Testing gravity with atom interferometry

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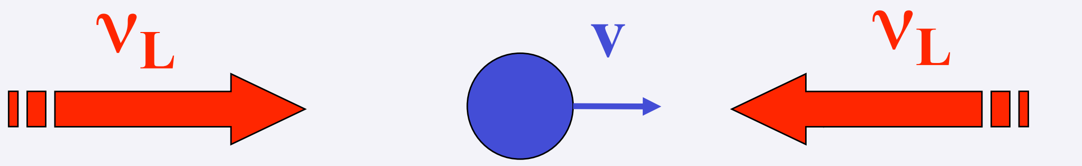
http://coldatoms.lens.unifi.it/

Outline

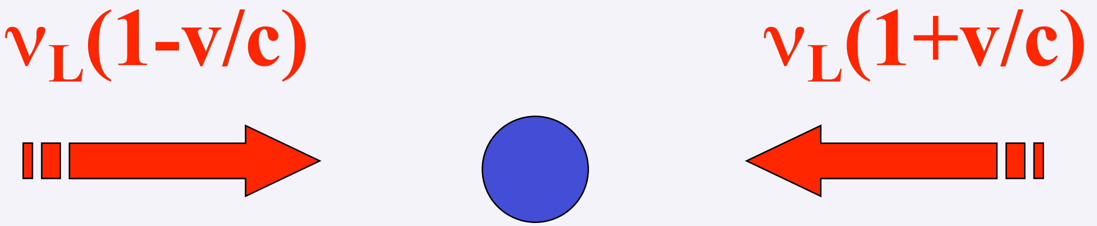
- *Laser cooling and manipulation of atoms*
- *Future optical clocks with trapped atoms*
- *Cold atom interferometry*
- *Fundamental physics experiments and applications on Earth and in space*

Laser cooling and manipulation of atoms

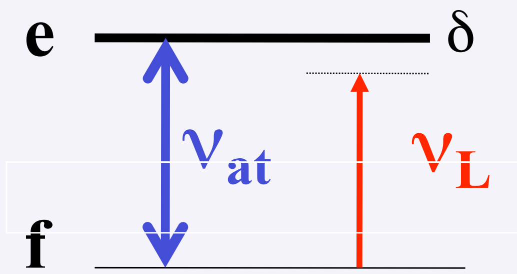
Optical molasses



Lab ref. frame



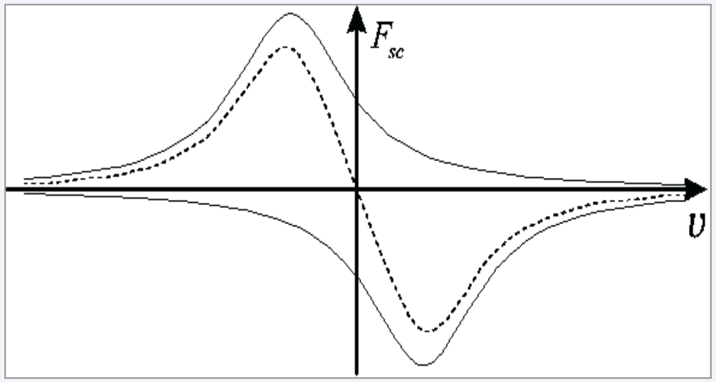
Atom ref. frame



$\nu_{at} > \nu_L$

$(I/I_0 \ll 1)$

$$F(\mathrm{v}) \simeq \frac{h\nu_L}{c} \times \frac{1}{2\pi} \times \left[\frac{I/I_0}{1 + I/I_0 + \frac{4}{\Gamma^2}(\delta - \frac{\nu_L}{c}\mathrm{v})^2} - \frac{I/I_0}{1 + I/I_0 + \frac{4}{\Gamma^2}(\delta + \frac{\nu_L}{c}\mathrm{v})^2} \right]$$



$$F(\mathrm{v}) \simeq \frac{h}{4\pi^2} \frac{\omega_L^2}{c^2} \frac{8\delta}{\Gamma} \frac{I/I_0}{[1+(\frac{2\delta}{\Gamma})^2]^2} \mathrm{v} = -\alpha \mathrm{v}$$

Idea: **T.W. Hänsch, A. Schawlow, 1975**

Exp. demonstration: **S. Chu et al., 1985**

Laser cooling: atomic temperatures

Atomic Temperature : $k_B T = \mathrm{Mv}^2_{\mathrm{rms}}$

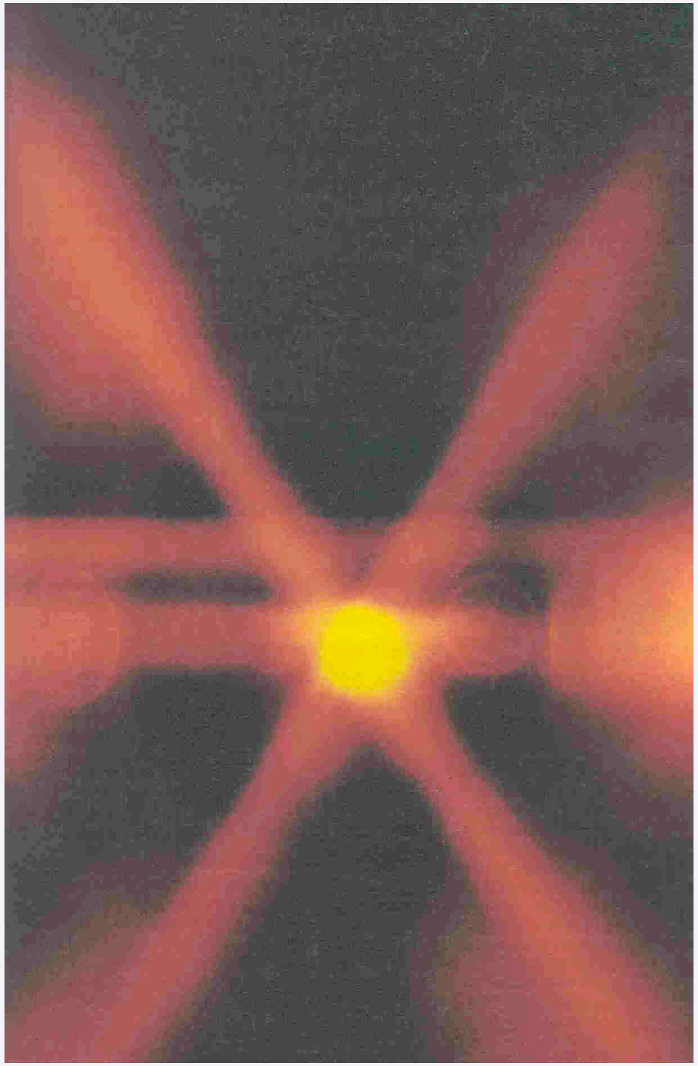
Minimum temperature for Doppler cooling: $k_B T_D = \frac{\hbar\Gamma}{2}$

Single photon recoil temperature: $k_B T_r = \frac{1}{M}\left(\frac{\hbar\nu_L}{c}\right)^2$

Examples:

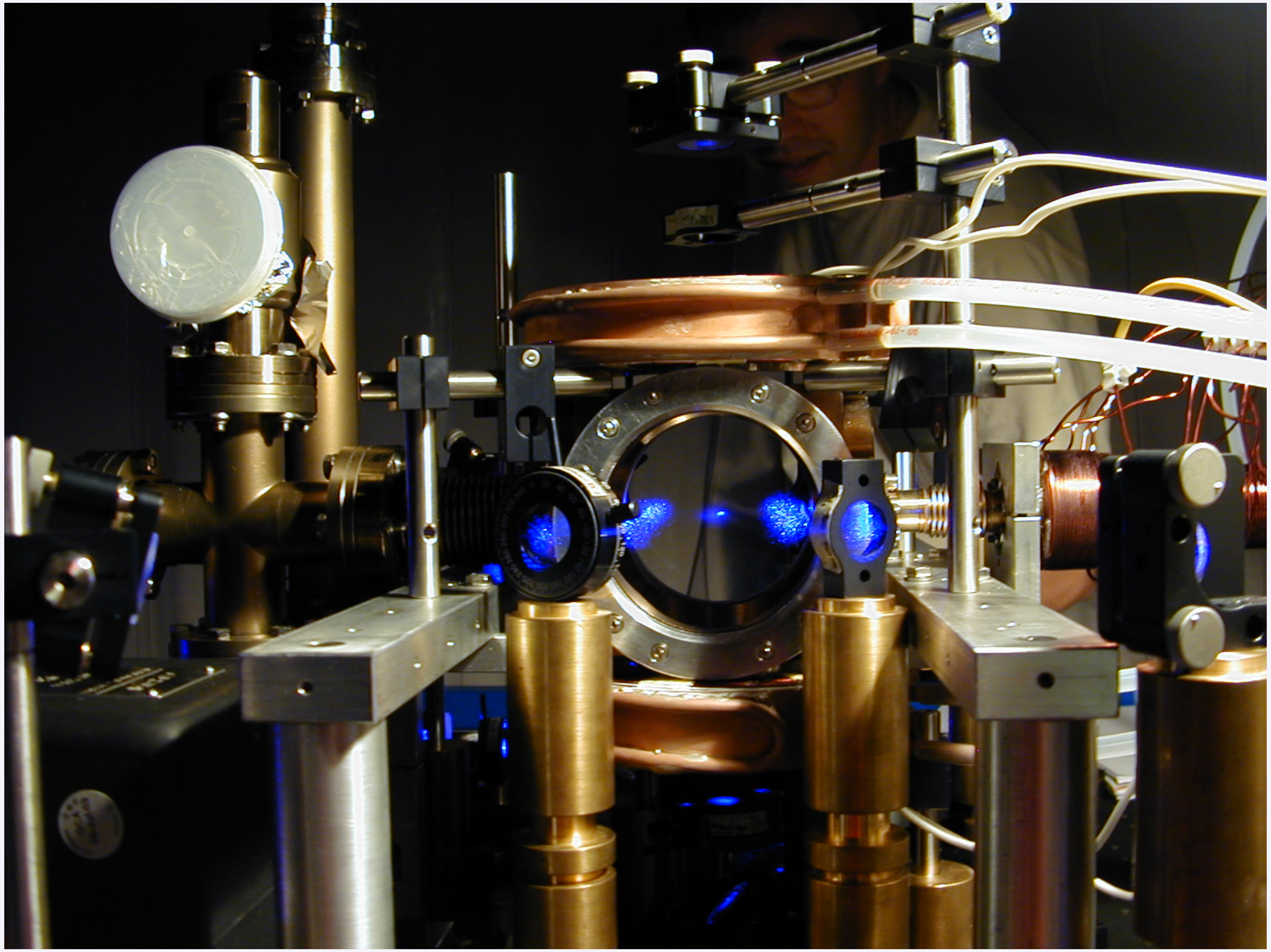
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK
Sr (**intercombination transition**)	180 nK	460 nK

3D molasses



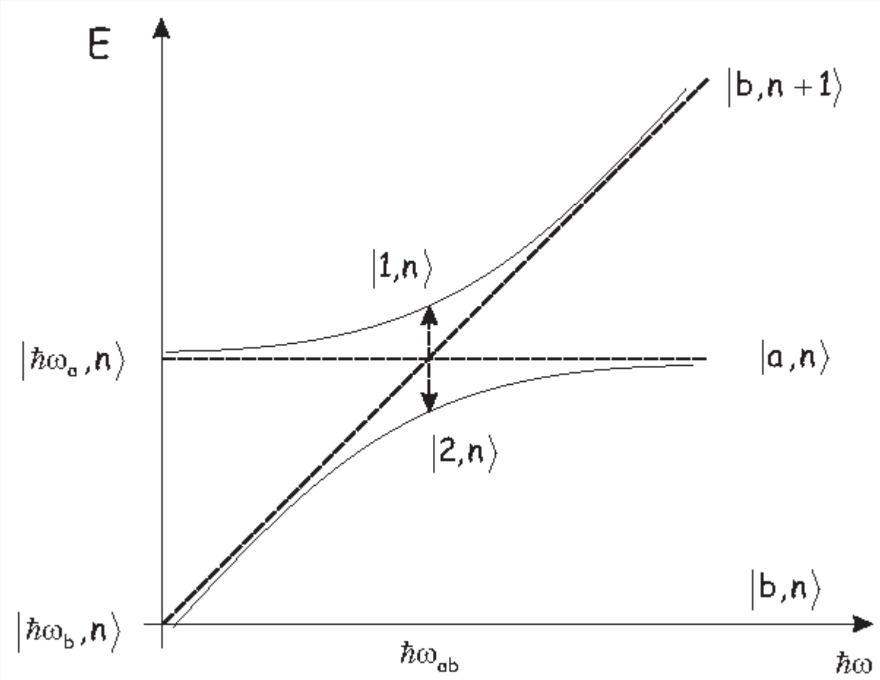
Na molasses

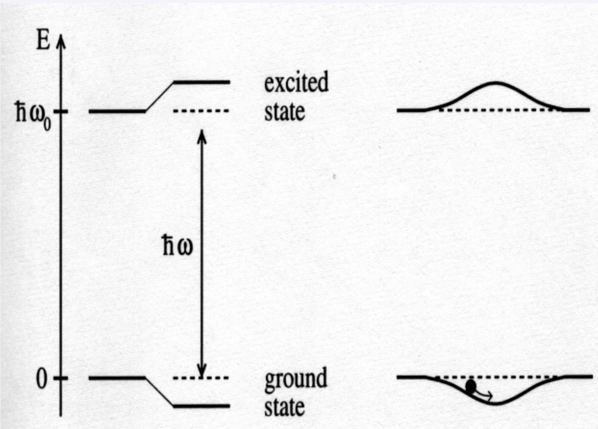
Sr MOT picture

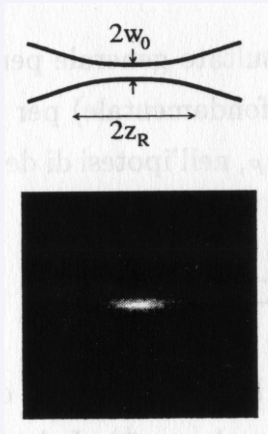


LENS, Firenze

Light shifts and optical traps



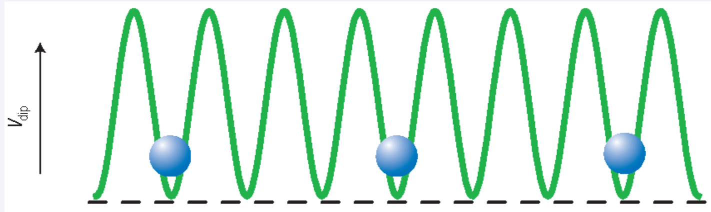




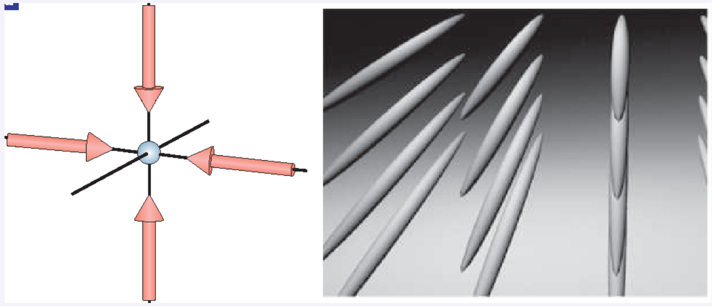
$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)|\mathbf{E}(\mathbf{r})|^2$$

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

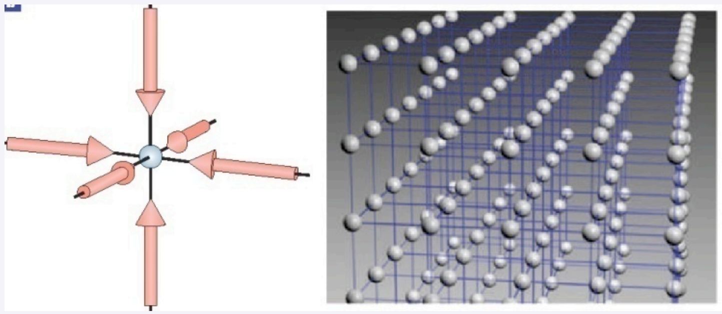
optical lattices



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



2 D optical lattice ⇒ array of 1D potential tubes

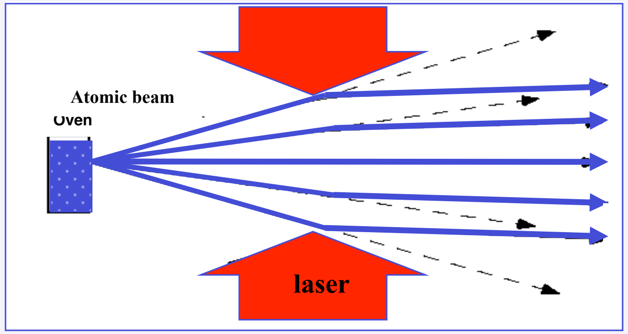


3 D optical lattice ⇒ 3D simple cubic array of h.o. potentials

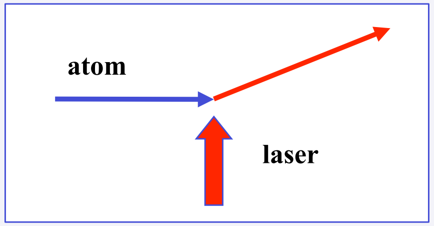
Review: **I. Bloch, 2005**

Atom optics

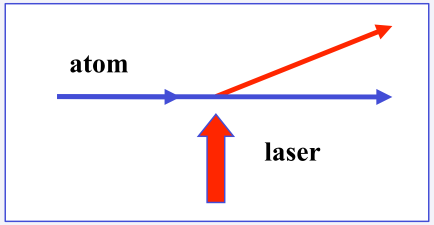
lenses



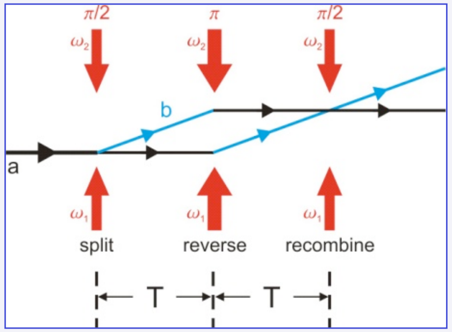
mirrors



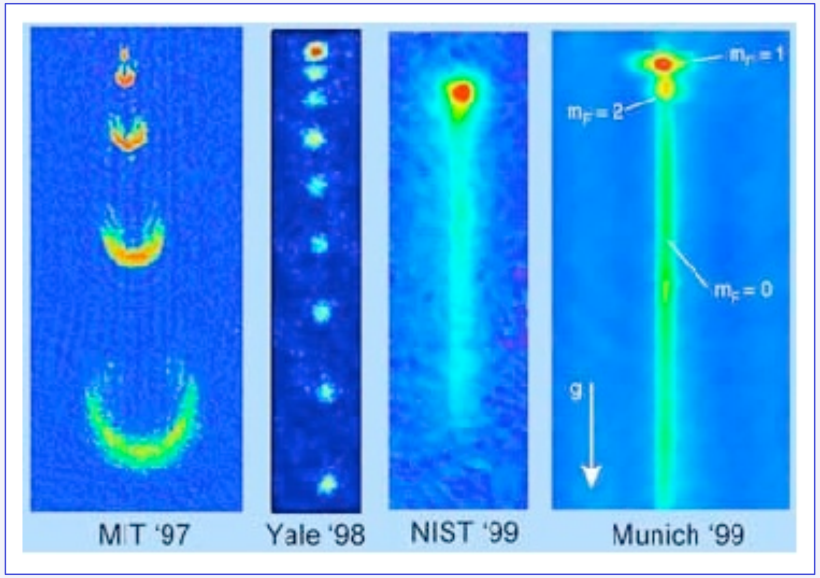
beam-splitters



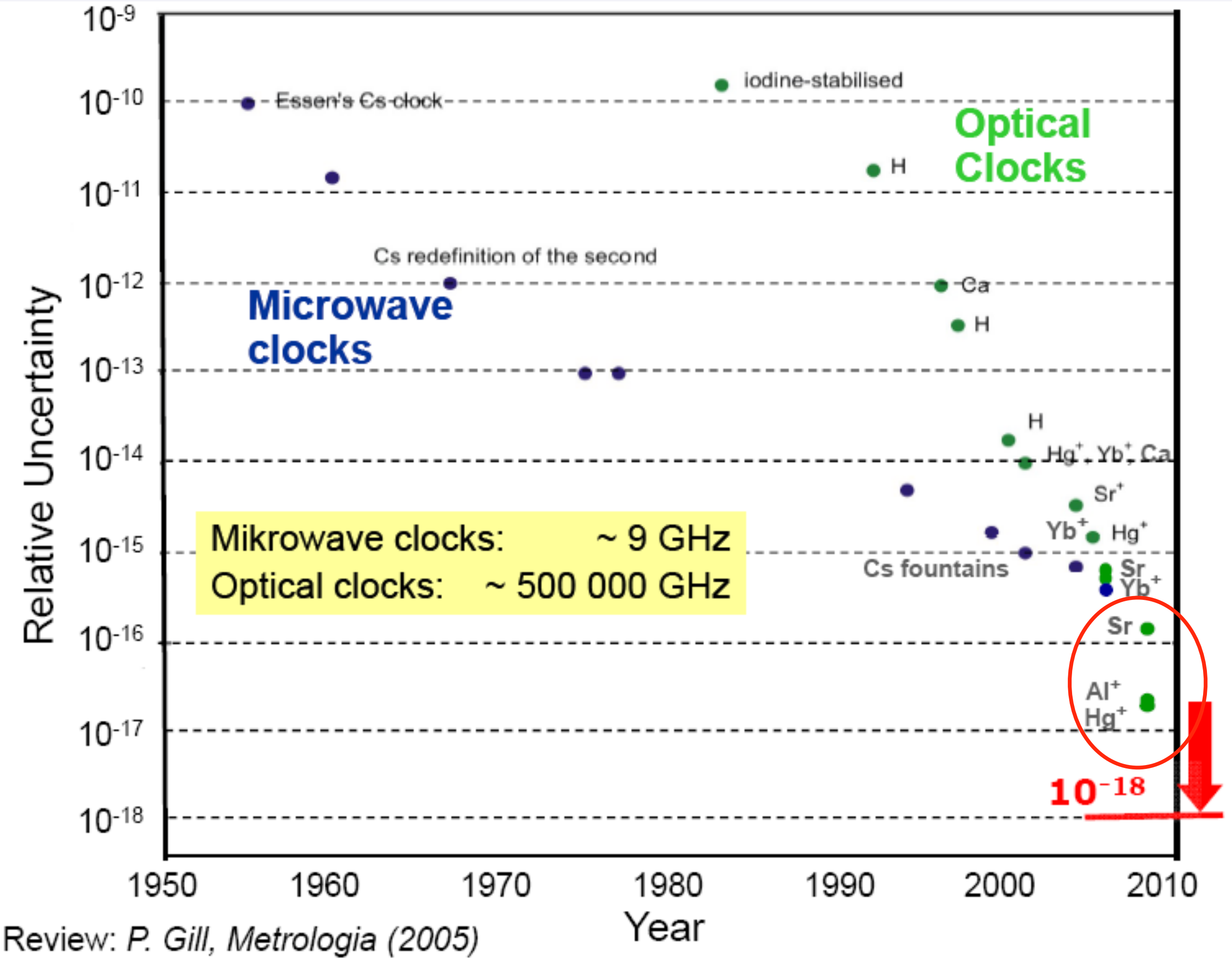
interferometers



atom laser



Optical vs microwave clocks



Review: *P. Gill, Metrologia (2005)*

- **Al+, Hg+ single ion clocks**

  T. Rosenband *et al.*,
  Science **319**, 1808 (2008)

- **Sr optical lattice clock**

  G. K. Campbell *et al.*,
  Science **324**: 360 (2009)

clock **stability**	$\sigma_y(\tau) \approx 10^{-15}\tau^{-1/2}$
clock **accuracy**	$\delta\nu/\nu < 10^{-17}$

Optical clocks: Towards 10^{-18}

- **Narrow optical transitions**

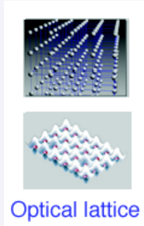
$\delta\nu_0 \sim$ 1-100 Hz, $\nu_0 \sim 10^{14}$-10^{15} Hz

$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N_{atom}}}\sqrt{\frac{T_{cycle}}{2\pi_{average}}}\frac{1}{C_{fringe}}$$

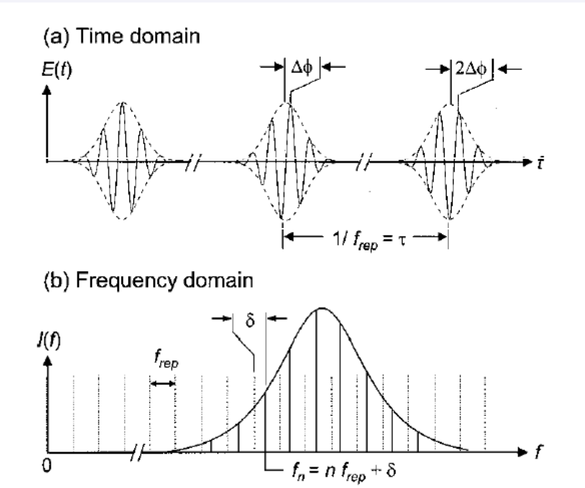
- **Candidate atoms**

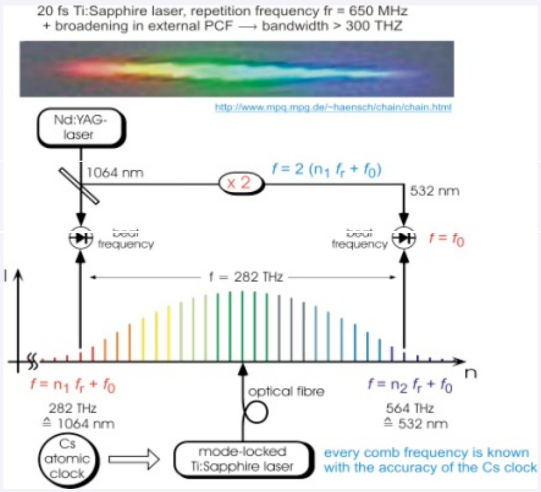
Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…

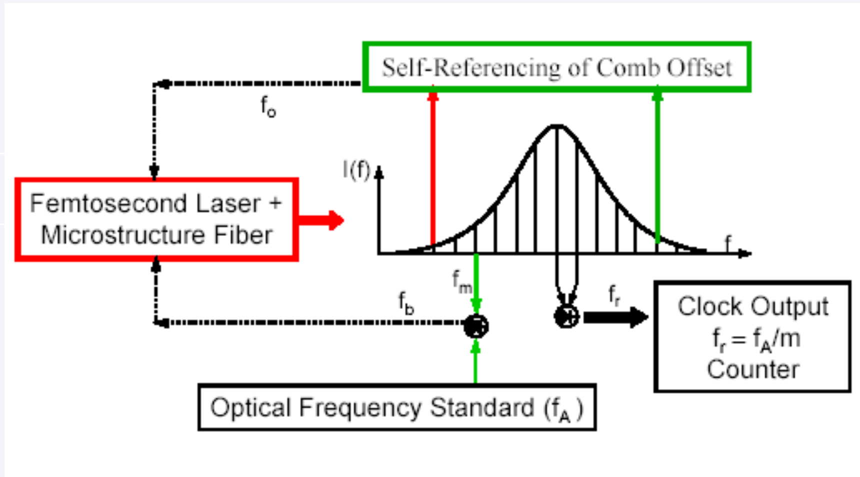
Cold neutral atoms: H, Ca, Sr, Yb,… (Fermions?)



- **Direct optical-μwave connection by optical frequency comb**

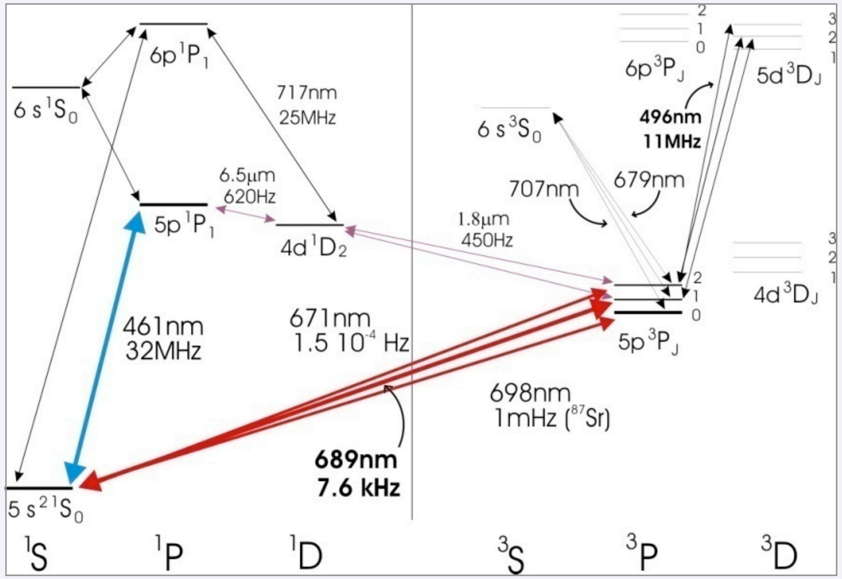


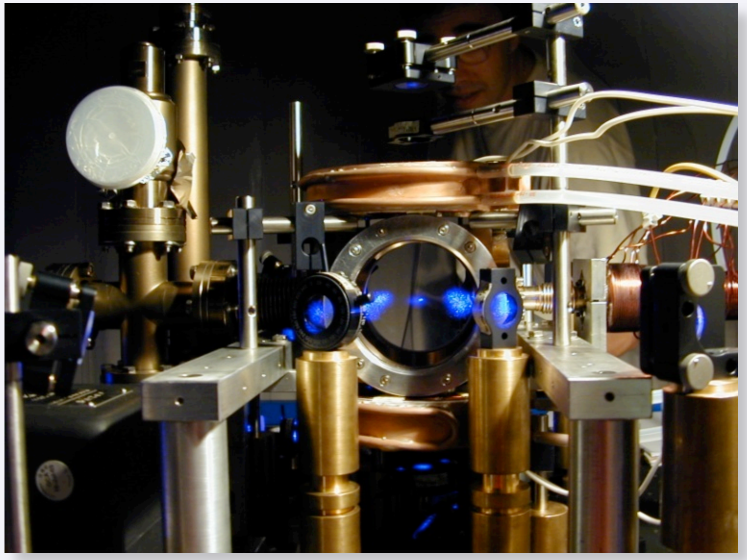




Th. Udem *et al.*, Nature 416 , 14 march 2002

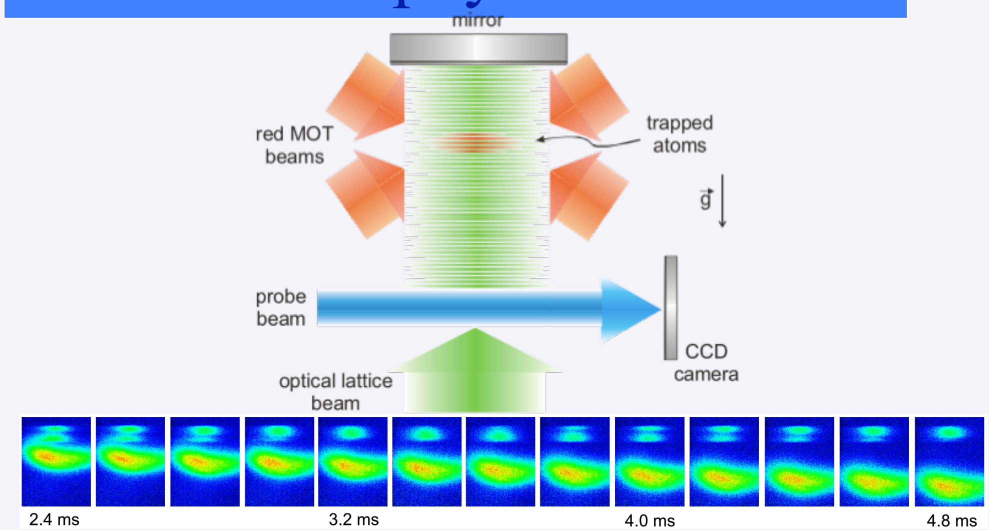
Ultracold Sr – The experiment in Firenze





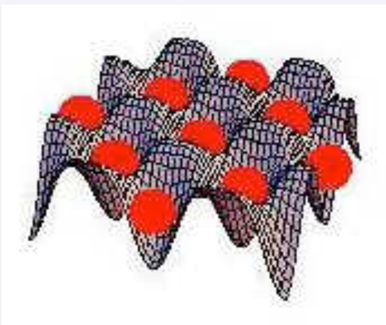
- Optical clocks using visible intercombination lines

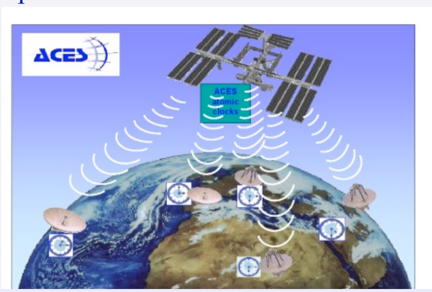
- New atomic sensors for fundamental physics tests



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)

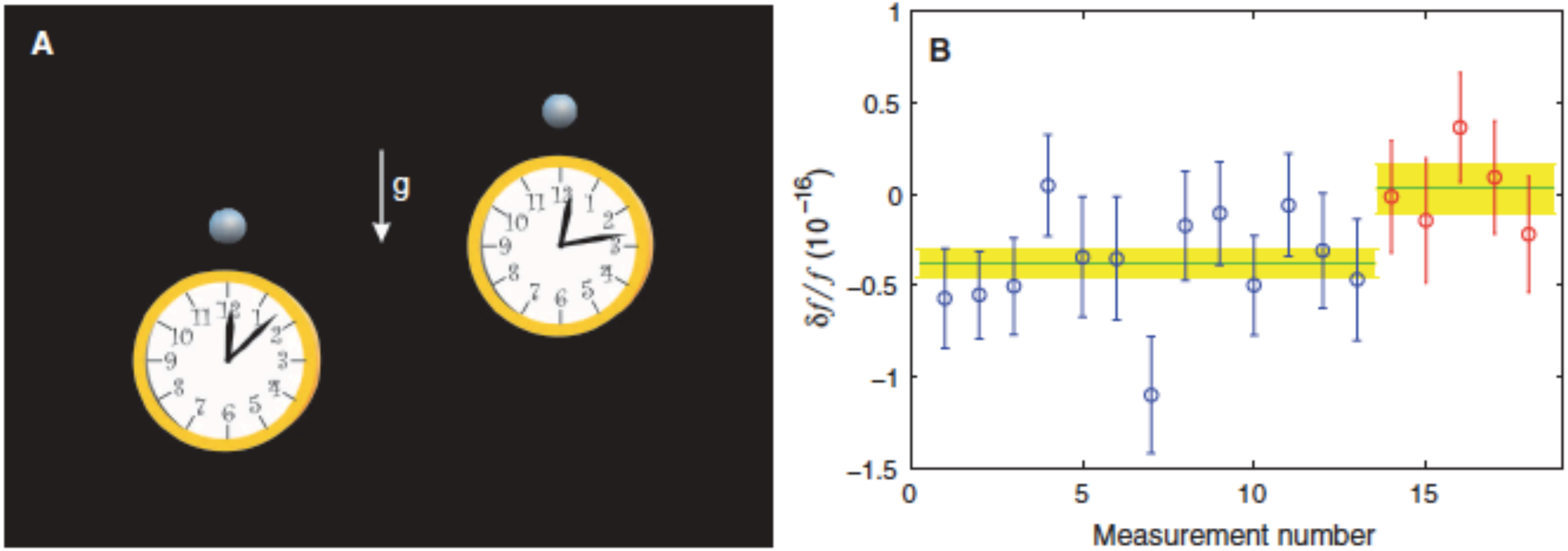


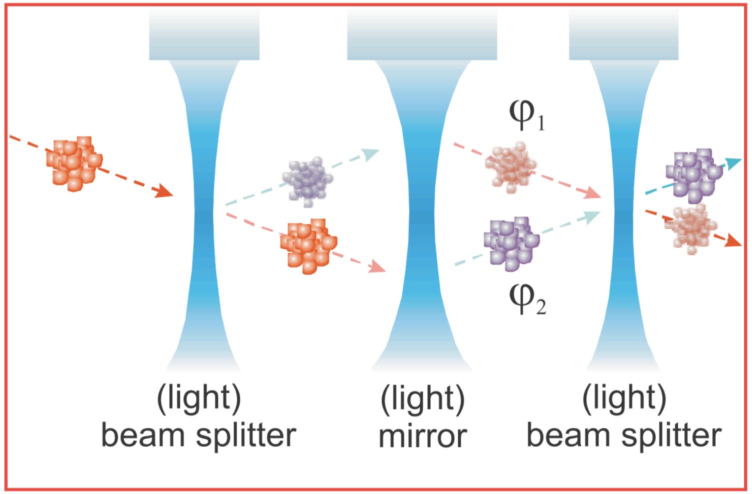
Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be $(4.1 \pm 1.6) \times 10^{-17}$. The vertical error bars represent statistical uncertainties (reduced $\chi^2 = 0.87$). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

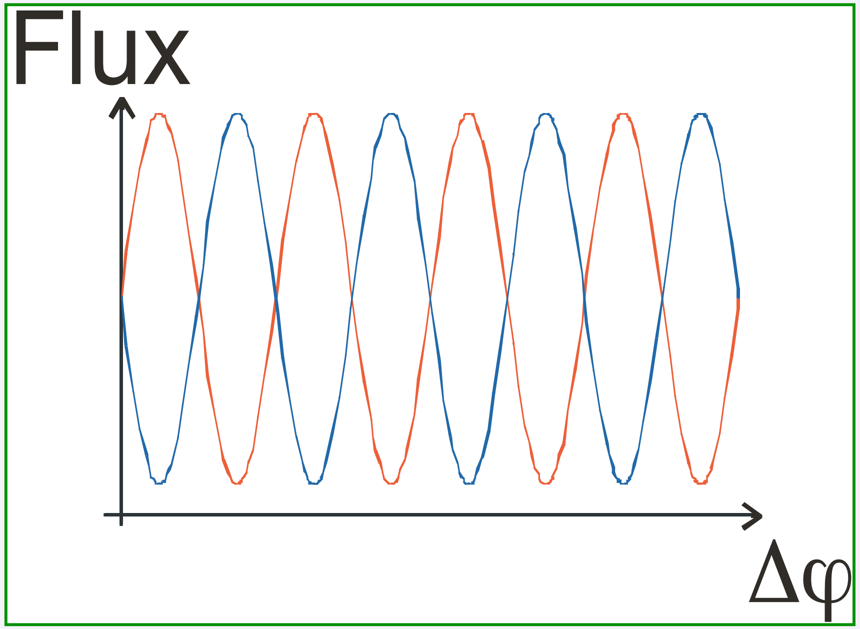
Optical Clocks and Relativity
C. W. Chou*, D. B. Hume, T. Rosenband and D. J. Wineland
Science Vol. 329 no. 5999 pp. 1630-1633 (2010)

Atom Interferometry

Atom interferometry

Atom interferometer





atomic flux at **exit** port **1**

at **exit** port **2**

Phase difference

$$\Delta\varphi = \varphi_1 - \varphi_2$$

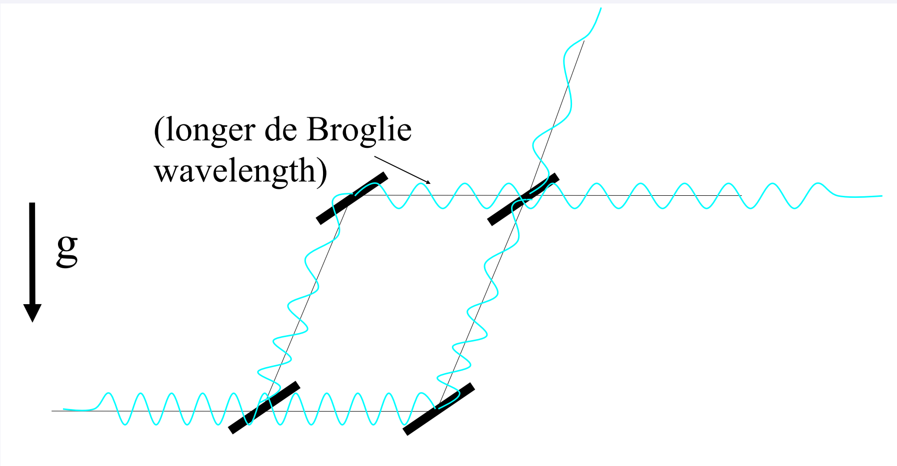
Atom interferometer force sensors

The quantum mechanical wave-like properties of atoms can be used to sense inertial forces.

$$\lambda_{DB} = \frac{h}{Mv}$$

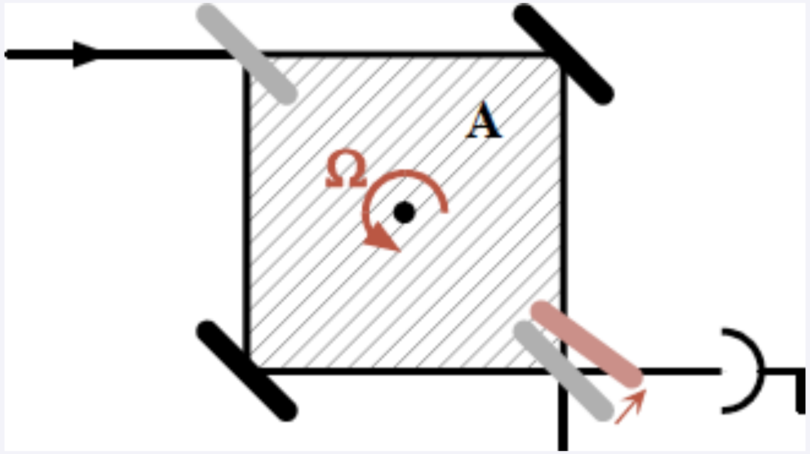
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



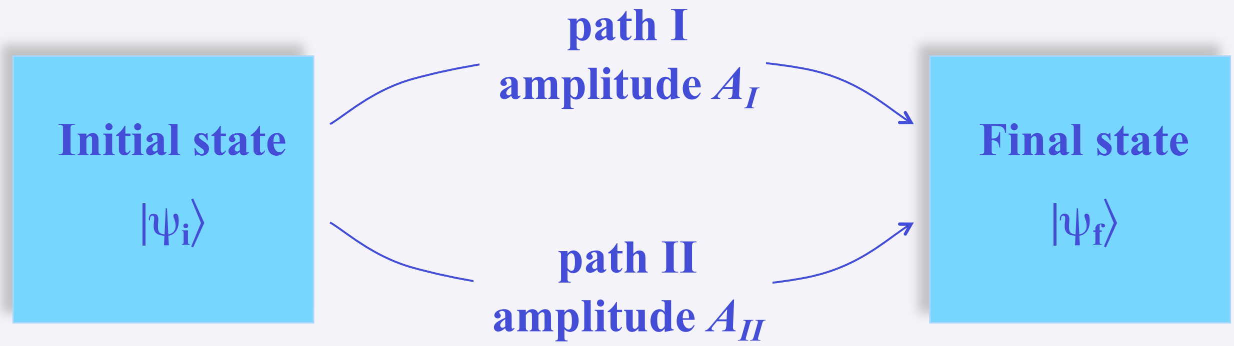
Rotations

Rotations induce path length differences by shifting the positions of beam splitting optics



From M. Kasevich

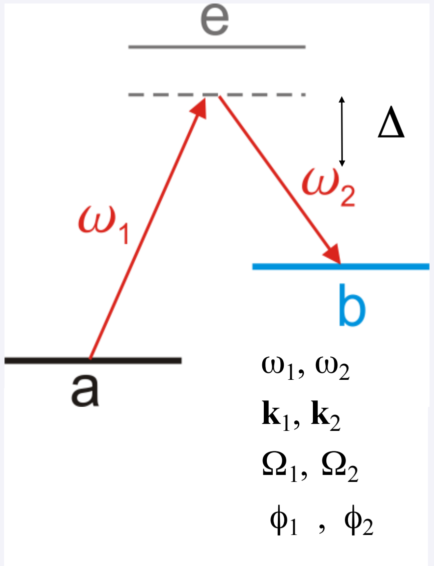
Quantum interference



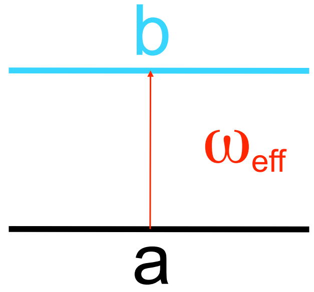
Interference of transition amplitudes

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

Raman pulse interferometer



$\Longrightarrow$

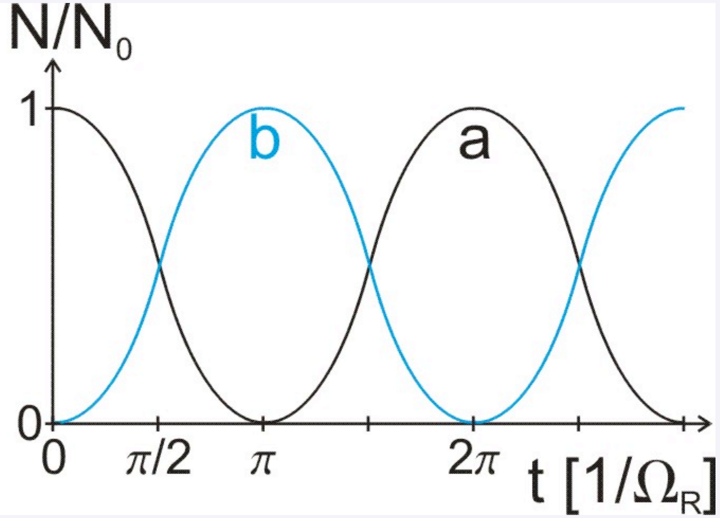


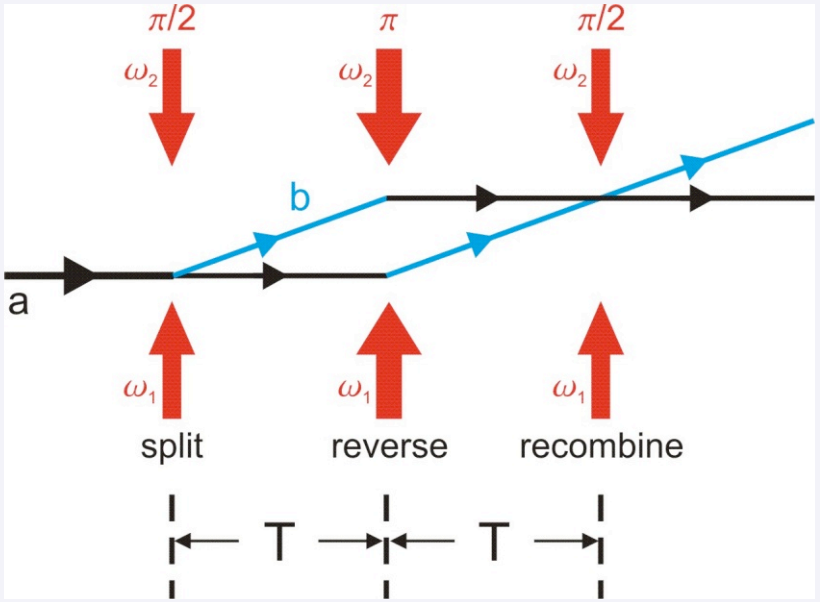
$\omega_{eff} = \omega_1 - \omega_2$

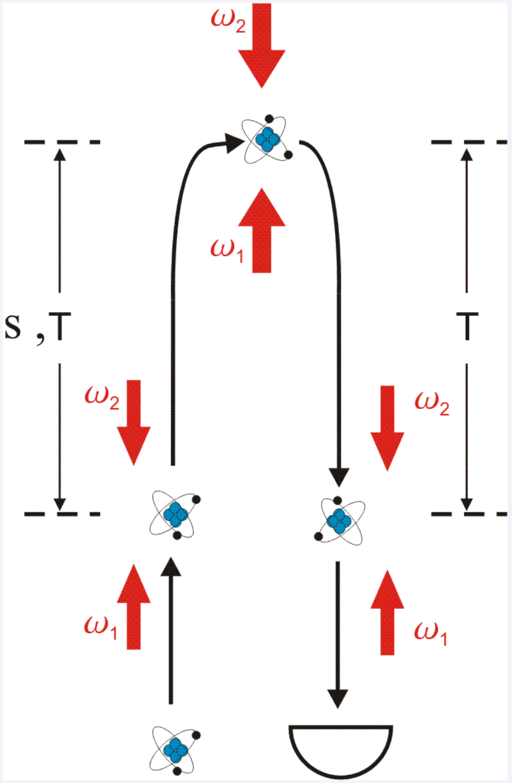
$\mathbf{k}_{eff} = \mathbf{k}_1 - \mathbf{k}_2$

$\Omega_{eff} = \Omega_1\Omega_2/\Delta$

$\phi_{eff} = \phi_1 - \phi_2$



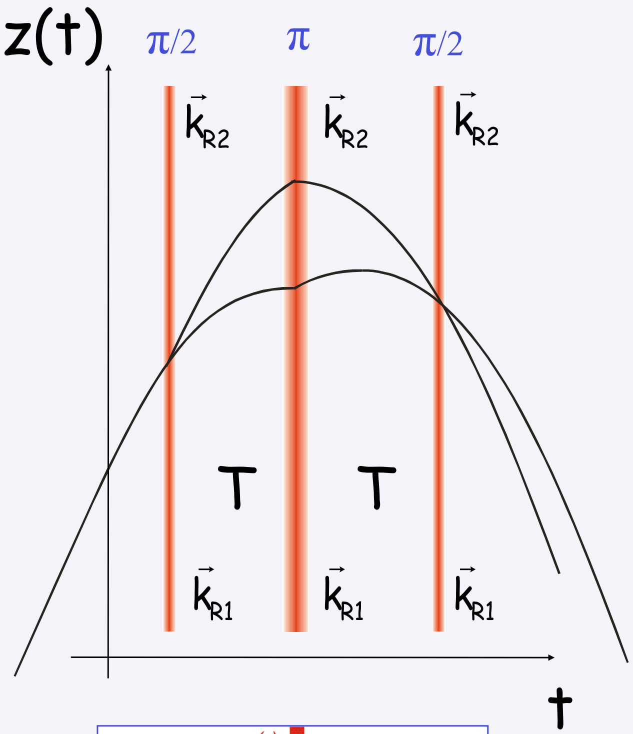




M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Raman interferometry in an atomic fountain

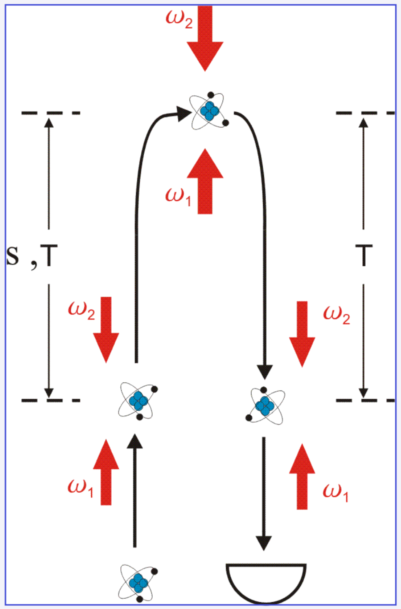


Phase difference between the paths:

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

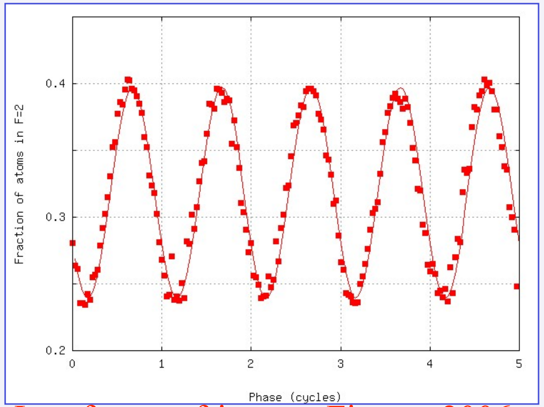
with $z(t) = -g\, t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Rightarrow \mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

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

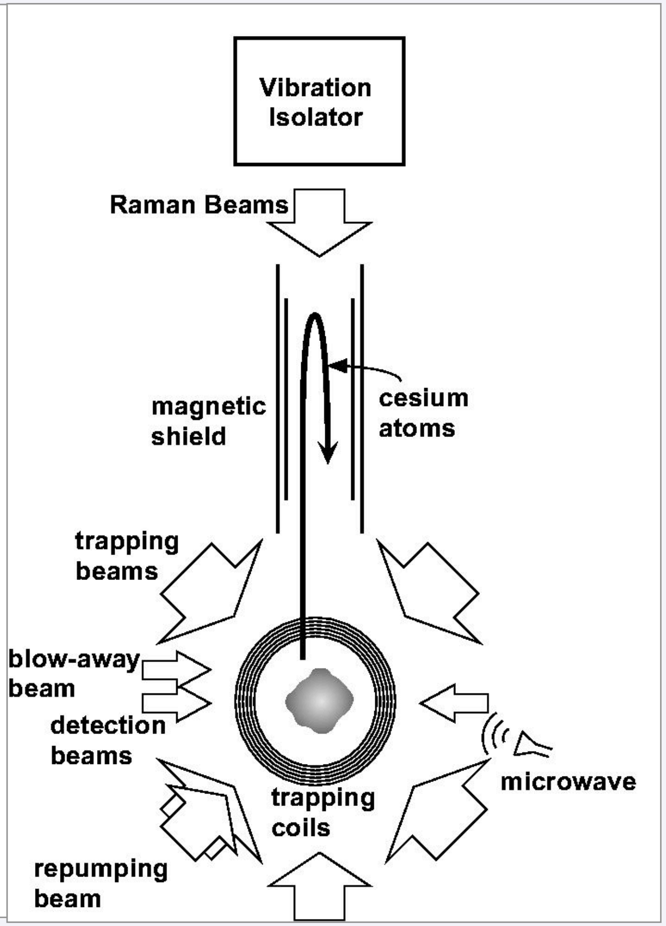
S/N = 1000

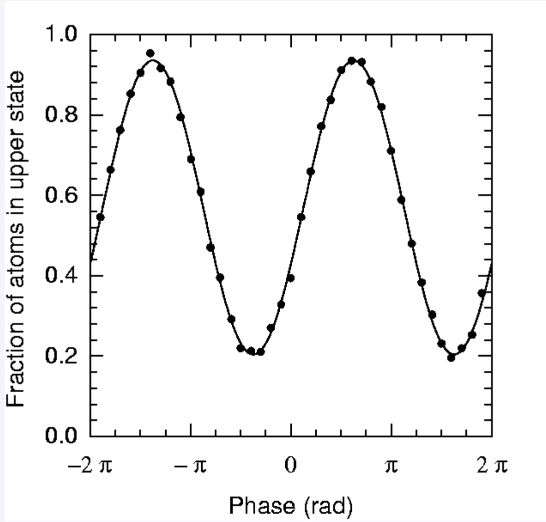
$\Rightarrow$ Sensitivity 10^{-9} g/shot

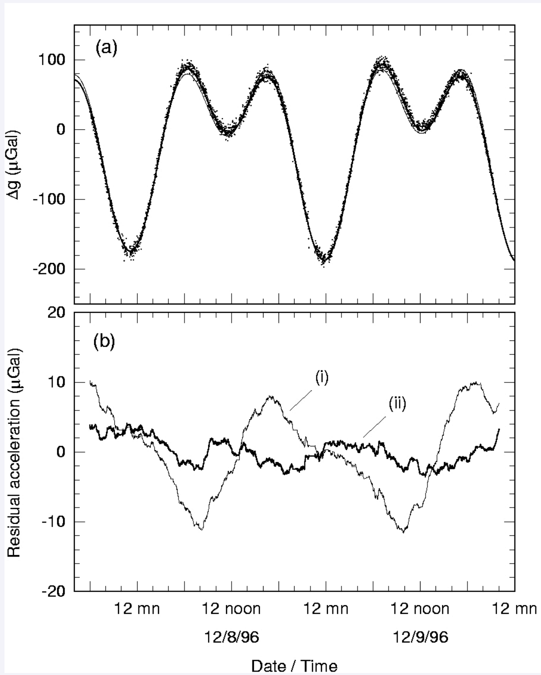
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Stanford atom gravimeter





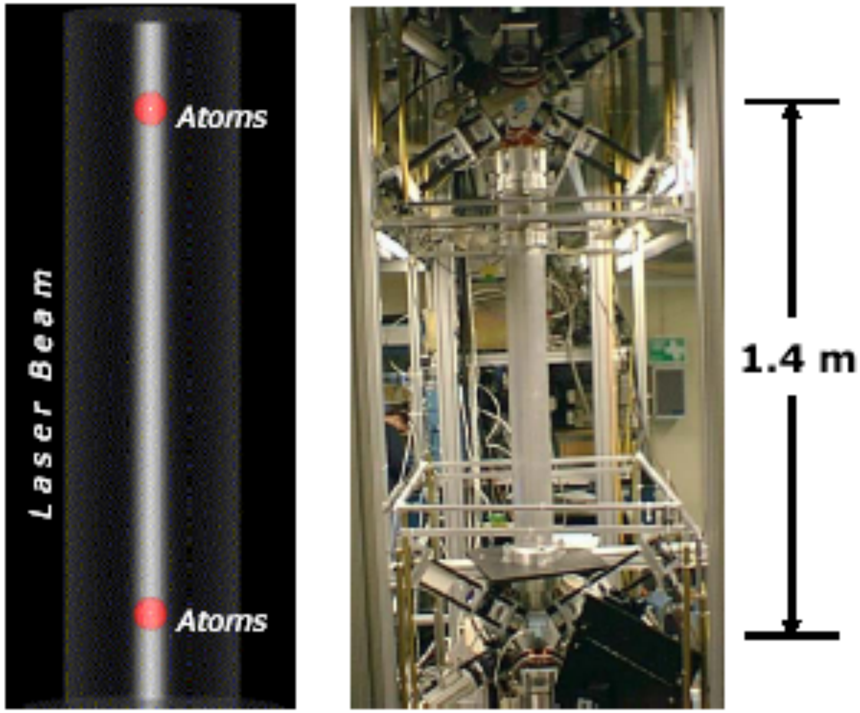


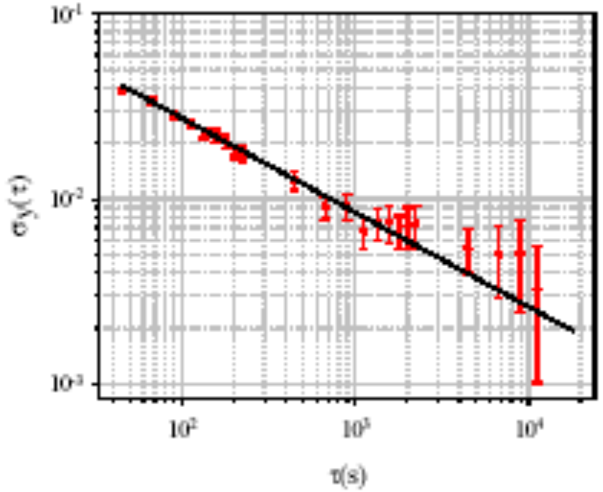
Resolution: $3x10^{-9}$ g after 1 minute

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

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:

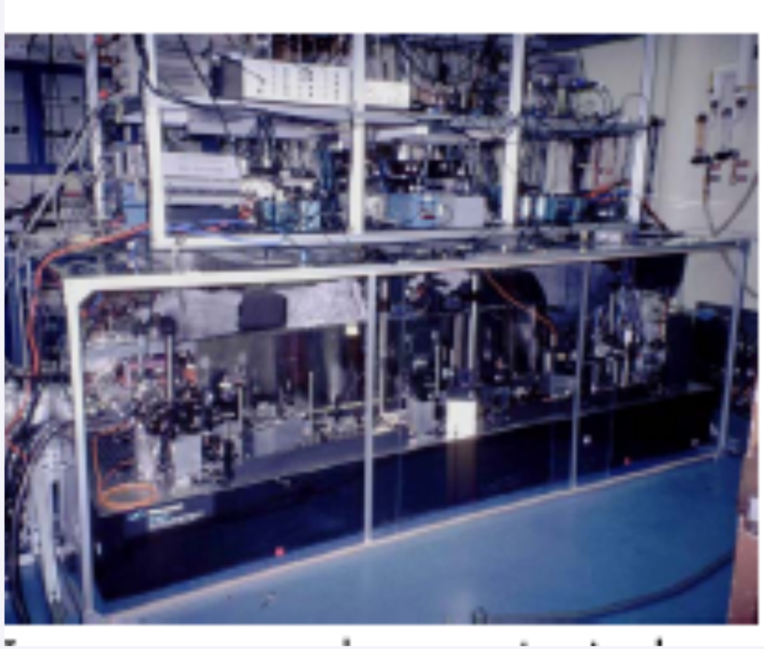
4×10^{-9} g/Hz$^{1/2}$

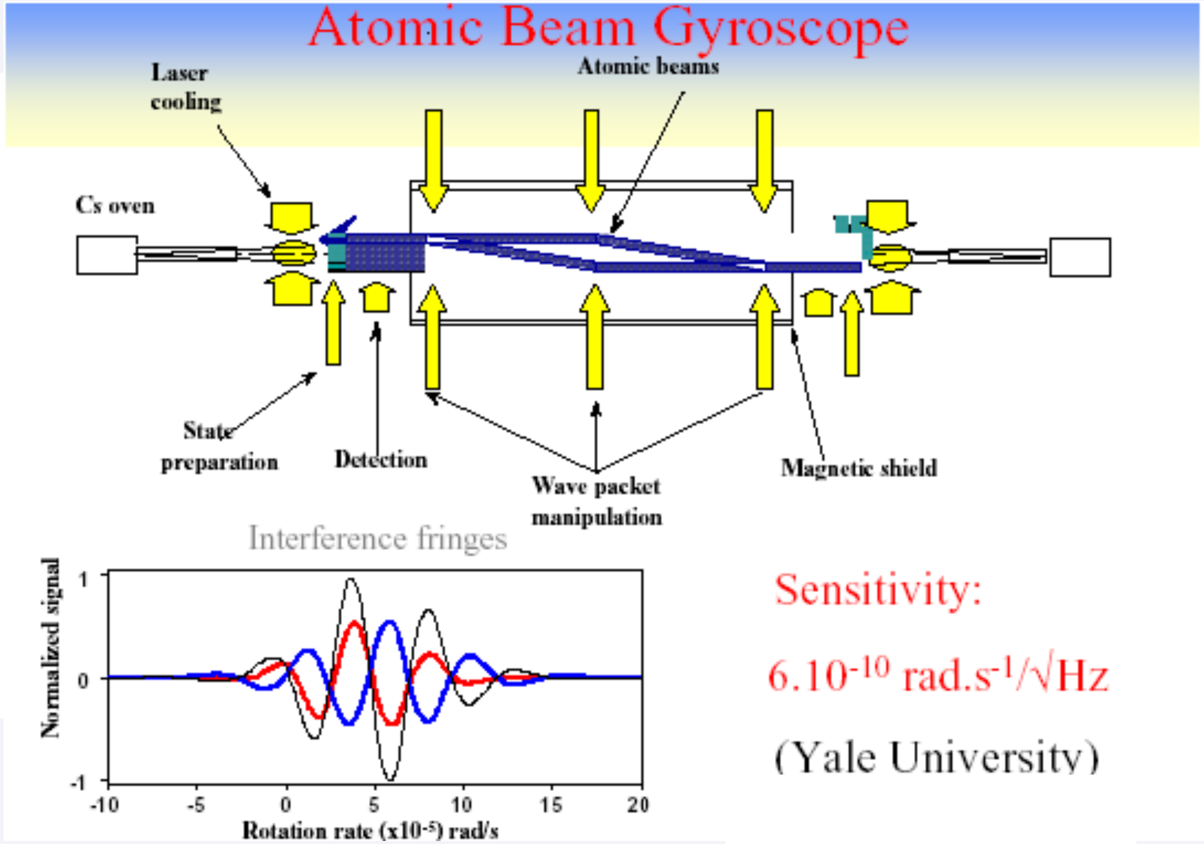
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

from M.A. Kasevich

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

Stanford/Yale gyroscope



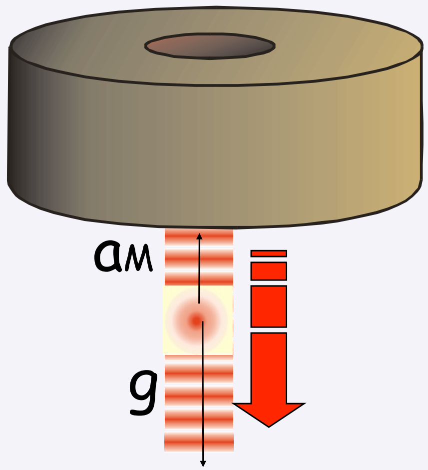


T.L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)

MAGIA

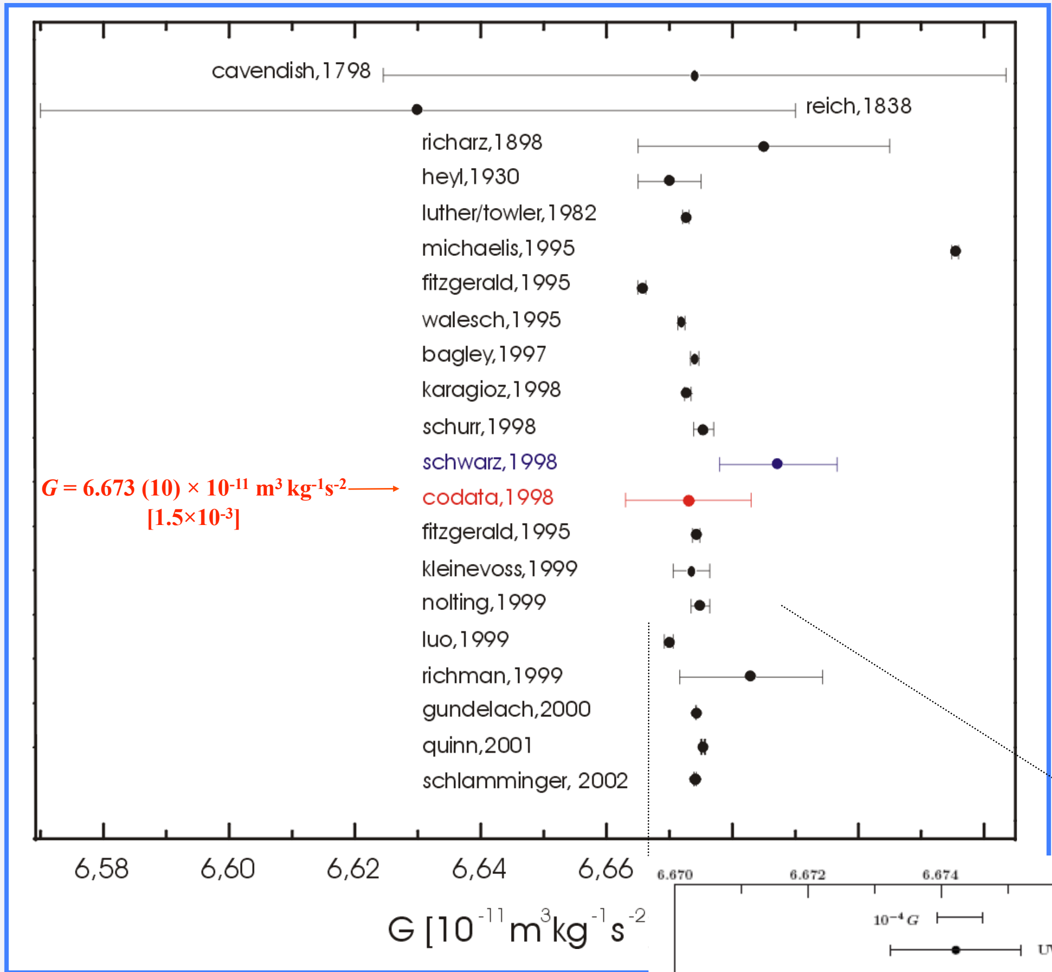
(Misura Accurata di G mediante Interferometria Atomica)

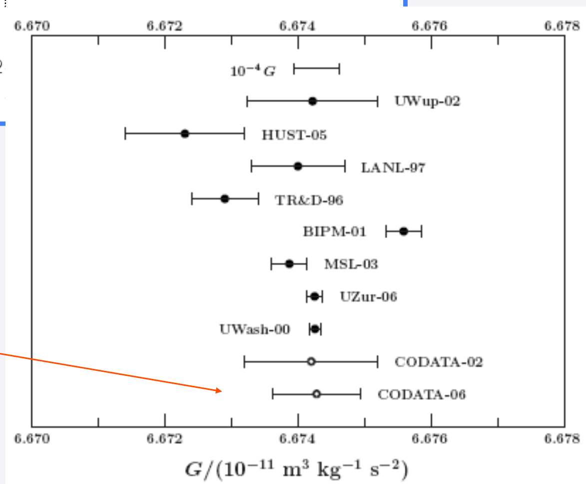
- Measure g by atom interferometry
- Add source masses
- Measure change of g

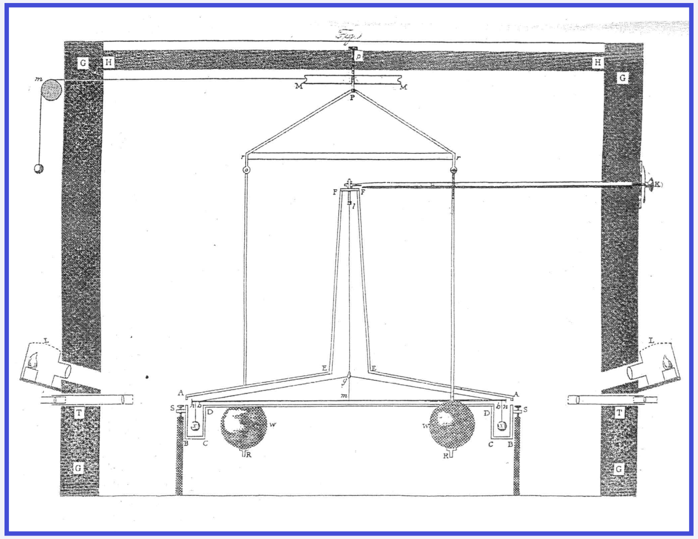


- *Precision measurement of G*
- *Test of Newtonian law at micrometric distances*

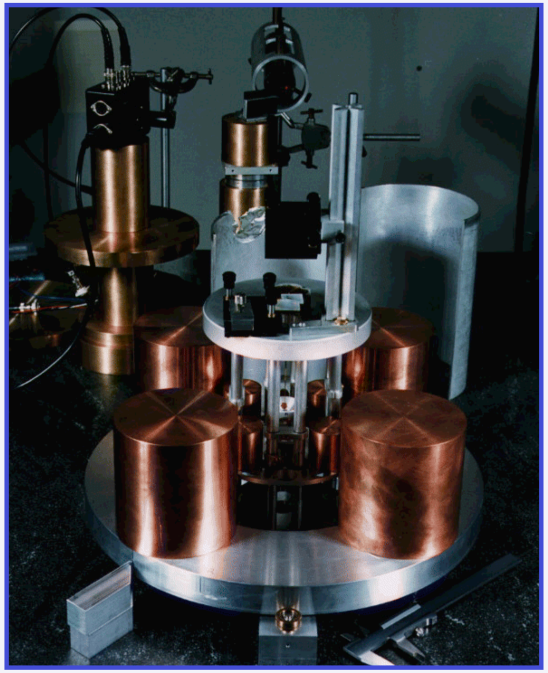
Measurements of the Newtonian gravitational constant G







Cavendish
1798



Quinn
2001

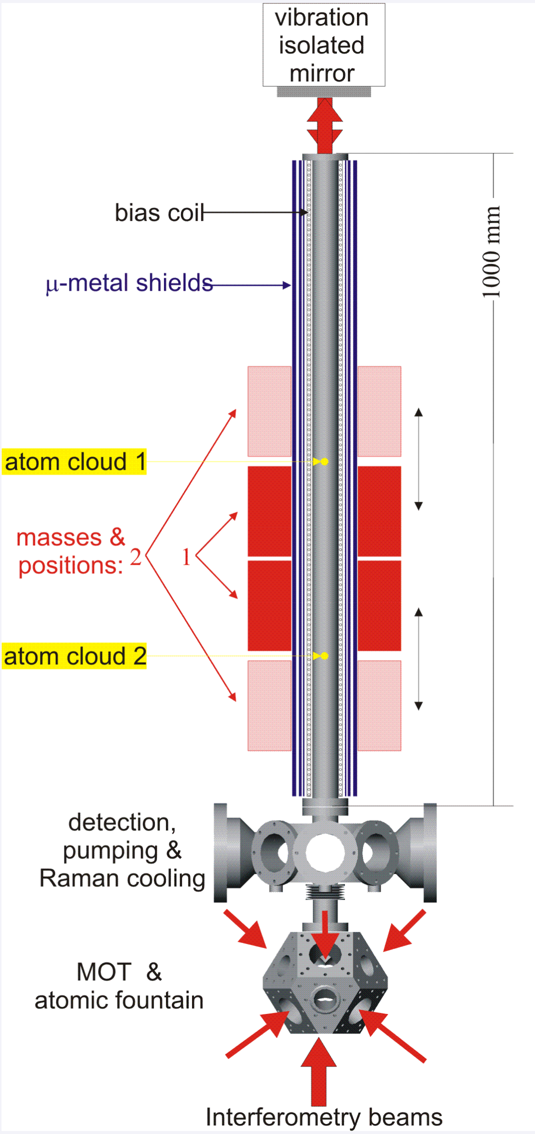
***G* = 6.674 28 (67) × 10^{-11} $m^3\,kg^{-1}s^{-2}$**
[1.0×10^{-4}]

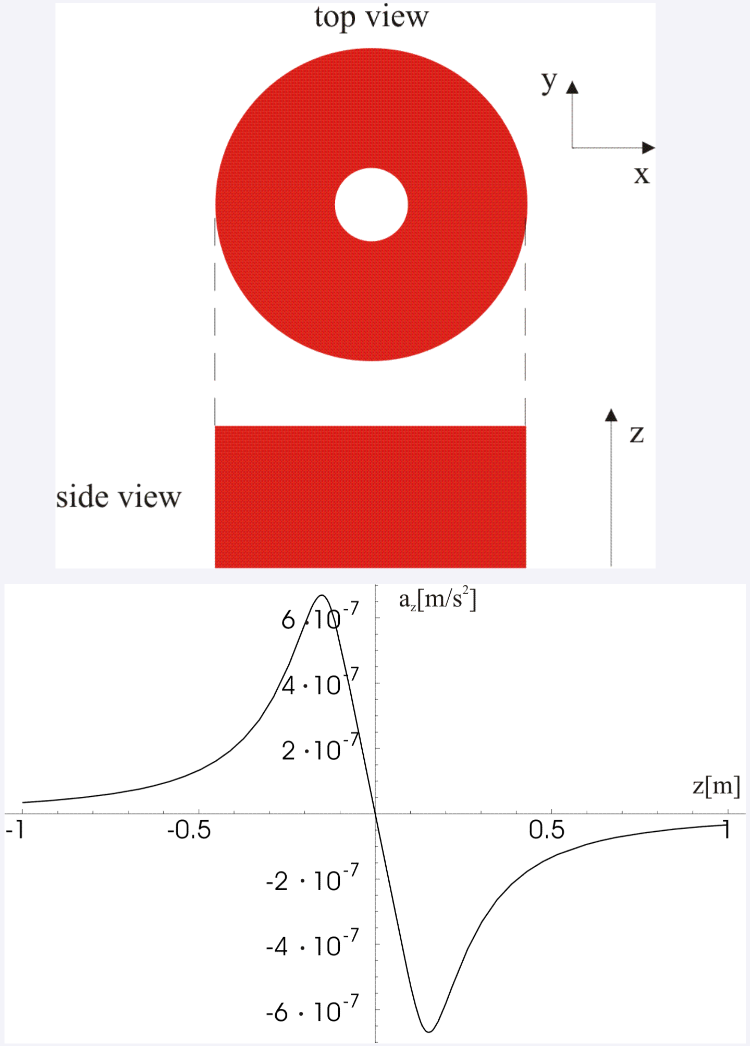
P.J. Mohr, B. N. Taylor, and D. B. Newell, *CODATA recommended values of the fundamental physical constants: 2006*, Rev. Mod. Phys. 80, 633 (2008)

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

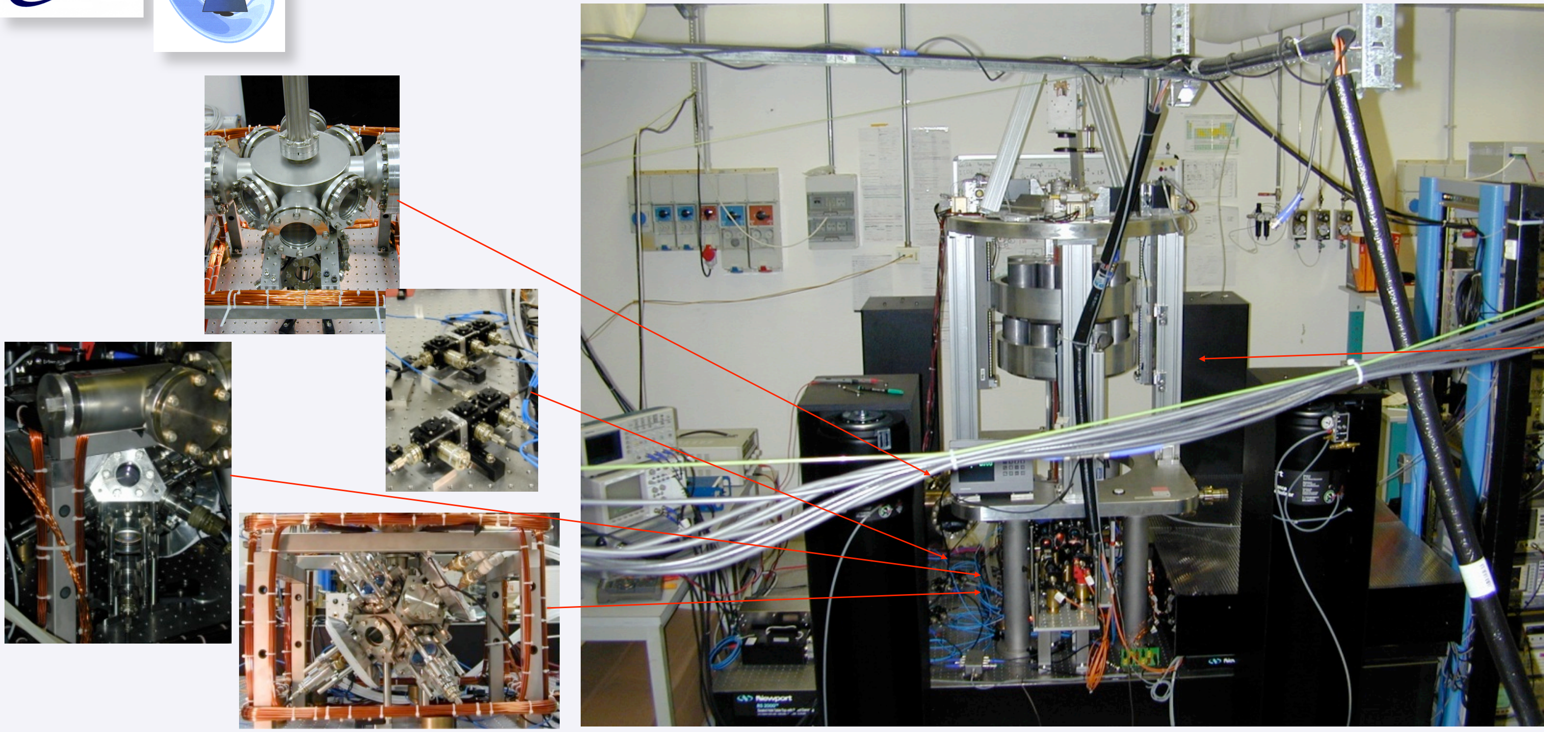
Sensitivity 10^{-9}g/shot

Peak mass acceleration $a_G \approx 10^{-7}$g

one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

10000 shots $\Rightarrow$ **$\Delta G/G \approx 10^{-4}$**

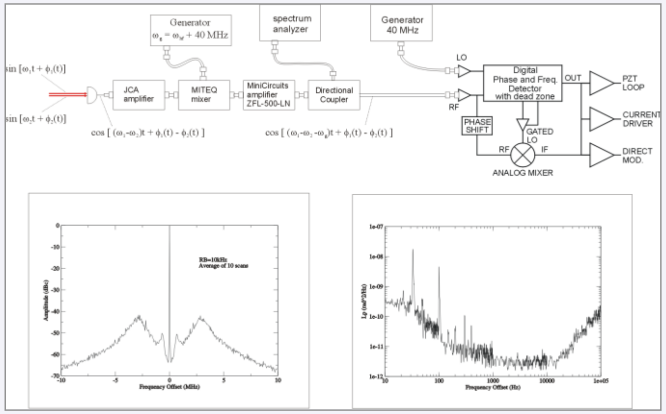
Atom gravity-gradiometer apparatus



Source masses and support

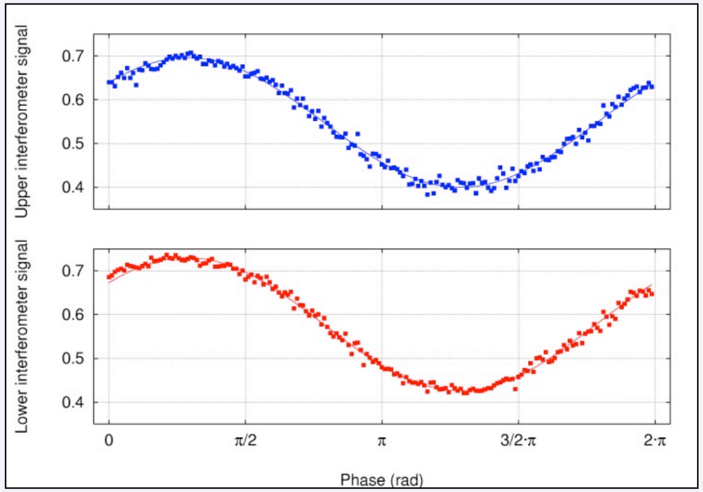
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G,* Rev. Scient. Instr. 78, 075109 (2007)

Laser and optical system



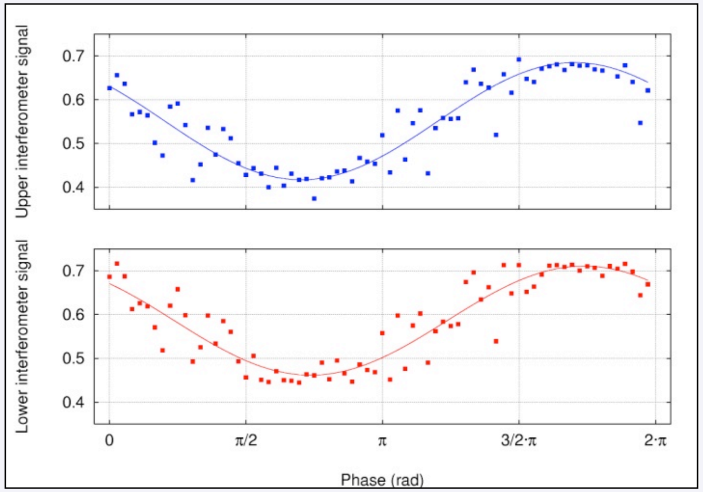
L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* Rev. Scient. Instr. 76, 053111 (2005)

Gradiometer



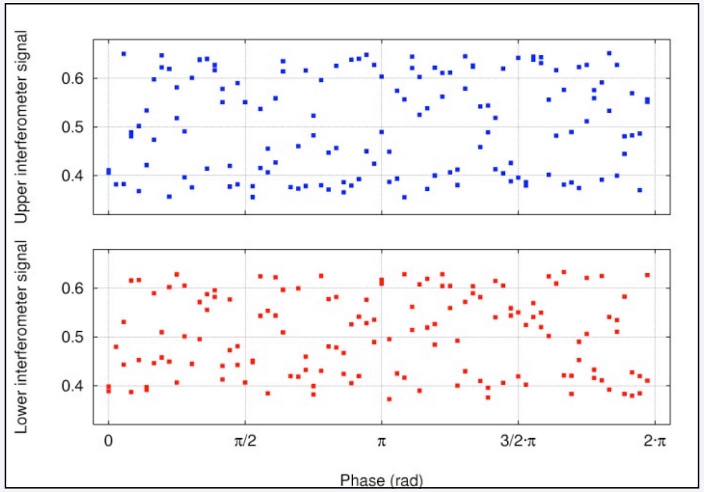
T=5 ms

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



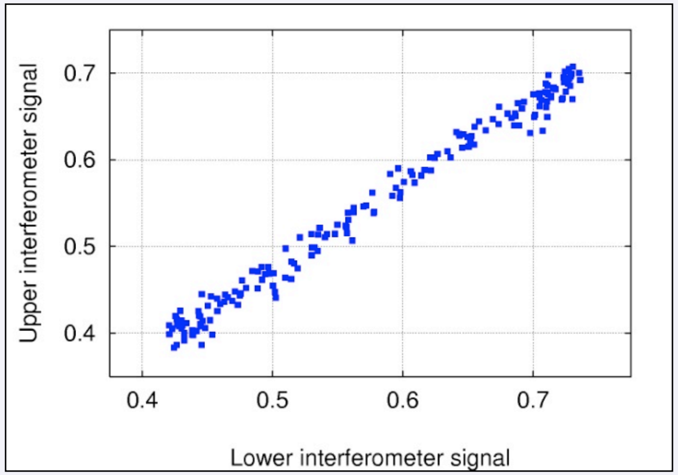
T=50 ms

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



T=150 ms

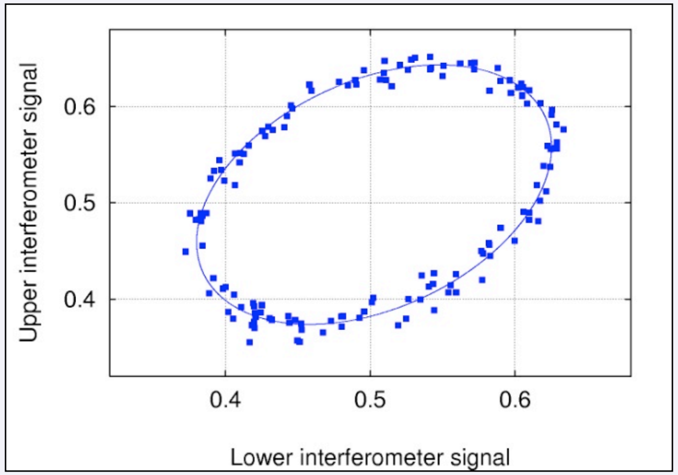
$\varphi(g) = 3.6 \cdot 10^6$ rad
$\varphi(\nabla g) = 380$ mrad
res = 290 mrad/$\sqrt{\text{Hz}}$
= 7.6 10^{-8} g/$\sqrt{\text{Hz}}$
= 3.2 10^{-8} g/shot



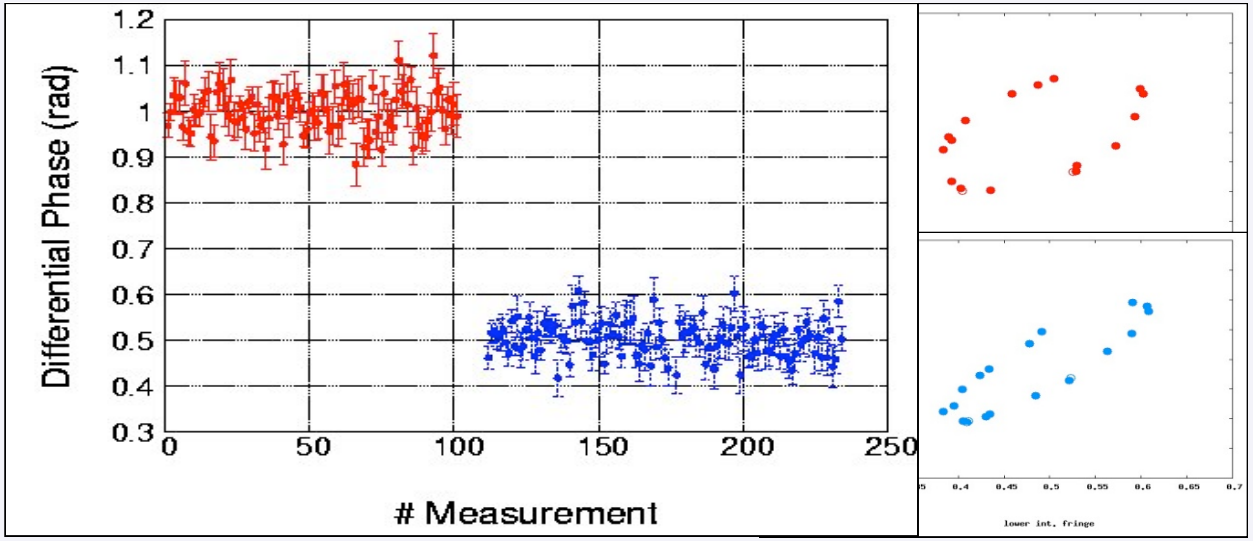
$$\Delta\varphi_{grad} = k_R \, \Delta g \, T^2$$

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

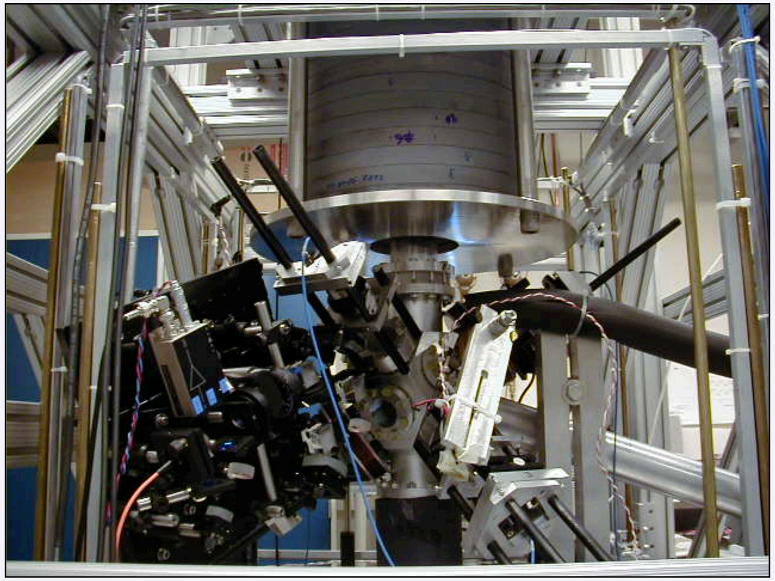
$$\Delta\varphi_B = 2\pi \, a_{II} \, B^2 \, \Delta t$$

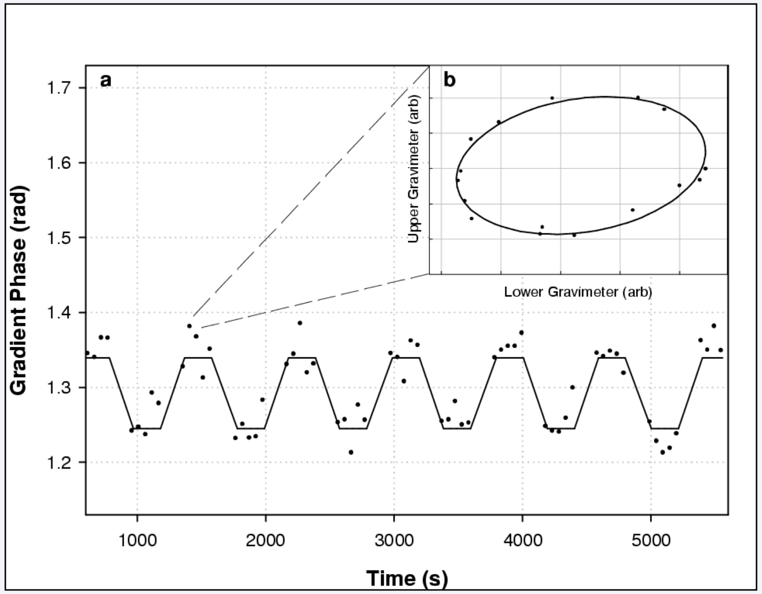


Ellipse fitting method: G.T. Foster et al., *Opt. Lett.* 27, 951 (2002)



A. Bertoldi G.Lamporesi , L. Cacciapuoti, M. deAngelis, M.Fattori, T.Petelski, A. Peters, M. Prevedelli, J. Stuhler, G.M. Tino,
Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G,
Eur. Phys. J. D 40, 271 (2006)





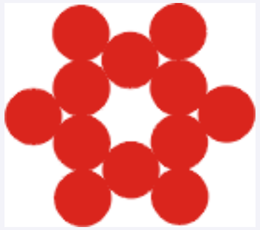
J. B. Fixler, G. T. Foster, J. M. McGuirk and M. A. Kasevich,
Atom Interferometer Measurement of the Newtonian Constant of Gravity,
Science 315, 74 (2007)

Source masses and support

INERMET 180K (95% W, 3.5% Ni, 1.5% Cu)
Hot isostatic pressing (1200 °C, 1500 atm)

Density= 18 g cm^{-3}
Resistivity= 12 x 10^{-8} Ωm
Thermal expansion = 5 x 10^{-6} K^{-1}
Surface roughness = 3 μm

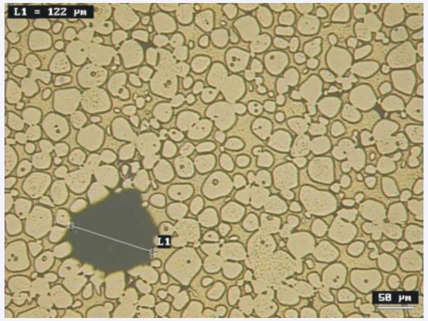
24 cylinders
External radius = 5 cm
Height = 15 cm
Cylinder mass = 20 kg
Total mass ~ 500 kg

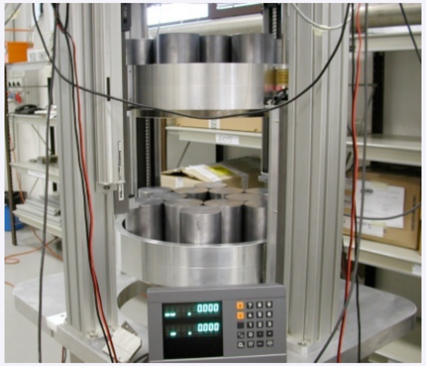


Hot Isostatic Pressing at 1200 C° and 1500 atm

Ultrasonic and destructive test of homogeneity of probe cylinders to 10-4

Oscillation of cylinders on air cushion reveal radial inhomogeneities

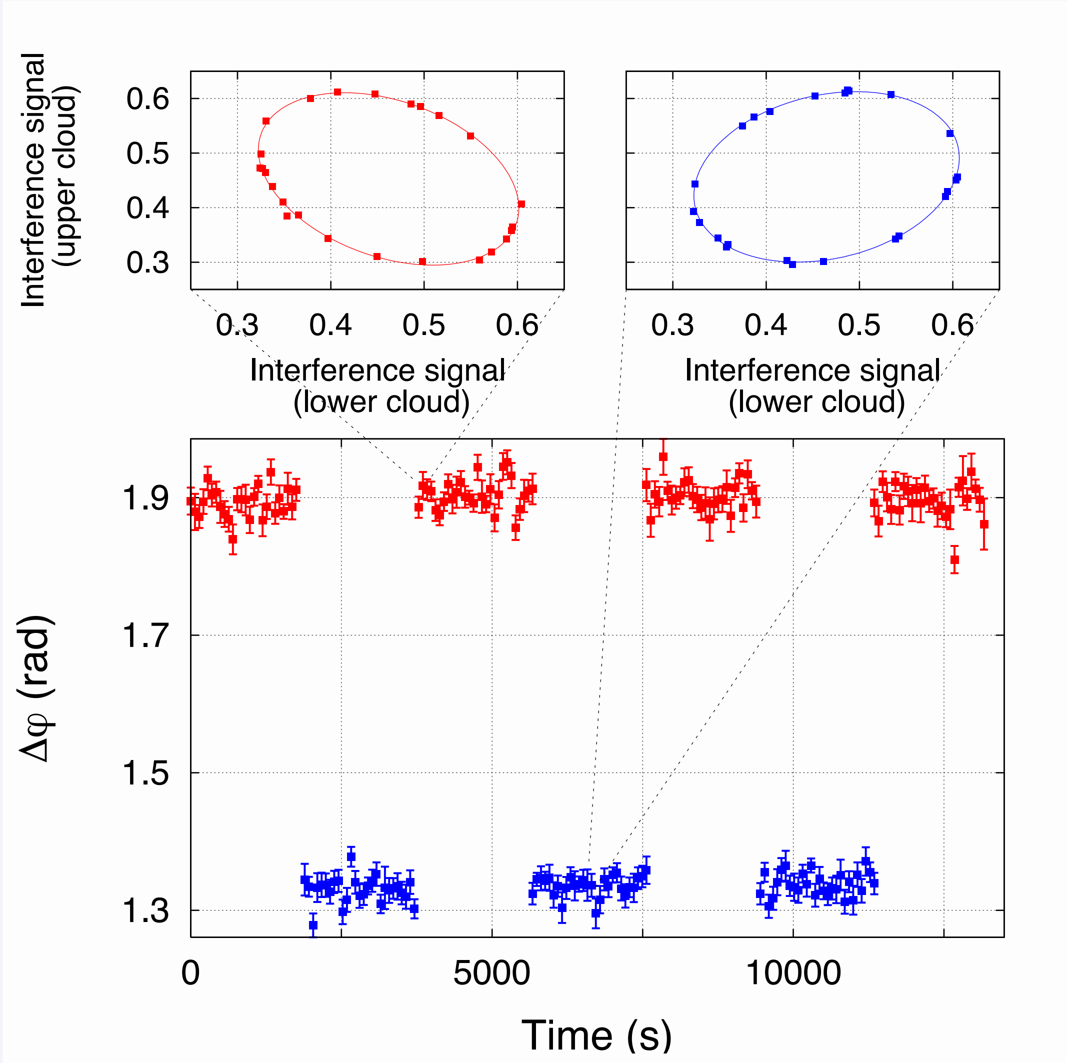


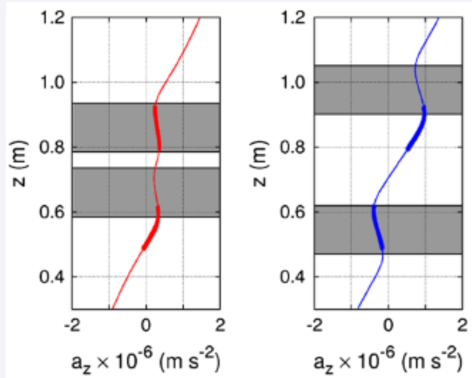


In collaboration with IMGC, Torino

In collaboration with LNF, Frascati

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)





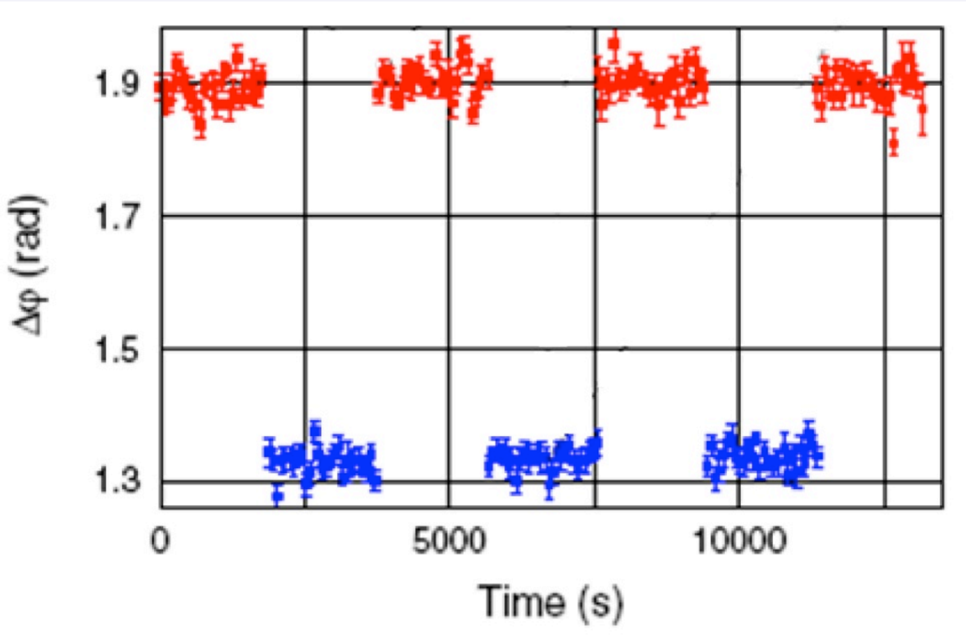
Results from MAGIA

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

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)

MAGIA

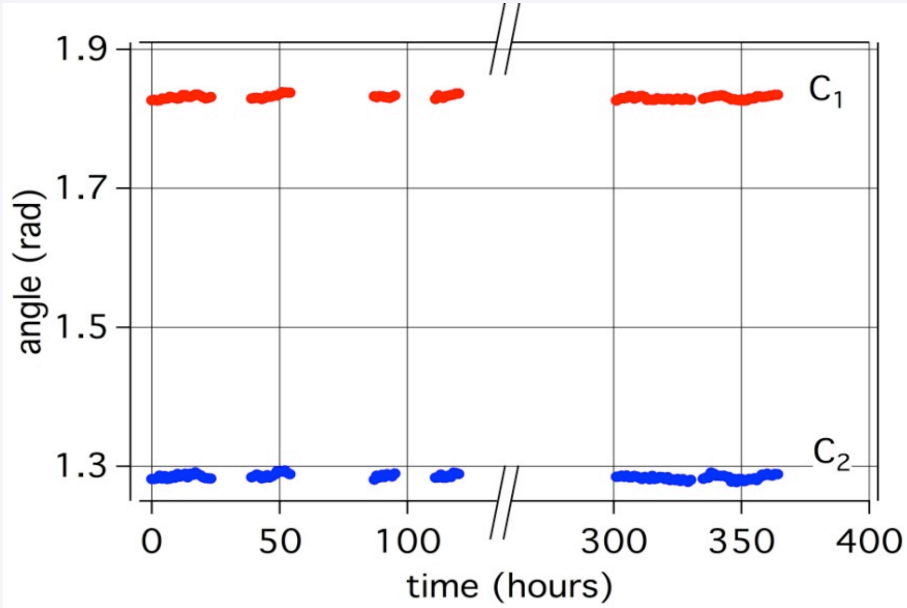
2008



Statistical uncertainty: 1.6 x 10^{-3}

G. Lamporesi, A. Bertoldi, L. Cacciapuoti, M. Prevedelli, G. M. Tino, **Phys. Rev. Lett. 100, 050801 (2008)**

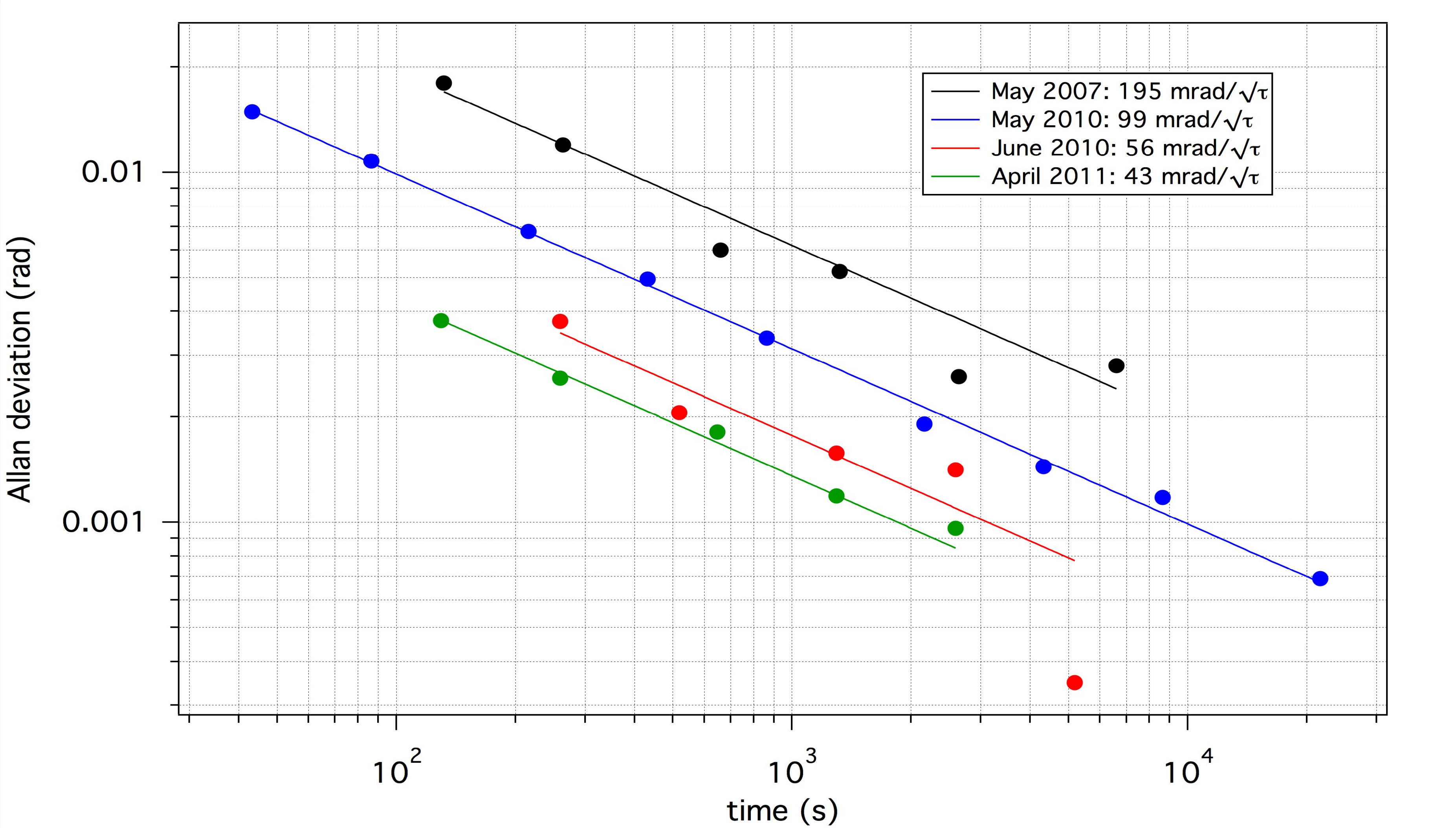
2010



Statistical uncertainty: 4 x 10^{-4}

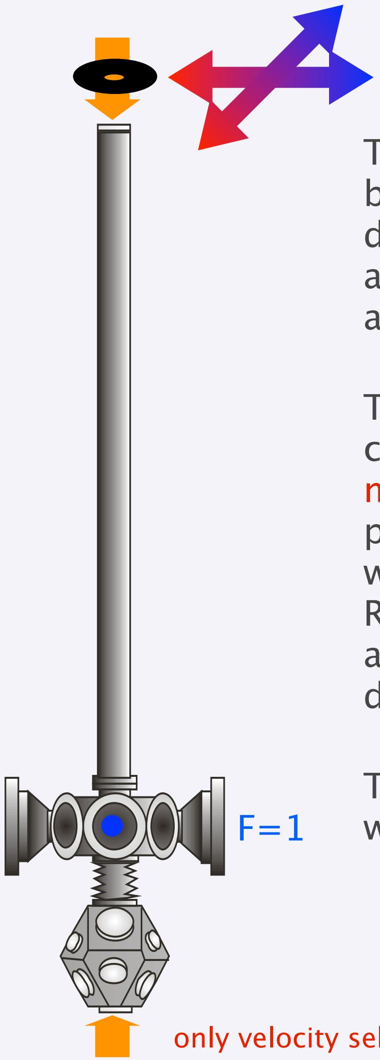
F. Sorrentino, Y.H. Lien, G. Rosi, L. Cacciapuoti, M. Prevedelli, G.M. Tino, **New J. Phys. 12, 095009 (2010)**

Upgrade of detection system



larger number of atoms and higher repetition rate (2D-MOT);
more powerful Raman laser sources;
minimized the stray light at detection photodiodes;
improved the contrast with triple-pulse velocity selection;
improved electronics for photodiodes readout: detection close to QPN

Atomic Cloud Trajectory

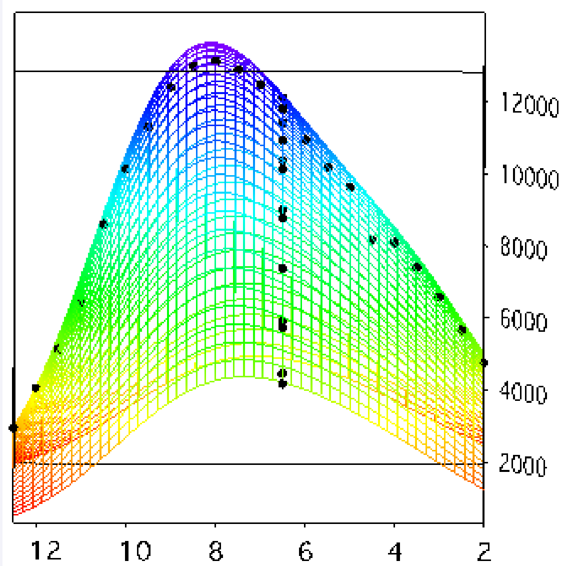


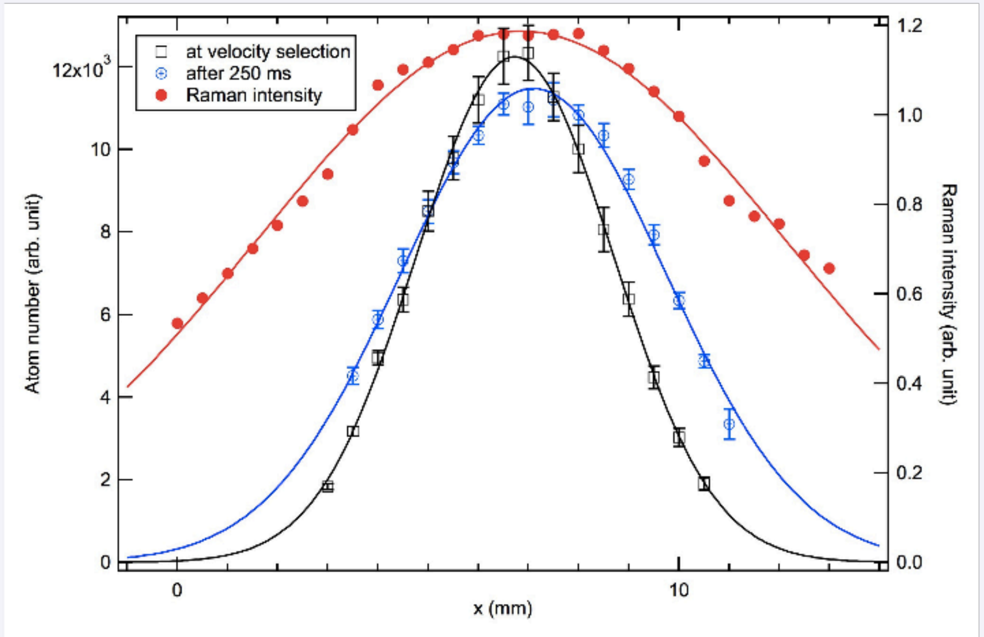
The atomic distribution is measured by scanning a horizontally movable diaphragm on the Raman beam path and detecting the F=1 population after velocity selection.

The horizontal position of atomic cloud can be determined with sub mm precision by fitting 2D population signal with a function which is a convolution of a gaussian Raman intensity profile and an asymmetric 2D gaussian for atomic distribution.

The vertical position is determined with sub mm precision by TOF signal.

only velocity selection pulse is applied





Systematics

SOURCE	Uncertainty	$\Delta G/G\,(10^{-4})$	Status
Cylinders radial positioning	10 μm	0.5	Done
Cylinder shape	10 μm	$\ll 1$	Done
Cylinder mass	10 mg	$\ll 1$	Done
Density radial homogeneity	2×10^{-3}	0.01	Done
Density vertical homogeneity	0.5×10^{-3}	0.25	Done
Support platform mass	60 g	0.8	To be improved
Cloud-Masses vertical distance	100 μm	0.02	Done
Cloud-Masses horiz. distance	100 μm	N/A	Partially done
Atomic horiz. distribution	100 μm	N/A	Partially done
Launch direction C/F	N/A	N/A	Not detectable
Raman mirror tilt C/F	0.1 μrad	0.3	Done

- MonteCarlo simulation of the experiment to implement correctly the clouds dynamic
- Launch direction changes induced by source mass below 0.1 mrad
  - Too small to be detected with cloud scanning method
  - Possible effect on $\Delta\Phi$ by Coriolis force (~ 3-4 mrad)
- Possible solutions:
  - Improve sensitivity on trasversal position measurements
  - Compensate Coriolis effect (rotating Raman mirror)

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

$$\Downarrow$$

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

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 fo
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)

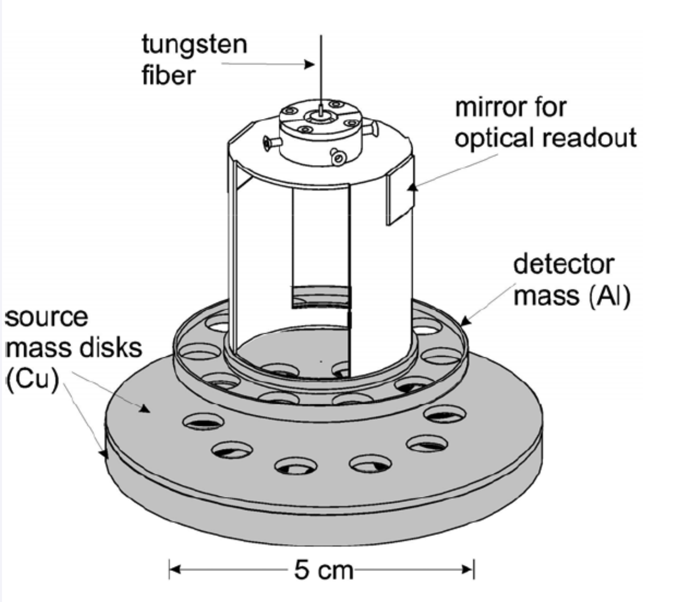
Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

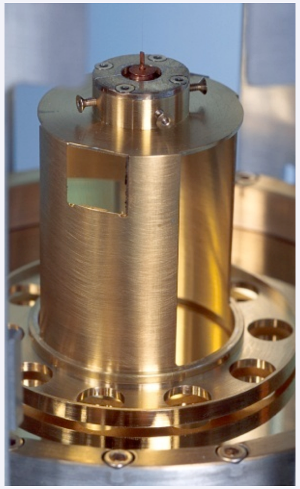
- **Small observed size of Einstein cosmological constant**

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

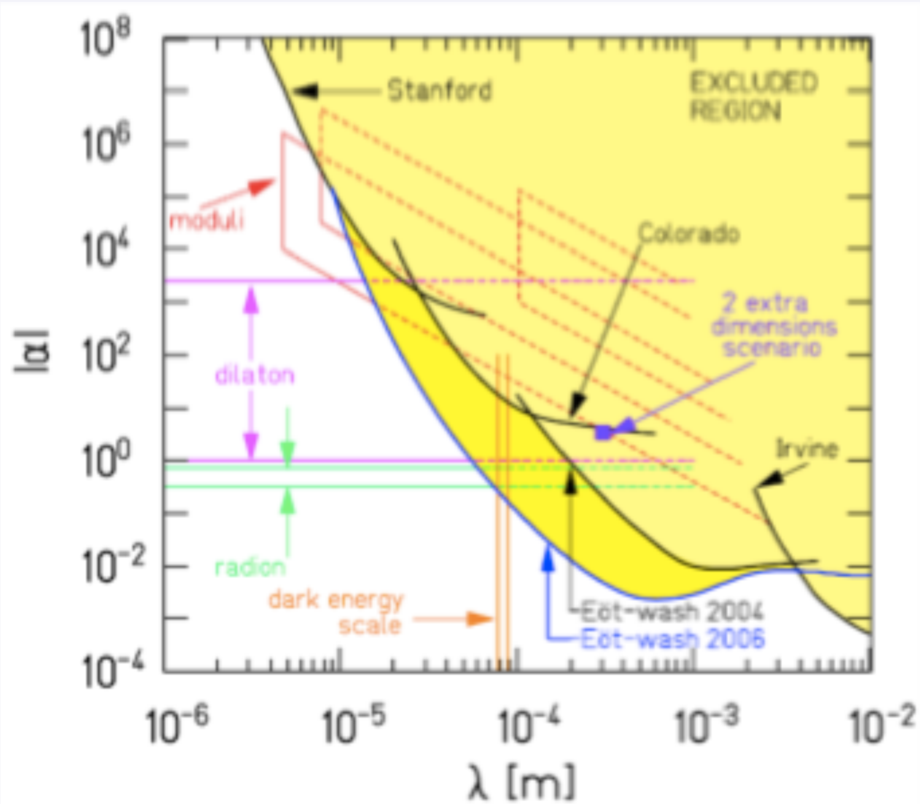
- **Experimental challenge**

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

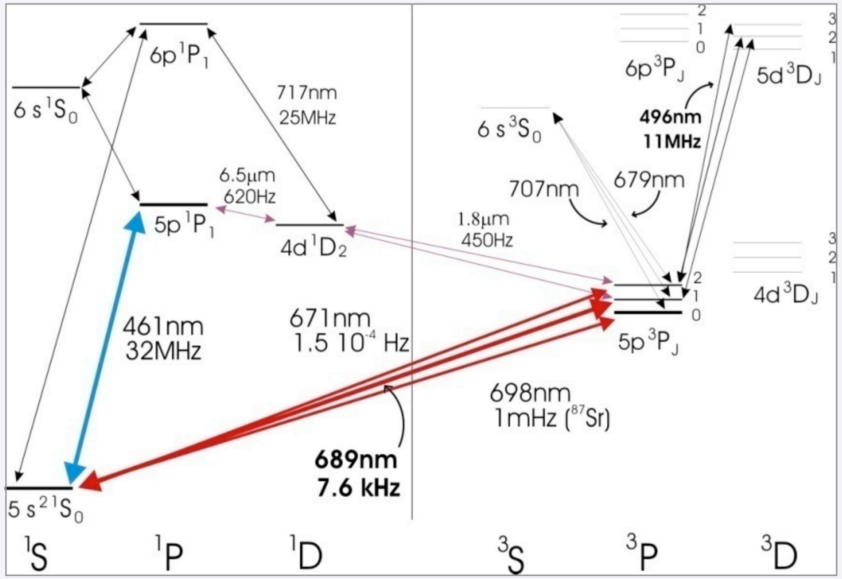


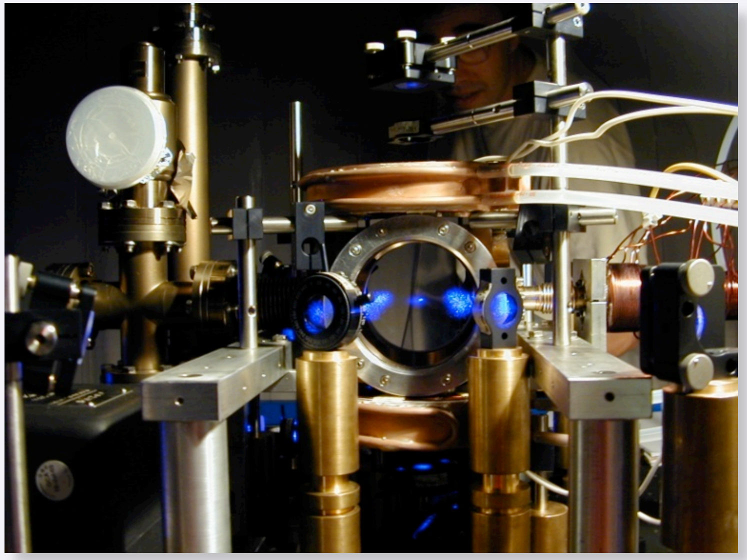
- **Distance from top of attractor to bottom of pendulum from 9.53 mm to 55 μm**

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)**

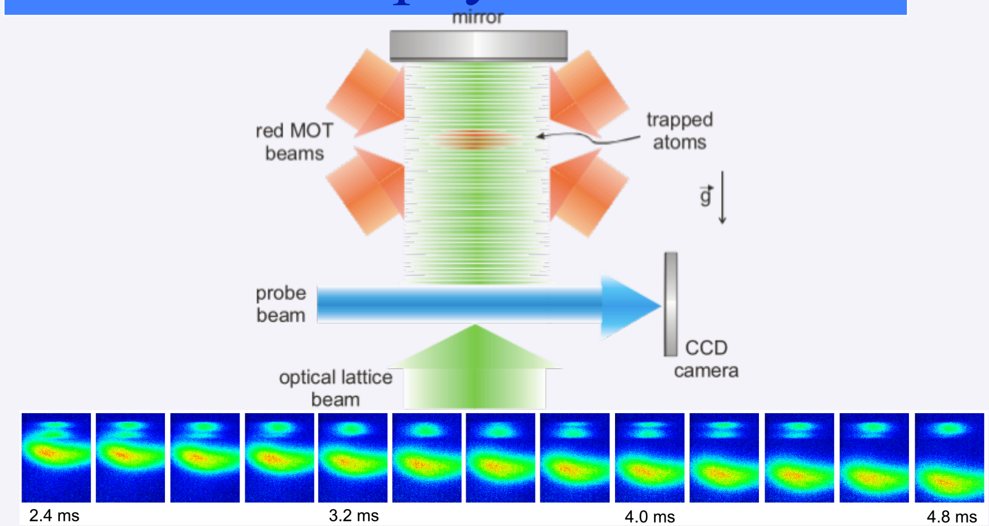
Ultracold Sr – The experiment in Firenze

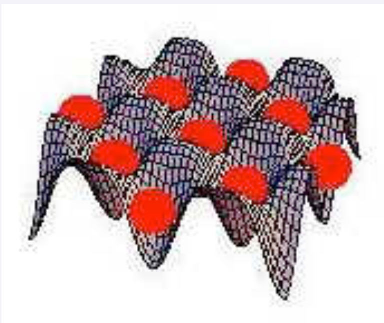


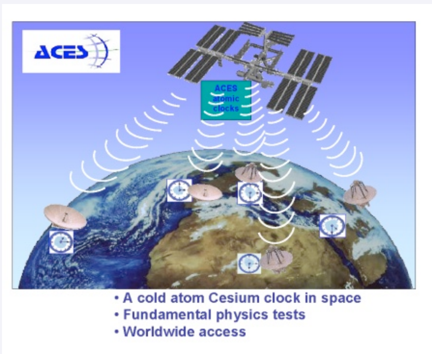


- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests

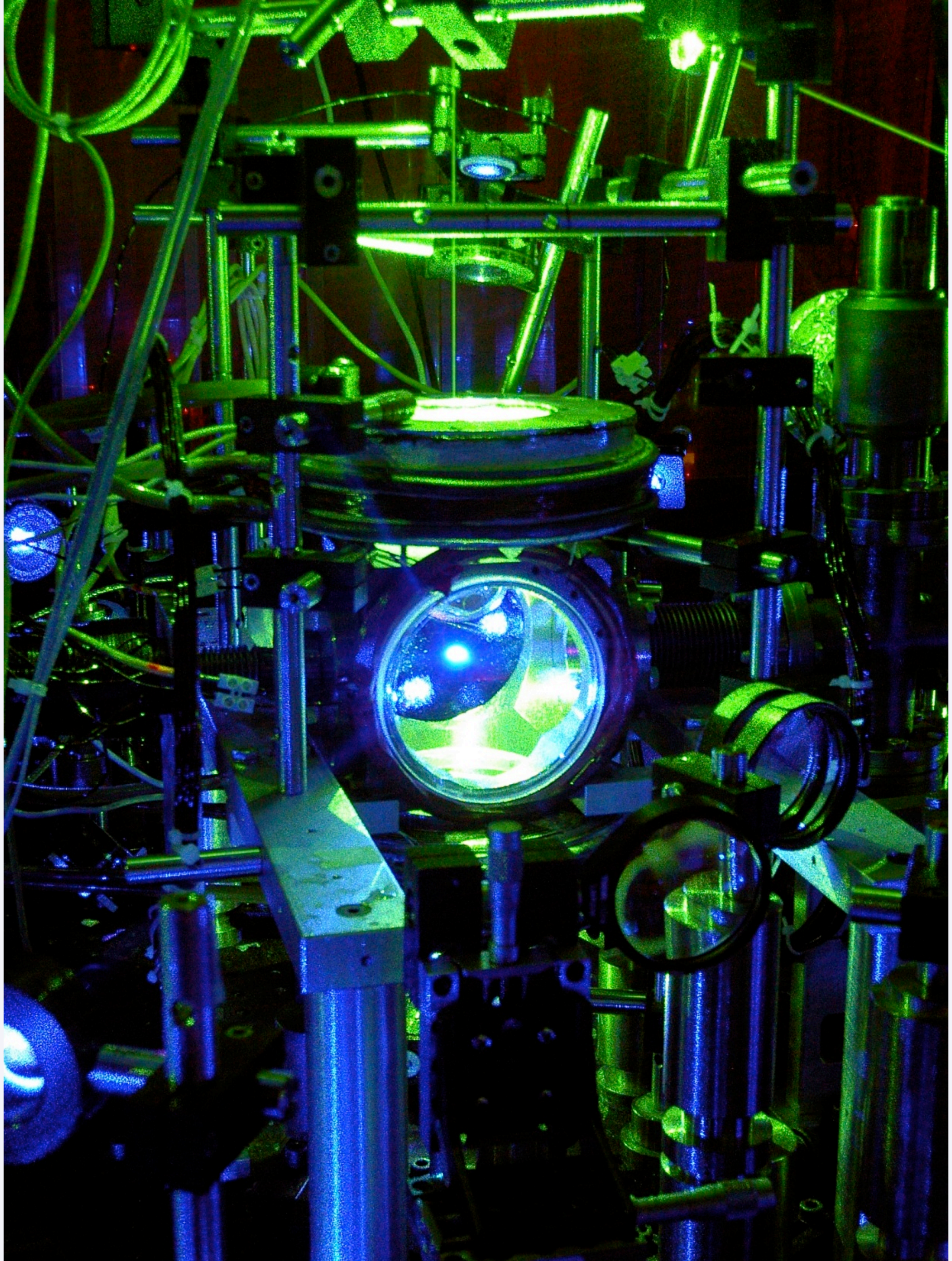




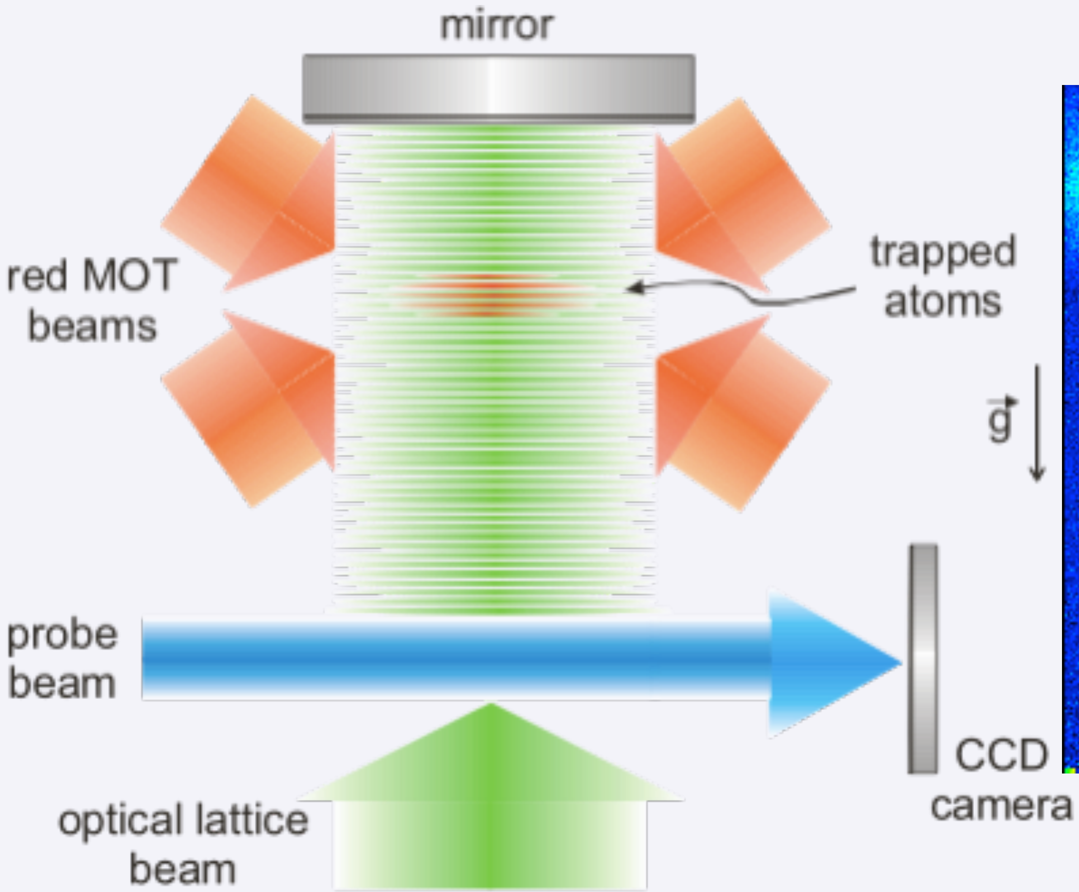


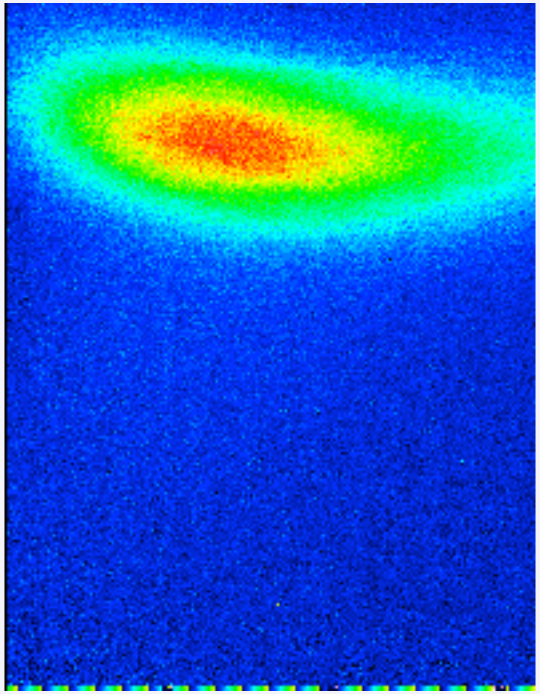
G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

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)



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

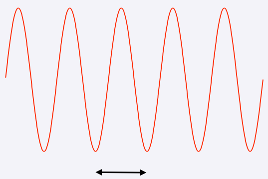




$\nu = m\, g\, \lambda / 2\, h$

Particle in a periodic potential:Bloch oscillations

periodic potential



$\lambda/2$

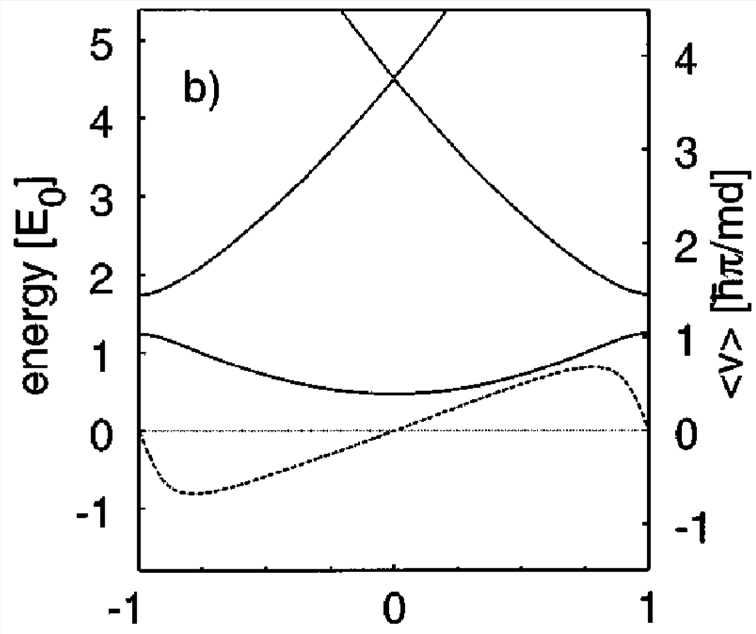
$V(z+\lambda/2) = V(z)$

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

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

Bloch's theorem

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



quasimomentum q [2π/λ]

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

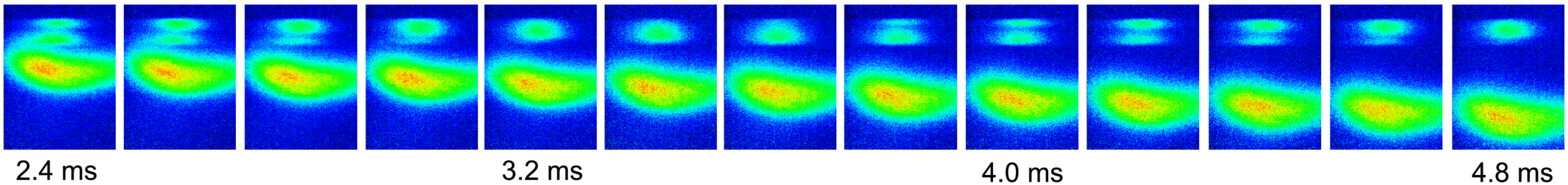
with a constant external force F

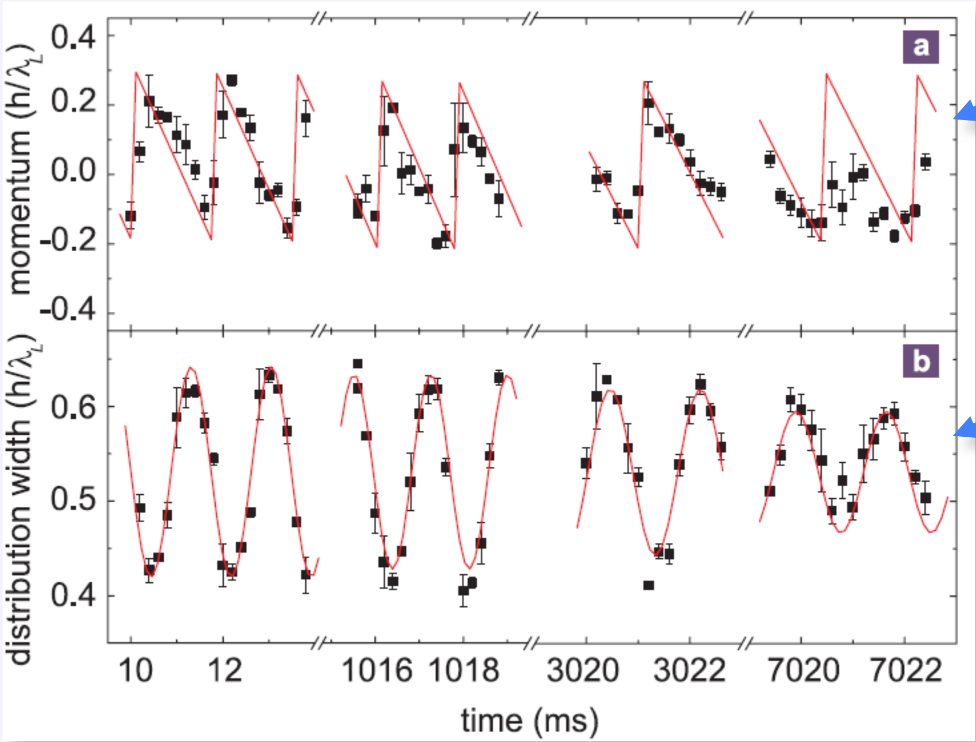
$$q(t) = q(0) + Ft/\hbar$$

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

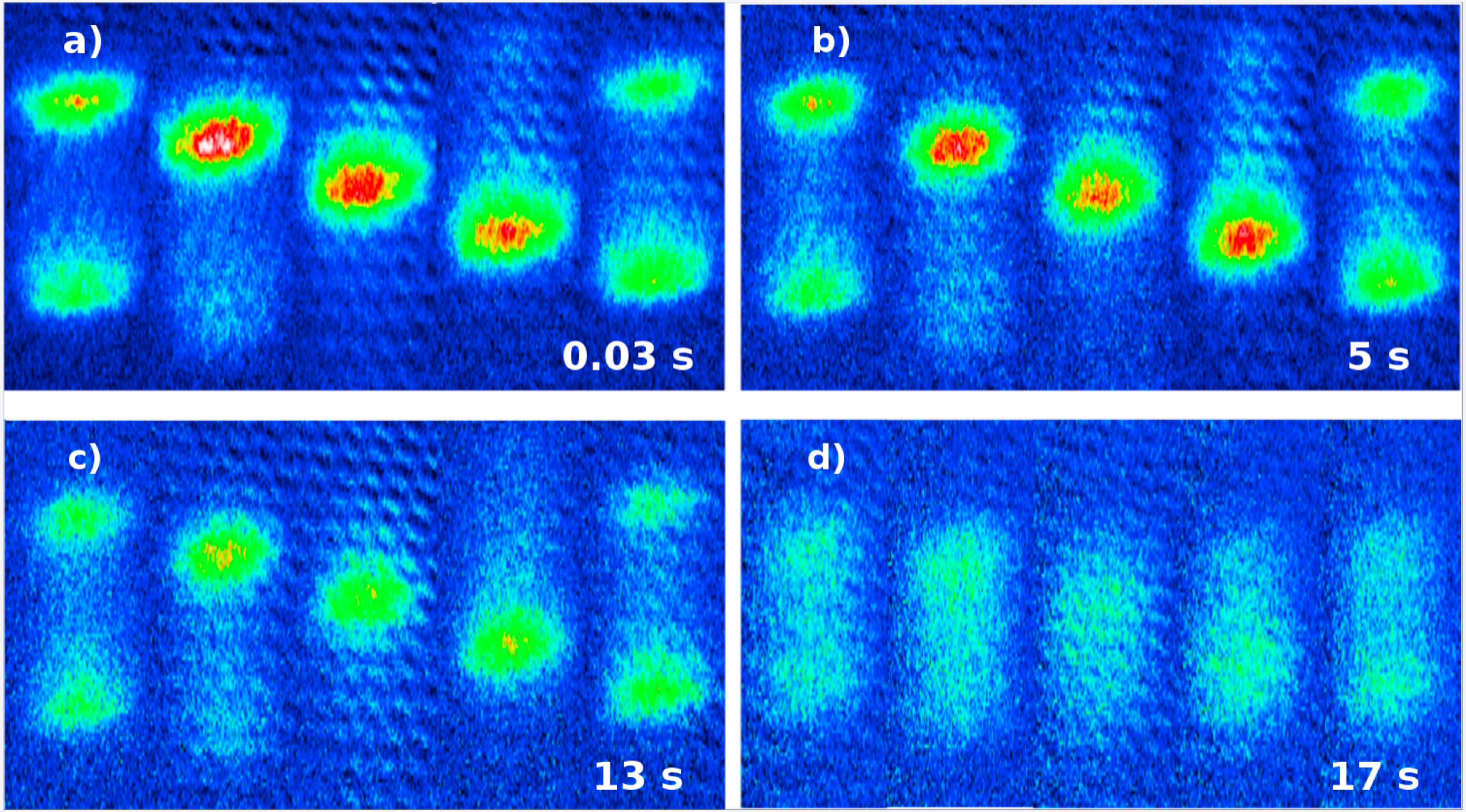
Bloch frequency $\nu_B = 574.568(3)$ Hz

damping time $\tau = 12$ s

8000 photon recoils in 7s

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

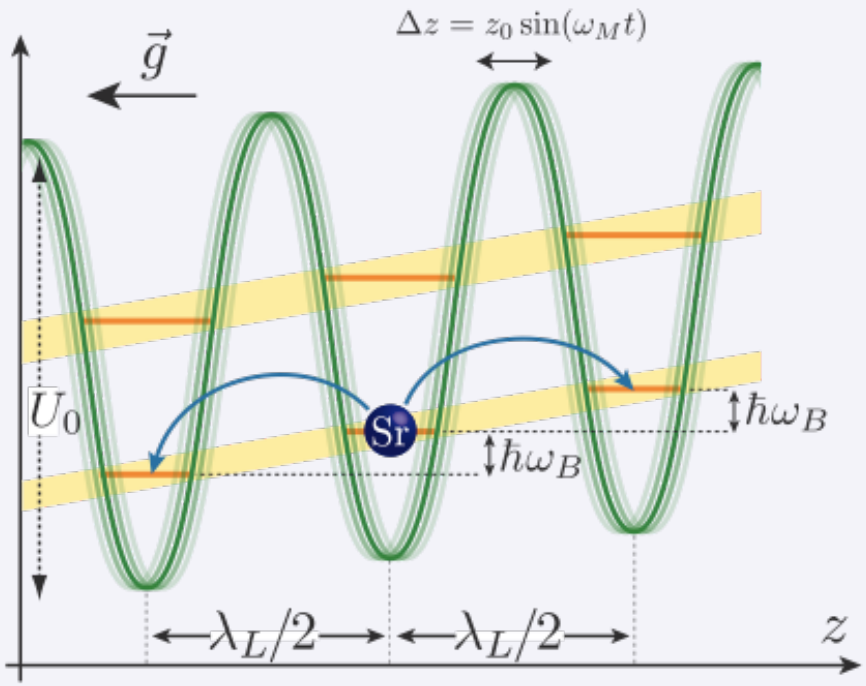
G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. 97, 060402 (2006)**



N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Phys. Rev. Lett. 106, 038501 (2011)

Modulation of optical lattices

Phase modulation

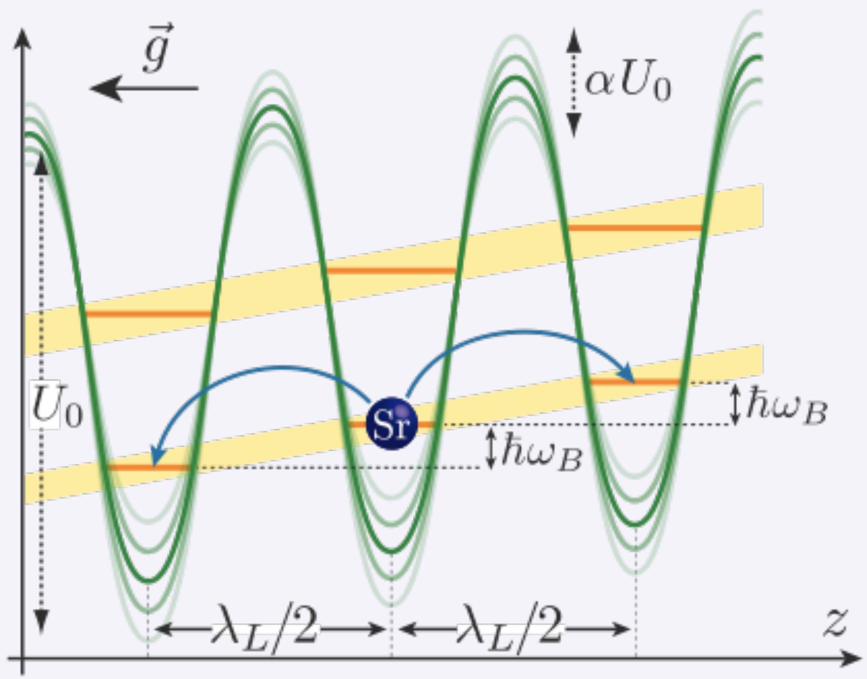


$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2} \cos\left\{2k_L[z - z_0 \sin(\omega_M t)]\right\} + mgz$$

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)

Amplitude modulation

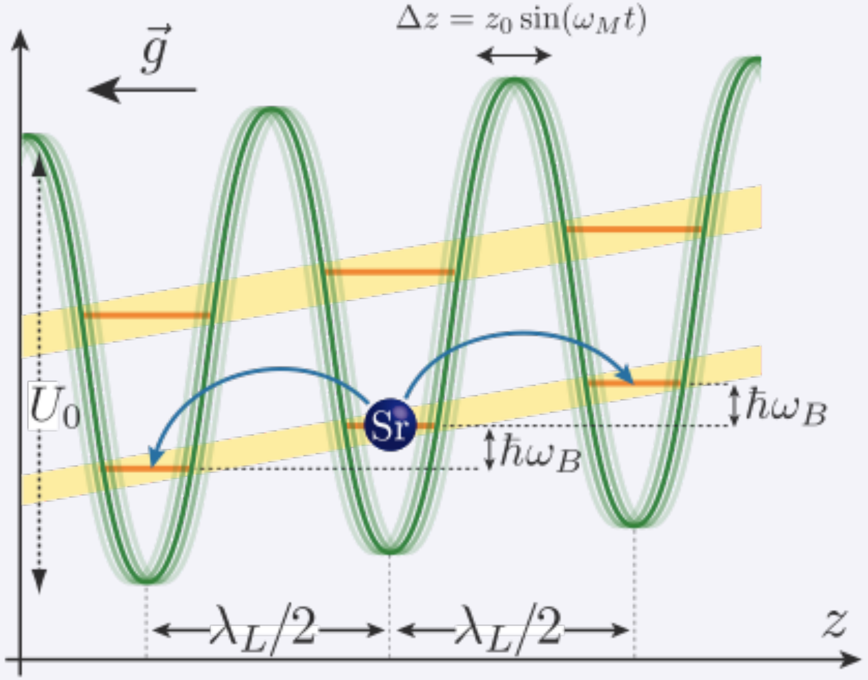


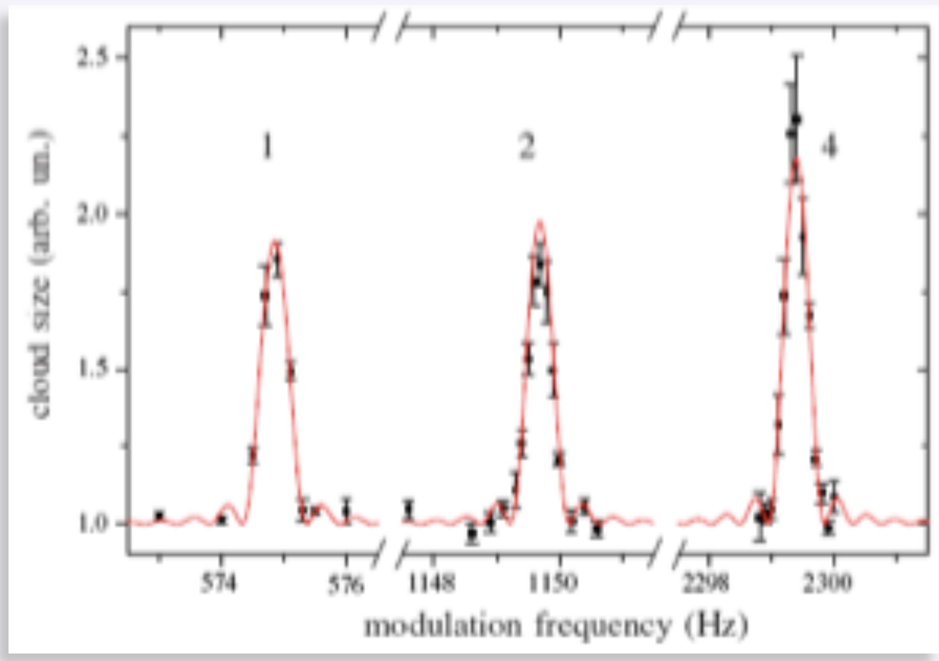
$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2} \cos(2k_L z)[1 + \alpha \sin(\omega_M t)] + mgz$$

A. Alberti, G. Ferrari, V.V. Ivanov, M. L. Chiofalo, G. M. Tino, *Atomic wave packets in amplitude-modulated vertical optical lattices*

New Journal of Physics 12, 065037 (2010)

Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials





ν_B = (574.8459 +/- 0.0015) Hz,

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

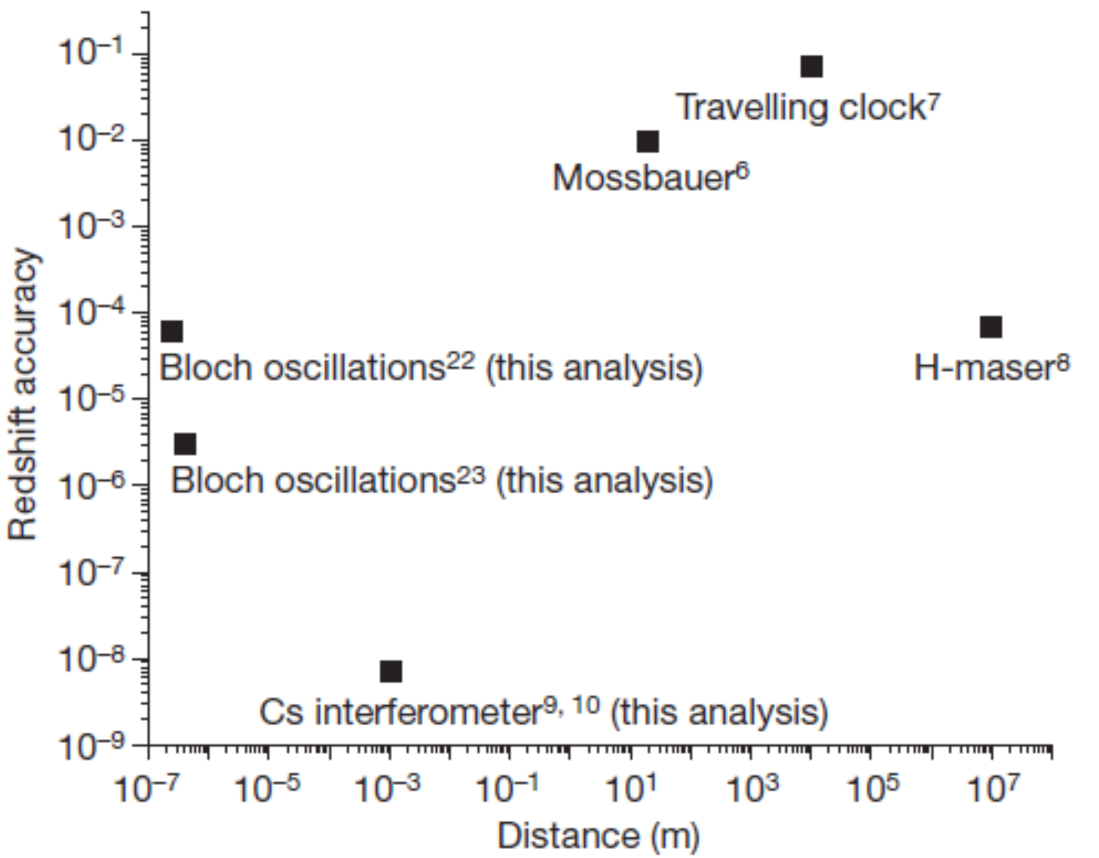
V.V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino,
Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials,
Phys. Rev. Lett. 100, 043602 (2008)

nature Vol 463|18 February 2010|doi:10.1038/nature08776

LETTERS

A precision measurement of the gravitational redshift by the interference of matter waves

Holger Müller[1,2], Achim Peters[3] & Steven Chu[1,2,4]



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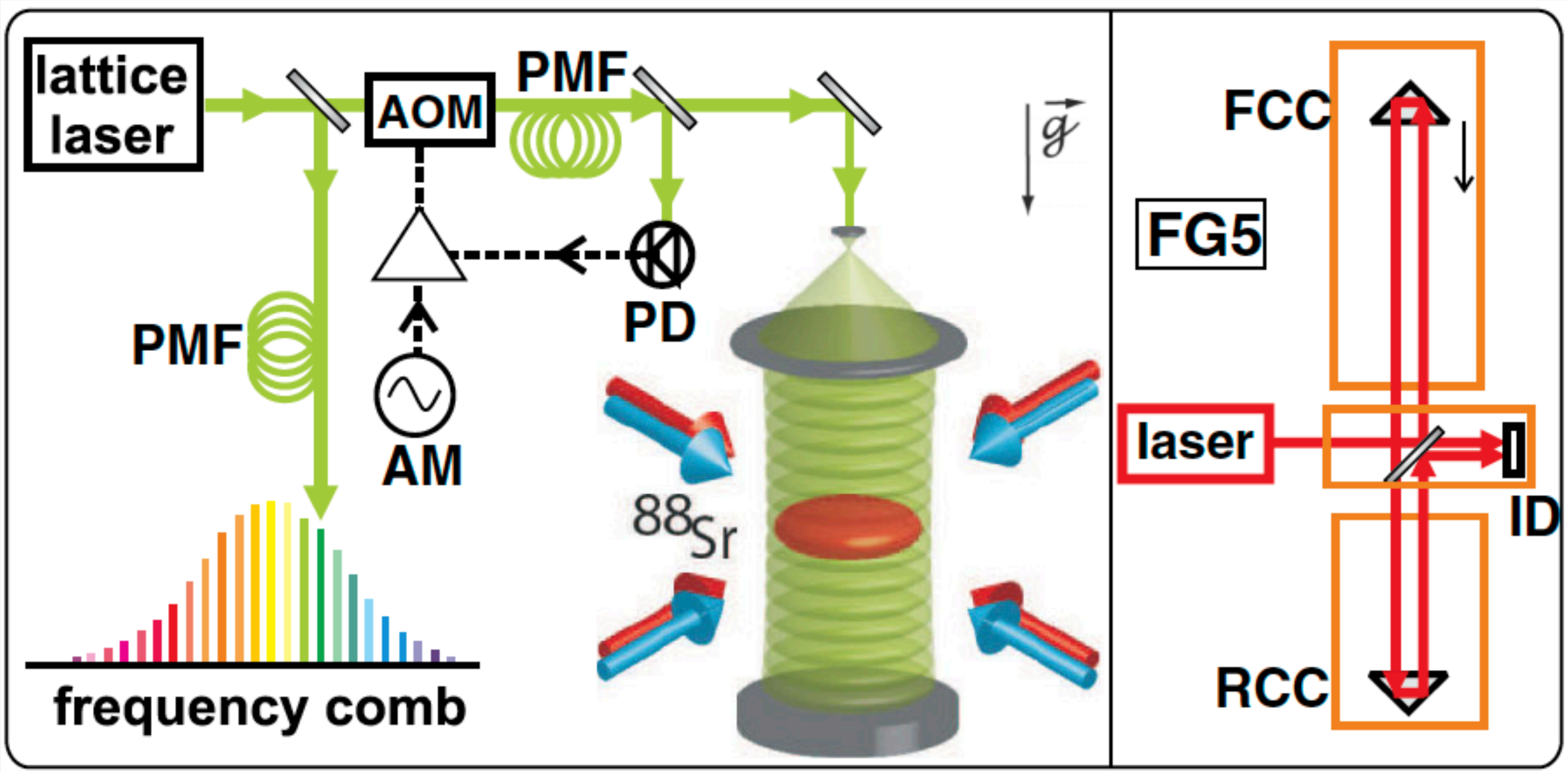
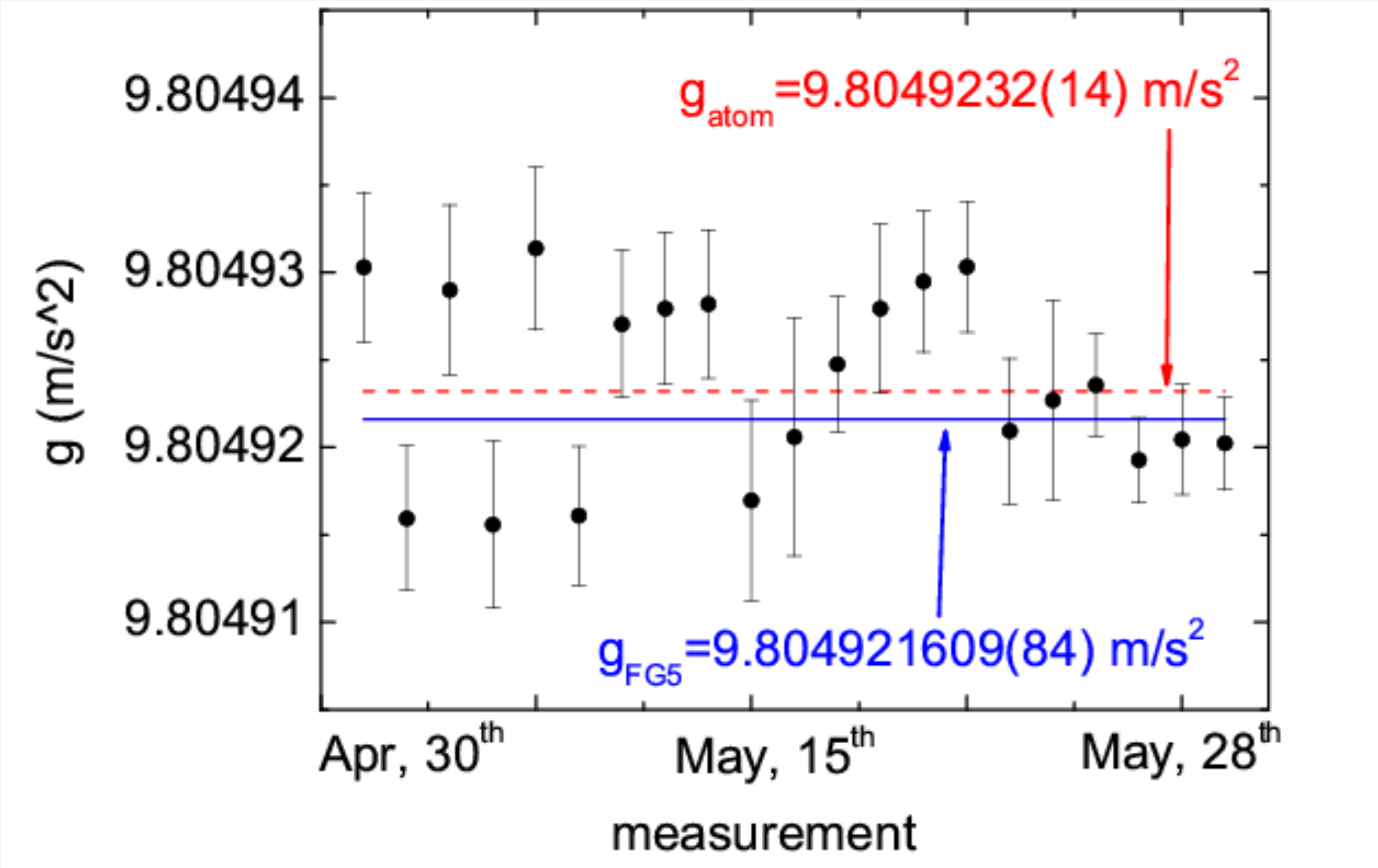
Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter



N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Phys. Rev. Lett. 106, 038501 (2011)

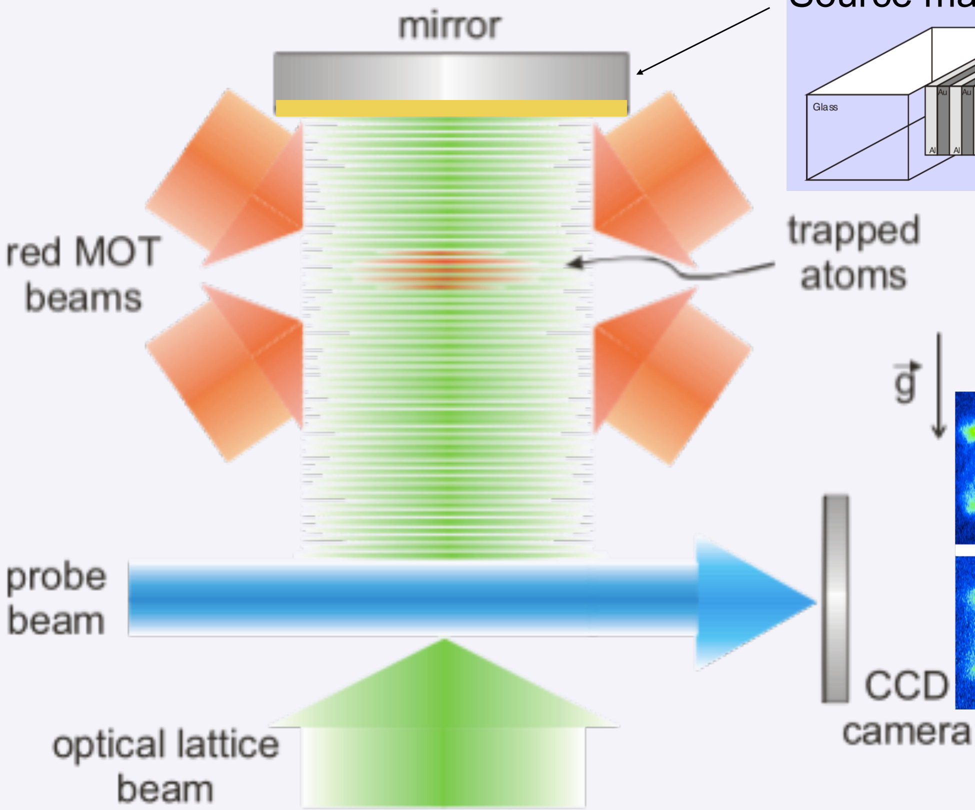
Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter

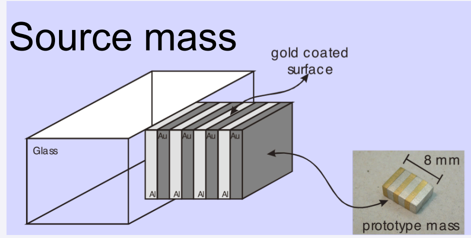


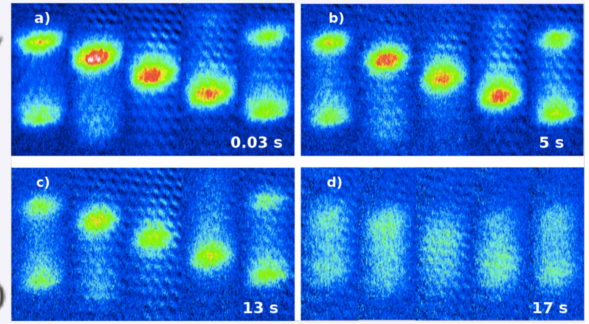
140 ppb relative uncertainty

N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Phys. Rev. Lett. 106, 038501 (2011)

Scheme for the measurement of small distance forces







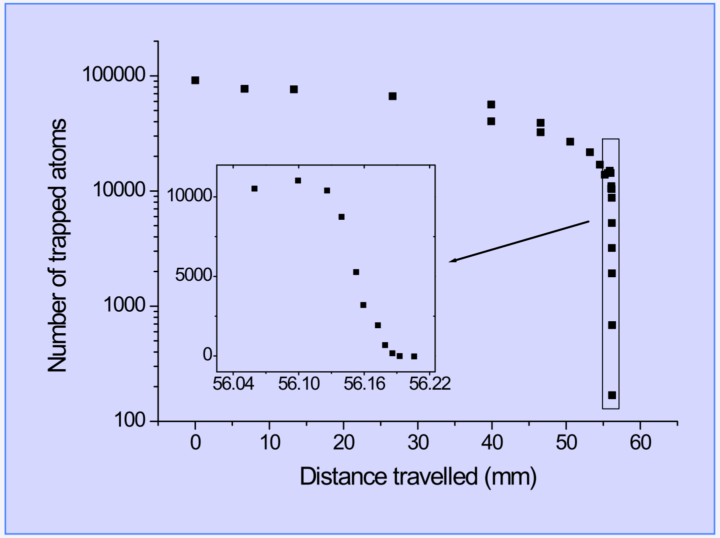
$\nu = m\,g\,\lambda/2h$

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

Objective: λ ***= 1-10*** μ***m,*** α ***=*** 10^3-10^4

F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, **Phys. Rev. A 79, 013409 (2009)**

Atom elevator

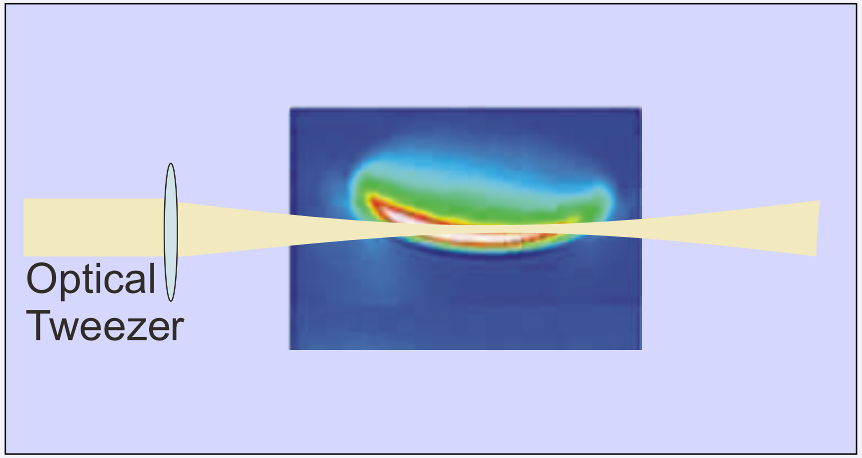


Vertical size of the atomic sample: 15 µm

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

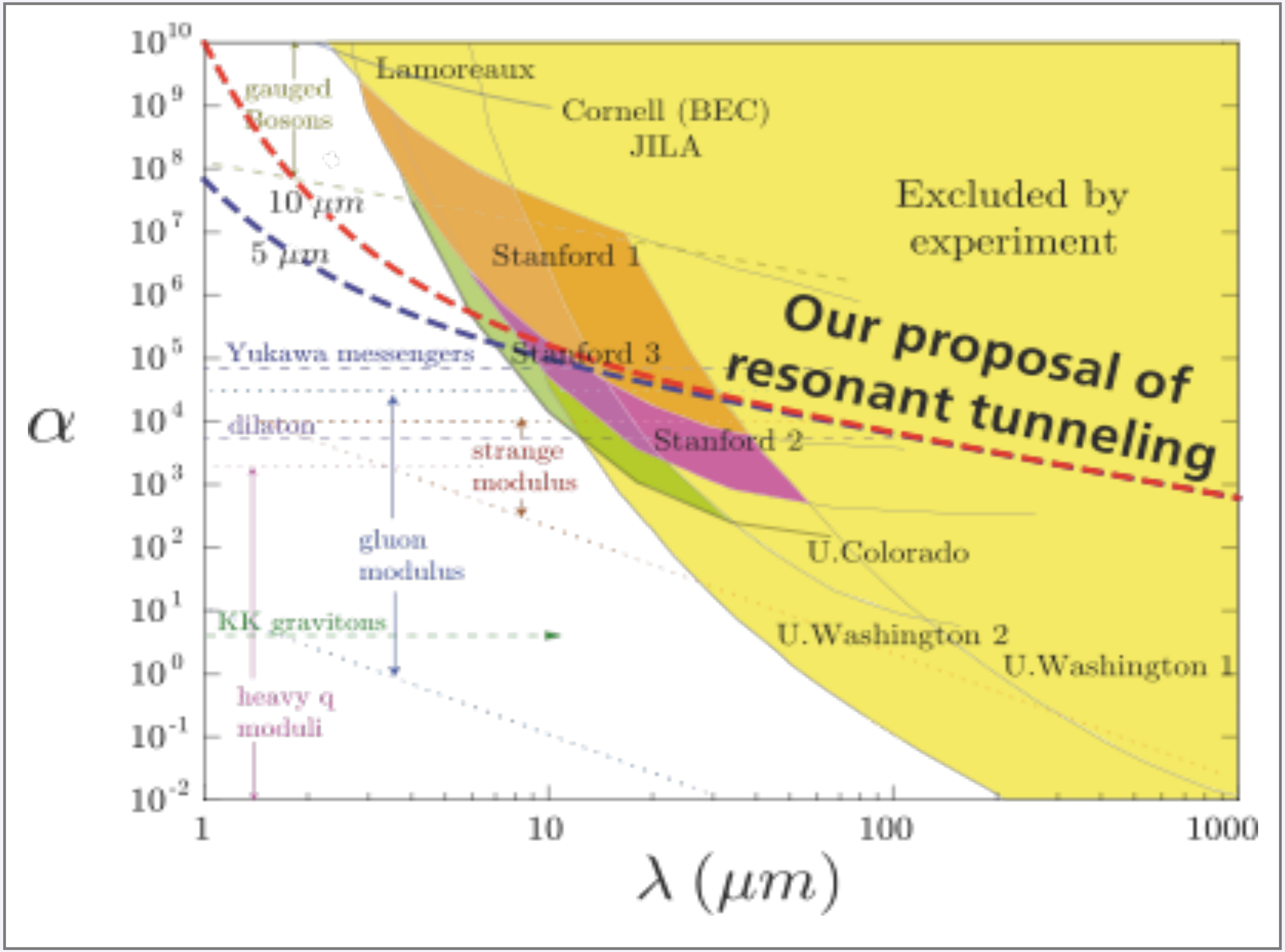
Vertical position fluctuations: 3 µm rms



•Vertical size reduced to 4 µm with an optical tweezer

F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 µm*, **Phys. Rev. A 79, 013409 (2009)**

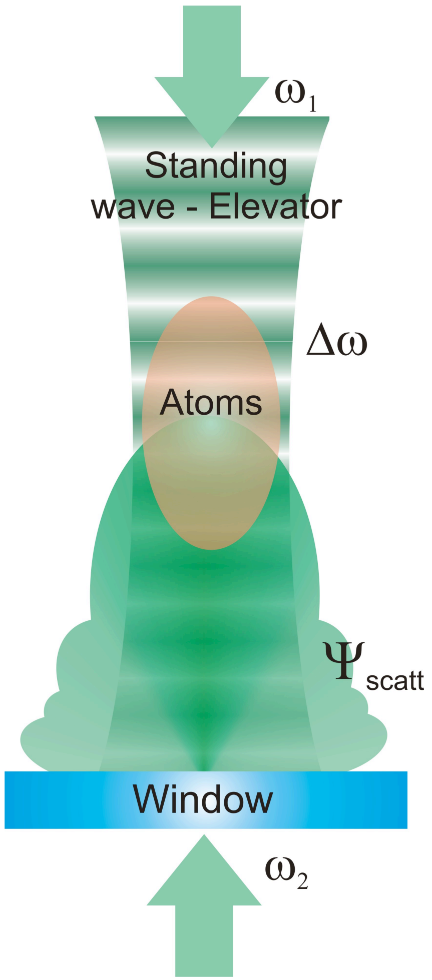
Accessible region with atomic probes



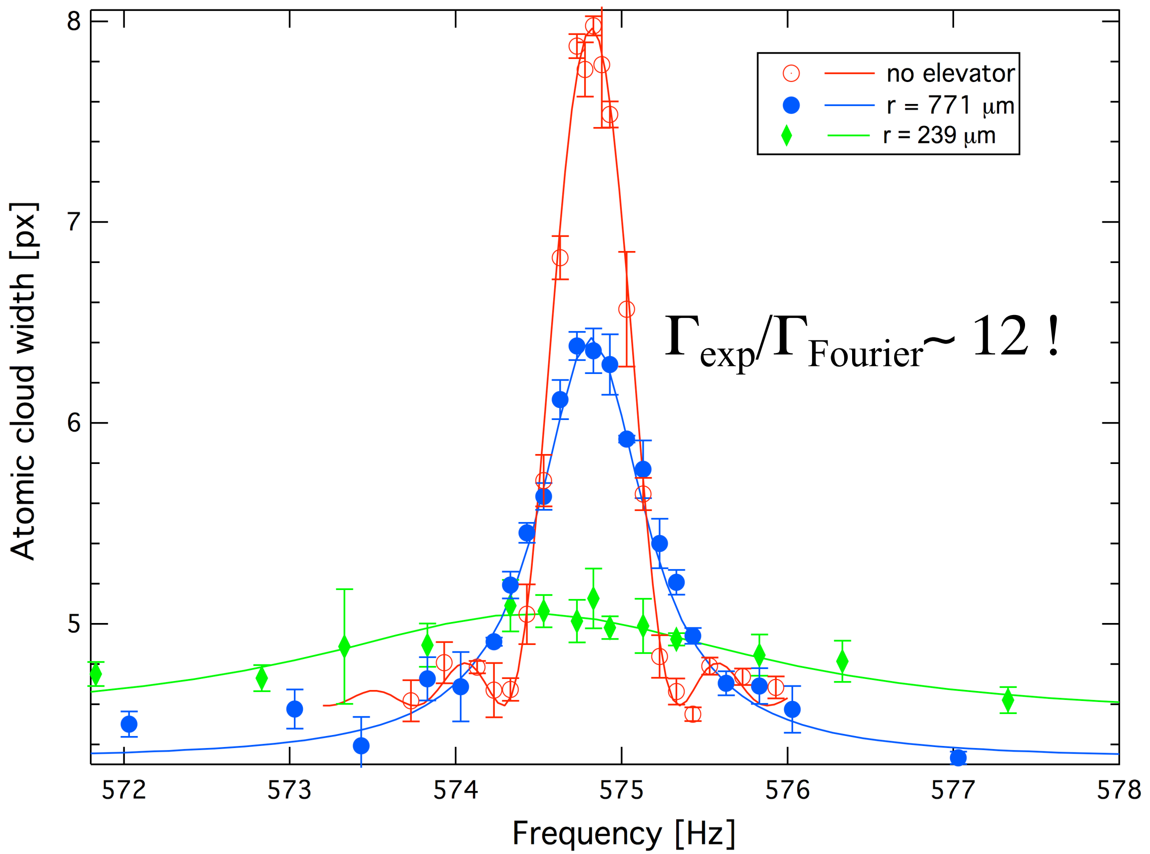
Short-distance measurements

- **Optical elevator** to bring atoms close to a sample surface: trying to measure Casimir-Polder force

⇒ AM measurement close to the surface (preliminary)



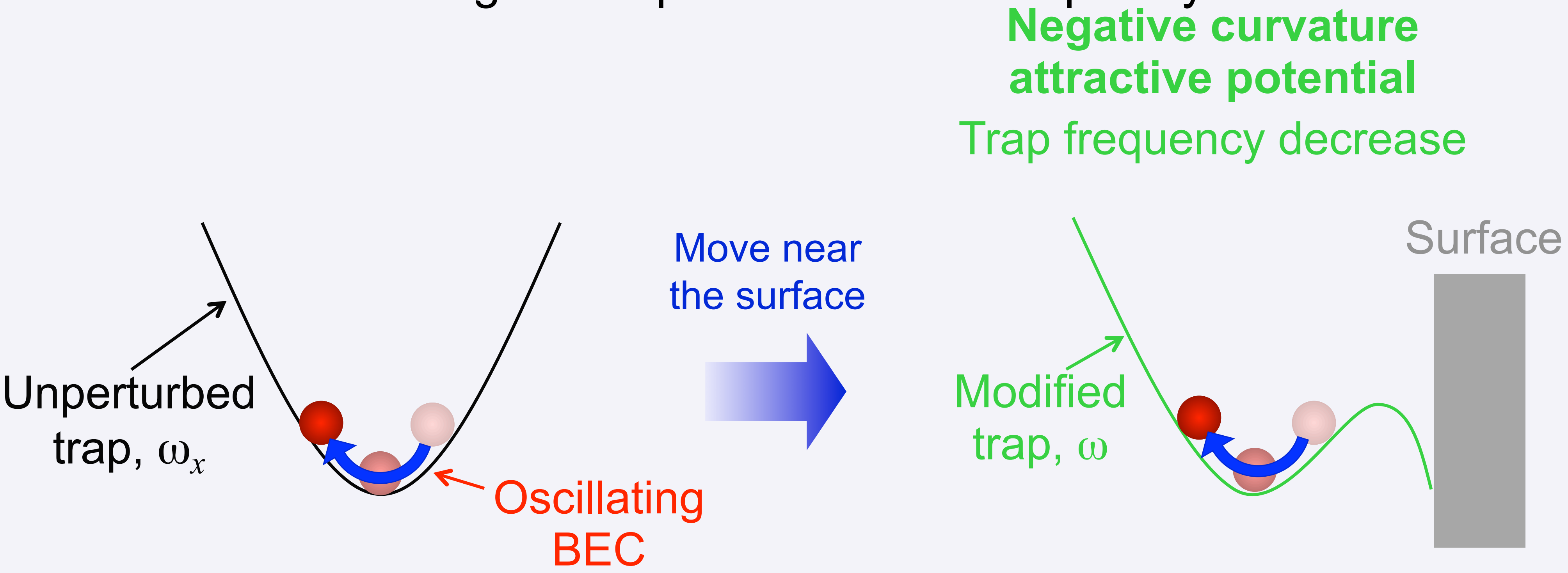
Getting closer:



Measuring atom-surface forces

Use trapped BEC as a mechanical oscillator

Measure changes in dipole oscillation frequency



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

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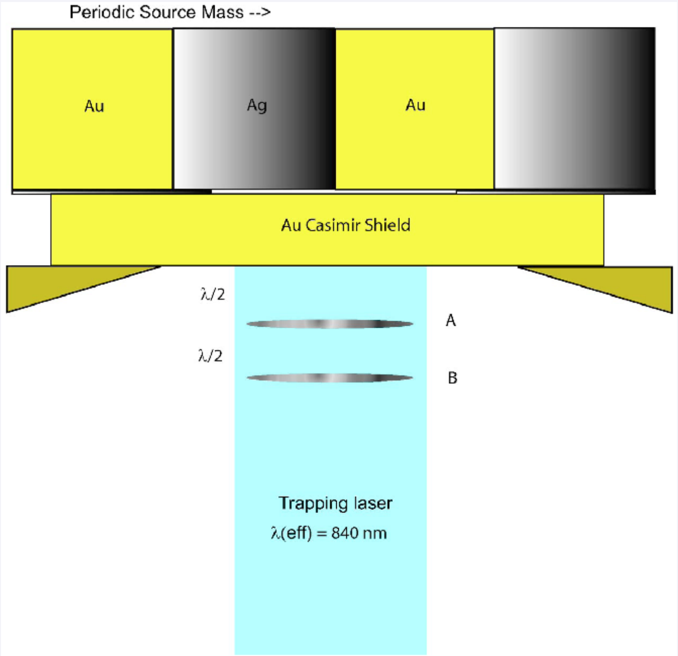
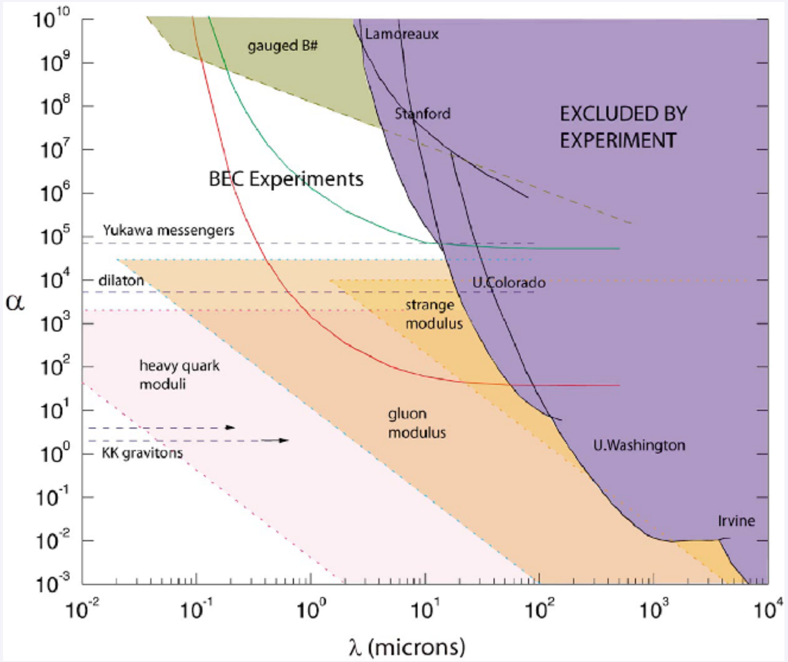
Other proposals





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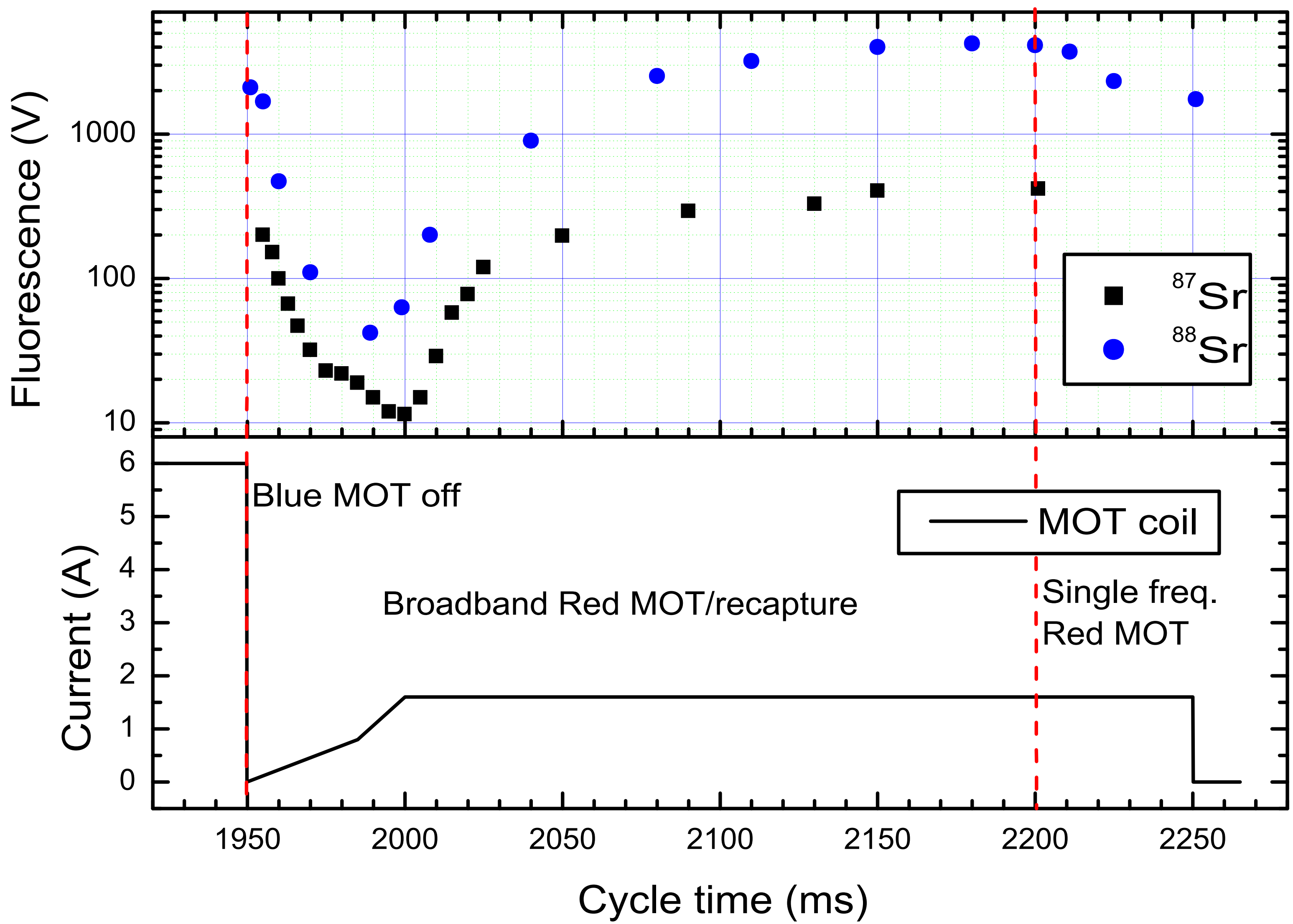
• Peter Wolf, et al., *From Optical Lattice Clocks to the Measurement of Forces in the Casimir Regime*, Phys. Rev. A 75, 063608 (2007)

Simultaneous trapping of ^{88}Sr and ^{87}Sr



STE-QUEST

Space-Time Explorer and Quantum Test of the Equivalence Principle

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STE-QUEST

http://sci.esa.int/ste-quest

Applications of new quantum sensors based on atom interferometry

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

Test of quantum gravity

PRL 103, 171302 (2009) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2009

Constraining the Energy-Momentum Dispersion Relation with Planck-Scale Sensitivity Using Cold Atoms

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We use the results of ultraprecise cold-atom-recoil experiments to constrain the form of the energy-momentum dispersion relation, a structure that is expected to be modified in several quantum-gravity approaches. Our strategy of analysis applies to the nonrelativistic (small speeds) limit of the dispersion relation, and is therefore complementary to an analogous ongoing effort of investigation of the dispersion relation in the ultrarelativistic regime using observations in astrophysics. For the leading correction in the nonrelativistic limit the exceptional sensitivity of cold-atom-recoil experiments remarkably allows us to set a limit within a single order of magnitude of the desired Planck-scale level, thereby providing the first example of Planck-scale sensitivity in the study of the dispersion relation in controlled laboratory experiments.

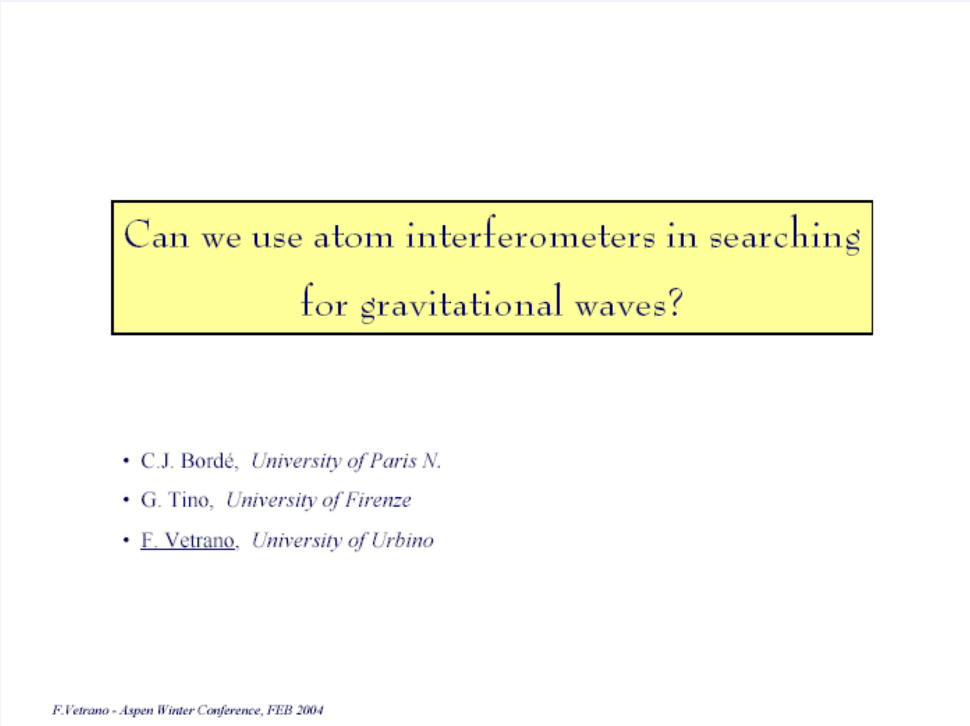
$$E = \sqrt{p^2 + m^2} + \Delta_{QG}(p, m, M_P)$$

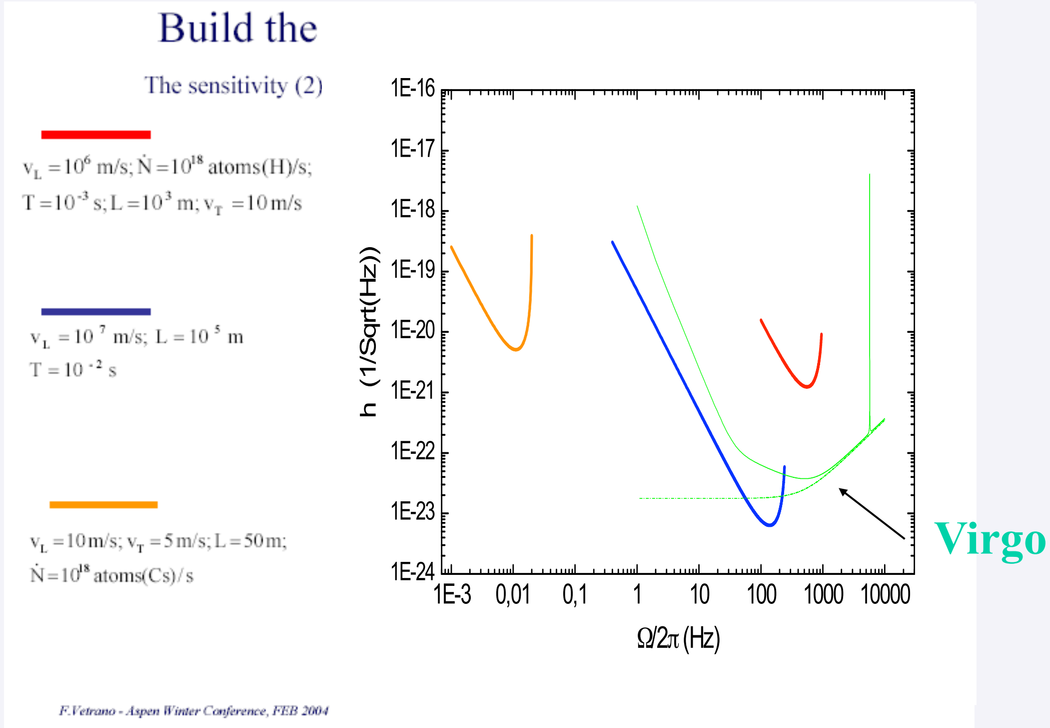
$$E \simeq m + \frac{p^2}{2m} + \frac{1}{2M_P}\left(\xi_1 m p + \xi_2 p^2 + \xi_3 \frac{p^3}{m}\right)$$

$|\xi_1| \sim 1$ to $|\xi_1| \sim 10^3$

$-6.0 < \xi_1 < 2.4$ $|\xi_2| \lesssim 10^9$

Gravitational wave detection





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October 14, 2008

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Gravitational Waves Detection with Atom Interferometry

Conference

Apply   Schedule

Organizers:

Guglielmo M. Tino, University of Firenze, Italy Flavio Vetrano, University of Urbino, Italy

Period: from 23-02-2009 to 24-02-2009

Deadline: 15-01-2009

Note: The number of participants is limited to 50 The participation fee for the Workshop is 150 Euros including registration, coffee-breaks, lunches and the social dinner. The fee should be paid cash on arrival at the registration desk

Abstract

The possibility of using atom interferometers to detect gravitational waves is attracting increasing interest as an alternative to other detectors. Several papers were published discussing theoretical and experimental aspects. Although the results show that dedicated technological developments are still needed to achieve the required sensitivity values which are beyond those presently available, new schemes for atom interferometers, beam splitters and high flux coherent atomic sources could lead to an increase in sensitivity and make atom interferometers competitive with other gravitational wave detectors. The Workshop on "Gravitational Waves Detection with Atom Interferometry" will bring together scientists interested in theoretical and experimental

Special issue on
Gravitational Waves Detection with Atom Interferometry
G.M. Tino, F. Vetrano, C. Laemmerzahl Editors,
General Relativity and Gravitation **43**, 1901 (2011)

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International School of Physics "Enrico Fermi"

Summer Course 2013 - "*Atom Interferometry*"

Varenna, 14 - 20 July 2013

Directors: G. M. Tino (Università di Firenze), M. A. Kasevich (Stanford University)

G. Tino team members

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Quentin Bodart	Post-doc, Università di Firenze/ESA
Yu-Hung Lien	Post-doc, Università di Firenze/ICTP
Marco Schioppo	Post-doc, LENS
Marco Tarallo	Post-doc, LENS
Gabriele Rosi	Post-doc, Università di Firenze
Denis Sutyrin	PhD student, Università di Pisa
Tommaso Mazzoni	Diploma student, Università di Firenze
Luigi Cacciapuoti	Long term guest, ESA-Noordwijk
Marella de Angelis	Long term guest, CNR
Marco Prevedelli	Long term guest, Università di Bologna
Elisa Tonelli	Secretary

Previous members and visitors

Andrea Alberti, PhD student
Andrea Bertoldi, Post-doc
Sergei Chepurov, Institute of Laser Physics, Novosibirsk, visitor
Robert Drullinger, NIST, Long term guest
Marco Fattori, PhD student
Gabriele Ferrari, Researcher, INFM/CNR
Antonio Giorgini, PhD and Post-doc
Vladyslav Ivanov, Post-doc
Marion Jacquey, Post-doc
Giacomo Lamporesi, PhD student
Chris Oates, NIST, visitor
Torsten Petelski, PhD student
Juergen Stuhler, Post-doc
Fu-Yuan Wang, Post-doc, Università di Firenze/ICTP

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