Gravity tests by atom interferometry: Measurement of G and test of Newtonian law at micrometric distances

Guglielmo M. Tino

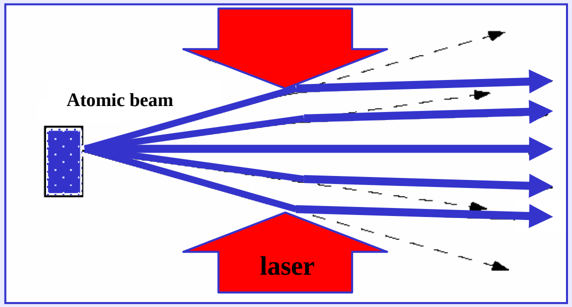
Università degli Studi di Firenze - Dipartimento di Fisica, LENS
Istituto Nazionale di Fisica Nucleare - Sezione di Firenze

Outline

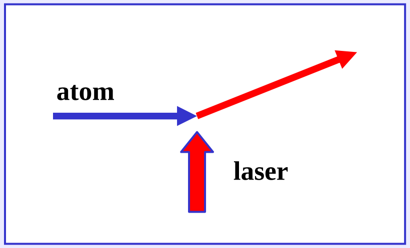
- *Atom interferometry*
- *Applications to gravity measurements*
- *Measuring G with atoms*
- *Precision gravity measurement at μm scale with laser-cooled Sr atoms in an optical lattice*
- *Prospects*

Atom optics

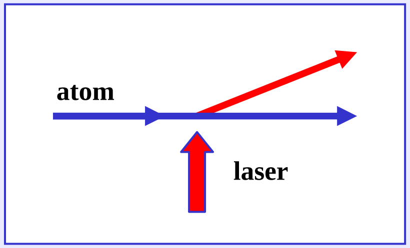
lenses



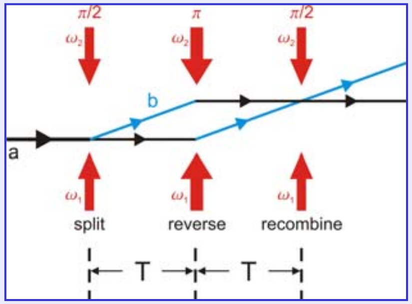
mirrors



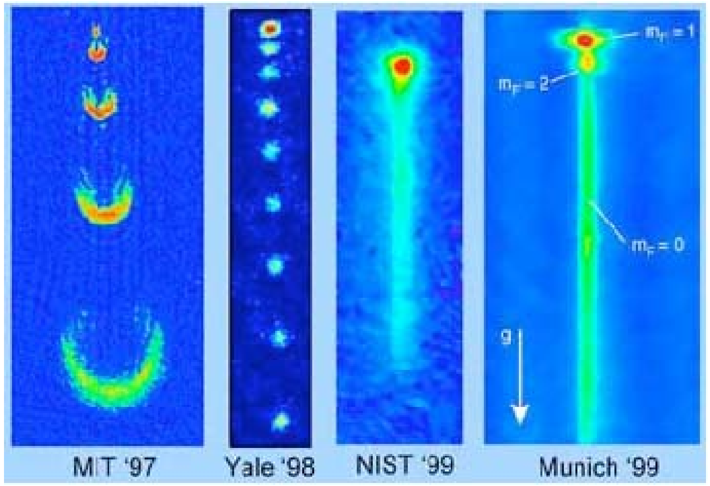
beam-splitters



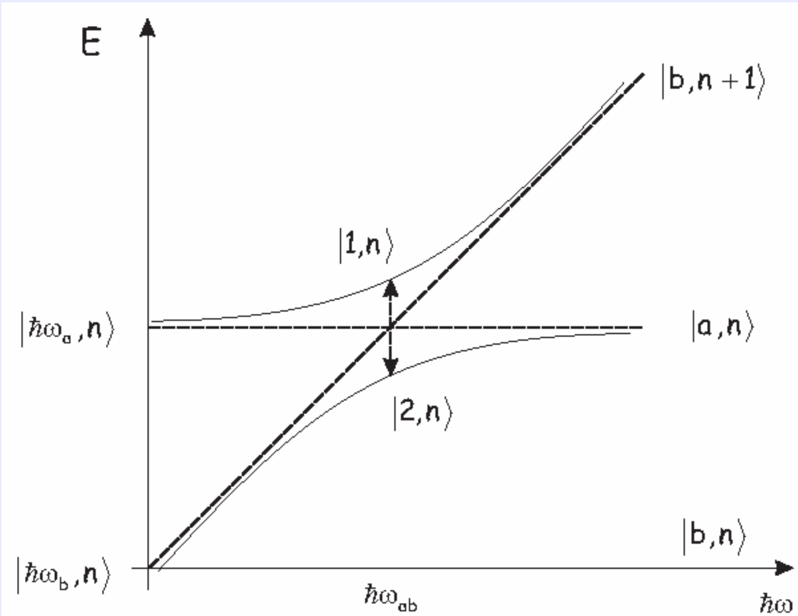
interferometers

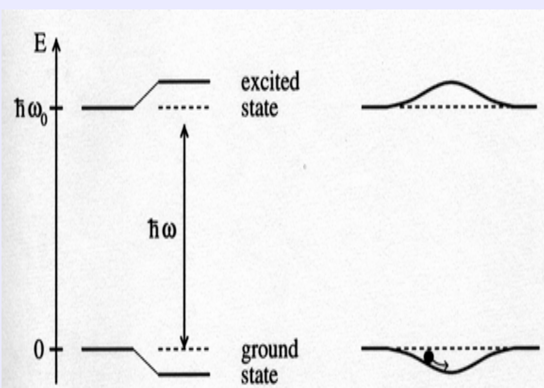


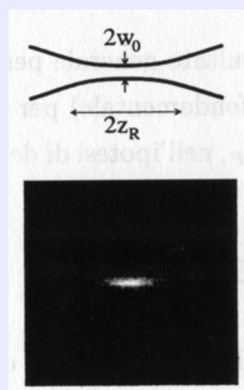
atom laser



Light shifts and optical traps



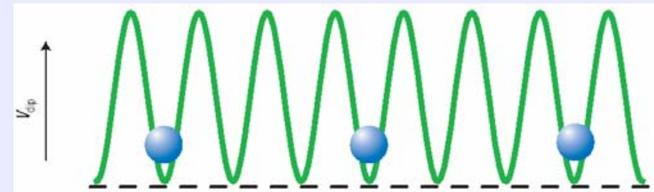




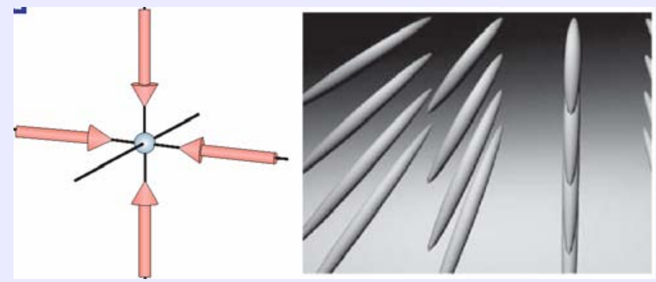
$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)|\mathbf{E}(\mathbf{r})|^2$$

First exp. demonstration: **S. Chu et al., 1986**

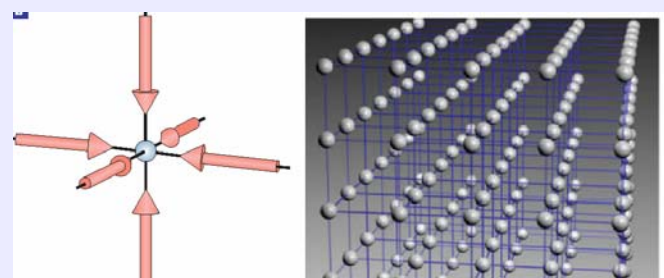
optical lattices



1D optical lattice ⇒ array of 2D disk-like trapping potentials



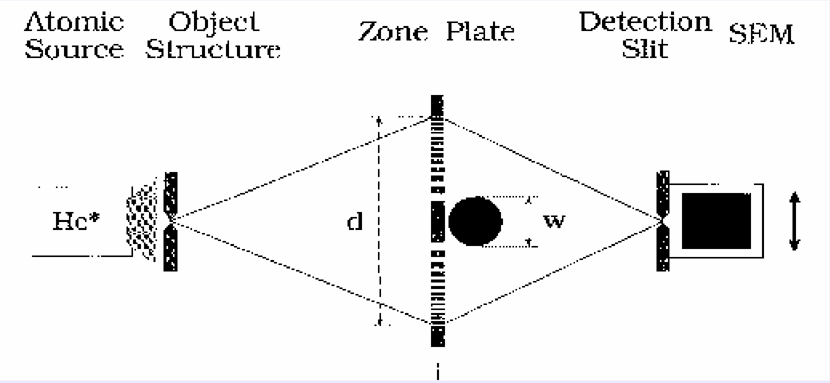
2 D optical lattice ⇒ array of 1D potential tubes

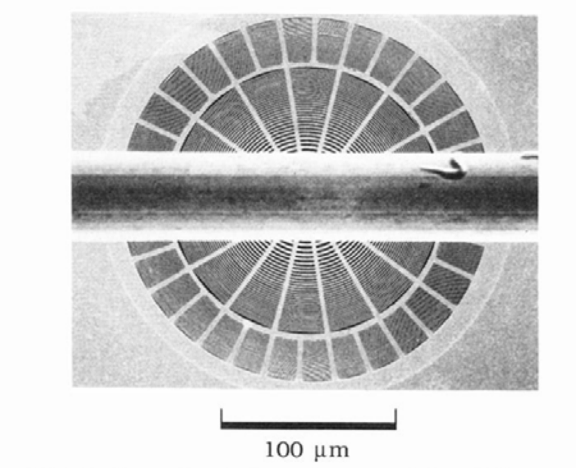


3 D optical lattice ⇒ 3D simple cubic array of h.o. potentials

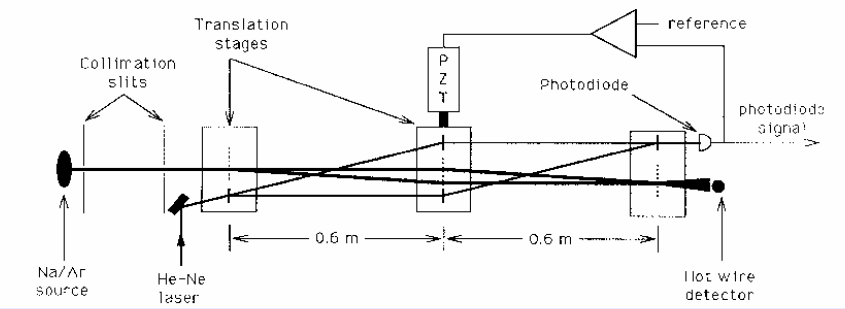
Review: **I. Bloch, 2005**

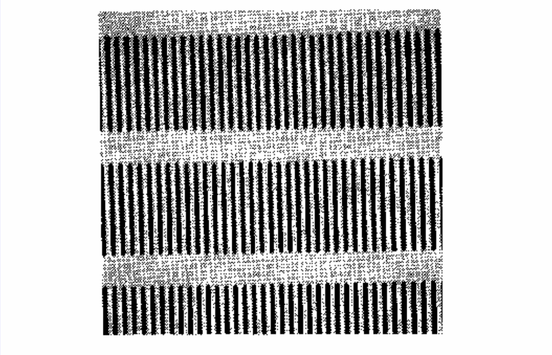
Microfabricated atom optics





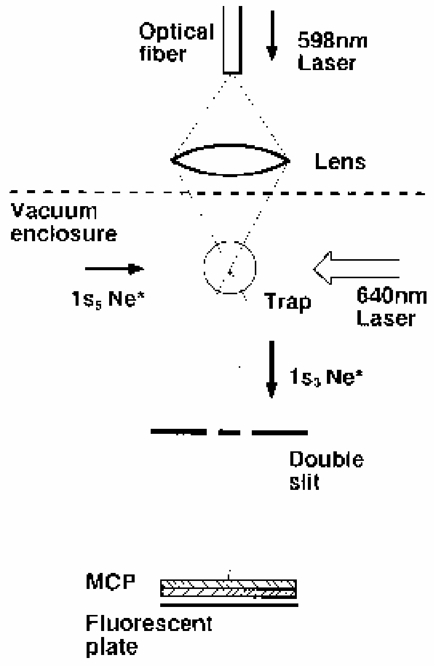
O. Carnal, M. Sigel, T. Sleator, H. Takuma, J. Mlynek, Phys. Rev. Lett. 67, 3231 (1991)

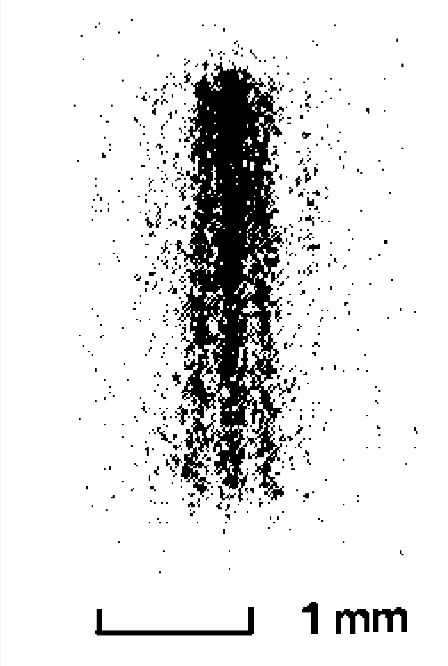


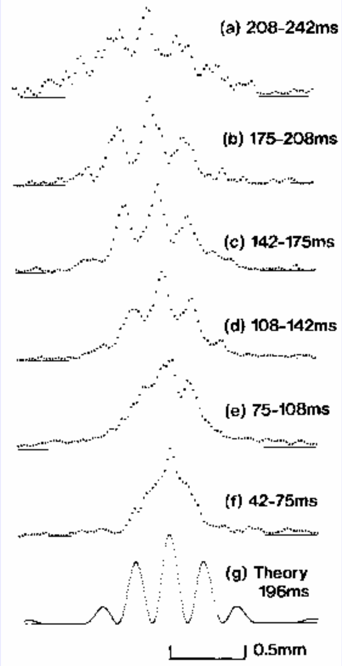


D. W. Keith, C. R. Ekstrom, Q. A. Turchette, D. E. Pritchard, Phys. Rev. Lett. 66, 2693 (1991)

Double slit interference with cold atoms

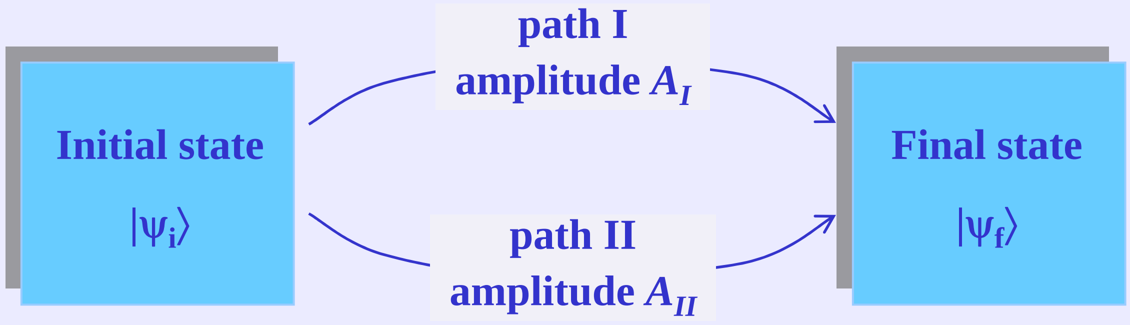






F. Shimizu et al., Phys. Rev. A 46, R17 (1992)

Quantum interference



Interference of transition amplitudes

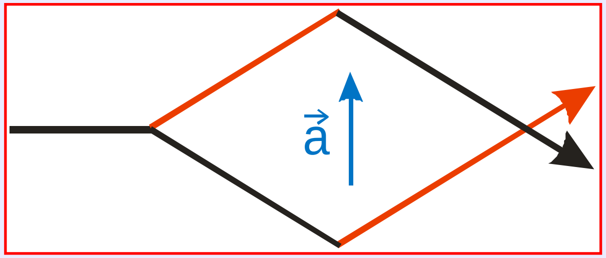
$$P\big(|\psi_i\rangle \Rightarrow |\psi_f\rangle\big) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2\,Re(A_I A_{II}^*)$$

$\Delta\varphi$ effects

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

Matter wave sensors

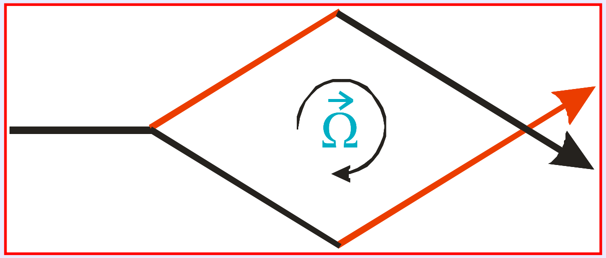
accelerations:



$$\Delta\Phi_{acc} = k\,T_{drift}^2 \cdot a$$

$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \left(\frac{c}{v_{at}}\right)^2 \approx 10^{11} - 10^{17}$$

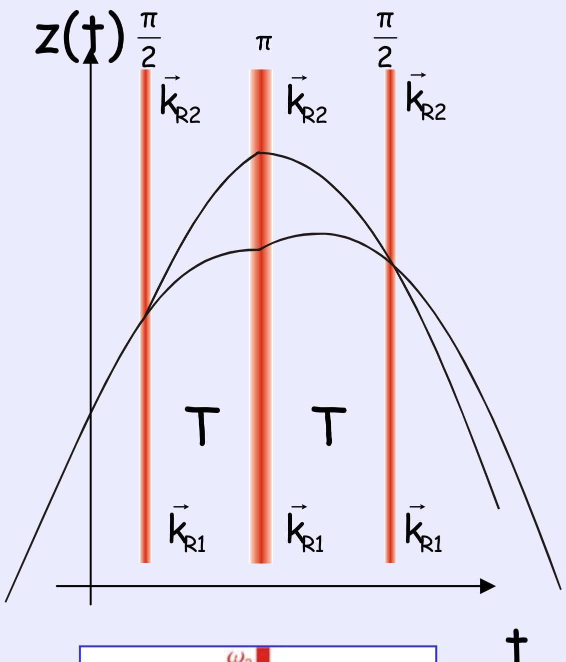
rotations:



$$\Delta\Phi_{rot} = 2\pi\,\frac{2\,m_{at}}{h}\,A \cdot \Omega$$

$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \frac{m_{at} \cdot \lambda \cdot c}{h} \approx 5 \cdot 10^{10}$$

Raman interferometry in an atomic fountain

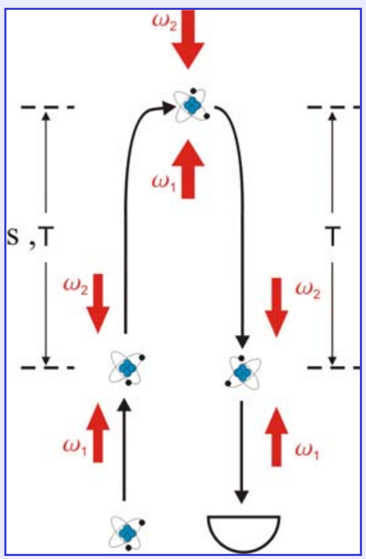


Phase difference between the paths:

$\Delta\Phi = k_e[z(0)-2z(T)+z(2T)]+\Phi_e$ $\quad$ $\mathbf{k_e = k_1 - k_2}$, $\omega_e = c\,\mathbf{k_e}$

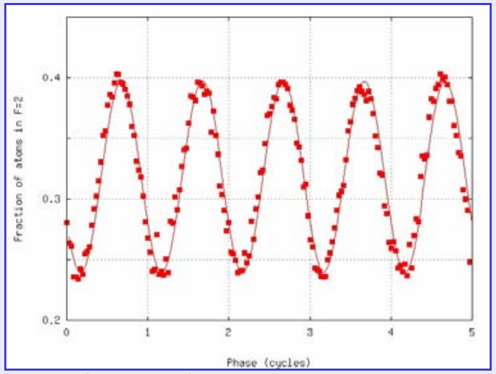
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0$ $\Rightarrow$ $\mathbf{\Delta\Phi = k_e g T^2}$

$\mathbf{g = \Delta\Phi / k_e T^2}$



Final population:

$\mathbf{N_a = N/2\,(1+\cos[\Delta\Phi])}$



Interference fringes – Firenze 2006

$T = 150$ ms $\Rightarrow 2\pi = 10^{-6}g$

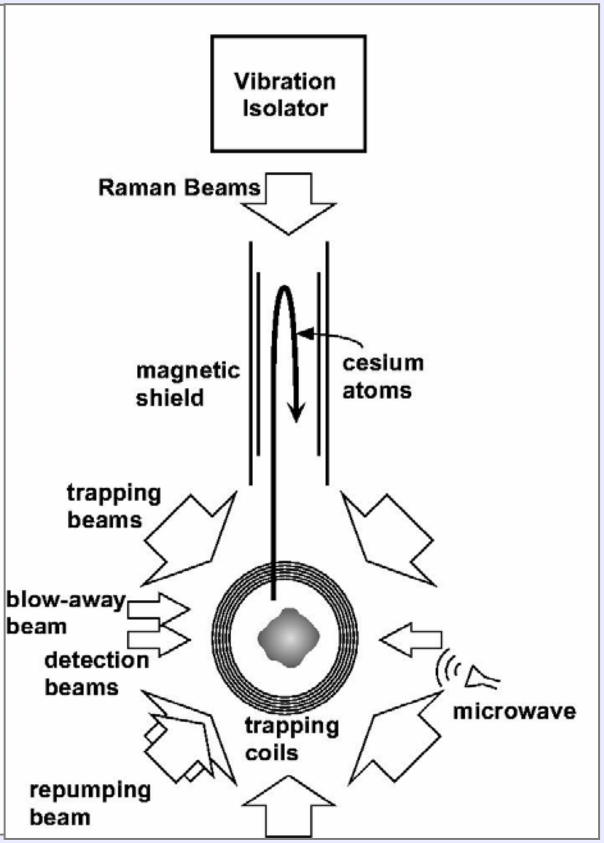
S/N = 1000

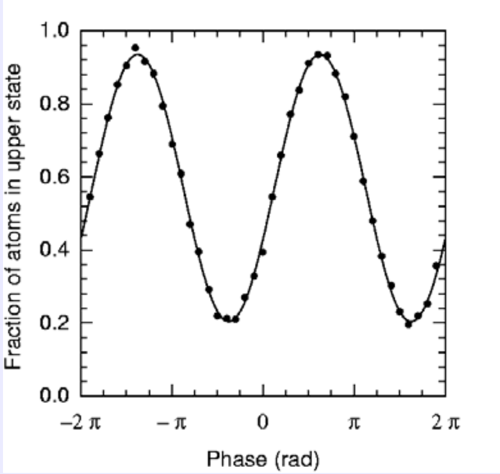
$\Rightarrow$ Sensitivity 10^{-9} g/shot

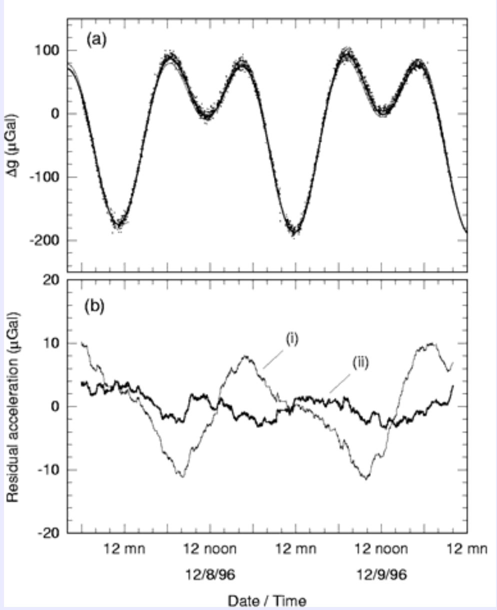
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Stanford atom gravimeter





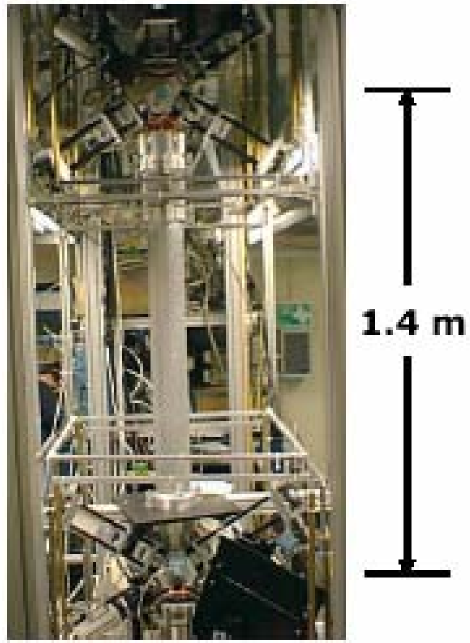


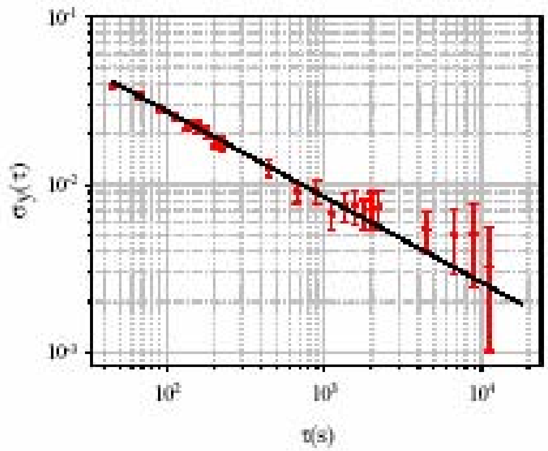
Resolution: 3x10^{-9} g after 1 minute

Absolute accuracy: $\Delta g/g<3\times10^{-9}$

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:

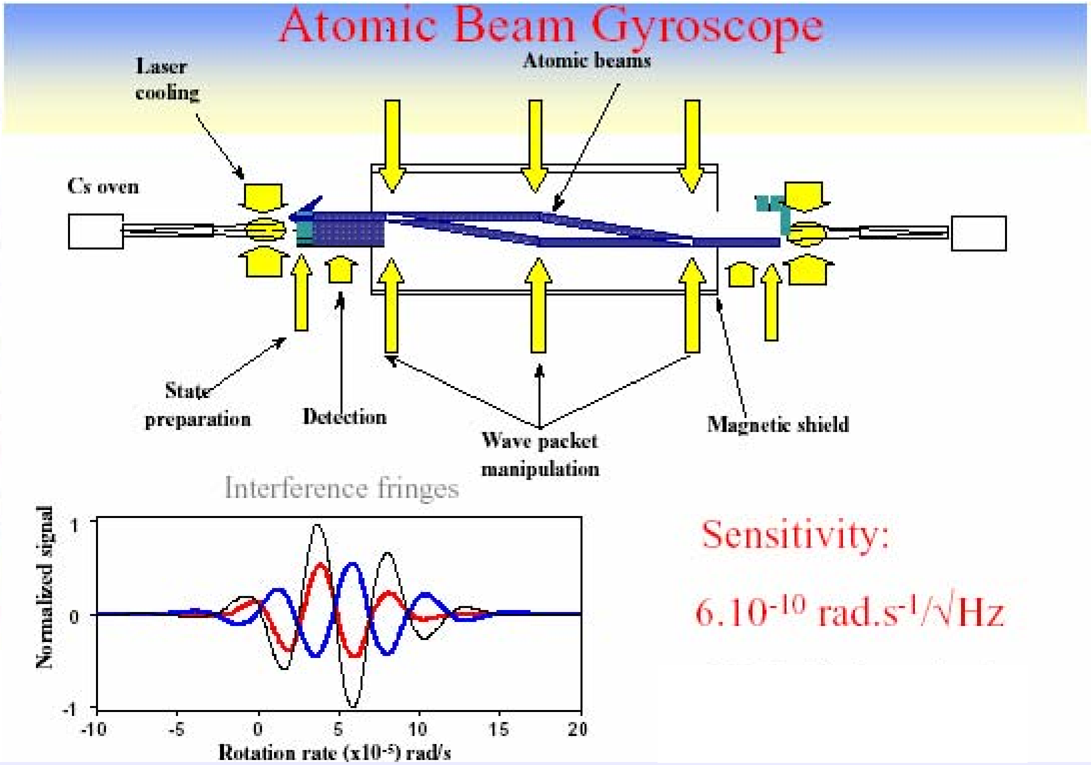
4×10^{-9} g/Hz$^{1/2}$

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

from M.A. Kasevich

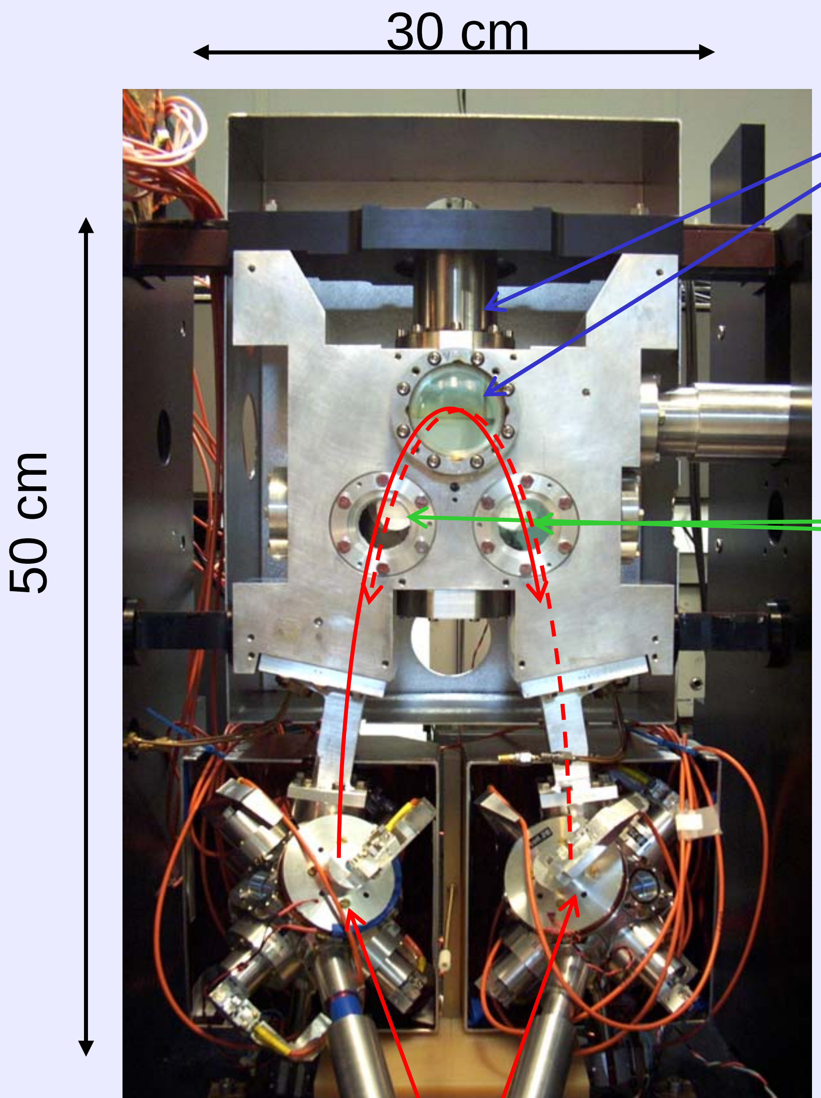
M.J. Snadden et al., Phys. Rev. Lett. 81, 971 (1998)

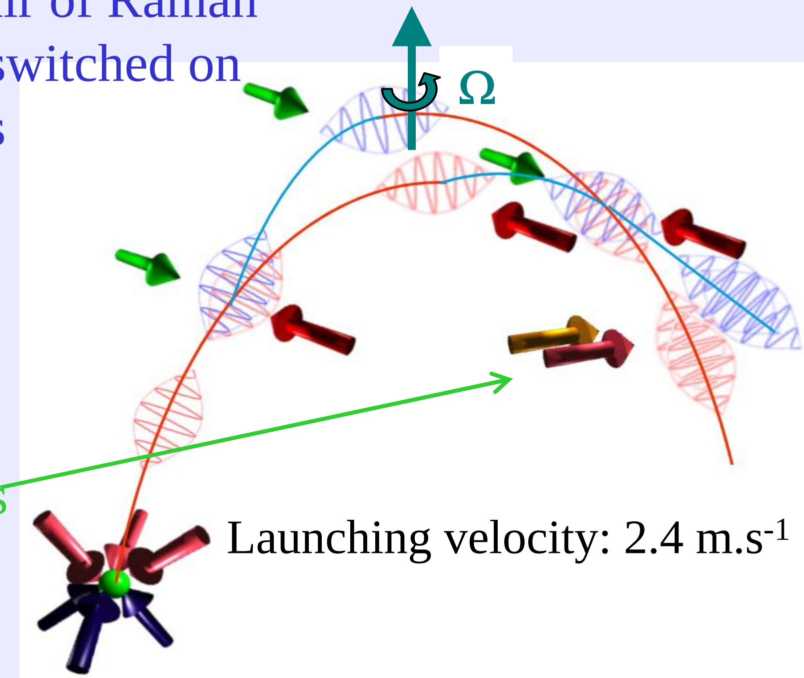
Stanford/Yale gyroscope



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

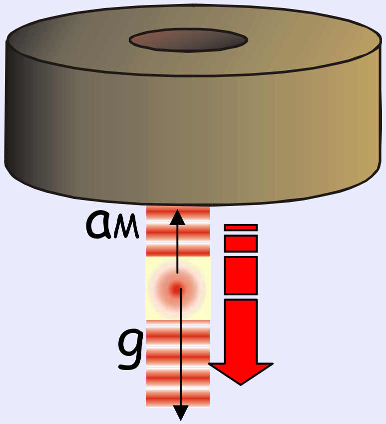
Cycling frequency 2Hz

Expected sensitivity (10^6 at):

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

MAGIA

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



➢ ***Precision measurement of G***

➢ ***Test of Newtonian law at micrometric distances***

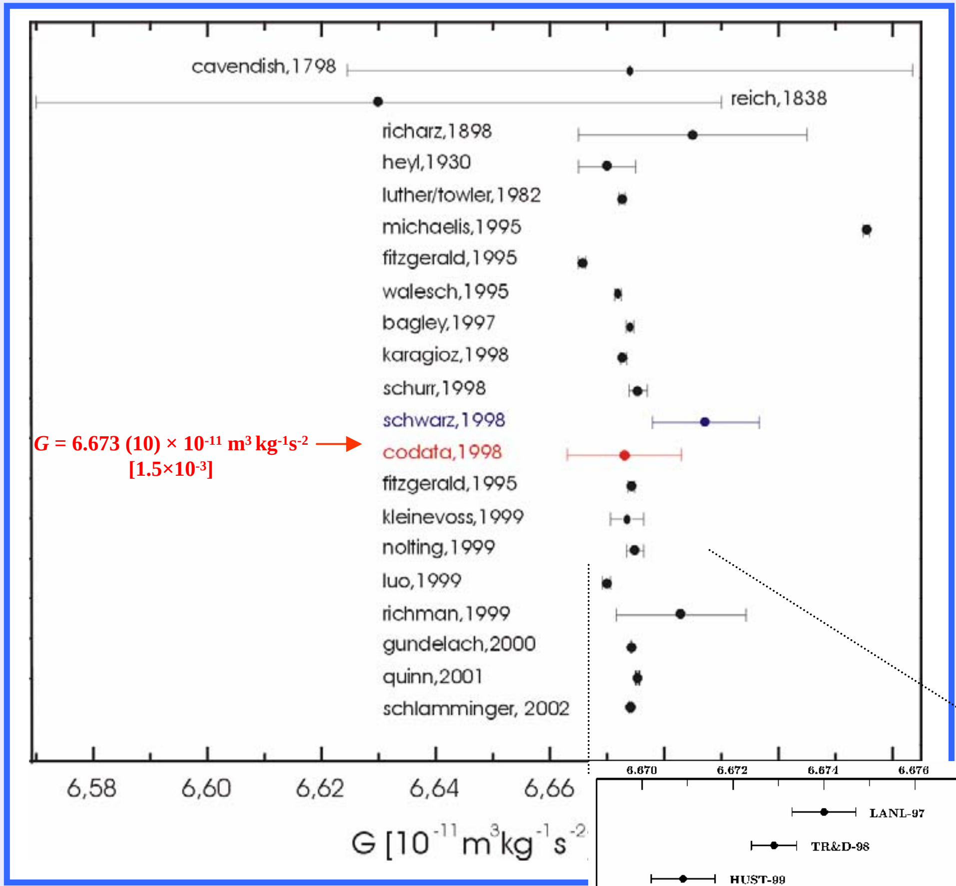
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

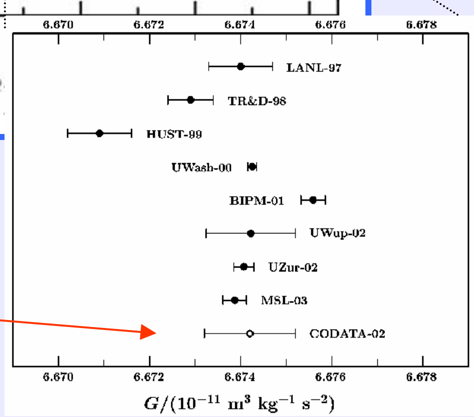
Why atoms?

- 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,…

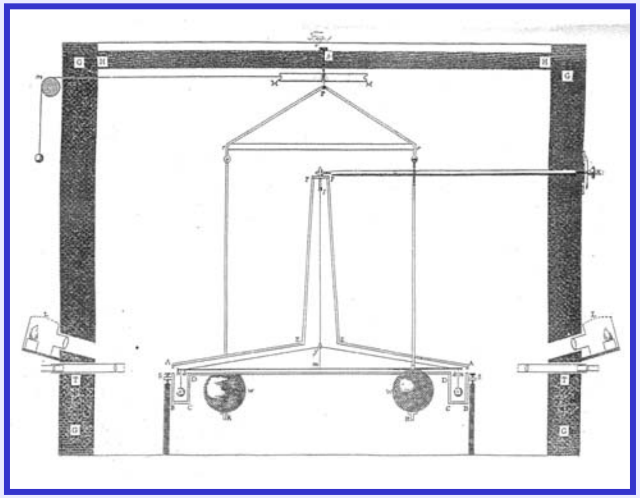
Measurement of the Newtonian gravitational constant G by atom interferometry

Measurements of the Newtonian gravitational constant G

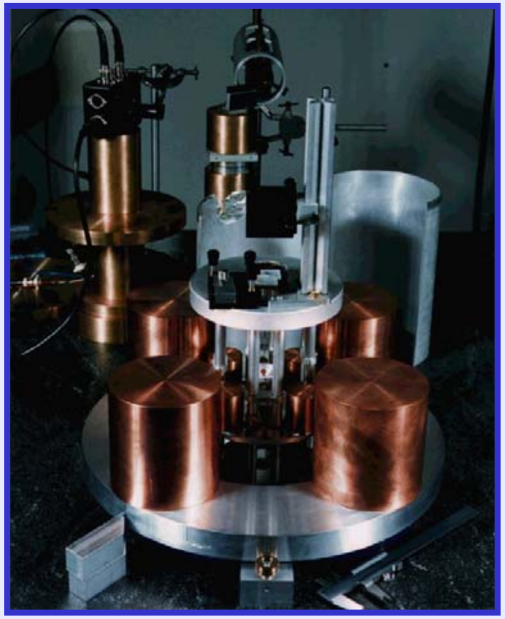




G = 6.6742 (10) × 10^{-11} $m^3\,kg^{-1}s^{-2}$
[1.5×10^{-4}]

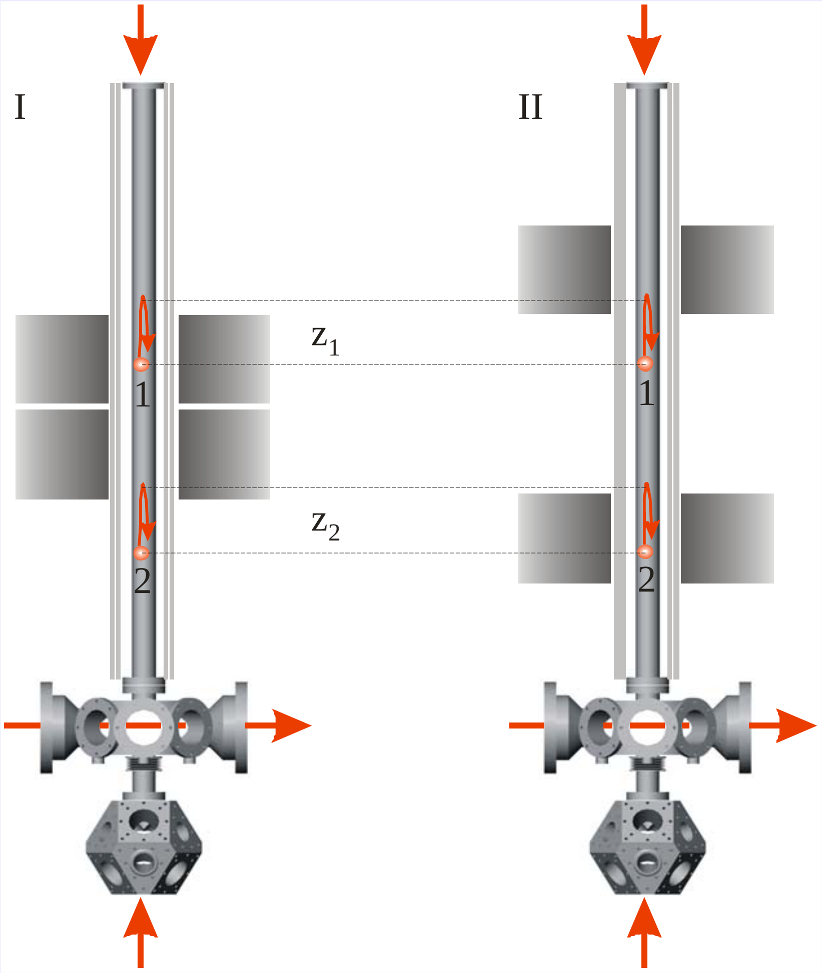


Cavendish 1798



Quinn 2001

MAGIA: Experimental procedure



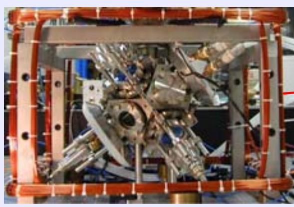
- trap, cool and launch 2 clouds of Rb atoms
- apply Raman light pulses
  masses in position 1
- detect atoms state selectively
- repeat several times
- plot N_a/N and fit the differential phase shift $\Delta\Phi_g$ between the clouds
- move masses to position 2
  repeat all procedure
- subtract the differential phase shifts for the two mass positions

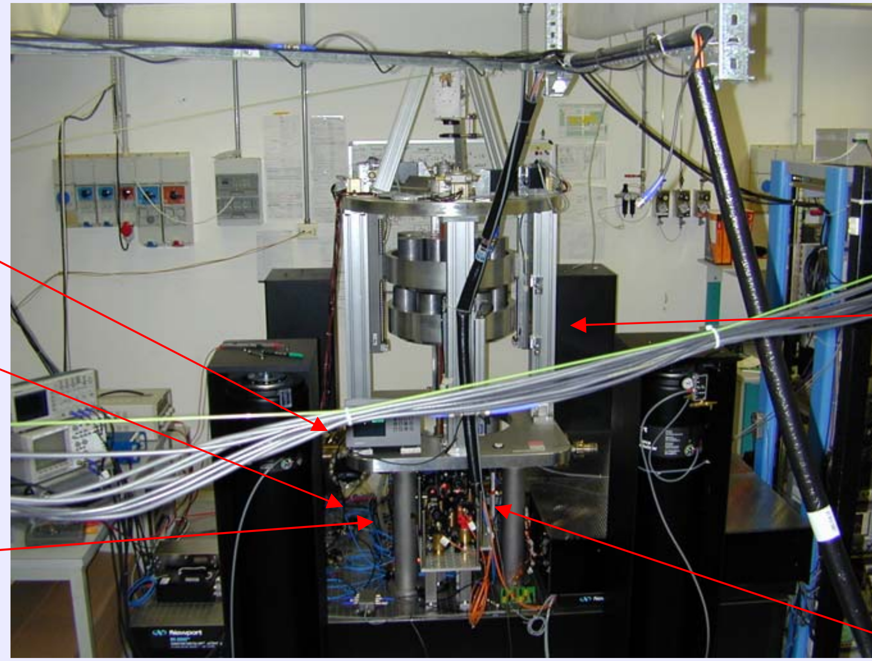
$$\phi_1^I - \phi_2^I = \phi_g(z_1) + \phi_{SM} + \phi_{Sys}(z_1, t_I) - \left(\phi_g(z_2) - \phi_{SM} + \phi_{Sys}(z_2, t_I)\right)$$

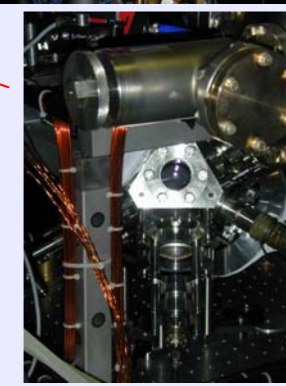
$$\phi_1^{II} - \phi_2^{II} = \phi_g(z_1) - \phi_{SM} + \phi_{Sys}(z_1, t_{II}) - \left(\phi_g(z_2) + \phi_{SM} + \phi_{Sys}(z_2, t_{II})\right)$$

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

Atom gravity gradiometer apparatus

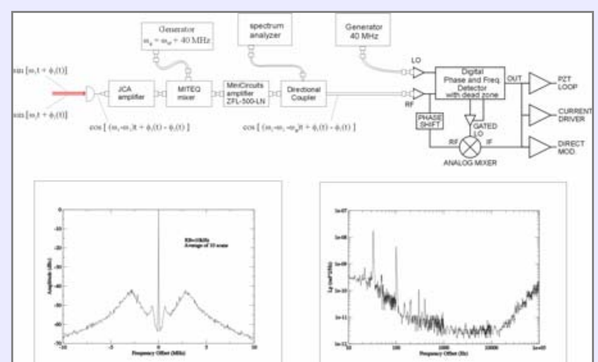






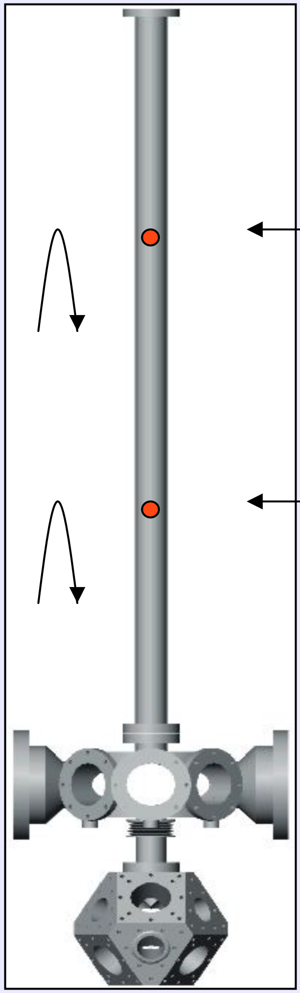
Source masses and support

Laser and optical system

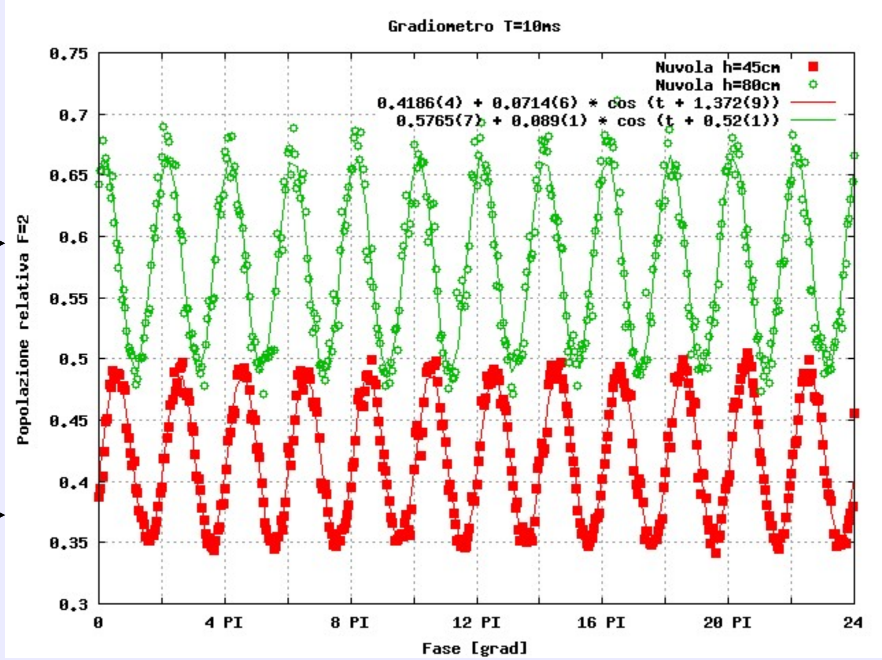


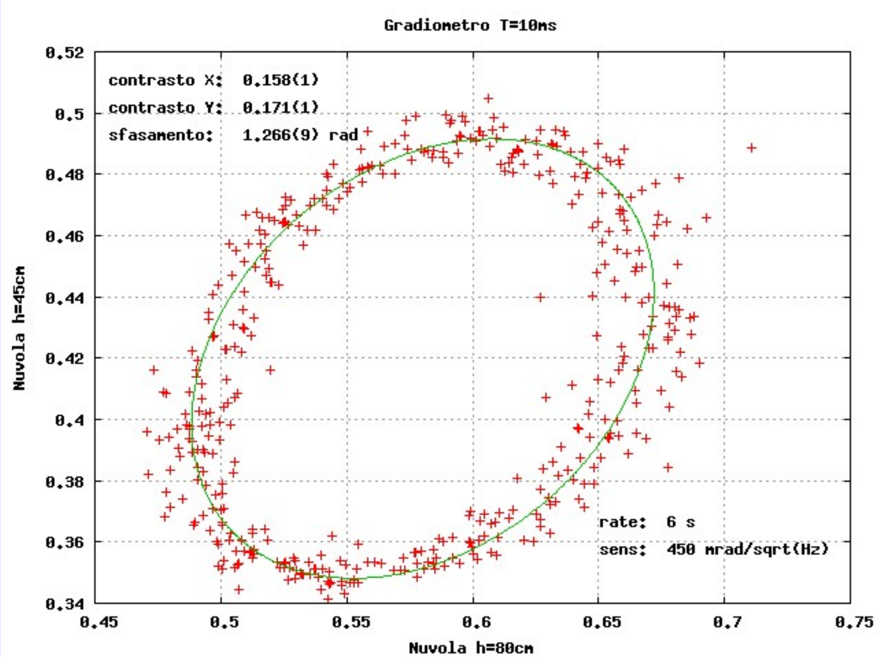
L. Cacciapuoti, M.de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M.Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers*, Rev. Scient. Instr. 76, 053111 (2005)

GRADIOMETER

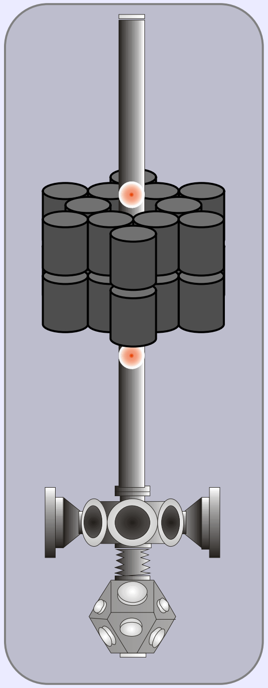


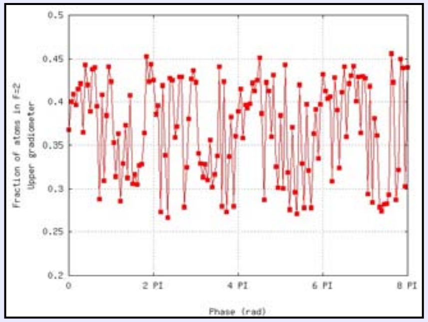
Atom interference fringes

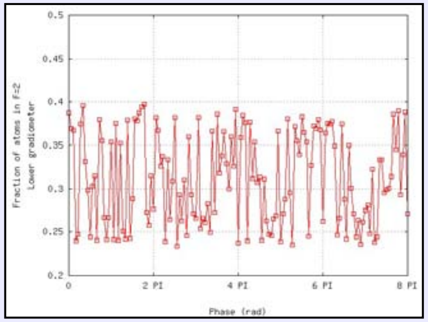


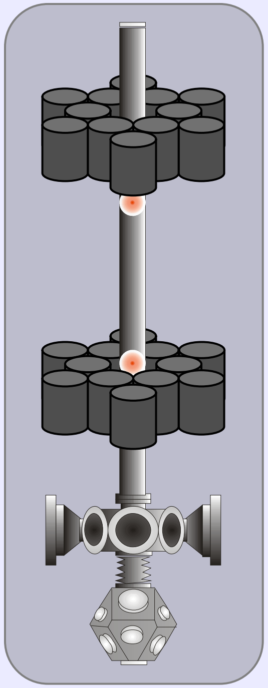


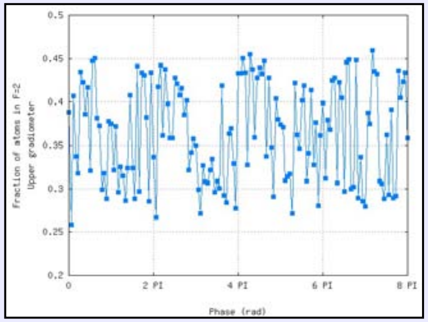
G: first result

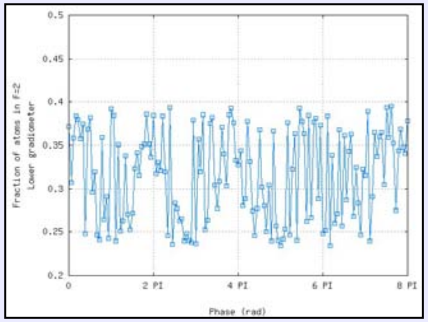


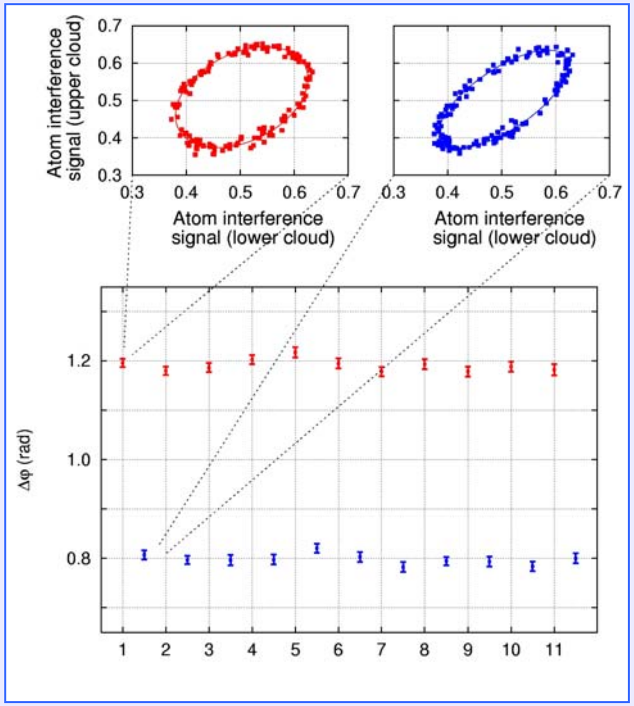


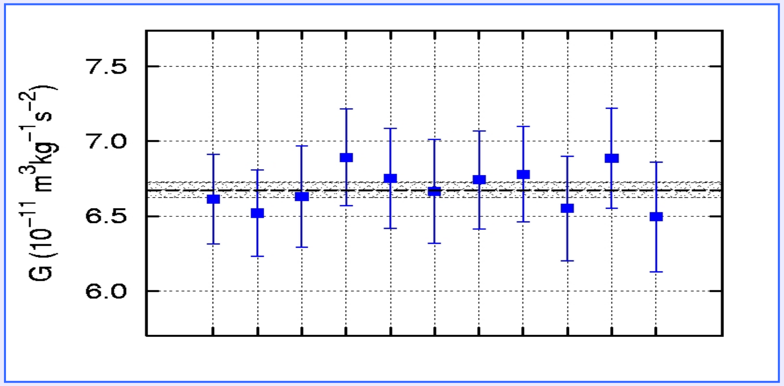












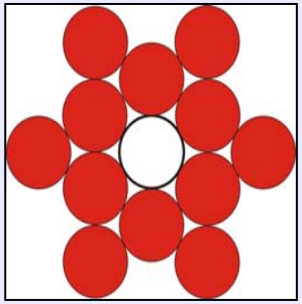
G = 6.64 (6) × 10^{-11} m^3 kg^{-1}s^{-2}

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, 2006
(available online as Highlight Paper) - `arXiv:physics/0606126`

SOURCE MASSES

Arrangement:
2x12 cylinders in a hexagonal arrangement

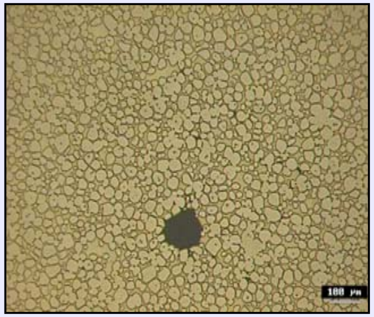
Material:INTERMET 180K
(95.3% W, 3,2% Ni, 1,5% Cu)
produced by PLANSEE



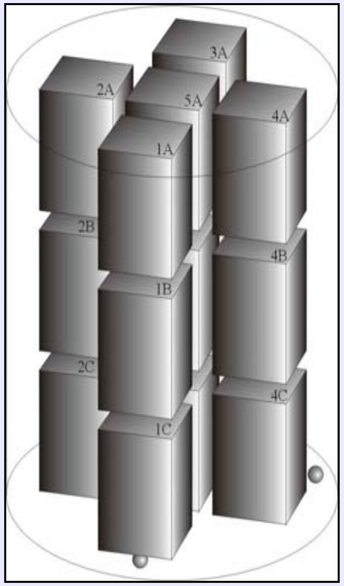
radius 5 cm
height 15 cm
mass 20 kg

Properties:
Density = 18 g cm^{-3}
Resistivity = $12x10^{-8}$ Wm
Non magnetic
Thermal expansion = $5x10^{-6}$ K^{-1}
Surface roughness = 3 μm

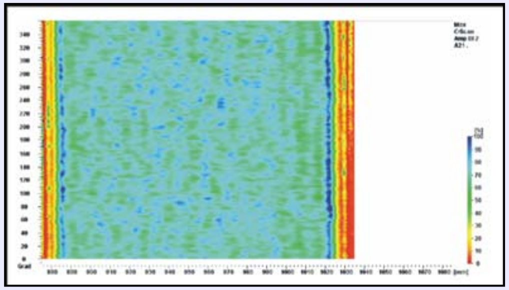
Characterization
Possible <u>holes</u> in the center of big blocks can change the average density of max 10^{-4}
(Simulations show maximum shift of G of less than 10^{-4})
•<u>Hot Isostatic Pressing</u> of cylinders at 1200°C and 1500 atm to reduce holes
•<u>Ultrasonic and destructive test</u>
•<u>Density comparison</u> at different points in cooperation with INRIM in Torino (relative measurement will reveal differences smaller than 0.002 g/cm^{-3})



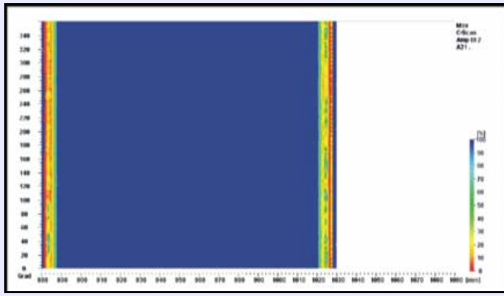
100 μm hole seen with a microscope



15 samples obtained from one cylinder for density comparison



HIP treatment

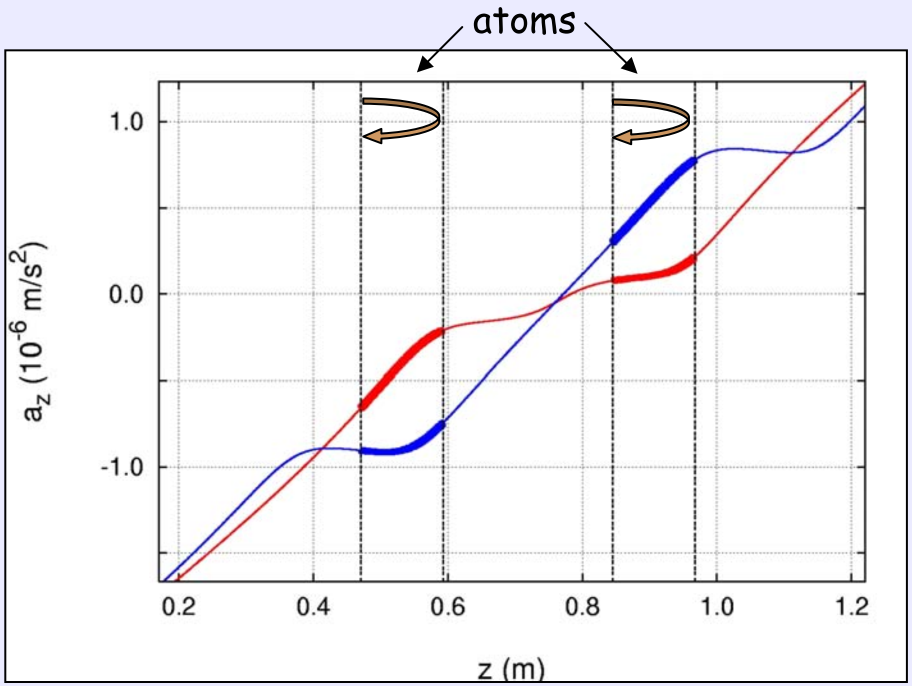


Ultrasonic tests on a simply sintered cylinder (above) and on an also HIPed one (below)

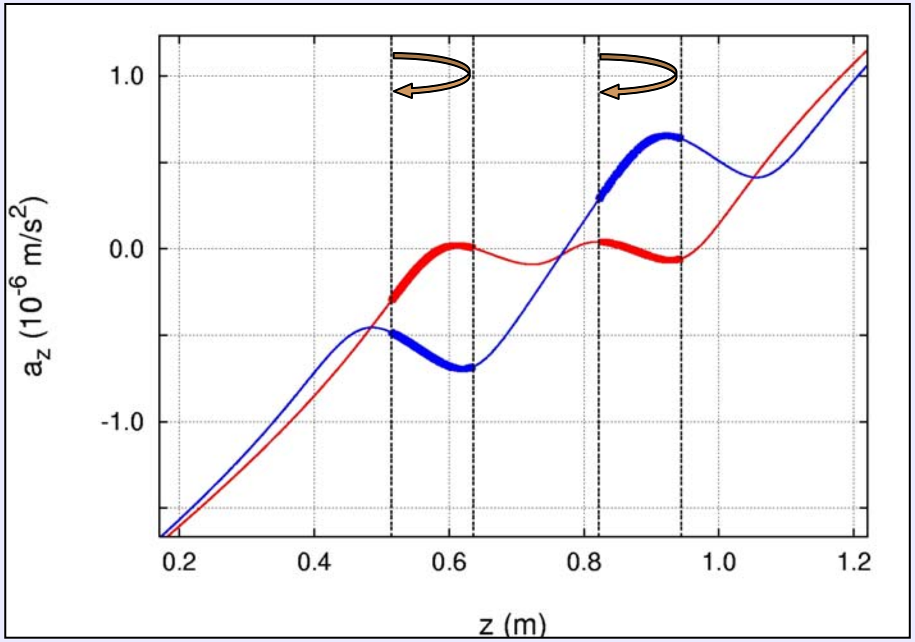
Appropriate trajectories

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



LEAD



TUNGSTEN

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)

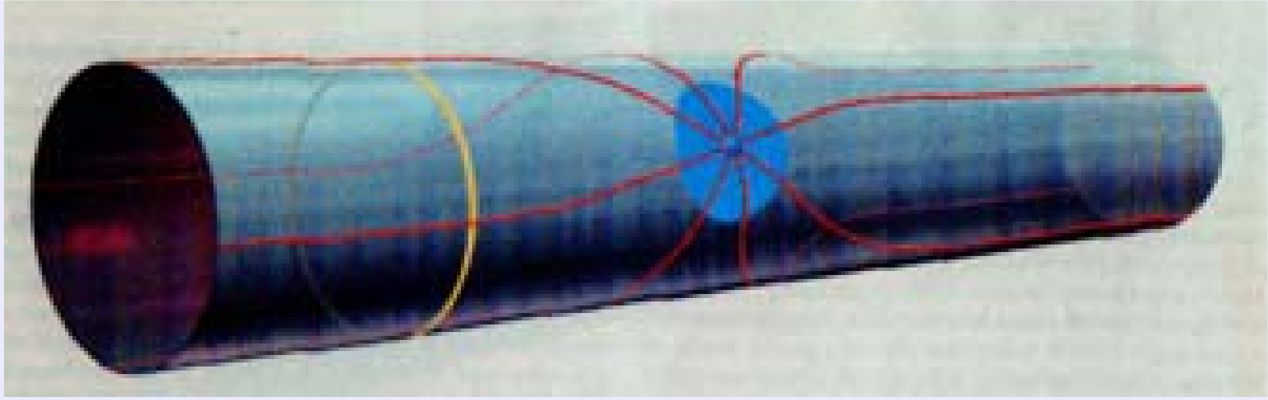
Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

- **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**

Extra Dimensions



1 extra dimension $\Rightarrow$ $F \propto 1/r^3$ size $\approx 10^{11}$ m
2 extra dimensions $\Rightarrow$ $F \propto 1/r^4$ size $\approx 10^{-4}$ m
3 extra dimensions $\Rightarrow$ $F \propto 1/r^5$ size $\approx 10^{-9}$ m
...

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B 429, 263 (1998)

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *Phenomenology, astrophysics, and cosmology of theories with submillimiter dimensions and TeV scale quantum gravity*, Phys. Rev. D 59, 086004 (1999)

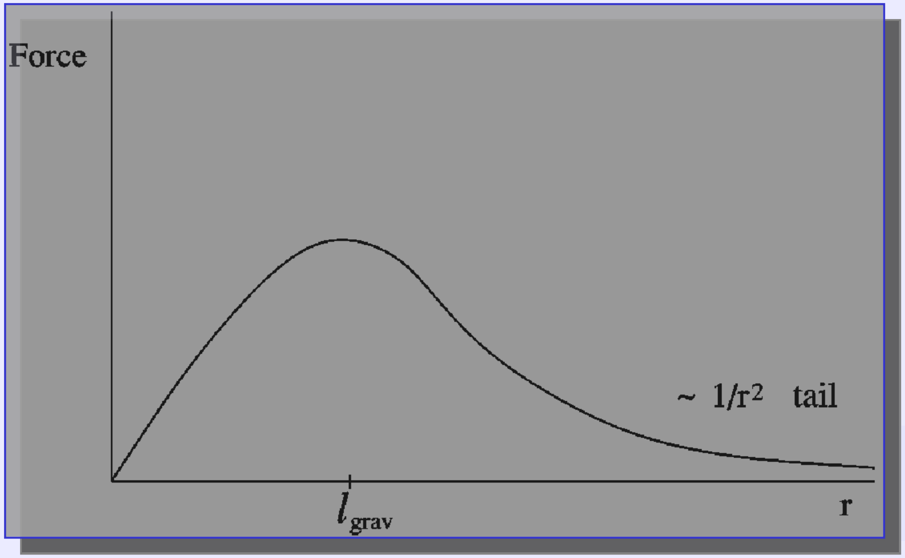
Cosmological constant problem and "fat" gravitons

Cosmological data ⇒ vacuum-energy density $\rho_{vac} \sim 3 \cdot 10^3$ eV/cm^3

⇩

$$l \sim (\hbar c/\rho_{vac})^{1/4} \sim 0.1 \text{ mm}$$

The graviton is "fat" at distances ≤ 1 mm ?
Solution to the CC Problem?



R. Sundrum, *Fat gravitons, the cosmological constant and submillimeter tests*, Phys. Rev. D 69, 044014 (2004)

$20\ \mu m \leq l_{grav} \leq 0.2$ mm

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**

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

→

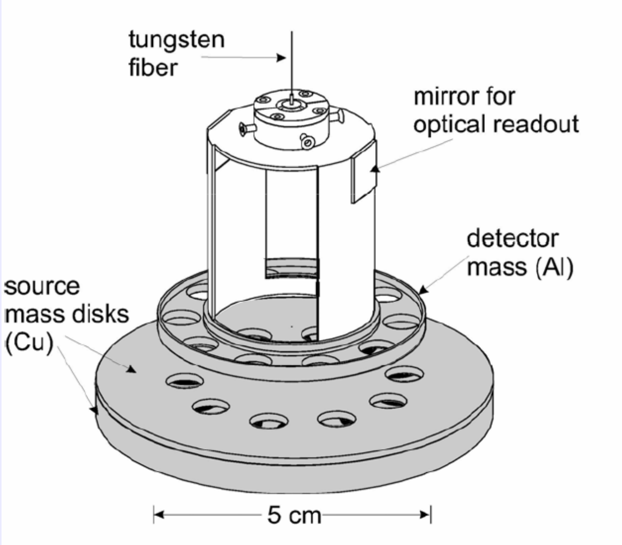
- Exchange of a boson with m = ħ/λc
- Extra dimensions

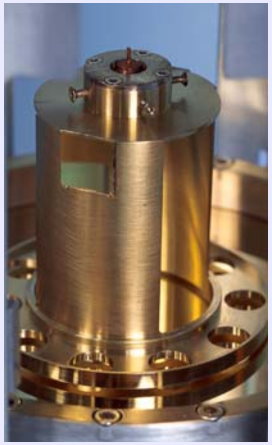
- **Modified power-law potential**

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

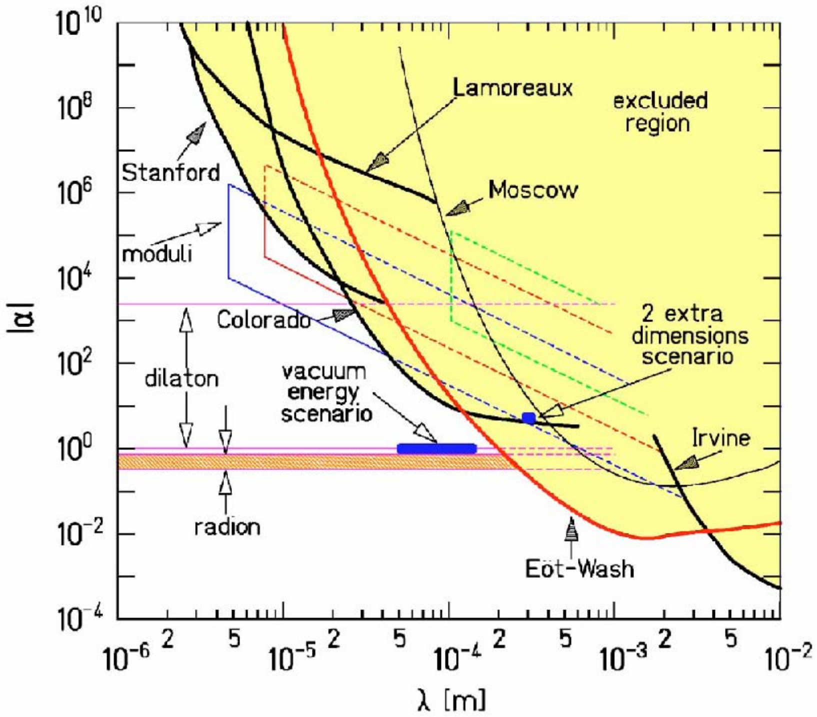
→ Exchange of 2 massless particles

Torsion balance - Washington experiment





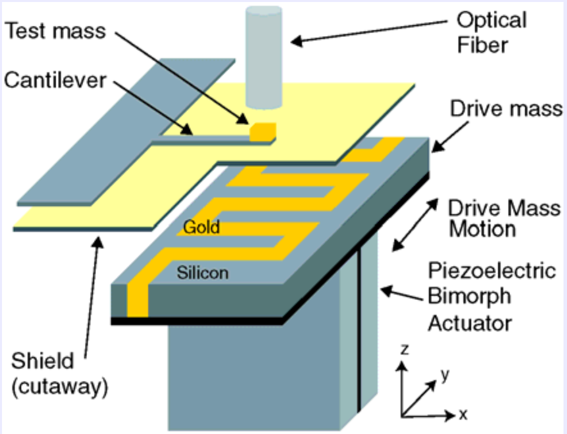
- **Test bodies: ''missing masses'' of holes bored into plates**
- **Torsion pendulum**
  7075 aluminum, gold coated
  disk height = 2 mm
  10 cylindrical holes evenly spaced about the azimuth
- **Attractor**
  high-purity copper disk
  top surface coated with gold
  10 cylindrical holes evenly spaced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

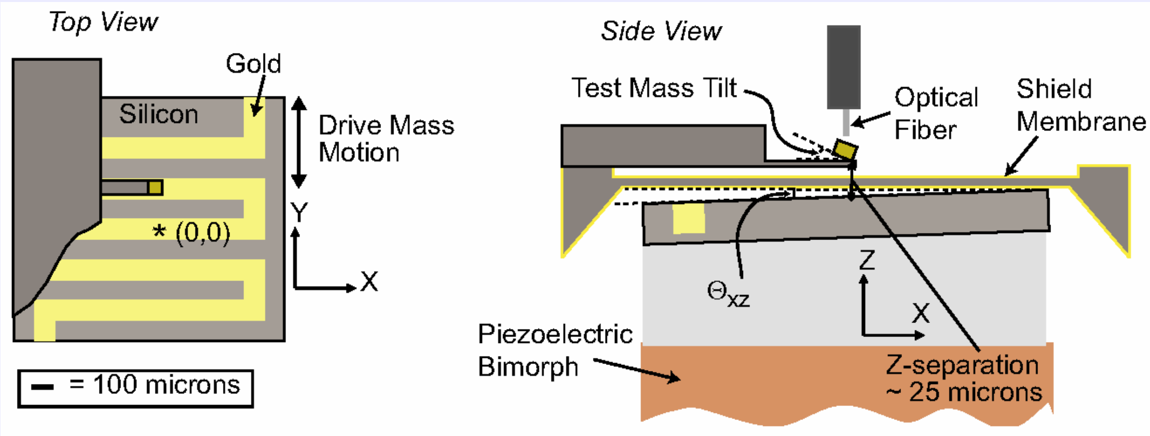


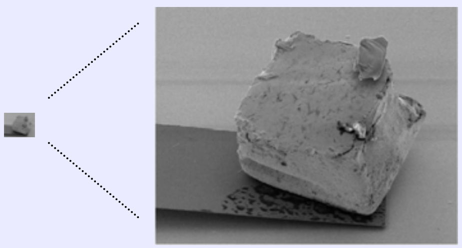
- **Distance from top of attractor to bottom of pendulum**
  from 10.77 mm to 137 μm

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)

Microcantilever - Stanford experiment

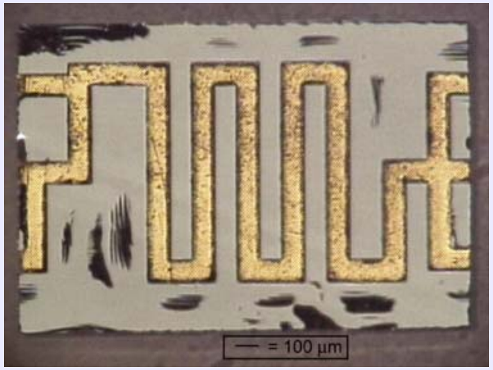






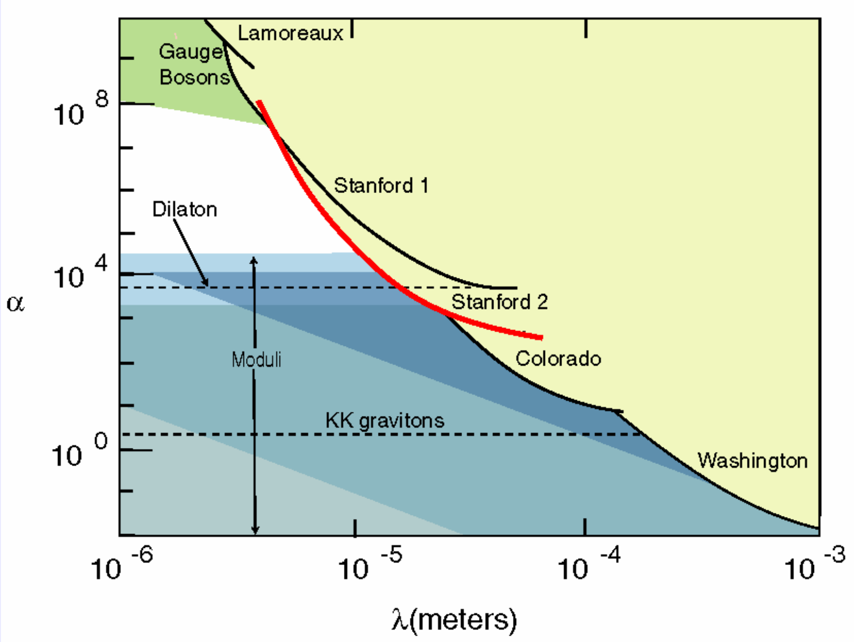
Probe mass (gold)
50 μm x 50 μm x 30 μm
m_t ~ 1.6 μg

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



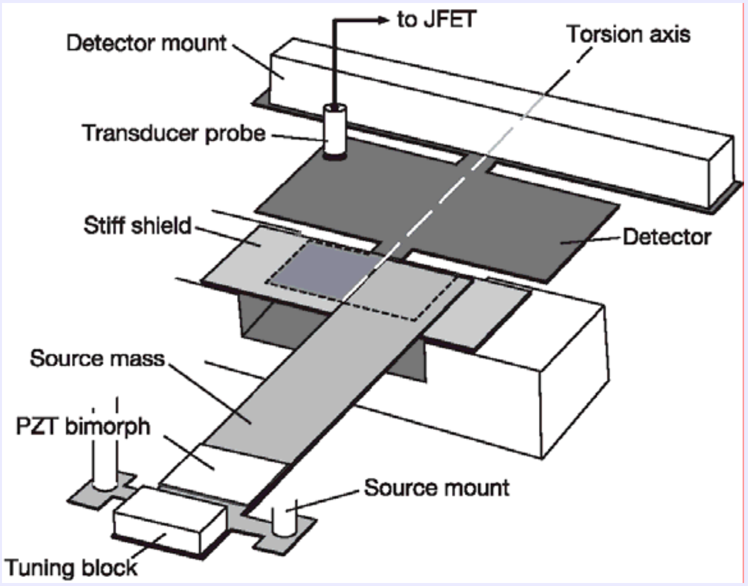
Source mass
5 sets of gold and silicon bars
100 μm x 1mm x 100 μm

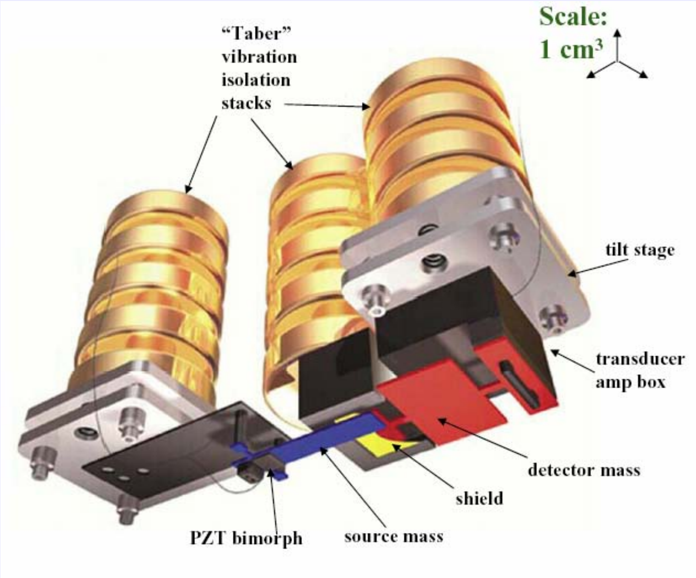
Separation 25 μm



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



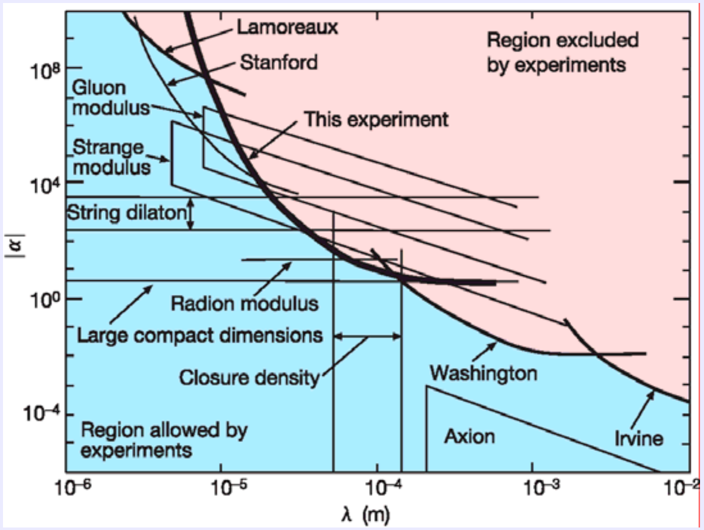


Detector (tungsten)
11.455 mm x 5.080 mm x 195 μm

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

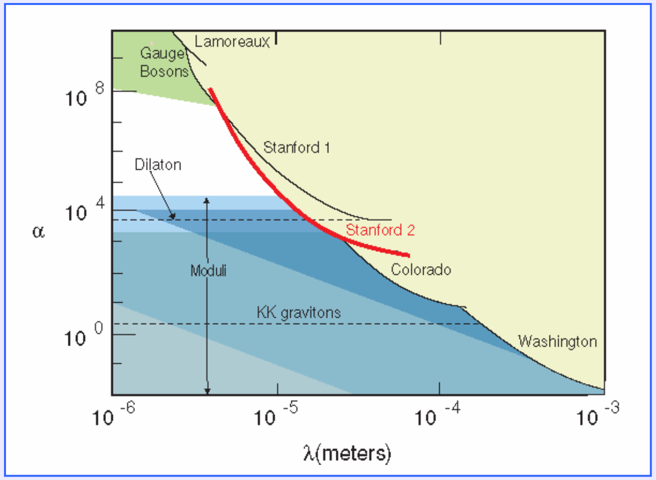
Also experiments on Casimir effect ($\lambda \leq$ 0.001 mm)

Departures observed at ~70 μm?

(Washington, Stanford)

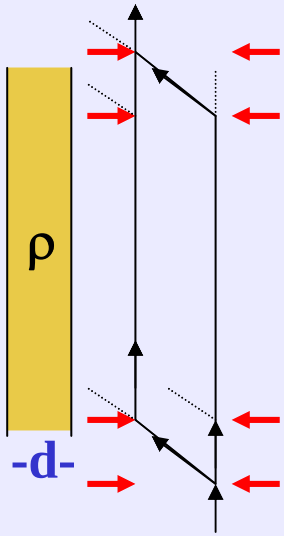
Experimental artifact?

Test of the gravitational $1/r^2$ law in the sub-mm range with atom interferometry sensors



95% confidence level constraints on a Yukawa violation of the gravitational inverse-square law. The vertical axis represents the strength of a deviation relative to that of Newtonian gravity while the horizontal axis designates its characteristic range. The yellow region has been excluded (From S. J. Smullin et al., 2005)

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



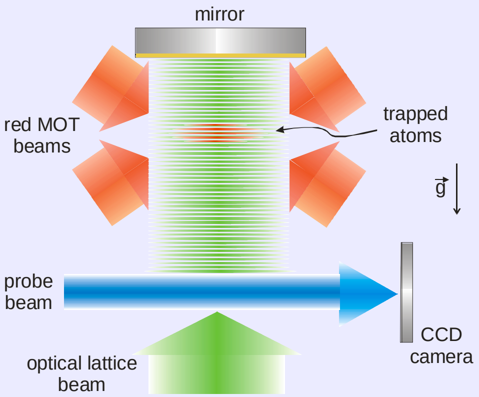
$a = 2\pi G\rho d$

Example:

$\rho_{Au} \sim 19\ g/cm^3$

$d \sim 200\ \mu m$

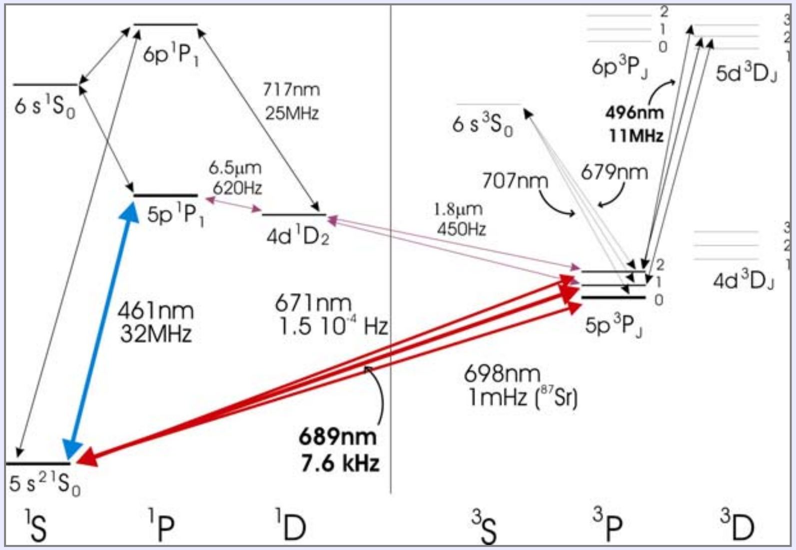
$a \sim 2 \times 10^{-9}\ ms^{-2}$

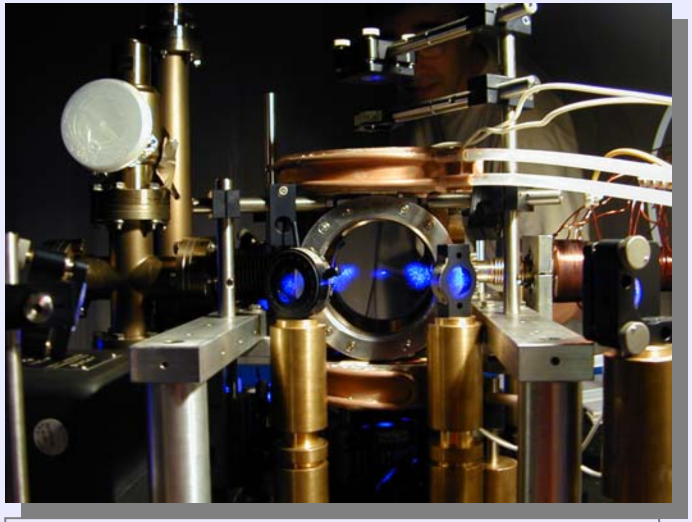


$\nu = m\, g\, \lambda / 2\, h$

- **G.M. Tino, *in "2001: A Relativistic Spacetime Odyssey", Firenze, 2001,* World Scientific (2003)**
- **G.M. Tino, Nucl. Phys. B 113, 289 (2002)**
- **G. Ferrari, N. Poli, F. Sorrentino & G. M. Tino, PRL 97, 060402 (2006)**

Ultracold Sr – The experiment in Firenze

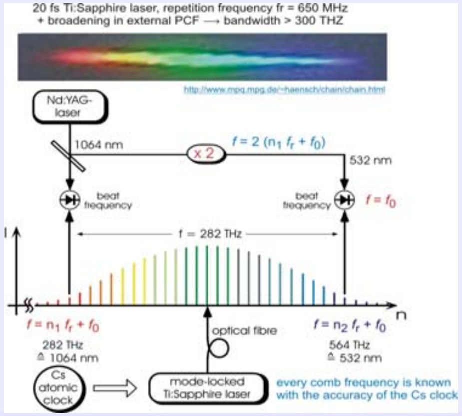


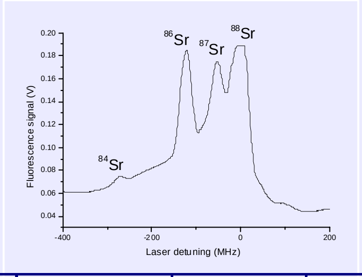


Firenze 2003, Magneto-optical trapping of all Sr isotopes

- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests





	Abundance
^{88}Sr	82.6%
^{86}Sr	9.9%
^{87}Sr	7.0%
^{84}Sr	0.6%

Isotope	I	transition	lifetime	λ	t_{int}	$\sigma_y\ t^{-1/2}$	abundance
^{88}Sr	0	$^1S_0$-$^3P_1$	20 μs	689 nm	10 μs	$2\ 10^{-13}$	83%
^{87}Sr	9/2	$^1S_0$-$^3P_0$	200 s	698 nm	0.5 s	10^{-17}	7%

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)

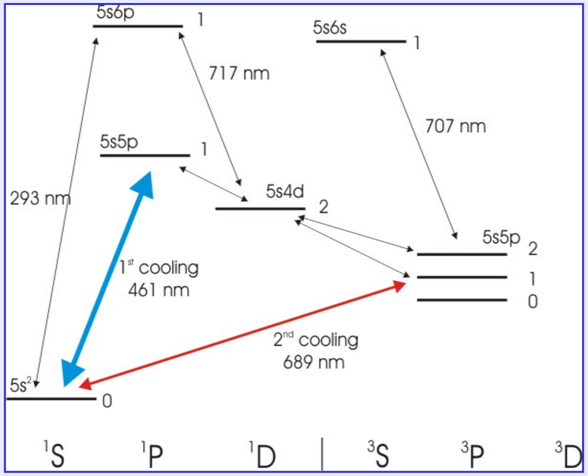
G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale, Phys. Rev. Lett. 97, 060402 (2006)

Why Sr atom?

- New quantum sensors
  - J = 0 ground state
  - Small collisional cross section
  - Fermionic and bosonic atoms

- Optical clocks on visible intercombination lines
  - $^1S_0$ - $^3P_1$ (7.5 kHz) (this work)
  - $^1S_0$ - $^3P_0$ (1 mHz, ^{87}Sr)
  - $^1S_0$ - $^3P_2$ (<1 mHz)
  - Optical trapping in optical lattices with negligible change of clock frequency

- Physics of ultracold atoms
  - Simple 0 - 1 transitions
  - $T_D \approx T_{rec}$ for $^1S_0$ - $^3P_1$ transition
  - Two-stage optical cooling and trapping
  - All-optical cooling to quantum degeneracy
  - Degenerate Bose and Fermi gases



Sr Isotope	Nuclear Spin I	Atomic Mass (10^{-27} Kg)	Natural Abundance
88	0	145,97068	82,6 %
87	9/2	144,315568	7,0 %
86	0	142,65567	9,8 %
84	0	139,34150	0,56 %

Optical frequency reference on Sr transition

- ^{88}Sr $^1S_0$-$^3P_1$ forbidden transition ($\Gamma=2\pi$ x 7.6 kHz)

  - Spectroscopy on free atoms (LENS, SYRTE, JILA-NIST)

    - LENS 434 829 121 311 (10) kHz

    - SYRTE 434 829 121 300 (20) kHz

    - JILA/NIST 434 829 121 312 334 (20 stat) (33 syst) Hz

G.Ferrari *et al*. PRL **91**,243002 (2003)

I. Courtillot *et al*. Eur. Phys. J. D **33**, 161 (2005)

T. Ido *et al*. Phys. Rev. Lett. **94**, 153001 (2005)

→ Both stability and accuracy limited by line Q

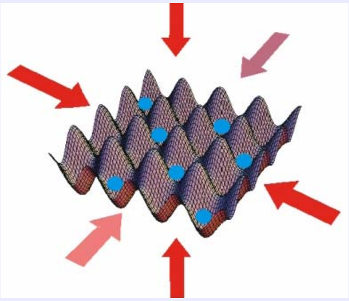
- ^{87}Sr $^1S_0$-$^3P_0$ doubly forbidden transition ($\Gamma=2\pi$ x 1 mHz)

  - Optical Lattice Clock (U. Tokyo, SYRTE, JILA-NIST)

    - Tokyo 429 228 004 229 952 (15 sys) Hz

    - JILA/NIST 429 228 004 229 869 (19 sys) (2.8 stat) Hz

    - SYRTE 429 228 004 229 879.4 (5.3 syst) (0.5 stat) Hz



M. Takamoto *et al*. Nature **435**, 321 (2005)

A. D. Ludlow *et al*. Phys. Rev. Lett. **96**, 033003 (2004)

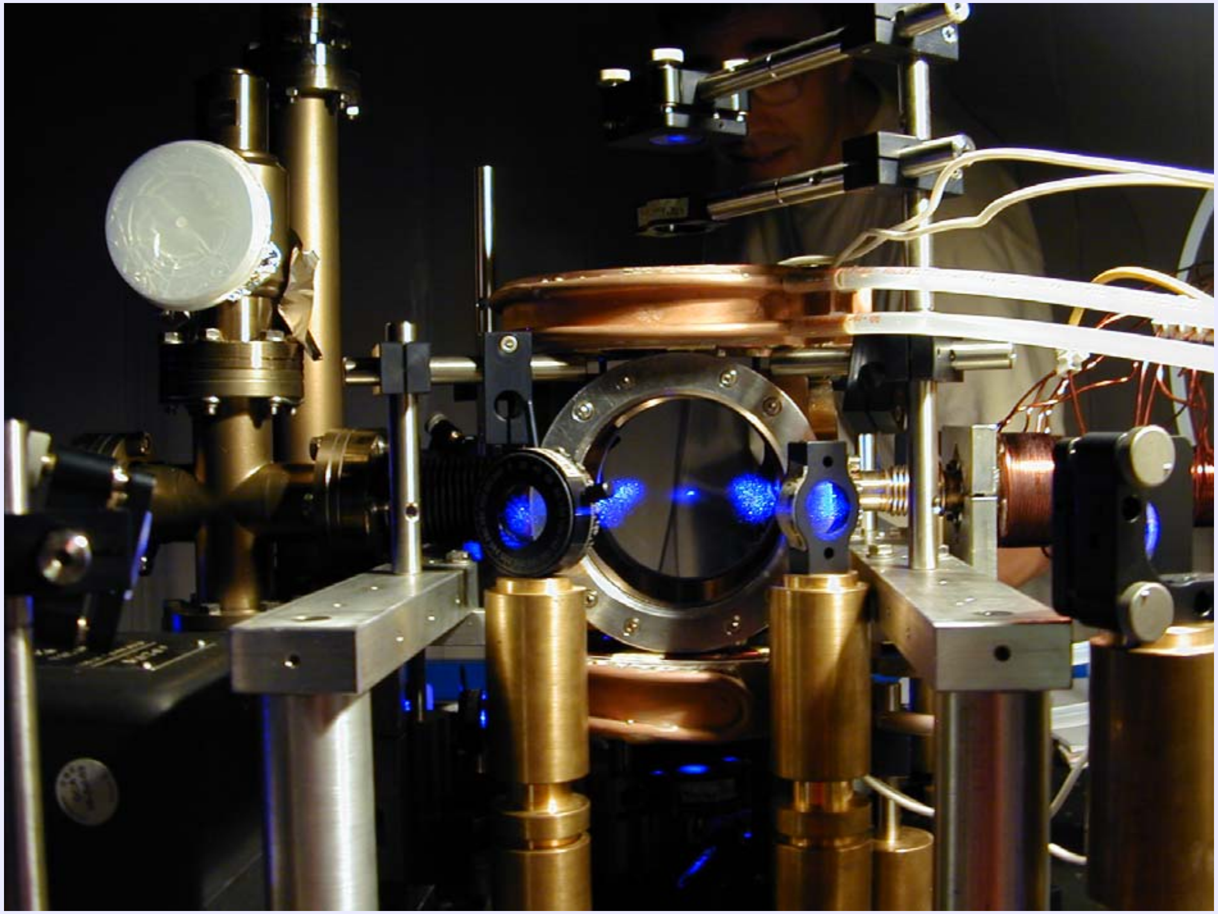
R. Le Targat *et al*. arXiv:physics/0605200 (2006)

→

$$\sigma_y(\tau) \approx 6 \times 10^{-14} \tau^{-1/2}$$

$$\delta\nu / \nu \approx 1.2 \times 10^{-14}$$

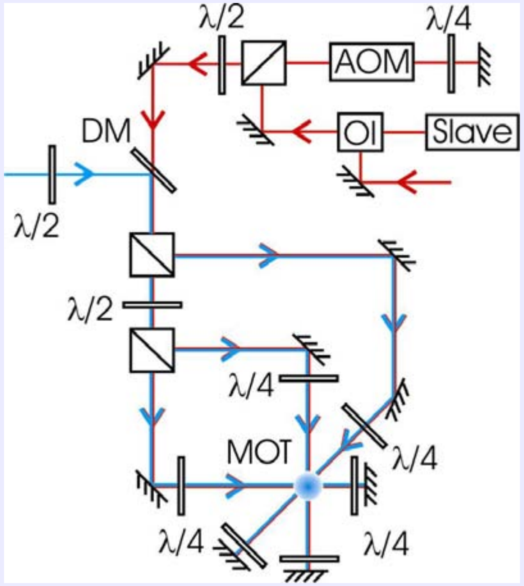
Sr MOT picture



LENS, Firenze, 2003

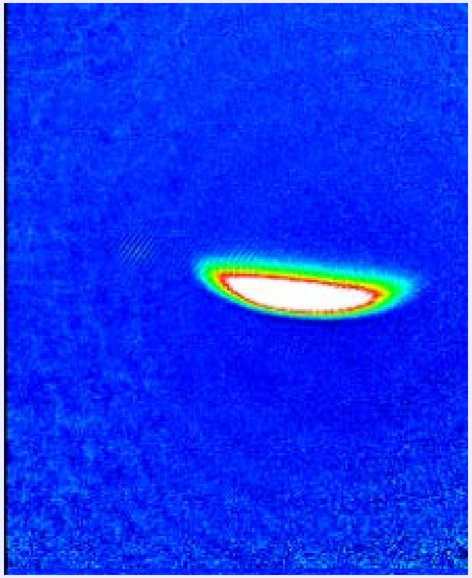
Double stage trapping and cooling of Sr atoms

- Optical setup



- MOT Picture

500 μm



- Capture Sequence:

- Blue MOT (Δt ~ 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* (Δt ~ 5 ms) $I \approx 0.06\ \text{Isat}$

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

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

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

- Red MOT ***broad band*** (Δt ~ 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*** (Δt ~ 10 ms)

$$\begin{cases} \delta = -350\ \text{kHz} \\ I = (10^3 \div 1)\ I_{sat} \\ dB/dz = 4\ \text{Gauss/cm} \end{cases} \rightarrow N_{max} = 3*10^6$$

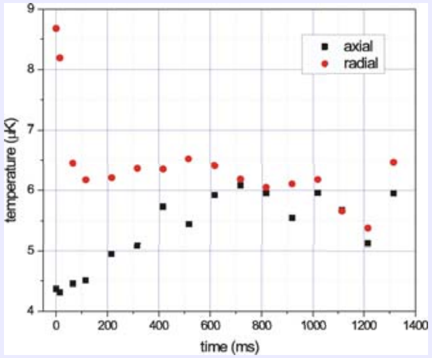
$\eta \approx 10\ \%$

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

Elastic collisions

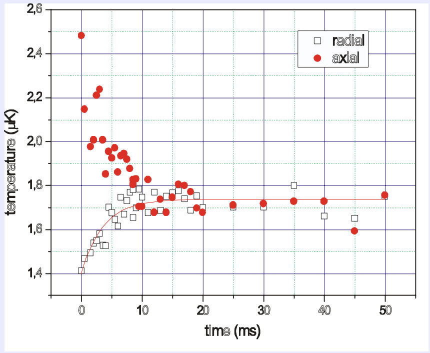
Thermalization rate ⇒ elastic cross section

^{88}Sr



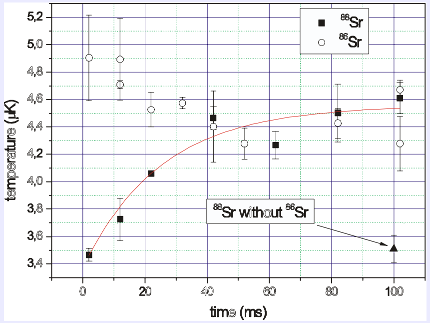
Very long thermalization time
possible effect of ergodic mixing
⇒ upper bound on elastic cross-section
$\boldsymbol{\sigma_{88} < 4 * 10^{-13}\ \mathrm{cm}^2}$

^{86}Sr



Short thermalization time
$\boldsymbol{\sigma_{86} = 1.3 \pm 0.5 * 10^{-10}\ \mathrm{cm}^2}$

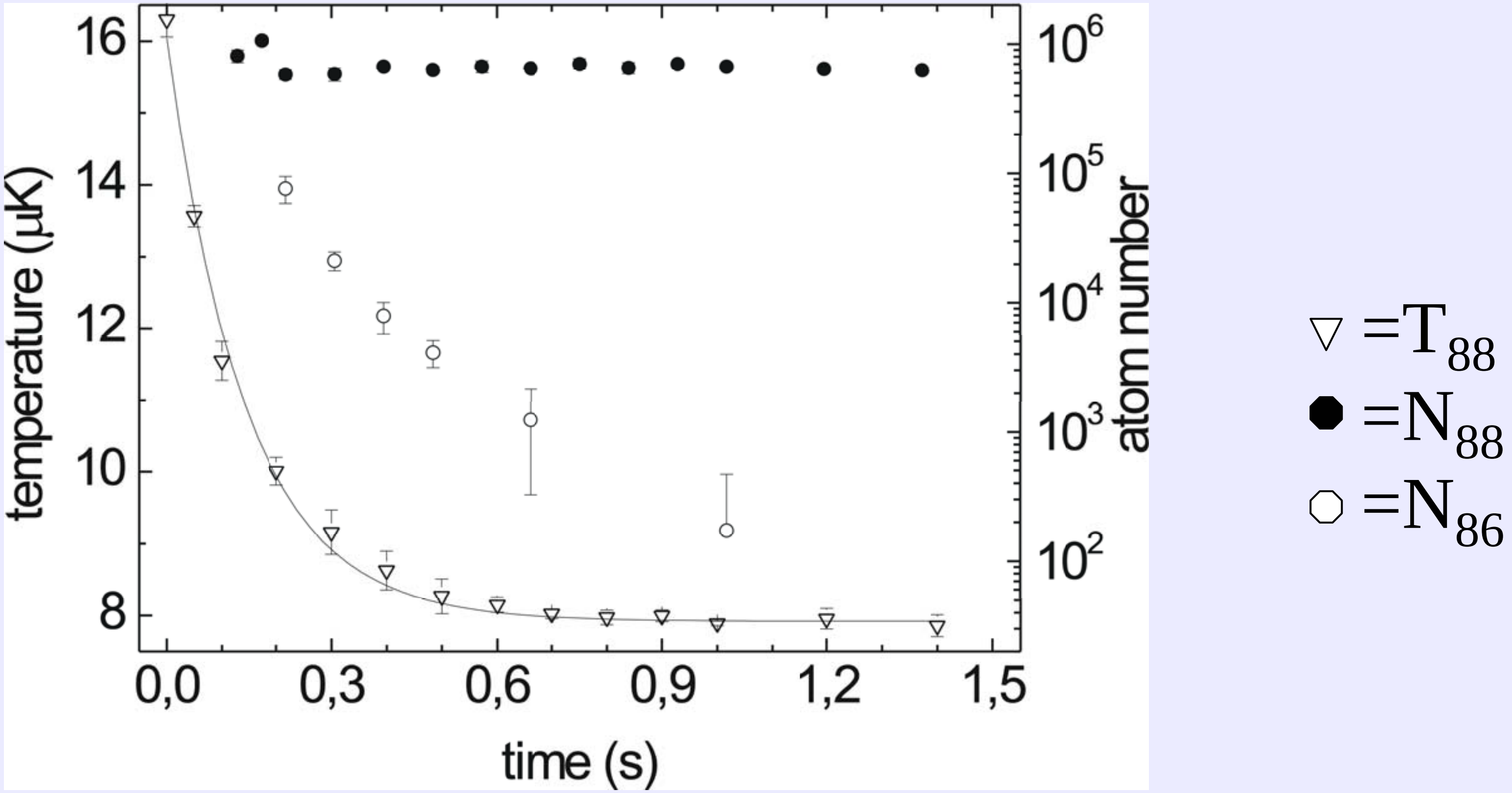
^{88}Sr-^{86}Sr



At least one order of magnitude larger than σ_{88}
$\boldsymbol{\sigma_{86-88} = 4 \pm 1 * 10^{-12}\ \mathrm{cm}^2}$

G. Ferrari et al., *Phys. Rev. A* 73, 023408 (2006)

Optical sympathetic cooling of ^{88}Sr with ^{86}Sr



- optical cooling of a small ^{86}Sr sample at low optical depth
- simultaneous trapping of a large ^{88}Sr sample dark to the ^{86}Sr light
- fast thermalization with respect to the optical cooling
- reduction of the density dependent heating by a factor 20: dT/dn = 2 μK/(10^{14} cm^{-3})

G. Ferrari et al., *Phys. Rev. A* 73, 023408 (2006)

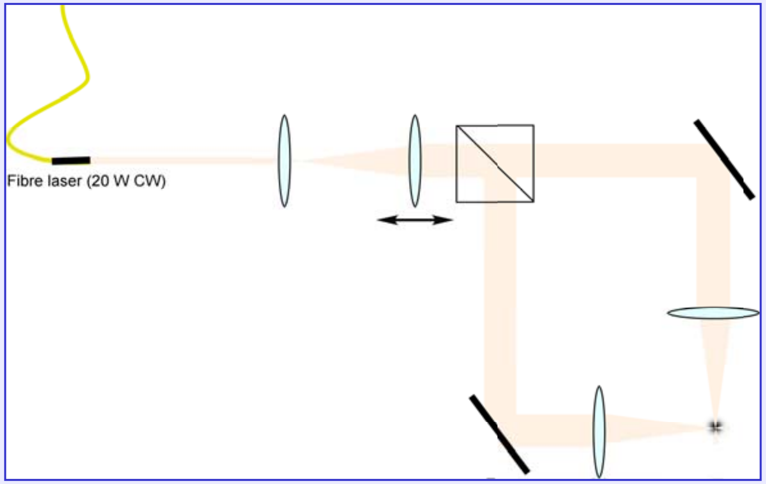
Towards BEC of Sr

- Maximum phase-space density achieved experimentally (optical-sympathetic cooling + evaporative cooling)

$$\rho = 0.2$$

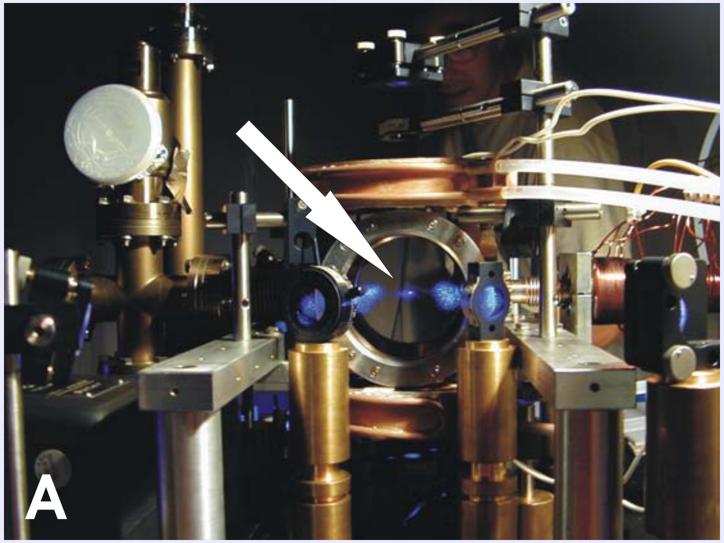
- G. Ferrari et al. *Phys. Rev. A* 73, 023408 (2006)
- F. Sorrentino et al., Mod. Phys. Lett. B Vol. 20, n.21 (2006), arXiv:physics/0609133

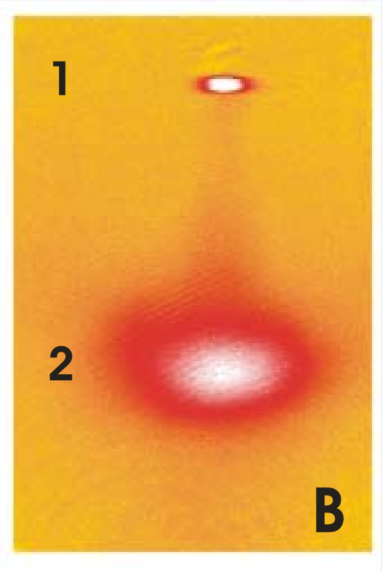
- Next step: Evaporation in compressible optical trap



D. J. Han et al. *Phys. Rev. A* 63, 023405 (2001)

Decoherence

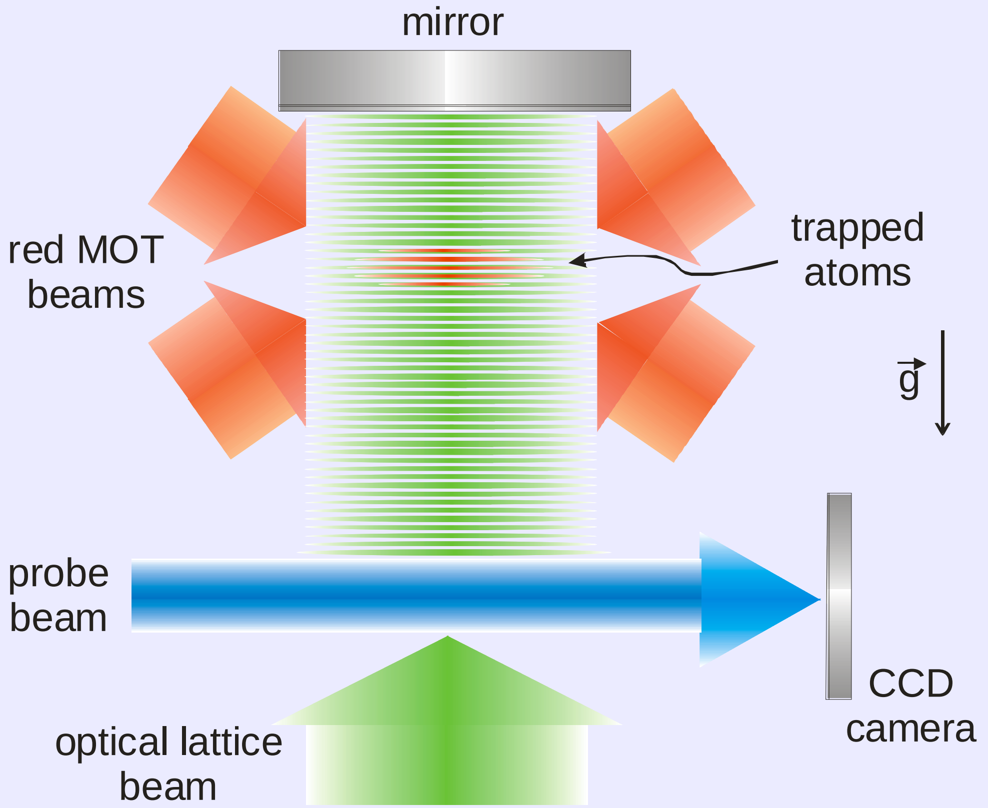


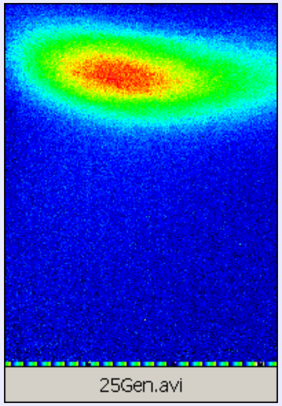


- ^{88}Sr: $\sigma_{88-88} = (3 \pm 1) \times 10^{-13}\ \mathrm{cm}^2$ ➡ τ_{coh} = 1-10 s
- ^{87}Sr: suppressed collisions for fermions at low temperatures

- **N. Poli, R.E. Drullinger, G. Ferrari, J. Leonard, F. Sorrentino, G.M. Tino,** ***Cooling and trapping of ultracold strontium isotopic mixtures,*** **Phys. Rev A 71, 061403 (R) (2005)**
- **G. Ferrari, R.E. Drullinger, N. Poli, F. Sorrentino, G.M. Tino,** ***Cooling of Sr to high phase-space density by laser and sympathetic cooling in isotopic mixtures,*** **Phys. Rev. A 73, 023408 (2006)**

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

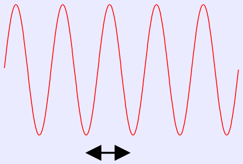




$\nu = m\, g\, \lambda / 2\, h$

Particle in a periodic potential: Bloch oscillations

periodic potential



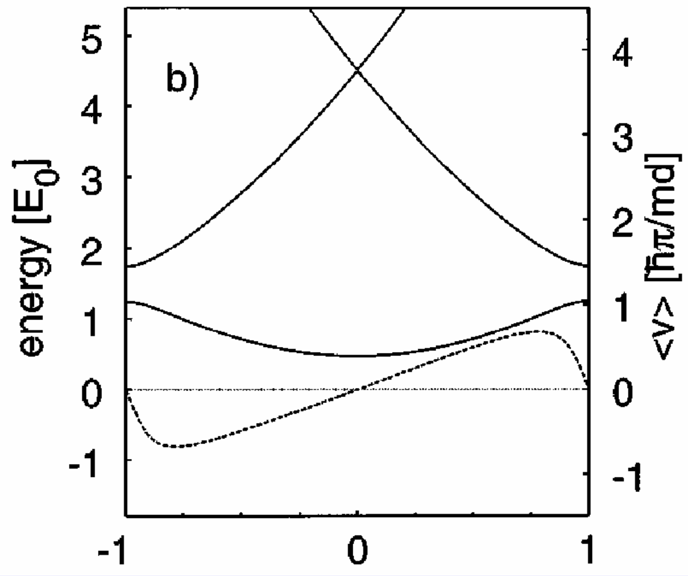
$V(z+\lambda/2) = V(z)$

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

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

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

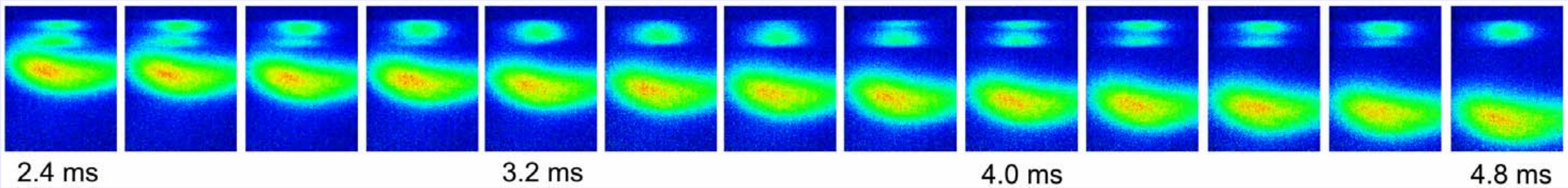
$$q(t) = q(0) + Ft/\hbar$$

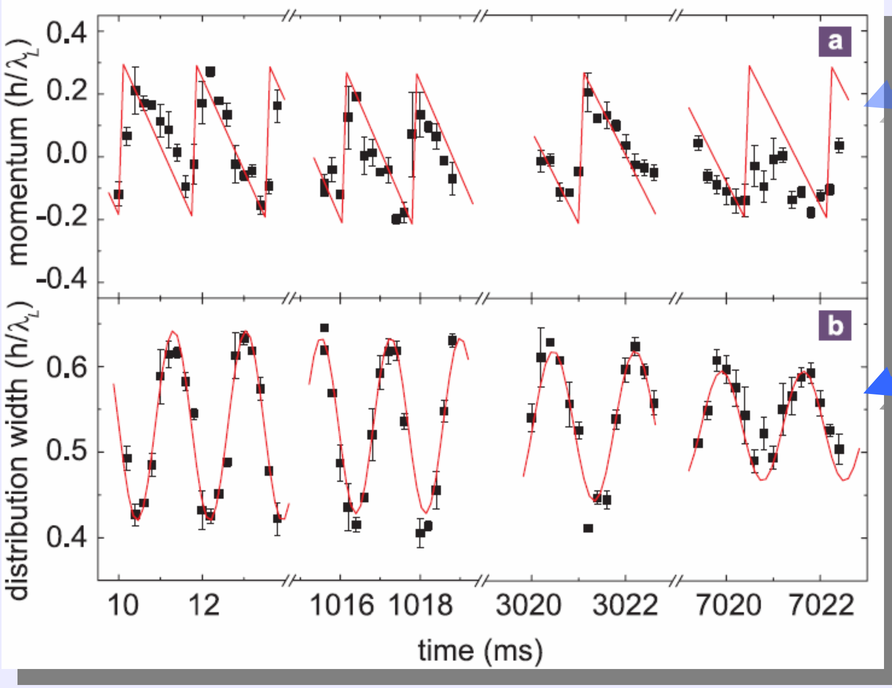
⬇

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

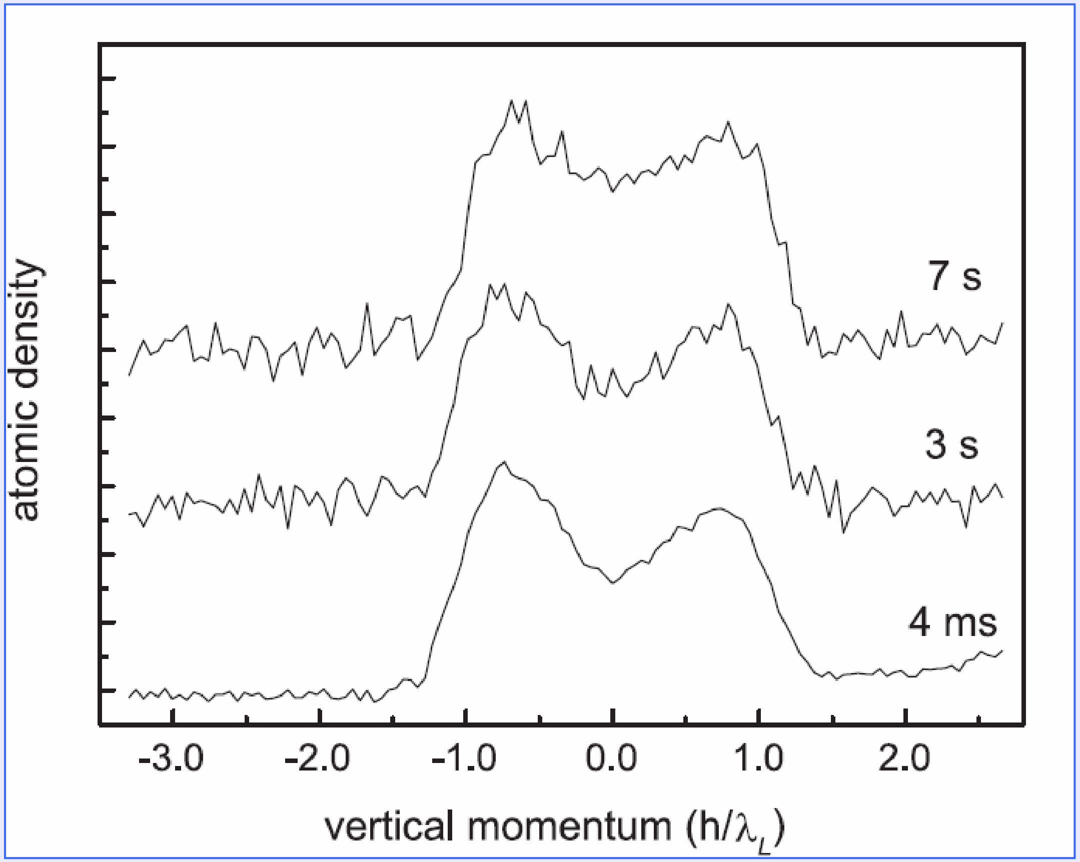
damping time $\tau = 12$ s

8000 photon recoils in 7s

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

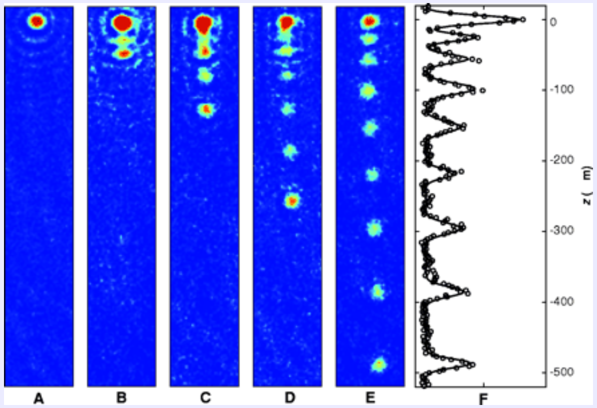
G. Ferrari, N. Poli, F. Sorrentino & G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale*, PRL 97, 060402 (2006)

Oscillation visibility vs time



Vertical momentum distribution of the atoms at the Bragg reflection recorded after an evolution time in the lattice of 4 ms, 3 s, and 7 s.

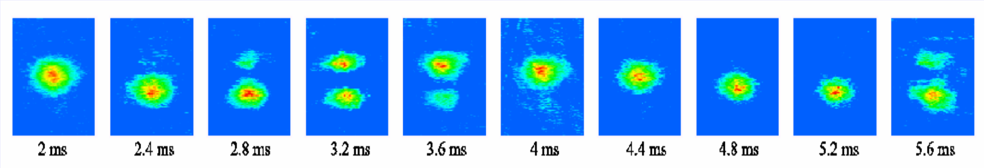
gravity measurement with quantum degenerate bosonic and fermionic atoms in optical lattices

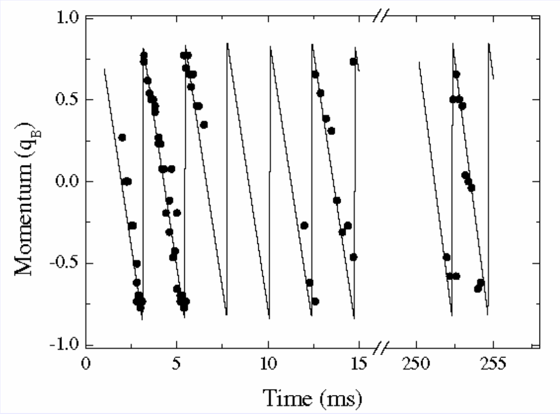


$g = 9.6\ (4)\ m/s^2$

$\delta g/g \sim 10^{-4}$ in 10 ms

B. P. Anderson, M. A. Kasevich, *Macroscopic Quantum Interference from Atomic Tunnel Arrays,* Science 282, 1686 (1998)





$g = 9.7372\ (9)\ m/s^2$

$\delta g/g \sim 10^{-4}$ in 250 ms

G. Roati, E. de Mirandes, F. Ferlaino, H. Ott, G. Modugno, M. Inguscio, *Atom Interferometry with trapped Fermi Gases,* PRL 92, 230402 (2004)

Precision gravity measurement with ultracold Sr atoms in an optical lattice:

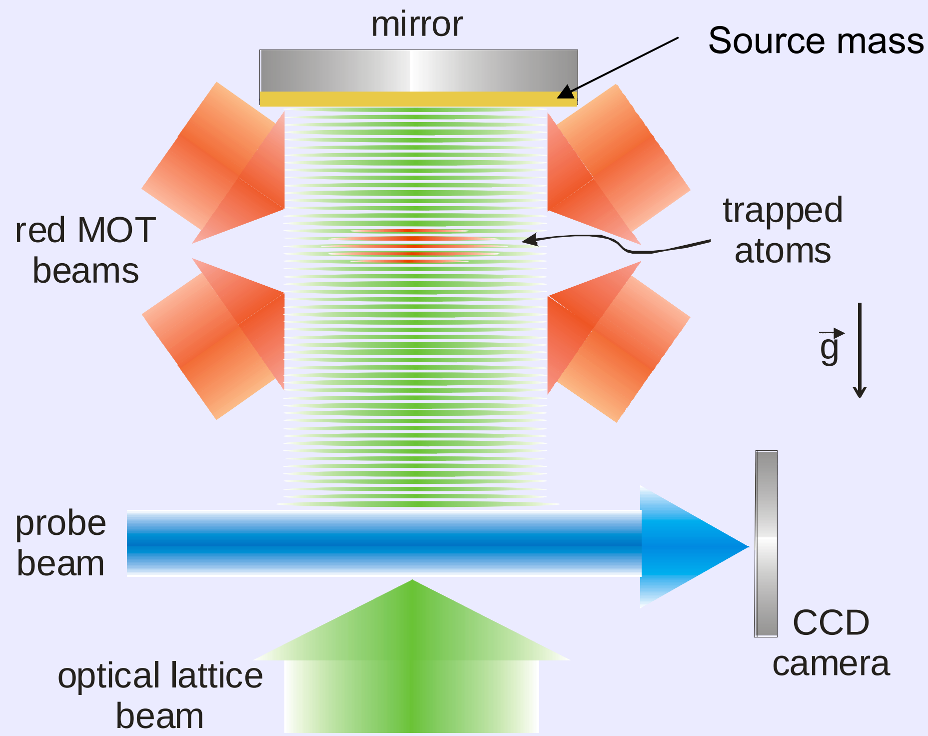
- **Measured gravity acceleration:** $g_{meas} = 9.80012\ (5)\ ms^{-2}$

  From geophysical data: $g_{ref} = 9.805046\ (9)\ ms^{-2}$

- **Present sensitivity:** $5 * 10^{-6}\ g$

- **Achievable sensitivity:** $\sim 10^{-7}\ g$

Scheme for the measurement of small distance forces

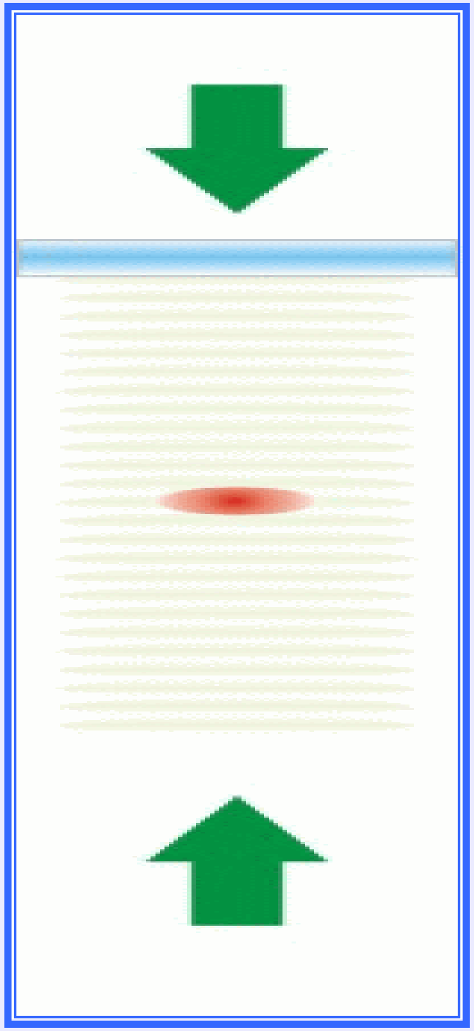


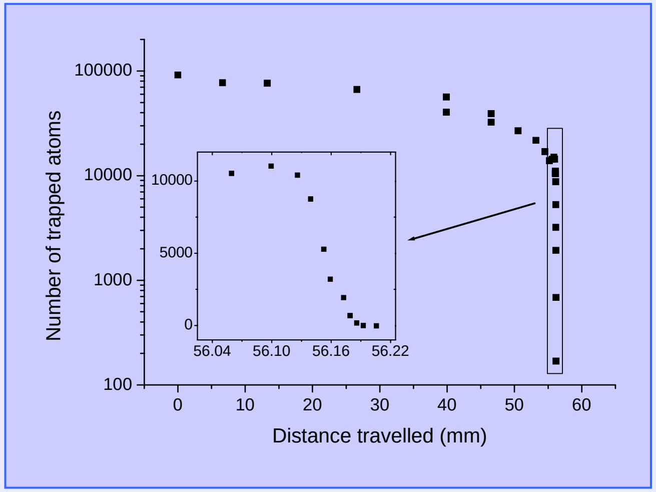
$$\nu = m\, a\, \lambda / 2h$$

Objective: λ = 1- 10 μm, $\alpha = 10^3$-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*, PRL 97, 060402 (2006)

Atom elevator



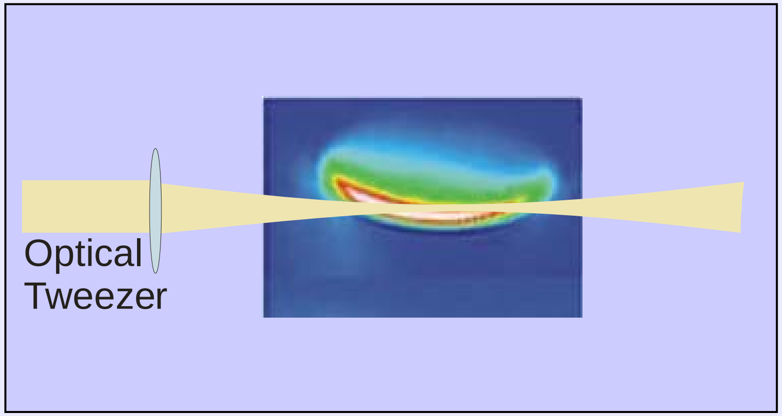


Vertical size of the atomic sample: 15 µm

Atom elevator:

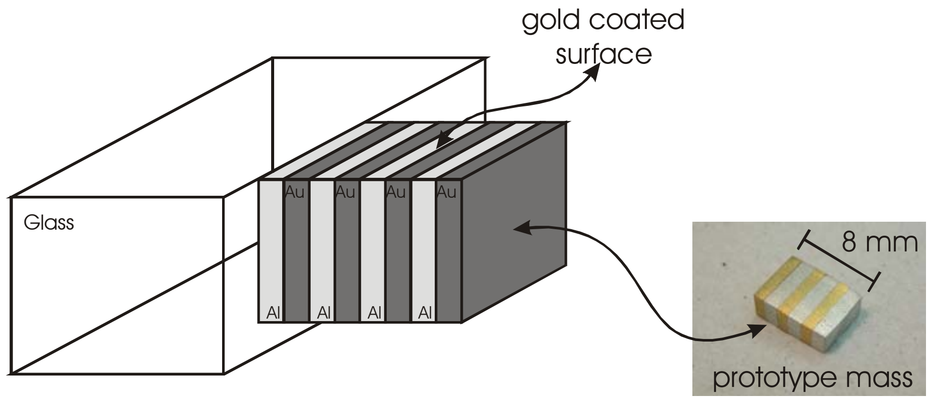
upward acceleration (1.35 g) for 10 ms
uniform velocity (133 mm/s) for variable time
downward acceleration (-1.35 g) for 10 ms
rest for 470 ms
reverse motion back to the starting point

Vertical position fluctuations: 3 µm rms



•Vertical size reduced to 4 µm with an optical tweezer

Source mass


gold coated surface
Glass
Au
Au
Au
Au
Al
Al
Al
Al
8 mm
prototype mass

Other experiments on atom-surface force

Hinds (1993)

Aspect-Westbrook (1997)

Vuletic (2004): effect of Casimir-Polder on atoms on chip

Shimuzu, Ketterle (2001,2005): effect of Casimir-Polder on quantum reflection

Cornell (2005): measurement of the Casimir-Polder force by oscillations of a BEC

Casimir-Polder and surface effects

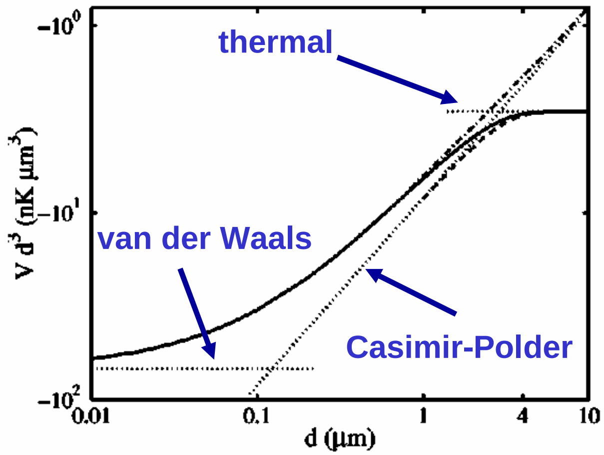


FIG. 3. The atom-surface potential is shown using the exact formula of Eq. (17) (solid line), the short-range approximation (21) (dash-dotted line), and the static approximation (26) (dashed line). The asymptotic van der Waals–London ($\sim 1/d^3$), Casimir-Polder ($\sim 1/d^4$), and high-T ($\sim 1/d^4$) potentials are also shown (dotted lines). The curves were obtained for a sapphire substrate at 300 K and for ^{87}Rb atoms in the condensate.

thermal

$$F_T = -\frac{3kT\alpha_0(\varepsilon_0 - 1)}{4z^4(\varepsilon_0 + 1)} \qquad z \gg \lambda_T$$

Casimir-Polder

$$F_{CP} = -\frac{3\hbar c\alpha_0(\varepsilon_0 - 1)\phi(\varepsilon_0)}{2\pi z^5(\varepsilon_0 + 1)} \qquad \lambda_{opt} \ll z \ll \lambda_T$$

^{87}Rb atoms
Sapphire substrate at 300 K
$\lambda_T = \hbar c/k_B T \sim 7.6\ \mu m$
$\lambda_{opt} \sim 0.1\ \mu m$

From M. Antezza et al., *Effect of the C-P force on the collective oscillations of a trapped BEC*, PRA 70, 053619 (2004)

surface-atom force
out of thermal equilibrium

$$F^{neq} = -\frac{\pi}{6}\frac{\alpha_0 k_B^2(T_{Surface}^2 - T_{Envir}^2)}{z^3 c\hbar}\frac{\varepsilon_0 + 1}{\sqrt{\varepsilon_0 - 1}}$$

M. Antezza et al., *New Asymptotic Behavior of the Surface-Atom Force out of Thermal Equilibrium* PRL 95, 113202 (2005)

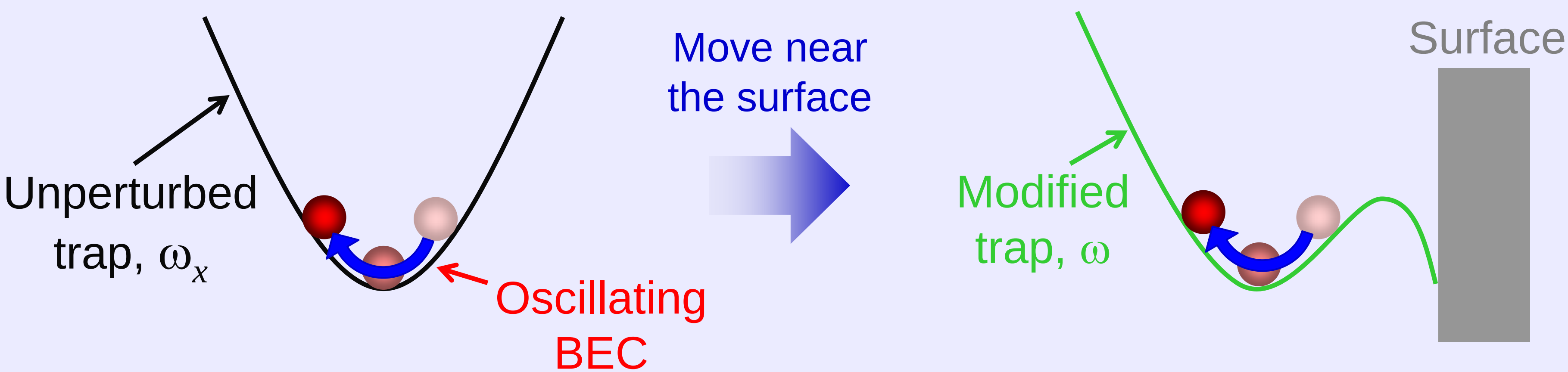
Measuring atom-surface forces

Use trapped BEC as a mechanical oscillator

Measure changes in dipole oscillation frequency

Negative curvature attractive potential

Trap frequency decrease

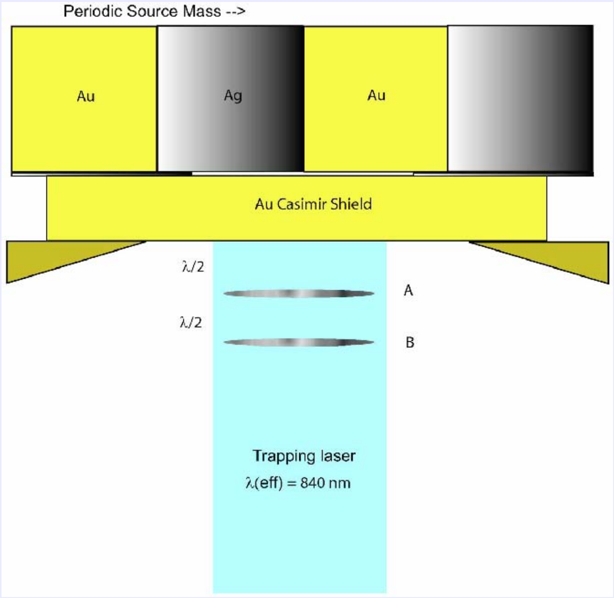


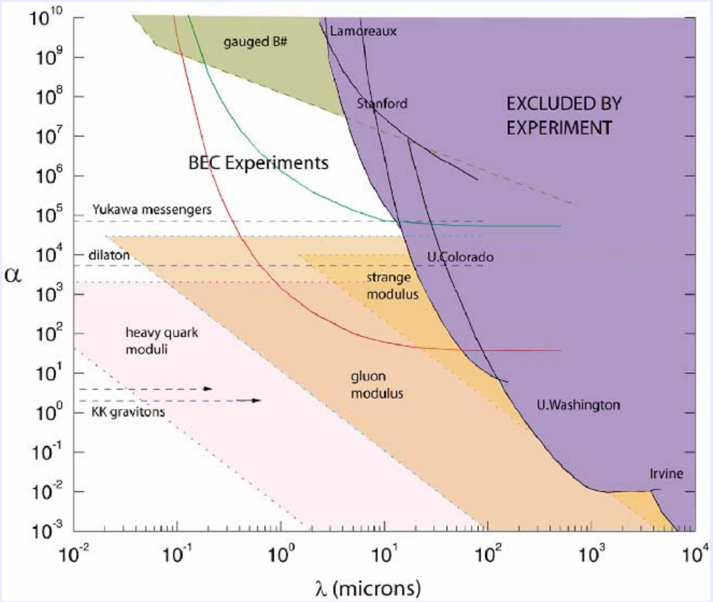
Express trap frequency changes as normalized frequency shifts:

$$\frac{\omega_x - \omega}{\omega_x} \approx -\frac{1}{2\omega_x^2 m}\frac{d^2U}{dx^2}$$

From E.A. Cornell
San Feliu Conference, 2005

Other proposals



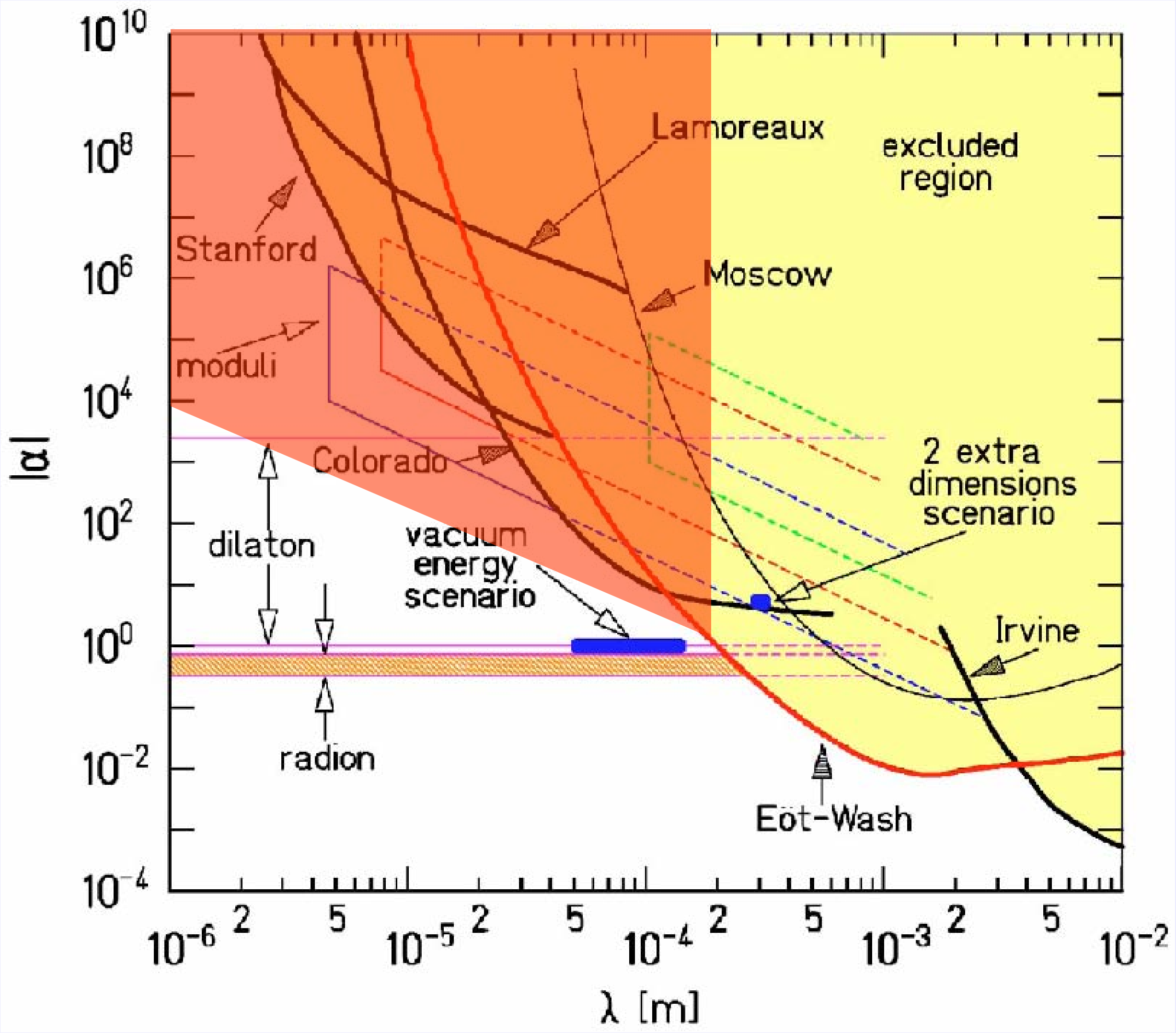


S. Dimopoulos, A. A. Geraci, *Probing submicron forces by interferometry of Bose-Einstein condensed atoms,* Phys. Rev. D 68, 124021 (2003)

• 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*, arXiv:physics/0608021

Accessible region with atomic probes



Applications of new quantum sensors based on atom interferometry

- Measurement of fundamental constants → α → G
- New definition of kg
- Test of equivalence principle
- Short-distances forces measurement
- Search for electron-proton charge inequality
- New detectors for gravitational waves ?
- Transportable sensors → geophysics → space

ESA-AO-2004

Atom Interferometry Sensors for Space Applications

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
Techno System	I
TOPTICA	D
THALES	F
IXSEA	F

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
Phone: +49 511 762-3242
Fax : +49 511 762-2211

Participants

Nr	Organisation name	Abbrev.	Town	Country
1	Institut für Quantenoptik, Universität Hannover	IQ	HANNOVER	D
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

See Poster

People

G. Lamporesi	PhD student, Università di Firenze
A. Giorgini	PhD student, Università di Napoli
N. Poli	Post-doc, LENS
F. Sorrentino	Post-doc, Università di Firenze
A. Bertoldi	Researcher, Università di Firenze
G. Ferrari	Researcher, INFM/CNR
L. Cacciapuoti	Long term guest, ESA-Noordwijk
M. de Angelis	Long term guest, CNR-Napoli
R. Drullinger	Long term guest, NIST-Boulder
M. Prevedelli	Long term guest, Università di Bologna
M. Fattori	ex-PhD student, now in Stuttgart
T. Petelski	ex-PhD student, now in Munich
J. Stuhler	ex-Post-doc, now in Stuttgart

Collaborations

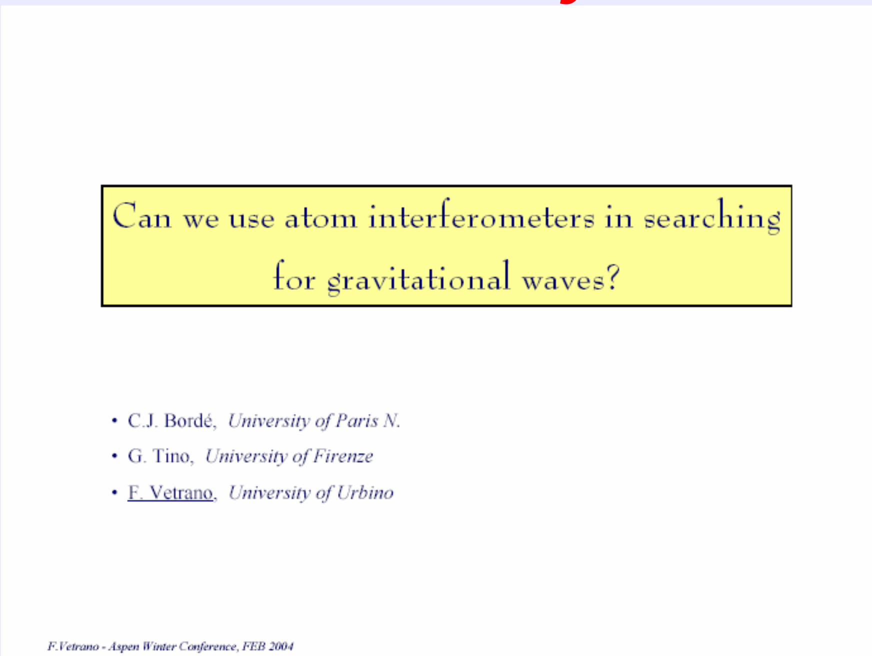
- **IEN, Torino**
- **IMGC, Torino**
- **Humboldt-Universitaet zu Berlin**
- **IQO, Hannover**
- **ENS and SYRTE, Paris**

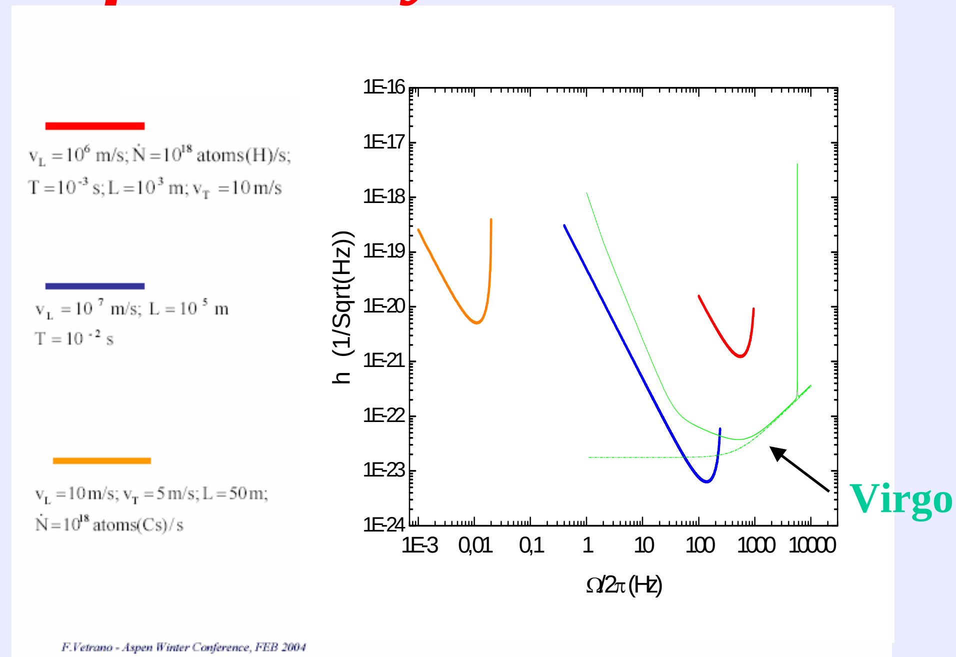
Support and funding

- ✓ **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)**

LINKS

Gravitational wave detection by atom interferometry





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

Chiao, Raymond Y.; Speliotopoulos, Achilles D. "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.

Roura, Albert; Brill, Dieter R.; Hu, B. L.; Misner, Charles W.; Phillips, William D. "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.

C. Bordè, G. M. Tino, F. Vetrano, "Is it possible to detect gravitational waves with atom interferometers?", to be published.