Atom Interferometric Gravity Wave Detectors

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Outline

- Basic concepts
- Current instrumentation
- AGIS detectors
  - Space-based/LEO
  - Terrestrial
  - Systematics
- Status of instrument development

Young’s double slit with atoms

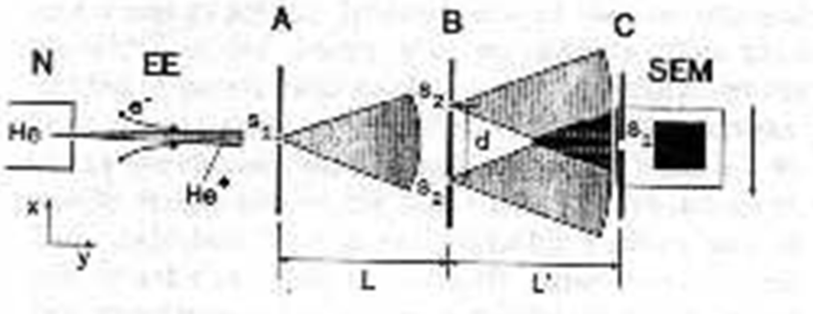

FIG. 2. Schematic representation of the experimental setup:

Young’s 2 slit with Helium atoms

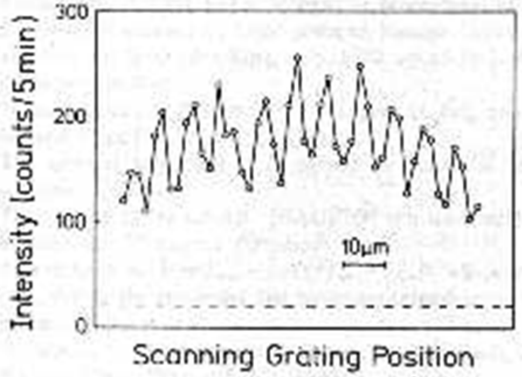

FIG. 5. Atomic density profile, monitored with the 8-μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

Interference fringes

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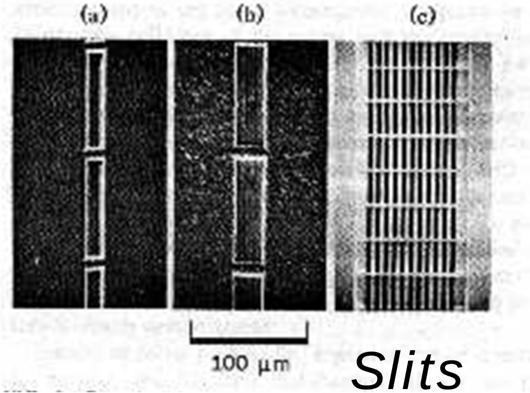
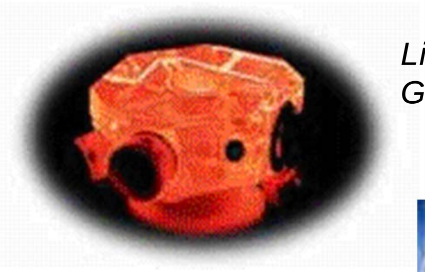


Slits

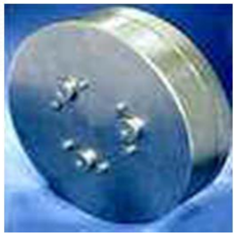
One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)

Inertial sensors

Optical Interferometry



Litton Ring Laser Gyroscope

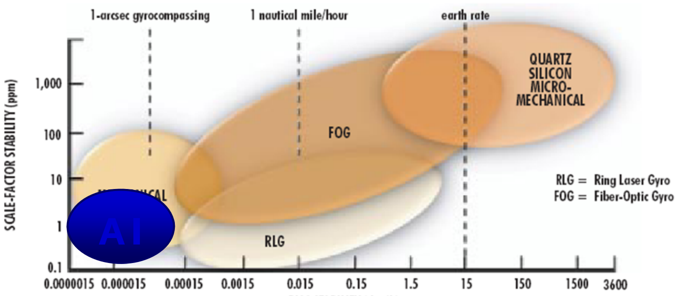


Fibersense Fiber-optic Gyroscope

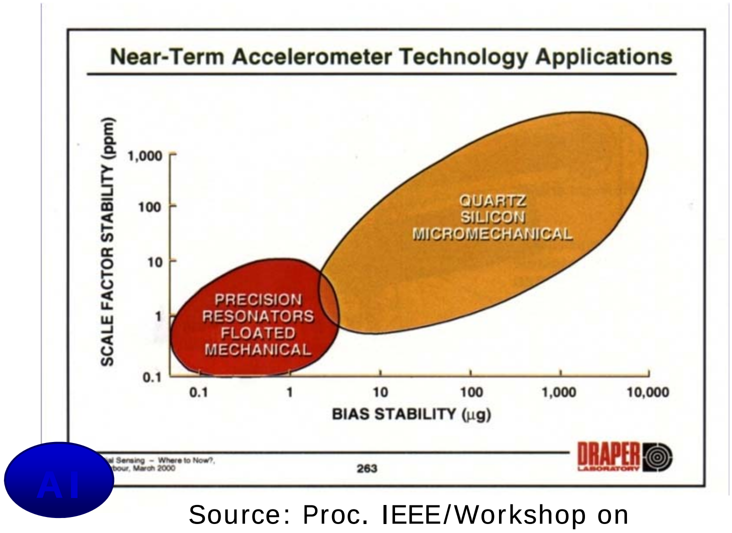
Atom Interferometry

- Future atom optics-based sensors may outperform existing inertial sensors by a factor of 10^6.
- Current (laboratory) atom optics-based sensors outperform existing sensors.

Performance of current generation atom interferometric sensors



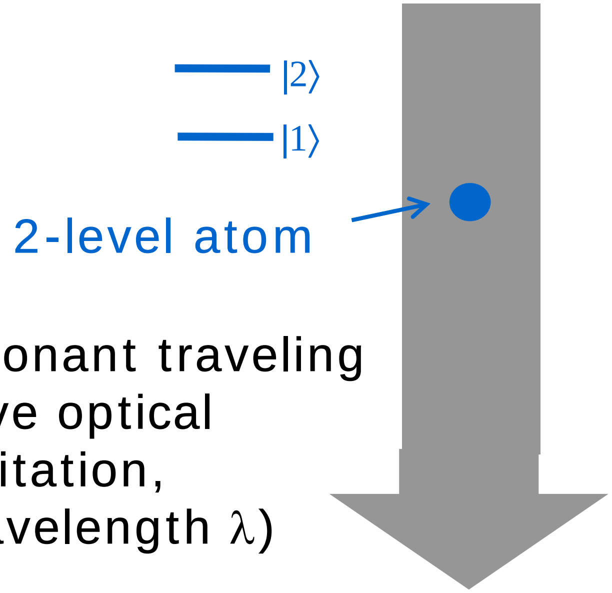
Fiaure 8



Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

(Light-pulse) atom interferometry

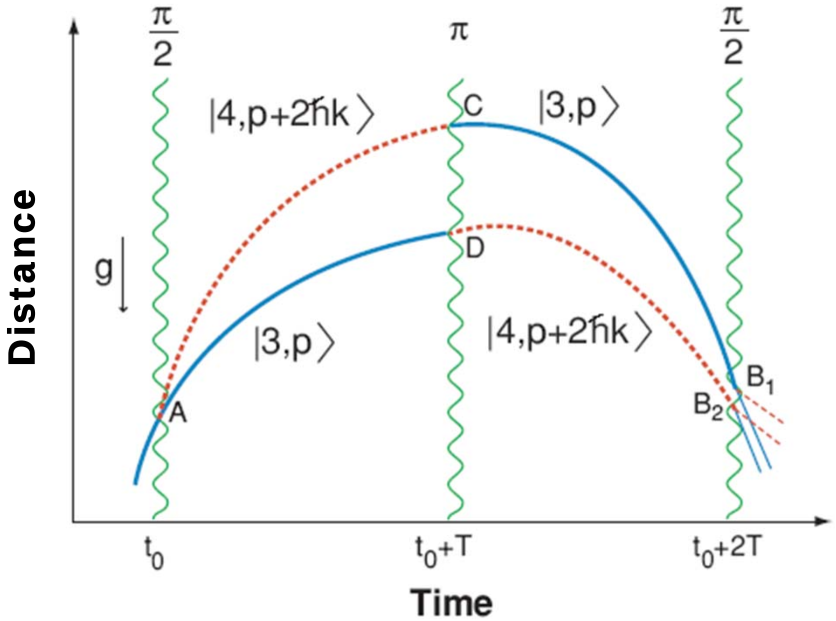
Resonant optical interaction



Resonant traveling wave optical excitation, (wavelength λ)

Recoil diagram

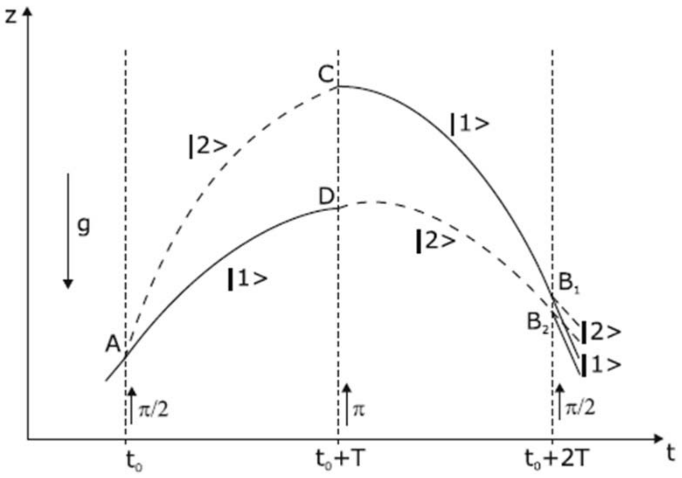
Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.



Phase shifts: Semi-classical approximation

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):

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

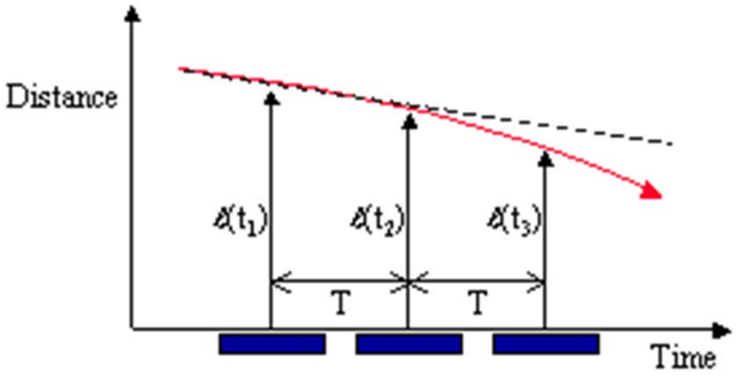
Wavepacket separation at detection:

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

See Bongs, et al., quant-ph/0204102 (2002) also App. Phys. B, 2006.

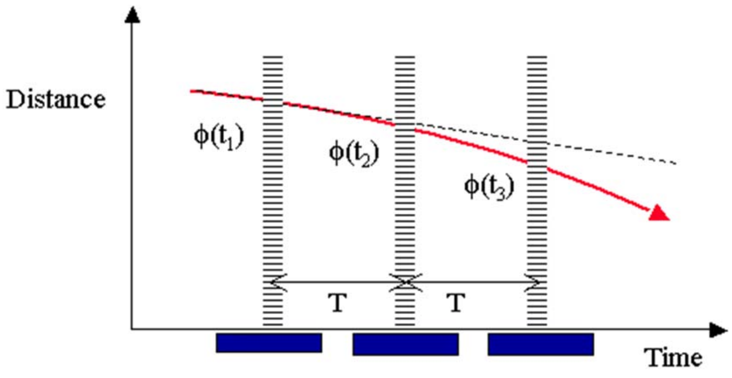
Approximate Kinematic Model

Falling rock



- Determine trajectory curvature with three distance measurements $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$
- For curvature induced by acceleration **a**,
  a ~ $[\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$

Falling atom

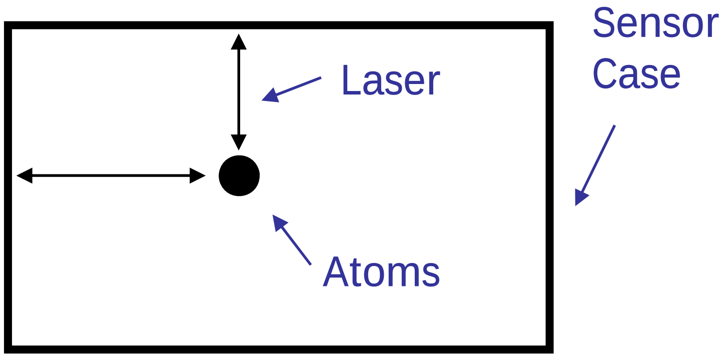


- Distances measured in terms of phases $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$ of optical laser field at position where atom interacts with laser beam
- Atomic physics processes yield
  a ~ $[\phi(t_1)-2\phi(t_2)+\phi(t_3)]$

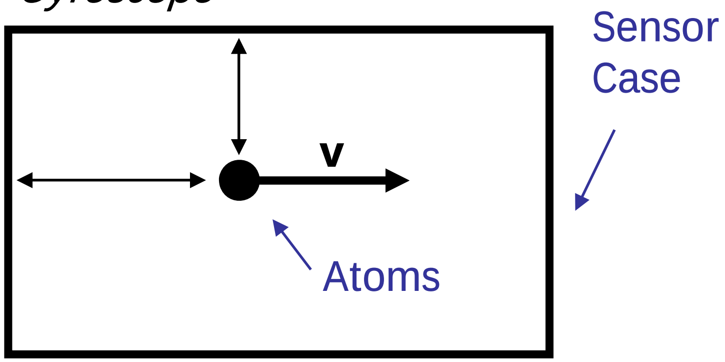
Light-pulse atom sensors

- **Atom is in a near perfect inertial frame of reference (*no spurious forces*).**
- **Laser/atomic physics interactions determine the the relative motion between the inertial frame (*defined by the atom deBroglie waves*) and the sensor case (*defined by the laser beams*).**
- **Sensor accuracy derives from the use of optical wavefronts to determine this relative motion.**
- **Sensor is kinematic: directly reads angular and linear displacements**

Accelerometer



Gyroscope



Laser cooling

Laser cooling techniques are used to achieve the required velocity (wavelength) control for the atom source.

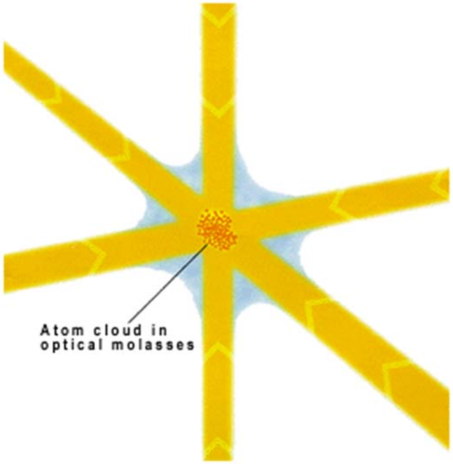
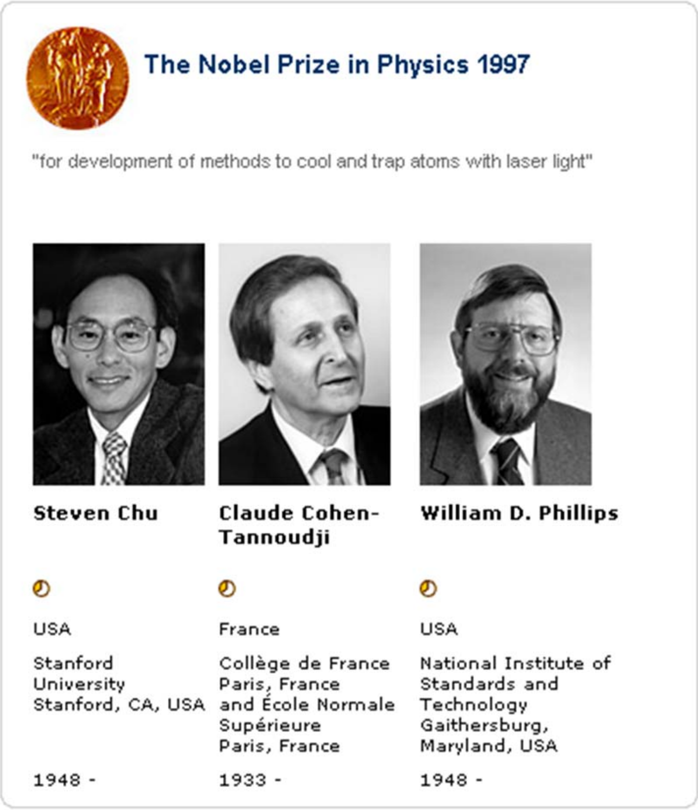


Image source:www.nobel.se/physics

Laser cooling: Laser light is used to cool atomic vapors to temperatures of $\sim 10^{-6}$ deg K.

<10 μm/sec velocity control is demonstrated with current methods.

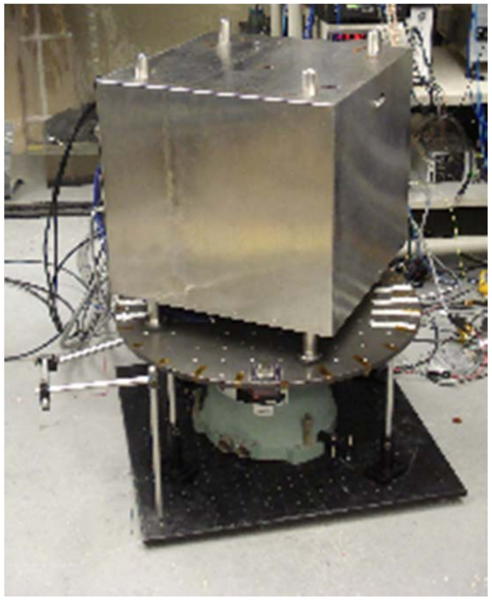


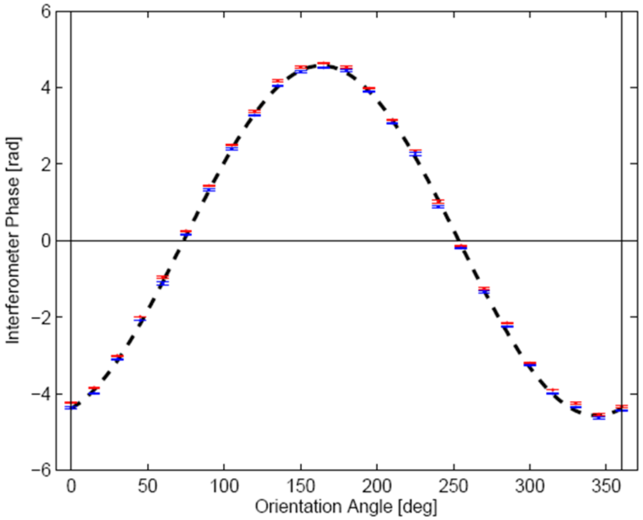
The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

Steven Chu	**Claude Cohen-Tannoudji**	**William D. Phillips**
USA	France	USA
Stanford University Stanford, CA, USA	Collège de France Paris, France and École Normale Supérieure Paris, France	National Institute of Standards and Technology Gaithersburg, Maryland, USA
1948 -	1933 -	1948 -

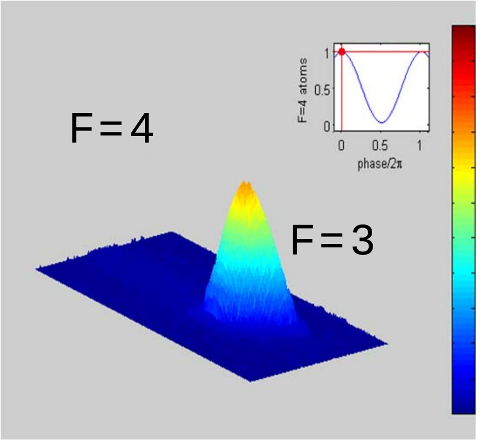
Gyroscope, Measurement of Earth rotation rate

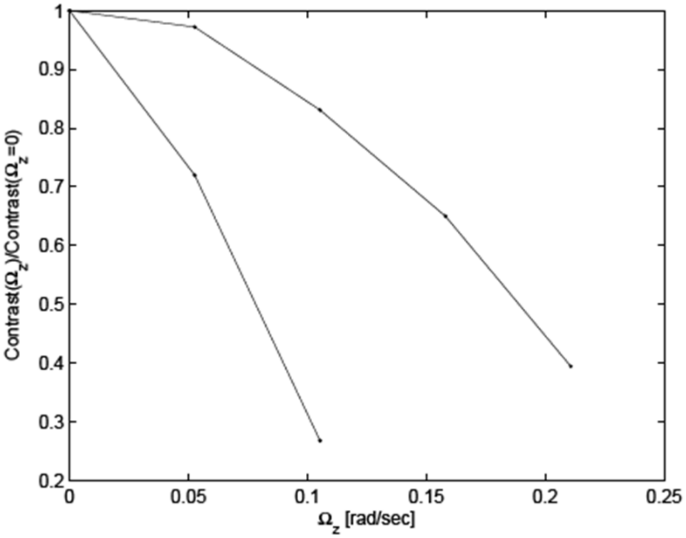




Gyroscope output vs.orientation.

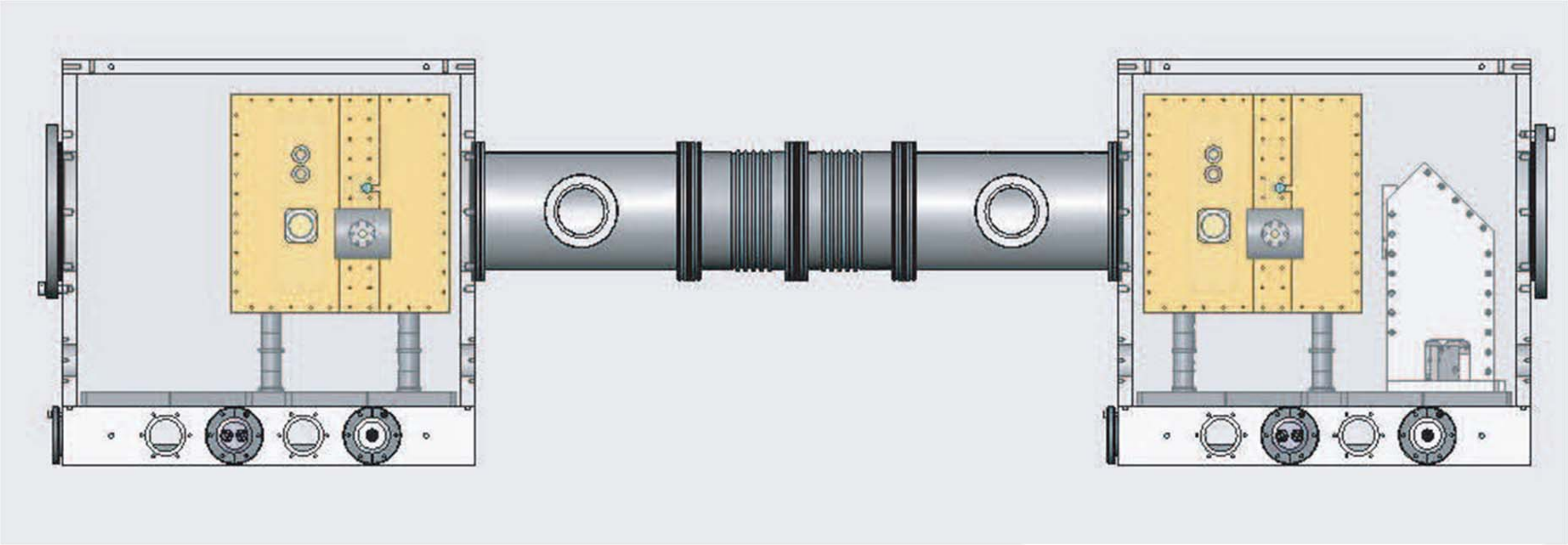
200 μdeg/hr$^{1/2}$

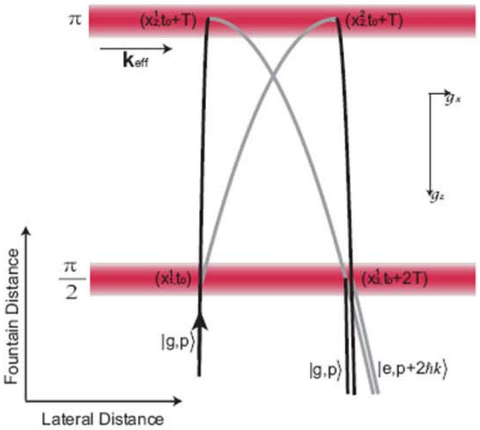




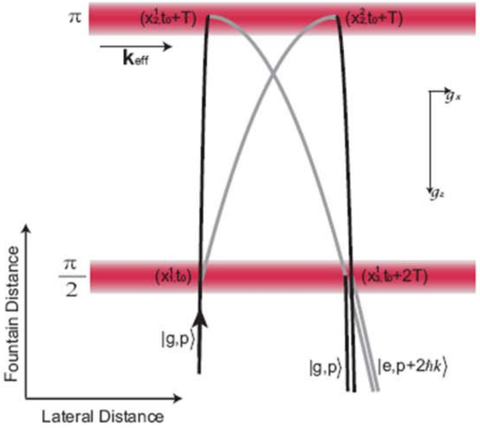
Contrast at high rotation rate (> 10 deg/sec)

Differential accelerometer



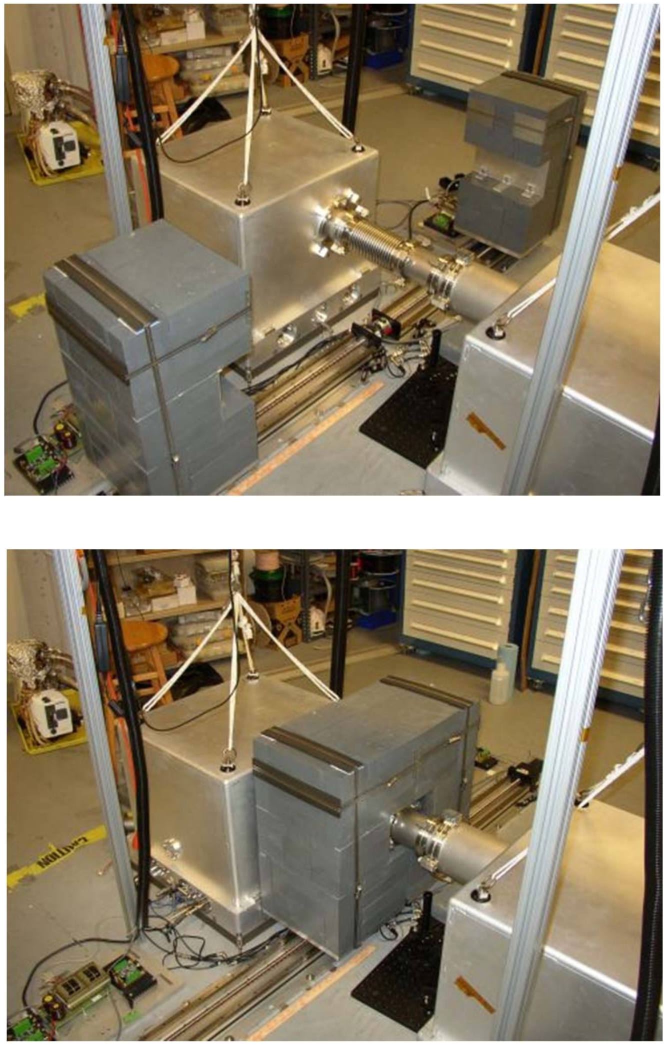


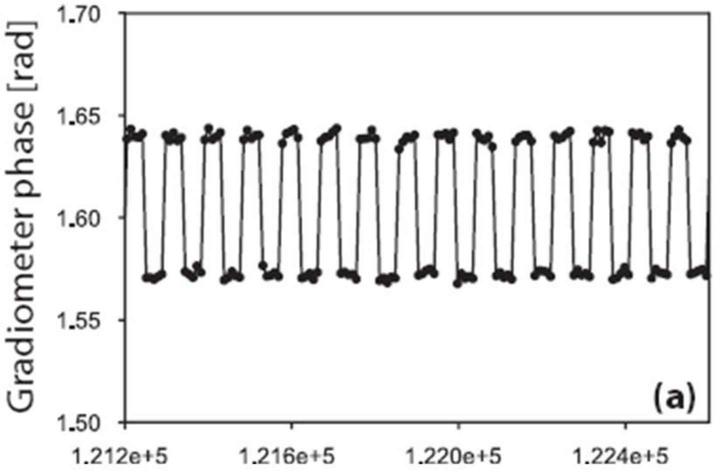
← ~ 1 m →

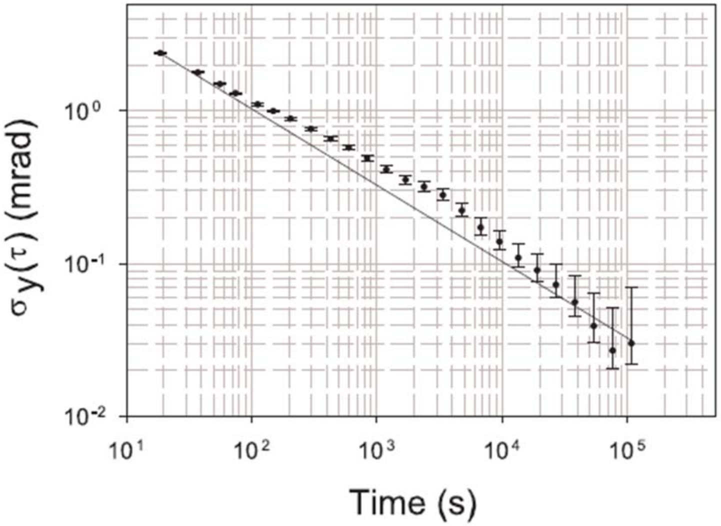


Applications in precision navigation and geodesy

Gravity gradiometer





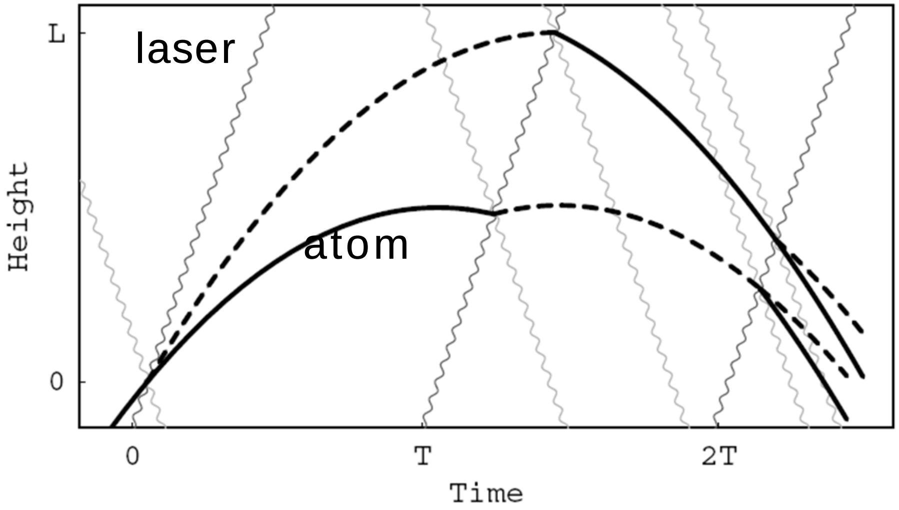


Demonstrated accelerometer resolution: ~10^{-11} g.

General Relativity/Phase shifts

Light-pulse interferometer phase shifts in GR:

- Geodesic propagation for atoms and light.
- Path integral formulation to obtain quantum phases.
- Atom-field interaction at intersection of laser and atom geodesics.

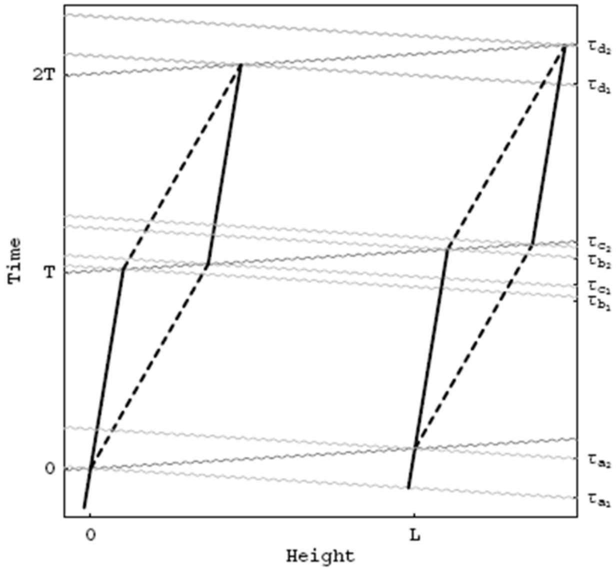


Atom and photon geodesics

Prior work, de Broglie interferometry: Post-Newtonian effects of gravity on quantum interferometry, Shigeru Wajima, Masumi Kasai, Toshifumi Futamase, Phys. Rev. D, 55, 1997; Bordé, et al.

Gravity waves

Metric (tt): $ds^2 = dt^2 - (1 + h\sin(\omega(t - z) + \phi_0))\,dx^2 - (1 - h\sin(\omega(t - z) + \phi_0))\,dy^2 - dz^2$

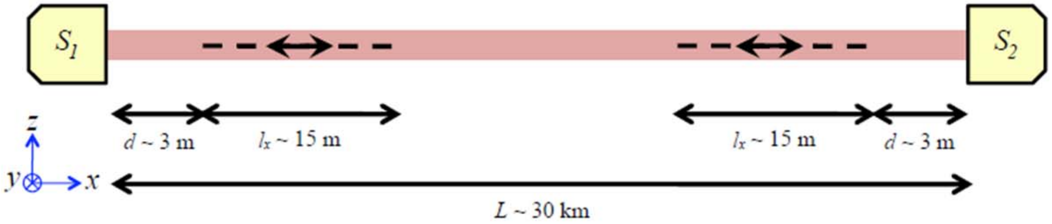


Differential accelerometer configuration for gravity wave detection.

Atoms provide inertially decoupled references (analogous to mirrors in LIGO)

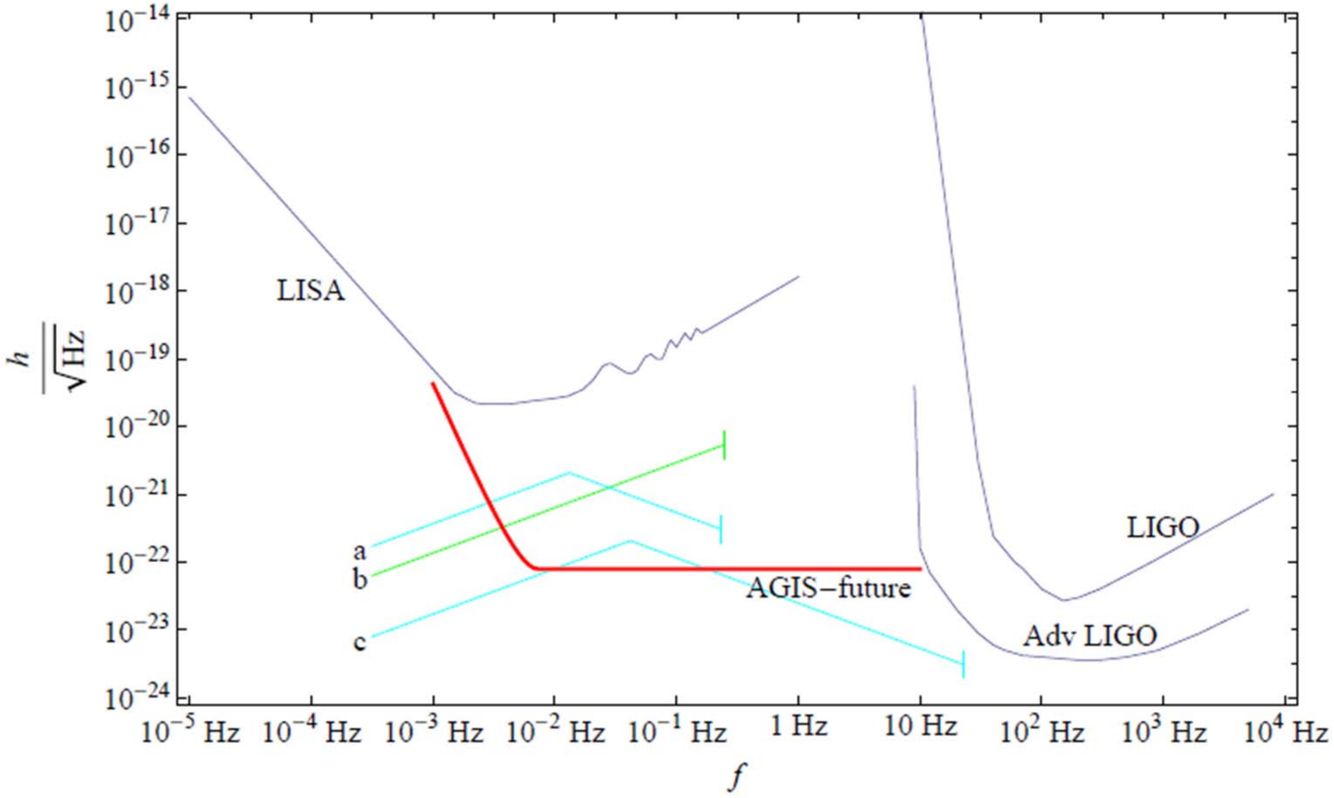
Gravity wave phase shift through propagation of optical fields.

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).



Satellite configuration (dashed line indicates atom trajectories)

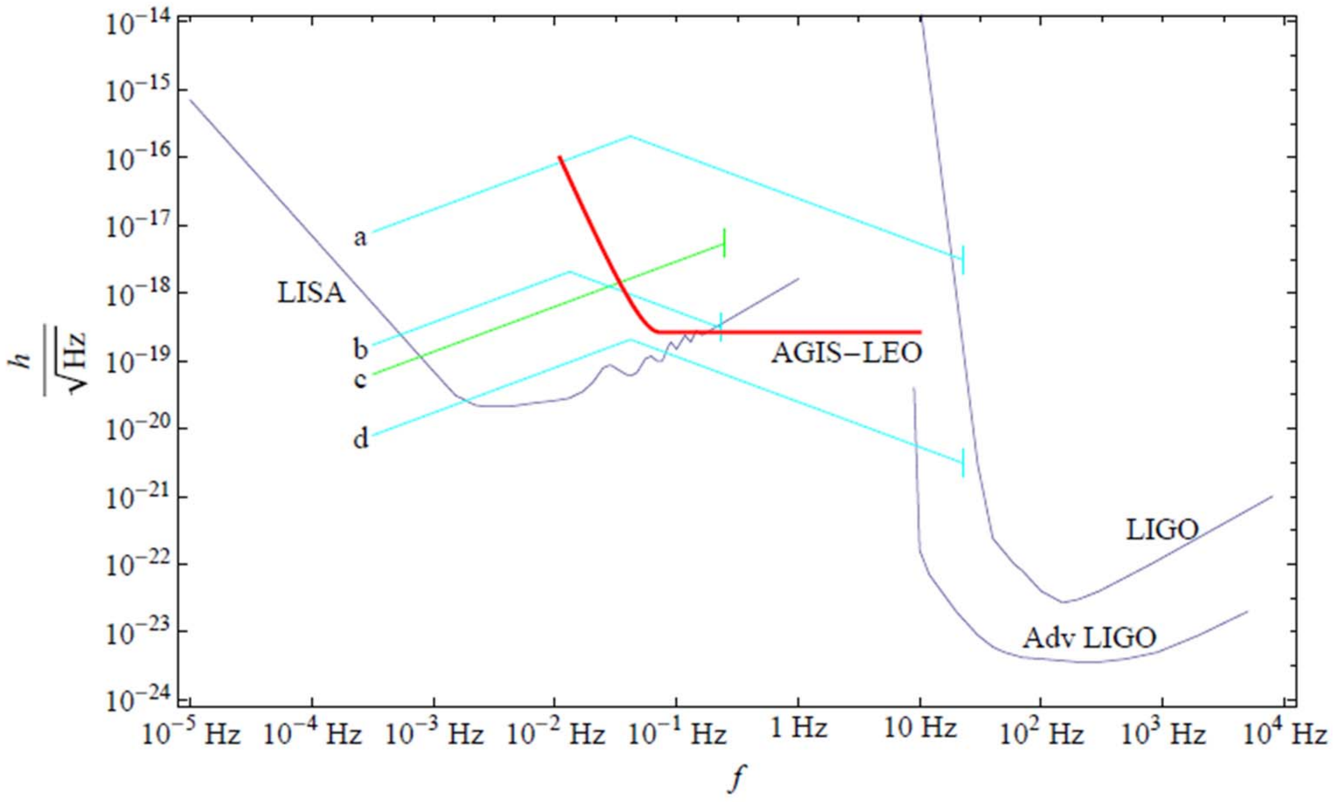
Space-based gravity wave detection (AGIS)



Possible sensitivity of AI gravity wave detector.

J. M. Hogan, D. M. S. Johnson, S. Dickerson, T. Kovachy, A. Sugarbaker, S. Chiow, P. W. Graham, M. A. Kasevich, B. Saif, S. Rajendran, P. Bouyer, B. D. Seery, L. Feinberg, and R. Keski-Kuha, 1009.2702 (2010).

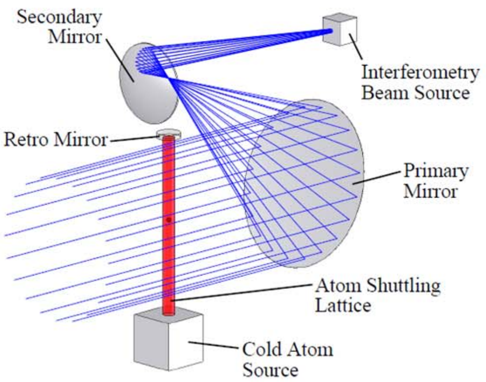
AGIS-LEO concept



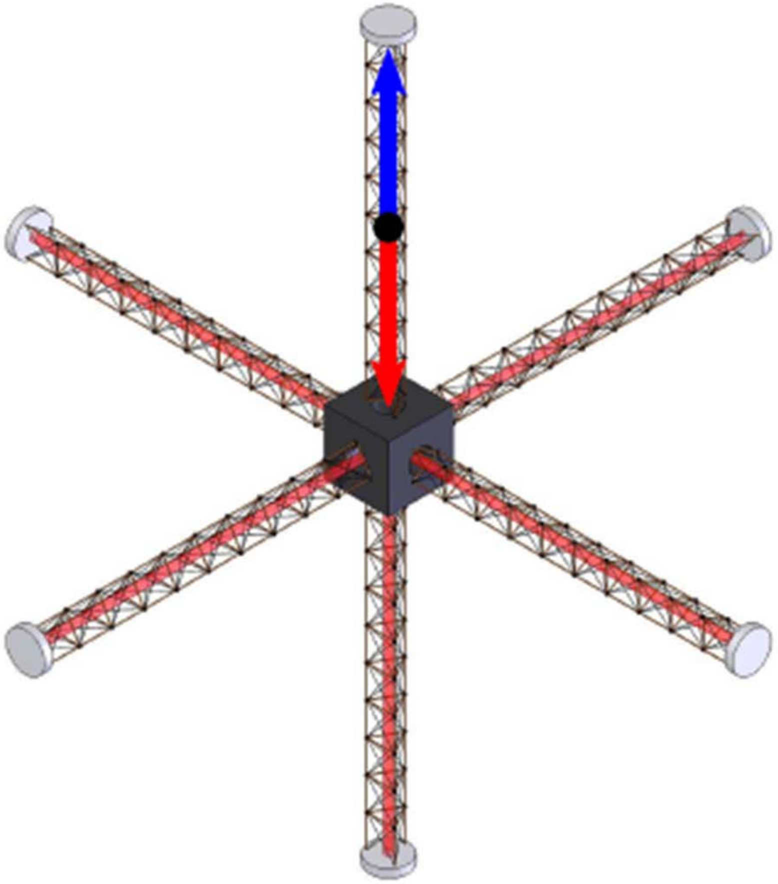
In collaboration with GSFC (Bernie Seery, Babak Saif and co-workers)

Considering ISS, free-flyer LEO configurations

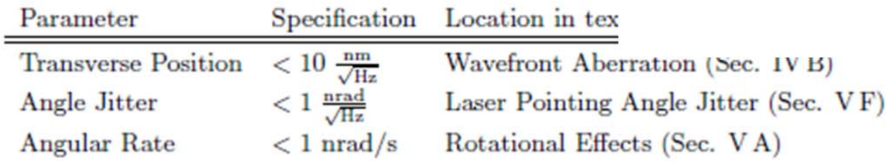
Boom implementation (free flyer/ISS)



Atom delivery and wavepacket manipulation telescope

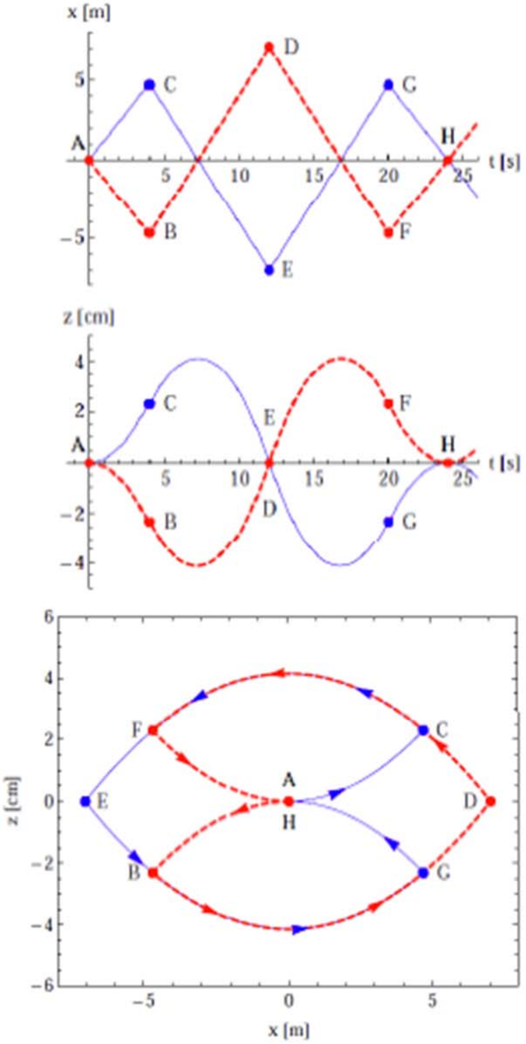


Boom lengths: ~30 m



Parameter	Specification	Location in tex
Transverse Position	$< 10 \frac{\text{nm}}{\sqrt{\text{Hz}}}$	Wavefront Aberration (Sec. IV B)
Angle Jitter	$< 1 \frac{\text{nrad}}{\sqrt{\text{Hz}}}$	Laser Pointing Angle Jitter (Sec. V F)
Angular Rate	< 1 nrad/s	Rotational Effects (Sec. V A)

Pulse sequences for LEO configurations



Developed atom interferometeric pulse sequences to mitigate Coriolis bias for orbiting apparatus.

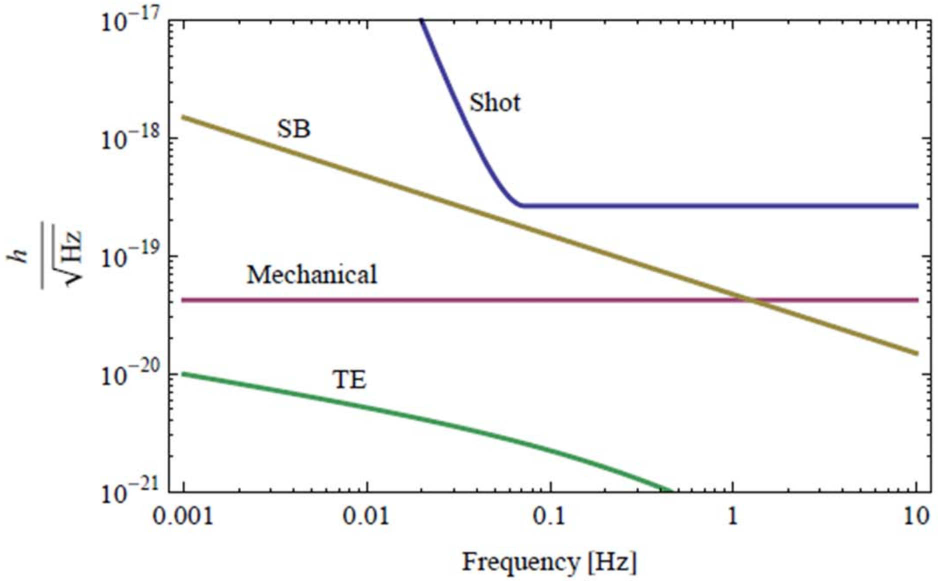
	Phase shift	Size (rad)
1	$-60Lk_{\text{eff}}\Omega_y^3\delta\Omega T^4$	-1.15
2	$60Lk_{\text{eff}}T_{\text{xx}}\Omega_y\delta\Omega T^4$	$+1.15$
3	$888Lk_{\text{eff}}\Omega_y^5\delta\Omega T^6$	$+3.67\times10^{-4}$
4	$444Lk_{\text{eff}}T_{\text{zz}}\Omega_y^3\delta\Omega T^6$	-3.67×10^{-4}
5	$-444Lk_{\text{eff}}T_{\text{xx}}T_{\text{zz}}\Omega_y\delta\Omega T^6$	$+3.67\times10^{-4}$
6	$30k_{\text{eff}}\delta v_z\Omega_y^3T^4$	$+1.92\times10^{-4}$
7	$15k_{\text{eff}}T_{\text{zz}}\delta v_z\Omega_yT^4$	-1.92×10^{-4}
8	$-444Lk_{\text{eff}}T_{\text{xx}}\Omega_y^3\delta\Omega T^6$	-1.84×10^{-4}
9	$-444Lk_{\text{eff}}T_{\text{xx}}^2\Omega_y\delta\Omega T^6$	-1.84×10^{-4}
10	$15k_{\text{eff}}T_{\text{xx}}\Omega_y\delta v_zT^4$	$+9.62\times10^{-5}$
11	$\frac{225L^2}{2R}k_{\text{eff}}T_{\text{zz}}\Omega_y^2\delta\Omega T^5$	-8.25×10^{-5}
12	$\frac{225L^2}{4R}k_{\text{eff}}T_{\text{zz}}^2\delta\Omega T^5$	$+8.25\times10^{-5}$
13	$-\frac{225L^2}{2R}k_{\text{eff}}T_{\text{xx}}\Omega_y^2\delta\Omega T^5$	-4.12×10^{-5}
14	$-\frac{225L^2}{4R}k_{\text{eff}}T_{\text{xx}}^2\delta\Omega T^5$	-2.06×10^{-5}
15	$\frac{30L^3}{R^2}k_{\text{eff}}T_{\text{zz}}\Omega_y\delta\Omega T^4$	-1.95×10^{-5}
16	$-\frac{45}{2}k_{\text{eff}}\Omega_y^4\delta xT^4$	-1.67×10^{-5}
17	$15k_{\text{eff}}T_{\text{xx}}\Omega_y^2\delta xT^4$	$+1.11\times10^{-5}$

Error model to understand sensitivity to atom velocity and laser beam pointing jitter.

Wavefront distortion: temporal variations

Time varying wavefront inhomogeneities will lead to non-common phase shifts between distant clouds of atoms

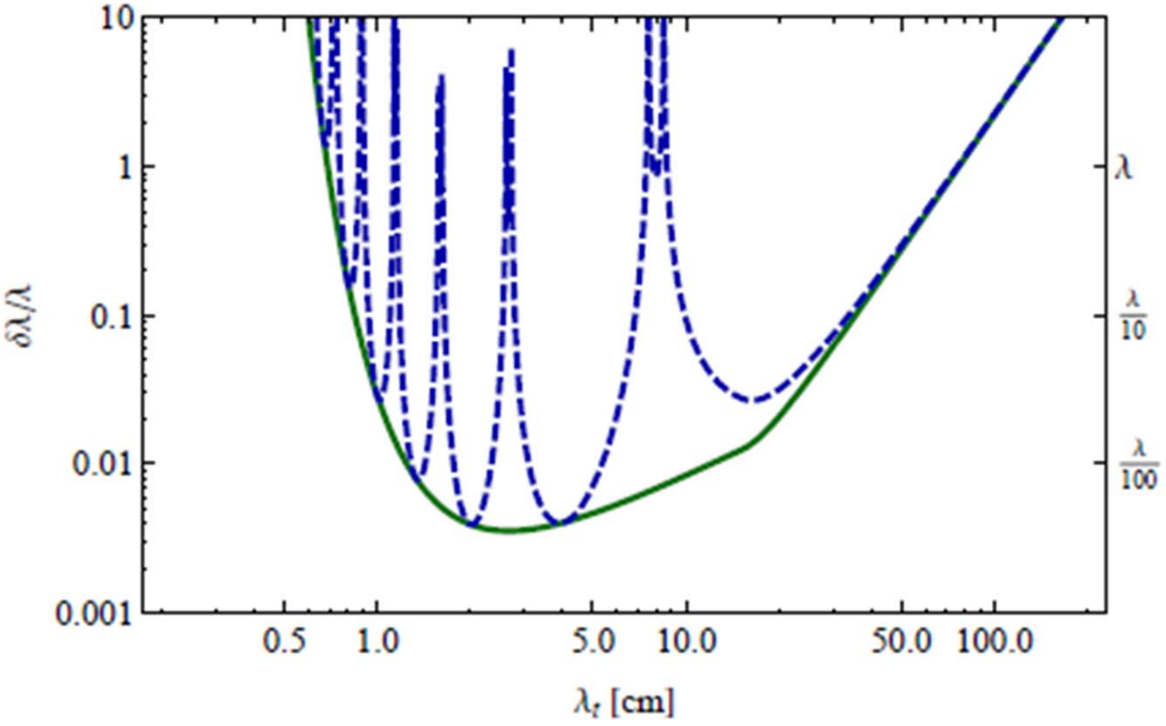
- High spatial frequencies diffract out of the laser beam as the beam propagates between atom clouds
- Limit for temporal stability of wavefronts determined by stability of final telescope mirror



Mirror: Be at 300K

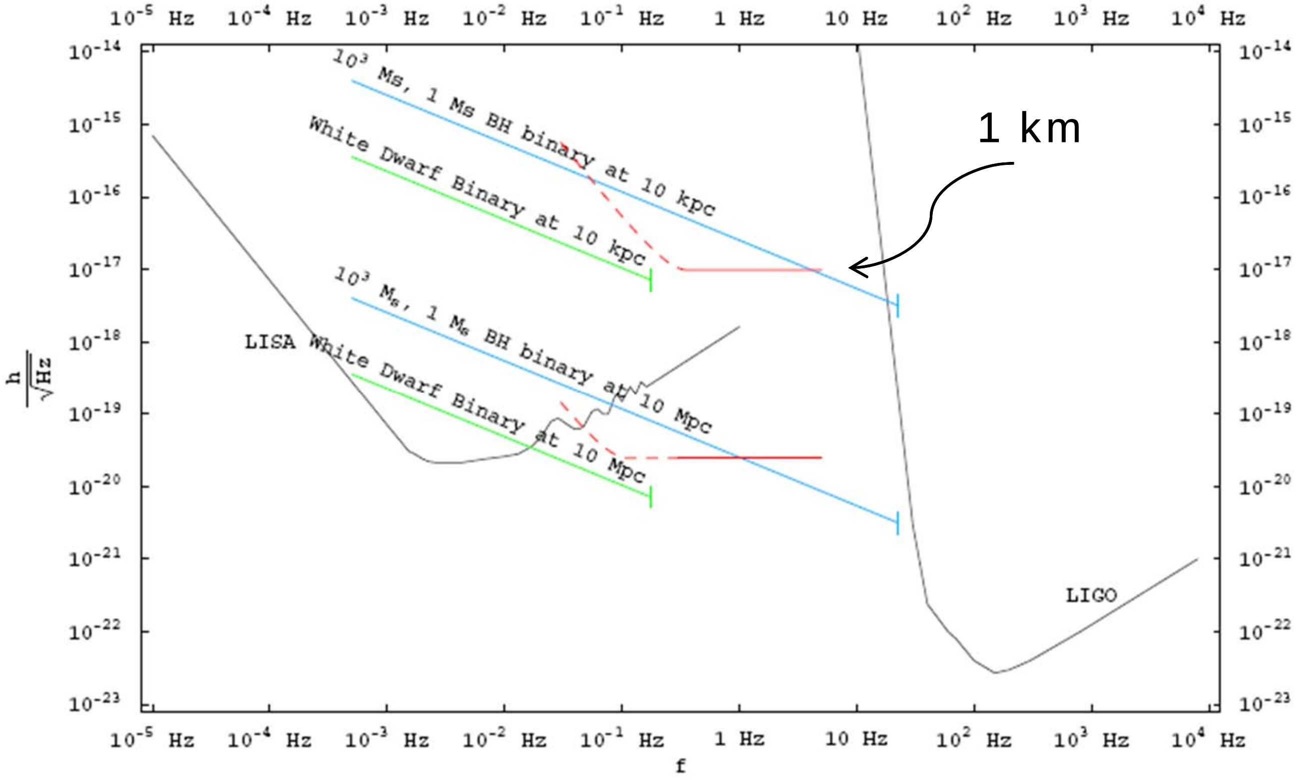
Atom cloud kinematic constrains

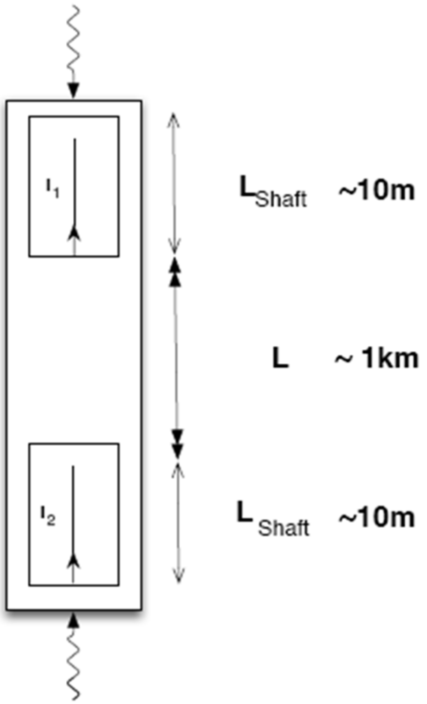
Shot-to-shot jitter in the position of the atom cloud with respect to the satellite/laser beams constrains static wavefront curvature



Wavefront error vs. spatial frequency, assuming 10 nm/Hz$^{1/2}$ position jitter

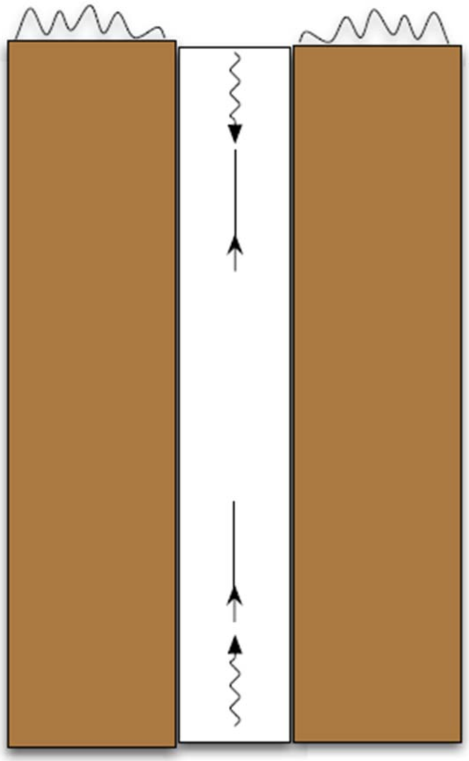
Terrestrial Sensor





1 km vertical shaft at, *e.g.*, Homestake mine.

Newtonian Noise



Seismic fluctuations give rise to Newtonian gravitational fluctuations which perturb atom trajectories.

Seismic noise induced strain analysis for LIGO (Thorne and Hughes, PRD **58**)

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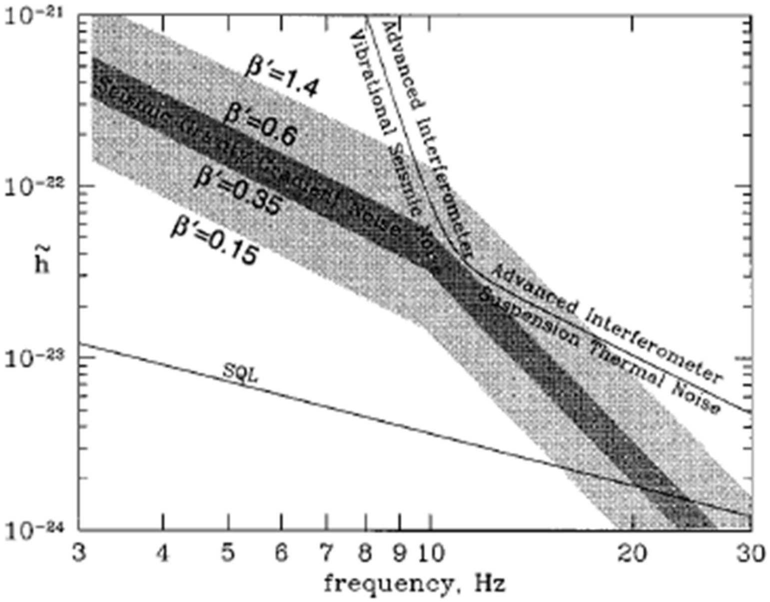

Primary disturbances are surface waves.
Suggests location in underground facility.

Also, atmospheric fluctuations.

References

References analyzing GW detection using AI

Satellite/LEO; Full analysis of wavefront errors	J. M. Hogan, D. M. S. Johnson, S. Dickerson, T. Kovachy, A. Sugarbaker, S. Chiow, P. W. Graham, M. A. Kasevich, B. Saif, S. Rajendran, P. Bouyer, B. D. Seery, L. Feinberg, and R. Keski-Kuha, 1009.2702 (2010).
Satellite; Terrestrial	S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, and S. Rajendran, Phys. Rev. D **78**, 122002 (2008).
General Relativity using Atom Interferometers	S. Dimopoulos, P. W. Graham, J. M. Hogan, and M. A. Kasevich, Phys. Rev. D **78**, 042003 (2008).

Laboratory Instrument

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- Sheng-wei Chiow, Post-doctoral fellow, Physics

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+ AOSENSE TEAM