Gravity in large quantum states & Aharonov-Bohm effect

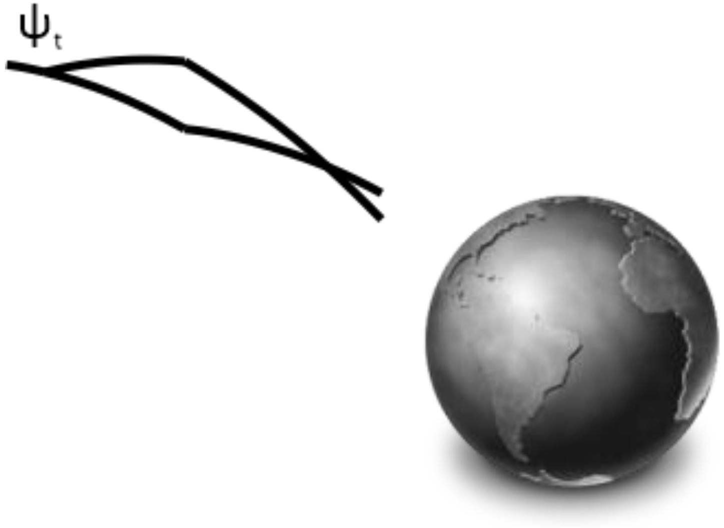
Peter Asenbaum

Mark Kasevich

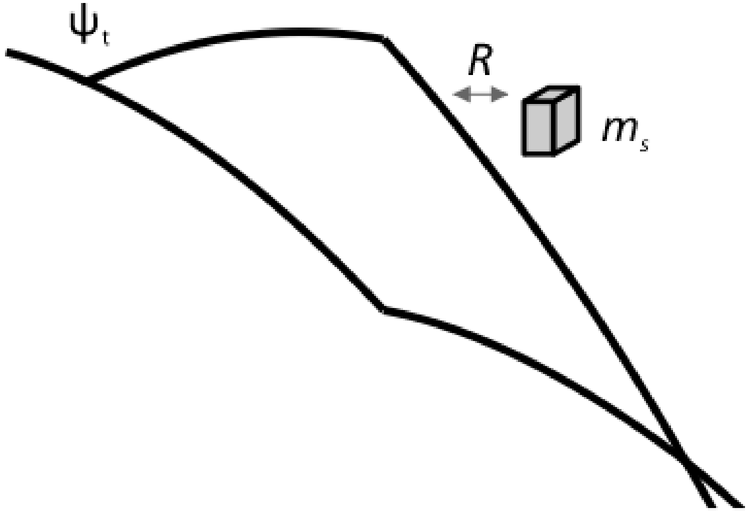
Chris Overstreet

Joe Curti

Minjeong Kim



classical

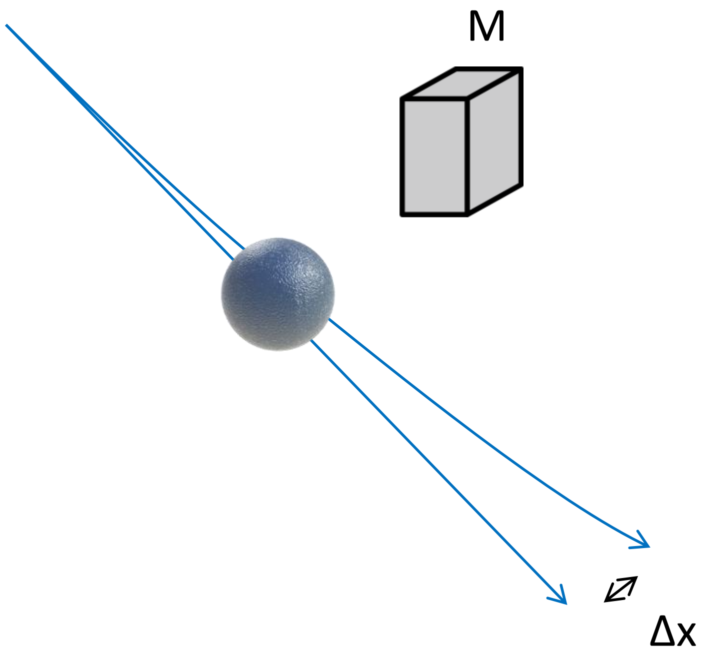


quantum

Humboldt-Kolleg, Kitzbühel 2022

Gravitational measurement

classical particle

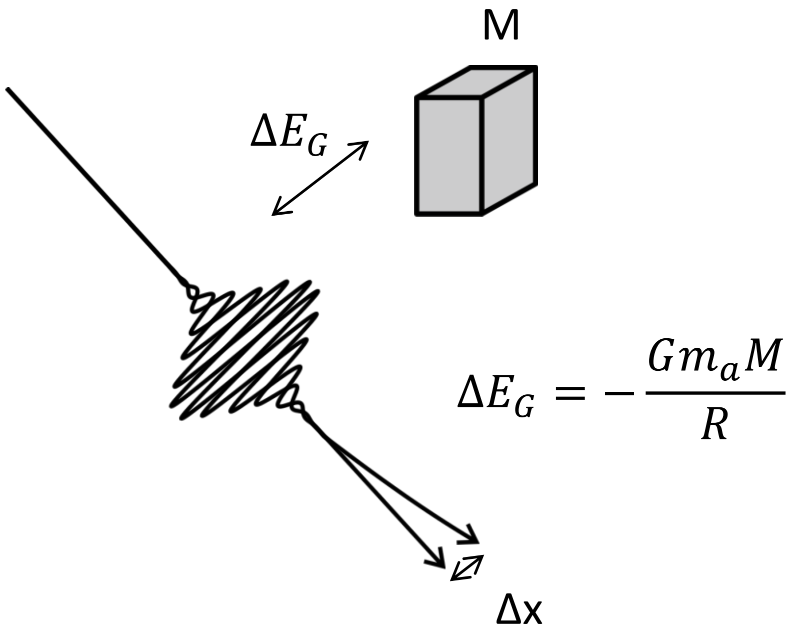


$\Delta x \; \propto \; G\, M/R^2$

Independent of m

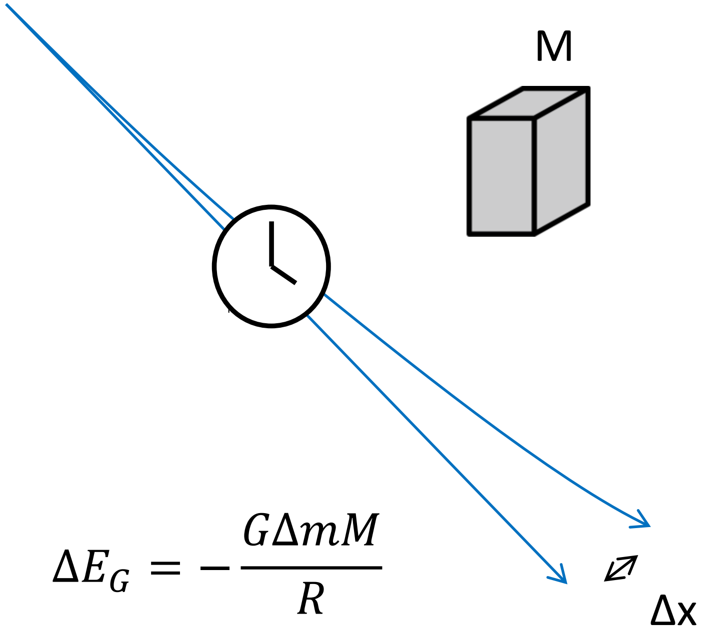
Use light-ruler ➡ $k\Delta x$

wave packet



m-dependent

clock

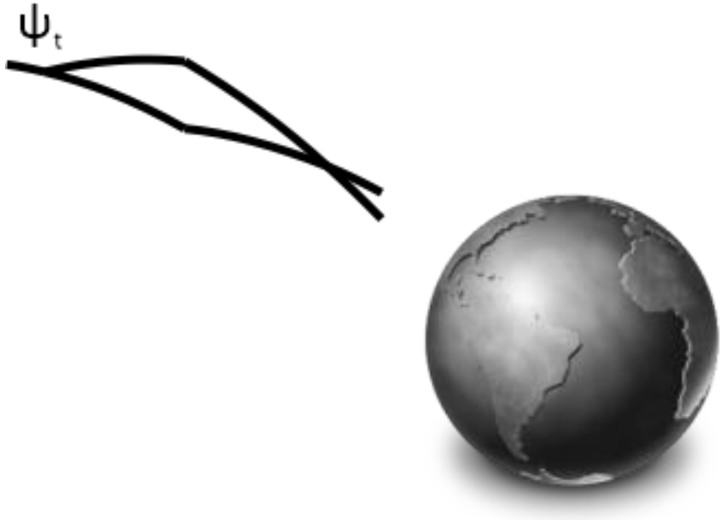


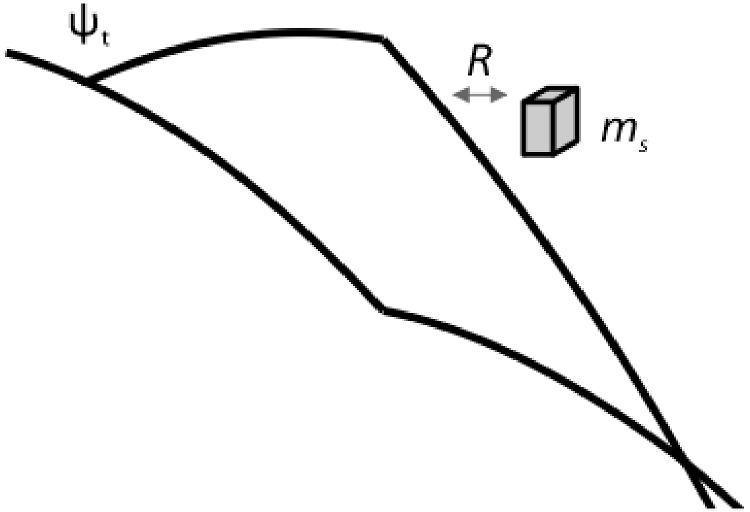
$\frac{\Delta m}{M} \approx 10^{-11}$

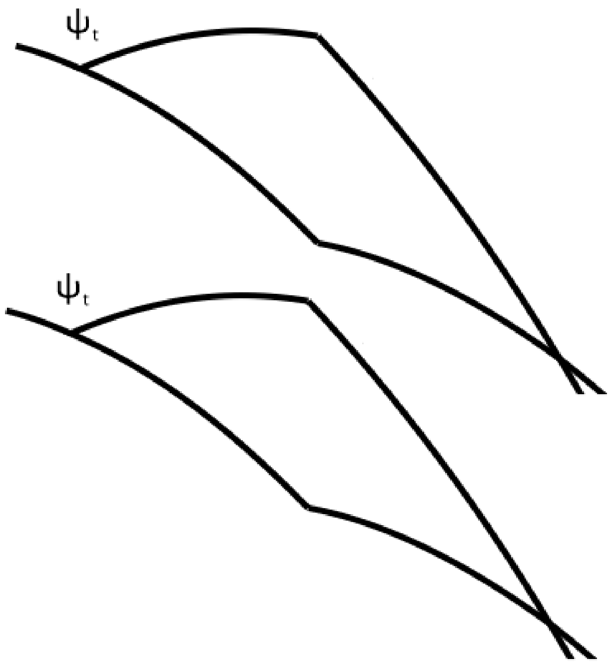
Lower sensitivity

How Quantum is Gravity?

ψ_t … spatial superposition state







classical

$$\phi = k\Delta \mathrm{x}$$

acceleration

quantum

$$\phi = \frac{m}{\hbar}\frac{GM}{R}\tau$$

Grav. Energy

entanglement

For two large quantum states:

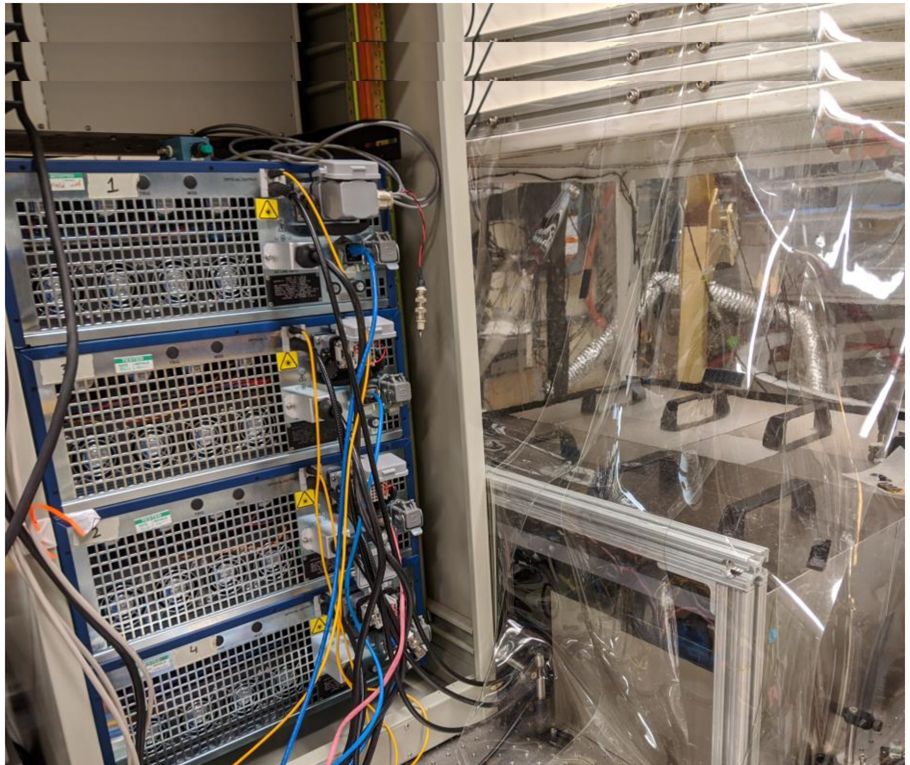
$$\phi = \frac{m_1}{\hbar}\frac{Gm_2}{R}\tau$$

Cold atoms & Interferometer

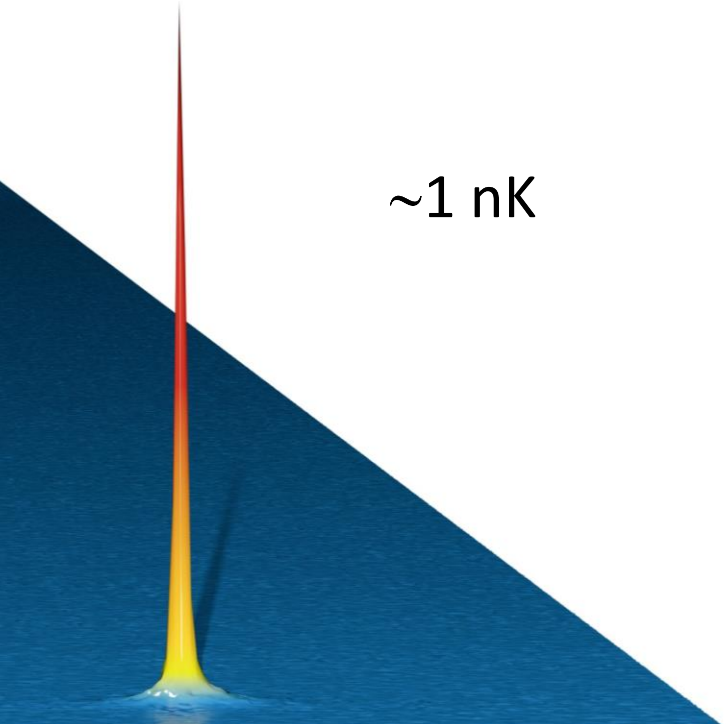
Vacuum

2.6 s free fall

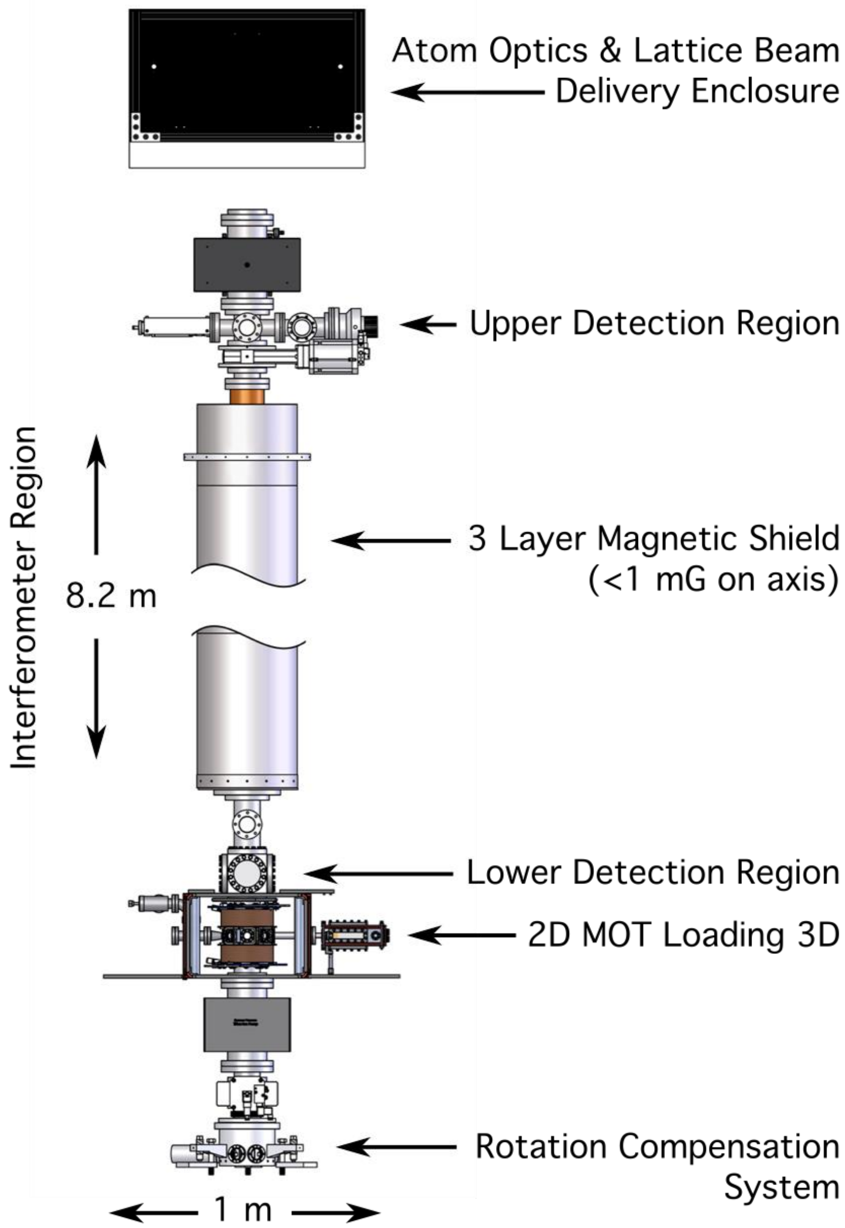
Laser Gratings



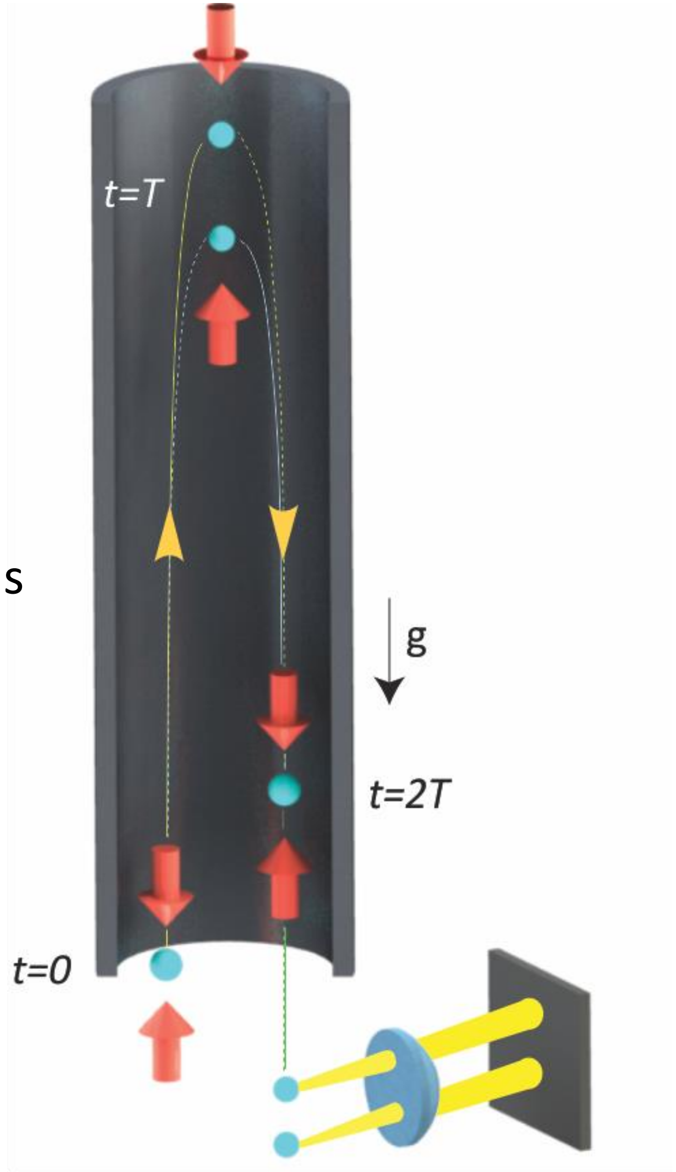
~1 nK



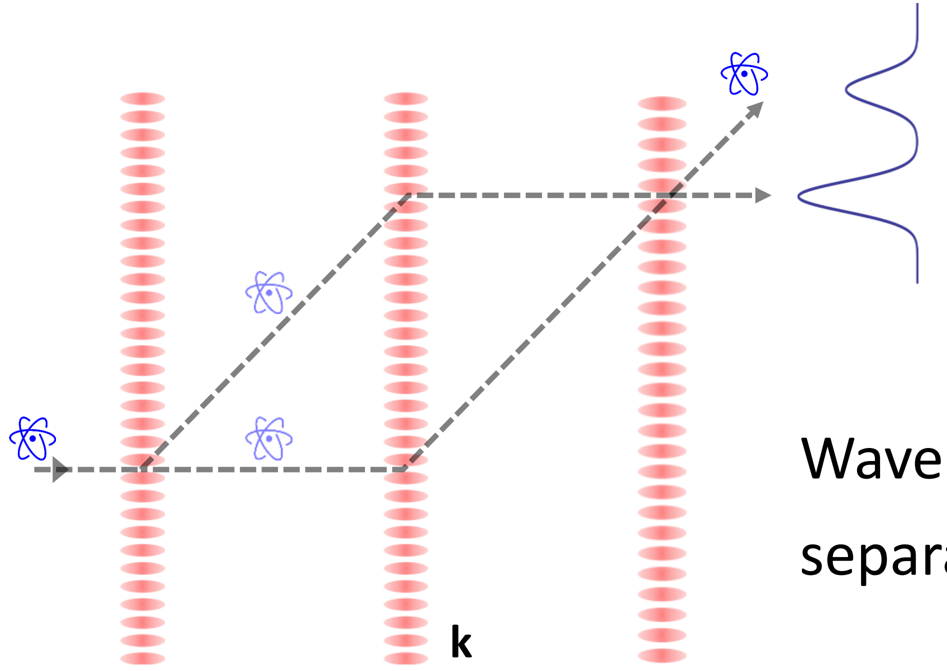
10 m atomic Fountain



T ≈ 1 s



Atom Interferometer



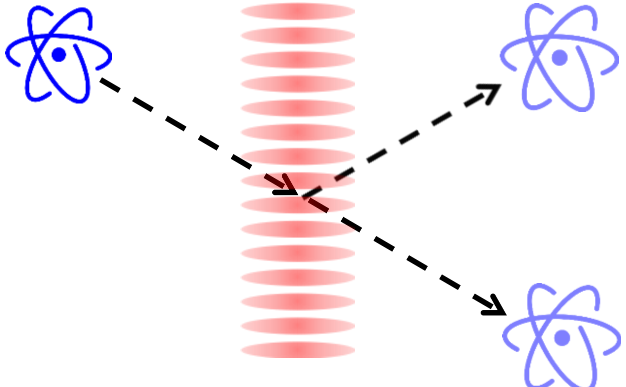
$$2\frac{P_1}{P_2 + P_1} - 1 = \cos\phi$$

Wave packet

separation $\frac{\hbar k}{m} T$

k inverse de-Broglie wavelength

Bragg beam splitter



Interferometer phase

$$\phi = \sum \boldsymbol{k_i}\, \boldsymbol{x_i} + \Delta S$$

$\boldsymbol{k_i}\, \boldsymbol{x_i}$ … “classical quantities”

ΔS … action difference

ΔS=0 for up to potential order 2
Antoine, Bordé (2003).

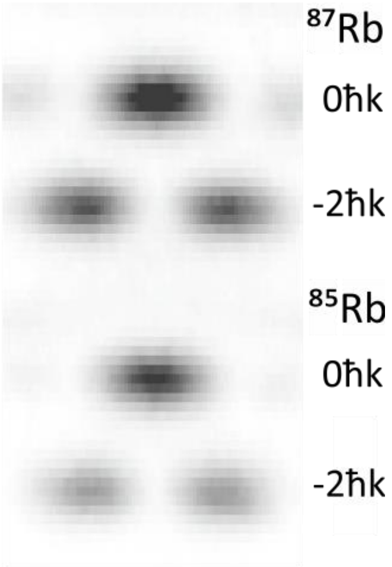
How well do we know its not dependending on the mass?

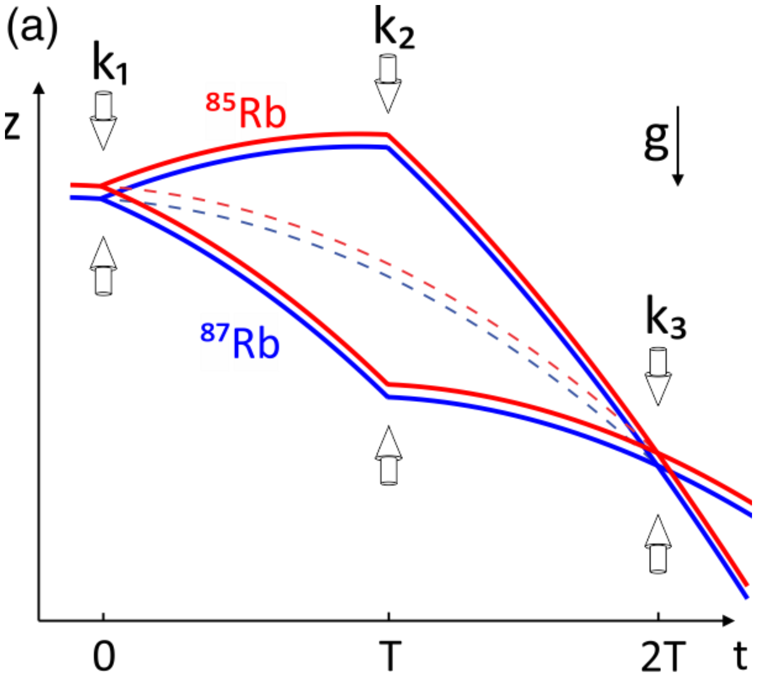
Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are suppressed by calibrating the angles and frequencies of the interferometry beams. We find an Eötvös parameter of $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$, consistent with zero violation of the equivalence principle. With a resolution of up to 1.4×10^{-11} g per shot, we demonstrate a sensitivity to η of $5.4 \times 10^{-11}/\sqrt{\mathrm{Hz}}$.



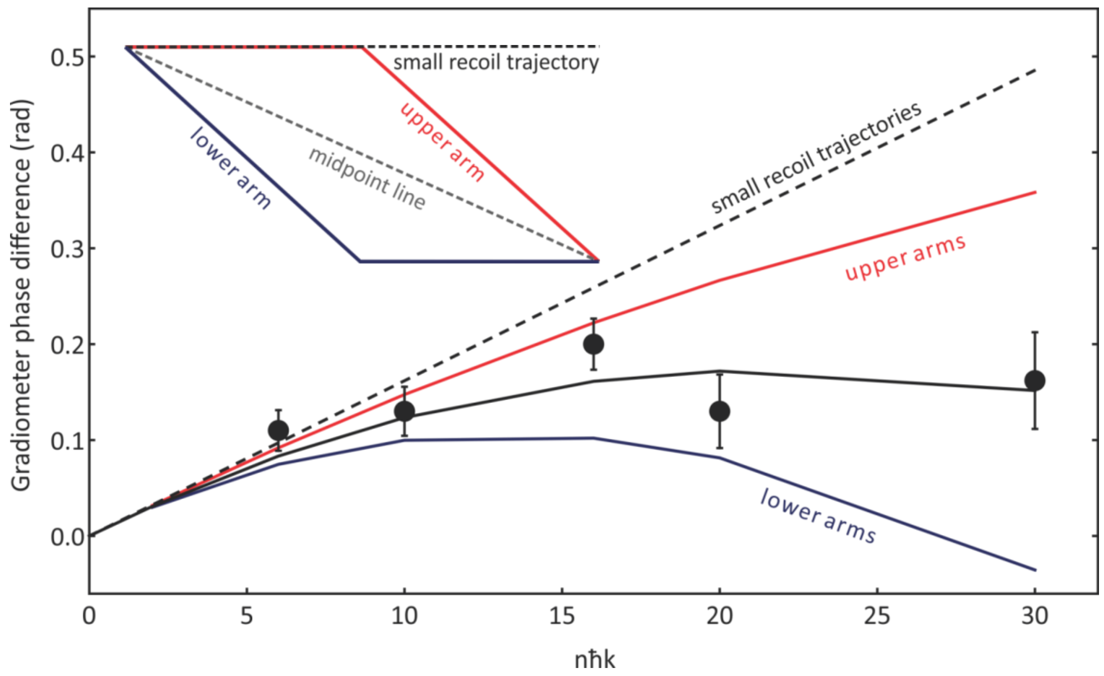


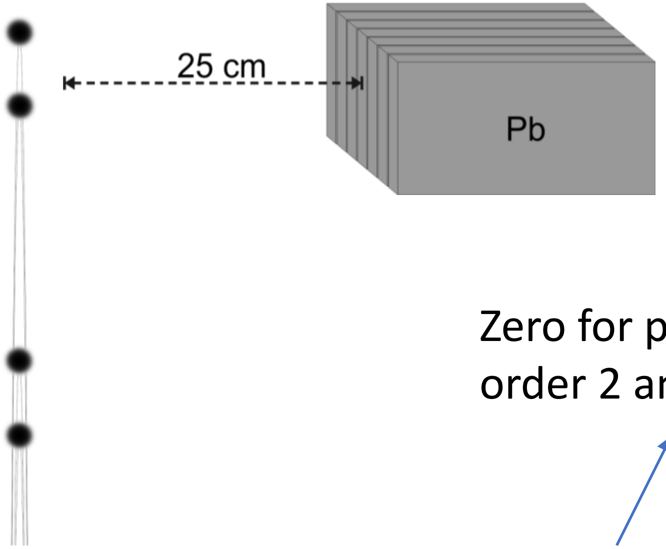
PRL 118, 183602 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function

Peter Asenbaum,[1] Chris Overstreet,[1] Tim Kovachy,[1] Daniel D. Brown,[2] Jason M. Hogan,[1] and Mark A. Kasevich[1]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
(Received 13 October 2016; published 1 May 2017)

Spacetime curvature induces tidal forces on the wave function of a single quantum system. Using a dual light-pulse atom interferometer, we measure a phase shift associated with such tidal forces. The macroscopic spatial superposition state in each interferometer (extending over 16 cm) acts as a nonlocal probe of the spacetime manifold. Additionally, we utilize the dual atom interferometer as a gradiometer for precise gravitational measurements.





Zero for potentials order 2 and lower

$$\phi = k\Delta x + \Delta S$$

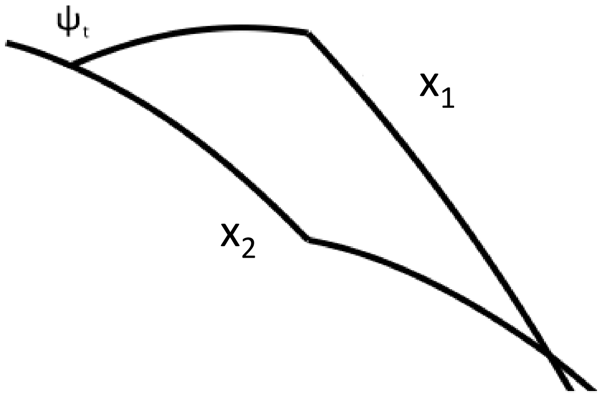
Significance of Electromagnetic Potentials in the Quantum Theory

Y. Aharonov and D. Bohm
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England
(Received May 28, 1959; revised manuscript received June 16, 1959)

EM: Potential vs Field

Gravity: pot. Energy or acceleration ?

Perturbation Theory



Interferometer phase ϕ

$$\phi = \frac{m}{\hbar}\int V_t(x_1) - V_t(x_2)dt$$

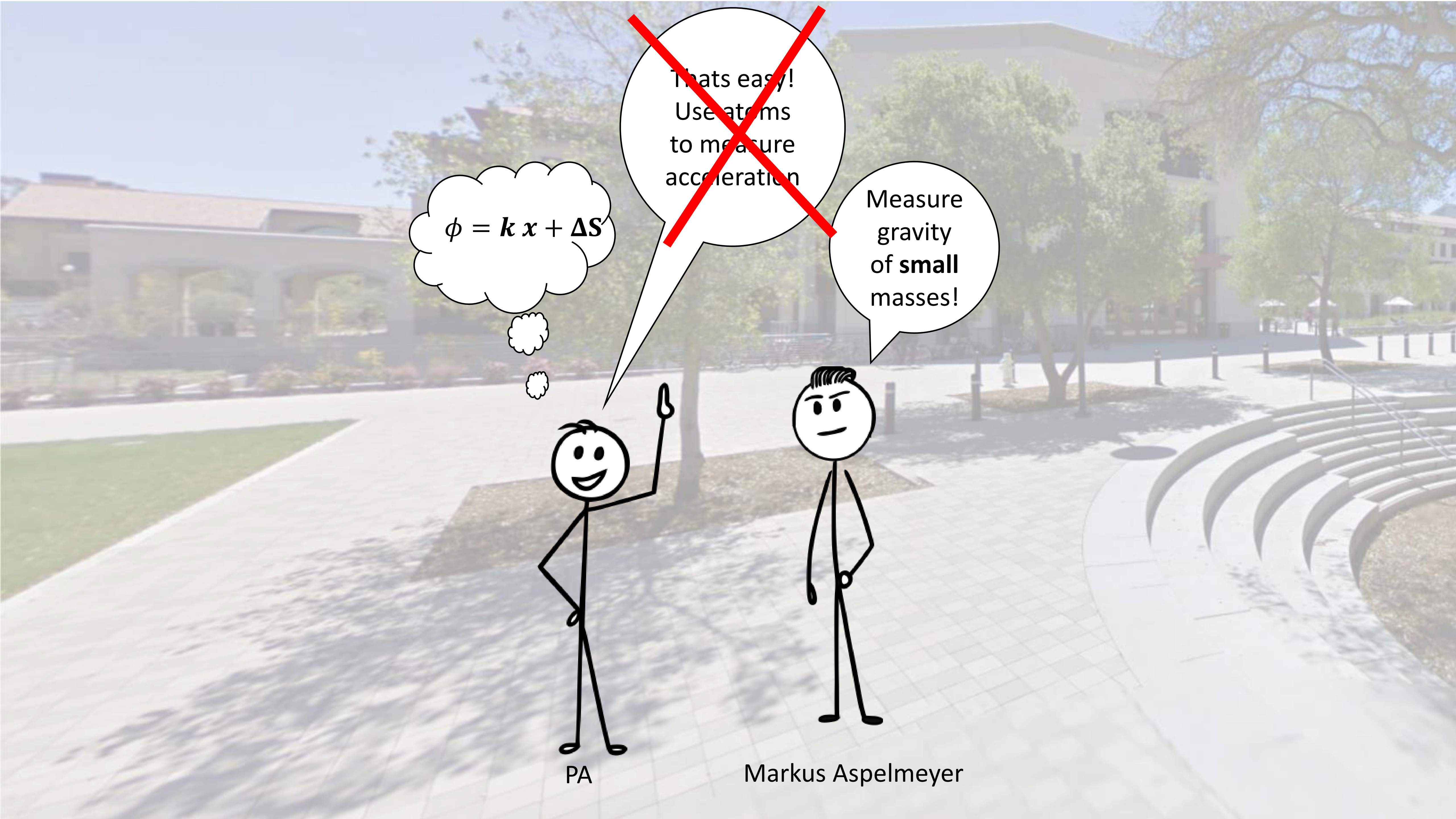
Aharonov-Bohm phase like $\phi_C = \frac{q}{\hbar}\int \Delta V_C dt$ with Coulomb Potential V_c?

For small quantum states (small k or large m)

$$V_t(x_1) - V_t(x_2) \propto \frac{\partial V}{\partial x} \cdot \hbar k/m$$

$$\phi \approx k\Delta x$$ ✓ $$\phi = k\Delta x + \overbrace{\Delta S}^{0}$$

k ➡ acceleration (classical quantity)


$\phi = k\,x + \Delta S$
Thats easy! Use atoms to measure acceleration
Measure gravity of **small** masses!
PA
Markus Aspelmeyer

Large quantum state regime

Perturbation Theory: $$\phi = \frac{m}{\hbar}\int V_t(x_1) - V_t(x_2)dt$$

Interferometer phase ϕ

For large quantum states (large k) $$\phi = \frac{m}{\hbar}\int V_t(x_1)dt$$

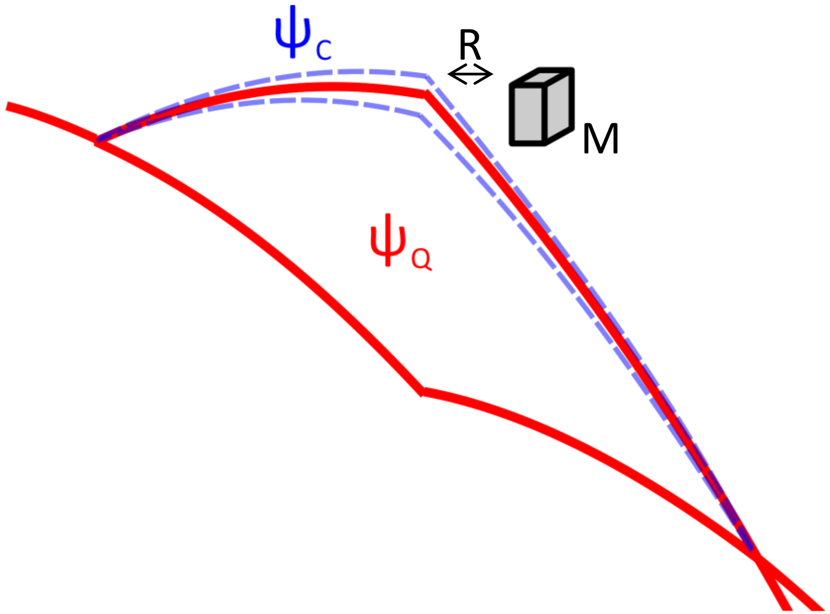
Depends on:

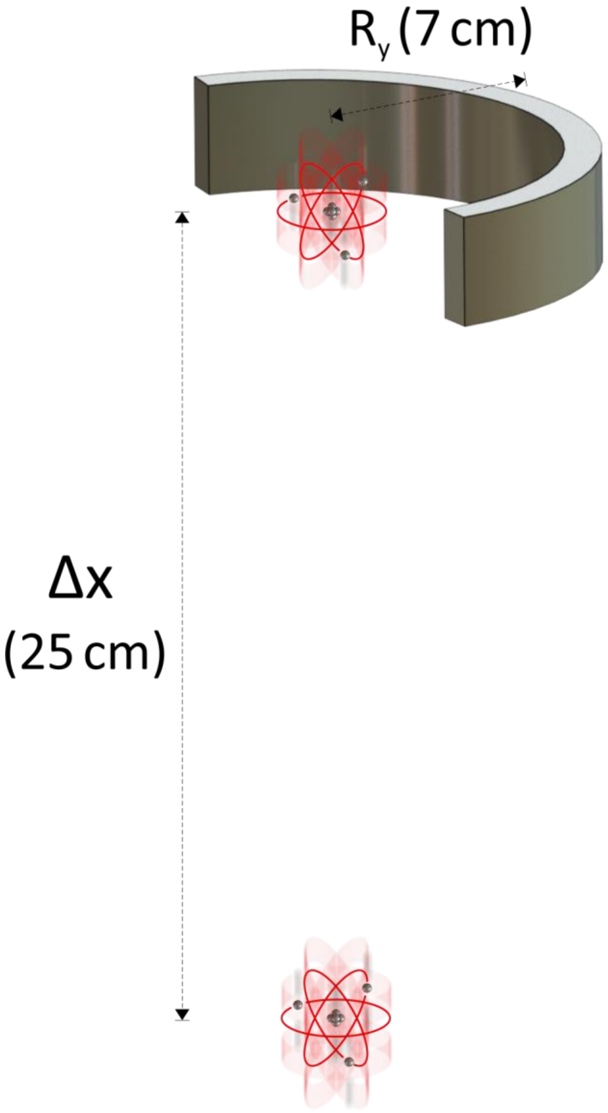
- gravitational mass of single atom
- Big G
- ħ

No dependence on size
Non-dispersive (no contrast loss)

m/ħ ➡ energy (quantum)

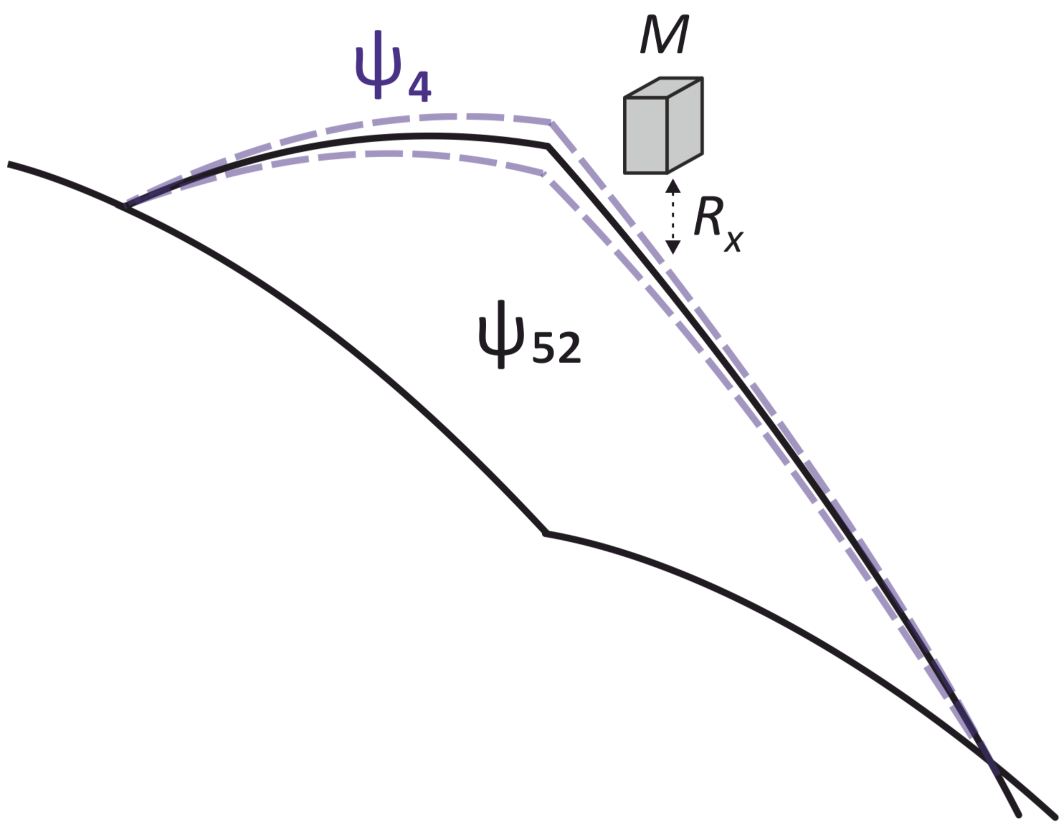
Interferometer geometry

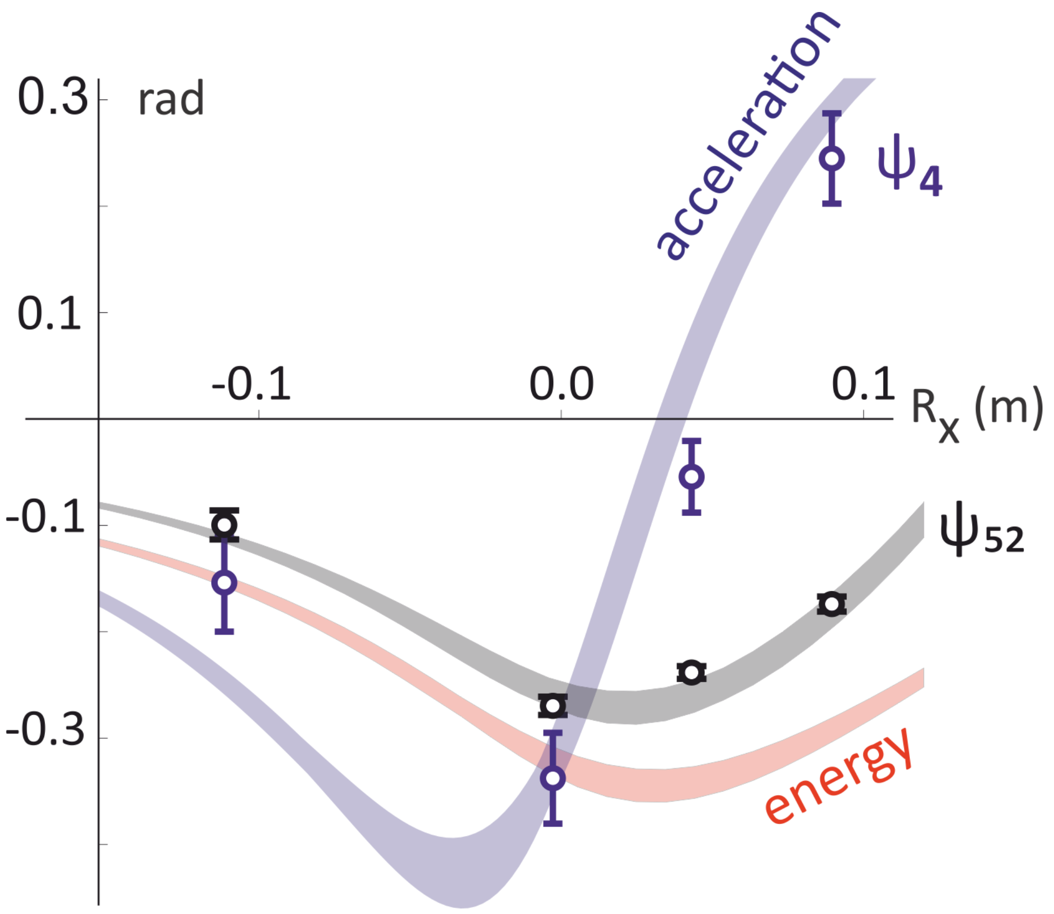




Observation of a gravitational Aharonov-Bohm effect
Science **375**, 226 (2022)

Acceleration vs grav. Energy





Grav. Energy is Significant!

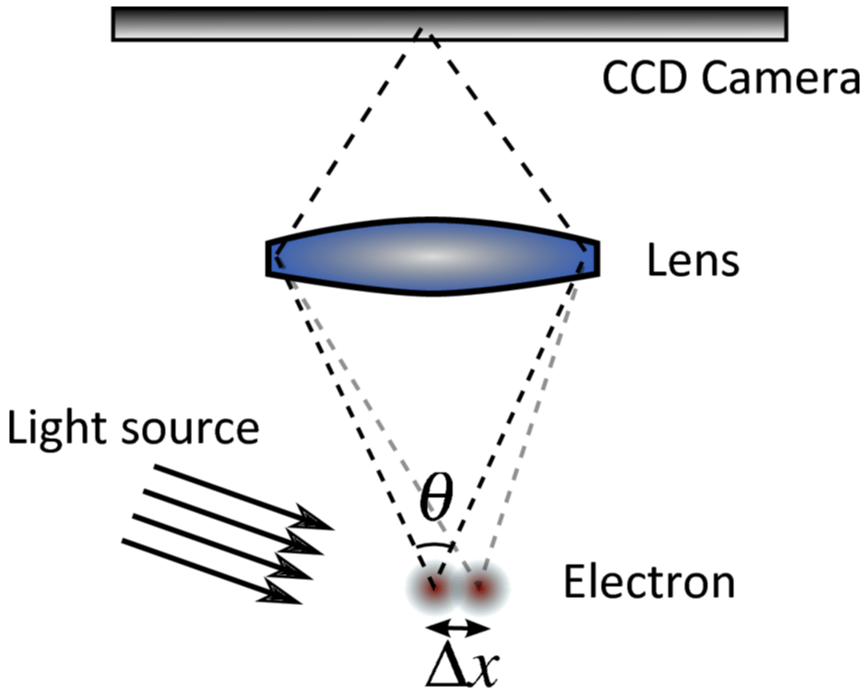
Acceleration stays hidden!

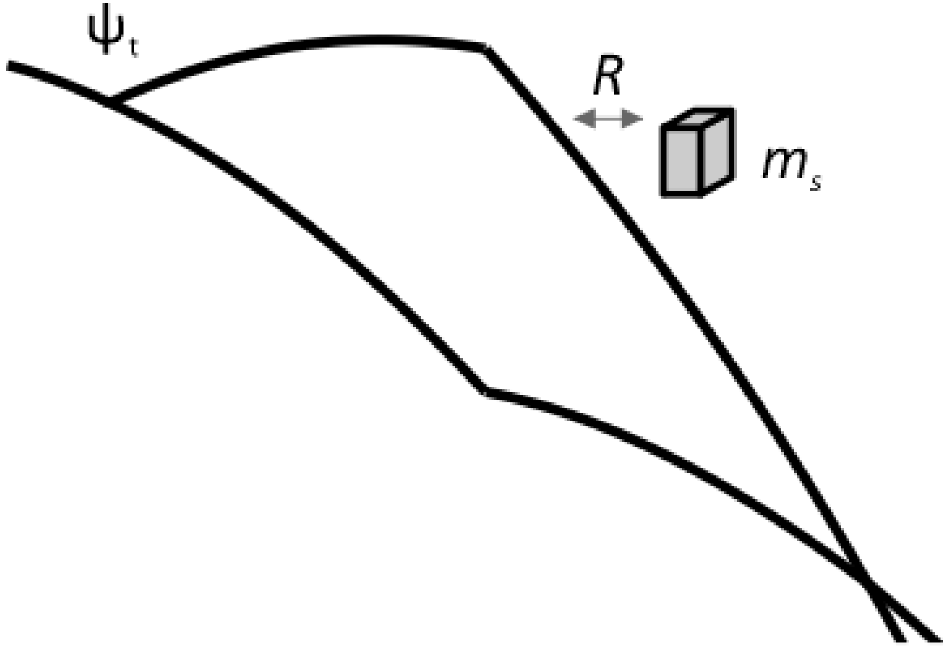
Quantum interaction test:

Heisenberg Error-disturbance relation

Busch, Lathi, Werner PRL 2013

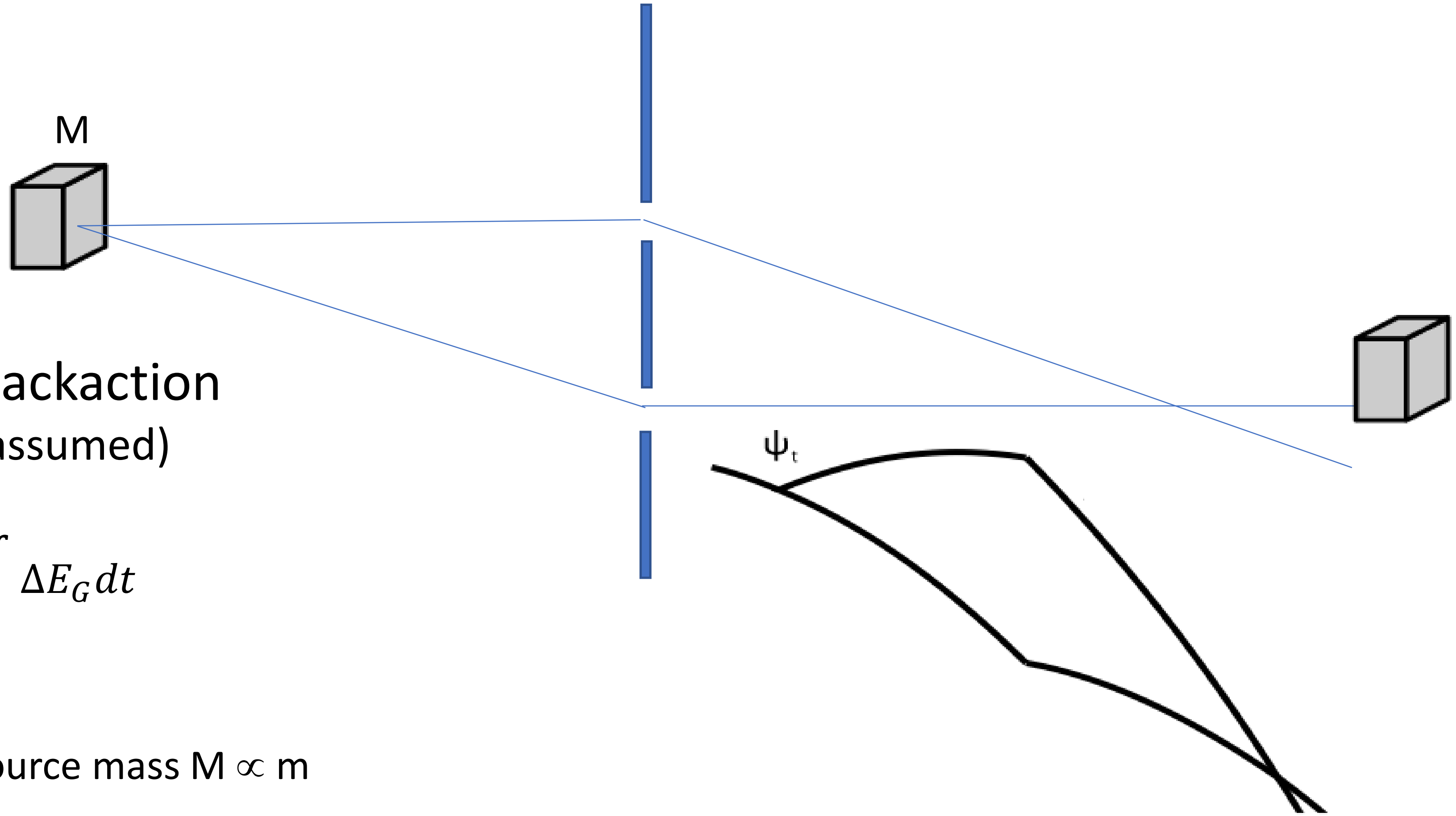
Heisenberg microscope





Position information is proportional to amount of momentum backaction

Heisenberg EDR



Information $\propto$ Backaction (assumed)

$$\phi = \frac{m}{\hbar}\int \frac{GM}{R}dt \qquad \int \Delta E_G dt$$

Backaction from atom on source mass M $\propto$ m

k dependent information on source mass would violate Heisenberg

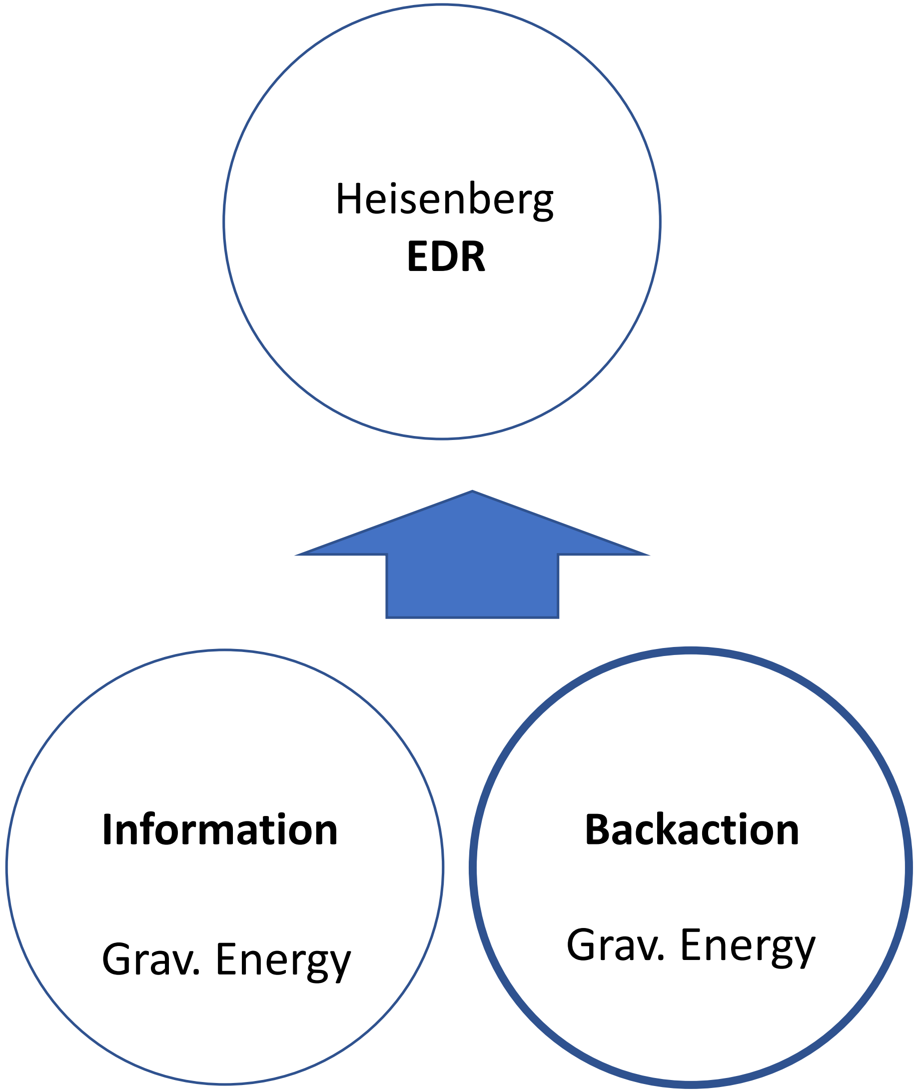
Independent of k ✓ (No acceleration)

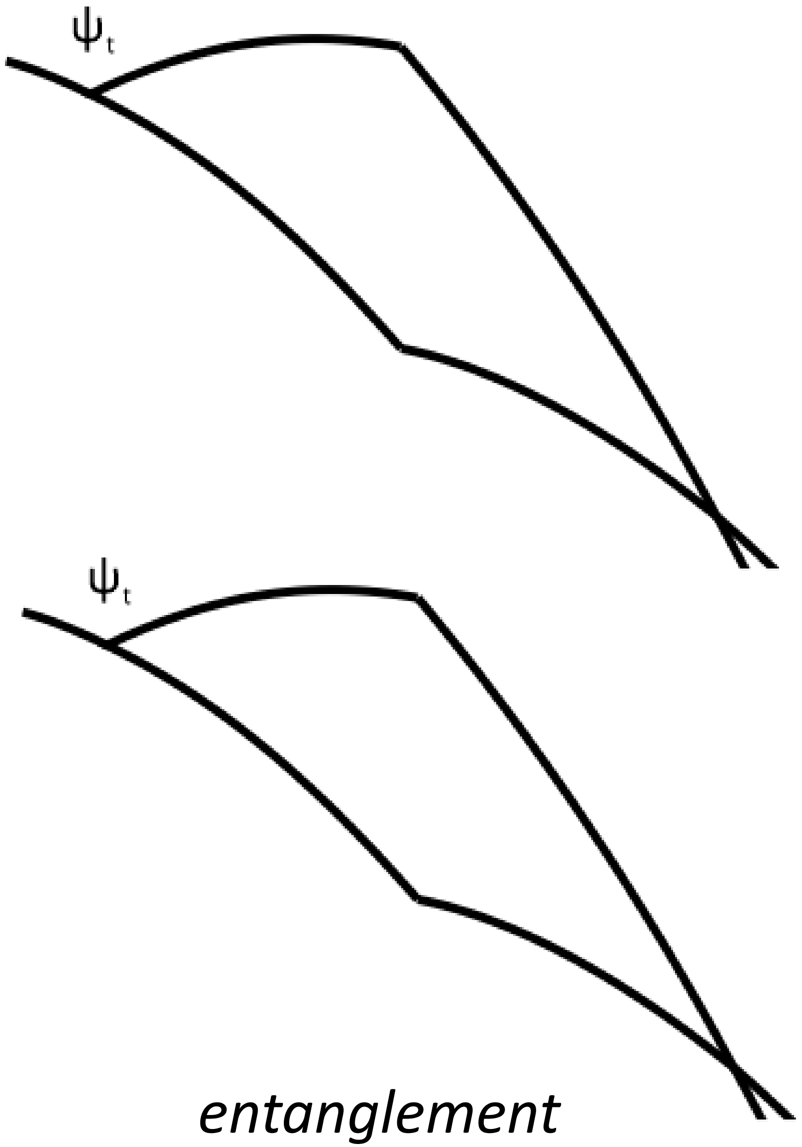
Information $\propto$ m ✓

Which-path detector:

Quantum state Ψ_t

Outlook


Heisenberg
EDR
Information
Grav. Energy
Backaction
Grav. Energy


ψ_t
ψ_t
entanglement

Summary

Comparision of Classical and Quantum measurement

Large quantum states cannot measure acceleration

Gravity does not allow for classical measurements (Heisenberg EDR)

Gravity measurement does not depend on $|\Psi^2|$