Gravity Wave Detection using Atom Interferometry

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Outline

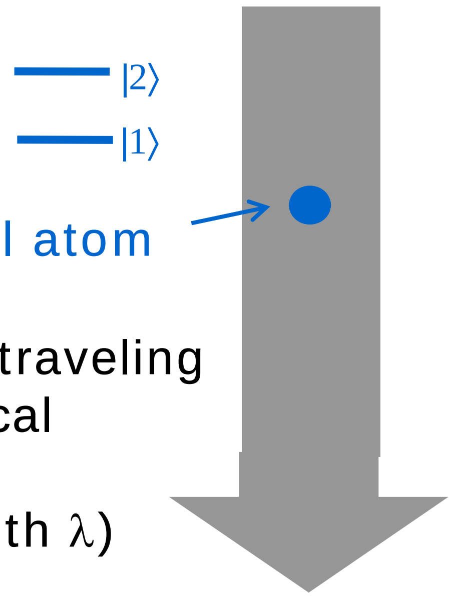
Light pulse de Broglie wave interferometry

Gravity Gradiometer/Differential Accelerometer

Gravity Wave Detection

(Light-pulse) Atom Interferometry

Resonant optical interaction

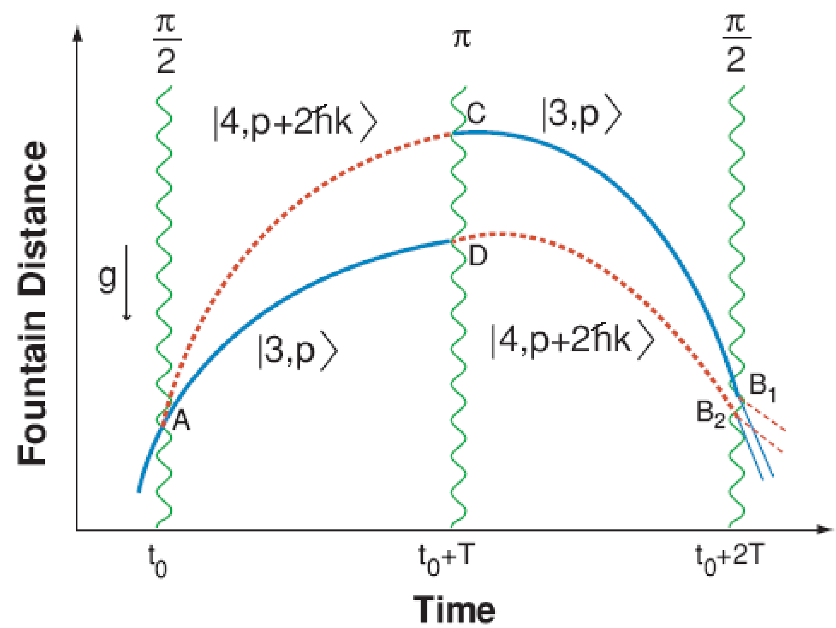


2-level atom

Resonant traveling wave optical excitation, (wavelength λ)

Recoil diagram

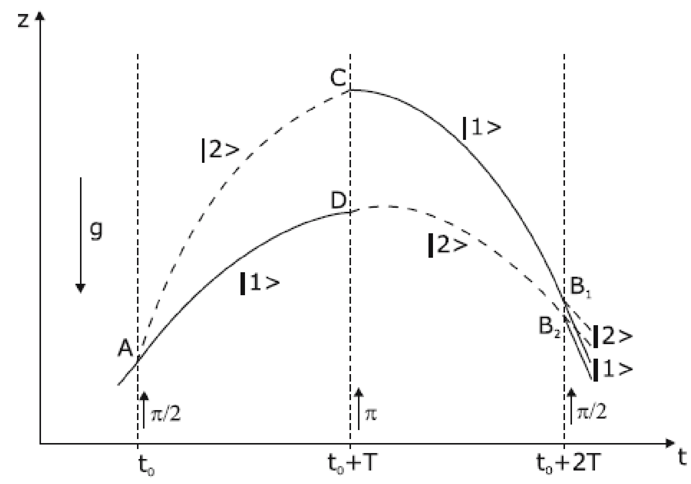
Momentum conservation between atom and laser light field (recoil effects) leads to spatial separation of atomic wavepackets.



Phase Shifts in the 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):

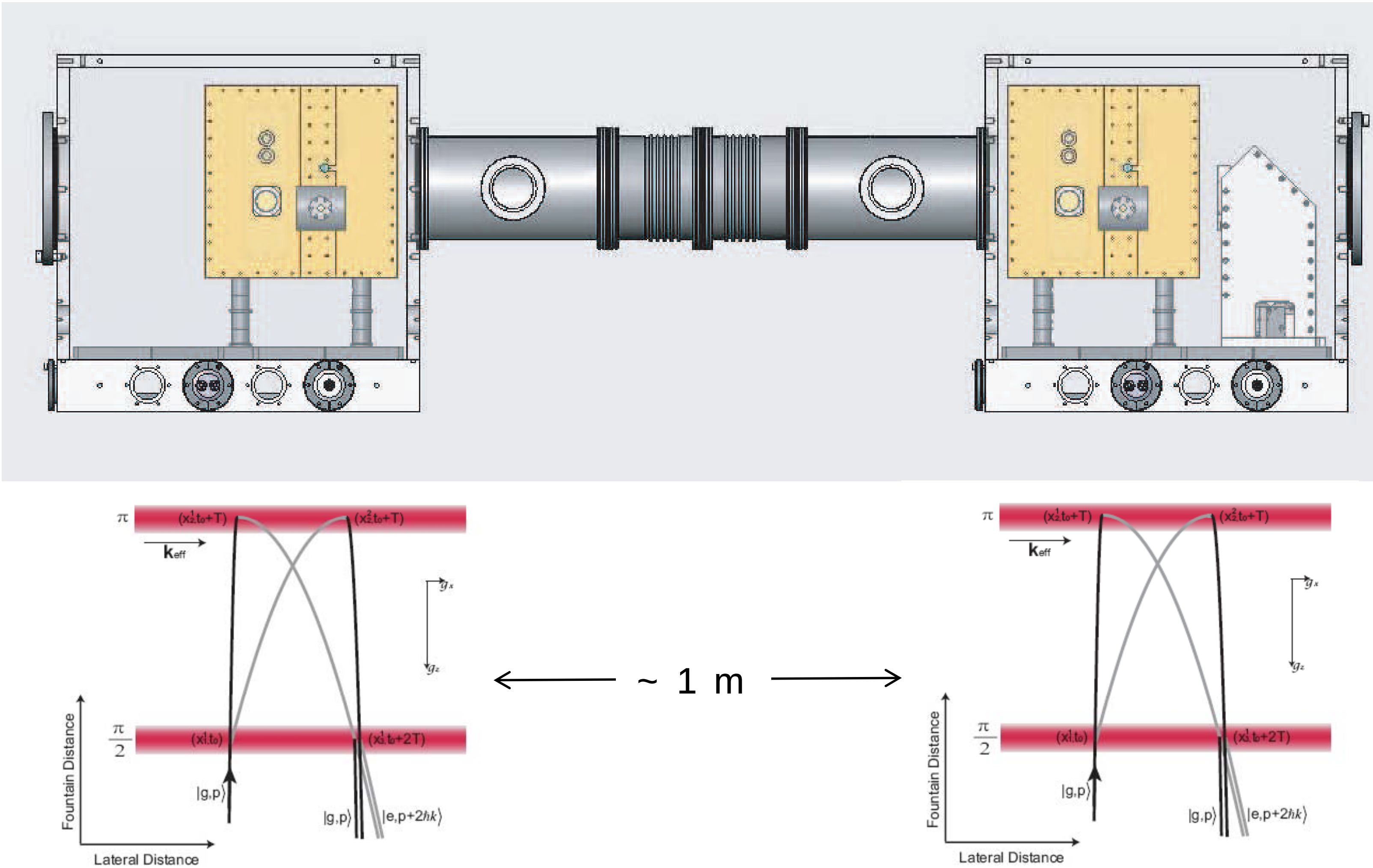
$$k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III}$$

Wavepacket separation at detection:

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

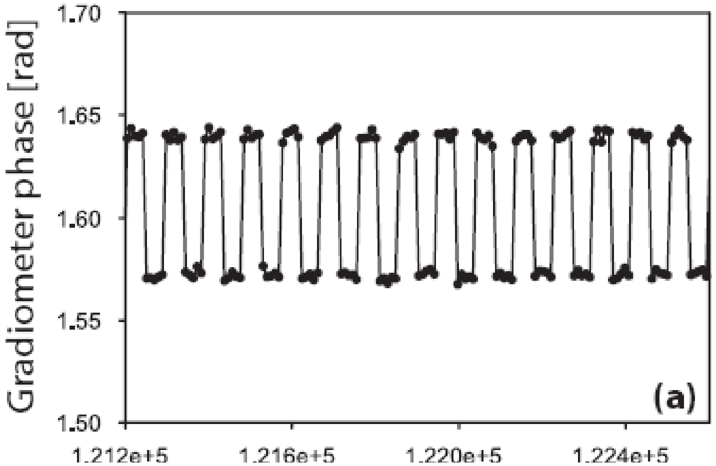
See Bongs, et al., quant-ph/0204102 (April 2002) also App. Phys. B, 2006.

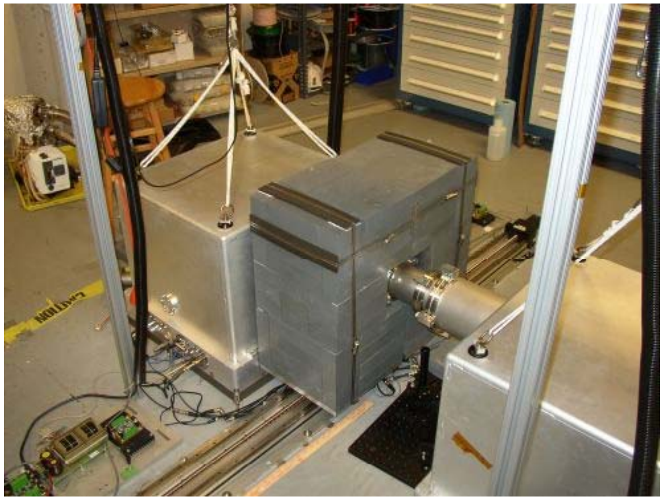
Differential Accelerometer

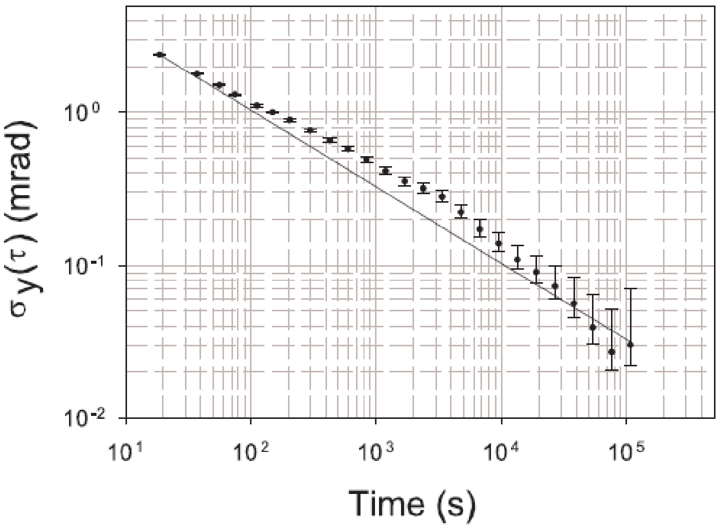


Differential accelerometer, horizontal configuration

Gravity Gradiometer





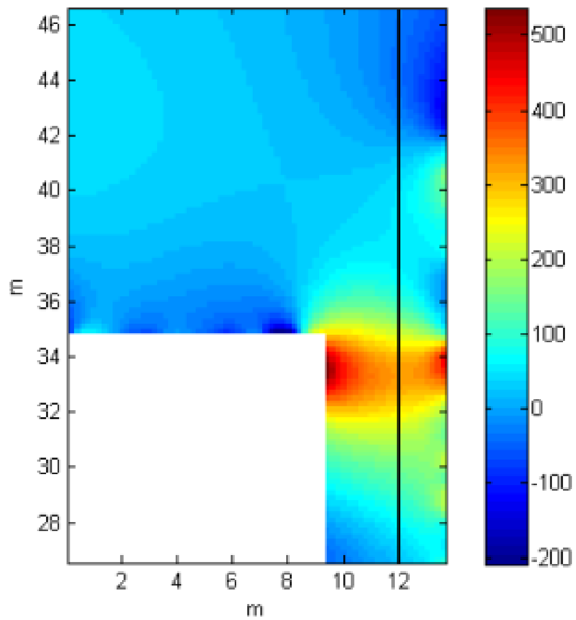


Demonstrated accelerometer resolution: ~6x10^{-12} g.

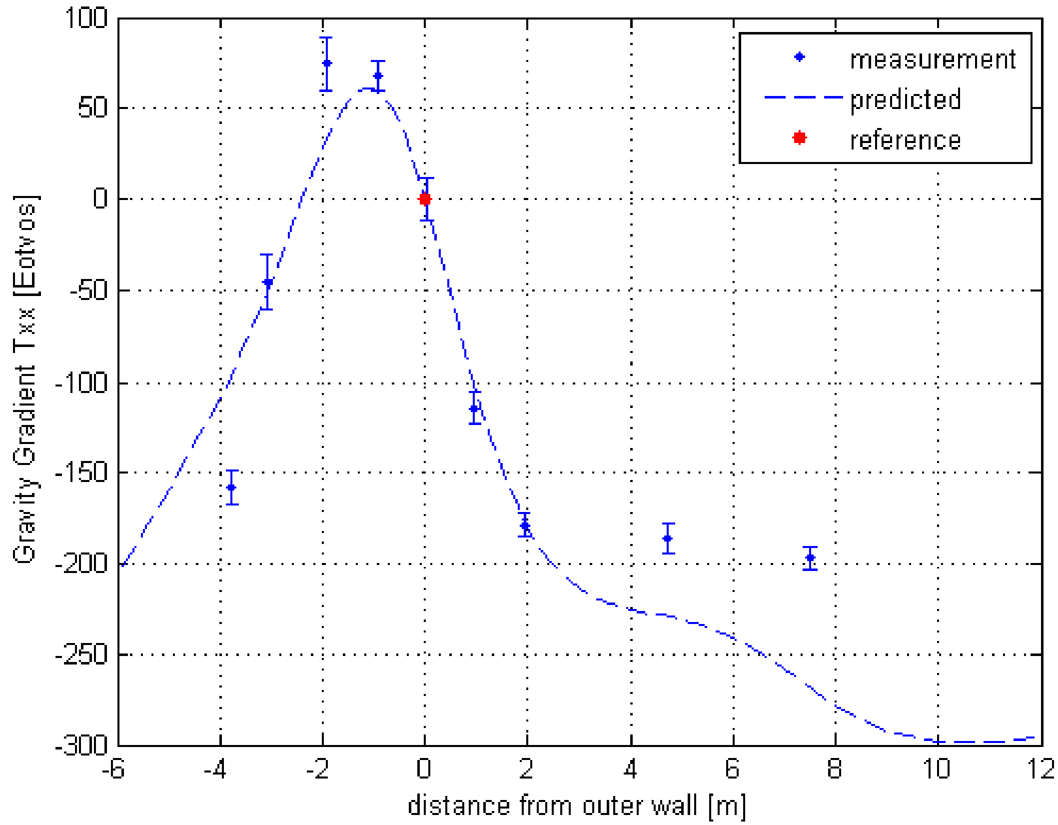
Mobile Gravity Gradient Survey

Sensor mounted in truck on gyro-stabilized platform

Gravity Gradient Survey

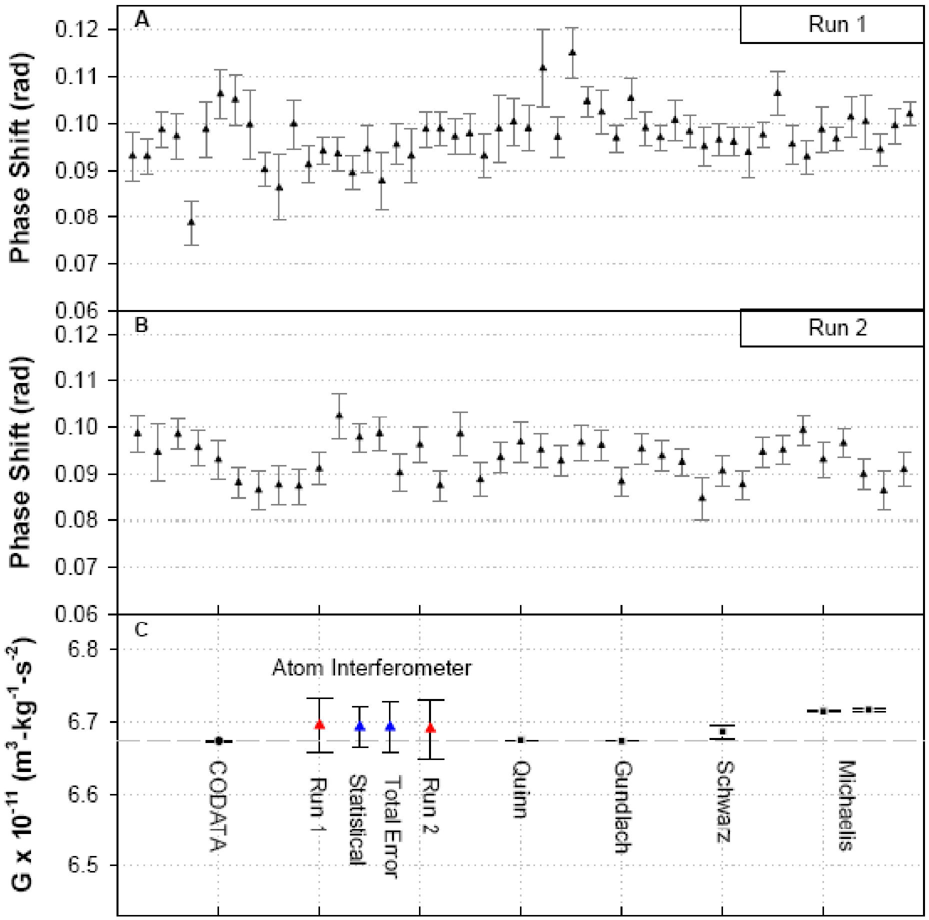


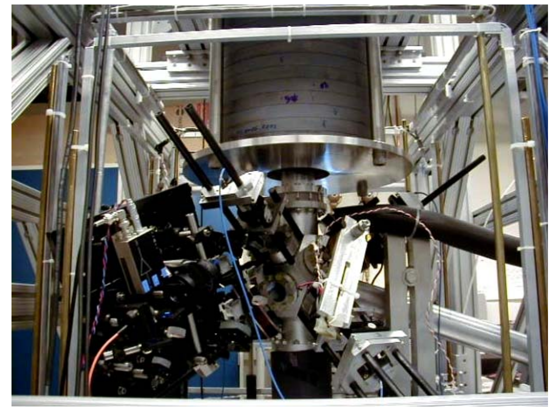
Gravity anomally map from ESIII facility (top view)



Gravity gradient survey of ESIII facility

Measurement of G



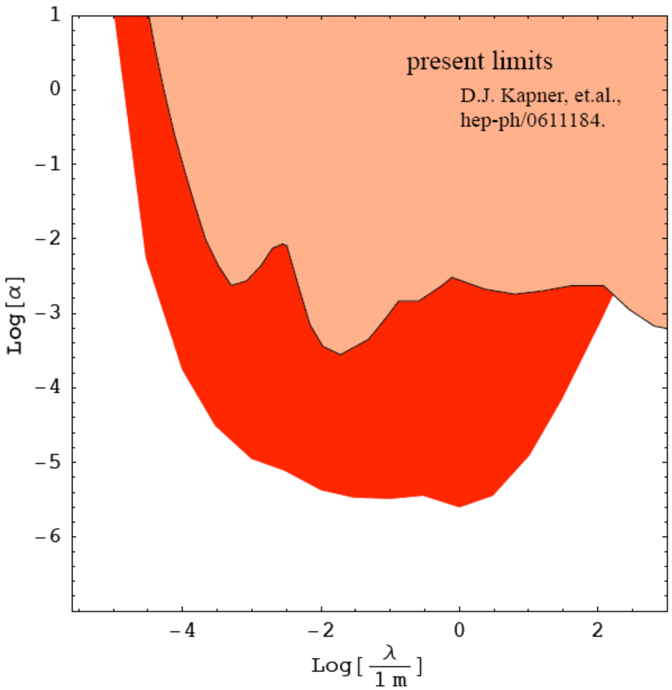


Systematic	$\delta G/G$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

Systematic error sources dominated by initial position/velocity of atomic clouds. $\delta G/G \sim 0.3\%$

Fixler PhD thesis, 2003;Fixler, et al., Science, 2007.

Test Newton's Inverse Square Law

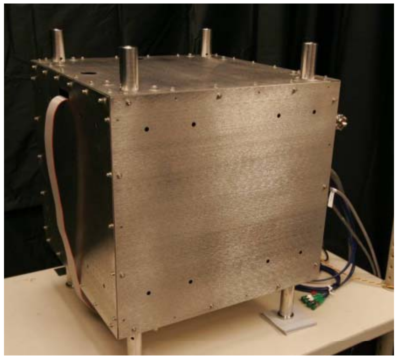


Theory in collaboration with S. Dimopoulos, P. Graham, J. Wacker.

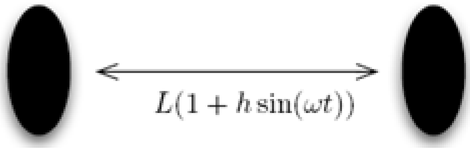
Using new sensors, we anticipate $\delta G/G \sim 10^{-5}$.

This will also test for deviations from the inverse square law at distances from $\lambda \sim$ 1 mm to 10 cm.

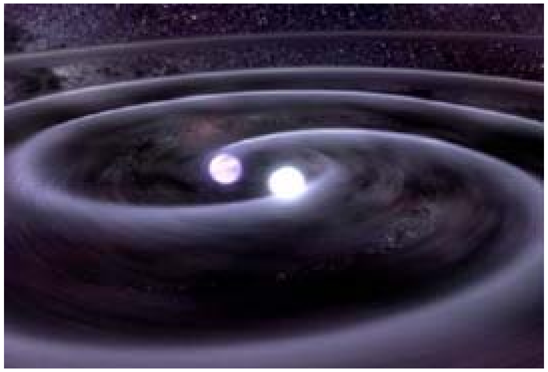
$$V(r) = -G\frac{m_1\, m_2}{r}\left[1 + \alpha\, e^{-r/\lambda}\right]$$



Gravity Wave Detection



Distance between objects modulates by *hL*, where *h* is strain of wave and *L* is their average separation.



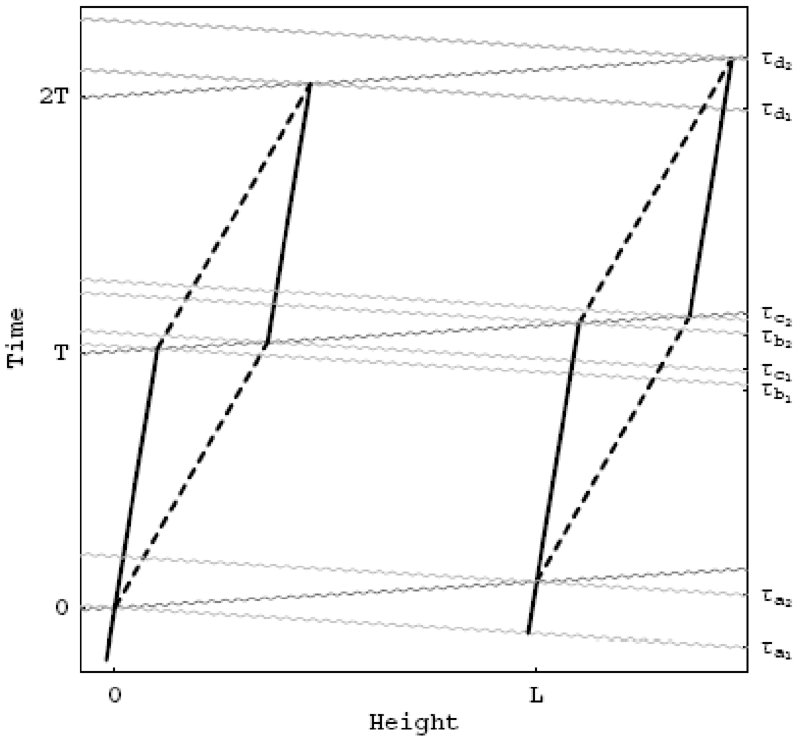
Interesting astrophysical objects (black hole binaries, white dwarf binaries) are sources of gravitational radiation in 0.01 – 10 Hz frequency band.

LIGO is existing sensor utilizing long baseline optical interferometry. Sensitive to sources at > 40 Hz.

Gravity Wave Detection

Metric:

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



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.

Gravity wave induced phase shift:

$$\Delta\phi \sim h\,L\,\sin^2(\omega T/2)$$

h is strain, L is separation, T is pulse separation time, ω is frequency of wave

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).

Phase Shift Calculation Methodology

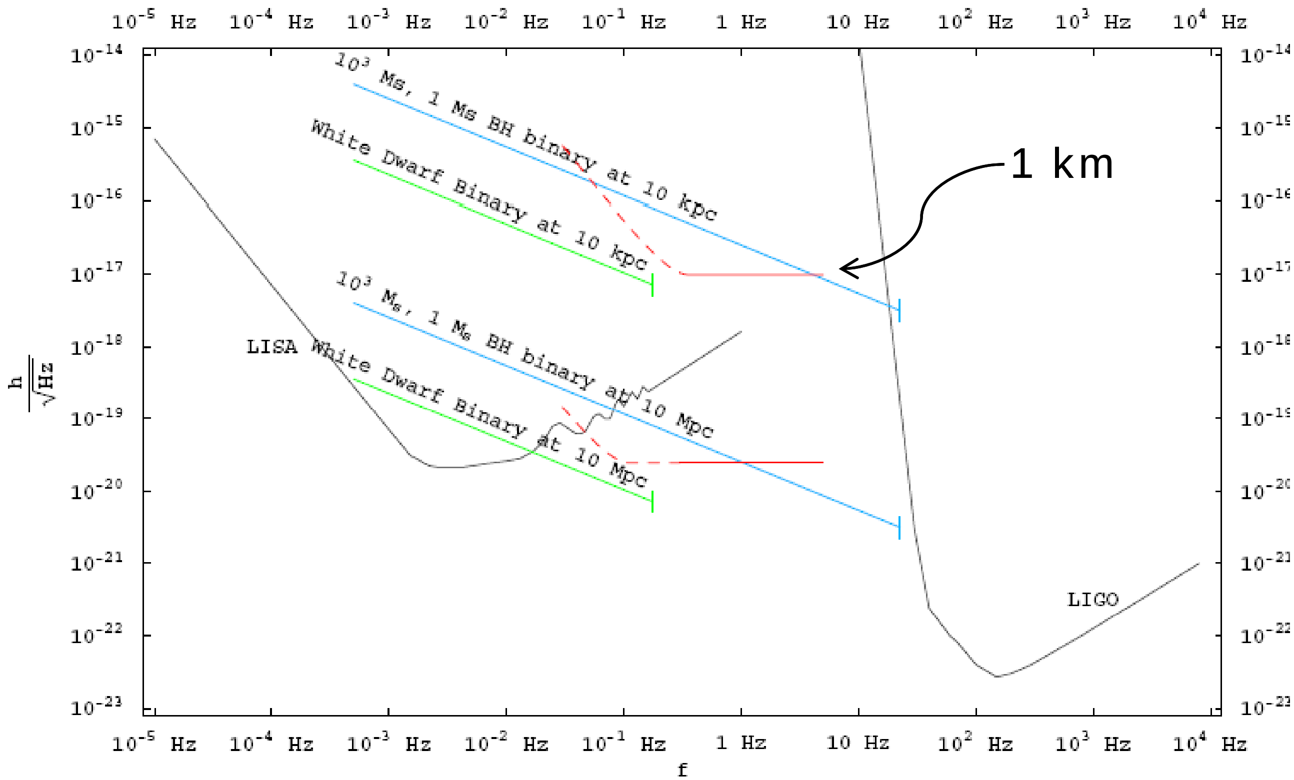
Preliminary

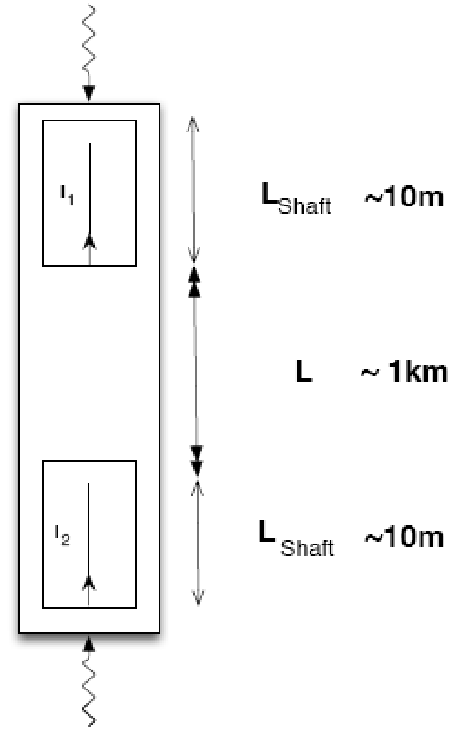
- Define metric
- Calculate geodesic equations for photons and atoms

Atom interferometer phase shift

- Initial coordinates for optical pulses, atom trajectories
- Find intersection coordinates for atom and photon geodesics (2 photons for Raman transitions)
- Evaluate scalar propagation phase
- Coordinate transformation to local Lorentz frame at each atom/photon intersection (Equivalence Principle) for atom/photon interaction (eg. apply Sch. Eq.).
- Coordinate transformation to local Lorentz frame at final interferometer pulse to evaluate separation phase

Proposed Terrestrial Detector Performance

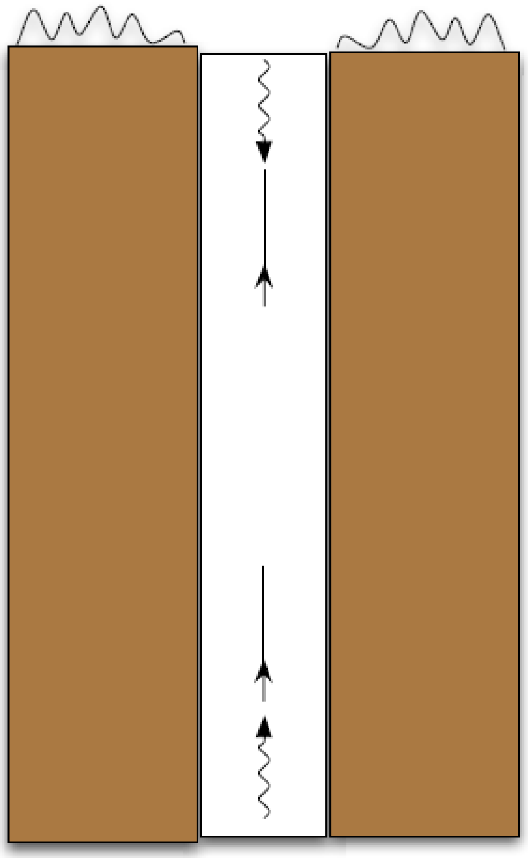




Setup	L	k_{eff}	T	I_L	Phase Sensitivity	f_d
Terrestrial 1	1 km	1.6×10^9 m^{-1}	1.4 s	10 m	10^{-4} rad	10 Hz
Terrestrial 2	4 km	1.6×10^{10} m^{-1}	4.5 s	100 m	10^{-5} rad	10 Hz

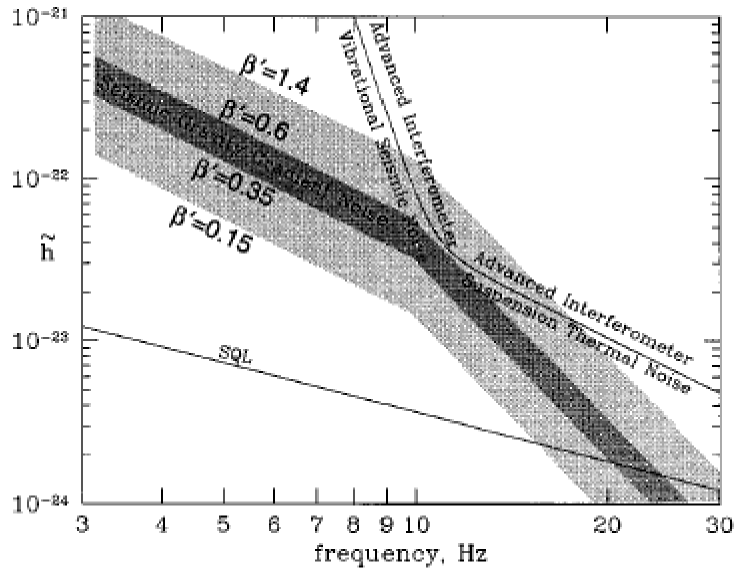
Dimopoulos, Graham, Hogan, Kasevich, Rajendran, 2008 (archiv)

Seismic Noise



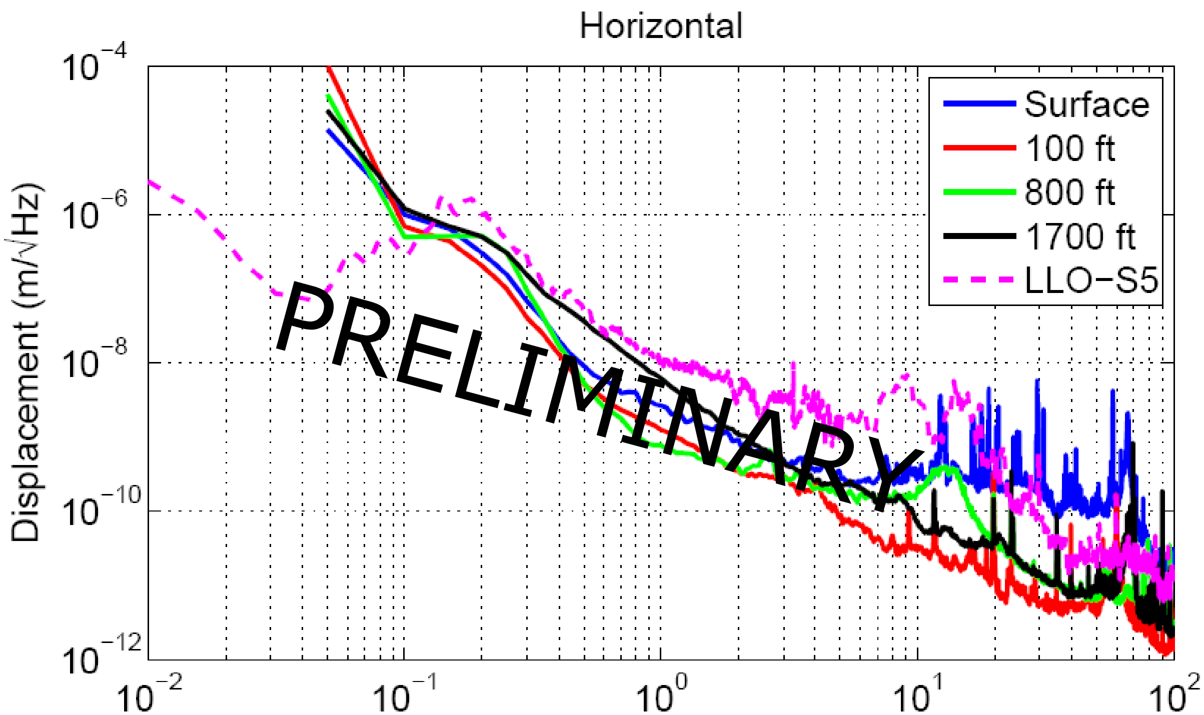
Seismic fluctuations give rise to Newtonian gravity gradients which can not be shielded.

Seismic noise induced strain analysis for LIGO.



From Thorne and Hughes, PRD **58**

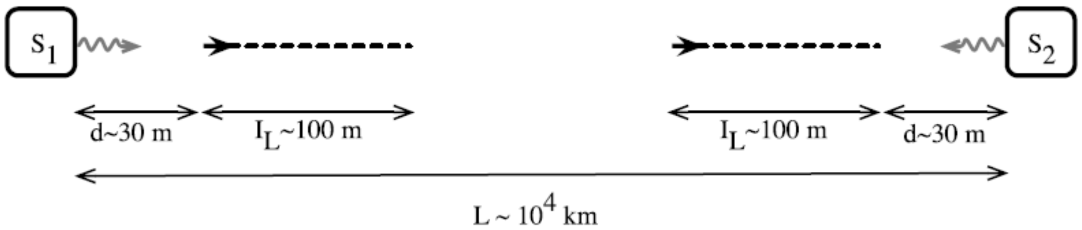
DUSEL: Preliminary Seismic Measurements

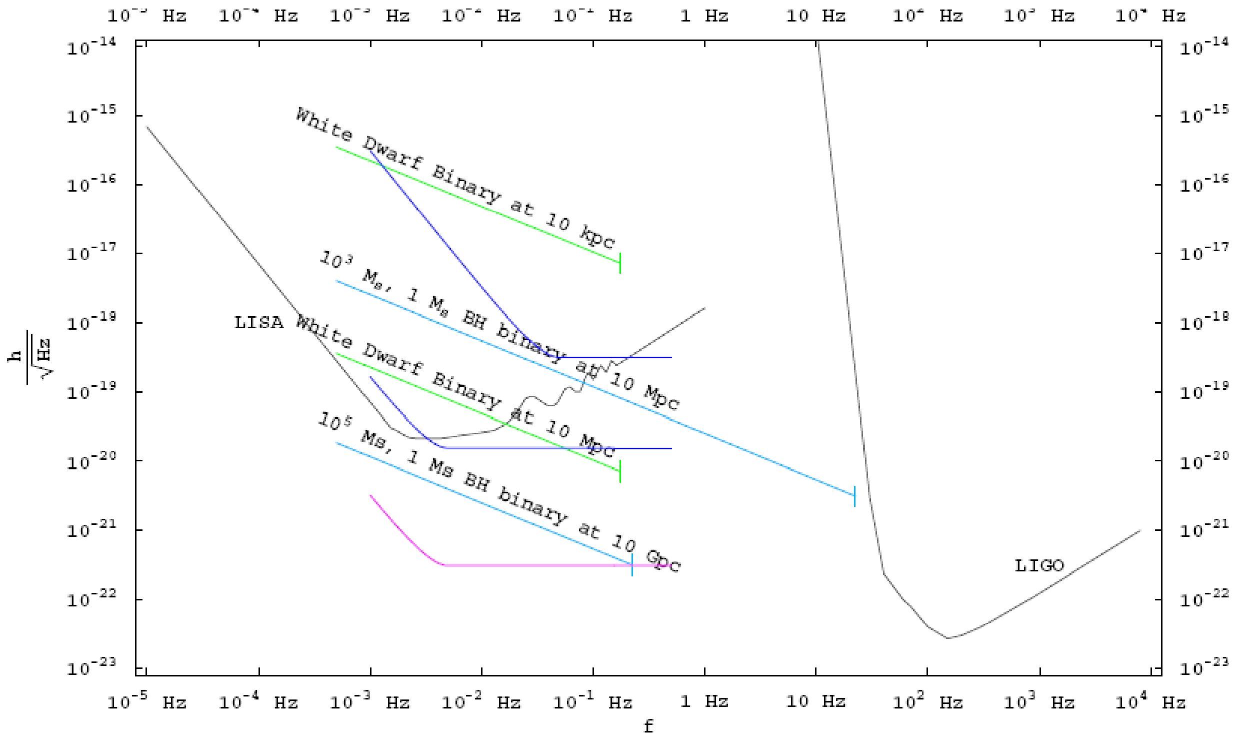


Data courtesy of Vuc Mandic.

Underground facilities may mitigate this noise source as primary disturbances are surface waves.

Satellite Configuration



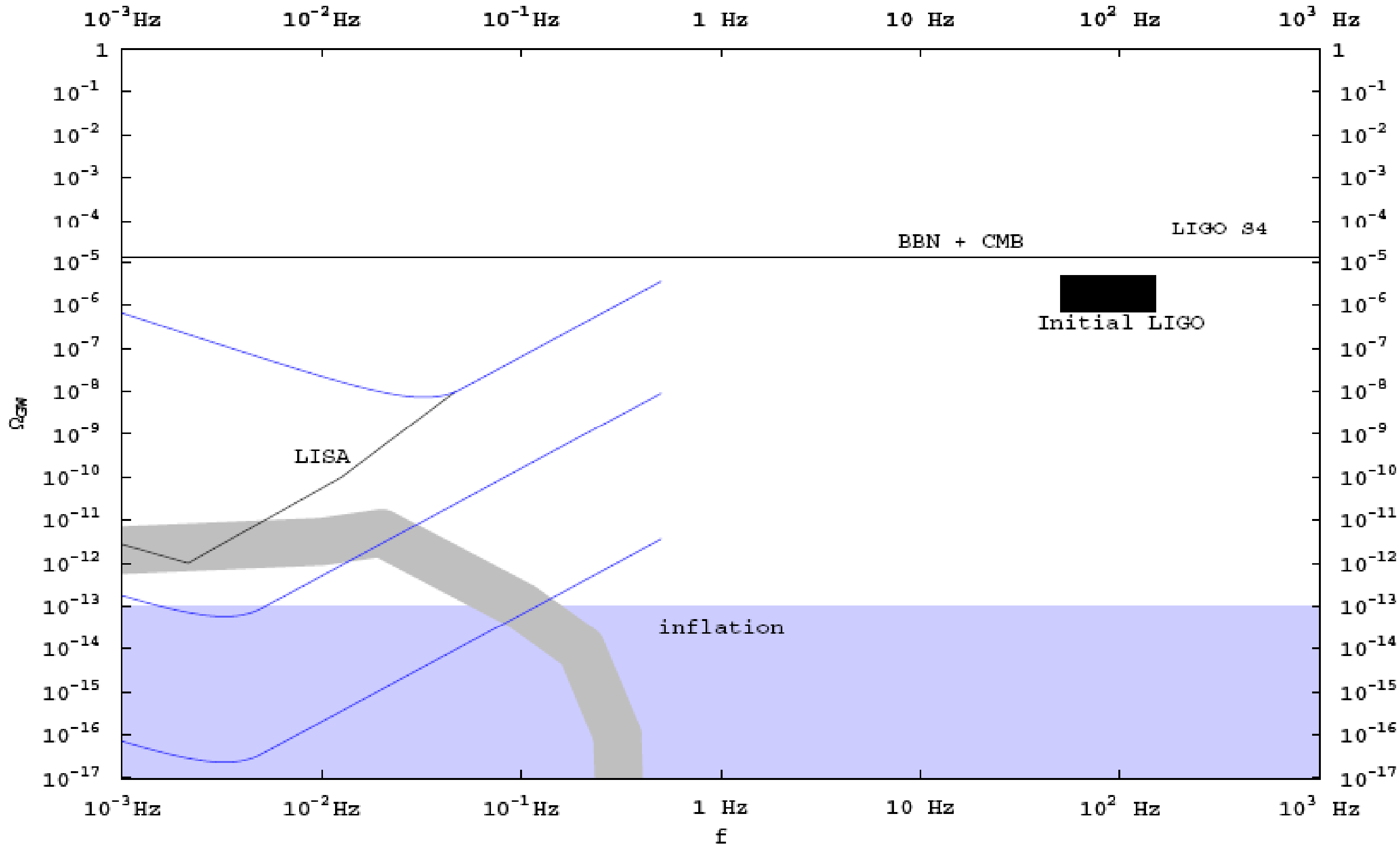


Setup	L	k_{eff}	T	I_L	Phase Sensitivity	f_d
Satellite 1	100 km	1.6×10^9 m^{-1}	10 s	100 m	10^{-4} rad	1 Hz
Satellite 2	10^3 km	3.2×10^9 m^{-1}	100 s	200 m	10^{-4} rad	1 Hz
Satellite 3	10^4 km	1.6×10^9 m^{-1}	100 s	100 m	10^{-5} rad	1 Hz

Lasers, optics and photodetectors located in satellites S1 and S2.

Atoms launched from satellites and interrogated by lasers away from S1 and S2.

Stochastic Gravity Waves



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Atomic Physics Technical Challenges

- Advanced, high flux atom source development
  - high rep rate, high flux source of cold atoms
  - 10 Hz, 10^8 atoms/shot
  - requires incremental advances in current technology

- Large momentum transfer atom optics
  - Enhances sensitivity
  - Demonstrated N ~ 10
  - Desired N ~ 100
  - Work in progress

Large Baseline Apparatus Under Construction

Long free-fall enables ground-based assessment of possible space-based sensor implementations.

Equivalence Principle

Use atom interferometric differential accelerometer to test EP

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

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

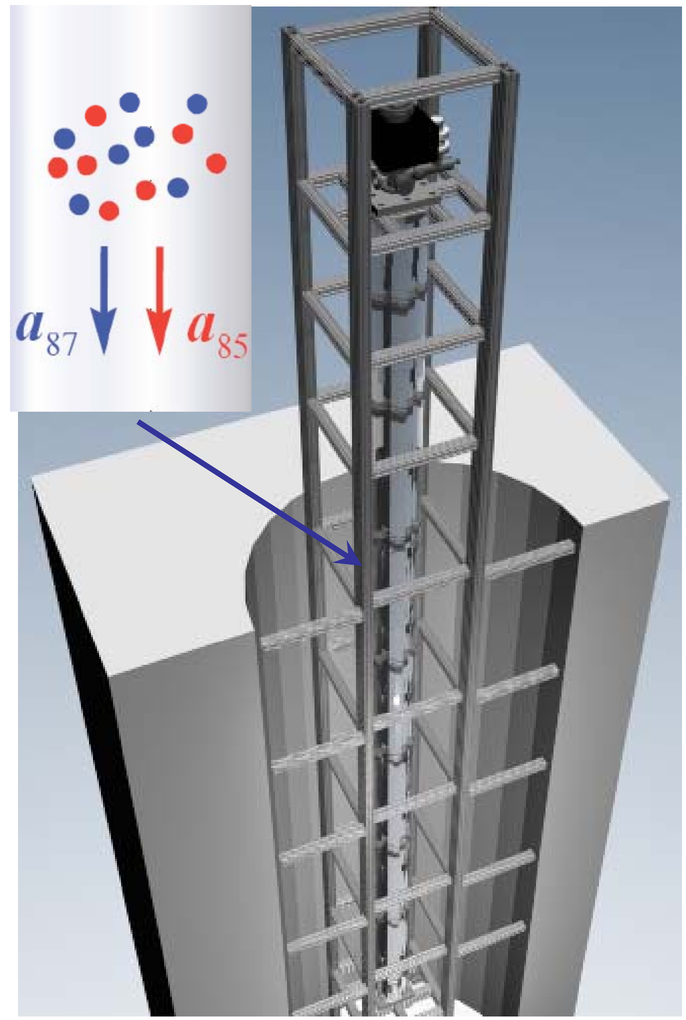
Statistical sensitivity

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

Systematic uncertainty

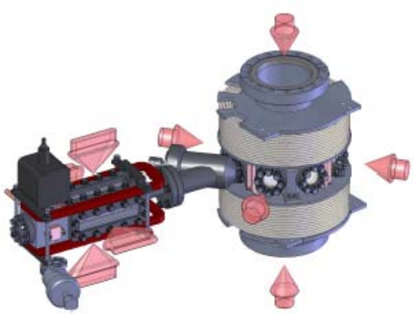
$\delta g \sim 10^{-16}$ g limited by magnetic field inhomogeneities and gravity anomalies.

10 m atom drop tower



10 m drop tower

Atomic source



Parameterized Post-Newtonian (PPN) analysis

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}

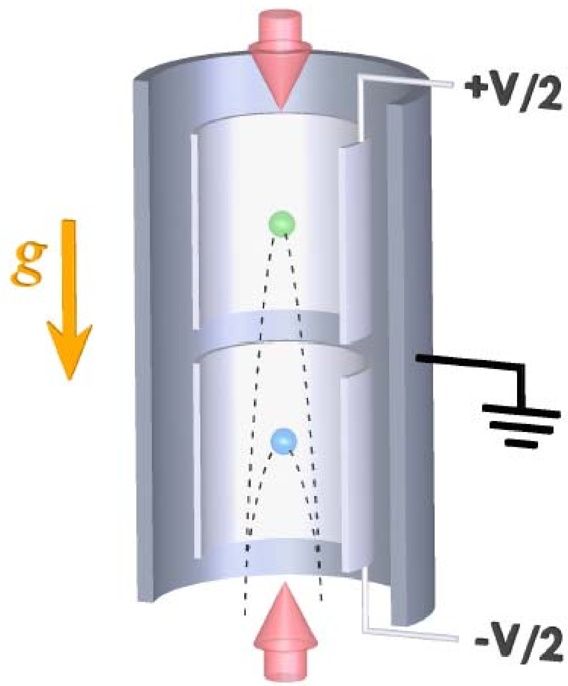
Steady path of apparatus improvements include:

- Improved atom optics (T. Kovachy)
- Taller apparatus
- Sub-shot noise interference read-out
- In-line, accelerometer, configuration (milliarcsec link to external frame NOT req'd).

(Dimopoulos, *et al.*, PRL 2007)

Atom Charge Neutrality

- Apparatus will support >1 m wavepacket separation
- Enables ultra-sensitive search for atom charge neutrality through scalar Aharonov-Bohm effect.



Phase shift: $\epsilon e \int \frac{V}{\hbar} dt$

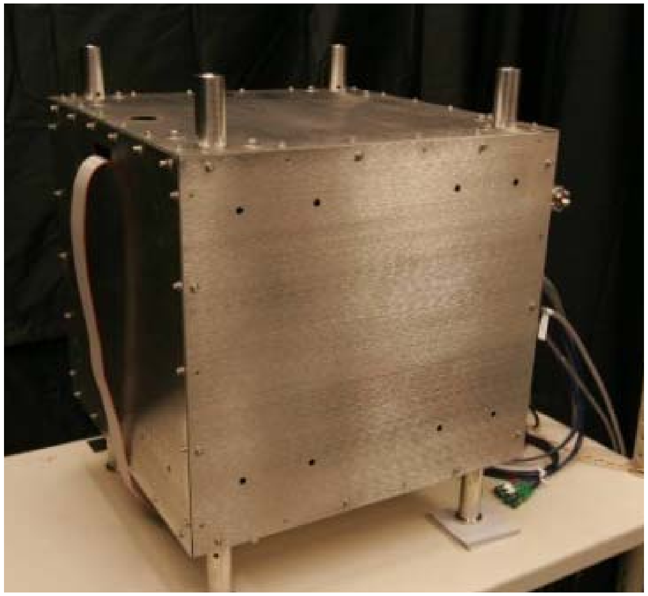
$\varepsilon \equiv \delta e/e \sim 10^{-26}$ for mature experiment using scalar Aharonov-Bohm effect

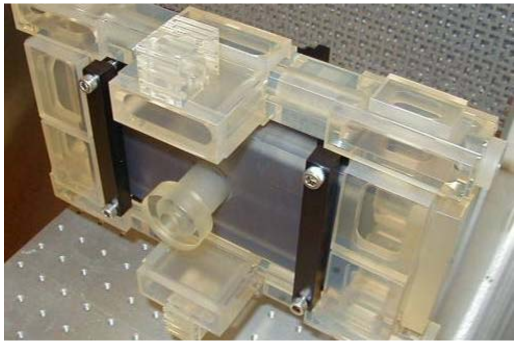
Current limit: $\delta e/e \sim 10^{-20}$ (Unnikrishnan *et al*., Metrologia **41**, 2004)

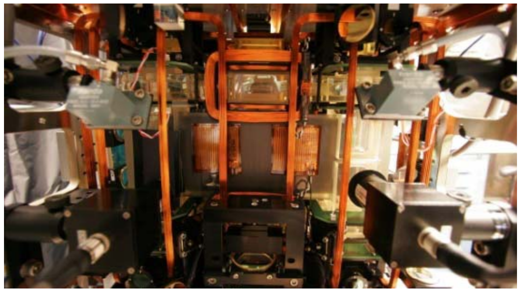
Impact of a possible observed imbalance currently under investigation.

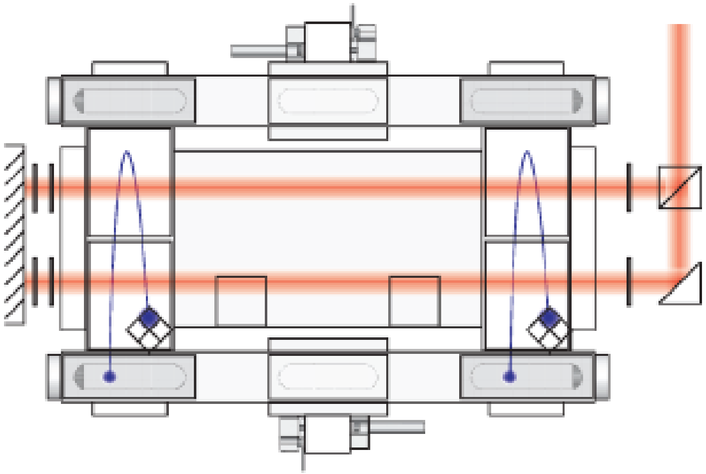
Arvanitaki, Dimopoulos, Geraci, Kasevich, PRL 2008.

Hybrid Sensor





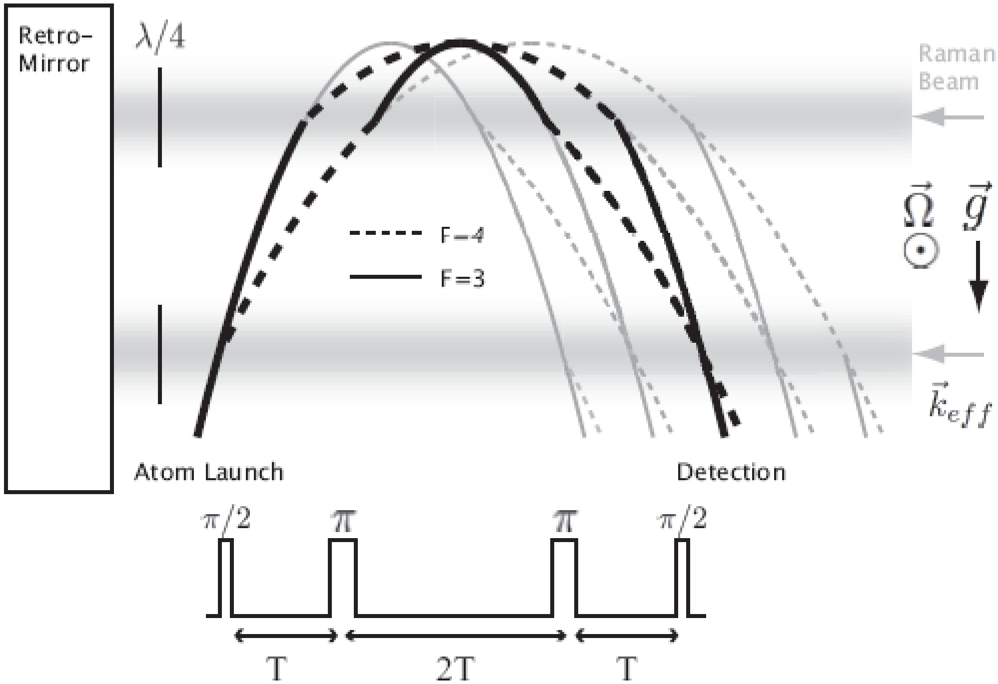




Raman interrogation demonstrated in PINS Phase I gyro.

POC Joe Gentile, SP-24; POC Jay Lowell, DARPA

Vertical Gyroscope Configuration



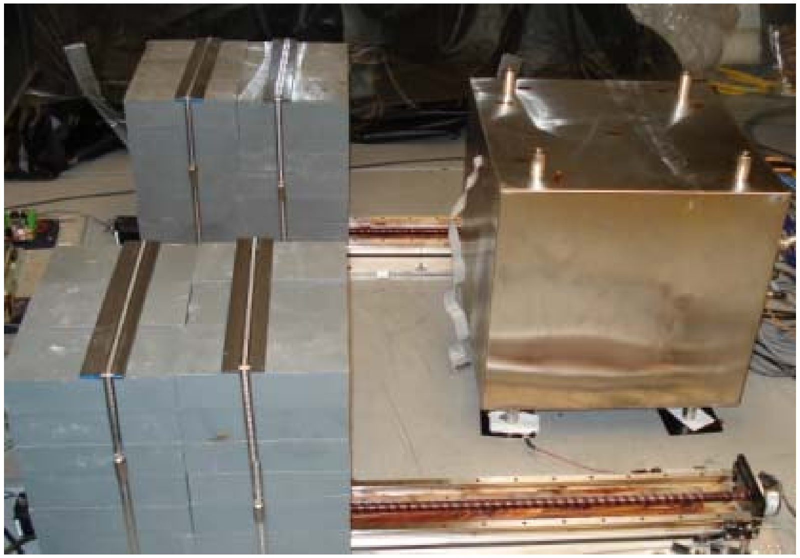
$$\phi = 6\mathbf{k}_{eff} \cdot ((\mathbf{\Omega}_F + \mathbf{\Omega}_E) \times (\mathbf{g} + \mathbf{a}))T^3$$
$$-2\mathbf{k}_{eff} \cdot (\mathbf{\Omega}_E \times \mathbf{g})T^3,$$

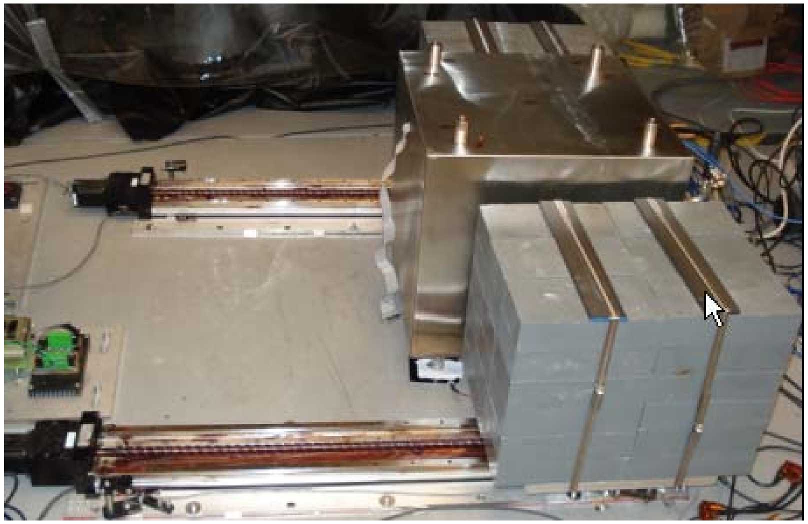
Sensor phase shift blends tilt response with true gyroscope response.

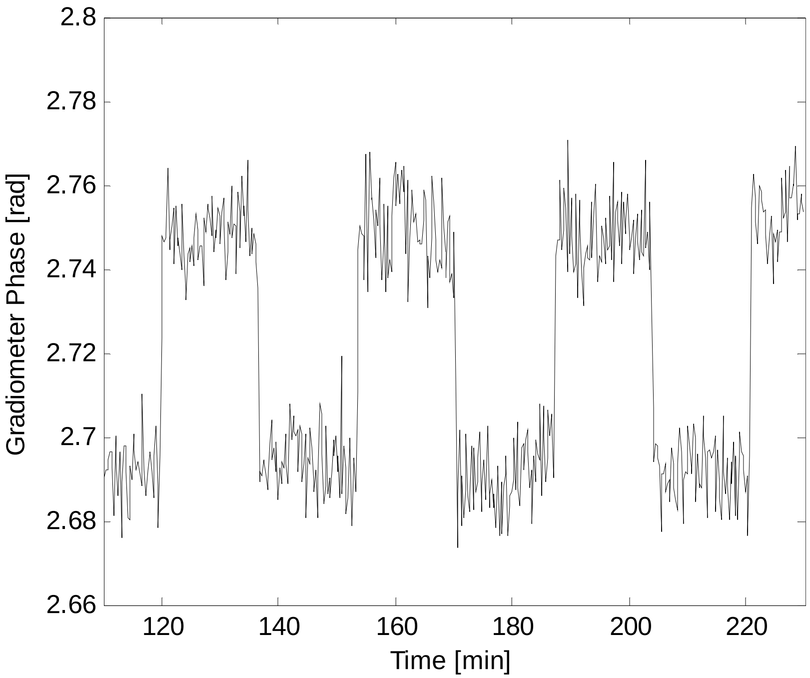
Care required in extracting inertial shifts.

Pulse timing skew is required to supress spurious interfering paths.

Gravity gradiometer



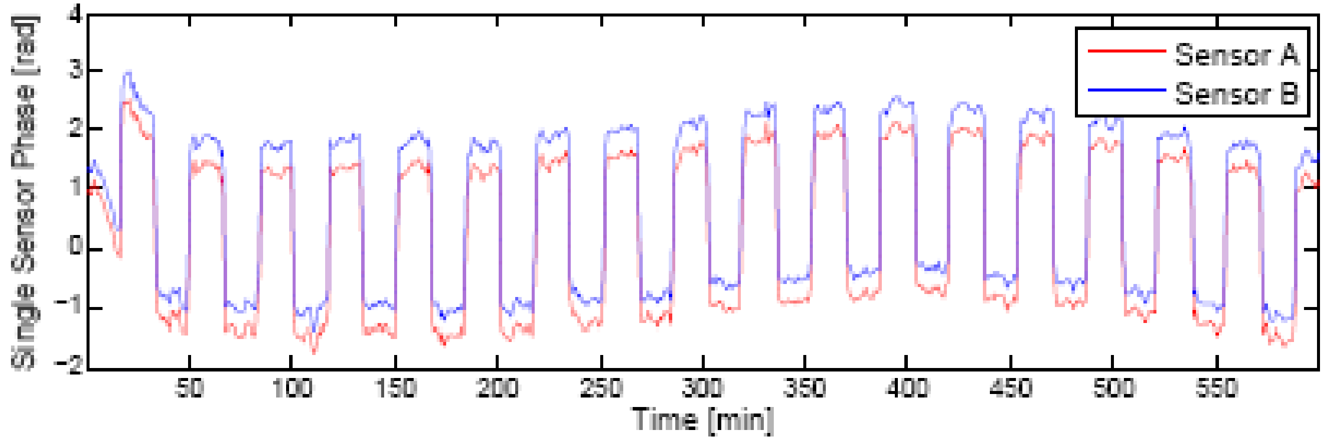




250 E/Hz$^{1/2}$ noise during quiet periods.

Signal has also been observed directly on individual accelerometers

Accelerometer



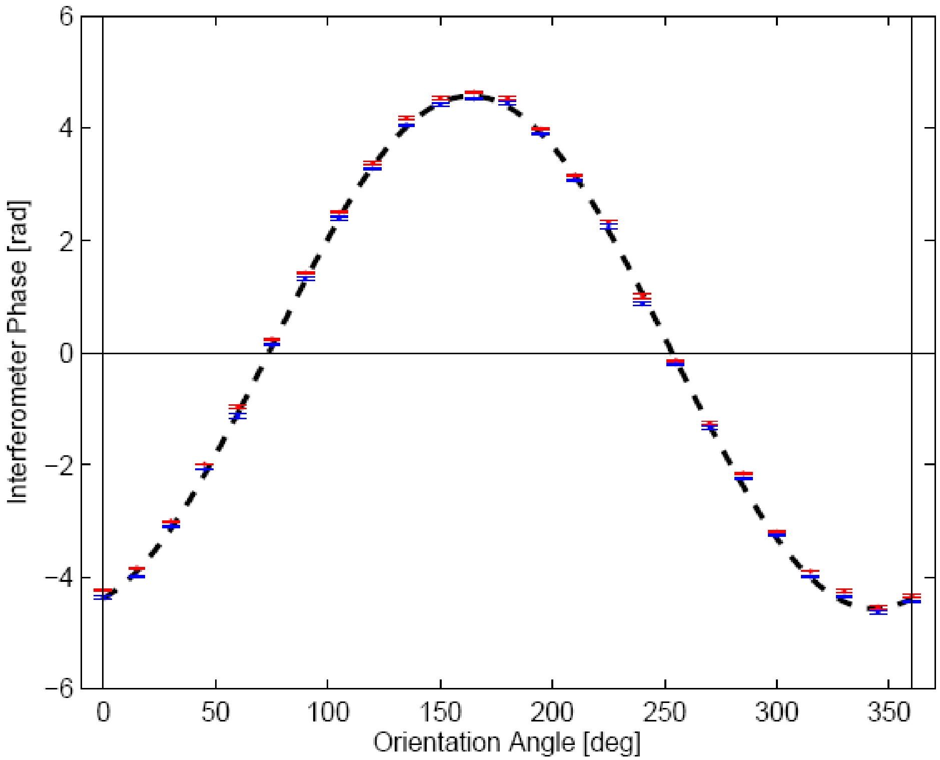
Direct accelerometer outputs.

Scale factor: 5×10^{-7} g/rad.

Demonstrated microGal resolution.

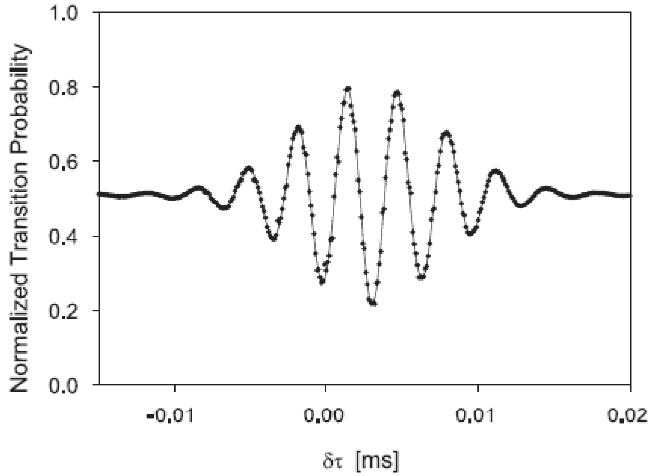
Gyroscope

Measured gyroscope output vs.orientation:

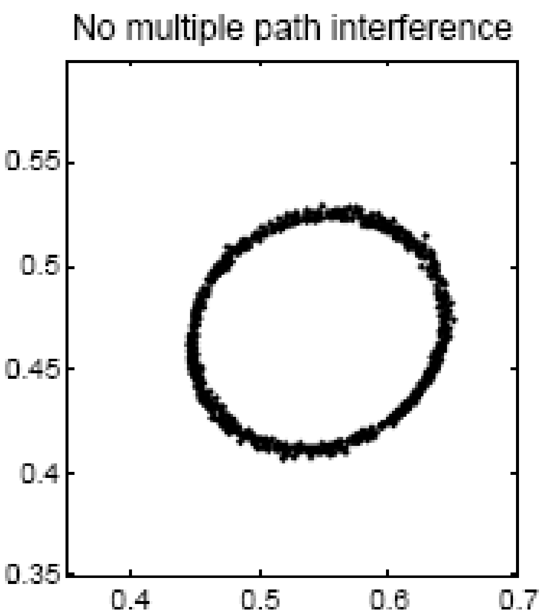


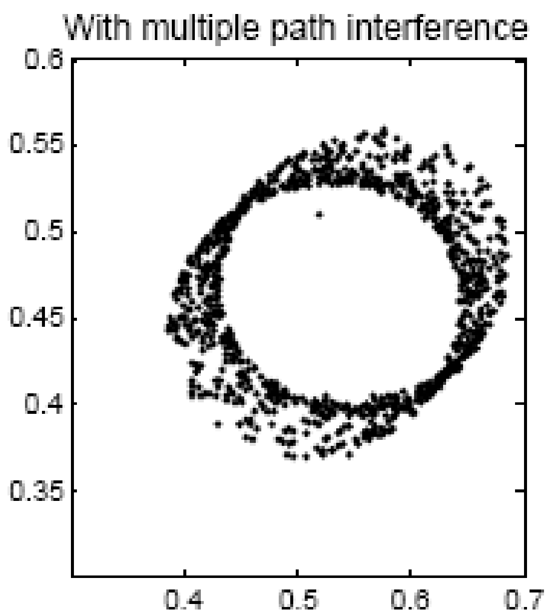
- Phase shift $\delta\phi = 6\mathbf{k}\cdot(\mathbf{g}\times\Omega)\, T^3$
- Inferred ARW: ~100 μdeg/hr$^{1/2}$
- 10 deg/s max input

A quantum sensor .... coherence length



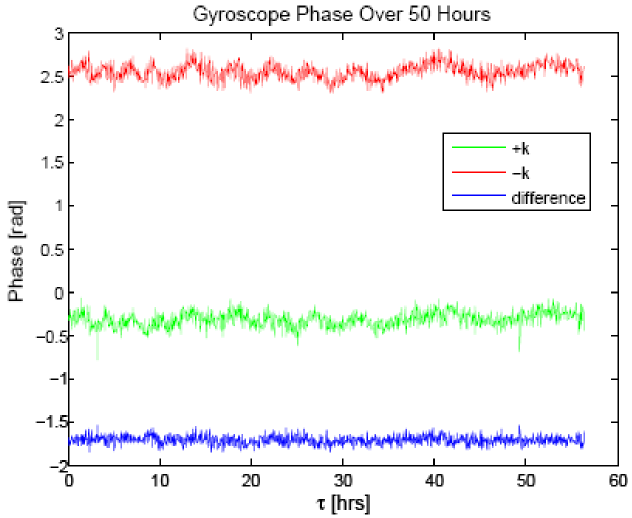
Measurement of coherence length of laser cooled atomic source (~ 100 nm)

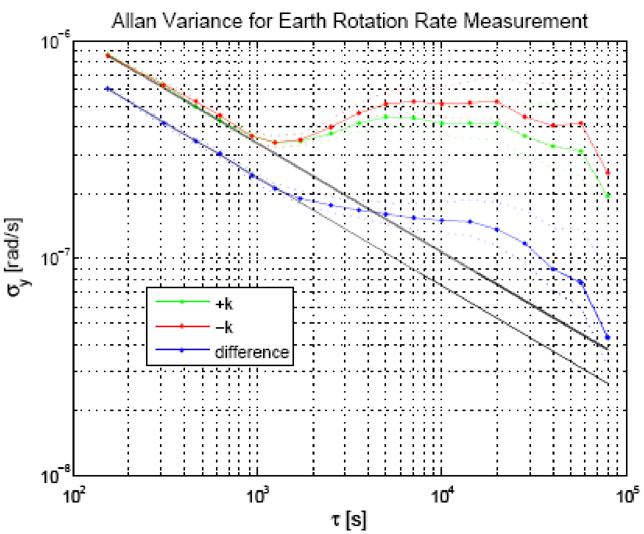




Time-skewed pulse sequence to reject spurious mutli-path interferences

Scale factor accuracy and bias stability





$$\Omega/\Omega_E = 1.0007 \pm 0.0005$$

Scale factor determined from **g** and known latitude.

Case reversal to suppress non-inertial phase shifts.

Stability limited by technical vibration noise of measurement platform.

Currently investigating vibration mitigation strategies.

Cosmology

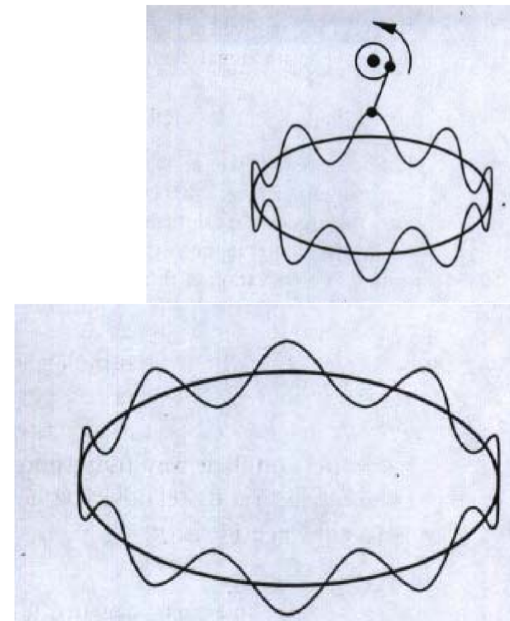
Are there (local) observable phase shifts of cosmological origin?

Analysis has been limited to simple metrics:

- FRW: $ds^2 = dt^2 - a(t)^2(dx^2+dy^2+dz^2)$
- McVittie: ~Schwarzchild + FRW

$$g = \left(\frac{1 - m(t)/2r}{1 + m(t)/2r}\right)^2 dt^2 - \left(1 + \frac{m(t)}{2r}\right)^4 a^2(t)\left(dr^2 + r^2 d\Omega^2\right).$$

Giulini, gr-qc/0602098



From MTW

No detectable (linear H) local signatures for Hubble expansion

Future theory: Consider phenomenology of exotic/speculative theories?

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- David Johnson, Graduate student, Physics
- Alex Sugarbaker, Graduate student, Physics
- Jason Hogan, Graduate student, Physics
- Sean Roy, Graduate student, Physics
- Tim Kovachy, Undergraduate
- Boris Dubestsky, Research Scientist
- Paul Bayer, Engineer

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