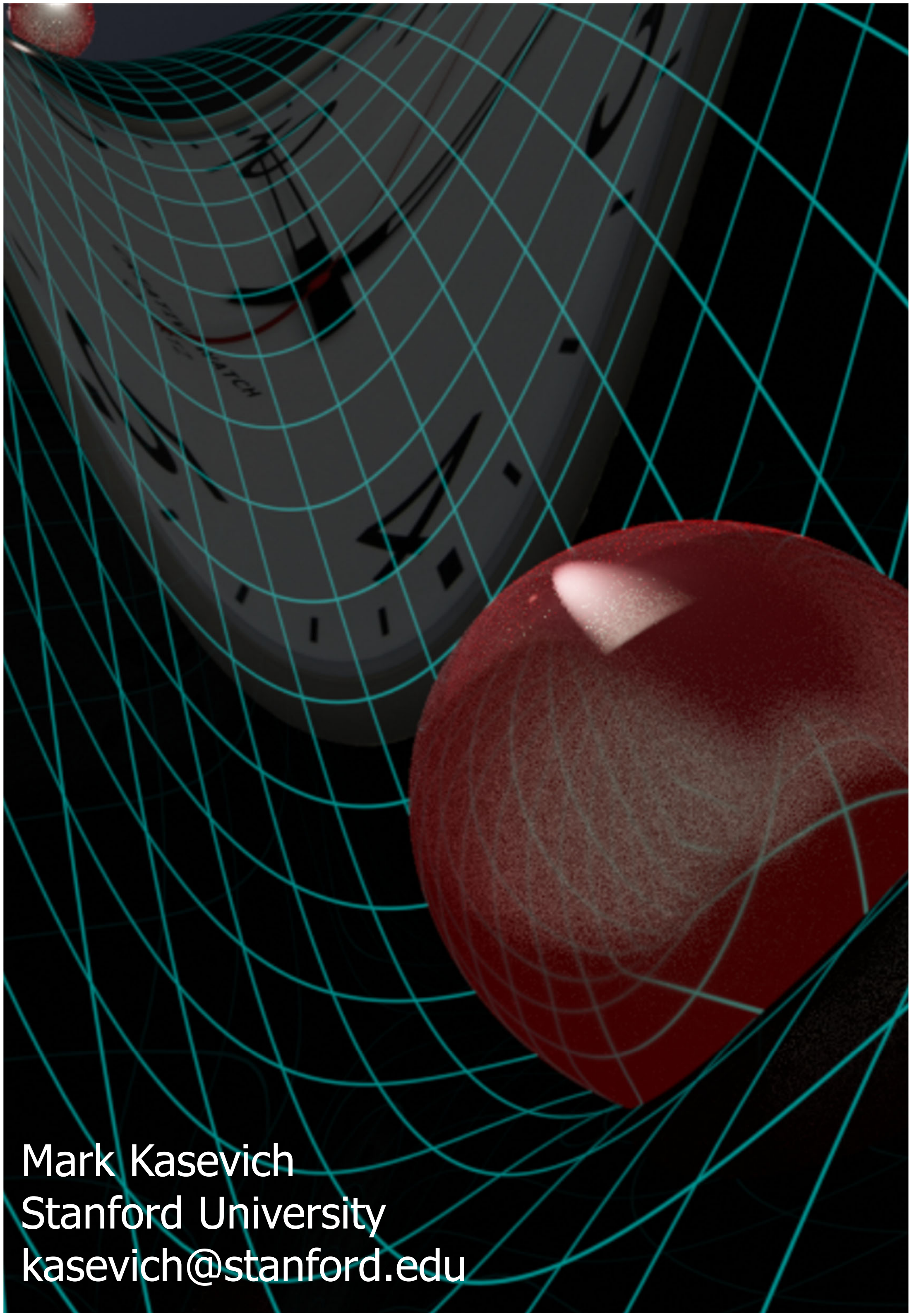
⟨Quantum|Gravity⟩Society

Observation of a Gravitational Aharonov-Bohm Effect

& Implications for quantum superpositions of Newtonian gravitational fields

Mark Kasevich



Observation of a gravitational Aharonov-Bohm effect

and

Implications for quantum superpositions of Newtonian gravitational fields

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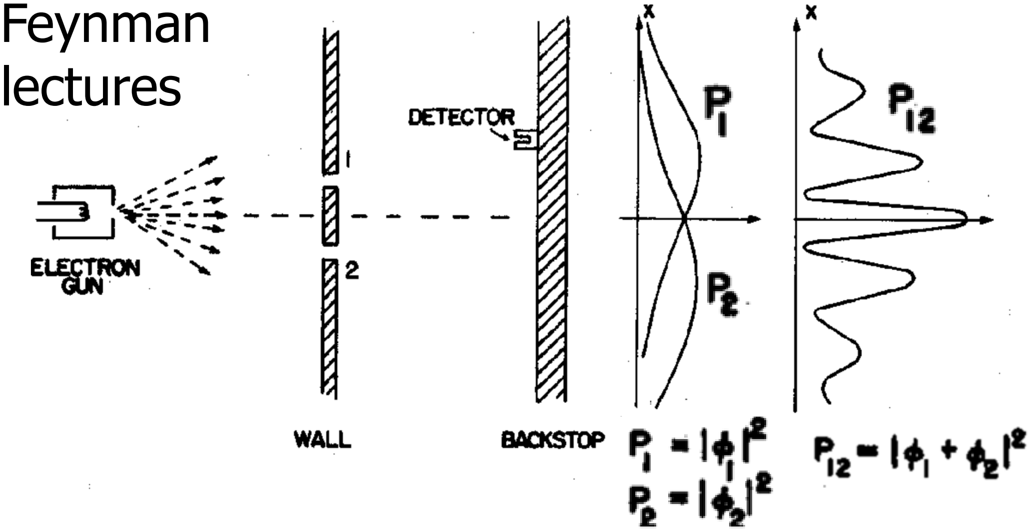
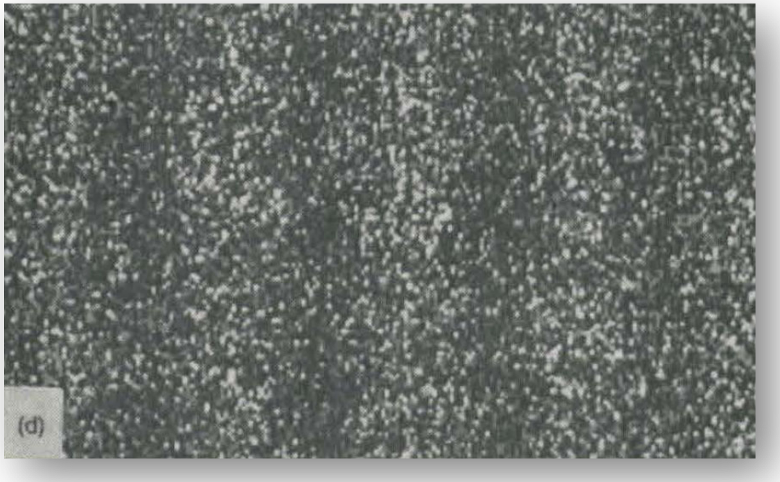
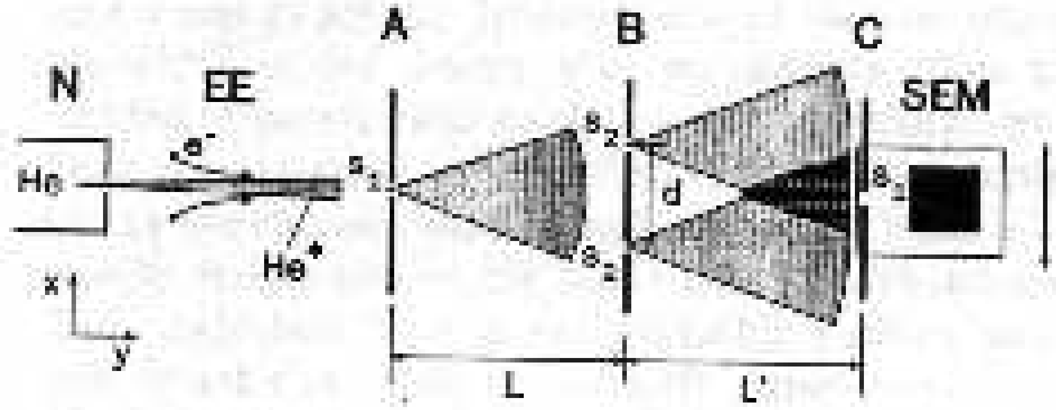
Young's double slit exp't with particles

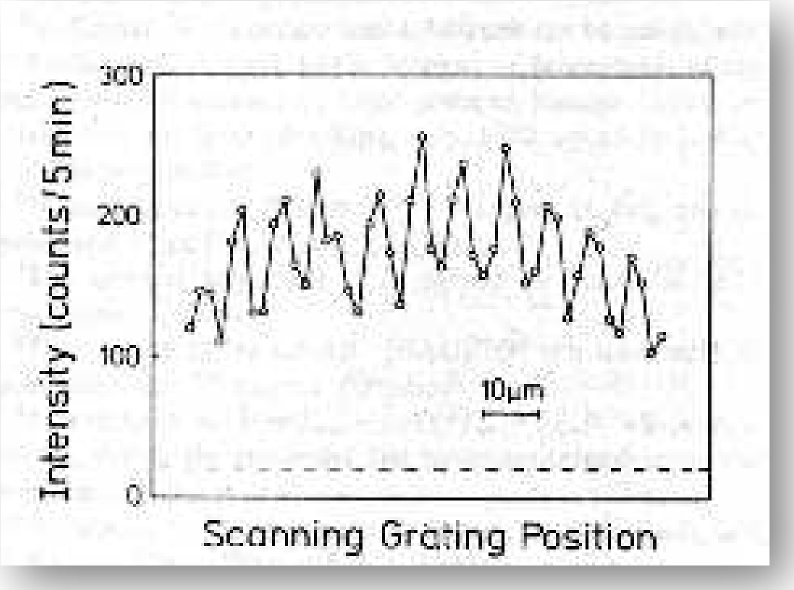
Feynman lectures





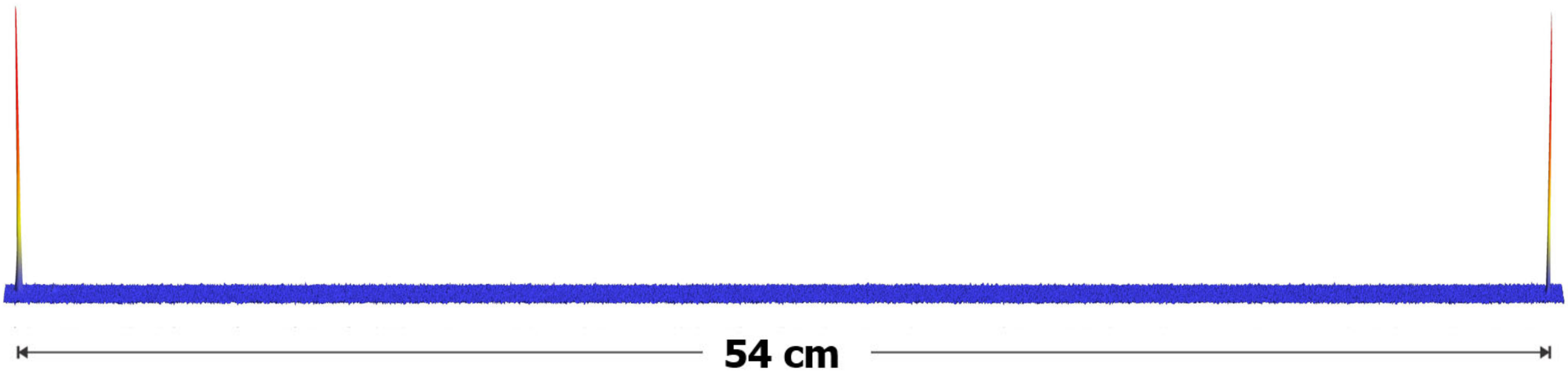
Tonomura, PRL, 1989





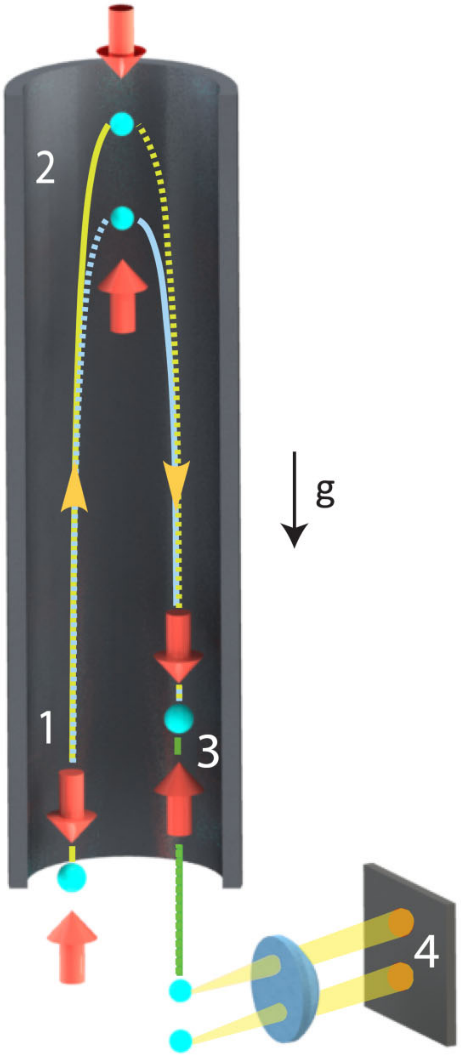
Mlynek, PRL, 1991

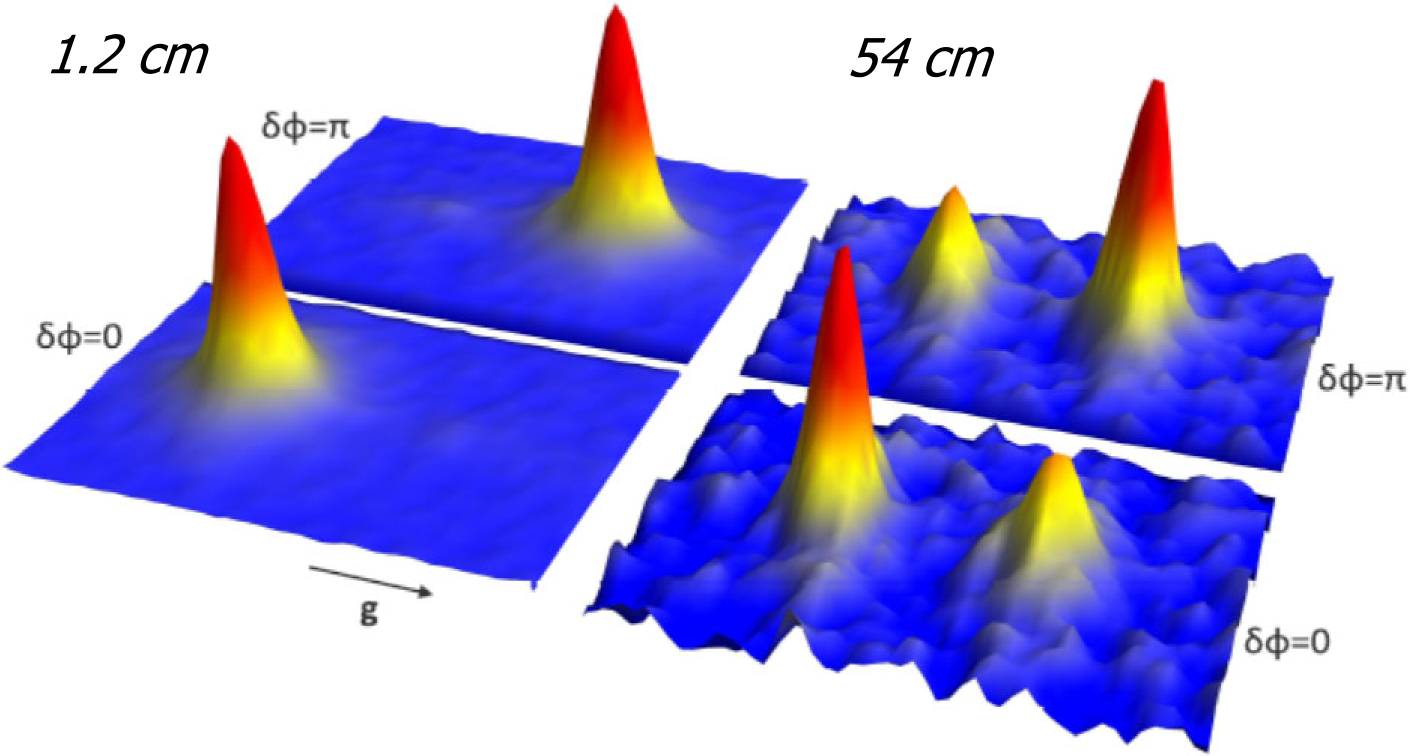
Atomic wavepacket superposition



Kovachy, et al., Nature (2015).

Interference at output ports

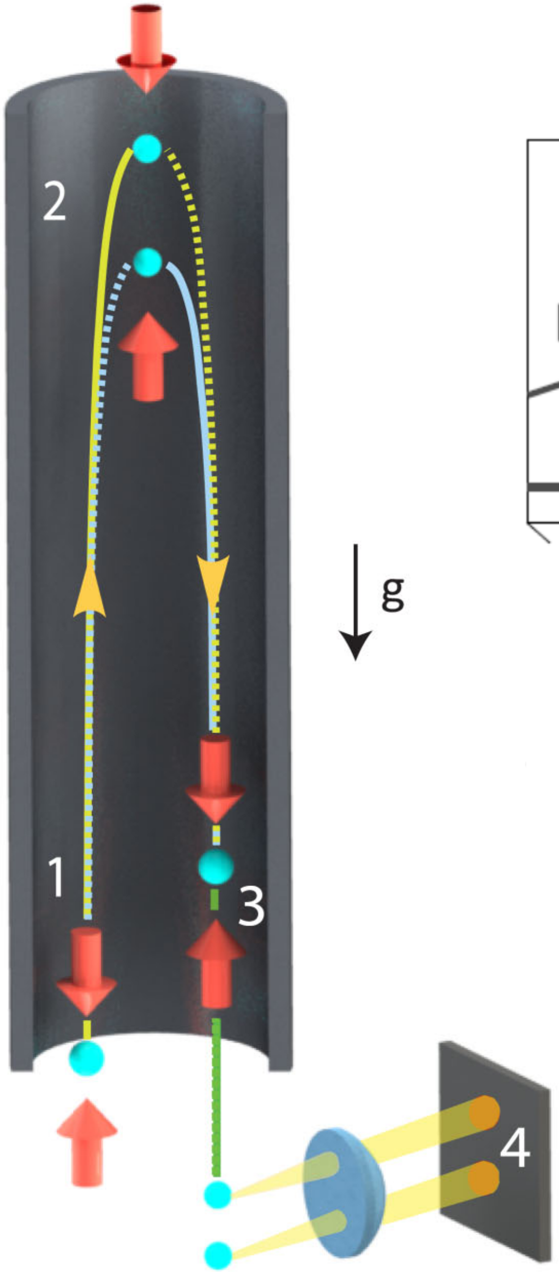


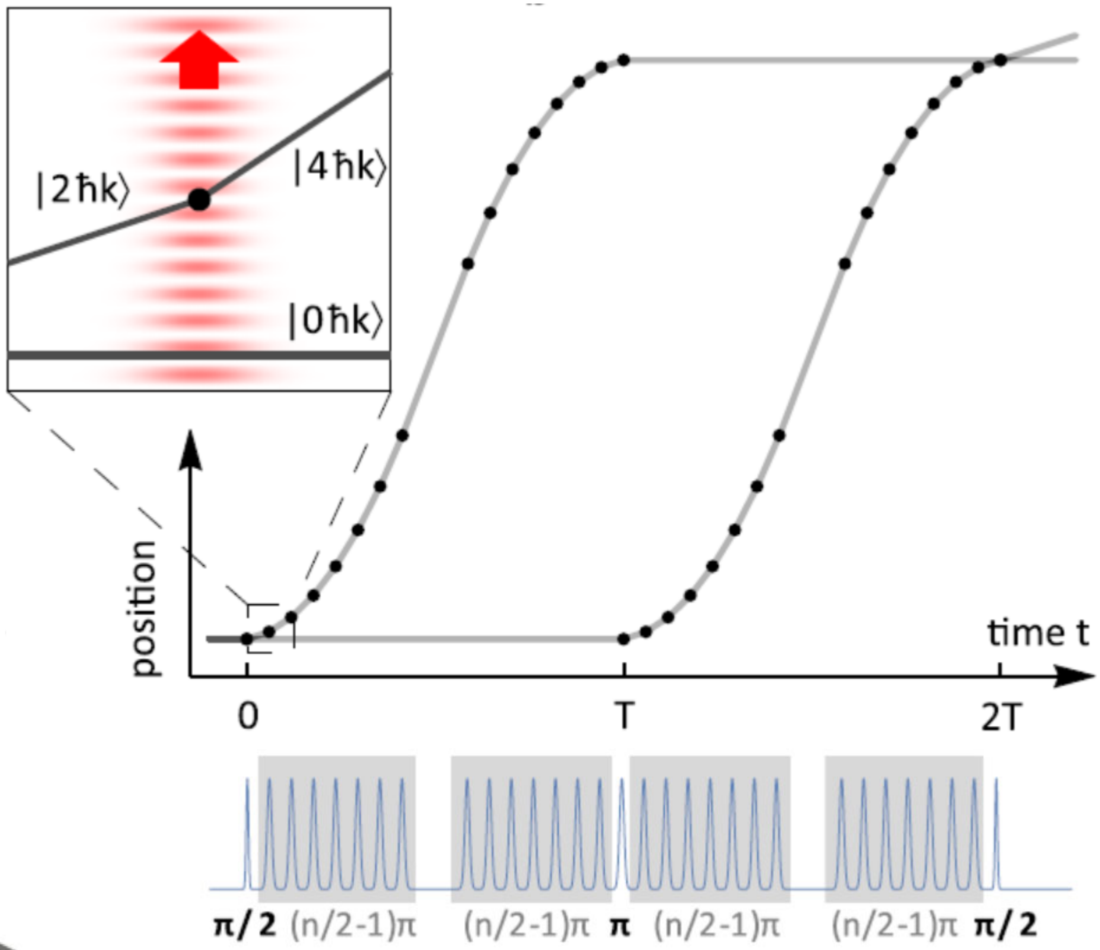


Interference causes population modulation between the output ports

T. Kovachy, et al., Nature (2015)

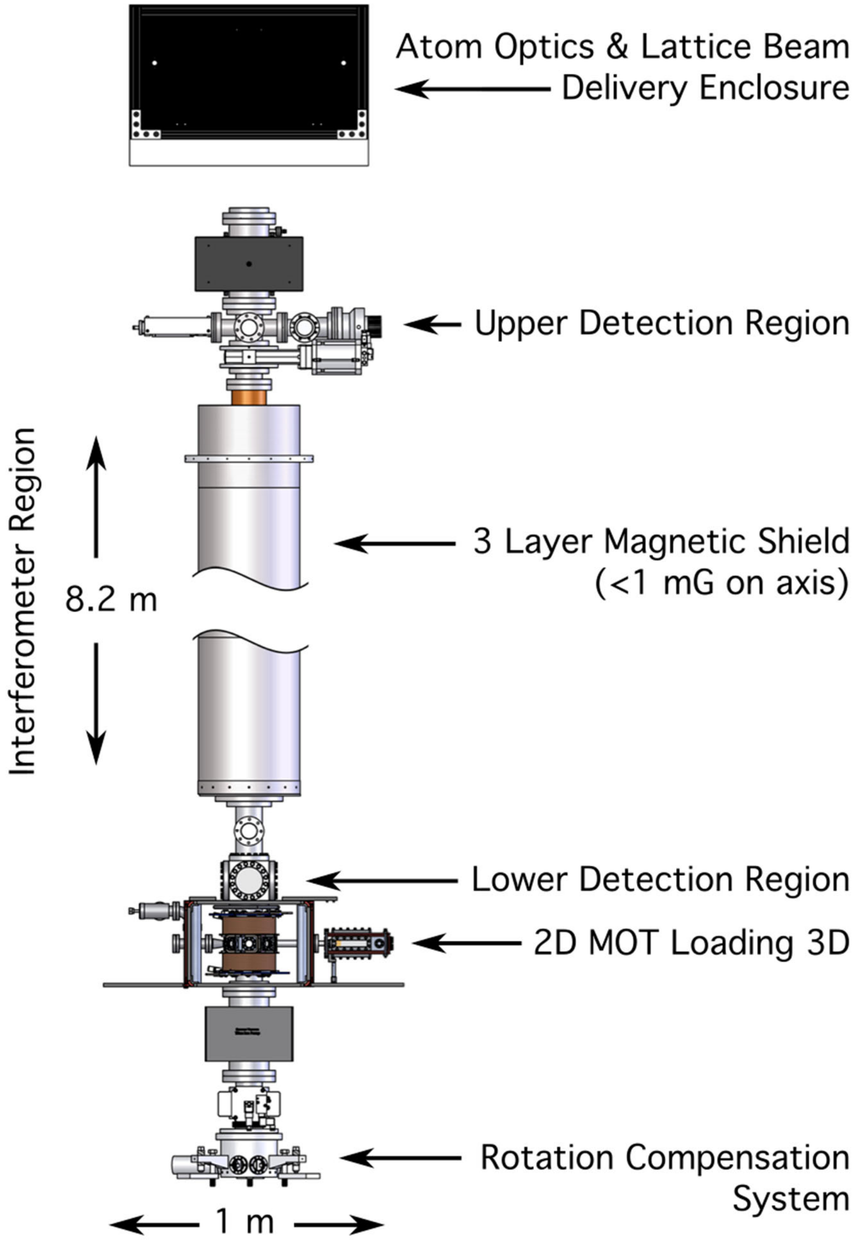
An interferometer for 87Rb based on pulses of light





A sequence of light pulses divide, re-direct and recombine atomic wavepackets

Apparatus



Atom Optics & Lattice Beam Delivery Enclosure

Upper Detection Region

Interferometer Region

8.2 m

3 Layer Magnetic Shield (<1 mG on axis)

Lower Detection Region

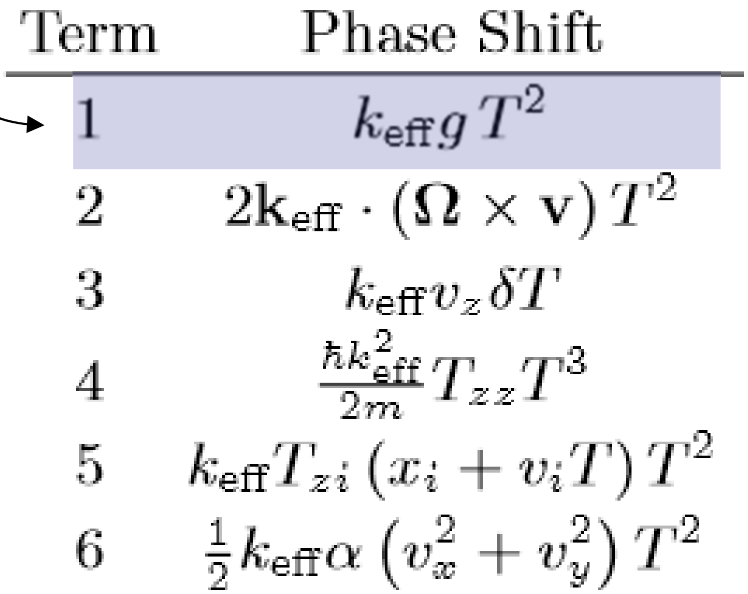
2D MOT Loading 3D

Rotation Compensation System

1 m

Phase shifts between interfering waves

8e9 rad



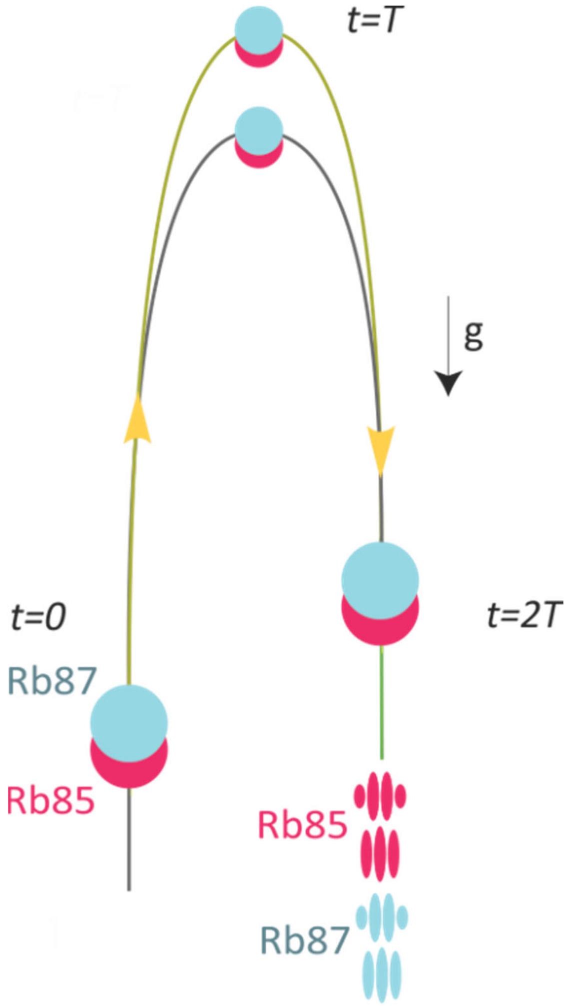
Term	Phase Shift
1	$k_{\text{eff}} g T^2$
2	$2\mathbf{k}_{\text{eff}} \cdot (\mathbf{\Omega} \times \mathbf{v}) T^2$
3	$k_{\text{eff}} v_z \delta T$
4	$\frac{\hbar k_{\text{eff}}^2}{2m} T_{zz} T^3$
5	$k_{\text{eff}} T_{zi} (x_i + v_i T) T^2$
6	$\frac{1}{2} k_{\text{eff}} \alpha \left(v_x^2 + v_y^2\right) T^2$

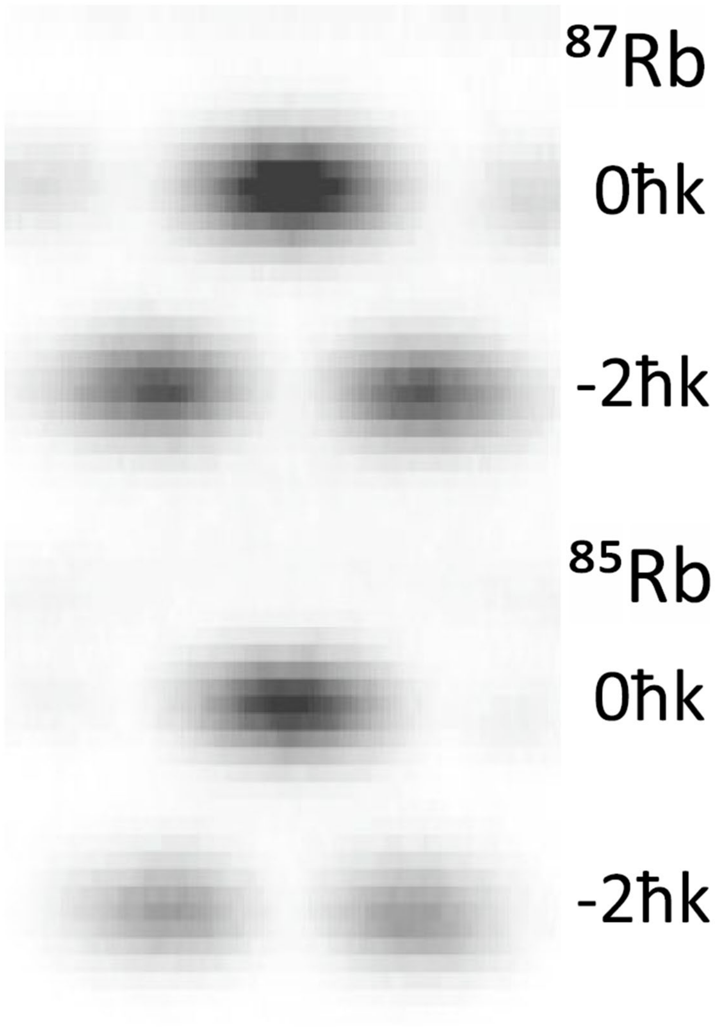
Gravity induced phase shift

g, acceleration due to gravity

T, time wavepackets are separated

k_{eff}, propagation vector of laser

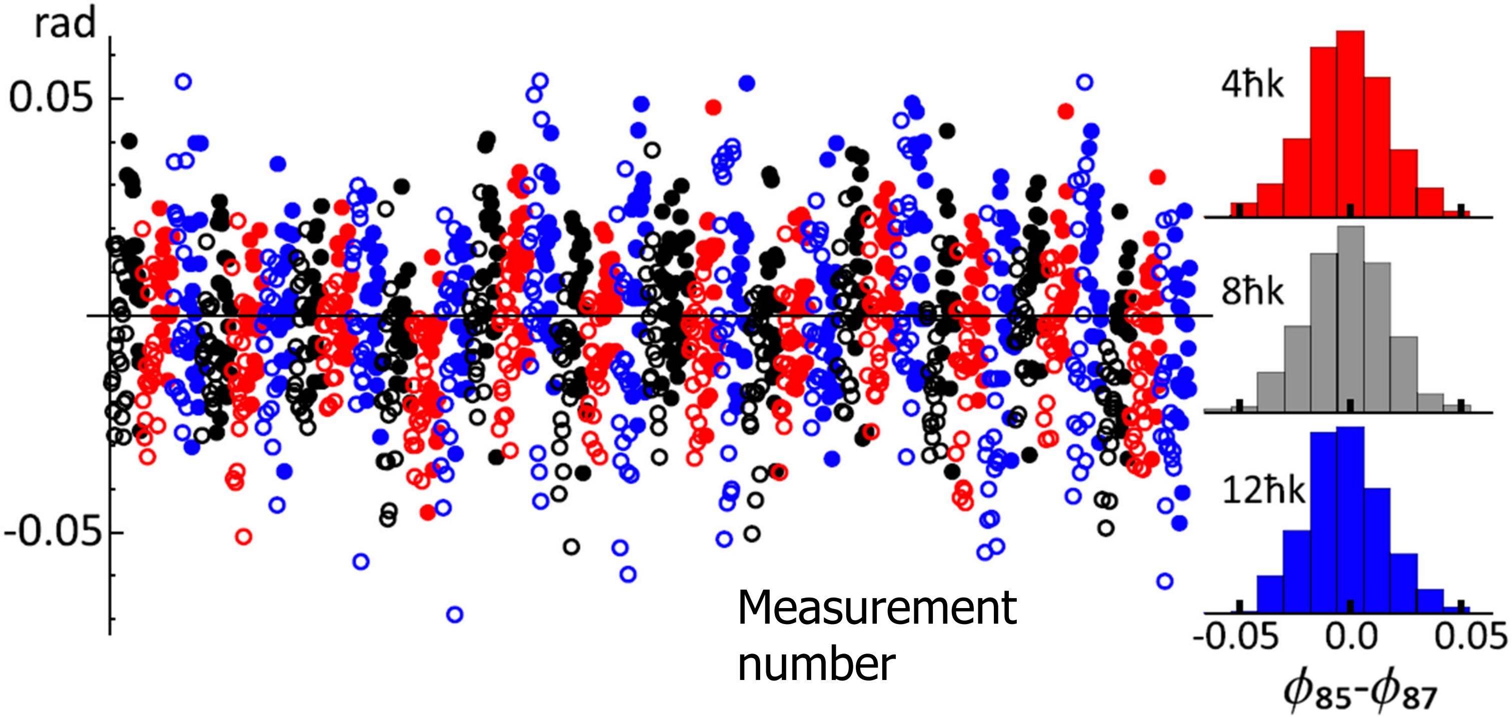




Overstreet, et al., PRL 2020

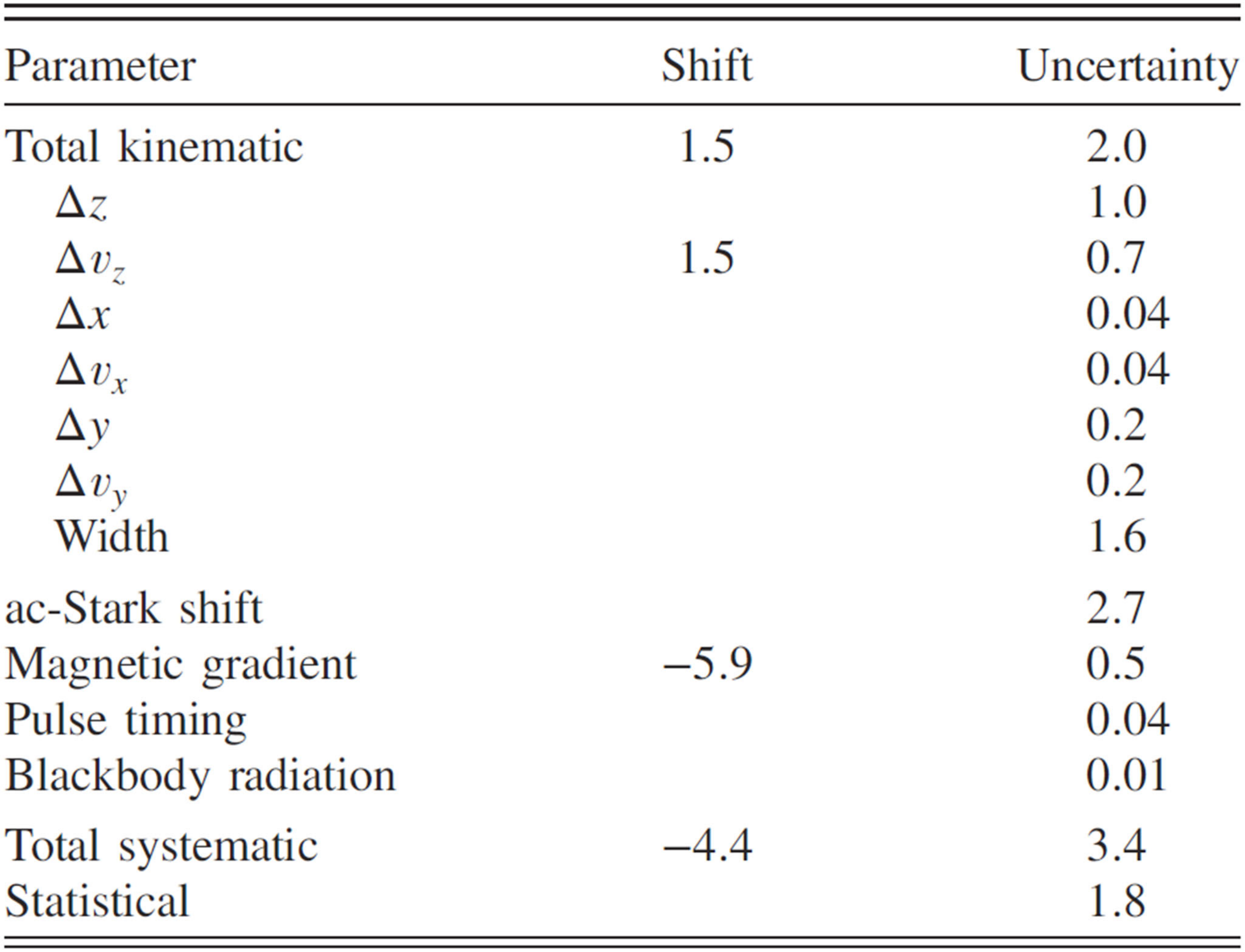
Data

The differential accelerations of 85Rb and 87Rb are inferred by comparing phase shifts for atom interferometers.



Equivalence Principle Test Results

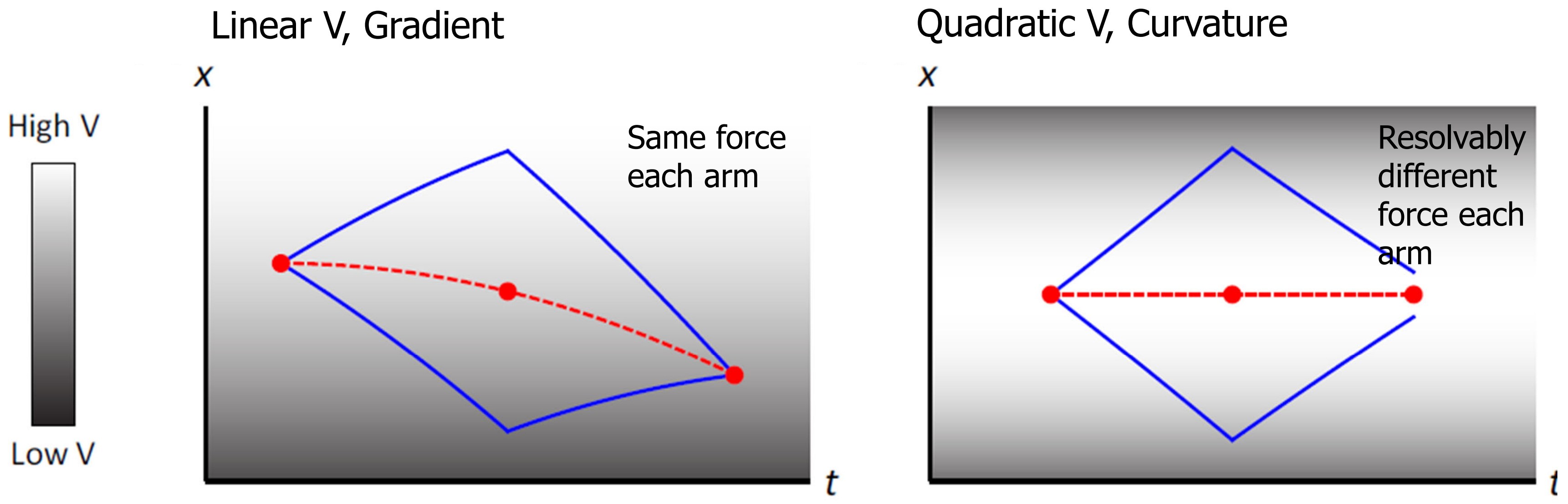
$$\eta = [1.6 \pm 1.8(\text{stat}) \pm 3.4(\text{syst})] \times 10^{-12}$$



Parameter	Shift	Uncertainty
Total kinematic	1.5	2.0
Δz		1.0
Δv_z	1.5	0.7
Δx		0.04
Δv_x		0.04
Δy		0.2
Δv_y		0.2
Width		1.6
ac-Stark shift		2.7
Magnetic gradient	−5.9	0.5
Pulse timing		0.04
Blackbody radiation		0.01
Total systematic	−4.4	3.4
Statistical		1.8

Overstreet, et al., PRL 2020

Atom interferometer vs. classical measurements



In both cases, interferometer phase shift is well described by the classical **mid-point** trajectory associated with the interferometer arms:

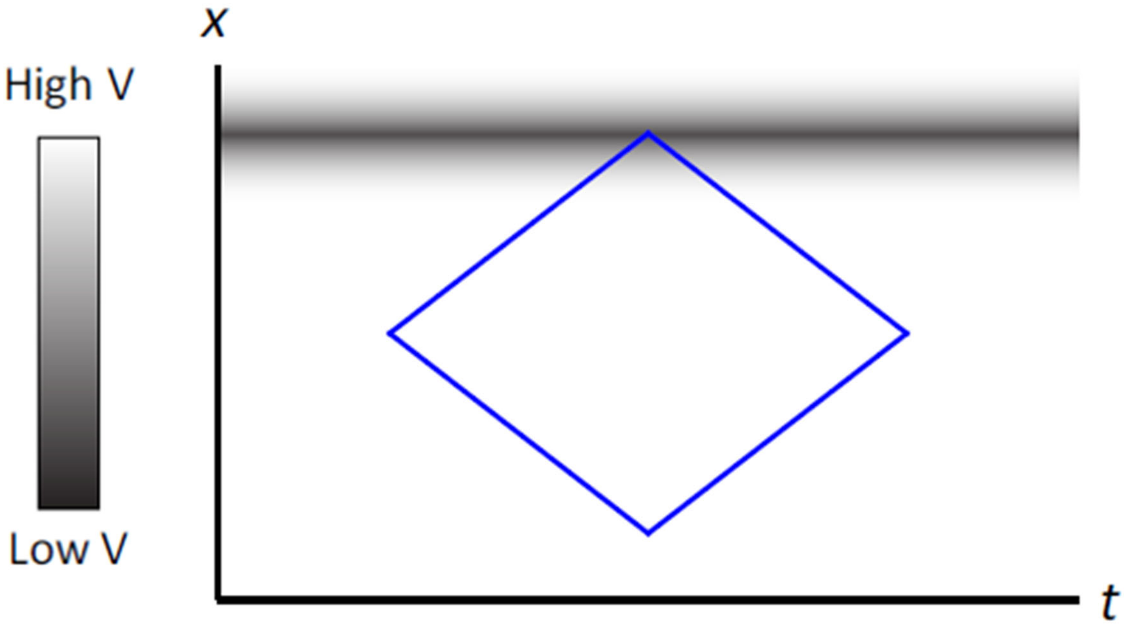
$$\phi_{\mathrm{MP}} \equiv \sum_{i=1}^{N} \left[(k_{1,i} - k_{2,i})\, \bar{x}_i - (\omega_{1,i} - \omega_{2,i})\, t_i + (\phi_{1,i} - \phi_{2,i}) \right].$$

(k_i and x_i are propagation vectors and wavepacket positions at the i^{th} pulse.)

These atom interferometric measurements are conceptually similar to classical measurements. Phase shift is given by the force acting on atomic wavepackets.

Antoine and Borde, JOSA B, 2013.
Overstreet, et al., AJP, 2021.

Mass dependent phase shifts



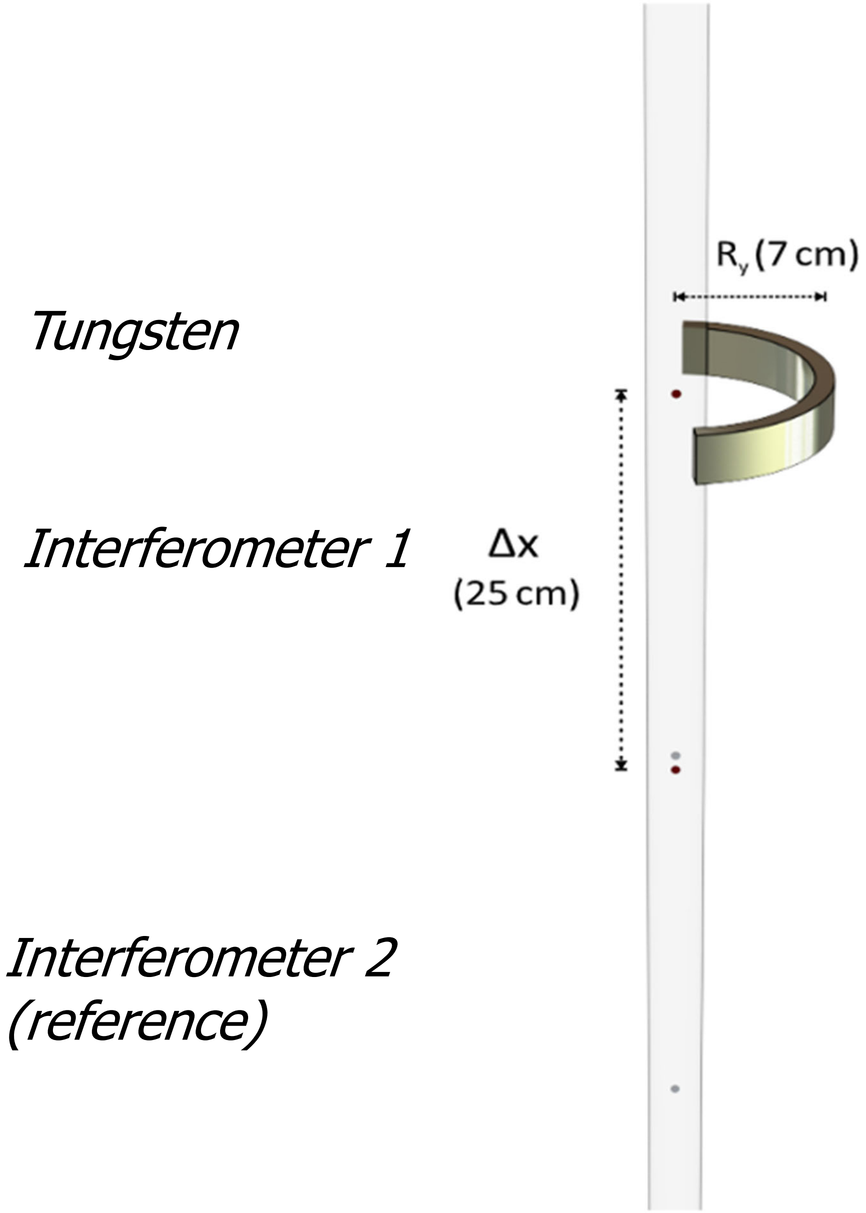
For higher order curvature, the midpoint theorem no longer holds and the phase shift is mass dependent.

Can be interpreted as a gravitational Aharonov-Bohm effect.

Systematic for future EP measurements based on atom interferometry.

Overstreet, et al., AJP, 2021.

Gravitational AB Experiment

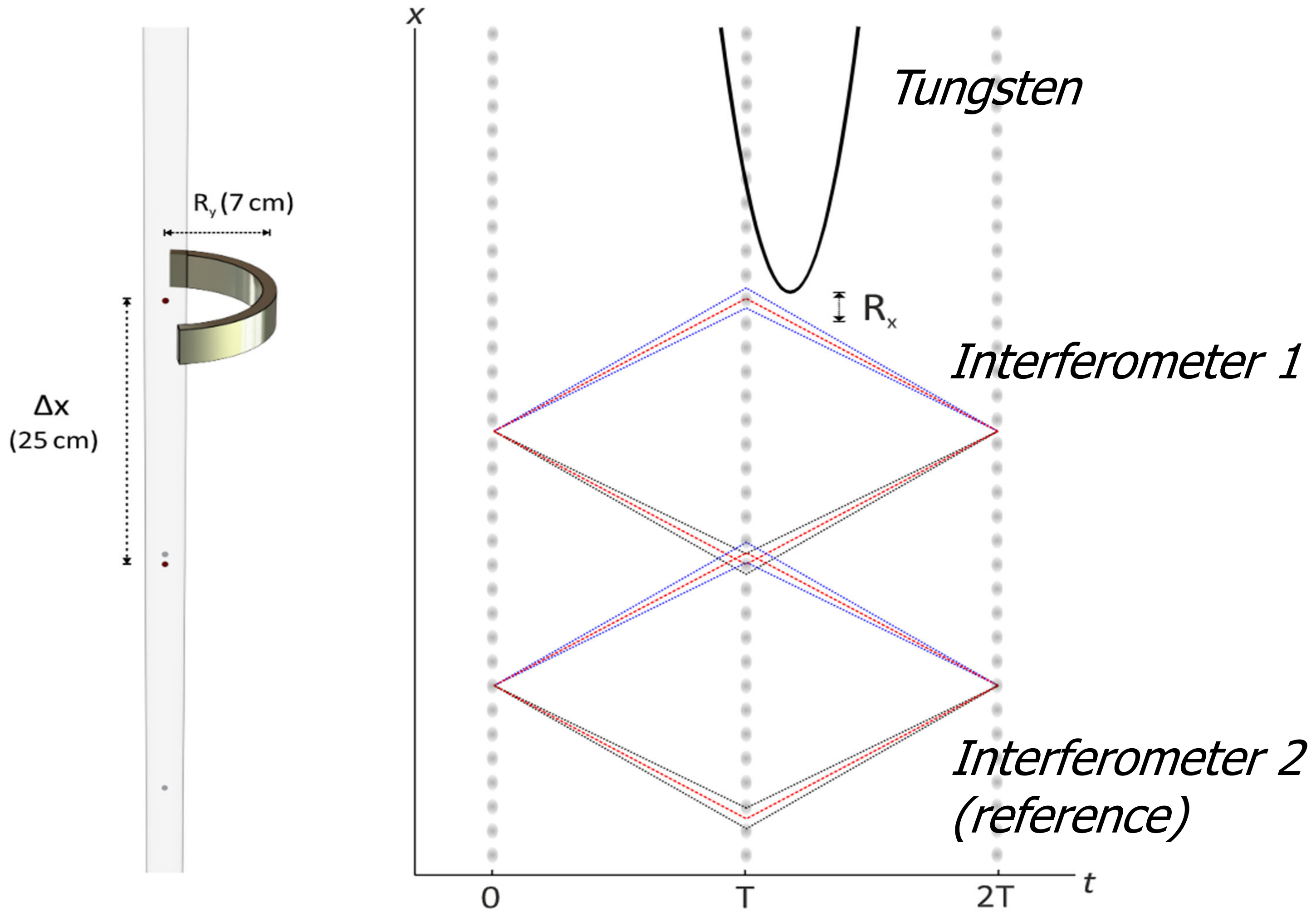


Wavepacket separation greater than distance of nearest wavepacket to source mass

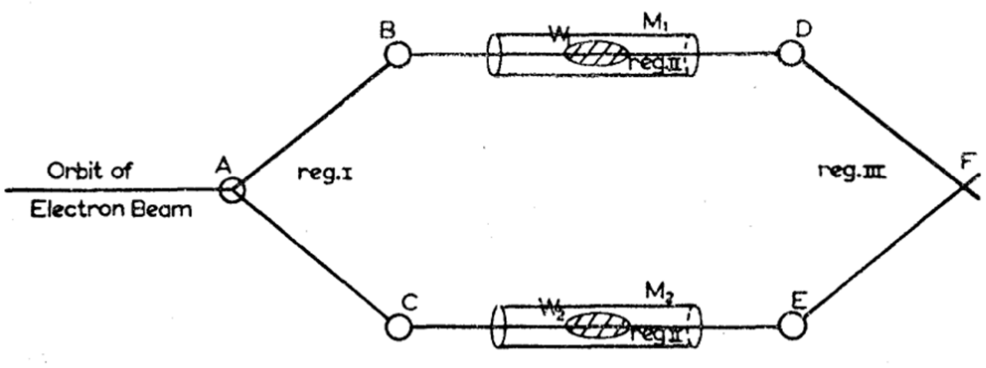
Overstreet, et al., 2022

Prior proposals:
Audretsch and Lammerzhal, 1983
Hohensee, et al., 2012

Interferometer trajectories in freely falling frame



Electric Aharonov-Bohm Effect



$$\psi=\psi_1{}^0 e^{-iS_1/\hbar}+\psi_2{}^0 e^{-iS_2/\hbar}$$

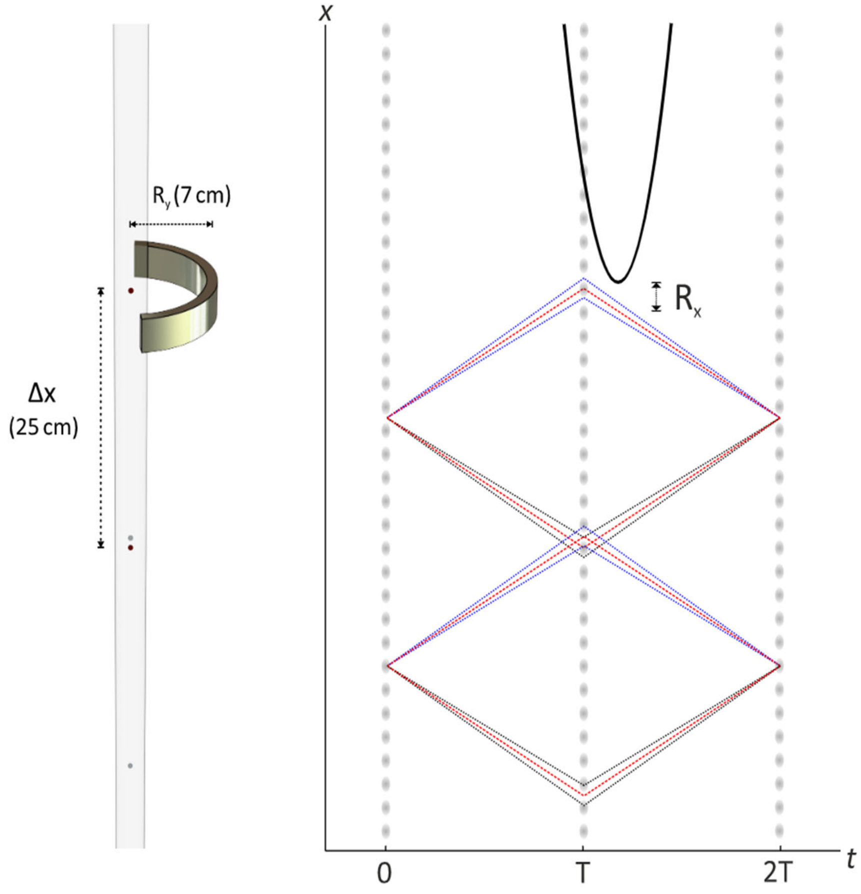
$$S_1=e\int\varphi_1 dt,\quad S_2=e\int\varphi_2 dt.$$

(negligible contribution to phase
shift from forces on wavepackets)

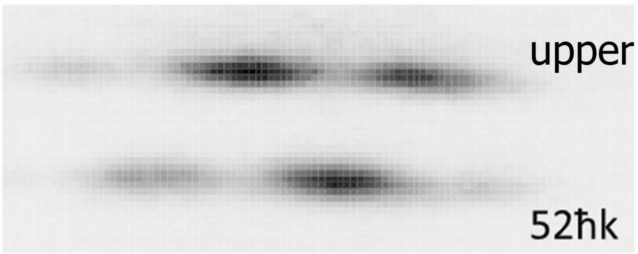
Aharonov and Bohm, Phys. Rev. 1959

Phase shift due to gravitational action

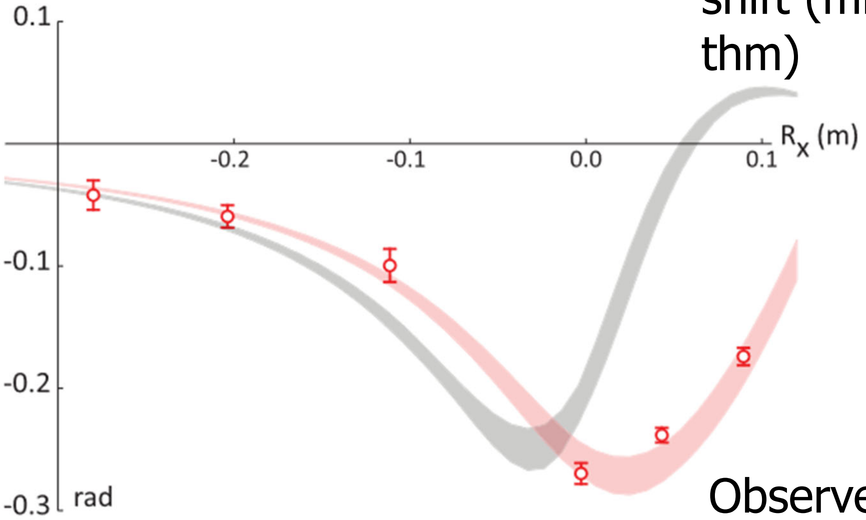
Interferometer geometry



Raw data



Phase shift

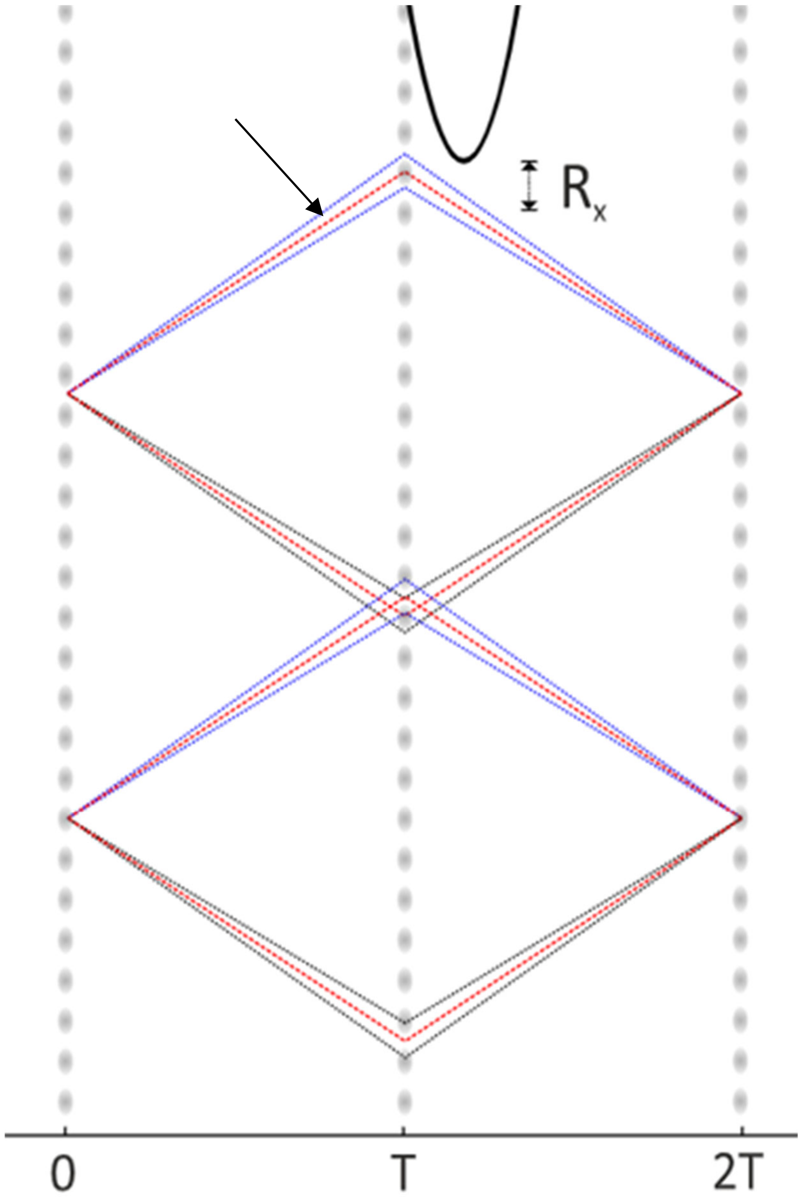


Deflection-induced phase shift (midpoint thm)

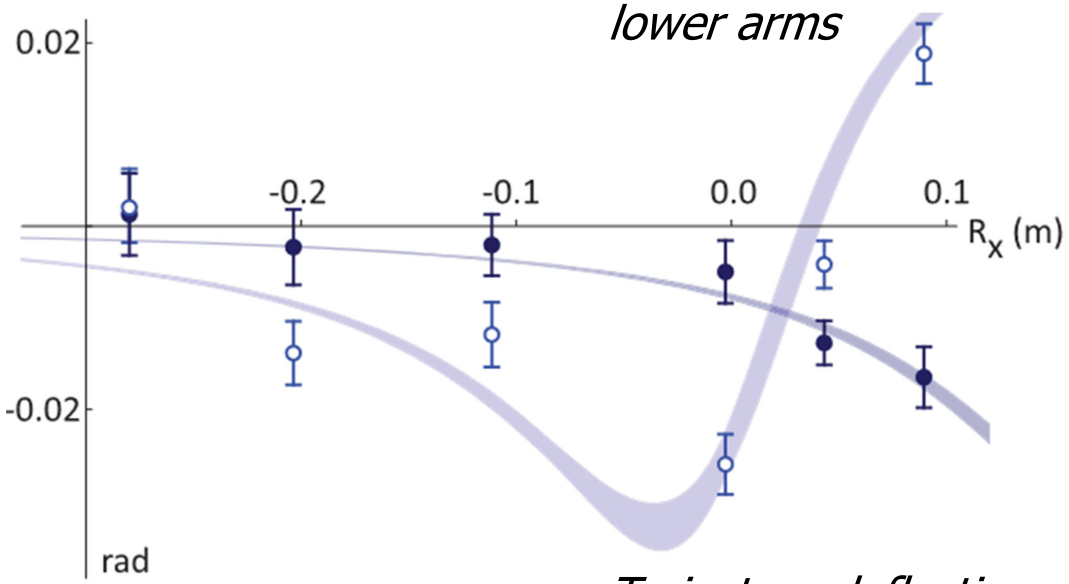
Observed phase shift

Overstreet, Science, 2022

Deflection-induced phase shifts



Auxilliary (small wavepacket separation) interferometers allow independent characterization of deflection-induced phase shifts



Trajectory deflections, lower arms

Trajectory deflections, upper arms

Newtonian gravitational field energy

Field energy:

$$E_{\mathrm{G}} = -\frac{1}{8\pi G}\int |\mathrm{g}|^2 dV$$

$$\boldsymbol{g} = \boldsymbol{g}_{atom} + \boldsymbol{g}_{tungsten}$$

Phase shift:

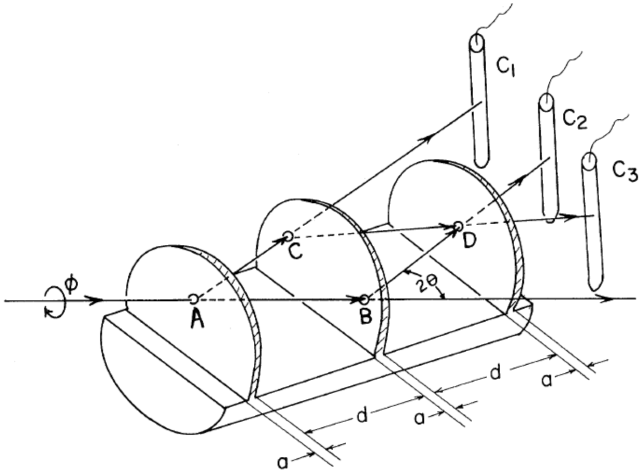
$$\phi = \frac{1}{\hbar}\int (E_1 - E_2)\, dt$$

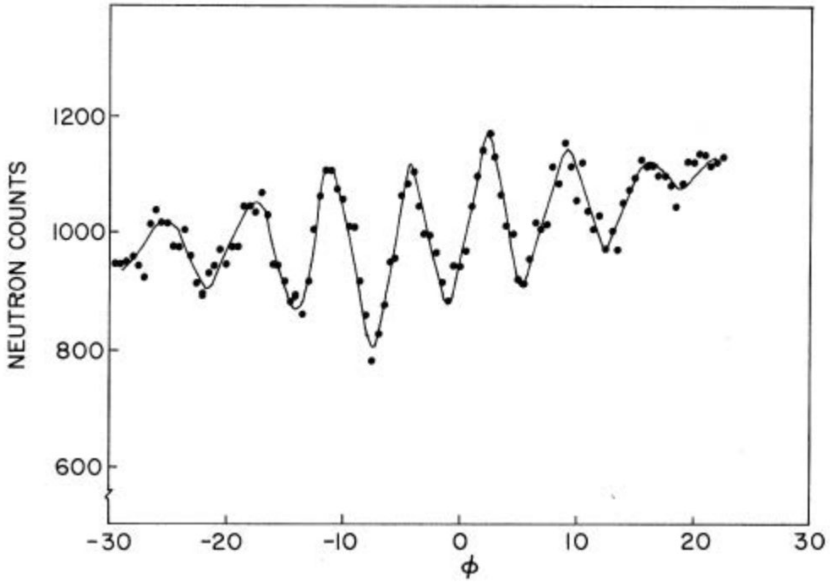
E_1, E_2 are gravitational energies for each arm.

$\boldsymbol{g}_{atom}$ is in spatial superposition since the atom is in a spatial superposition.

Phase shift can be interpreted as resulting from superposition of the atom’s gravitational fields

Collela, Overhauser and Werner (1975)



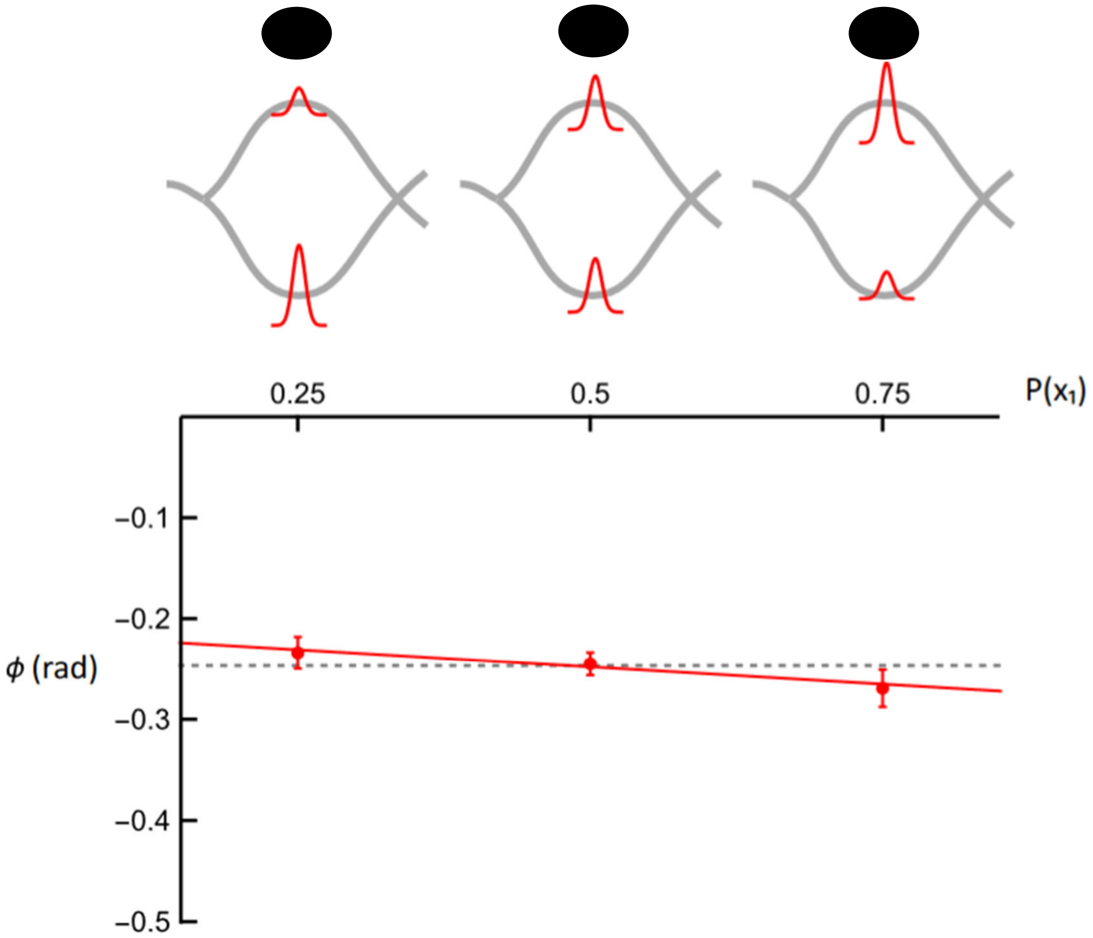


Uniform gravitational field implies gravitational action phase shift is zero (uniform gravitational fields are not observable)

Physical original of phase shift: relative (kinematic) displacement of Si crystal with respect to de Broglie waves due to non-gravitational forces.*

*textbook treatments use perturbation theory, which masks the physical origin of the phase shift.

Exp’t to test semiclassical theories



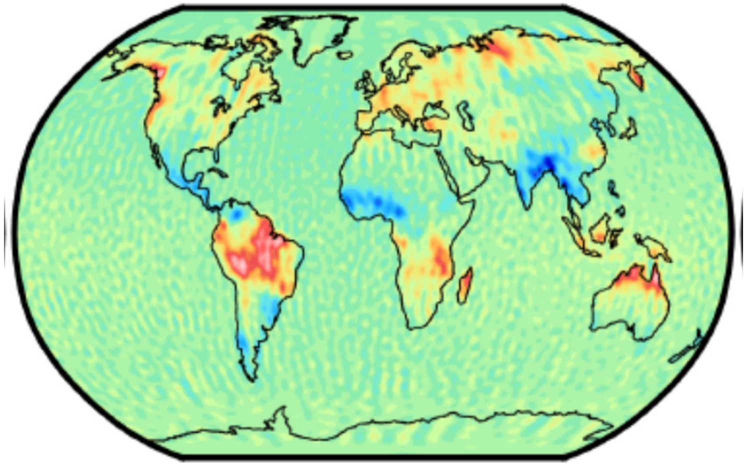
Change population ratio in interferometer arms.

Observe no statistically significant change in phase shift due to tungsten.

Overstreet, in preparation

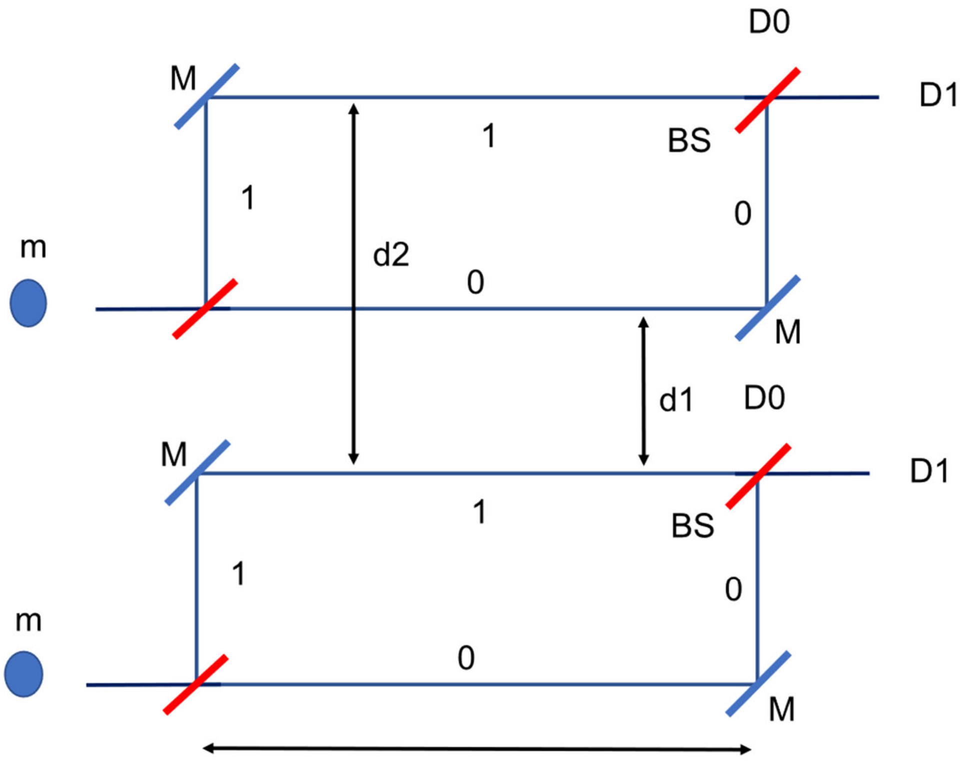
Satellite geodesy

Prototype for 1e-5 E/$H^{1/2}$ space-based sensor



Earth's gravitational anomaly map
Image credit: S. Luthke, NASA GSFC

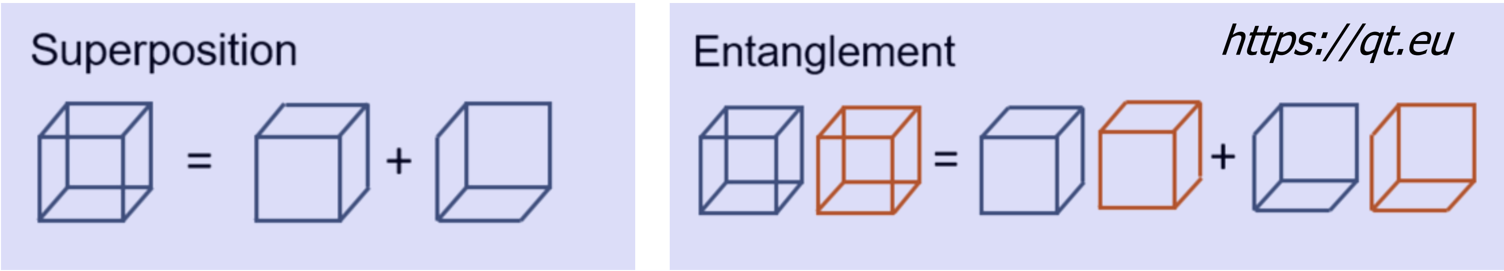
Gravitationally induced entanglement



Marletto and Vedral, 2017

Interferometer outputs are entangled by the Newtonian interaction

? What additional constraints are placed on (quantum) gravitational fields by this class of experiments



https://qt.eu

Thanks

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