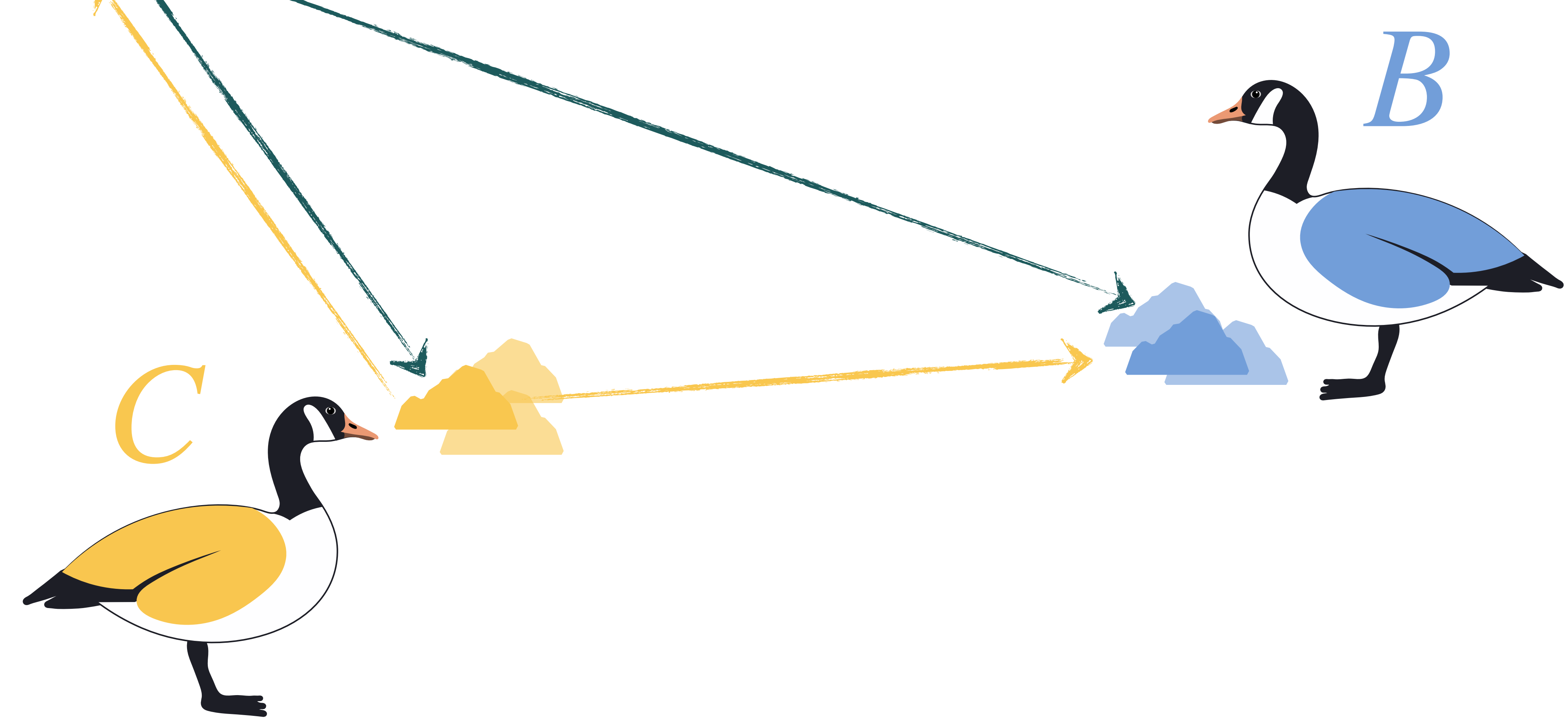


Can we "attach" a reference frame to an object whose state is in a superposition of classical states (in some basis)?



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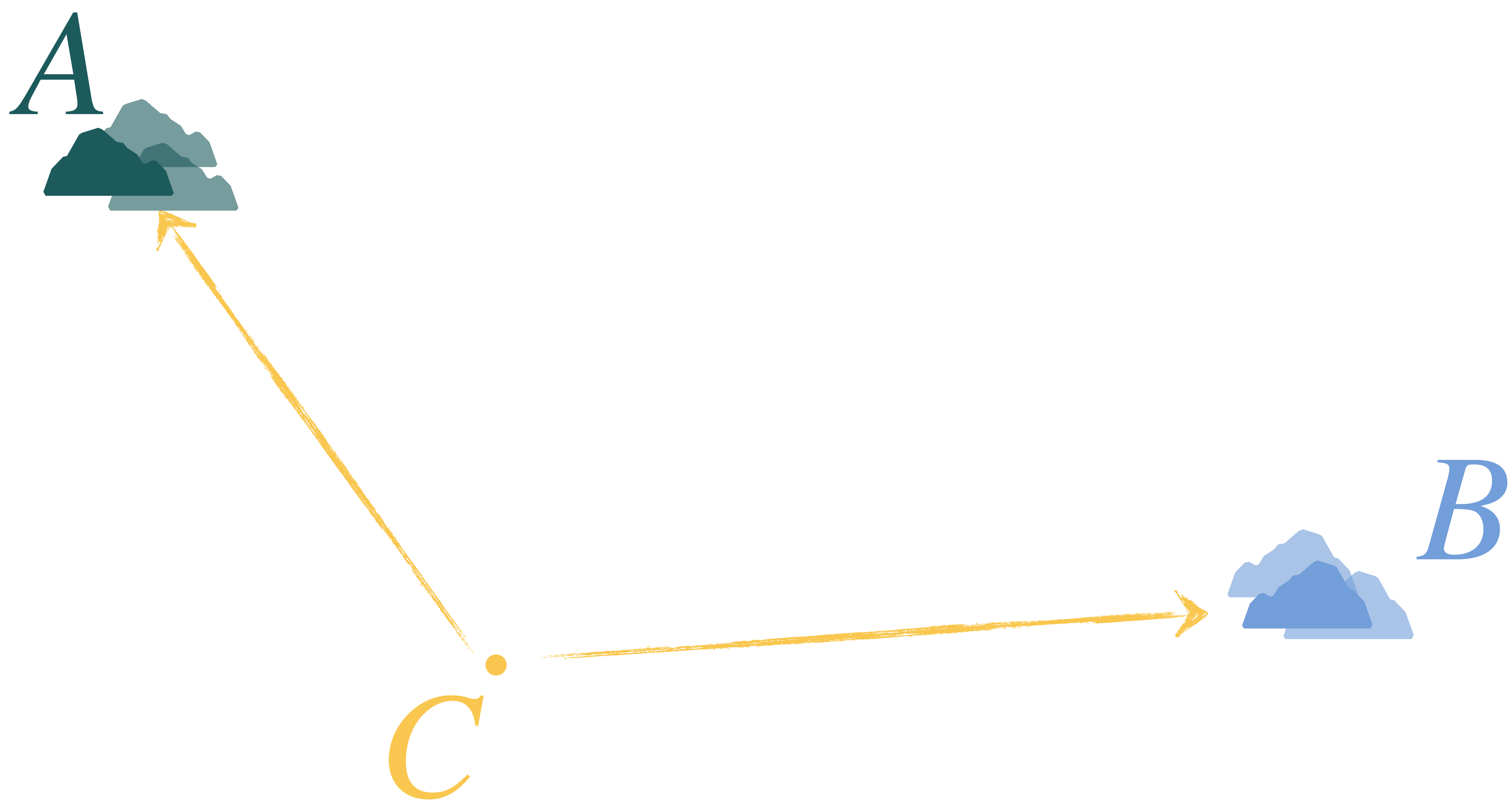


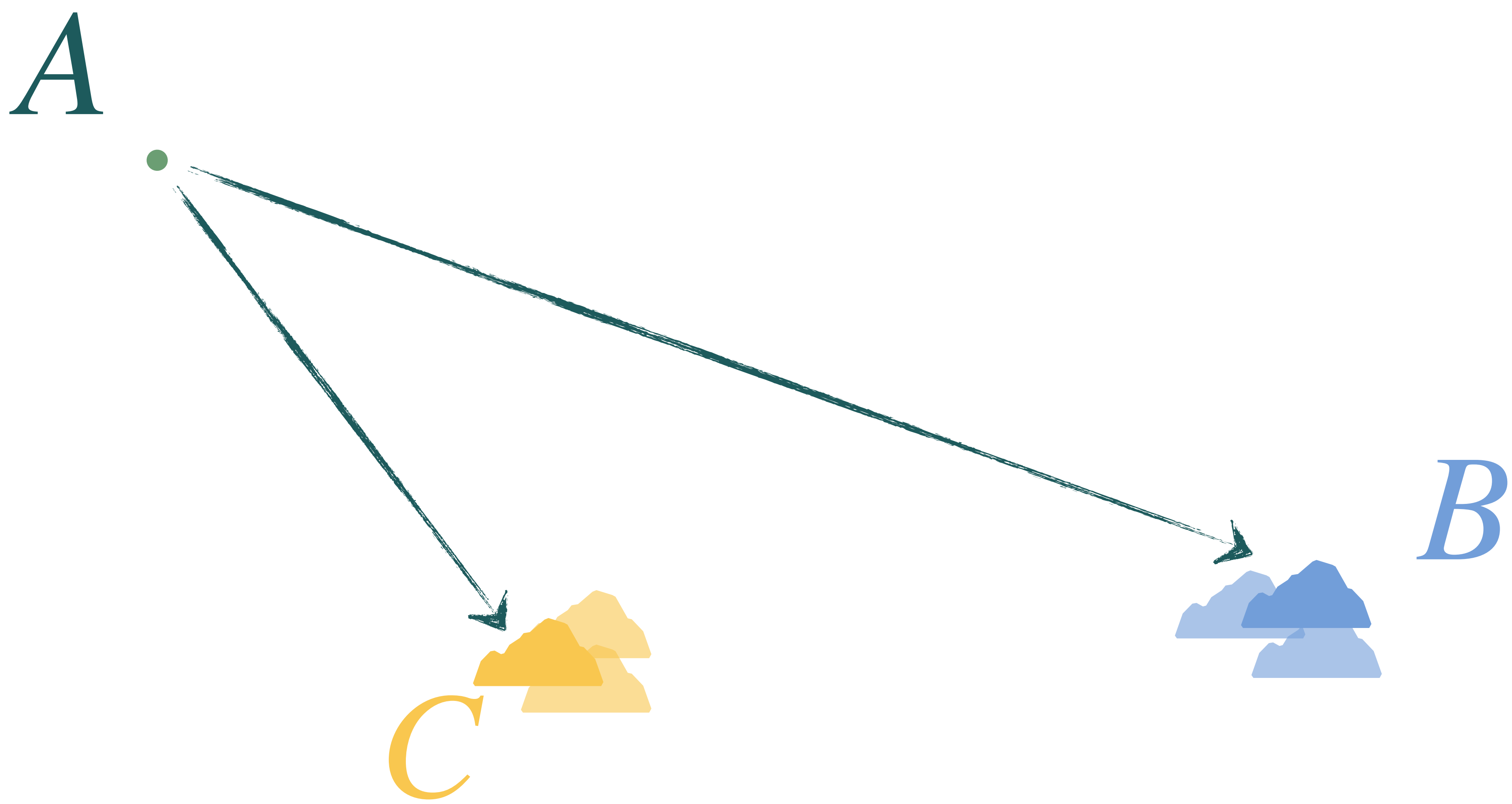
What are reference frames?

A

B

C

What are reference frames?



Superpositions of spacetimes

LIGHTEST GRAVITY SOURCE: 90 *mg*

Article | Published: 10 March 2021

Measurement of gravitational coupling between millimetre-sized masses

Tobias Westphal, Hans Hepach, Jeremias Pfaff & Markus Aspelmeyer

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

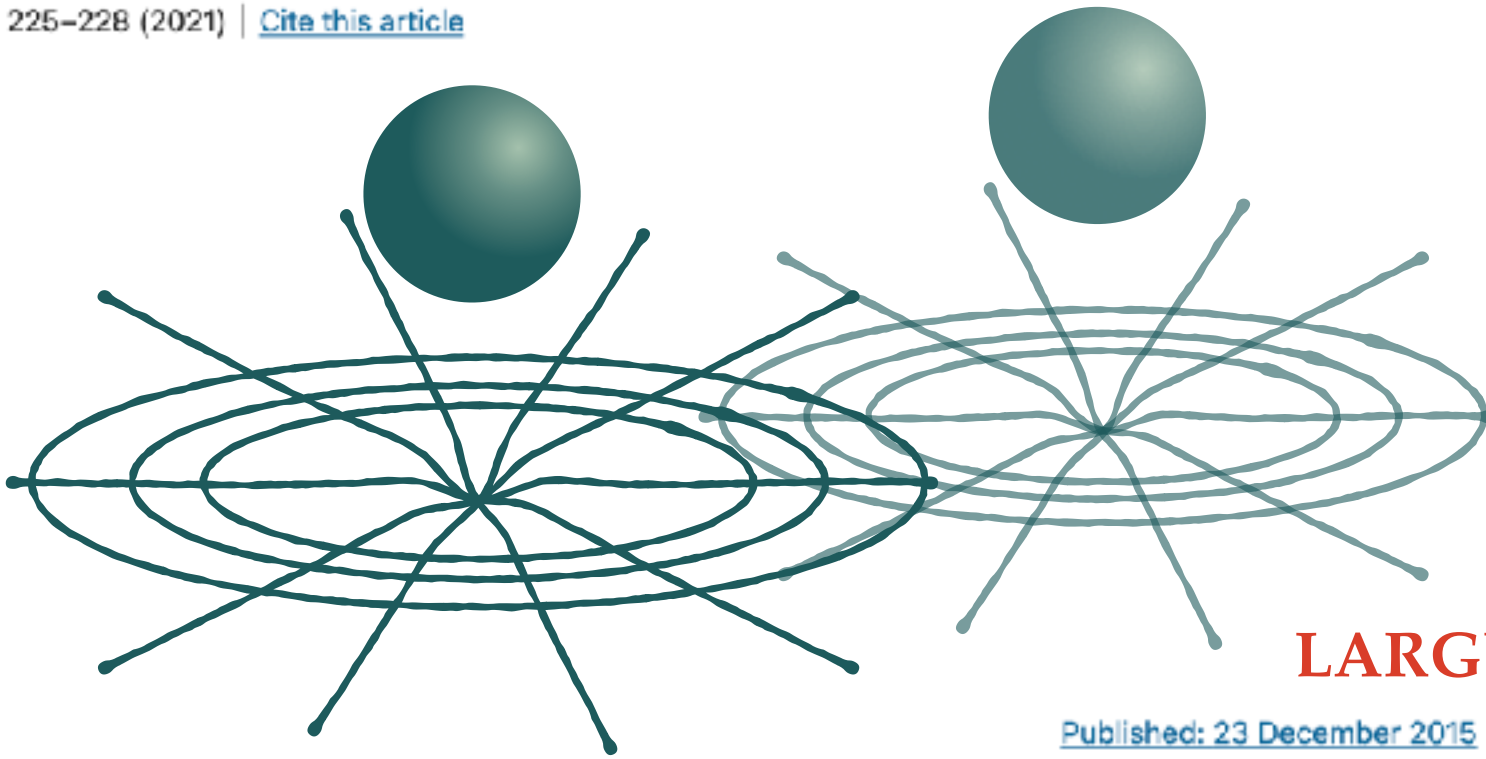
HEAVIEST SUPERPOSED MASS: $10^{-20}g$

Letter | Published: 23 September 2019

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



LARGEST SUPERPOSITION: 0.5 *m*

Published: 23 December 2015

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

$$m \cdot \Delta x \approx 10^{-25}\, g \cdot m$$ **(Aspelmeyer, 2203.05587)**

1

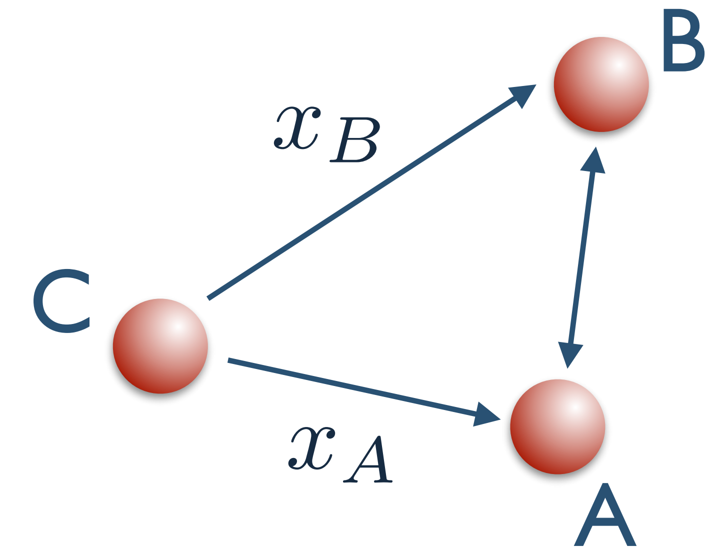
QUANTUM REFERENCE FRAMES IN QUANTUM MECHANICS

Quantum reference frames

Transformation to relative coordinates

$x_A \mapsto -q_C$

$x_B \mapsto q_B - q_C$



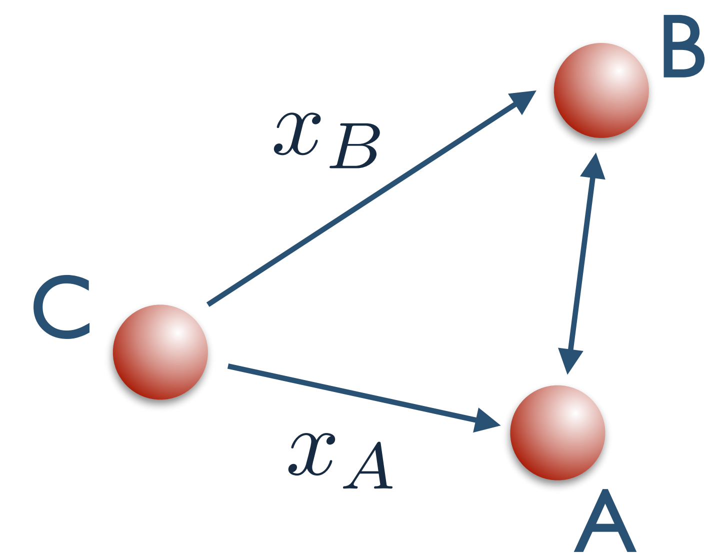
FG, E. Castro Ruiz, C. Brukner, Nat Commun. (2019), arXiv:1712.07207

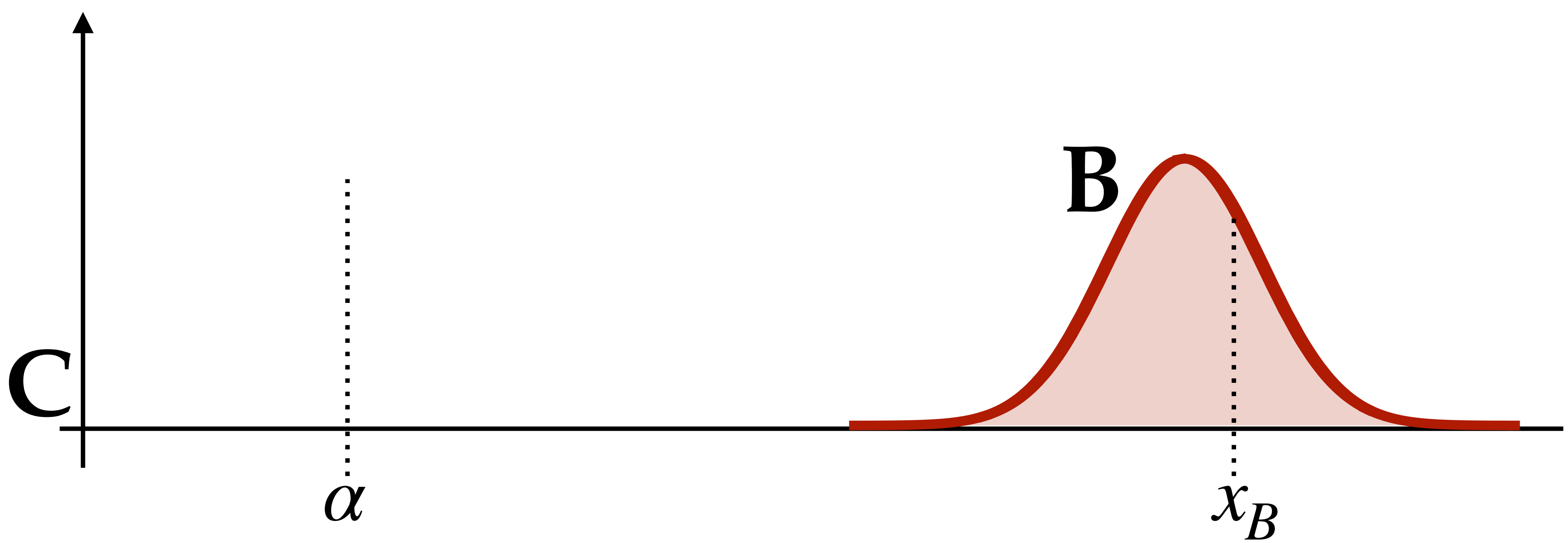
Quantum reference frames

Transformation to relative coordinates

$$x_A \mapsto -q_C$$

$$x_B \mapsto q_B - q_C \qquad e^{\frac{i}{\hbar}\alpha\hat{p}_B}|x\rangle_B = |x-\alpha\rangle_B$$





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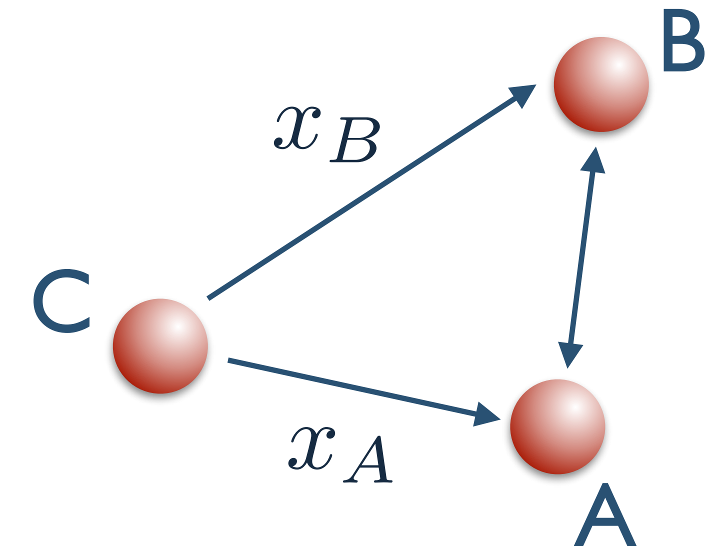

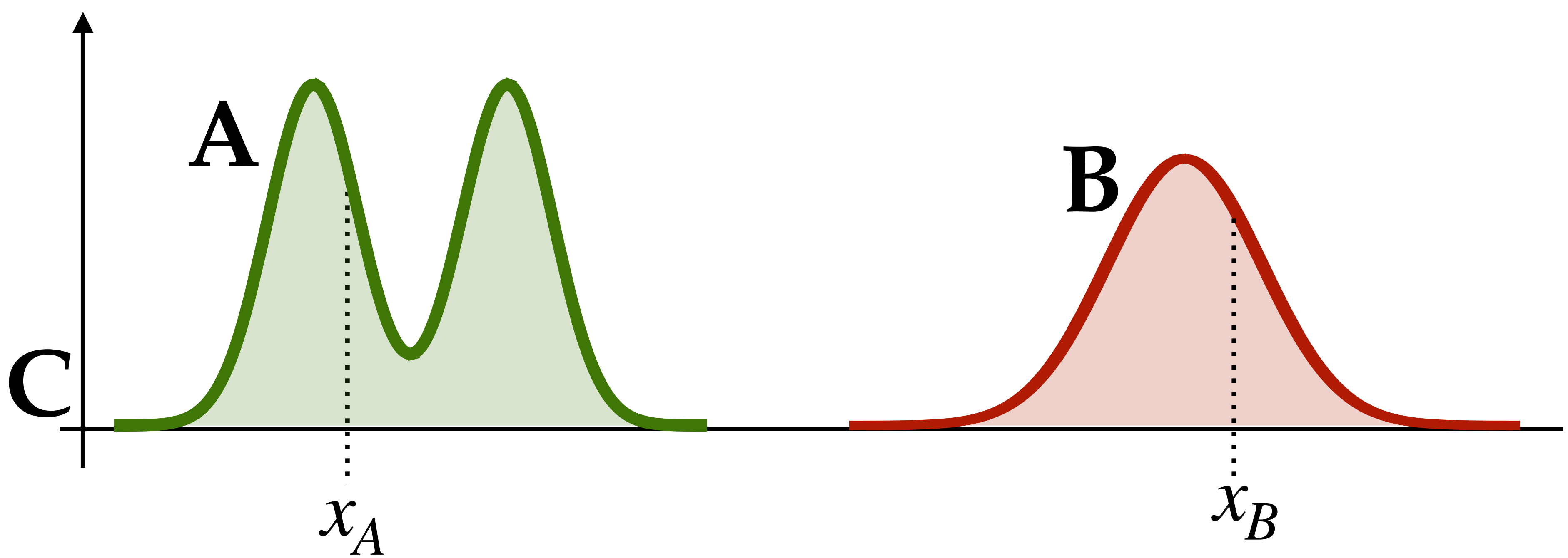

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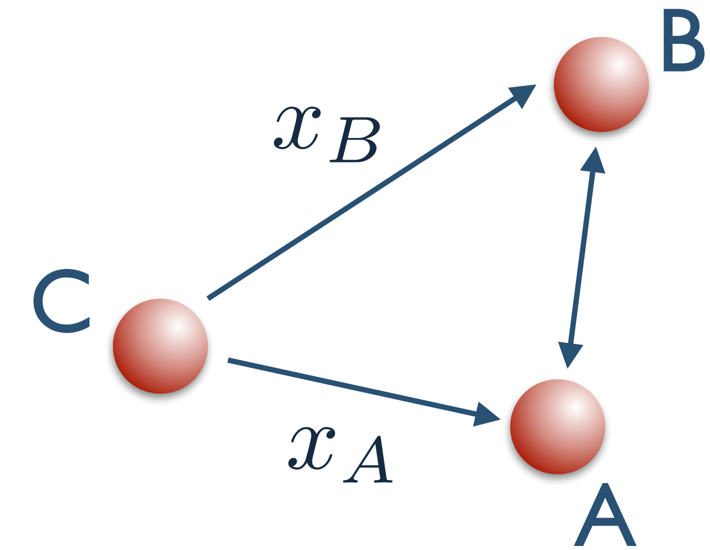

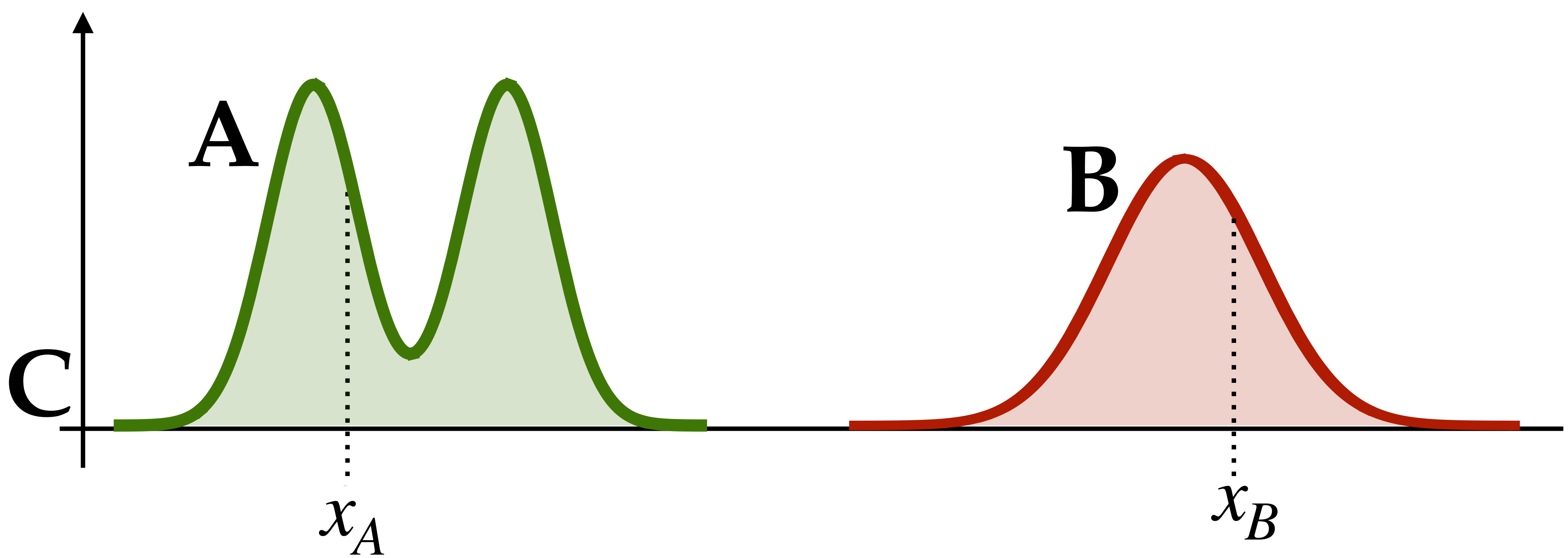

$e^{\frac{i}{\hbar}\hat{x}_A \hat{p}_B} |\phi\rangle_A |\psi\rangle_B$

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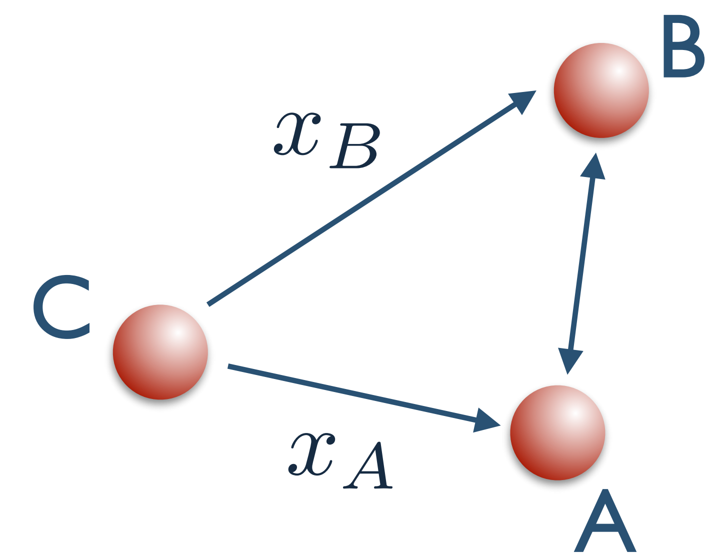

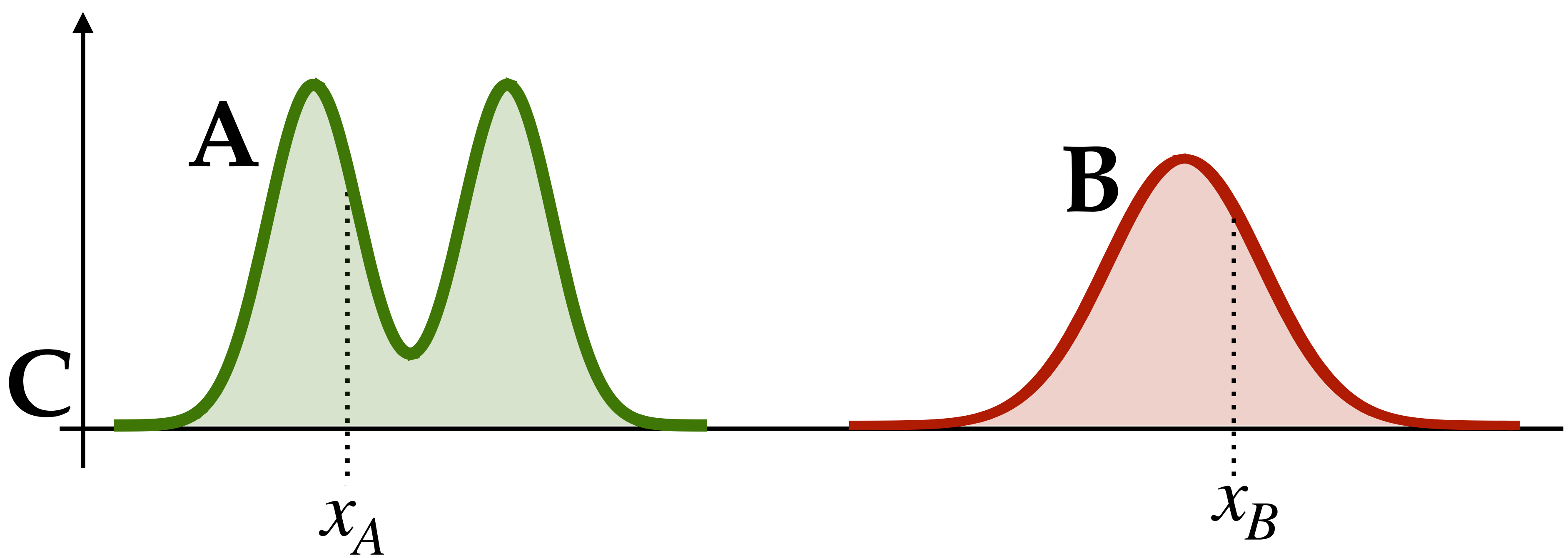

$$e^{\frac{i}{\hbar}\hat{x}_A\hat{p}_B}|\phi\rangle_A|\psi\rangle_B$$

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

$$\mathscr{P}_{AC}\hat{x}_A\mathscr{P}_{AC}^{\dagger} = -\hat{q}_C$$

parity-swap operator

$$\rho_{BC}^{(A)} = \hat{S}_x \rho_{AB}^{(C)} \hat{S}_x^{\dagger}$$

FG, E. Castro Ruiz, C. Brukner, Nat Commun. (2019), arXiv:1712.07207

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A: new reference frame;
B: quantum system; C: old reference frame

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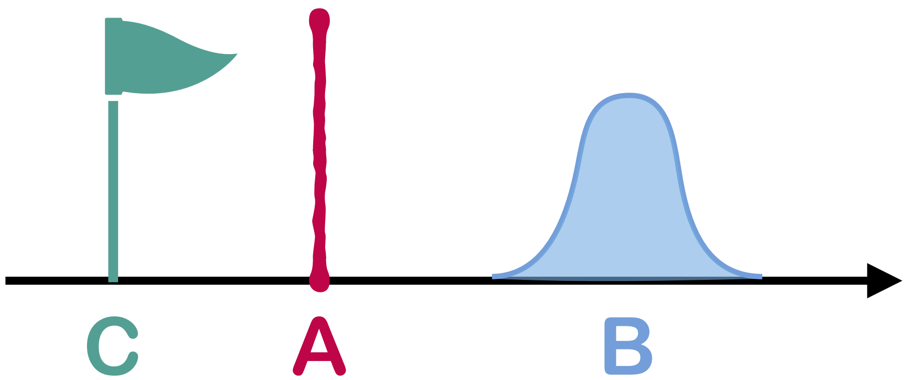

From C: $|x\rangle_A |\phi\rangle_B$

FG, E. Castro Ruiz, C. Brukner, Nat Commun. (2019), arXiv:1712.07207

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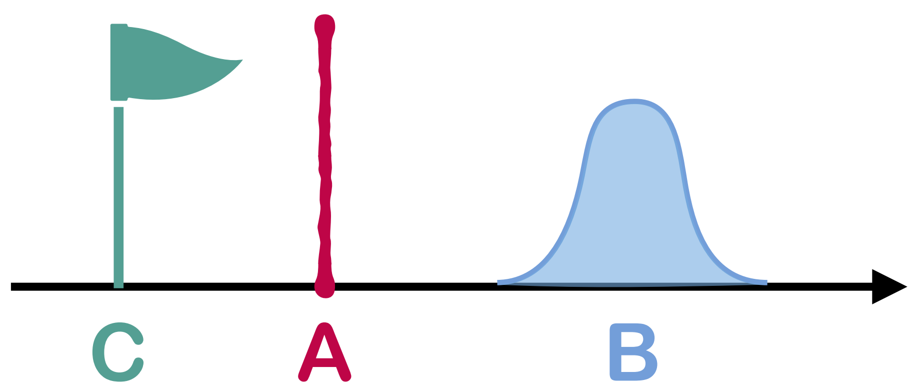

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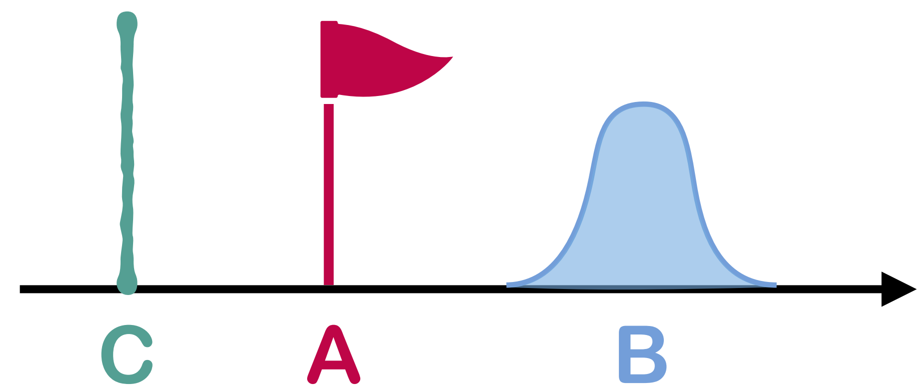

From A: $e^{-\frac{i}{\hbar}x\hat{p}_B} |\phi\rangle_B |-x\rangle_C$

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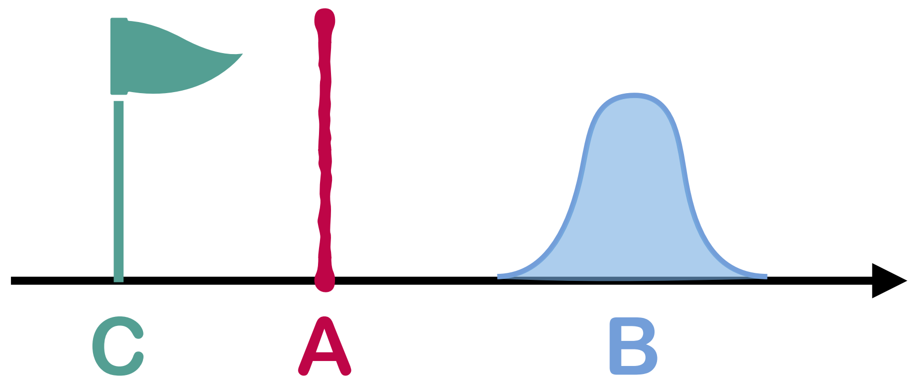
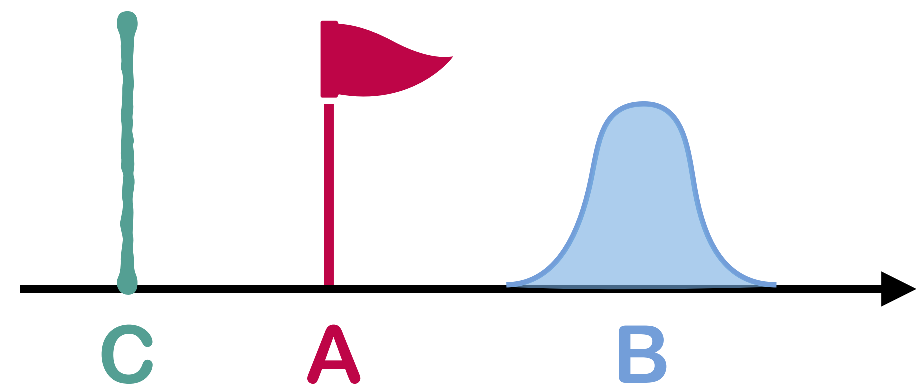


From C: $|x\rangle_A |\phi\rangle_B$



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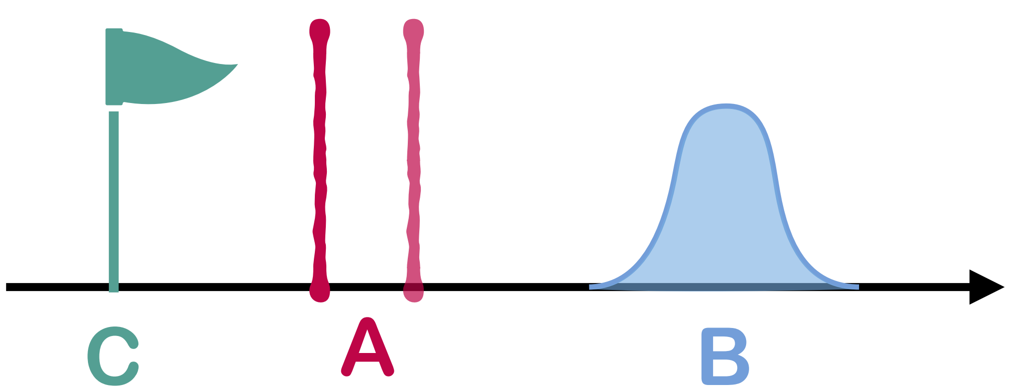

From C: $\frac{1}{\sqrt{2}}(|x_1\rangle_A + |x_2\rangle_A)|\phi\rangle_B$

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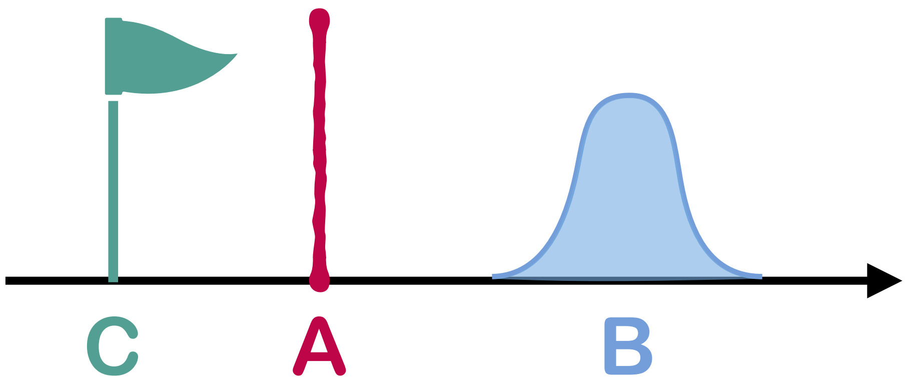

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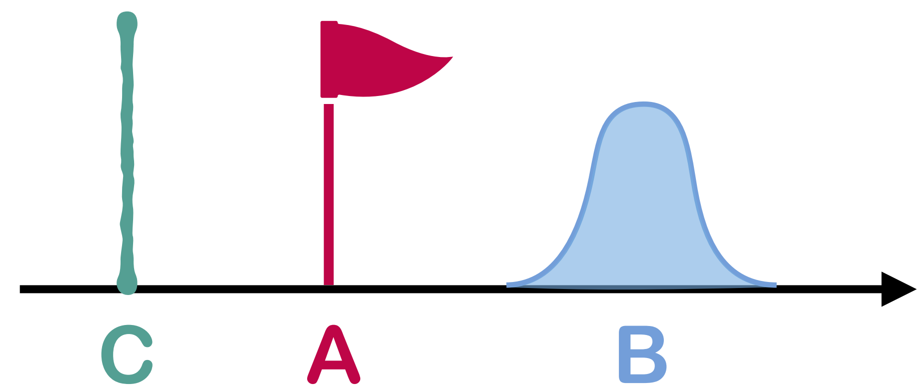

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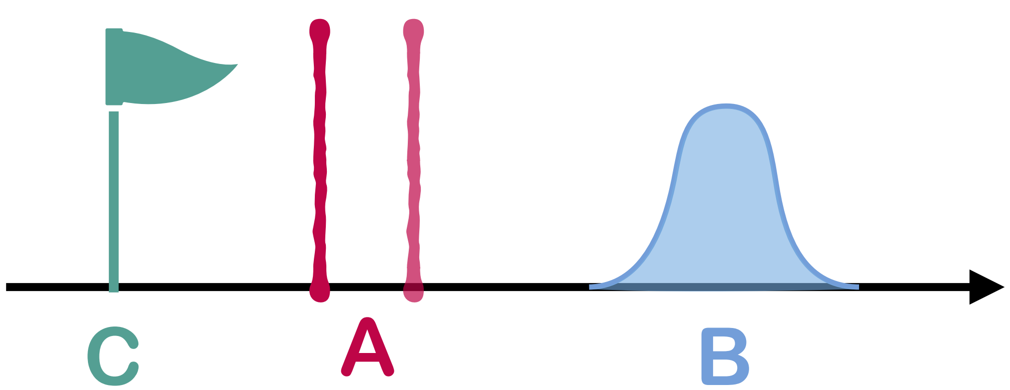
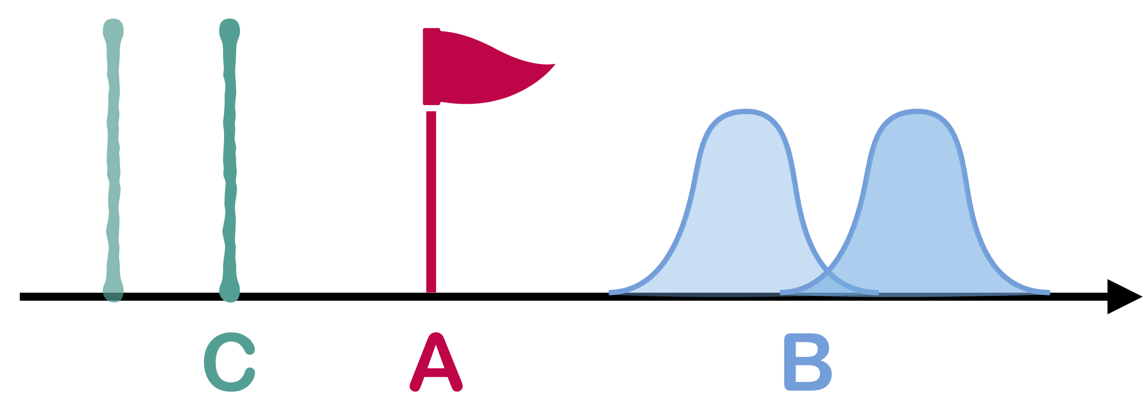


From C: $\frac{1}{\sqrt{2}}(|x_1\rangle_A + |x_2\rangle_A)|\phi\rangle_B$



From A: $\frac{1}{\sqrt{2}}\left(e^{-\frac{i}{\hbar}x_1\hat{p}_B}|\phi\rangle_B|-x_1\rangle_C + e^{-\frac{i}{\hbar}x_2\hat{p}_B}|\phi\rangle_B|-x_2\rangle_C\right)$

FG, E. Castro Ruiz, C. Brukner, Nat Commun. (2019), arXiv:1712.07207

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Extended Galilean transformations…

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

FG, E. Castro Ruiz, C. Brukner,
Nat Commun. (2019) arXiv:1712.07207

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Spatial translations

$$X(t) = X_0$$

$$\hat{U}_x$$

Galilean boosts

$$X(t) = vt$$

$$\hat{U}_v$$

Accelerated reference frame

$$X(t) = \frac{1}{2}at^2$$

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Hamiltonian of the system

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

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$$\hat{H} = \frac{\hat{p}^2}{2m} \quad \rightsquigarrow \quad \hat{H}' = \frac{\hat{p}^2}{2m} + m\ddot{X}\hat{x}$$

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Hamiltonian of the system

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In QRFs: Hamiltonian of the system **AND** of the QRF!

$$\hat{H} = \frac{\hat{p}^2}{2m} \rightsquigarrow \hat{H}' = \frac{\hat{p}^2}{2m} + m\ddot{X}\hat{x}$$

FG, E. Castro Ruiz, C. Brukner,
Nat Commun. (2019) arXiv:1712.07207

…and their superpositions!

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$$\hat{U}_T = \sum_i \hat{U}_{x_i} \otimes |x_i\rangle\langle x_i|$$

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Controlled superposition of the transformation on some additional Hilbert space

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Operational meaning

Quantum Reference Frames

F.G. E. Castro Ruiz, C. Brukner, Nat. Commun. (2019)

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Extension of the covariance of physical laws

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Extended symmetries of the dynamics

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Extended symmetries of the dynamics

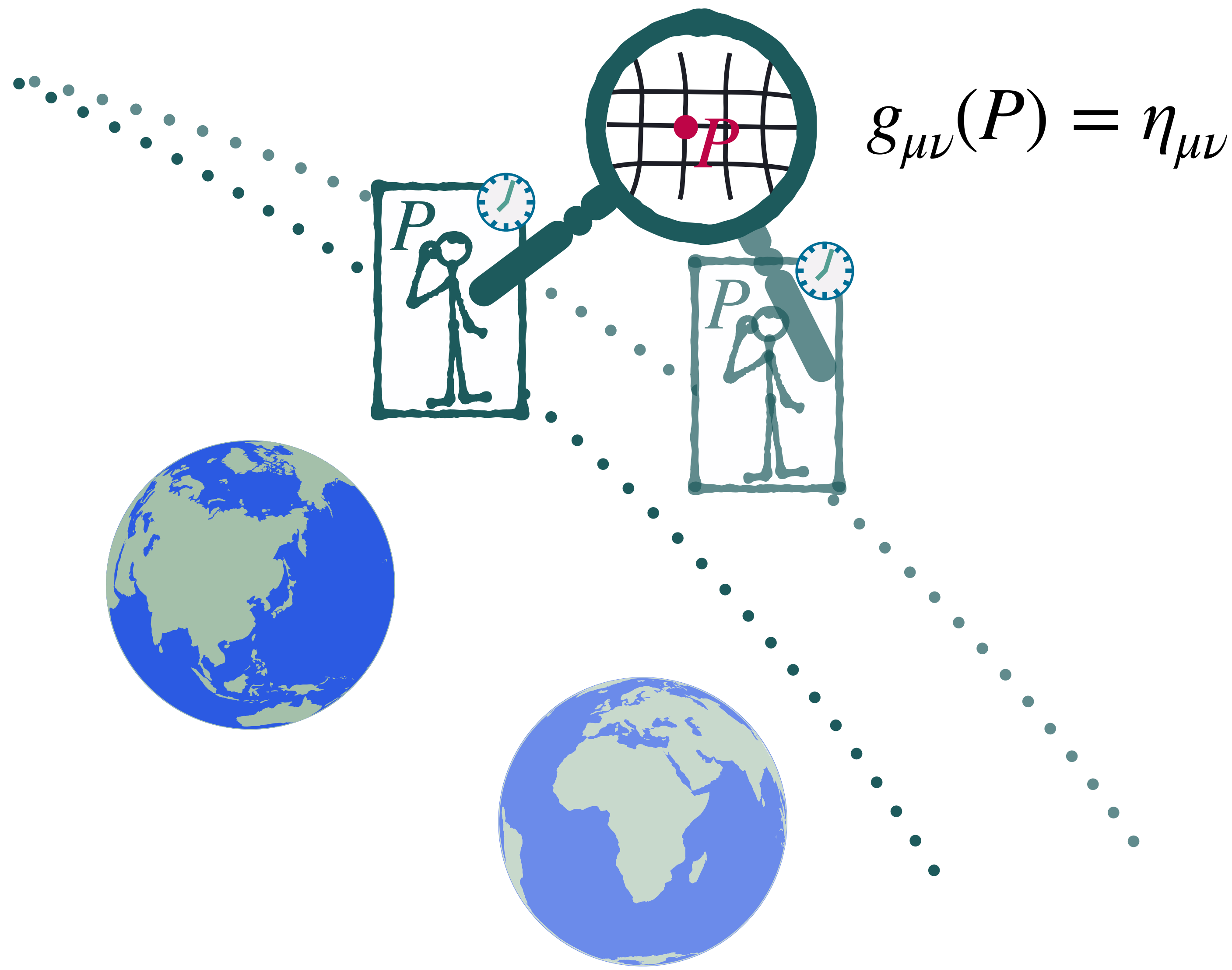
$$\hat{H}^{(C)}_{AB} = \frac{\hat{p}_A^2}{2m_A} + \frac{\hat{p}_B^2}{2m_B} \quad \rightsquigarrow \quad \hat{H}^{(A)}_{BC} = \frac{\hat{p}_B^2}{2m_B} + \frac{\hat{p}_C^2}{2m_C}$$

F.G. E. Castro Ruiz, C. Brukner, Nat. Commun. (2019)

2

QUANTUM REFERENCE FRAMES AND GRAVITY?

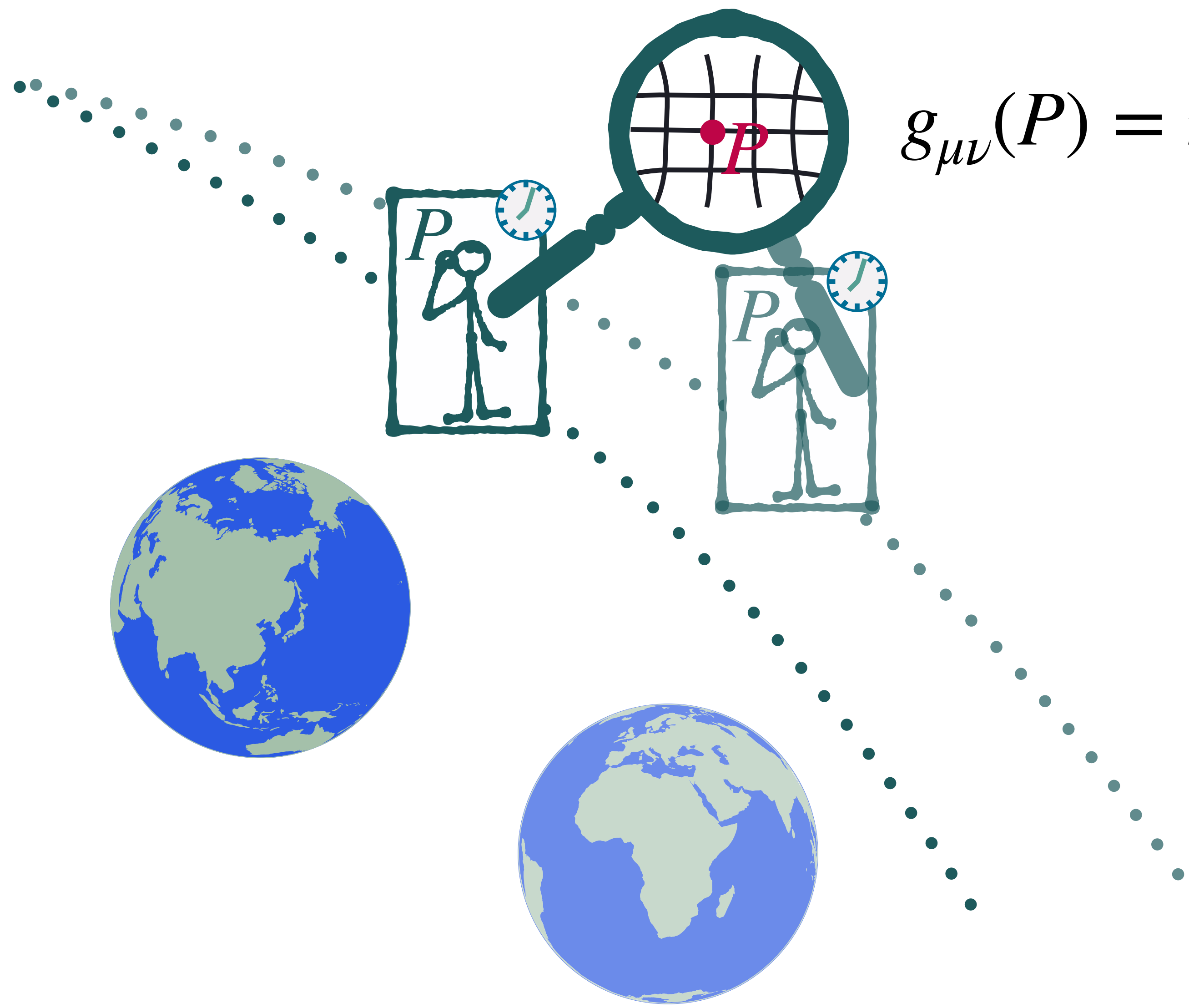
Equivalence Principle in QRFs



Reconciliation of EEP and Principle of Linear Superposition

F.G., Brukner, 2012.13754 (2020)
F.G., Brukner, AVS Quantum Science (2022)

Equivalence Principle in QRFs



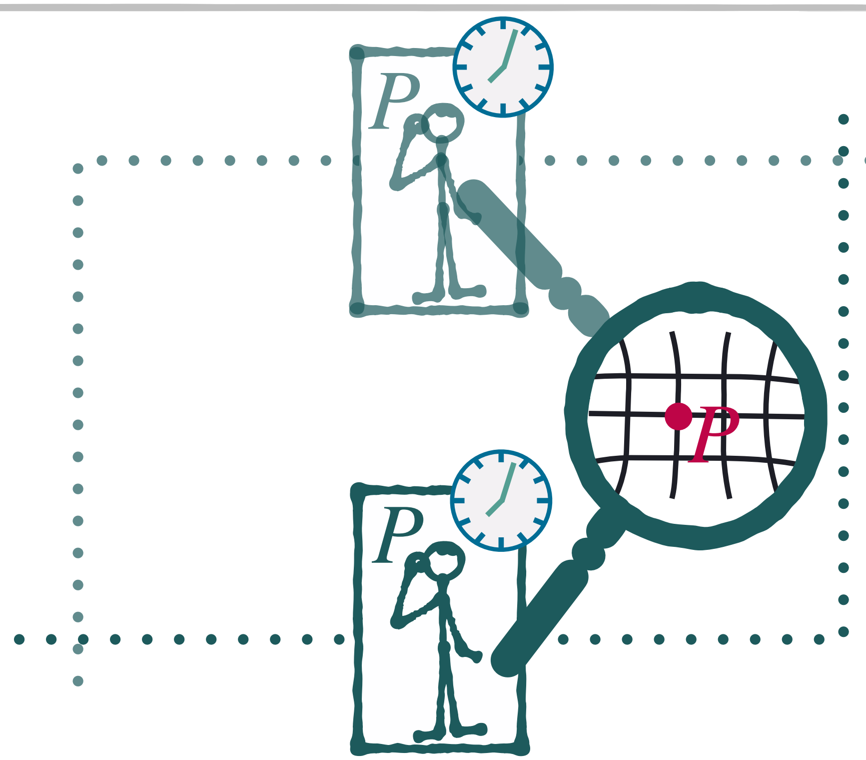
$$g_{\mu\nu}(P) = \eta_{\mu\nu}$$

Reconciliation of EEP and Principle of Linear Superposition

Overcomes Penrose's spontaneous state reduction

F.G., Brukner, 2012.13754 (2020)
F.G., Brukner, AVS Quantum Science (2022)

Test of the generalised EEP



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Test of EEP for QRFs in atom interferometer with quantum clocks

Cepollaro, F.G., 2112.03303 (2021)

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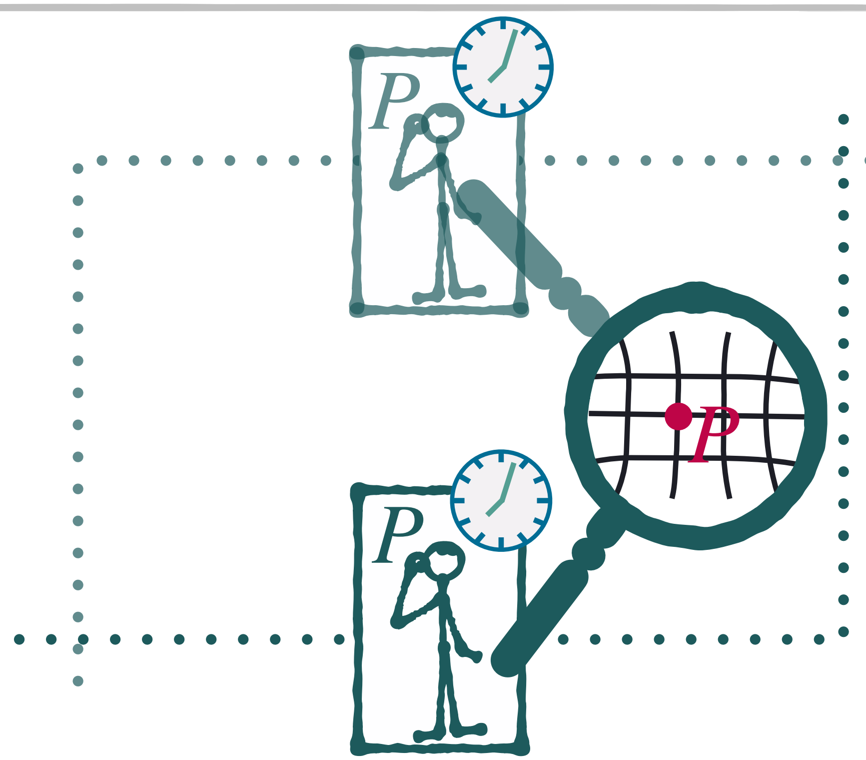


$g_{\mu\nu}(P) = \eta_{\mu\nu}$

Test of EEP for QRFs in atom interferometer with quantum clocks

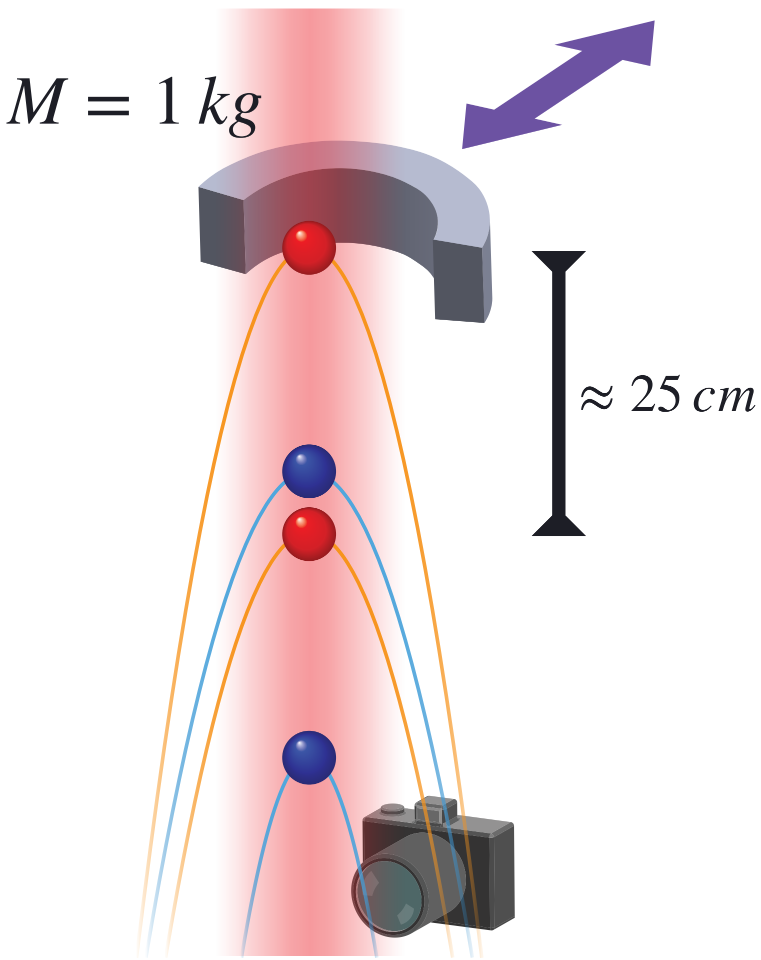
If EEP for QRF not valid, it is not possible to define time evolution in a QRF

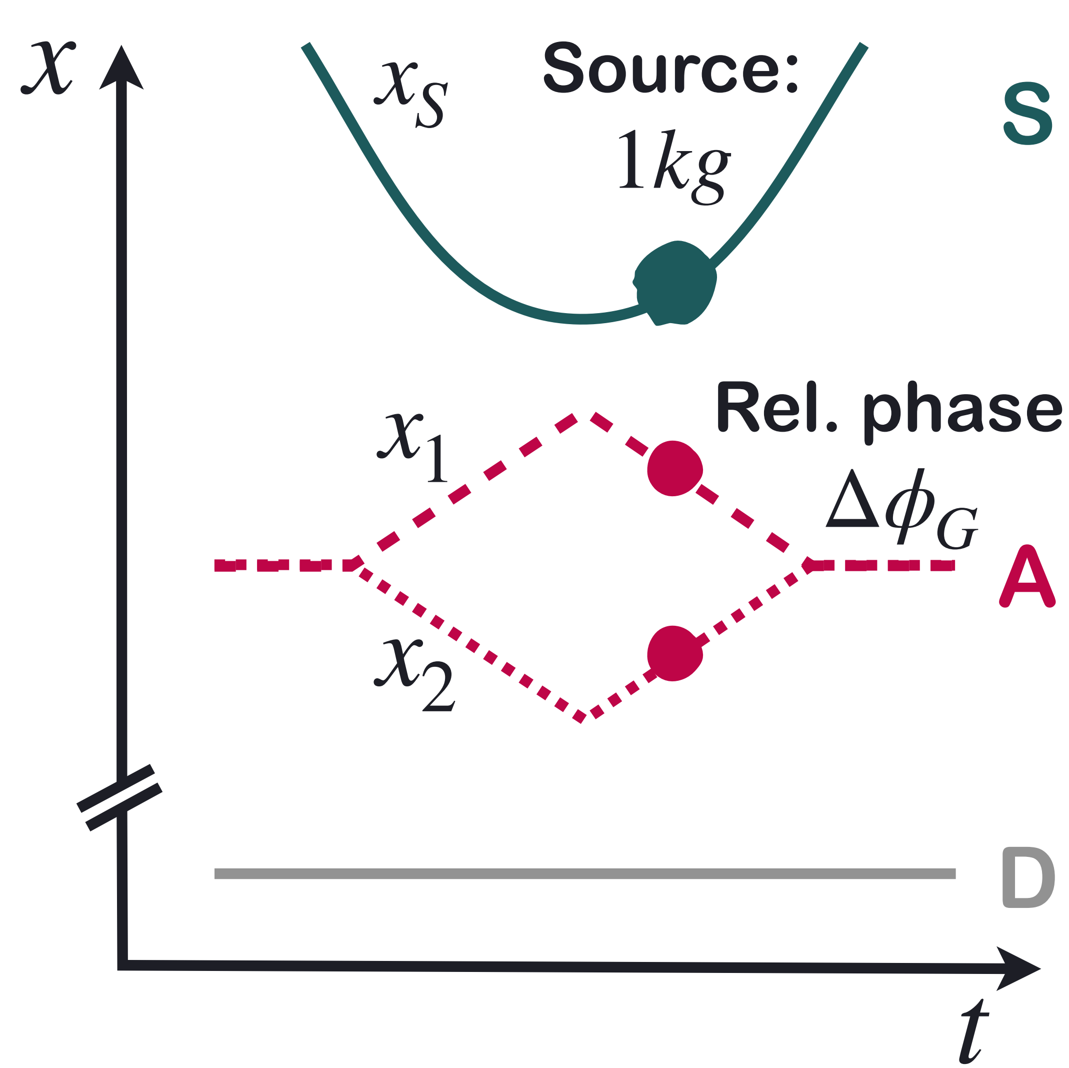
Cepollaro, F.G., 2112.03303 (2021)

Nonclassical spacetime

Is the superposition of gravitational fields a relative concept?

Gravitational Aharonov-Bohm experiment





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

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

What we know from experiments

- Gravity is tested for masses as light as $90\,mg$

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

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

  MICROSCOPE Mission, September 2022

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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)

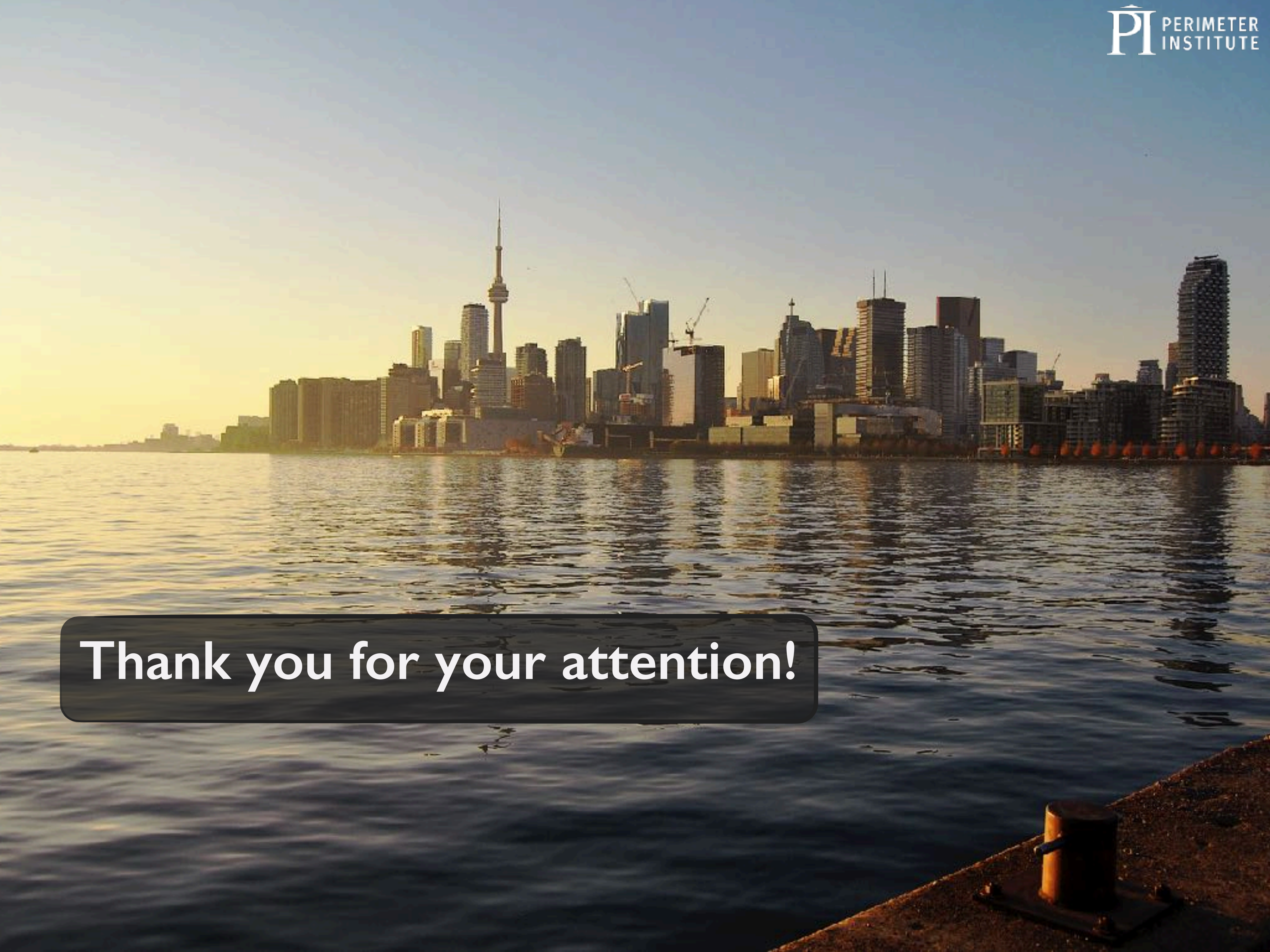
Overstreet, Kim, Curti, Asenbaum, Kasevich, Giacomini, 2209.02214 (2022)

Summary

Operational and relational formalism for quantum reference frames:
associate a reference frame to a quantum system.

In quantum mechanics:
Frame-dependence of entanglement and superposition
Generalisation of covariance
Generalisation of the weak equivalence principle
Operational definition of the rest frame of a quantum system (relativistic spin)

In gravity:
Generalisation of the Einstein Equivalence Principle
Penrose decoherence


Thank you for your attention!