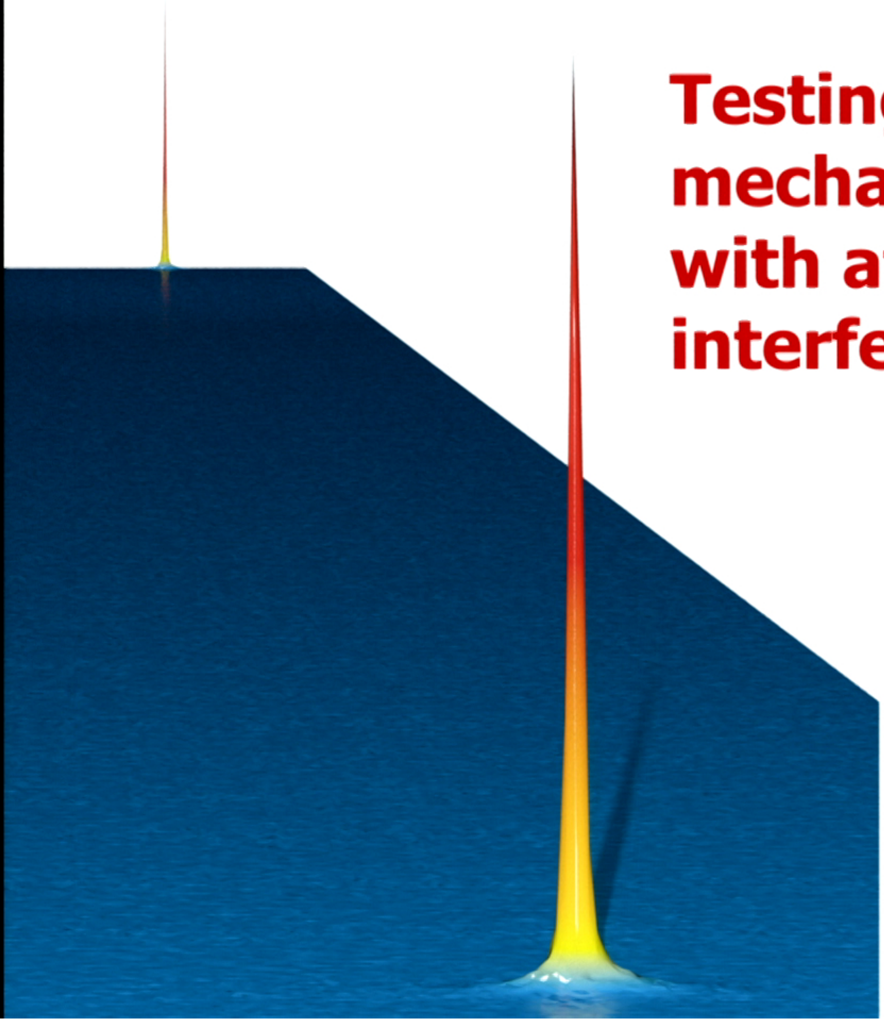
Title: Testing gravity and quantum mechanics using atom interferometry

Date: Aug 22, 2017 04:30 PM

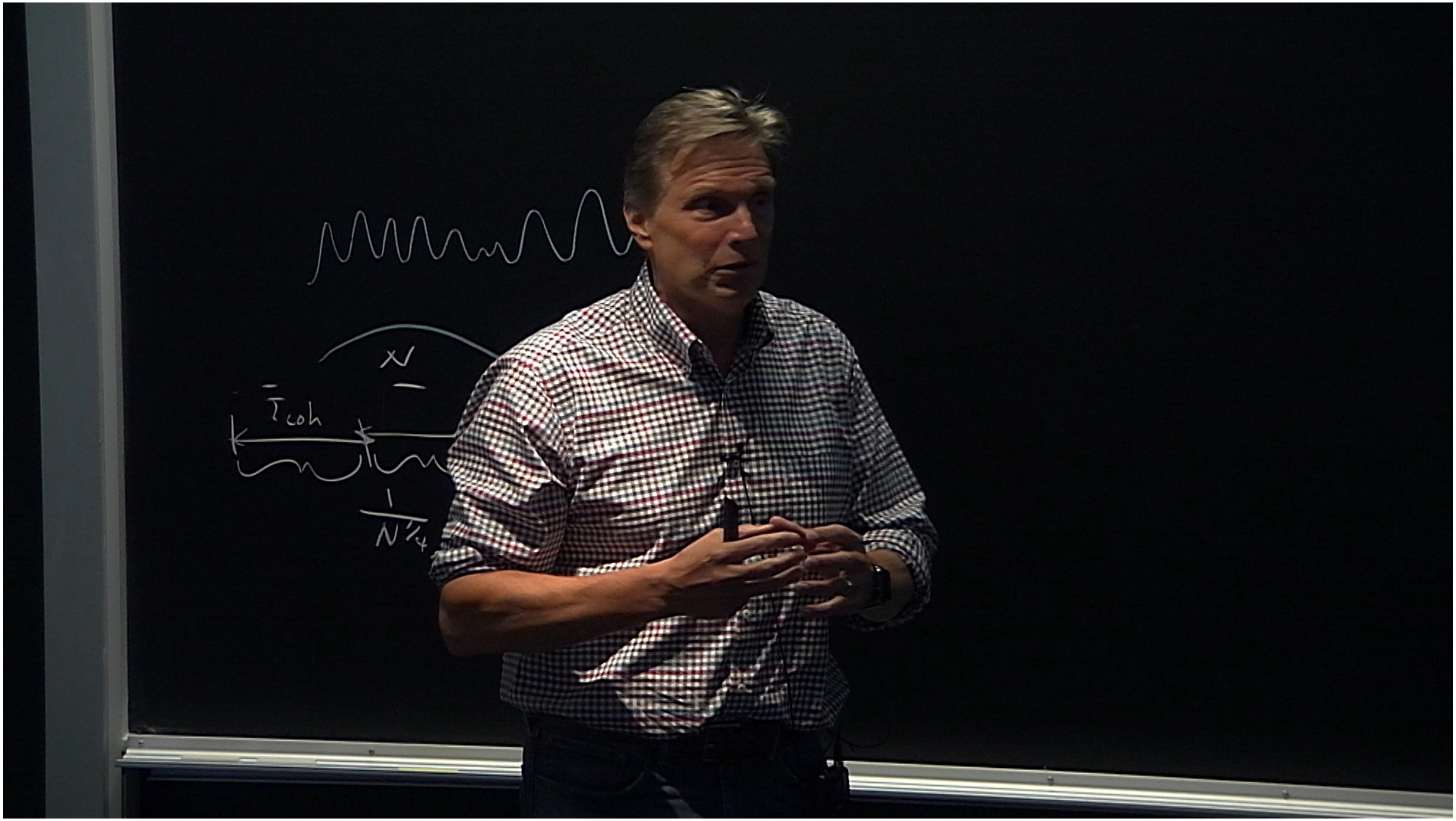
URL: http://pirsa.org/17080027

Abstract:

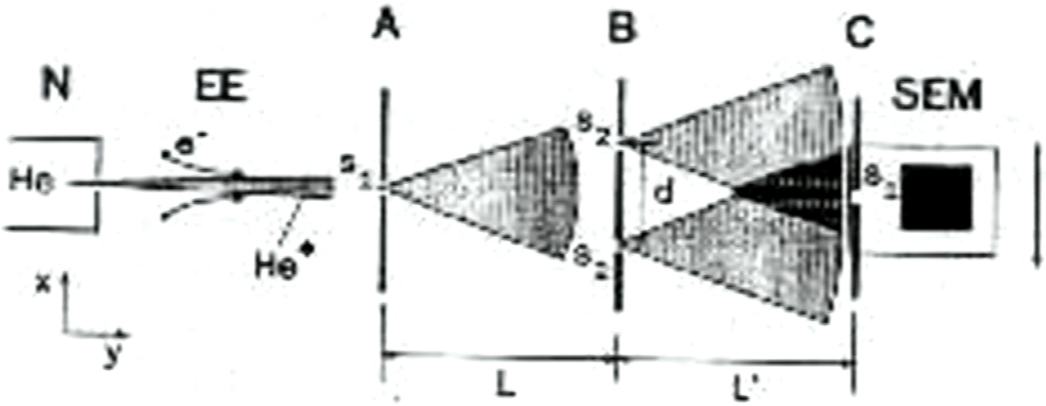


Testing quantum mechanics and gravity with atom interferometry

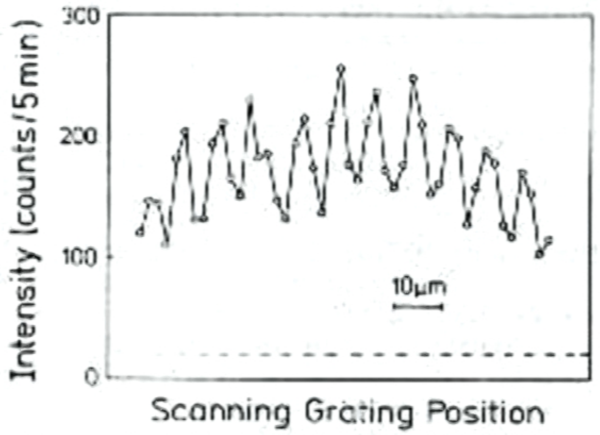
Mark Kasevich
Stanford University
kasevich@stanford.edu

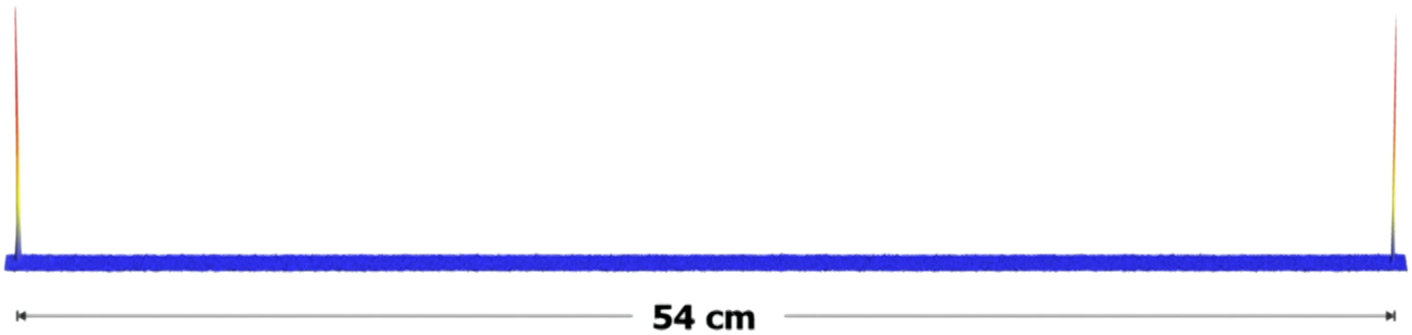

N
τ_coh
1/N^{1/4}

Young's double slit interferometer with atoms



Mlynek, PRL, 1991





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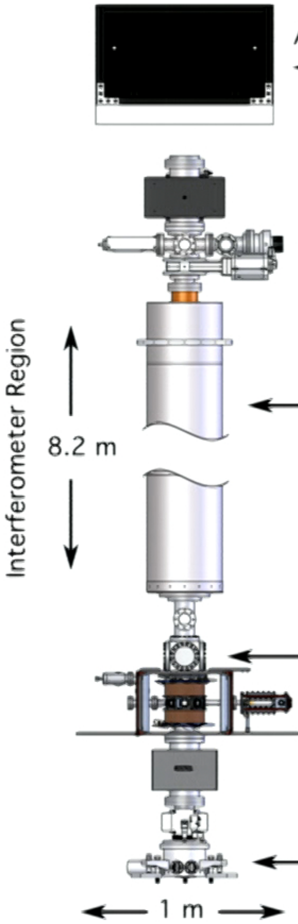
Atomic fountain



Atom Optics & Lattice Beam Delivery Enclosure

Upper Detection Region

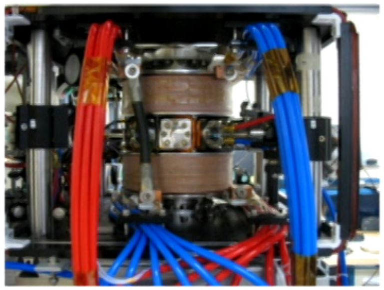
3 Layer Magnetic Shield (<1 mG on axis)

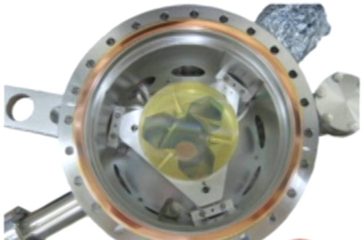
Lower Detection Region

2D MOT Loading 3D

Rotation Compensation System

~ 100 pK
1e5 atoms/shot





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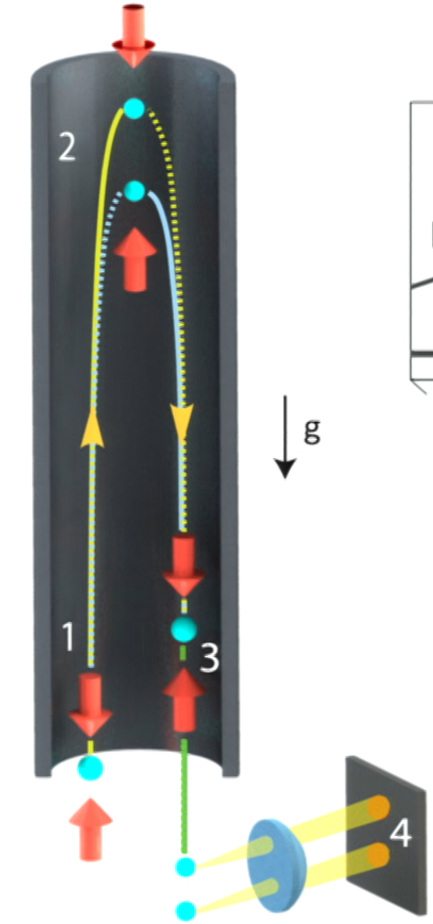
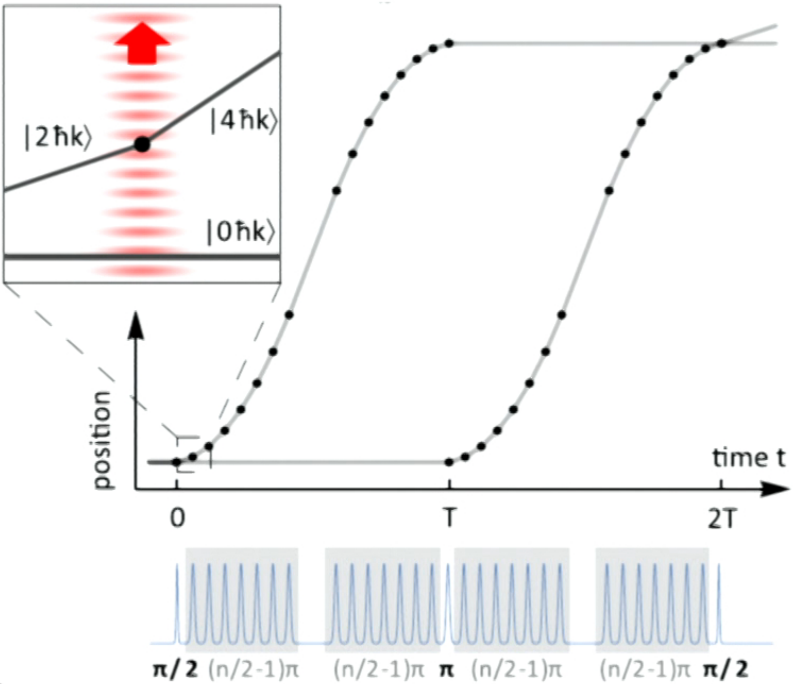
Light Pulse Atom Interferometry





Pulse sequence duration: 2.08 s

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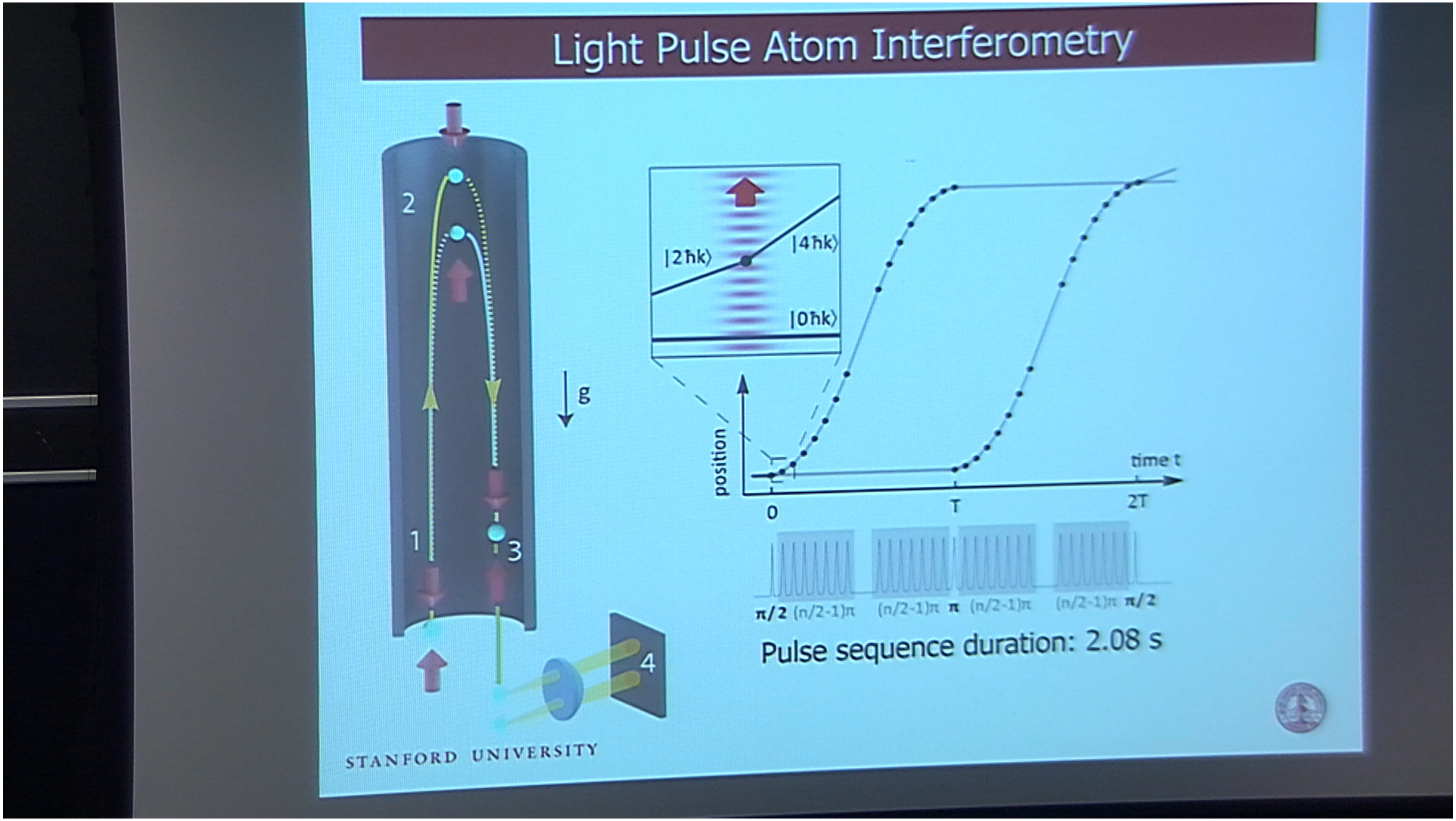

Light Pulse Atom Interferometry

Pulse sequence duration: 2.08 s

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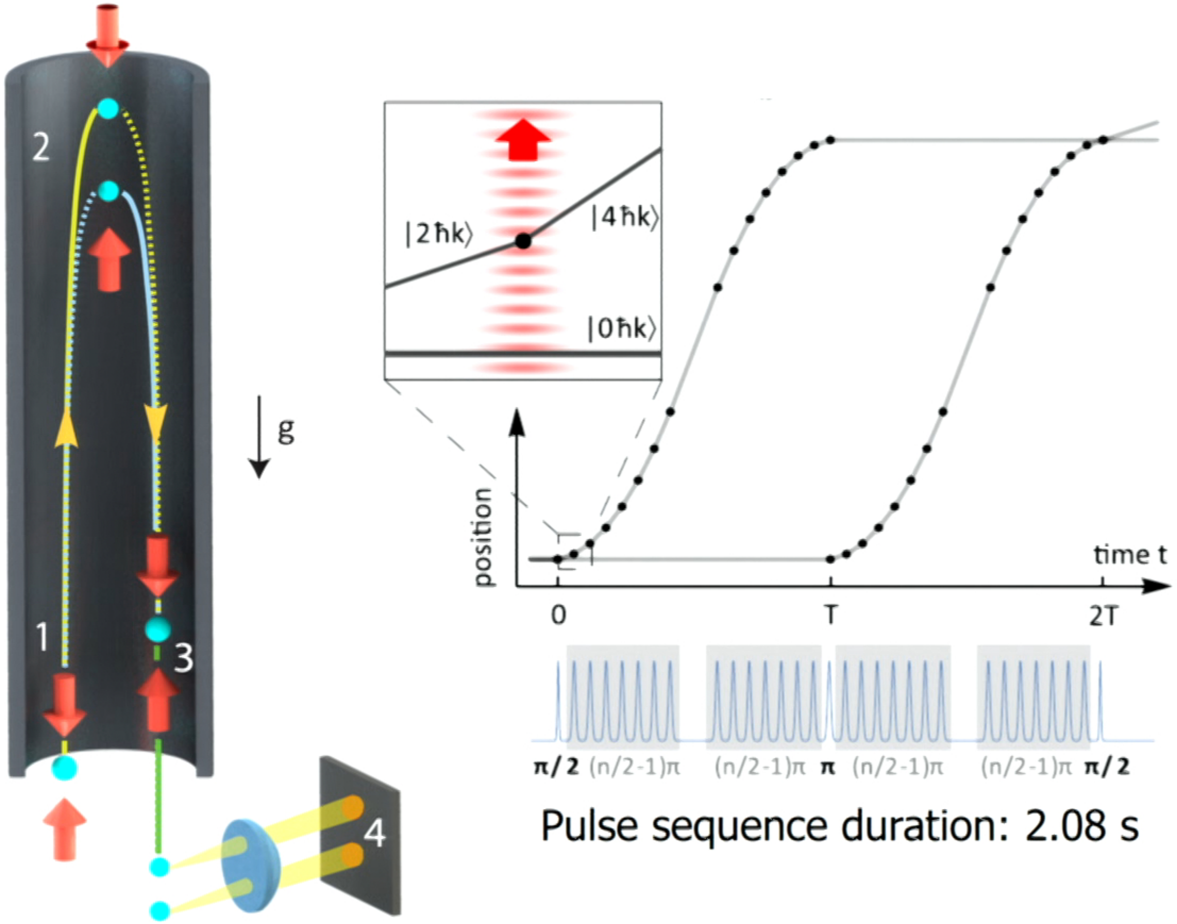
Light Pulse Atom Interferometry



Pulse sequence duration: 2.08 s

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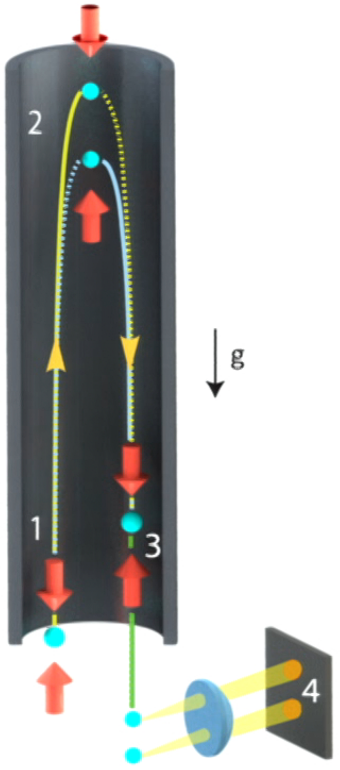
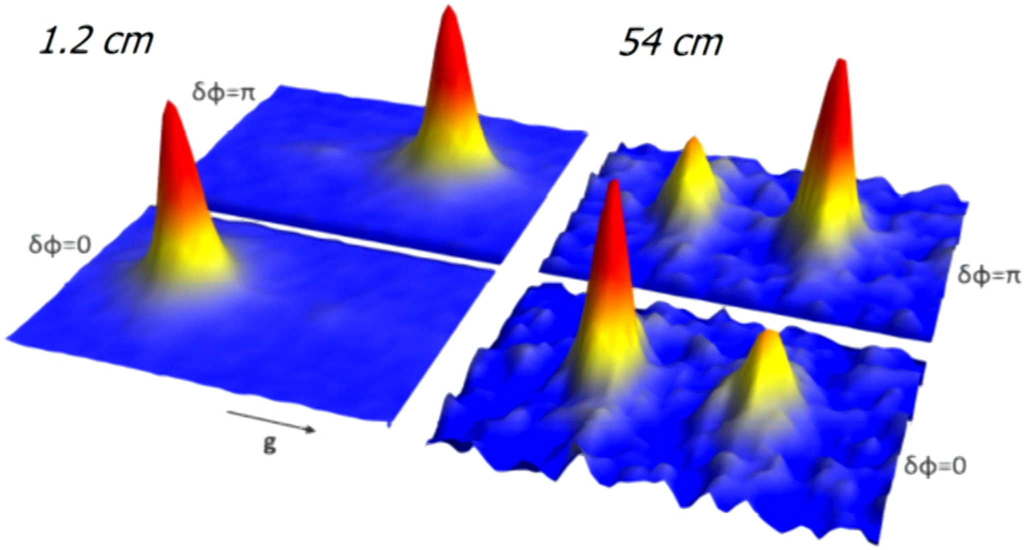
Interference at output ports

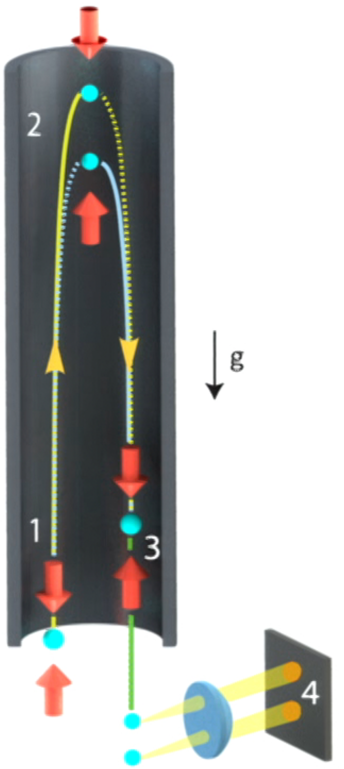


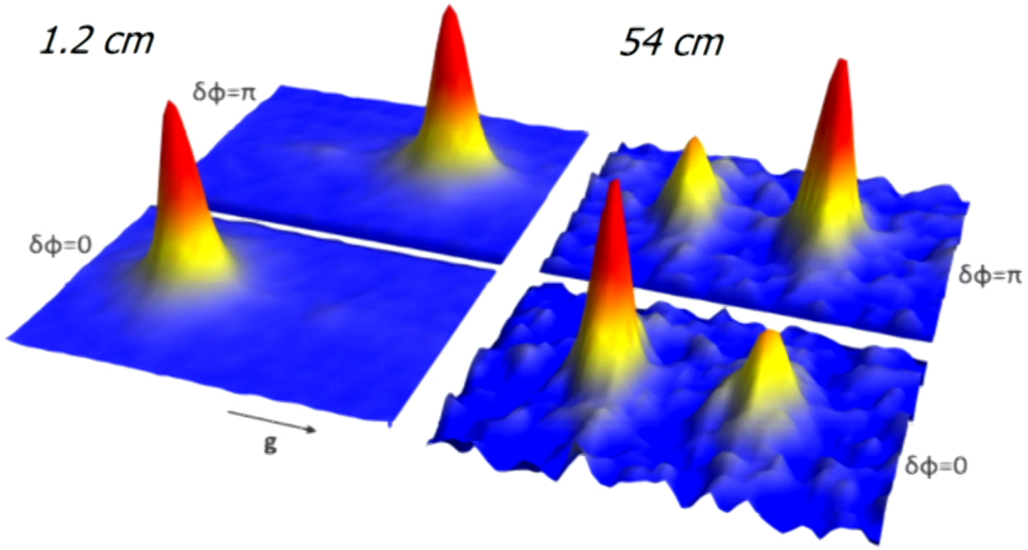


Interference causes population modulation between the output ports

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

Interference at output ports





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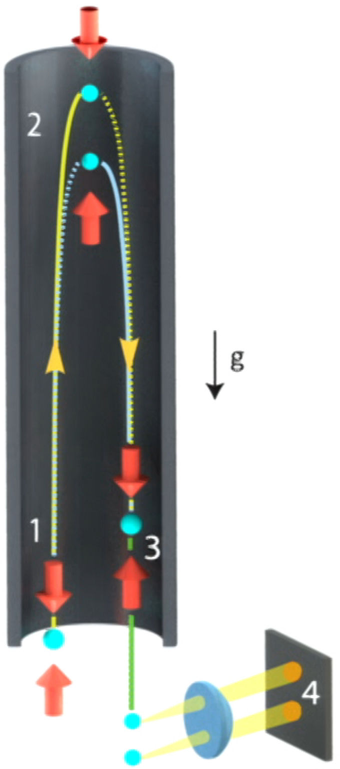

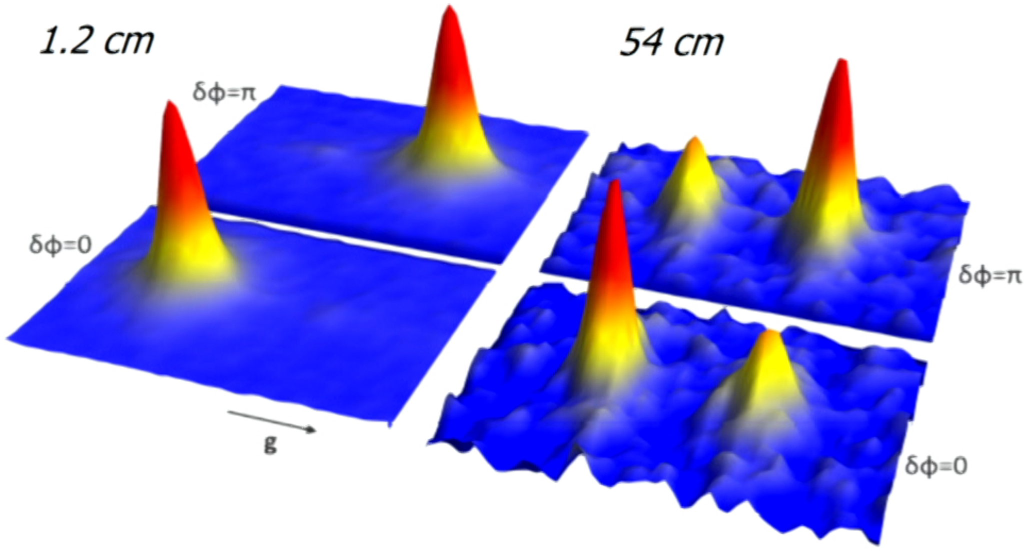

Interference causes population modulation between the output ports

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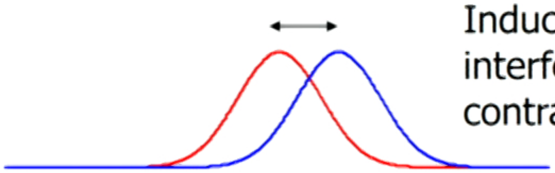
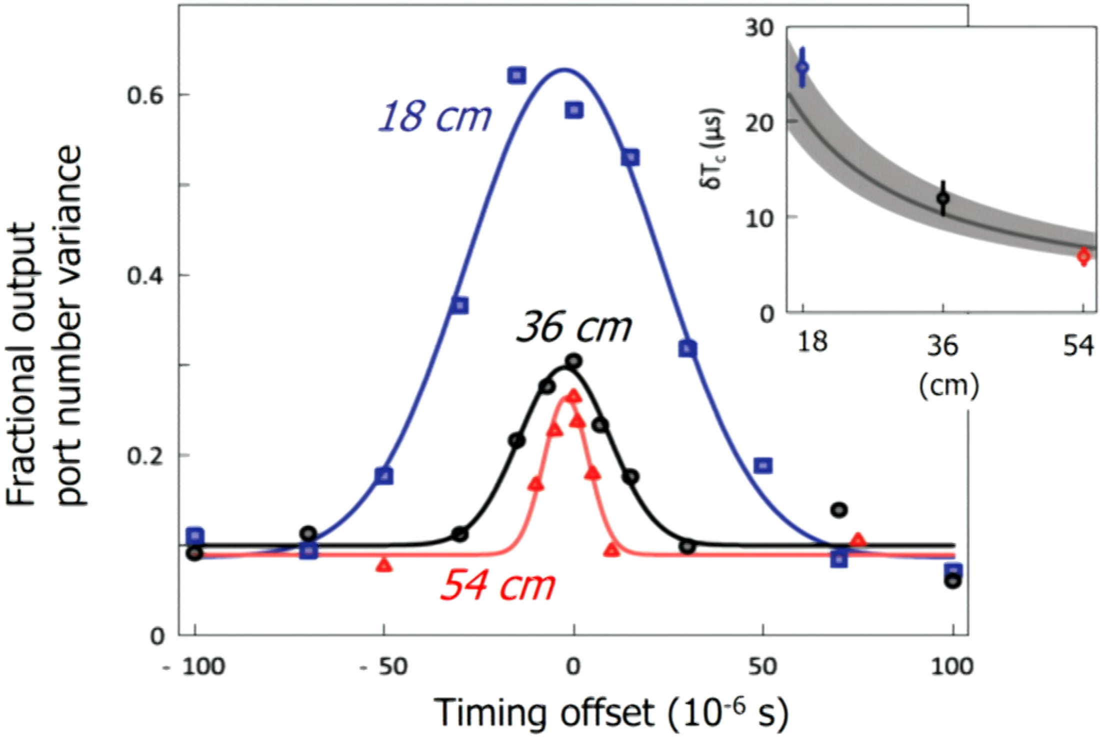
T. Kovachy, et al., Nature (2015)

Contrast envelope



Induce spatial offset between interfering wavepackets to observe contrast envelope



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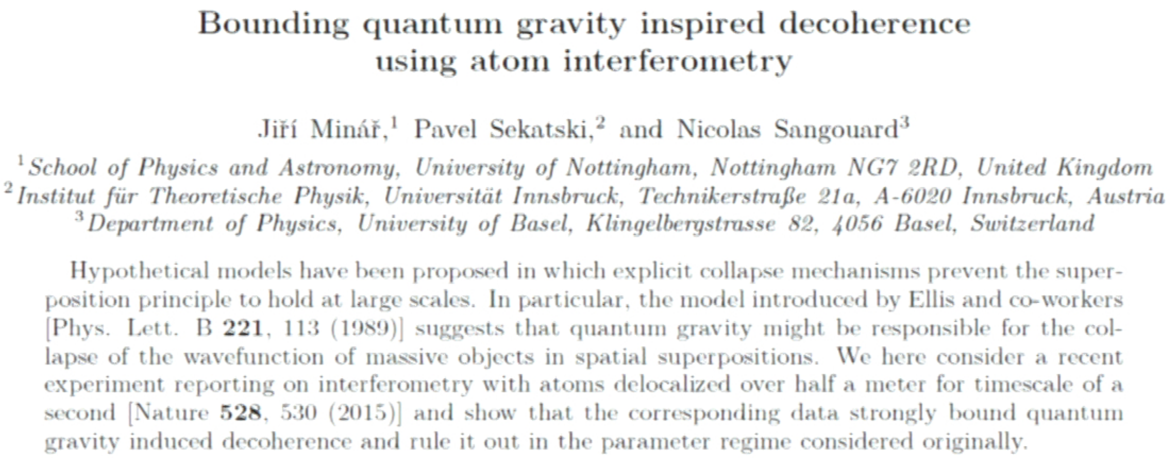
Bounds for Ellis model (1989)



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.

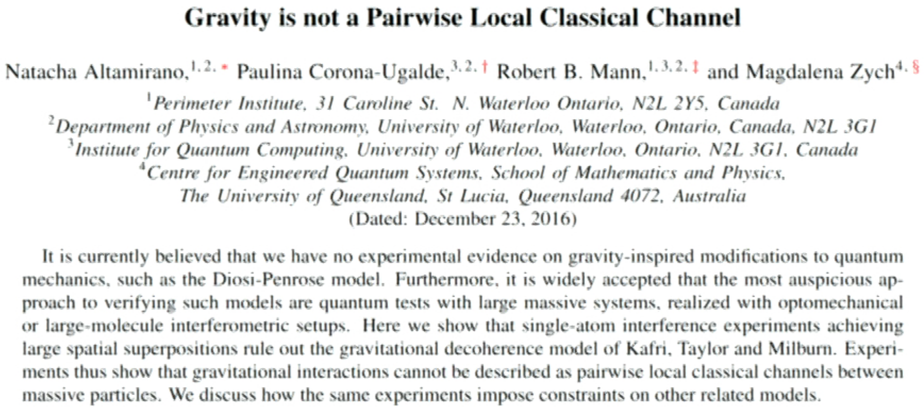
http://arxiv.org/abs/1604.07810v1

PHYSICAL REVIEW A **94**, 062111 (2016)

Wormhole scattering leads to loss of interference:

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

Bounds for KTM model



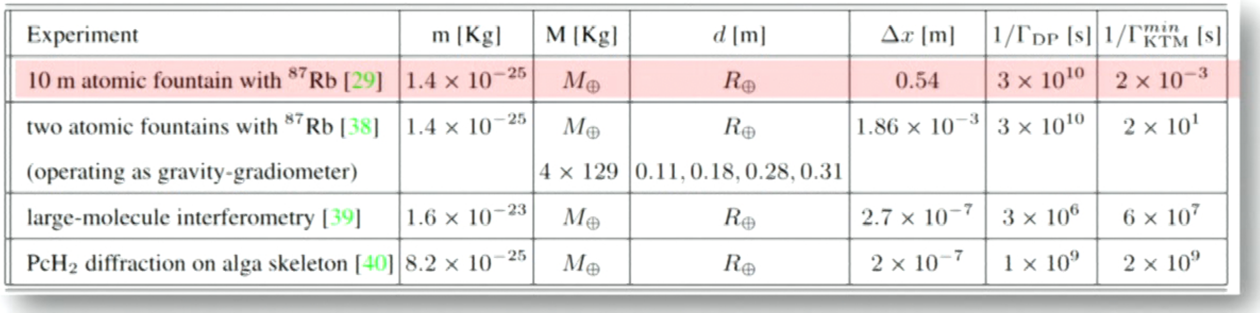
Gravity is not a Pairwise Local Classical Channel

Natacha Altamirano,[1,2,*] Paulina Corona-Ugalde,[3,2,†] Robert B. Mann,[1,3,2,‡] and Magdalena Zych[4,§]

[1] *Perimeter Institute, 31 Caroline St. N. Waterloo Ontario, N2L 2Y5, Canada*
[2] *Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1*
[3] *Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[4] *Centre for Engineered Quantum Systems, School of Mathematics and Physics,*
The University of Queensland, St Lucia, Queensland 4072, Australia

(Dated: December 23, 2016)

It is currently believed that we have no experimental evidence on gravity-inspired modifications to quantum mechanics, such as the Diosi-Penrose model. Furthermore, it is widely accepted that the most auspicious approach to verifying such models are quantum tests with large massive systems, realized with optomechanical or large-molecule interferometric setups. Here we show that single-atom interference experiments achieving large spatial superpositions rule out the gravitational decoherence model of Kafri, Taylor and Milburn. Experiments thus show that gravitational interactions cannot be described as pairwise local classical channels between massive particles. We discuss how the same experiments impose constraints on other related models.



Experiment	m [Kg]	M [Kg]	d [m]	Δx [m]	$1/\Gamma_{\mathrm{DP}}$ [s]	$1/\Gamma^{min}_{\mathrm{KTM}}$ [s]
10 m atomic fountain with ^{87}Rb [29]	1.4×10^{-25}	$M_\oplus$	$R_\oplus$	0.54	3×10^{10}	2×10^{-3}
two atomic fountains with ^{87}Rb [38]	1.4×10^{-25}	$M_\oplus$	$R_\oplus$	1.86×10^{-3}	3×10^{10}	2×10^{1}
(operating as gravity-gradiometer)		4×129	$0.11, 0.18, 0.28, 0.31$			
large-molecule interferometry [39]	1.6×10^{-23}	$M_\oplus$	$R_\oplus$	2.7×10^{-7}	3×10^{6}	6×10^{7}
PcH$_2$ diffraction on alga skeleton [40]	8.2×10^{-25}	$M_\oplus$	$R_\oplus$	2×10^{-7}	1×10^{9}	2×10^{9}

KTM decoherence is distinct from Diosi-Penrose decoherence

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

Large wavepacket separation AI constrains the KTM model

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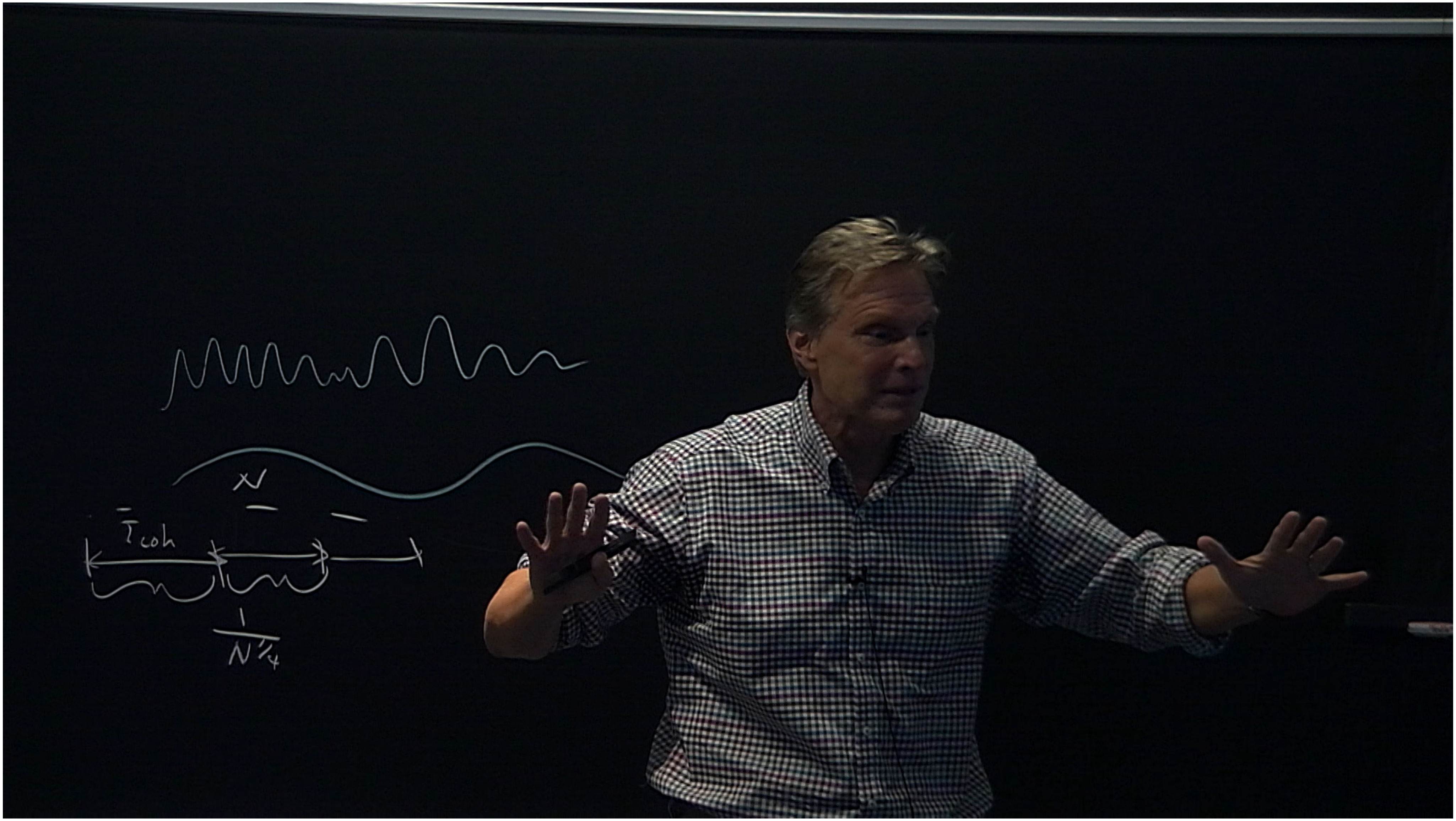
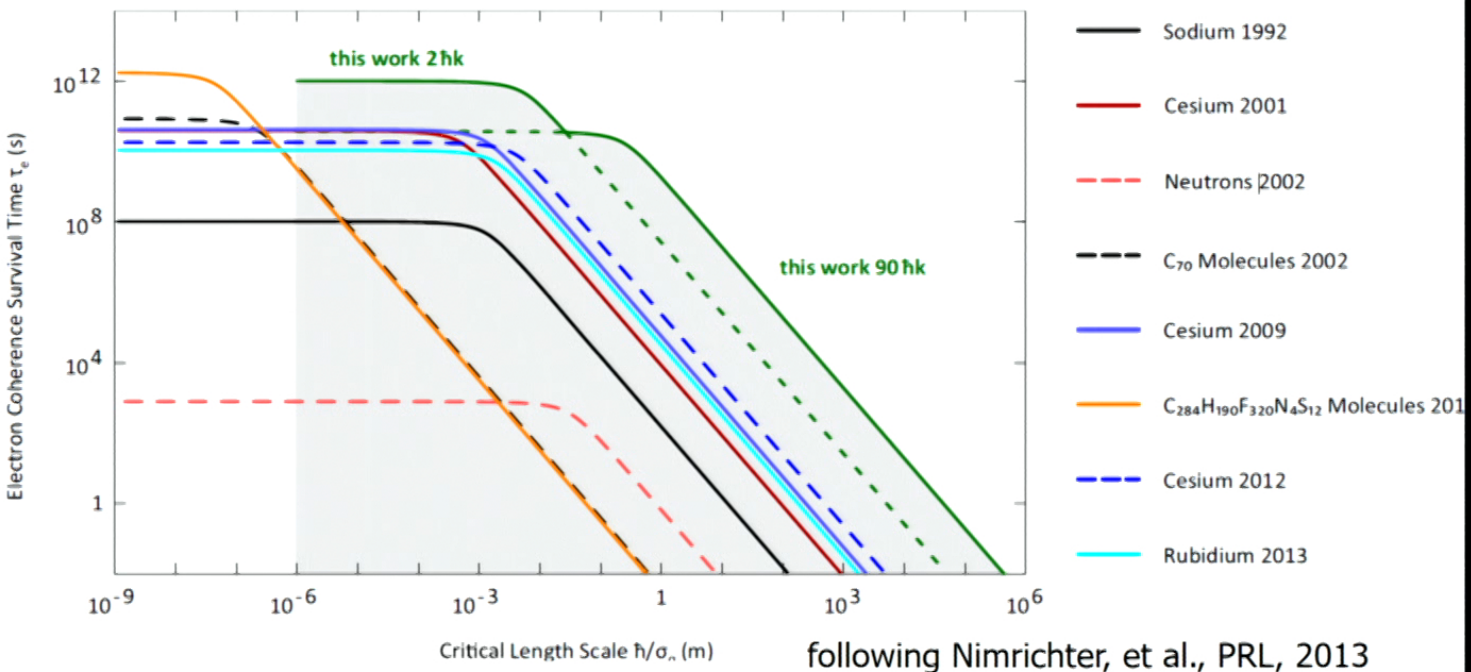

N
τ_coh
1/N^{1/4}

"Macroscopicity" and CSL



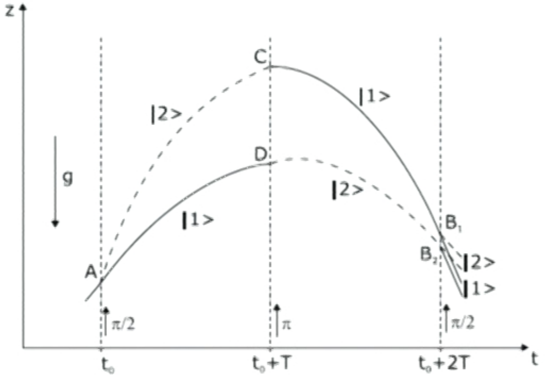
following Nimrichter, et al., PRL, 2013

*Assumes atoms can be treated as an ensemble of non-interacting, non-degenerate, single particles. (see D. Stamper-Kurn, Nature 2017 and our response, Nature 2017).

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 (Raman 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.

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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
	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

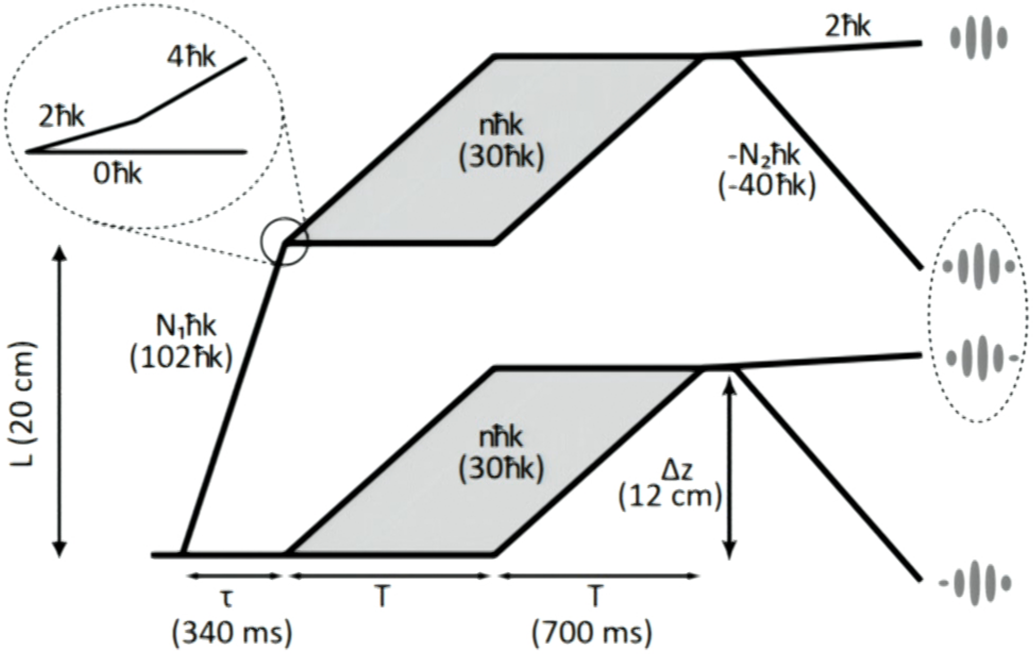
v_i, velocity; x_i, initial position

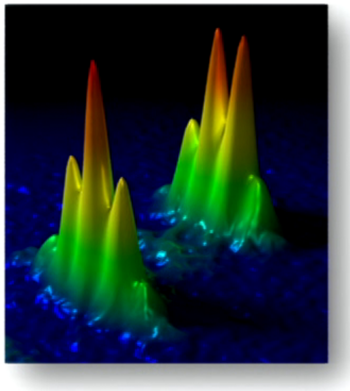
g, acceleration due to gravity

T, interrogation time

k_{eff}, effective propagation vector

Tidal forces on a wavefunction

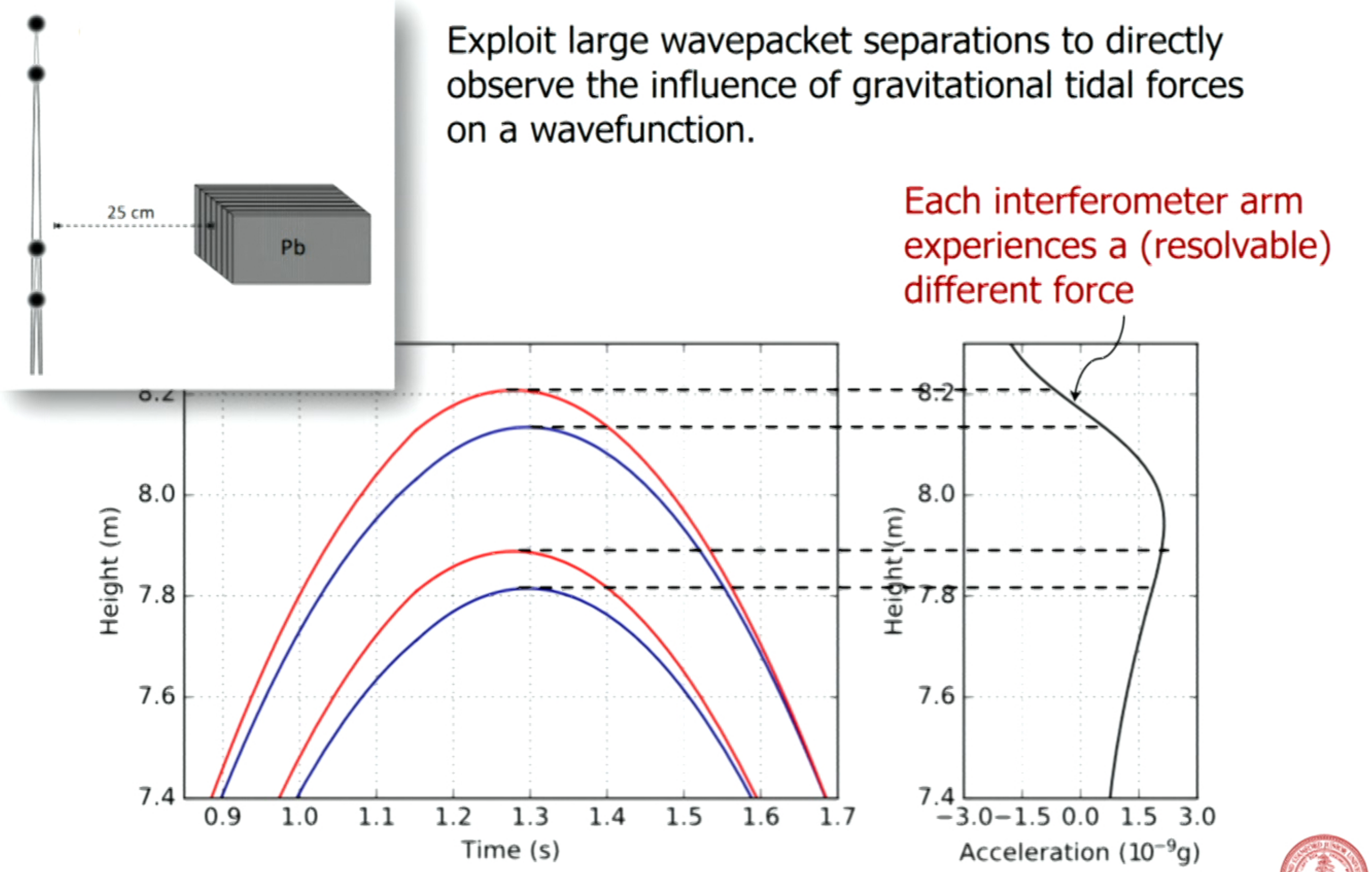




Use gravity gradiometer configuration to isolate quantum curvature phase shifts

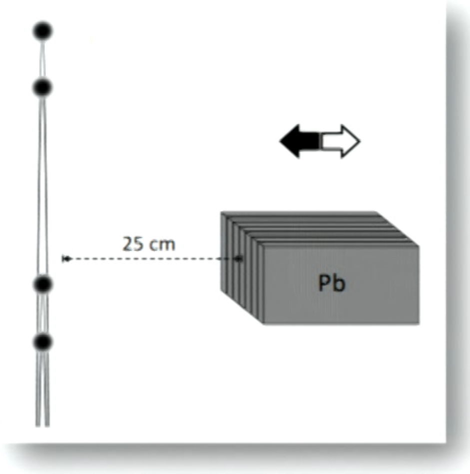
Tidal forces on a wavefunction

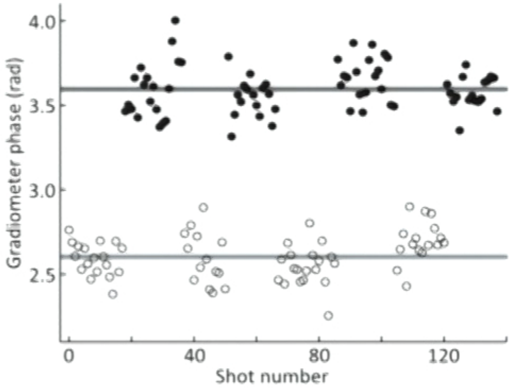
Exploit large wavepacket separations to directly observe the influence of gravitational tidal forces on a wavefunction.

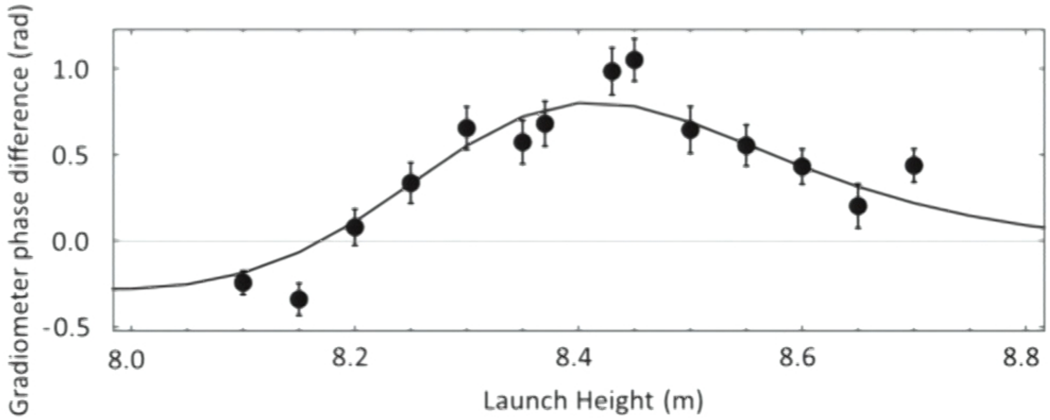


Each interferometer arm experiences a (resolvable) different force

Observation of tidal forces on a wavefunction







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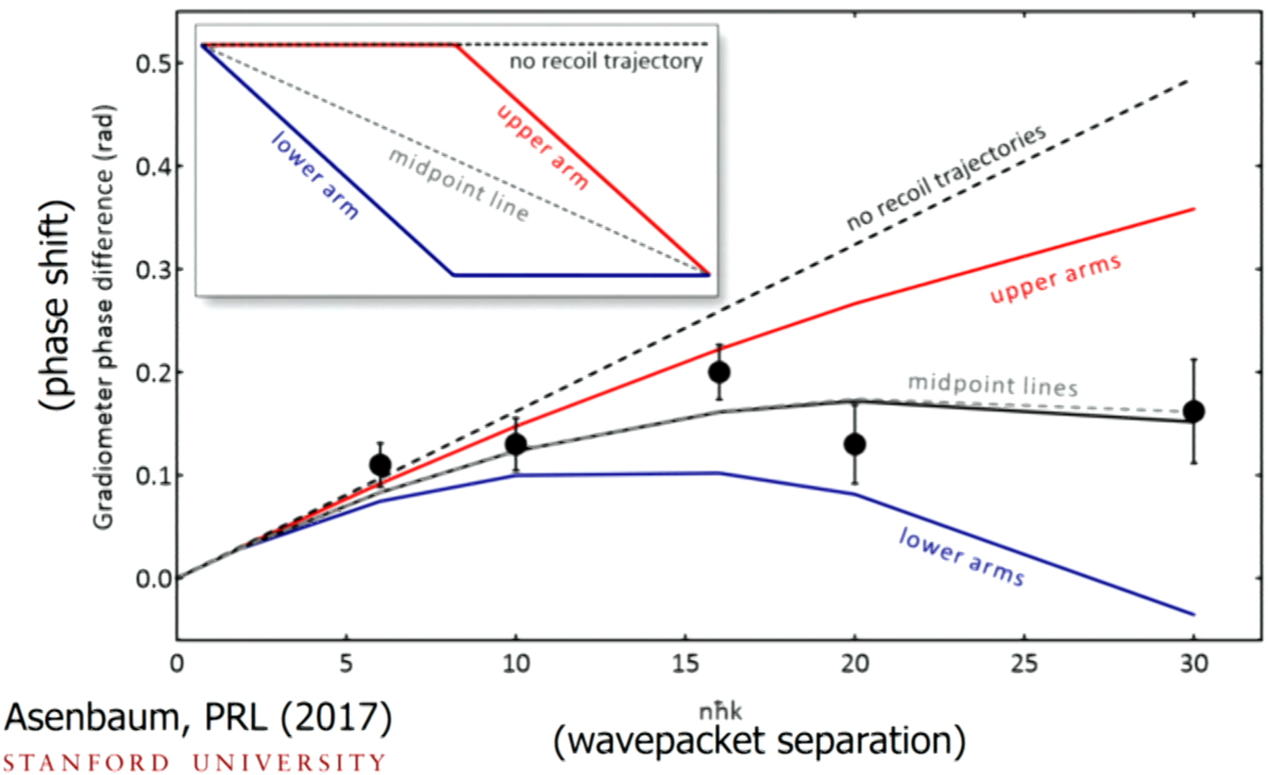
Gravity and quantum mechanics

In GR, gravity manifests through space-time curvature.

First observation of the influence of gravitational curvature on any quantum system.



Asenbaum, PRL (2017)

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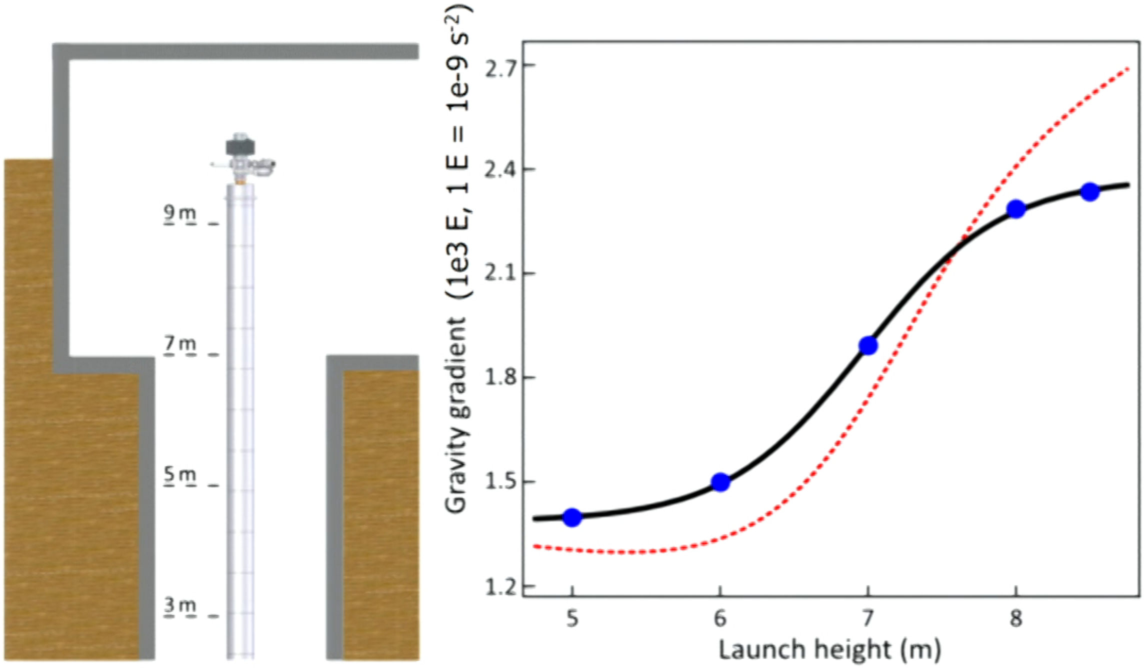
Gravity gradiometery



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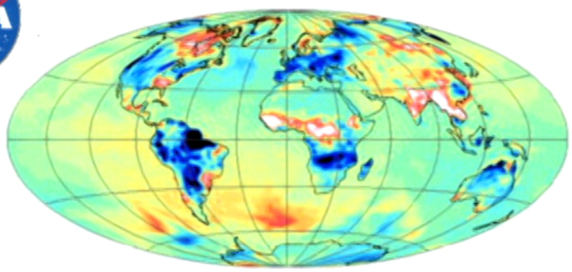
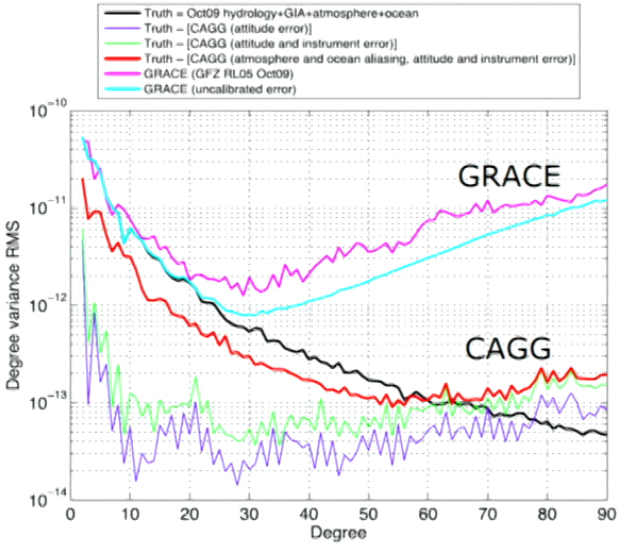
Satellite geodesy





Analysis from S. Luthke, GSFC

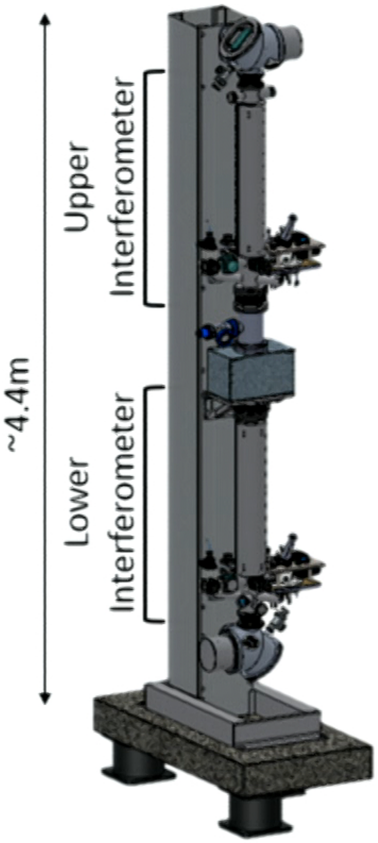
Simulation of hydrology map from space-borne atom interferometer gravity gradiometer.

~ 1 cm equivalent water height resolution.

Instrument:

- 4 m baseline
- single-axis
- rotation compensation
- 1e-4 E design resolution

Development of prototype recently funded by NASA; Instrument built by AOSense, Inc.



NASA IIP prototype flight gradiometer (AOSense, A. Sugarbaker, PM)

Equivalence Principle

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

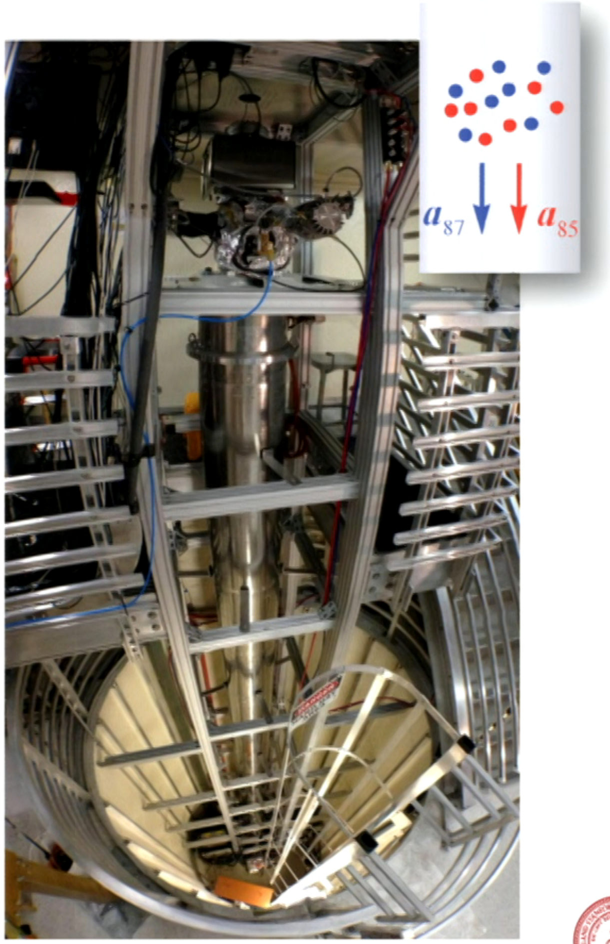
Statistical sensitivity

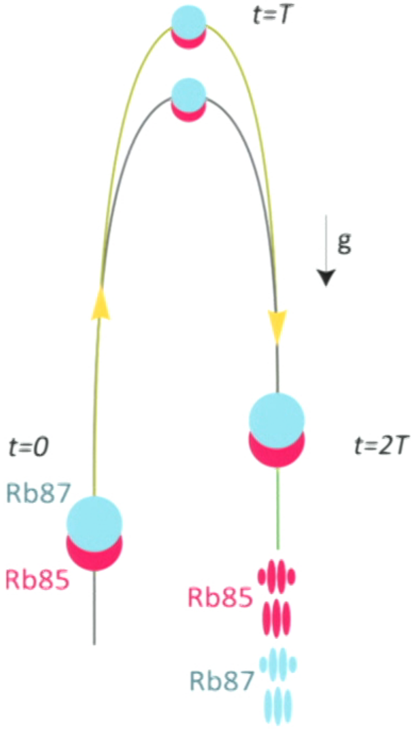
$\delta g \sim 10^{-15}$ g with 1 month data collection.

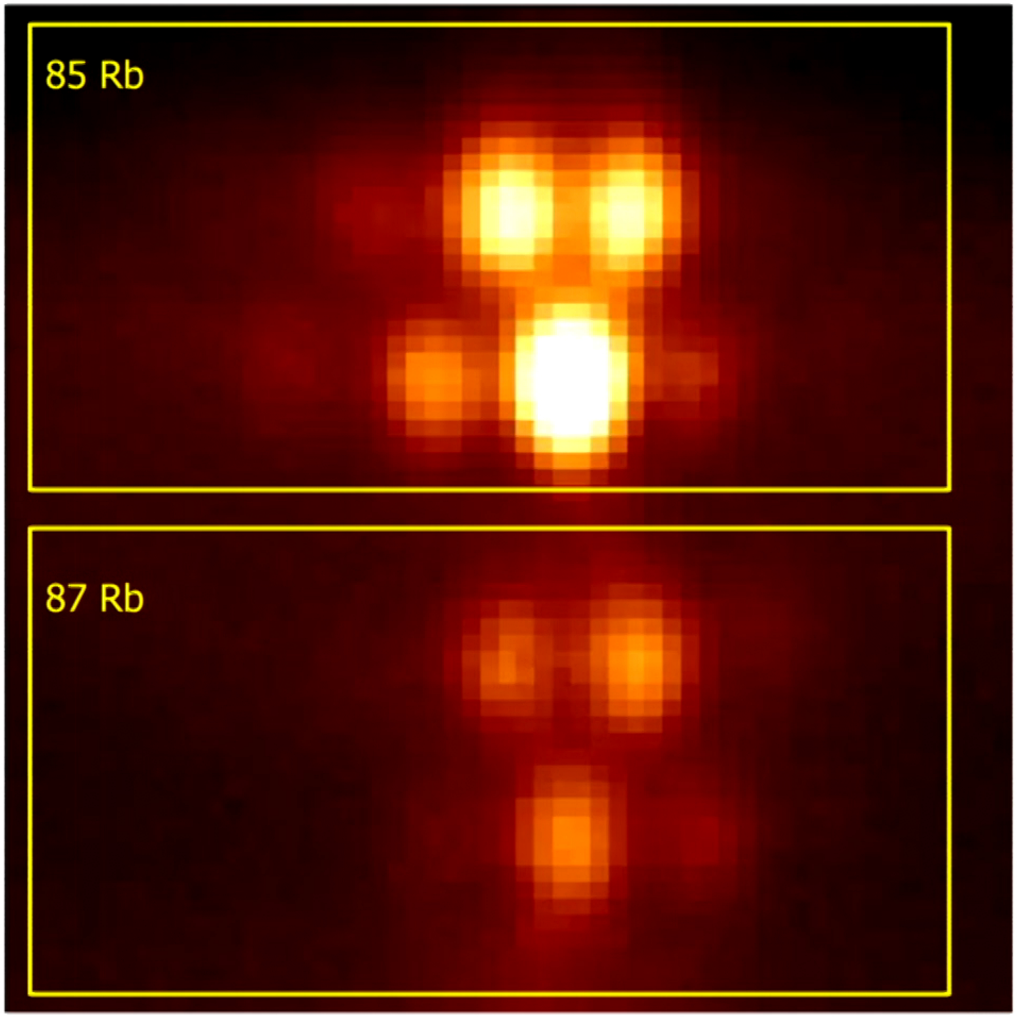
Limited by atom number.

Systematic uncertainty

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







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

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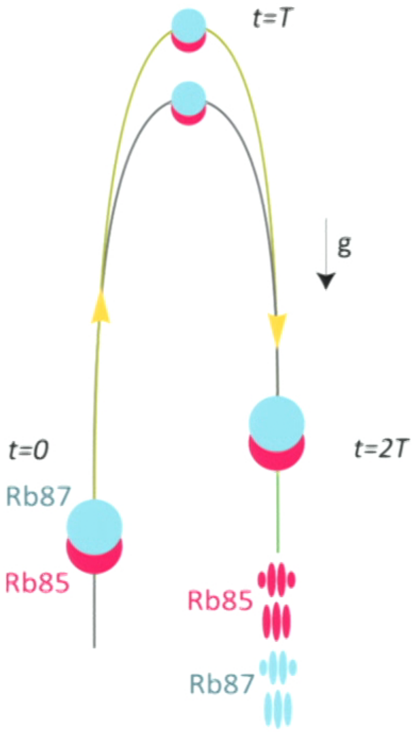

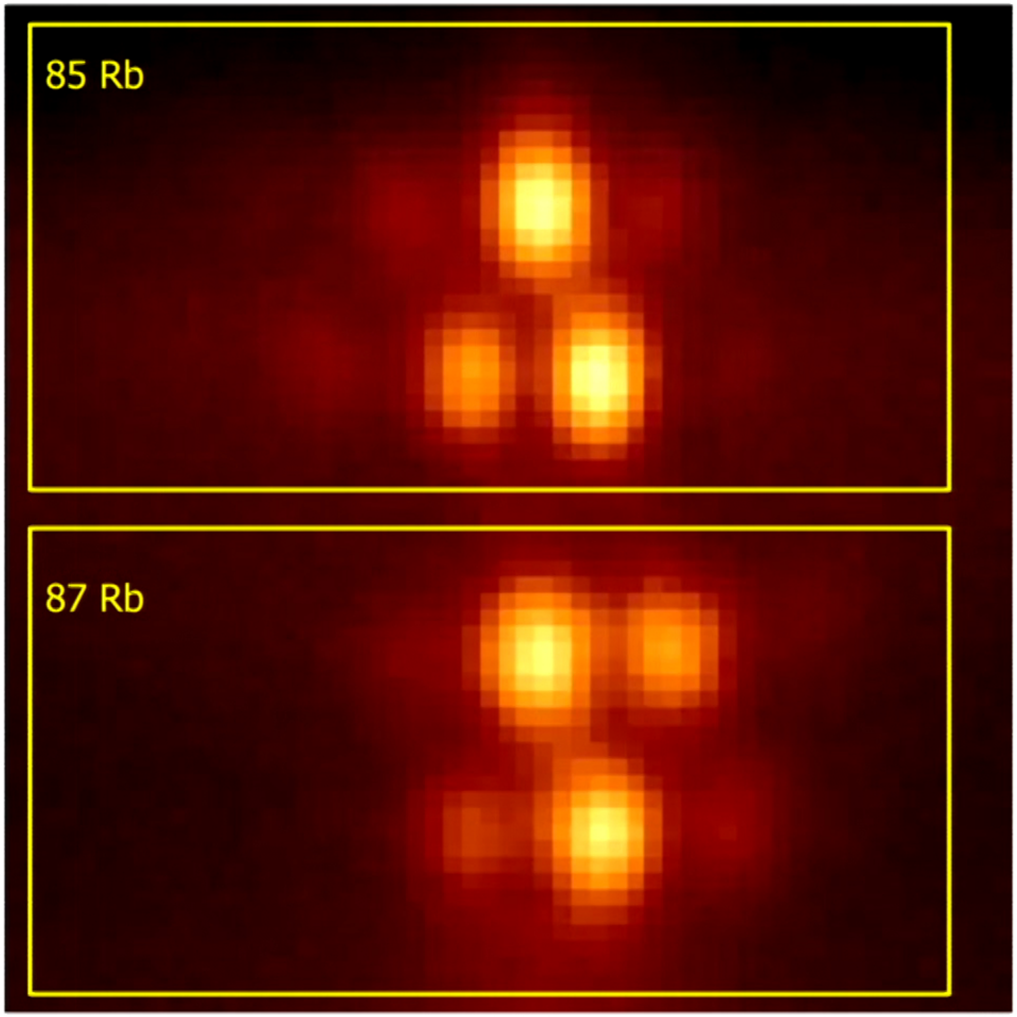

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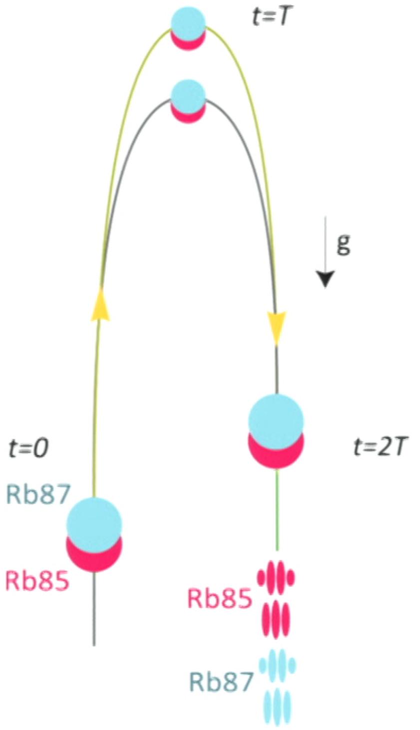

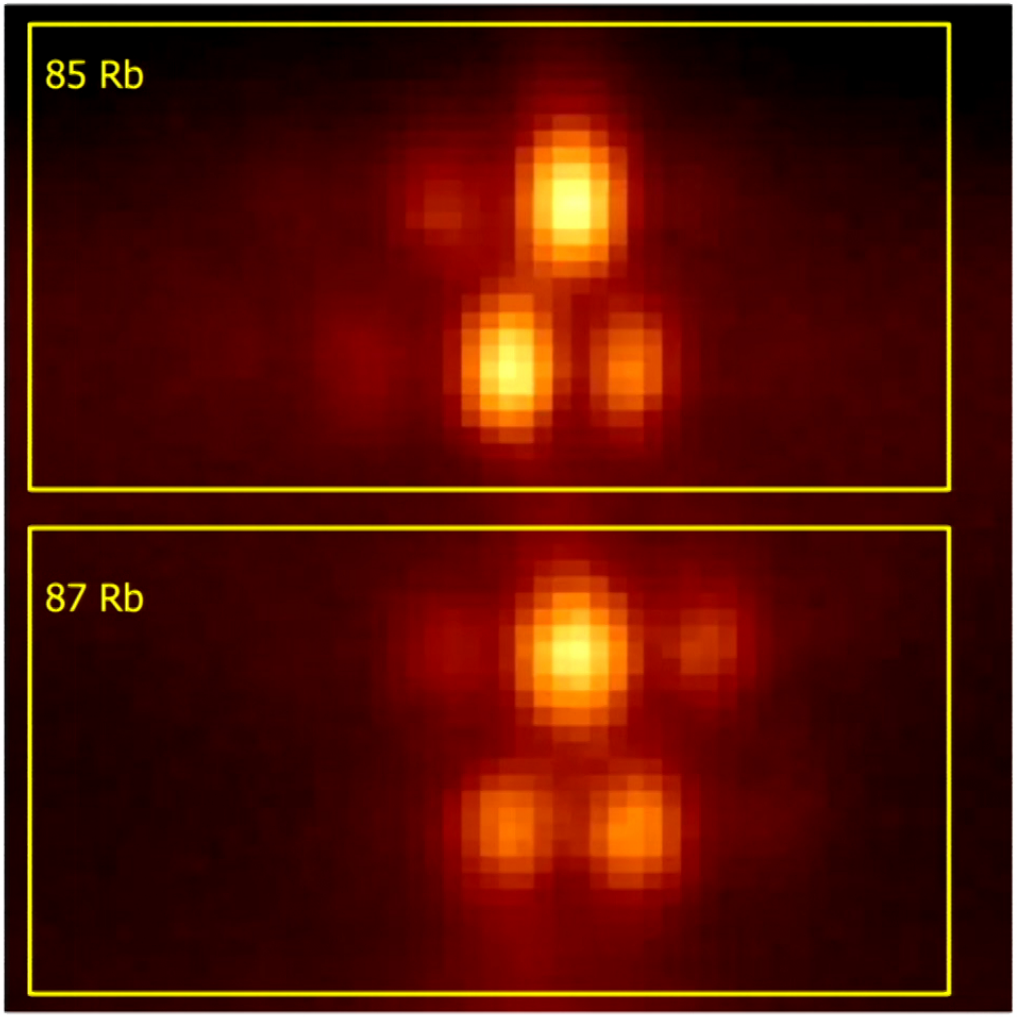

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5.4 cm wavepacket separation

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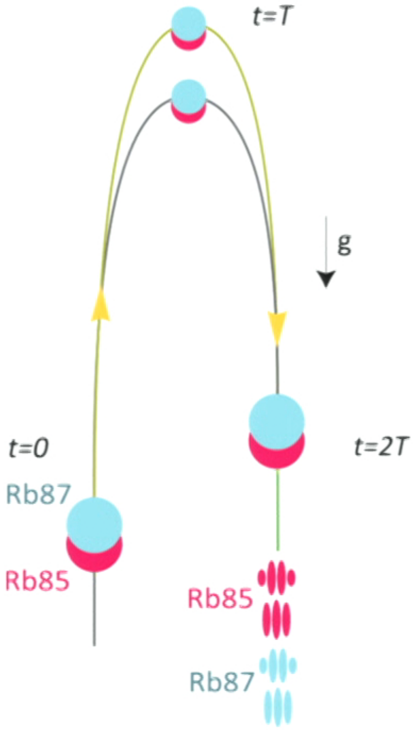

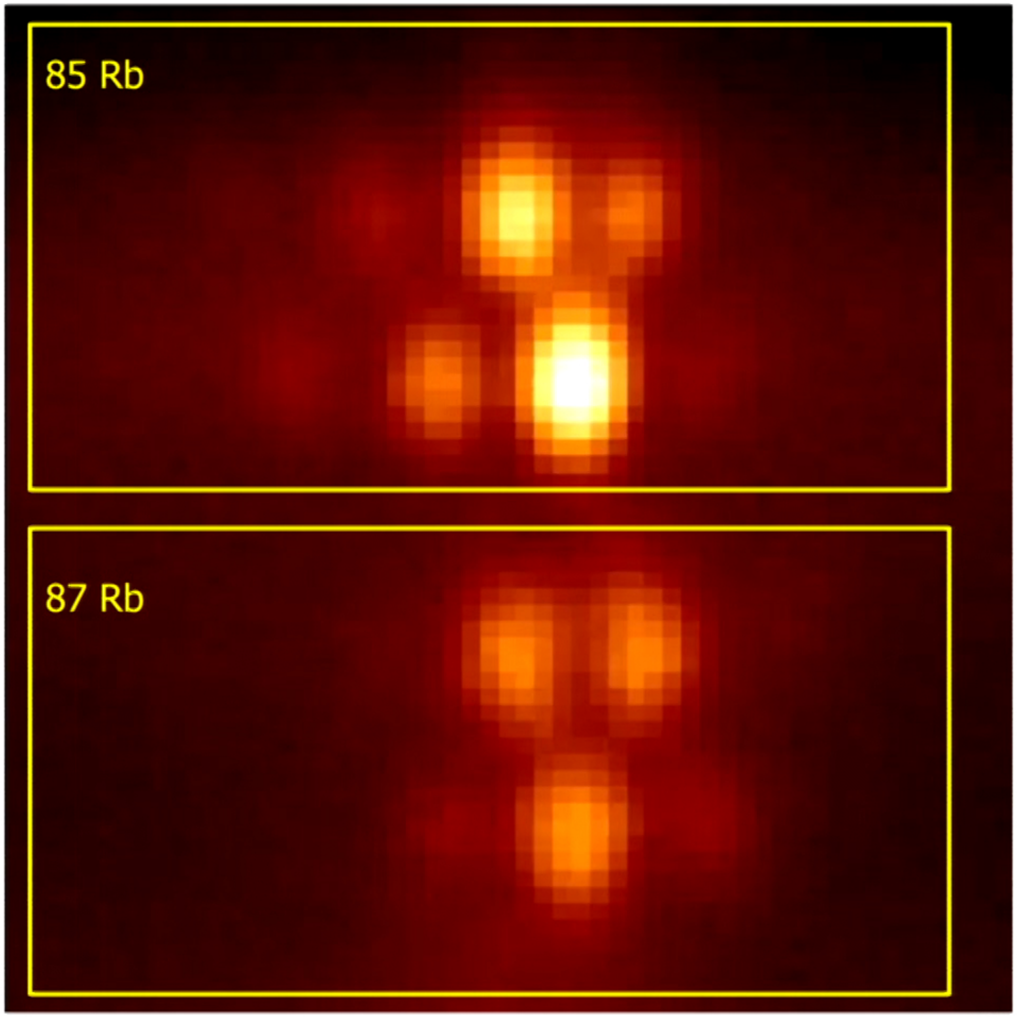

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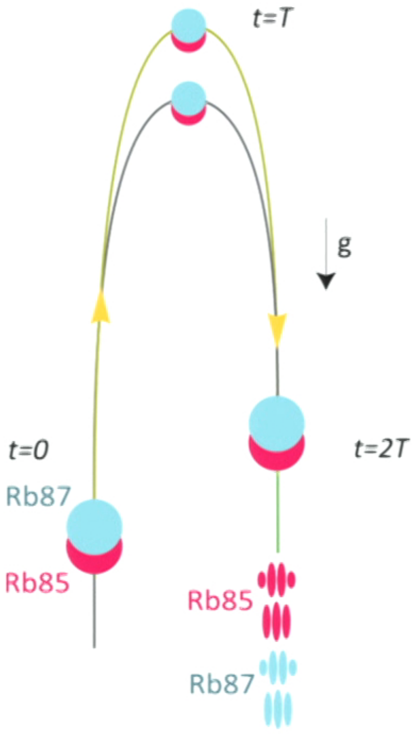
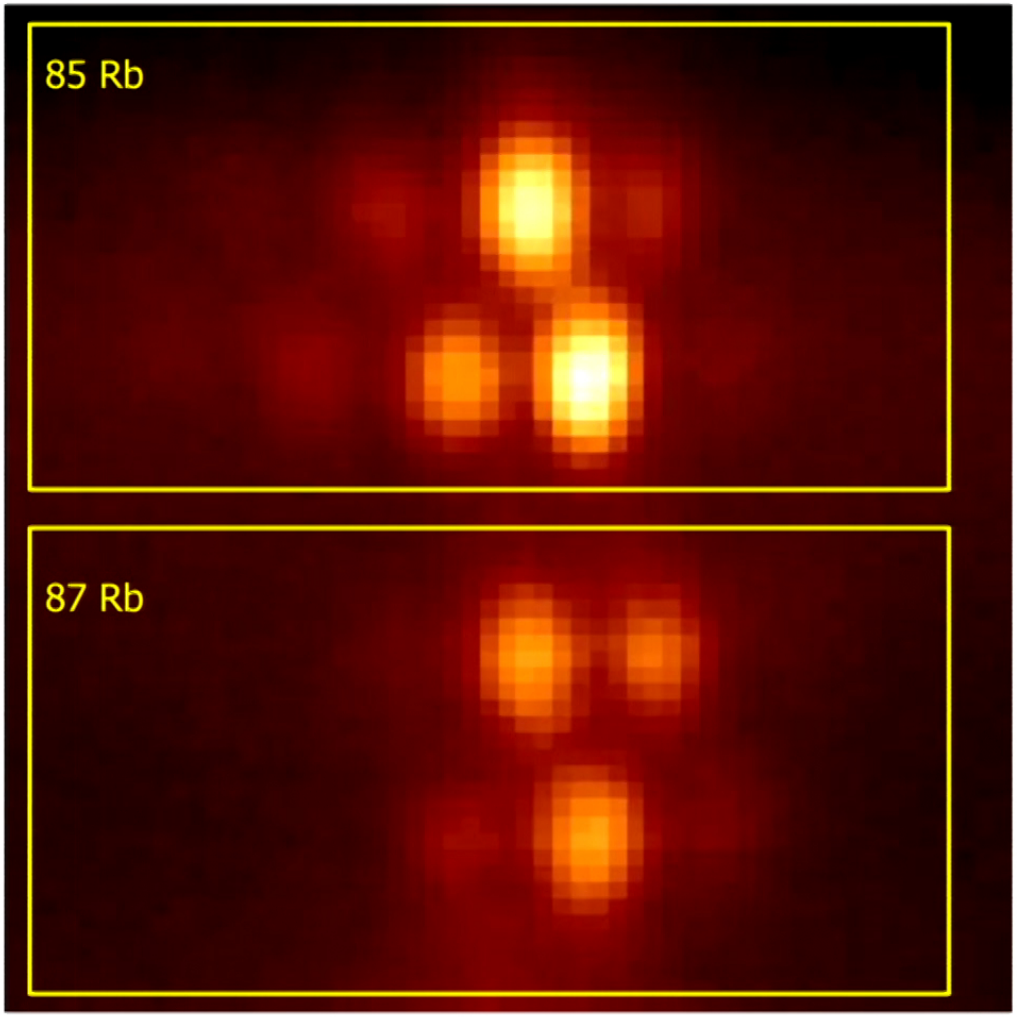
5.4 cm wavepacket separation





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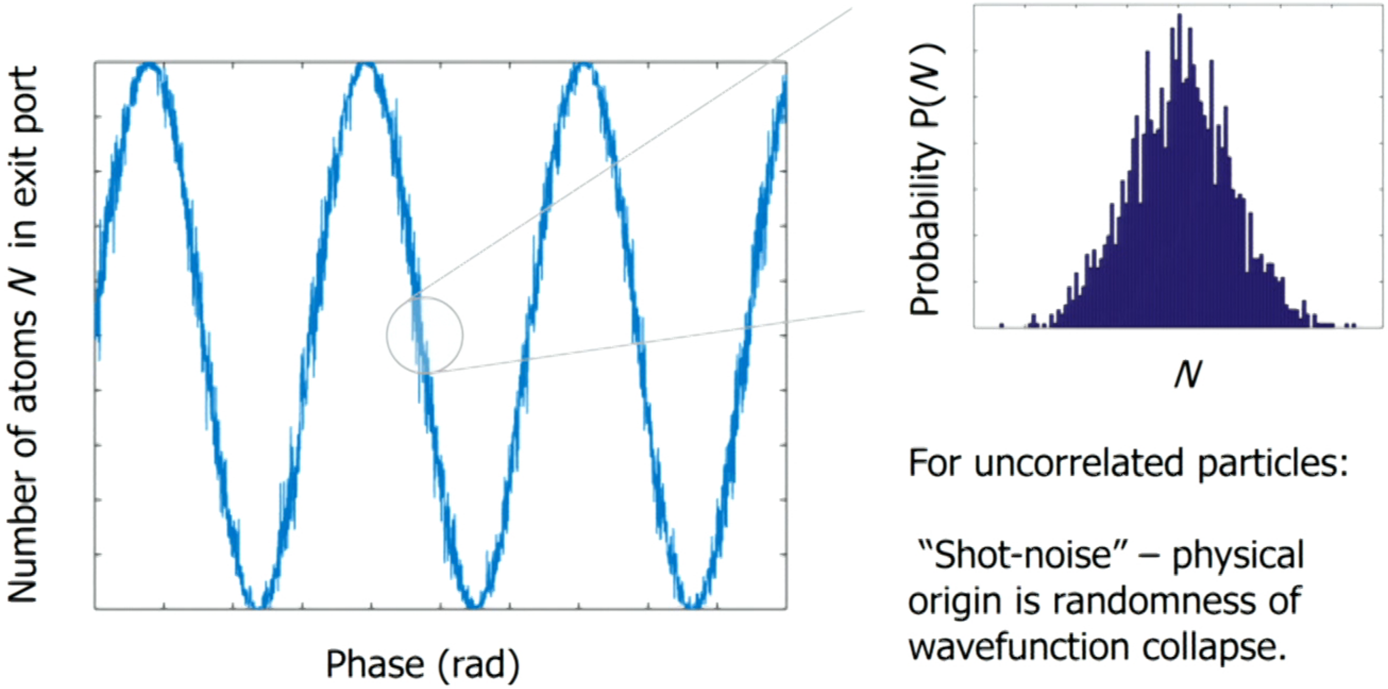
Ground-based EP (target precision ~1e-14 $\delta g/g$)
5.4 cm wavepacket separation

Well engineered atomic sensors are approaching physical performance limits imposed by atomic density.

Quantum entanglement provides a route to further performance gains.

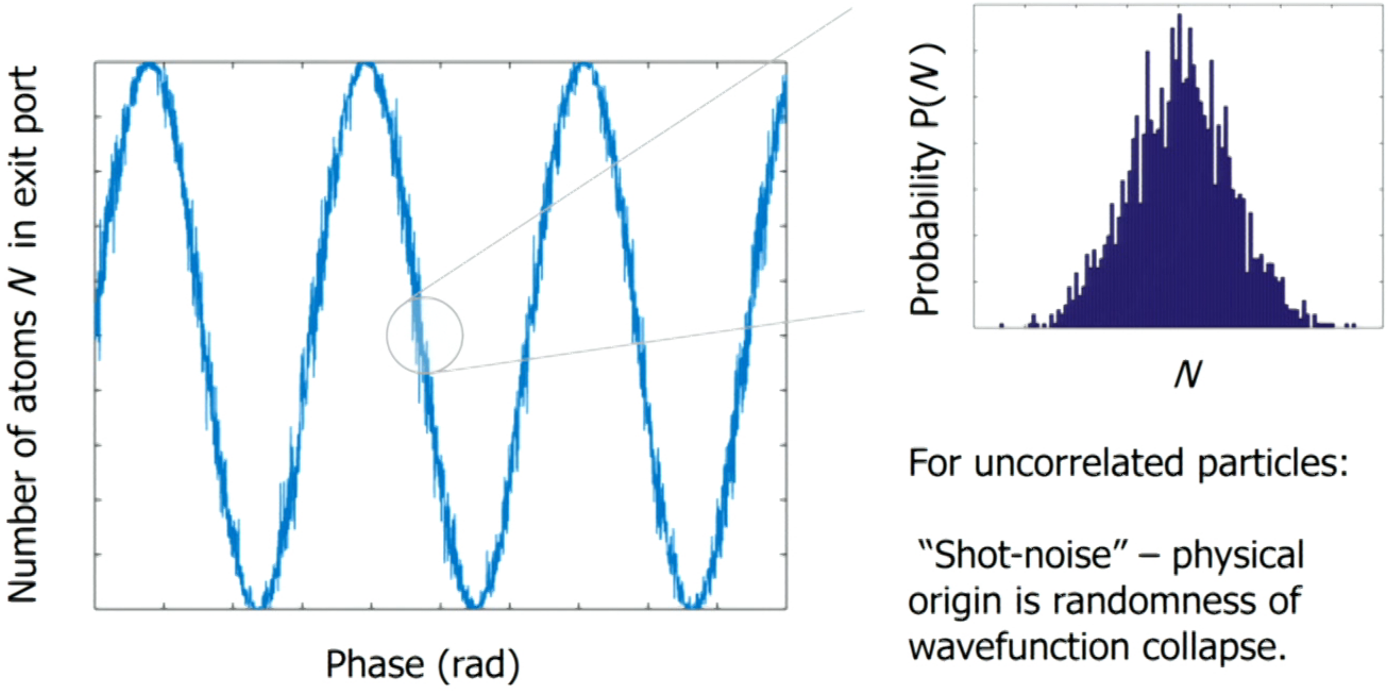
Noise in interferometric sensors



For uncorrelated particles:

"Shot-noise" – physical origin is randomness of wavefunction collapse.

Noise in interferometric sensors



For uncorrelated particles:

"Shot-noise" – physical origin is randomness of wavefunction collapse.

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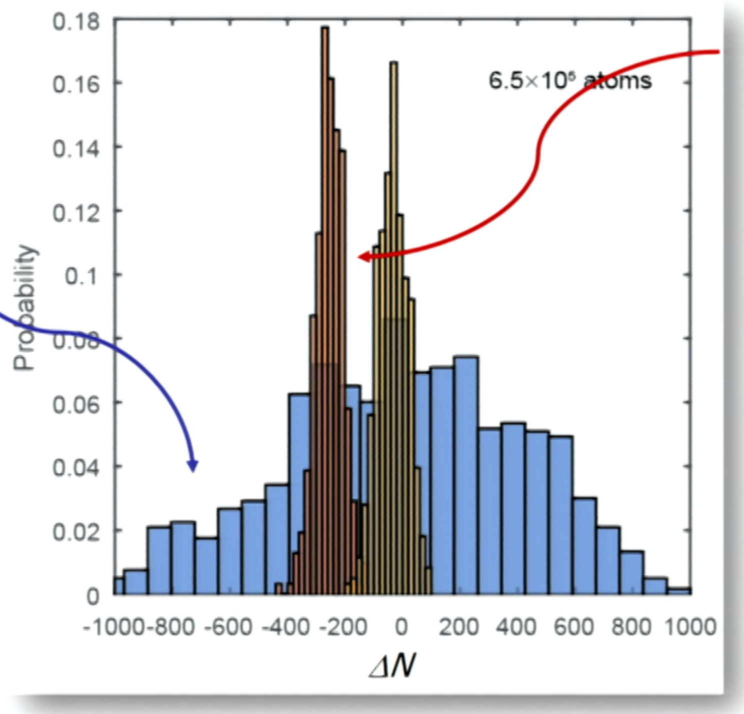
Quantum correlated (entangled) atomic ensembles

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

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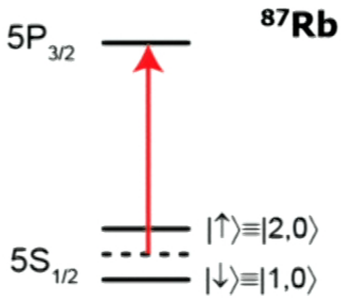
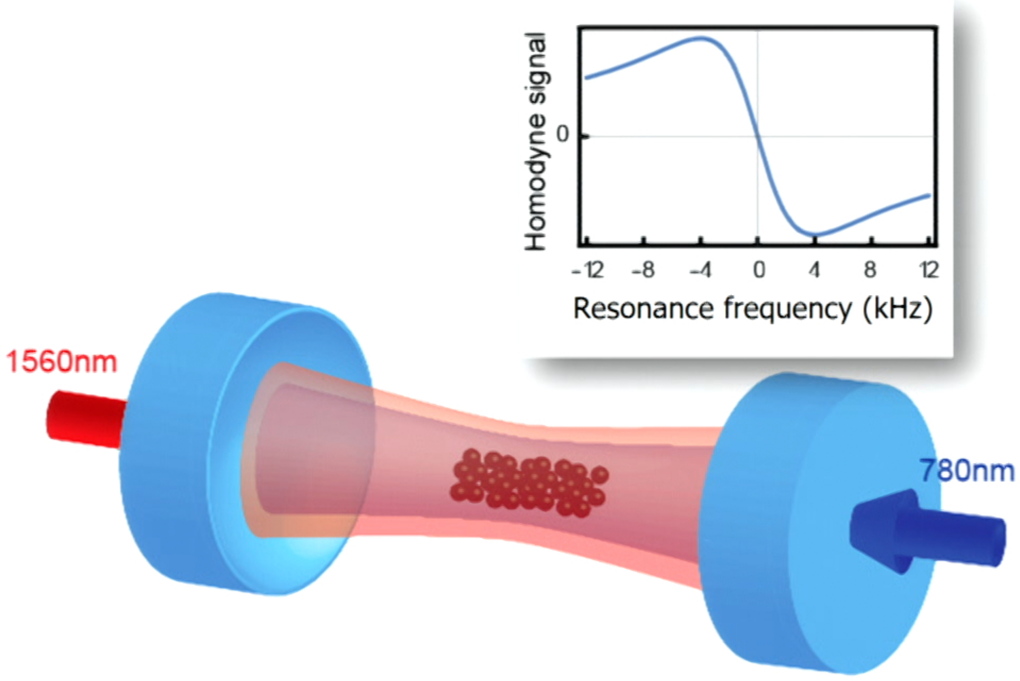
O. Hosten, et al., Nature (2016).

Cavity implementation

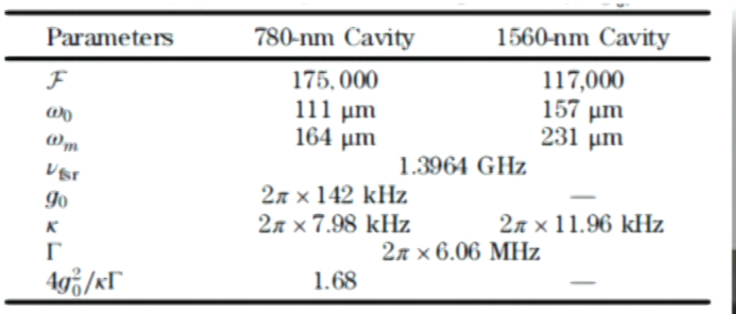
Dispersive atom-cavity interactions are used to realize a quantum non-demolition measurement of atom number.

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

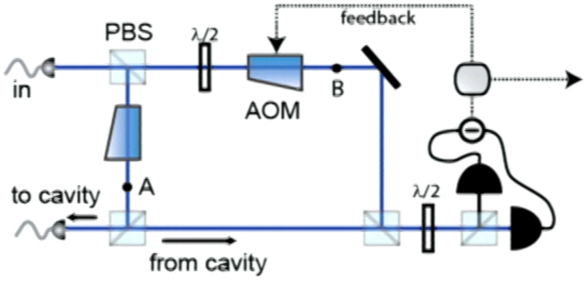




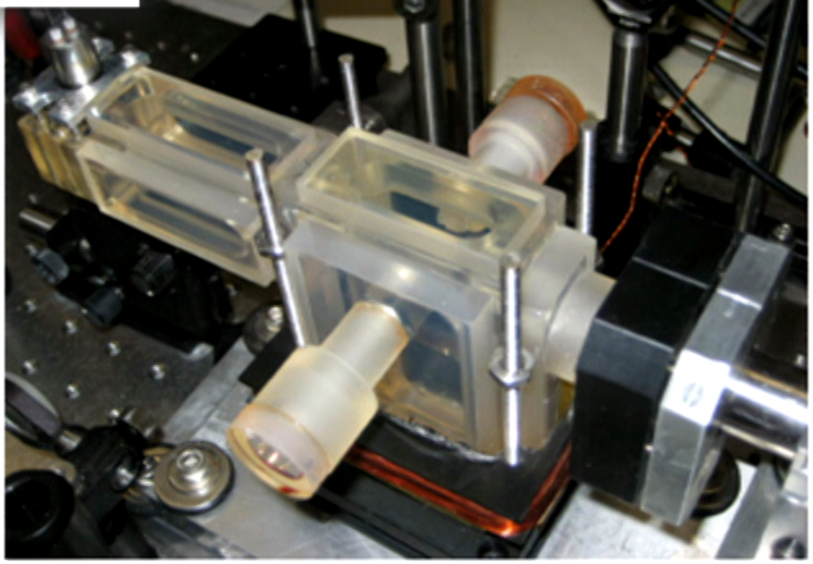
Apparatus



Parameters	780-nm Cavity	1560-nm Cavity
$\mathcal{F}$	175,000	117,000
ω_0	111 μm	157 μm
ω_m	164 μm	231 μm
ν_{fsr}	1.3964 GHz	
g_0	$2\pi \times 142$ kHz	—
κ	$2\pi \times 7.98$ kHz	$2\pi \times 11.96$ kHz
Γ	$2\pi \times 6.06$ MHz	
$4g_0^2/\kappa\Gamma$	1.68	—



Homodyne read-out



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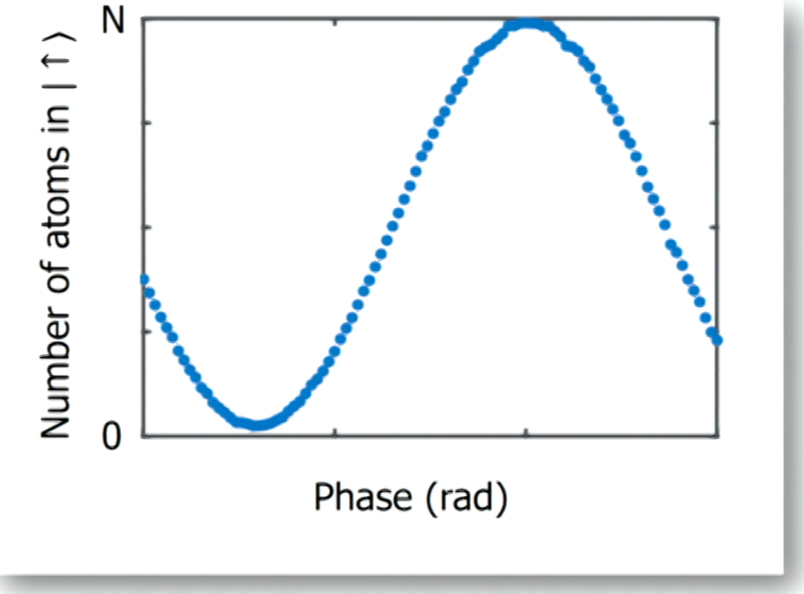
Coherence

Measurement sequence:

1) Prepare atoms in $|\downarrow\rangle$ state
2) Excitation (microwave) to $(|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}$
3) Engtangle/squeeze with optical (780 nm) probe;
4) Analysis pulse (microwave, scan excitation phase).



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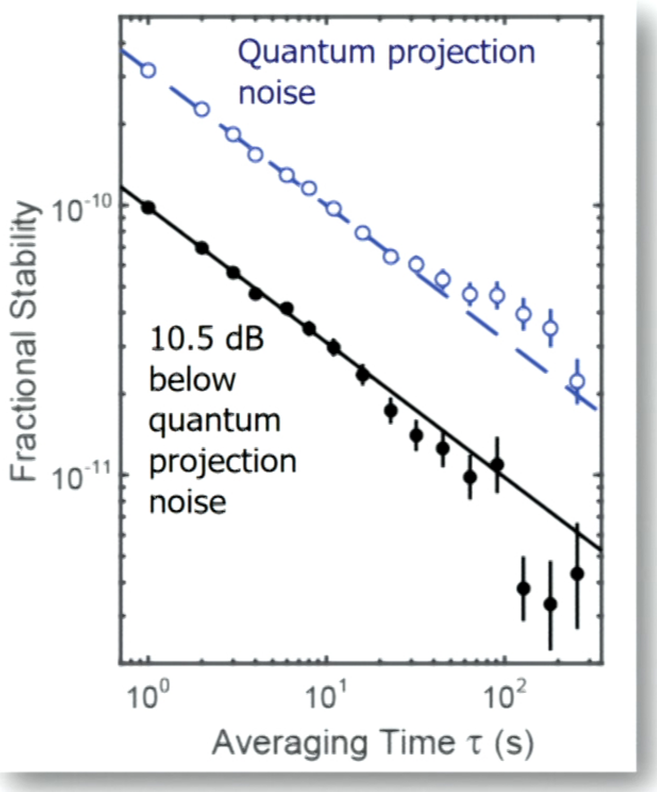
Atomic clock implementation

1×10^5 atoms

220μs interrogation time

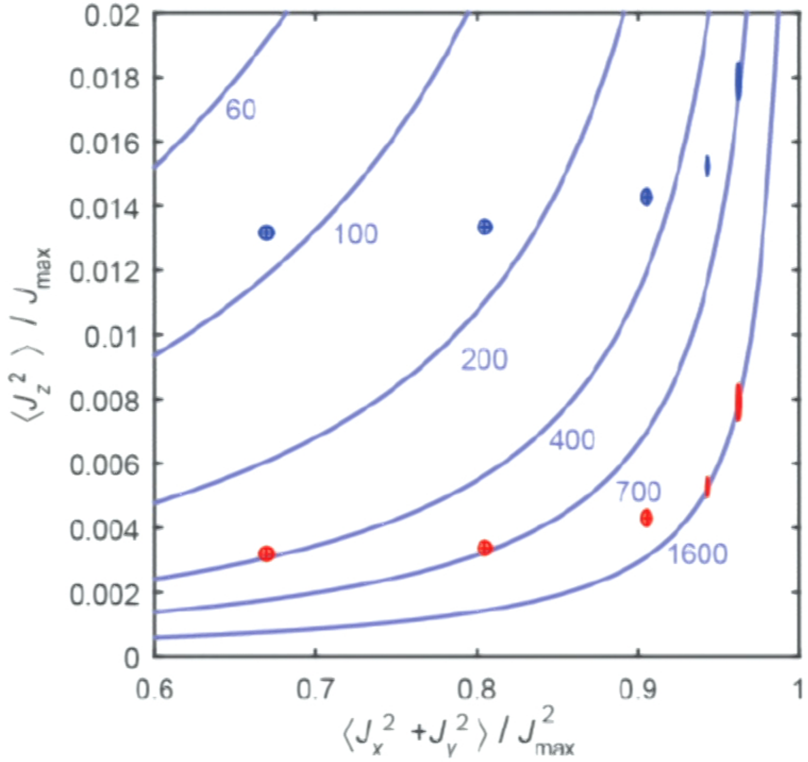
1 s update rate



Limited by μ-wave LO phase noise

Entanglement Depth

States are entangled. By how much?



Red: theory assuming no coupling inhomogeneity, 1600 atoms entangled, following B. Lucke, PRL 112 (2014).

Blue: inferred coupling inhomogeneity, 680 atoms entangled.

Recent theory (unpublished): 1200 atoms entangled.

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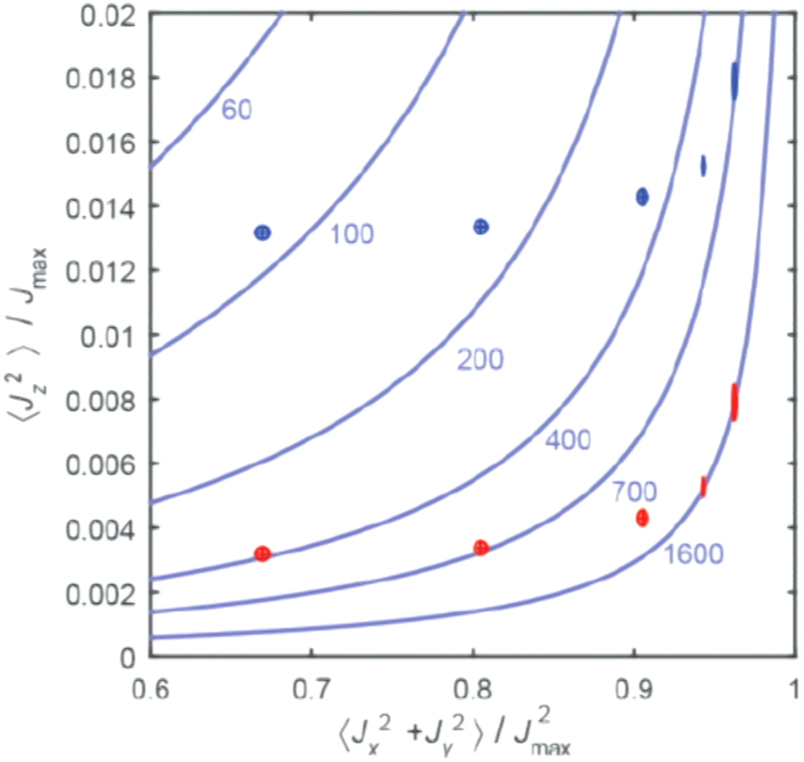
Entanglement Depth

States are entangled. By how much?



Red: theory assuming no coupling inhomogeneity, 1600 atoms entangled, following B. Lucke, PRL 112 (2014).

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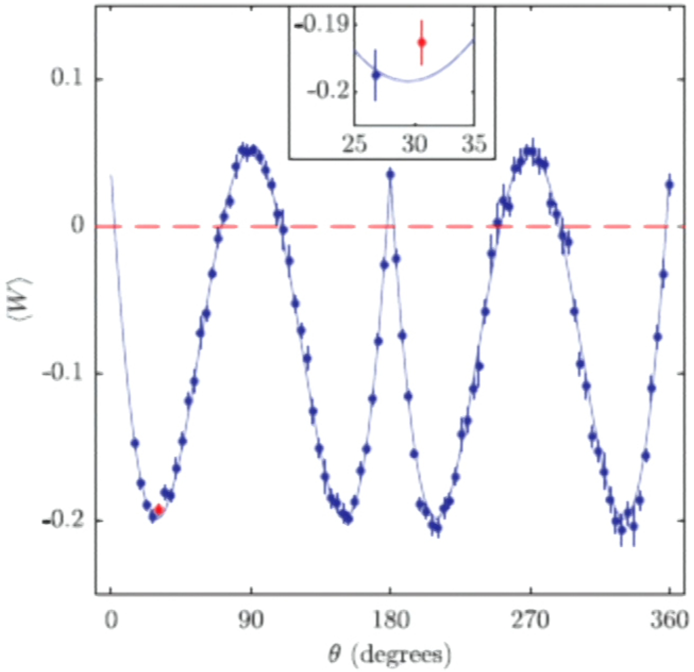
Bell witness

Bell witness for many-particle entangled states:

$$\langle W\rangle = -\left|\mathcal{J}_{1,\mathbf{n}}\right| + (\mathbf{z}\cdot\mathbf{n})^2\,\mathcal{J}_{2,\mathbf{z}} + 1 - (\mathbf{z}\cdot\mathbf{n})^2 \geq 0$$

Engelsen, et al., PRL 2017, following Schmied, et al., Science (2016)



56 σ violation of witness criterion

Future

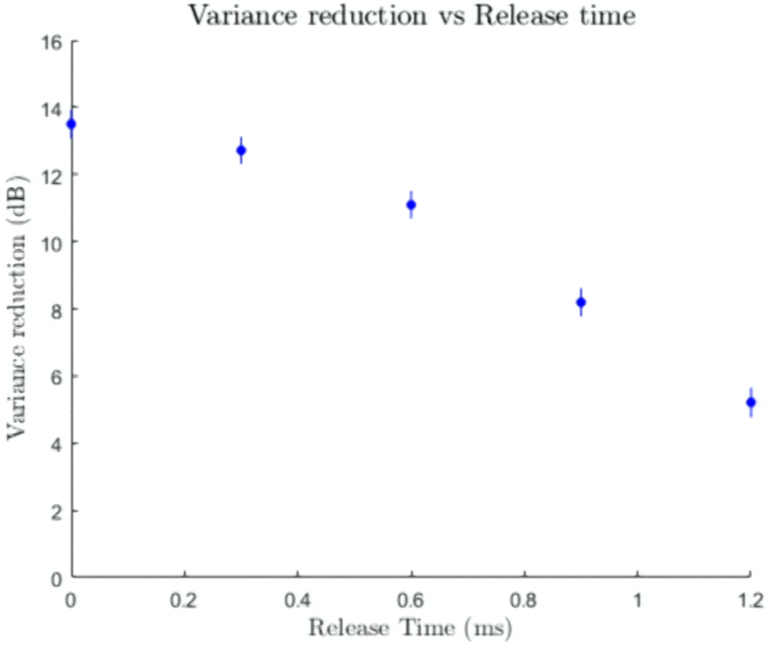
Massively entangled states
interfering over meter scales

Applications to precision
gravitational physics and geodesy

Free-space squeezed state evolution

Exploit uniform cavity coupling to demonstrate free-space sub-shot noise measurement

Work in progress:



Protocol:
Squeeze in lattice, release, recapture with lattice, probe

Loss in contrast due to mismatch between cavity coupling for squeezing and detection.

Thanks

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