Precision Experiments on Gravity by Atom Interferometry

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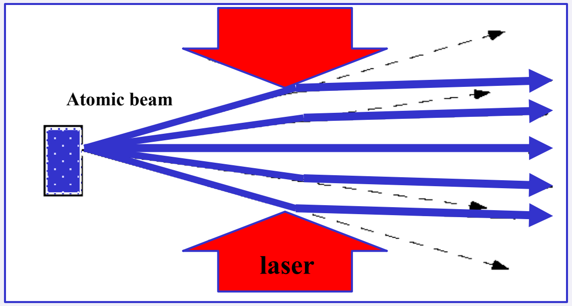
Outline

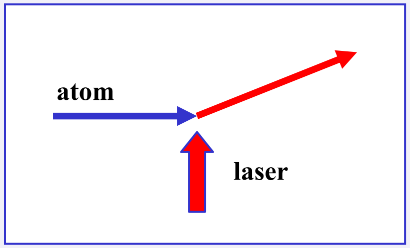
- *Interferometry with cold atoms*
- *Measuring G with atoms*
- *Precision gravity measurement at μm scale with laser-cooled Sr atoms in an optical lattice*
- *Future experiments in space*

Atom optics

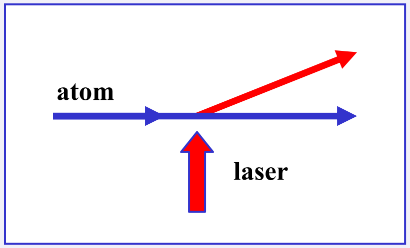
lenses



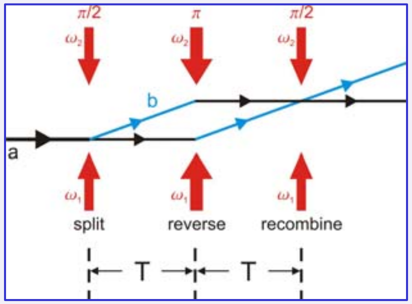
mirrors



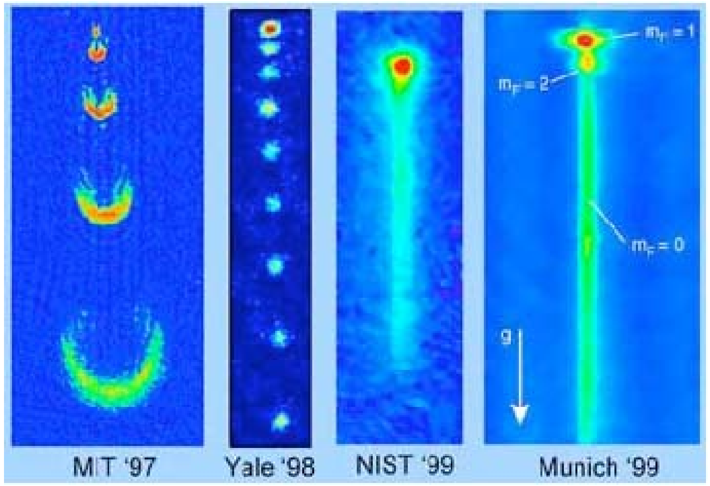
beam-splitters



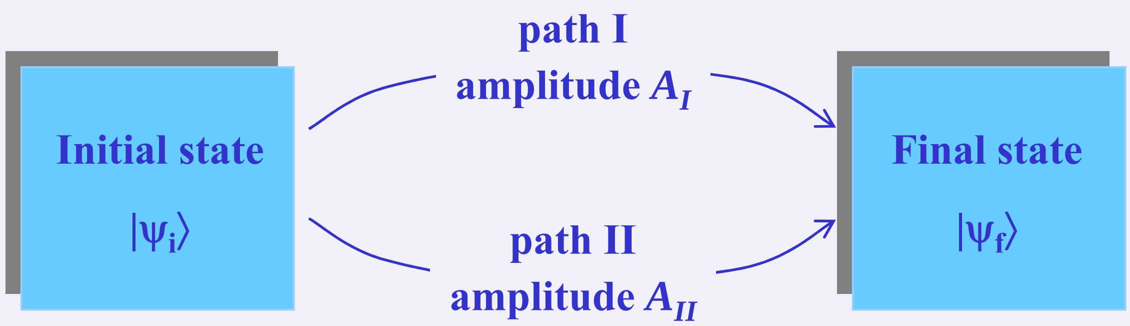
interferometers



atom laser



Quantum interference



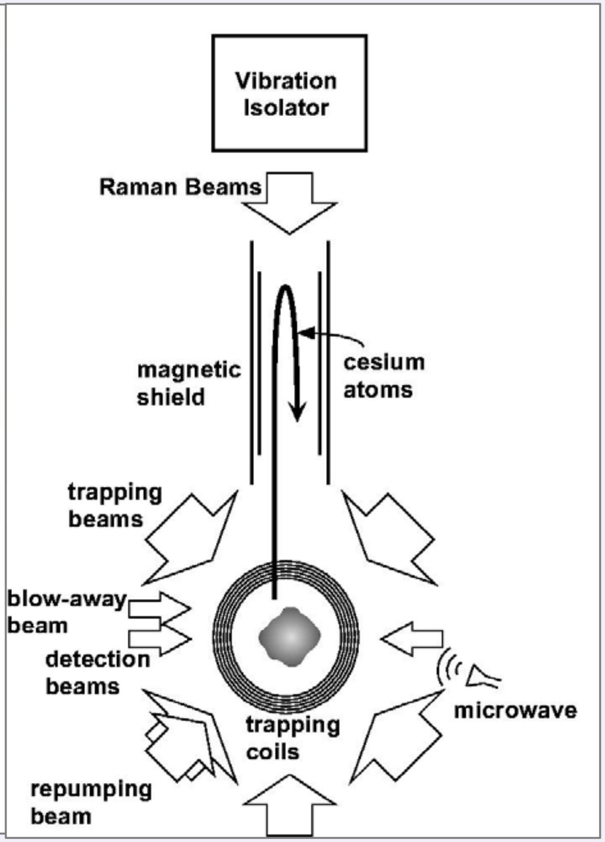
Interference of transition amplitudes

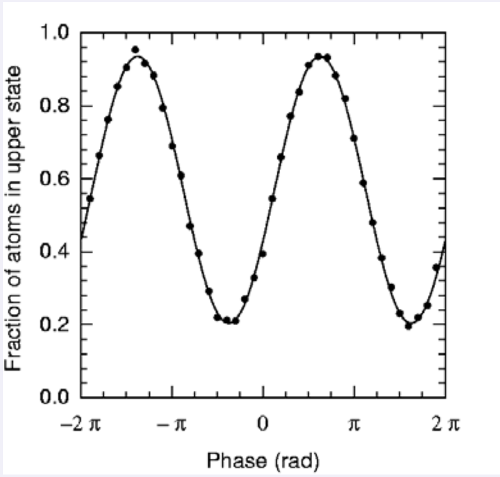
$$P(|\psi_i\rangle \Rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2\,Re(A_I A_{II}^*)$$

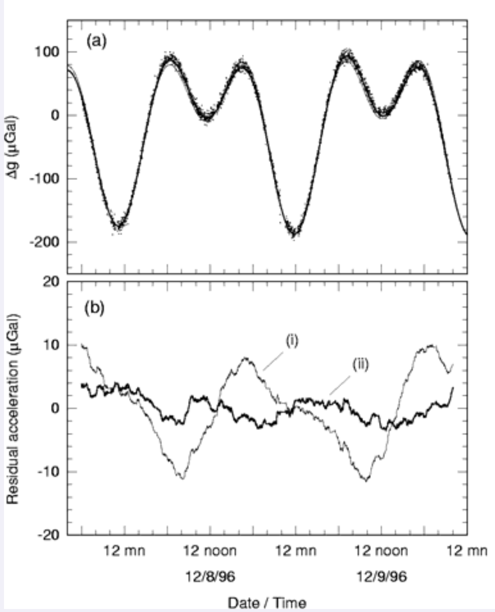
$\Delta\varphi$ effects

- Accelerations
- Rotations
- Laser frequency detuning
- Laser phase
- Photon recoil
- Electric/magnetic fields
- Interactions with atoms and molecules

Stanford atom gravimeter





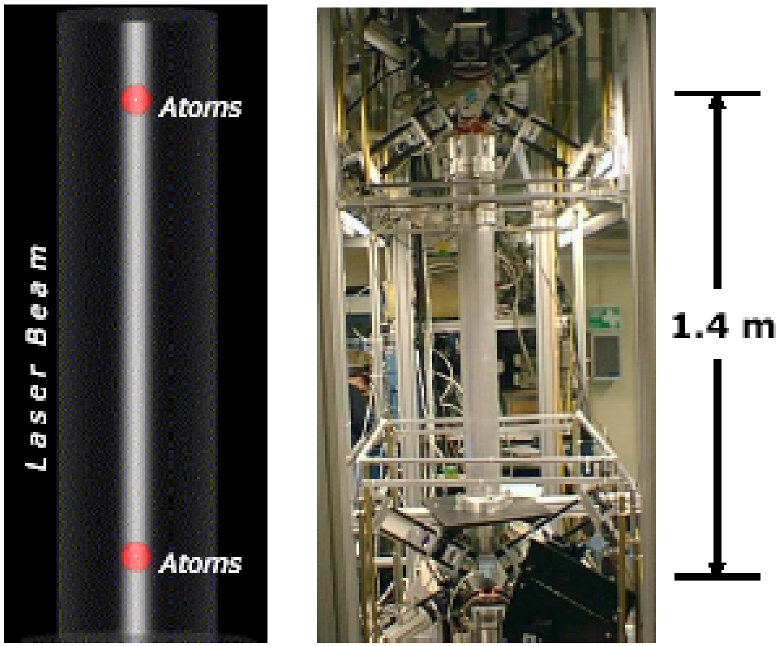


Resolution: $3x10^{-9}$ g after 1 minute

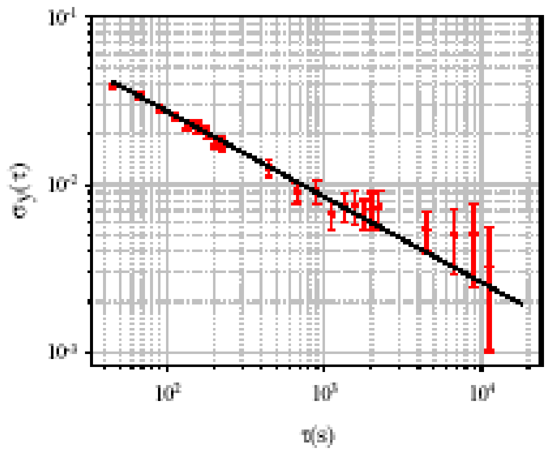
Absolute accuracy: $\Delta g/g<3x10^{-9}$

A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

Stanford/Yale gravity gradiometer



Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.



Demonstrated diffential acceleration sensitivity:

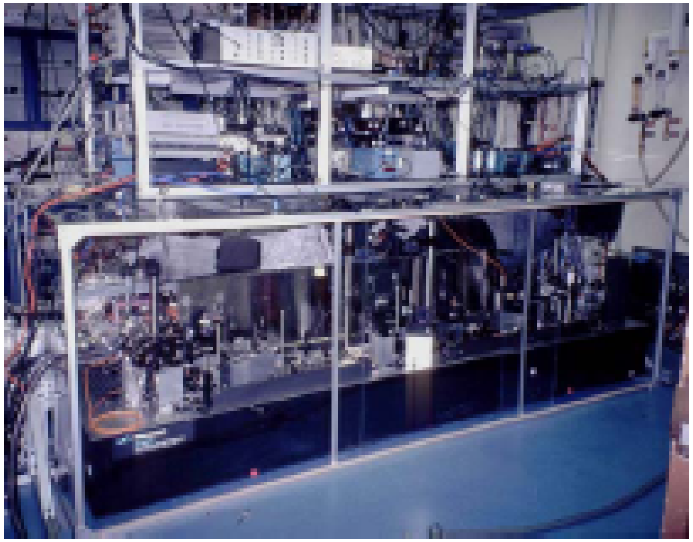
4×10^{-9} g/Hz$^{1/2}$

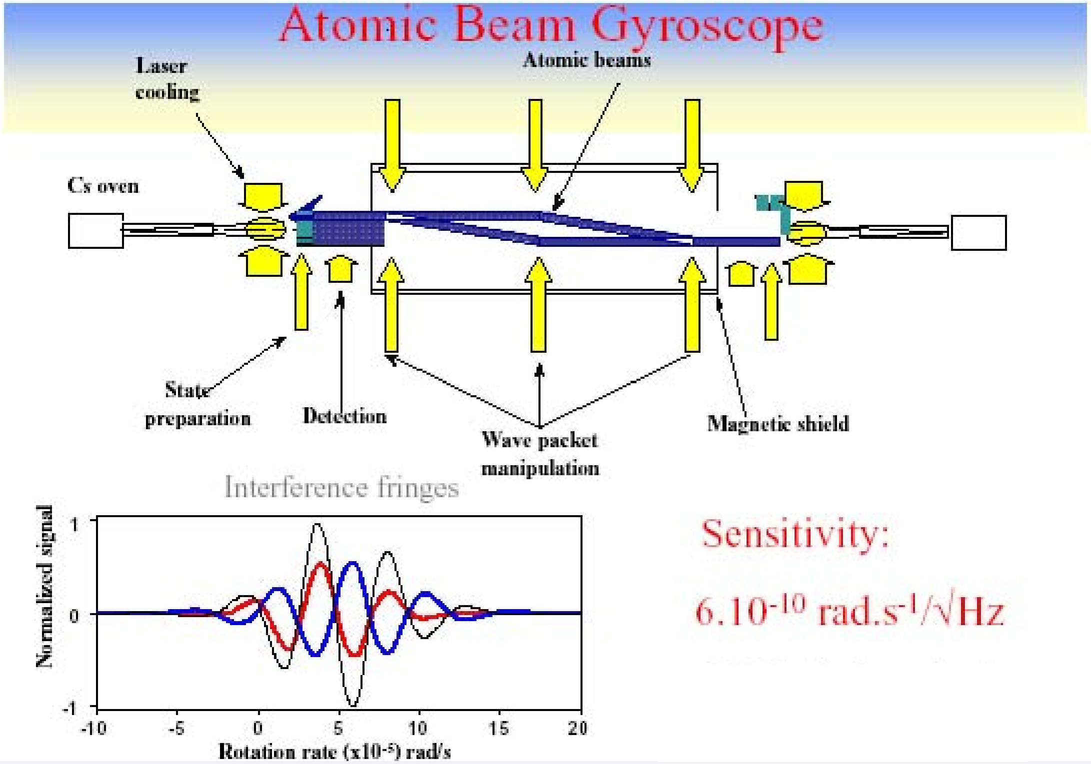
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

from M.A. Kasevich

M.J. Snadden et al., Phys. Rev. Lett. 81, 971 (1998)

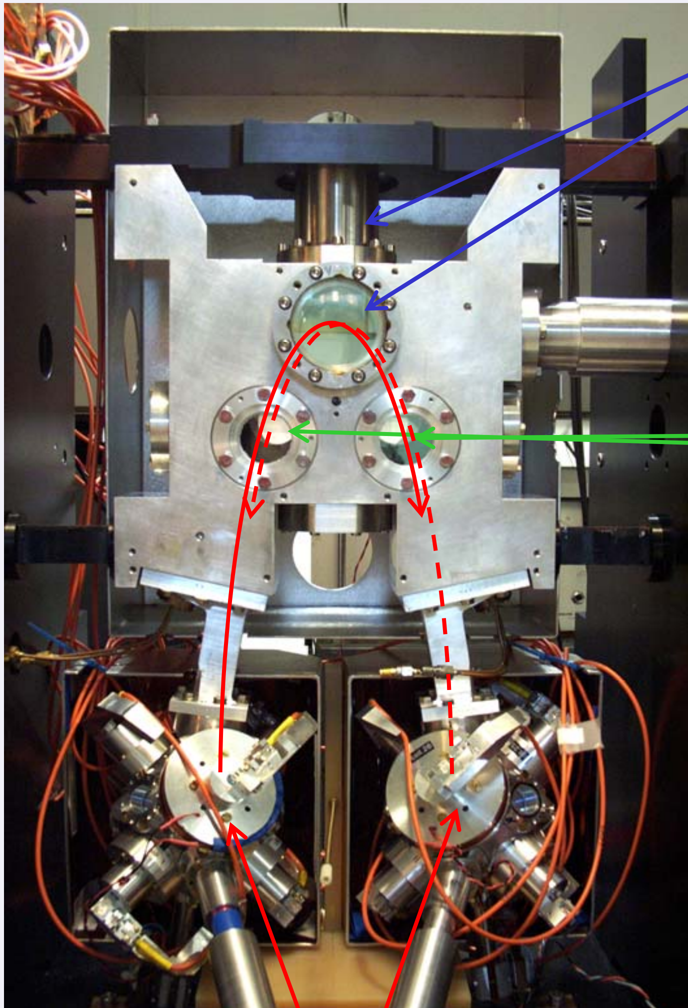
Stanford/Yale gyroscope

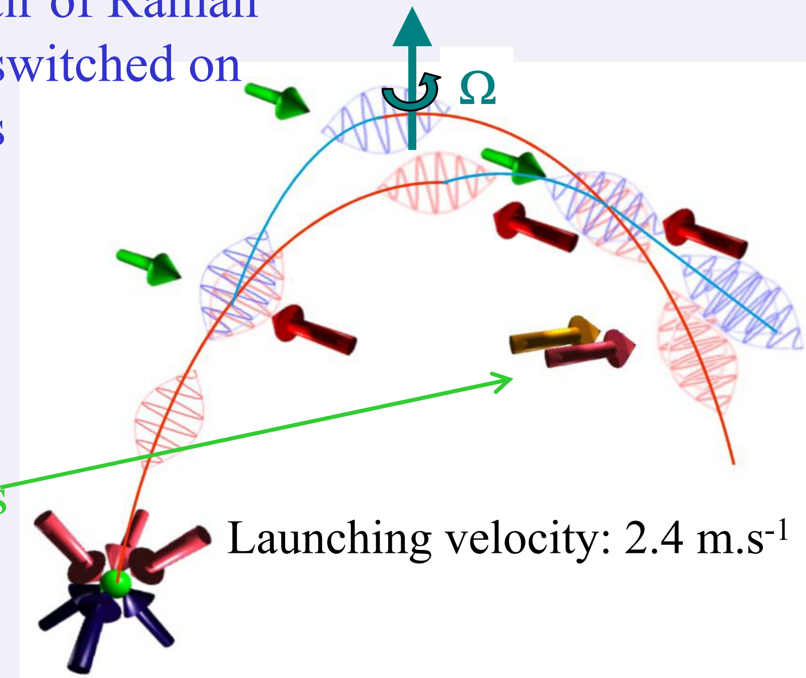




T.L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)

SYRTE cold atom gyroscope





Maximum interaction time : 90 ms

3 rotation axes

2 acceleration axes

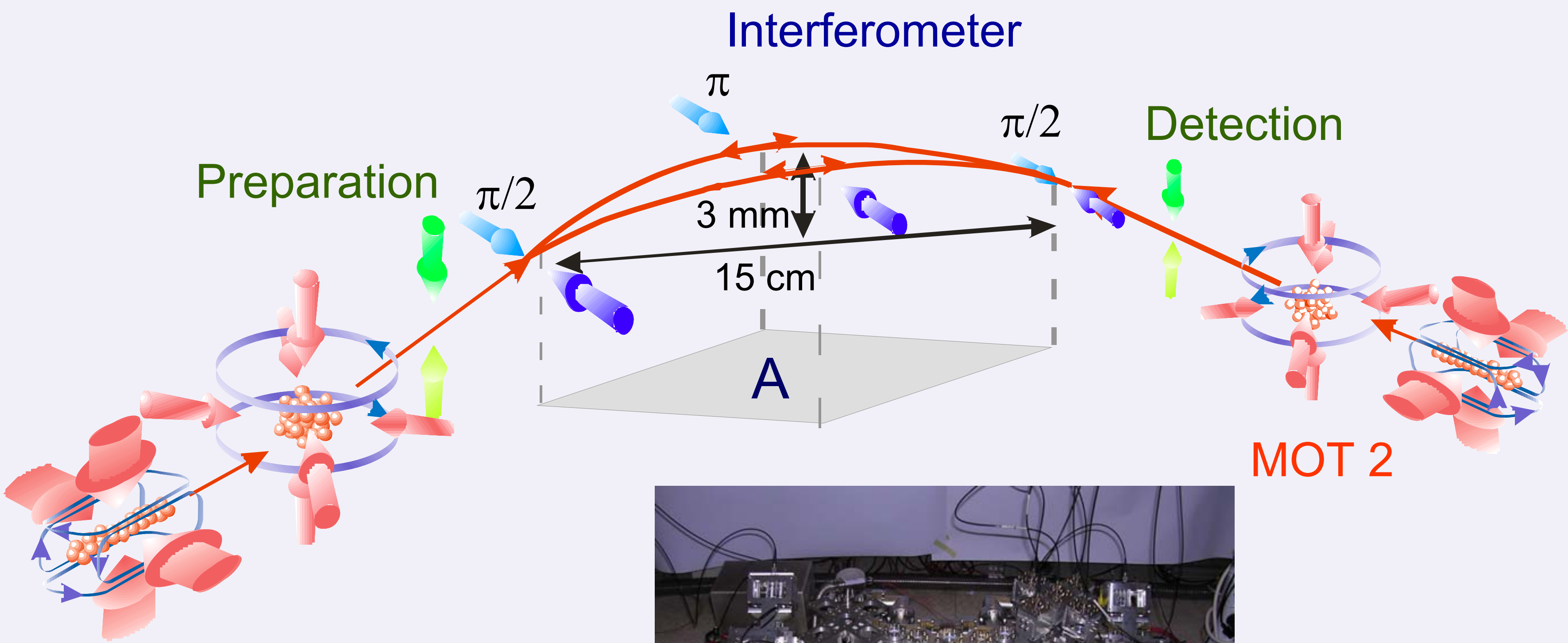
Cycling frequency 2Hz

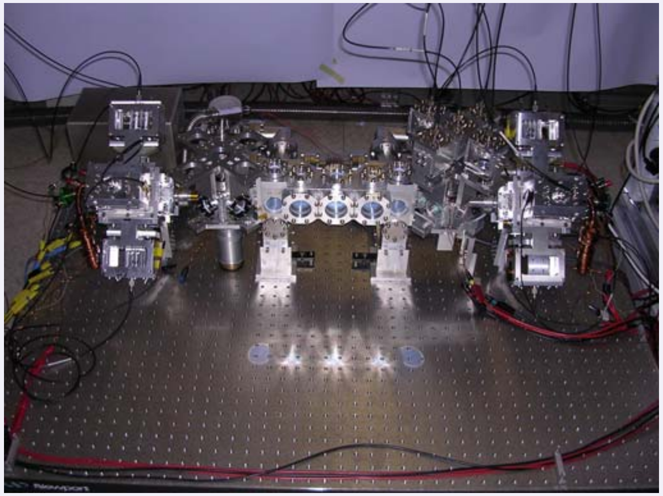
Expected sensitivity (10^6 at):

- gyroscope : $4\ 10^{-8}$ rad.s^{-1}.Hz$^{-1/2}$
- accelerometer : $3\ 10^{-8}$ m.s^{-2}.Hz$^{-1/2}$

B. Canuel et al., **Six-Axis Inertial Sensor Using Cold-Atom Interferometry**, PRL **97,** 010402 (2006)

IQO Cold Atom Sagnac Interferometer



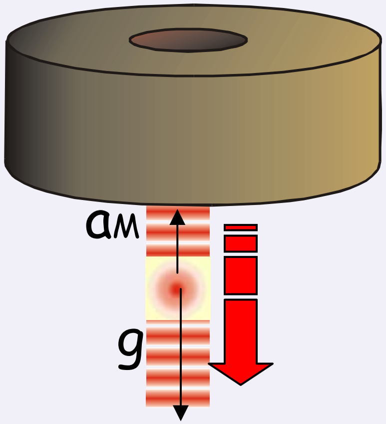


C. Jentsch, T. Müller, E. Rasel, and W. Ertmer, Gen. Rel. Grav, 36, 2197 (2004)

MAGIA

(Misura Accurata di G mediante Interferometria Atomica)

- **Measure g by atom interferometry**
- **Add source masses**
- **Measure change of g**

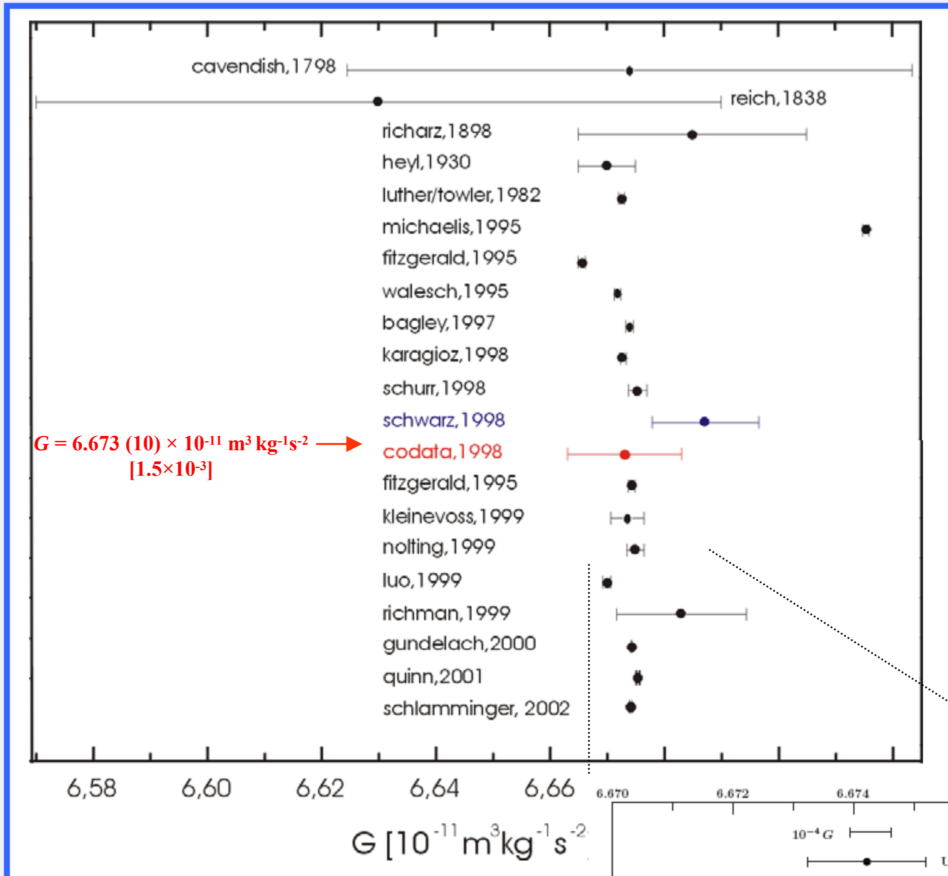


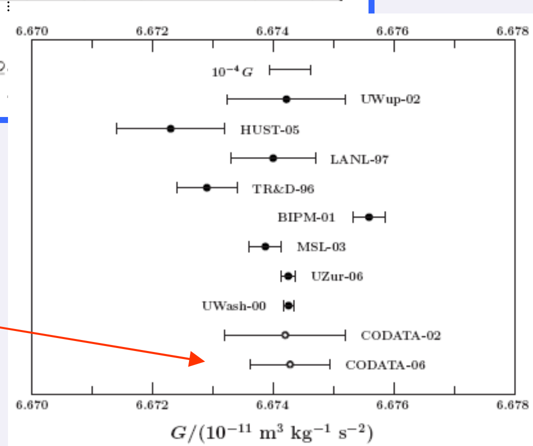
- ***Precision measurement of G***
- ***Test of Newtonian law at micrometric distances***

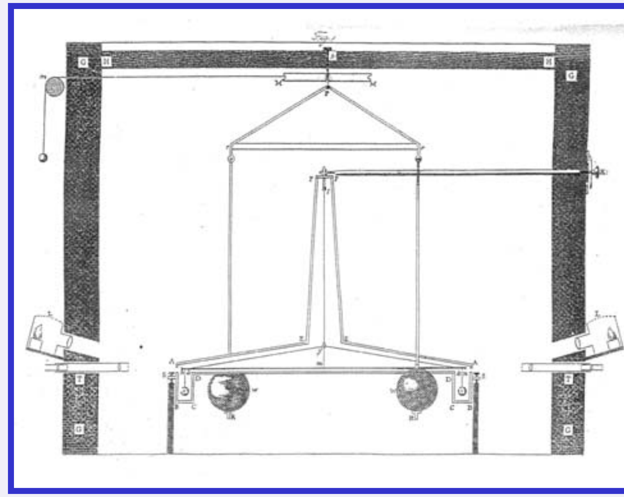
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Measurement of the Newtonian gravitational constant G by atom interferometry

Measurements of the Newtonian gravitational constant G







Cavendish 1798

Quinn 2001

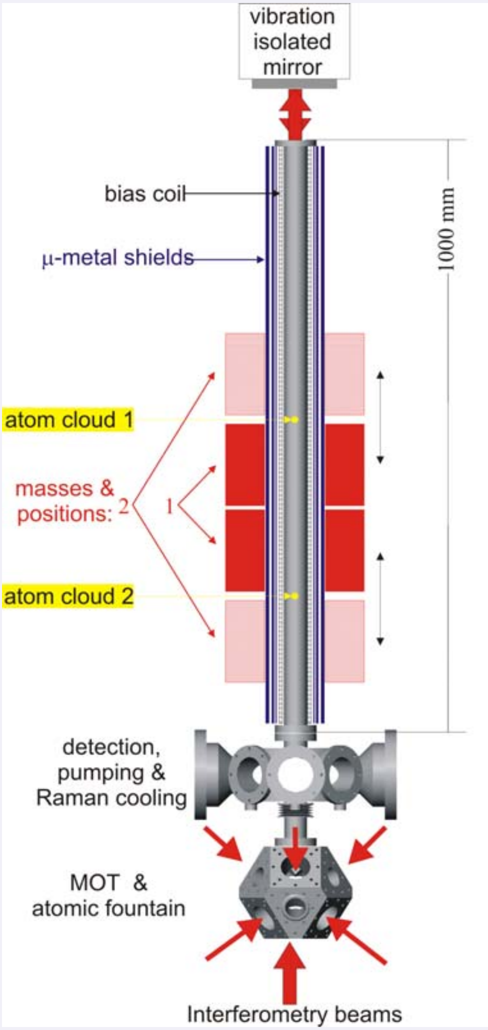
G = 6.674 28 (67) × 10^{-11} $m^3\,kg^{-1}s^{-2}$
[1.0×10^{-4}]

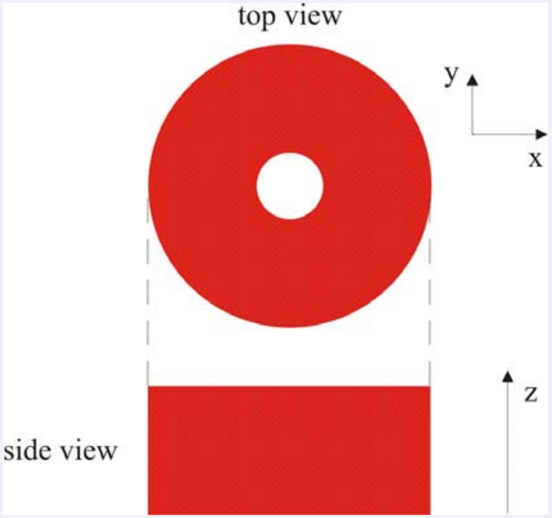
P.J. Mohr, B. N. Taylor, and D. B. Newell, *CODATA recommended values of the fundamental physical constants: 2006*, Rev. Mod. Phys. 80, 633 (2008)

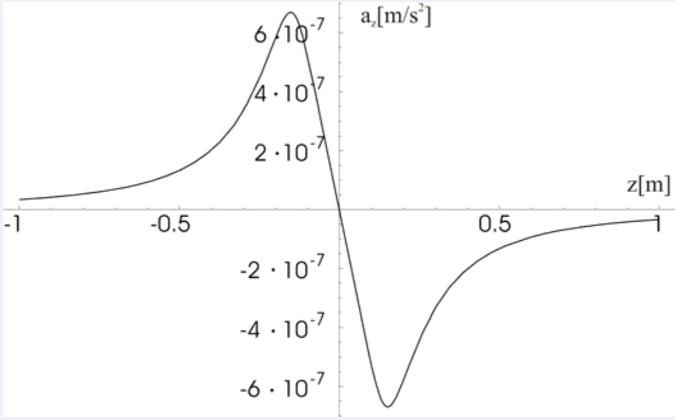
Why atoms?

- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects
- Different states, isotopes,…

MAGIA: atom gravimeter + source mass



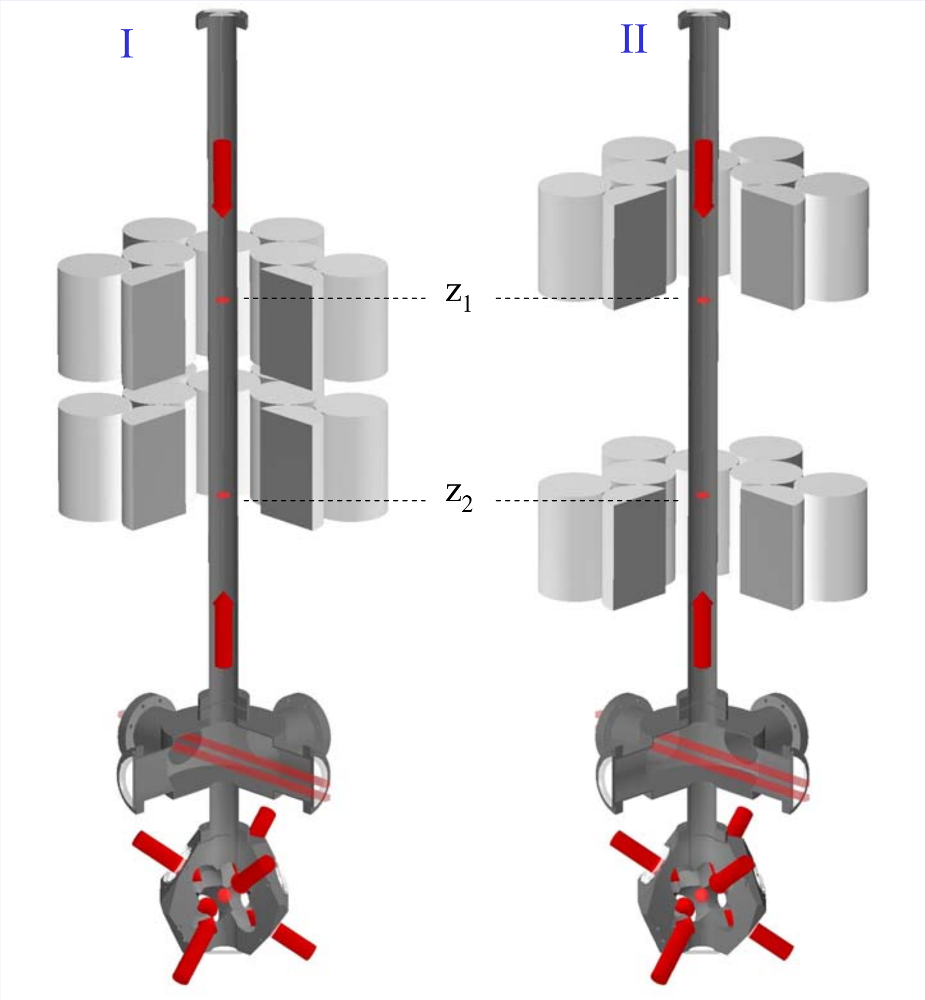




500 kg tungsten mass

Sensitivity 10^{-9}g/shot	Peak mass acceleration $a_G \approx 10^{-7}$g
one shot $\Rightarrow \Delta G/G \approx 10^{-2}$	10000 shots $\Rightarrow$ **$\Delta G/G \approx 10^{-4}$**

MAGIA: Experimental procedure



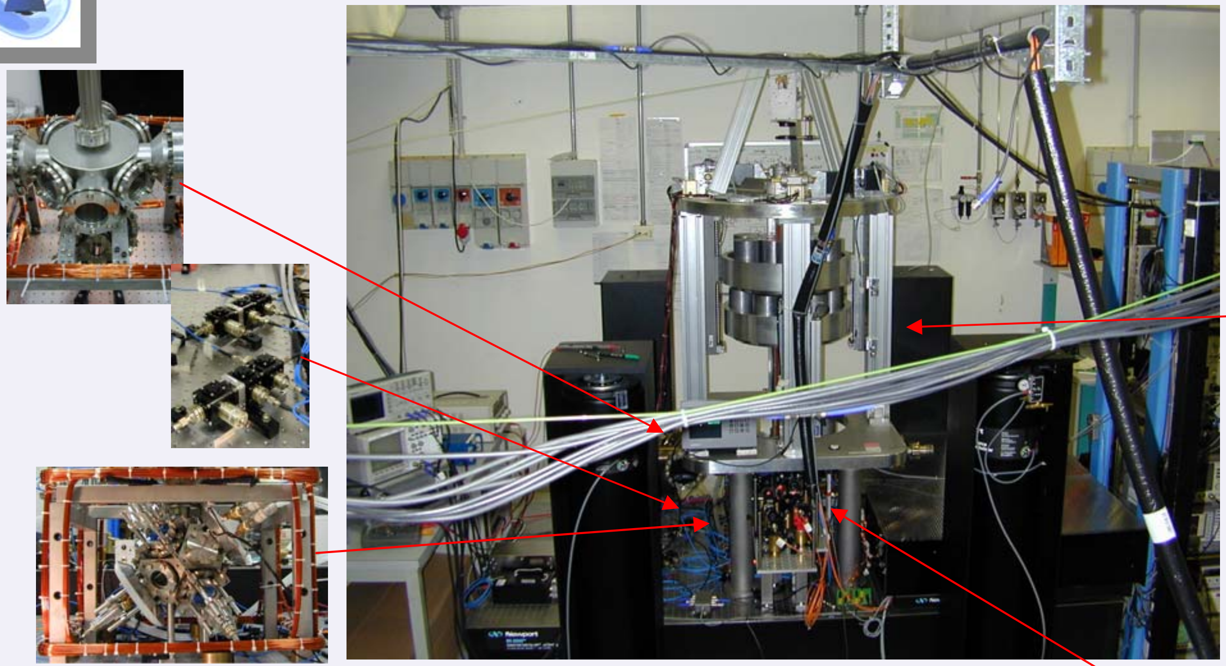
- trap, cool and launch two clouds of Rb atoms
- apply Raman light pulses
  masses in position I
- detect atoms state selectively
- repeat several times
- plot N_a/N and fit the differential phase shift $\Delta\Phi_g$ between the clouds
- move masses to position II
  repeat all procedure
- subtract the differential phase shifts for the two mass positions

$$\phi_1^I - \phi_2^I = \phi_g(z_1) + \phi_{SM} + \phi_{Sys}(z_1, t_I) - \left(\phi_g(z_2) - \phi_{SM} + \phi_{Sys}(z_2, t_I)\right)$$

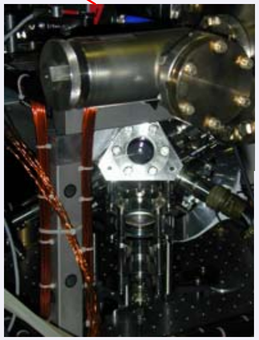
$$\phi_1^{II} - \phi_2^{II} = \phi_g(z_1) - \phi_{SM} + \phi_{Sys}(z_1, t_{II}) - \left(\phi_g(z_2) + \phi_{SM} + \phi_{Sys}(z_2, t_{II})\right)$$

$$\Rightarrow (\phi_1^I - \phi_2^I) - (\phi_1^{II} - \phi_2^{II}) = 4\phi_{SM} + \phi_{Sys}(\Delta z, \Delta t)$$

Atom gravity-gradiometer apparatus

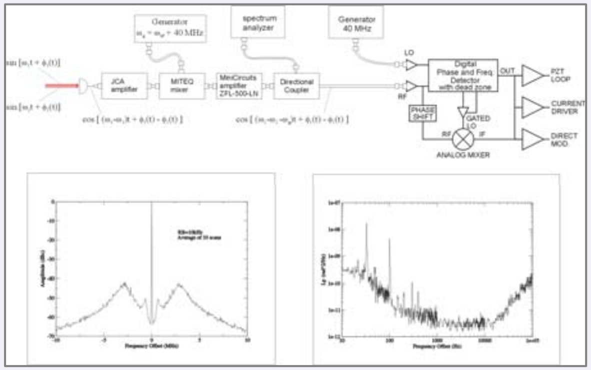


Source masses and support



G. Lamporesi et al., *Source Masses and Positioning System for an Accurate Measurement of G,* **Rev. Scient. Instr. 78, 075109 (2007)**

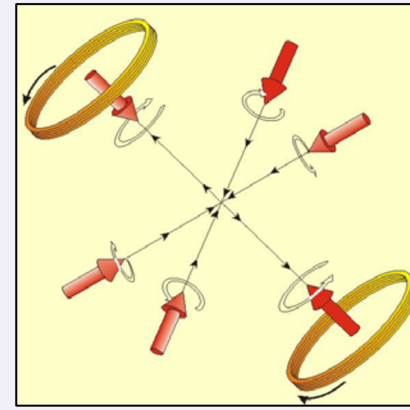
Laser and optical system

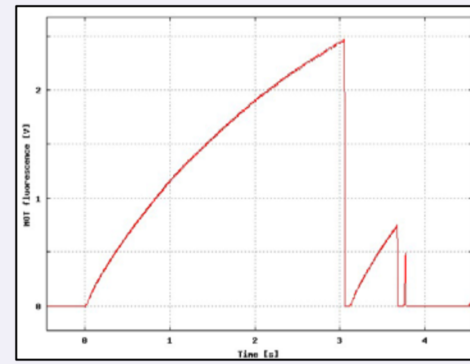


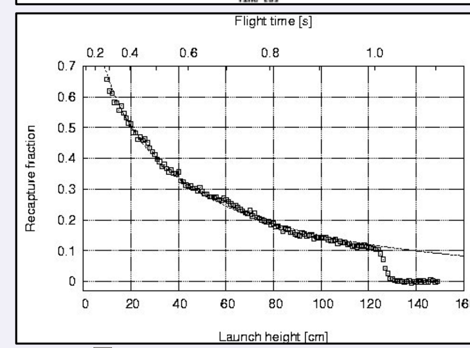
L.Cacciapuoti, M.de Angelis, M.Fattori, G.Lamporesi, T.Petelski, M.Prevedelli, J.Stuhler, G.M.Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* **Rev.Scient.Instr. 76, 053111 (2005)**

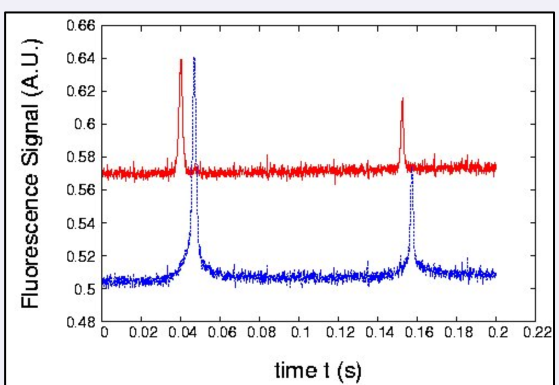
Experimental sequence

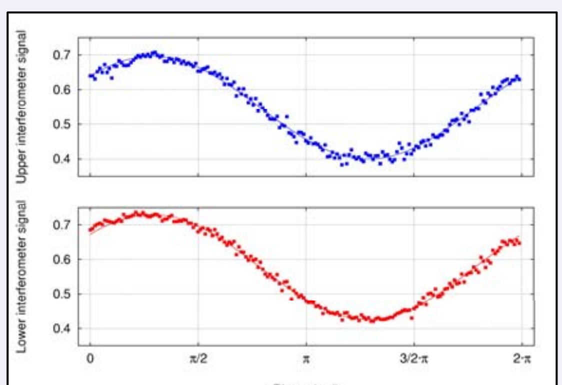
Trapping	N=5x10^8 ^{87}Rb	Laser cooling - MOT
Cooling	T=4 μK	Laser cooling - Optical molasses
Launch	h=20-120 cm	Moving opt. mol. - Atomic fountain
Double launch	Δt=80 ms Δz=30 cm	Juggling
Selection	F=1 m_F=0 $\Delta v_z = v_{rec}/2$	Two-photon Raman transition
Interferometer	Δφ	π/2 – π – π/2 Raman sequence with phase locked lasers
Detection	N_1 , N_2	Fluorescence detection

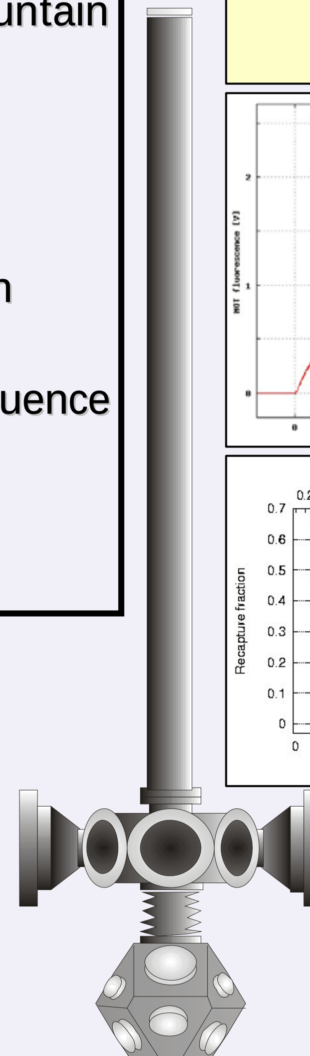


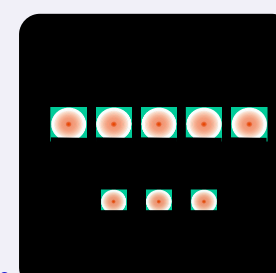




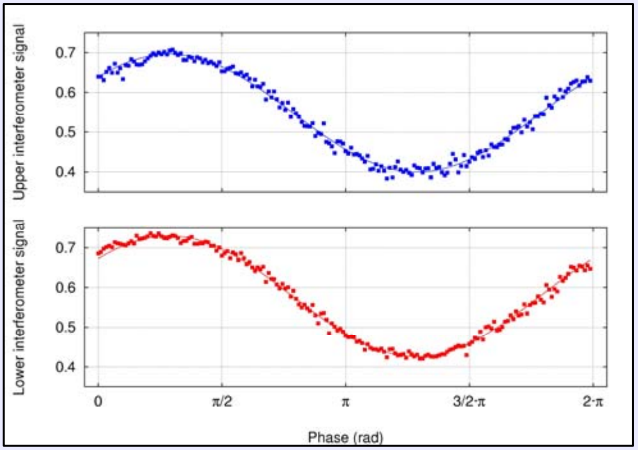






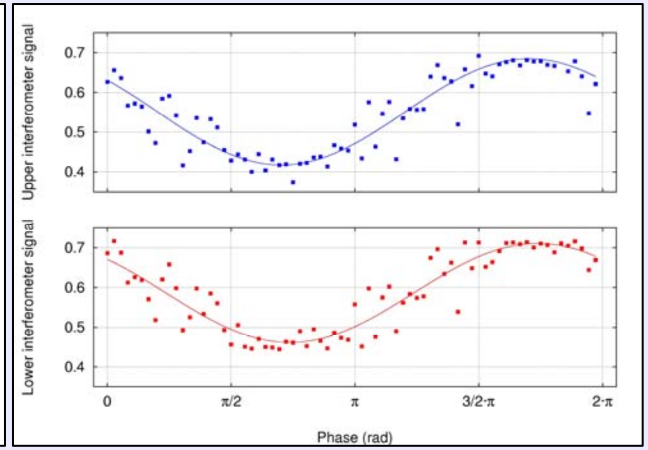


Gradiometer



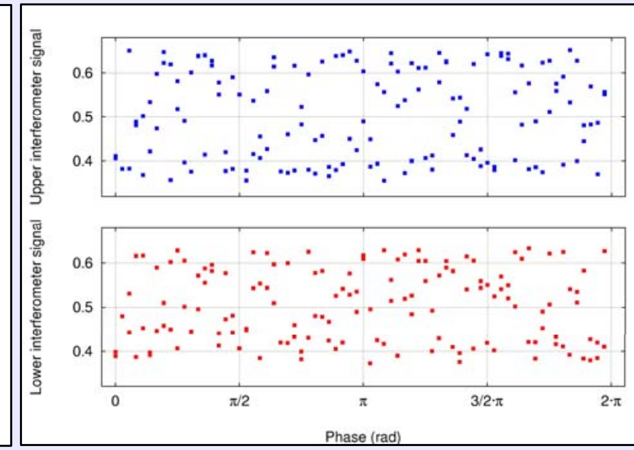
T=5 ms

$\varphi(g) = 4.0 \cdot 10^3$ rad
$\varphi(\nabla g) = 0.4$ mrad
res = 220 mrad/√Hz
= $5.5\ 10^{-5}$ g/√Hz
= $2.3\ 10^{-5}$ g/shot



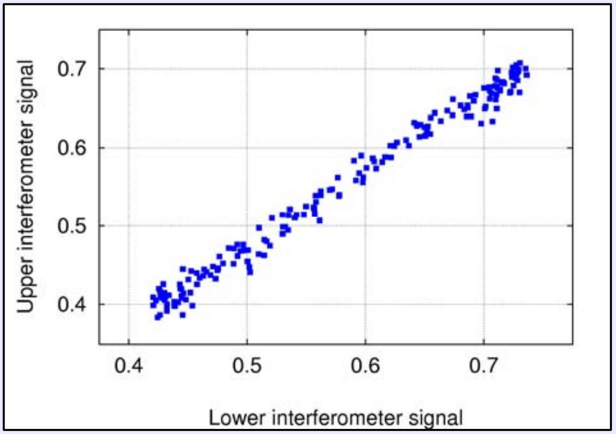
T=50 ms

$\varphi(g) = 4.0 \cdot 10^5$ rad
$\varphi(\nabla g) = 40$ mrad
res = 1.0 rad/√Hz
= $2.5\ 10^{-6}$ g/√Hz
= $1.0\ 10^{-6}$ g/shot



T=150 ms

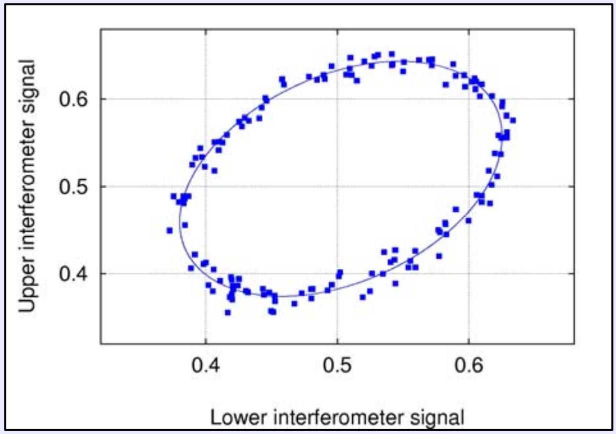
$\varphi(g) = 3.6 \cdot 10^6$ rad
$\varphi(\nabla g) = 380$ mrad
res = 290 mrad/√Hz
= $7.6\ 10^{-8}$ g/√Hz
= $3.2\ 10^{-8}$ g/shot



$$\Delta\varphi_{grad} = k_R\ \Delta g\ T^2$$

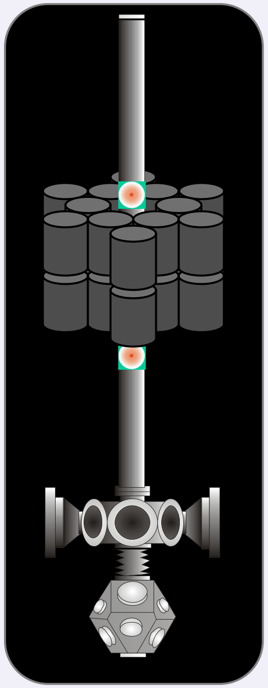
$$\Delta\varphi_{rot} = -2\Omega\ \Delta v_{EW}\ k_R T^2 \cos\theta_{lat}$$

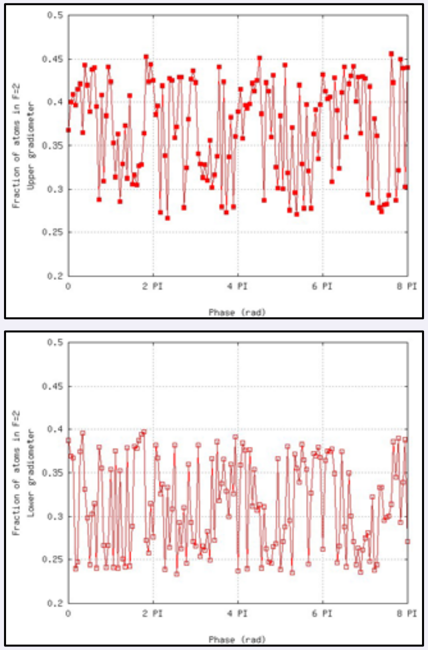
$$\Delta\varphi_B = 2\pi\ a_{||}\ B^2\ \Delta t$$

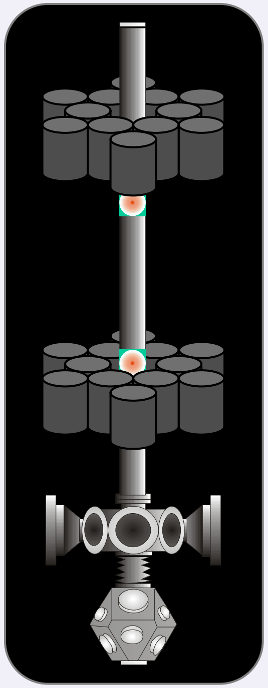


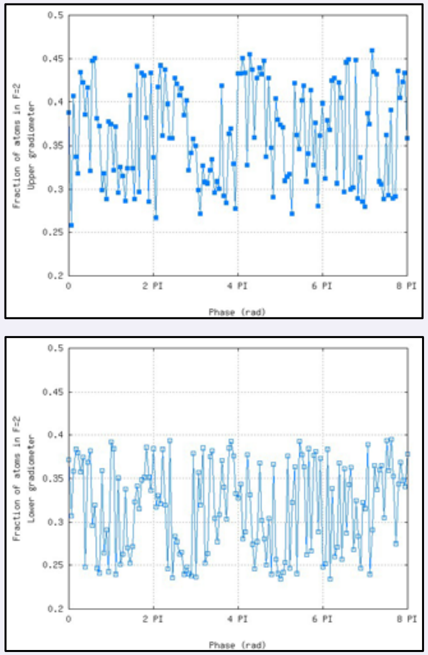
Ellipse fitting method: G.T. Foster et al., *Opt. Lett.* **27**, 951 (2002).

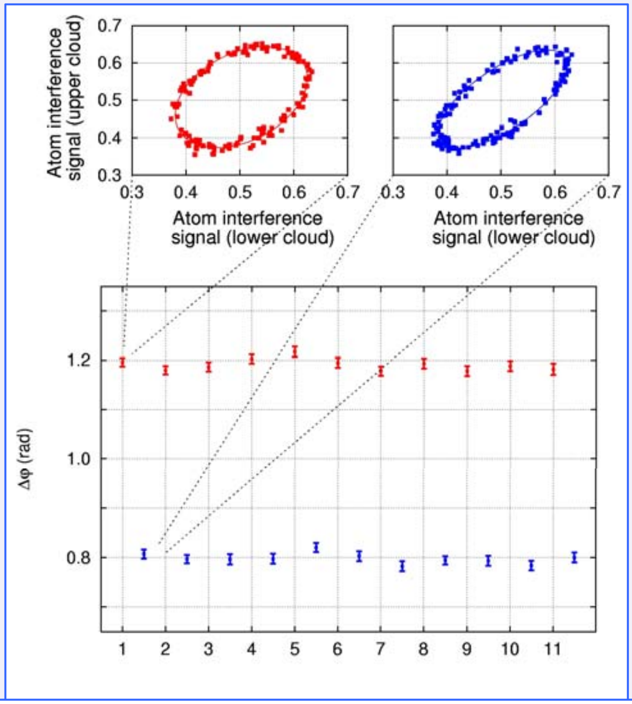
G: first result

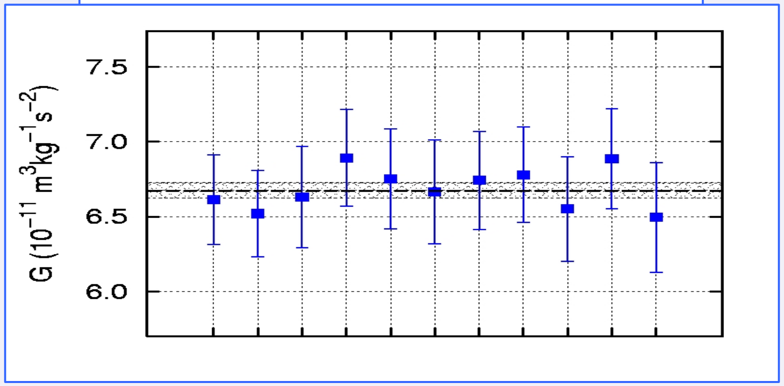






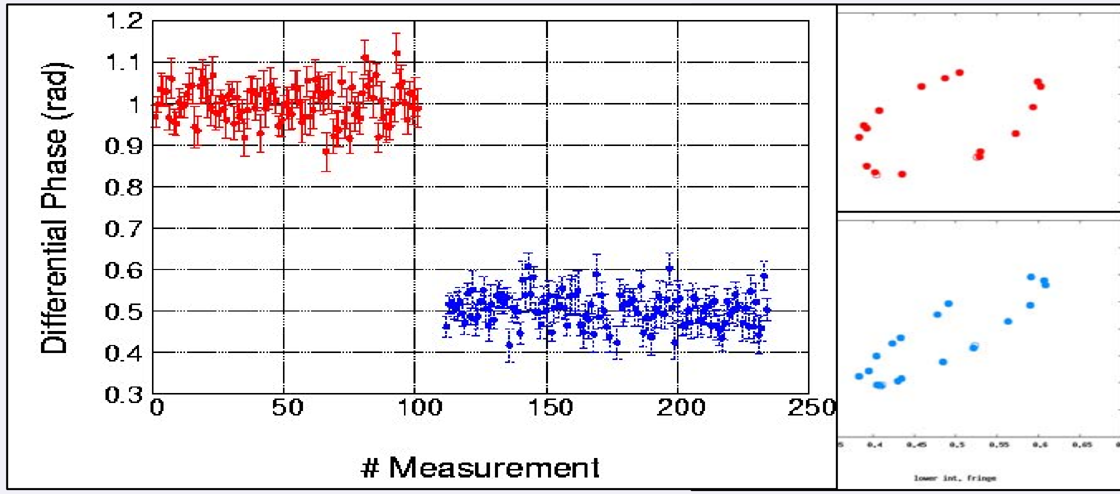




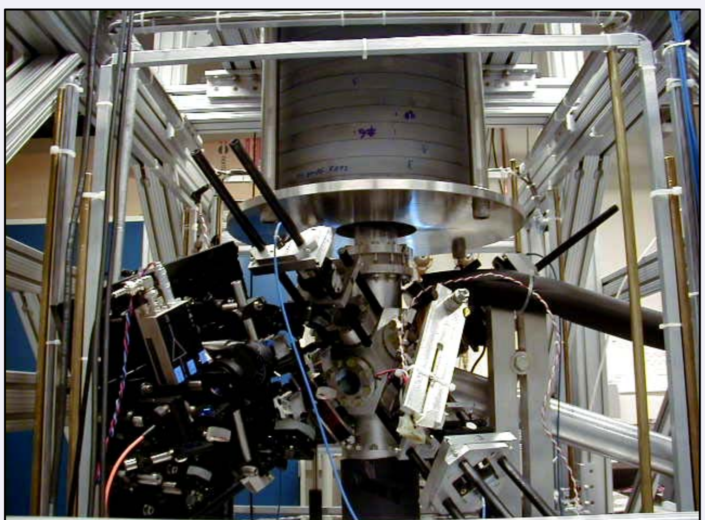


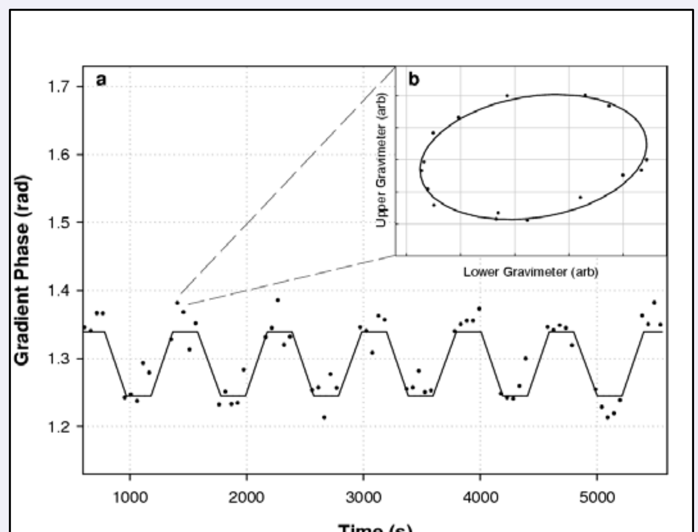
***G* = 6.64 (6) × 10^{-11} m^3 kg^{-1}s^{-2}**

A. Bertoldi, G. Lamporesi , L. Cacciapuoti, M. de Angelis, M. Fattori, T. Petelski, A. Peters, M. Prevedelli, J. Stuhler, G. M. Tino, **Eur. Phys. J D 40, 271 (2006)** **(available online as Highlight Paper)**



A. Bertoldi et al., *Eur. Phys. J. D* **40**, 271 (2006)





J.B. Fixler et al., *Science* **315**, 74 (2007)

Source mass

COMPOSITION

PROPERTIES

REALIZATION

INTERMET IT 180
(PLANSEE)

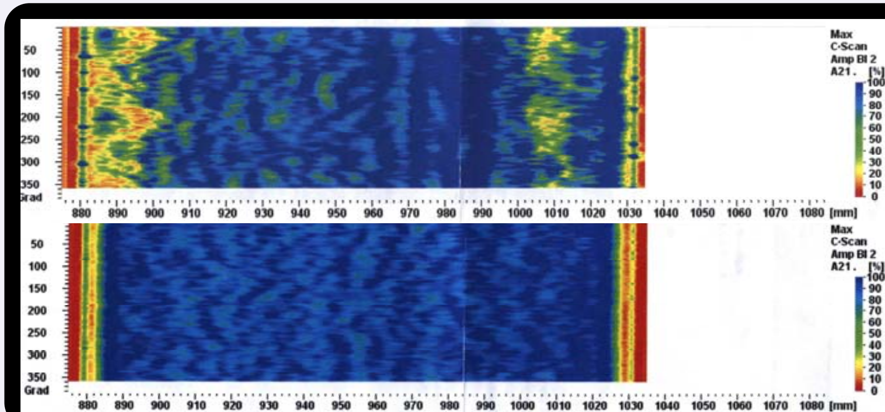
Density	18 kg/m^3
Resistivity	12×10^{-8} Ωm
Amagnetic	
CTE	5×10^{-6} K^{-1}
Roughness	3 μm

SINTERING
T=1500°C - P=1 bar

Hot Isostatic Pressing
T=1200°C - P=1000 bar

MICROSCOPE ANALYSIS

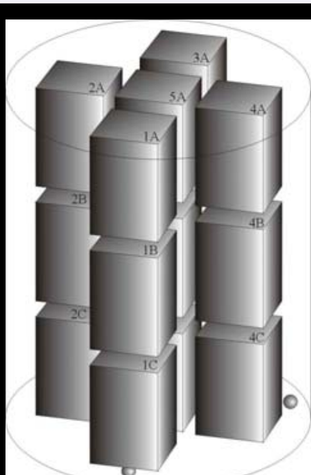
holes: Ø ~ 100 μ m



ULTRASONIC TEST

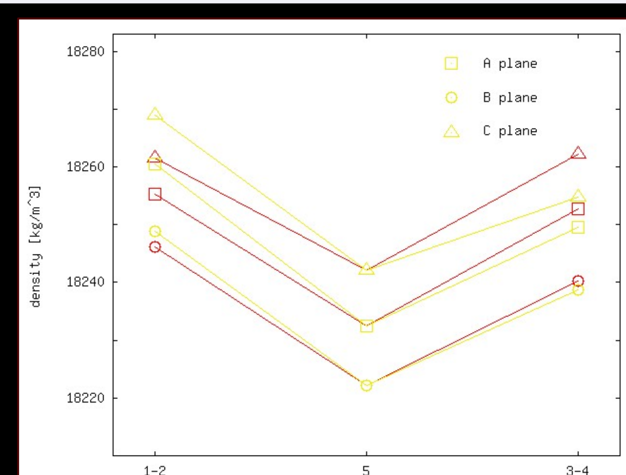
Before HIP

After HIP



DENSITY TEST
(INRIM, Torino)

ρ = 18249 kg/m^3
res: 10 mg/m^3
σ_ρ = 12 kg/m^3 ($6\ 10^{-4}$)
$\Delta\rho$ =47 kg/m^3 ($2\ 10^{-3}$)

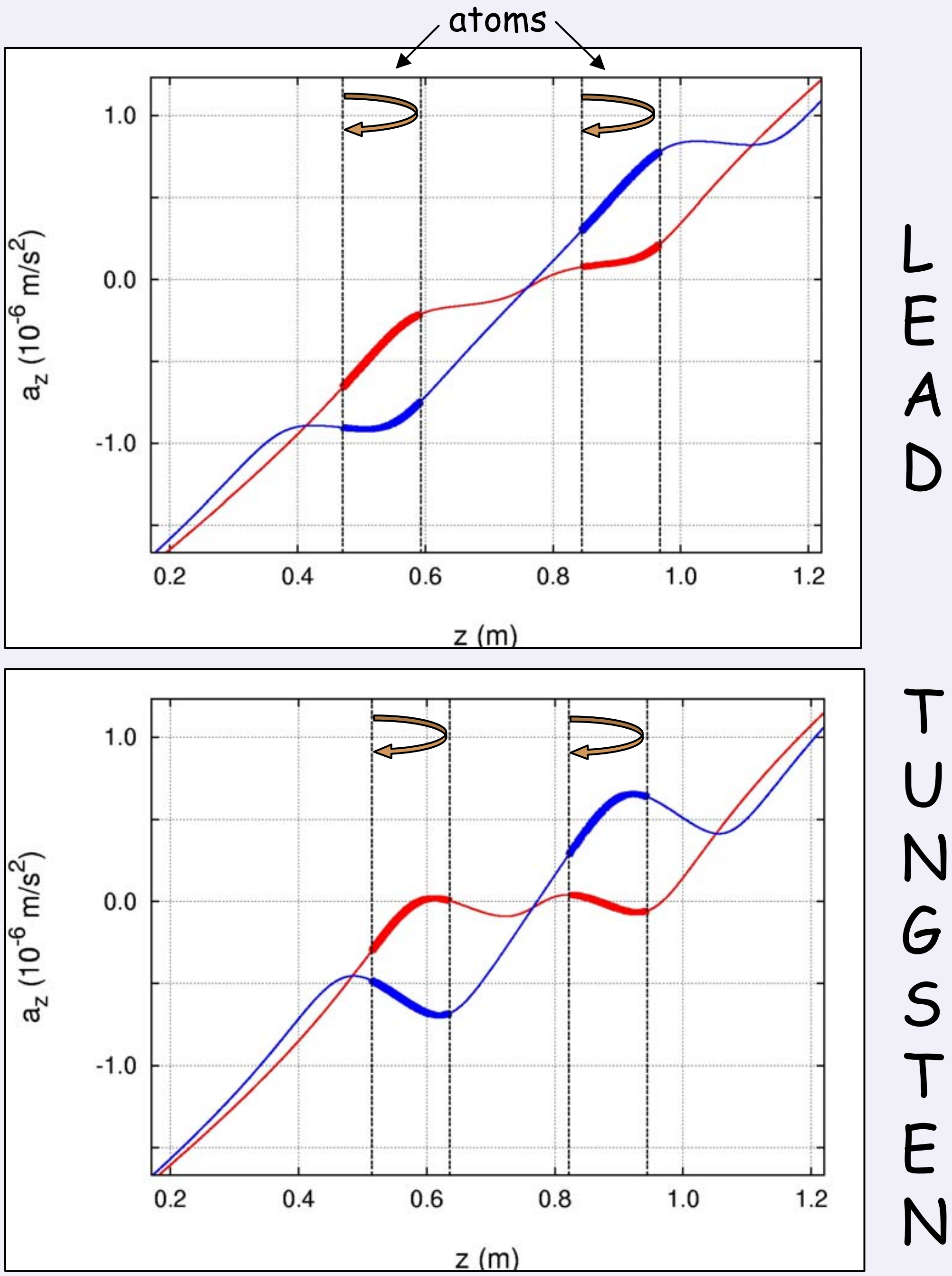


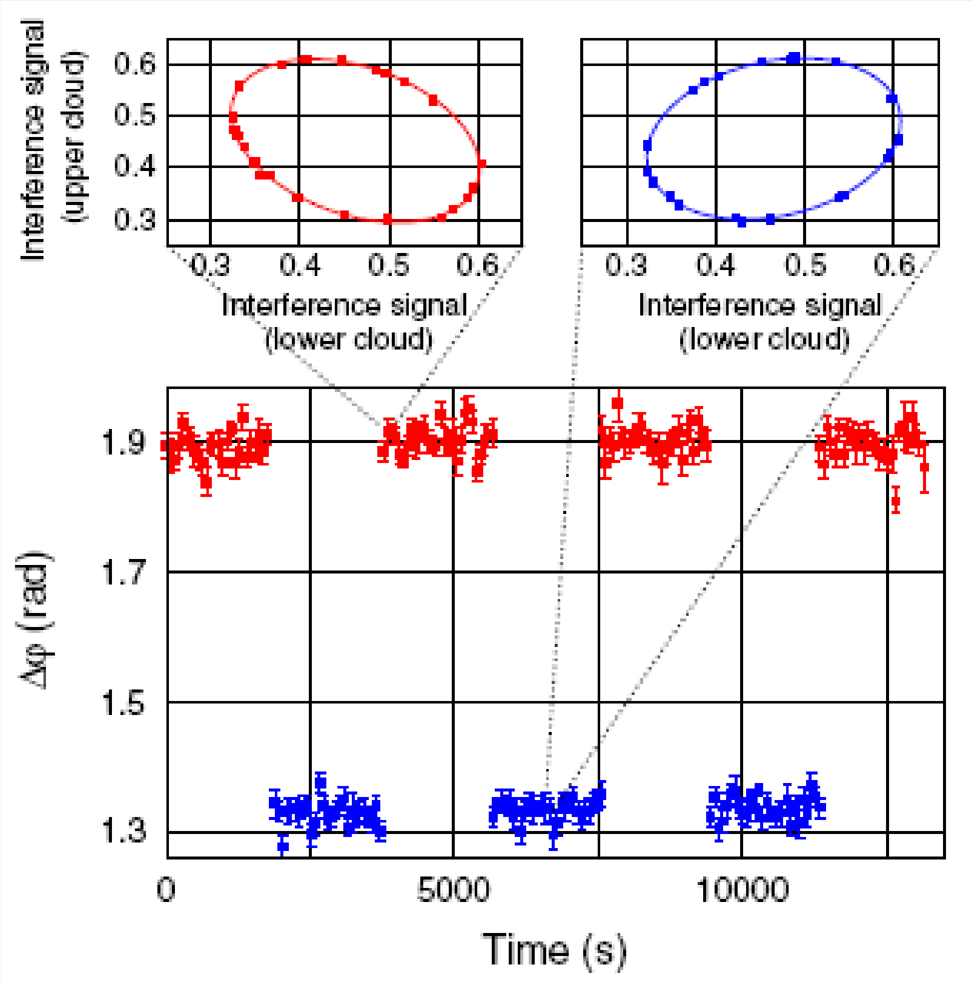
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G*, Rev. Scient. Instr. 78, 075109 (2007)

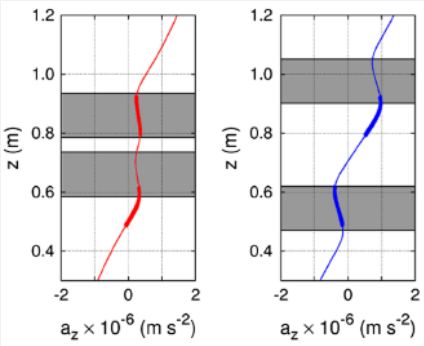
Appropriate trajectories

Masses separation in the two configurations and atomic clouds initial position have been chosen in order to minimize the dependence on atomic initial parameters and reach the accuracy on G of 10^{-4}.

• the interferometer is realized around an acceleration max/min
• the Earth's gravity gradient must be over-compensated
• only high density material can be used



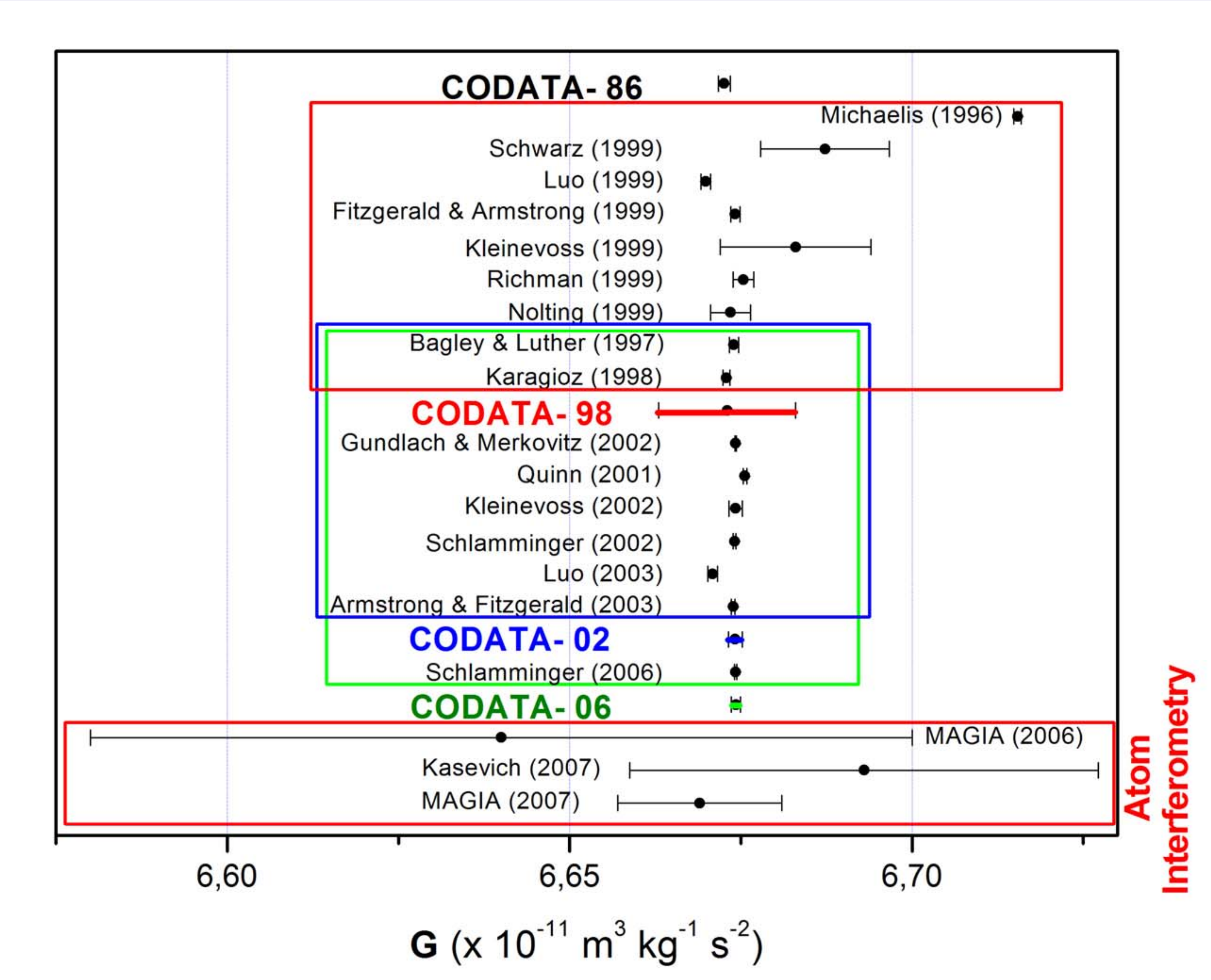




New results from MAGIA

$G = 6.667\ (11)\ (3)\ m^3\ kg^{-1}\ s^{-2}$

G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino
Determination of the Newtonian Gravitational Constant Using Atom Interferometry
Phys. Rev. Lett. 100, 050801 (2008)


CODATA- 86
Michaelis (1996)
Schwarz (1999)
Luo (1999)
Fitzgerald & Armstrong (1999)
Kleinevoss (1999)
Richman (1999)
Nolting (1999)
Bagley & Luther (1997)
Karagioz (1998)
CODATA- 98
Gundlach & Merkovitz (2002)
Quinn (2001)
Kleinevoss (2002)
Schlamminger (2002)
Luo (2003)
Armstrong & Fitzgerald (2003)
CODATA- 02
Schlamminger (2006)
CODATA- 06
MAGIA (2006)
Kasevich (2007)
MAGIA (2007)
Atom Interferometry
6,60
6,65
6,70
G (x 10^-11 m^3 kg^-1 s^-2)

Present error budget

Systematic effect	$\Delta G/G$ ($\times 10^{-4}$)
Radial position	1.2
Vertical position in C_1	2.7
Vertical position in C_2	2.1
Cylinders mass	0.9
Cylinders density inhomogeneity	0.21
Support platforms mass	0.8
Initial position of the atomic clouds	0.18
Initial velocity of the atomic clouds	2.3
Gravity gradient	1
Stability of the on-axis B-field	0.3
Stability of the launch direction	0.6
Total	4.6

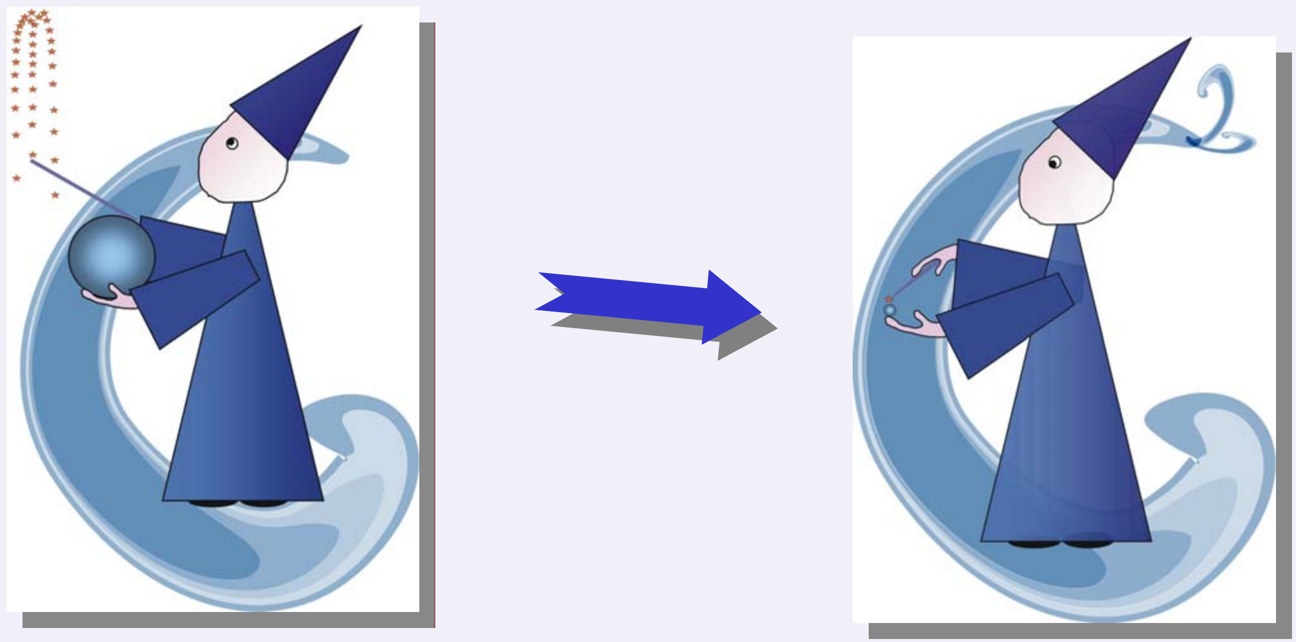
MAGIA – Relevant numbers

- time separation between pulses T=150 ms
- 10^6 atoms
- shot noise limited detection
- launch accuracy: 1 mm e $\Delta v \sim 5$ mm/s
- knowledge of the masses dimensions and relative positions: 10 μm
- 10000 measurements

⇓

$$\Delta G/G \leq 10^{-4}$$

Experiments on gravity at small spatial scale



Motivation

- **Physics beyond the standard model**

Extra space-time dimensions

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429, 263 (1998)
N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Rev. D 59, 086004 (1999)

Deviations from $1/r^2$ law
Hierarchy problem: why is gravity so weak?

New boson-exchange forces

Radion – low-mass spin-0 fields with gravitational-strength couplings
Moduli – massive scalar particles producing gravitylike forces
Dilaton – Light scalar in string theory, coupling to nucleons
Axion – pseudoscalar particles explaining smallness of CP violation in QCD for strong nuclear force
Multi-particle exchange forces

S. Dimopoulos and G. F. Giudice, Phys. Lett. B 379, 105 (1996)
I. Antoniadis, S. Dimopoulos, and G. Dvali, Nuc. Phys. B 516,70 (1998)

T.R. Taylor, G. Veneziano, Phys. Lett. B 213, 450 (1988)
D. B. Kaplan, M. B. Wise, J. High Energy Phys. 8, 37 (2000)

Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

- **Small observed size of Einstein cosmological constant**

S.R. Beane, Gen. Rel. Grav. 29, 945 (1997)
R. Sundrum, Phys. Rev. D 69, 044014 (2004)

- **Experimental challenge**

Parametrizations for deviations from Newtonian gravity

- **Modification of power law in Newton-type force**

$$F(r) = G\frac{M_1 M_2}{r^{2+\delta}}$$

- **Newton+Yukawa potential**

$$V(r) = -G\frac{M_1 M_2}{r}\left[1 + \alpha e^{-\frac{r}{\lambda}}\right]$$

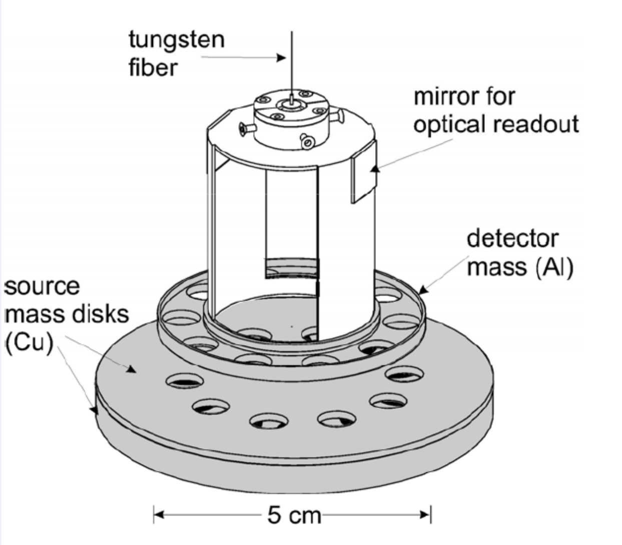
→
- Exchange of a boson with m = ħ/λc
- Extra dimensions

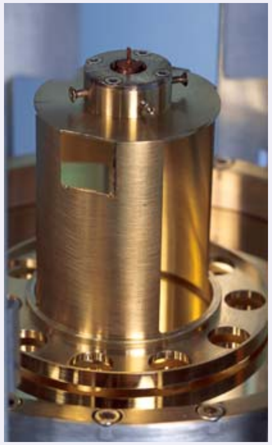
- **Modified power-law potential**

$$V(r) = -G\frac{M_1 M_2}{r}\left[1 + \alpha_N \left(\frac{r_0}{r}\right)^{N-1}\right]$$

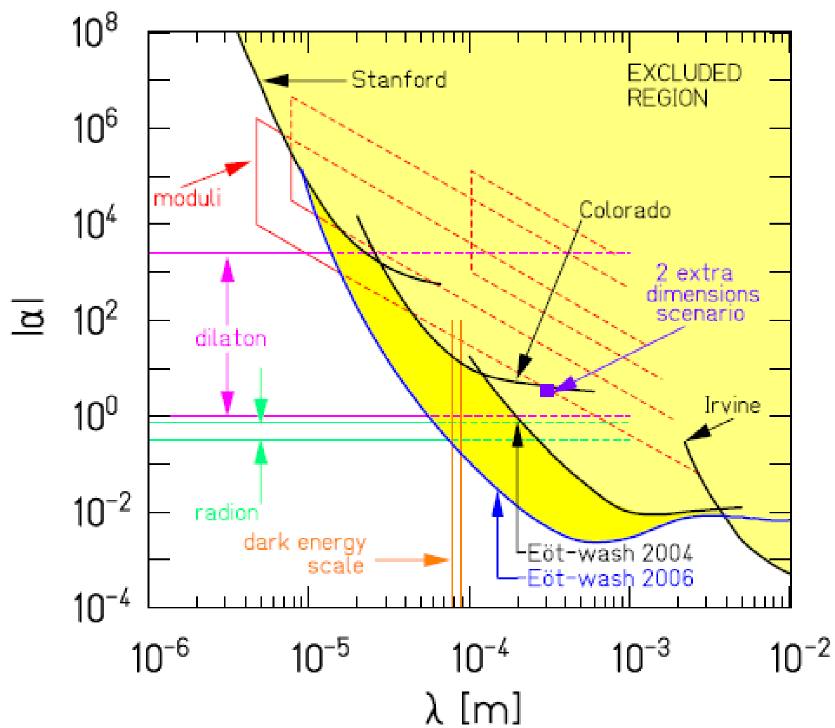
→ Exchange of 2 massless particles

Torsion balance - Washington experiment





- Test bodies: "missing masses" of holes bored into plates
- Torsion pendulum
  7075 aluminum, gold coated
  disk height = 2 mm
  10 cylindrical holes evenly spaced about the azimuth
- Attractor
  high-purity copper disk
  top surface coated with gold
  10 cylindrical holes evenly spaced about the azimuth
  uniformly rotating
- Electrostatic shield
  tightly stretched 20-μm-thick BeCu foil

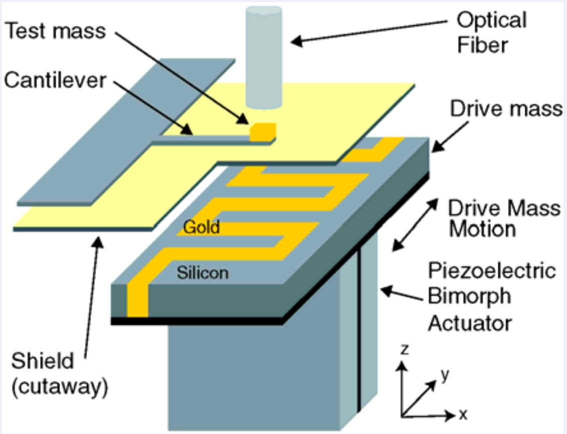


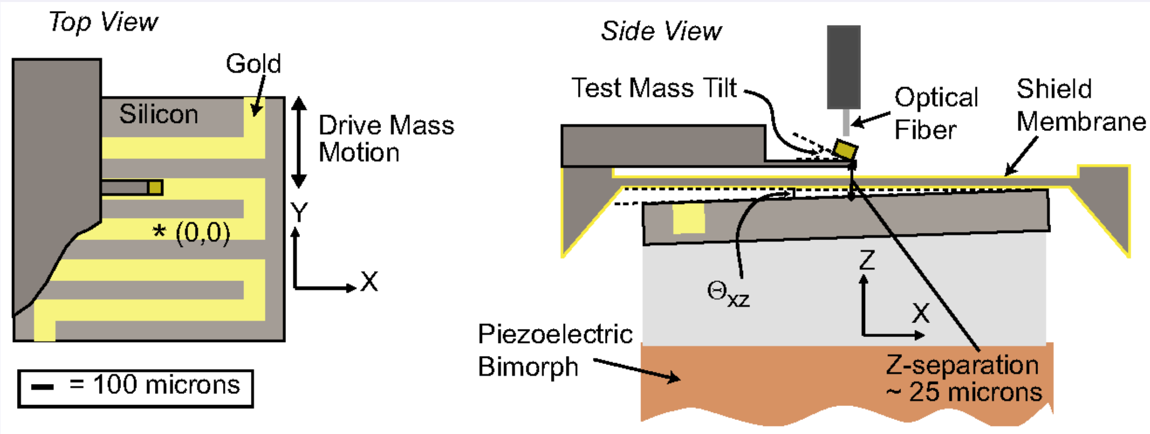
- Distance from top of attractor to bottom of pendulum
  from 9.53 mm to 55 μm

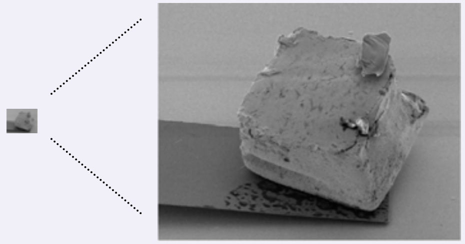
C. D. Hoyle, D. J. Kapner, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt, H. E. Swanson, ***Submillimeter tests of the gravitational inverse-square law,*** **PRD 70, 042004 (2004)**

D. J. Kapner, T. S. Cook, E. G. Adelberger, J.H. Gundlach, B. R. Heckel, C. D. Hoyle, H. E. Swanson, *Tests of the Gravitational Inverse-Square Law below the Dark-Energy Length Scale,* **PRL 98, 021101 (2007)**

Microcantilever - Stanford experiment

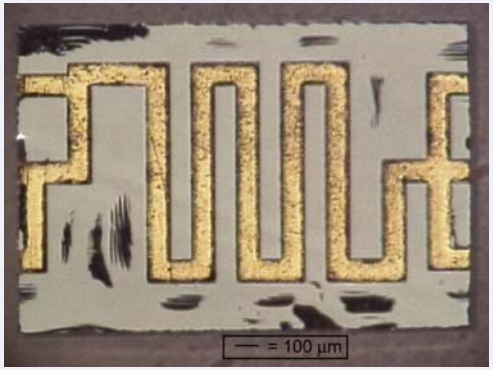






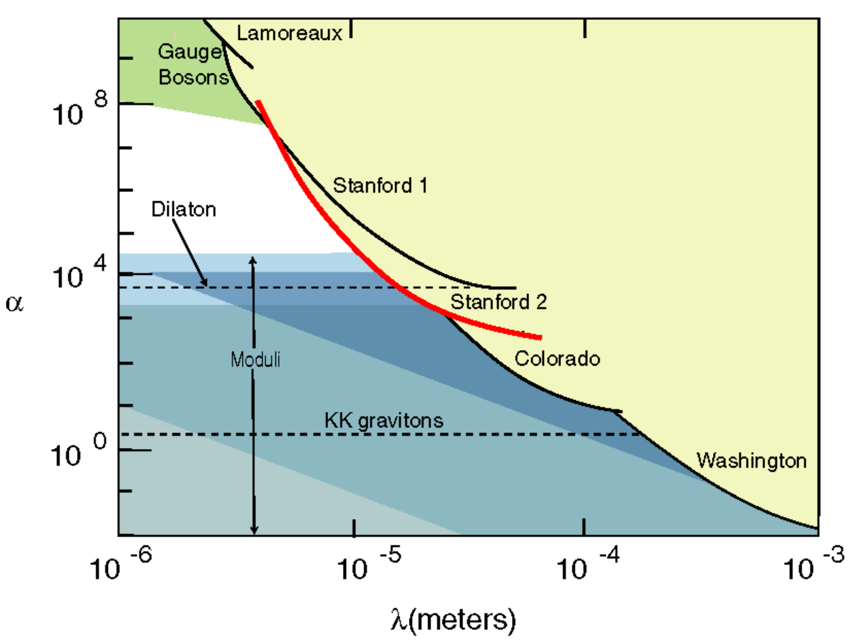
Probe mass (gold)
50 µm x 50 µm x 30 µm
$m_t \sim 1.6$ µg

Cantilever (<100> Si)
50 µm x 250 µm x 0.33 µm
Q ~ 80 000
$\omega_o \sim (k/m_t)^{1/2} \sim 300$ Hz



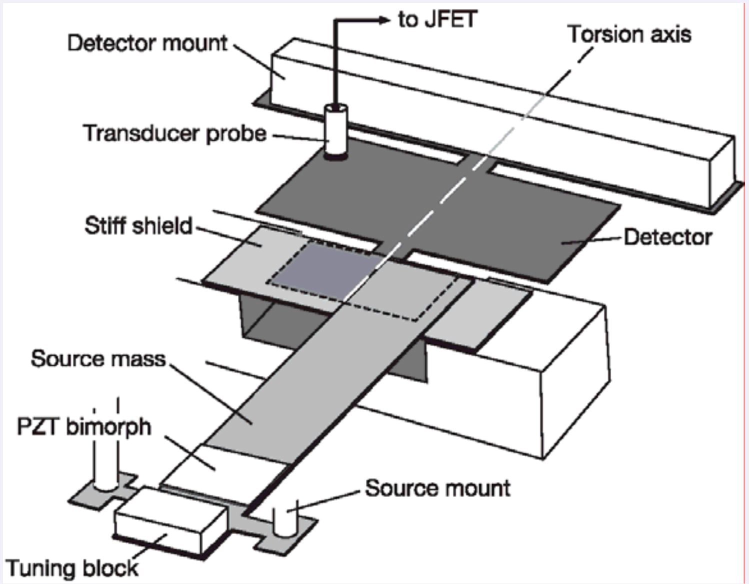
Source mass
5 sets of gold and silicon bars
100 µm x 1mm x 100 µm

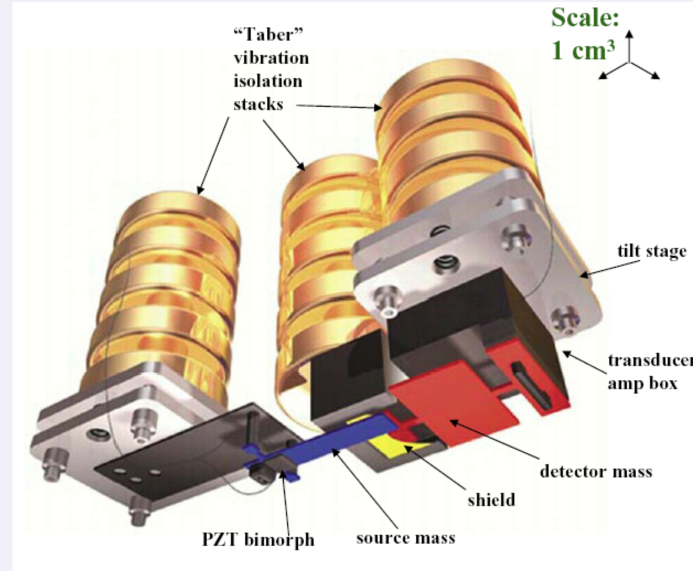
Separation 25 µm

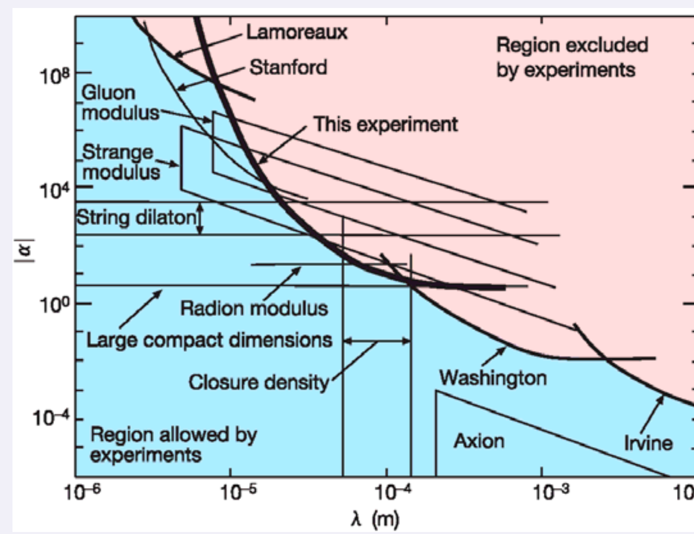


S. J. Smullin, A. A. Geraci, D. M. Weld, J. Chiaverini, S. Holmes, A. Kapitulnik, *Constraints on Yukawa-type deviations from Newtonian gravity at 20 microns*, Phys. Rev. D 72, 122001 (2005)

Microcantilever - Colorado experiment







Detector (tungsten)
11.455 mm x 5.080 mm x 195 μm

Q ~ 25 000
ω_o ~ 1173 Hz

Source mass (tungsten)
35 mm x 7 mm x 305 μm

Separation 108 μm

J.C. Long, H.W. Chan, A.B. Churnside, E.A. Gulbis, M.C.M. Varney, J.C. Price, *Upper limits to submillimetre-range forces from extra space-time dimensions*, Nature 421, 922 (2003)

Experiments on gravity at small spatial scale

Experiments based on torsion balances ($\lambda \leq 1$ mm)

J. Gundlach and E. Adelberger (Washington) – torsion balance

R. Newman and P. Boynton (Irvine, Washington) – cryogenic torsion balance

Experiments based on high-frequency oscillators ($\lambda \leq 0.1$ mm)

J. Long and J. Price group (Colorado) – torsional oscillator

A. Kapitulnik group (Stanford) - microcantilever

R. Decca and E. Fischbach group (Purdue, Indiana) – torsional oscillator

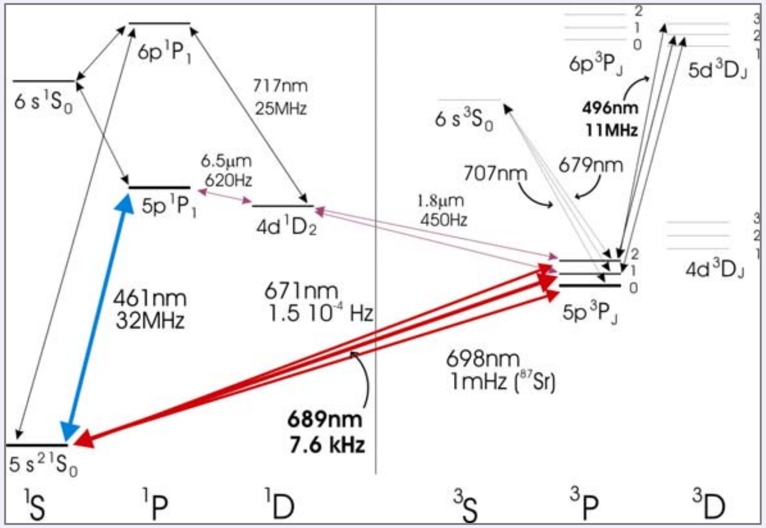
New experiments based on atomic probes ($\lambda \leq 0.01$ mm)

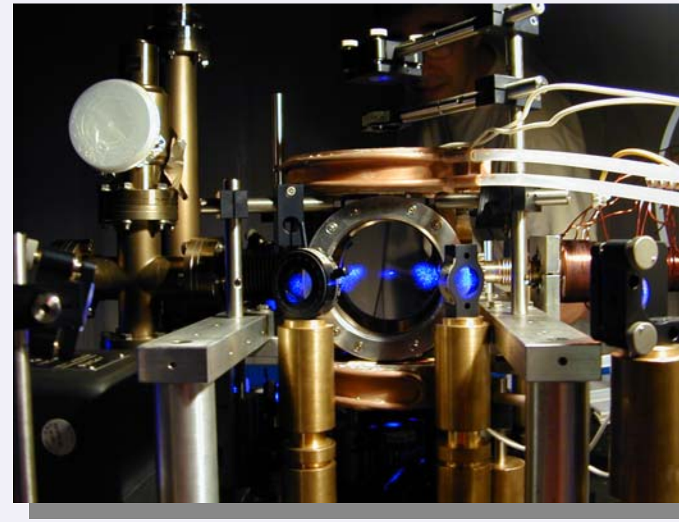
E.A. Cornell group (Colorado) – Oscillations of a Bose-Einstein condensate

G.M. Tino group (Firenze) – Atom interferometry

Also experiments on Casimir effect ($\lambda \leq 0.001$ mm)

Ultracold Sr – The experiment in Firenze



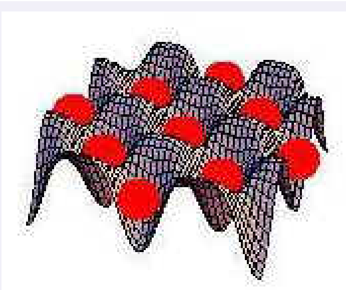


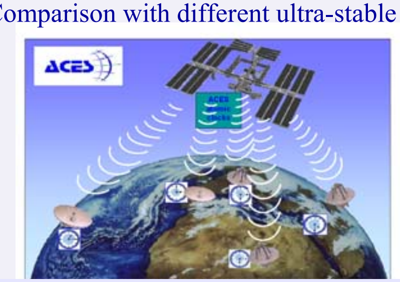
- Optical clocks using visible intercombination lines

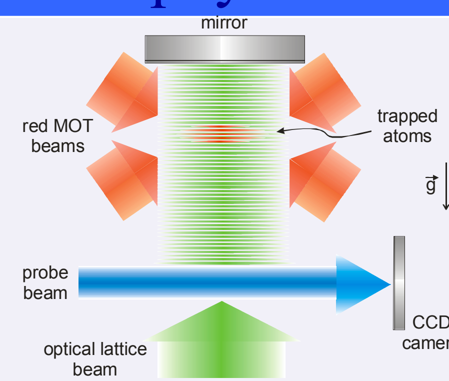
- New atomic sensors for fundamental physics tests

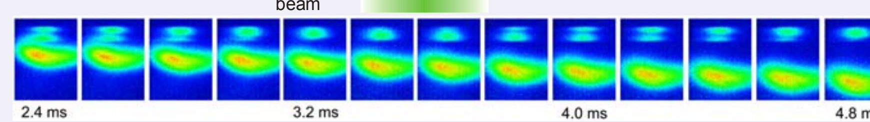
Optical clocks using visible intercombination lines

- $^1S_0$ - $^3P_1$ (7.5 kHz)
- $^1S_0$ - $^3P_0$ (1 mHz, ^{87}Sr)
- $^1S_0$ - $^3P_2$ (0.15 mHz)
- Optical trapping in Lamb-Dicke regime with negligible change of clock frequency
- Comparison with different ultra-stable clocks







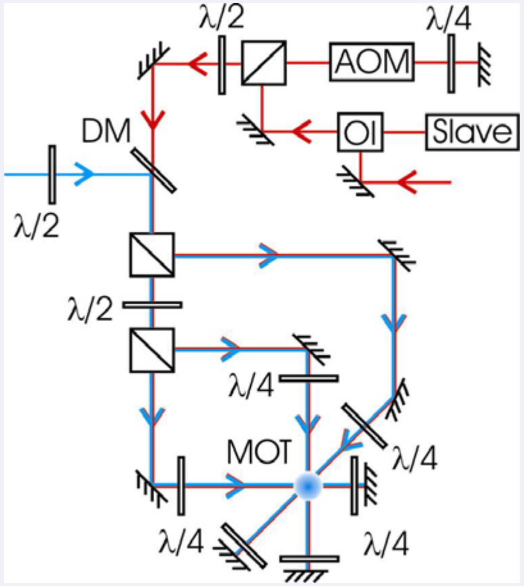


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

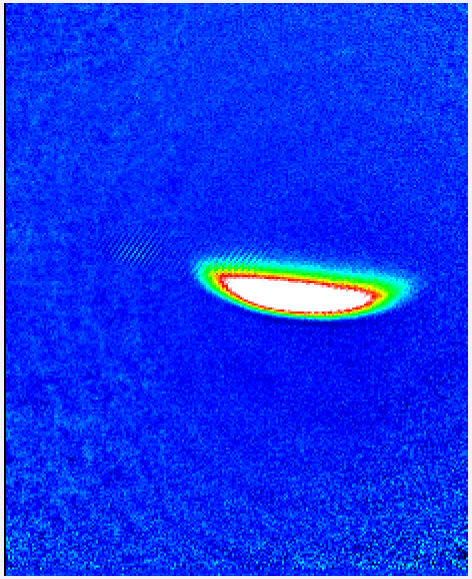
G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

Double stage trapping and cooling of Sr atoms

- Optical setup



- MOT Picture



- Capture Sequence:

  - Blue MOT ($\Delta t \sim 100$ ms)

$$\begin{cases} T_{oven} = 500\ °C \\ \delta = -40 \text{ MHz} \\ dB/dz = 60 \text{ Gauss/cm} \\ I \approx 0.4 \text{ Isat} \end{cases}$$

↓

  - Blue *molasses* ($\Delta t \sim 5$ ms) $\quad I \approx 0.06$ Isat

$\rightarrow \begin{cases} N = 3*10^7 \\ T = 2 \text{ mK} \end{cases}$

$v_{RMS} \approx 40$ cm/s

$\delta\omega_D \approx k_{689} v_{RMS} \approx 2\pi * 600$ kHz

  - Red MOT ***broad band*** ($\Delta t \sim 100$ ms)

$$\begin{cases} \Delta\nu = 2 \text{ MHz} \\ f = 50 \text{ kHz} \\ \delta = -1.2 \text{ MHz} \\ dB/dz = 4 \text{ Gauss/cm} \end{cases}$$

$\rightarrow I_{sidebands} = 40\ I_{sat}$

$\eta \approx 25\ \%$

  - Red MOT ***Single frequency*** ($\Delta t \sim 10$ ms)

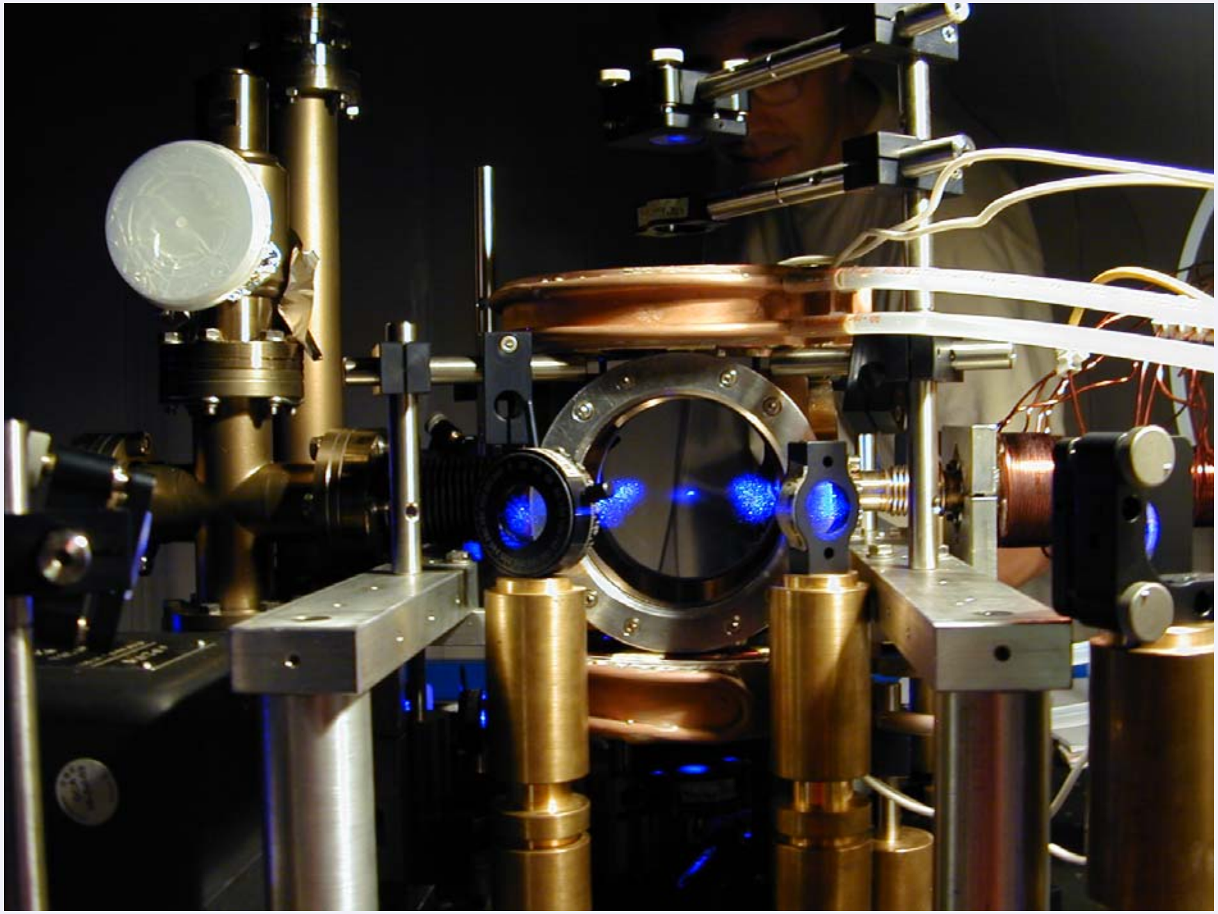
$$\begin{cases} \delta = -350 \text{ kHz} \\ I = (10^3 \div 1)\ I_{sat} \\ dB/dz = 4 \text{ Gauss/cm} \end{cases}$$

$\rightarrow N_{max} = 3*10^6$

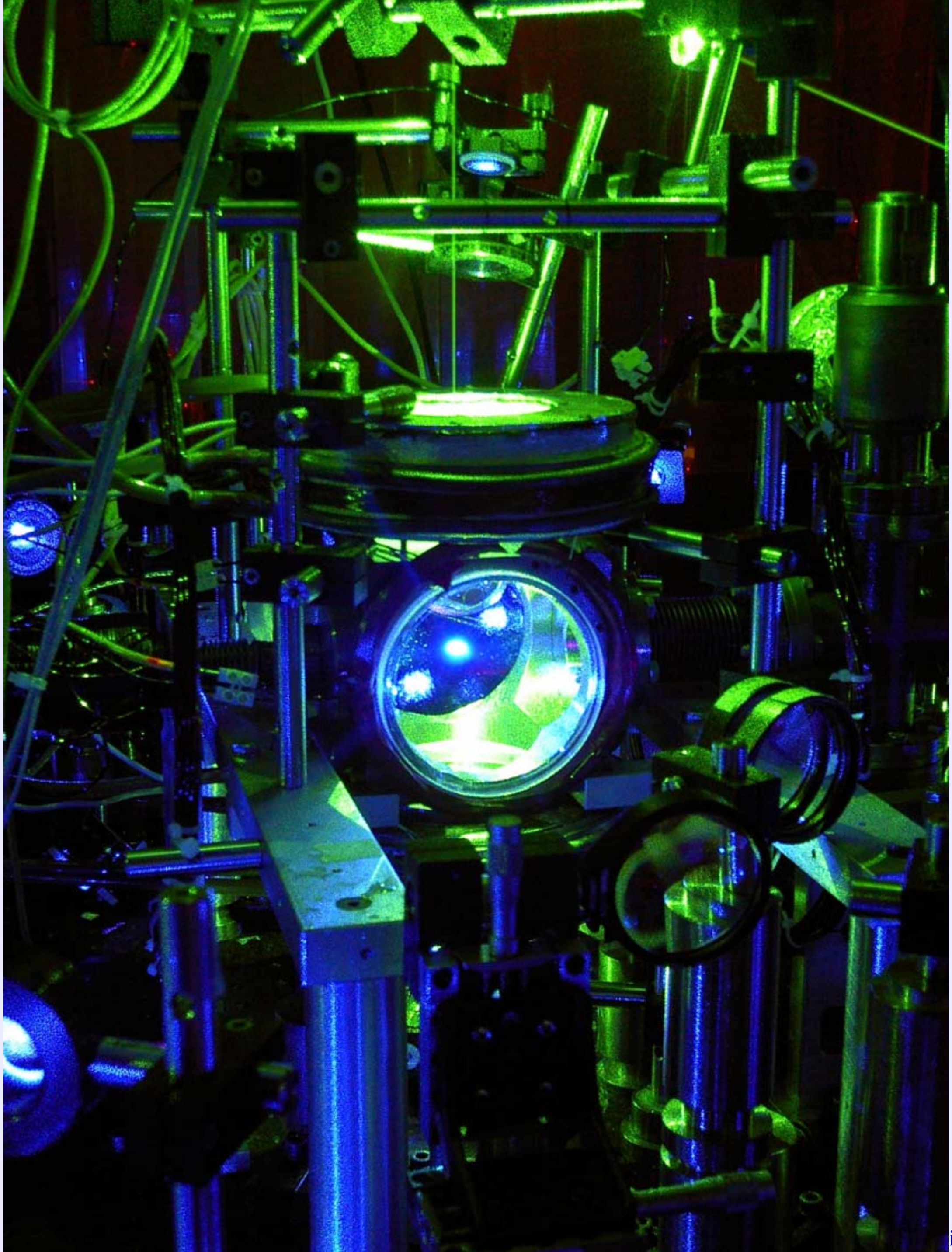
$\eta \approx 10\ \%$

$\begin{cases} N = 5*10^5 \text{ atoms} \\ T = 400 \text{ nK} \end{cases}$

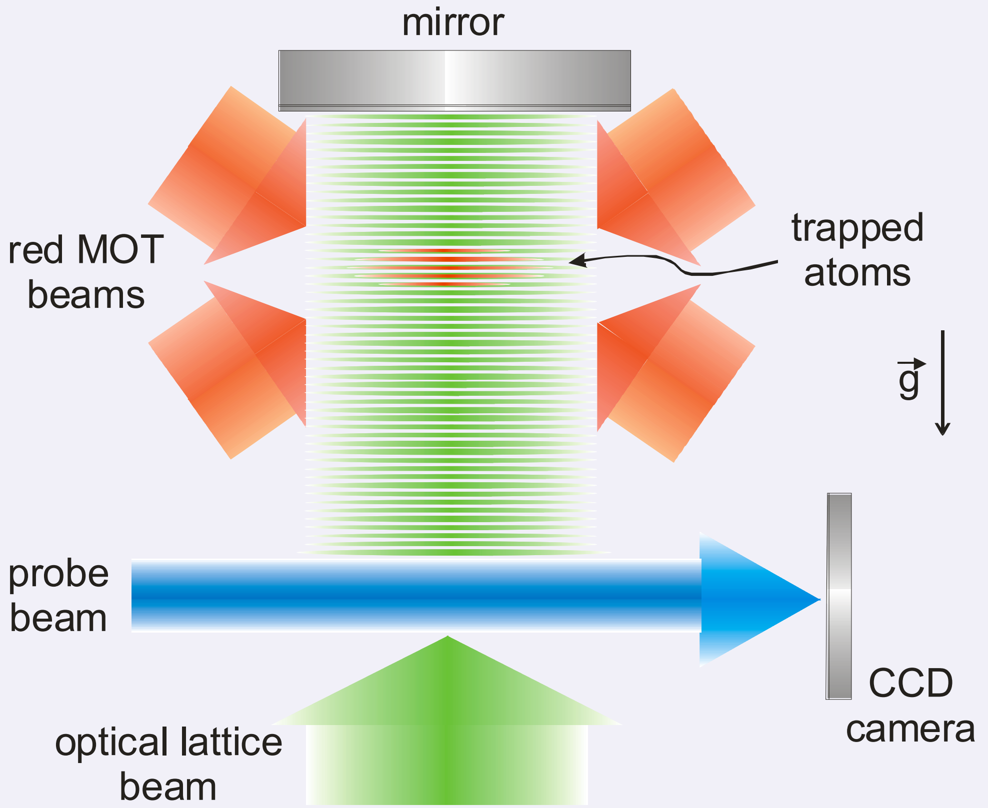
Sr MOT picture



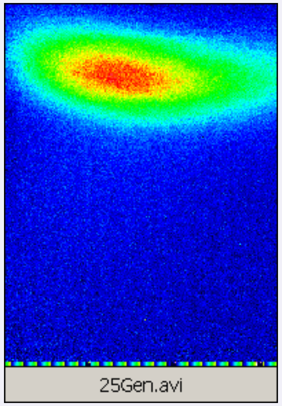
LENS, Firenze



Precision gravity measurement at μm scale with Bloch oscillations of Sr atoms in an optical lattice

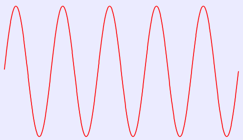


$\vec{g}$



$\nu = m\, g\, \lambda / 2\, h$

Particle in a periodic potential: Bloch oscillations

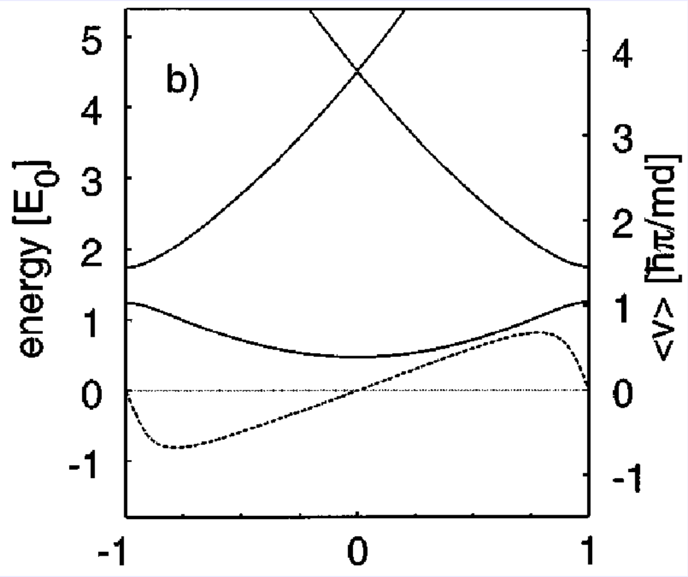
periodic potential  $V(z+\lambda/2)=V(z)$

$$\Psi(z)=e^{i\frac{\mathbf{q}}{\hbar}z}\,u(z)$$

$$u(z+\lambda/2)=u(z)$$

Bloch's theorem

$$\Psi(z+\lambda/2)=e^{i\frac{\mathbf{q}}{\hbar}\cdot\frac{\lambda}{2}}\,\Psi(z)$$



quasimomentum q [2π/λ]

$$\langle v\rangle_n(q(t)) = \frac{1}{\hbar}\frac{dE_n(R(q(t)))}{dq}$$

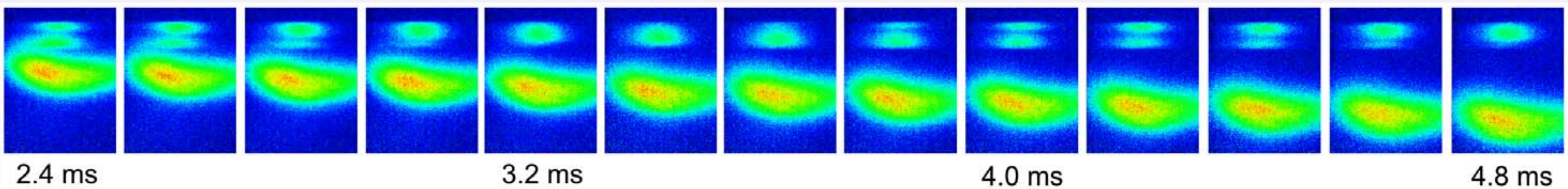
with a constant external force F

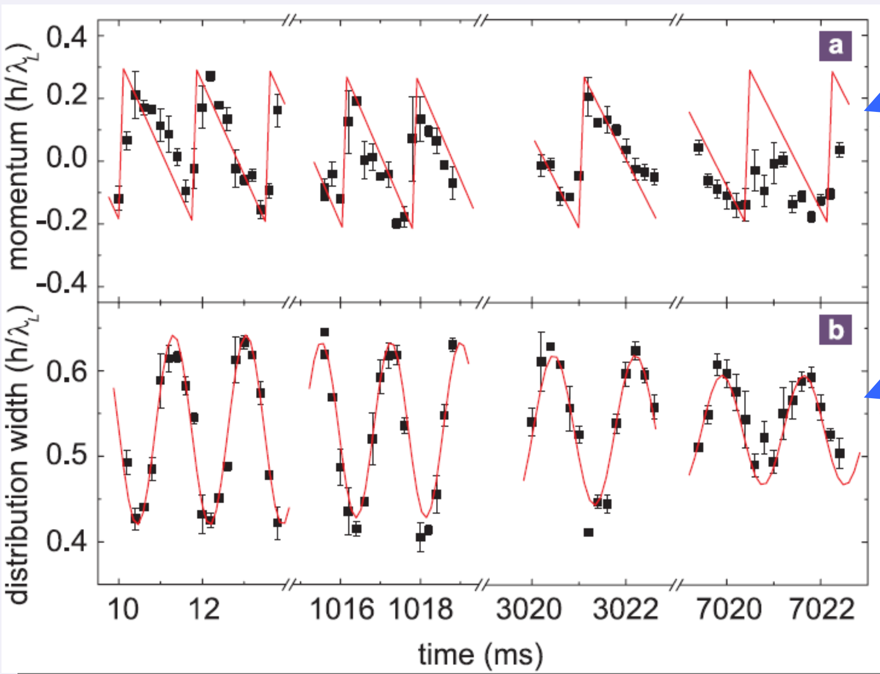
$$q(t) = q(0) + Ft/\hbar$$

Bloch oscillations

Quantum theory for electrons in crystal lattices: **F. Bloch, Z. Phys. 52, 555 (1929)**
Never observed in natural crystals (evidence in artificial superlattices)
Direct observation with Cs atoms: **M.Ben Dahan, E.Peik, J.Reichel, Y.Castin, C.Salomon, PRL 76, 4508 (1996)**

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency $\nu_B = 574.568(3)$ Hz

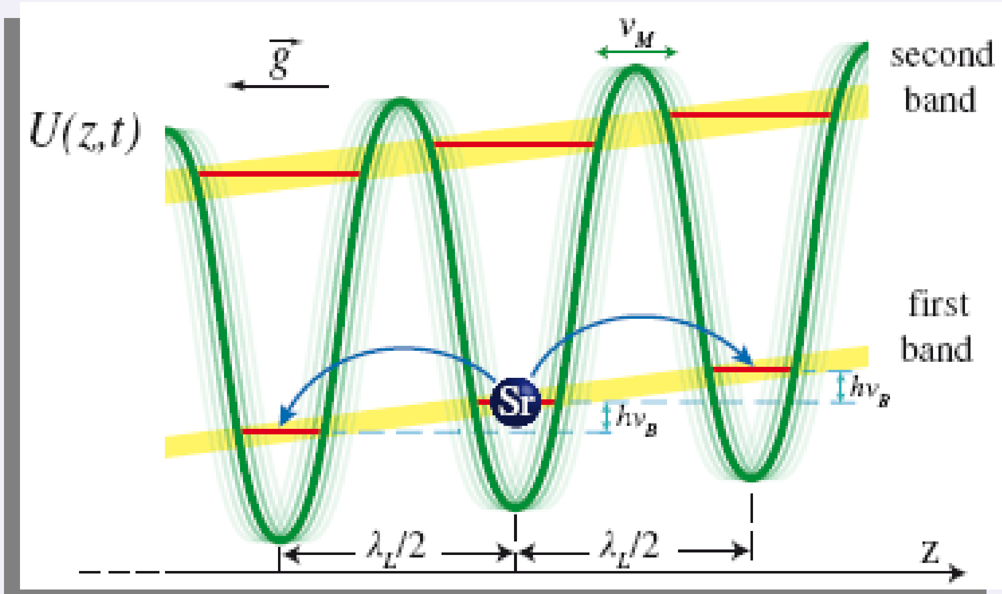
damping time $\tau = 12$ s

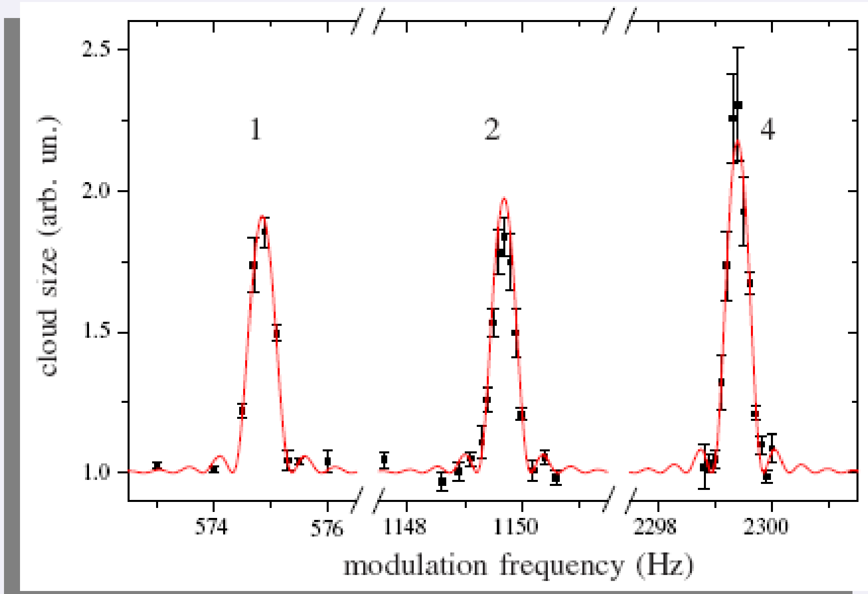
8000 photon recoils in 7s

$g_{meas} = 9.80012(5)$ ms^{-2}

G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. 97, 060402 (2006)**

Coherent Delocalization of AtomicWave Packets in Driven Lattice Potentials



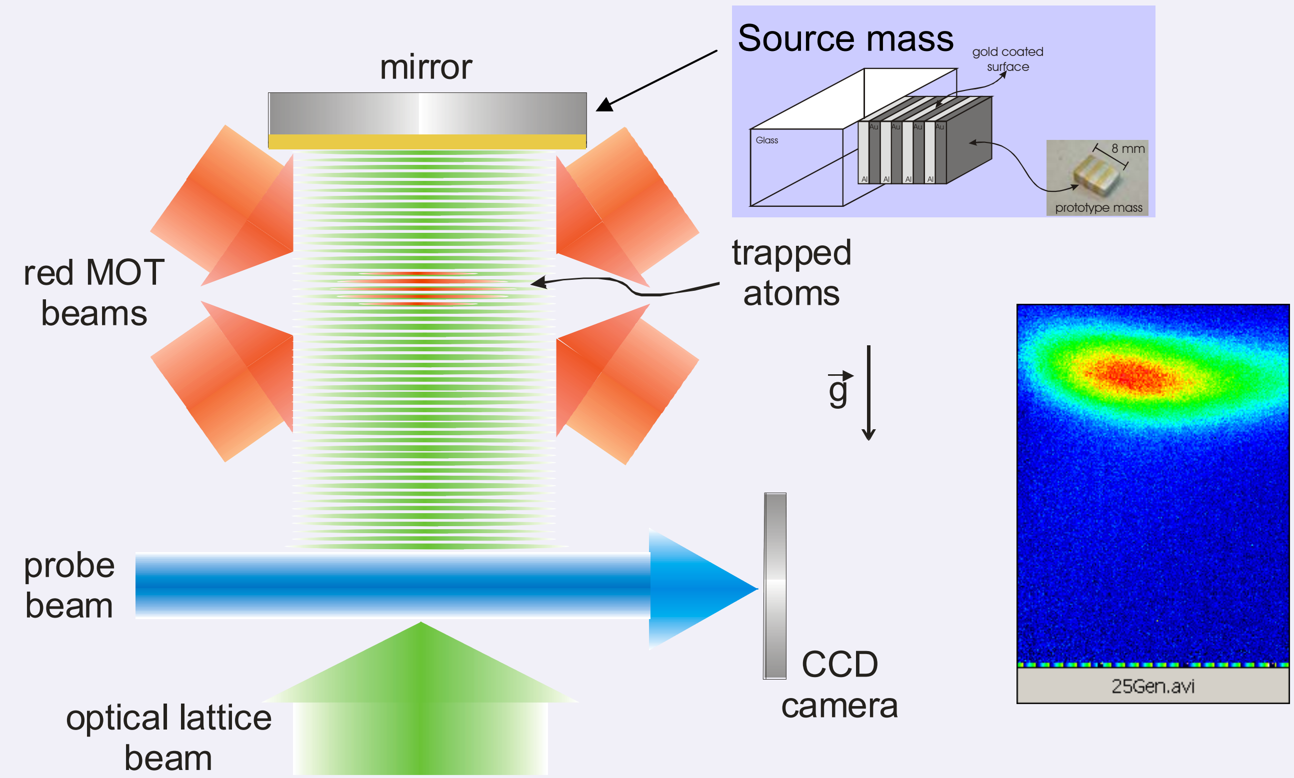


ν_B = (574.8459 +/- 0.0015) Hz,

g = (9.805301 +/- 0.000026) m/s^2

V.V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino,
Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials,
Phys. Rev. Lett. 100, 043602 (2008)

Scheme for the measurement of small distance forces



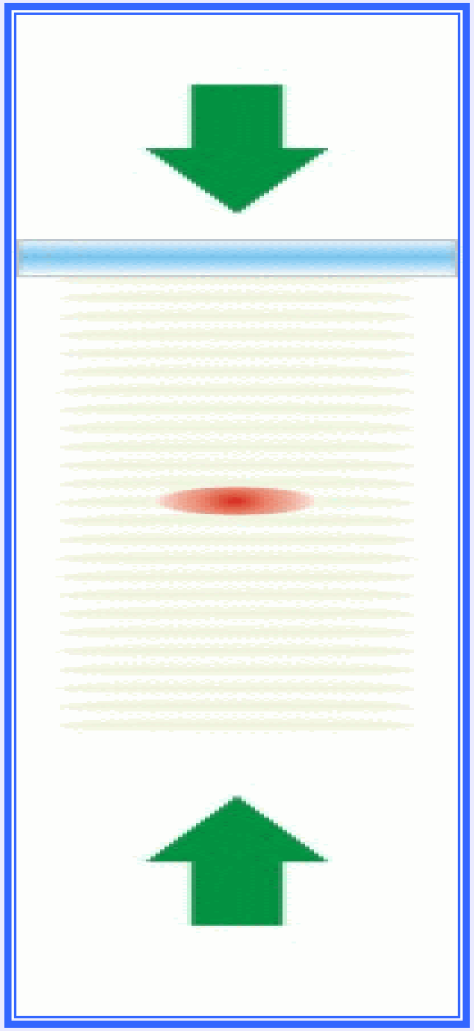
$\nu = m\, g\, \lambda / 2\, h$

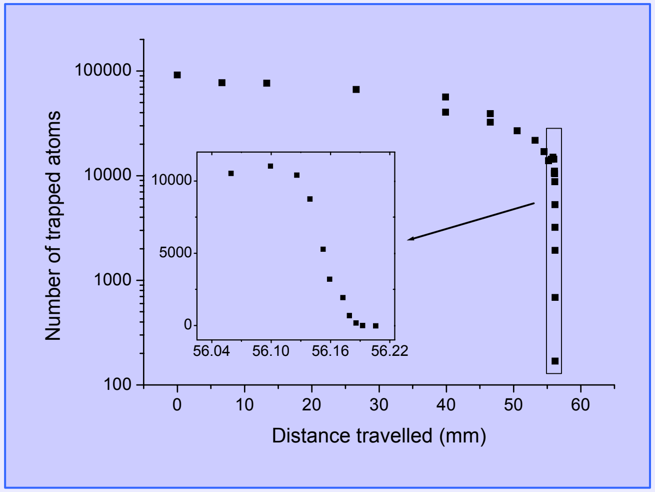
$\nu = m\, a\, \lambda / 2\, h$

Objective: λ = 1-10 μm, α = 10^3-10^4

G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* Phys. Rev. Lett. 97, 060402 (2006)

Atom elevator



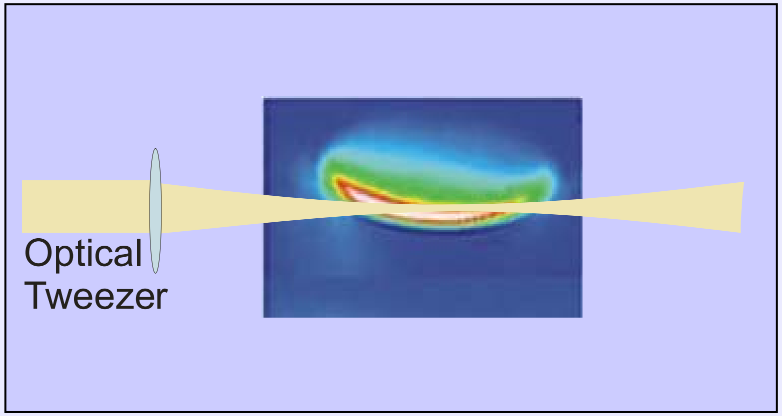


Vertical size of the atomic sample: 15 μm

Atom elevator:

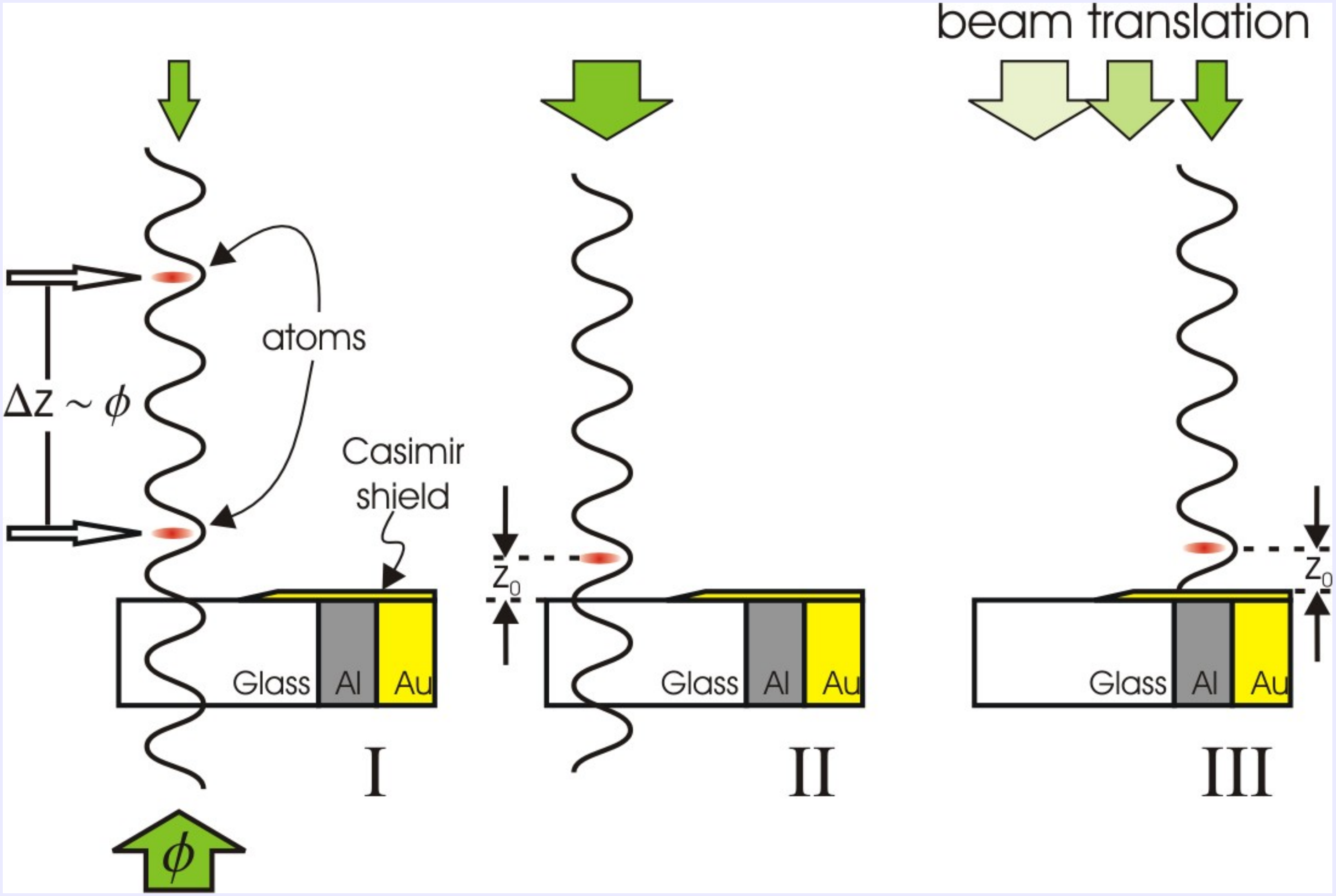
upward acceleration (1.35 g) for 10 ms
uniform velocity (133 mm/s) for variable time
downward acceleration (-1.35 g) for 10 ms
rest for 470 ms
reverse motion back to the starting point

Vertical position fluctuations: 3 μm rms

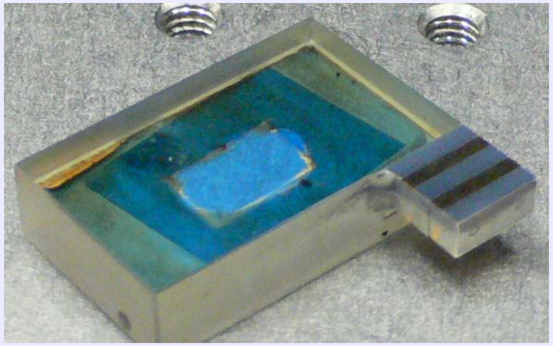


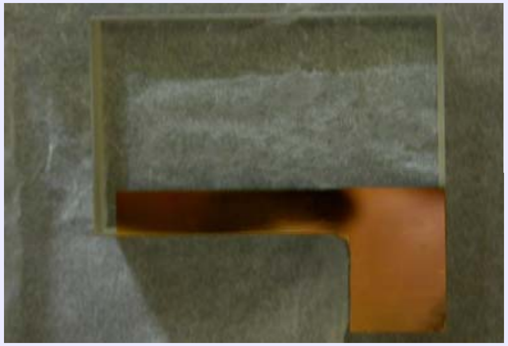
• Vertical size reduced to 4 μm with an optical tweezer

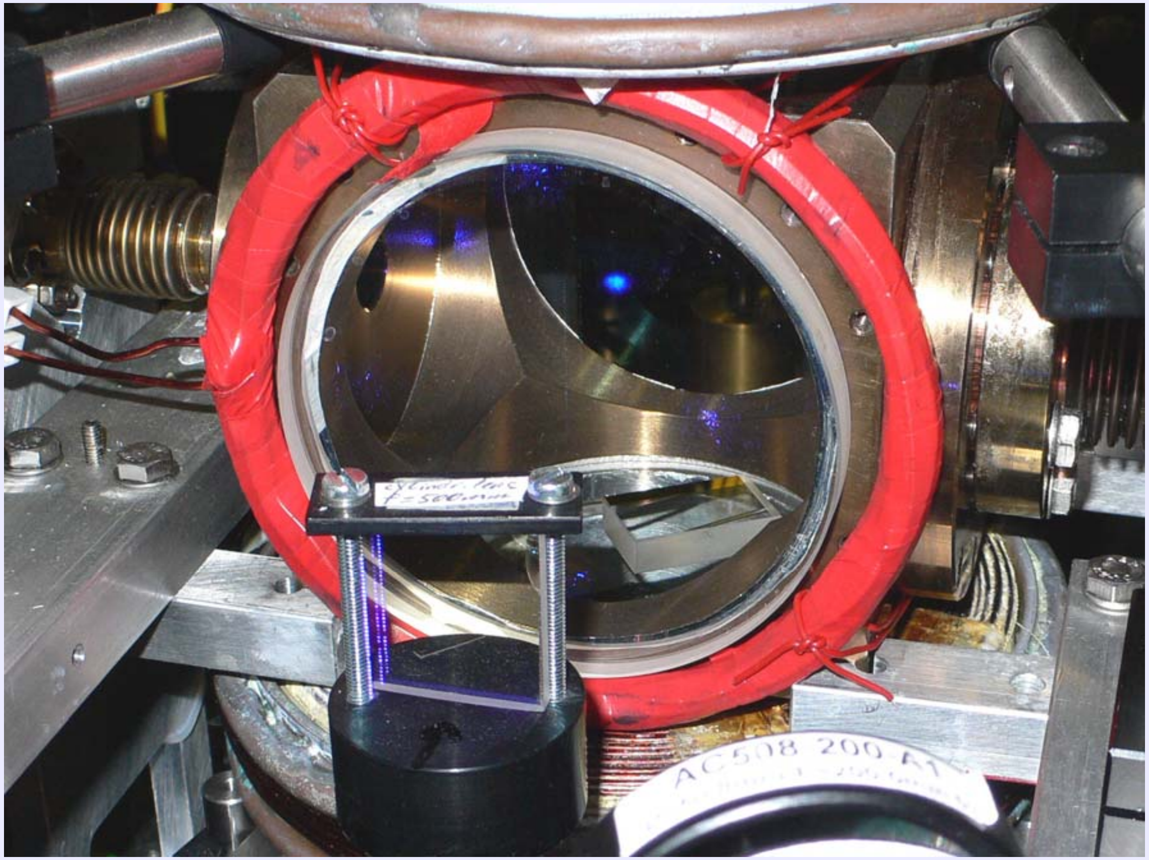
Measuring close to a surface



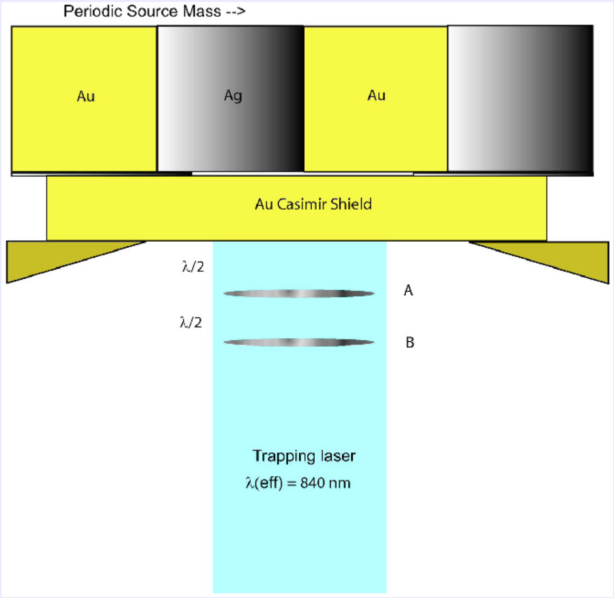
Source mass

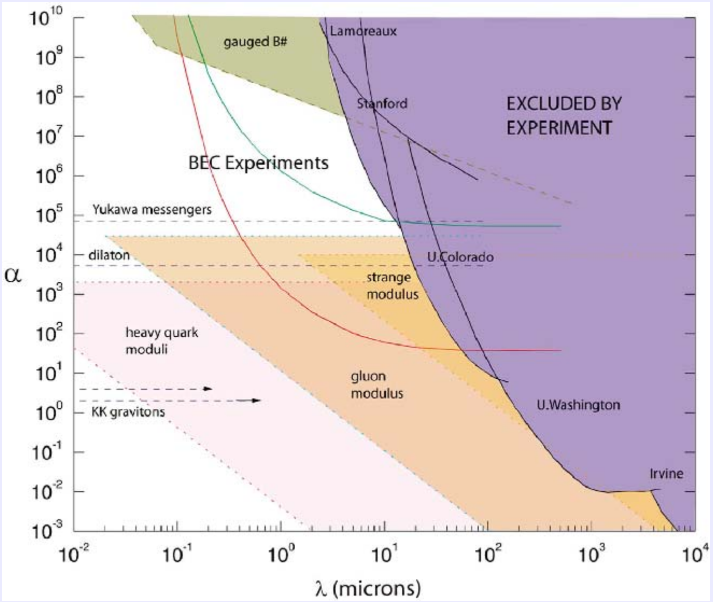






Other proposals



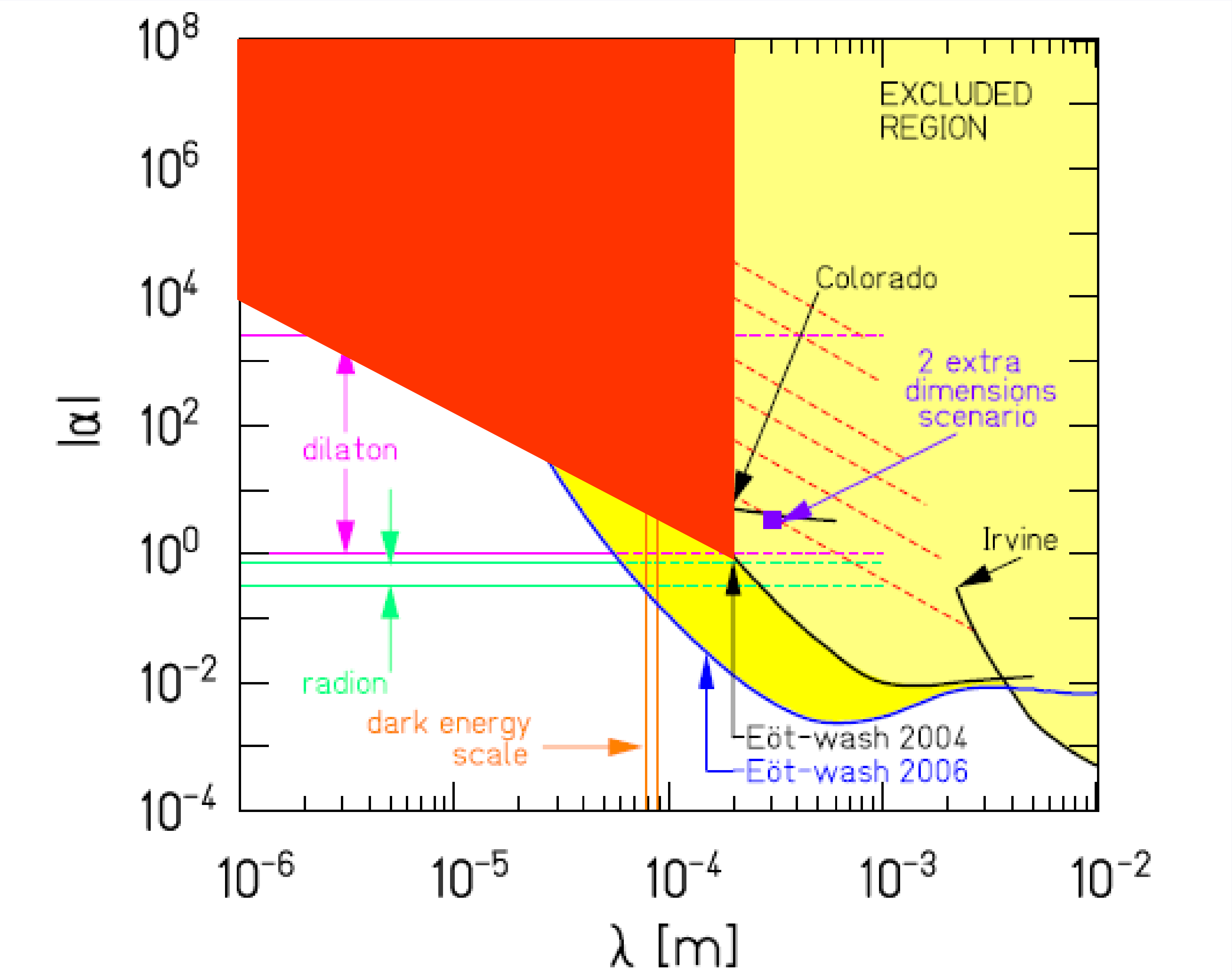


• S. Dimopoulos, A. A. Geraci, *Probing submicron forces by interferometry of Bose-Einstein condensed atoms,* Phys. Rev. D 68, 124021 (2003)

• I. Carusotto et al., *Sensitive measurement of forces at micron scale using Bloch oscillations of ultracold atoms*, Phys. Rev. Lett. 95, 093202 (2005)

• Peter Wolf, et al., *From Optical Lattice Clocks to the Measurement of Forces in the Casimir Regime*, Phys. Rev. A 75, 063608 (2007)

Accessible region with atomic probes



Applications of new quantum sensors based on atom interferometry

- Measurement of fundamental constants → *G*, → α
- New definition of kg
- Test of equivalence principle
- Short-distances forces measurement
- Search for electron-proton charge inequality
- New detectors for gravitational waves ?
- Development of transportable atom interferometers → geophysics, → space

Conclusions

- New atomic quantum devices can be developped with unprecedented sensitivity using ultracold atoms and atom optics
- Applications: Fundamental physics, Earth science, Space research
- Well developped laboratory prototypes
- Work in progress for transportable/space-compatible systems

Team members

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Nicola Poli	Researcher, Università di Firenze
Fiodor Sorrentino	Post-doc, Università di Firenze
Marion Jacquey	Post-doc, LENS
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Gabriele Rosi	Diploma student , Università di Firenze
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Marella de Angelis	Long term guest, CNR
Marco Prevedelli	Long term guest, Università di Bologna

Previous members

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Robert Drullinger, Long term guest
Giacomo Lamporesi, PhD student
Marco Fattori, PhD student
Torsten Petelski, PhD student
Juergen Stuhler, Post-doc

Support and funding

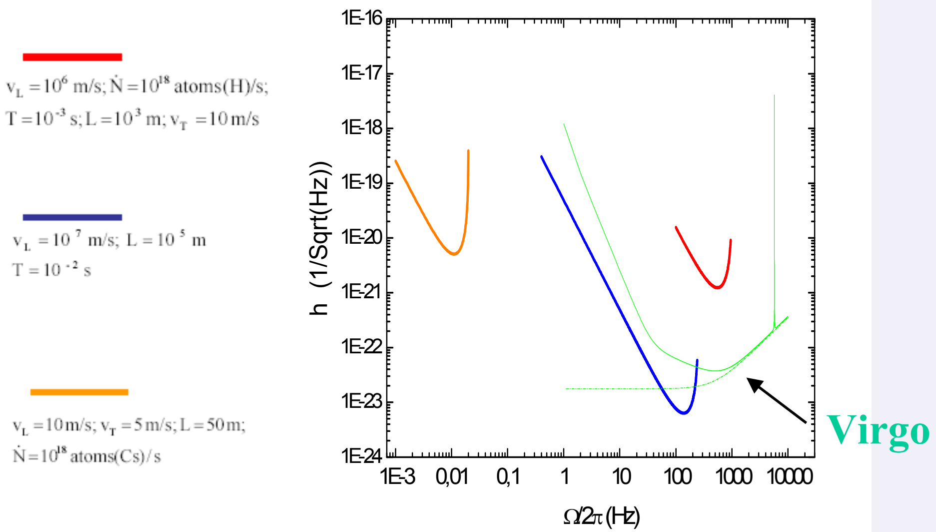
- ✓ **Istituto Nazionale di Fisica Nucleare (INFN)**
- ✓ **European Commission (EC)**
- ✓ **Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)**
- ✓ **European Laboratory for Non-linear Spectroscopy (LENS)**
- ✓ **Ente Cassa di Risparmio di Firenze (CRF)**
- ✓ **European Space Agency (ESA)**
- ✓ **Agenzia Spaziale Italiana (ASI)**
- ✓ **Istituto Nazionale per la Fisica della Materia (INFM)**
- ✓ **Istituto Nazionale Geofisica e Vulcanologia (INGV)**

Gravitational wave detection by atom interferometry

Can we use atom interferometers in searching for gravitational waves?

- C.J. Bordé, *University of Paris N.*
- G. Tino, *University of Firenze*
- F. Vetrano, *University of Urbino*

F.Vetrano - Aspen Winter Conference, FEB 2004



F.Vetrano - Aspen Winter Conference, FEB 2004

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- C. Bordè, G. M. Tino, F. Vetrano, "Can we use atom interferometers in searching for gravitational waves?", 2004 Aspen Winter College on Gravitational Waves. Available online at: http://www.ligo.caltech.edu/LIGO_web/Aspen2004/pdf/vetrano.pdf
- R.Y. Chiao, A. D. Speliotopoulos, "Towards MIGO, the matter-wave interferometric gravitational-wave observatory, and the intersection of quantum mechanics with general relativity", Journal of Modern Optics (2004), 51(6-7), 861-899
- A. Roura, D.R. Brill, B. L. Hu, C.W. Misner, W.D. Phillips, "Gravitational wave detectors based on matter wave interferometers (MIGO) are no better than laser interferometers (LIGO)", Physical Review D: Particles and Fields (2006), 73(8), 084018/1-084018/14
- S. Dimopoulos, P.W. Graham, J.M. Hogan, M. A. Kasevich, S. Rajendran, "Gravitational Wave Detection with Atom Interferometry", arXiv:0712.1250v1 – "An Atomic Gravitational Wave Interferometric Sensor (AGIS)", arXiv:0806.2125v1

ESA-AO-2004

Atom Interferometers for Space

Proposal coordinator: Prof. Guglielmo M. Tino
Dipartimento di Fisica/LENS
Università di Firenze, Italy

Participants

__Academic Teams__

• Dipartimento di Fisica, Università di Firenze	I	(UNIFI)
• Institut d'Optique, Orsay (+ ONERA)	F	(IOTA)
• Institut für Quantenoptik, Universität Hannover	D	(IQO)
• Universität Hamburg	D	(UH)
• Institut für Physik, Humboldt-Universität zu Berlin	D	(HUB)
• SYRTE, Observatoire de Paris	F	(SYRTE)
• LENS, Firenze	I	(LENS)
• Universität Ulm	D	(ULM)
• ZARM, University of Bremen	D	(ZARM)

__Industrial Partners__

• Carlo Gavazzi Space	I
• EADS Astrium	D
• Galileo Avionica	I
• IXSEA	F
• Kayser Italia	I
• Techno System	I
• THALES	F
• TOPTICA	D

Space Atom Interferometer - SAI

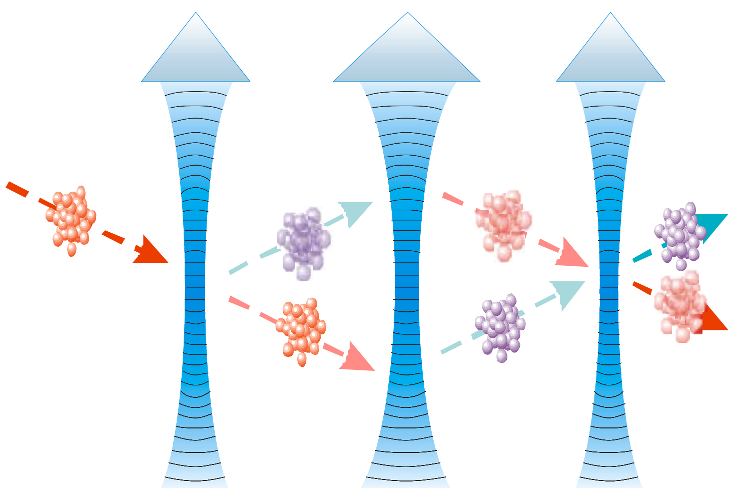
Space Atom Interferometer: Pre-phase A study of a space instrument based on matter-wave interferometry for inertial sensing in space

Team: Firenze Univ. (I), IOTA (F), IQ (D), Hamburg Univ. (D), HU Berlin (D), SYRTE (F), LENS (I), Ulm Univ. (D), ZARM (D)

Objective: Ground based prototype of an atom interferometer for precision measurements

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding



From M. Kasevich

	Demonstrated on ground	**Anticipated on ground**	**Projected in space**
Gyroscope			
ARW Bias stability Scale factor	2x10^{-6} deg/hr$^{1/2}$ 6x10^{-5} deg/hr 5 ppm	<1x10^{-6} deg/hr$^{1/2}$ <10^{-5} deg/hr <1 ppm	<10^{-8} deg/hr$^{1/2}$ <10^{-7} deg/hr <1 ppm
Accelerometer			
Sensitivity Bias stability Scale factor	10^{-9} g/Hz$^{1/2}$ <10^{-10} g <10^{-10}	<10^{-10} g/Hz$^{1/2}$ <10^{-10} g <10^{-10}	<10^{-13} g/Hz$^{1/2}$ <10^{-16} g ? <10^{-12}

ESA-AO-2004
Life and Physical Sciences and Applied Research Projects

Life and Physical Sciences and Applied Research Projects

Coordinator: **S. Schiller, Universität Düsseldorf, Germany**

Team members: P. Lemonde (SYRTE Paris), C. Salomon (ENS Paris), U. Sterr (PTB Braunschweig), A. Görlitz (Universität Düsseldorf), G. Tino (Universita di Firenze)

Proposal Title: Space Optical Clocks

Abstract

Prepare a brief description of the application stating the broad, long-term objectives and specific aims of the proposed work. Describe concisely the research design and methods for achieving these objectives and aims. This abstract is meant to serve as a succinct and accurate description of the proposed work when separated from this application. Limit abstract to 300 words or fewer.

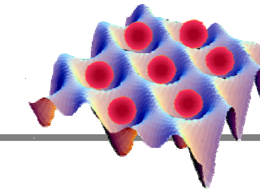
Optical atomic clocks based on ensembles of ultracold neutral atoms stored in periodic potentials generated by standing-wave light fields will lead to the next leap in accuracy and stability in clock technology. The expected improvement is by a factor of 100 compared to microwave cold atom clocks now in operation in several national metrology laboratories worldwide and under deployment for the ISS within the ACES project. Space represents the best environment for such ultrastable clocks because the well-defined location and the microgravity environment maximize accuracy and stability.

The goal of this project is to demonstrate operation and characterize the performance of an optical clock ensemble in a space environment, with an expected accuracy 10 times higher than ACES. Time transfer to earth will be demonstrated with 10^-17 accuracy. An adequate carrier is the ISS, but tests on the FOTON carrier are desirable.

The aim of the first funding period (three years) is to implement several optical clock laboratory demonstrator systems using Strontium and Ytterbium as atomic systems, to characterize and compare them, to test and validate different operational procedures and specifications required for operation in space. Subcomponents of the clock demonstrator with the added specification of transportability and using techniques that are suitable for later space use, such as all-solid-state lasers, low power consumption, and small volume, will be developed and validated.

At the end of the 3-year project, the specifications for a space clock will be finalized, enabling the start of Phase B.

The clock development will be based on the experience that the team members have acquired in the field of precision optical measurements and quantum optics, in particular on their successful laboratory microwave and optical clock developments based on cold atoms, which have resulted in the space clock PHARAO.



Space Optical Clocks - SOC

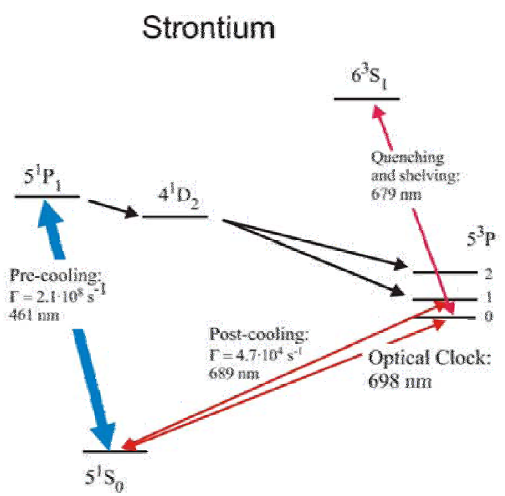
Space Optical Clocks: Pre-phase A study of an atomic clock ensemble in space based on the optical transitions of strontium and ytterbium atoms. Optical clocks will take advantage of the ACES heritage and will push stability and accuracy of atomic frequency standards down to the 10^{-18} regime.

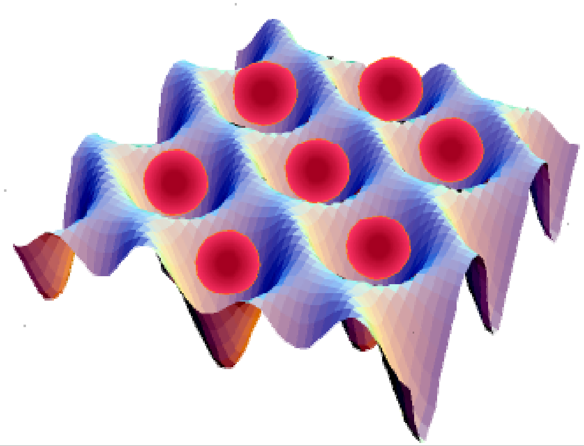
Team: Düsseldorf Univ. (D), SYRTE (F), ENS (F), PTB (D), Firenze Univ. (I)

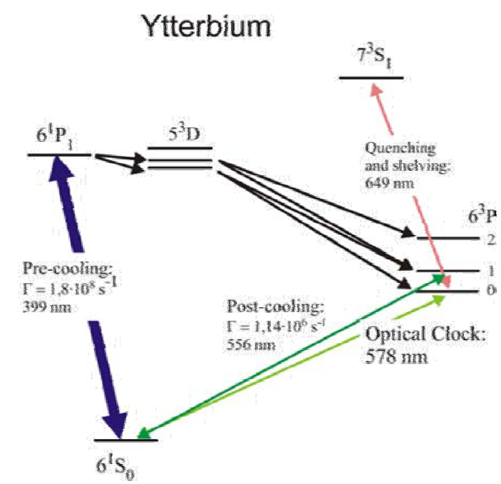
Objective: Ground based prototypes of atomic clocks based on Sr and Yb optical clocks

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding







Future Inertial Atomic Quantum Sensors

FINAQS

A Specific Targeted Research Project (STREP)

FULL Proposal

for

NEST-2003-1 ADVENTURE

Duration: 3 years

Co-ordinator: Prof. Dr. Wolfgang Ertmer
Contact: Email: ertmer@iqo.uni-hannover.de
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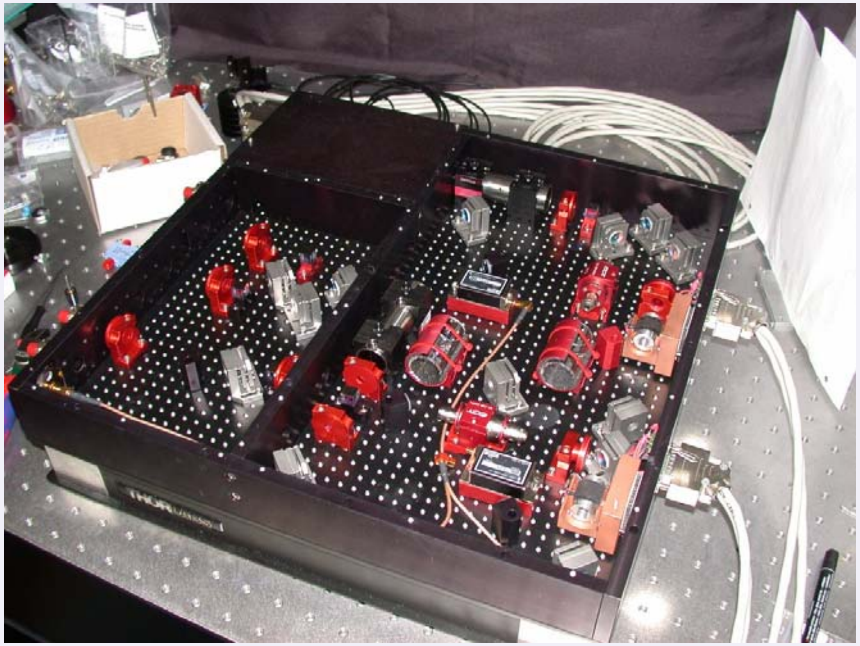
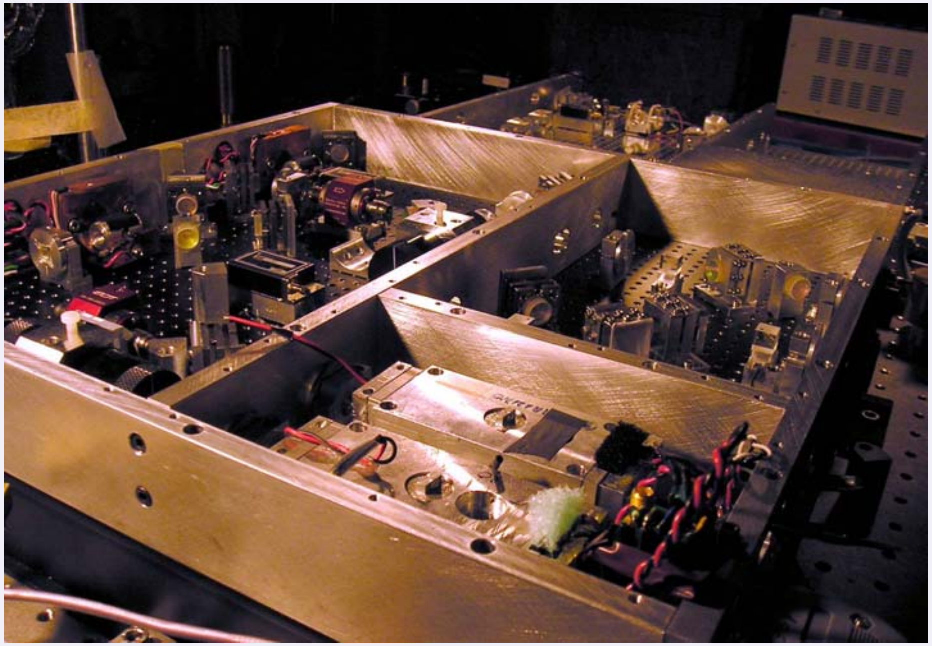
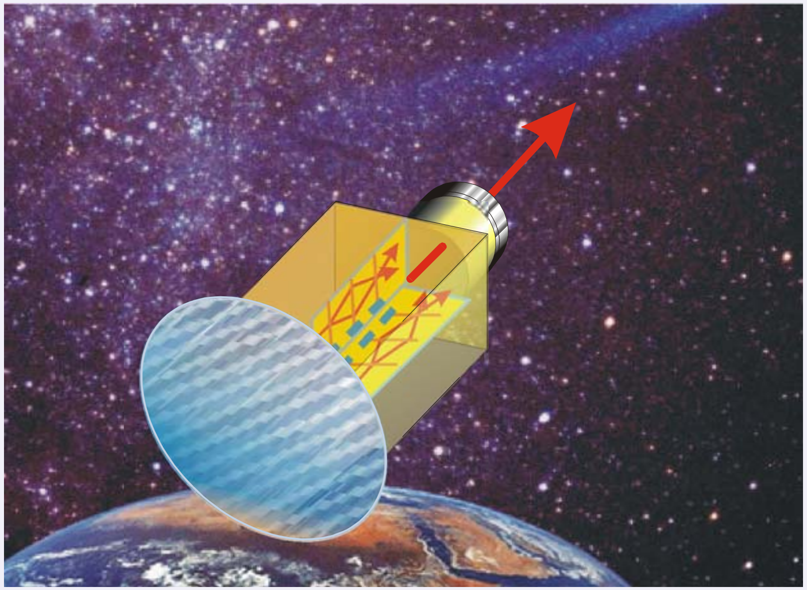
2	Laboratoire Charles Fabry de l'Institut d'Optique	IOTA	ORSAY	F
3	Système de Références Temps – Espace, Observatoire de Paris	BNM/SYRTE	PARIS	F
4	AG Optische Metrologie / Institut für Physik Humboldt-Universität zu Berlin	HUB	BERLIN	D
5	Dipartimento di Fisica, Università di Firenze	UNIFI	FIRENZE	I

FINAQS
compact laser systems





HYPER

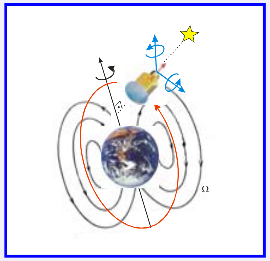


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

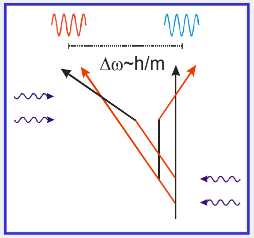
Resolution: 3×10^{-12} rad/s /√Hz

- Expected Overall Performance: 3×10^{-16} rad/s over one year of integration i.e. a S/N~100 at twice the orbital frequency

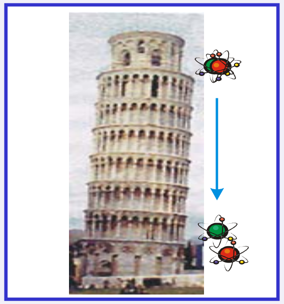
Mapping Lense-Thirring effect close to the Earth



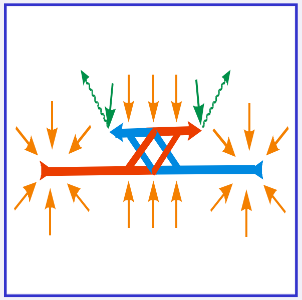
Improving knowledge of fine-structure constant



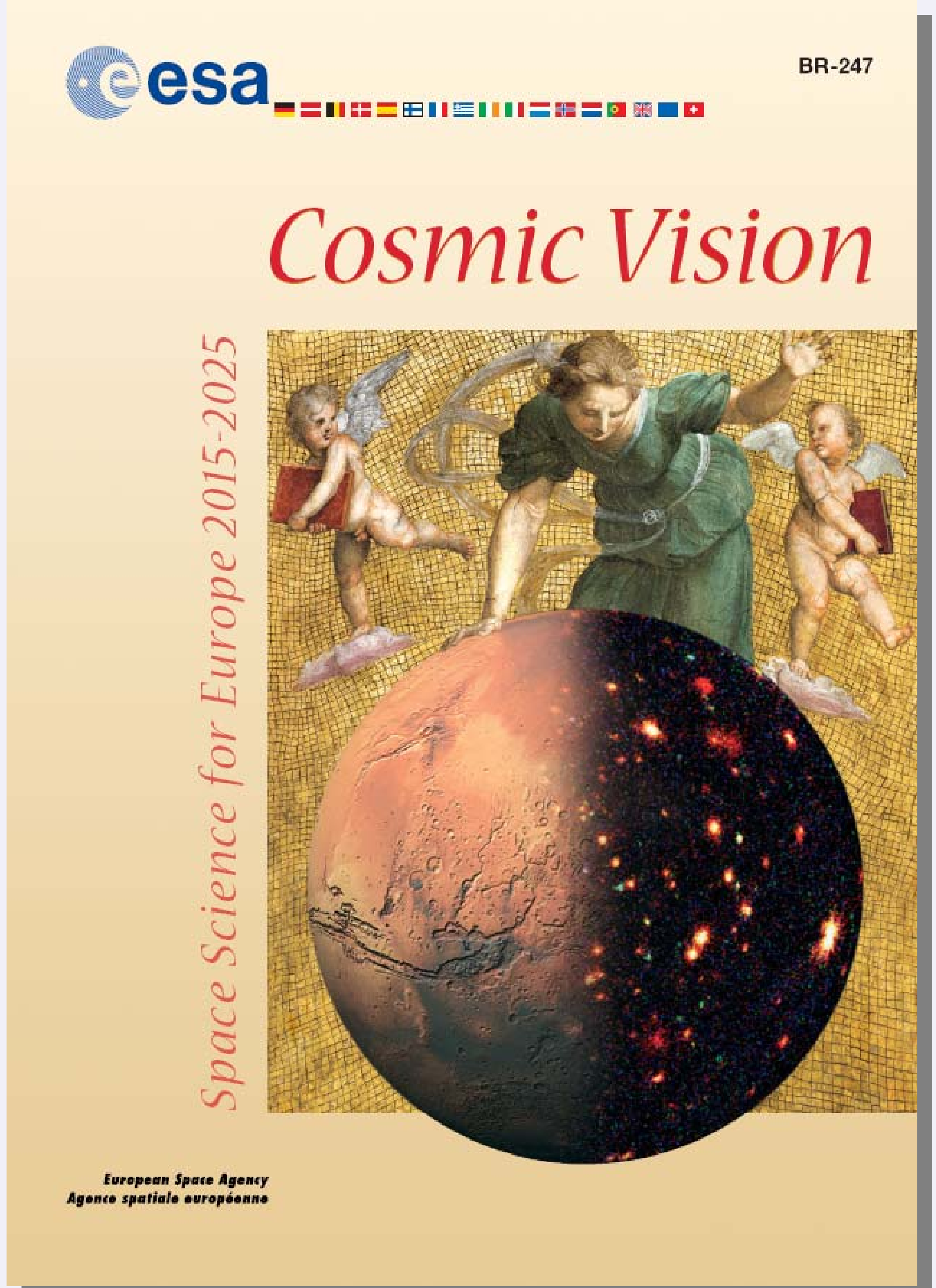
Testing EP with microscopic bodies



Atomic gyroscope control of a satellite



http://sci.esa.int/home/hyper/index.cfm


esa
BR-247
Cosmic Vision
Space Science for Europe 2015-2025
European Space Agency
Agence spatiale européenne

DLR

Implementation

- Free Fall: up to 9 sec
- Duration > 1 BEC-Experiment
- 3 flights per day
- Test of a robust BEC Facilities
  Dimensions < 0.6 ∅ x 1.5 m
  < 234 kg
- Height 110 m


ICE
Concept
ICE Cube
The Lasers
News
I.C.E
Interferometry with Coherent Sources for Applications in Space
Project members
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Robert NYMAN
Gael VAROQUAUX
Jean-Francois CLEMENT
Jean-Philippe BRANTUT
Arnaud LANDRAGIN
Frank PEREIRA
Alexandre BRESSON
Yannick BIDEL
Pierre TOUBOUL
THE PROJECT
The objective of ICE is to produce an accelerometer for space with coherent atomic source. It uses a mixture of Bose-Einstein condensates with 2 species of atoms (Rb and K).
The major objective for 2007 is to carry out a first µg campaign, in parabolic flight for example, to test the various components together and to carry out a first comparison of accelerations measured by the 2 atomic species.
Partners
Institut d'Optique
OPTIQUE ATOMIQUE
ONERA
GROUPE ATOMES FROIDS
l'Observatoire de Paris
SYRTE
GROUPE SENSEURS INERTIELS
cnes
Internal Pages

International Workshop on
"ADVANCES IN PRECISION TESTS AND EXPERIMENTAL GRAVITATION IN SPACE"
Arcetri, Firenze (Italy), September 28-30, 2006

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S. Leon	CNES, France
A. Nobili	University of Pisa, Italy
C. Nary Man	CNRS-OCA, France
W. Phillips	NIST, USA
S. Reynaud	LKB, France
C. Salomon	LKB, France
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