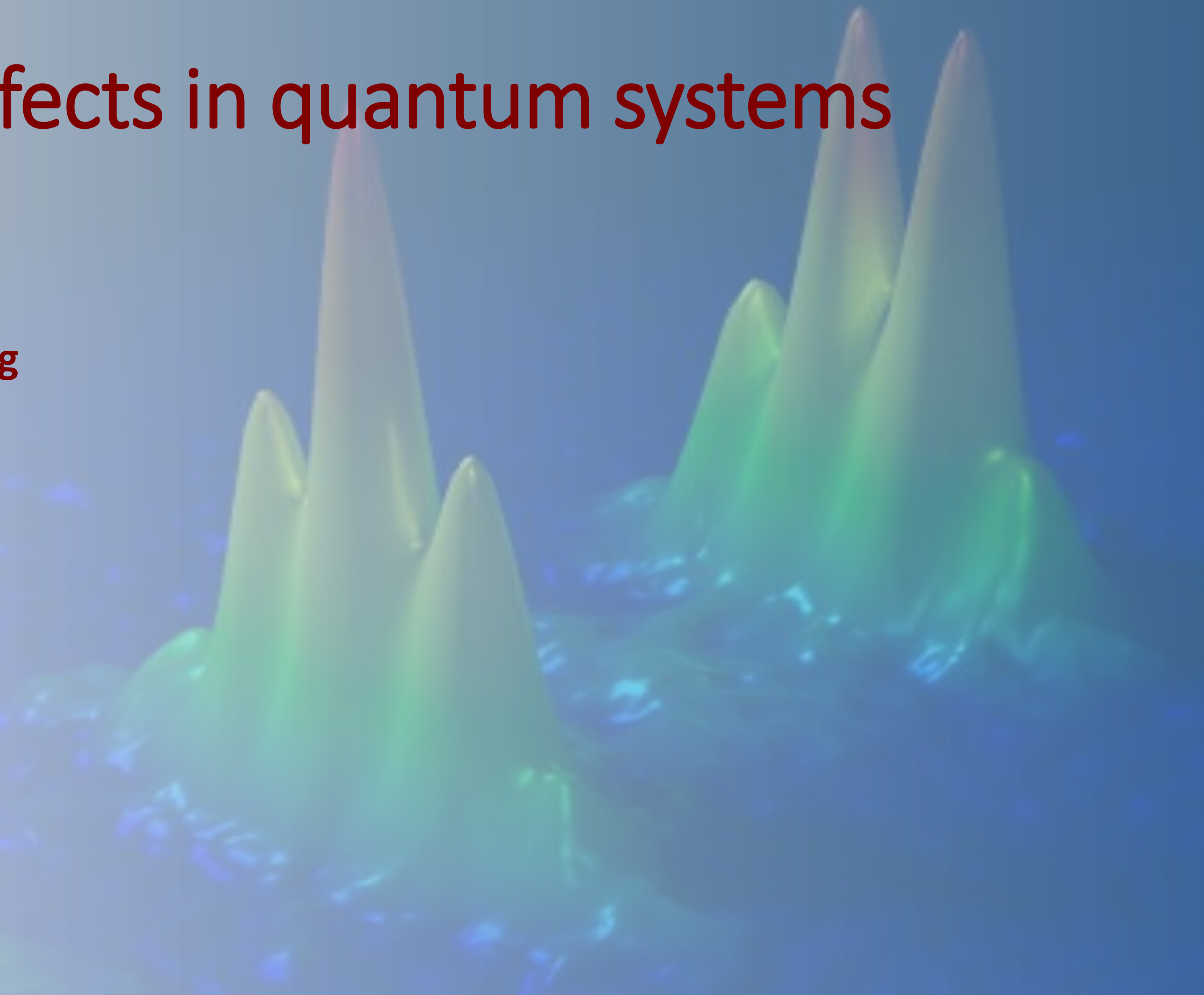
Gravitational effects in quantum systems



MAGIS group meeting
December 7, 2022

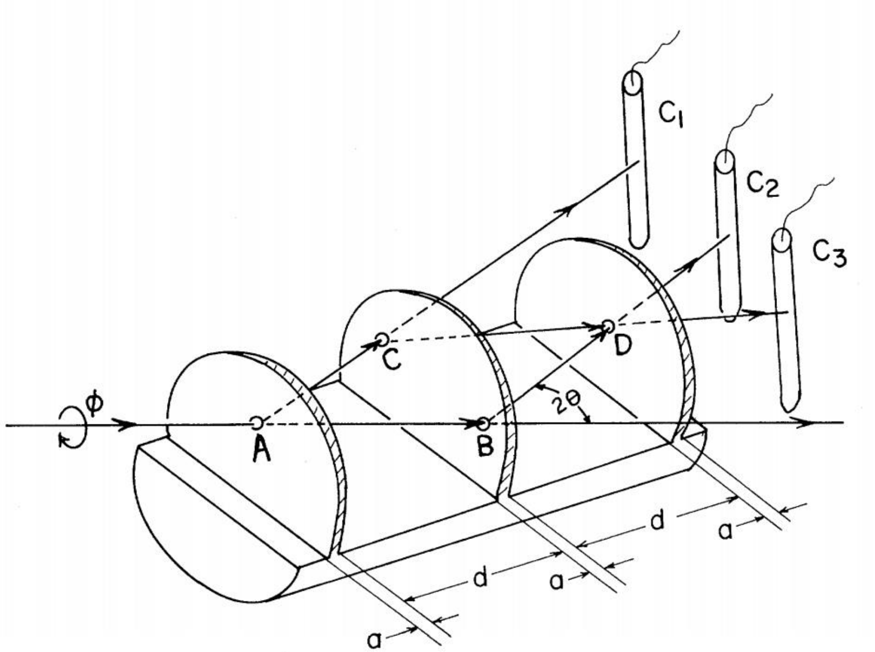
Chris Overstreet

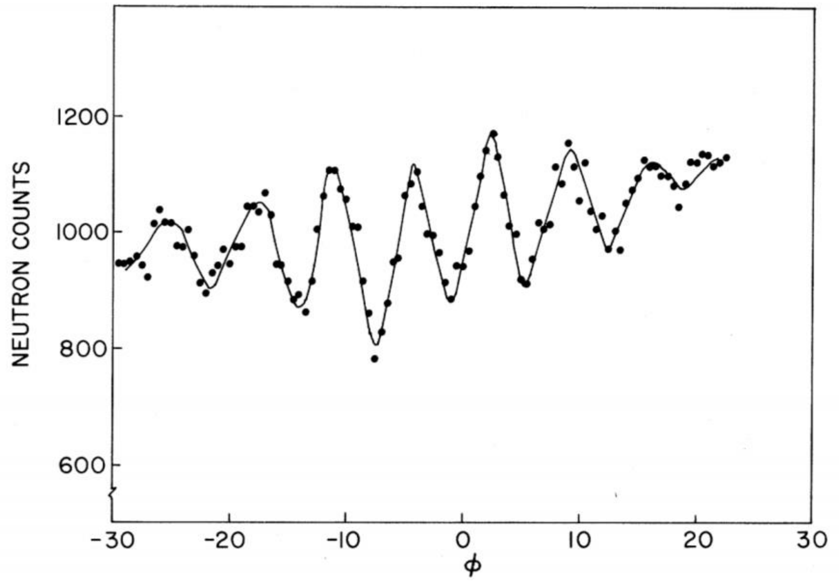
Outline

1. Spacetime curvature across a quantum state
2. Gravitational Aharonov-Bohm effect
3. Implications for gravitational field superposition
4. Future directions and prospects for MAGIS

Background: the COW experiment

A neutron interferometer in an approximately uniform gravitational field





Phase:

$$\Phi = 4\pi\,\lambda\,g\,h^{-2}\,M^2\,d\,(d + a\cos\theta)\,\tan\theta\,\sin\phi$$

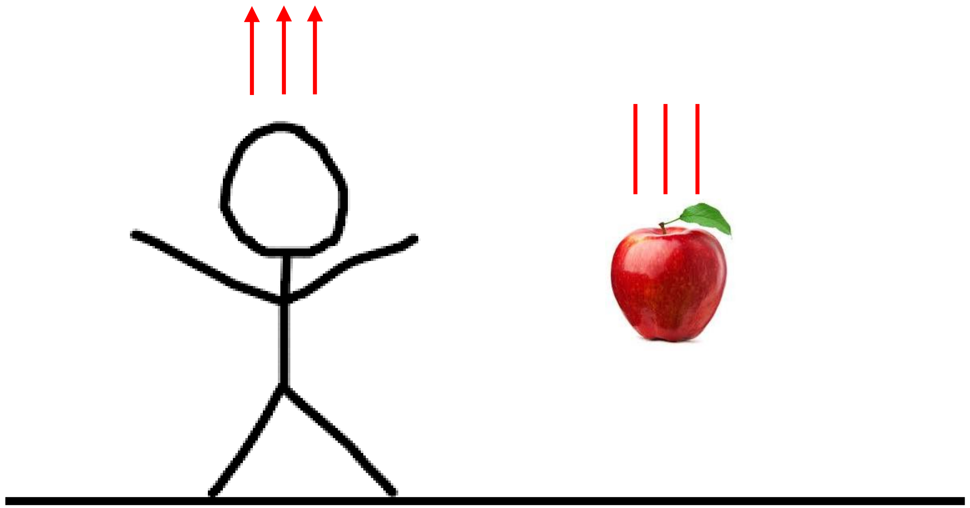
$$= k\,g\,T^2\,\cos\theta\,\sin\phi$$

R. Collela, A. W. Overhauser, and S. A. Werner, *Phys. Rev. Lett.* **34**, 23 (1975)

The equivalence principle

Gravity is a purely nonlocal phenomenon

Gravity cannot be observed in any local measurement



Implication: uniform gravitational fields are not observable

A nonlocal interferometer

-EP says that there are no local gravitational effects

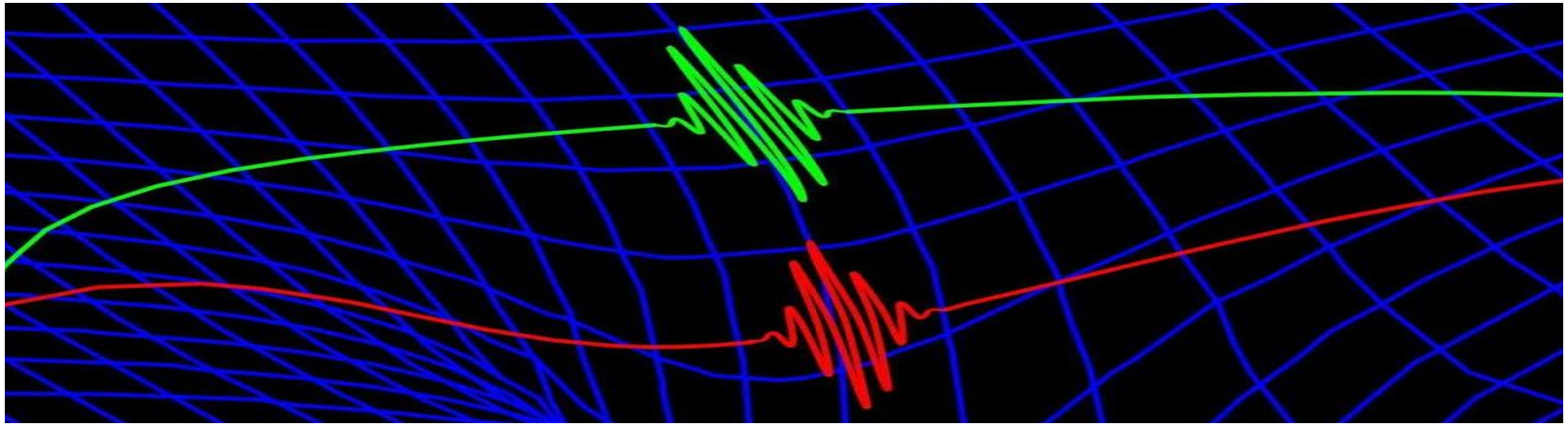
-To observe gravity, need a nonlocal interferometer

-Resolvable relative acceleration between interferometer arms:

$$\left| \frac{\partial^2 V}{\partial x^2} \cdot \Delta x \right| > \delta g$$

Gravity as spacetime curvature

-Tidal forces across wavefunction

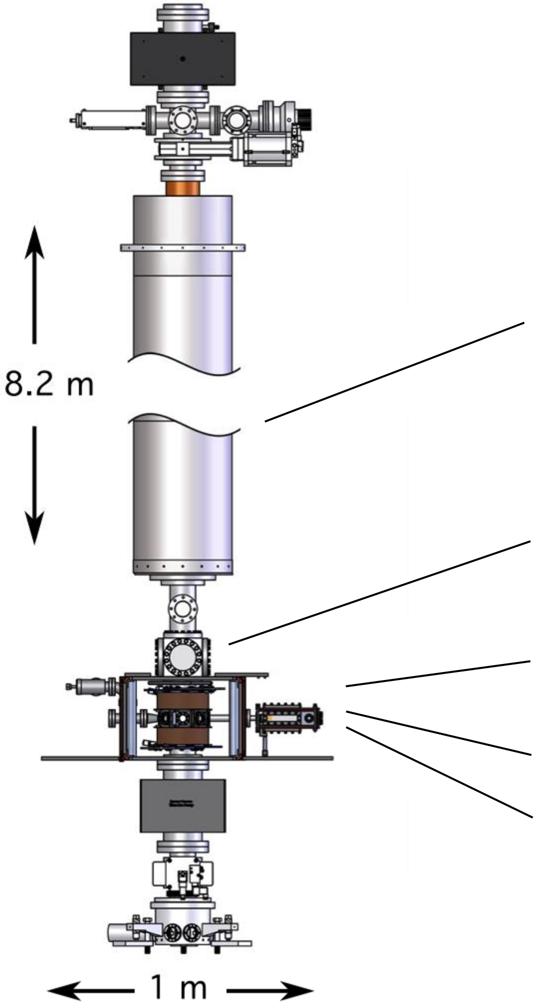


Tidal phase shift: $$\phi_{\text{tidal}} = \frac{\hbar}{2m} n^2 k^2 T_{zz} T^3$$

indicates “genuine gravitational effects in quantum interference as opposed to a mere test of the equivalence principle.”

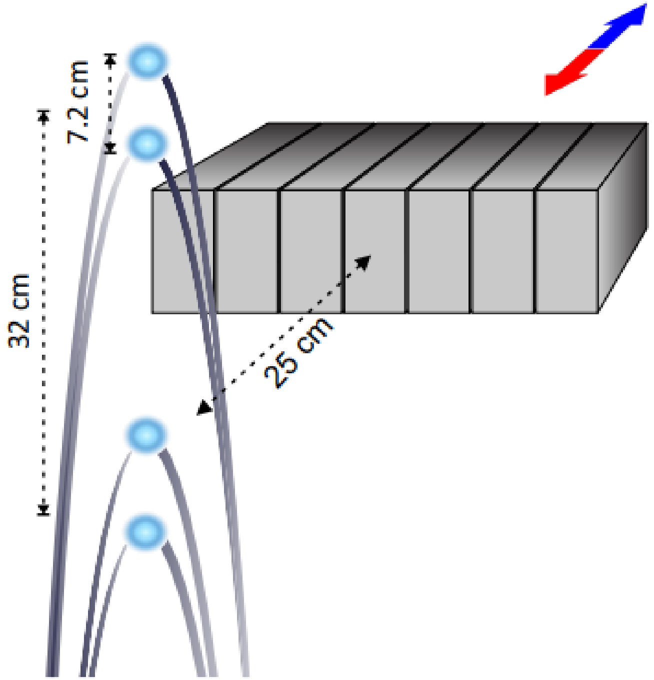
J. Anandan, *Phys. Rev. D* **30**, 8 (1984)

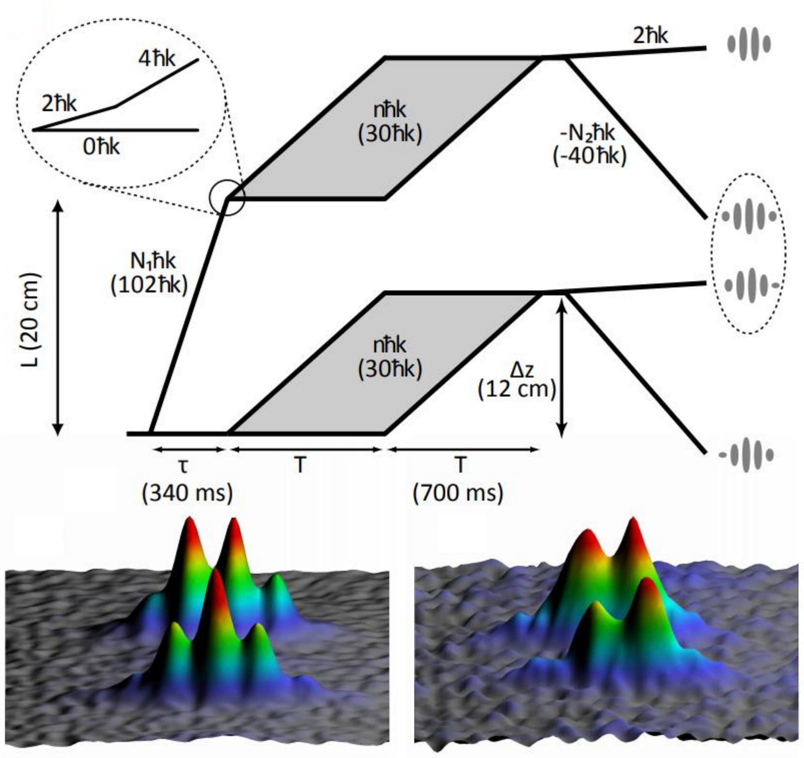
Apparatus



4. Atom interferometry
5. Fluorescence imaging
3. Lattice launch
2. Magnetic lens
1. MOT and evaporation

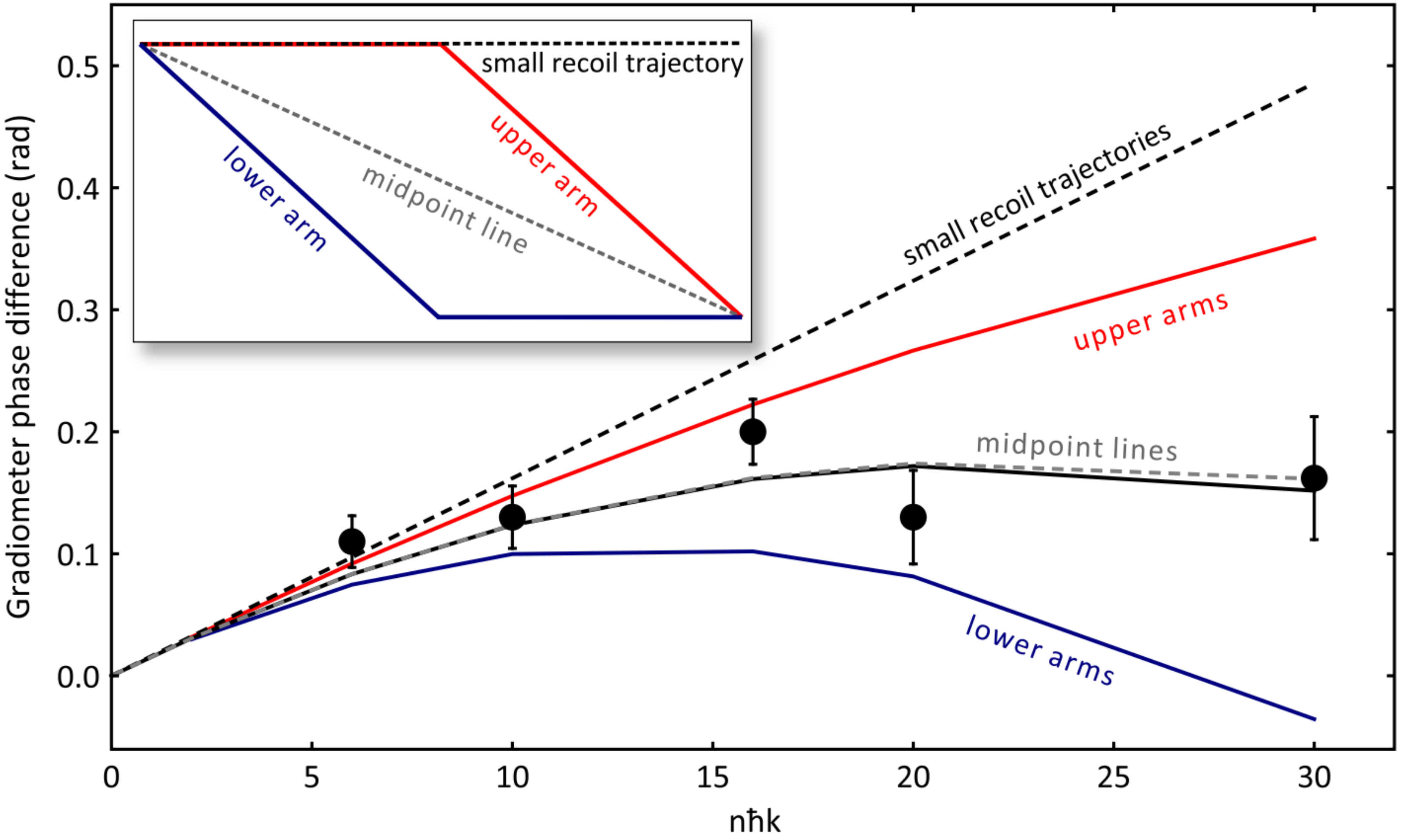
Nonlocal interferometer: implementation





P. Asenbaum et al., *Phys. Rev. Lett.* **118**, 183602 (2017)

Observation of the tidal phase shift



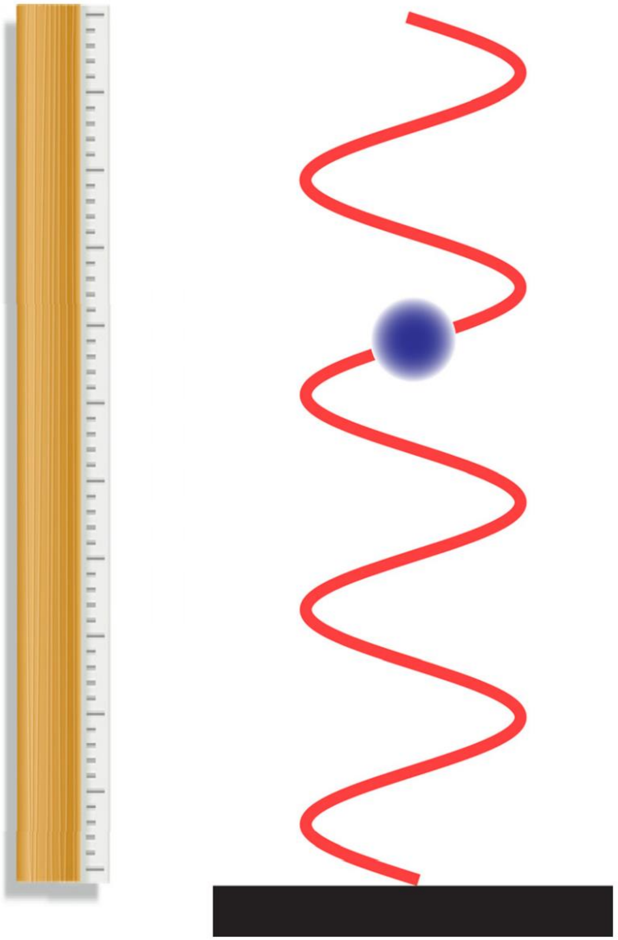
P. Asenbaum et al., *Phys. Rev. Lett.* **118**, 183602 (2017)

Outline

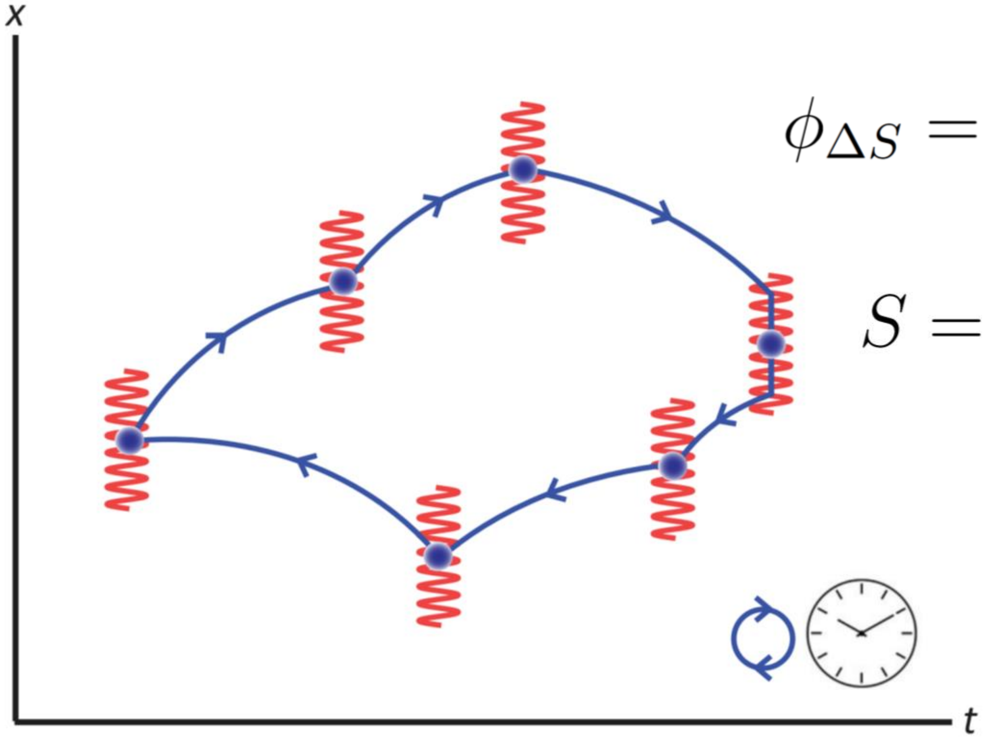
1. Spacetime curvature across a quantum state
2. Gravitational Aharonov-Bohm effect
3. Implications for gravitational field superposition
4. Future directions and prospects for MAGIS

Beyond the midpoint theorem

$$\phi = \phi_{\mathrm{MP}}$$



$$\phi = \phi_{\mathrm{MP}} + \phi_{\Delta S}$$



$$\phi_{\Delta S} = \frac{\Delta S}{\hbar}$$

$$S = \int \mathcal{L}(x, \dot{x}, t)\, dt$$

C. Overstreet et al., *Am. J. Phys.* **89**, 324 (2021)

The Aharonov-Bohm effect

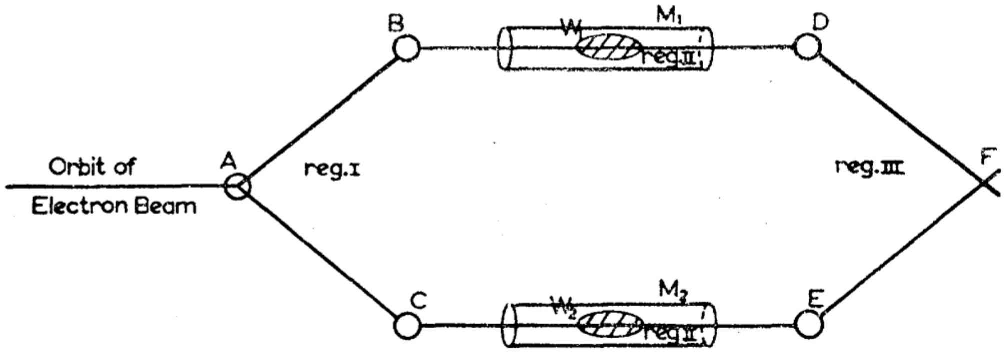


FIG. 1. Schematic experiment to demonstrate interference with time-dependent scalar potential. A, B, C, D, E: suitable devices to separate and divert beams. W_1, W_2: wave packets. M_1, M_2: cylindrical metal tubes. F: interference region.

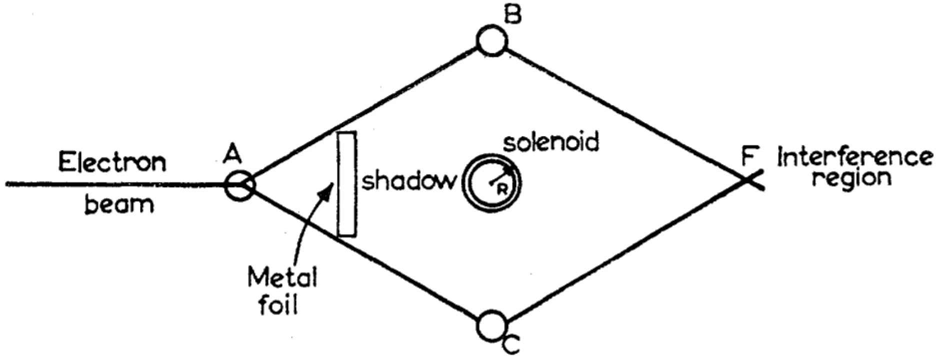


FIG. 2. Schematic experiment to demonstrate interference with time-independent vector potential.

Aharonov and Bohm, *Phys. Rev.* (1959)

Previous gravitational experiments: $\phi_{\Delta S} = 0, \ \phi = \phi_{\mathrm{MP}}$

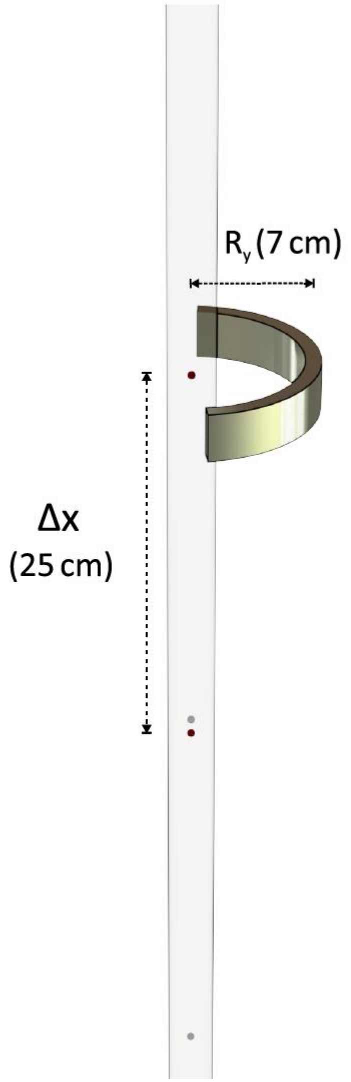
Aharonov-Bohm experiments: $\phi_{\mathrm{MP}} = 0, \ \phi = \phi_{\Delta S}$

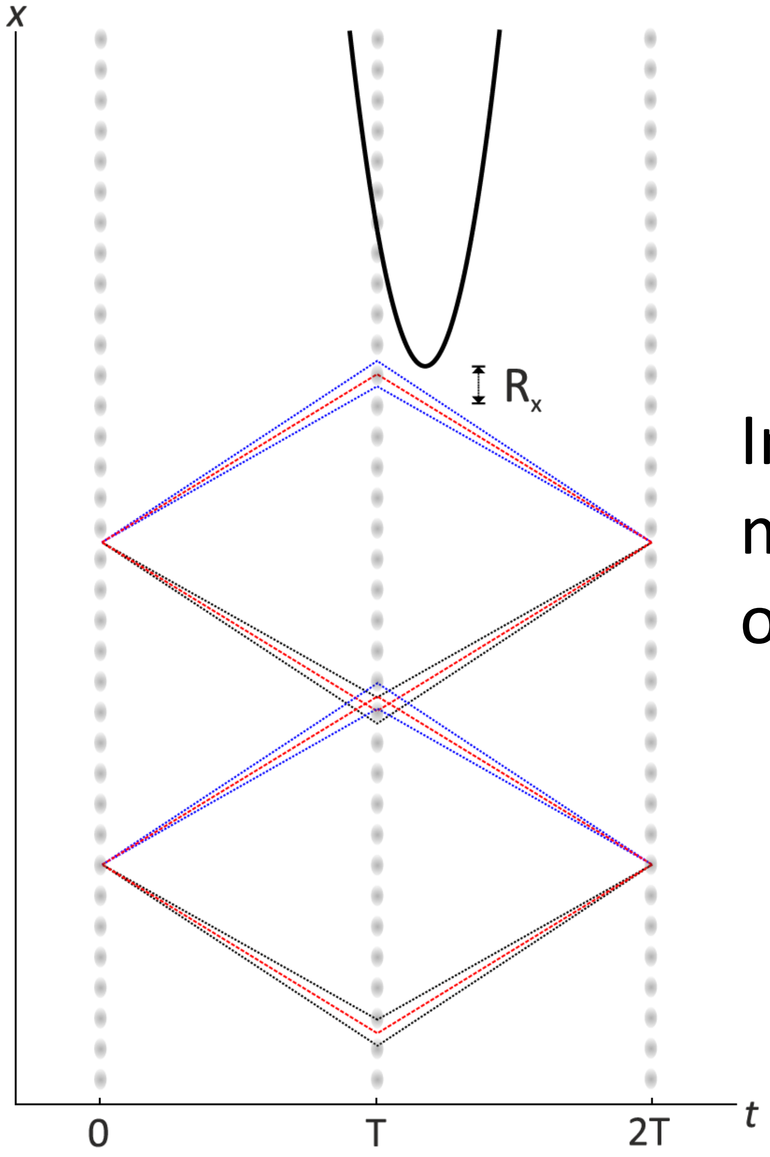
Gravitational Aharonov-Bohm?

J. Audretsch and C. Lämmerzahl, *J. Phys. A* (1983)
M. A. Hohensee et al., *Phys. Rev. Lett.* (2012)

Gravitational Aharonov-Bohm effect: ingredients

High-order potential
$R < \Delta x$

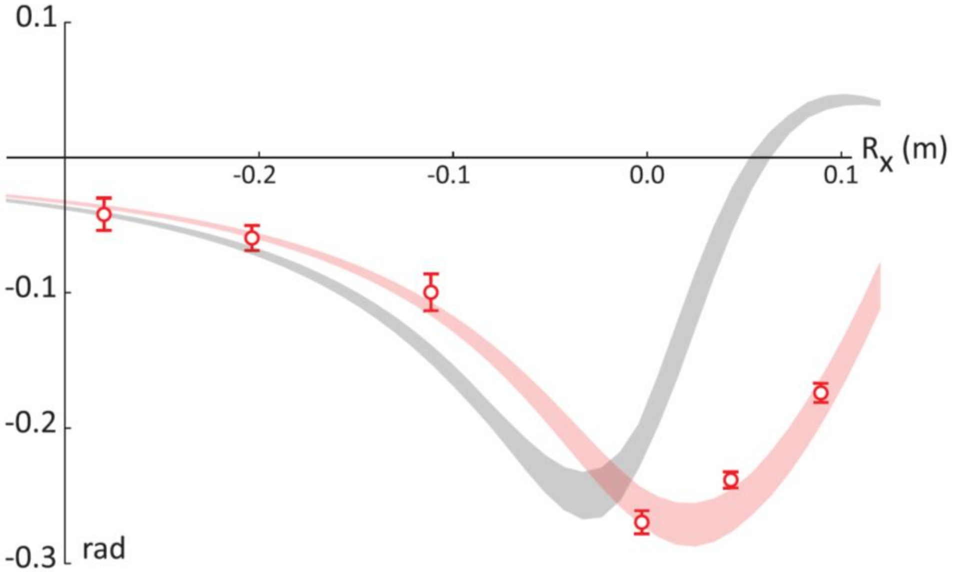




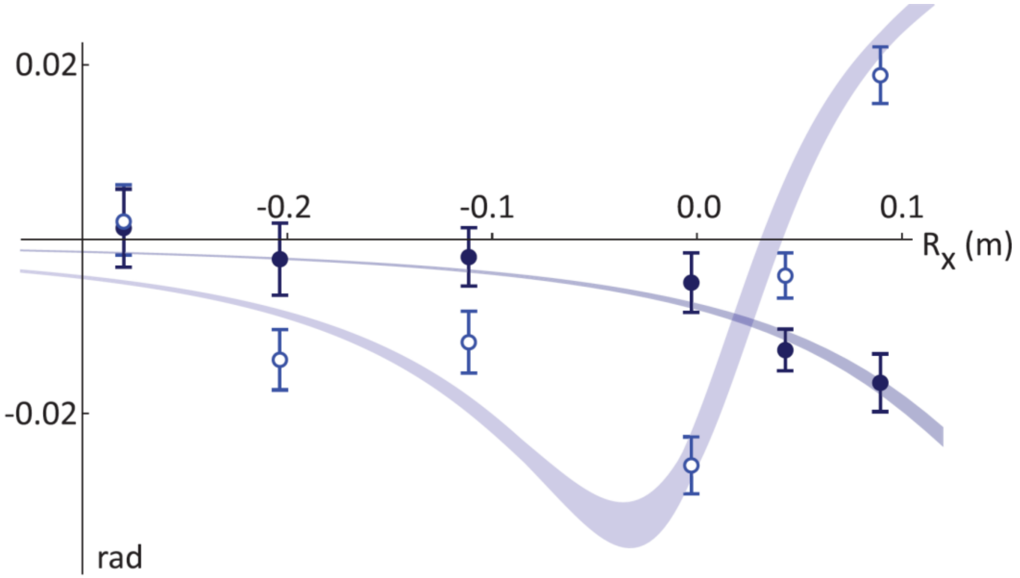
Independent measurement of deflections

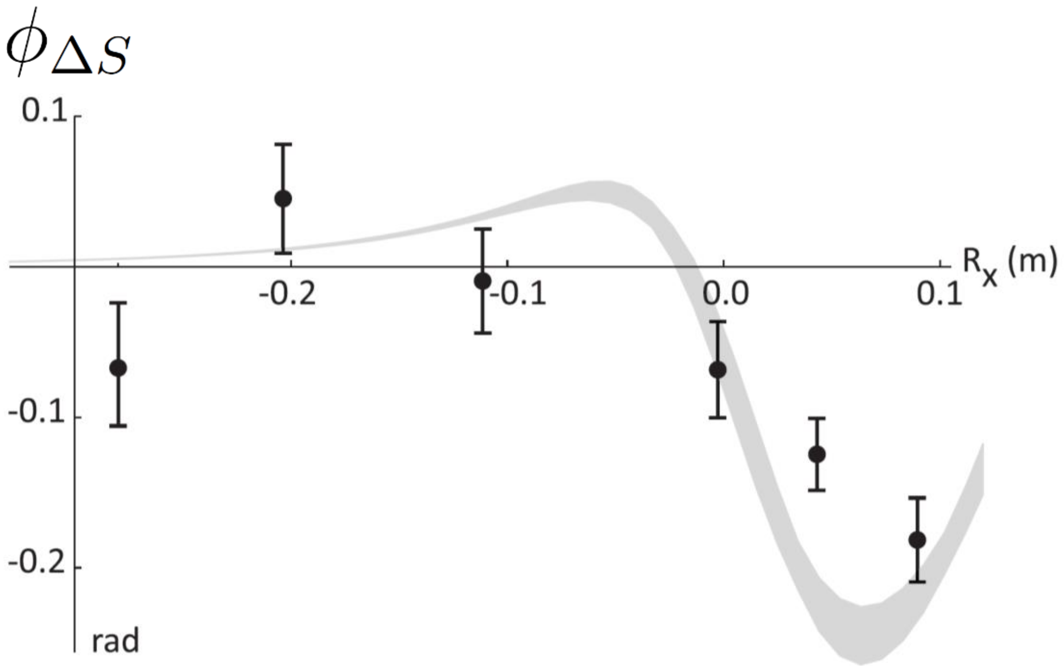
C. Overstreet, P. Asenbaum, et al., *Science* **375**, 226 (2022)

Gravitational Aharonov-Bohm effect: results



$$\phi_{\mathrm{MP}} = \frac{52}{4} \cdot \frac{1}{2} \left(\phi_{\mathrm{upper}} + \phi_{\mathrm{lower}}\right)$$





C. Overstreet, P. Asenbaum, et al., *Science* **375**, 226 (2022)

Outline

1. Spacetime curvature across a quantum state
2. Gravitational Aharonov-Bohm effect
3. Implications for gravitational field superposition
4. Future directions and prospects for MAGIS

Motivation: is gravity quantum or classical?

The success of quantum field theory in describing all other interactions suggests that gravity is quantum.

Gravity is well-described in the low-energy (linearized) limit as a spin-2 quantum field.

BUT:

-GR QFT is not perturbatively renormalizable.
-Our best theory of gravity (GR) is classical.
-Semiclassical gravity is mathematically well-defined.

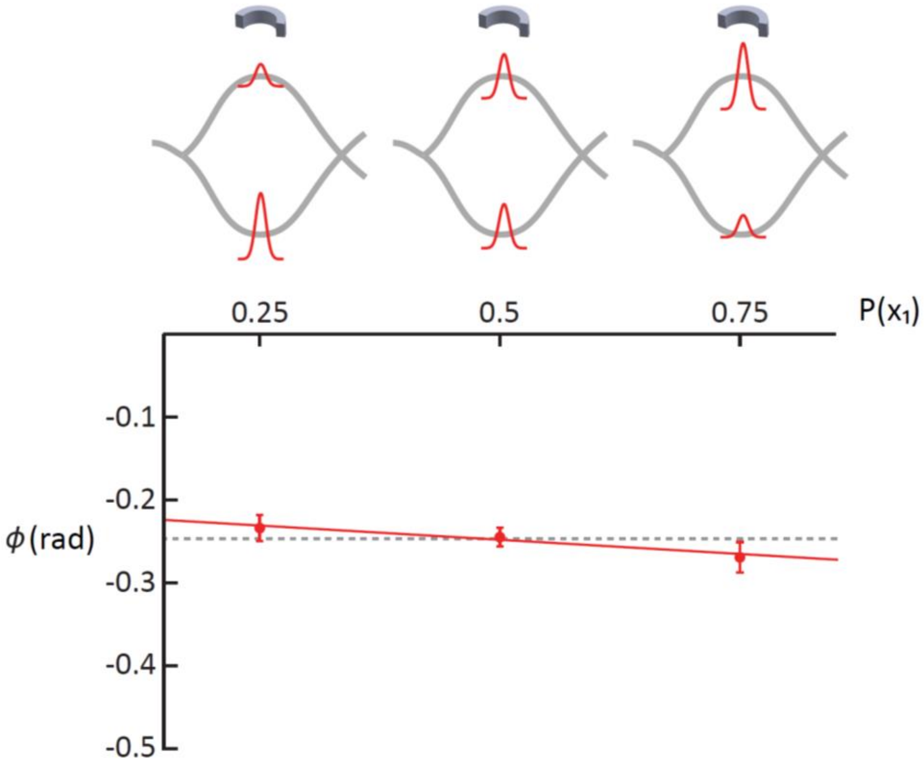
Problem: no experimental input!

Field energy principle

Classical physics: potential energy of a particle = energy of the field

$$U_{\mathrm{EM}} = qV_{\mathrm{EM}} = \frac{1}{2}\epsilon_0 \int |\mathbf{E}|^2 dV$$

-Also true in quantum mechanics



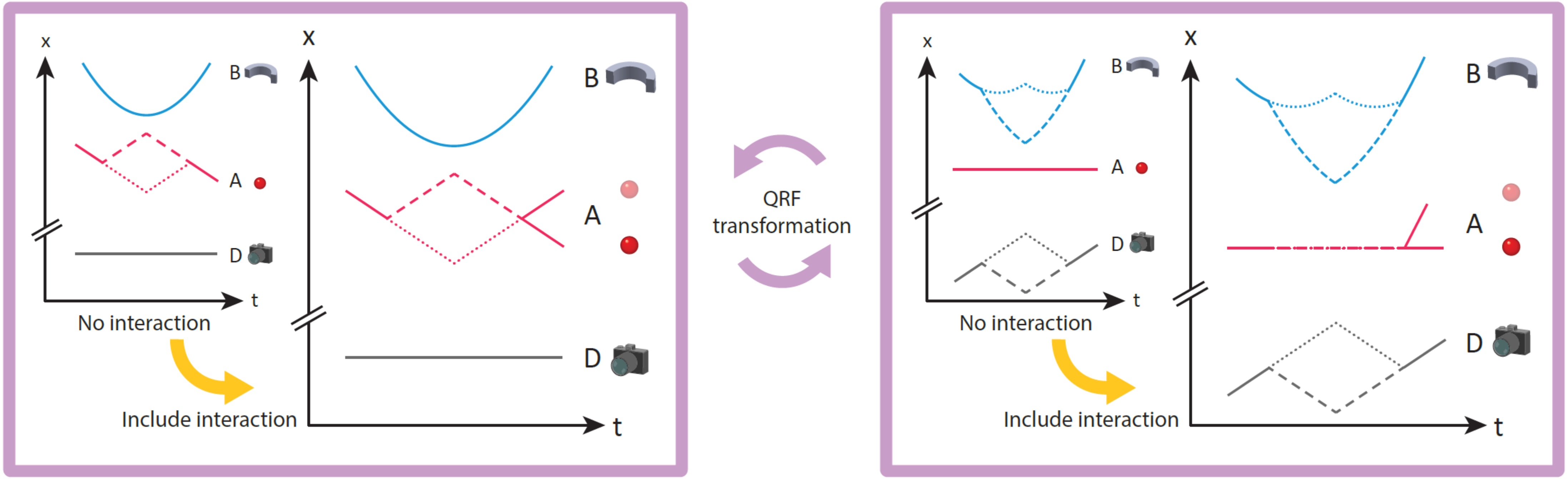
Field energy principle: potential energy
is located in the field

C. Overstreet et al., arXiv:2209.02214 (2022)

Quantum relativity principle

Relativity principle (RP): laws of physics take the same form in every coordinate system

Quantum relativity principle (QRP): extends RP to quantum reference frames



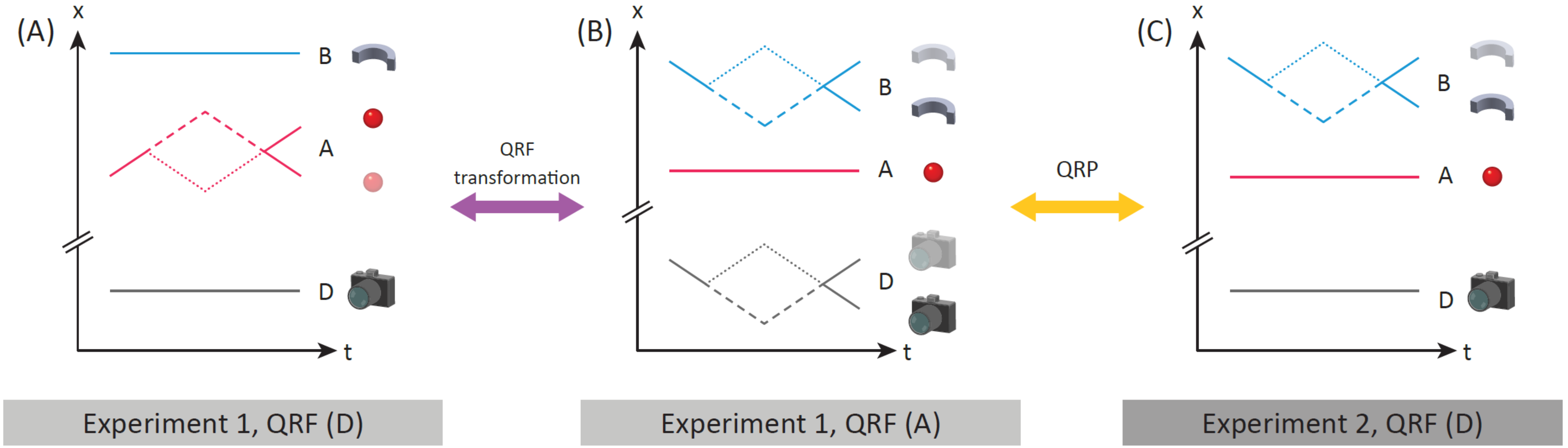
C. Overstreet et al., arXiv:2209.02214 (2022)

Implications for the nature of gravity

-Semiclassical gravitational models must reject field energy principle and quantum relativity principle

-Schrödinger-Newton, Oppenheim models not ruled out

-QRP test: effect of lower-mass particle on a higher-mass superposition



C. Overstreet et al., arXiv:2209.02214 (2022)

Outline

1. Spacetime curvature across a quantum state
2. Gravitational Aharonov-Bohm effect
3. Implications for gravitational field superposition
4. Future directions and prospects for MAGIS

Direction 1: how do quantum systems react to gravity?

What we've learned: the trajectory and the action of a quantum system in a Newtonian gravitational field are correctly predicted by quantum mechanics.

Next steps: beyond the Newtonian approximation (GR phase shifts)

-Nonlinearity of gravity

-Gravitation of kinetic energy

-Others?

Simulation/design work could be useful here!

S. Dimopoulos et al., *Phys. Rev. D* **78**, 042003 (2008)

Direction 2: how do quantum systems source gravity?

To test semiclassical gravity, need to create a high-mass superposition state (~10^{12} amu)

State of the art: 2.5 x 10^4 amu (Fein 2019)

Idea: use atoms! The effective mass of N entangled atoms of mass m is Nm.

Goal: > 10^{10} highly entangled atoms in a spatial superposition

-Note that 10^6 atoms with 20 dB squeezing would improve the state of the art!

Acknowledgments

EP team: Minjeong Kim, Joseph Curti, Mark Kasevich

EP alumni: Jason Hogan, Dave Johnson, Sheng-wey Chiow, Susannah Dickerson, Alex Sugarbaker, Christine Donnelly, Remy Notermans, Tim Kovachy, Peter Asenbaum