Atom Interferometry

Prof. Mark Kasevich
Dept. of Physics and Applied Physics
Stanford University, Stanford CA

Young's double slit with atoms

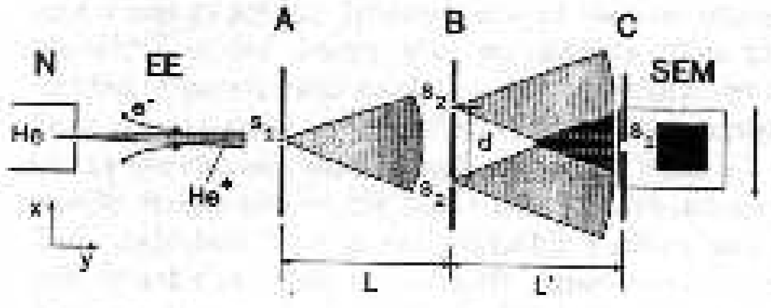


FIG. 2. Schematic representation of the experimental setup:

Young's 2 slit with Helium atoms

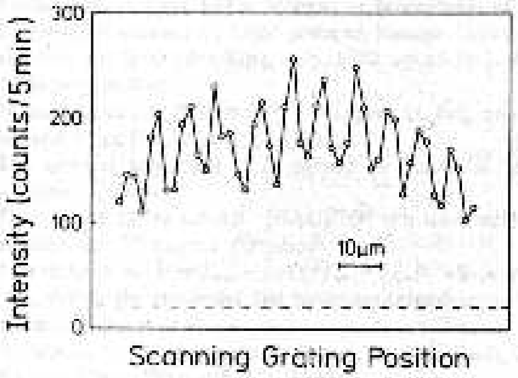
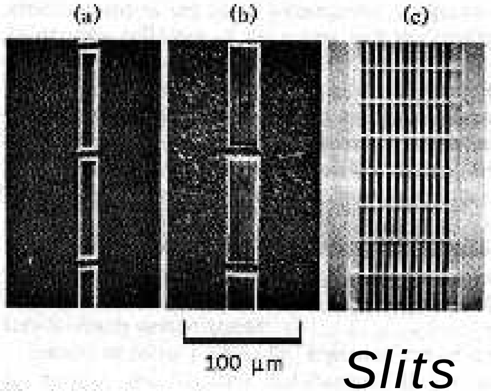


FIG. 5. Atomic density profile, monitored with the 8-µm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

Interference fringes

2691

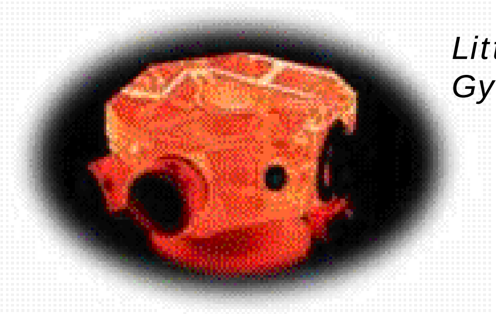


Slits

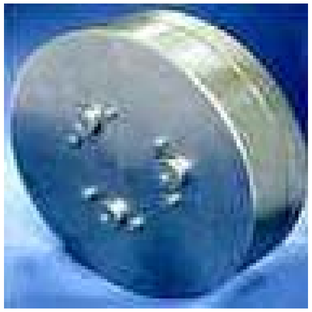
One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)

Interferometric sensors

Optical Interferometry



Litton Ring Laser Gyroscope



Fibersense Fiber-optic Gyroscope

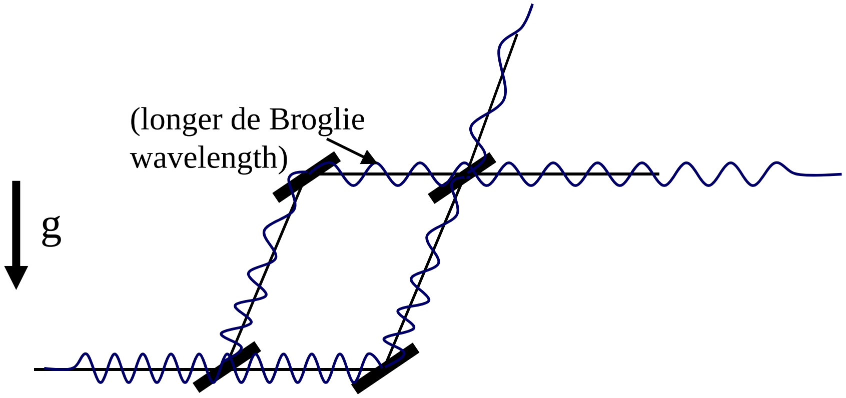
Atom Interferometry

- 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.

Simple models for inertial force sensitivity

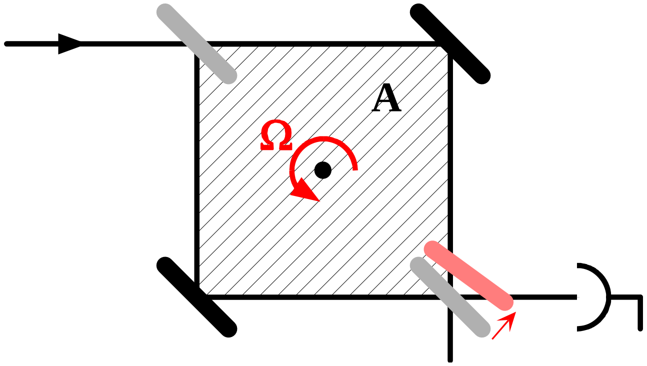
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

Sagnac effect for de Broglie waves



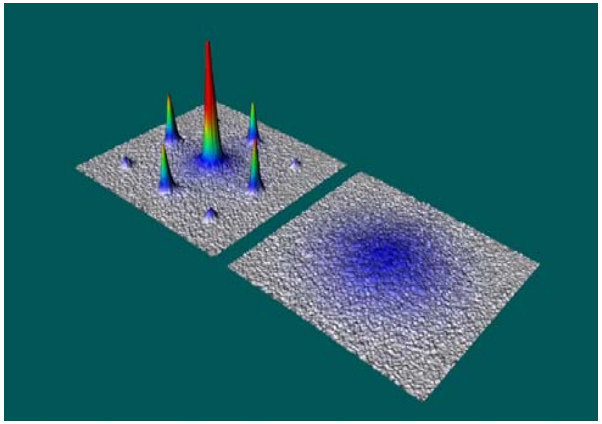
Current ground based experiments with atomic Cs:

Wavepacket spatial separation ~ 1 cm

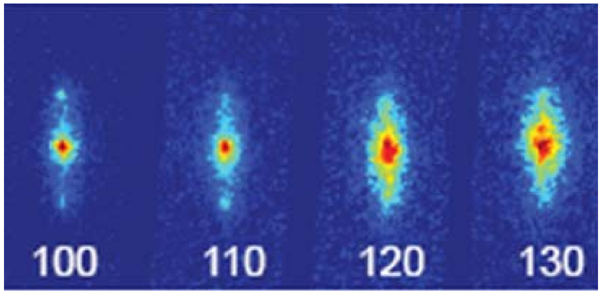
Phase shift resolution ~ 10^{-5} rad

(Previous experiments with neutrons)

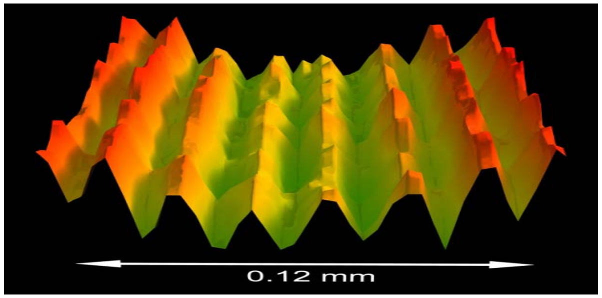
Atom interferometry as probe for long-range order



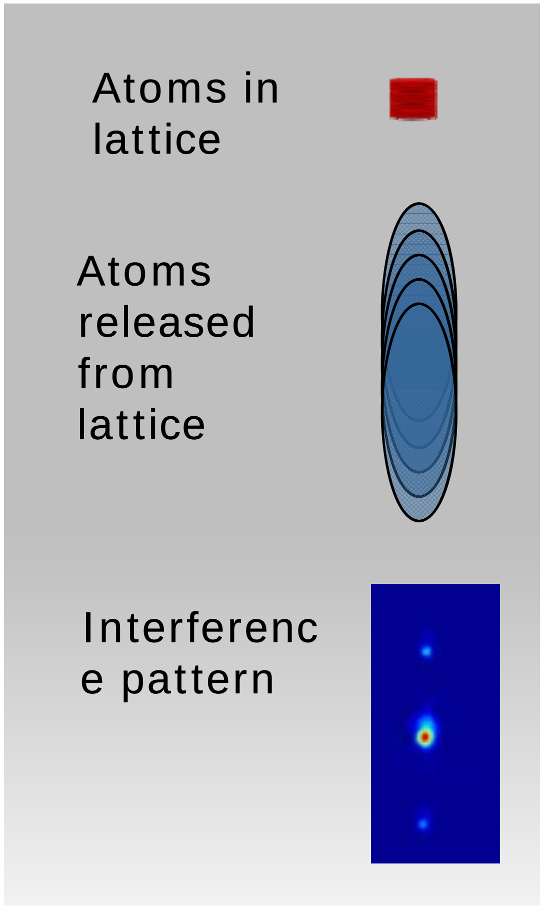
Mott-Insulator (Munich)



Deconfinement transition in layered superfluids (Stanford)



Interference of BEC's (MIT)



Atoms in lattice

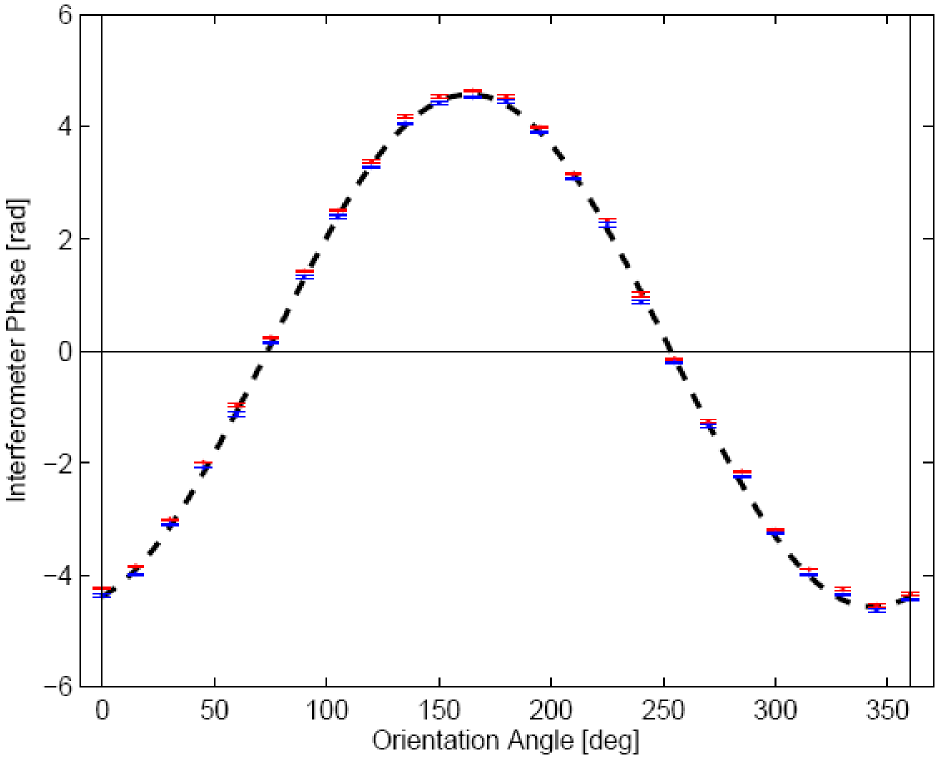
Atoms released from lattice

Interference pattern

Atom interferometry has emerged as a tool to understand phase ordering in ultracold atomic systems**.**

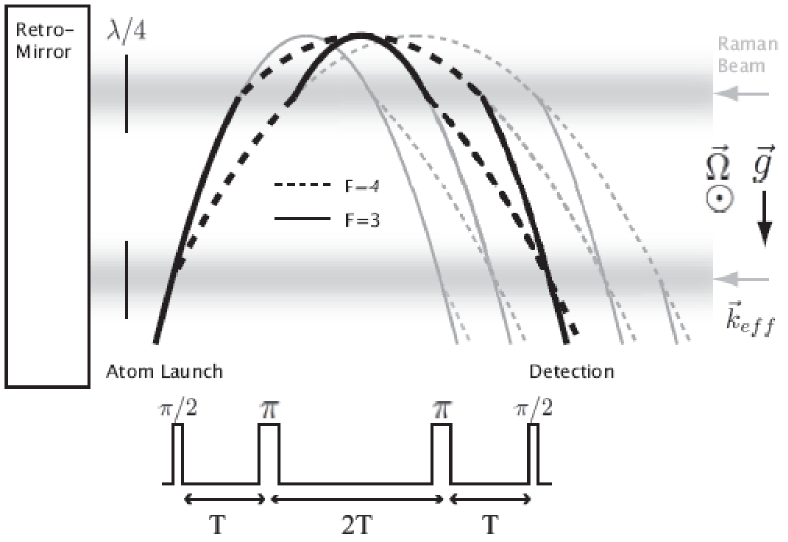
Gyroscope

Measured gyroscope output vs.orientation:



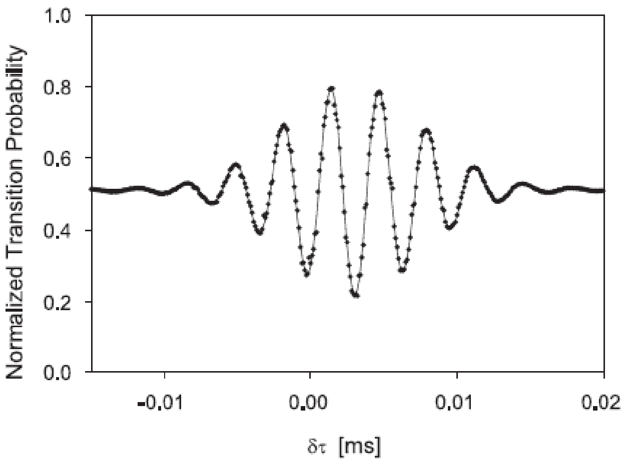
- Inferred ARW: < 100 μdeg/hr$^{1/2}$
- 10 deg/s max input
- <100 ppm absolute accuracy

Gyroscope configuration



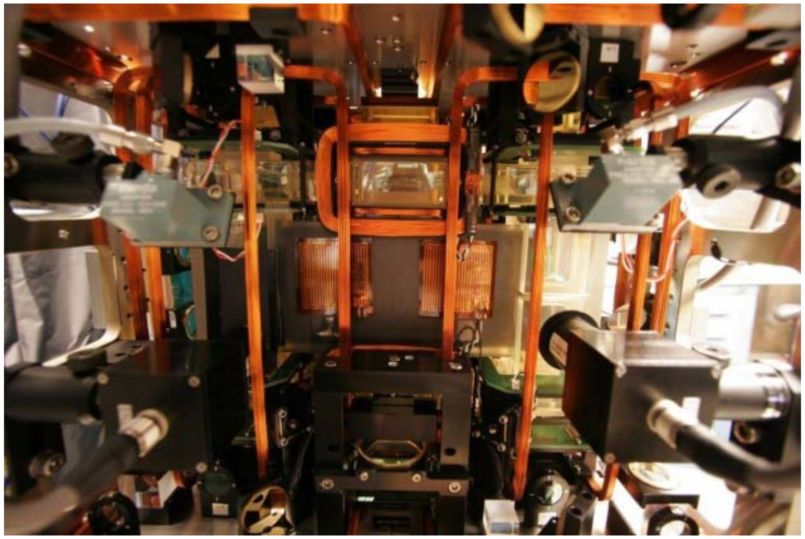
$$\begin{aligned}\phi &= 6\mathbf{k}_{eff}\cdot((\Omega_F+\Omega_E)\times(\mathbf{g}+\mathbf{a}))T^3\\ &\quad -2\mathbf{k}_{eff}\cdot(\Omega_E\times\mathbf{g})T^3,\end{aligned}$$

Phase shift has contributions from rotation of Earth gravity vector in addition to rotation of reference frame.

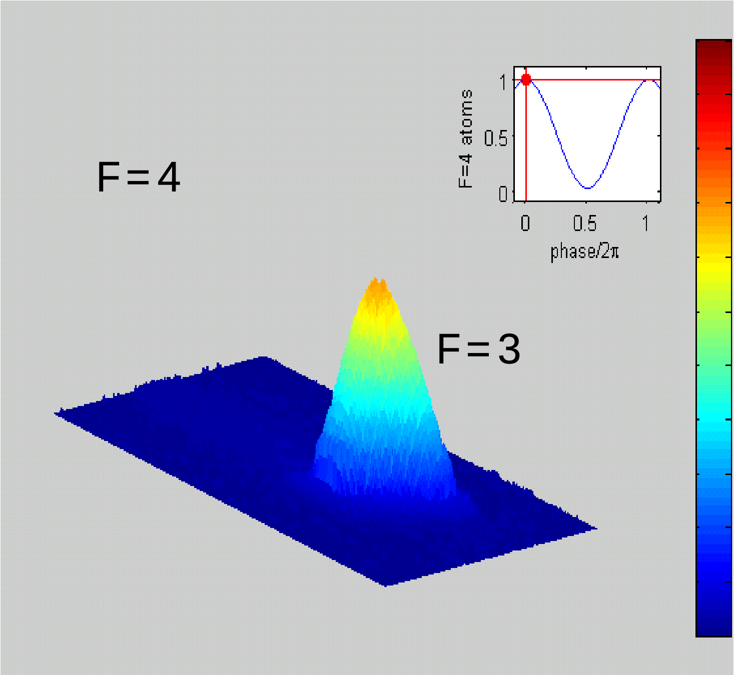


Measurement of coherence length of laser cooled atomic source (~ 100 nm)

Gyroscope operation



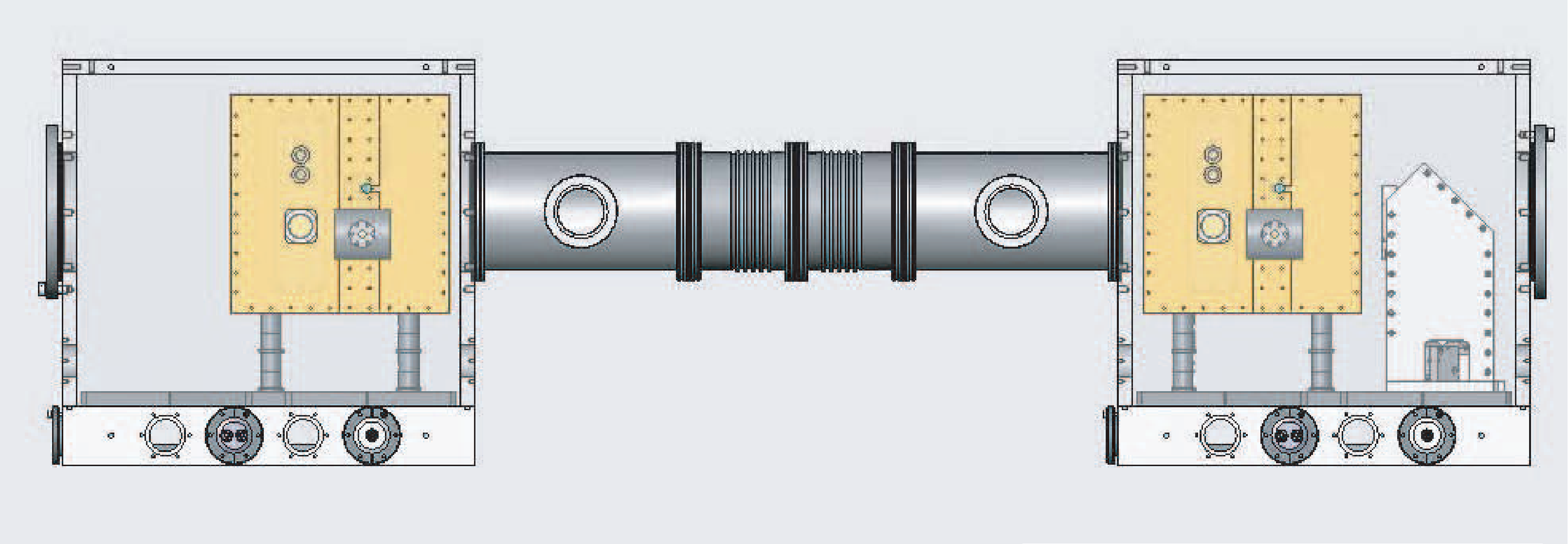
Interior view of sensor

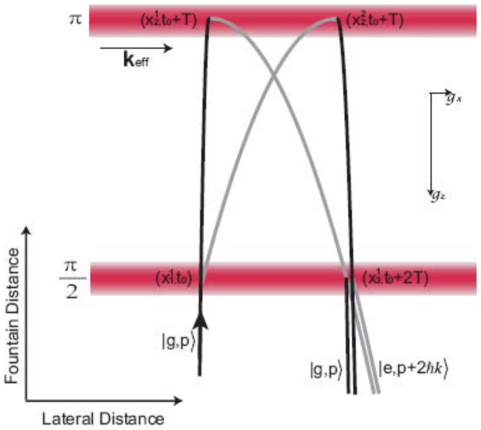


Interference fringes are recorded by measuring number of atoms in each quantum state.

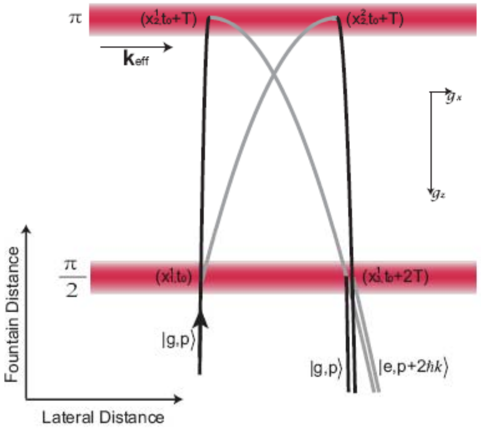
Fringes are scanned electro-optically.

Differential accelerometer



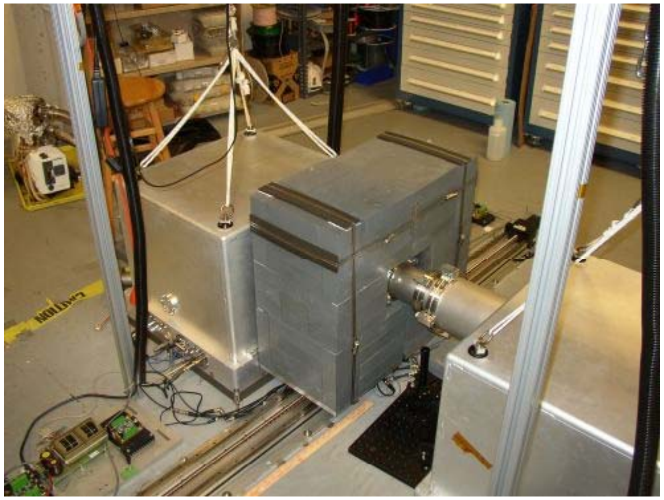


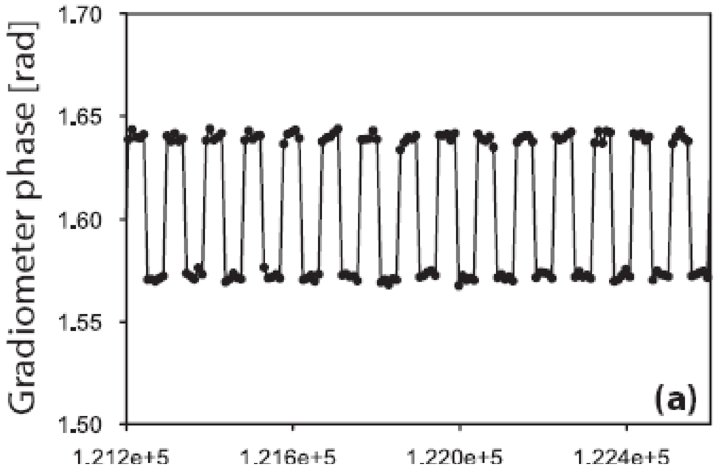
← ~ 1 m →

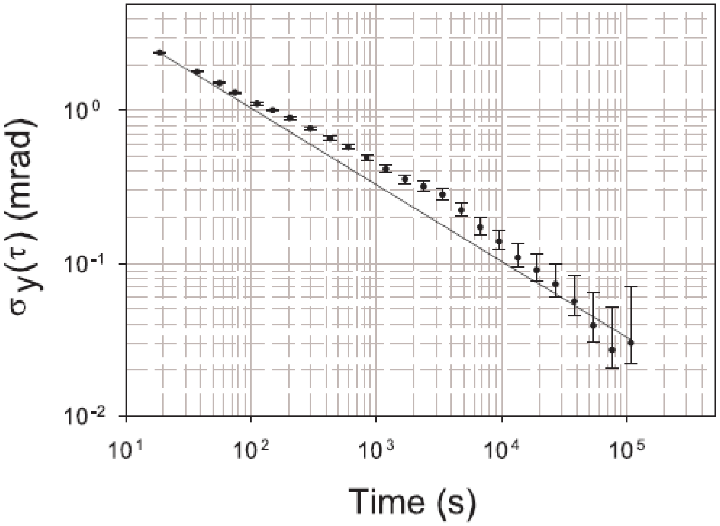


Applications in precision navigation and geodesy

Gravity gradiometer







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

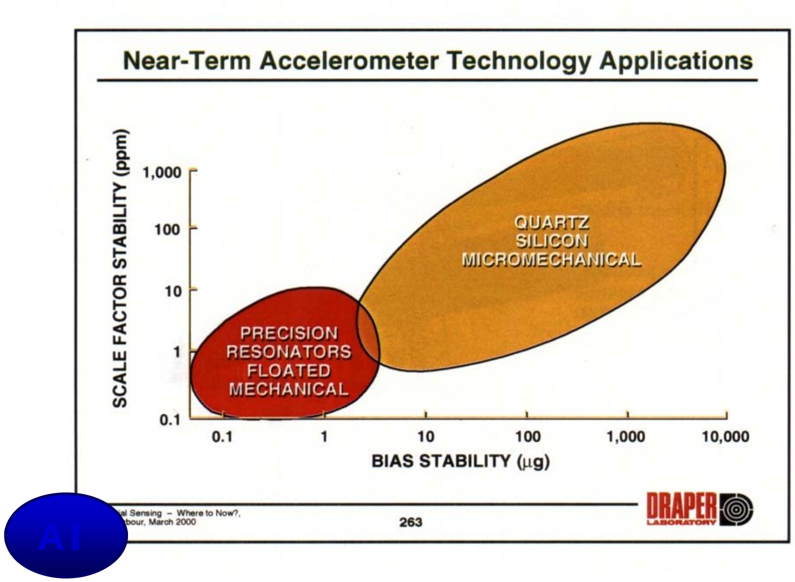
Technology/Applications

- Gravimetric
    - Geodesy/Earthquake prediction
    - Oil/mineral/resource management
    - Gravity anomaly detection
- Low cost, compact, navigation grade IMU
    - Autonomous vehicle navigation
- Gravity compensated IMU (grav grad/gyro)
    - GPS-free high accuracy navigation

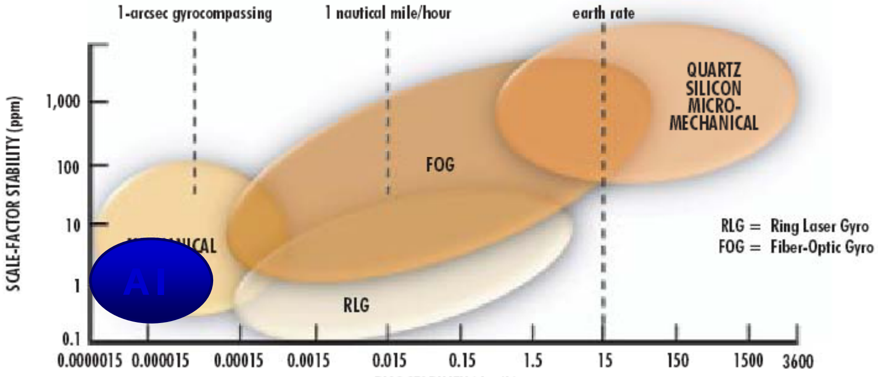
Funding:
DARPA PINS, POC J. Lowell
SP-24/Navy, POC J. Gentile
NGA, POC S. Malys

Sensor characteristics

Light-puse AI accelerometer characteristics



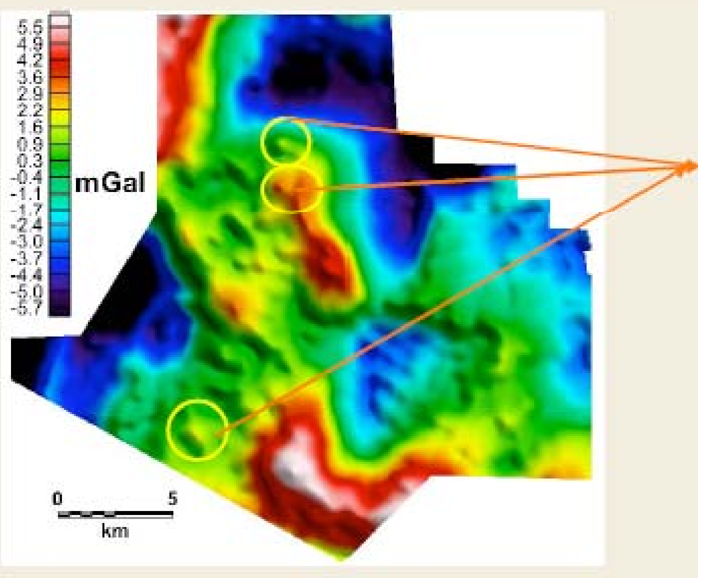
Light-puse AI gyroscope characteristics



Fiaure 8

Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

Airborne surveys



Ore depos

False color image of airborn gravity survey (courtesy M. Dransfield, FUGRO).

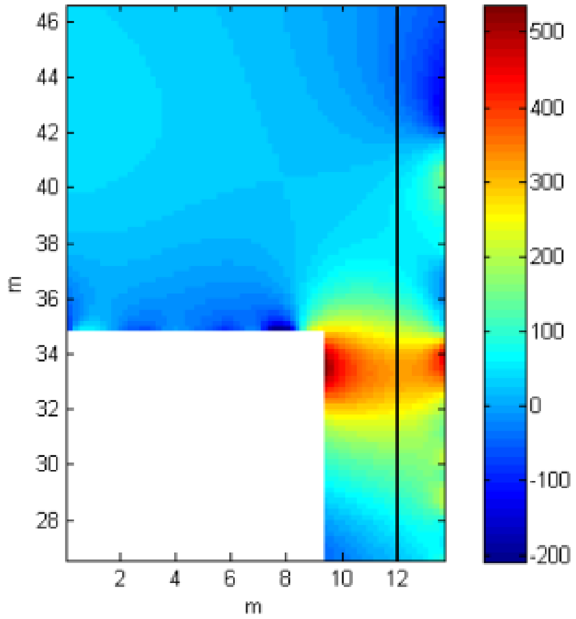
Sanders Geophysics

Existing technology,
LM Niagra/Bell Aerospace

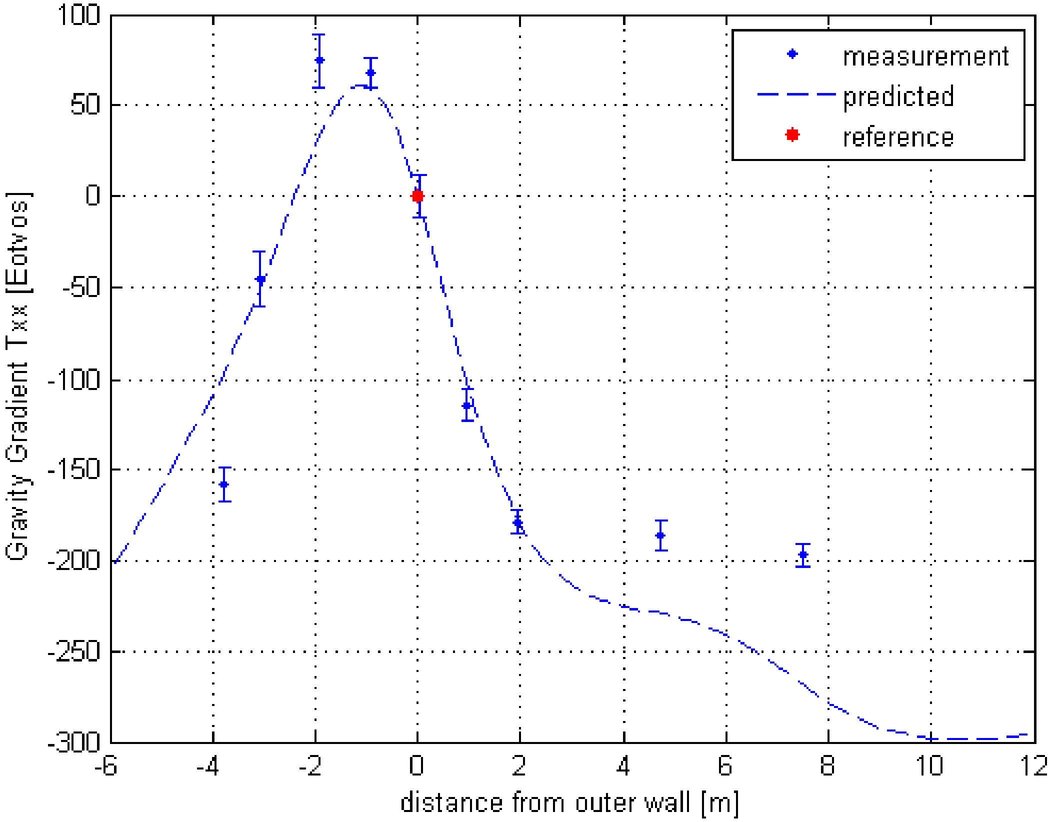
Airborne gravity gradiometry has become an accepted tool for oil/mineral discovery (pioneering work by M. Dransfield, FUGRO).

Example: Kimberlite pipes in Northwest Territories.

AI gravity gradient survey



Gravity anomally map from ESIII facility (top view)



Gravity gradient survey of ESIII facility

Science

- Gravitational physics
  - Equivalence Principle
  - Gravity-wave detection
  - Post-Newtonian gravity, tests of GR
  - Tests of the inverse square law
  - Dark matter/energy signatures?

- Beyond Standard model
  - Charge neutrality
  - h/m, tests of QED

Equivalence Principle

Use atom interferometric differential accelerometer to test EP

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

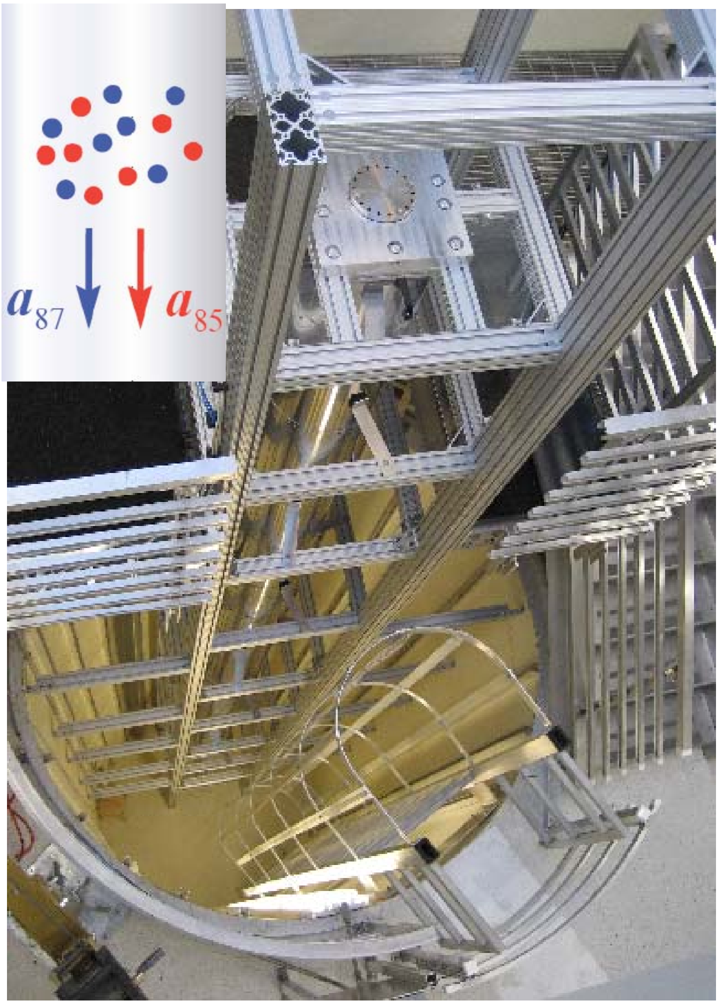
Evaporatively cool to < 1 μK to enforce tight control over kinematic degrees of freedom

Statistical sensitivity

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

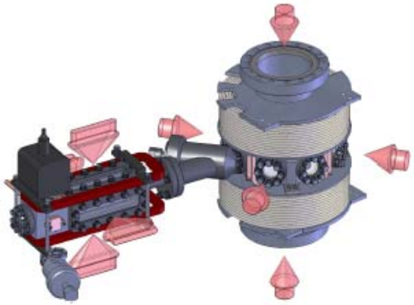
Systematic uncertainty

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



10 m drop tower

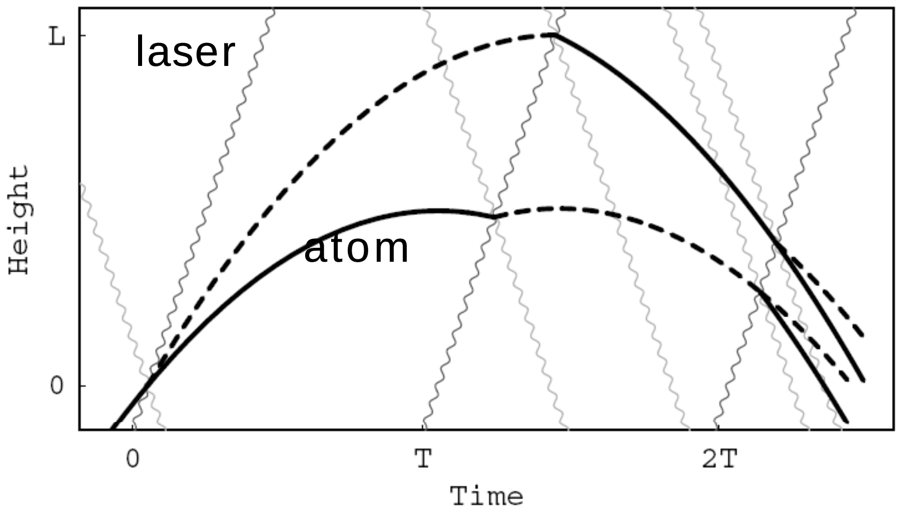
Atomic source



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:

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

Newton's Gravity

Gravity Gravitates

Kinetic Energy Gravitates

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.

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.	$-3 k_{\text{eff}} g T^2 v_L$	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.	$-5 k_{\text{eff}} g T^2 v_L^2$	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:

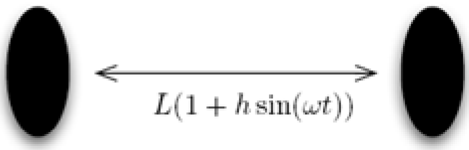
Tested Effect	current limit	AI initial	AI upgrade	AI future	AI far future
PoE	3×10^{-13}	10^{-15}	10^{-16}	10^{-17}	10^{-19}
PPN (β, γ)	10^{-4}-10^{-5}	10^{-1}	10^{-2}	10^{-4}	10^{-6}

Steady path of apparatus improvements include:

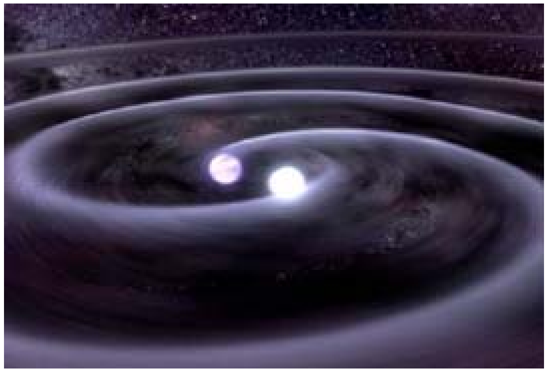
- Improved atom optics
- Taller apparatus
- Sub-shot noise interference read-out
- In-line, accelerometer, configuration (milliarcsec link to external frame not req'd).

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

Gravity Wave Detection



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



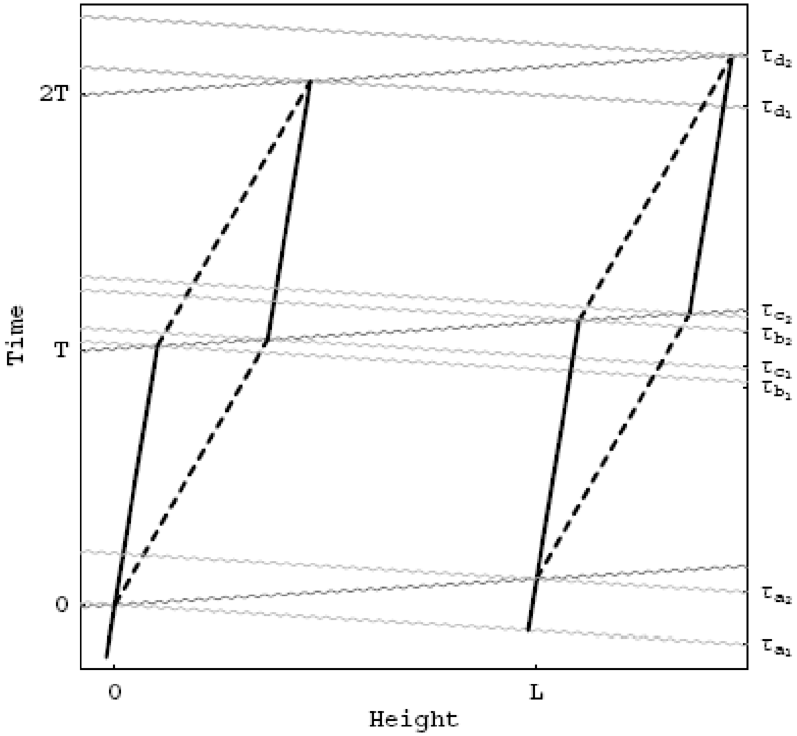
Interesting astrophysical objects (black hole binaries, white dwarf binaries) are sources of gravitational radiation in 0.01 – 10 Hz frequency band.

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.

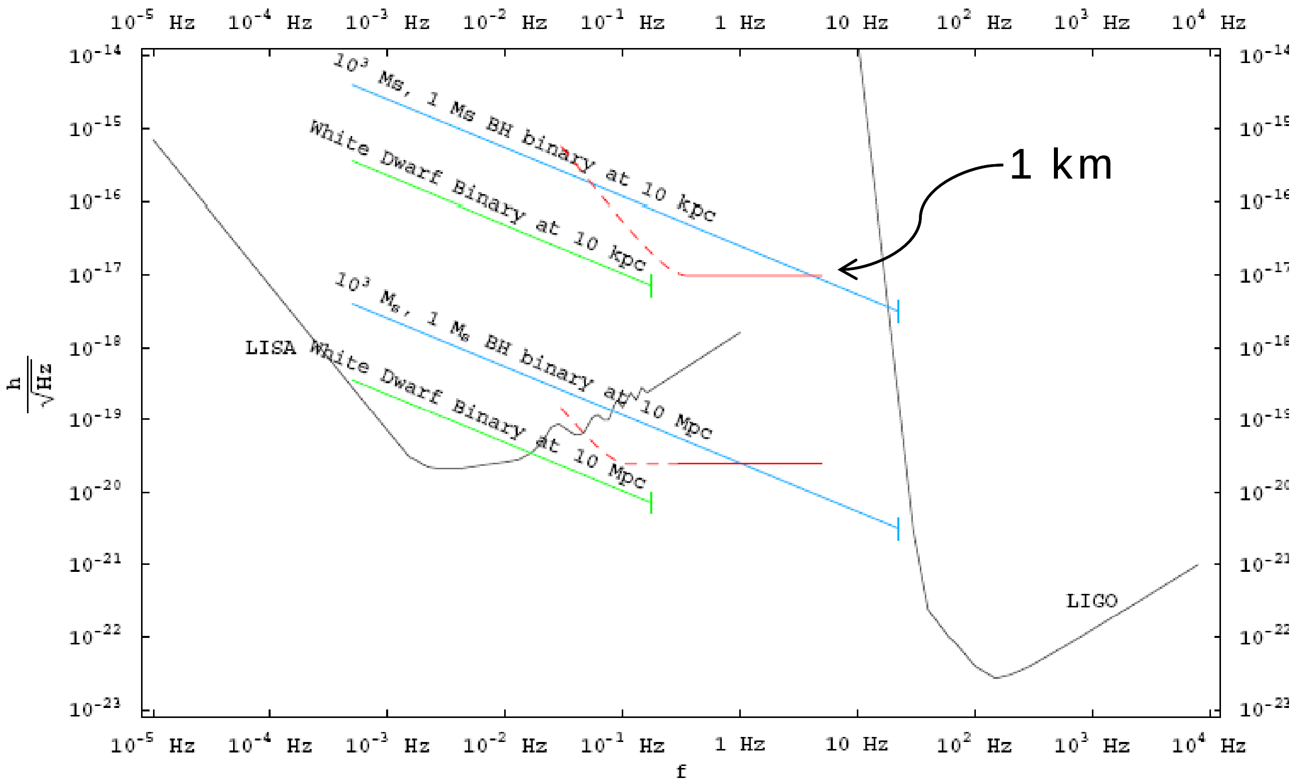
Gravity wave induced phase shift:

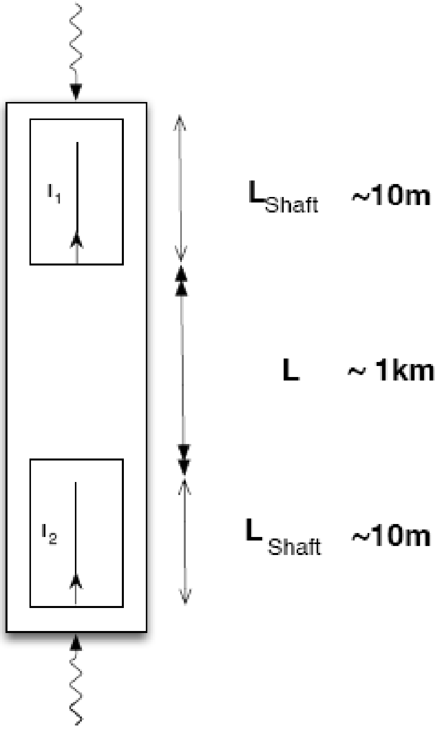
$$\Delta\phi \sim h\,L\,\sin^2(\omega T/2)$$

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).

Proposed Terrestrial Detector Performance



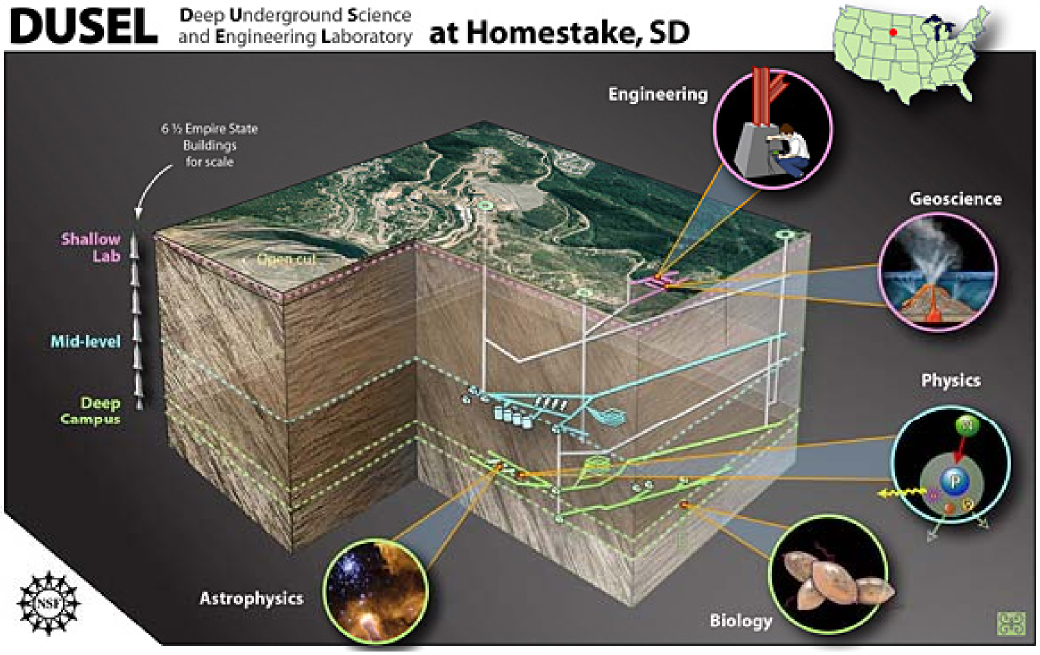


Setup	L	k_{eff}	T	I_L	Phase Sensitivity	f_d
Terrestrial 1	1 km	1.6×10^9 m^{-1}	1.4 s	10 m	10^{-4} rad	10 Hz
Terrestrial 2	4 km	1.6×10^{10} m^{-1}	4.5 s	100 m	10^{-5} rad	10 Hz

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

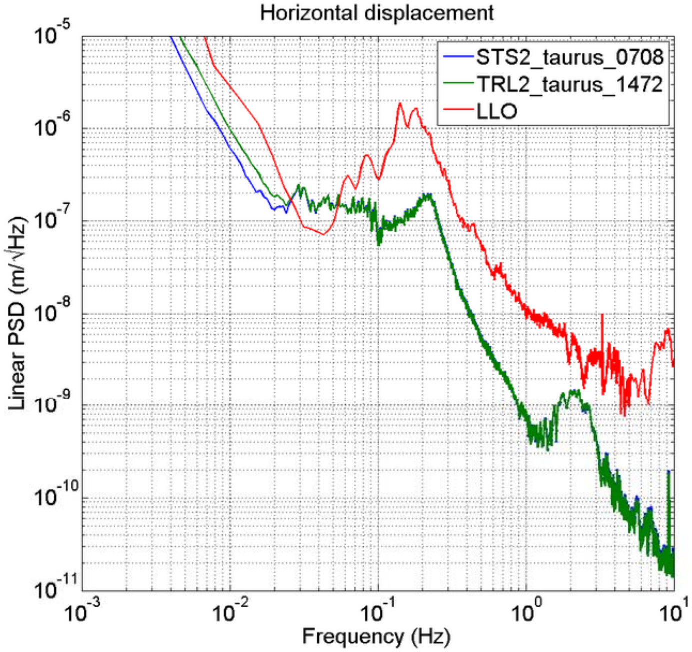
(Possible) DUSEL Installation

Sub-surface installation may be sufficiently immune to seismic noise to allow interesting ground-based sensitivity limits.



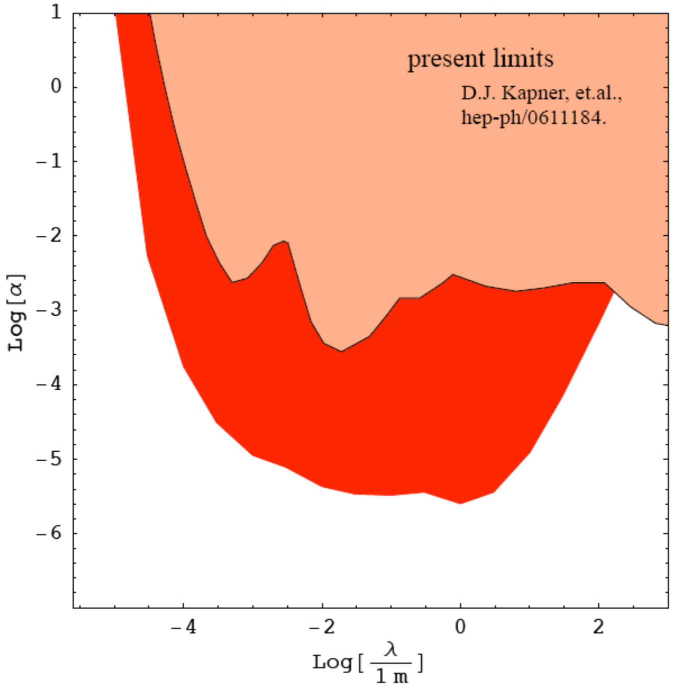
Collaboration with SDSU, UofTenn, NASA Ames to install protoptype sensor.

Also, next generation seismic sensors (John Evans, USGS).



(data courtesy of Vuk Mandic, UofM)

Test Newton's Inverse Square Law



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

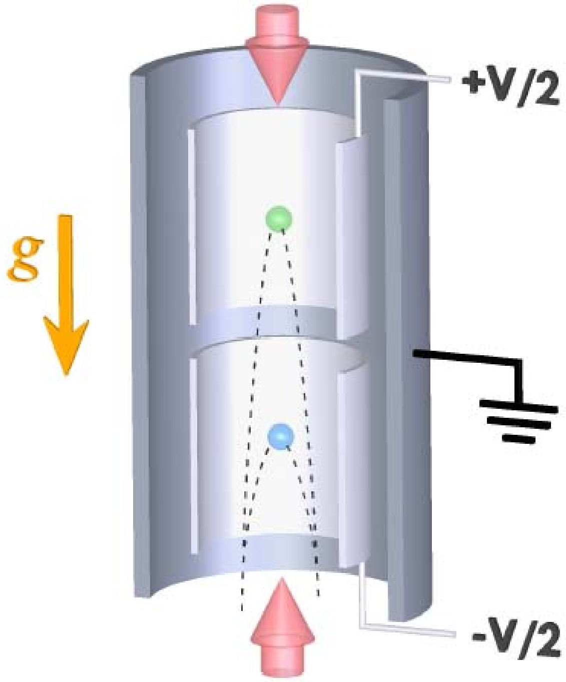
Using new sensors, we anticipate $\delta G/G \sim 10^{-5}$.

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

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

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.

Theory collaborators:
A. Arvanitaki, S. Dimopoulos,
A. Geraci

Quantum sensitivity limits?

1) Wavepackets separated by $z = 10$ m, for $T = 1$ sec.
   For Earth gravity field: $\Delta\phi \sim mgzT/\hbar \sim 2\times10^{11}$ rad

2) Signal-to-noise for read-out: SNR ~ 10^5:1 per second.

3) Resolution to changes in g per shot:
   $\delta g \sim 1/(\Delta\phi\ SNR) \sim 4\times10^{-17}$ g

4) 10^6 seconds data collection: $\delta g \sim 4\times10^{-20}$ g (!)

How do we exploit this sensitivity?

Improved atomic sources

Sensitivity scales with count rate.

Improved high-flux sources through:

- Atom laser
- Improved atomic beams
- New, efficient cooling mechanisms

Possible >100x improvement in statistical sensitivity

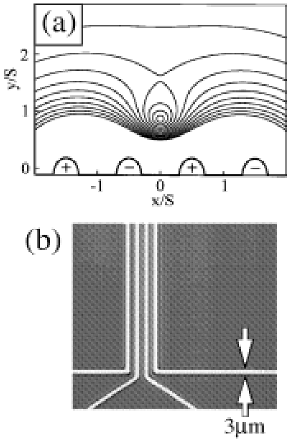
Improved atom optics

New techniques to enable increased wavepacket separation with controlled spurious systematic phase errors.

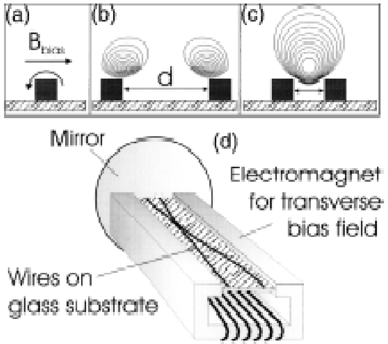
How?

- Atoms in waveguides
- Optical lattice manipulations
- Multiple-light pulse beams splitters
- Diffraction from material surfaces (He on Si/LiF?)
- ...

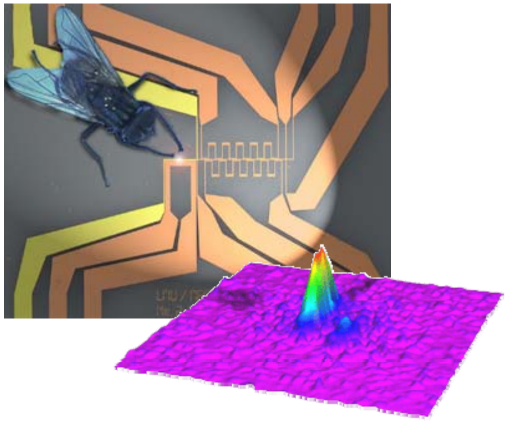
Waveguide AI Sensors



Prentiss, Harvard

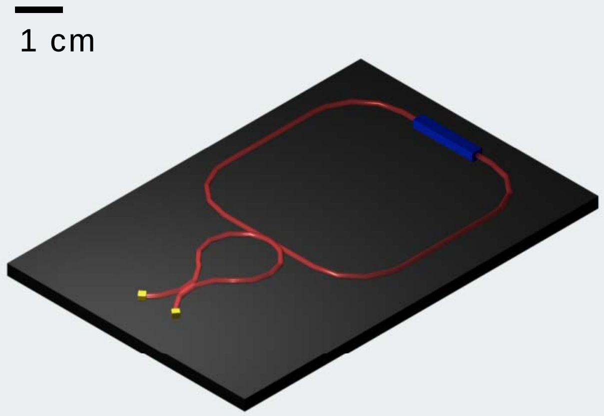


Anderson, JILA



MPQ, Garching

Technology vision:
Compact, sensitive,
highly integrated



Atom Laser Gyroscope

Towards macroscopic quantum interference

Gravitational phase shift scales linearly with mass of interfering particle (quasi-particle).

$\Delta\phi \sim mgzT/\hbar$

Therefore, improved sensitivity with increased mass for interfering particle.

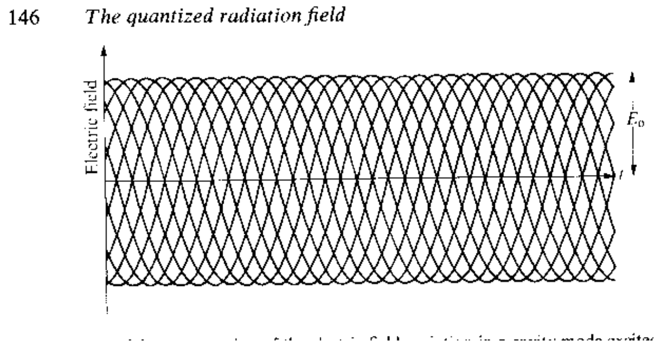
How?

- Molecules, C60, *etc.*
- Nano-fabricated structures
- QND correlated many-body states
- Weakly bound quasi-particles

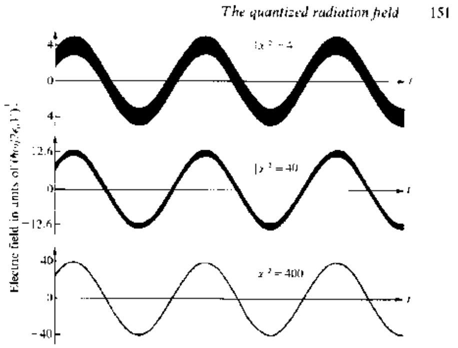
Possible >100x improvement in statistical sensitivity.

QND measurement/Sensitivity enhancement

Number squeezed state:



Coherent state:



(from Loudon, Quant. Theory of Light)

Poorly defined phase,
well defined amplitude

$$|\Psi\rangle = e^{-\frac{1}{2}|\alpha|^2}\sum_n \frac{\alpha^n}{(n!)^{1/2}}|n\rangle$$

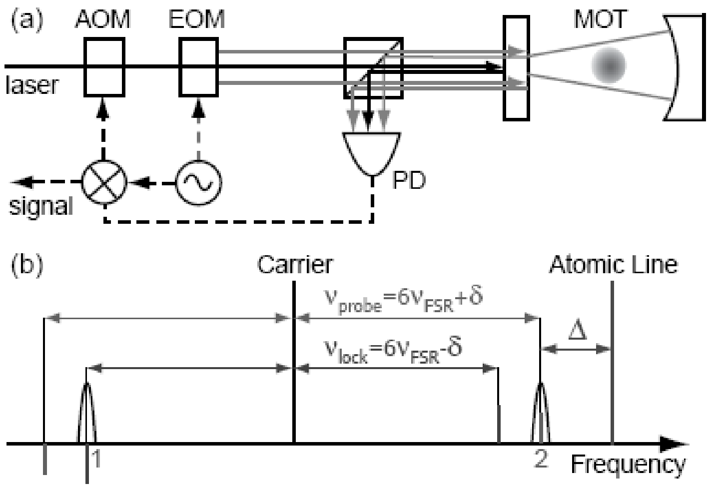
Number-phase uncertainty

Number squeezed states can improve optical interferometer performance (Holland, Burnett).

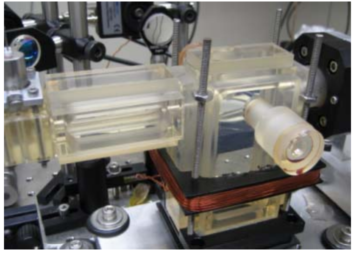
Ensemble of independent

QND atom detection in high finesse cavity

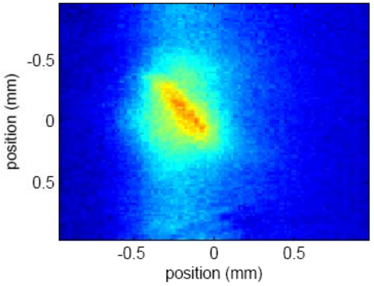
MOT located in 300 μm waist of 200K finesse (3 kHz linewidth) optical cavity.



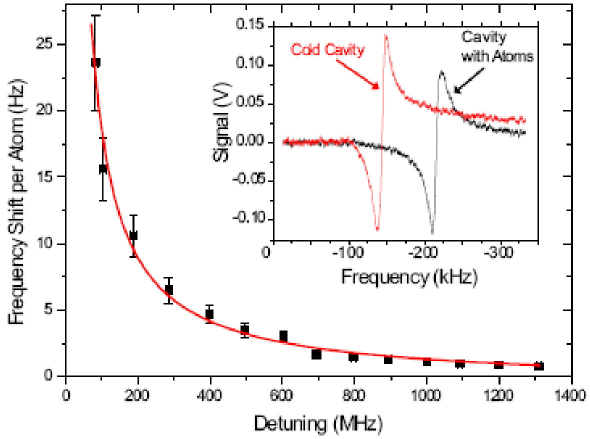
Apparatus:



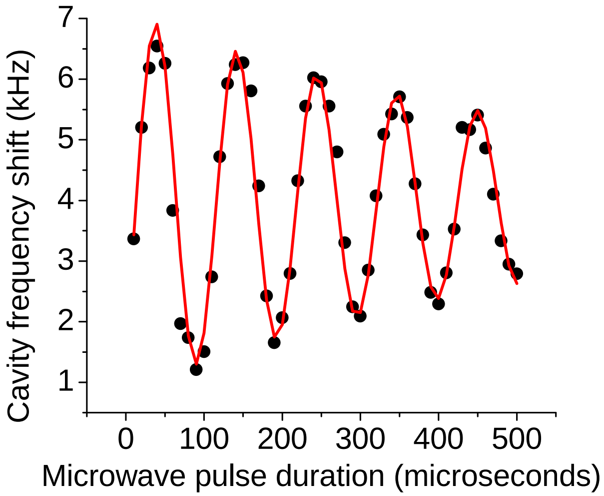
Atoms in cavity:



(MIT, Stanford,...)



Dispersive cavity shift



Rabi oscillations detected via cavity shift

Fundamental limits?

Are there fundamental limits?

Penrose decoherence
Non-linearity in quantum mechanics
Space-time fluctuations (eg. due to
Planck–scale fluctuations)

In coming years, AI methods will provide a $>10^6$-fold improvement in sensitivity to such new physics.