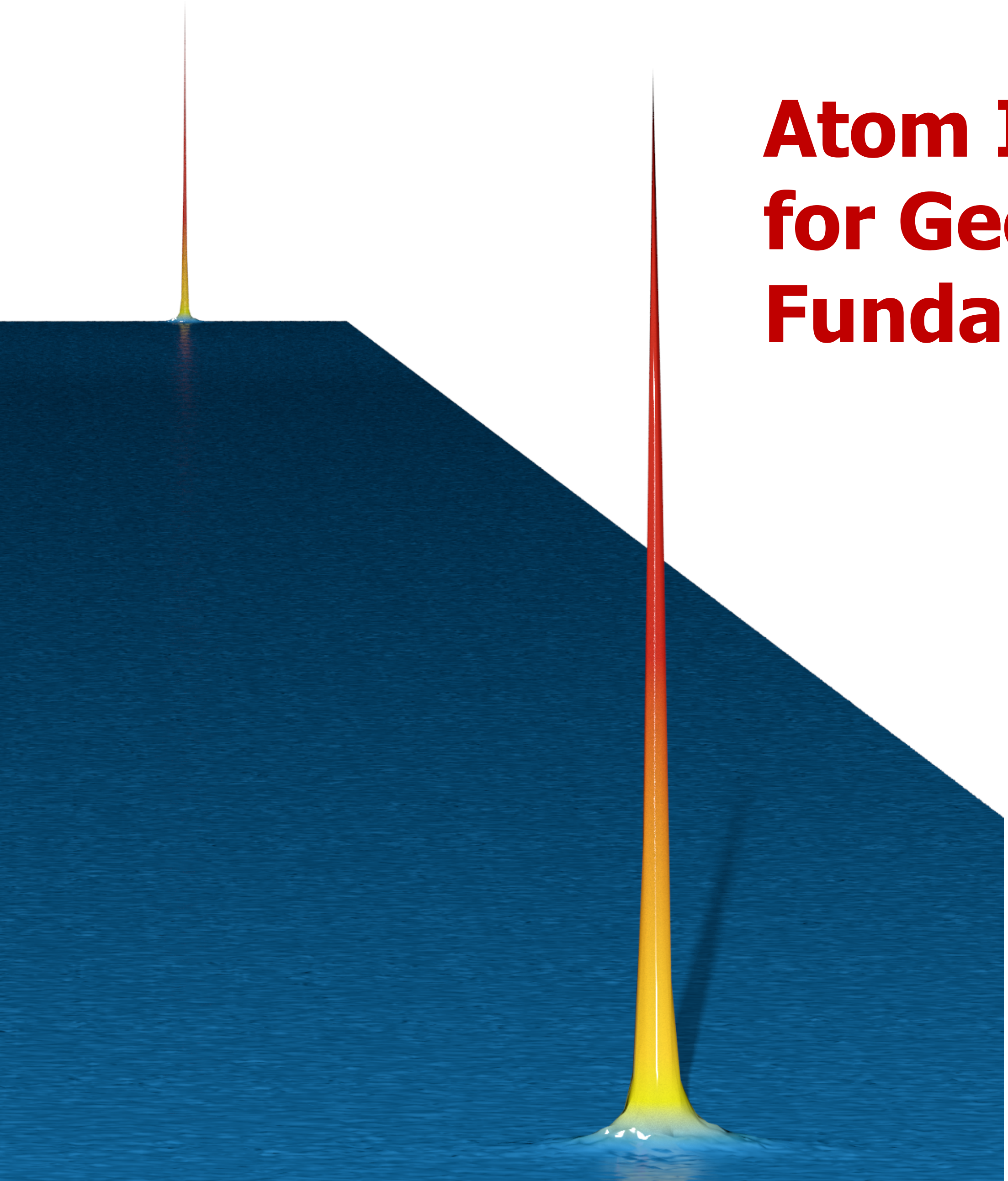
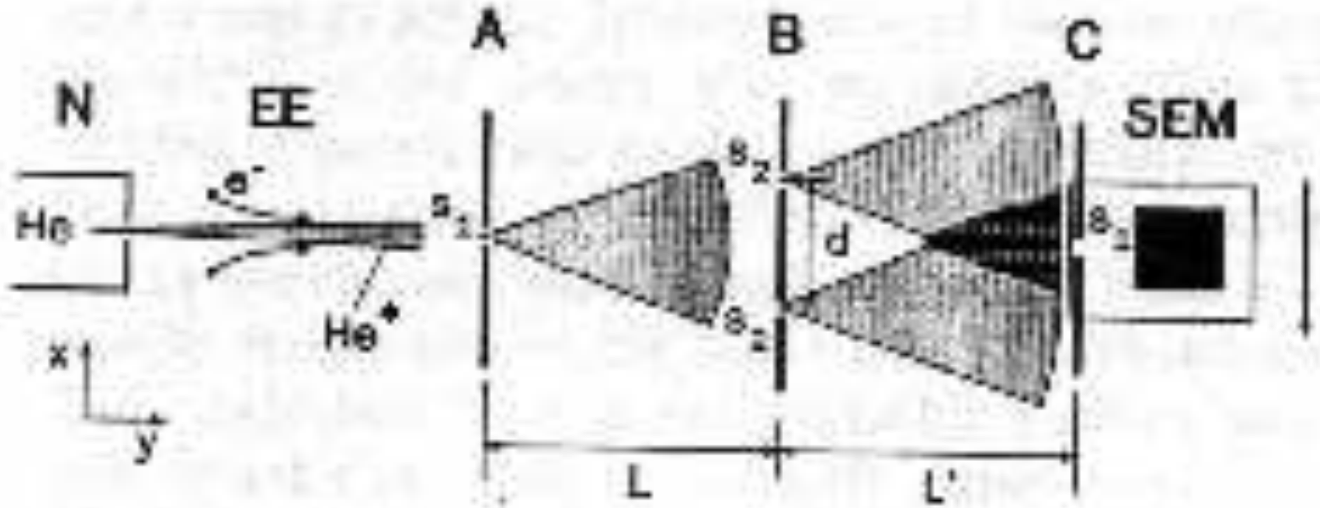


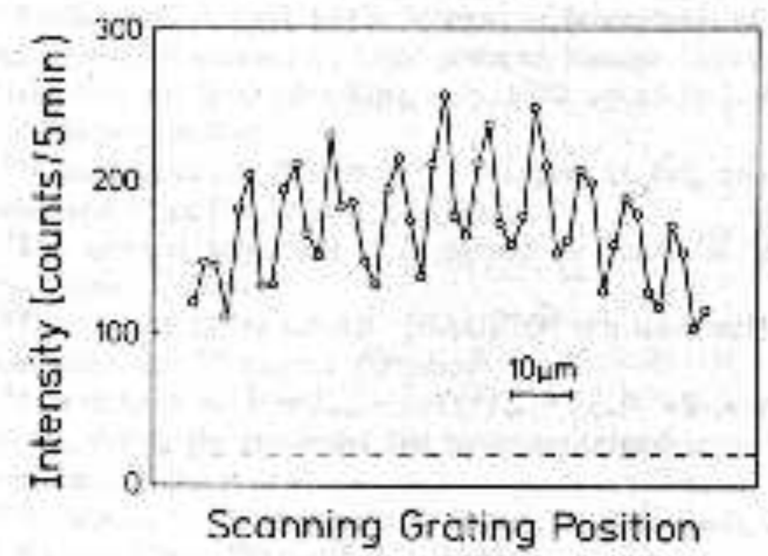
Atom Inteferometry for Geodesy and Fundamental Physics

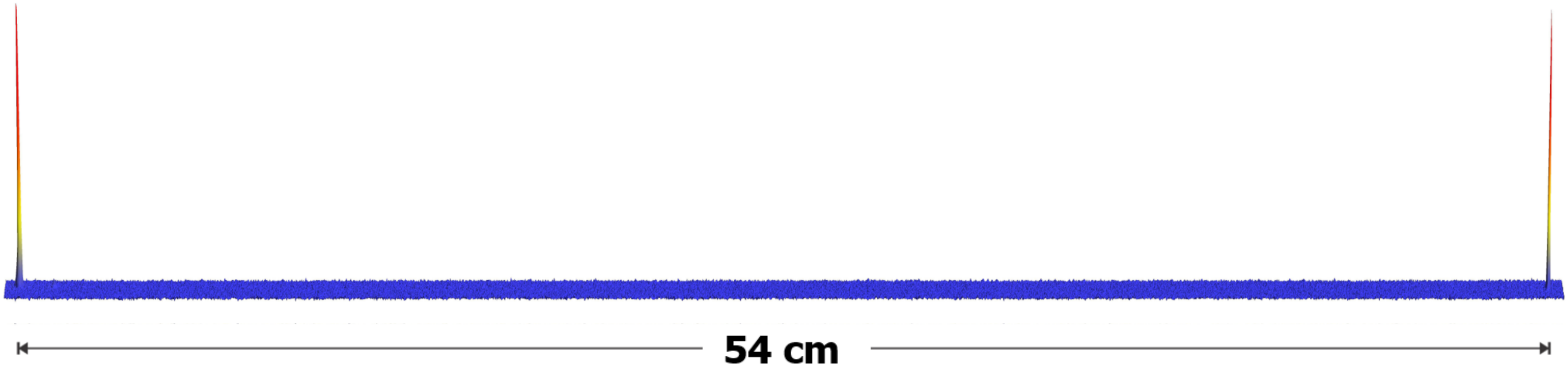
Mark Kasevich
Stanford University
kasevich@stanford.edu

Young’s double slit interferometer with atoms

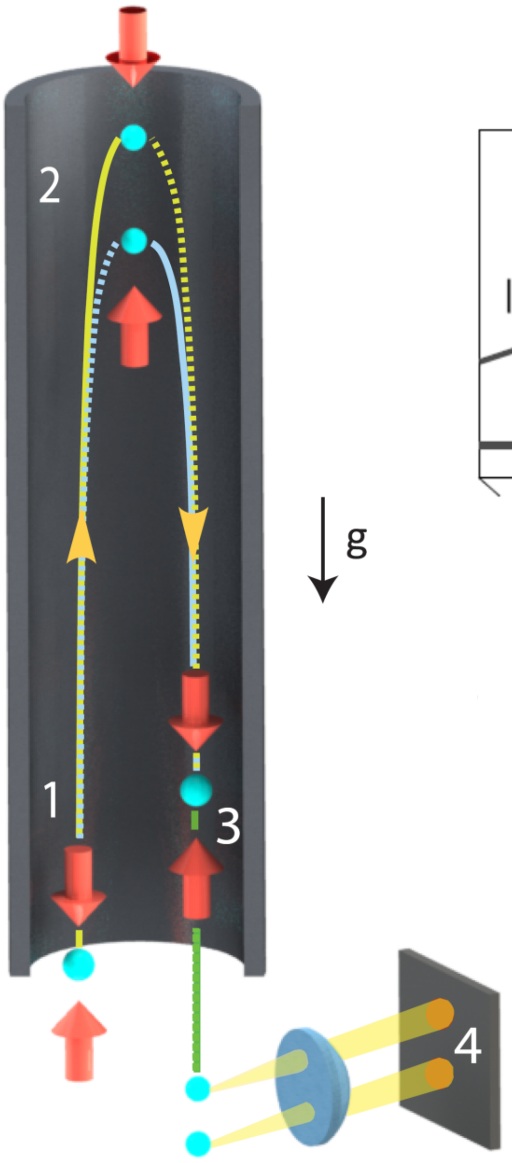


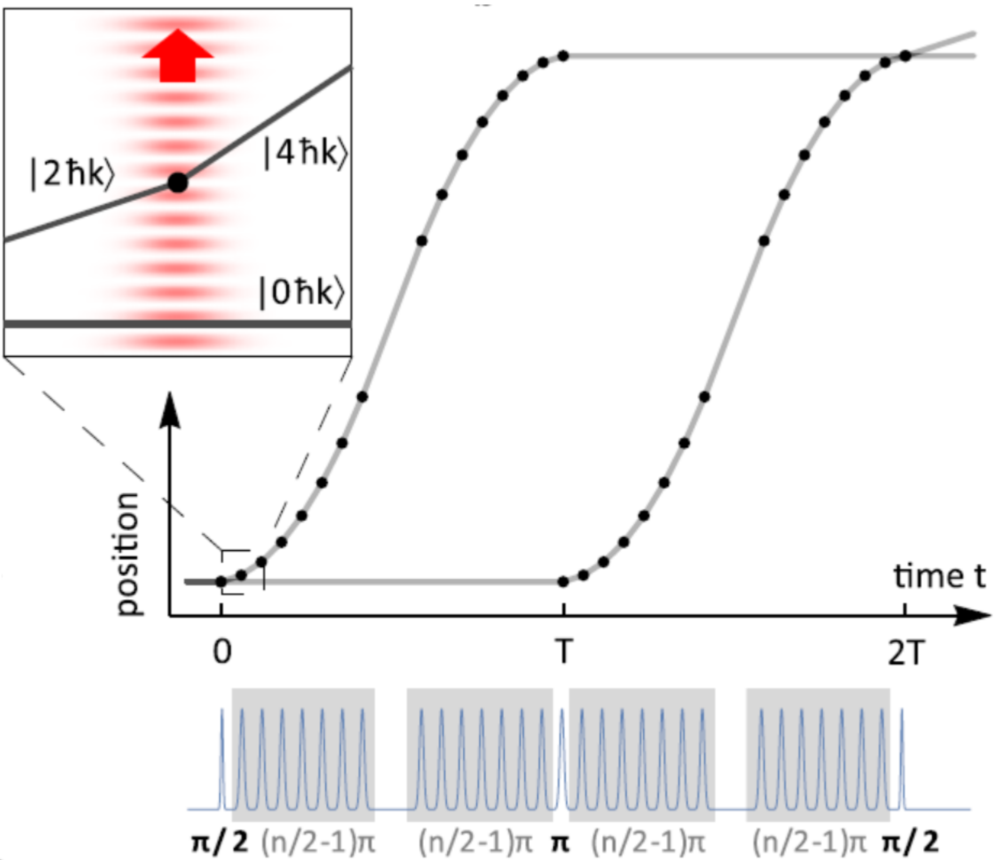
Mlynek, PRL, 1991




54 cm

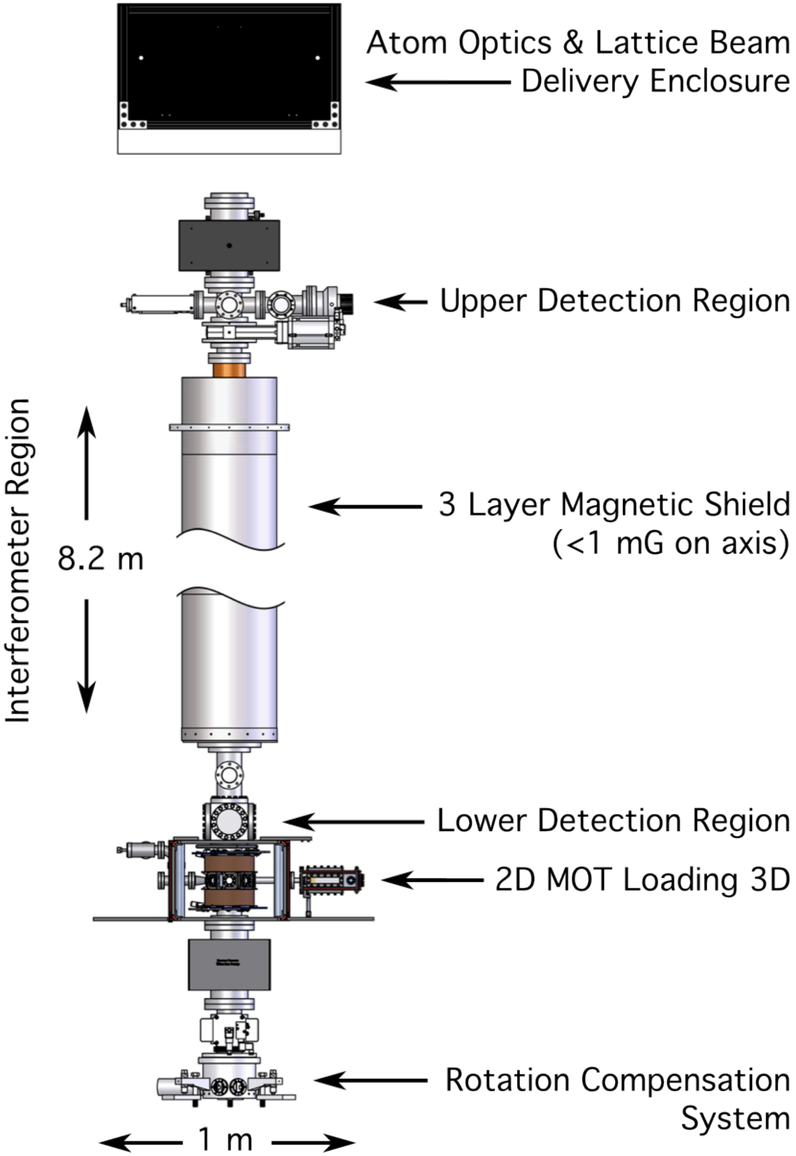
Light Pulse Atom Interferometry





Pulse sequence duration: 2.08 s

Atomic fountain



Atom Optics & Lattice Beam Delivery Enclosure

Upper Detection Region

Interferometer Region

8.2 m

3 Layer Magnetic Shield (<1 mG on axis)

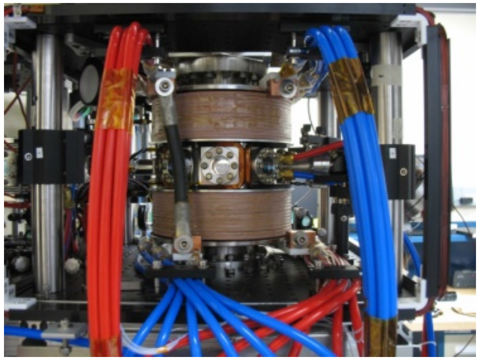
Lower Detection Region

2D MOT Loading 3D

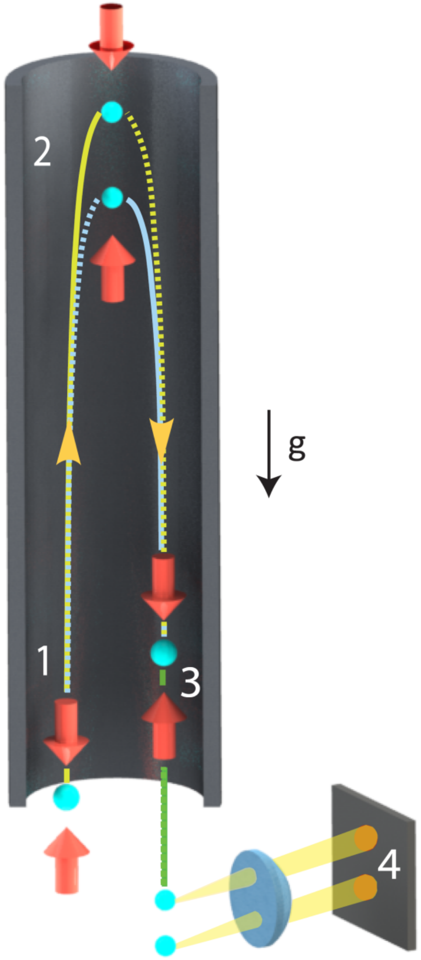
Rotation Compensation System

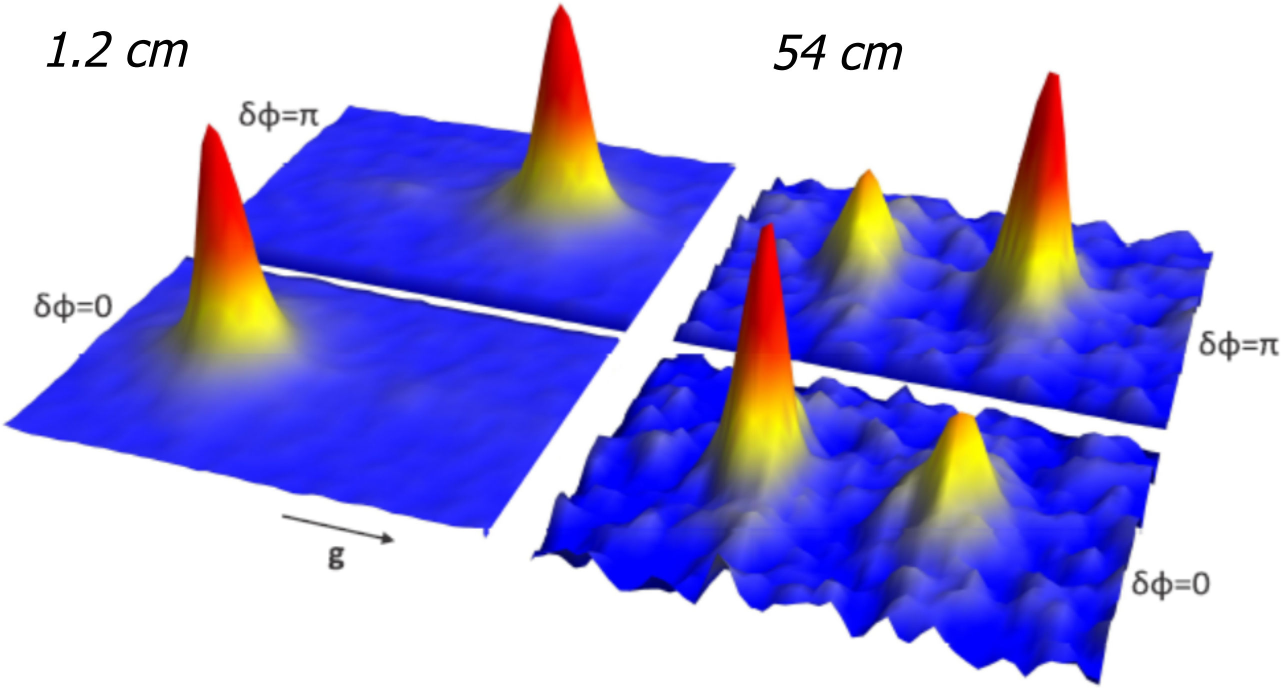
1 m

~ 100 pK
1e5 atoms/shot



Interference at output ports





Interference causes population modulation between the output ports

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

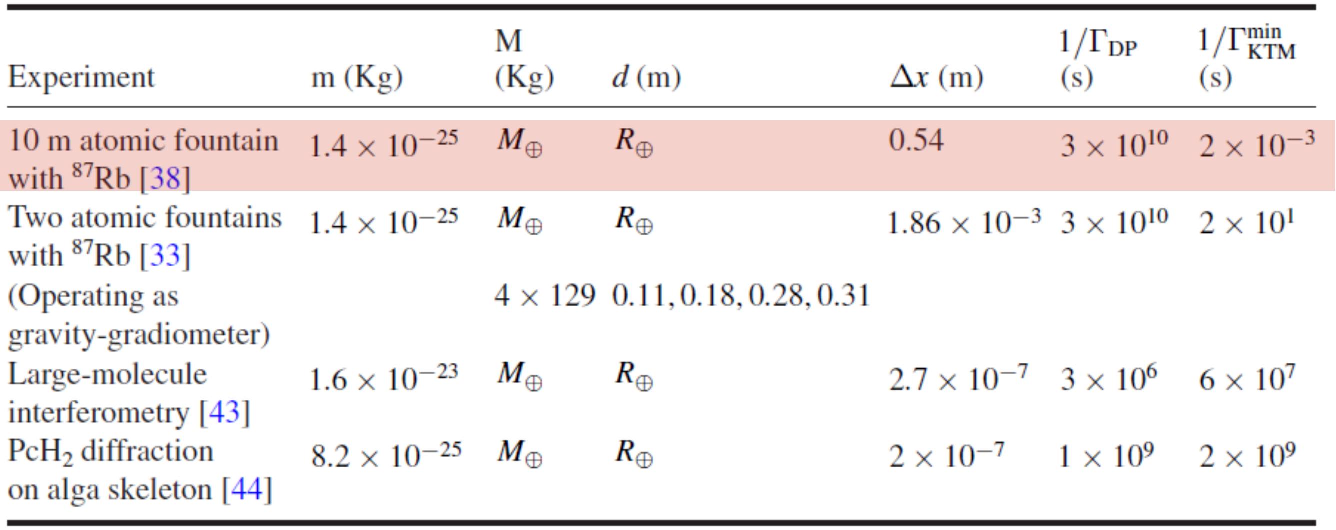
Bounds for KTM model

IOP Publishing
Classical and Quantum Gravity
Class. Quantum Grav. **35** (2018) 145005 (18pp)
https://doi.org/10.1088/1361-6382/aac72f

Gravity is not a pairwise local classical channel

Natacha Altamirano[1,2], Paulina Corona-Ugalde[2,3], Robert B Mann[1,2,3] and Magdalena Zych[4,5]

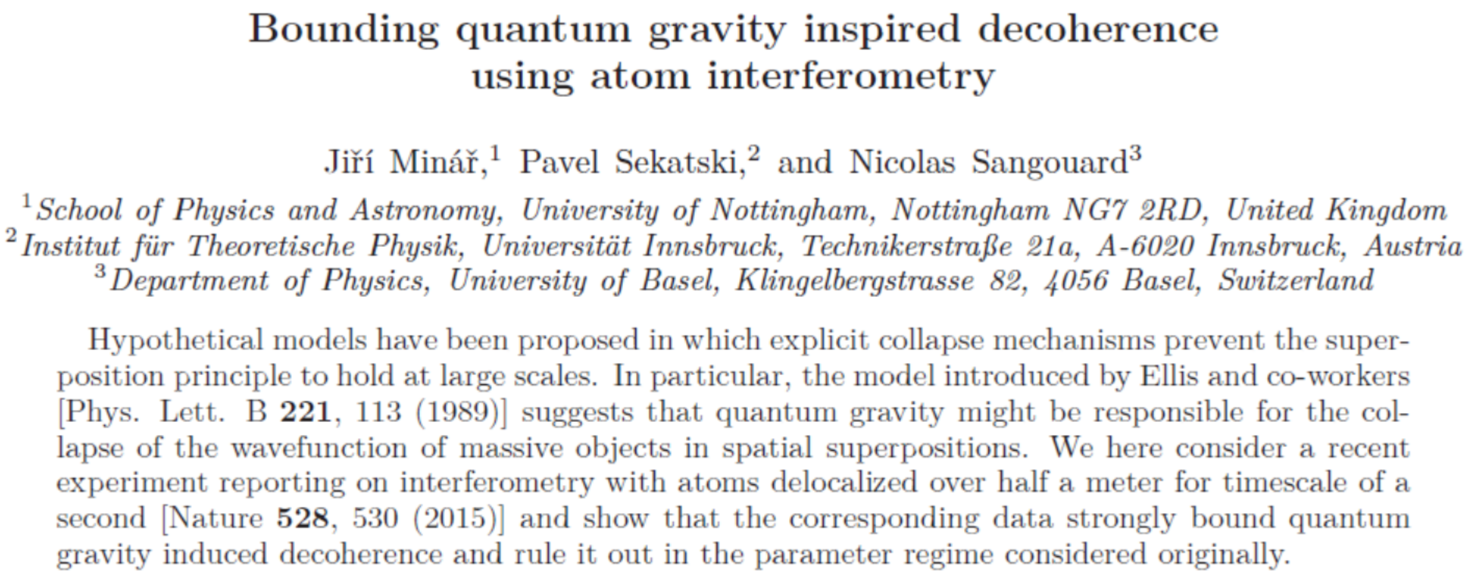
$$\tilde{\Gamma}^{C}_{\text{KTM}} = C\frac{GMm}{\hbar R^3}\Delta x^2$$



Experiment	m (Kg)	M (Kg)	*d* (m)	Δx (m)	$1/\Gamma_{\text{DP}}$ (s)	$1/\Gamma^{\text{min}}_{\text{KTM}}$ (s)
10 m atomic fountain with ^{87}Rb [38]	1.4×10^{-25}	$M_\oplus$	$R_\oplus$	0.54	3×10^{10}	2×10^{-3}
Two atomic fountains with ^{87}Rb [33] (Operating as gravity-gradiometer)	1.4×10^{-25}	$M_\oplus$ 4×129	$R_\oplus$ $0.11, 0.18, 0.28, 0.31$	1.86×10^{-3}	3×10^{10}	2×10^{1}
Large-molecule interferometry [43]	1.6×10^{-23}	$M_\oplus$	$R_\oplus$	2.7×10^{-7}	3×10^{6}	6×10^{7}
PcH_2 diffraction on alga skeleton [44]	8.2×10^{-25}	$M_\oplus$	$R_\oplus$	2×10^{-7}	1×10^{9}	2×10^{9}

Large wavepacket separation AI constrains the KTM model

Bounds for Ellis model (1989)



Bounding quantum gravity inspired decoherence using atom interferometry

Jiří Minář,[1] Pavel Sekatski,[2] and Nicolas Sangouard[3]

[1] *School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom*
[2] *Institut für Theoretische Physik, Universität Innsbruck, Technikerstraße 21a, A-6020 Innsbruck, Austria*
[3] *Department of Physics, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

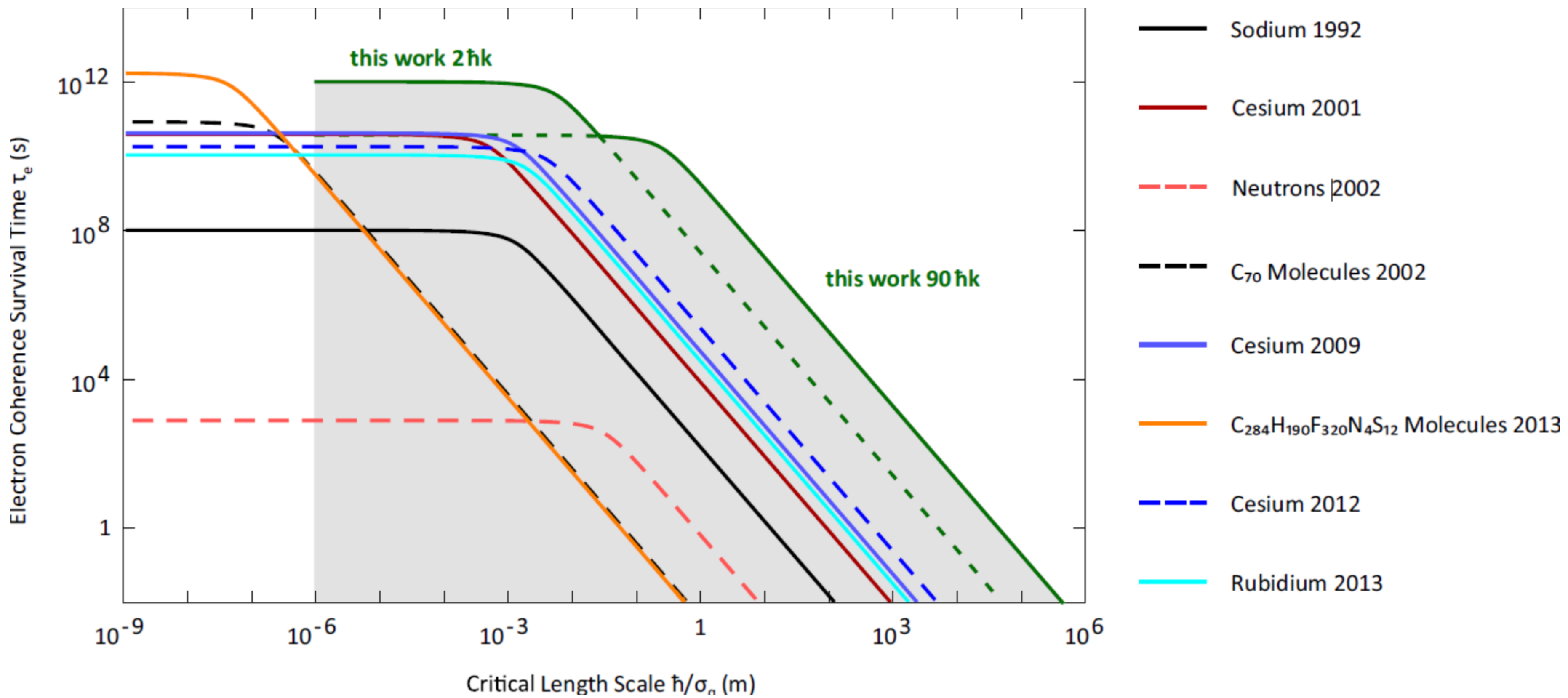
Hypothetical models have been proposed in which explicit collapse mechanisms prevent the superposition principle to hold at large scales. In particular, the model introduced by Ellis and co-workers [Phys. Lett. B **221**, 113 (1989)] suggests that quantum gravity might be responsible for the collapse of the wavefunction of massive objects in spatial superpositions. We here consider a recent experiment reporting on interferometry with atoms delocalized over half a meter for timescale of a second [Nature **528**, 530 (2015)] and show that the corresponding data strongly bound quantum gravity induced decoherence and rule it out in the parameter regime considered originally.

http://arxiv.org/abs/1604.07810v1

Wormhole scattering leads to loss of interference:

$$|\mathbf{p}\rangle \rightarrow i\int d^3\mathbf{p}' e^{i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{X}}\delta(|\mathbf{p}|-|\mathbf{p}'|)\frac{F(\mathbf{p}')}{|\mathbf{p}'|}\,|\mathbf{p}'\rangle$$

Testing QM: “Macroscopicity”

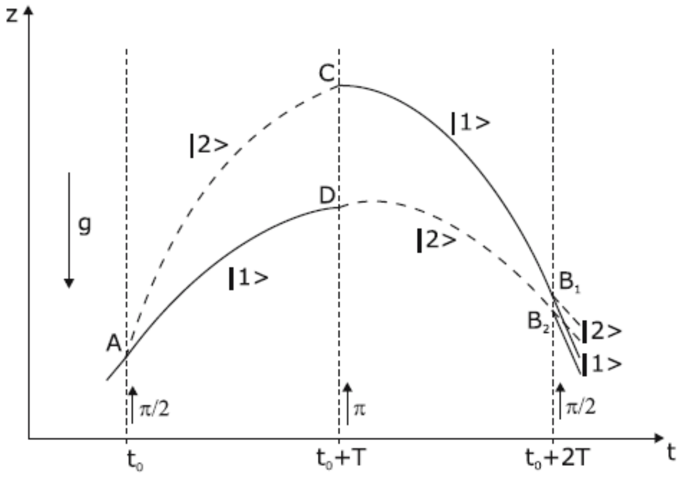


Nimrichter, et al., PRL, 2013

Phase shifts

Three contributions to interferometer phase shift:

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$



Propagation shift:

$$\frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar}$$

Laser fields (Bragg interaction):

$$k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III}$$

Wavepacket separation at detection:

$$\vec{p} \cdot \Delta\vec{r}/\hbar$$

Storey and CCT, J. Physique II, 1994; Bongs, et al., App. Phys. B, 2006.

Phase shifts (non-relativistic)

	Term	Phase Shift	
8e9 rad	1	$k_{\text{eff}} g T^2$	Gravity
	2	$2\mathbf{k}_{\text{eff}} \cdot (\boldsymbol{\Omega} \times \mathbf{v}) T^2$	Coriolis
	3	$k_{\text{eff}} v_z \delta T$	Timing asymmetry
635 rad	4	$\frac{\hbar k_{\text{eff}}^2}{2m} T_{zz} T^3$	Curvature, quantum (tidal)
	5	$k_{\text{eff}} T_{zi} (x_i + v_i T) T^2$	Gravity gradient
	6	$\frac{1}{2} k_{\text{eff}} \alpha \left(v_x^2 + v_y^2\right) T^2$	Wavefront

T_{ij}, gravity gradient

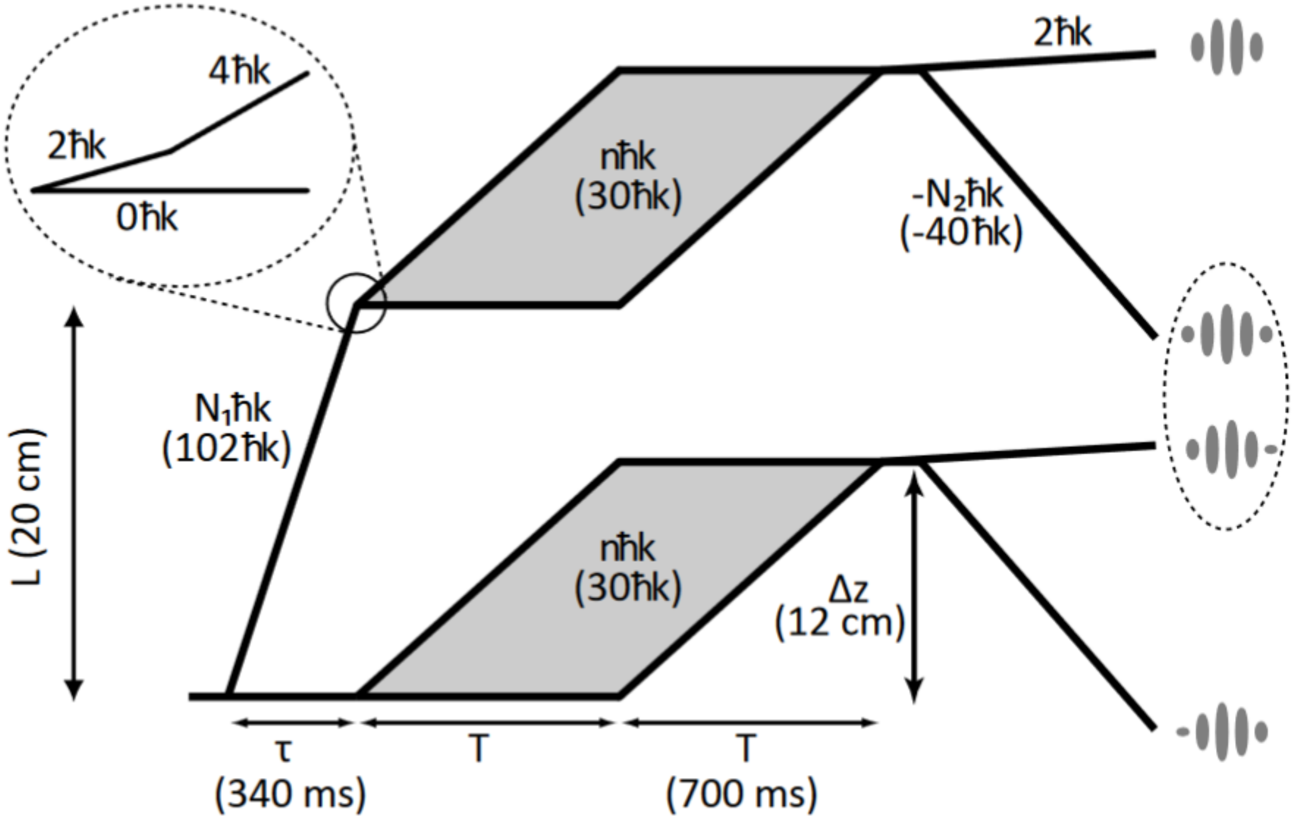
v_i, velocity; x_i, initial position

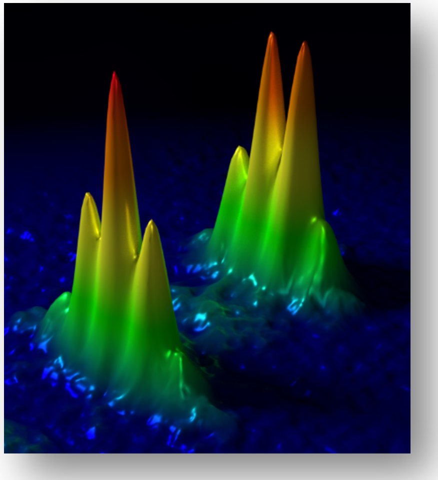
g, acceleration due to gravity

T, interrogation time

k_{eff}, effective propagation vector

Curvature, quantum (tidal) phase shift observation



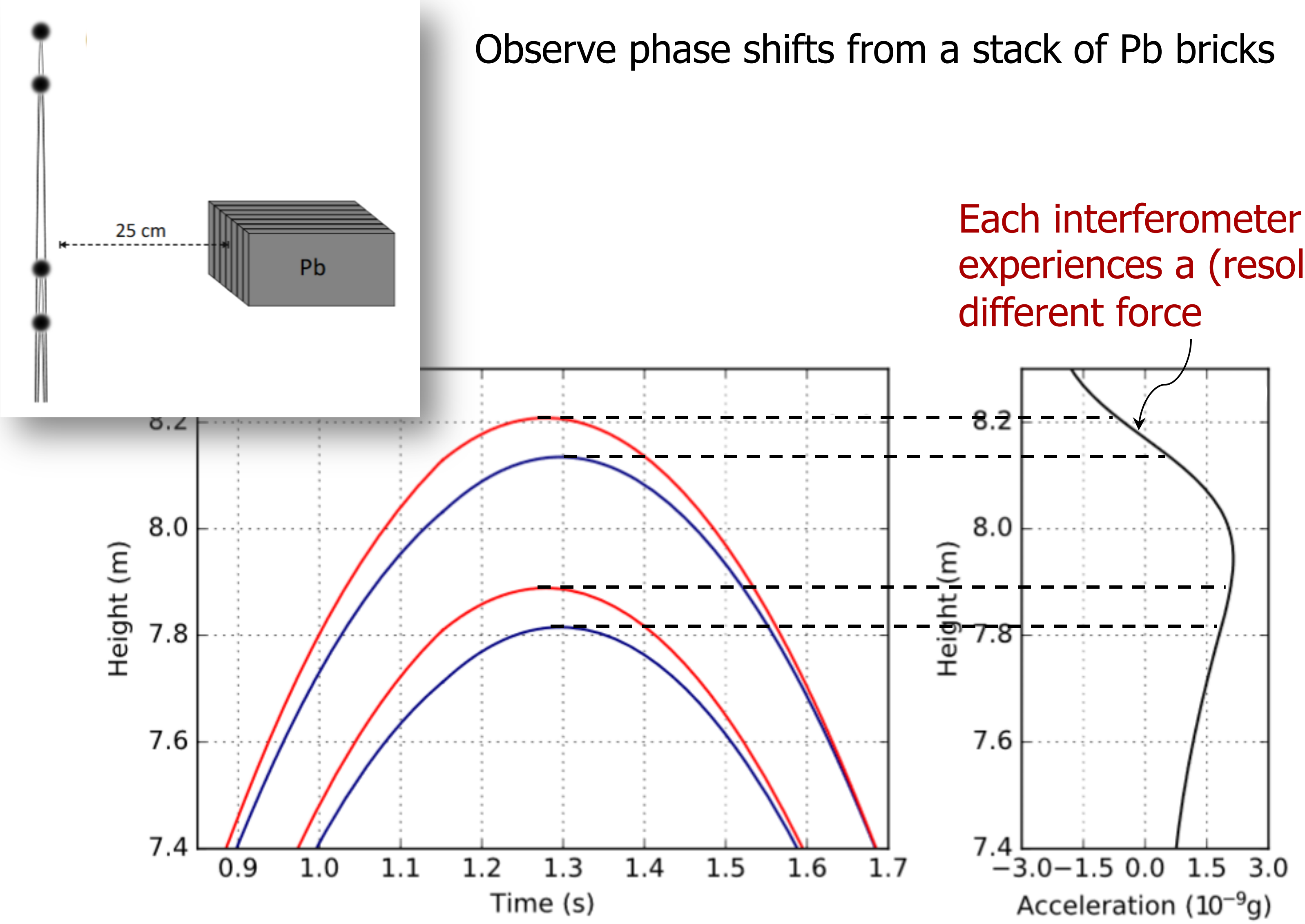


Resolution: 2e-9/s^2
per shot
(7e-4 Earth
gradient/shot)

Use gravity gradiometer configuration to isolate quantum curvature phase shifts

Tidal forces on a wavefunction

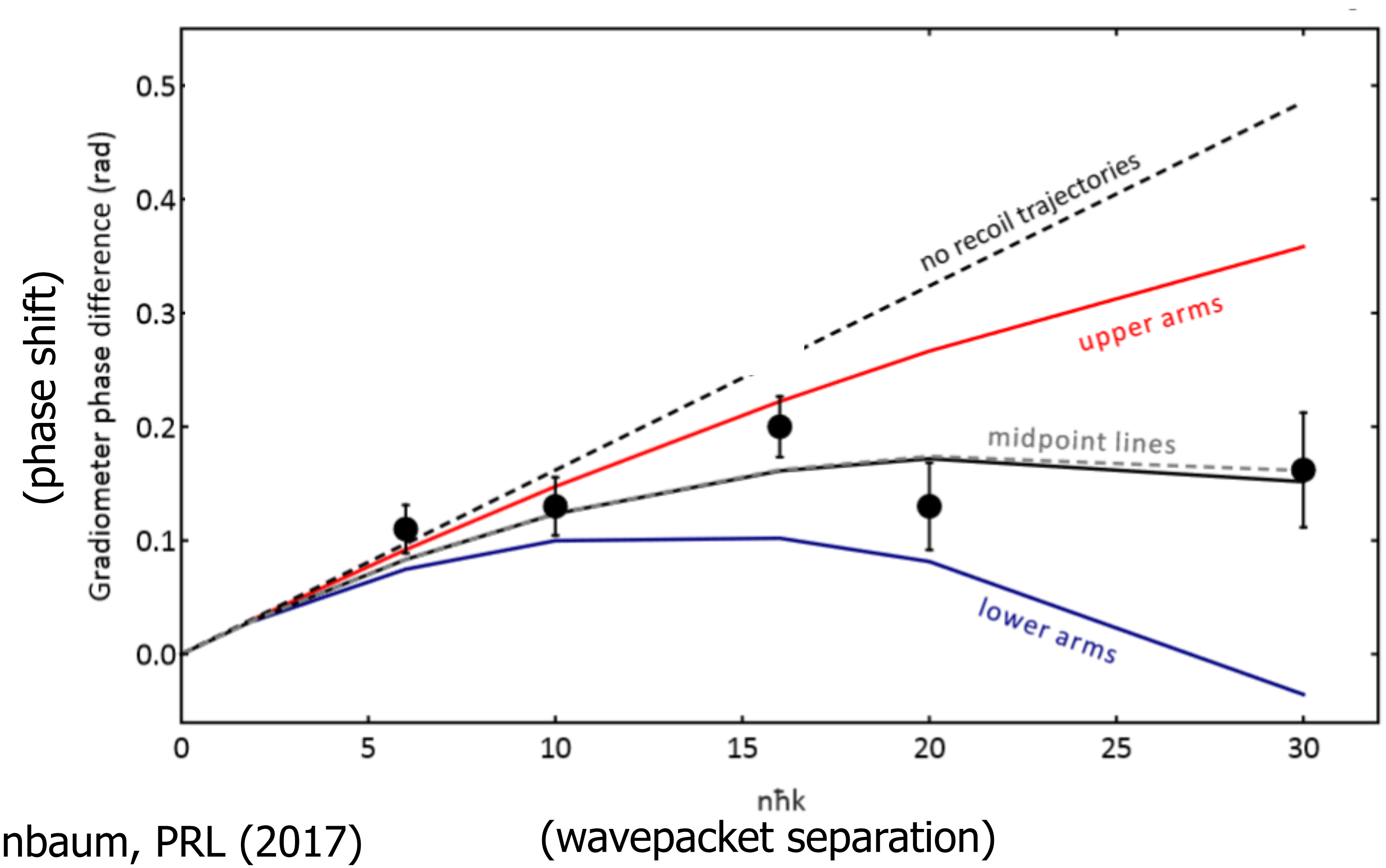
Observe phase shifts from a stack of Pb bricks



Each interferometer arm experiences a (resolvable) different force

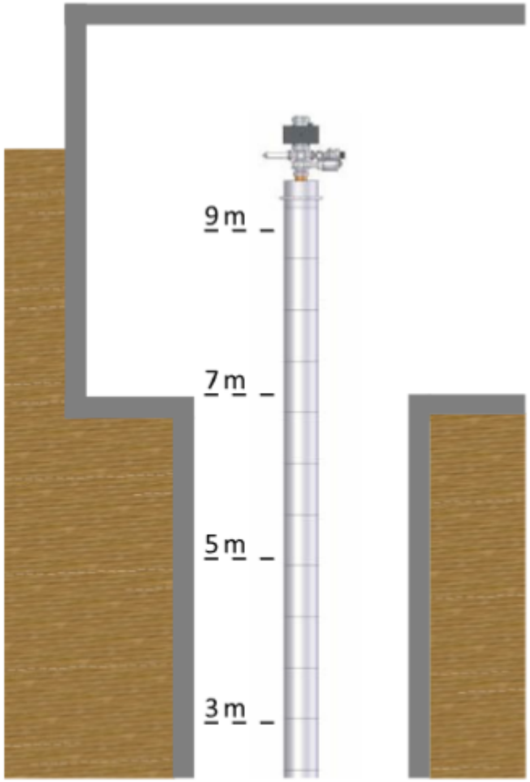
Gravity and quantum mechanics

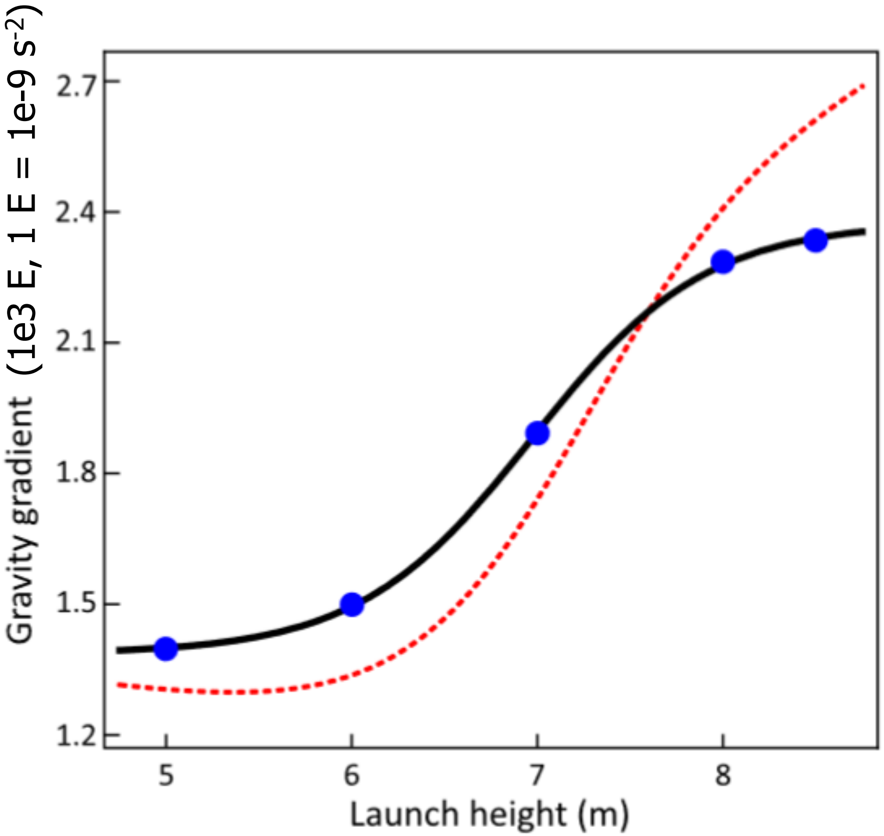
First observation of the influence of gravitational curvature on any quantum system (see Audretsch, PRA 1994; Anandan, PRD, 1984).



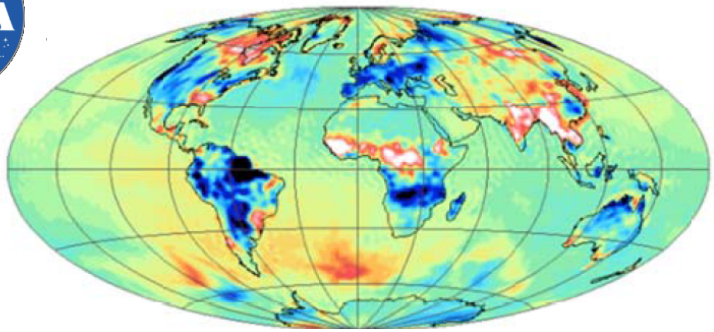
Asenbaum, PRL (2017)

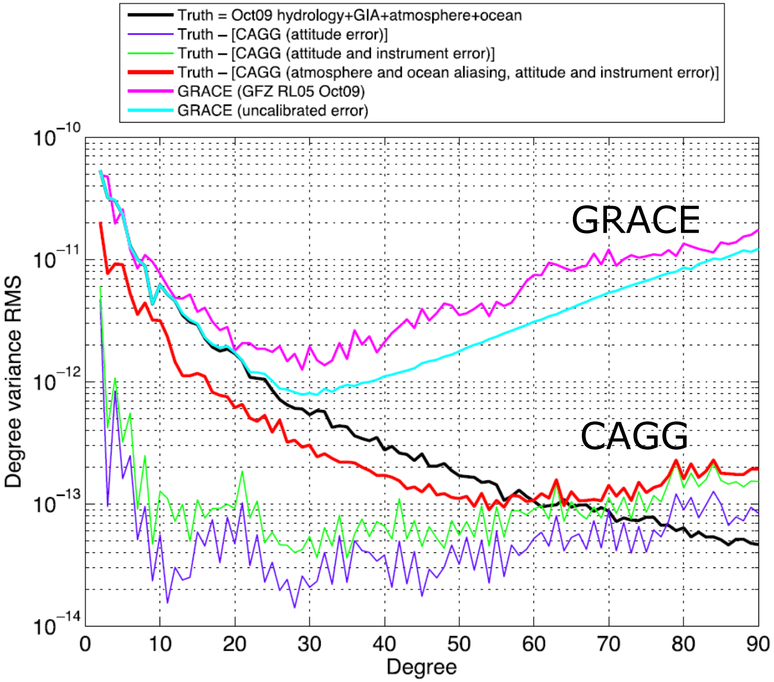
Gravity gradiometery





Satellite gravity gradiometry





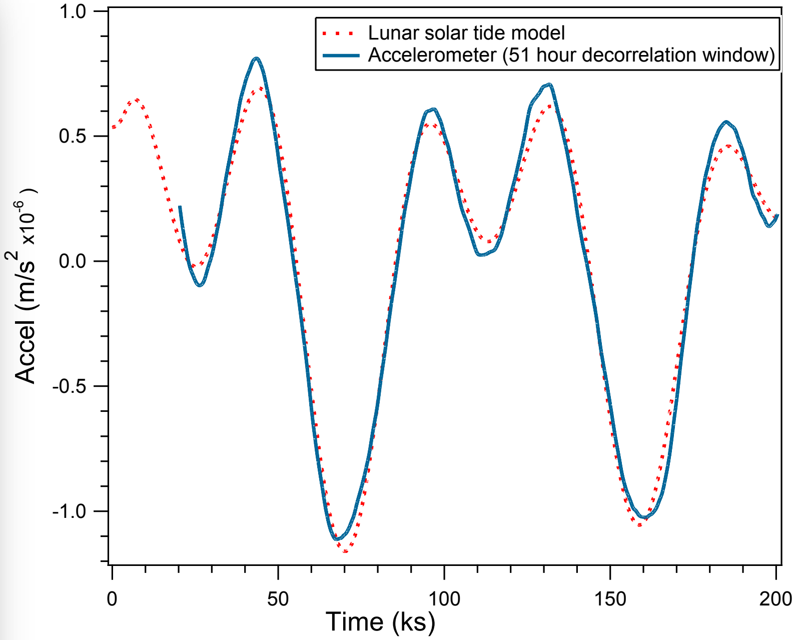
Analysis from S. Luthke, GSFC

Simulation of hydrology map from space-borne atom interferometer gravity gradiometer.

Gravity gradiometer

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

Commercial absolute atom interferometer gravimeter (2011)



Lunar solar variations in Earth's gravitational field as observed by atom interferometer

AOSense

Atom interferometer gyroscope

Rotations sensed through Coriolis acceleration

Performance competitive with commercial ring laser gyroscope

Equivalence Principle

Acceleration of co-falling ^{85}Rb and ^{87}Rb ensembles is measured using light-pulse atom interferometry

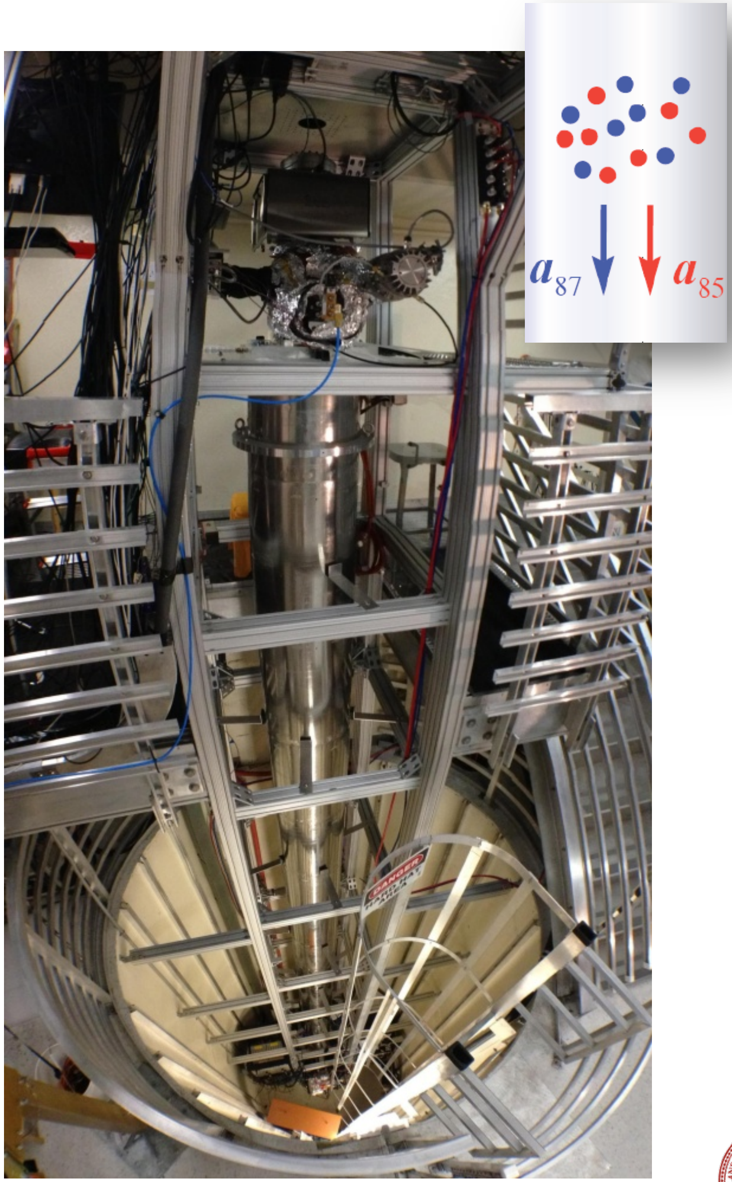
Statistical sensitivity

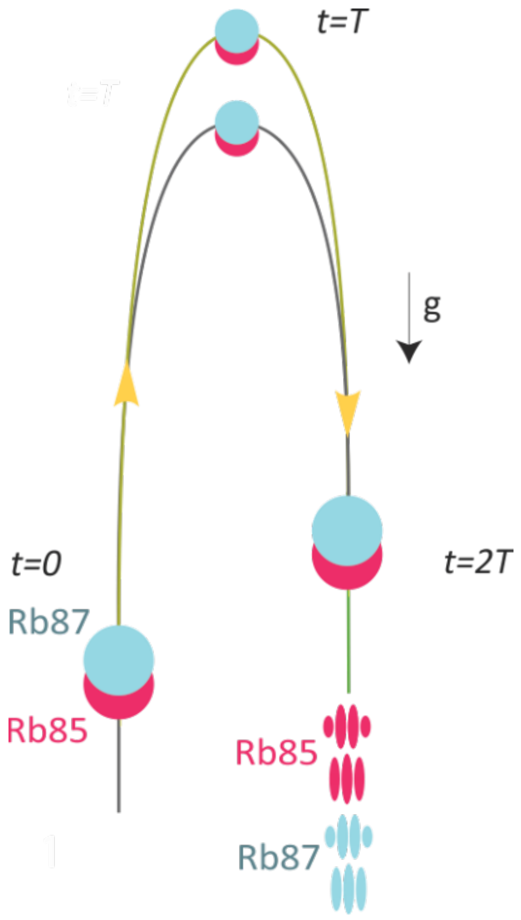
$\delta g \sim 10^{-15}$ g with 1 month data collection.

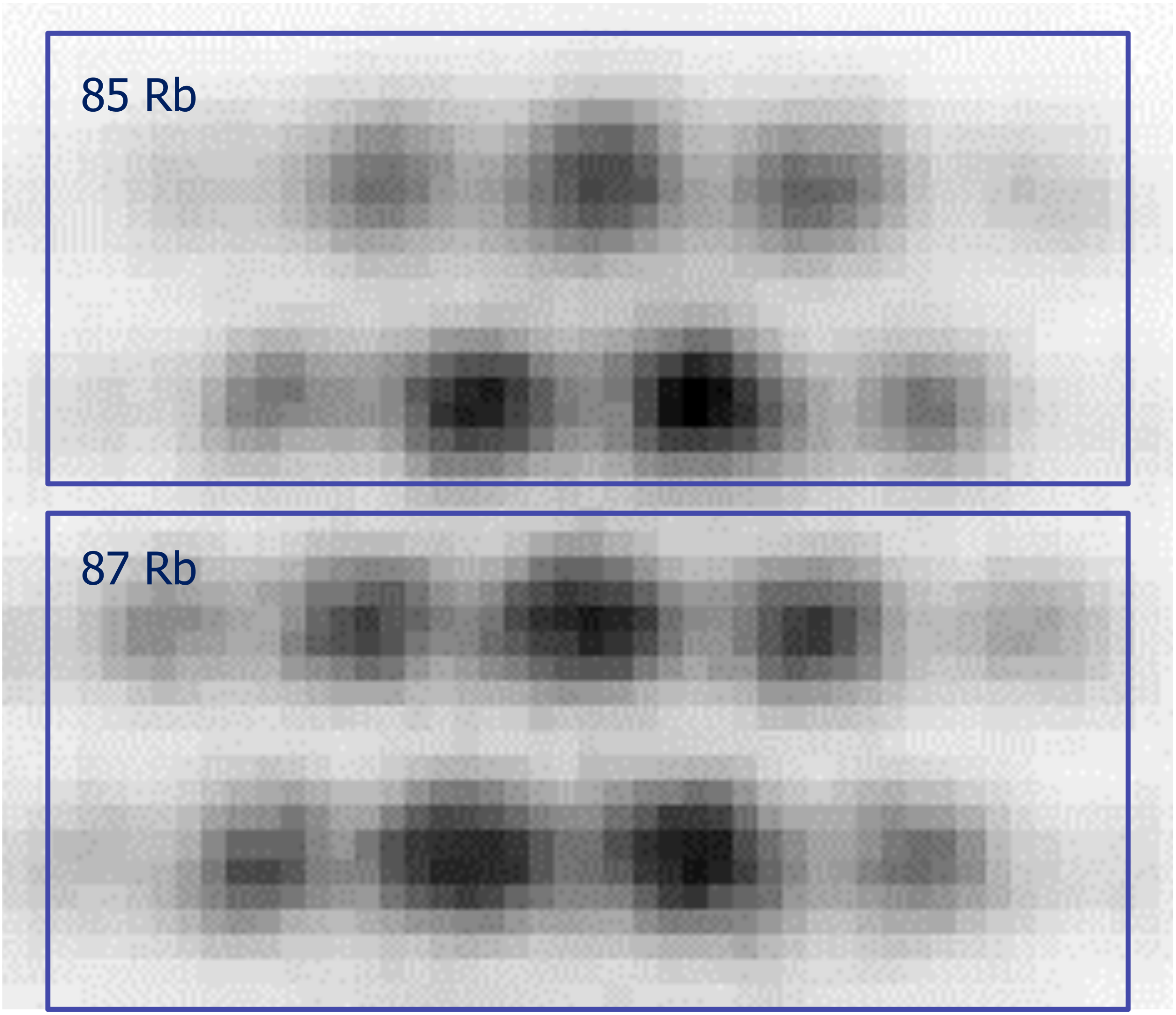
Limited by atom number.

Systematic uncertainty

$\delta g/g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies







Ground-based EP (target precision ~1e-14 δg/g)
5.4 cm wavepacket separation

Engineered atomic sensors are approaching physical performance limits

Quantum entanglement provides a route to further performance gains

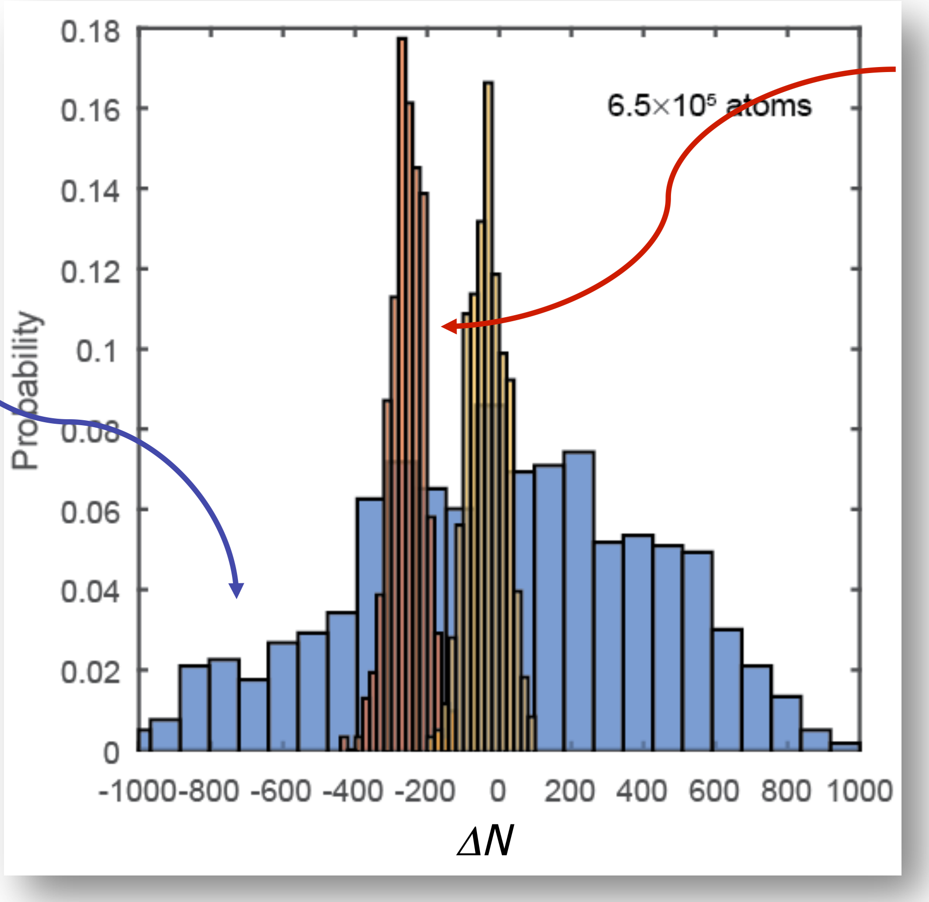
Quantum correlated (entangled) atomic ensembles

Consider N = 6.5e5, 2-state atoms, each in a quantum superposition of ground and excited state.

Measure probability of finding atoms in excited state:

Uncorrelated atoms

"Shot-noise"
Coin-toss statistics



Entangled atoms

Reduced
read-out noise

This data: 20 dB
variance
reduction

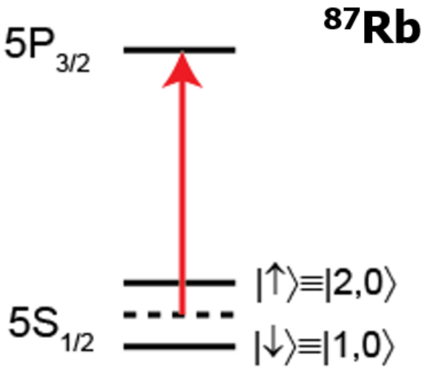
STANFORD UNIVERSITY

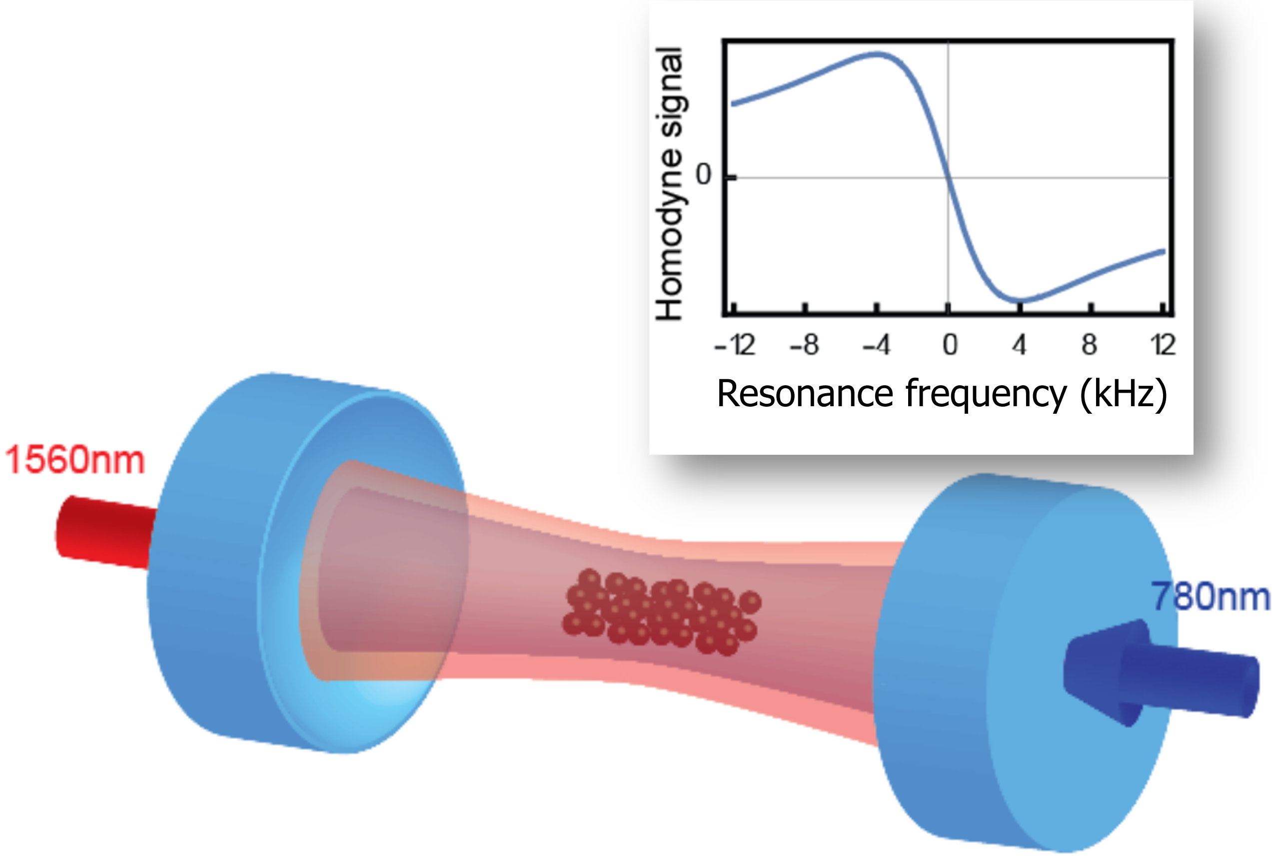
O. Hosten, et al., Nature (2016).

Cavity implementation

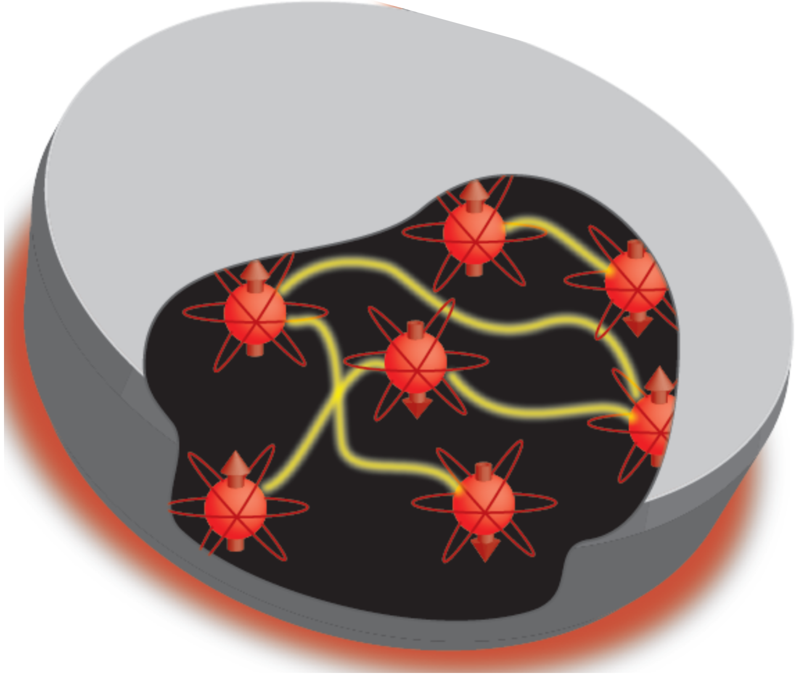
Dispersive atom-cavity interactions are used to realize a quantum non-demolition measurement of atom number.

Measurement results in a metrologically useful many-atom entangled state.

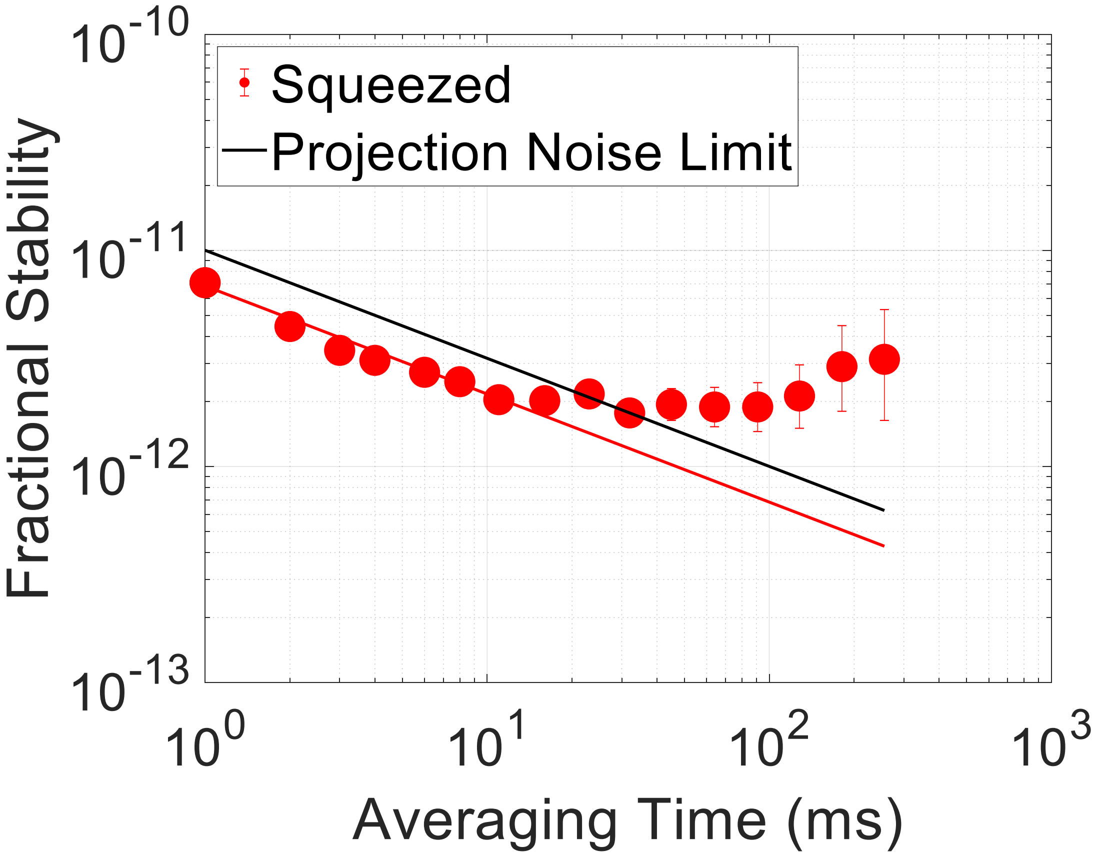




Entanglement



Entangled state clock

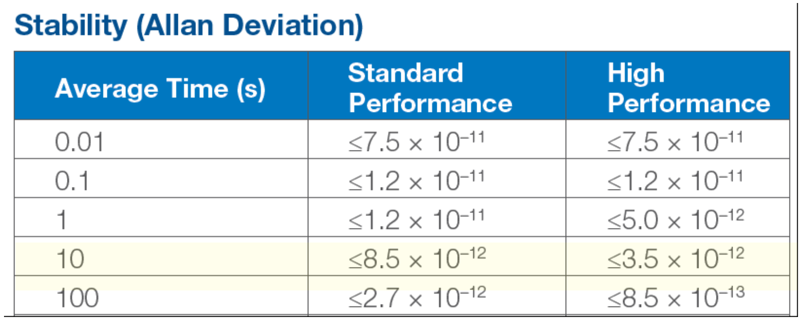


-3 dB below atomic shot noise limit, 3.5e5 atoms

Comparison with Microsemi 5071A

Microsemi

~2x better than Microsemi 5071A High Performance spec at 10 s



Stability (Allan Deviation)

Average Time (s)	Standard Performance	High Performance
0.01	$\leq 7.5 \times 10^{-11}$	$\leq 7.5 \times 10^{-11}$
0.1	$\leq 1.2 \times 10^{-11}$	$\leq 1.2 \times 10^{-11}$
1	$\leq 1.2 \times 10^{-11}$	$\leq 5.0 \times 10^{-12}$
10	$\leq 8.5 \times 10^{-12}$	$\leq 3.5 \times 10^{-12}$
100	$\leq 2.7 \times 10^{-12}$	$\leq 8.5 \times 10^{-13}$

Future

Massively entangled states
interfering over meter scales

Applications to precision
gravitational physics and geodesy

Thanks

Peter Asenbaum
Yunfan Wu
Ben Pichler
Julian Martinez
Chris Overstreet
Remy Notermans

Jason Hogan (Stanford)
Onur Hosten (IST, Vienna)
Tim Kovachy (Northwestern)