A Gravitational Wave Detector Based on an Atom Interferometer

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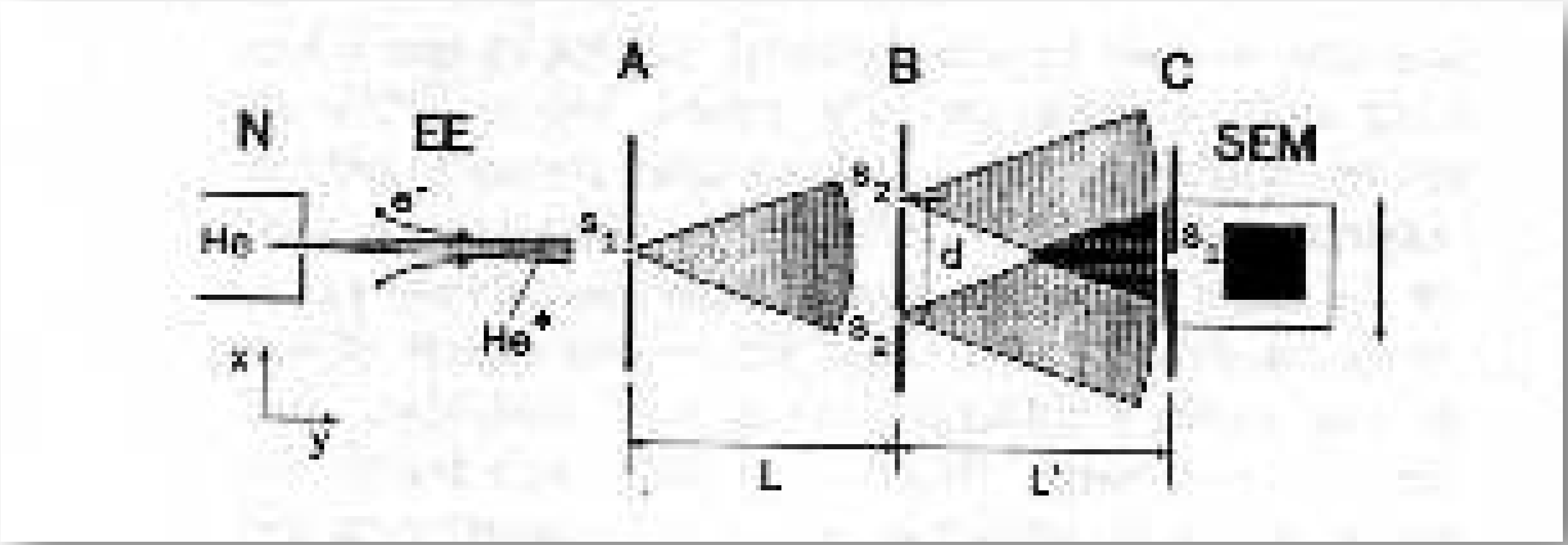
GSFC, NASA

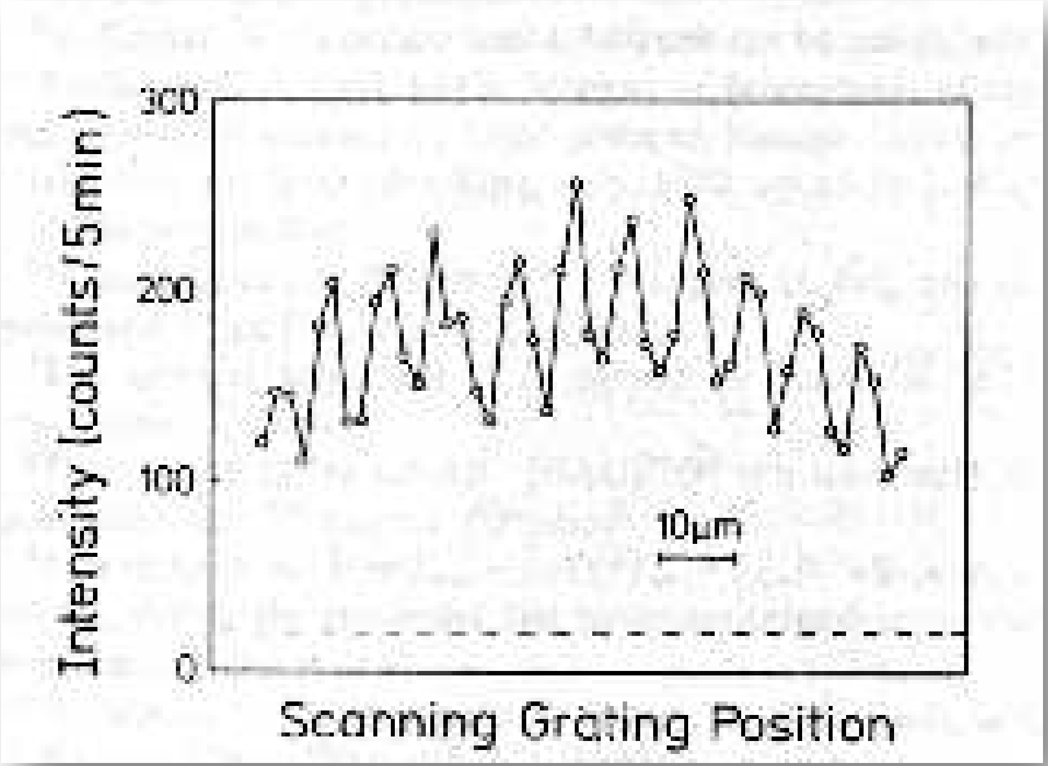
(background image, *Scientific American*, Oct. *2013*)

Young's double slit interferometer with atoms



Mlynek, PRL, 1991

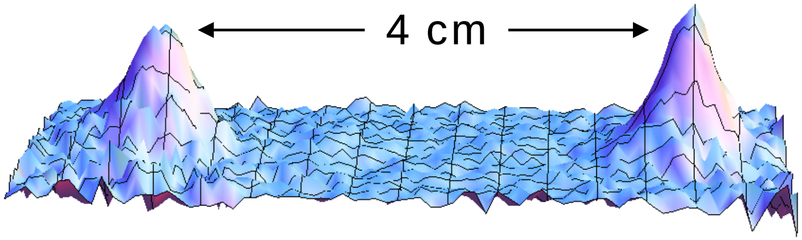
Young's double slit interference fringes



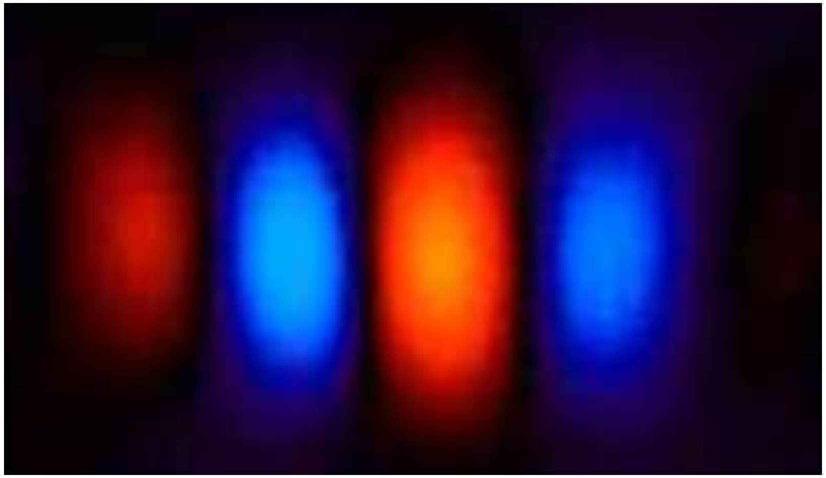
Mlynek, PRL, 1991

10 m Atom Interferometer (2013)

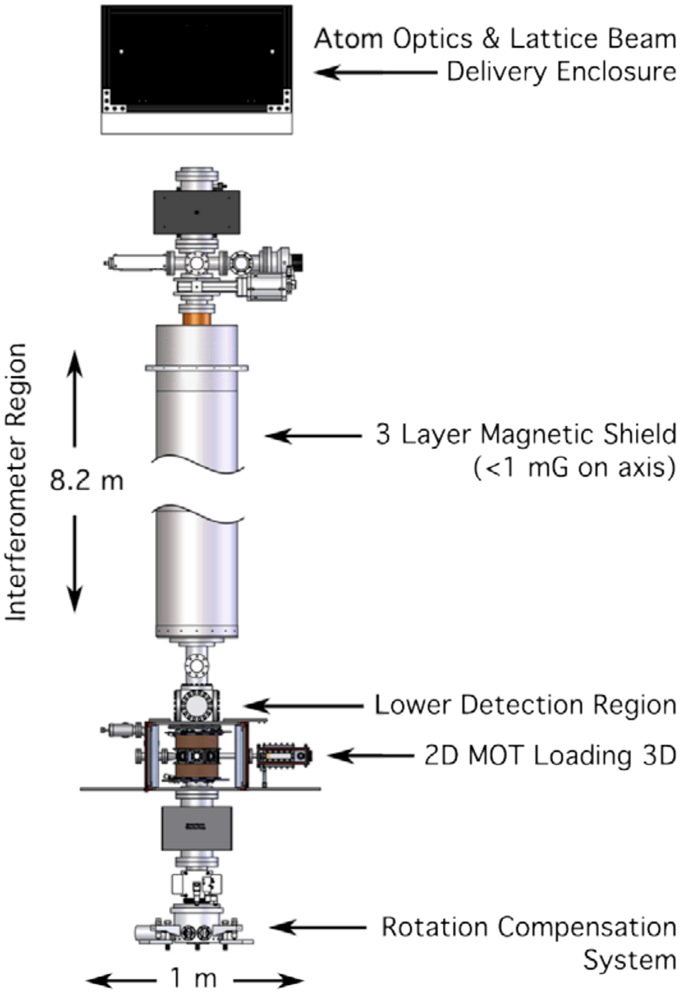
Wavepackets at apex

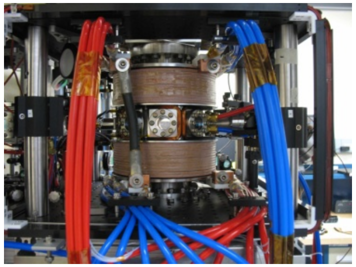


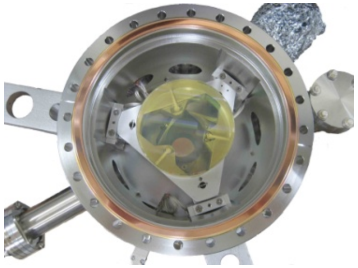
Interference at exit port



Apparatus







Ultracold atom source

- $>10^6$ atoms at 50 nK
- 3e5 at 3 nK

Optical Lattice Launch

- 13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry

- 2 cm $1/e^2$ radial waist
- 500 mW total power
- Dynamic nrad control of laser angle with precision piezo-actuated stage

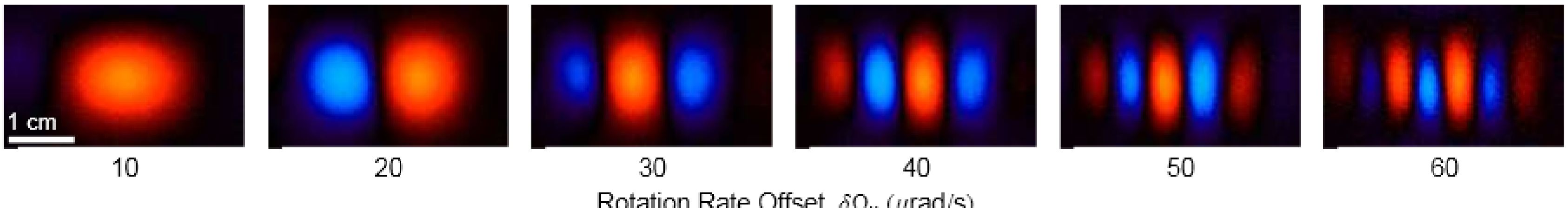
Detection

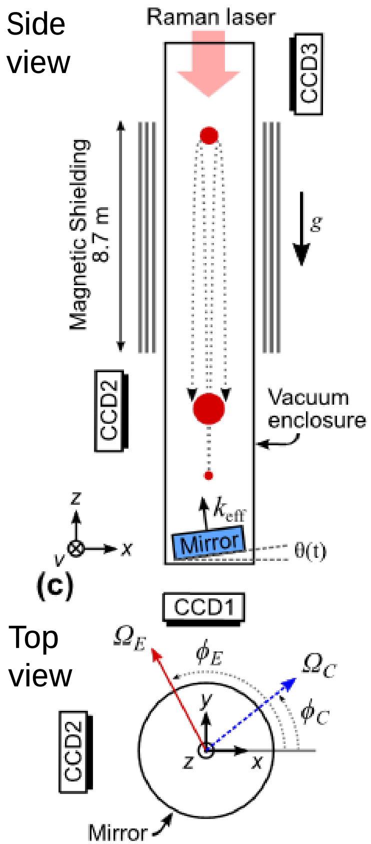
- Spatially-resolved fluorescence imaging
- Two CCD cameras on perpendicular lines of sight

Current demonstrated statistical resolution, ~5e-13 g in 1 hr (87Rb)

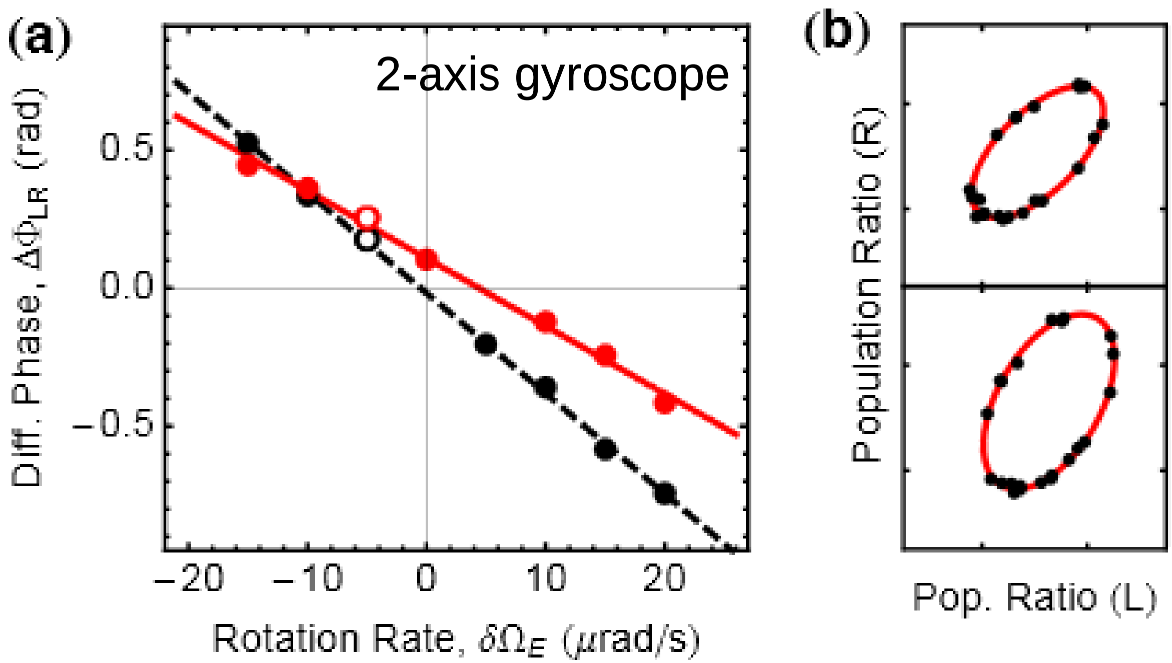
Multi-axis inertial (2 gyro., 1 accel.) operation

Interference patterns for rotating platform:





Measurement Geometry



Measurement of rotation rate near null rotation operating point.

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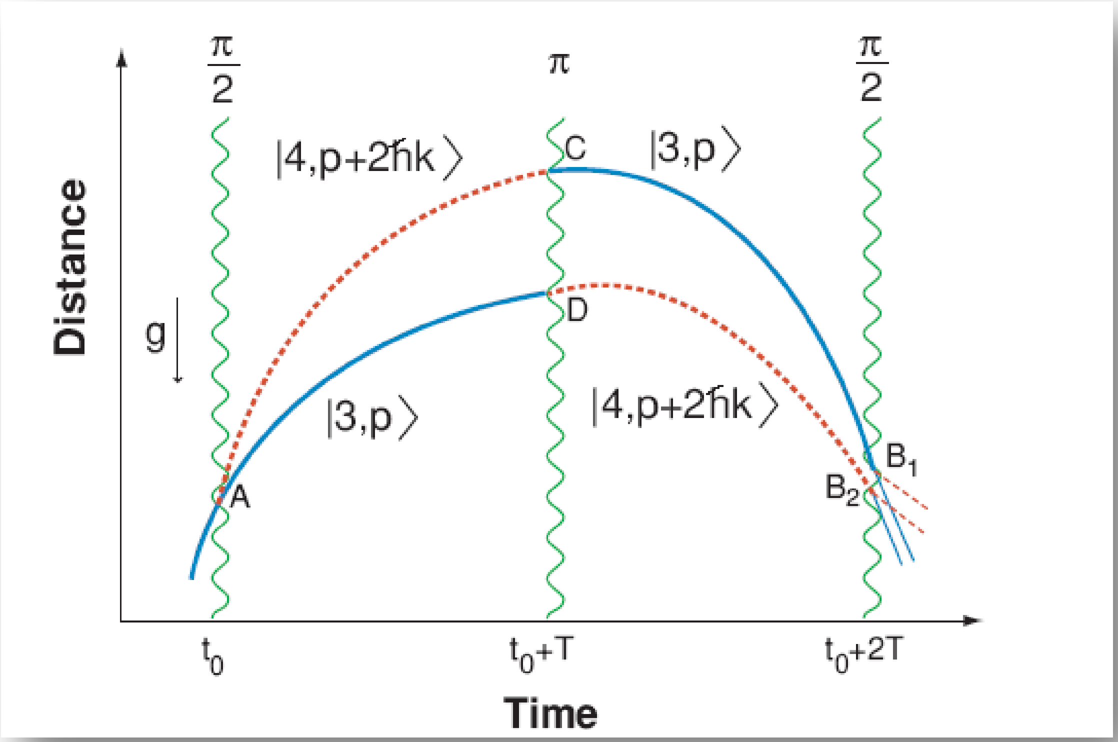
Dickerson, et al., arXiv:1305.1700, PRL (2013)

Light-pulse atom interferometry

Pulses of light are used to coherently manipulate atom de Broglie waves:

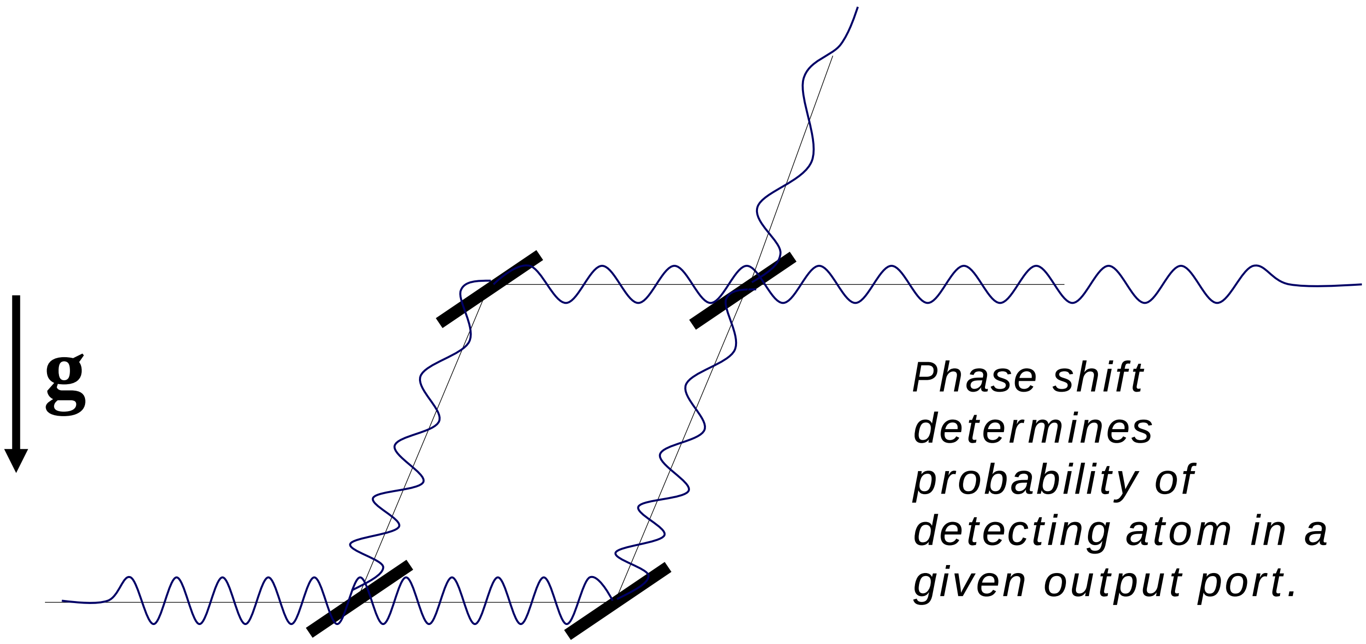


Phase shift read-out by counting atoms at each output port.

Kasevich and Chu, PRL, 1991

Simple model for acceleration sensitivity

As atom climbs gravitational potential, velocity decreases and de Broglie wavelength increases ….



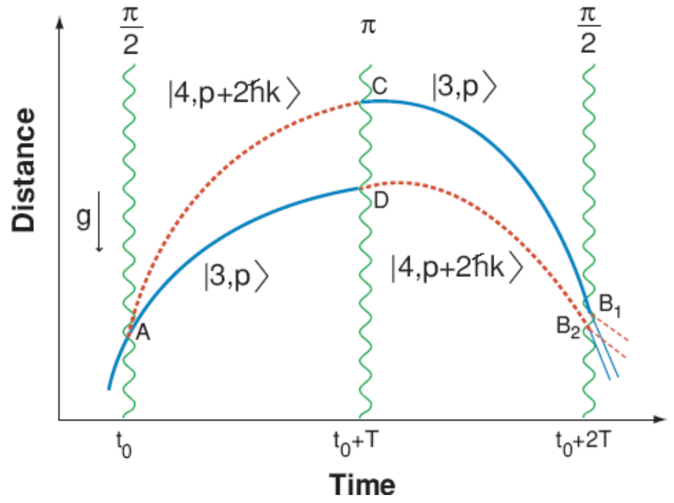
Phase shift determines probability of detecting atom in a given output port.

Physical sensitivity limits (10 m apparatus)

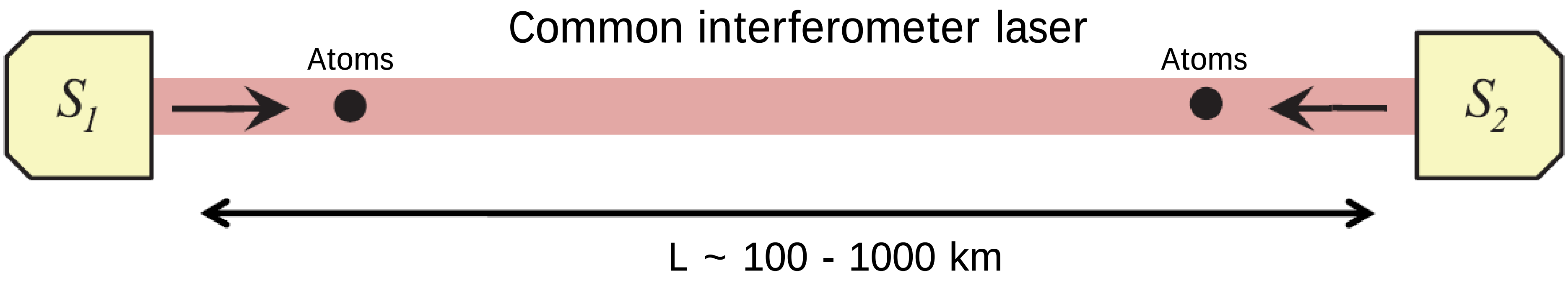
Quantum limited accelerometer resolution: ~ 7×10^{-20} g

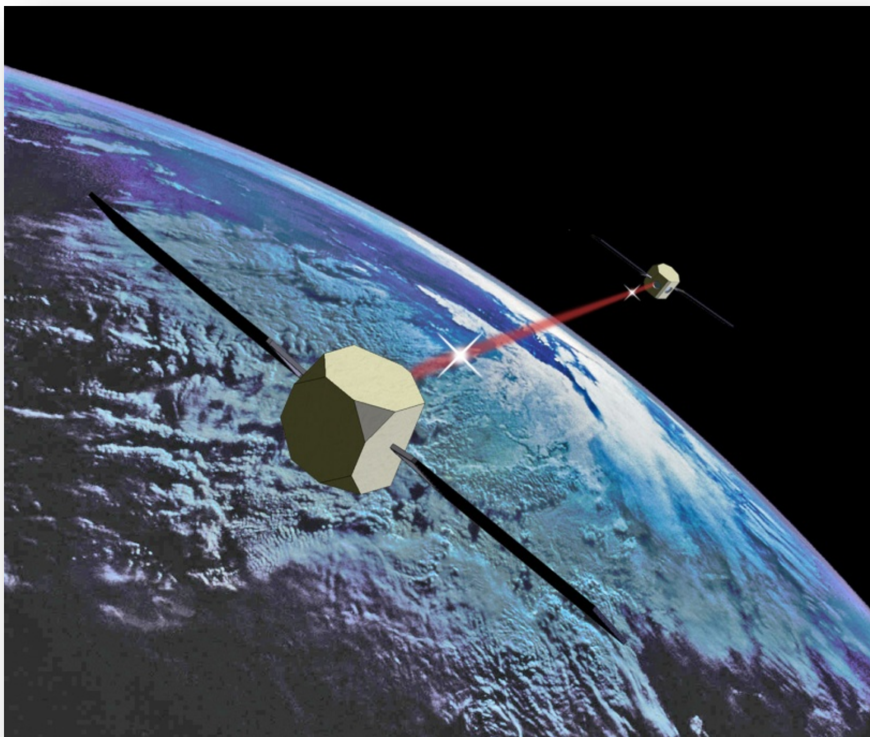
Assumptions:

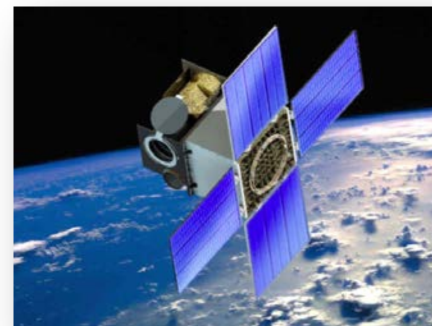
1) Wavepackets (Rb) separated by z = 10 m, for T = 1 sec. For 1 g acceleration: $\Delta\phi \sim mgzT/\hbar \sim 1.3 \times 10^{11}$ rad
2) Signal-to-noise for read-out: SNR ~ 10^5:1 per second.
3) Resolution to changes in g per shot: $\delta g \sim 1/(\Delta\phi\ SNR) \sim 7 \times 10^{-17}$ g
4) 10^6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

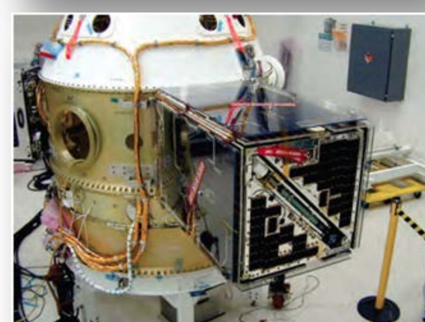


Satellite GW Antenna









JMAPS bus/ESPA deployed

Atom-based Gravitational Wave Detection

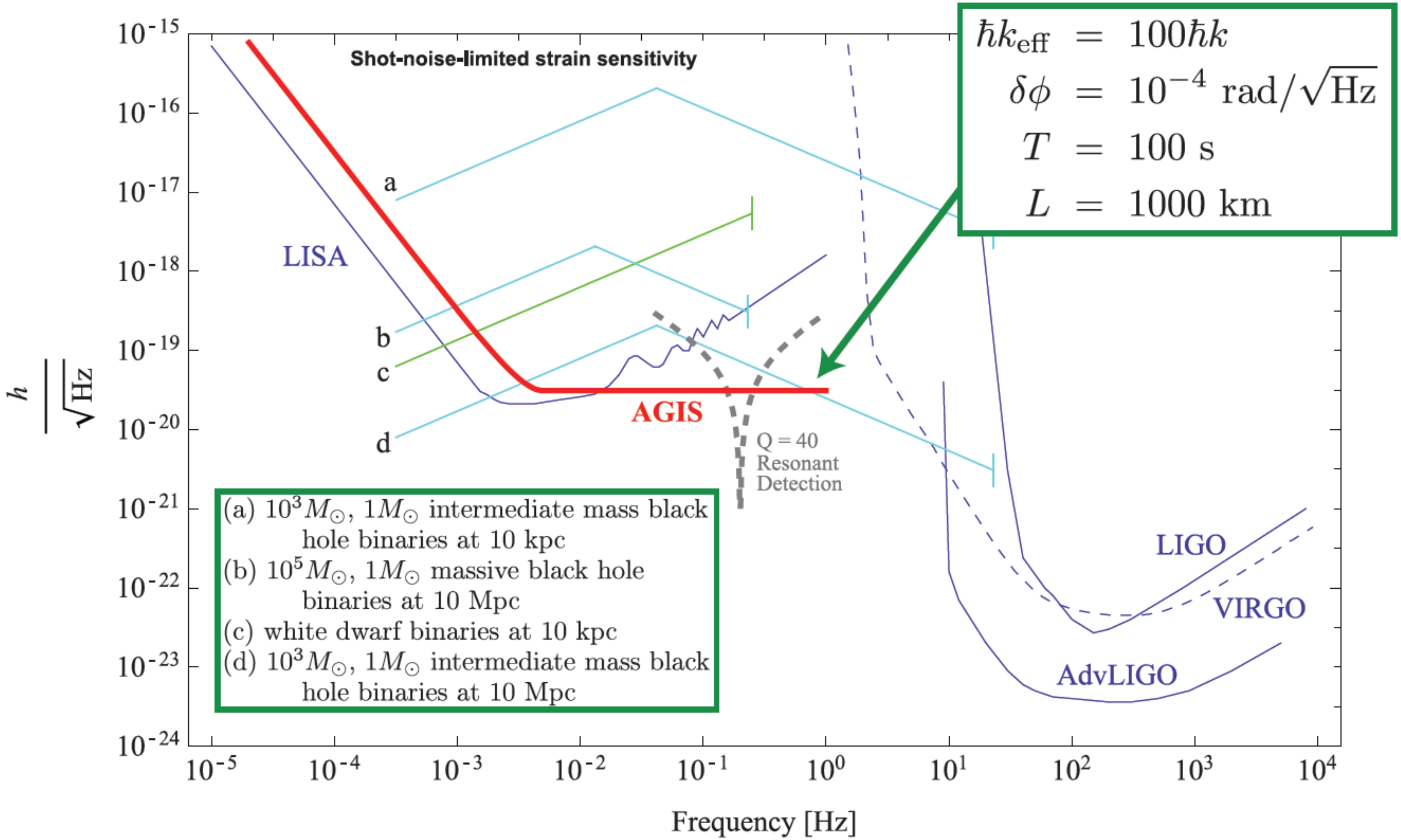
Why consider atoms?

1) Neutral atoms are excellent proof masses
   - atom interferometry

2) Atoms are excellent clocks
   - optical frequency standards

Literature: 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), Dimopoulos, et al., PRD (2008), Graham, et al., PRL (2013).

Potential Strain Sensitivity



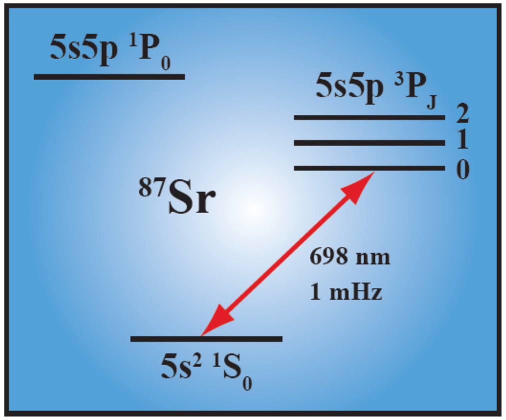
J. Hogan, et al., GRG **43**, 7 (2011).

AGIS Instrument Risk

Noise source	Risk	
Magnetic Fields	Low	
AC Stark	Low	
Laser intensity jitter	Low	
Atom source velocity jitter	Mid	NIAC
Laser pointing jitter	Mid	NIAC
Solar radiation	Low	
Blackbody	Low	
Atom flux	Low	
Laser wavefront noise	High?	NIAC
Atom detection noise	High?	NIAC
Gravity gradient	Mid	NIAC

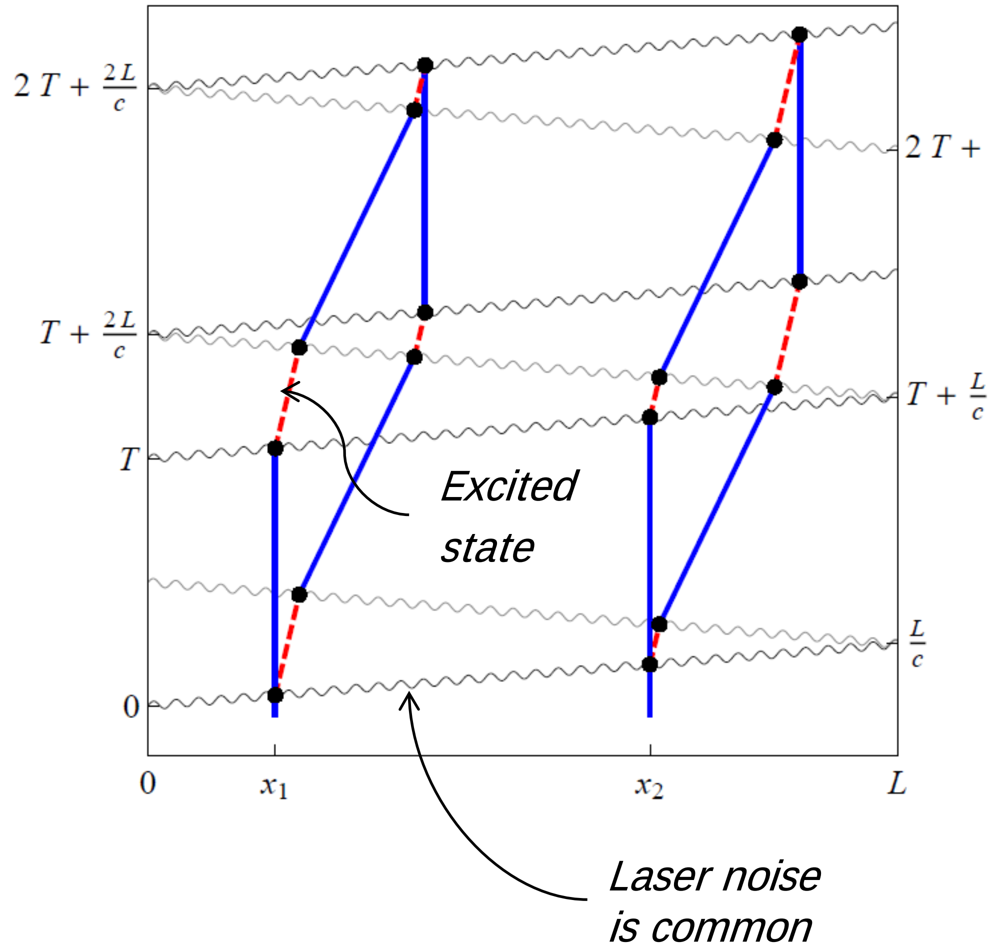
See analysis in Graham, *et al.*, arXiv:1206.0818, PRL (2013); J. Hogan, et al., GRG **43**, 7 (2011).

Laser frequency noise insensitive detector



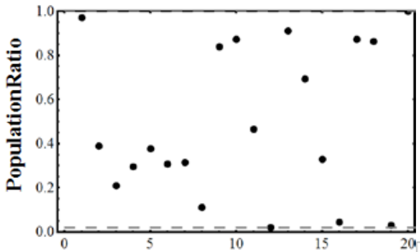
Clock transition in candidate atom ^{87}Sr

- Long-lived single photon transitions (e.g. clock transition in Sr, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

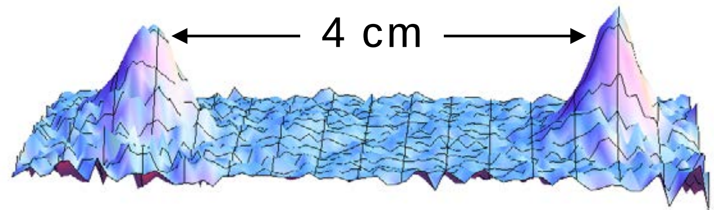


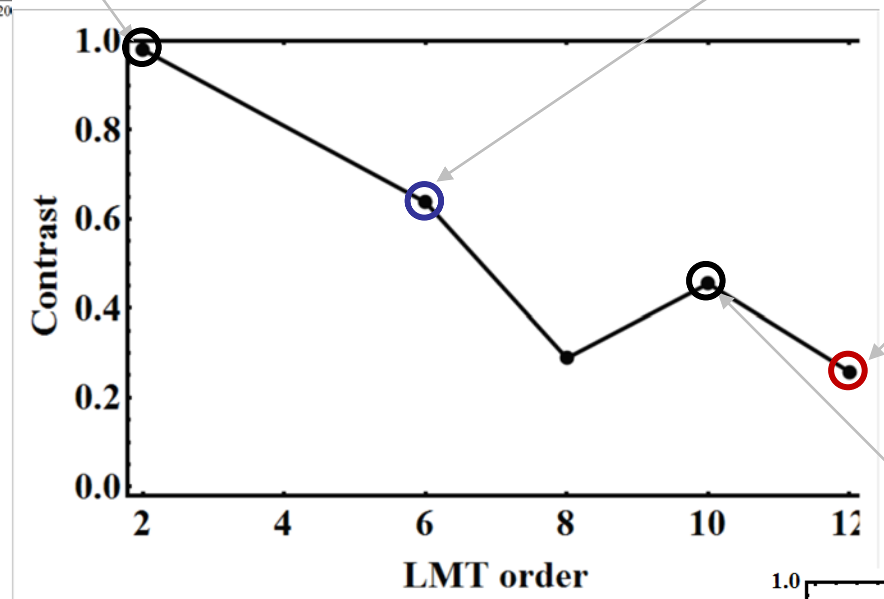
Graham, *et al.*, arXiv:1206.0818, PRL (2013)

Contrast vs. momentum recoil at 2T = 2.3 s

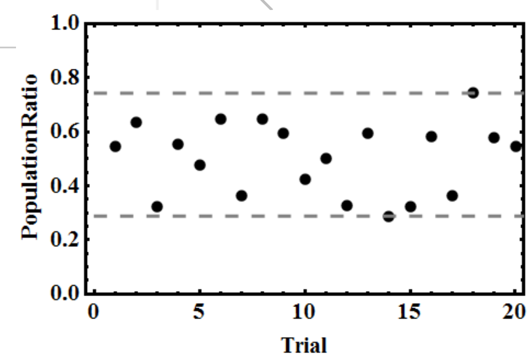


>98% contrast (!)





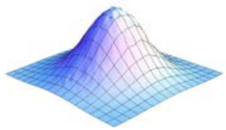
8 cm wavepacket separation (!!)



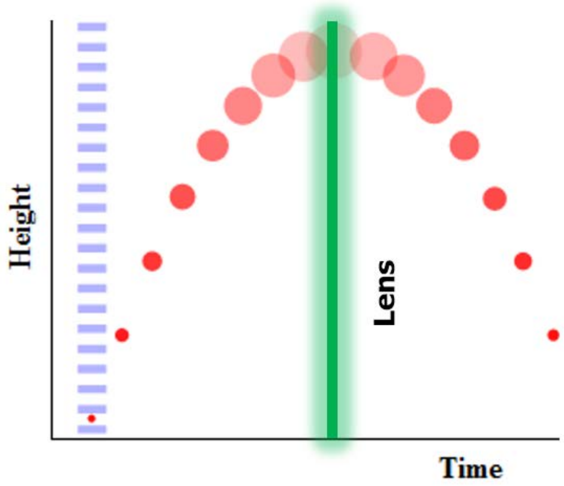
Large momentum transfer demonstration at 2T = 2.3 s (unpublished).

Ultra-ultra cold atoms

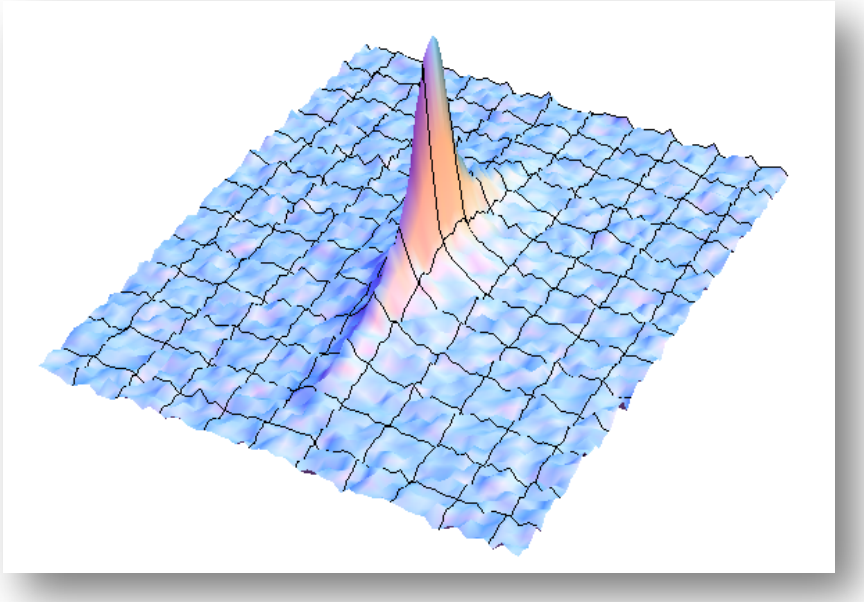
A lens for atom clouds is realized using a laser beam:



Laser beam profile used in exp't.



Atom cloud refocused to <200 microns (resolution limited) after 2.6 seconds drift.



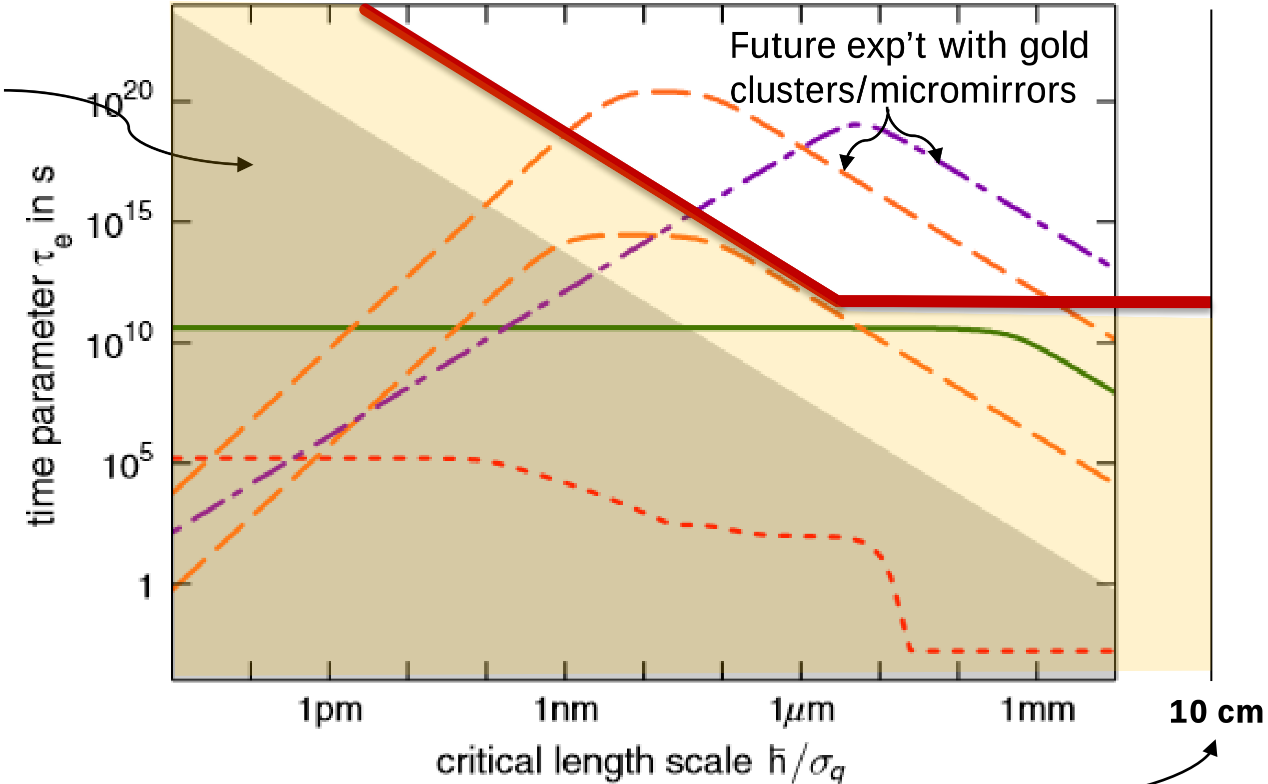
Collimated cloud has inferred temperature of <15 picoKelvin (rms velocity spread <50 microns/sec).

Meets GW detector spec.

Tests of QM: "Macroscopicity"

We are testing QM at unprecedented energy, length and time scales.

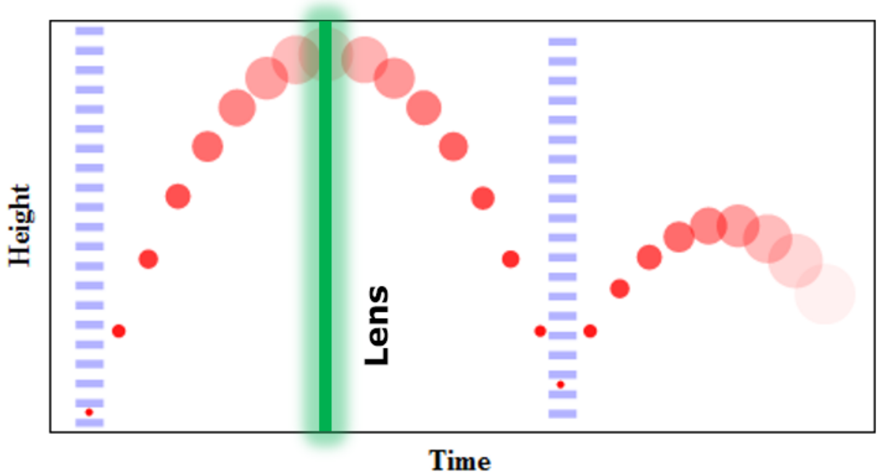
Excluded by NIAC work



Near future NIAC work to push this to 1 m length scales

Nimrichter, et al., PRL, 2013

5 s quasi-inertial free-fall



Launched to 9.375 meters;
Relaunched to 6 meters

GW impact: Enables ground-based tests of long free-fall configurations

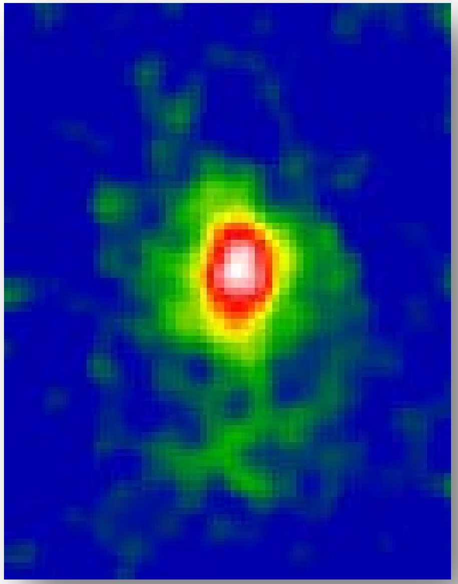
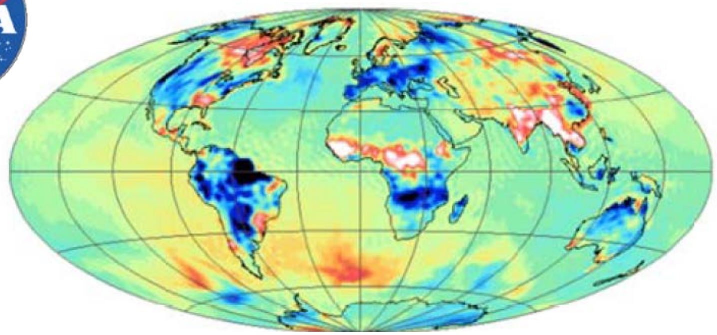
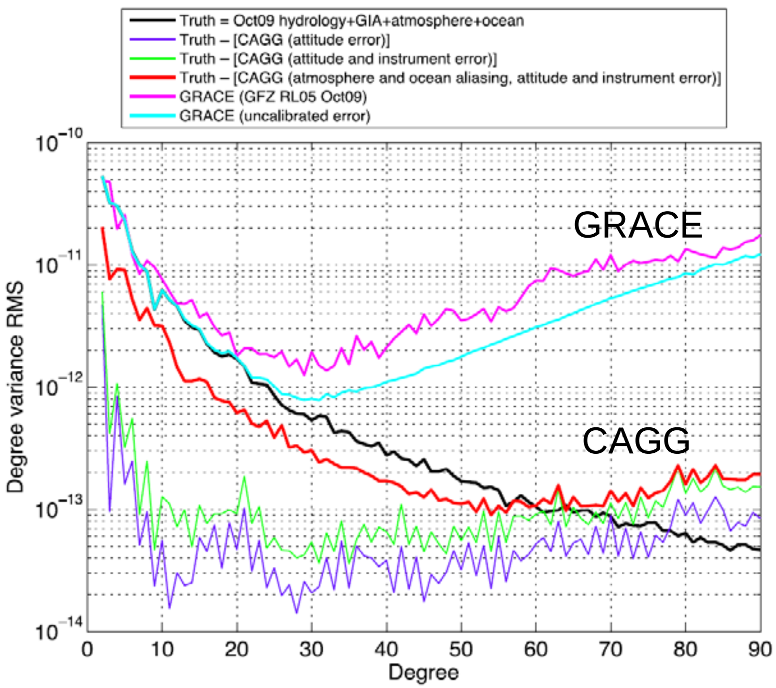


Image of atom cloud after 5 sec nearly inertial free-fall

Satellite geodesy





Analysis from S. Luthke, GSFC

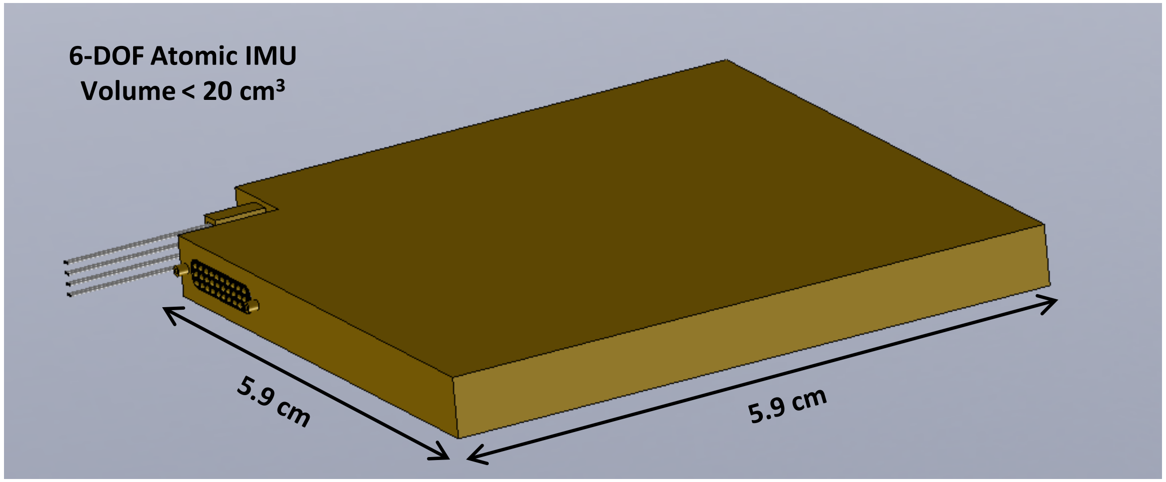
Simulation of hydrology map from space-borne atom interferometer gravity gradiometer.

~ 1 cm equivalent water height resolution.

Instrument:
- 1 m baseline
- single-axis
- rotation compensation

Development of prototype recently funded by NASA IIP (Saif, PI); Instrument to be built by AOSense, Inc.

AOSense Compact IMU



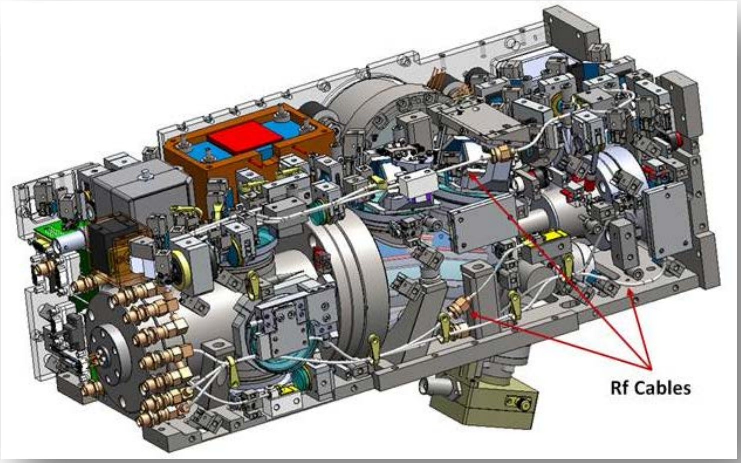
DARPA C-SCAN, PM R. Lutwak

Operating Principle:
Atom Interferometry

AOSense

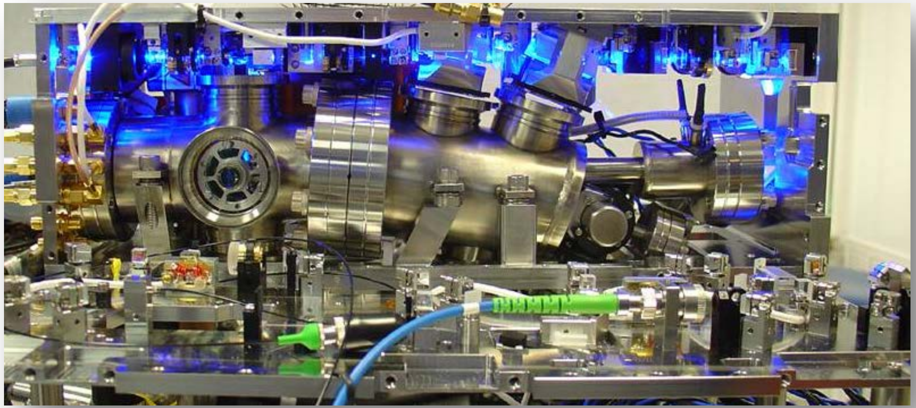
(Courtesy M. Cashen, AOSense, Inc.)

Sr compact optical clock



6 liter physics package.

(Courtesy T. Loftus, AOSense, Inc.)



As built view with front panel removed in order to view interior.

408-735-9500
AOSense.com
Sunnyvale, CA

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