Gravitational Physics using Atom Interferometry

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Young's double slit with atoms

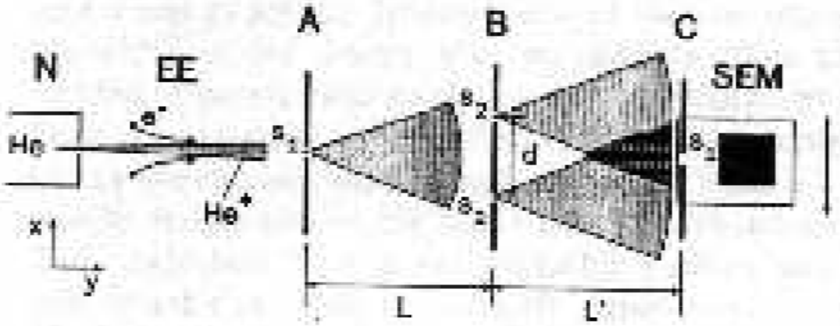


FIG. 2. Schematic representation of the experimental setup:

Young's 2 slit with Helium atoms

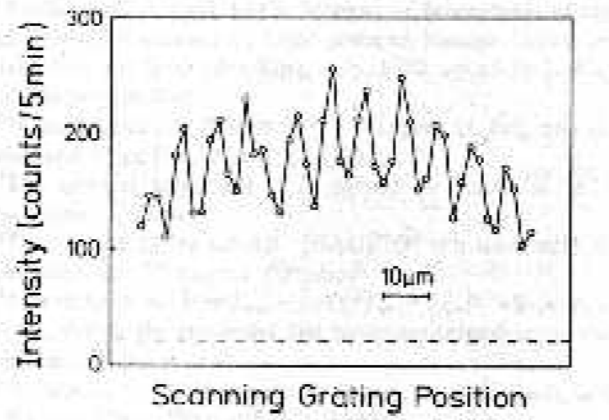
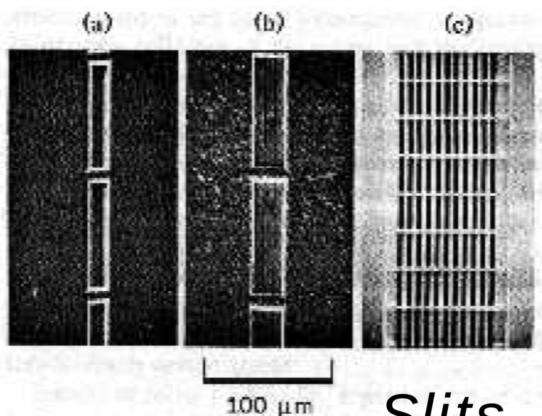


FIG. 5. Atomic density profile, monitored with the 8-μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

Interference fringes 2691

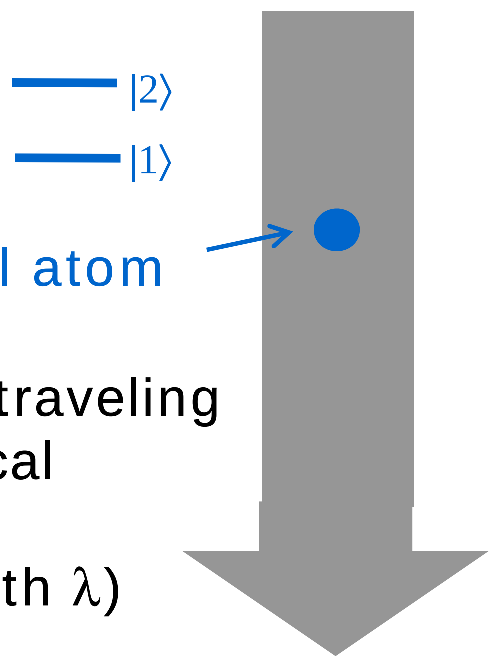


Slits

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

(Light-pulse) atom interferometry

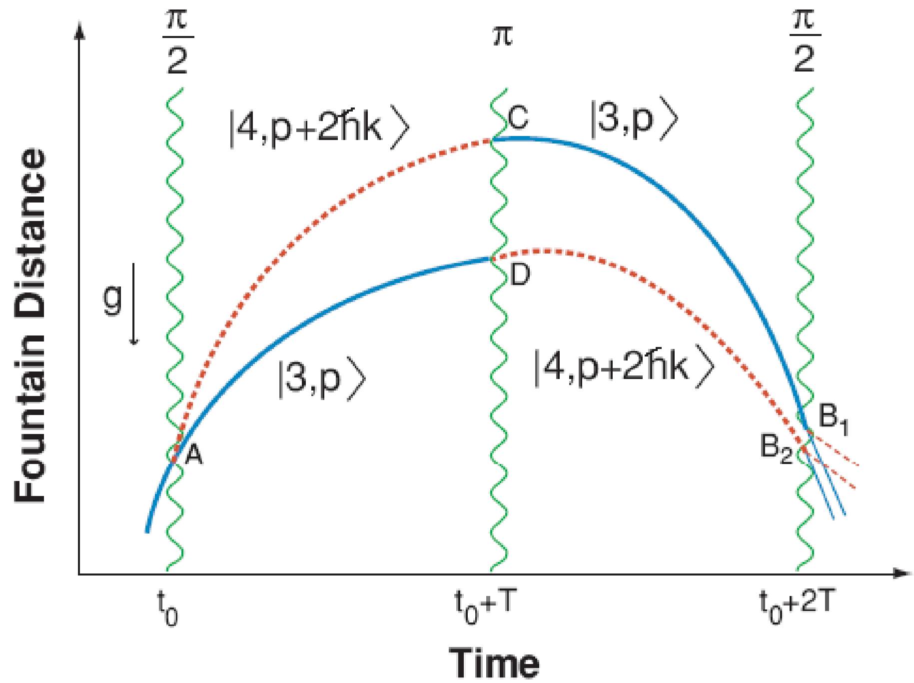
Resonant optical interaction



Resonant traveling wave optical excitation, (wavelength λ)

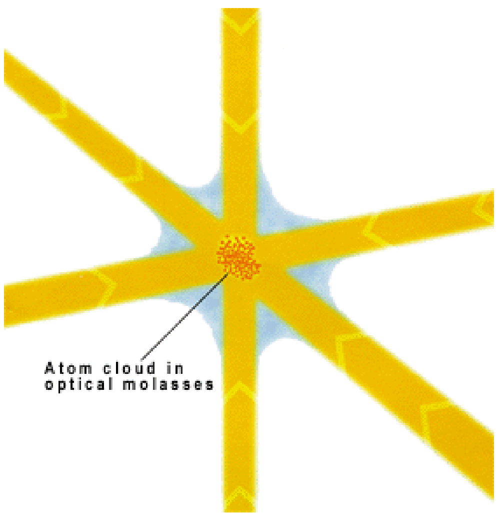
Recoil diagram

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



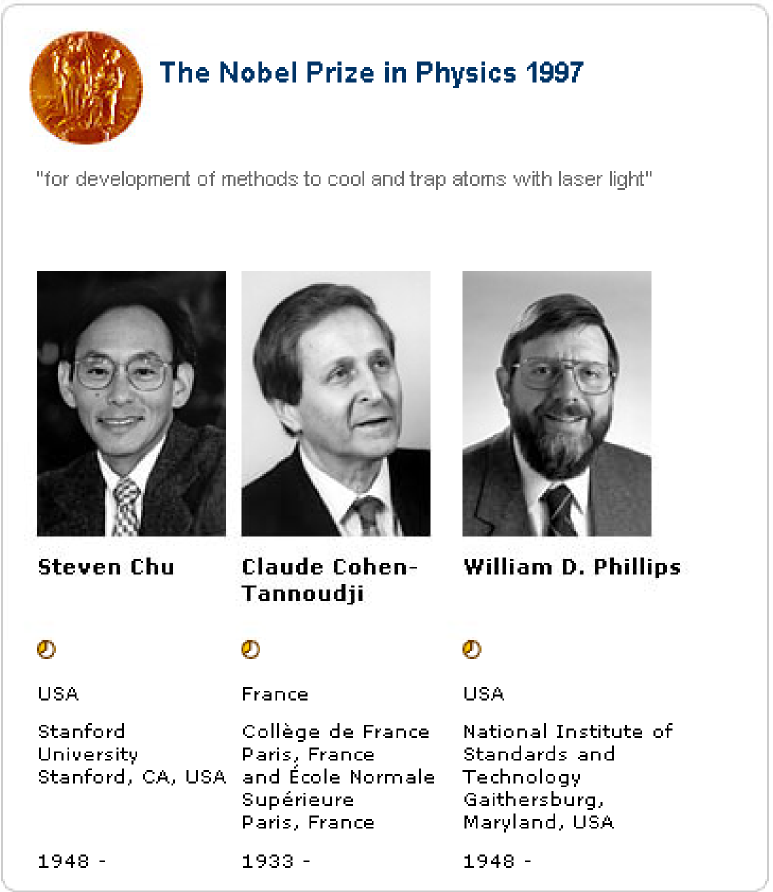
Laser cooling

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



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

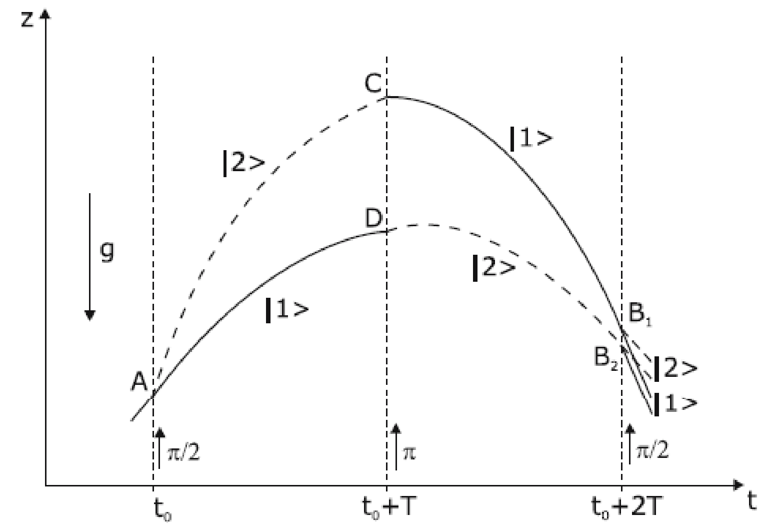
Image source:www.nobel.se/physics



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:

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

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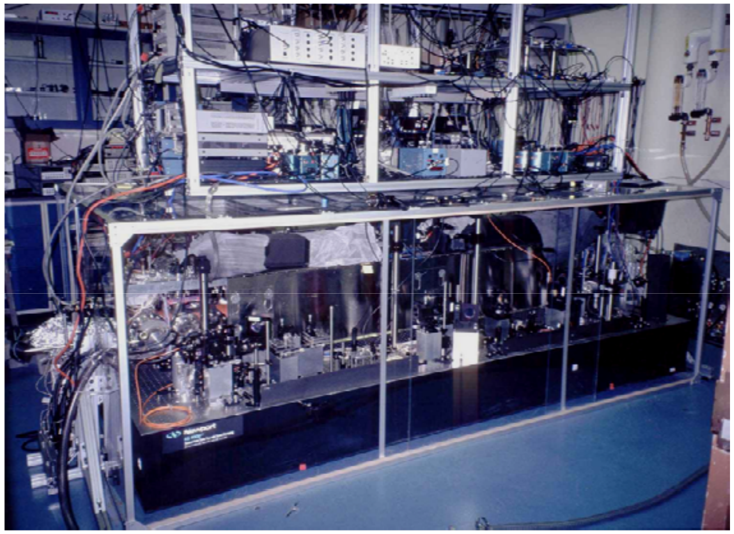
See Bongs, et al., quant-ph/0204102 (April 2002) also App. Phys. B, 2006.

Laboratory gyroscope



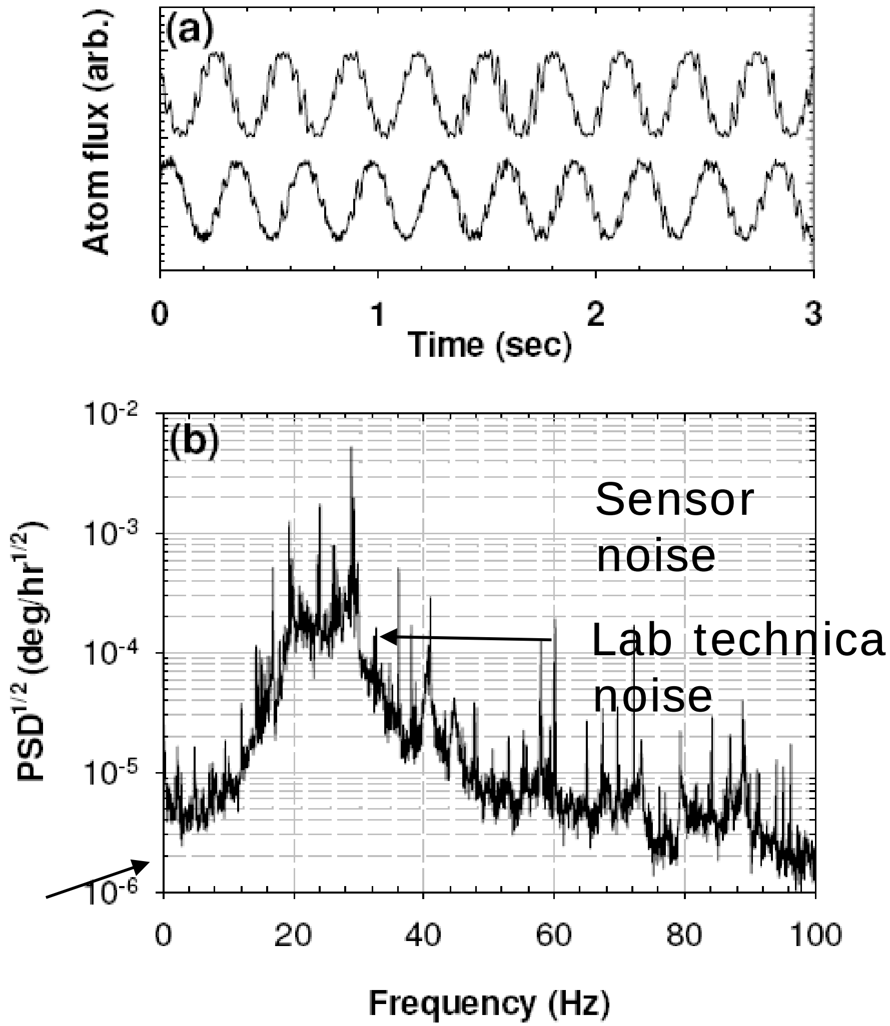
AI gyroscope

Noise: $3\ \mu deg/hr^{1/2}$

Bias stability: $< 60\ \mu deg/hr$

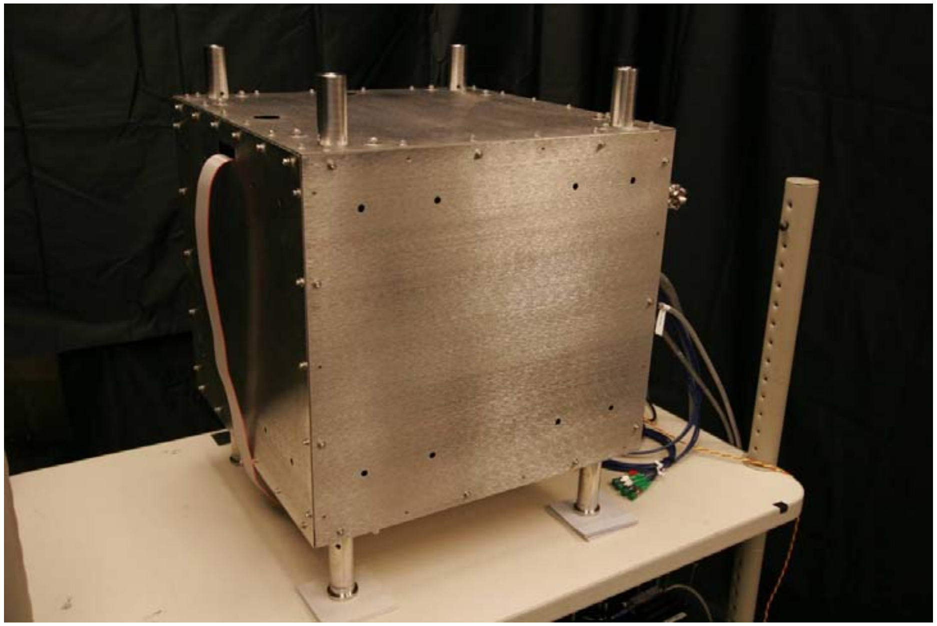
Scale factor: < 5 ppm

Gyroscope interference fringes:

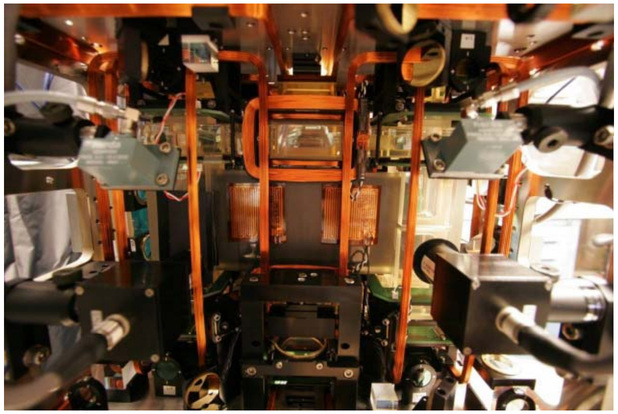


Gustavson, et al., PRL, 1997,
Durfee, et al., PRL, 2006

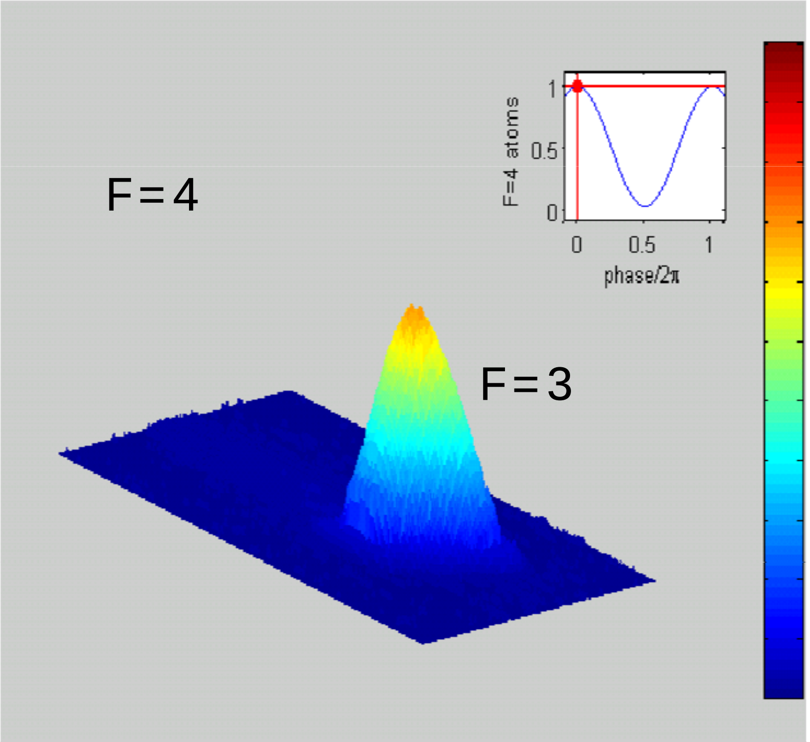
Compact gyroscope/accelerometer



Multi-function sensor measures rotations and linear accelerations along a single input axis.

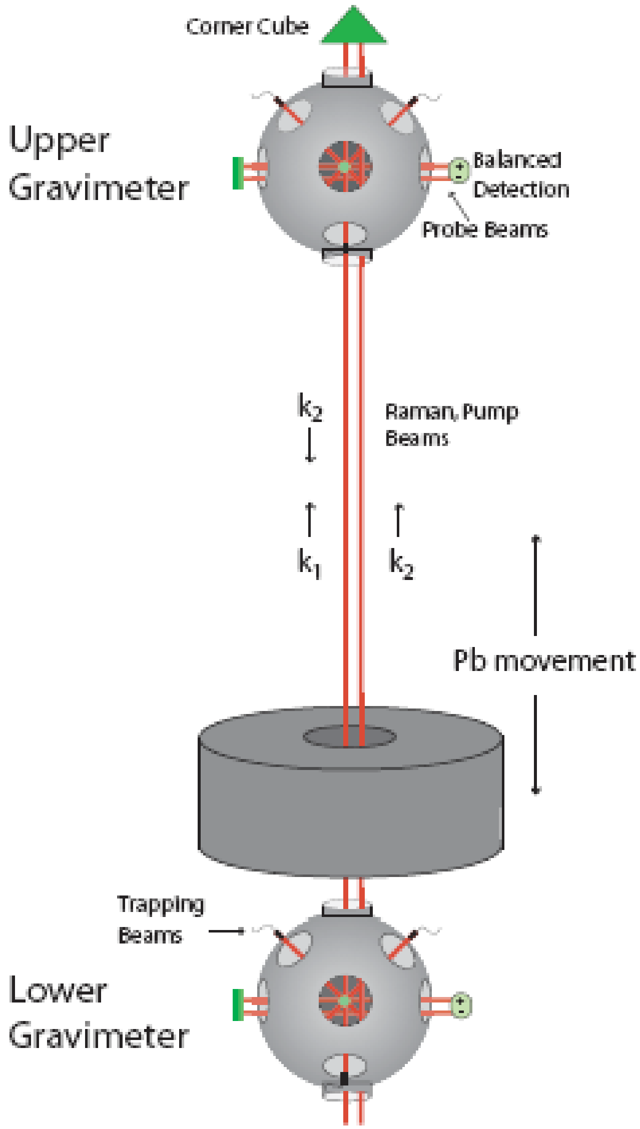


Interior view

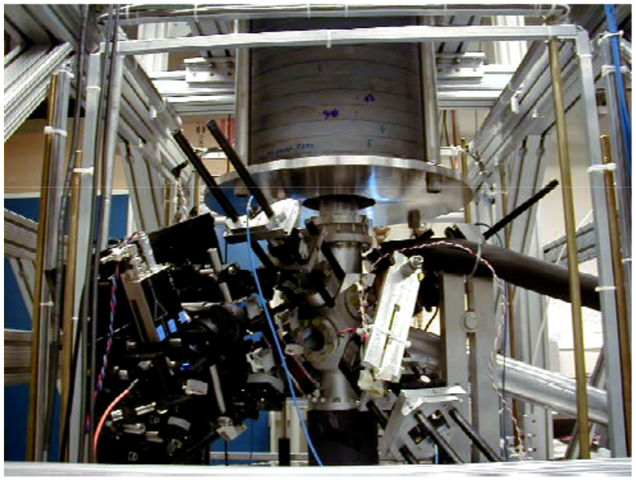


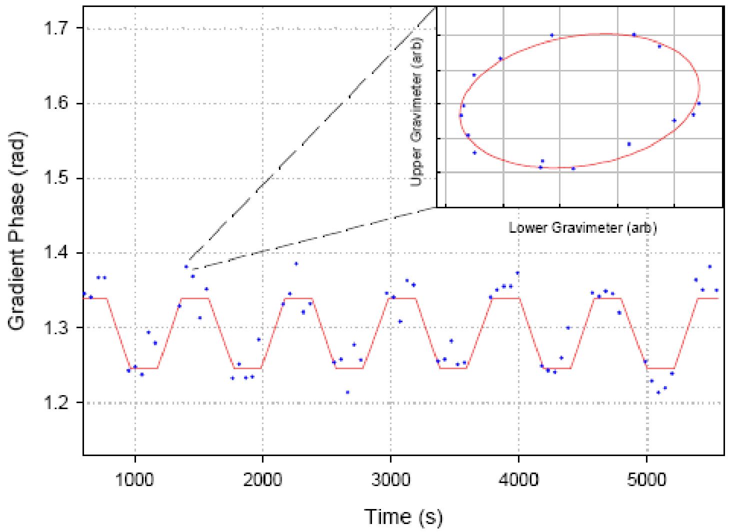
Interference fringes are recorded by measuring number of atoms in each quantum state

Measurement of Newton's Constant

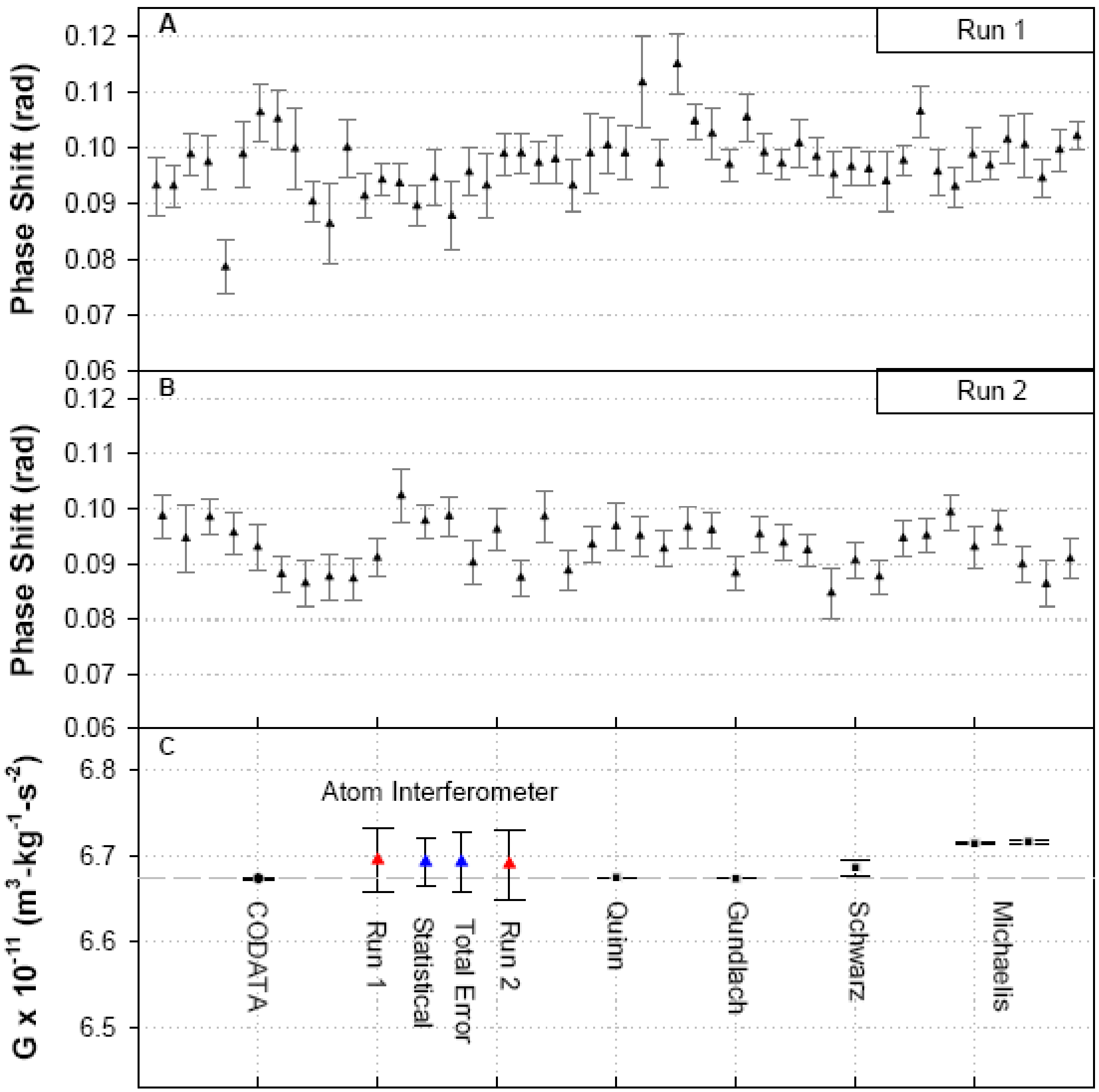


Pb mass translated vertically along gradient measurement axis.





Measurement of G



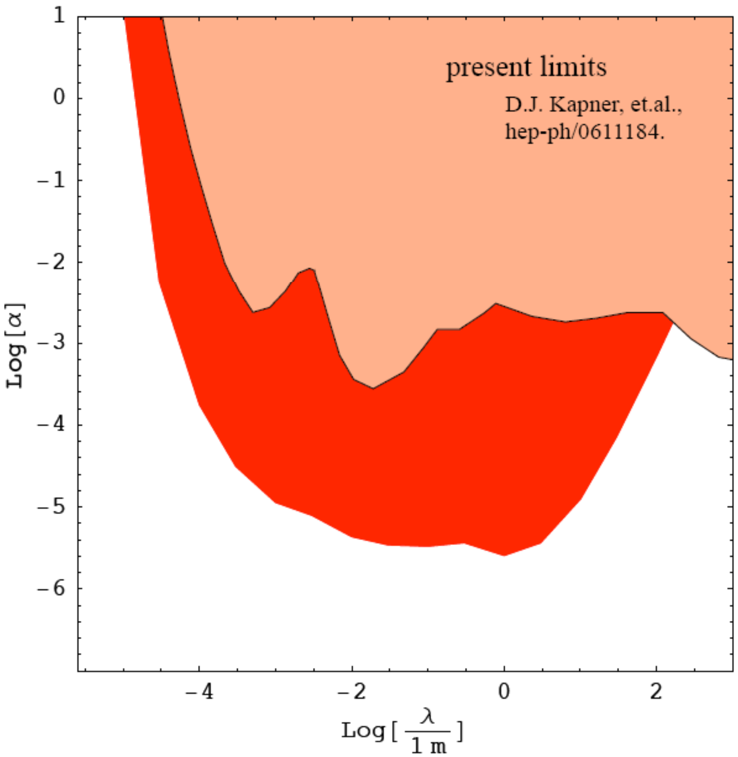
Systematic	$\delta G/G$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source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

Systematic error sources dominated by initial position/velocity of atomic clouds.

$\delta G/G$ ~ 0.3%

Fixler, et al., Science, 2007

Next generation experiment (in progress)

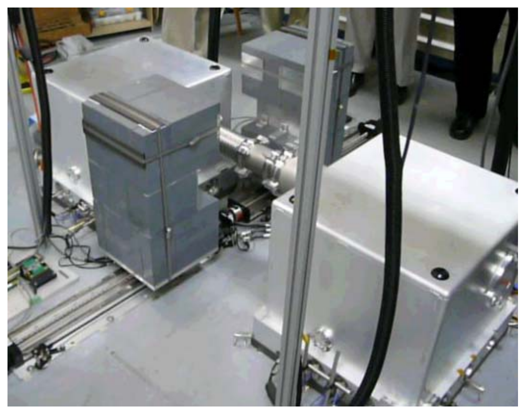


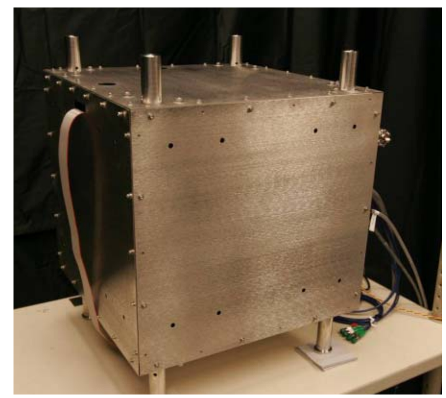
Theory in collaboration with S. Dimopoulos, P. Graham, J. Wacker.

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.

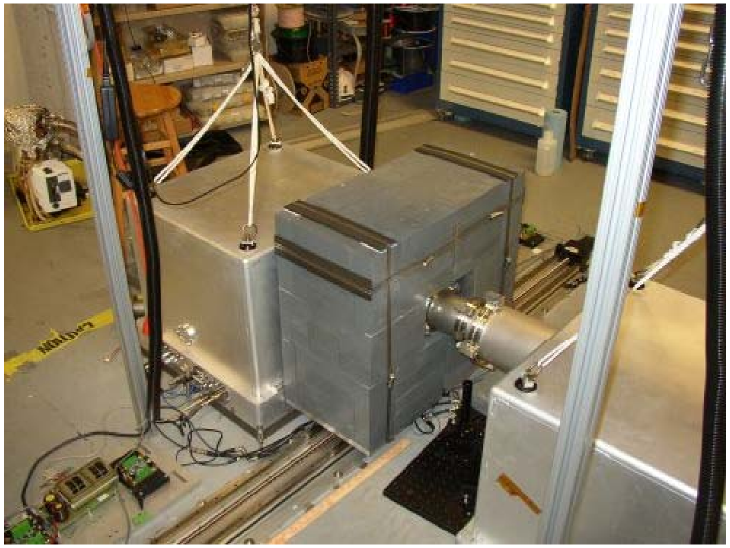
$$V(r) = -G\frac{m_1\, m_2}{r}\left[1 + \alpha\, e^{-r/\lambda}\right]$$

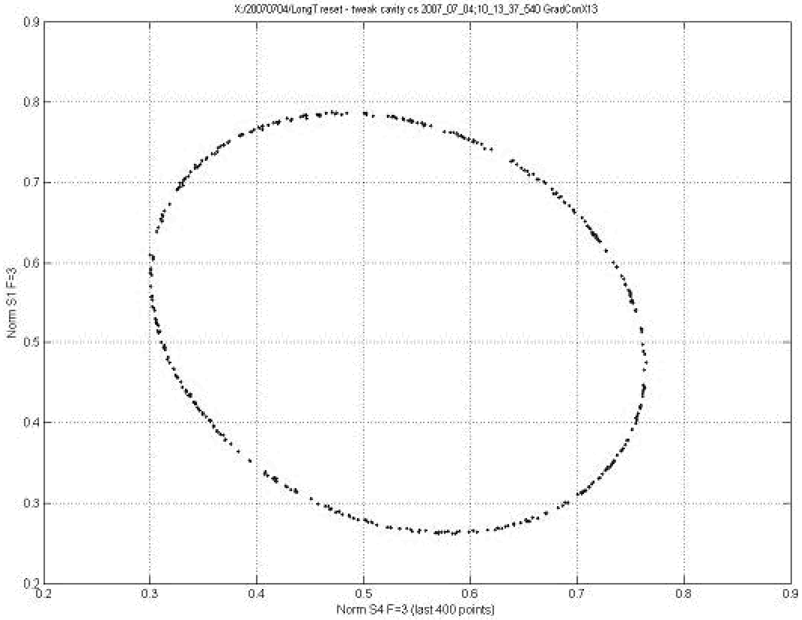


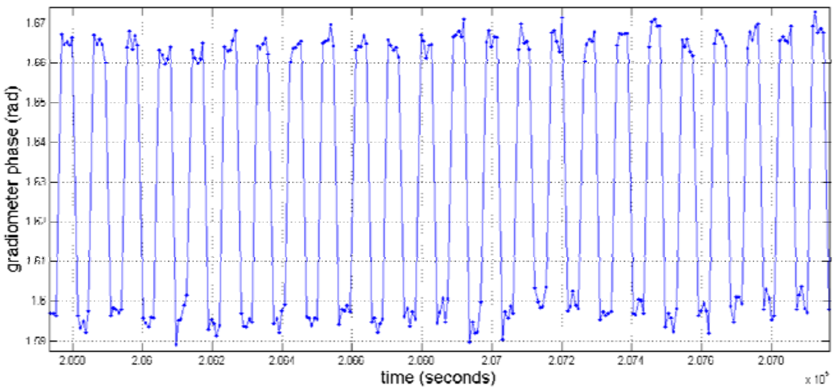


Sensors in use for next generation G measurements.

Experiment in progress



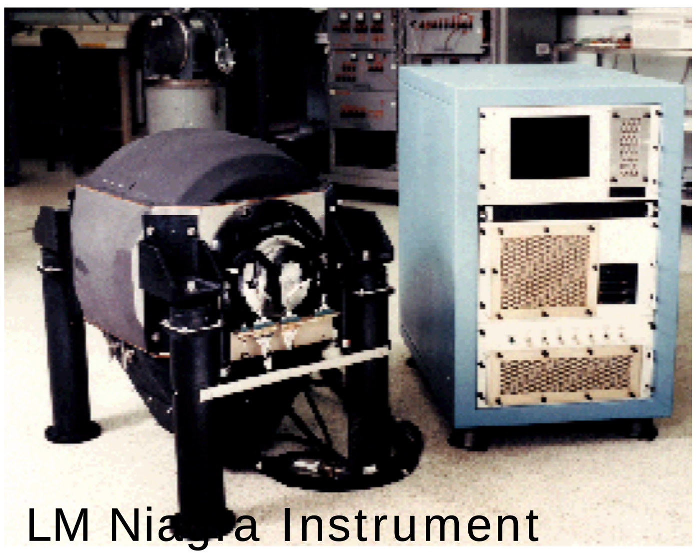




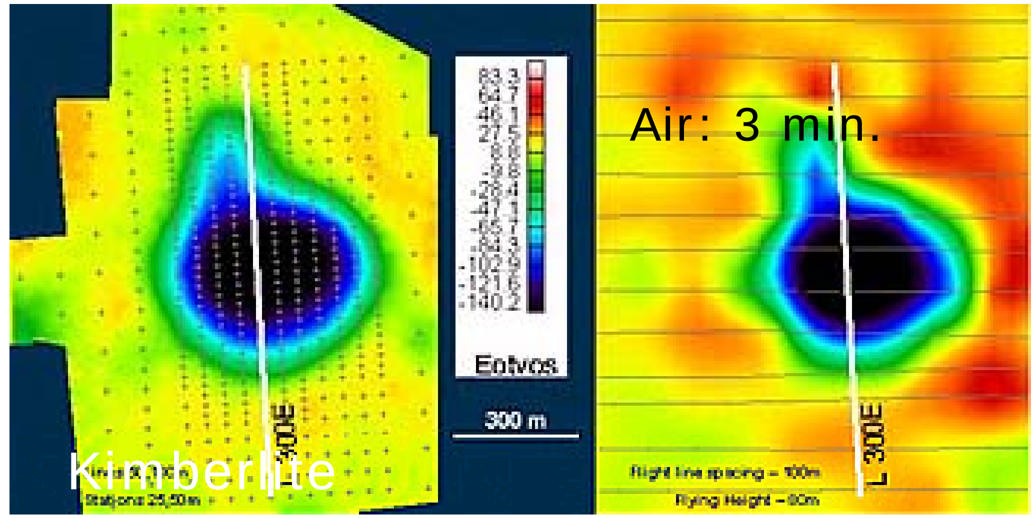
Currently achieved statistical sensitivity at ~2x10^{-4} G.

Airborne Gravity Gradiometer

Existing technology



Land: 3 wks.



AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

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

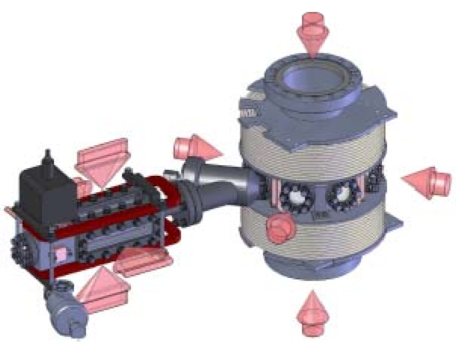
$\delta g \sim 10^{-15}$ g with 1 month data collection

Systematic uncertainty

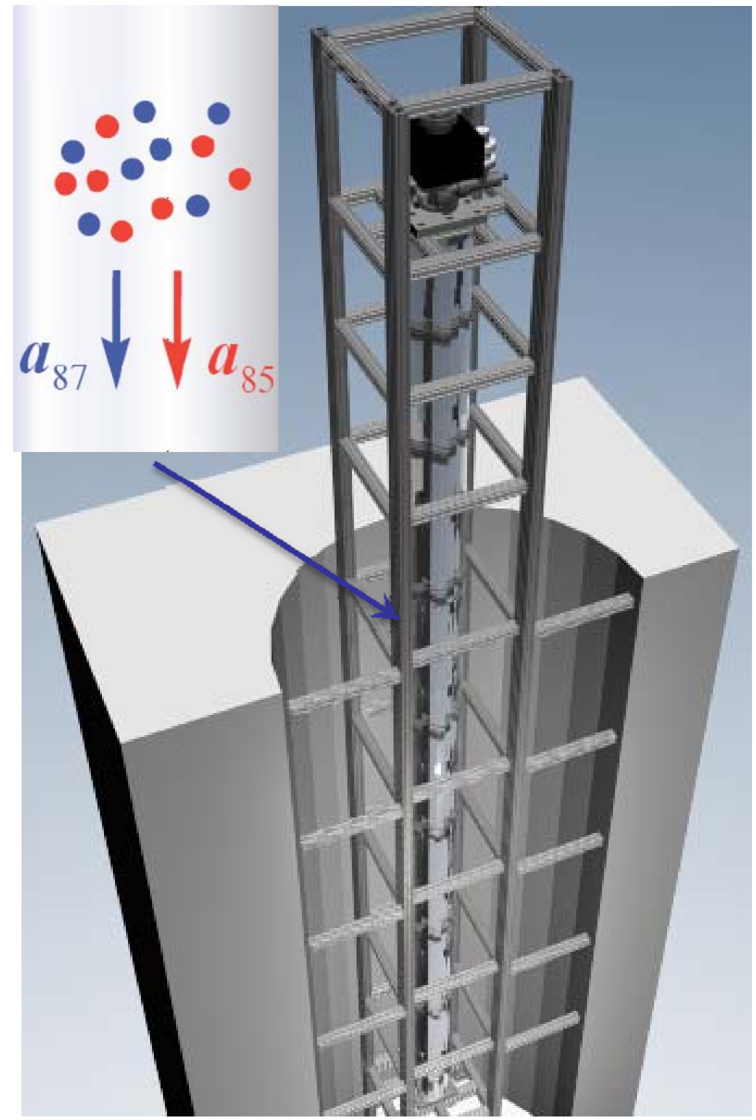
$\delta g \sim 10^{-16}$ limited by magnetic field inhomogeneities and gravity anomalies.

Also, new tests of General Relativity

Atomic source



10 m atom drop tower

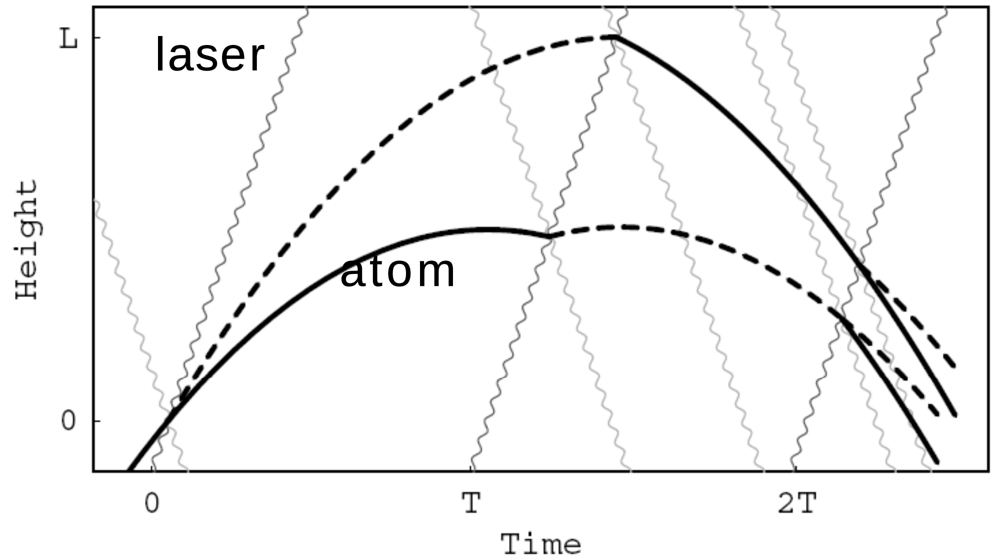


10 m drop tower

Post-Newtonian Gravitation

Light-pulse interferometer phase shifts for Schwarzchild metric:

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



Post-Newtonian trajectories for classical particle:

$$\frac{d\mathbf{v}}{dt} = -\nabla(\phi + 2\phi^2 + \psi) - \frac{\partial \boldsymbol{\zeta}}{\partial t} + \mathbf{v} \times (\nabla \times \boldsymbol{\zeta}) + 3\mathbf{v}\frac{\partial \phi}{\partial t} + 4\mathbf{v}(\mathbf{v}\cdot\nabla)\phi - \mathbf{v}^2\nabla\phi$$

From Weinberg, Eq. 9.2.1

Collaborators: Savas Dimopoulos, Peter Graham, Jason Hogan.

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.

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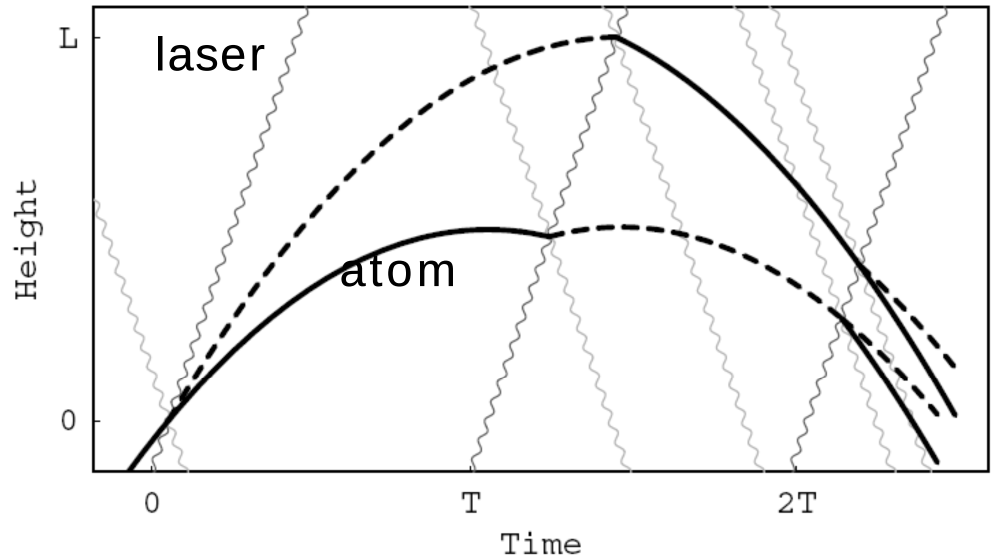

Post-Newtonian trajectories for classical particle:

$$\frac{d\vec{v}}{dt} = -\nabla\phi \qquad -\nabla\phi^2 \qquad -\vec{v}^2\nabla\phi$$

Newton's Gravity	Gravity Gravitates	Kinetic Energy Gravitates

From Weinberg, Eq. 9.2.1

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Theory

Initial

- 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) to for atom/photon interaction (eg. apply Sch. Eq.).
- Coordinate transformation to local Lorentz frame at final interferometer pulse to evaluate separation phase

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.	$-12k_{\text{eff}} g^2 T^3 v_L$	-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
- 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)

Equivalence Principle Installation

Cosmology

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

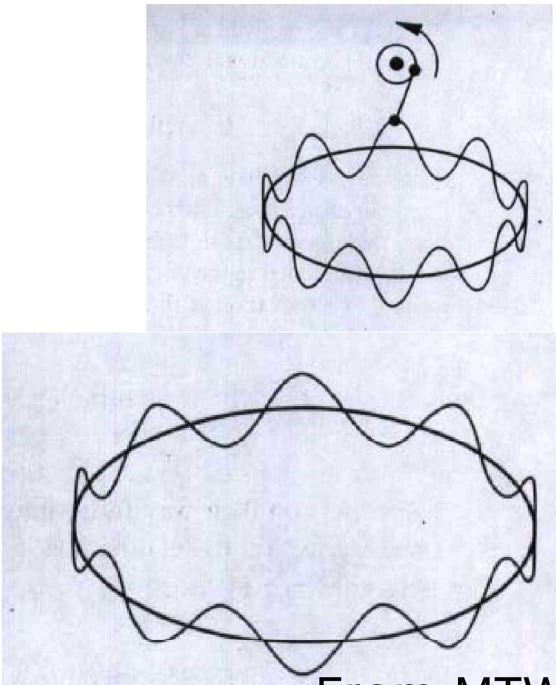
Analysis has been limited to simple metrics:

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

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

- Gravity waves

Giulini, gr-qc/0602098



From MTW

Work in progress ...

Future theory: Consider phenomenology of exotic/speculative theories (after validating methodology)

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- Chetan Mahadeswaraswamy, Graduate student, Mechanical engineering
- David Johnson, Graduate student, Aero/Astro engineering
- Geert Vrijsen, Graduate student, Applied physics
- Jason Hogan, Graduate student, Physics
- Nick Ciczek, Graduate student, Applied Physics
- Mike Minar, Graduate student, Applied Physics
- Sean Roy, Graduate student, Physics
- Larry Novak, Senior assembly technician
- Paul Bayer, Optomechanical engineer

+ THEORY COLLABORATORS!