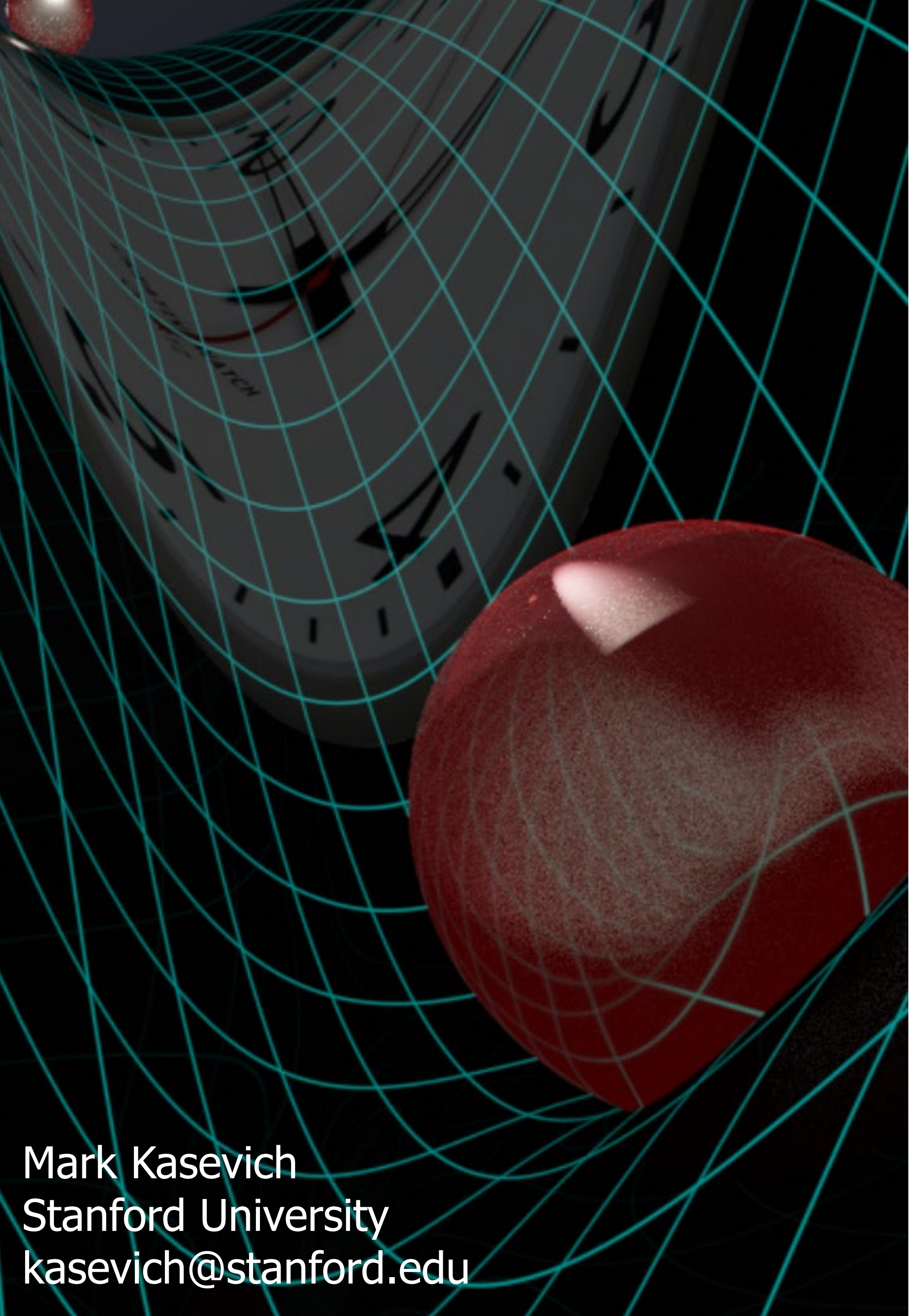

Observation of a gravitational Aharonov-Bohm effect

and

Implications for quantum superpositions of Newtonian gravitational fields

Mark Kasevich
Stanford University
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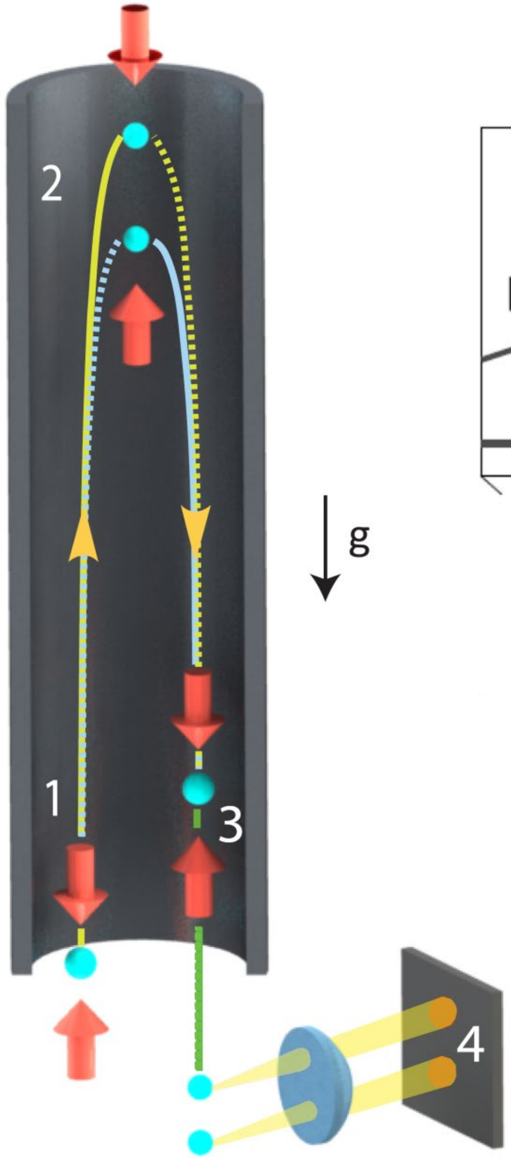
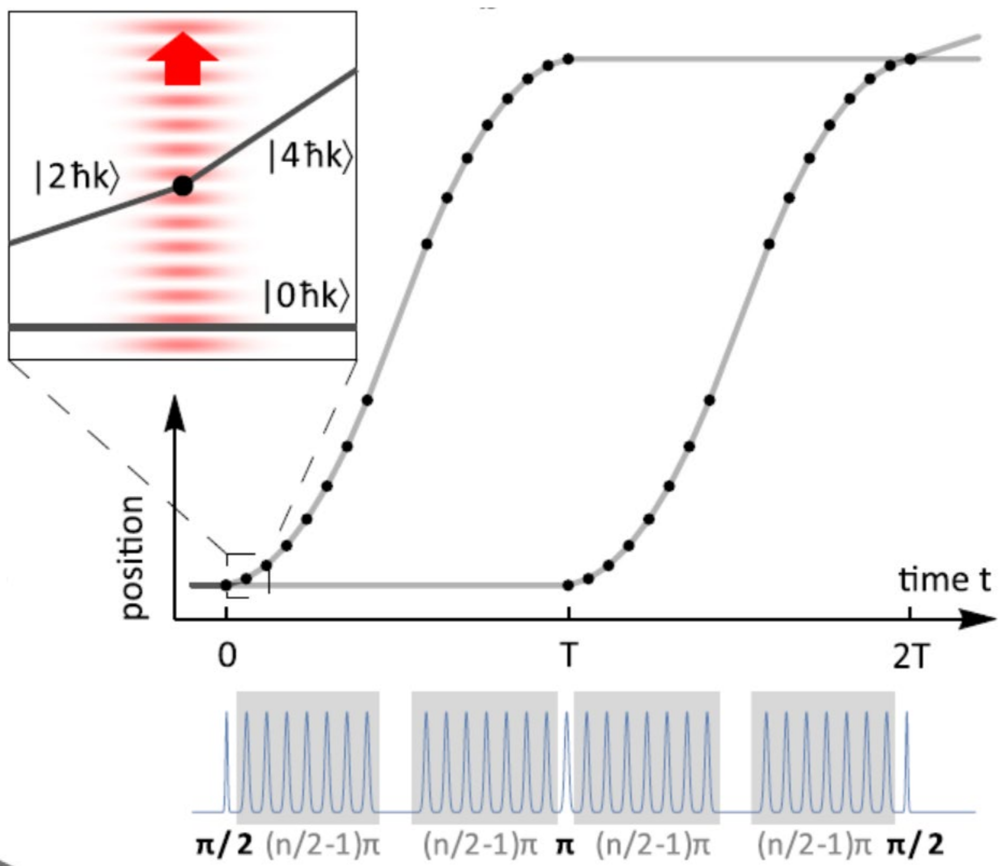
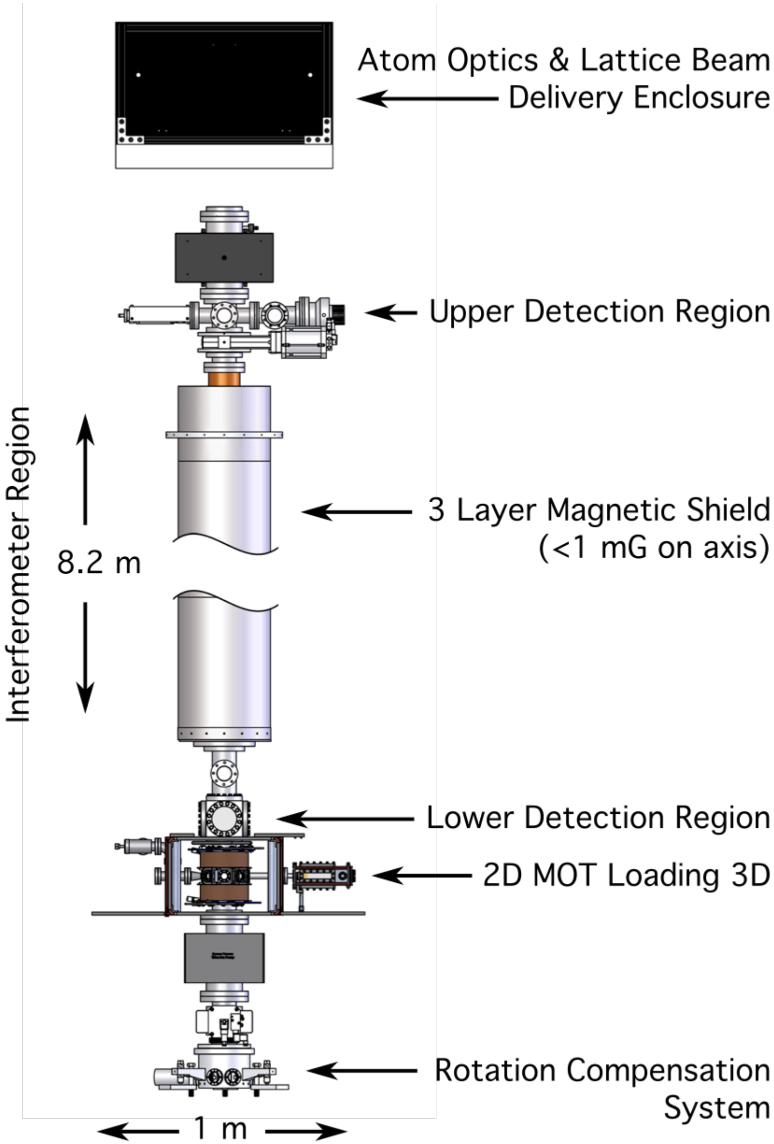
Light pulse 87Rb/85Rb interferometer





A sequence of light pulses coherently 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

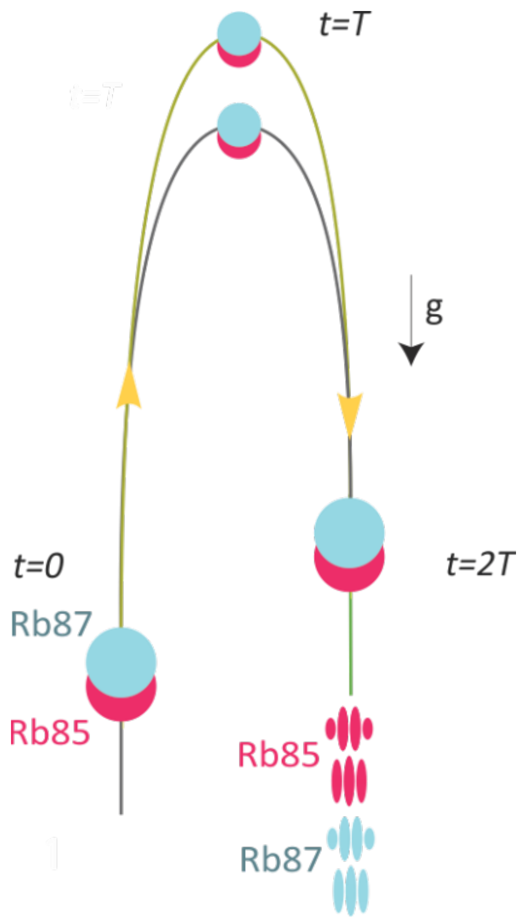
Term	Phase Shift
1	$k_{\text{eff}} g T^2$
2	$2\mathbf{k}_{\text{eff}} \cdot (\mathbf{\Omega} \times \mathbf{v}) T^2$
3	$k_{\text{eff}} v_z \delta T$
4	$\frac{\hbar k_{\text{eff}}^2}{2m} T_{zz} T^3$
5	$k_{\text{eff}} T_{zi} (x_i + v_i T) T^2$
6	$\frac{1}{2} k_{\text{eff}} \alpha \left(v_x^2 + v_y^2\right)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

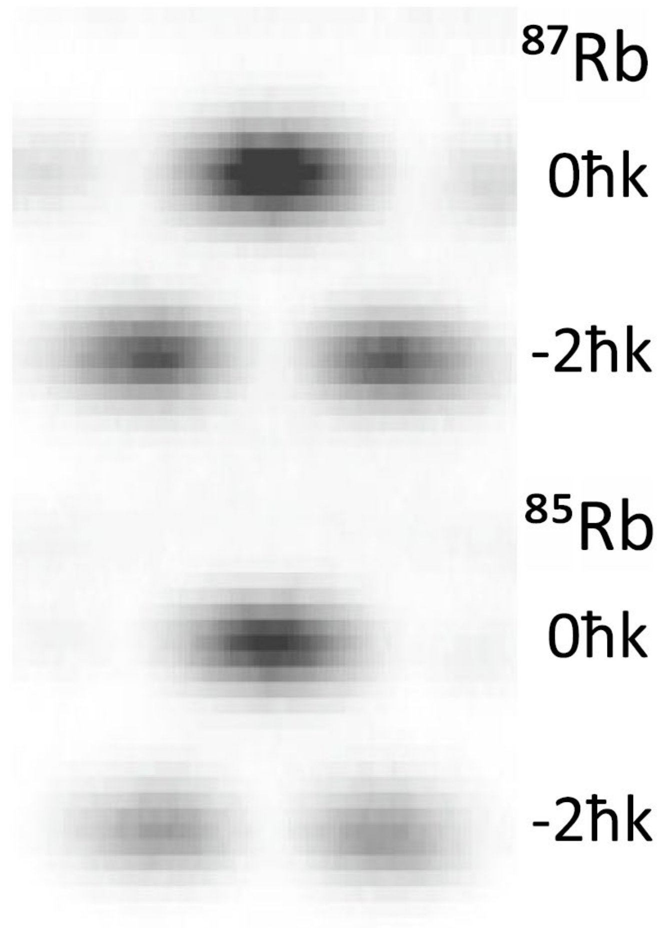
Gravity induced phase shift

g, acceleration due to gravity

T, time wavepackets are separated

k_{eff}, propagation vector of laser

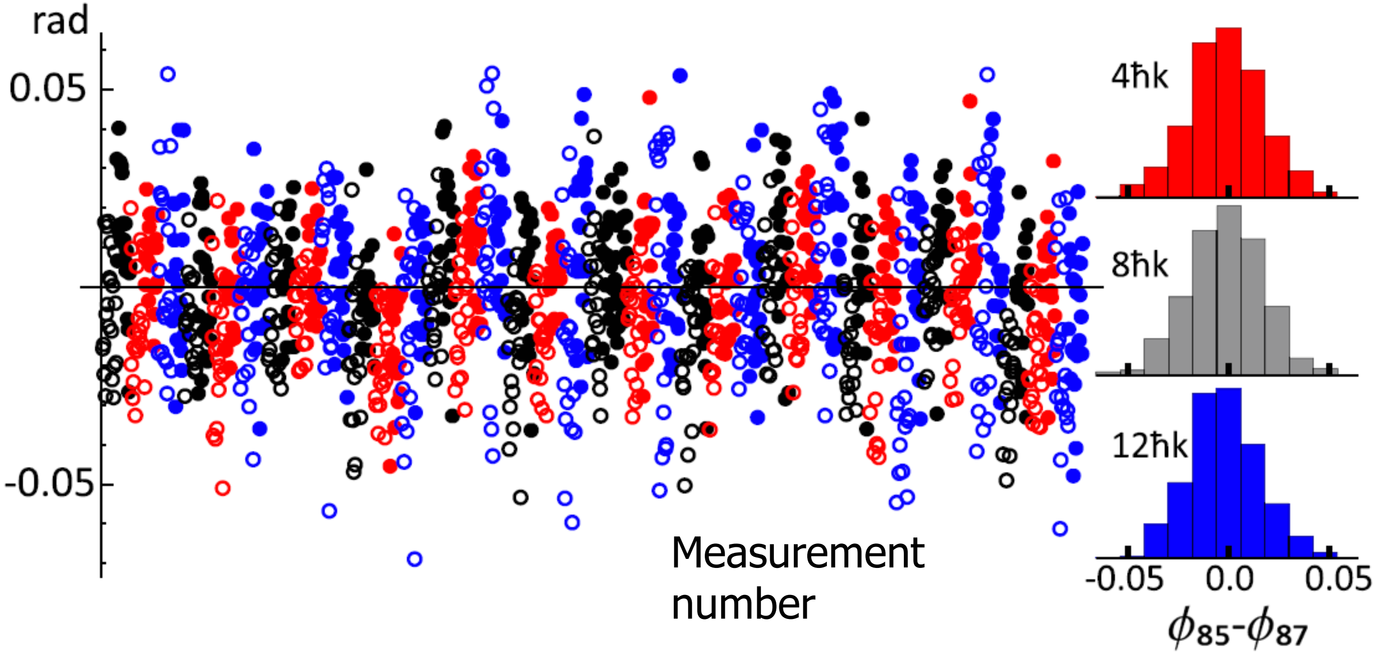




Overstreet, et al., PRL 2020

Equivalence Principle Data

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



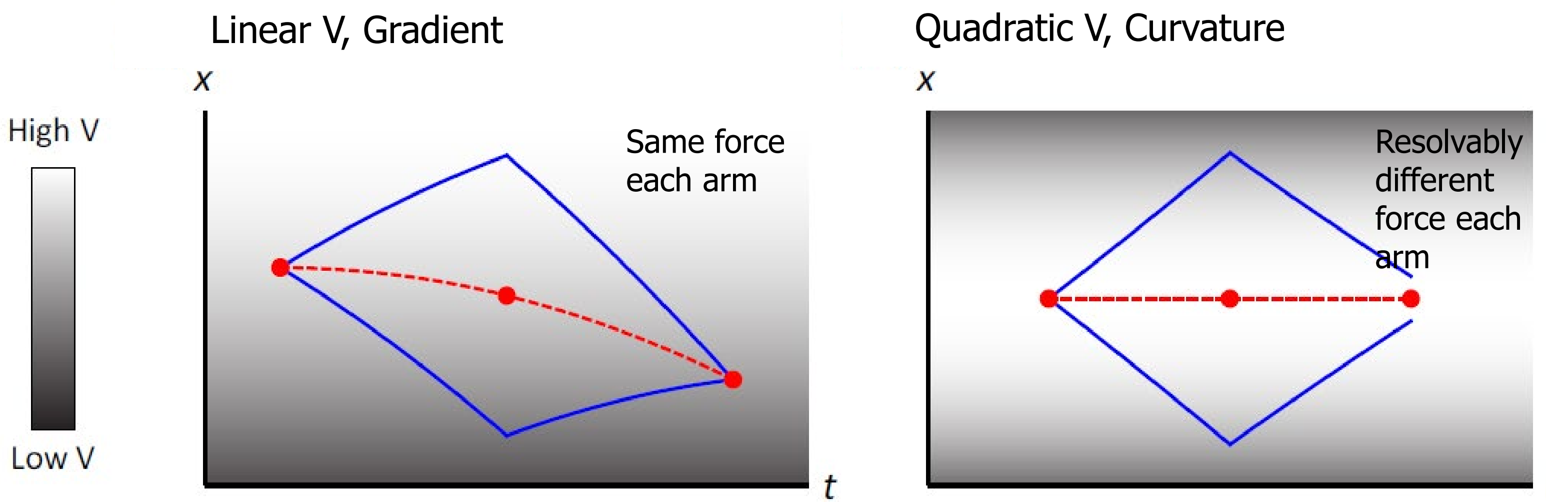
Equivalence Principle Test Results

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

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 trajectories associated with the interferometer arms:

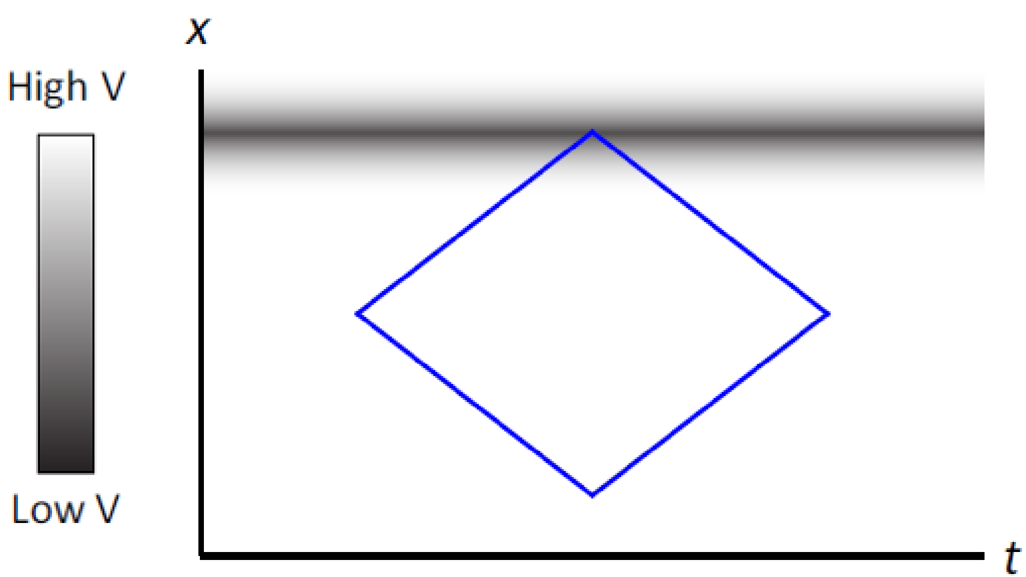
$$\phi_{\mathrm{MP}} \equiv \sum_{i=1}^{N} [(k_{1,i} - k_{2,i})\, \bar{x}_i - (\omega_{1,i} - \omega_{2,i})\, t_i + (\phi_{1,i} - \phi_{2,i})].$$

(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 phase shift is mass dependent.

Can be interpreted as a gravitational Aharonov-Bohm effect.

Possible systematic for future EP measurements based on atom interferometry.

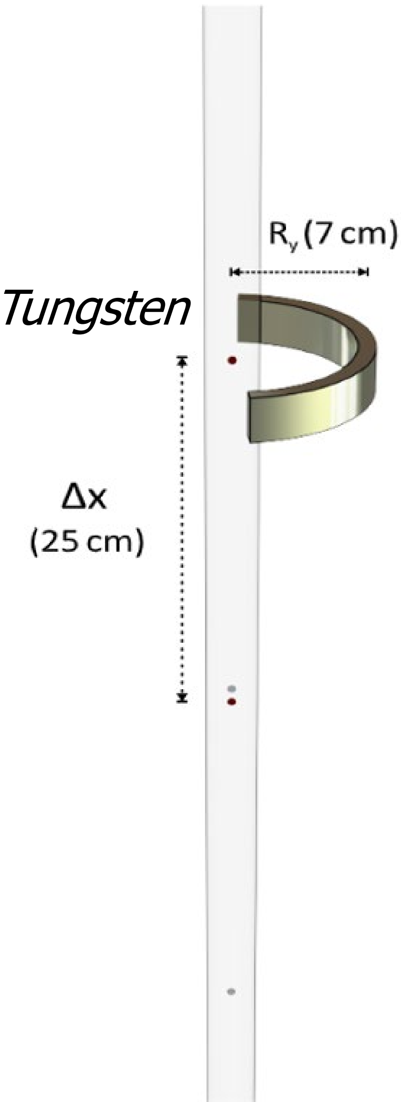
Overstreet, et al., AJP, 2021.

Gravitational Aharonov-Bohm Experiment

Tungsten

Interferometer 1

Interferometer 2 (reference)

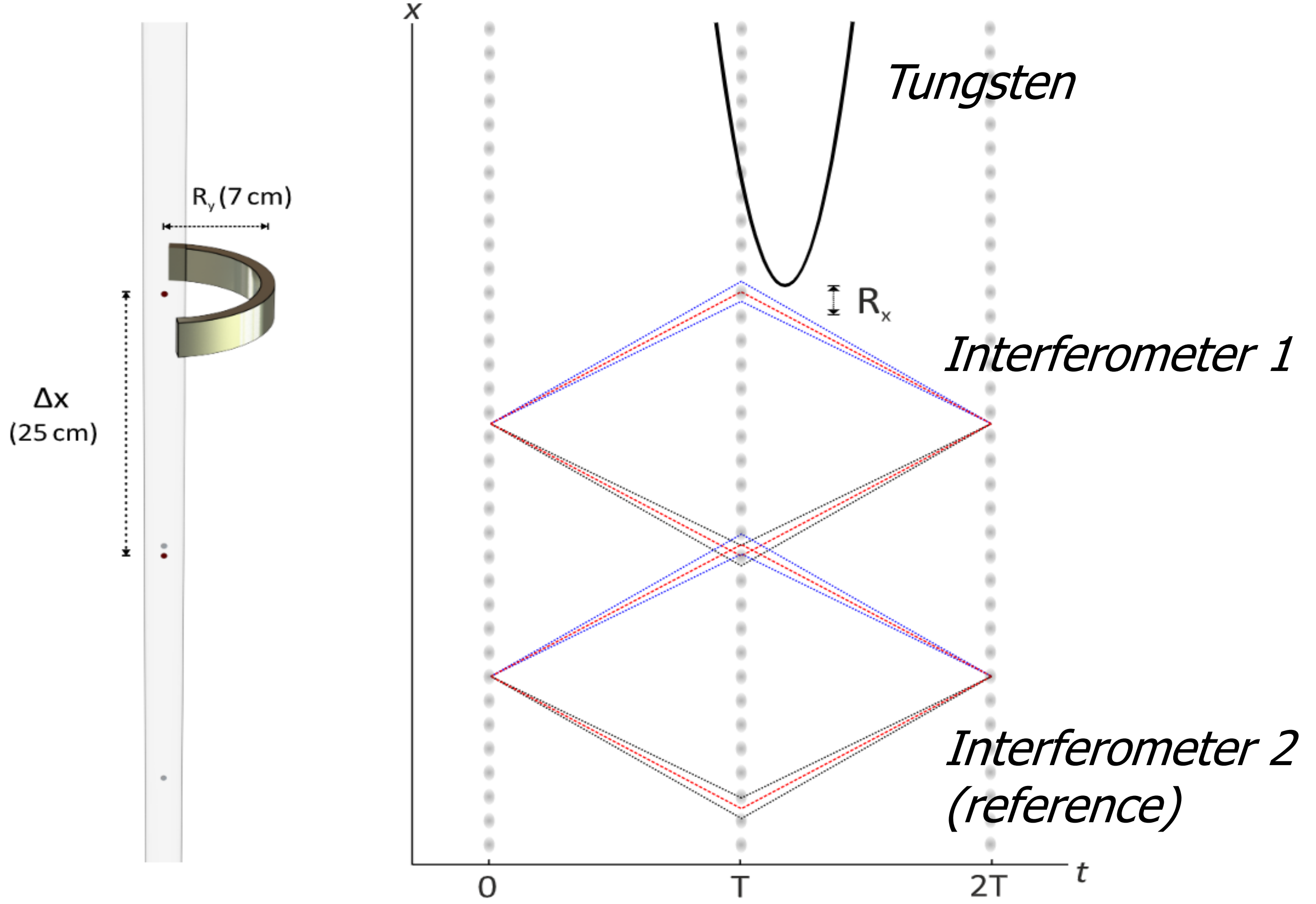


Wavepacket separation greater than distance of nearest wavepacket to source mass

Overstreet, et al., Science, 2022

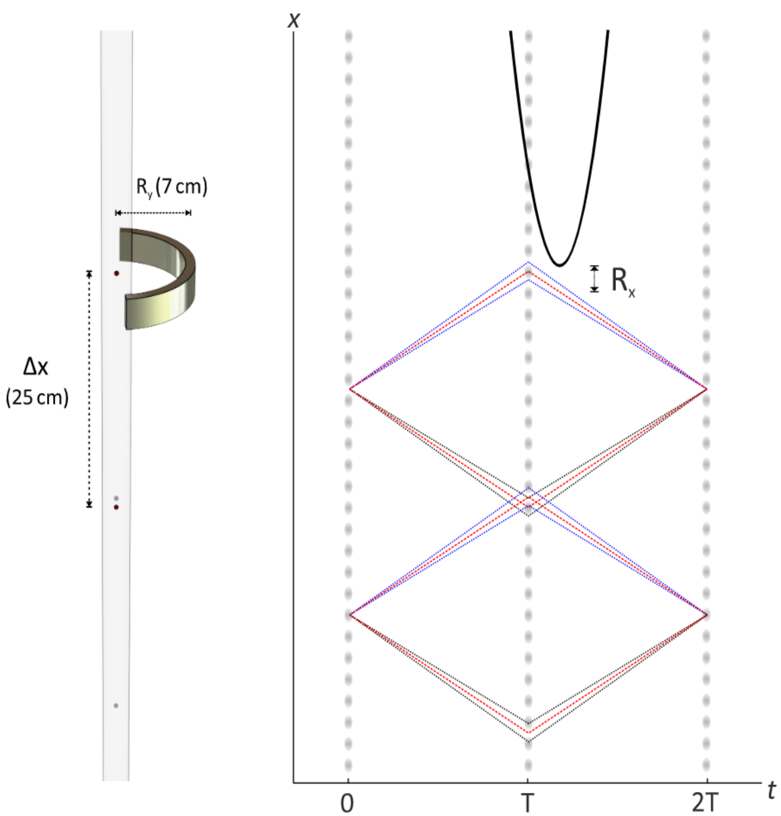
Prior proposals:
Audretsch and Lammerzhal, 1983
Hohensee, et al., 2012

Interferometer trajectories in freely falling frame



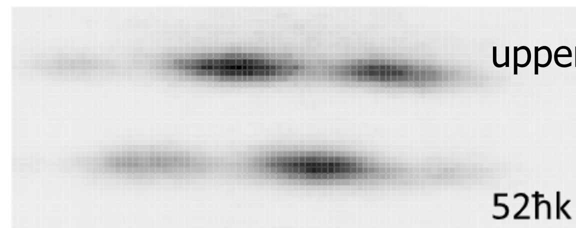
Phase shift due to gravitational action

Interferometer geometry

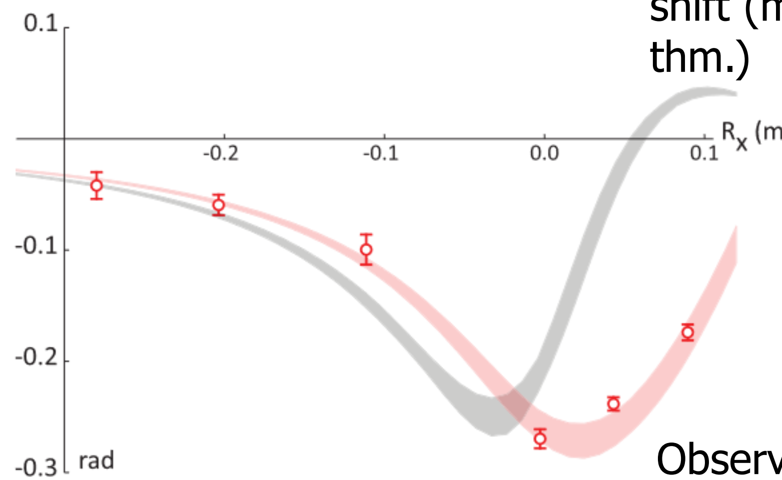


(~7e-12 g/shot resolution for each accelerometer)

Raw data



Phase shift

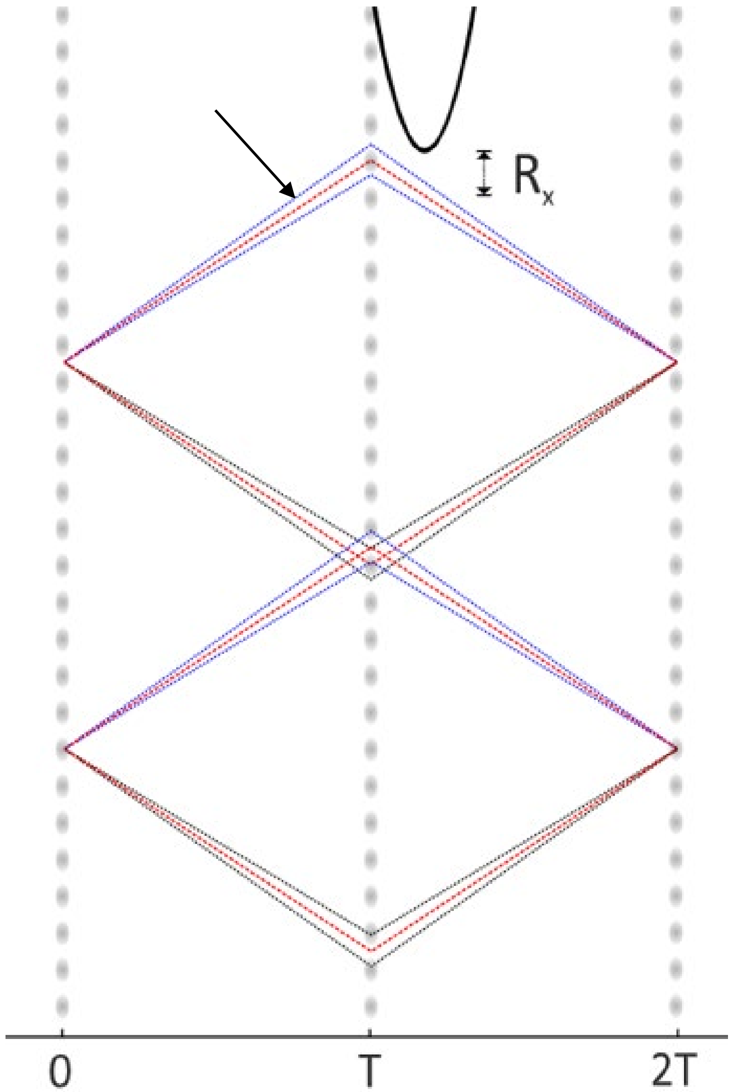


Deflection-induced phase shift (midpoint thm.)

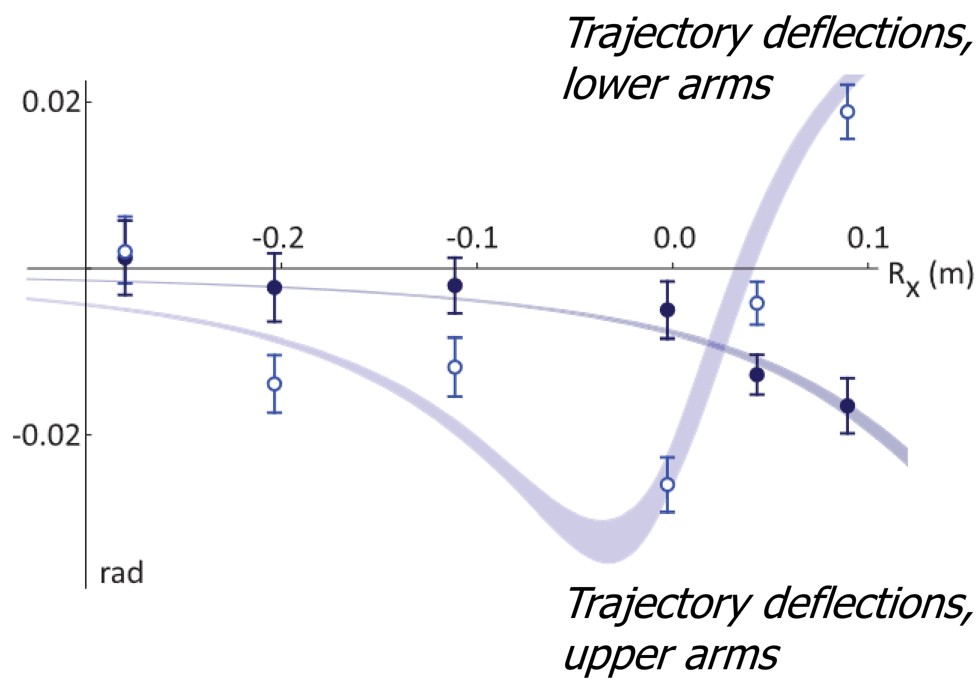
Observed phase shift

Overstreet, at al., Science, 2022

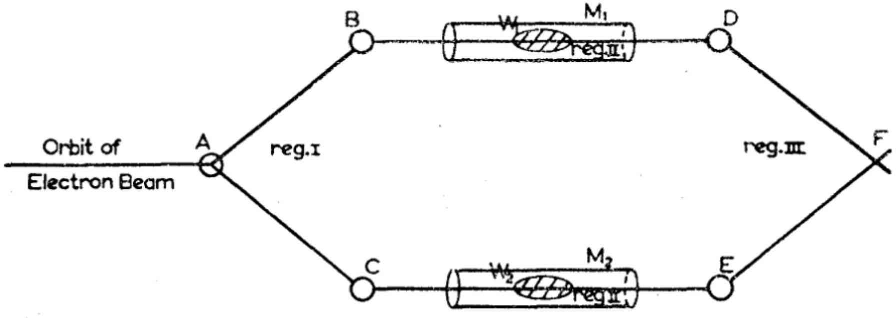
Deflection-induced phase shifts



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



Scalar Aharonov-Bohm Effect



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

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

Aharonov and Bohm, Phys. Rev. 1959

Negligible contribution to phase shift from forces on wavepackets (!)

One interpretation: physical original of the phase shift is the energy required to establish potential in the presence of the electron's electric field. Implies electron electric field is in superposition.

By analogy, observation of the gravitational Aharonov-Bohm shift implies the atom's gravitational field is in superposition.

Newtonian gravitational field energy

Field energy (weak field limit):

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

$$\mathbf{g} = \mathbf{g}_{\mathrm{atom}} + \mathbf{g}_{\mathrm{tungsten}}$$

Phase shift:

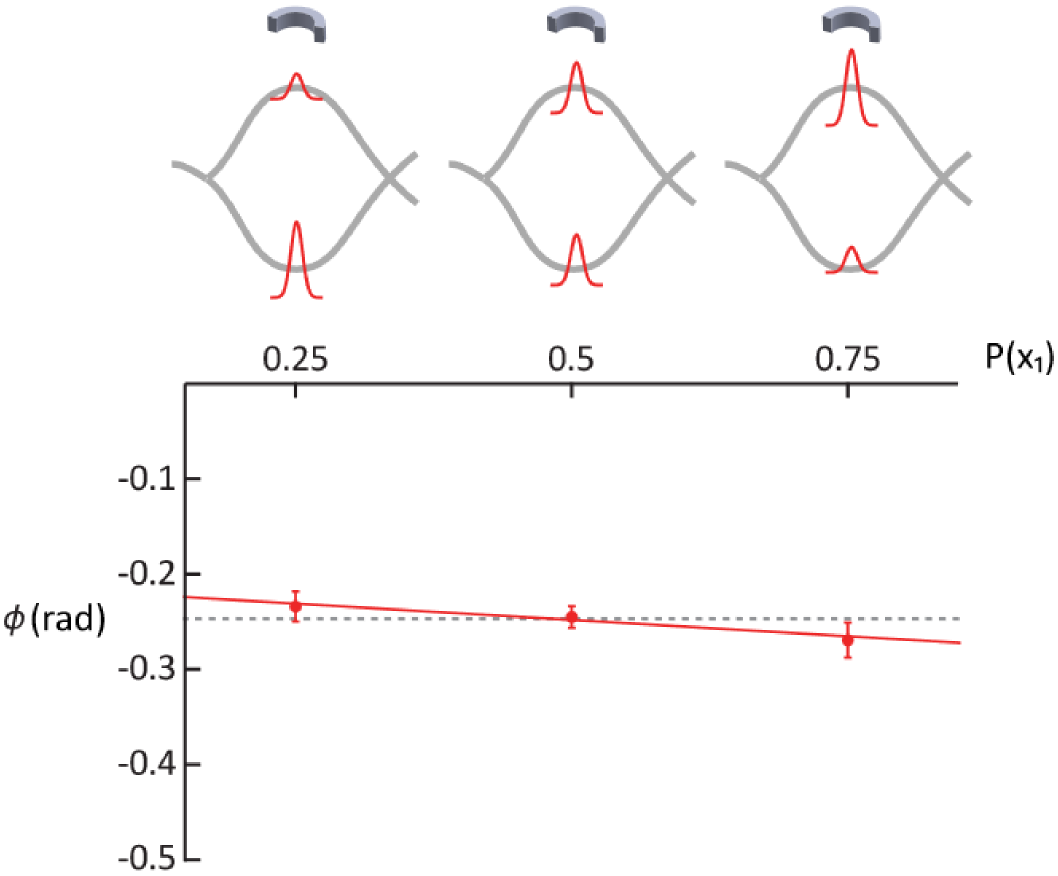
$$\phi = \frac{1}{\hbar}\int (E_1 - E_2)\, dt$$

E_1, E_2 are gravitational energies for each arm.

Phase shift is interpreted as resulting from energy stored in superposed gravitational fields.

Overstreet, et al. arXiv:2209.02214

Experiment to test semiclassical theories



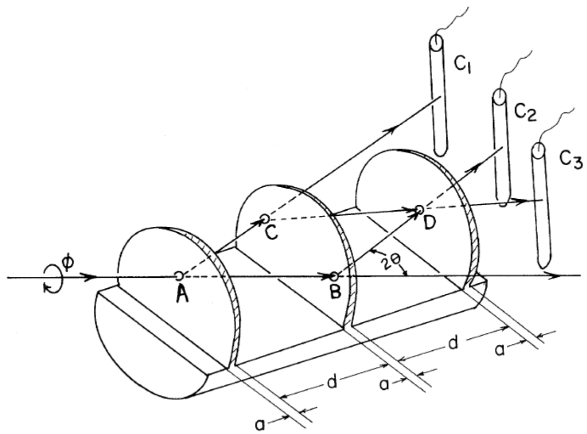
Change population ratio in interferometer arms.

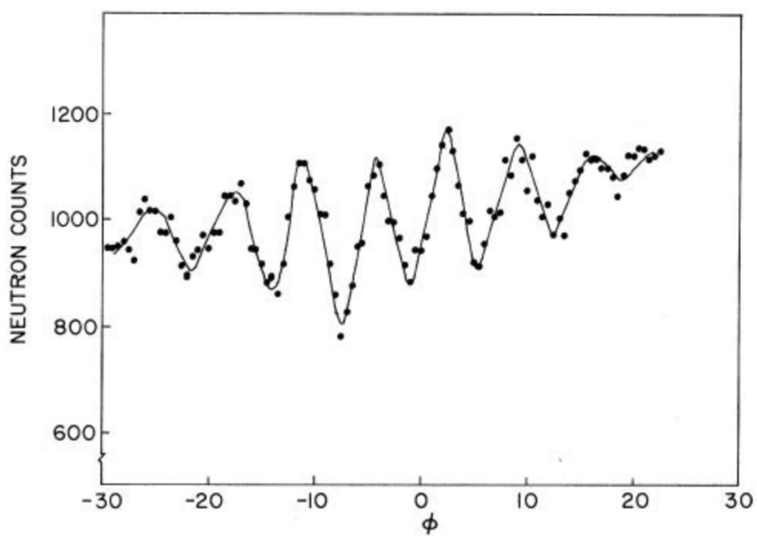
Observe no statistically significant change in phase shift due to tungsten.

Rules out theories where the atom's gravitational field is given by its wavefunction probability distribution.

Overstreet, et al. arXiv:2209.02214

Collela, Overhauser and Werner (1975)





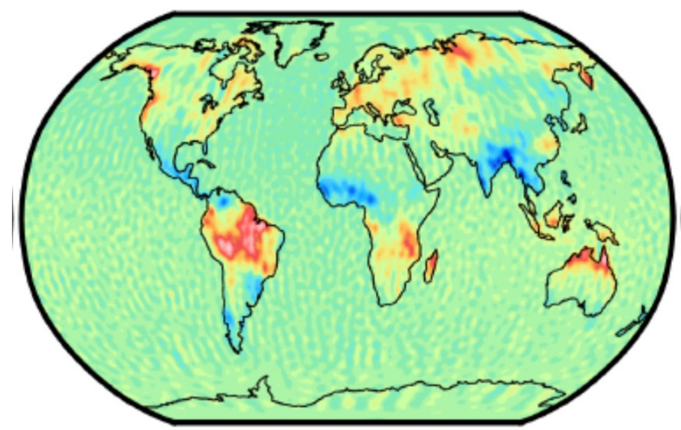
Uniform gravitational field implies gravitational action phase shift is zero -- uniform gravitational fields are not observable.

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.

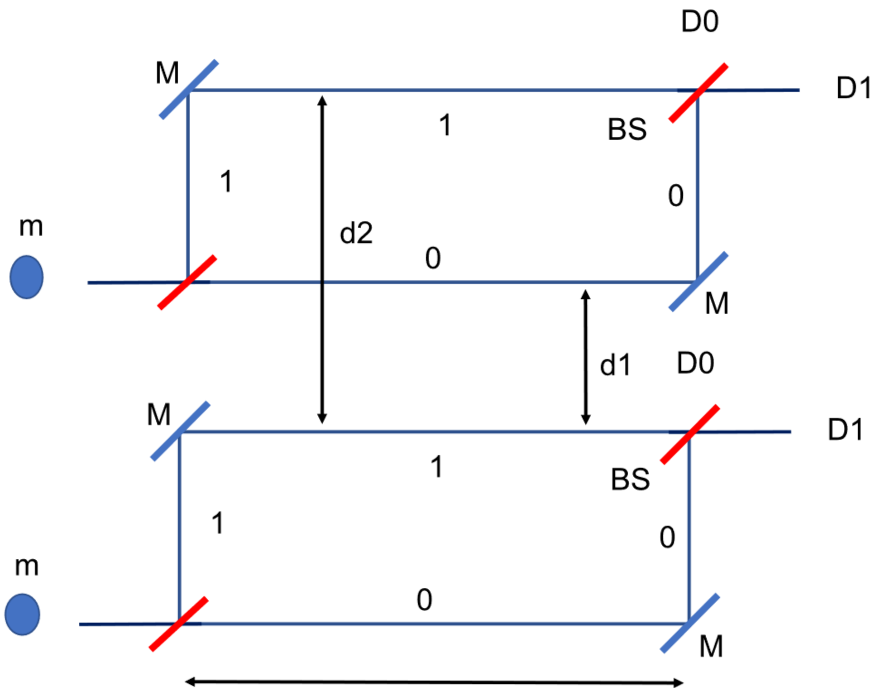
Satellite geodesy

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



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

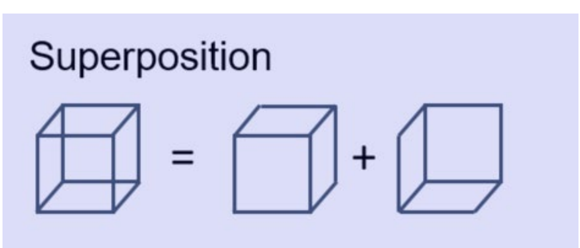
Gravitationally induced entanglement

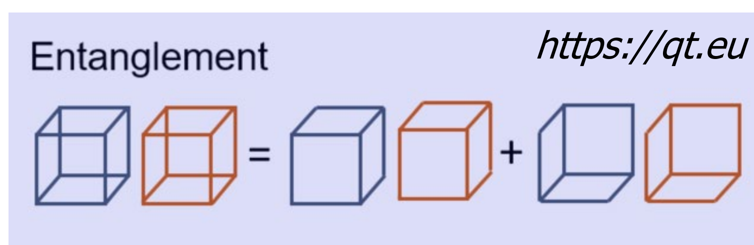


Marletto and Vedral, 2017

Interferometer outputs are entangled by the Newtonian interaction

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

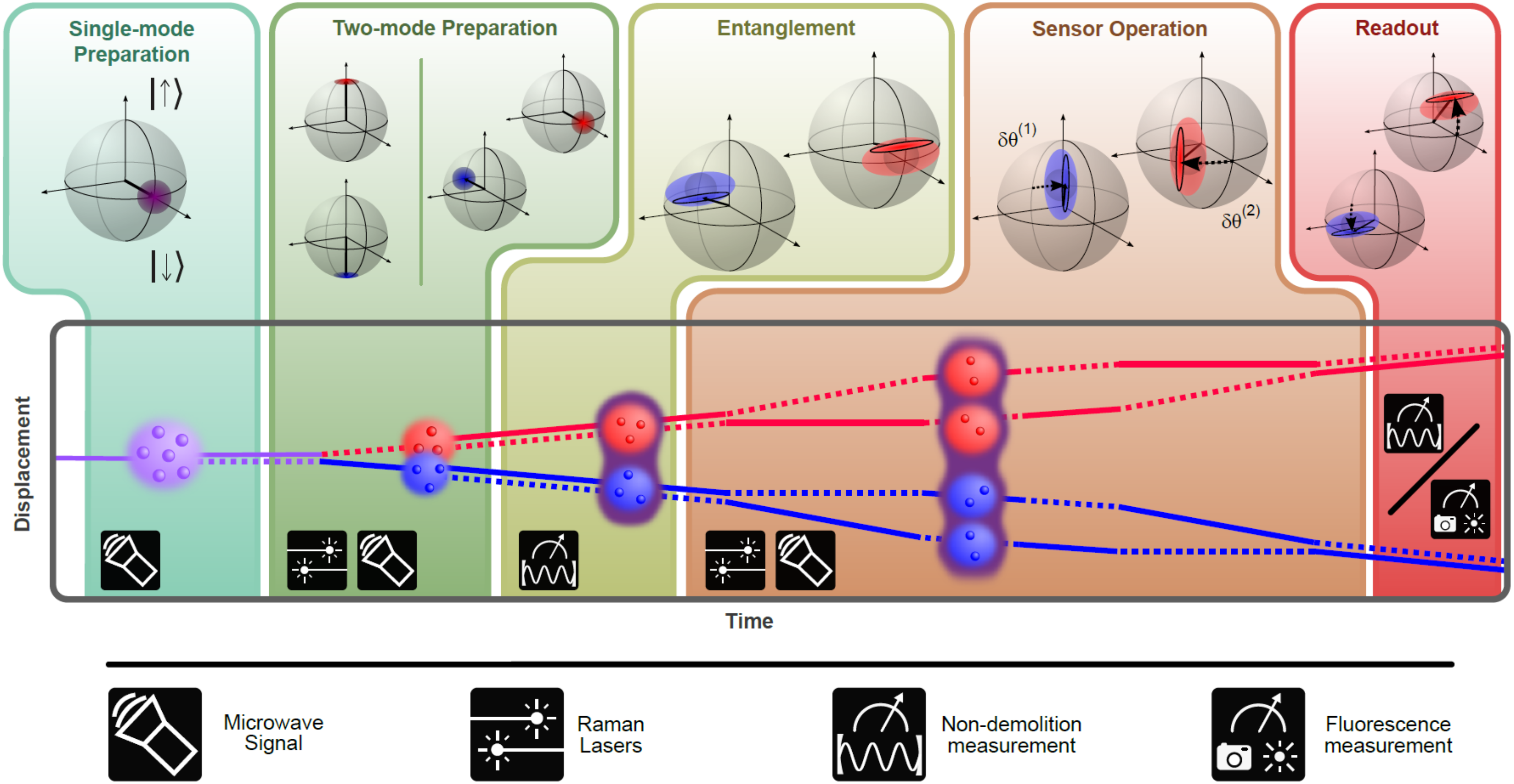




Overstreet, et al. arXiv:2209.02214

Differential sensing with entangled atomic networks

Entangled interferometer networks can be used to increase the mass of the gravitating quantum superpositions.



STANFORD UNIVERSITY

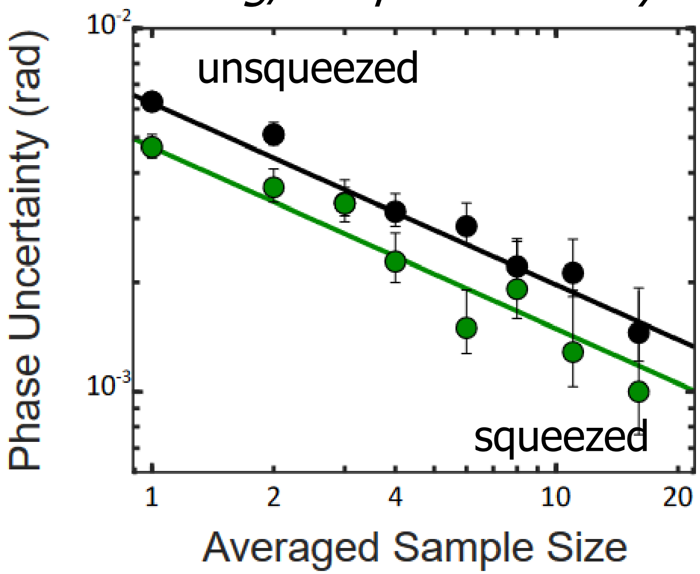
Malia, et al., arXiv:2205.06382, Nature, to be published.

Entangled differential atom interferometers

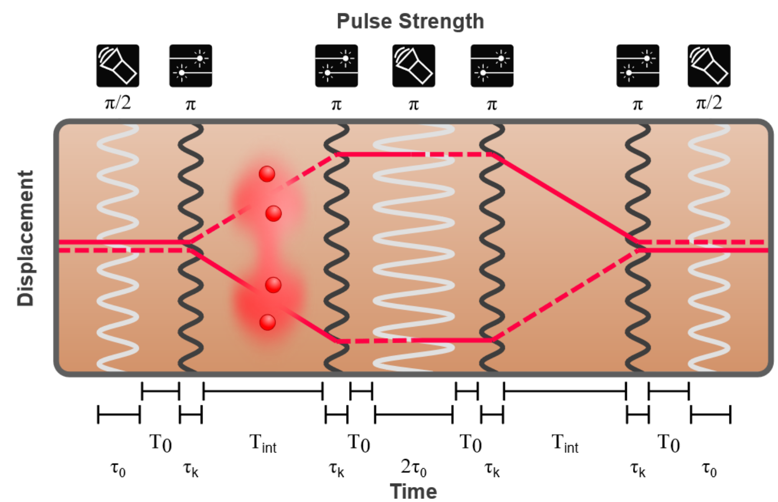
Two-mode squeezed atomic source is used for differential atom interferometry.

Entanglement is distributed across spatial modes. Protocol mitigates the need for very low noise local oscillators.

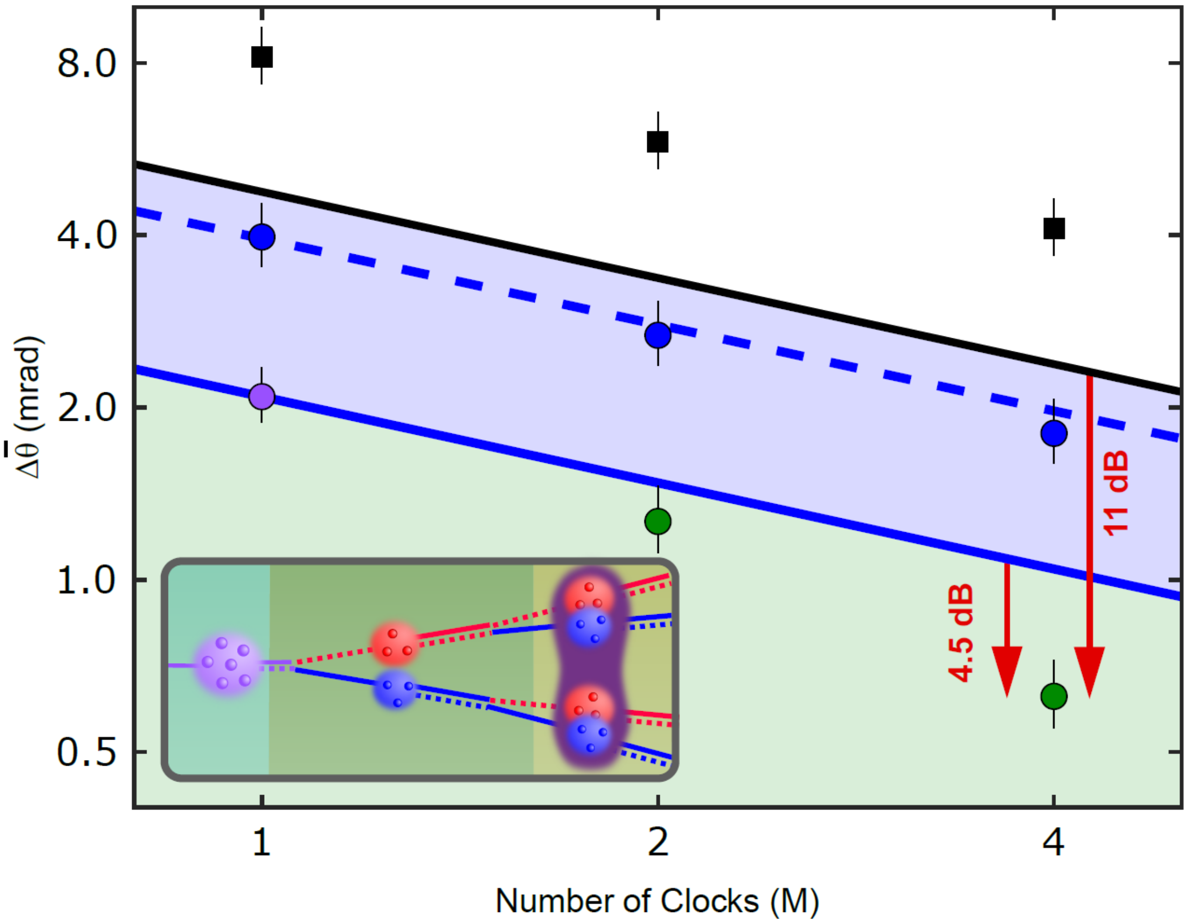
1e-3 g/sample sensitivity



Interferometer pulse sequence



Entangled clock network performance



Clock ensembles separated by ~20 microns.

Each ensemble has ~45,000 atoms.

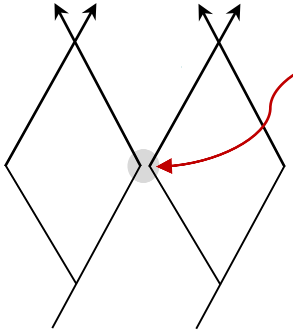
4-node networks operates 11 dB below the projection noise limit.

Future

Interferometry with entangled atomic ensembles separated by meter-scale distances.

- New tests of QM
- superb sensitivity for future fundamental physics

Interferometry with entangled ensembles large enough induce observable gravitational phase shifts from the ensembles.



Gravitational interaction creates phase shift

Thanks

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Yunfan Wu
Julian Martinez

Flaminia Giacomini (Perimeter)