Tests of Gravity and Quantum Mechanics with Atom Interferometry

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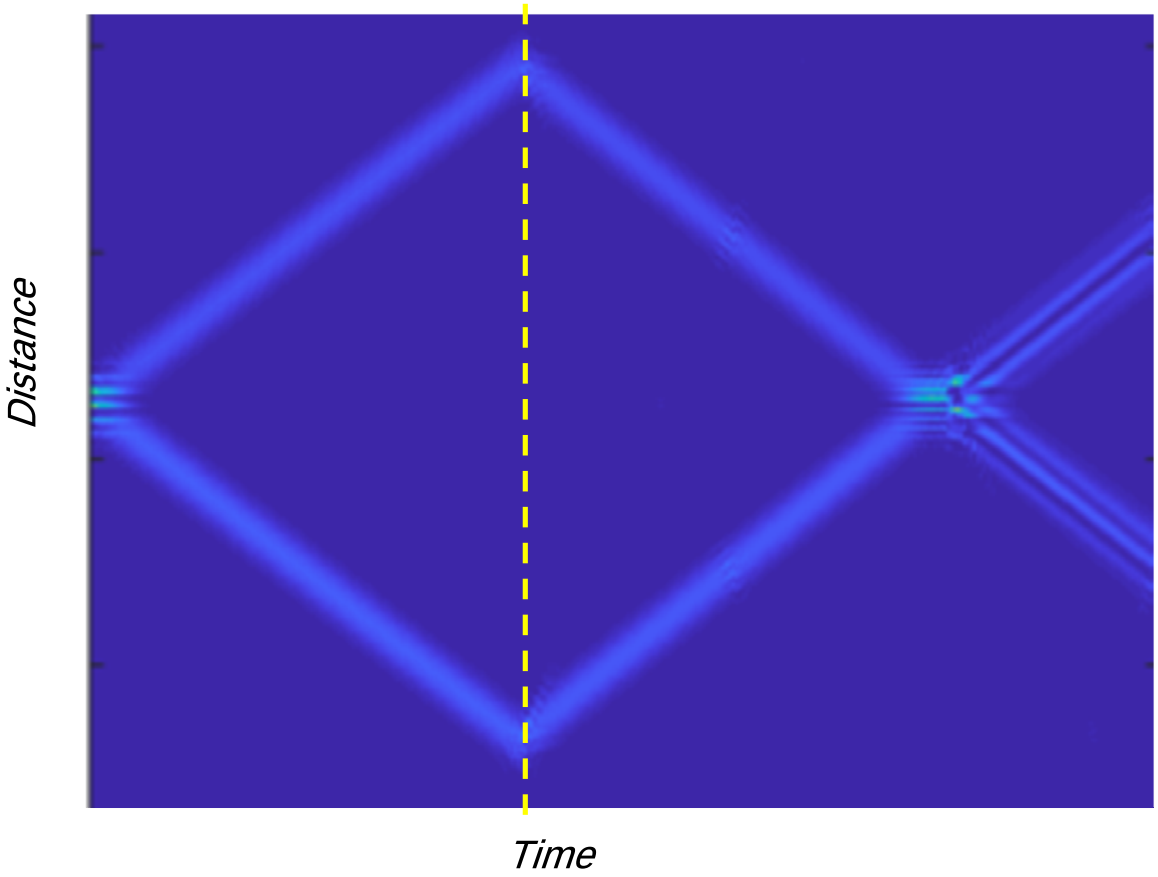
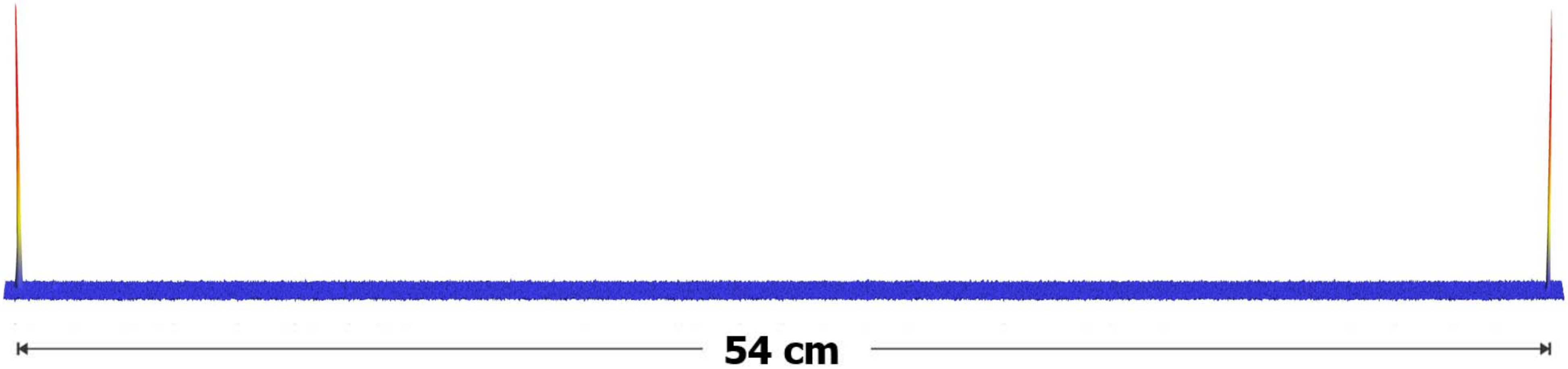
Atom interferometry

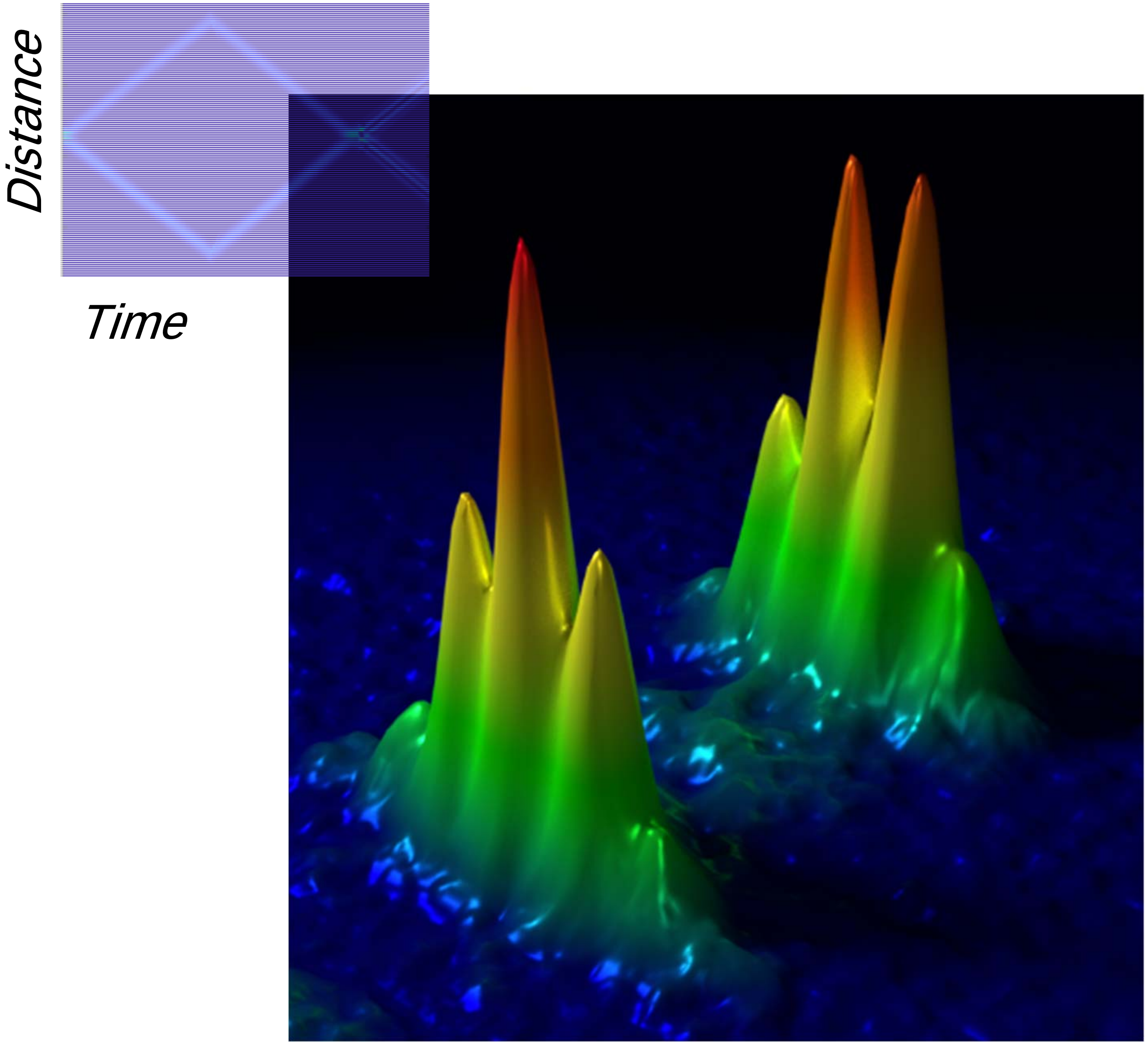


Atomic wavepacket superposition

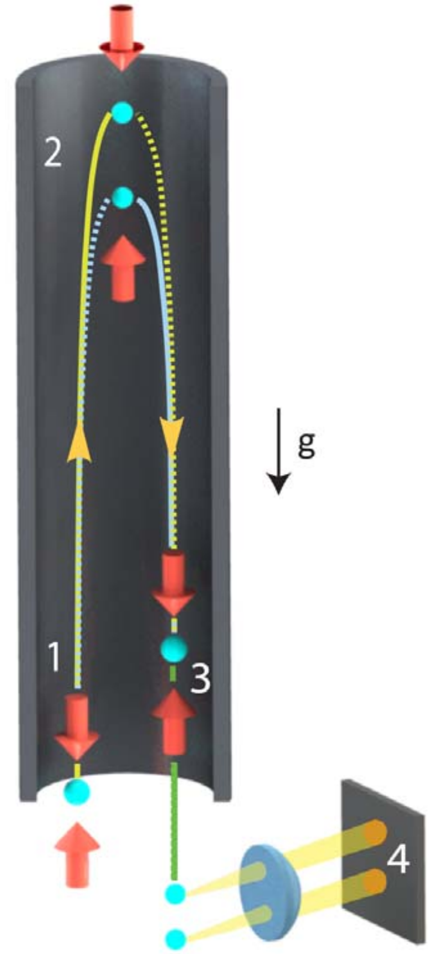


Kovachy, et al., Nature (2015).

Atomic wavepacket interference

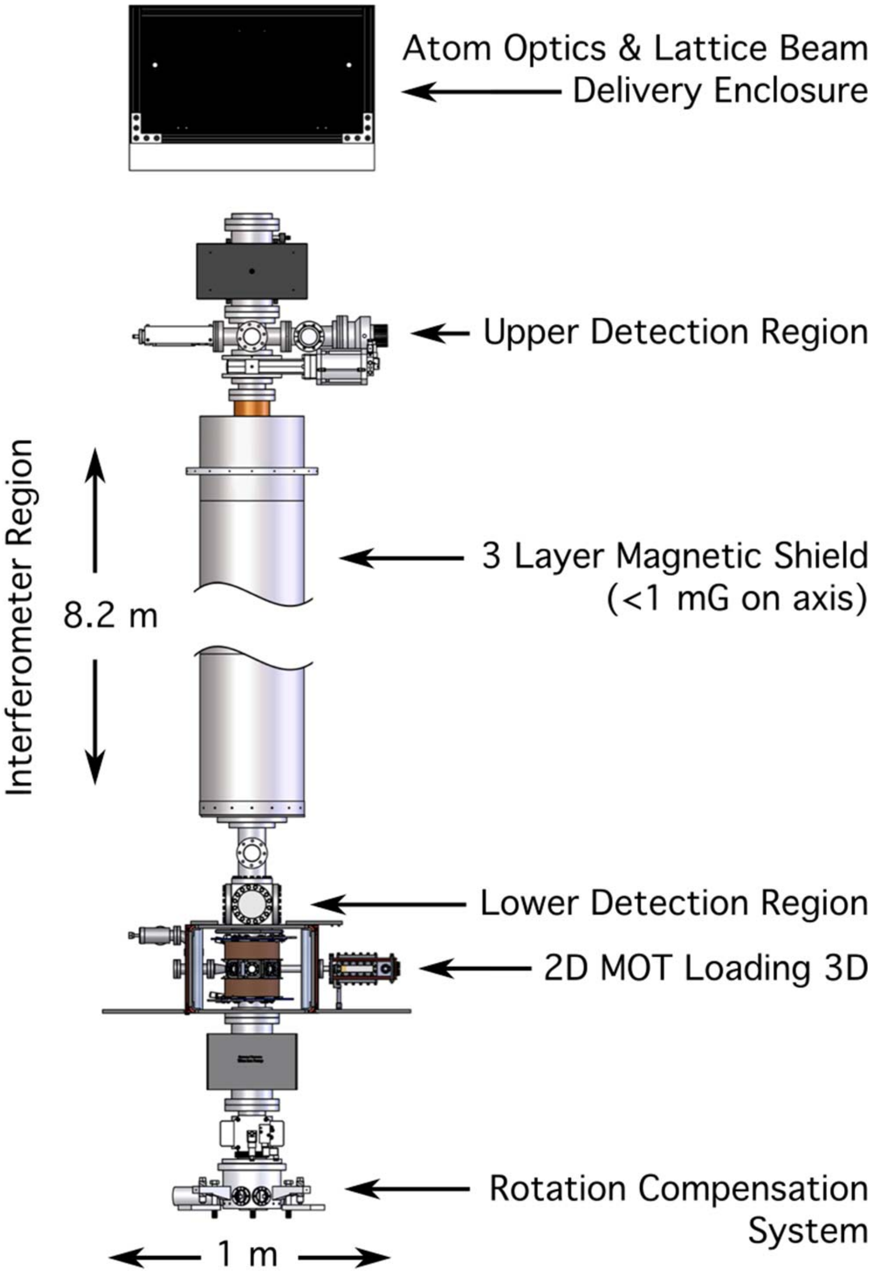


Superposed atomic wavepackets interfere

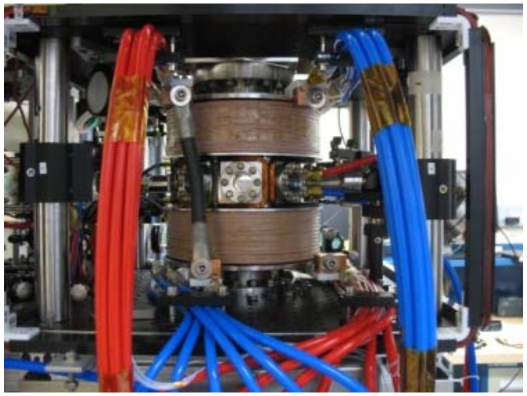


Asenbaum, PRL (2017).

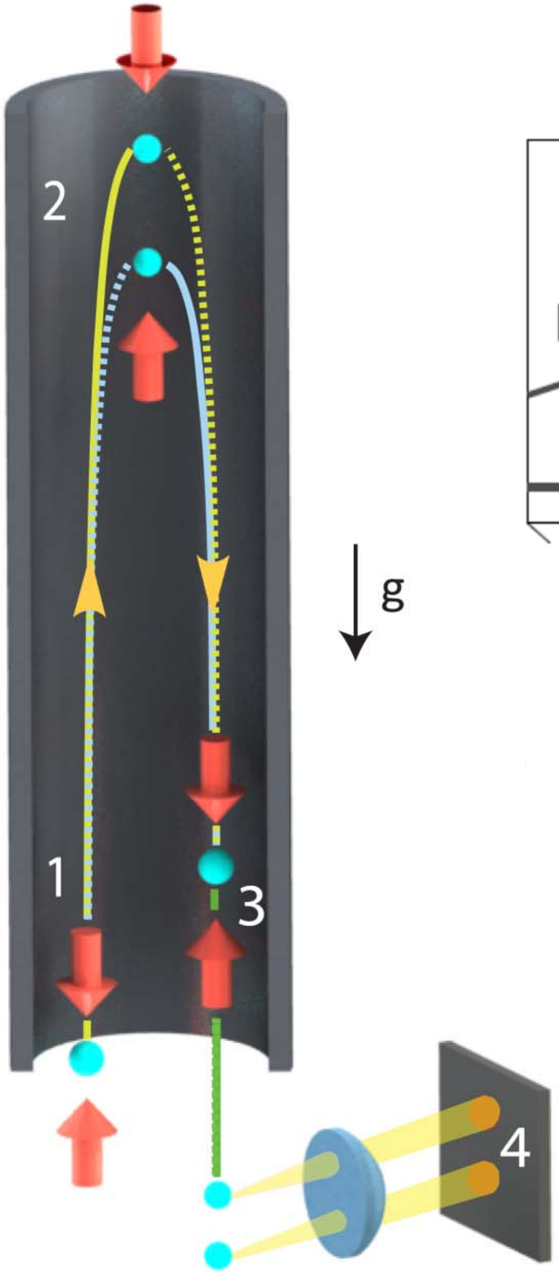
Atomic fountain

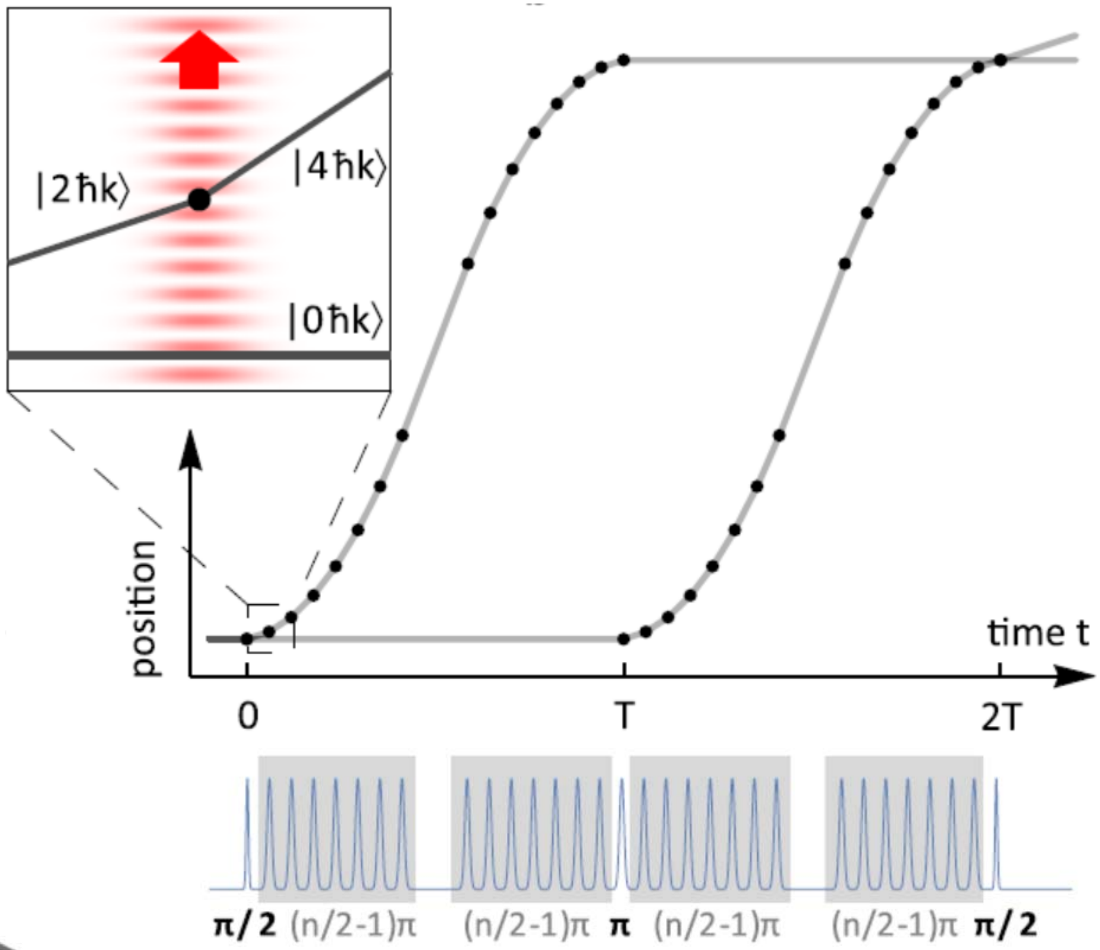


~ 100 pK
1e5 atoms/shot



Sequential Bragg atom optics





Pulse sequence duration: 2.08 s

Bounds for KTM model

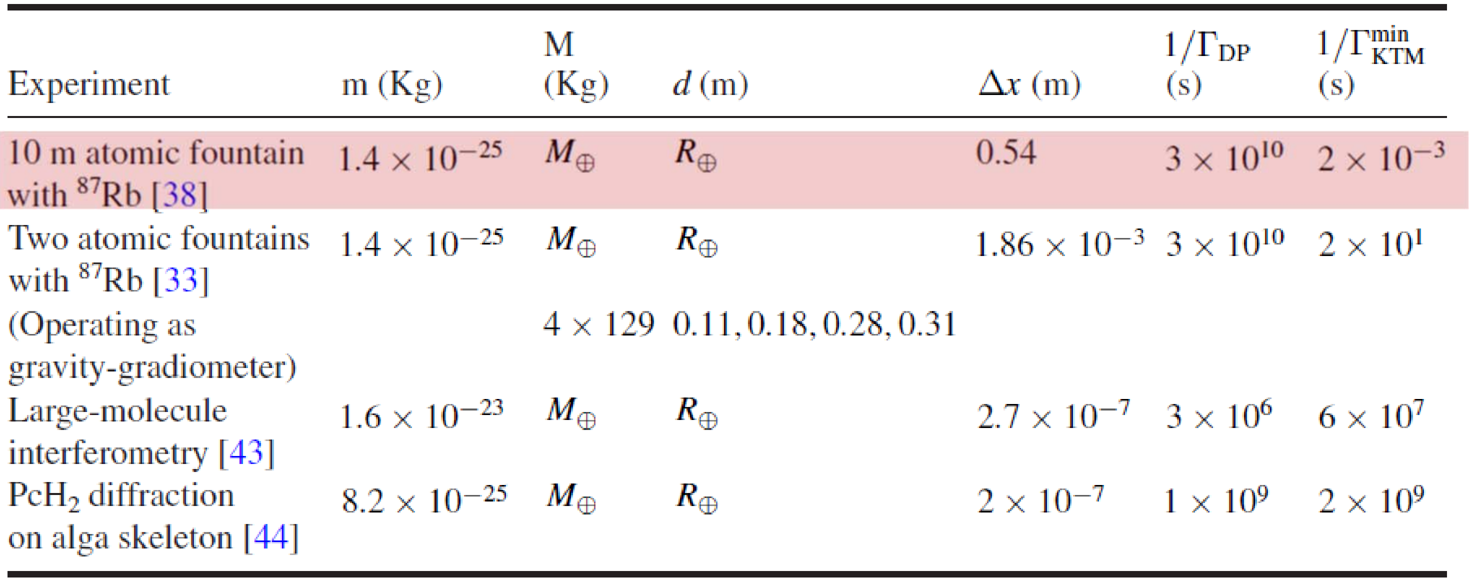
IOP Publishing Classical and Quantum Gravity

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

Gravity is not a pairwise local classical channel

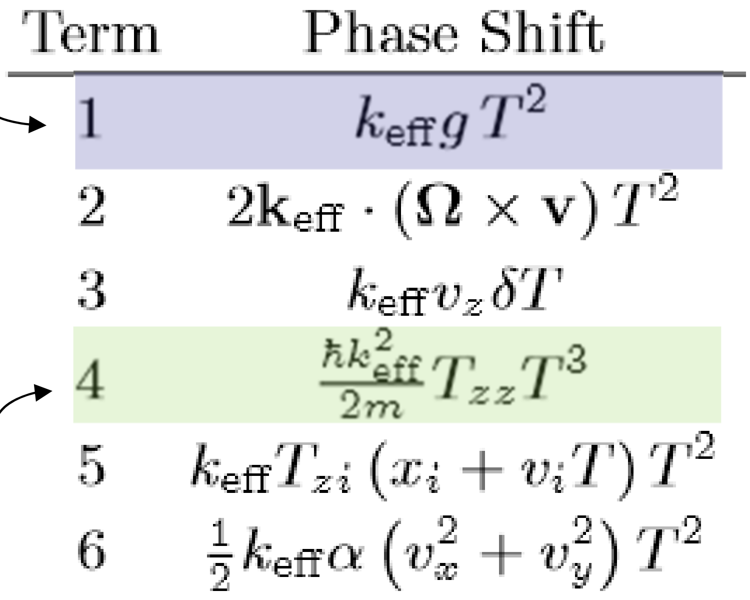
Natacha Altamirano[1,2], **Paulina Corona-Ugalde**[2,3], **Robert B Mann**[1,2,3] and **Magdalena Zych**[4,5]

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



Experiment	m (Kg)	M (Kg)	d (m)	Δx (m)	$1/\Gamma_{\mathrm{DP}}$ (s)	$1/\Gamma^{\mathrm{min}}_{\mathrm{KTM}}$ (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]	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 [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}

Phase shifts (non-relativistic)



Term	Phase Shift	
1	$k_{\text{eff}} g T^2$	Gravity
2	$2\mathbf{k}_{\text{eff}} \cdot (\mathbf{\Omega} \times \mathbf{v}) T^2$	Coriolis
3	$k_{\text{eff}} v_z \delta T$	Timing asymmetry
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	$\frac{1}{2} k_{\text{eff}} \alpha (v_x^2 + v_y^2) T^2$	Wavefront

8e9 rad

635 rad

T_{ij}, gravity gradient

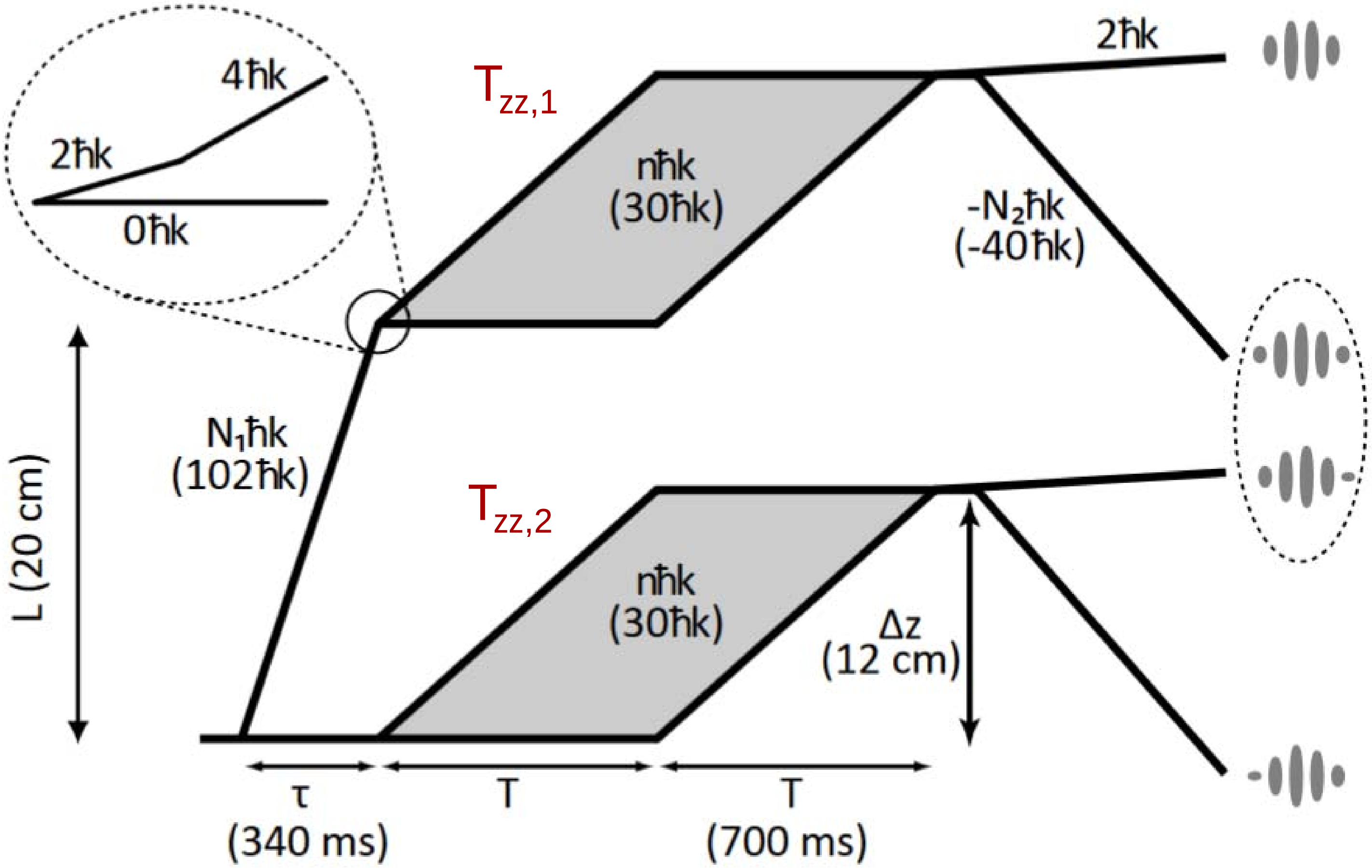
v_i, velocity; x_i, initial position

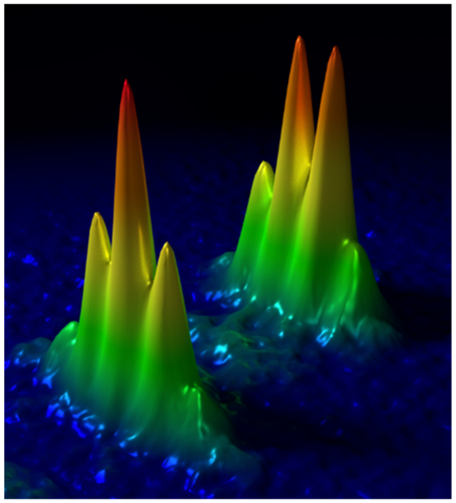
g, acceleration due to gravity

T, interrogation time

k_{eff}, effective propagation vector

Curvature, quantum (tidal) phase shift observation





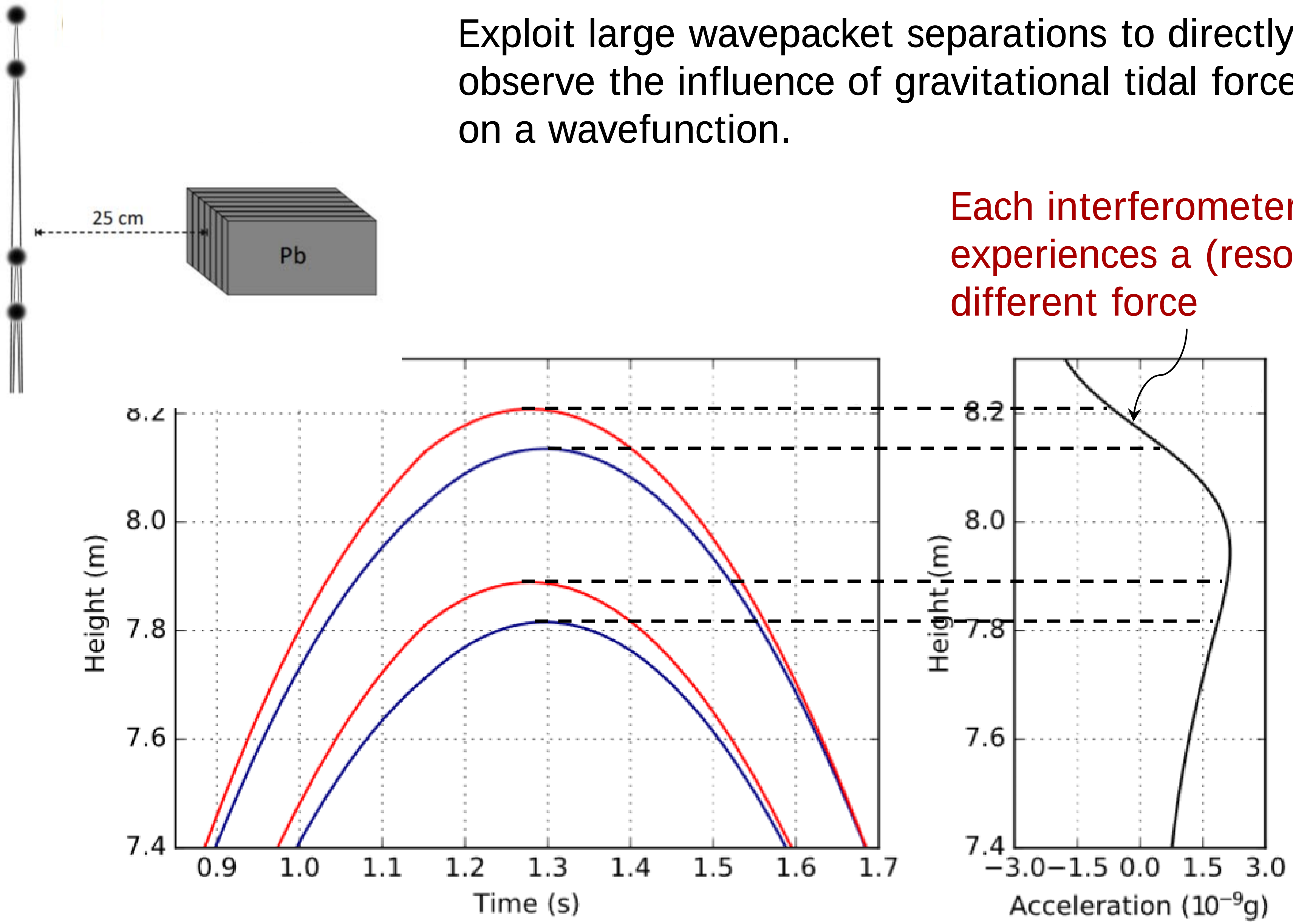
Resolution: 2e-9/s^2
per shot
(7e-4 Earth
gradient/shot)

Use gravity gradiometer configuration to isolate quantum curvature phase shifts

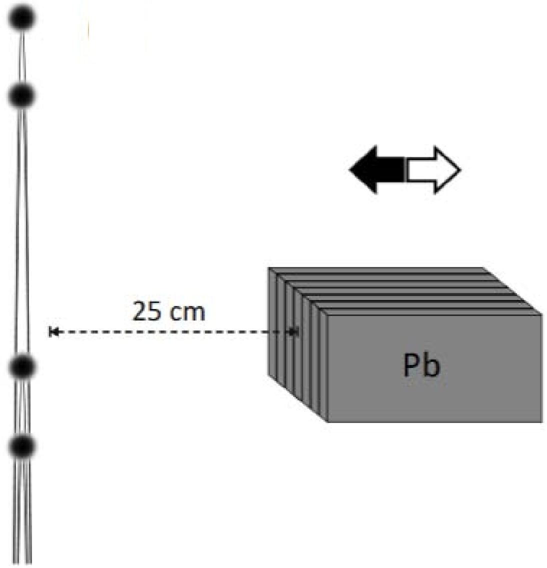
Tidal forces on a wavefunction

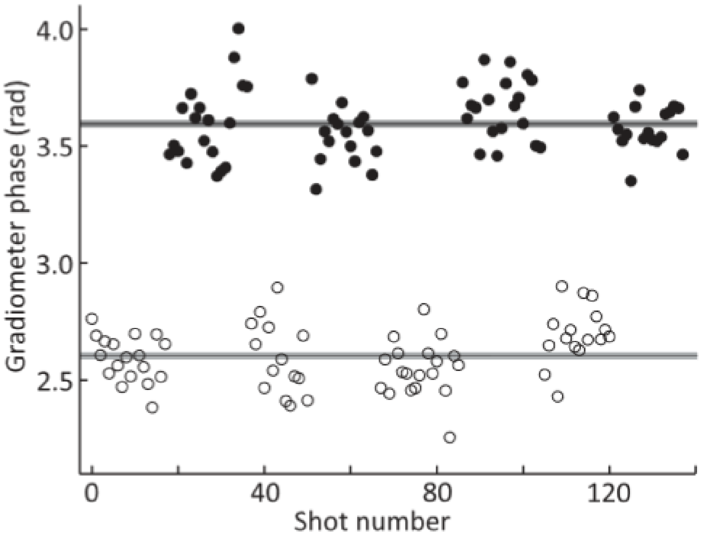
Exploit large wavepacket separations to directly observe the influence of gravitational tidal forces on a wavefunction.

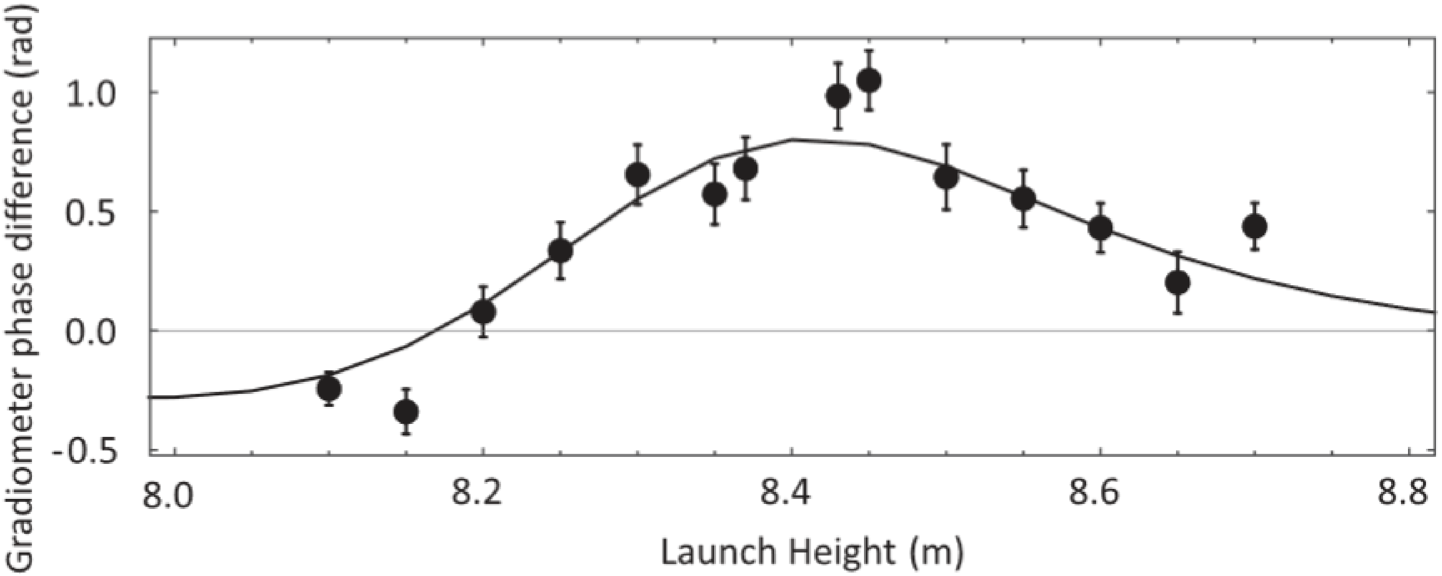
Each interferometer arm experiences a (resolvable) different force



Observation of tidal forces on a wavefunction

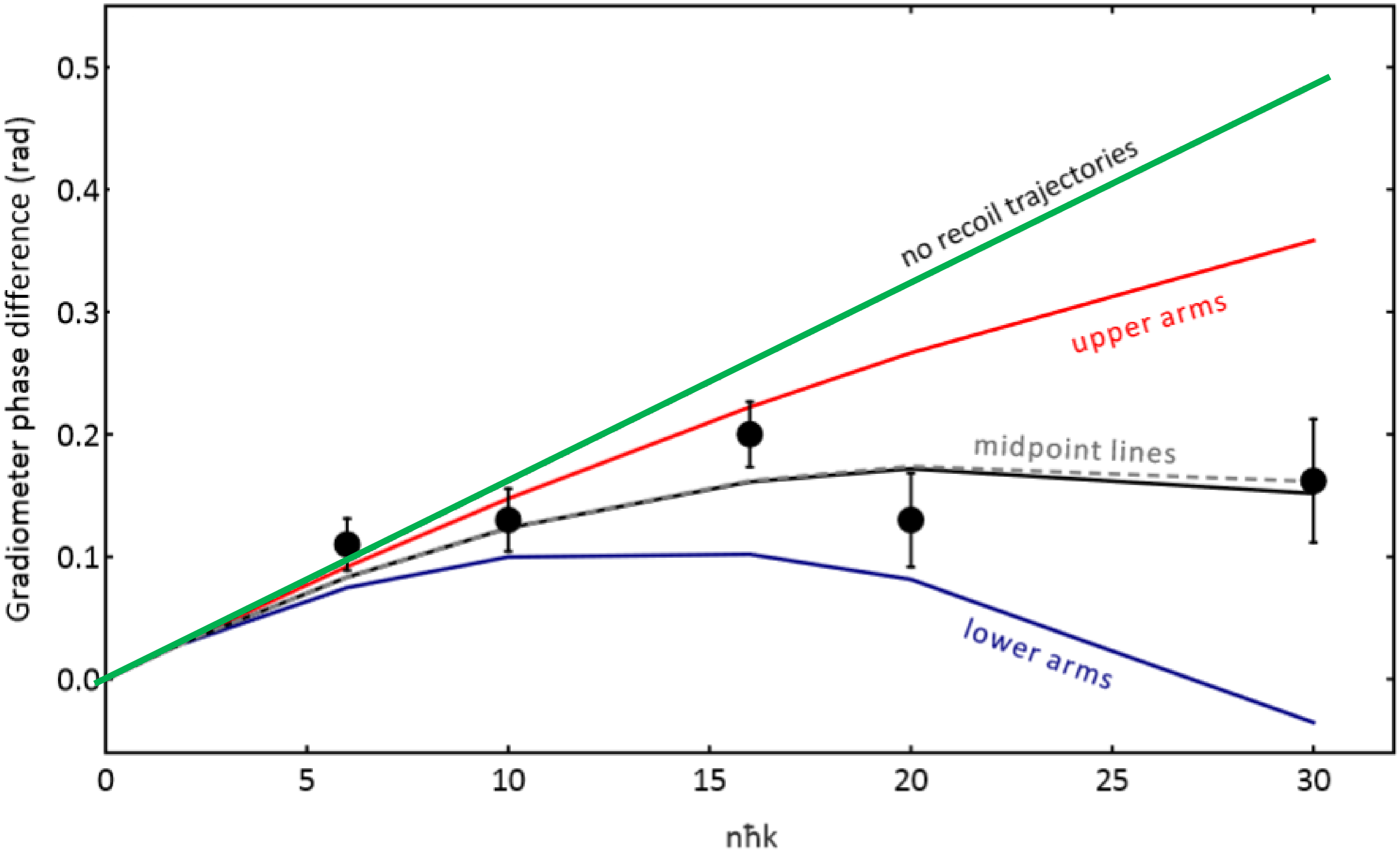






Gravity and quantum mechanics

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

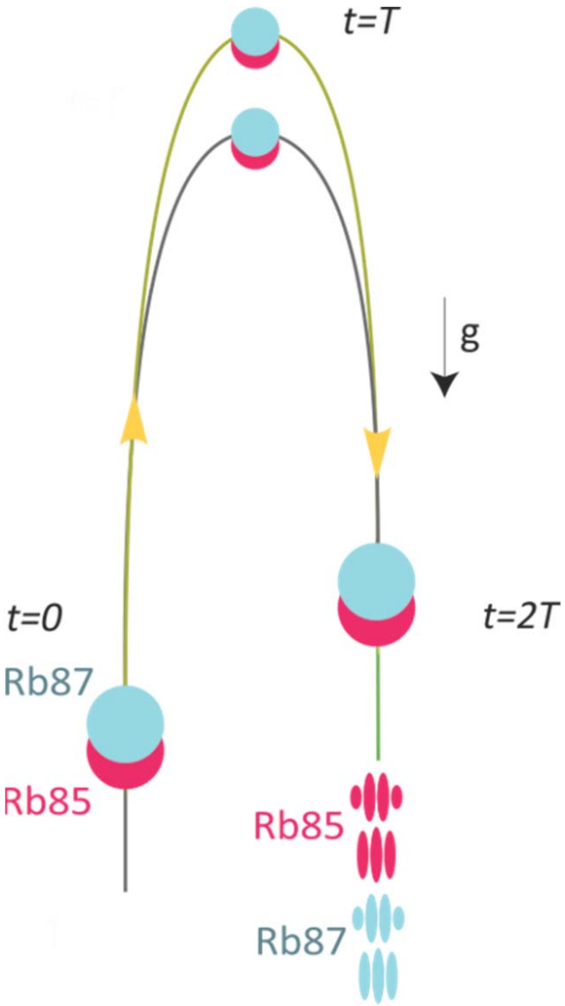


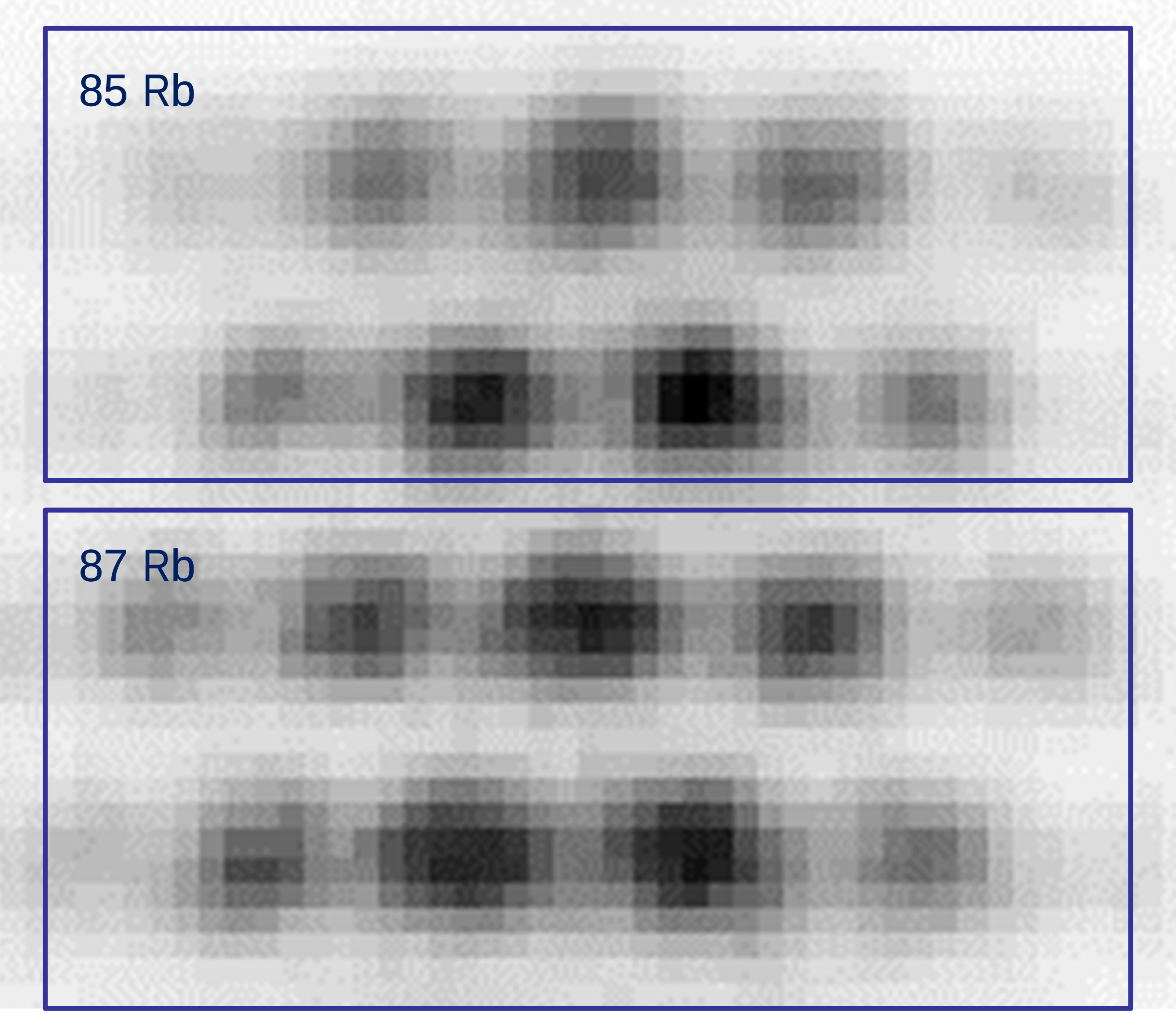
(phase shift)

(wavepacket separation)

Asenbaum, PRL (2017)

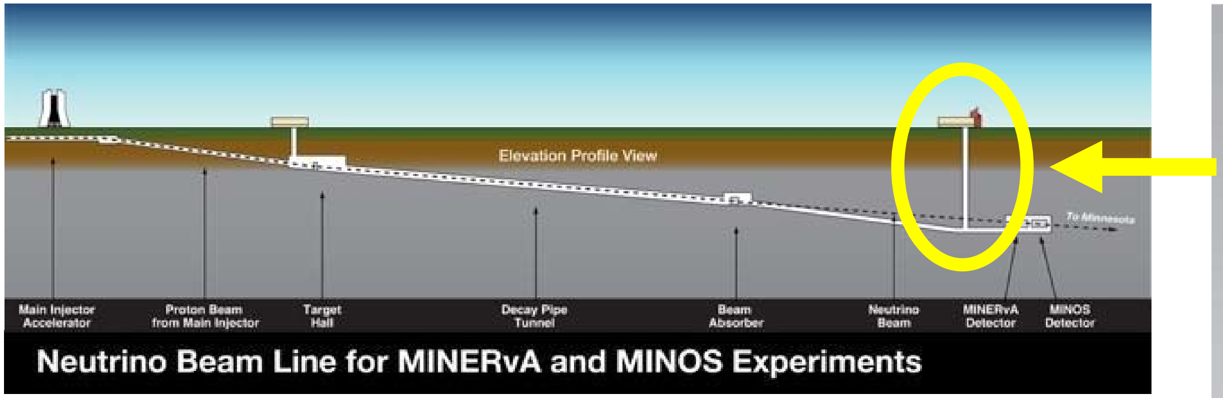
Equivalence Principle Test

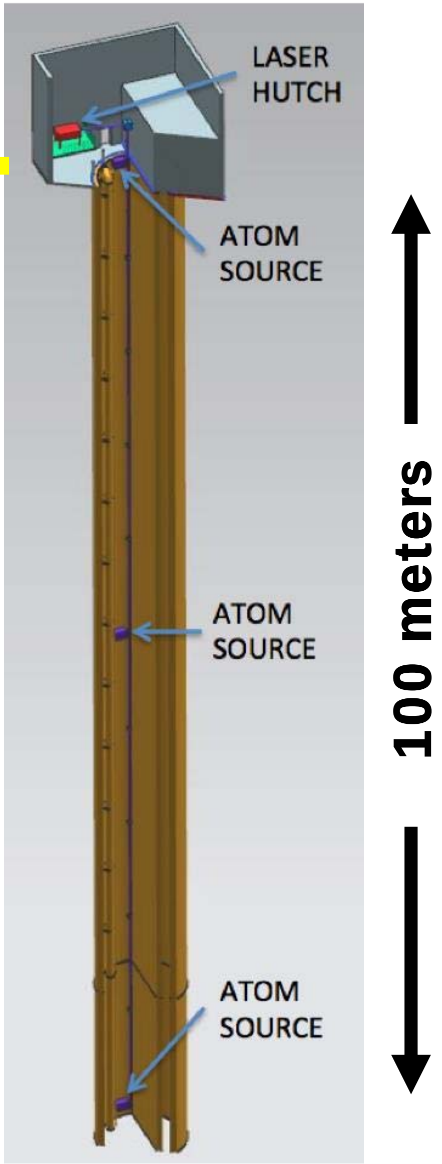


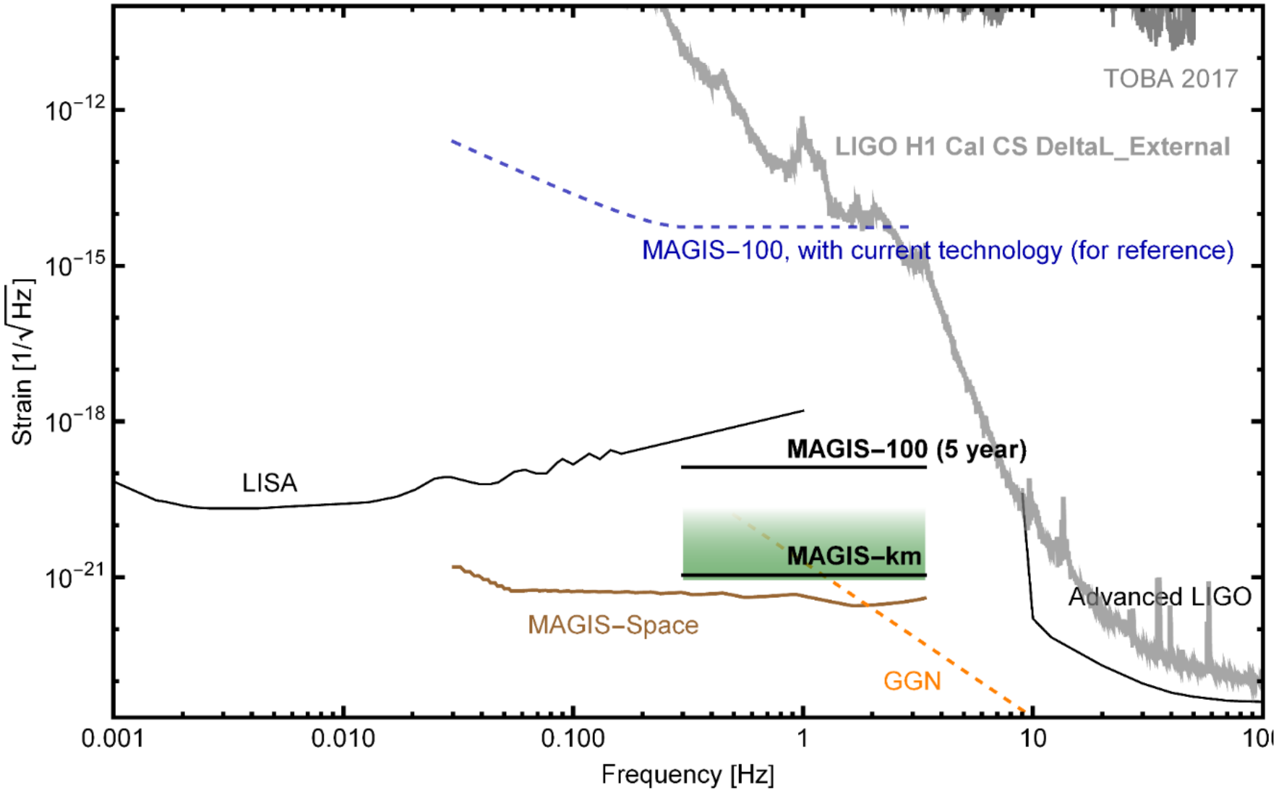


Ground-based EP (target precision ~1e-14 $\delta g/g$)
5.4 cm wavepacket separation

MAGIS-100: GW detector prototype at Fermilab

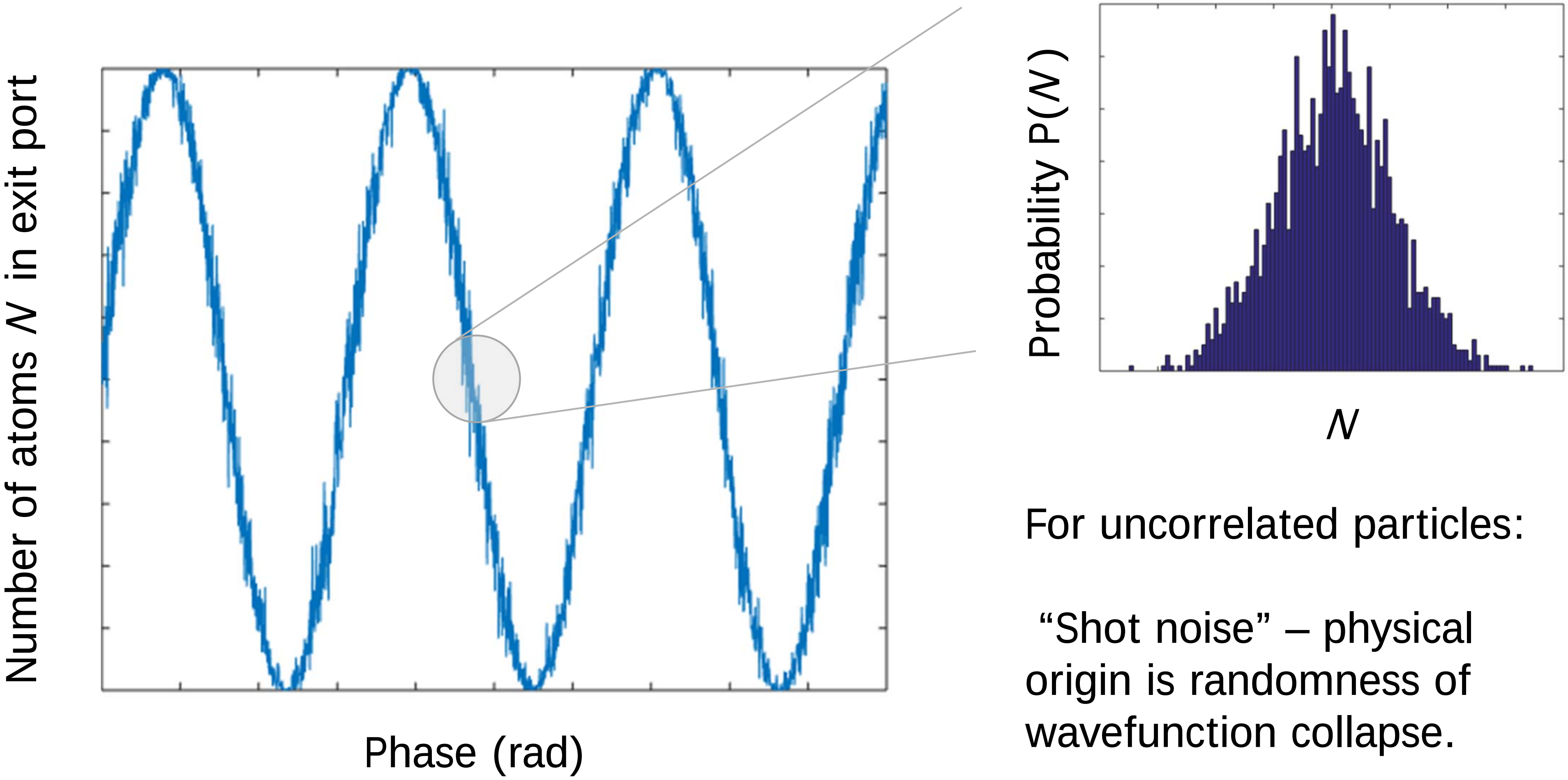






STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

Noise in interferometric sensors



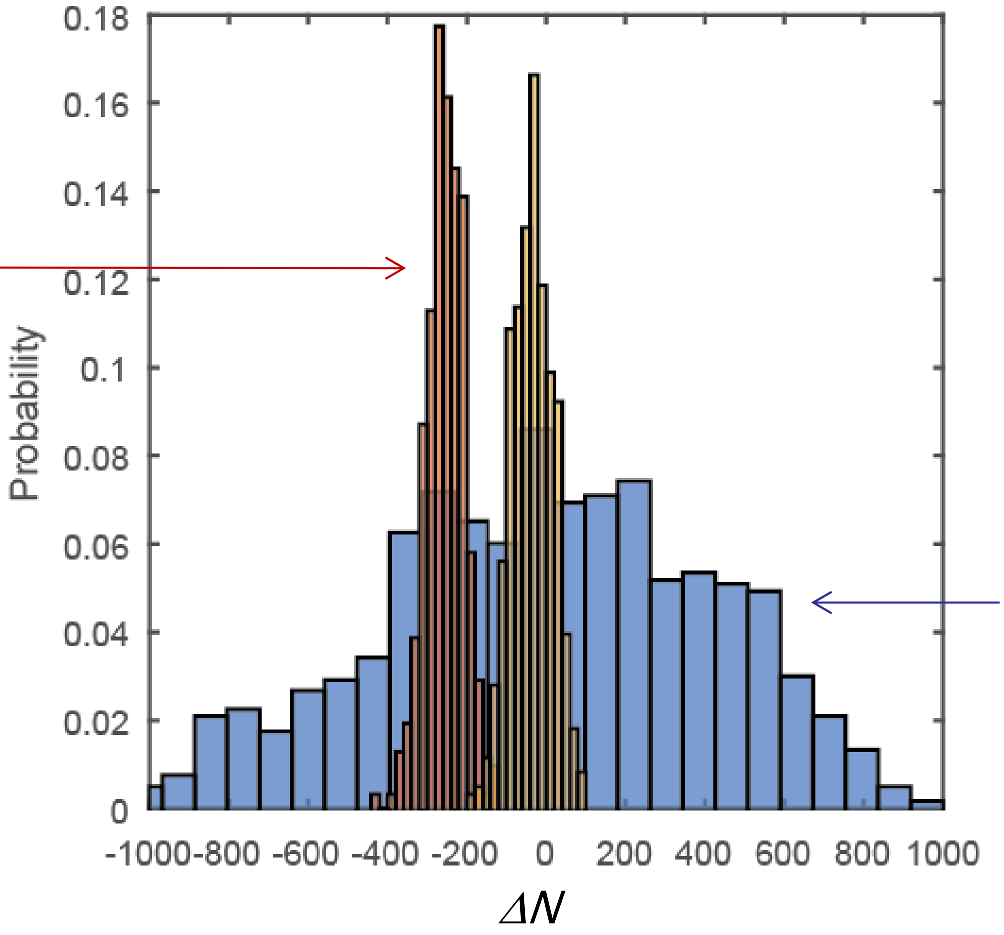
For uncorrelated particles:

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

Quantum correlated (entangled) atomic ensembles

Consider N ~ 1e6 atoms, each in a quantum superposition of two ground state energy levels.

Measure probability of finding atoms in one of these states:



Entangled atoms

Reduced read-out noise

This data: 20 dB variance reduction

Uncorrelated atoms

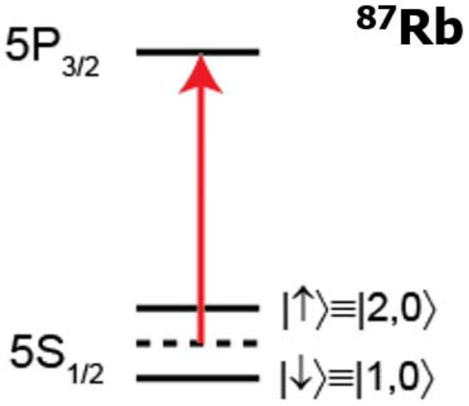
"Shot-noise" Coin-toss statistics

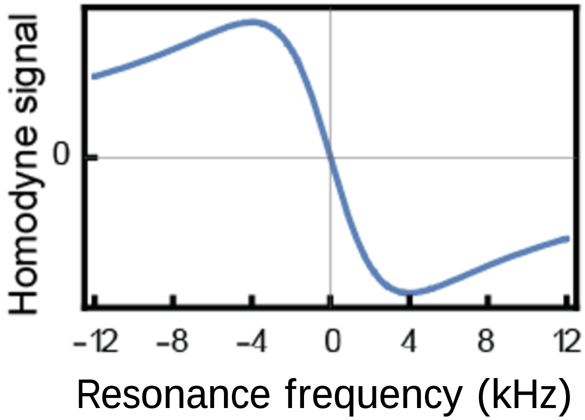
O. Hosten, et al., Nature (2016).

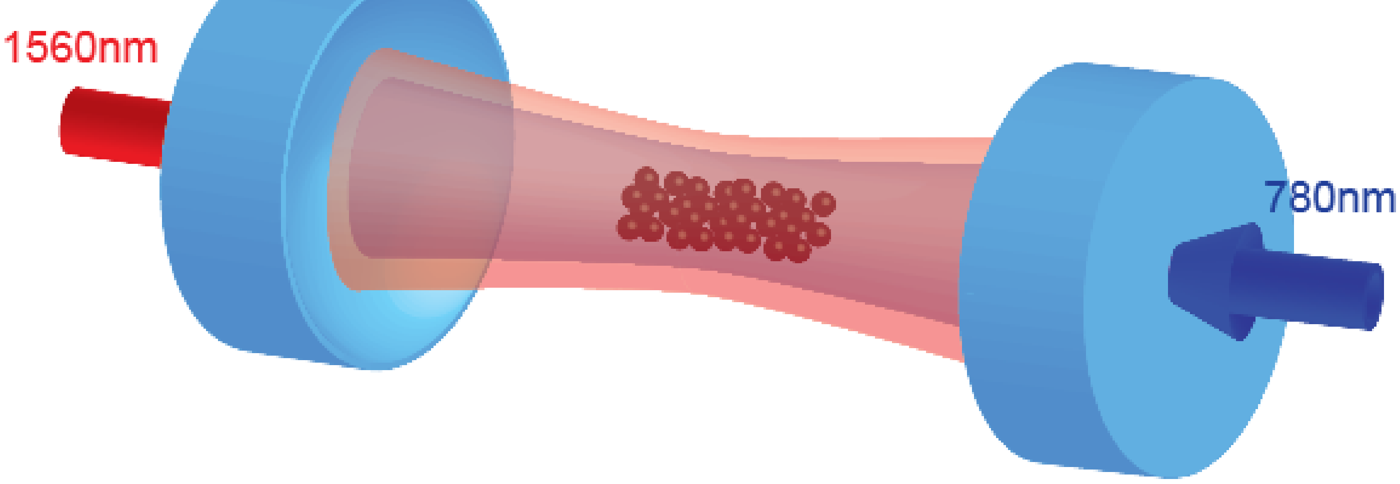
Cavity-assisted entanglement

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.



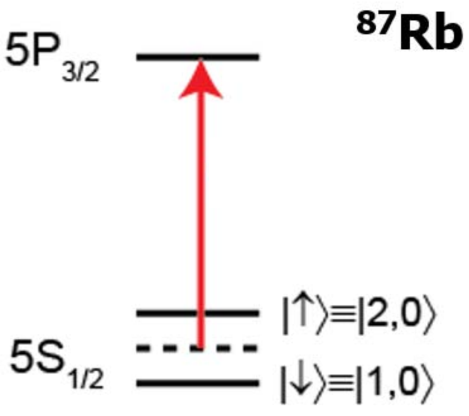


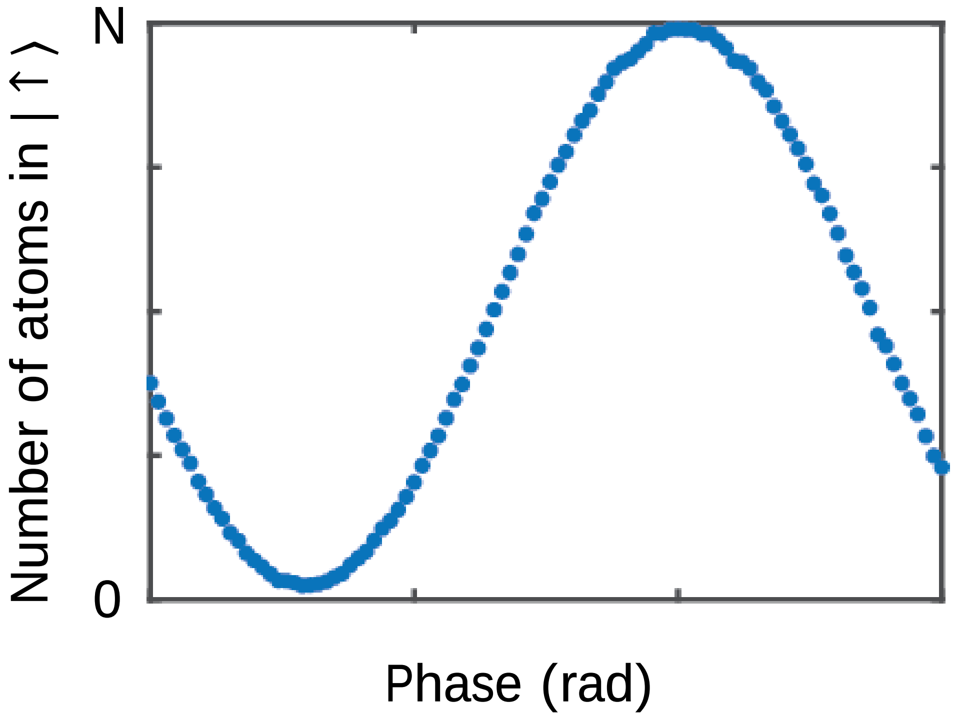


Coherence

Measurement sequence:

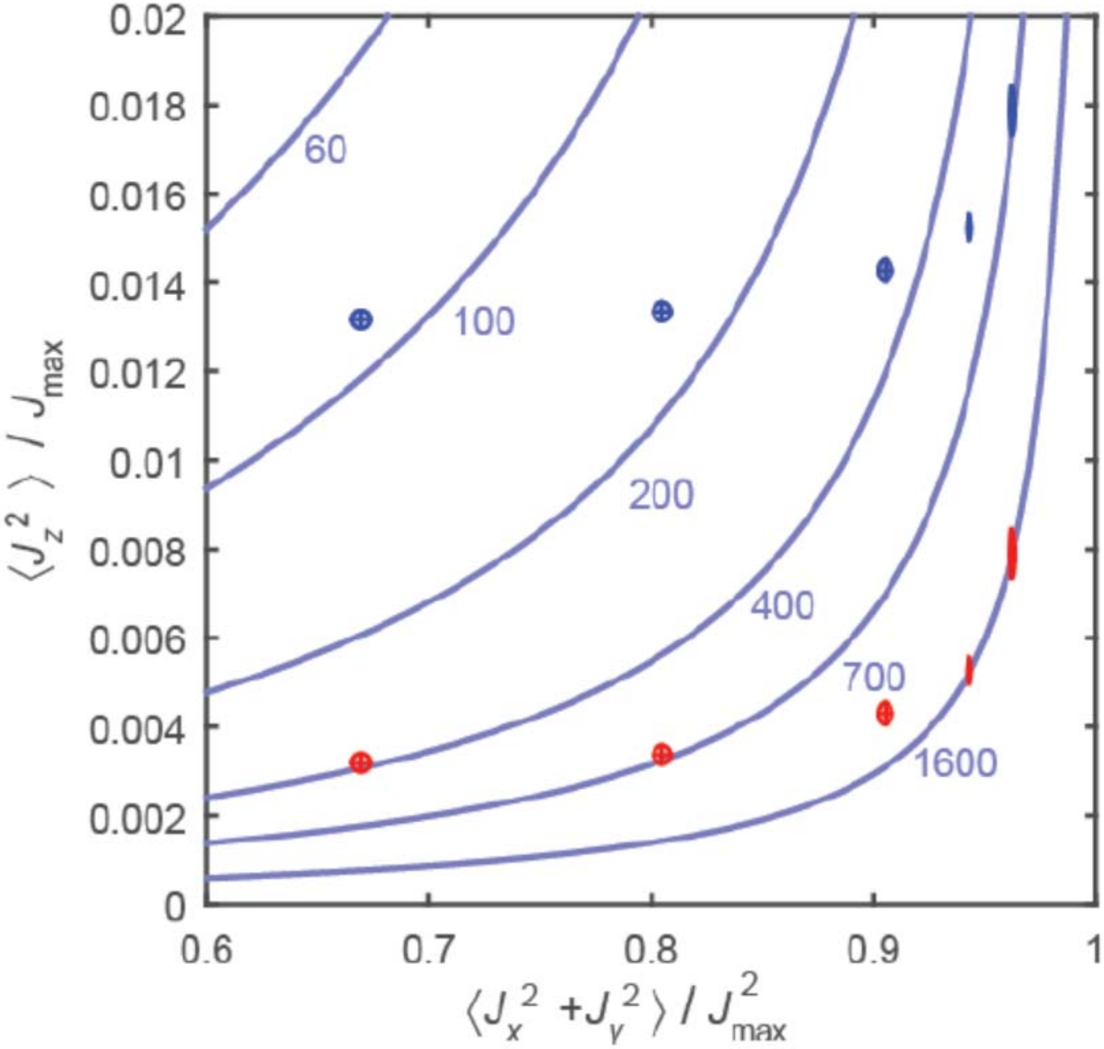
1) Prepare atoms in $|\downarrow\rangle$ state
2) Excitation (microwave) to $(|\downarrow\rangle + |\uparrow\rangle)/\sqrt{2}$
3) Entangle/squeeze with optical (780 nm) probe;
4) Analysis pulse (microwave, scan excitation phase).





Entanglement depth

States are entangled. By how much?



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

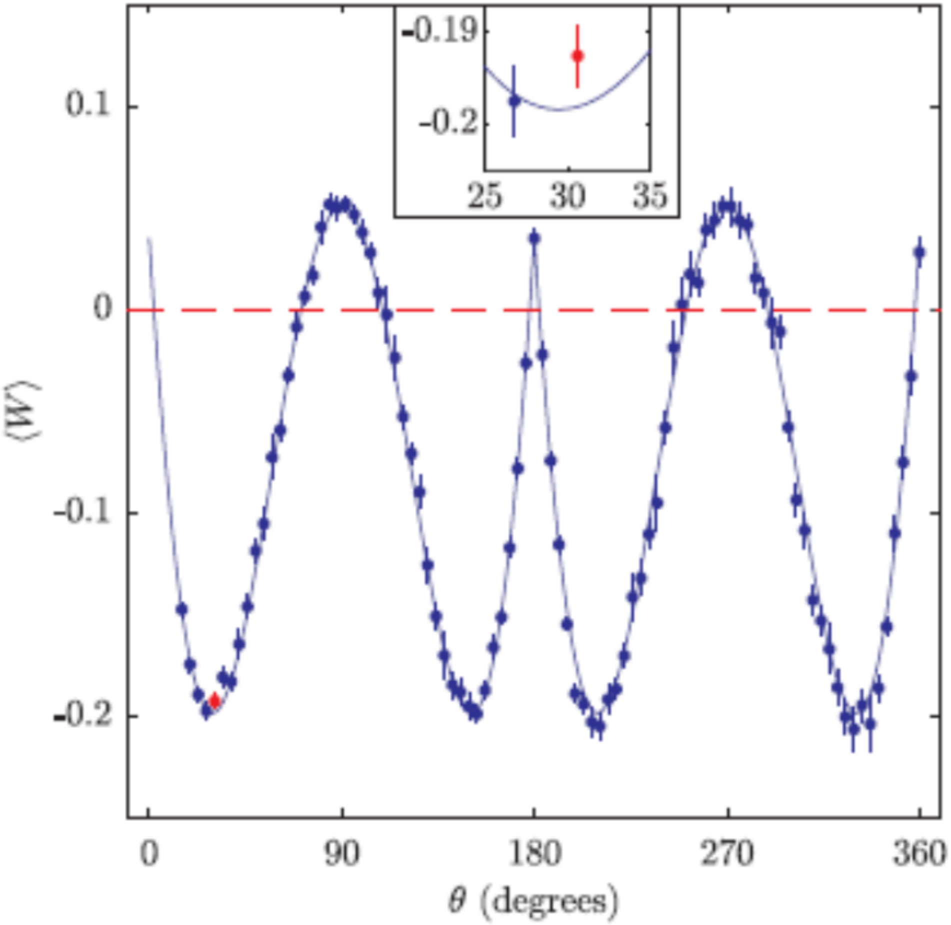
Blue: inferred coupling inhomogeneity, 680 atoms entangled.

Bell witness

Bell witness for many-particle entangled states:

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

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



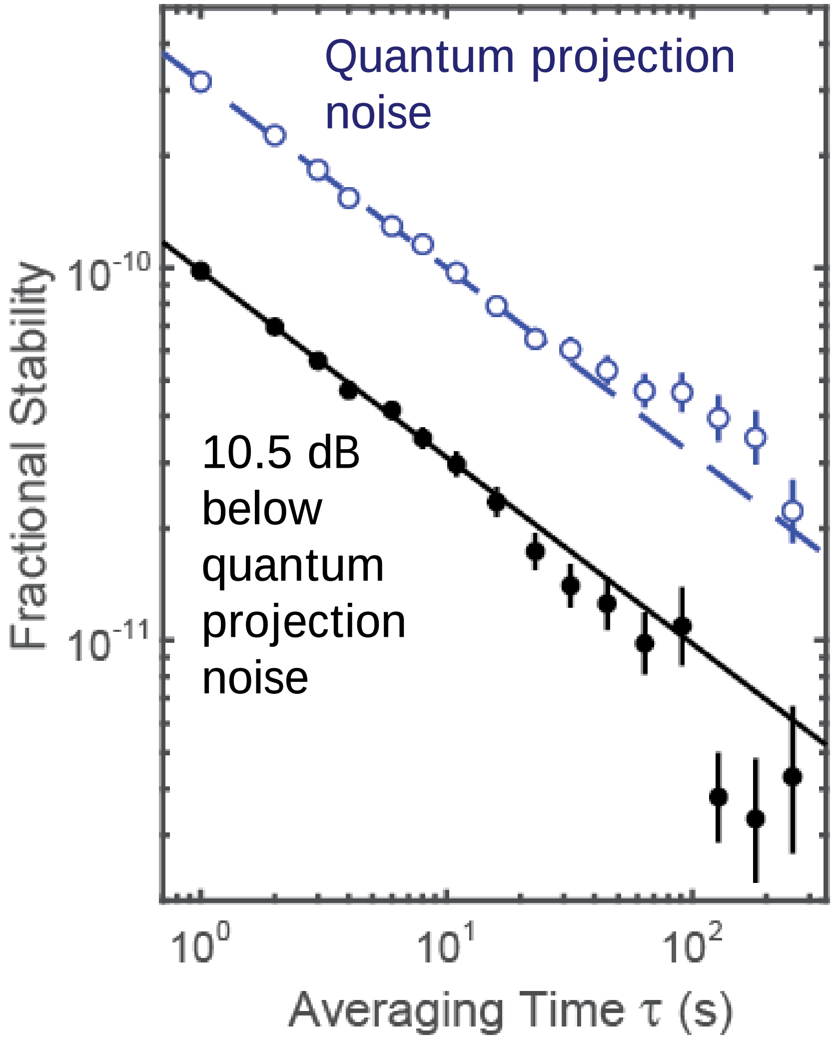
56 σ violation of witness criterion

Atomic clock implementation

1×10^5 atoms

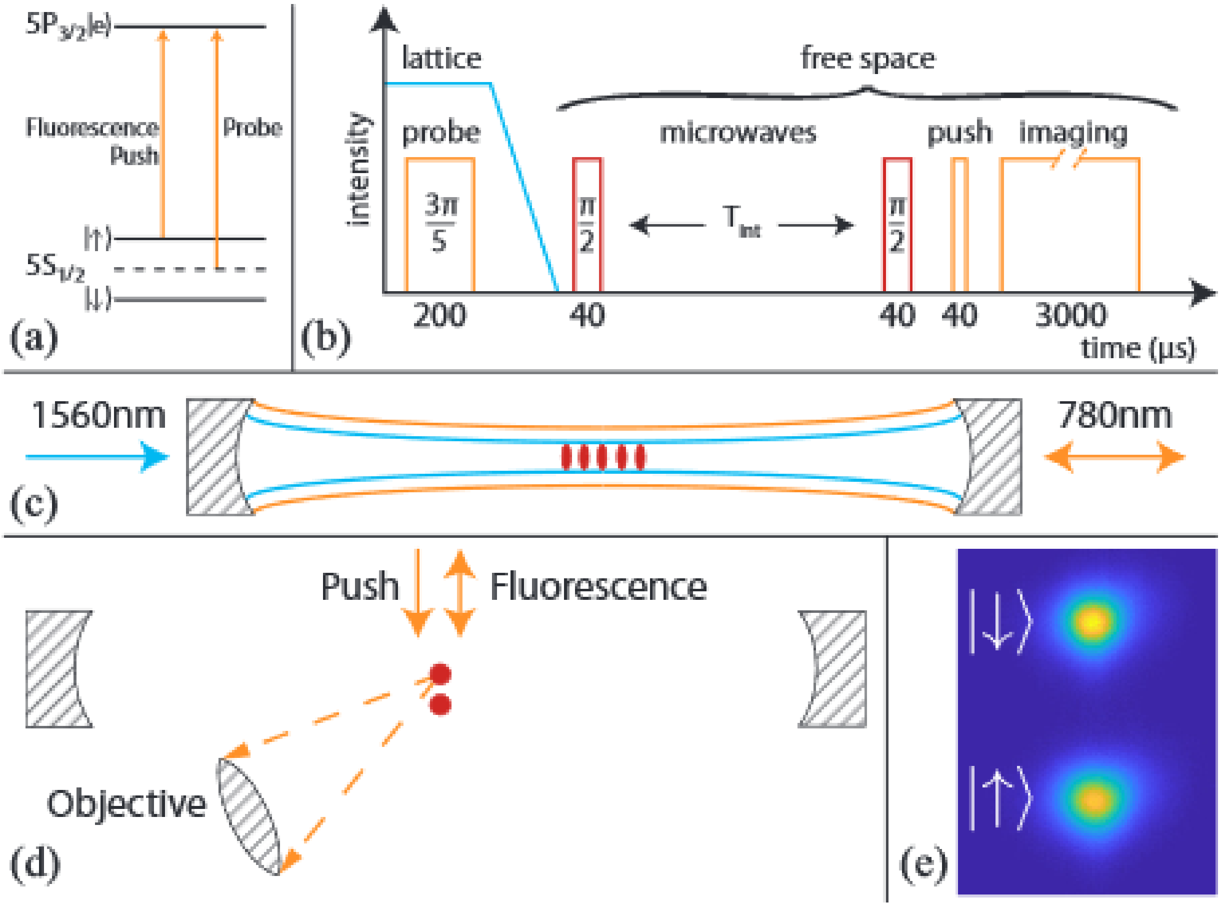
220μs interrogation time

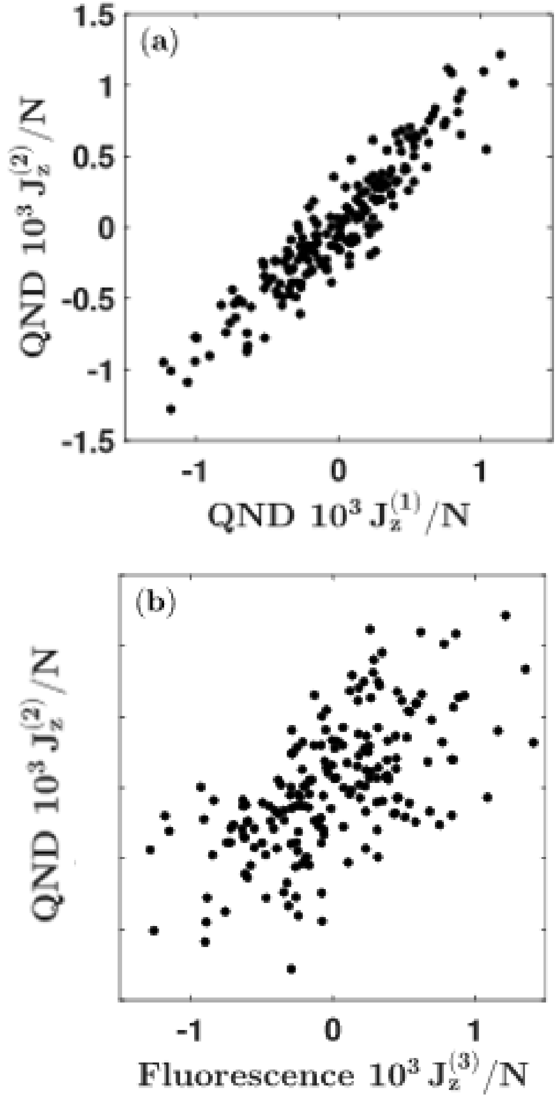
1 s update rate



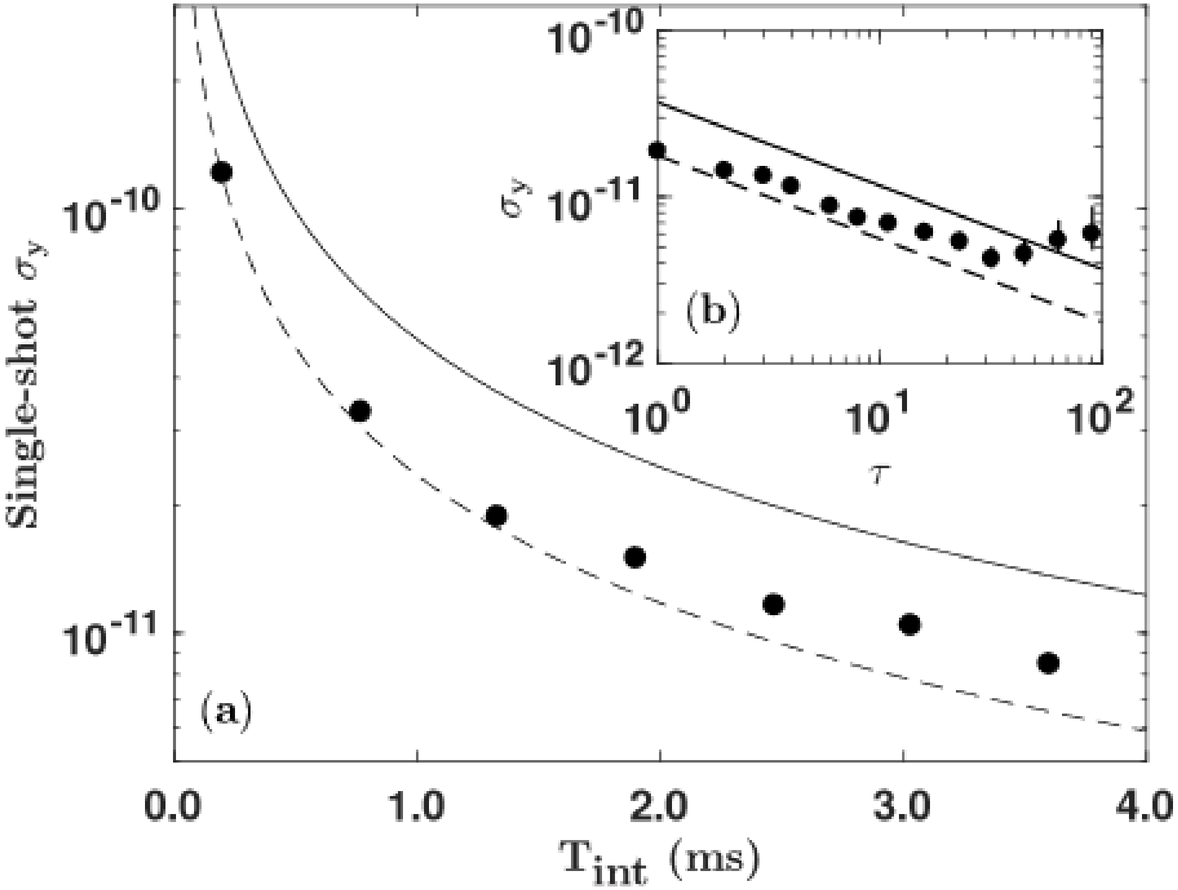
Limited by μ-wave LO phase noise. Nature (2016)

Fluorescence detection





Entangled state, free-space, clock



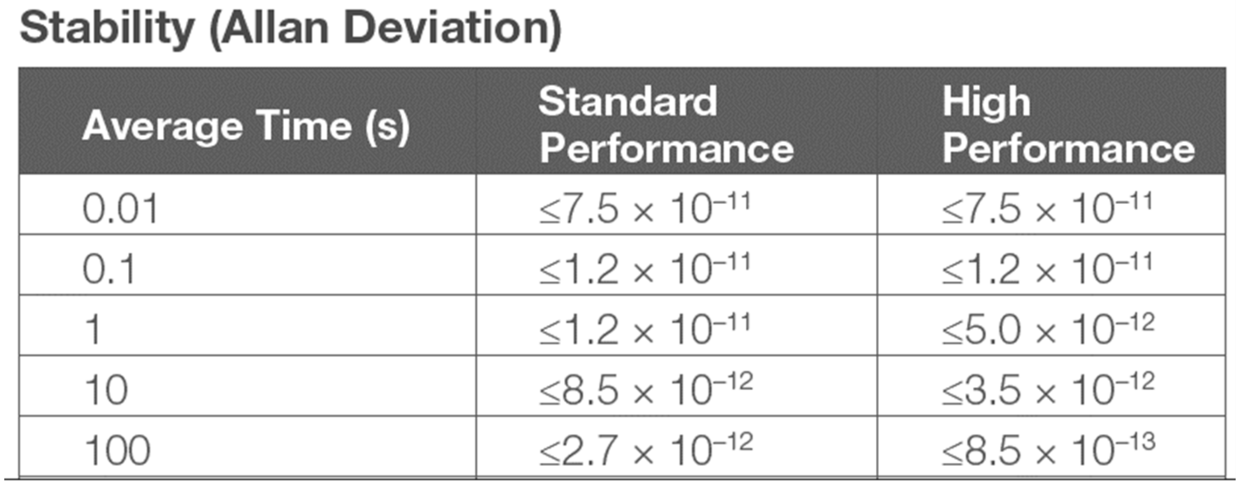
-6.4 dB below the classical (projection) noise limit

Limited by technical noise in read-out CCD

Many atom entanglement persists over distances of mm and time scales of msec ….

Comparison with Microsemi 5071A

Spin-squeezed clocks are now comparable to Microsemi 5071A High Performance spec.



Stability (Allan Deviation)

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

Future

Massively entangled states interfering over meter scales

Applications to precision gravitational physics and geodesy

Thanks

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