Precision Atom Interferometry

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Young's double slit with atoms

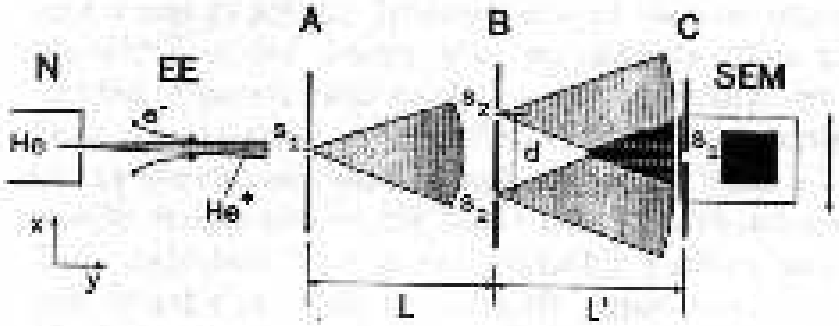


FIG. 2. Schematic representation of the experimental setup:

Young's 2 slit with Helium atoms

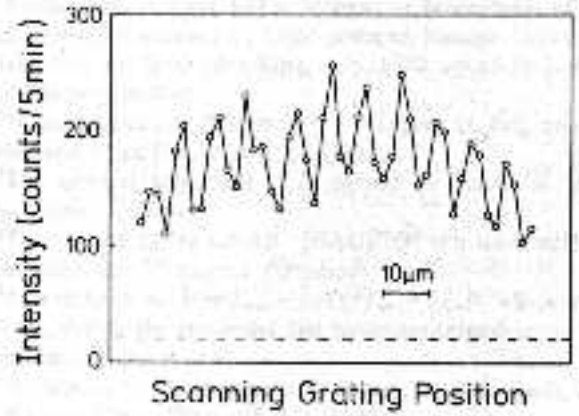
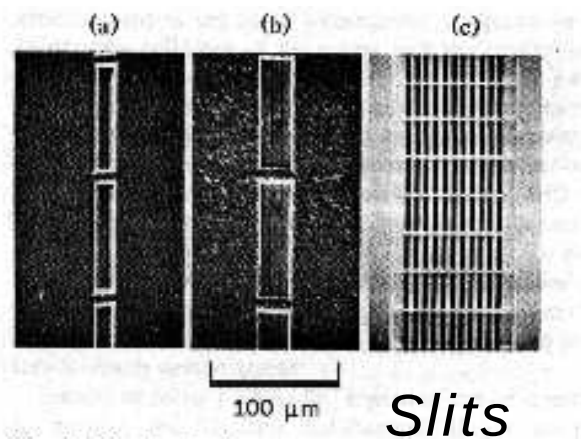


FIG. 5. Atomic density profile, monitored with the 8-μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

Interference fringes



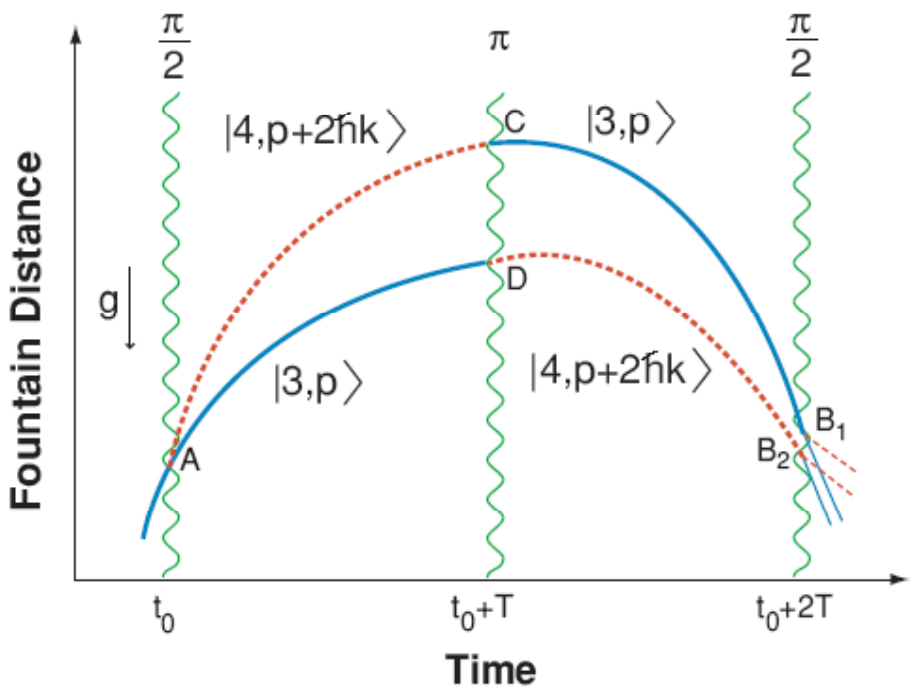
Slits

One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)

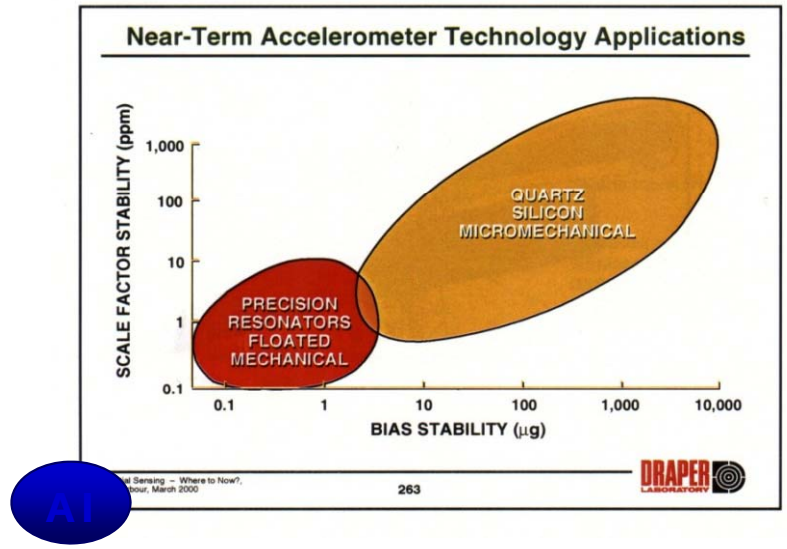
Atom interferometric inertial sensors

Performance of current generation atom interferometric sensors

Pulses of light are used to coherently manipulated the center-of-mass motion of atomic wavepackets



Accelerometer



Gyroscope

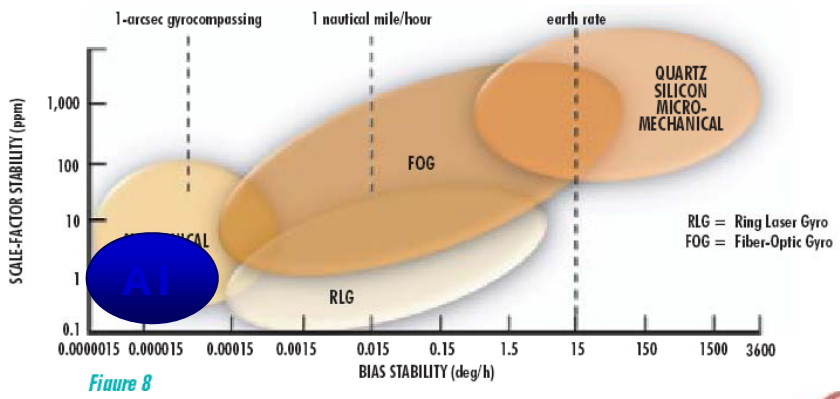
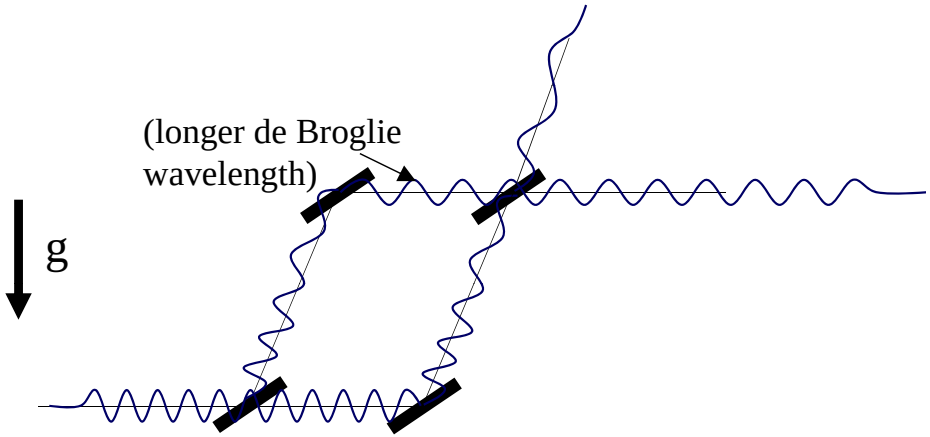


Figure 8

Simple models for inertial force sensitivity

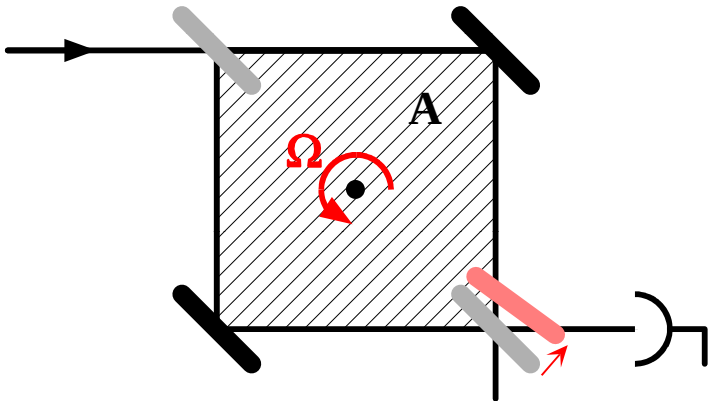
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases

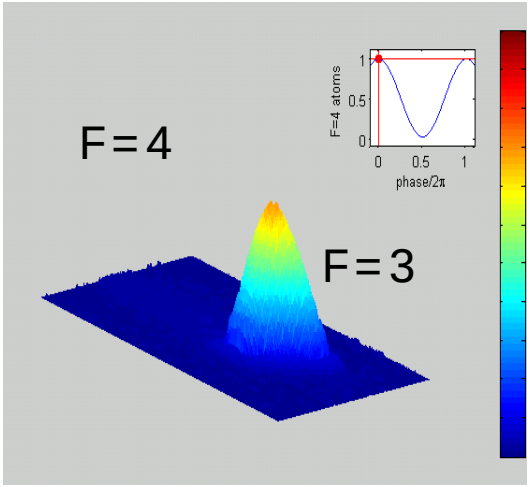


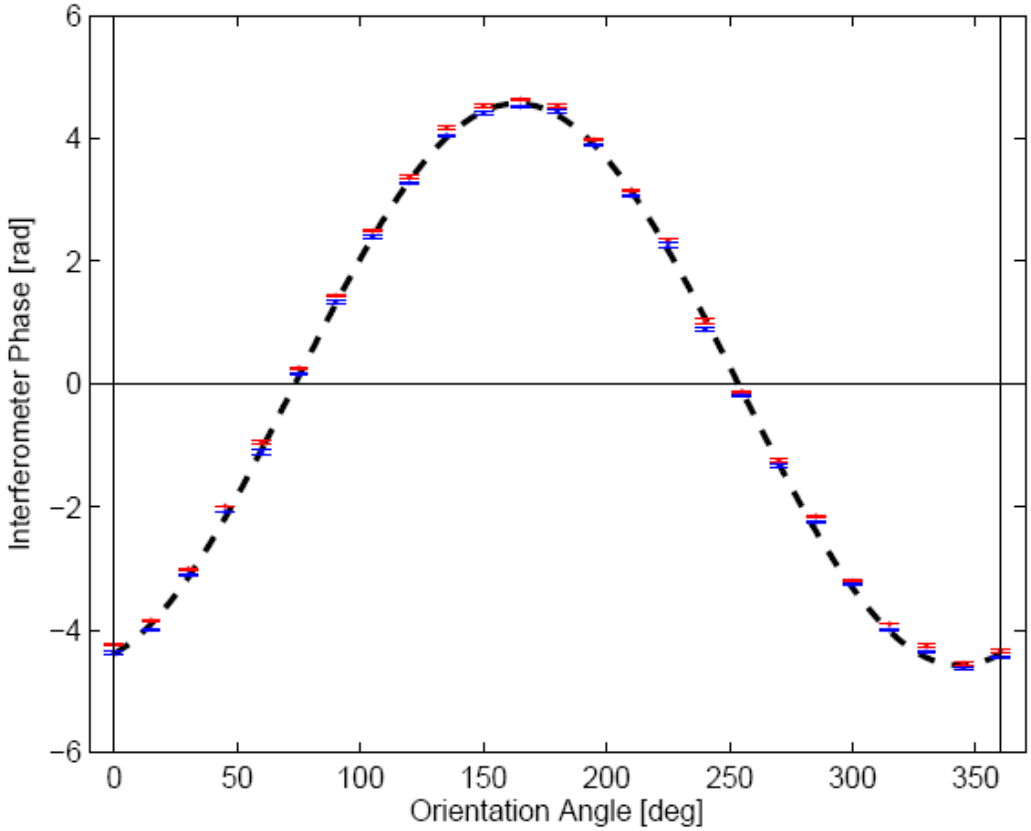
Rotations

Sagnac effect for de Broglie waves



Gyroscope, Measurement of Earth rotation rate



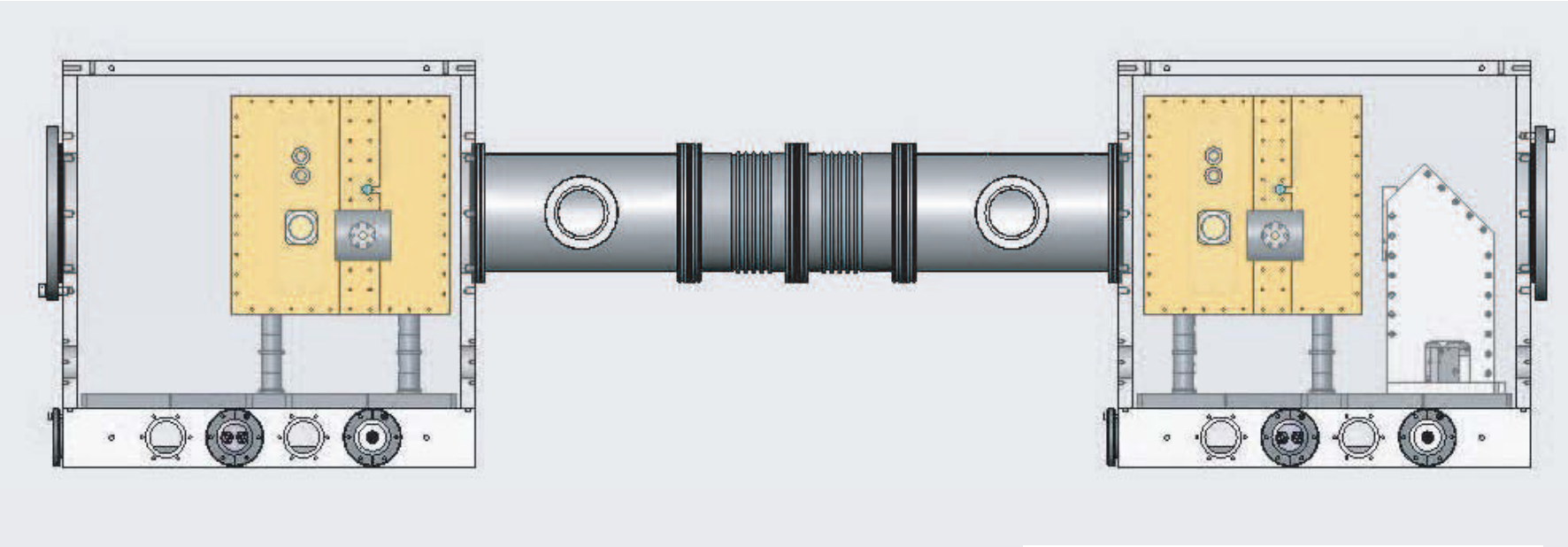


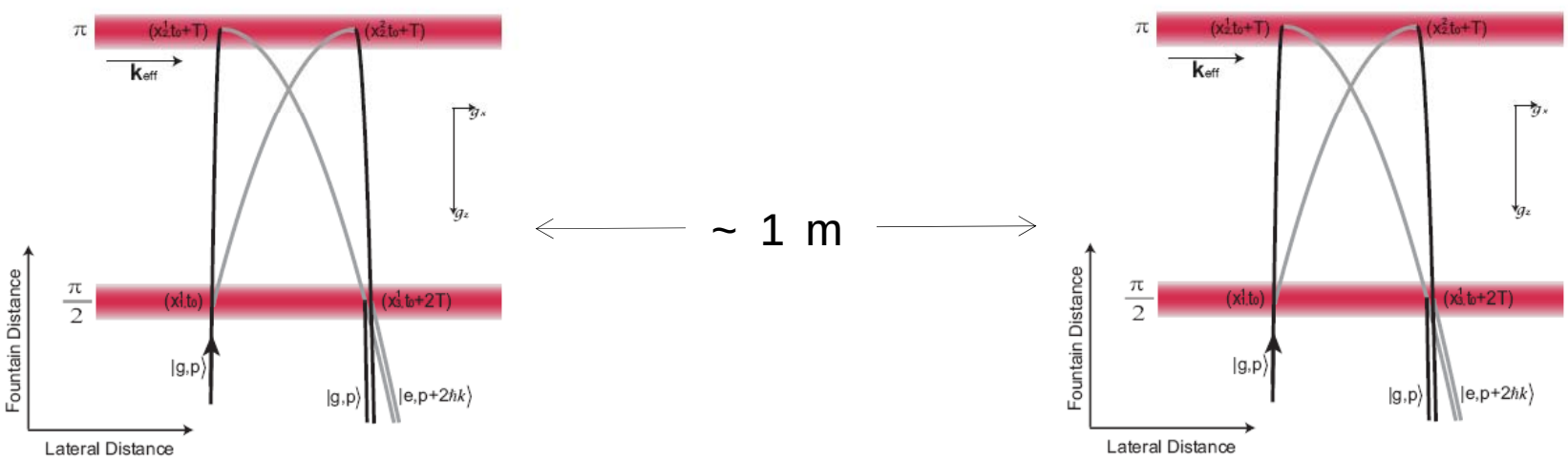
Gyroscope output vs.orientation.

200 μdeg/hr$^{1/2}$

Stockton, PRL (2011)

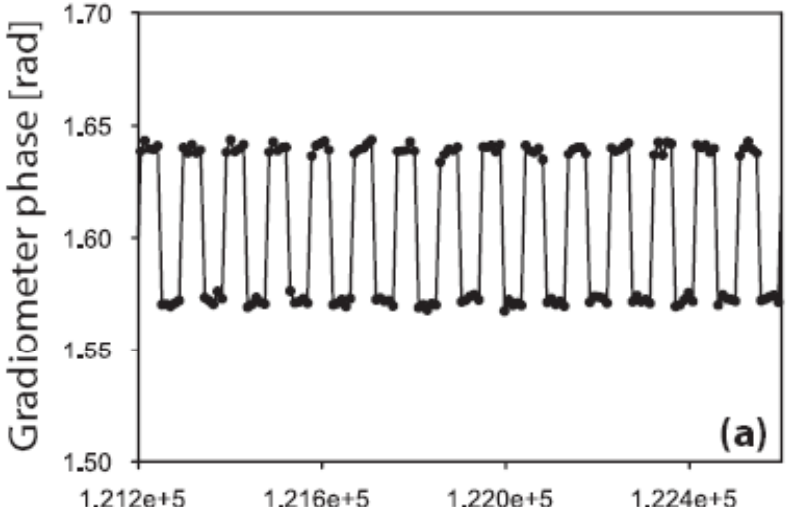
Differential accelerometer

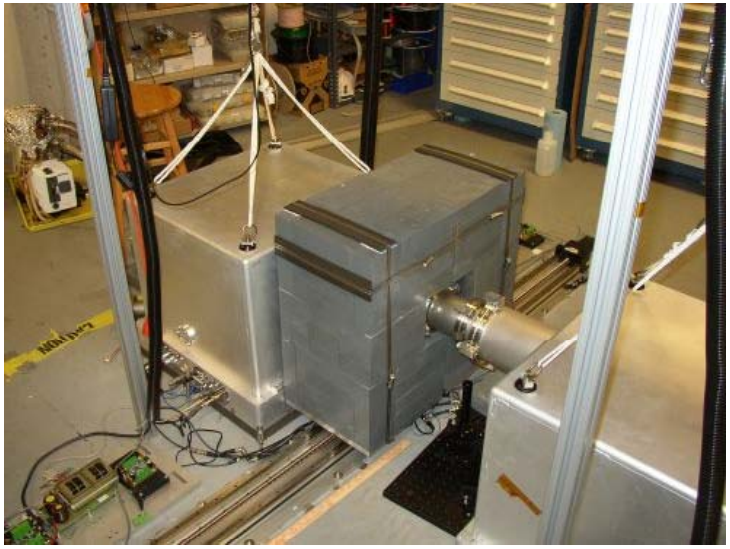


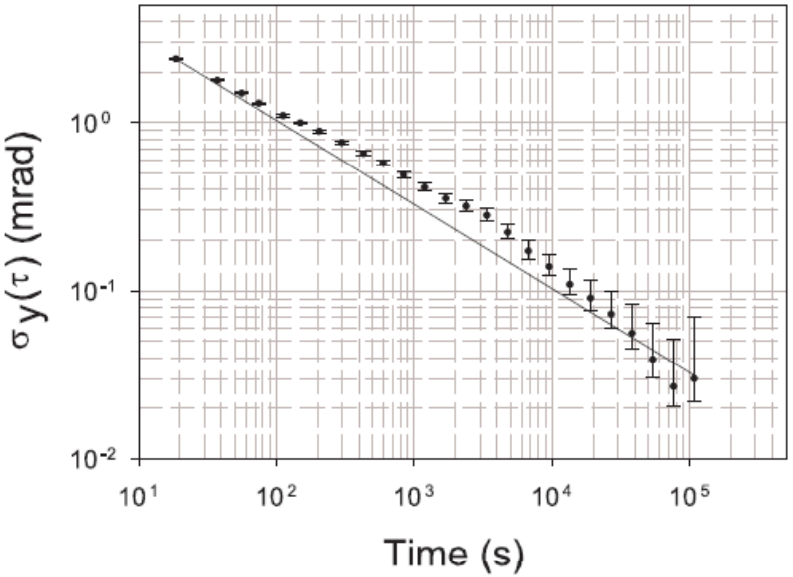


Applications in precision navigation and geodesy

Gravity gradiometer







Biederman, PhD thesis, 2009

Demonstrated accelerometer resolution: ~10^{-11} g.

AOSense AI gravimeter

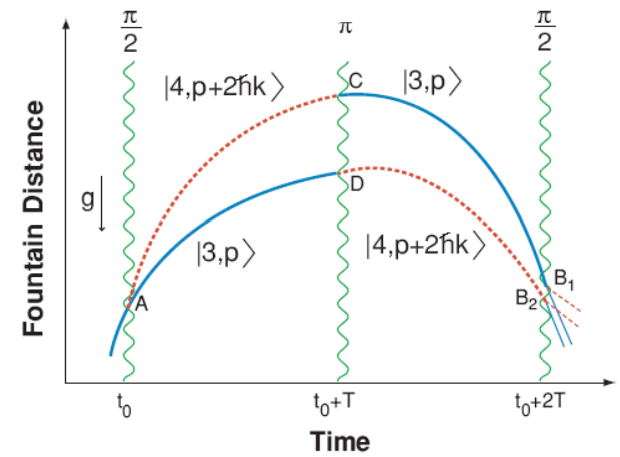
AOSense commercial AI gravimeter (12/2010)

Physical sensitivity limits (10 m apparatus)

Quantum limited accelerometer resolution: ~ 7×10^{-20} g

Assumptions:

1) Wavepackets (Rb) separated by z = 10 m, for T = 1 sec. For 1 g acceleration: $\Delta\phi \sim mgzT/\hbar \sim 1.3\times10^{11}$ rad
2) Signal-to-noise for read-out: SNR ~ 10^5:1 per second.
3) Resolution to changes in g per shot: $\delta g \sim 1/(\Delta\phi\ SNR) \sim 7\times10^{-17}$ g
4) 10^6 seconds data collection



We will exploit this sensitivity for:

Gravity wave detection, tests of General Relativity, new atom charge neutrality tests, tests of QED (photon recoil measurements), searches for anomalous forces…

Equivalence Principle

Co-falling ^{85}Rb and ^{87}Rb ensembles

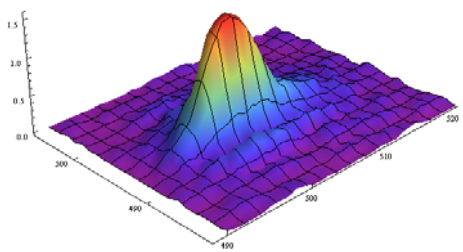
Evaporatively cool to < 1 μK to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

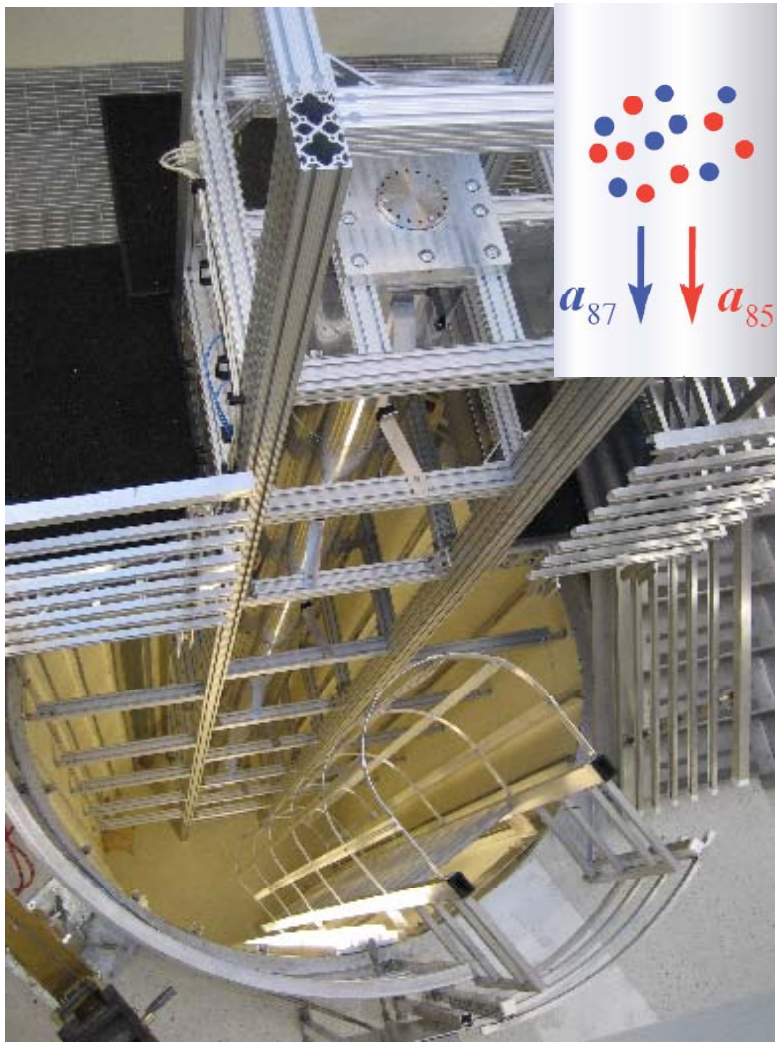
$\delta g \sim 10^{-15}$ g with 1 month data collection

Systematic uncertainty

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



Evaporatively cooled atom source



10 m drop tower

Tests of General Relativity

Schwazchild metric, PPN expansion:

$$ds^2 = (1 + 2\phi + 2\beta\phi^2)dt^2 - (1 - 2\gamma\phi)dr^2 - r^2 d\Omega^2$$

$$\frac{d\vec{v}}{dt} = -\vec{\nabla}[\phi + (\beta + \gamma)\phi^2] + \gamma[3(\vec{v} \cdot \hat{r})^2 - 2\vec{v}^2]\vec{\nabla}\phi + 2\vec{v}(\vec{v} \cdot \vec{\nabla}\phi).$$

Corresponding AI phase shifts:

	Phase Shift	Size (rad)	Interpretation
1.	$-k_{\text{eff}} g T^2$	3×10^8	gravity
2.	$-k_{\text{eff}}(\partial_r g) T^3 v_L$	-2×10^3	1st gradient
3.	$-3k_{\text{eff}} g T^2 v_L$	4×10^1	Doppler shift
4.	$(2 - 2\beta - \gamma) k_{\text{eff}} g \phi T^2$	2×10^{-1}	GR
5.	$-\frac{7}{12} k_{\text{eff}}(\partial_r^2 g) T^4 v_L^2$	8×10^{-3}	2nd gradient
6.	$-5k_{\text{eff}} g T^2 v_L^2$	3×10^{-6}	GR
7.	$(2 - 2\beta - \gamma) k_{\text{eff}} \partial_r (g\phi) T^3 v_L$	2×10^{-6}	GR 1st grad
8.	$-12 k_{\text{eff}} g^2 T^3 v_L$	-6×10^{-7}	GR

Projected experimental limits:

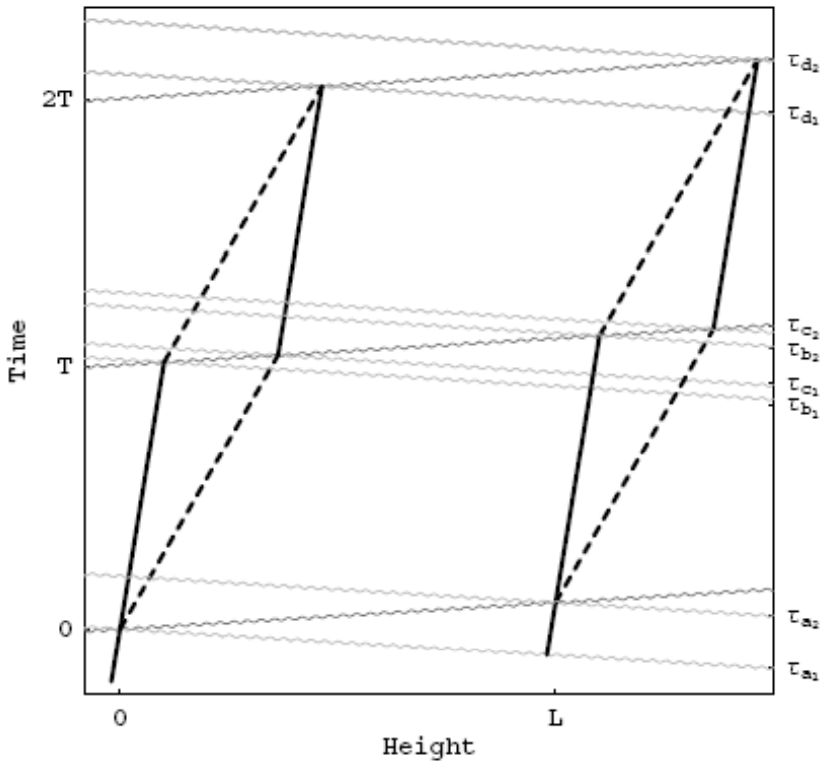
Tested Effect	current limit	AI initial	AI upgrade	AI future	AI far future
PoE	3×10^{-13}	10^{-15}	10^{-16}	10^{-17}	10^{-19}
PPN (β, γ)	10^{-4}-10^{-5}	10^{-1}	10^{-2}	10^{-4}	10^{-6}

Steady path of apparatus improvements include:

- Improved atom optics
- Longer baseline
- Sub-shot noise interference read-out

(Dimopoulos, *et al.*, PRL 2007; PRD 2008)

Gravity waves

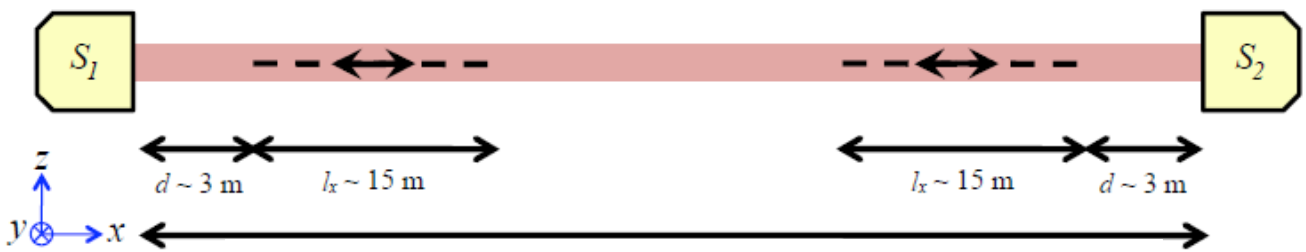


Atoms provide inertially decoupled references

Gravity wave phase shift through propagation of optical fields

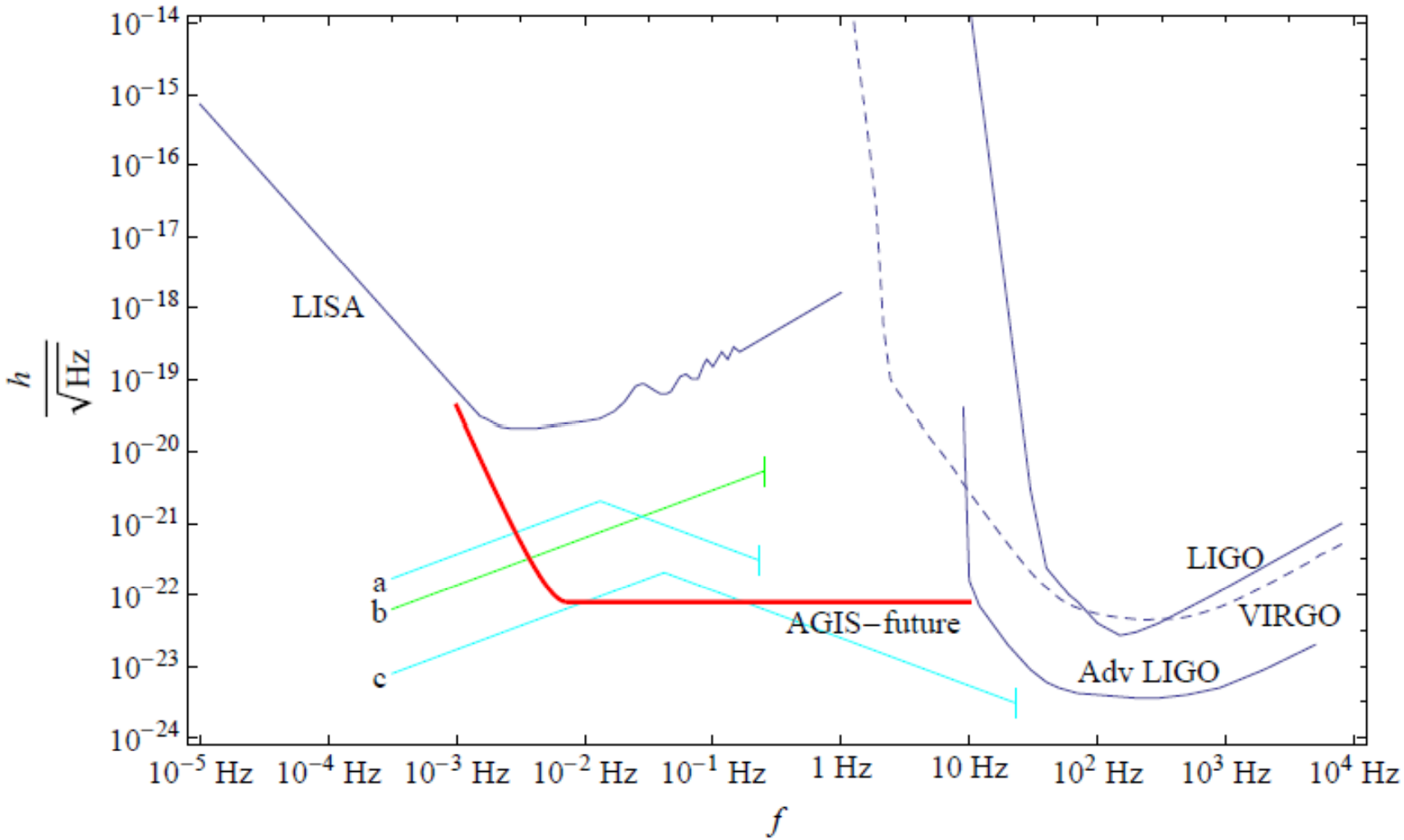
Evades quantum measurement noise (photon scattering regularized by non-linear atom/photon interaction; prepare fresh atom ensemble each shot)

Previous work: B. Lamine, et al., Eur. Phys. J. D **20**, (2002); R. Chiao, et al., J. Mod. Opt. **51**, (2004); S. Foffa, et al., Phys. Rev. D **73**, (2006); A. Roura, et al., Phys. Rev. D **73**, (2006); P. Delva, Phys. Lett. A **357** (2006); G. Tino, et al., Class. Quant. Grav. **24** (2007).



Possible satellite configuration

Possible sensitivity



200 photon recoil beamsplitters, 10^4 km baseline

J. M. Hogan, Gen. Rel. and Grav. (2011); PRD (2011).

Future questions

Can sensitivity be improved with new classes of atom optics?

- Large momentum transfer atom optics

Can precision atom interferometric methods be extended to massive particles?

- sensitivity scales with particle mass

Can quantum metrology approaches be used to improve interferometer sensitivity?

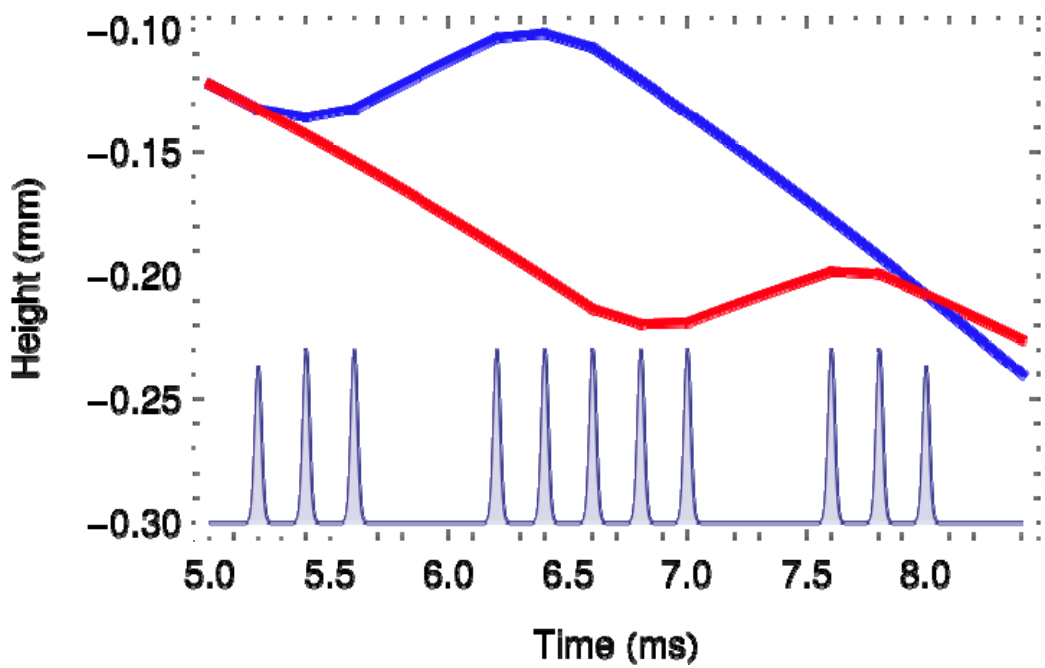
- sub-shot-noise interferometry
- 10x – 100x sensitivity improvement

Large Momentum Transfer (LMT) Atom Optics

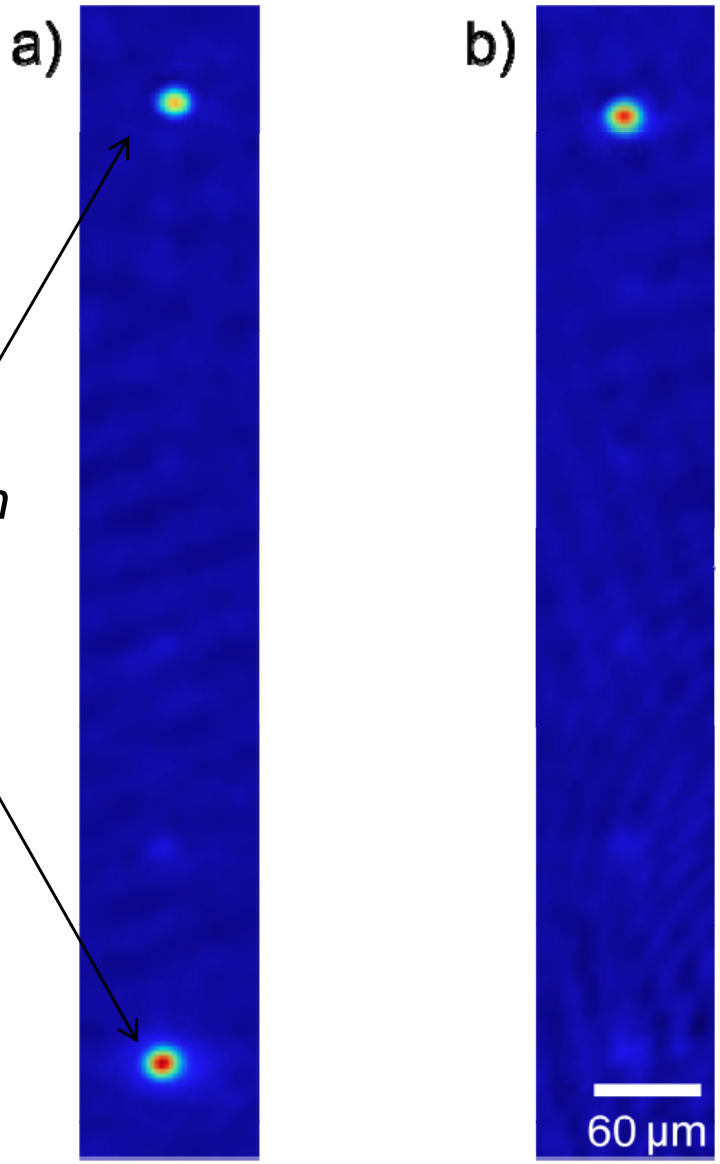
Atom interferometer sensitivity proportional to momentum splitting between arms. Current state-of-the-art functions with **2 photon recoil momenta** (stimulated Raman transitions)

Recently: **102 photon recoils**, based on sequential multi-photon Bragg pulses for rapid, highly efficient momentum transfer.

Sample interferometer pulse sequence:



Sequential Bragg pulse atom optics



Wavepackets in coherent superposition state

Beamsplitter *Mirror*

30 photon recoil momenta (20 cm/s) beam splitter and mirror pulses.

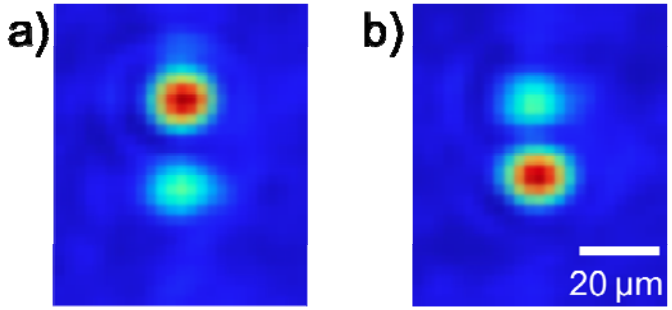
Comprised of 5 sequential 6 photon recoil Bragg pulses

Wavepacket separation of ~1 mm

High Contrast LMT Atom Interferometers

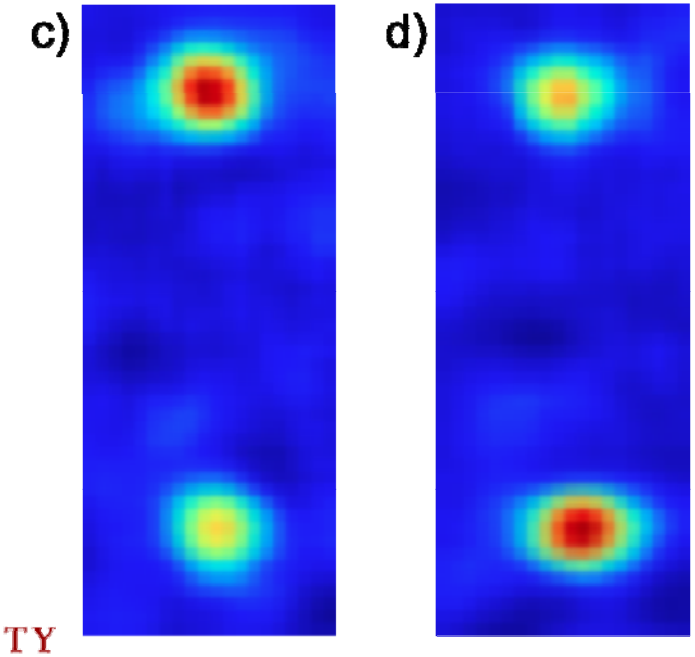
We achieve high contrast atom interferometers with momentum splittings of up to $102\hbar k$, corresponding velocity separations of ~1 meter/second

30 recoil momenta fringes



70% contrast

102 recoil momenta fringes



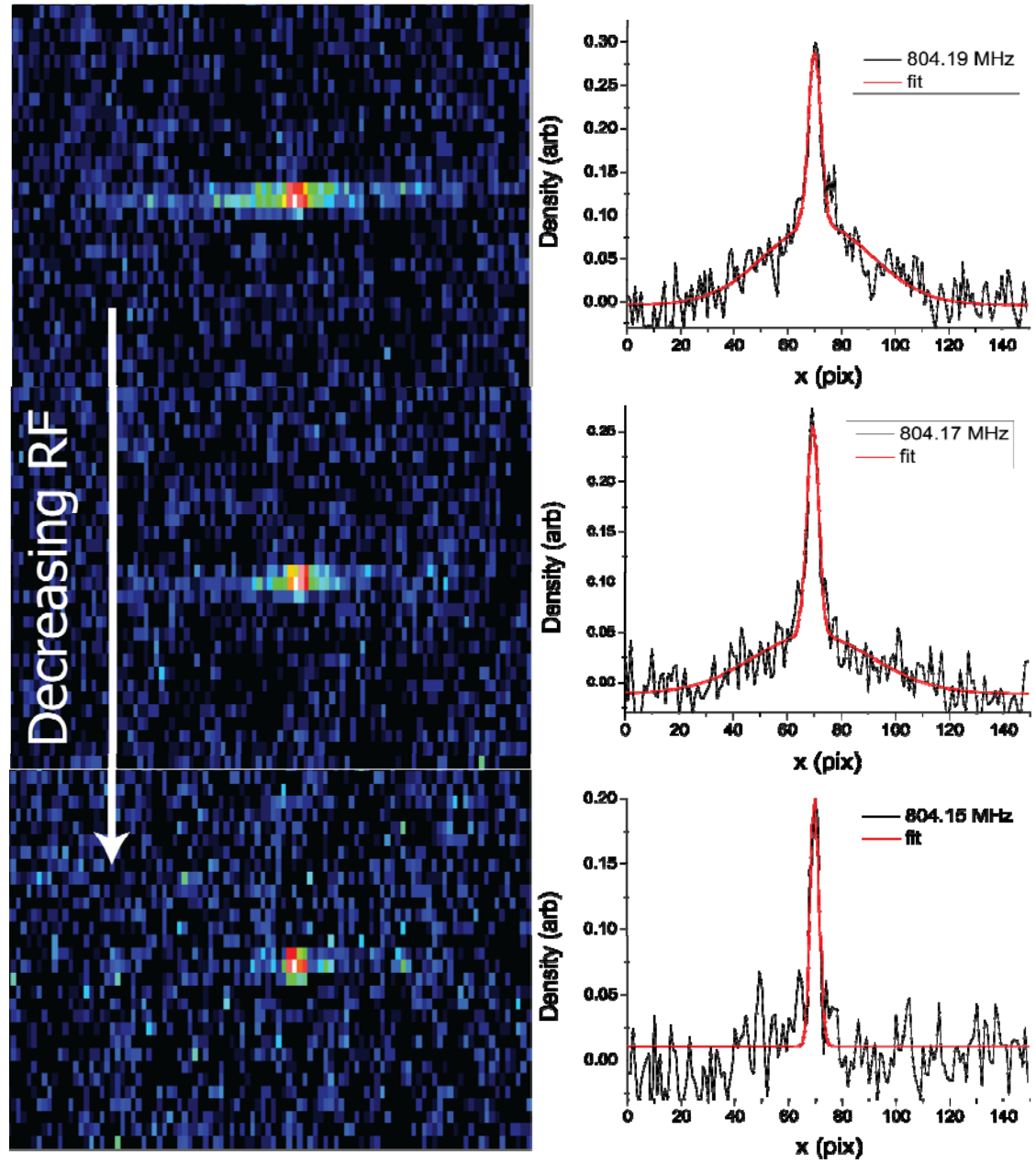
18% contrast

Chiow, PRL (2011)

Massive particle interferometry with atomic solitons

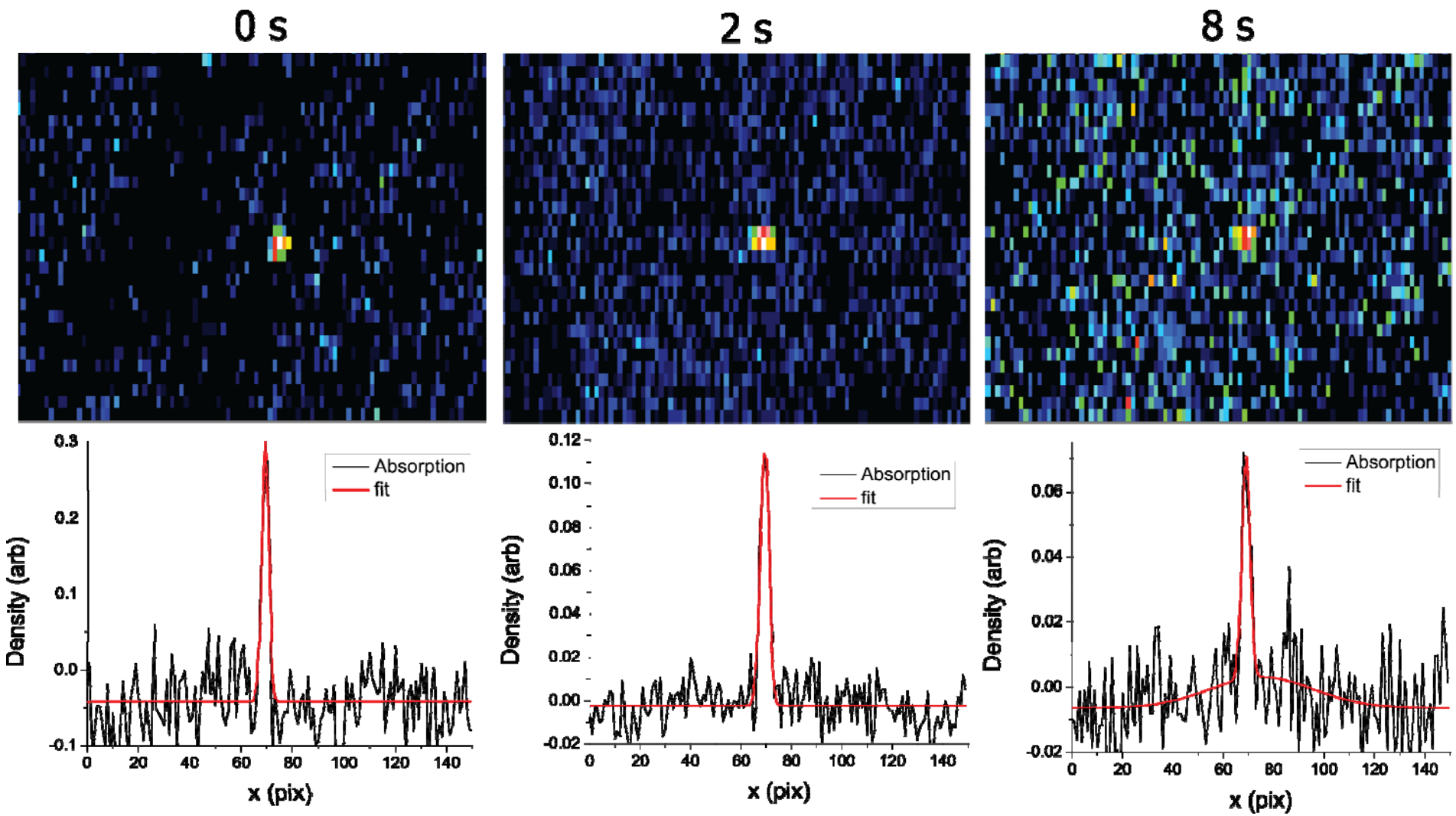
~100 atom solitons produced by forced evaporation of (attractively interacting) ^{7}Li

Under appropriate conditions solitons behave as single particles. In principle, 100x improved sensitivity for interferometers…

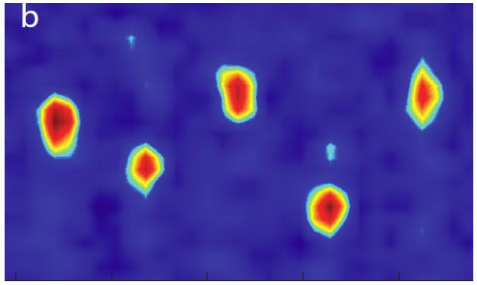


Soliton lifetime

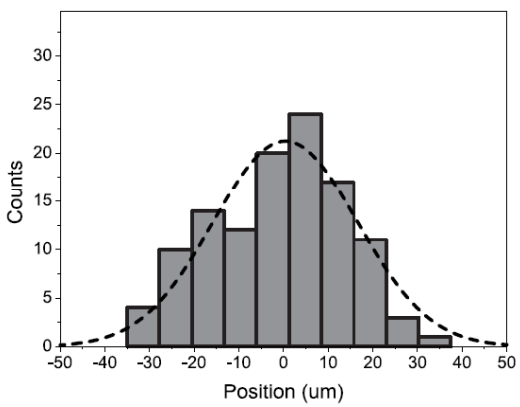
Soliton lifetime ~ 10 s. Enables precise force sensing applications.



Soliton center-of-mass wavefunction dynamics

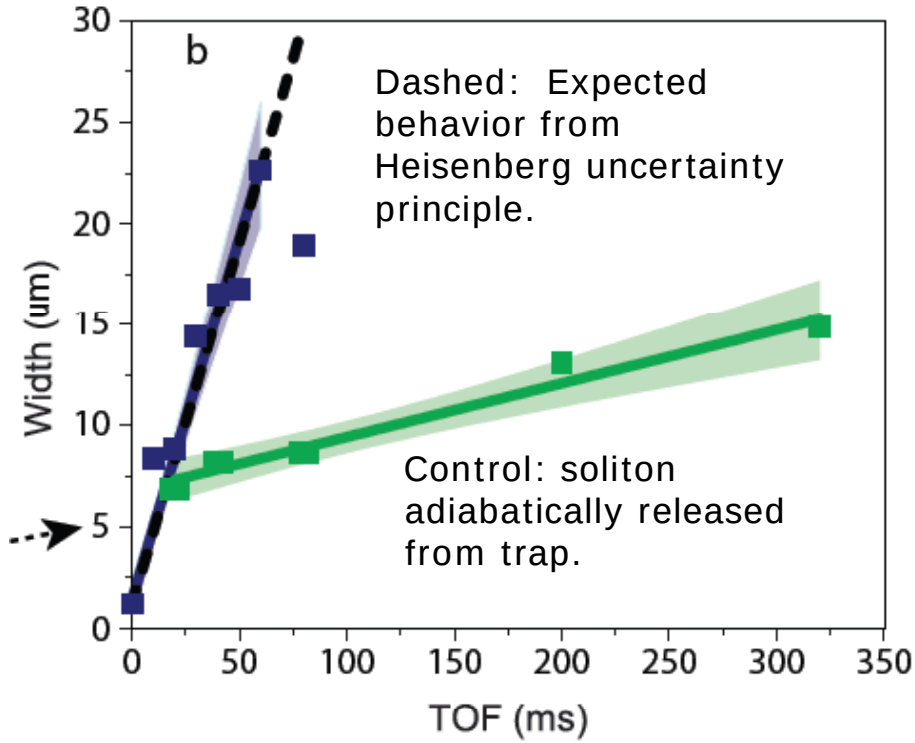


Sequence of images of ~100 atom solitons suddenly released from a tight optical trap.



Histogram of observed soliton positions at a 60 msec time of flight following release from the trap.

Center-mass-wavefunction spreading for single solitons released from tight traps.



.... Precursor to soliton interferometry experiments

Quantum Metrology: Sub-shot noise detection

Atom shot noise limits sensor performance.

Recently evolving ideas in quantum information science have provided a road-map to exploit exotic quantum states to significantly enhance sensor performance.

Sensor noise scales as 1/N where N is the number of particles

- "Heisenberg" limit
- Shot-noise ~ $1/N^{1/2}$ limits existing sensors

Challenges:

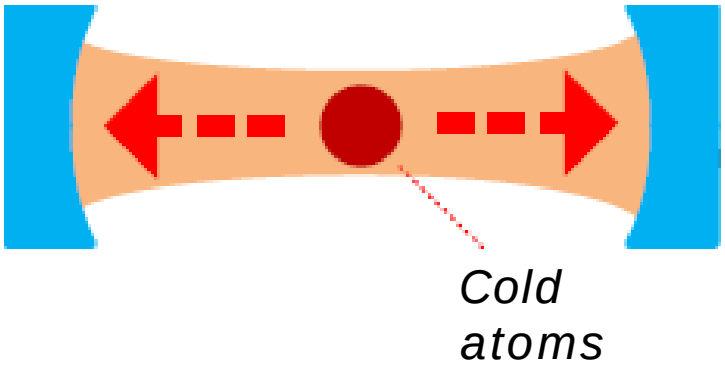
- Demonstrate basic methods in laboratory
- Begin to address engineering tasks for realistic sensors

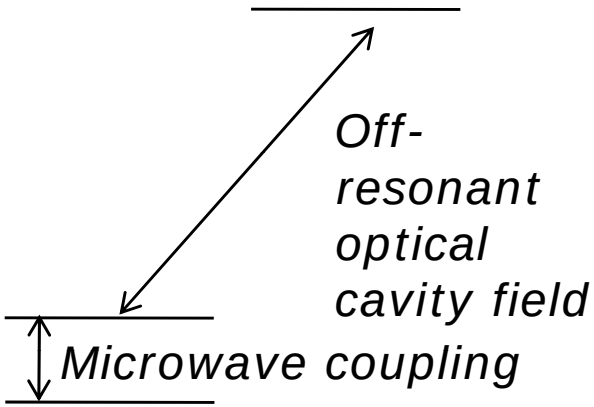
Impact of successful implementation for practical position/time sensors could be substantial. Possible 10x – 100x reduction in sensor noise.

Enables crucial trades for sensitivity, size and bandwidth.

3-level system in high finesse optical cavity

Implementation with atoms in high finesse optical cavity



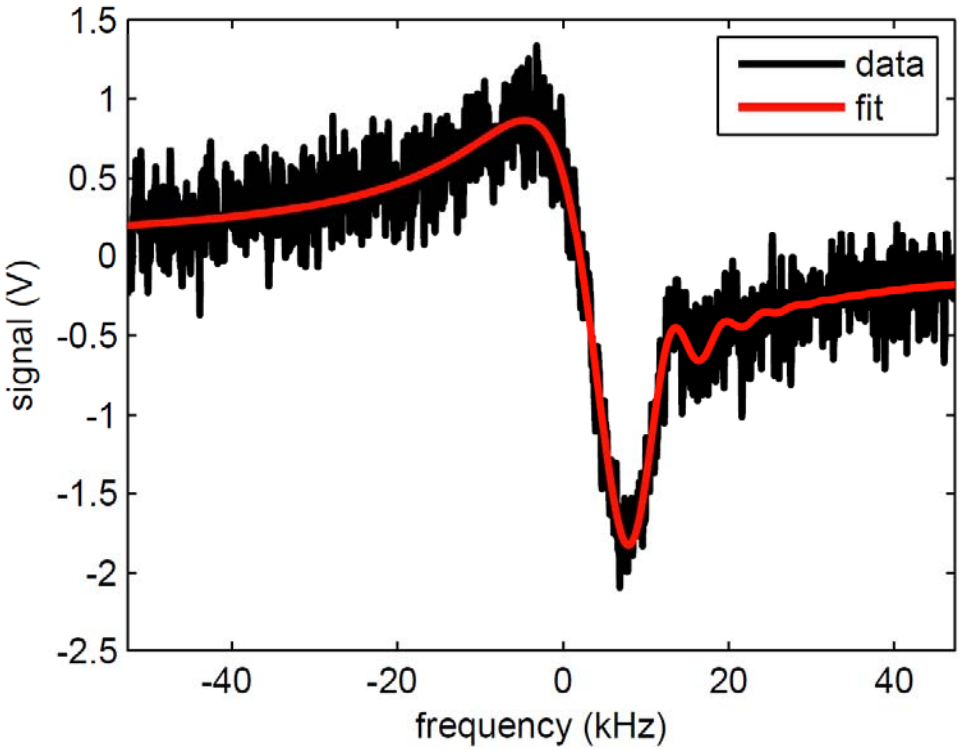


Atomic level scheme

Cavity resonance frequency is used as meter for number of atoms in cavity.

"Quantum non-demolition" measurement of atom number

This data: ~0.5 atom resolution



Acknowledgements

– Grant Biedermann, PhD, Physics
– Ken Takase, PhD, Physics
– Igor Teper, Post-doctoral fellow
– John Stockton, Post-doctoral fellow
– Louis Delsauliers, Post-doctoral fellow
– Xinan Wu, PhD, Applied physics
– Jongmin Lee, Graduate student, Applied physics
– Chetan Mahadeswaraswamy, PhD, Mechanical engineering
– David Johnson, PhD, Physics
– Geert Vrijsen, Graduate student, Applied physics
– Jason Hogan, Post-doctoral fellow, Physics
– Sean Roy, Graduate student, Physics
– Tim Kovachy, Graduate student, Physics
– Alex Sugarbaker, Graduate student, Physics
– Susannah Dickerson, Graduate student, Physics
– Onur Hosten, Post-doctoral fellow, Physics
– Simon Bernon, CNRS
– Mike Minar, Graduate student, Physics
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