Precision gravity measurements with cold atom interferometry

Guglielmo M. Tino

Dipartimento di Fisica & Astronomia e LENS – Università di Firenze

Istituto Nazionale di Fisica Nucleare, Sezione di Firenze

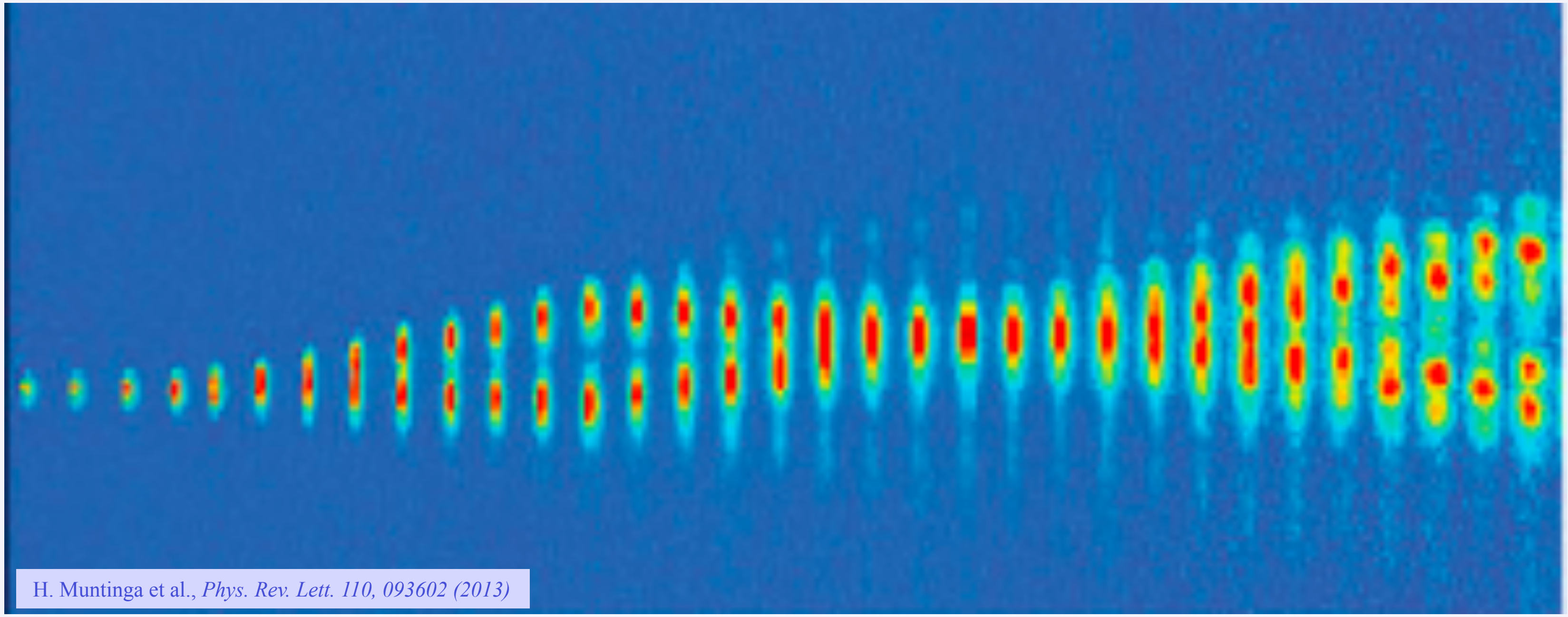
http://coldatoms.lens.unifi.it/

Workshop *Quantum Theory and Gravity: Which Way?*
LNF-INFN, 18 December 2014

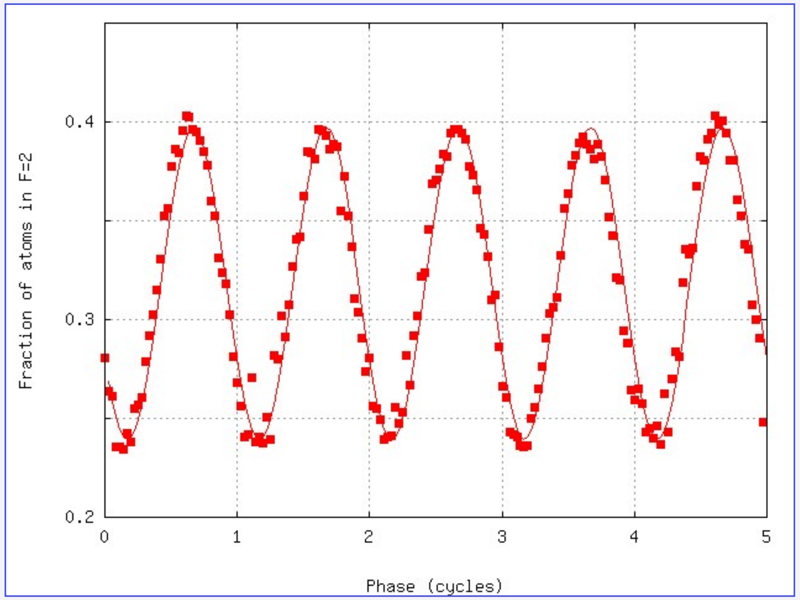
Outline

- *Precision measurement of the gravitational constant G with a Rb Raman interferometer*
- *Gravity measurement at μm scale with ultracold Sr atoms in an optical lattice*
- *Test of the equivalence principle for 0-spin and half-integer-spin Sr atoms: Search for spin-gravity coupling effects*
- *Measurement of the gravity-field curvature by atom interferometry*
- *Prospects*

Atom Interferometry



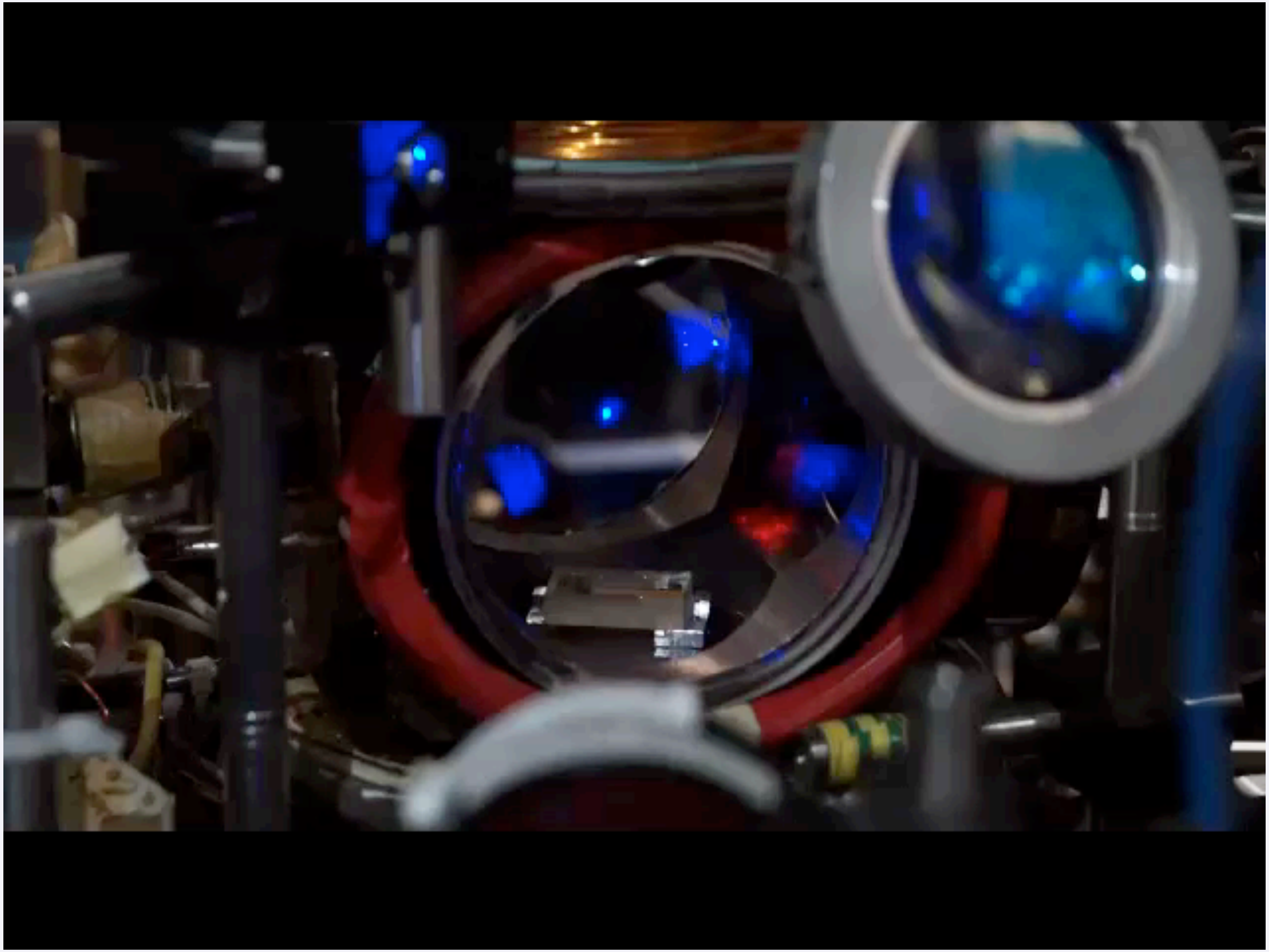
H. Muntinga et al., *Phys. Rev. Lett. 110, 093602 (2013)*



Interference fringes – Firenze 2006

Sr Magneto-Optical Trap (MOT)

LENS - Firenze



Laser cooling: Atomic temperatures

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

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

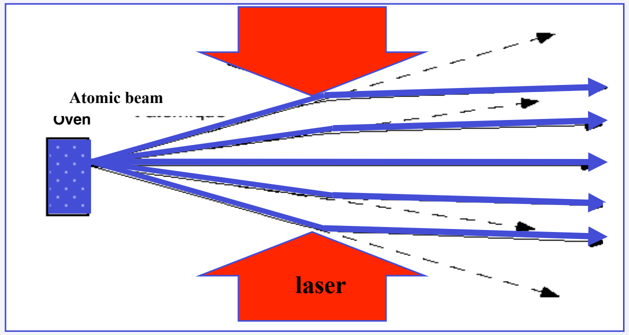
Single photon recoil temperature: $\boxed{k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2}$

Examples:

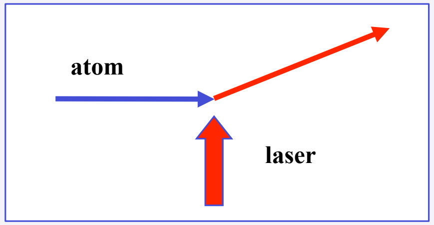
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK
Sr (**intercombination transition**)	180 nK	460 nK

Atom optics

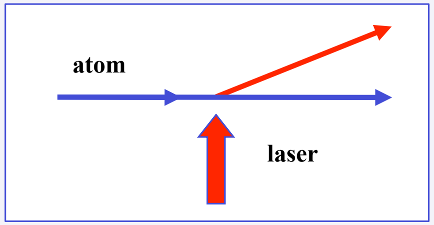
lenses



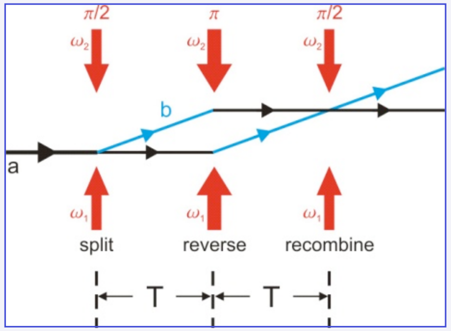
mirrors



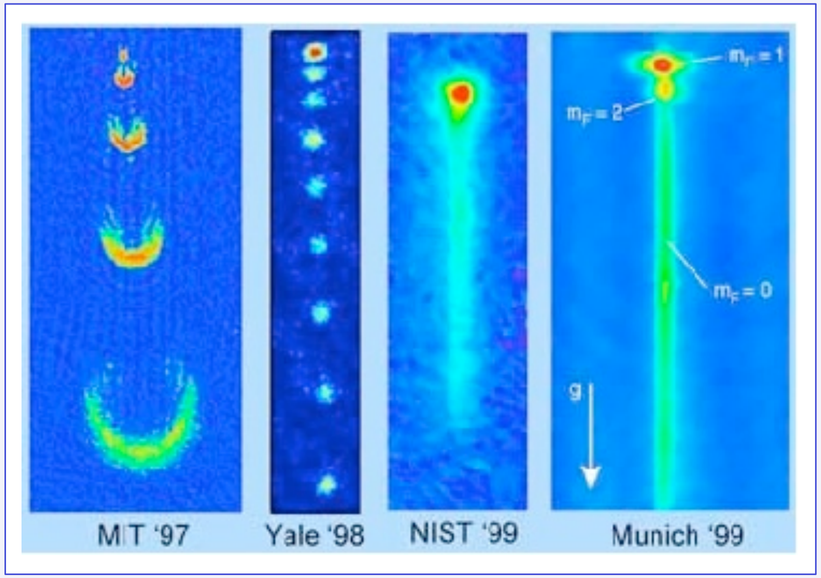
beam-splitters



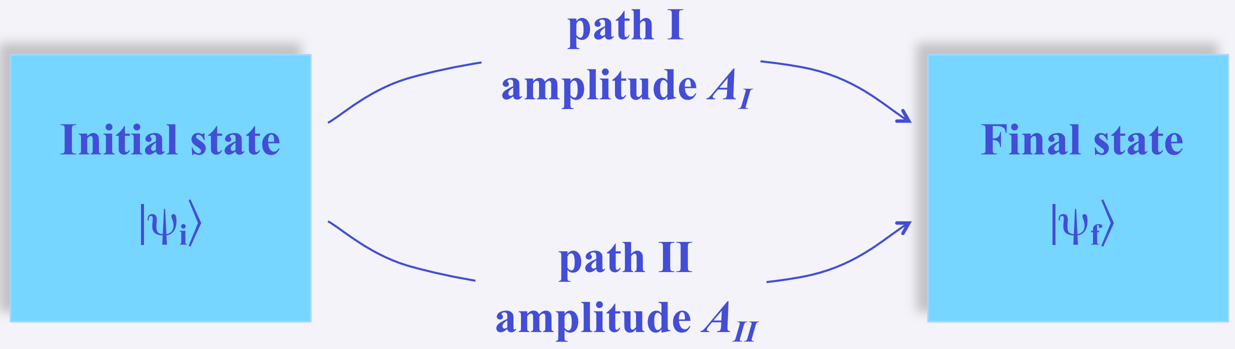
interferometers



atom laser



Quantum interference



Initial state

$|\psi_i\rangle$

path I

amplitude A_I

path II

amplitude A_{II}

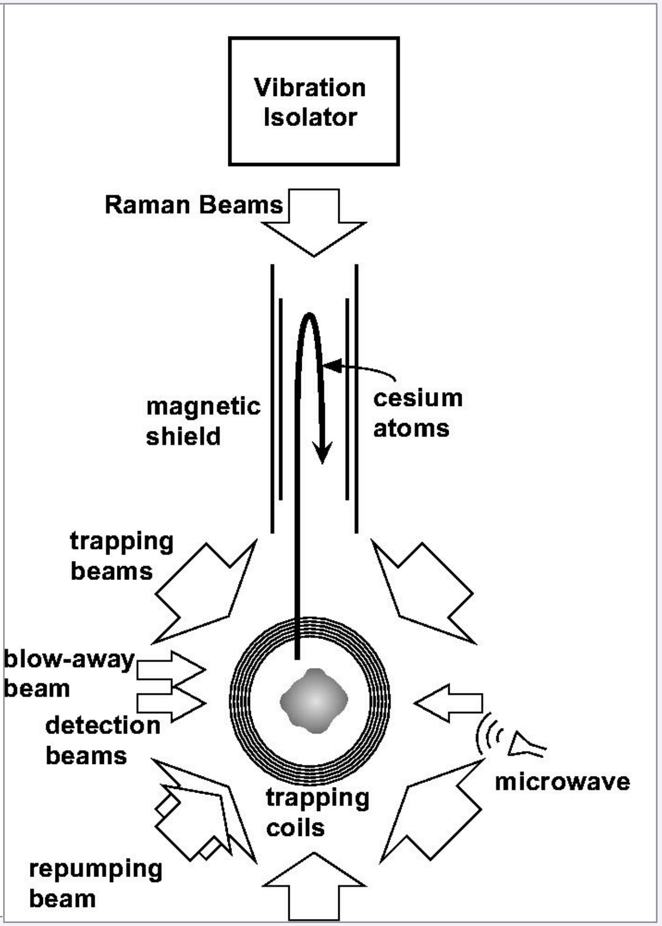
Final state

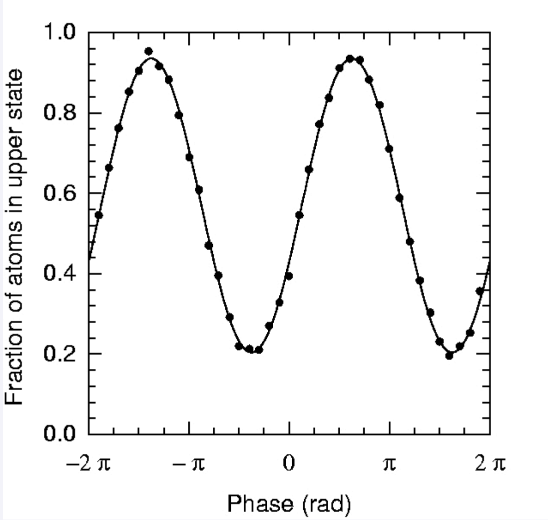
$|\psi_f\rangle$

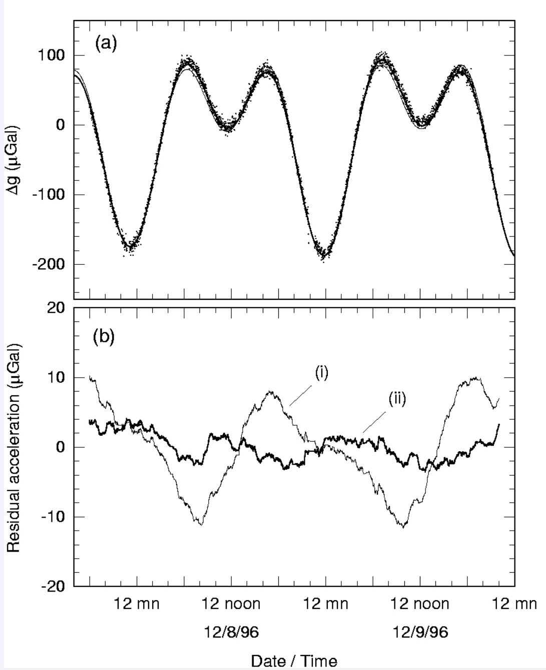
Interference of transition amplitudes

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

Stanford atom gravimeter







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

Absolute accuracy: Δg/g<3x10^{-9}

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

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **20** (2009) 022001 (16pp) doi:10.1088/0957-0233/20/2/022001

TOPICAL REVIEW

Precision gravimetry with atomic sensors

M de Angelis[1,2], A Bertoldi[3], L Cacciapuoti[4], A Giorgini[2,5], G Lamporesi[6], M Prevedelli[7], G Saccorotti[8], F Sorrentino[2] and G M Tino[2]

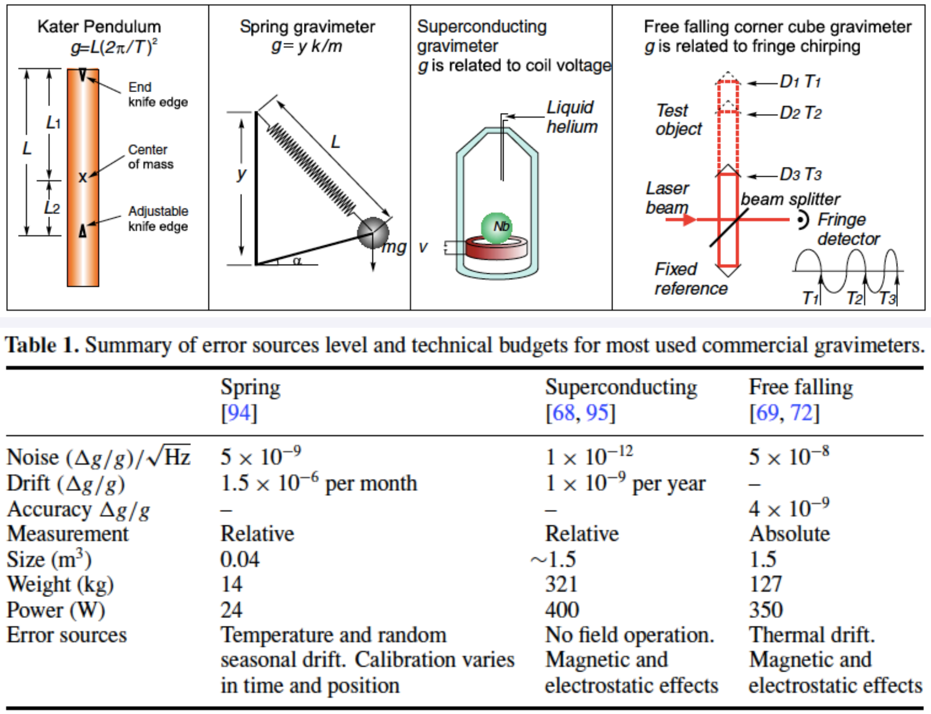


Table 1. Summary of error sources level and technical budgets for most used commercial gravimeters.

	Spring [94]	Superconducting [68, 95]	Free falling [69, 72]
Noise $(\Delta g/g)/\sqrt{\mathrm{Hz}}$	5×10^{-9}	1×10^{-12}	5×10^{-8}
Drift $(\Delta g/g)$	1.5×10^{-6} per month	1×10^{-9} per year	–
Accuracy $\Delta g/g$	–	–	4×10^{-9}
Measurement	Relative	Relative	Absolute
Size (m^3)	0.04	~1.5	1.5
Weight (kg)	14	321	127
Power (W)	24	400	350
Error sources	Temperature and random seasonal drift. Calibration varies in time and position	No field operation. Magnetic and electrostatic effects	Thermal drift. Magnetic and electrostatic effects

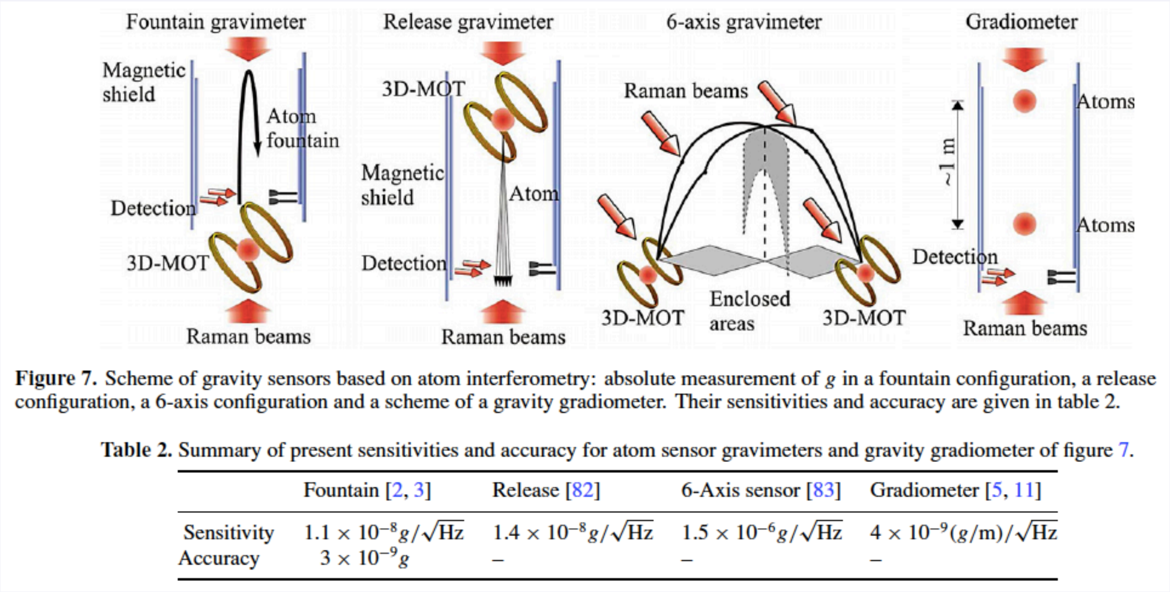


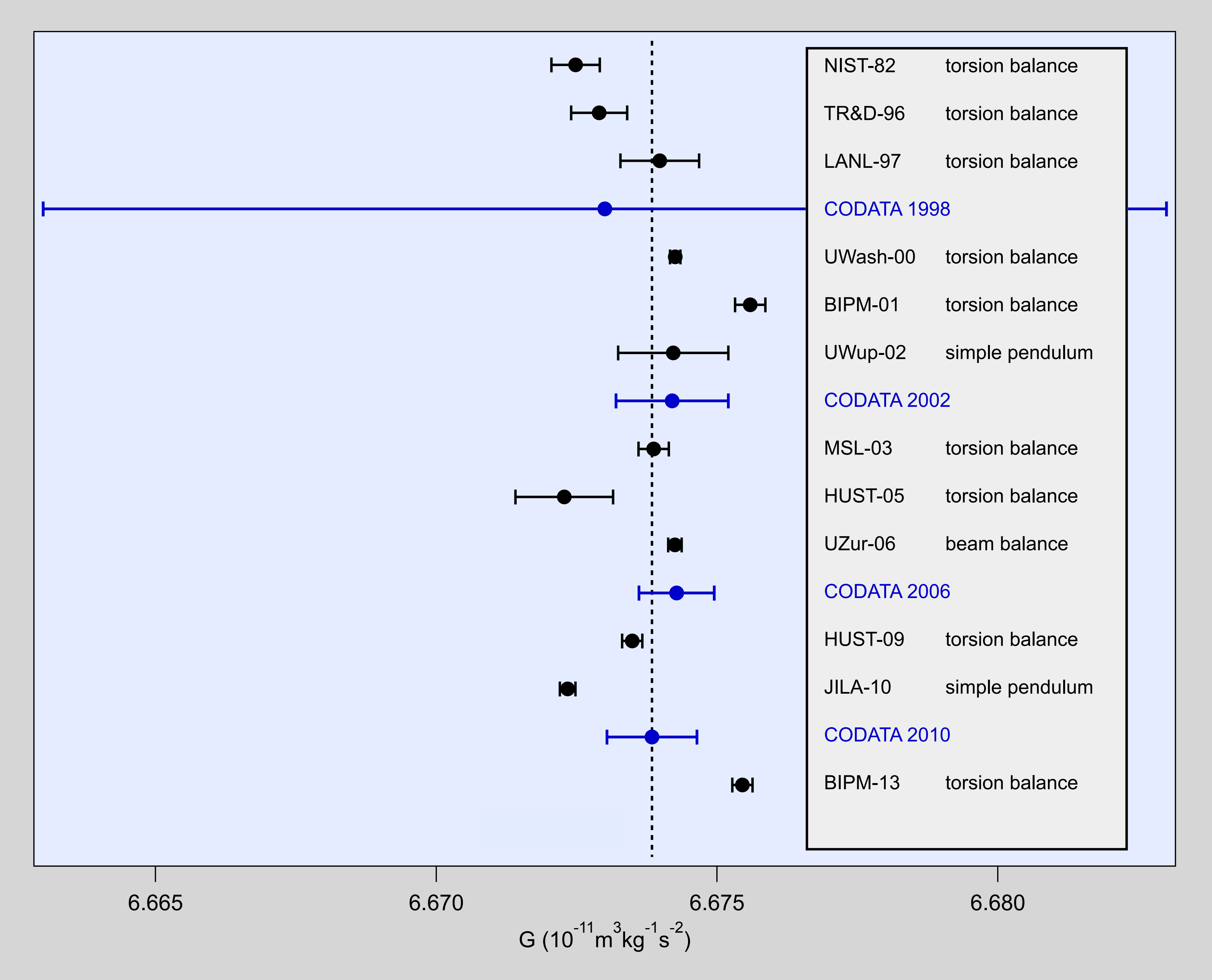
Figure 7. Scheme of gravity sensors based on atom interferometry: absolute measurement of g in a fountain configuration, a release configuration, a 6-axis configuration and a scheme of a gravity gradiometer. Their sensitivities and accuracy are given in table 2.

Table 2. Summary of present sensitivities and accuracy for atom sensor gravimeters and gravity gradiometer of figure 7.

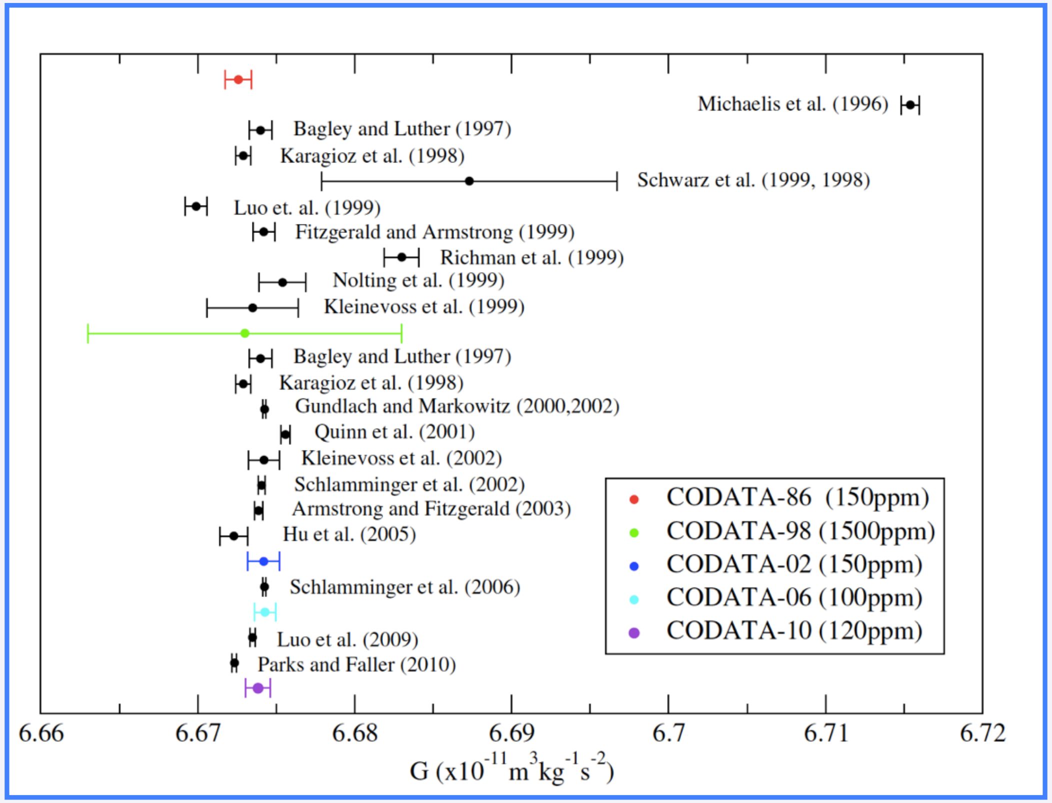
	Fountain [2, 3]	Release [82]	6-Axis sensor [83]	Gradiometer [5, 11]
Sensitivity	$1.1 \times 10^{-8} g/\sqrt{\mathrm{Hz}}$	$1.4 \times 10^{-8} g/\sqrt{\mathrm{Hz}}$	$1.5 \times 10^{-6} g/\sqrt{\mathrm{Hz}}$	$4 \times 10^{-9} (g/\mathrm{m})/\sqrt{\mathrm{Hz}}$
Accuracy	$3 \times 10^{-9} g$	–	–	–

Measurement of the gravitational constant G by atom interferometry

Measurements of the Newtonian gravitational constant G

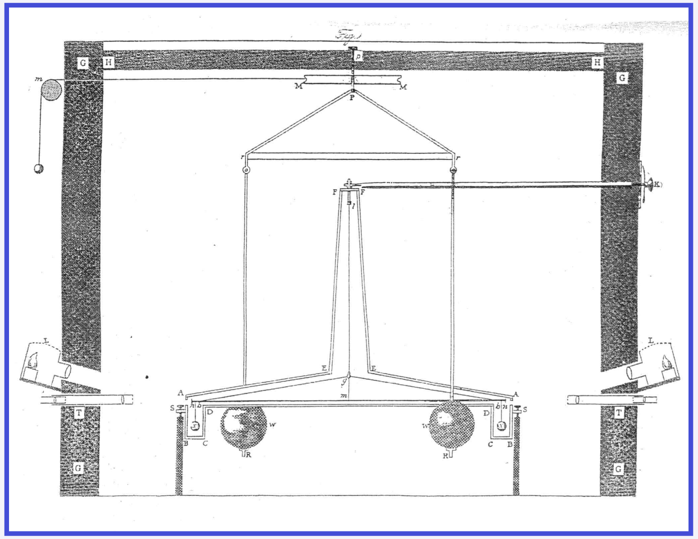


Measurements of the Newtonian gravitational constant G

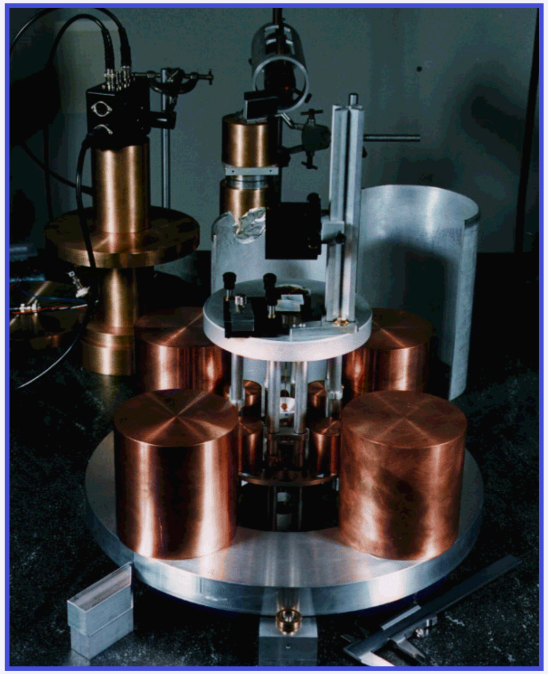


$$G = 6.67384\,(80) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}s^{-2}}$$
$$[1.2\times10^{-4}]$$

P.J. Mohr, B. N. Taylor, and D. B. Newell, *CODATA recommended values of the fundamental physical constants: 2010*, Rev. Mod. Phys., Vol. 84, No. 4, (2012)



Cavendish 1798

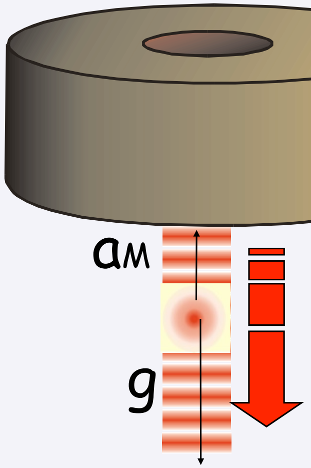


Quinn 2001

MAGIA

(Misura Accurata di G mediante Interferometria Atomica)

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



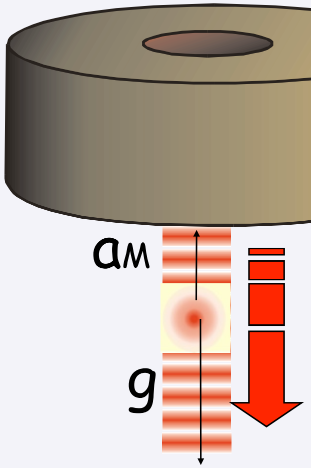
➢ ***Precision measurement of G***

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

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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



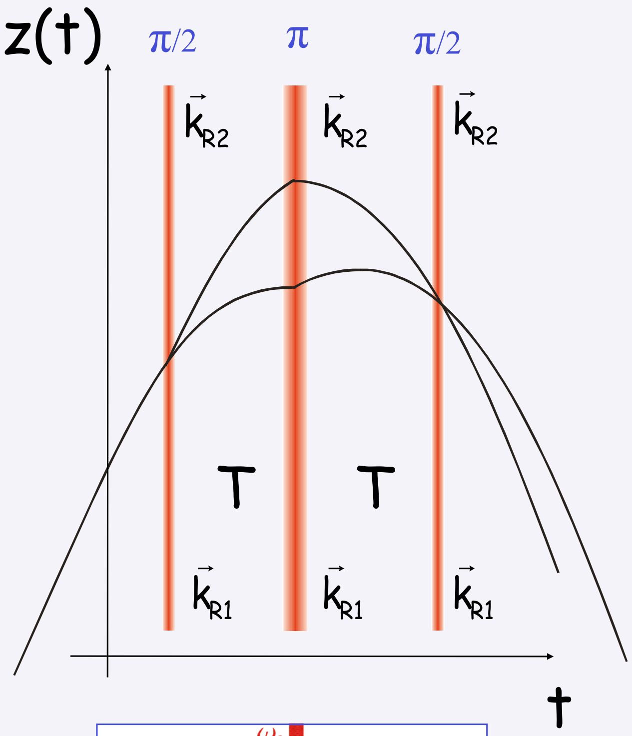
- ***Precision measurement of G***
- ***Test of Newtonian law***

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

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,…

Raman interferometry in an atomic fountain

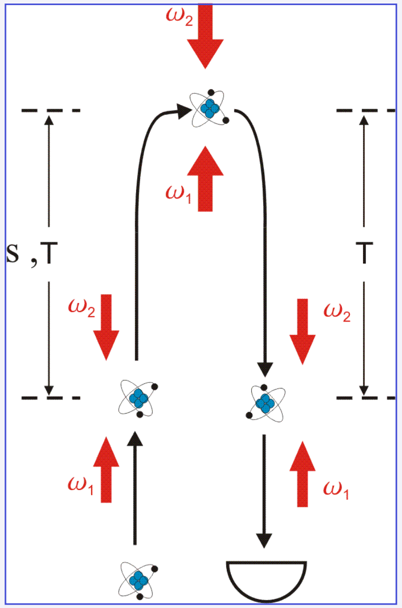


Phase difference between the paths:

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

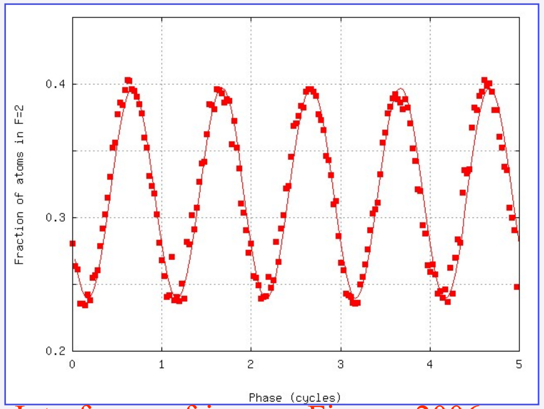
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Rightarrow \mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

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

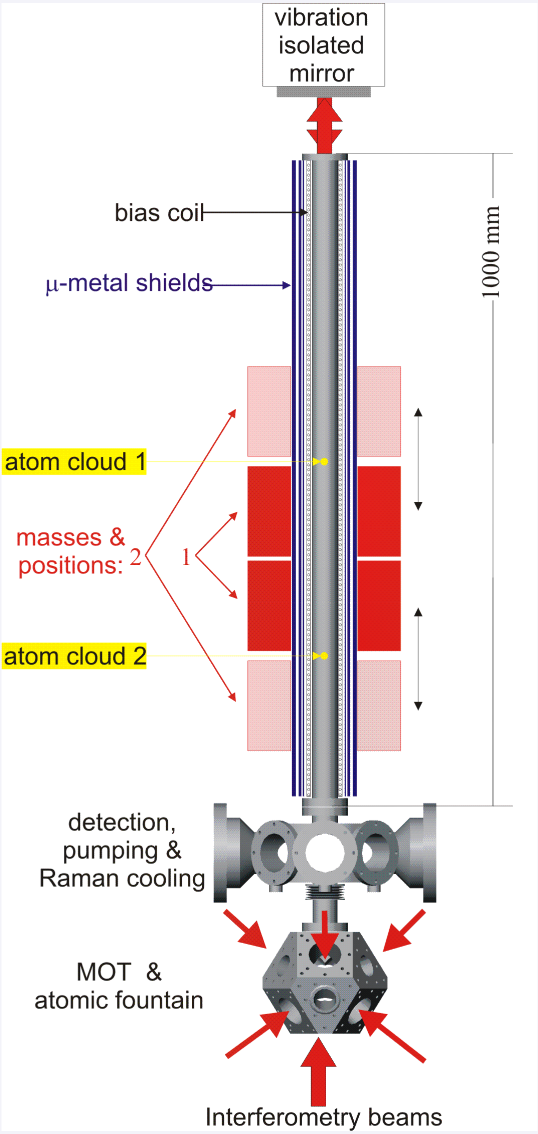
$S/N = 1000$

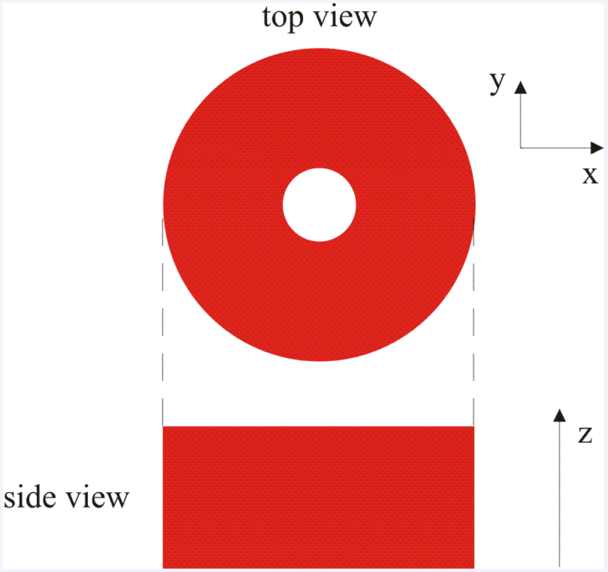
$\Rightarrow$ Sensitivity 10^{-9} g/shot

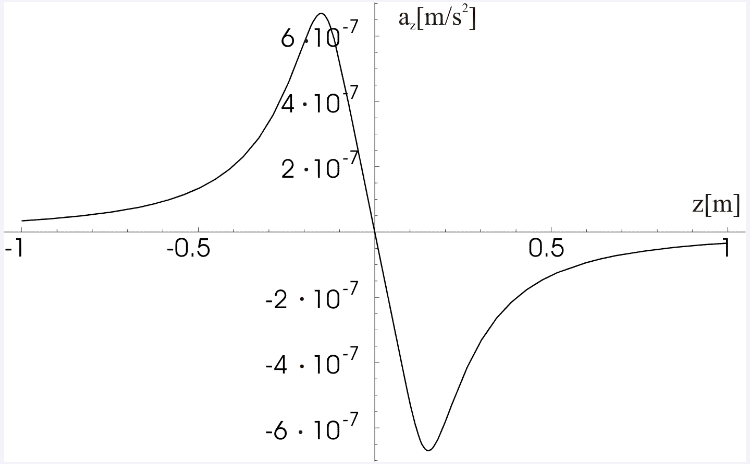
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Atom gravimeter + source mass







500 kg tungsten mass

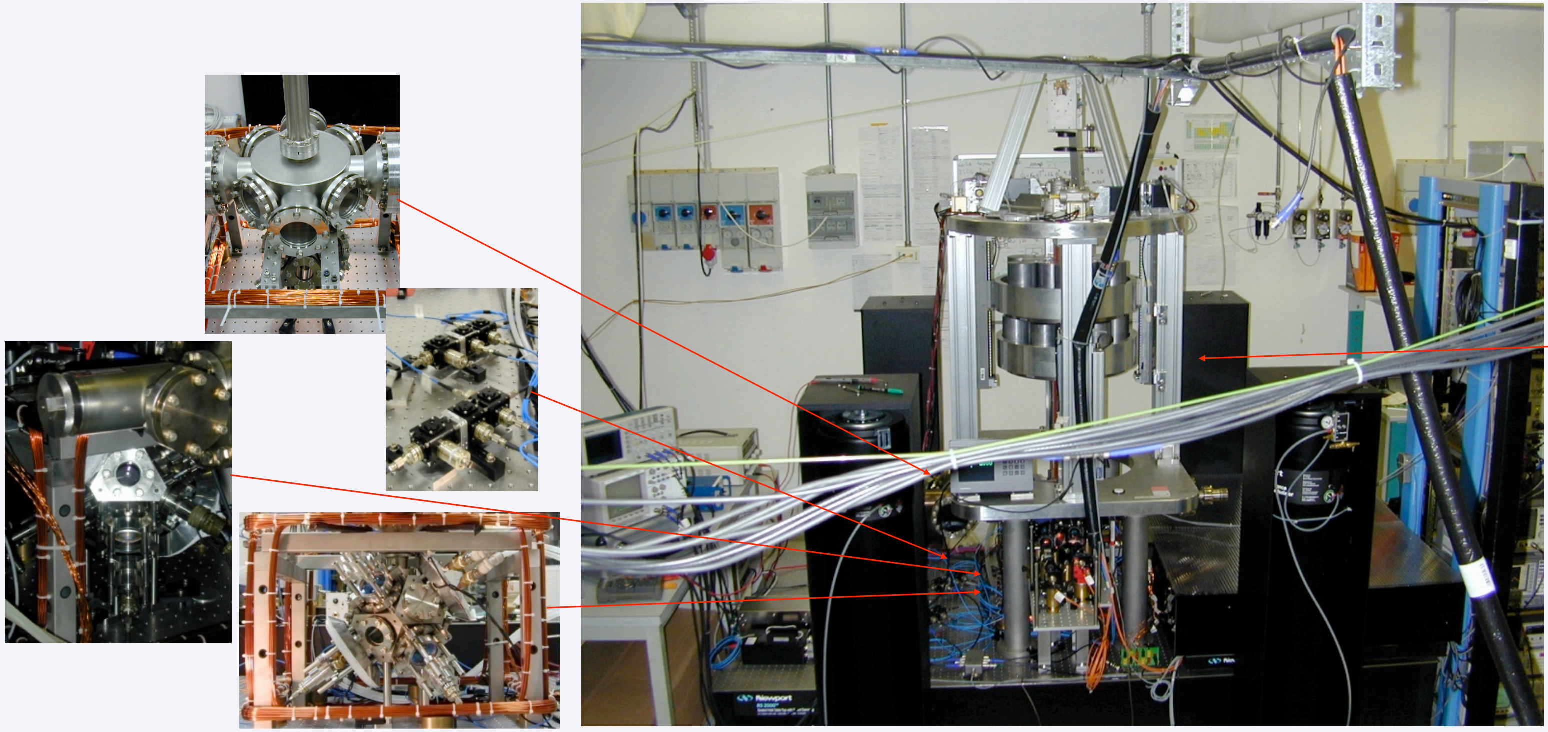
Sensitivity 10^{-9}g/shot

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

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

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

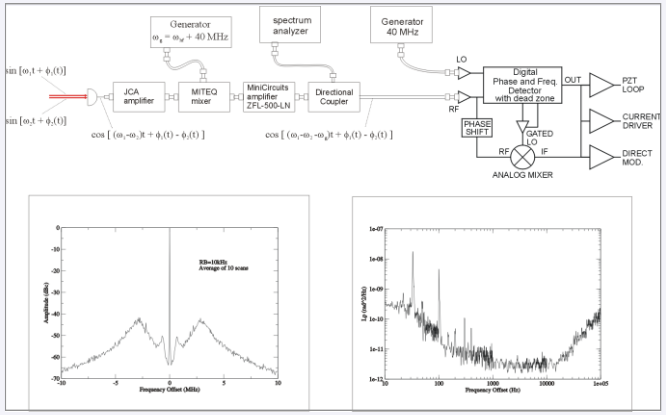
MAGIA apparatus



Source masses and support

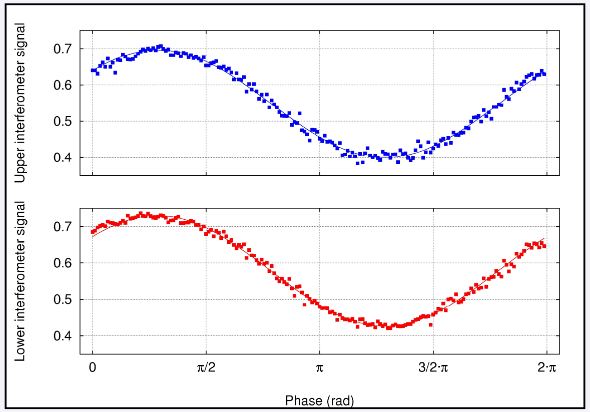
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G,* **Rev. Scient. Instr. 78, 075109 (2007)**

Laser and optical system



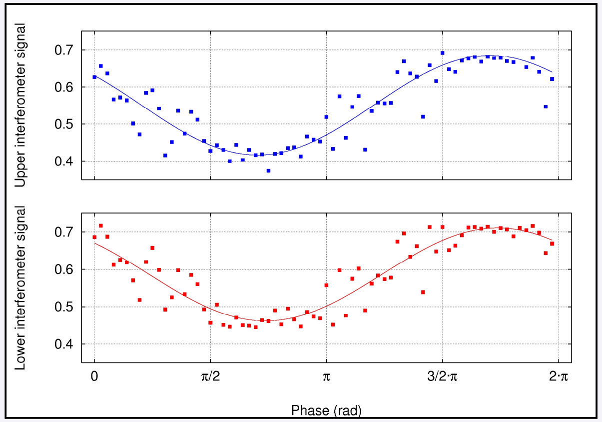
L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* **Rev. Scient. Instr. 76, 053111 (2005)**

Gravity gradiometer



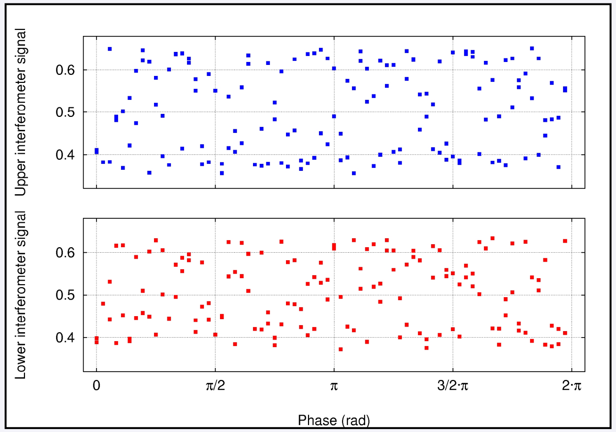
T=5 ms

$\text{resol.} = 2.3 \times 10^{-5}\,\text{g/shot}$



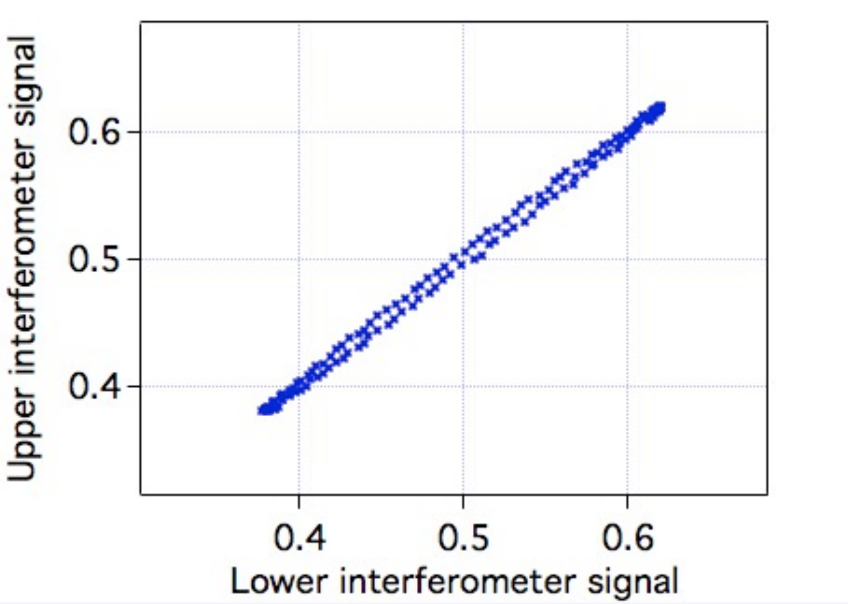
T=50 ms

$\text{resol.} = 1.0 \times 10^{-6}\,\text{g/shot}$

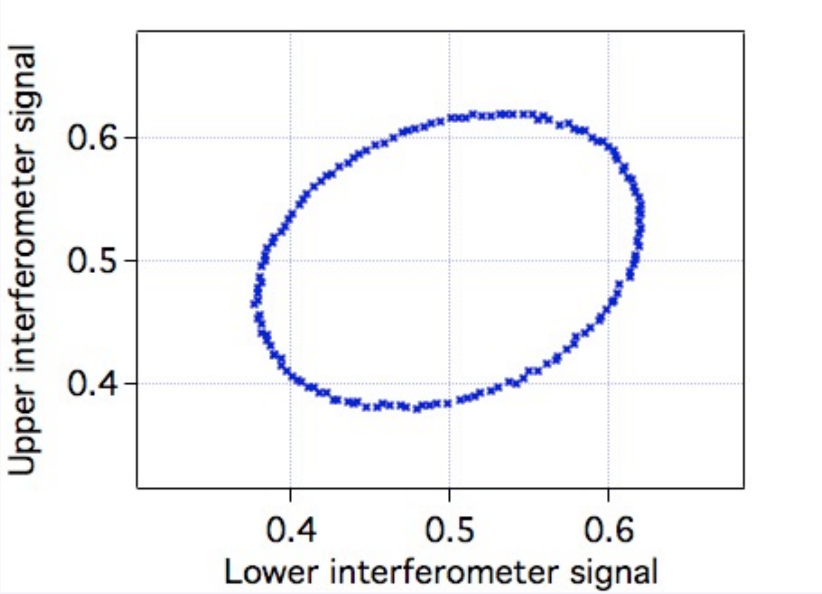


T=150 ms

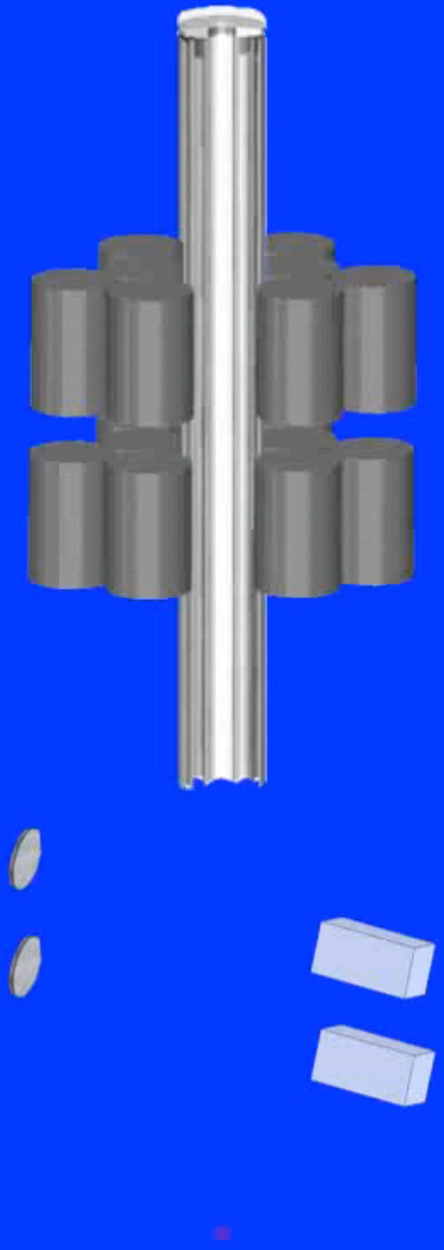
$\text{resol.} = 3.2 \times 10^{-8}\,\text{g/shot}$

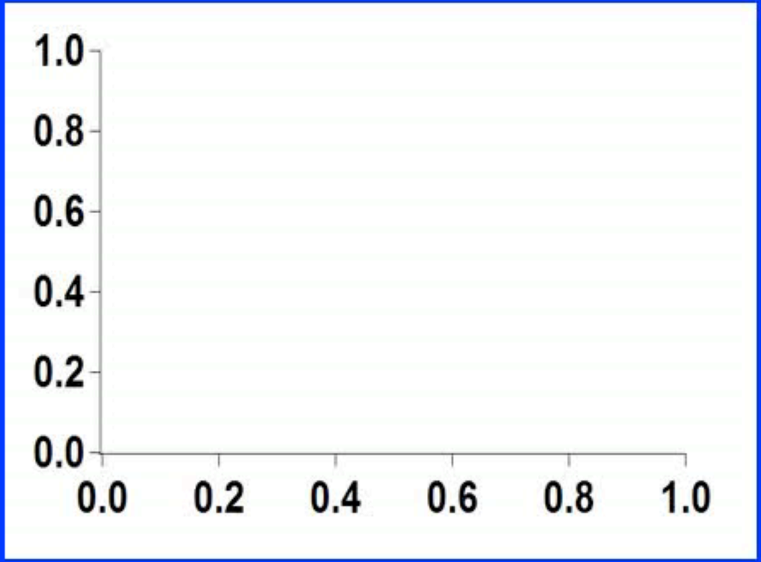


$$\Delta\Phi = k_e g T^2$$



G. T. Foster et al., Opt. Lett **27**, 951 (2002)




1.0
0.8
0.6
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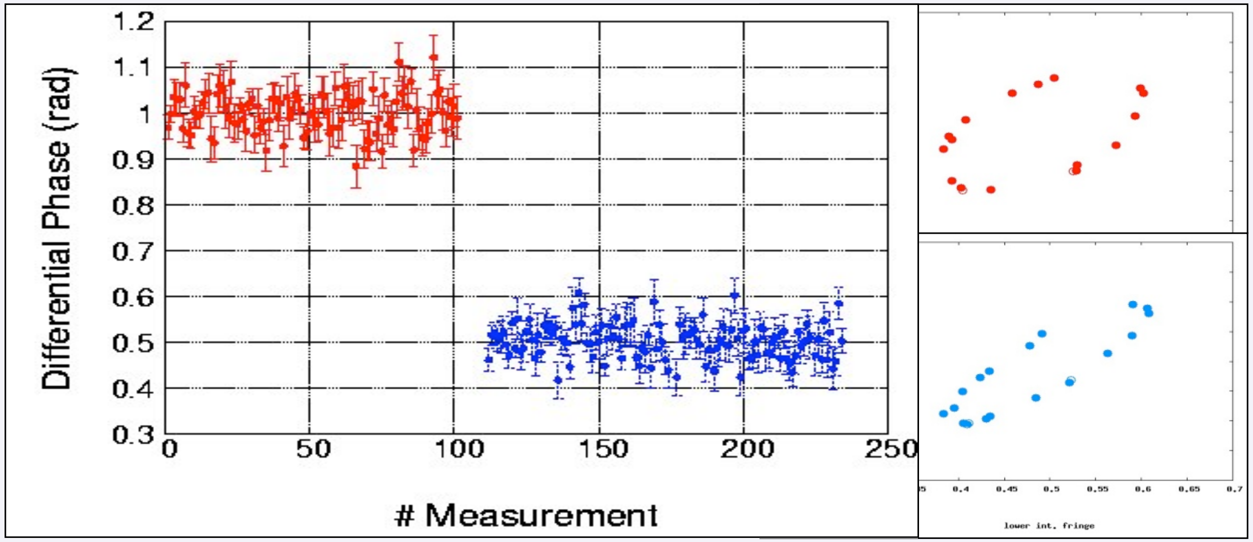
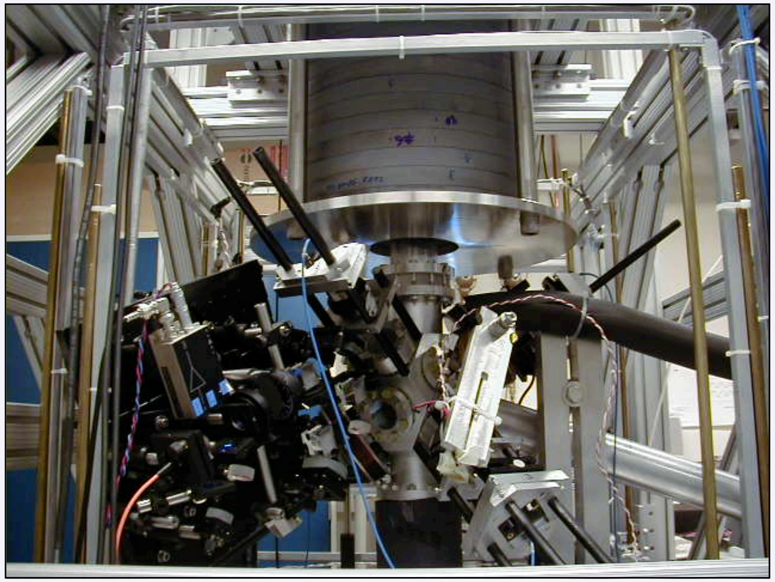
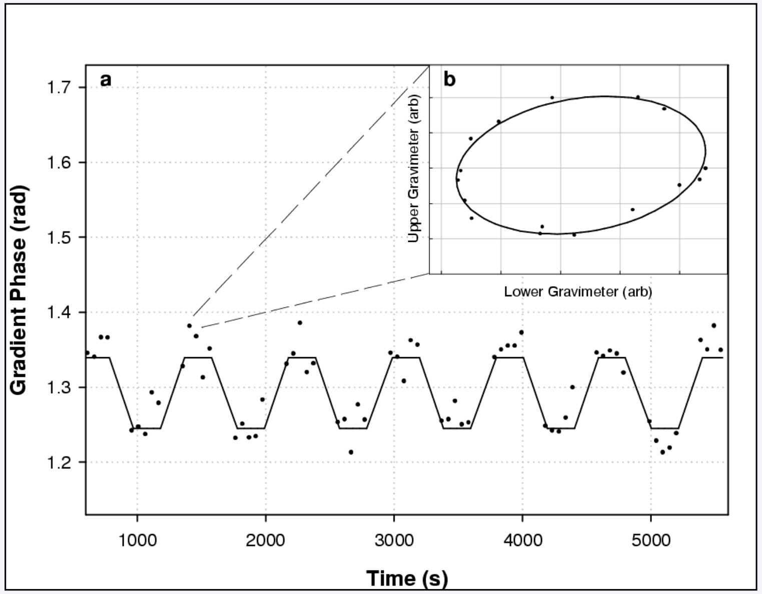
1.0

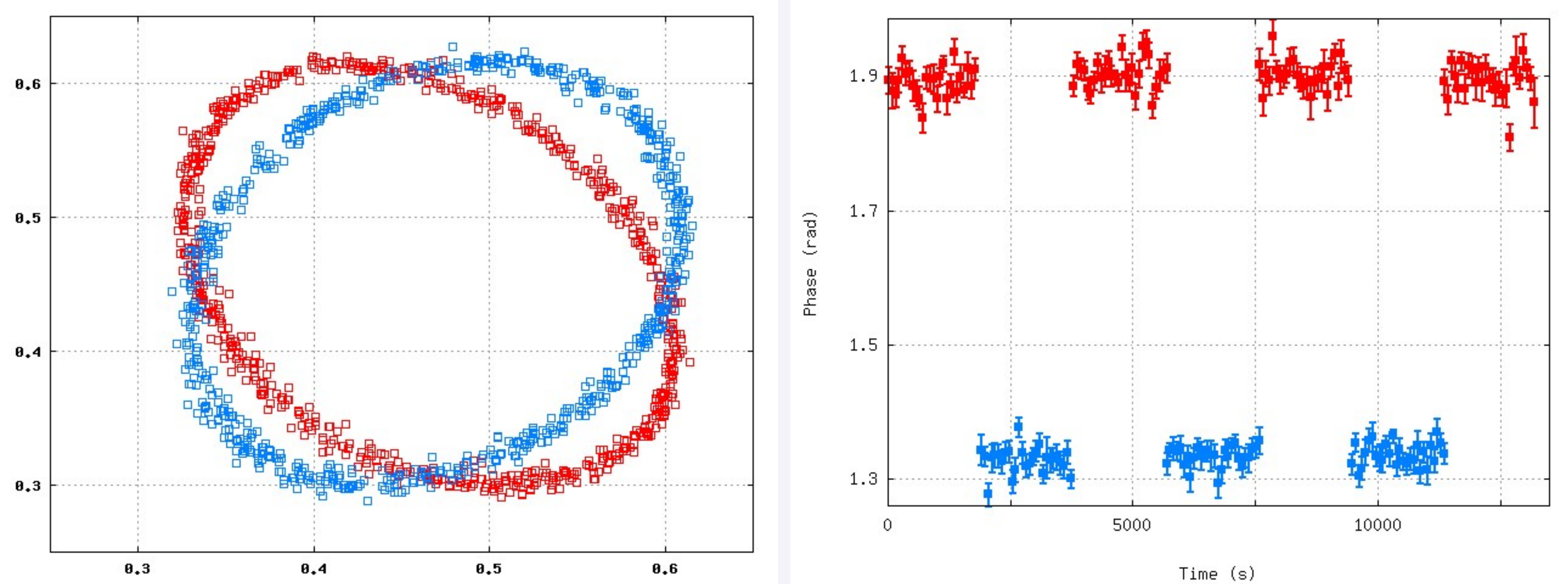


A. Bertoldi G.Lamporesi , L. Cacciapuoti, M. deAngelis, M.Fattori, T.Petelski, A. Peters, M. Prevedelli, J. Stuhler, G.M. Tino,
Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G,
Eur. Phys. J. D 40, 271 (2006)





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)



2007 MAGIA Result

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

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

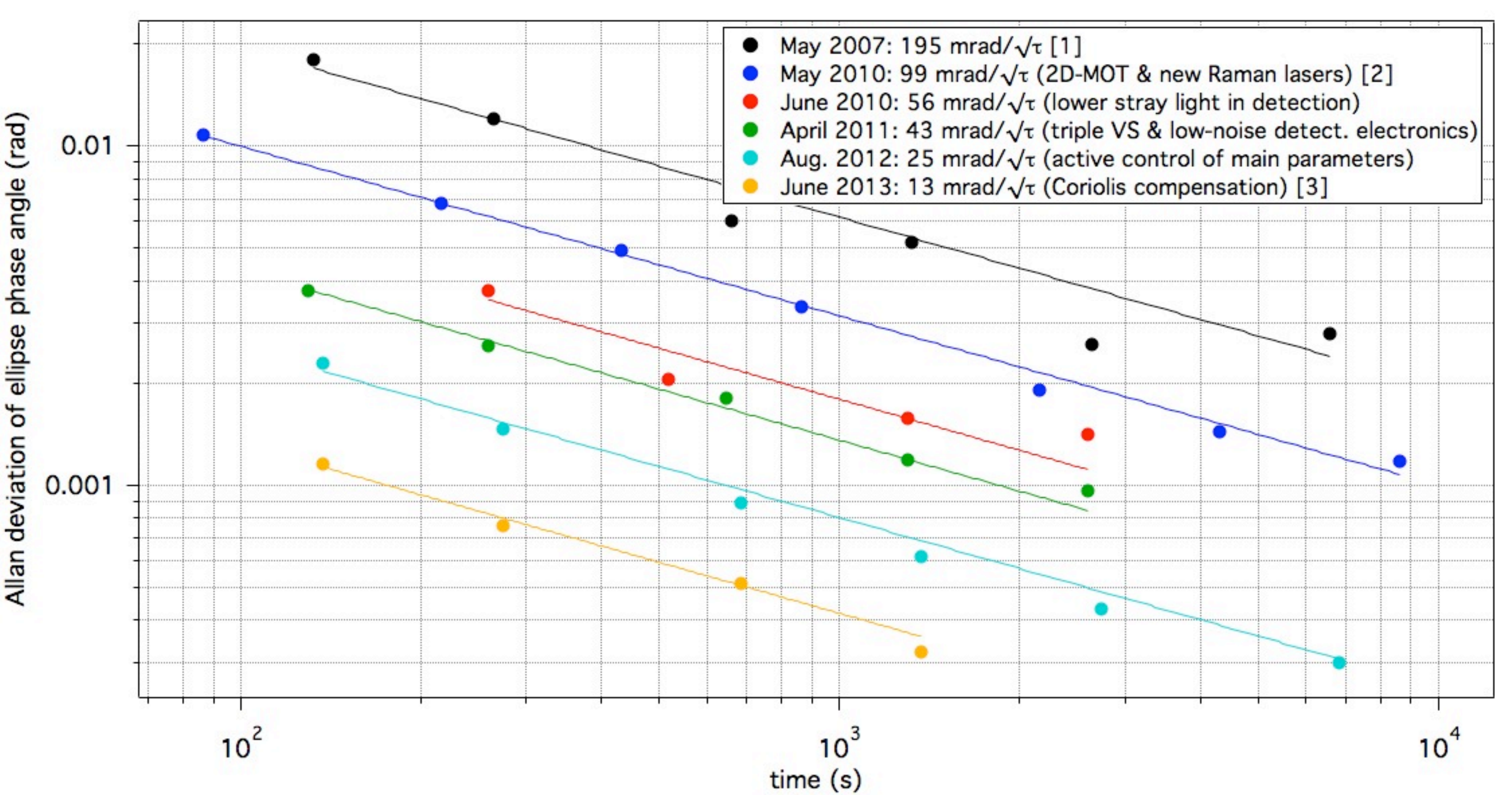
MAGIA: From proof-of-principle to the measurement of G

- Sensitivity
  - 15-fold improvement of the instrument sensitivity from 2008 to 2013
  - integration time for the target 100 ppm reduced by more than a factor 200
- Accuracy
  - systematic uncertainty reduced by a factor ~10 since 2008, mostly due to
    - better characterization of source masses
    - control & mitigation of Coriolis acceleration
    - excellent control of atomic trajectories
- Data analysis
  - developed a reliable model accounting for all of the relevant effects
    - gravitational potential generated by source masses along atomic path
    - quantum mechanical phase shift of atomic probes
    - detection efficiency
  - measured data compared with a Montecarlo simulation

Improving the sensitivity

- Larger number of atoms: 2D-MOT and higher power Raman lasers
- Lower detection noise: minimize stray light and use ultra-low noise electronics
- Larger contrast: remove thermal atoms with better velocity selection
- Lower fluctuations of main experimental parameters
- ...

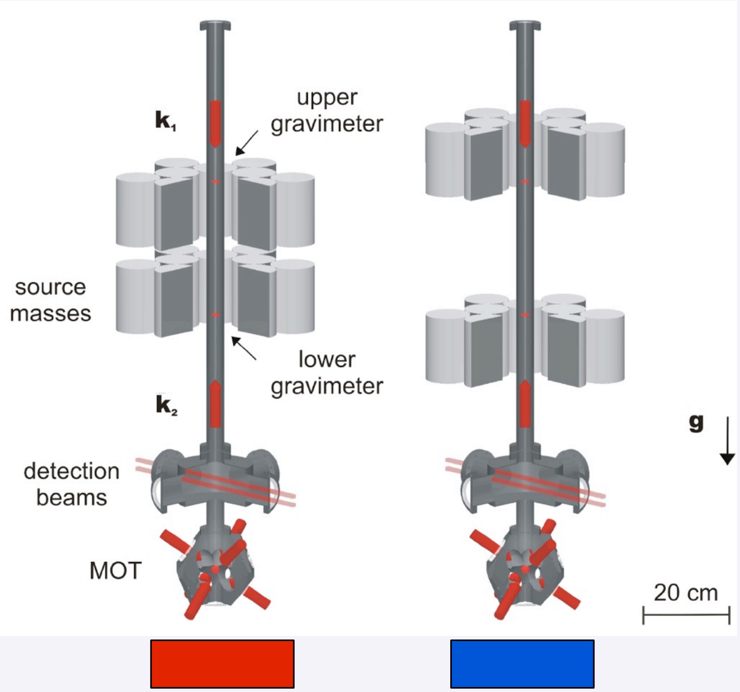
MAGIA: increasing sensitivity



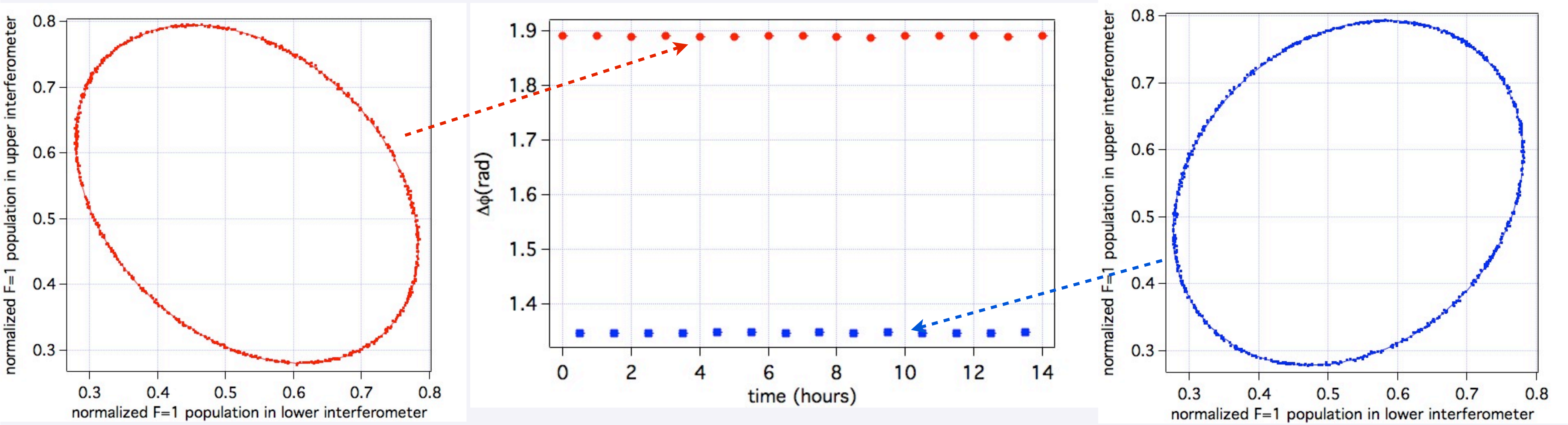
Current sensitivity to differential acceleration: 3×10^{-9} g @ 1s (=QPN for 4×10^5 atoms)

[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)
[2] F. Sorrentino et al., New J. Phys. 12, 095009 (2010)
[3] F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)

MAGIA: Final sensitivity



- Repetition period of experimental cycle: 1.9 s
- Number of points per ellipse: 720 (23 min)
- Number of launched atoms: ~10^9 per cloud
- Number of detected atoms: ~4×10^5 per cloud
- Sensitivity to ellipse angle: ~ 9 mrad/shot
- Sensitivity to differential gravity: 3×10^{-9} g /√Hz
- Sensitivity in *G* measurements: 5.7×10^{-2}/√Hz
- Integration time to *G* at 10^{-4}: 100 hours



MAGIA: Systematics

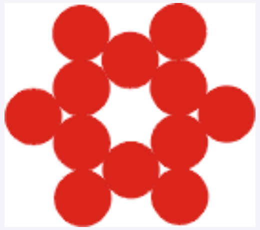
- Precise characterization of source masses (weight, density homogeneity, shape, position)
- Precise characterization of atomic trajectories
- Calibration of relative detection efficiency in the two interferometer outputs
- Removal of k-independent biases (Zeeman shift)
- Removal of k-dependent biases (Coriolis acceleration)

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

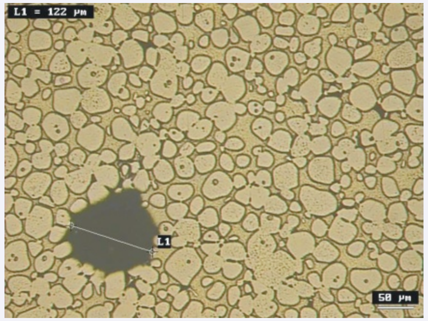
24 cylinders
External radius = 5 cm
Height = 15 cm
Cylinder mass = 20 kg
Total mass ~ 500 kg

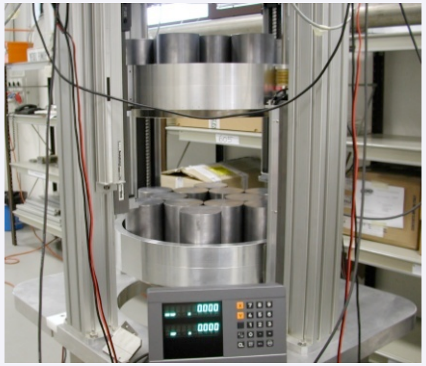


Hot Isostatic Pressing at 1200 C° and 1500 atm

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

Oscillation of cylinders on air cushion reveal radial inhomogeneities



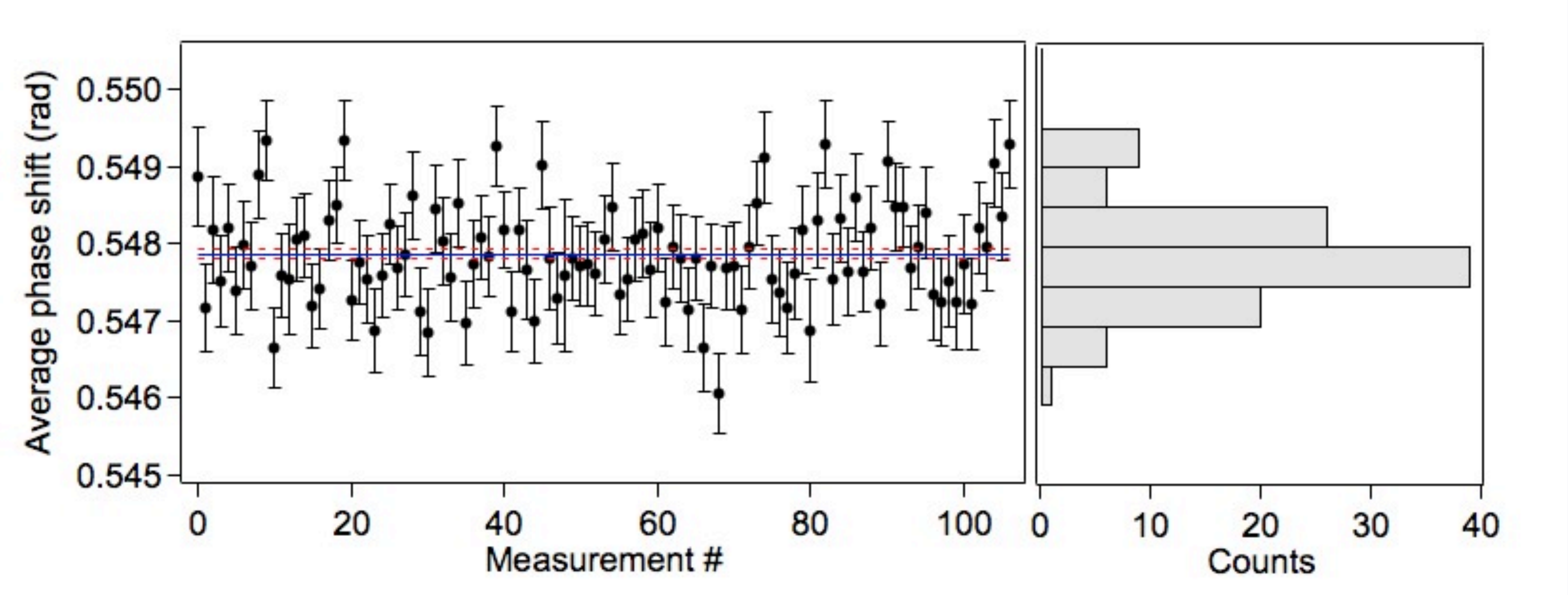


In collaboration with IMGC, Torino

In collaboration with LNF, Frascati

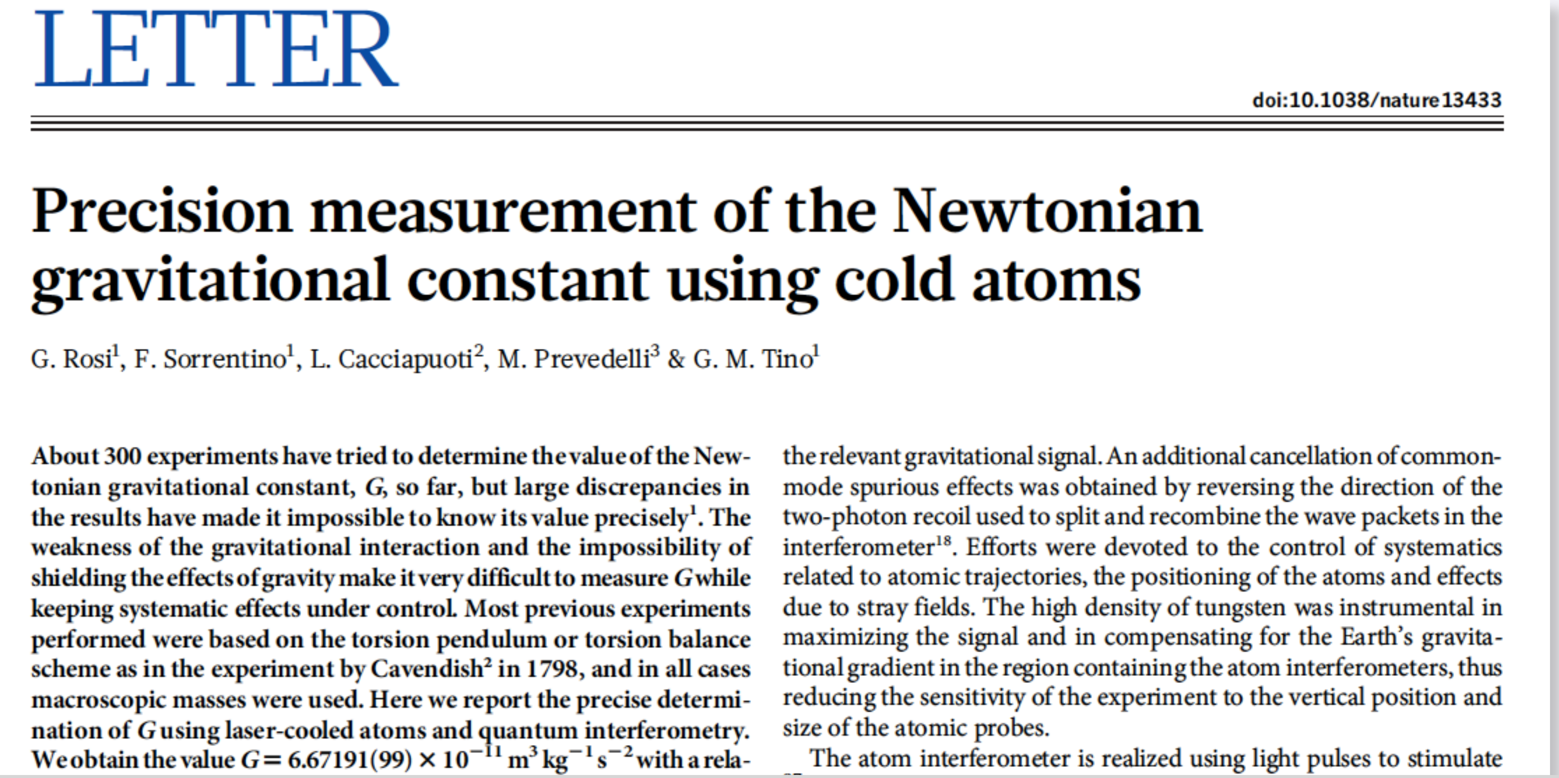
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G,* **Rev. Scient. Instr. 78, 075109 (2007)**

G measurement



(July 2013)

Relative uncertainty ~ 116 ppm (statistical)



LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]

About 300 experiments have tried to determine the value of the Newtonian gravitational constant, *G*, so far, but large discrepancies in the results have made it impossible to know its value precisely[1]. The weakness of the gravitational interaction and the impossibility of shielding the effects of gravity make it very difficult to measure *G* while keeping systematic effects under control. Most previous experiments performed were based on the torsion pendulum or torsion balance scheme as in the experiment by Cavendish[2] in 1798, and in all cases macroscopic masses were used. Here we report the precise determination of *G* using laser-cooled atoms and quantum interferometry. We obtain the value $G = 6.67191(99) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$ with a rela-

the relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer[18]. Efforts were devoted to the control of systematics related to atomic trajectories, the positioning of the atoms and effects due to stray fields. The high density of tungsten was instrumental in maximizing the signal and in compensating for the Earth's gravitational gradient in the region containing the atom interferometers, thus reducing the sensitivity of the experiment to the vertical position and size of the atomic probes.

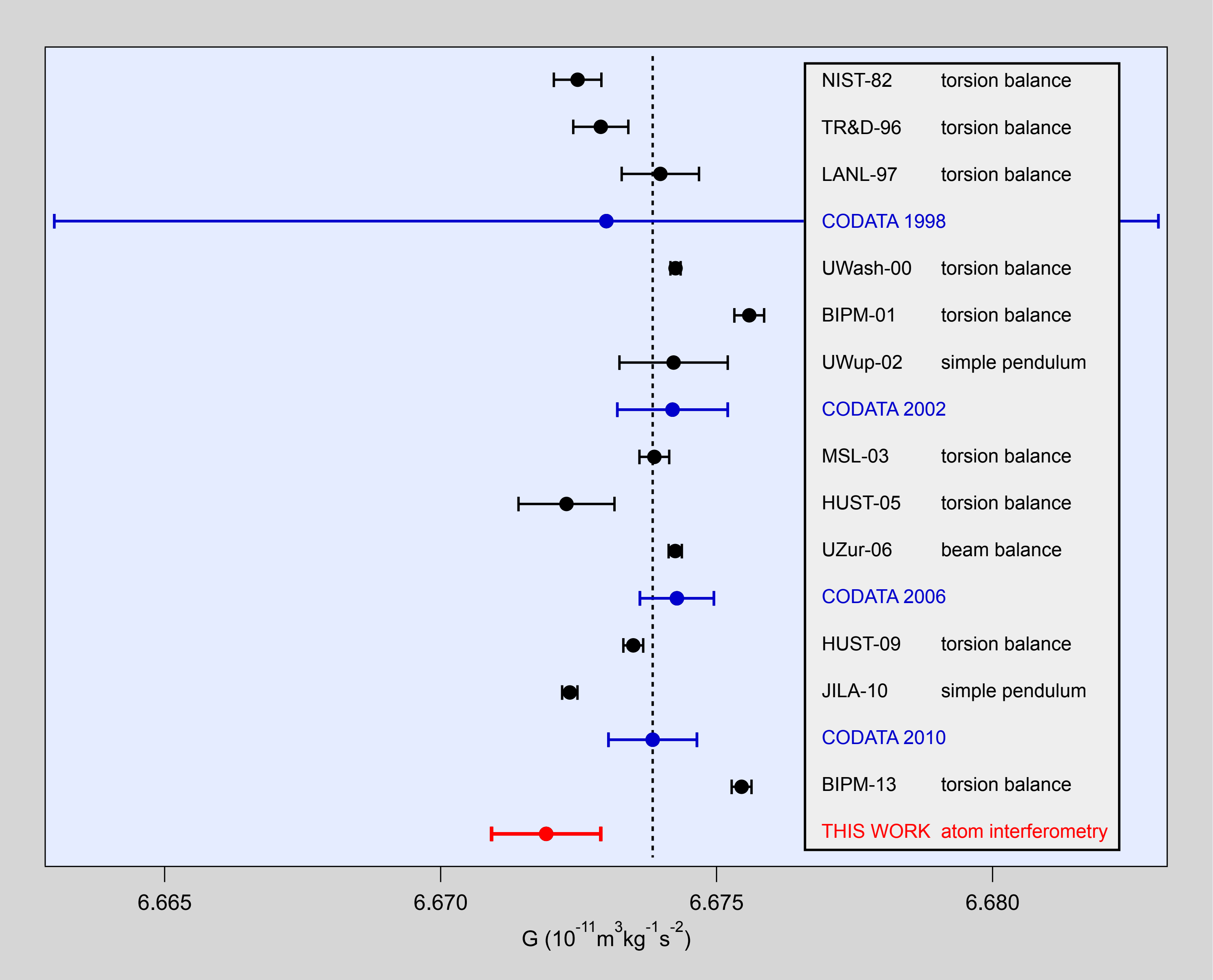
The atom interferometer is realized using light pulses to stimulate

$$G = 6.67191(77)(62) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$$

Relative uncertainty: 150 ppm

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms
NATURE vol. 510, p. 518 (2014)

Determination of G



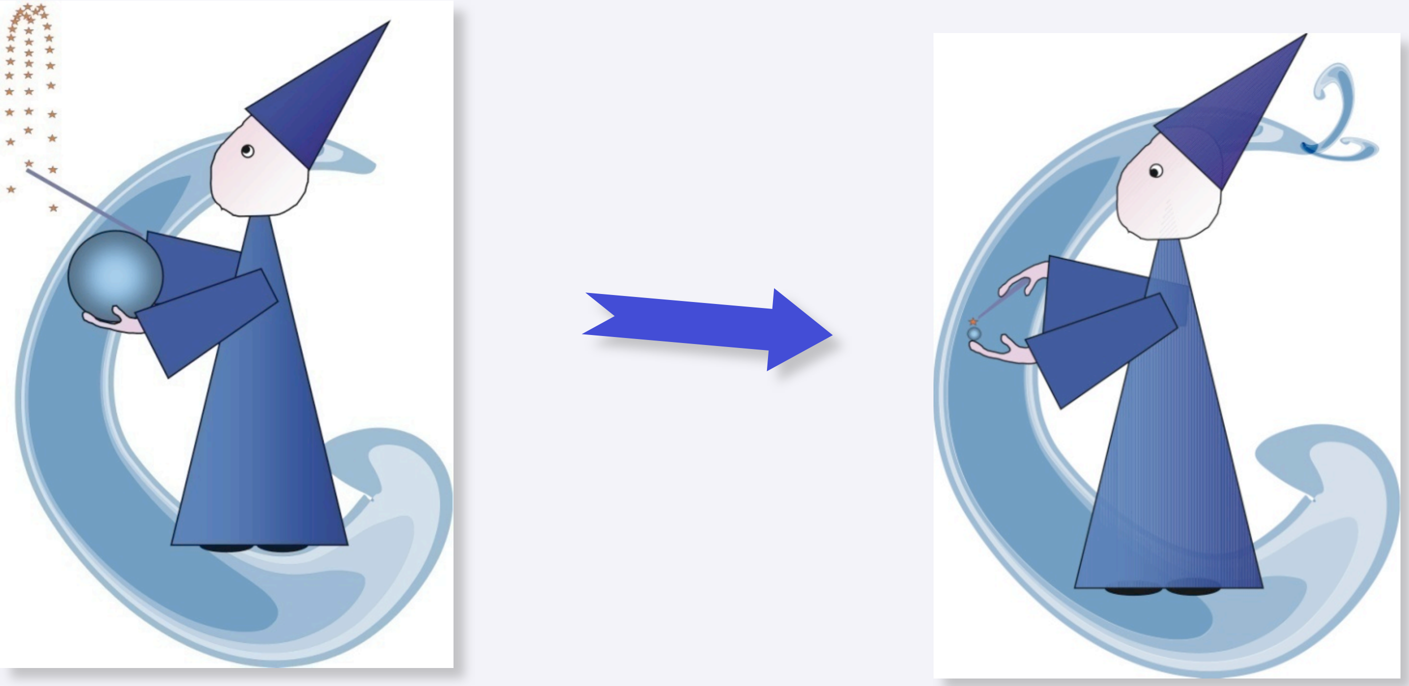
G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms
NATURE vol. 510, p. 518 (2014)

MAGIA error budget

Effect	Uncertainty	Correction to G (ppm)	Relative uncertainty $\Delta G/G$ (ppm)
Air density	10 %	60	6
Apogee time	30 μs		6
Atomic clouds horizontal size	0.5 mm		24
Atomic clouds vertical size	0.1 mm		56
Atomic clouds horizontal position	1 mm		37
Atomic clouds vertical position	0.1 mm		5
Atoms launch direction change C/F	8 μrad		36
Cylinders density inhomogeneity	10^{-4}	91	18
Cylinders radial position	10 μm		38
Ellipse fitting		-13	4
Size of detection region	1 mm		13
Support platforms mass	10 g		5
Translation stages position	0.5 mm		6
Other effects		<2	1
Systematic uncertainty			92
Statistical uncertainty			116
Total		137	148

M. Prevedelli, L. Cacciapuoti, G. Rosi, F. Sorrentino and G. M. Tino,
Measuring the Newtonian constant of gravitation G with an atomic interferometer,
in ‘Newtonian constant of gravitation’, **Philosophical Transactions A, 372, 20140030 (2014)**

Experiments on gravity at small spatial scale



Motivation

- **Physics beyond the standard model**

Extra space-time dimensions

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

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)

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)

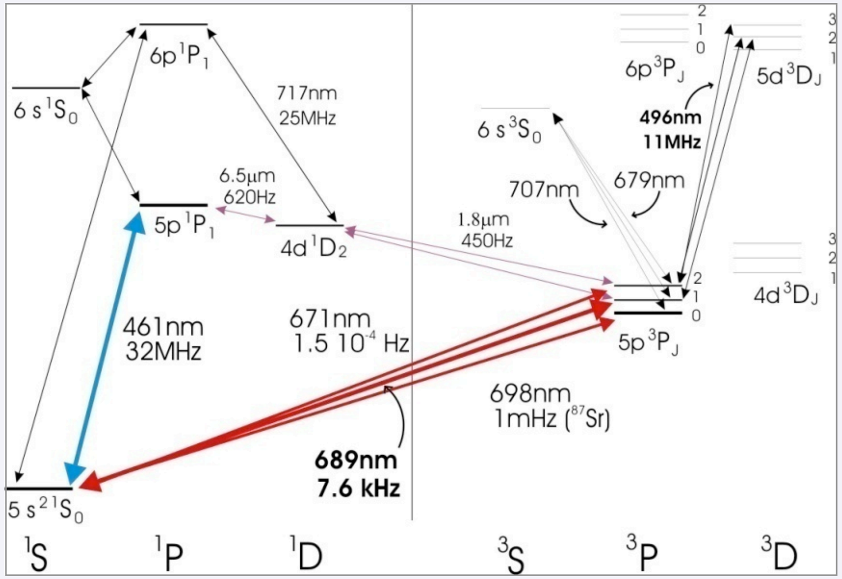
Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

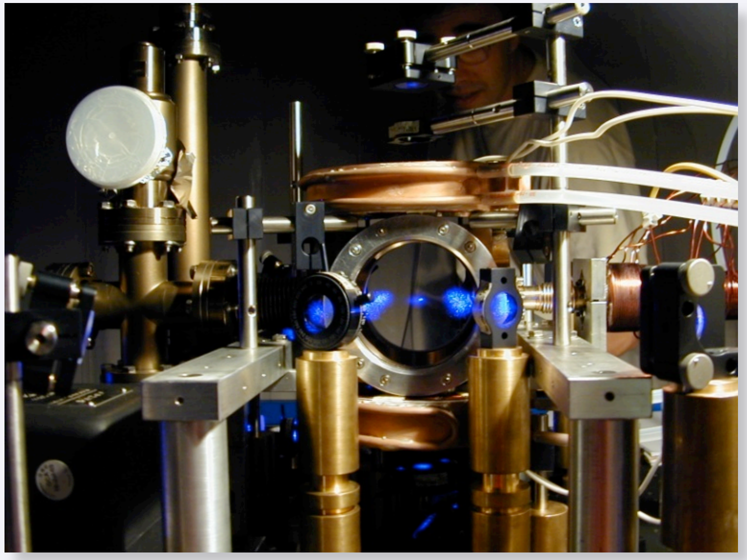
- **Small observed size of Einstein cosmological constant**

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

- **Experimental challenge**

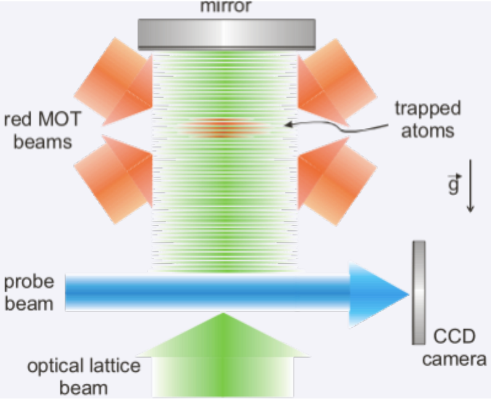
Ultracold Sr - Experiments in Firenze

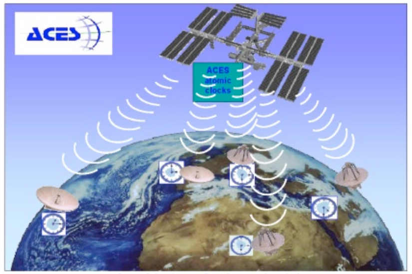




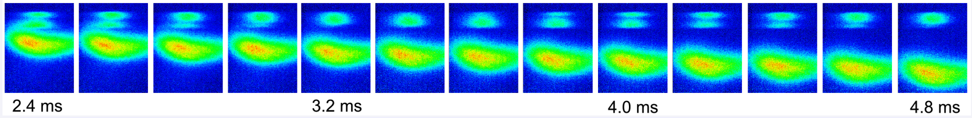
- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests





- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access

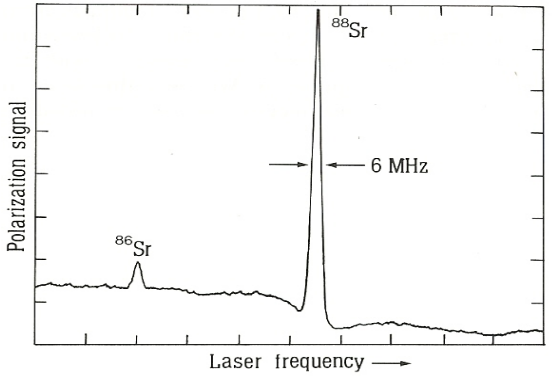


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

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)

1992

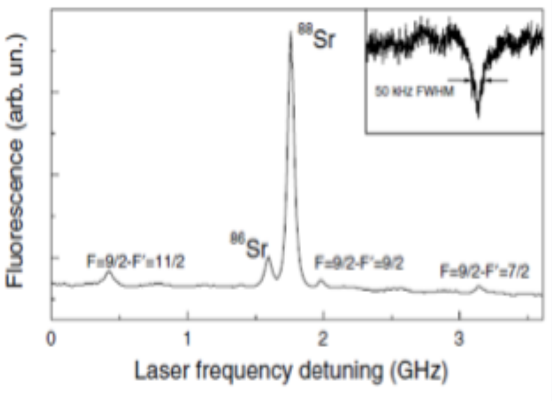
sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line



G.M. Tino, M. Barsanti, M. de Angelis, L. Gianfrani, M. Inguscio, *Spectroscopy of the 689 nm intercombination line of strontium using an extended cavity InGaP/ InGaAlP diode laser*, Appl. Phys. B 55, 397 (1992)

2003

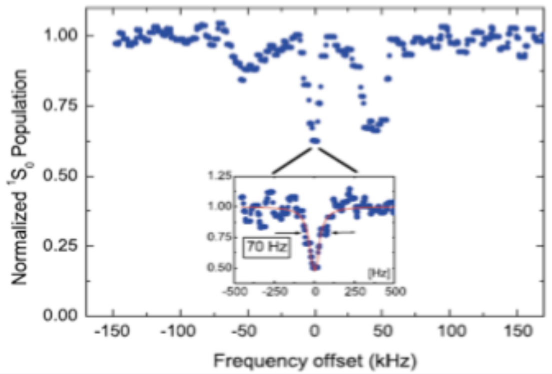
saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line



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)

2009

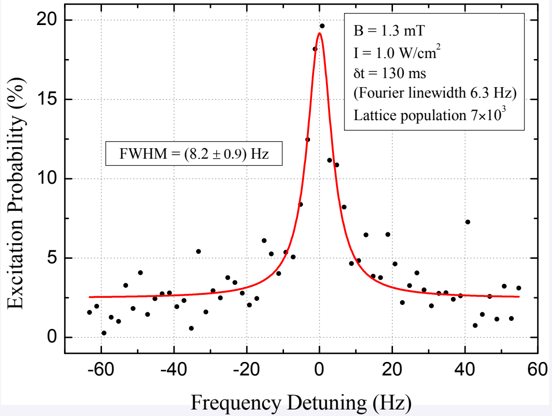
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



N. Poli, M.G. Tarallo, M. Schioppo, C.W. Oates, G.M. Tino, *A simplified optical lattice clock*, Appl. Phys. B 97, 27 (2009)

2012

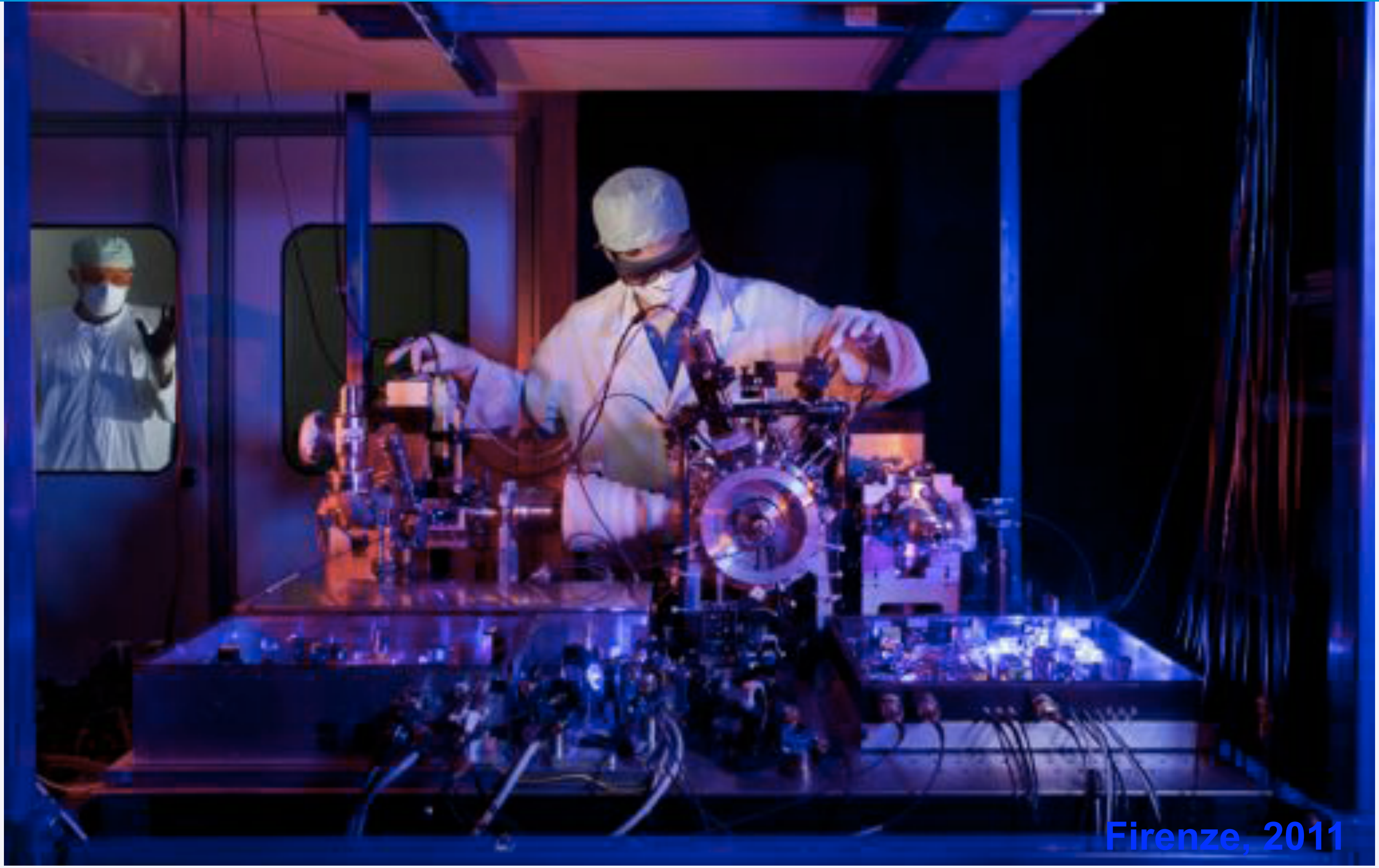
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B (October 2014) DOI:10.1007/s00340-014-5932-9, arXiv:1409.4572v2

N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks,* Rivista del Nuovo Cimento 36, n. 12, 555 (2013), arXiv:1401.2378

Space Optical Clock


Firenze, 2011

N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B (October 2014) DOI: 10.1007/s00340-014-5932-9, arXiv:1409.4572v2

Laser cooling of ^{88}Sr

2000 ms

500 °C vapor from oven

Zeeman slower

Slow-down
$a \sim 5 \times 10^5$ m/s^2

Blue MOT

$\lambda = 461\,\mathrm{nm}$ (blue laser)
$T \sim 1\,\mathrm{mK} \quad N \sim 5 \times 10^7$

200 ms

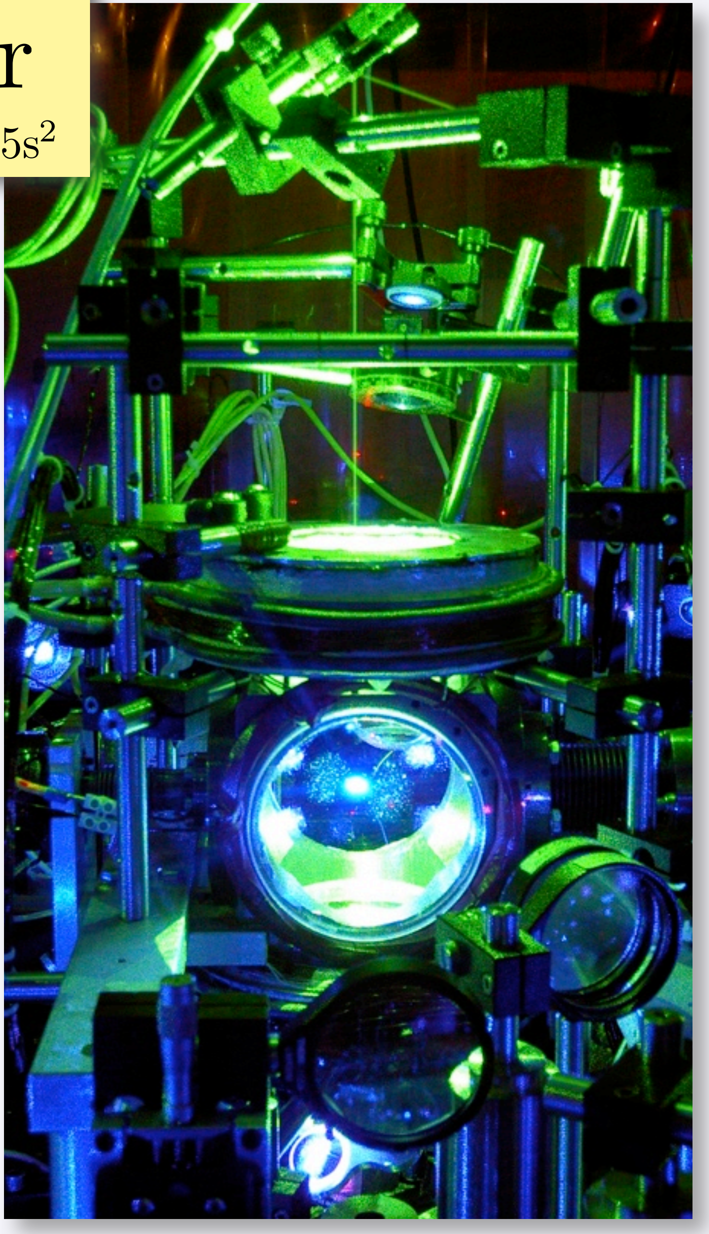
Red MOT

$\lambda = 689\,\mathrm{nm}$ (red laser)
$T \sim 1\,\mu\mathrm{K} \quad N \sim 2 \times 10^6$

Vertical optical lattice

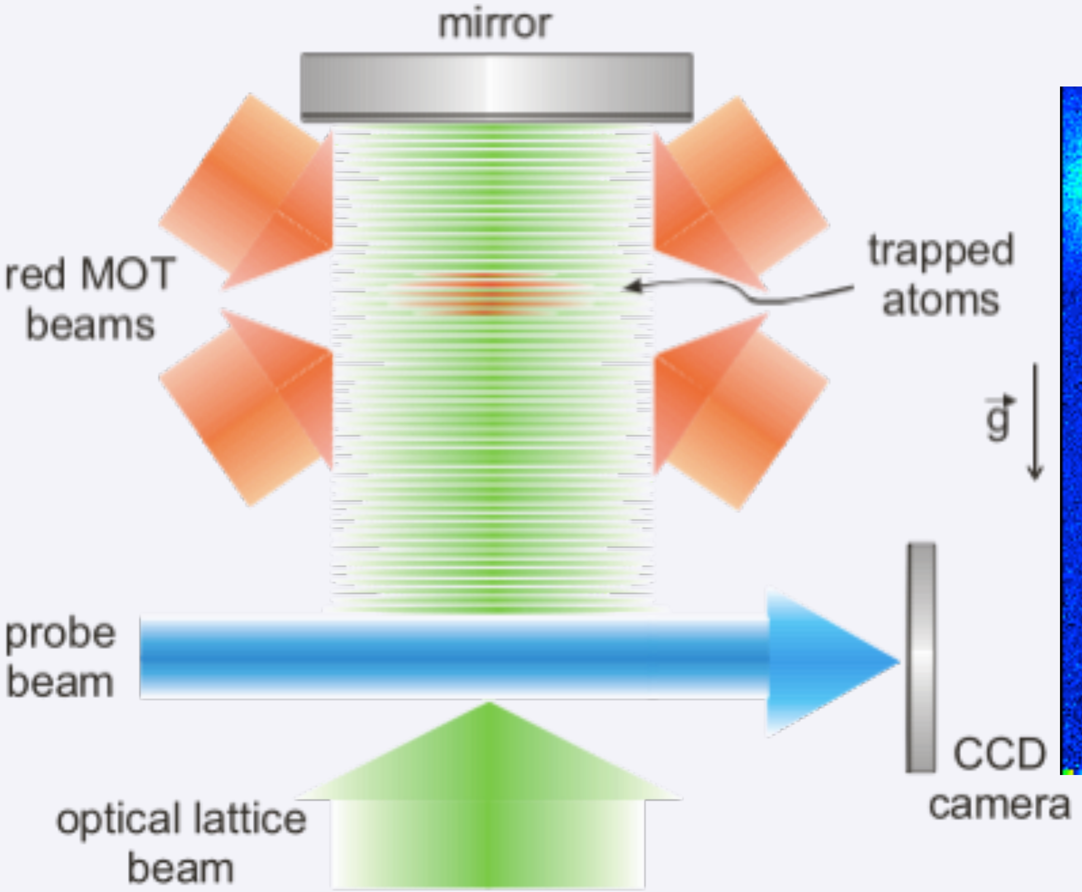
$\lambda = 532\,\mathrm{nm}$
(Nd:YVO$_4$ green laser)
$T \sim 1\,\mu\mathrm{K} \quad N \sim 10^5$

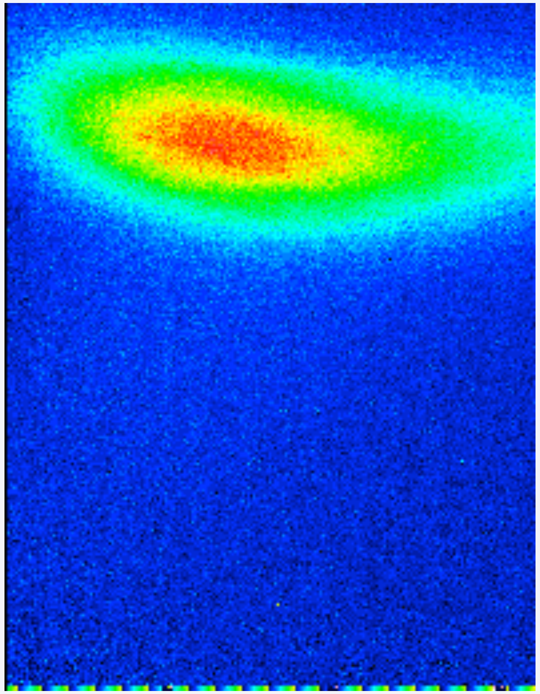
88 38
Sr
[Kr]5s^2



λ	T_R	T_D	I_s	a_{max}
461 nm	1 μK	760 μK	42 mW/cm^2	$10^5 \times g$
689 nm	460 nK	180 nK	3 μW/cm^2	$16 \times g$

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



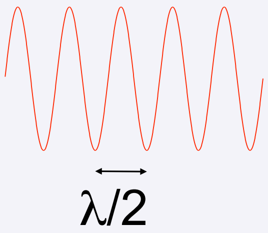


$$\nu = m\, g\, \lambda /2\, h$$

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)**

Particle in a periodic potential:Bloch oscillations

periodic potential



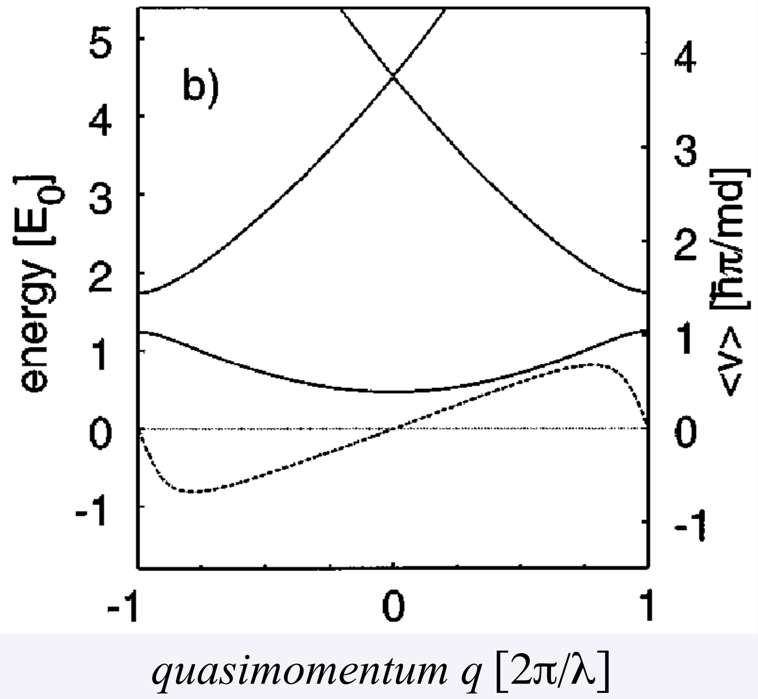
$$V(z+\lambda/2) = V(z)$$

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

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

Bloch's theorem

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



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

with a constant external force F

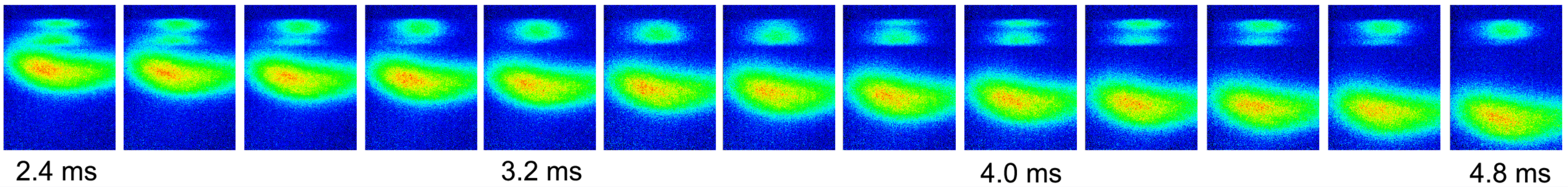
$$q(t) = q(0) + Ft/\hbar$$

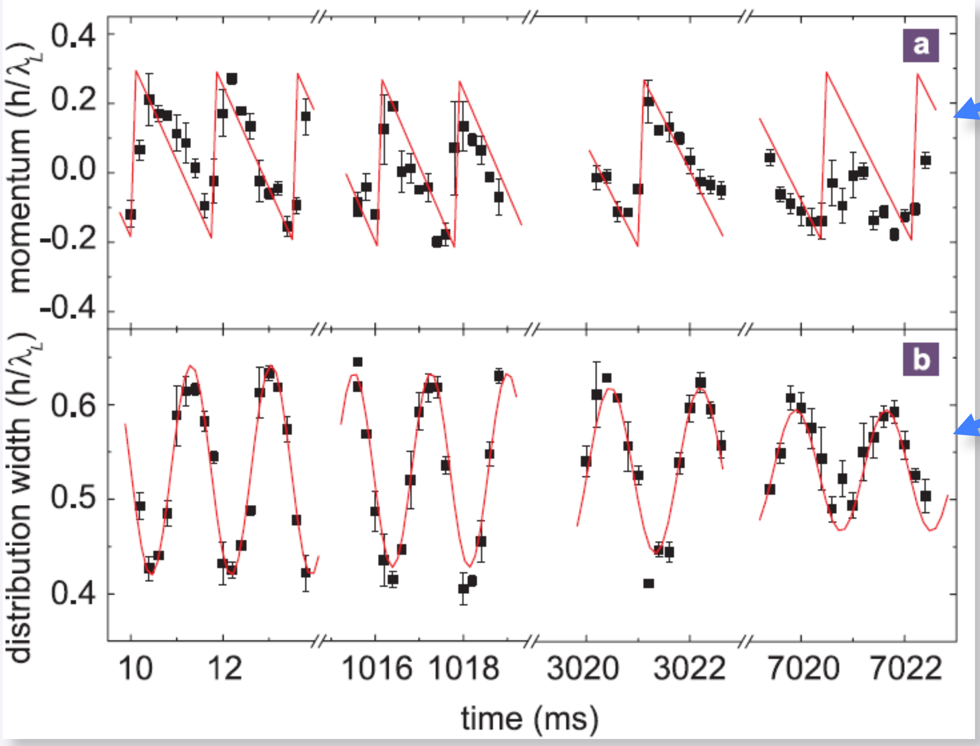
$$\Downarrow$$

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

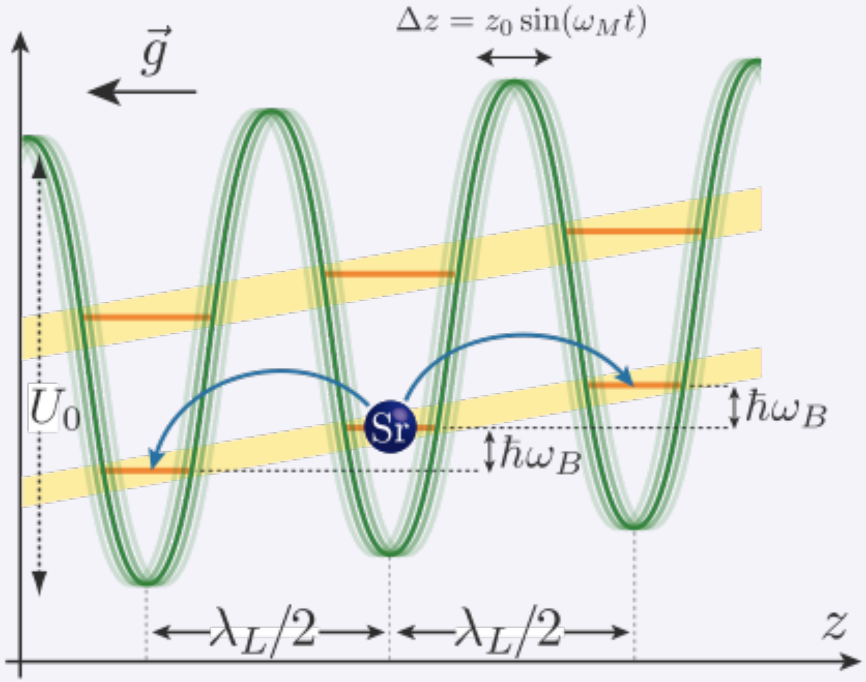
8000 photon recoils in 7s

$g_{meas} = 9.80012(5)$ 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)**

Modulation of optical lattices

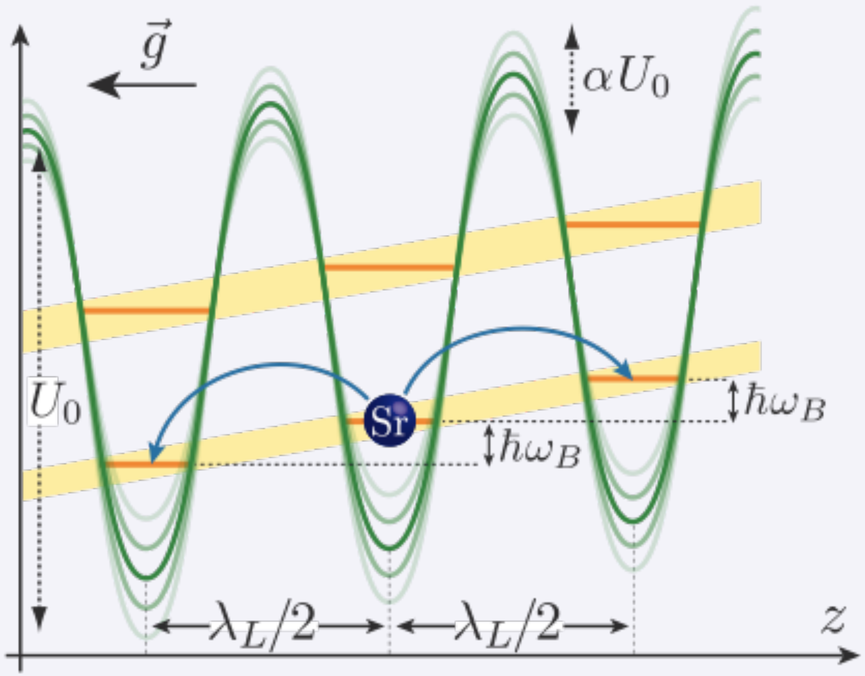
Phase modulation



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

V. 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)**

M. G. Tarallo, A. Alberti, N. Poli, M. L. Chiofalo, F.-Y. Wang, G. M. Tino, *Delocalization-enhanced Bloch oscillations and driven resonant tunneling in optical lattices for precision force measurements,* **Phys. Rev. A 86, 033615 (2012)**

Direct measurement of Bloch frequency in real space – Resonant tunneling

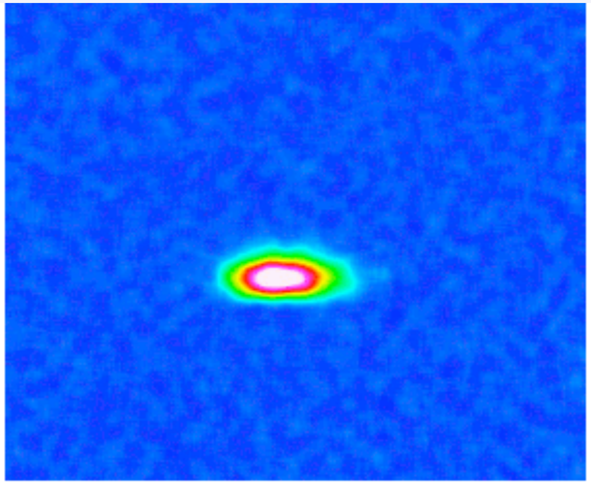
- Transport dynamics depends on δ. On resonance the system is described by Bloch states → coherent delocalization of the atomic wavepacket

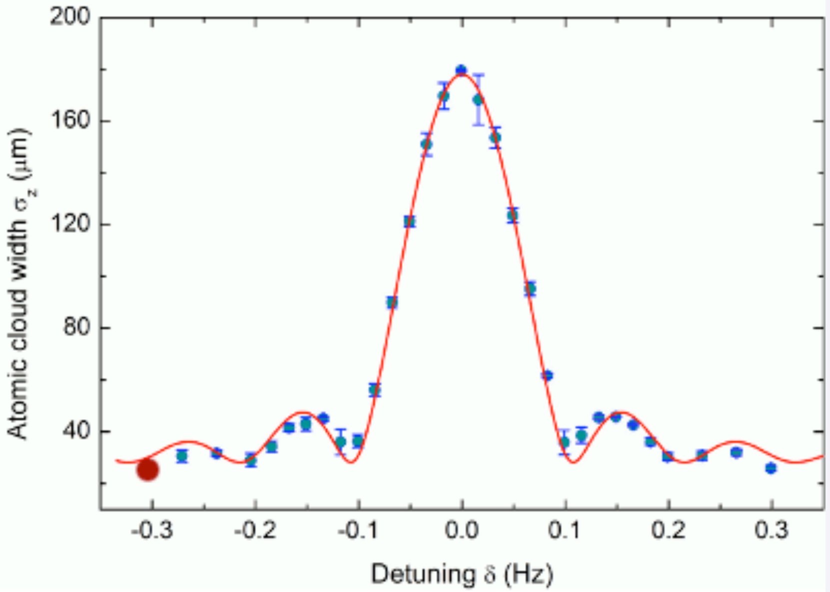
$$\boxed{\sigma_z = \sqrt{\sigma_0 + {v_\ell}^2 t^2 \mathrm{sinc}^2\left(\frac{\delta}{\Gamma}\right)}}$$

- Direct measurement of ω_B by recording the atomic distribution broadening

^{88}Sr

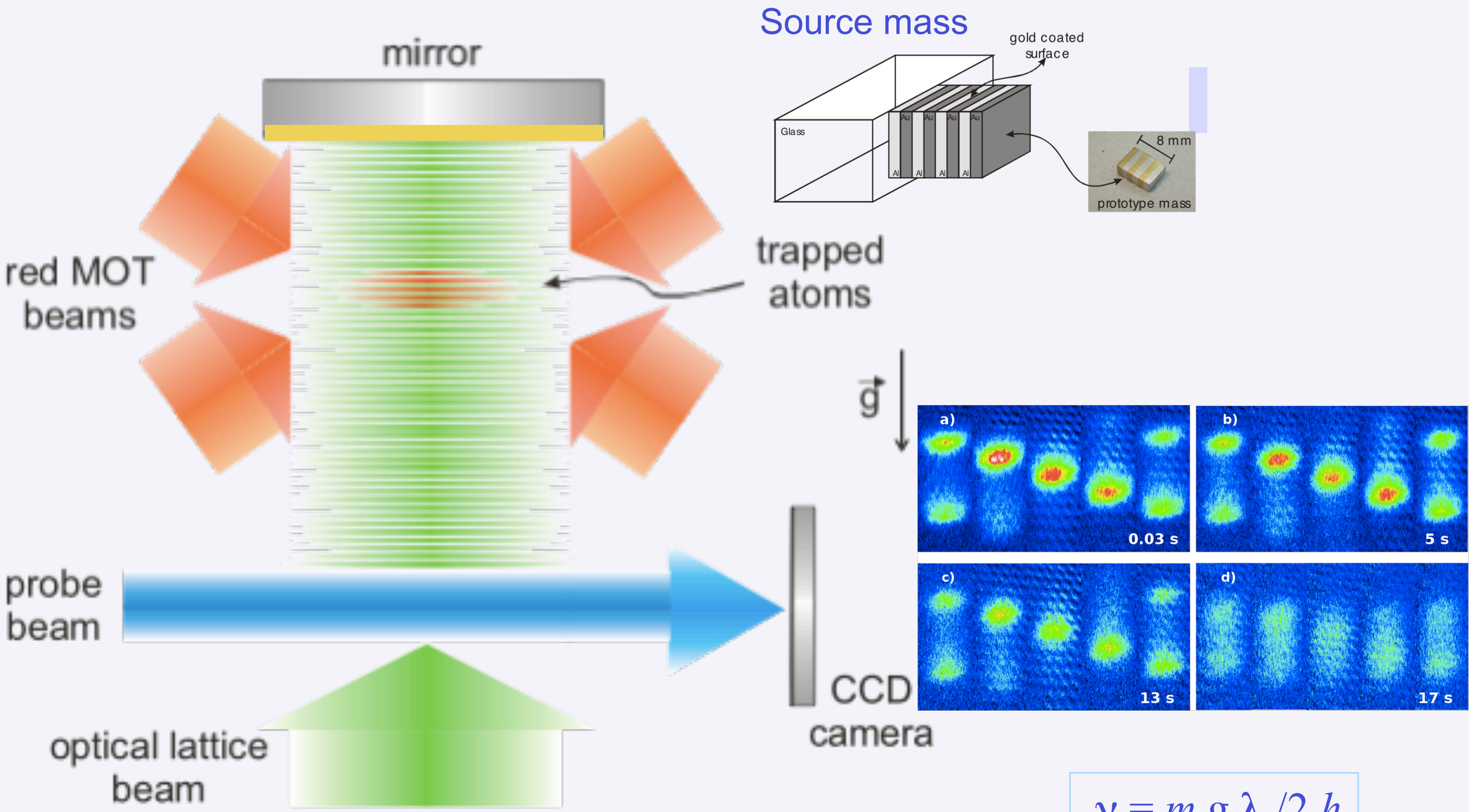
- Interrogation up to $\ell = 6$ sixth harmonic
- Modulation time over 10 s
- Fourier-limited linewidth $\Gamma/2\pi = 1/\pi t$
- Sensitivity $\Delta\omega_B = \frac{3}{\pi t^2 v_\ell \ell}\Delta\sigma \sim 1.5 \times 10^{-7}\omega_B$





M. G. Tarallo, A. Alberti, N. Poli, M. L. Chiofalo, F.-Y. Wang, G. M. Tino,
Delocalization-enhanced Bloch oscillations and driven resonant tunneling in optical lattices for precision force measurements,
Phys. Rev. A 86, 033615 (2012)

Scheme for the measurement of small distance forces



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

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

***Objective:* λ = 1-10 μm, $\alpha = 10^3$-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)**

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**

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

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

- **Modified power-law potential**

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

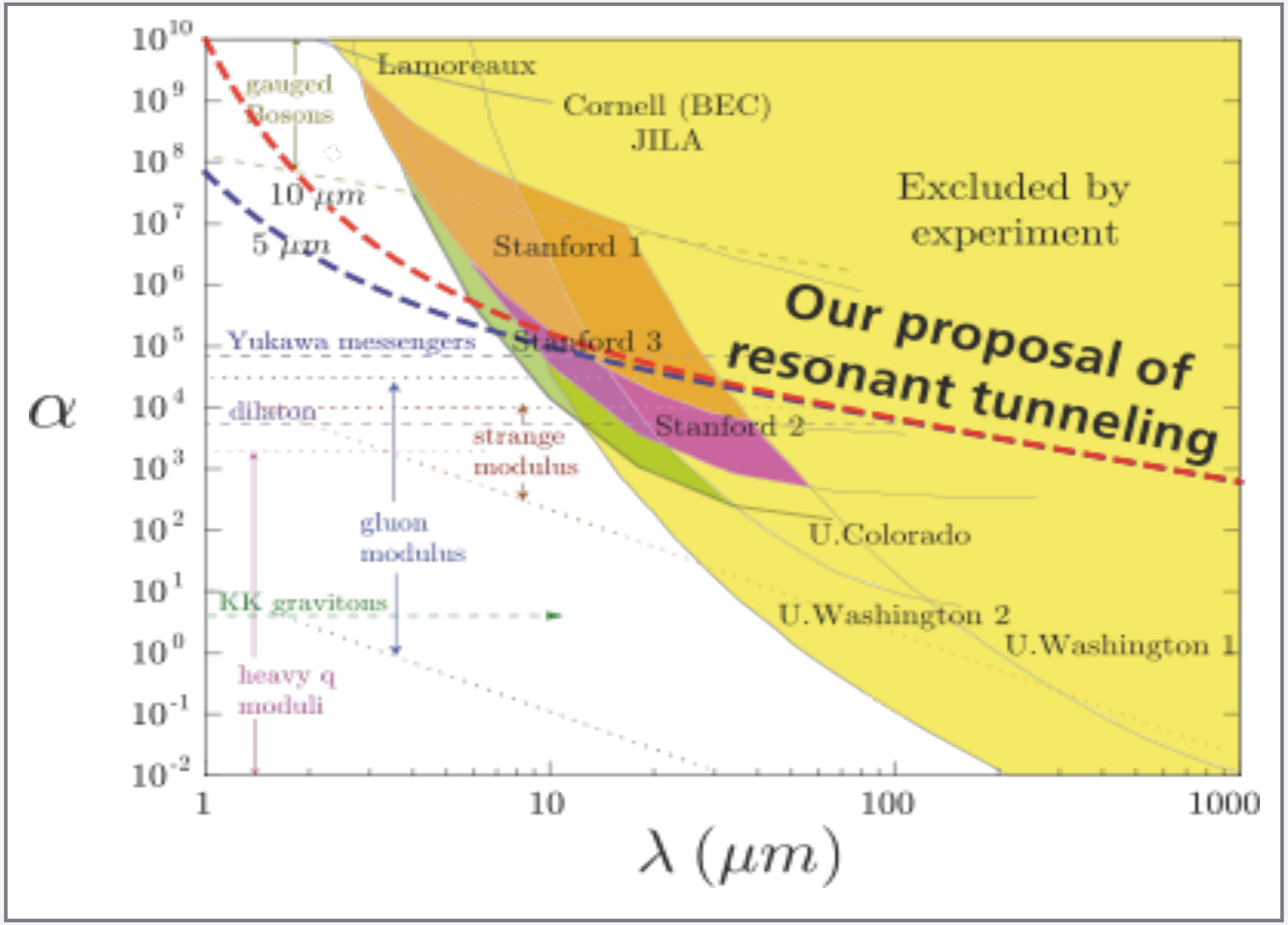
Exchange of 2 massless particles

Accessible region with atomic probes

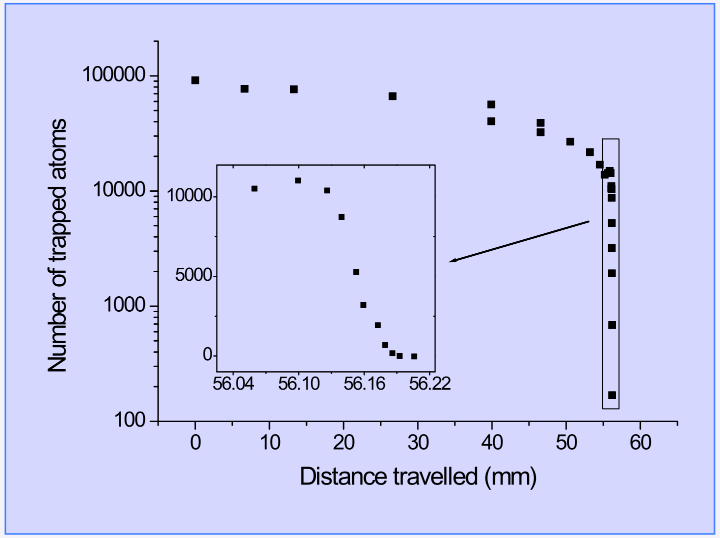
- **Newton+Yukawa potential**

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

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



Atom elevator

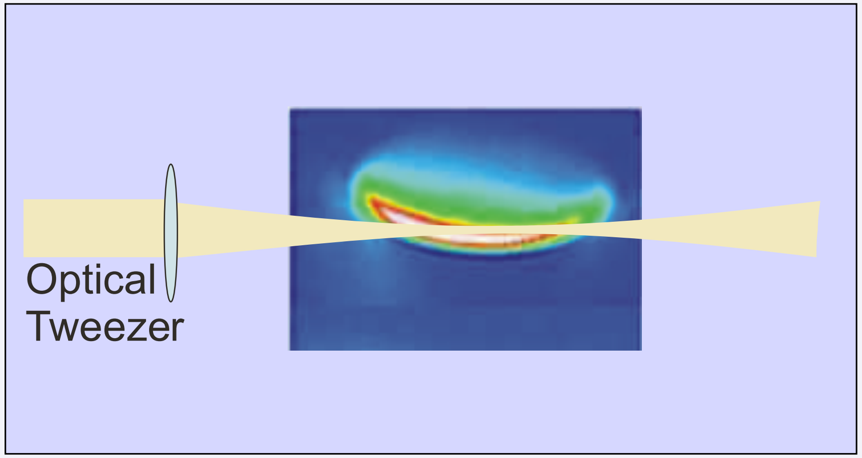


Vertical size of the atomic sample: 15 μm

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



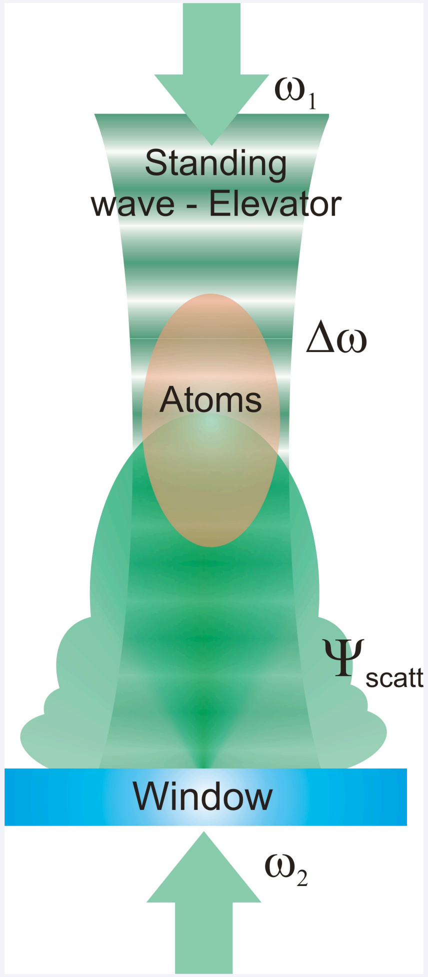
- **Vertical size reduced to 4 μm with an optical tweezer**

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)**

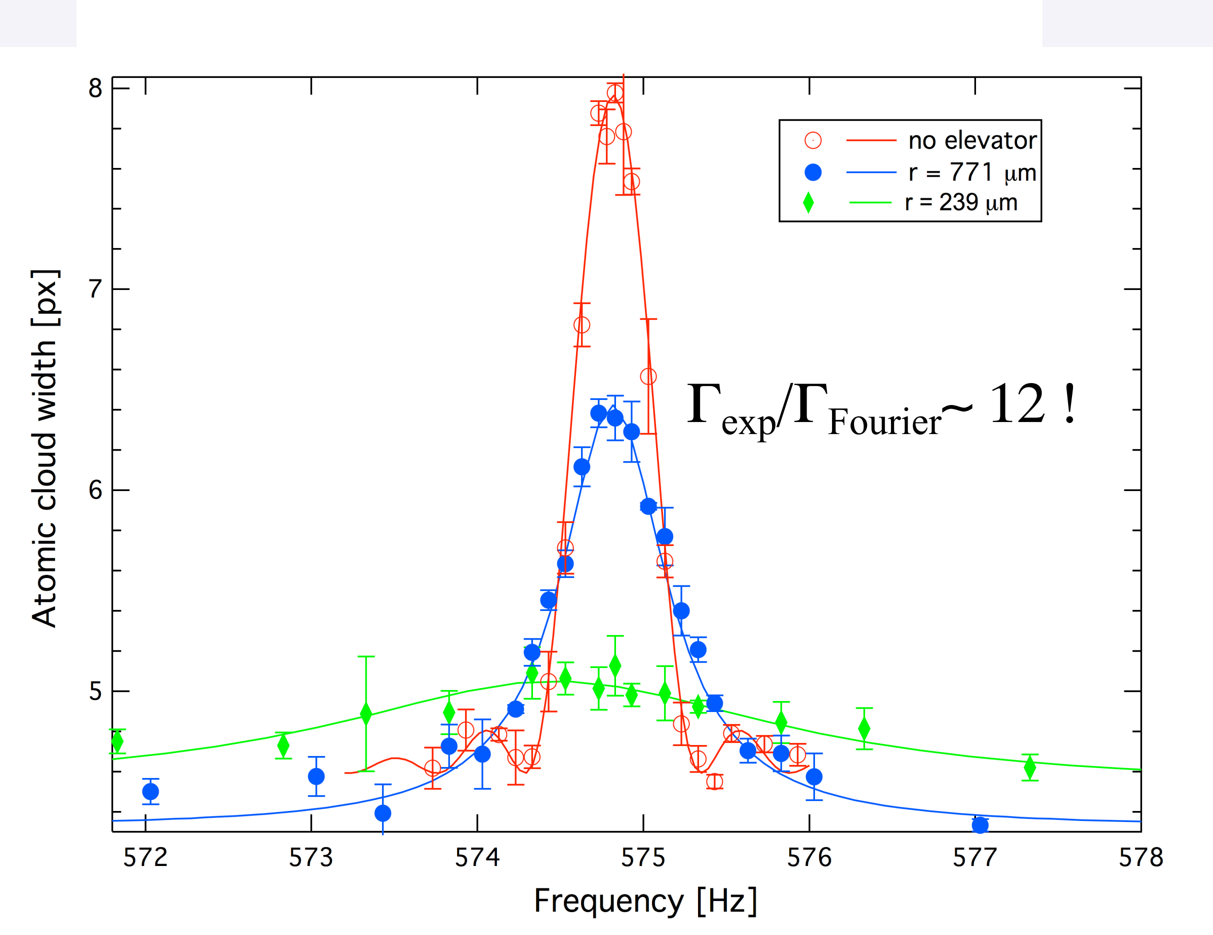
Short-distance measurements

- **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:



Test of the equivalence principle with atoms

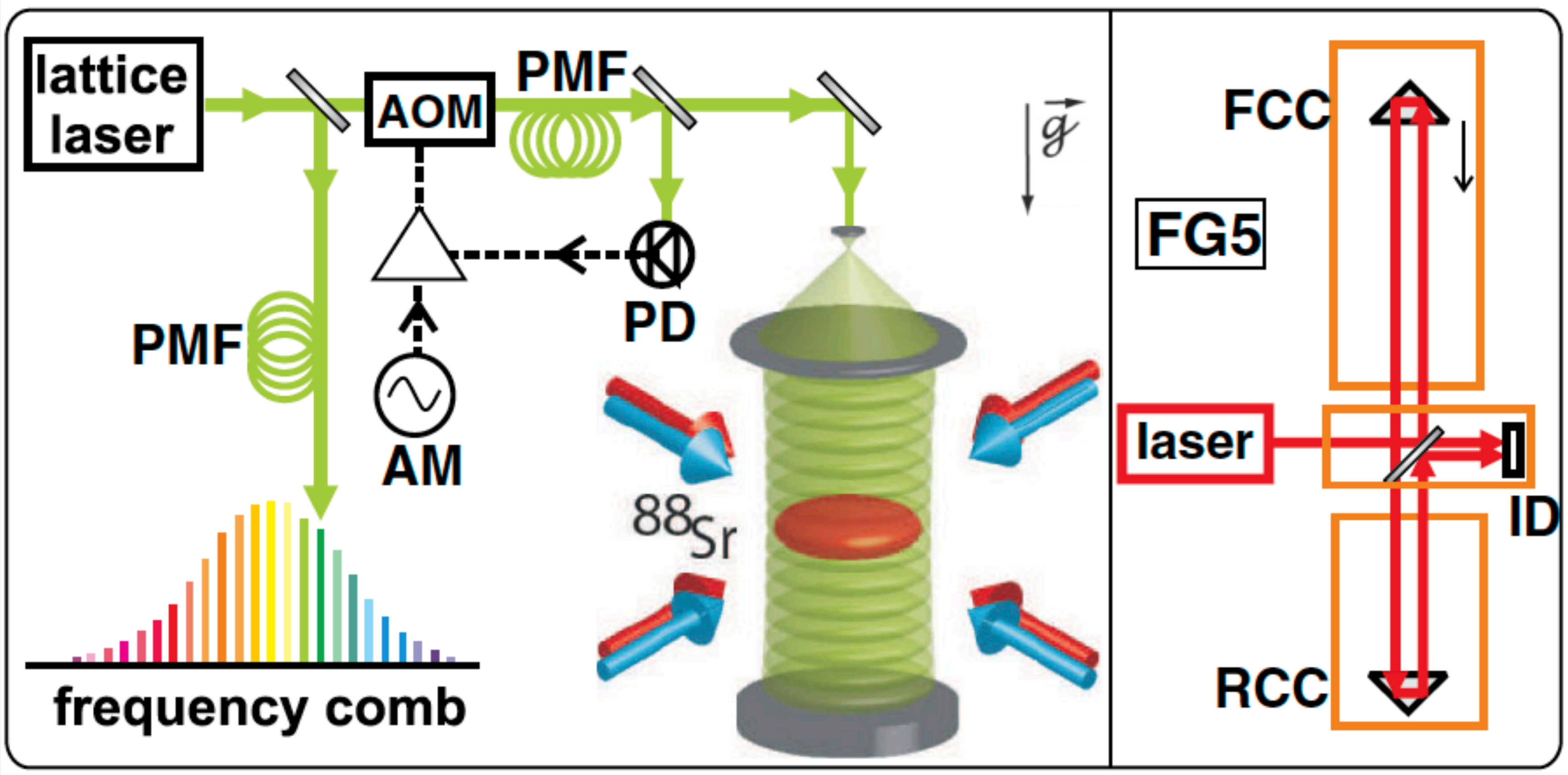
atom vs macroscopic mass

A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)	**^{133}Cs atoms vs classical gravimeter**
S. Merlet, Q. Bodart, N. Malossi, A. Landragin, F. P. D. Santos, O. Gitlein, and L. Timmen, Metrologia 47, L9 (2010).	**^{87}Rb atoms vs classical gravimeter**
N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino, Phys. Rev. Lett. 106, 038501 (2011)	**^{88}Sr atoms vs classical gravimeter**

different atoms

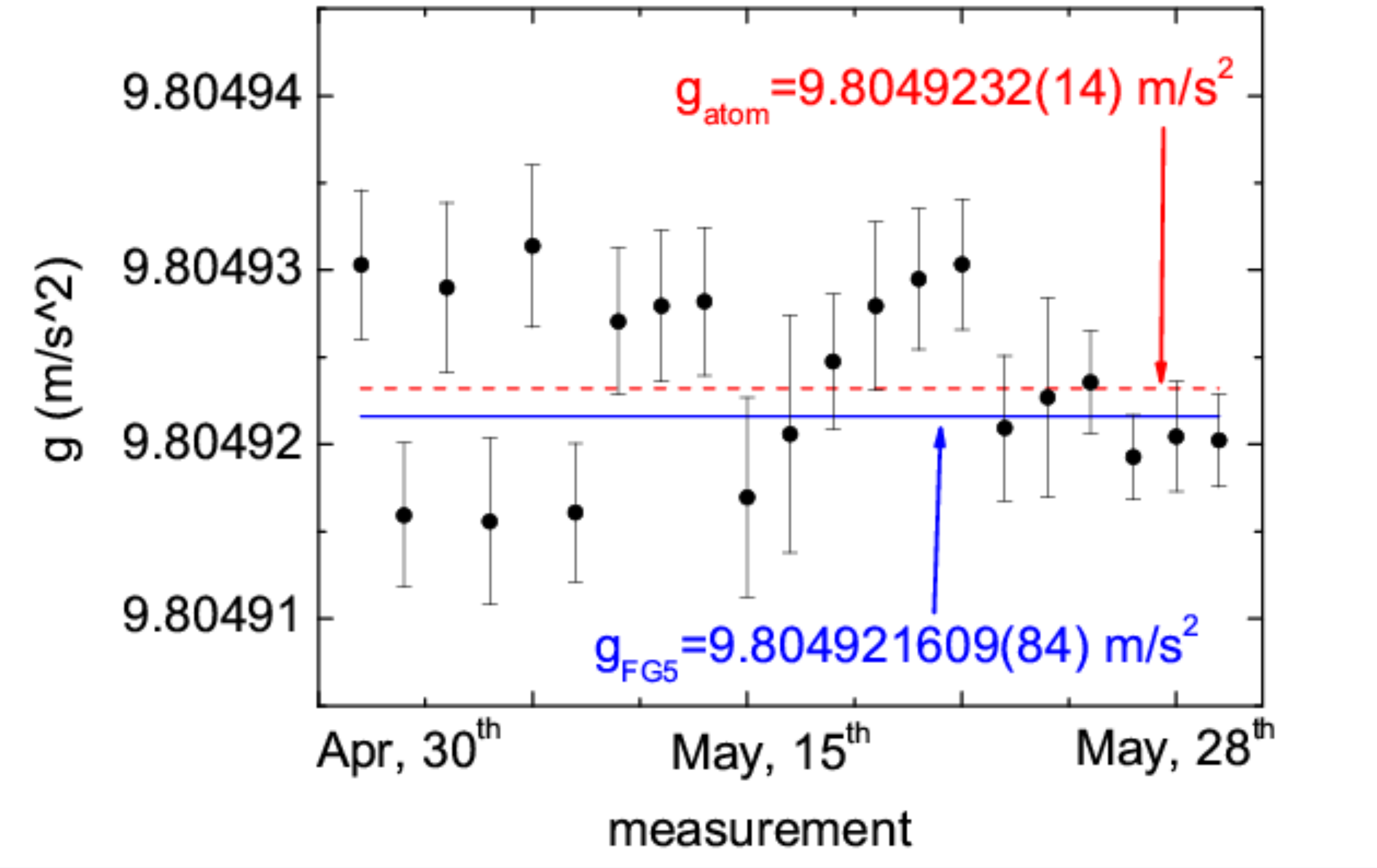
S. Fray, C. A. Diez, T.W. Hänsch, and M. Weitz, Phys. Rev. Lett. 93, 240404 (2004).	**^{87}Rb vs ^{85}Rb**
A. Bonnin, N. Zahzam, Y. Bidel, and A. Bresson, Phys. Rev. A 88, 043615 (2013).	**^{87}Rb vs ^{85}Rb**
D. Schlippert, J. Hartwig, H. Albers, L. L. Richardson, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer, and E. M. Rasel, PRL 112, 203002 (2014)	**^{87}Rb vs ^{39}K**
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, Phys. Rev. Lett. 113, 023005 (2014)	**^{87}Sr vs ^{88}Sr**
A. Kellerbauer, et al. (AEGIS collaboration), Nucl. Instr. Meth. Phys. Res. B 266, 351 (2008) A.E. Charman, et al. (ALPHA collaboration), Nat. Commun. 4, 1785 (2013) P. Hamilton, et al, Phys. Rev. Lett. 112, 121102 (2014)	**H vs anti-H**

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,
Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,
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,
Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,
Phys. Rev. Lett. 106, 038501 (2011)

Test of the equivalence principle for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects

Test of EP with two isotopes of strontium atom:

^{88}Sr

- Boson
- Total spin I = 0

^{87}Sr

- Fermion
- Total spin ≡ nuclear spin I = 9/2

Comparison of the acceleration of ^{88}Sr and ^{87}Sr under the effect of gravity
by measuring the respective Bloch frequencies in a vertical optical lattice

Suitable system to search for EP violations due to spin-gravity coupling effects

Search for spin-gravity coupling effects

- General theoretical framework

- C. M. Will, *The Confrontation between General Relativity and Experiment*, Living Rev. Relativity 9, (2006)

- Spin-gravity coupling

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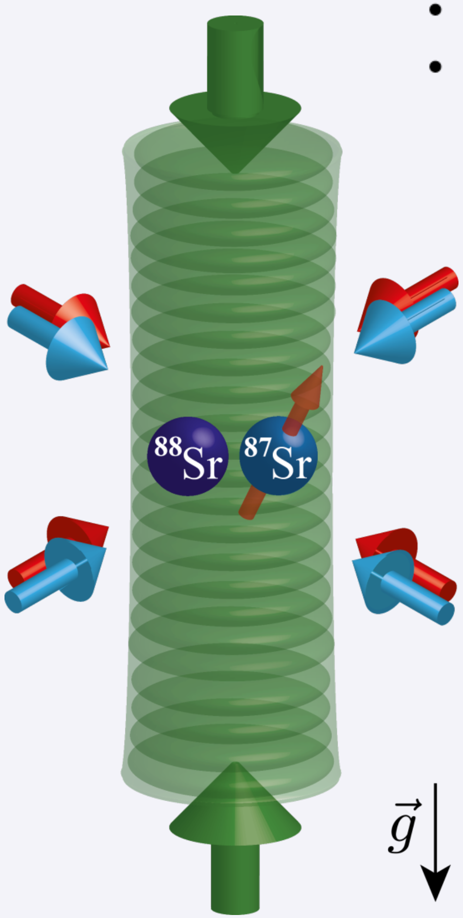
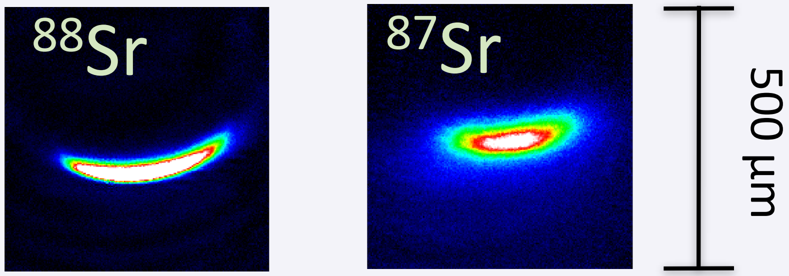
- Silenko & Teryaev, Phys. Rev. D 76 (2007) 061101(R).
- W.-T. Ni, *Searches for the role of spin and polarization in gravity*. Reports on Progress in Physics 73 (2010) 6901.

Test of the equivalence principle with ^{88}Sr and ^{87}Sr atoms



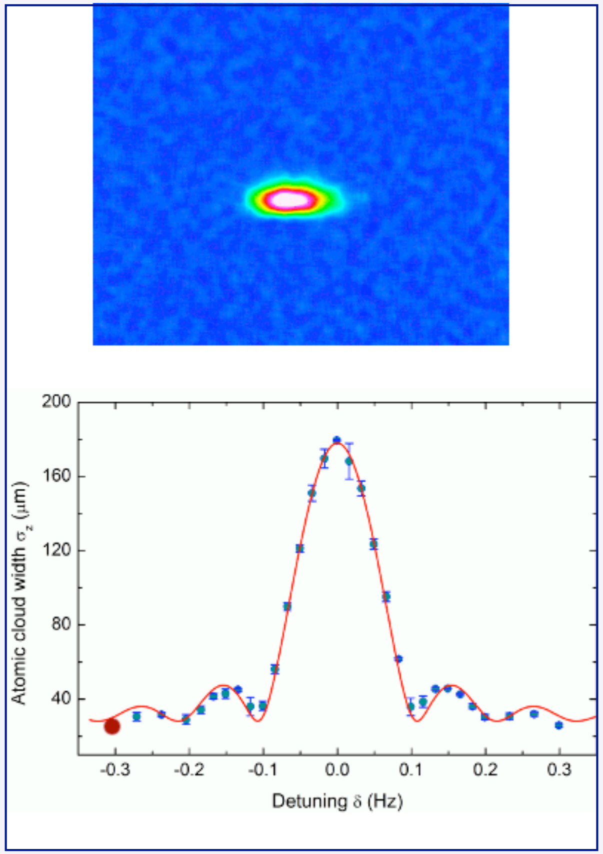
- Atomic beam from an oven at 430°C
- Zeeman-slowed down to 50 m/s
- Two cooling stages sequence in MOT
  - ○ Broad transition 461 nm, $\gamma = 32$ MHz
  - ○ Narrow transition 689 nm, $\gamma = 7$ kHz

Loaded alternately in a vertical OL @ 532 nm
- waist 300 µm
- $U_0 = 6E_R$
- lifetime >10 s



8×10^6 atoms
T: 1 µK

1×10^6 atoms
T: 1.4 µK



Differential gravity measurements for ^{88}Sr and ^{87}Sr – Equivalence Principle test

Weak Equivalence Principle test with coherent probe masses with and without nuclear spin: ^{88}Sr ($I = 0$) and ^{87}Sr ($I = 9/2$)

Measuring **Eötvös ratio** that depends only on Bloch frequencies and mass ratio $R_m = \frac{m_{88}}{m_{87}}$ (*)

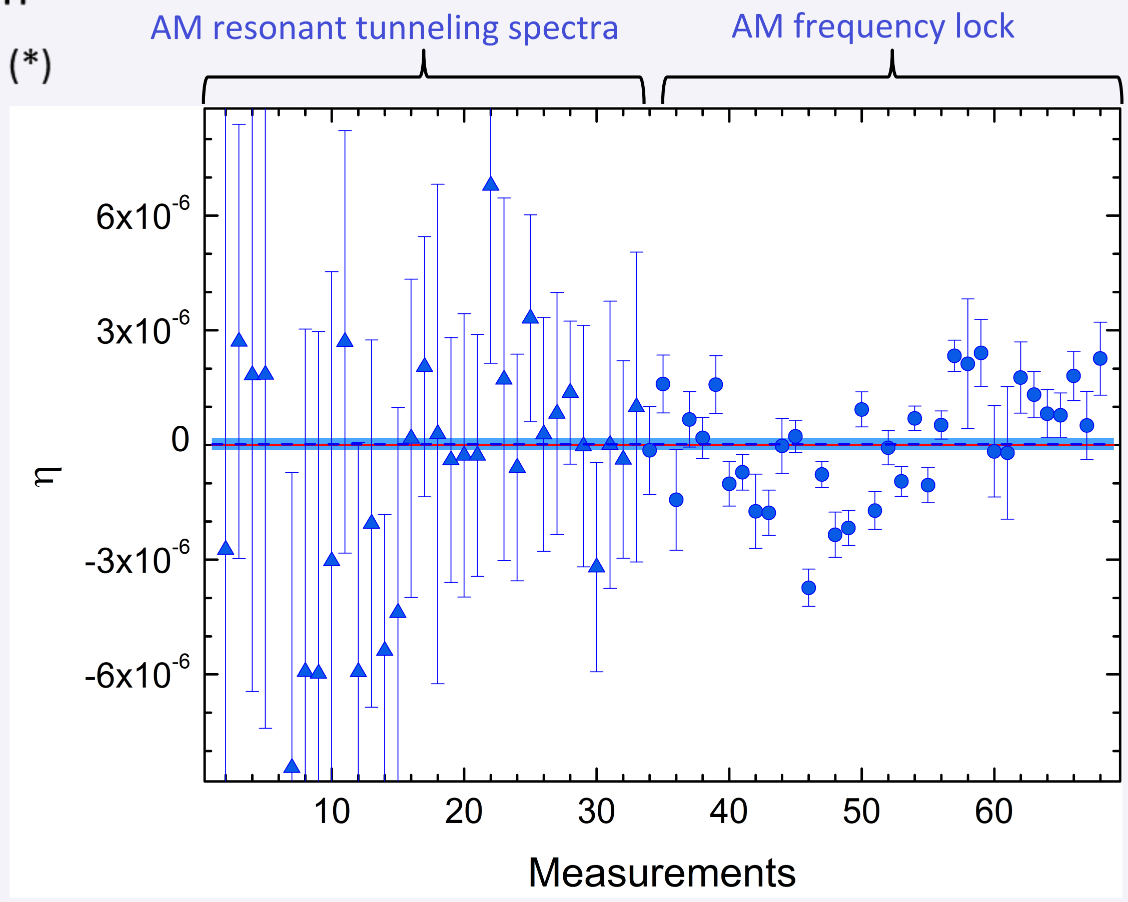
$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

Uncertainty for each point is the quadratic sum of statistical error and systematics uncertainty

Final result:

$$\eta = (0.2 \pm 1.6) \times 10^{-7}$$

Where uncertainty corresponds to the standard error of the weighted mean



(*) known better than 10^{-10} : Rana *et al.*, PRA 86, 050502 (2012)

M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

Search for spin-gravity coupling

We consider possible EEP violation due to **spin-gravity coupling** generated by a gravitational potential of the form

$$V_{g,A}(z) = (1 + \beta_A + kS_z)m_A gz$$

m_A is the rest mass of the atom

S_z is the projection of the spin along gravity direction

k is the model-dependent spin-gravity coupling strength

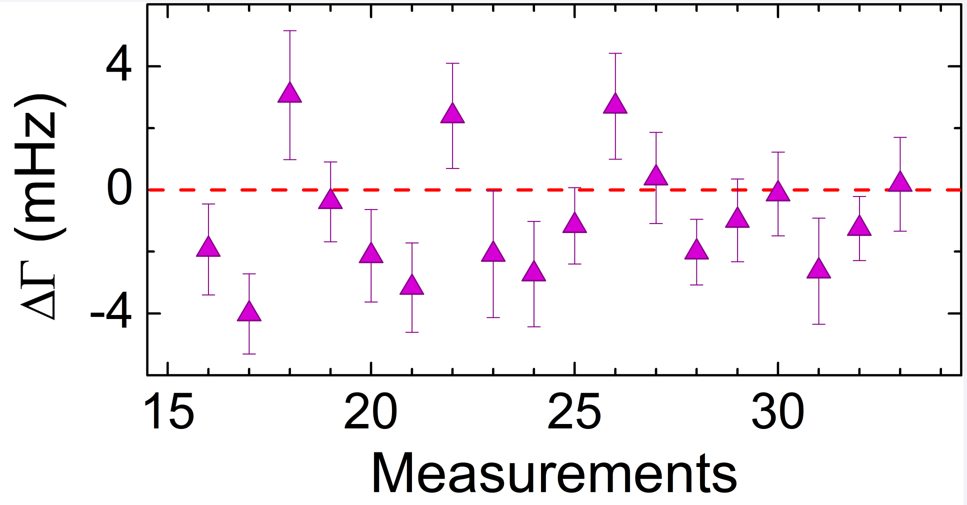
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

Deviations $\Delta\Gamma$ of measured linewidth from Fourier linewidth, corrected by systematics (two-body collisions, residual magnetic field)

→ Upper limit on spin-gravity coupling k

$$\Delta\Gamma = 2I_{87}kl\nu_{87}$$

$$\Longrightarrow \qquad k = (0.5 \pm 1.1) \times 10^{-7}$$



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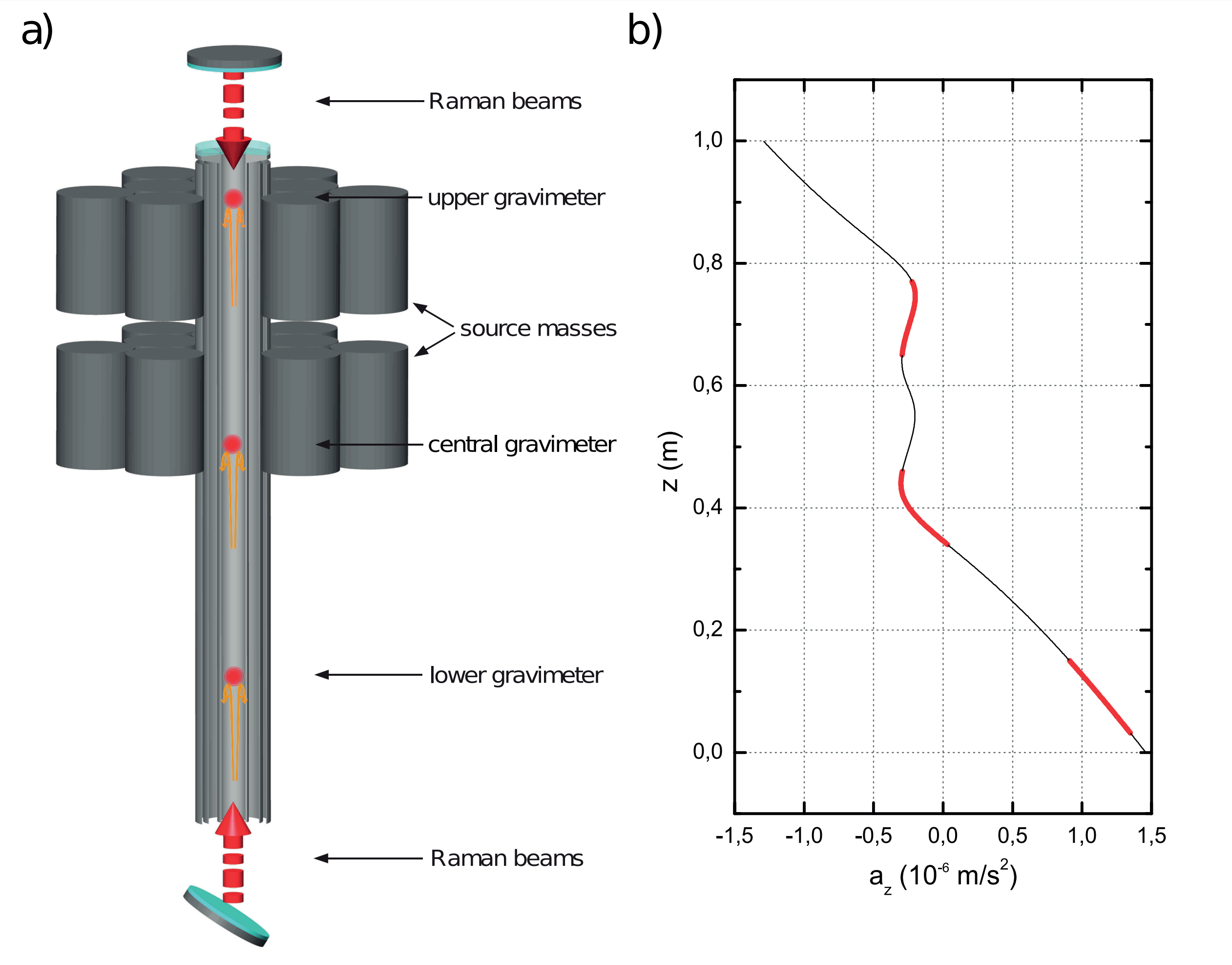
Measurement of the Gravity-Field Curvature by Atom Interferometry



G. Rosi, L. Cacciapuoti, F. Sorrentino, M. Menchetti, M. Prevedelli, G. M. Tino,
Measurement of the Gravity-Field Curvature by Atom Interferometry,
Phys. Rev. Lett., in press (2014)

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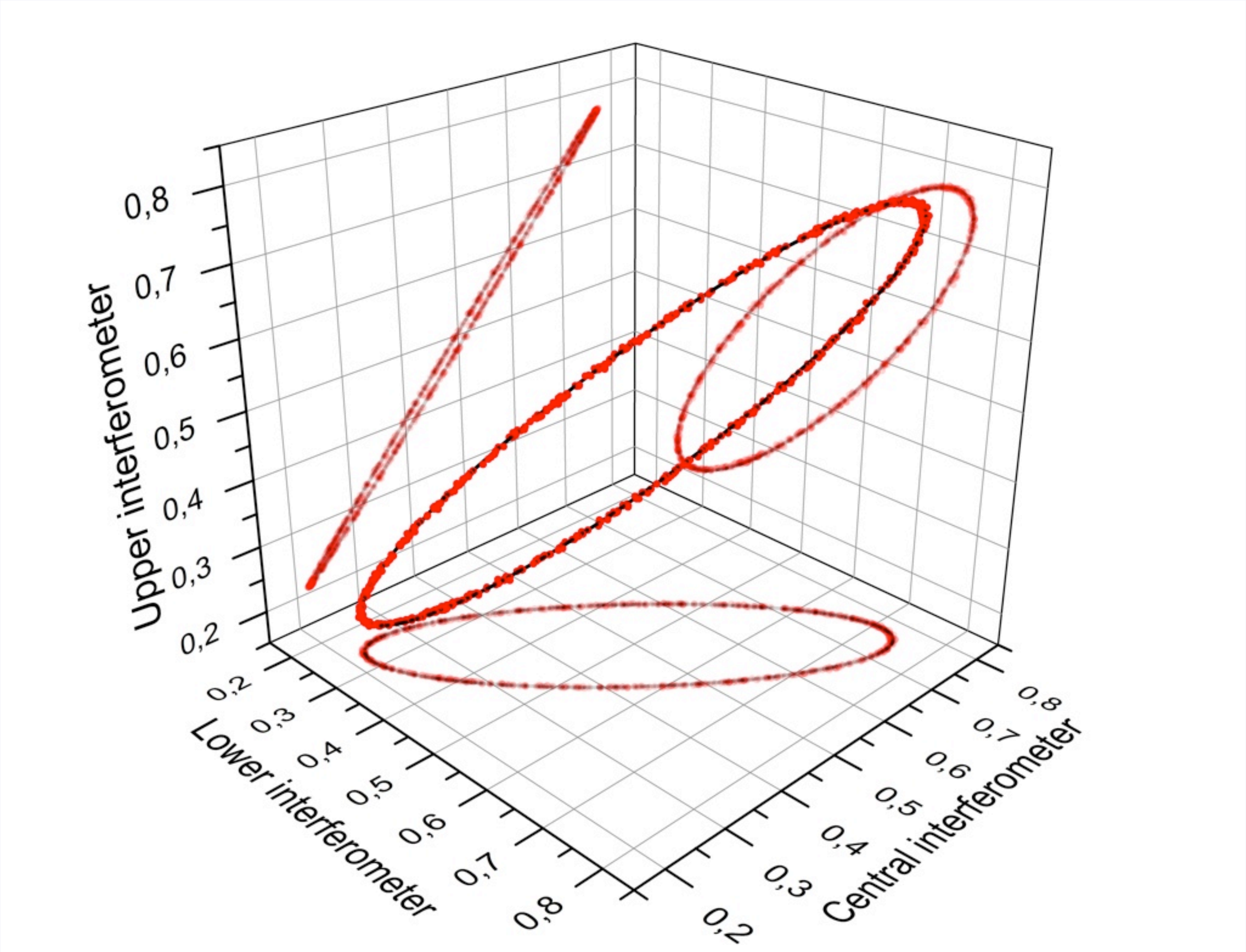

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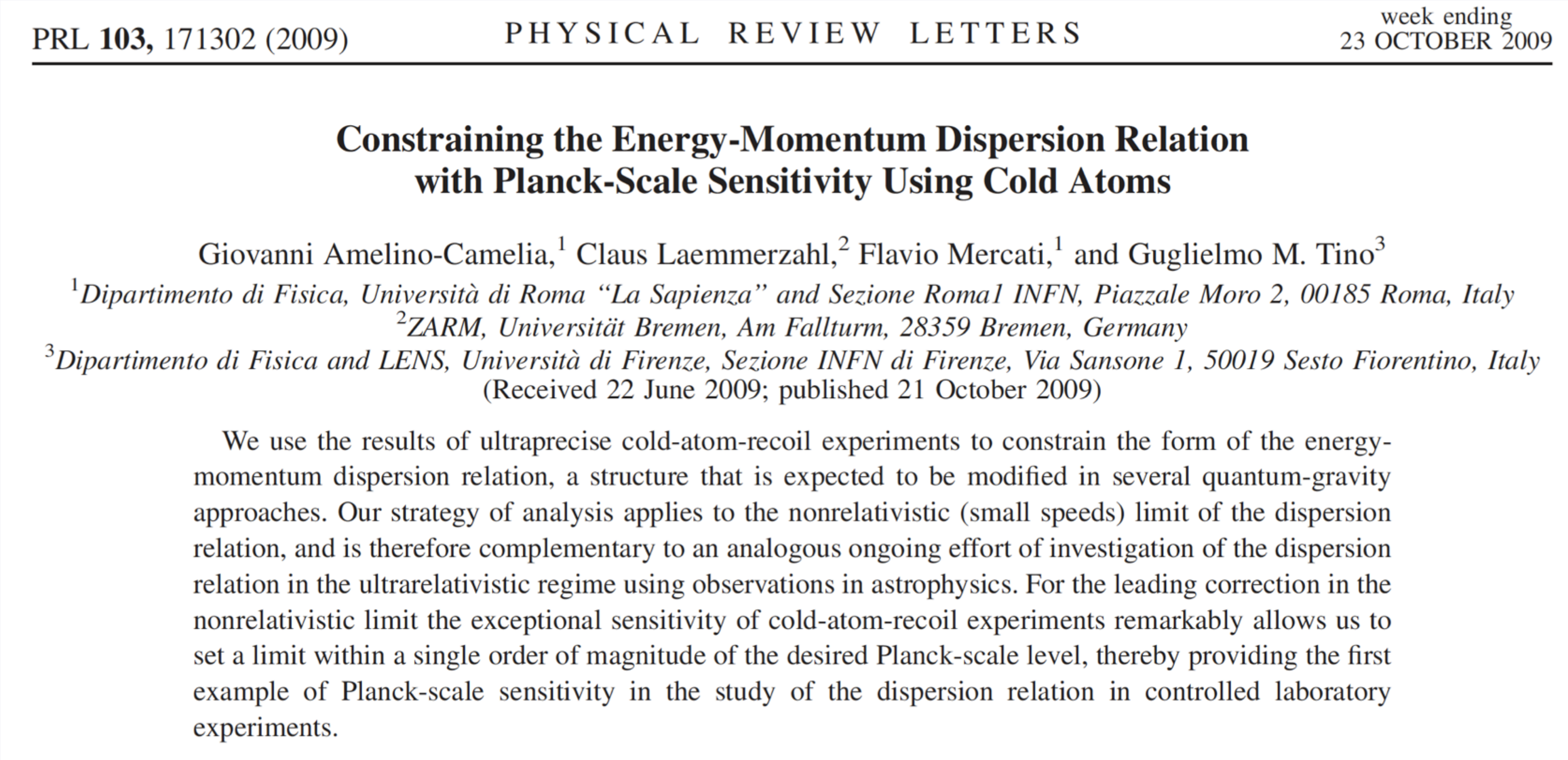
Test of quantum gravity models



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

Giovanni Amelino-Camelia,[1] Claus Laemmerzahl,[2] Flavio Mercati,[1] and Guglielmo M. Tino[3]
[1]*Dipartimento di Fisica, Università di Roma "La Sapienza" and Sezione Roma1 INFN, Piazzale Moro 2, 00185 Roma, Italy*
[2]*ZARM, Universität Bremen, Am Fallturm, 28359 Bremen, Germany*
[3]*Dipartimento di Fisica and LENS, Università di Firenze, Sezione INFN di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy*

(Received 22 June 2009; published 21 October 2009)

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.

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

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

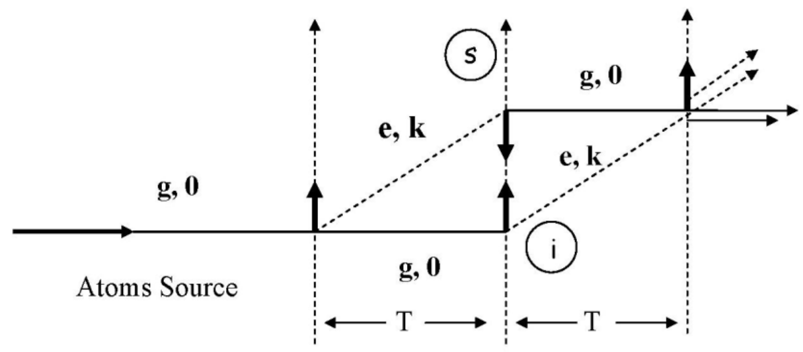
$|\xi_1| \sim 1$ to $|\xi_1| \sim 10^3$

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

Gravitational waves detection with atom interferometry

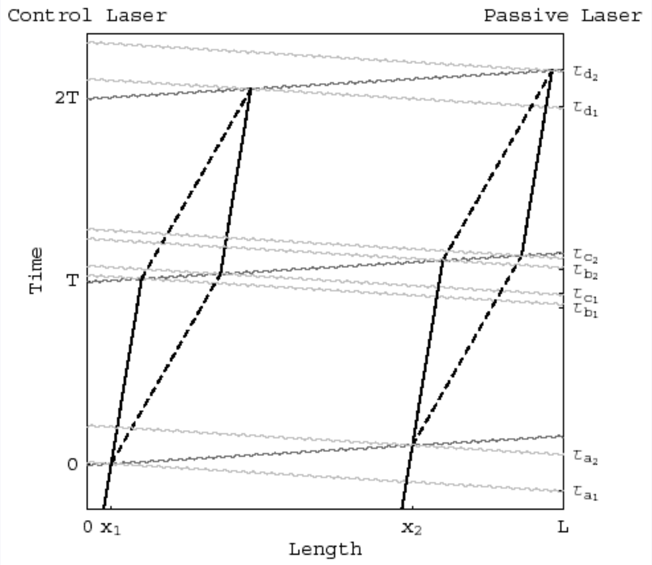
- *Single atom interferometer*

G.M. Tino and F. Vetrano, *Is it possible to detect gravitational waves with atom interferometers?* Class. Quantum Grav. 24, 2167 (2007)



- *Differential scheme*

S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, *Atomic gravitational wave interferometric sensor,* Phys. Rev. D 78, 122002 (2008)



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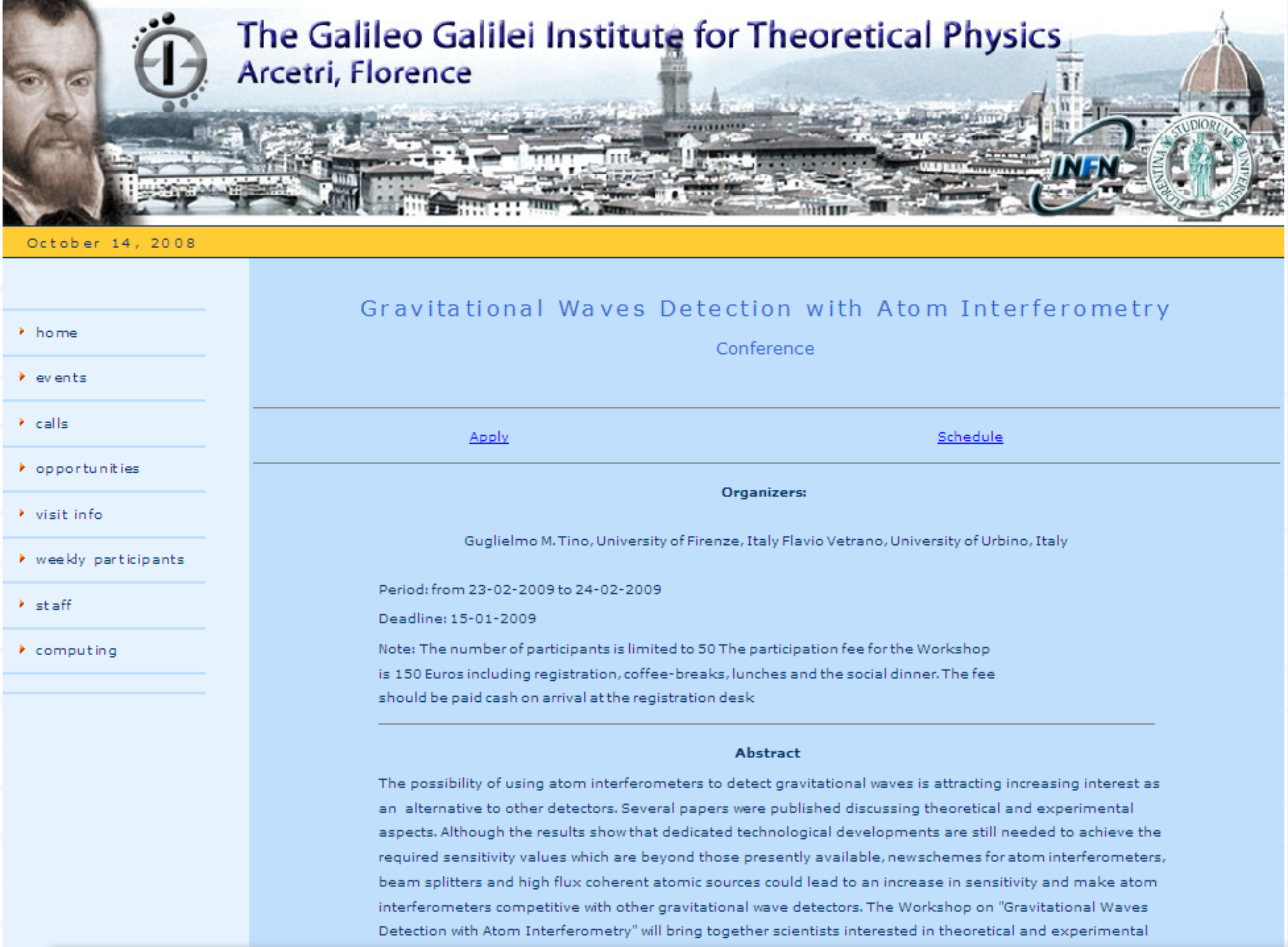

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Gravitational Waves Detection with Atom Interferometry

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

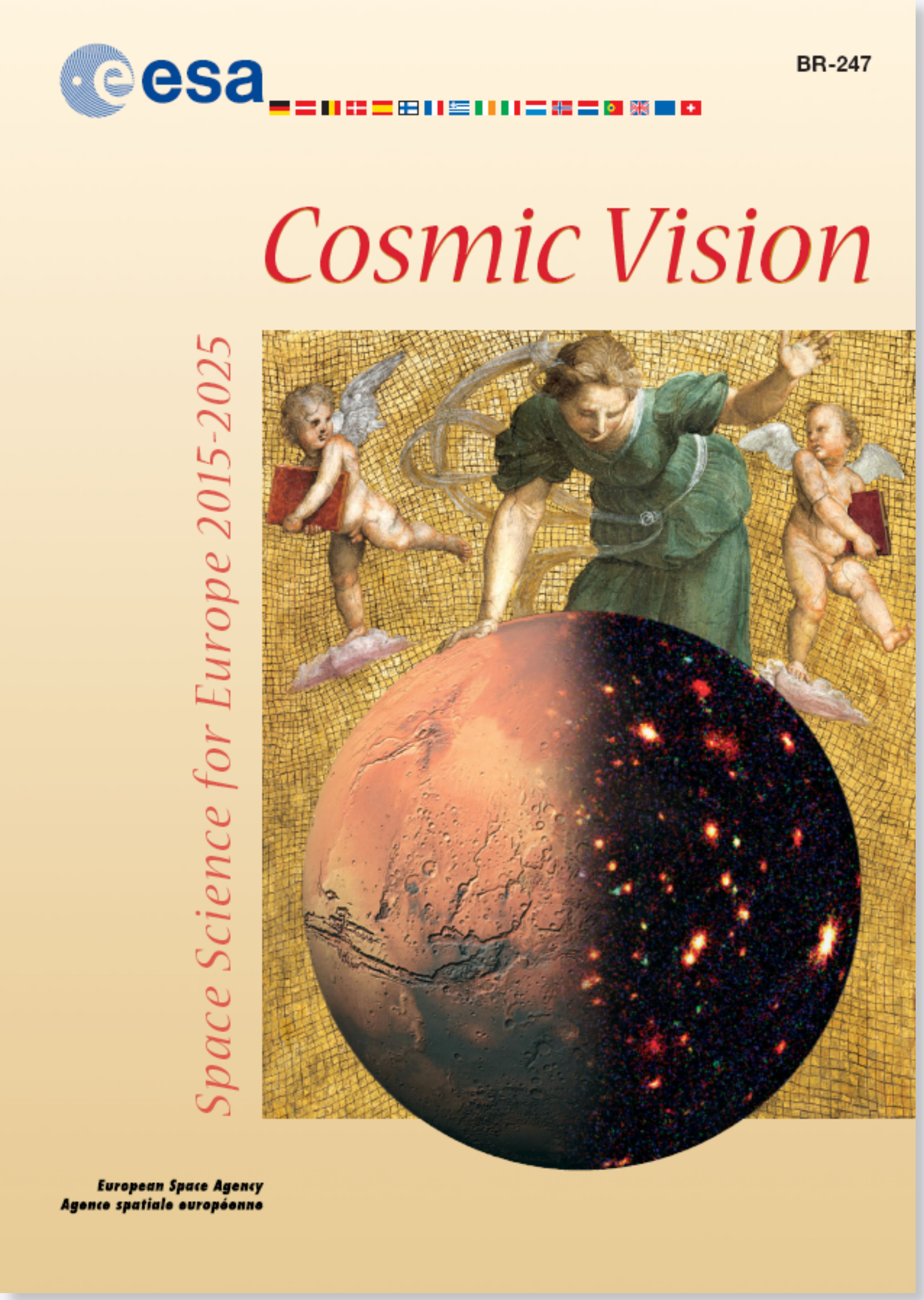
Abstract

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)

- STE-QUEST Mission -

Test of Gravitational Red Shift and Equivalence Principle



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Space Science for Europe 2015-2025

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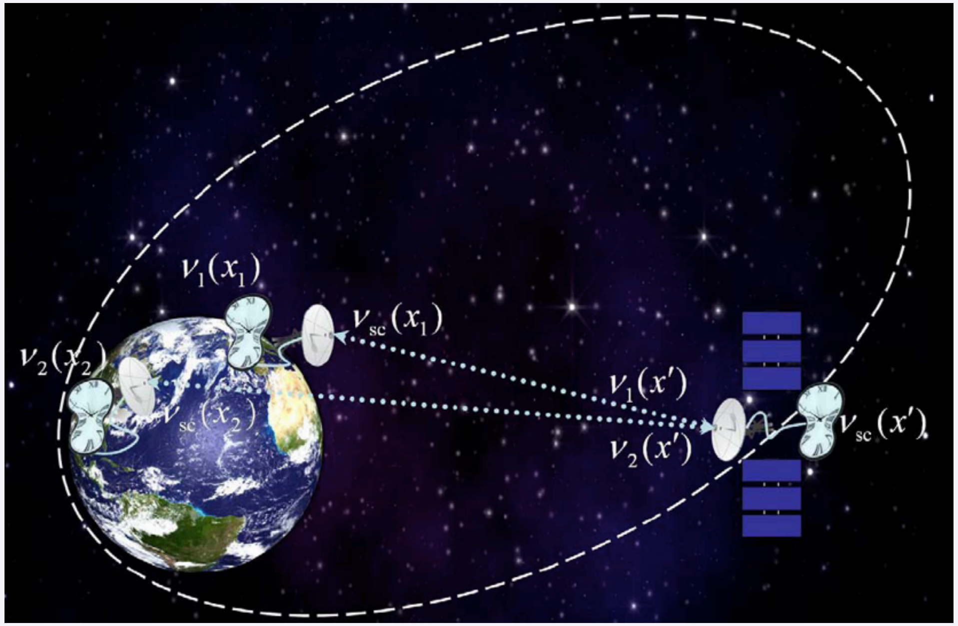

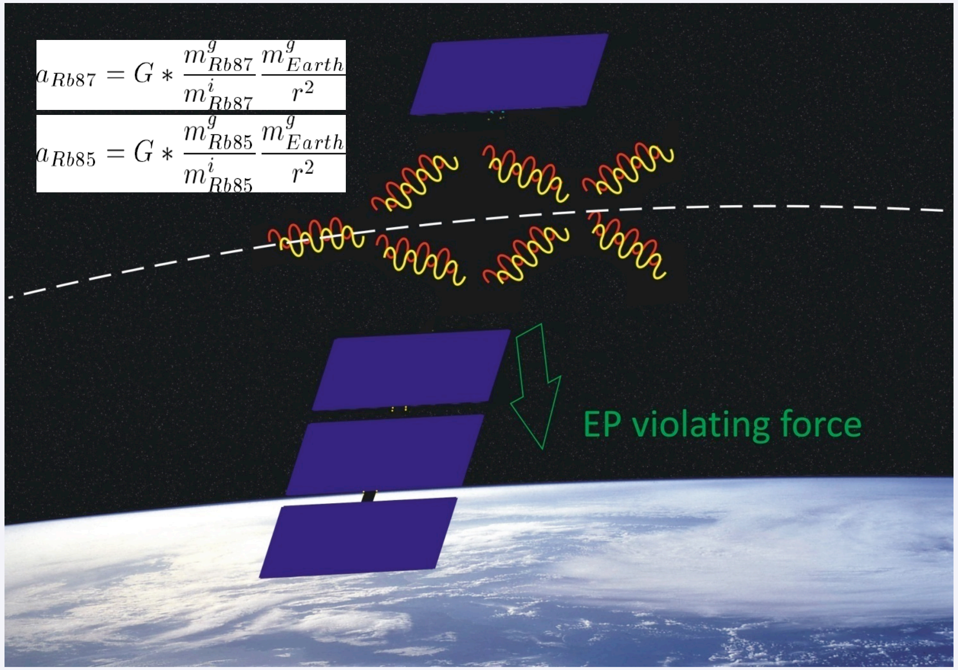

$$a_{Rb87} = G * \frac{m^g_{Rb87}}{m^i_{Rb87}} \frac{m^g_{Earth}}{r^2}$$

$$a_{Rb85} = G * \frac{m^g_{Rb85}}{m^i_{Rb85}} \frac{m^g_{Earth}}{r^2}$$

COURSE
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Atom Interferometry

edited by G. M. Tino and M. A. Kasevich

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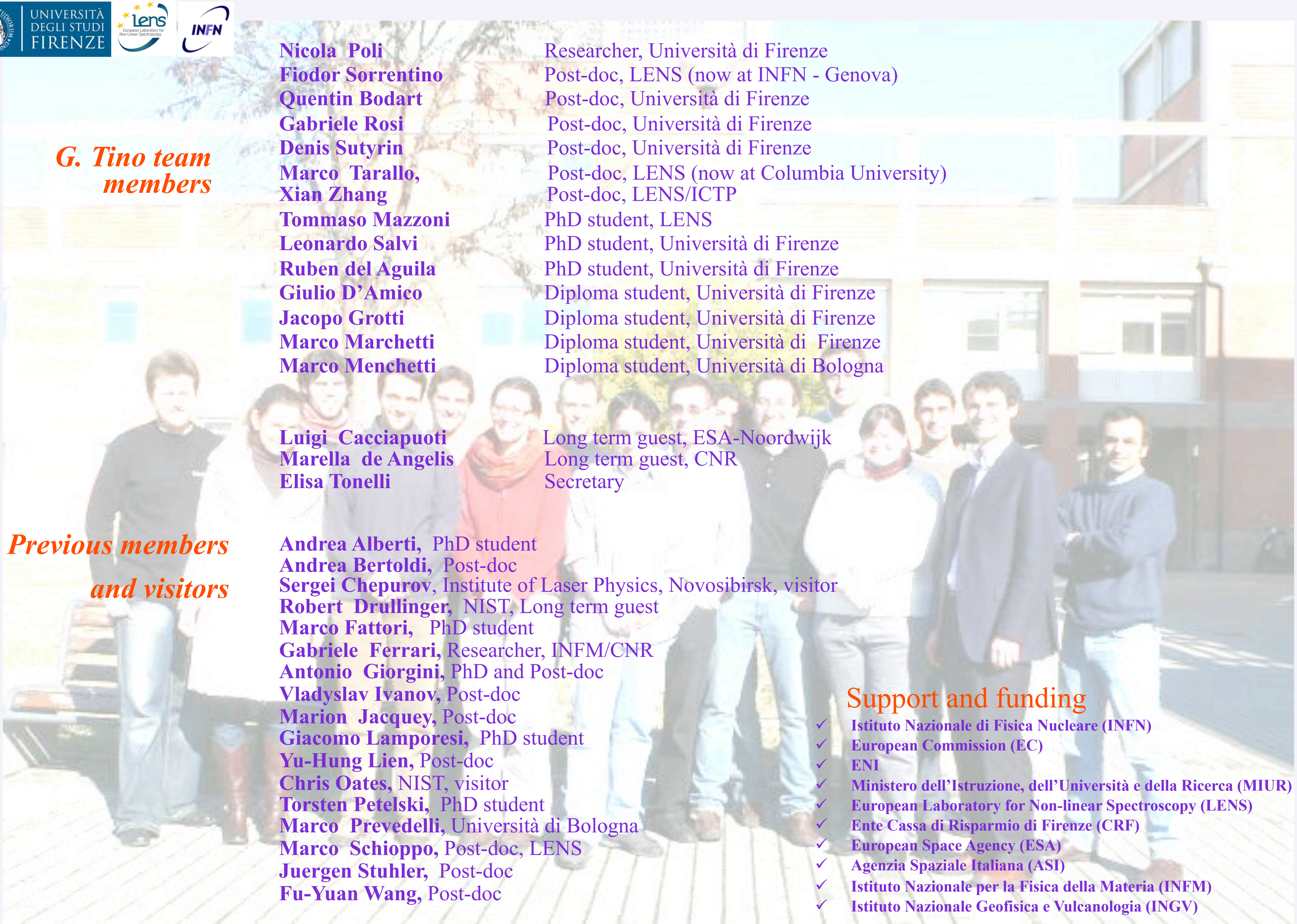

G. Tino team members

Nicola Poli	Researcher, Università di Firenze
Fiodor Sorrentino	Post-doc, LENS (now at INFN - Genova)
Quentin Bodart	Post-doc, Università di Firenze
Gabriele Rosi	Post-doc, Università di Firenze
Denis Sutyrin	Post-doc, Università di Firenze
Marco Tarallo,	Post-doc, LENS (now at Columbia University)
Xian Zhang	Post-doc, LENS/ICTP
Tommaso Mazzoni	PhD student, LENS
Leonardo Salvi	PhD student, Università di Firenze
Ruben del Aguila	PhD student, Università di Firenze
Giulio D’Amico	Diploma student, Università di Firenze
Jacopo Grotti	Diploma student, Università di Firenze
Marco Marchetti	Diploma student, Università di Firenze
Marco Menchetti	Diploma student, Università di Bologna

Luigi Cacciapuoti	Long term guest, ESA-Noordwijk
Marella de Angelis	Long term guest, CNR
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
Yu-Hung Lien, Post-doc
Chris Oates, NIST, visitor
Torsten Petelski, PhD student
Marco Prevedelli, Università di Bologna
Marco Schioppo, Post-doc, LENS
Juergen Stuhler, Post-doc
Fu-Yuan Wang, Post-doc

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- ✓ **European Commission (EC)**
- ✓ **ENI**
- ✓ **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)**
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