Experimental Gravity with Cold Atoms

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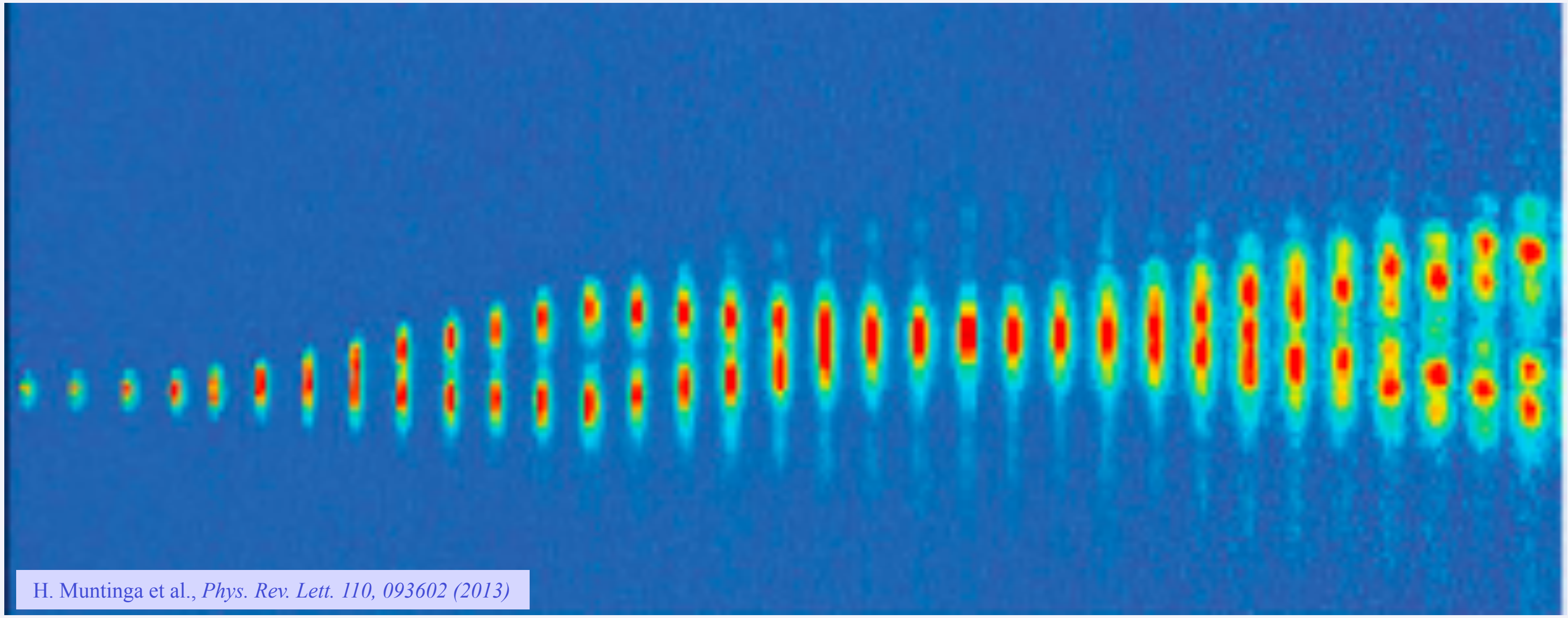
http://coldatoms.lens.unifi.it/

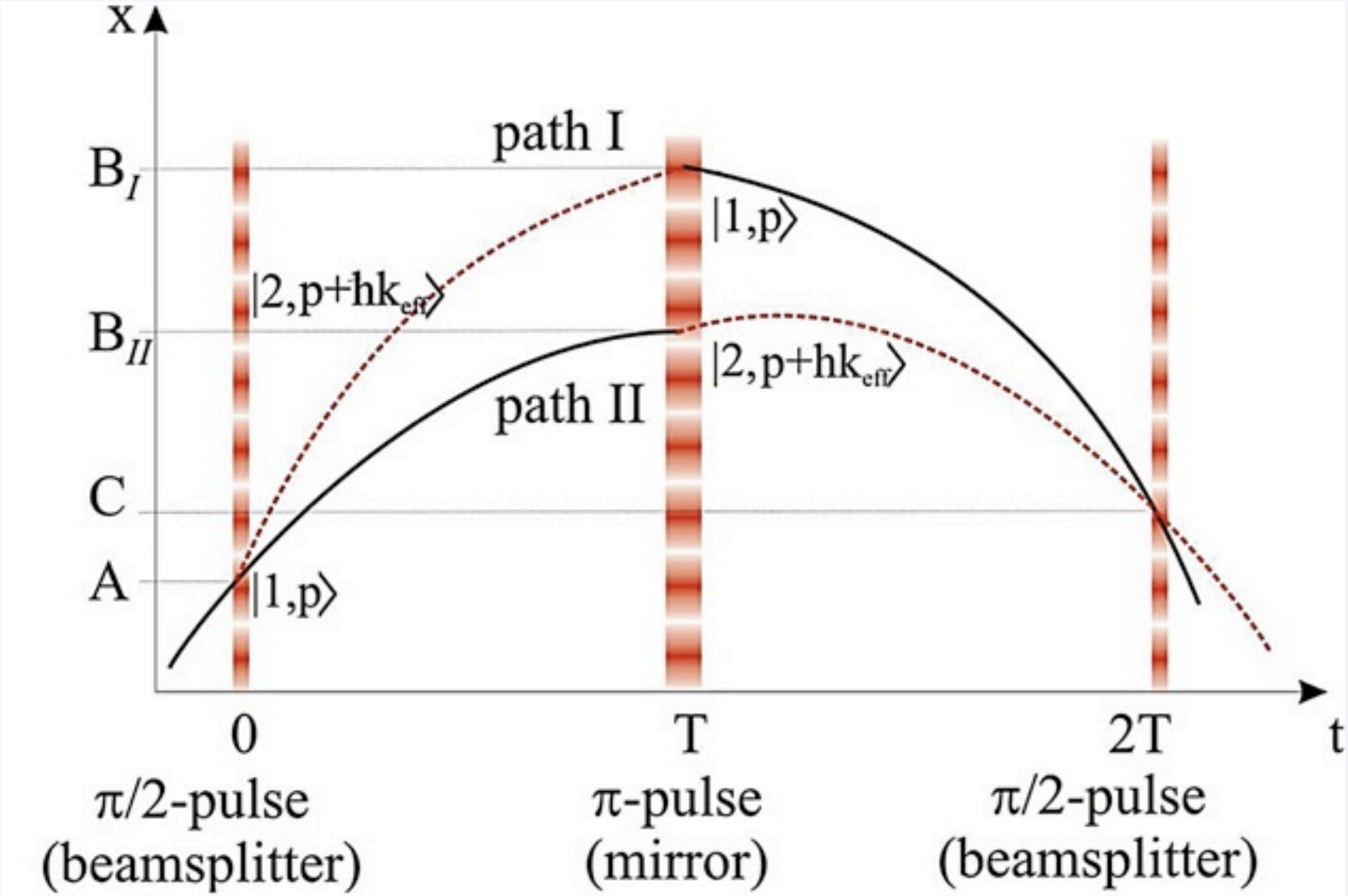
What Next INFN
Arcetri, 4/5/2015

Atom Interferometry

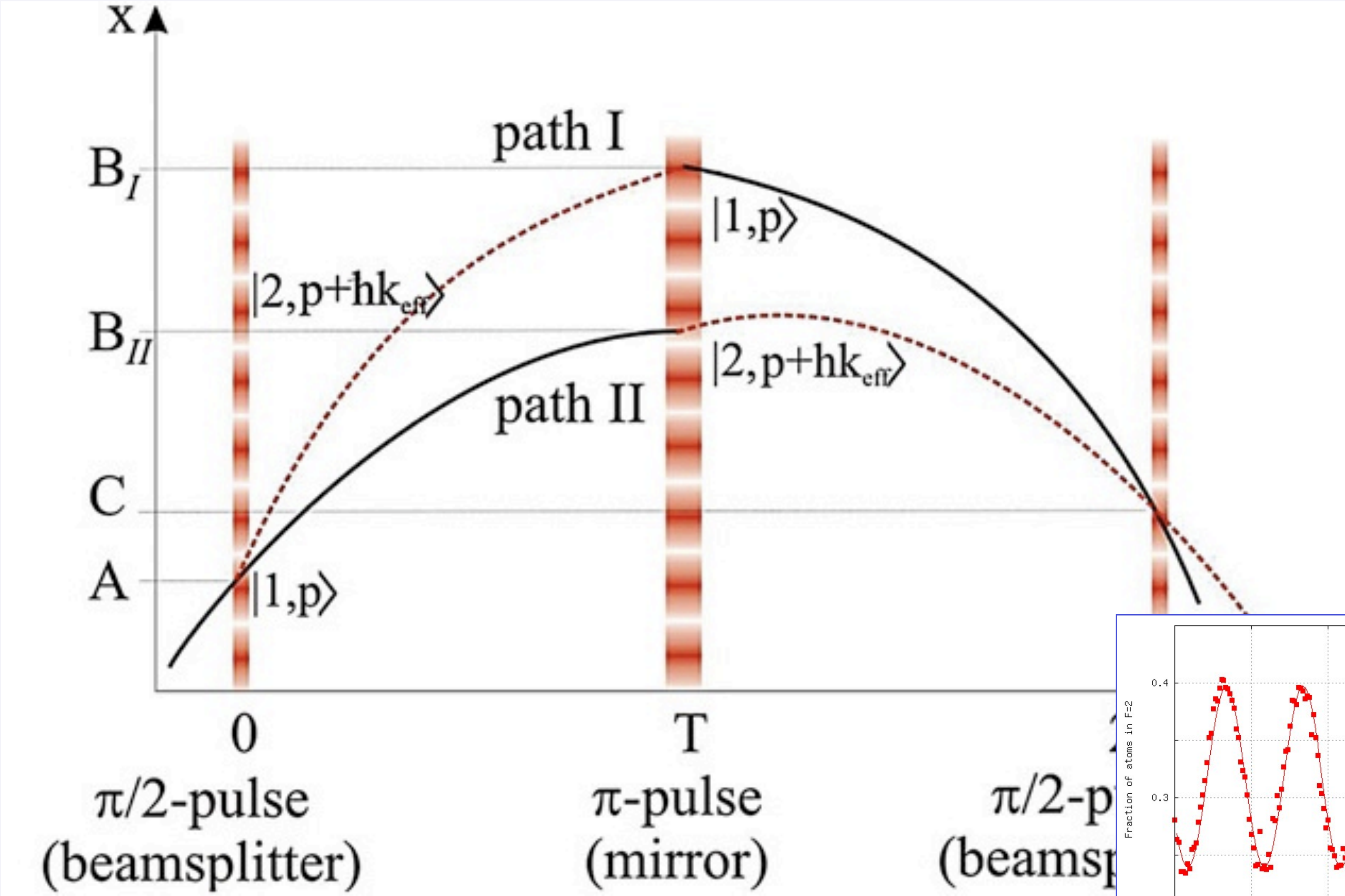


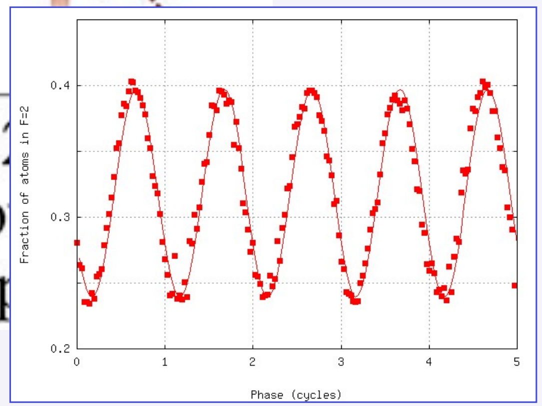
H. Muntinga et al., *Phys. Rev. Lett. 110, 093602 (2013)*

Atom interferometry and gravity



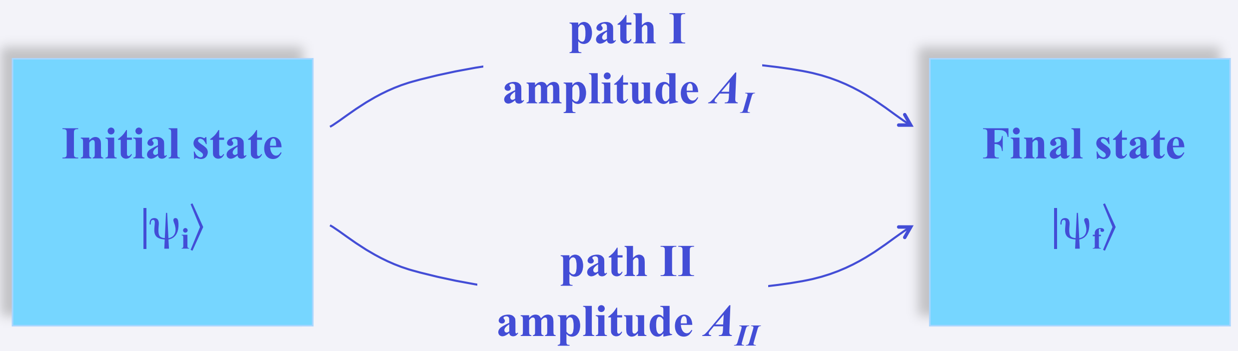
Atom interferometry and gravity





Interference fringes – Firenze 2006

Quantum interference



Interference of transition amplitudes

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

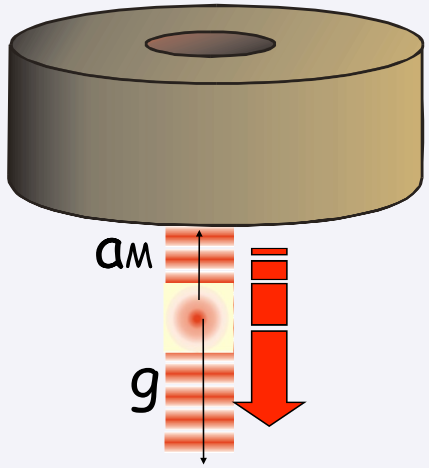
Why atoms?

- 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

(Misura Accurata di G mediante Interferometria Atomica)

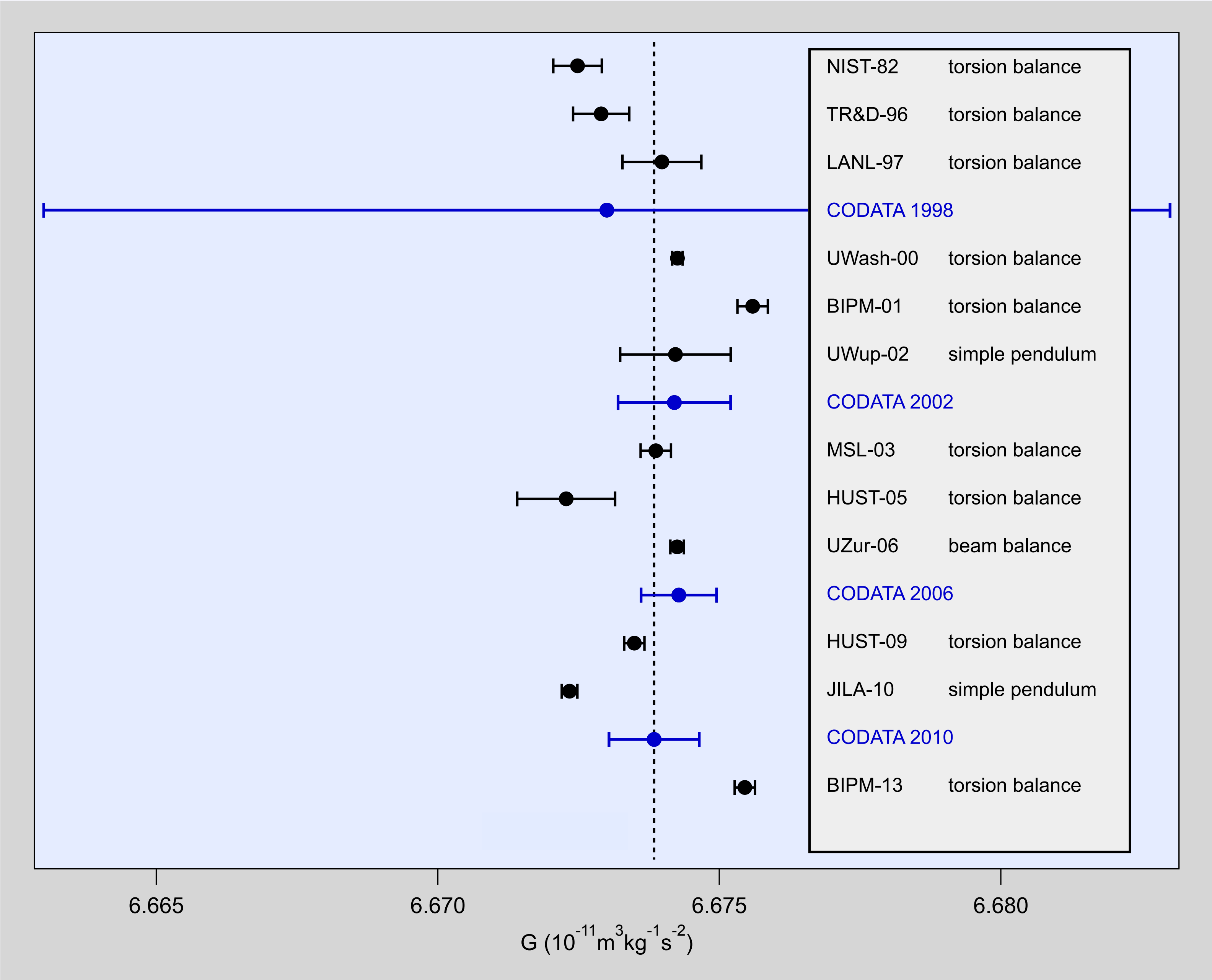
- **Measure g by atom interferometry**
- **Add source masses**
- **Measure change of g**



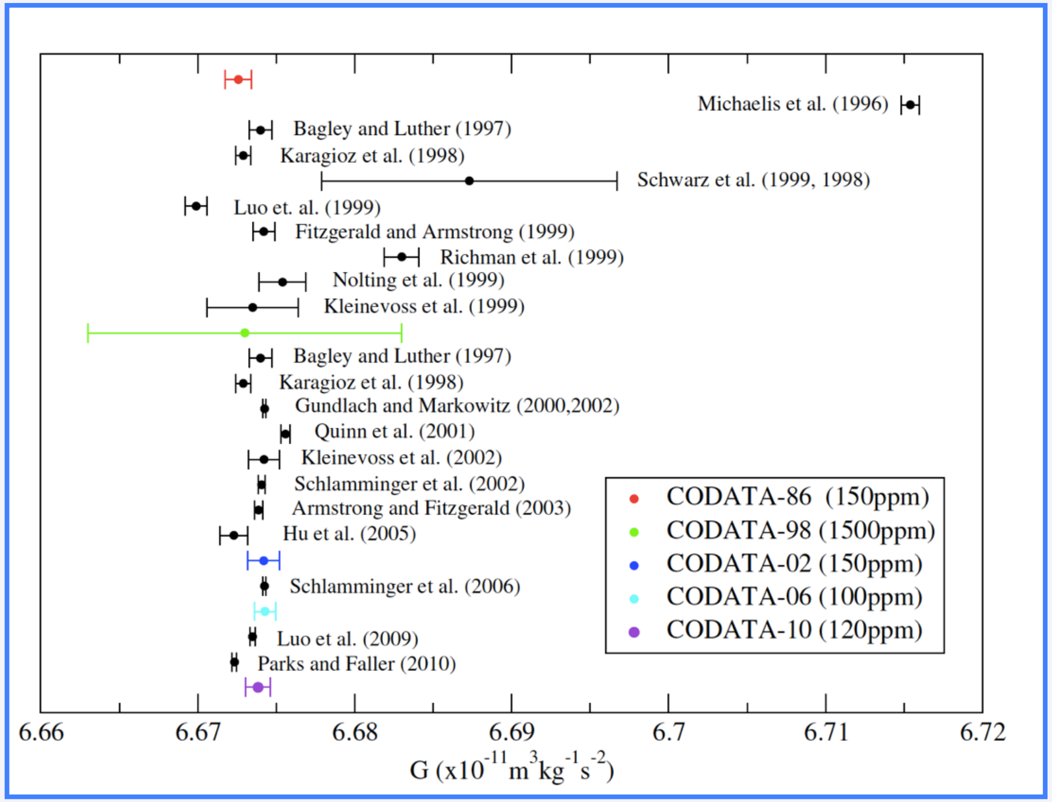
> ***Precision measurement of G***
> ***Test of Newtonian law***

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

Measurements of the Newtonian gravitational constant G

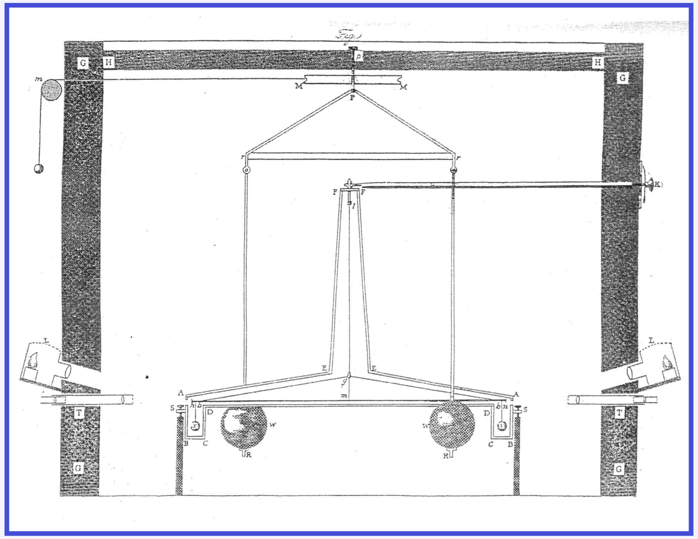


Measurements of the Newtonian gravitational constant G

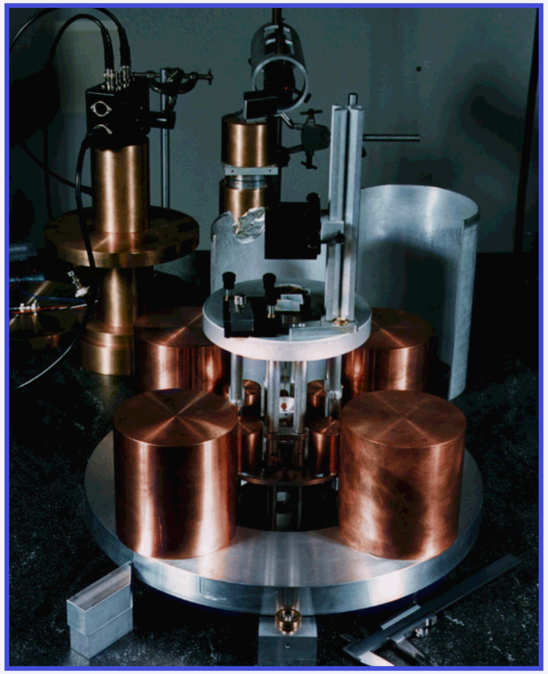


G = 6.67384 (80) × 10^{-11} $m^3\,kg^{-1}s^{-2}$
[1.2×10^{-4}]

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)

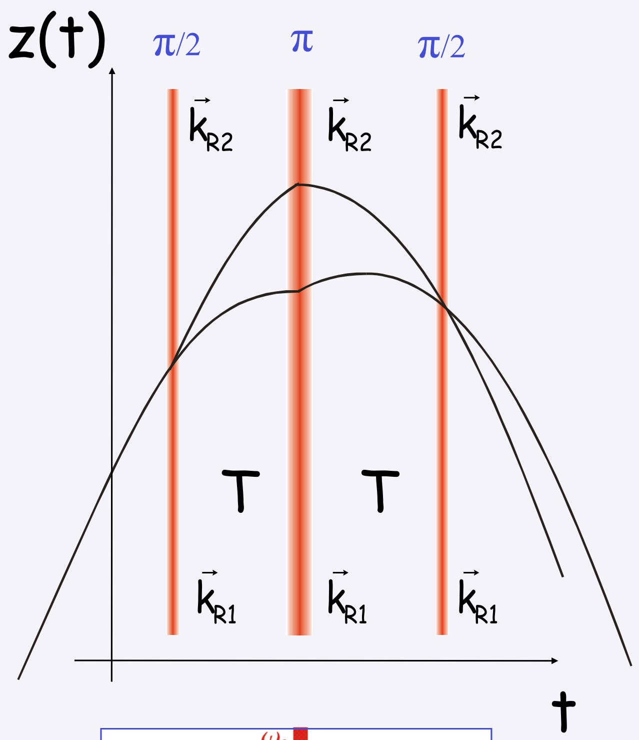


Cavendish 1798



Quinn 2001

Raman interferometry in an atomic fountain

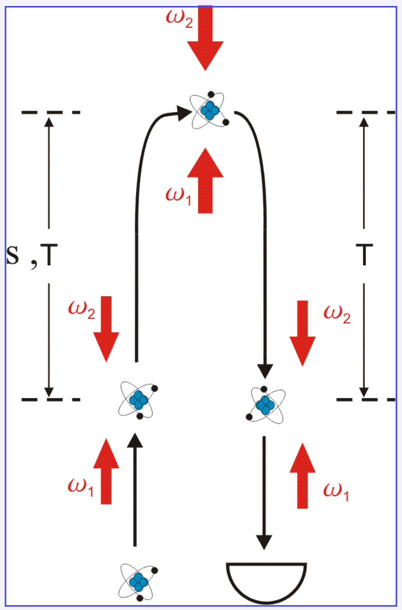


Phase difference between the paths:

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

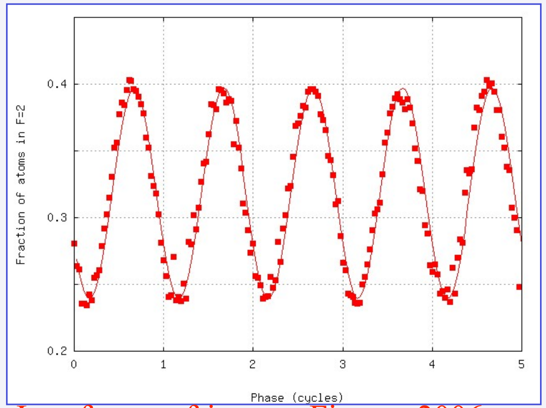
with $z(t) = -g\, t^2/2 + v_0 t + z_0$ & $\Phi_e = 0$ $\Rightarrow$ $\mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

10^6 Rb atoms

S/N = 1000

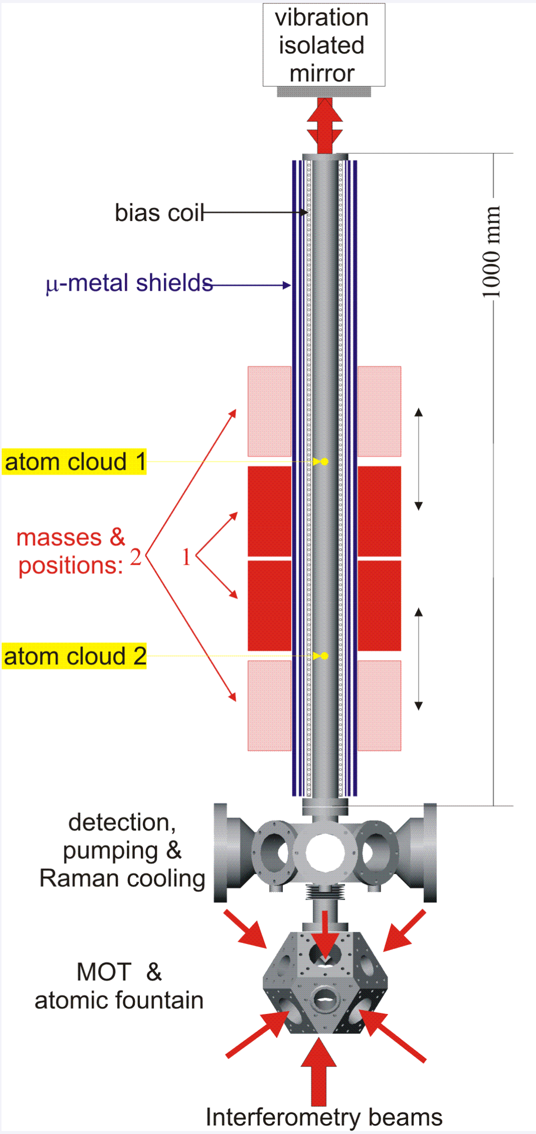
T = 150 ms $\Rightarrow 2\pi = 10^{-6}$g

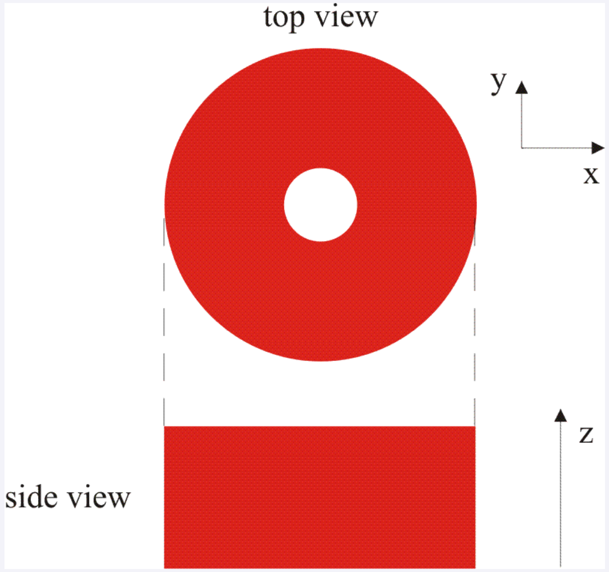
$\Rightarrow$ Sensitivity 10^{-9} g/shot

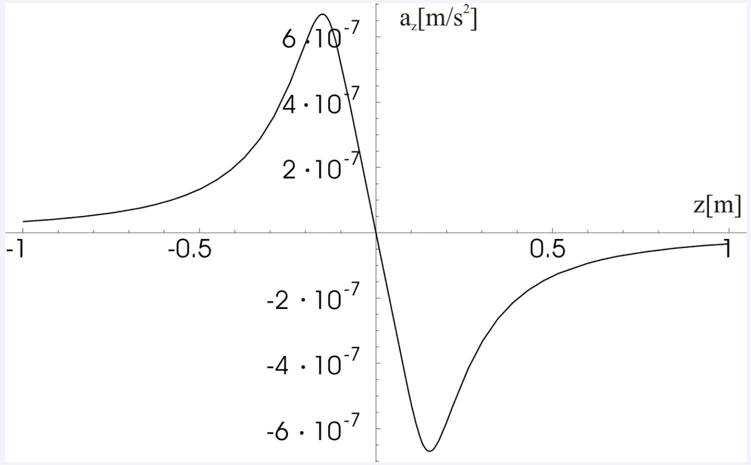
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Atom gravimeter + source mass







500 kg tungsten mass

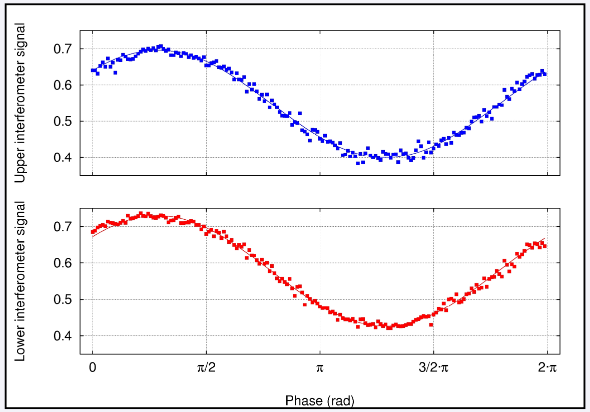
Sensitivity 10^{-9}g/shot

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

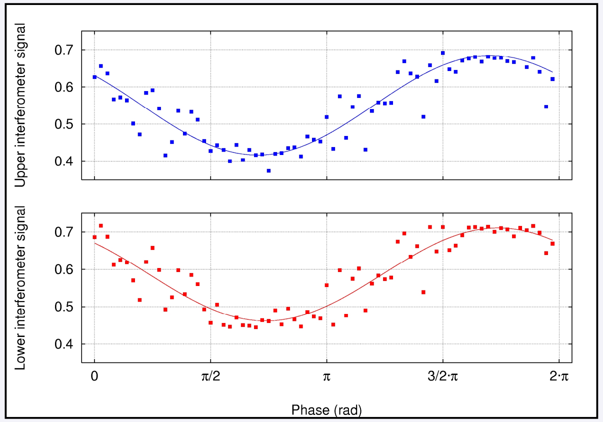
one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

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

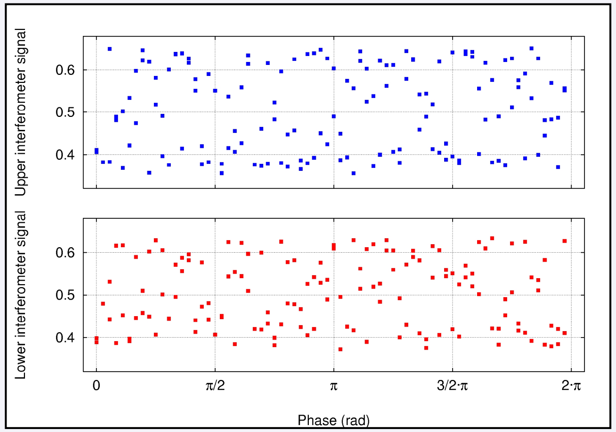
Gravity gradiometer



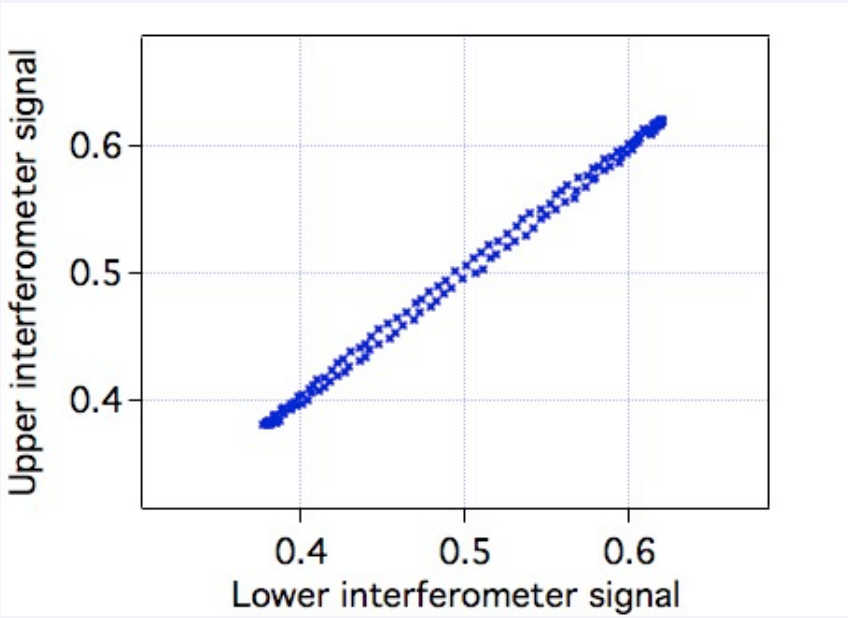
T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot



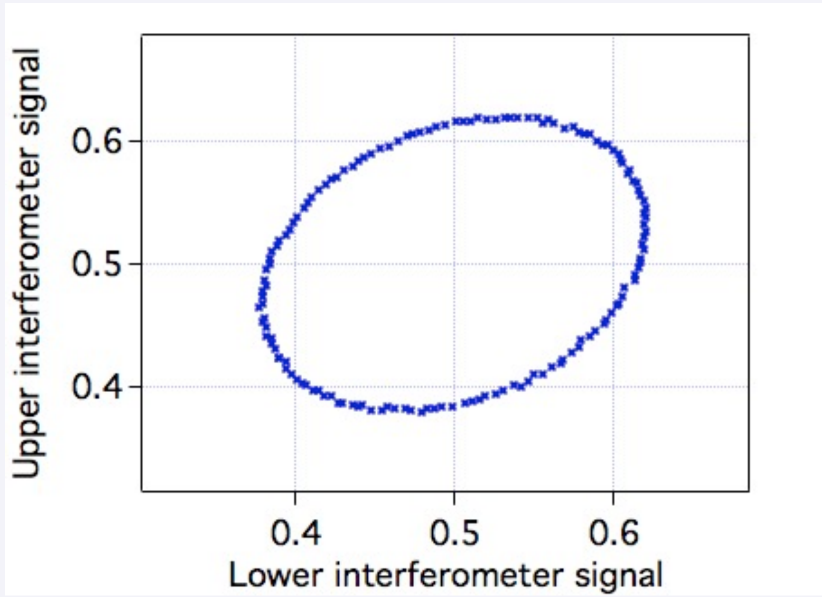
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot



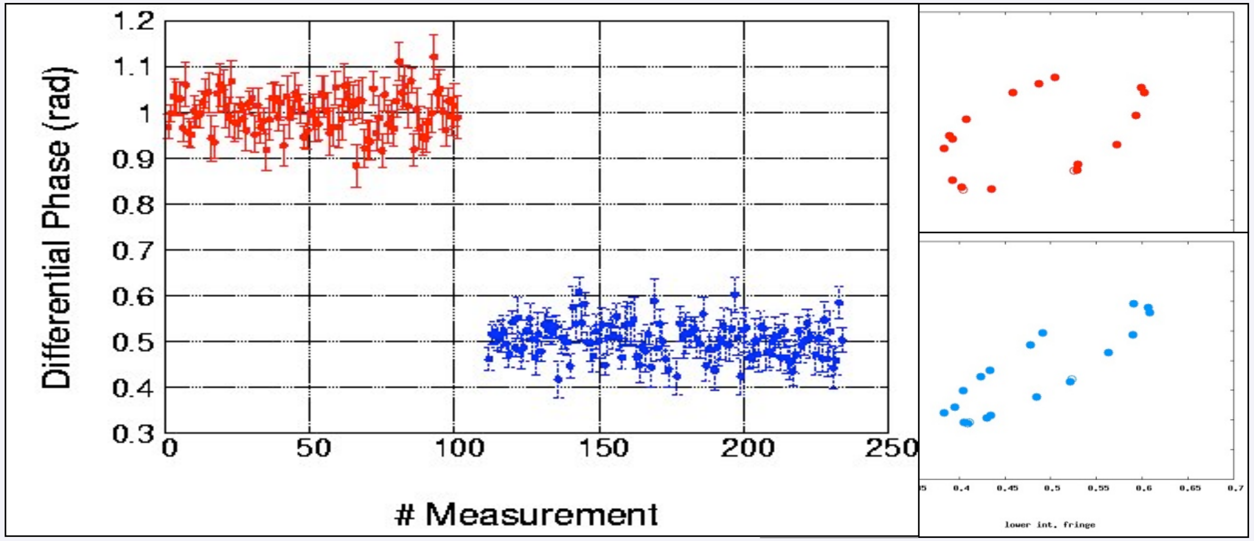
T=150 ms
resol. $= 3.2 \times 10^{-8}$g/shot



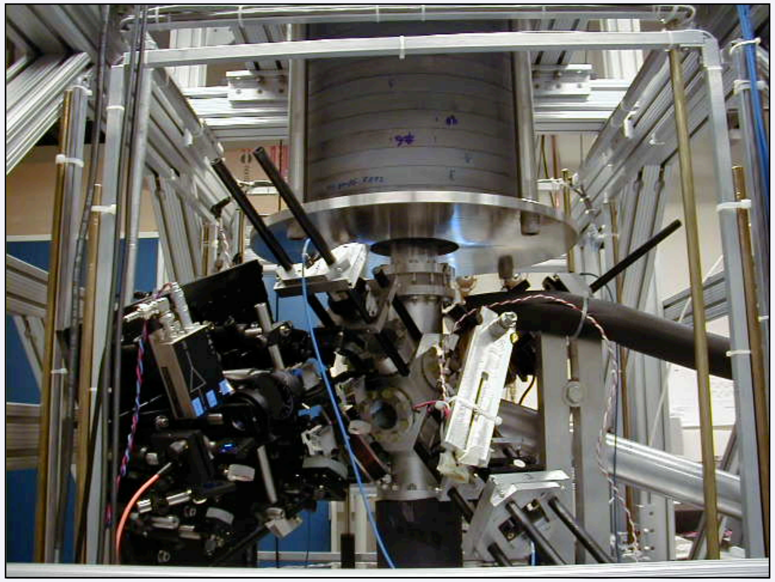
$$\Delta\Phi = k_e g T^2$$

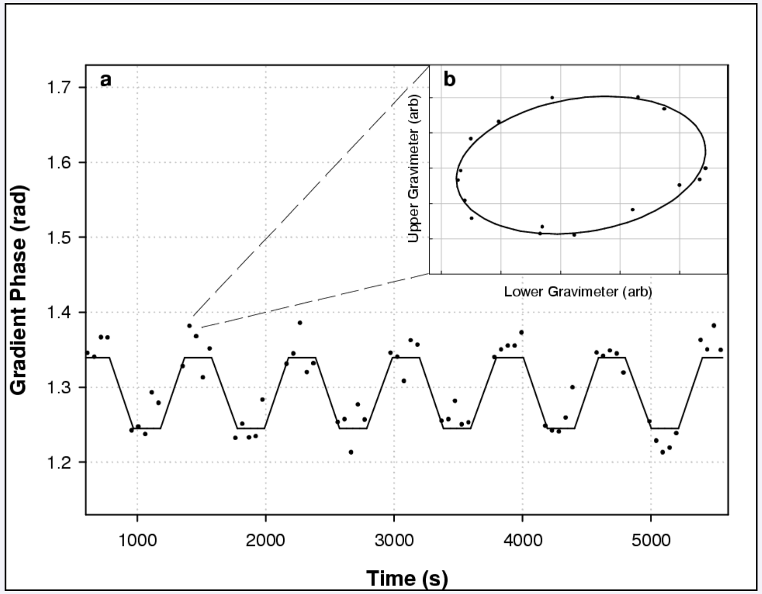


G. T. Foster et al., Opt. Lett **27**, 951 (2002)



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)



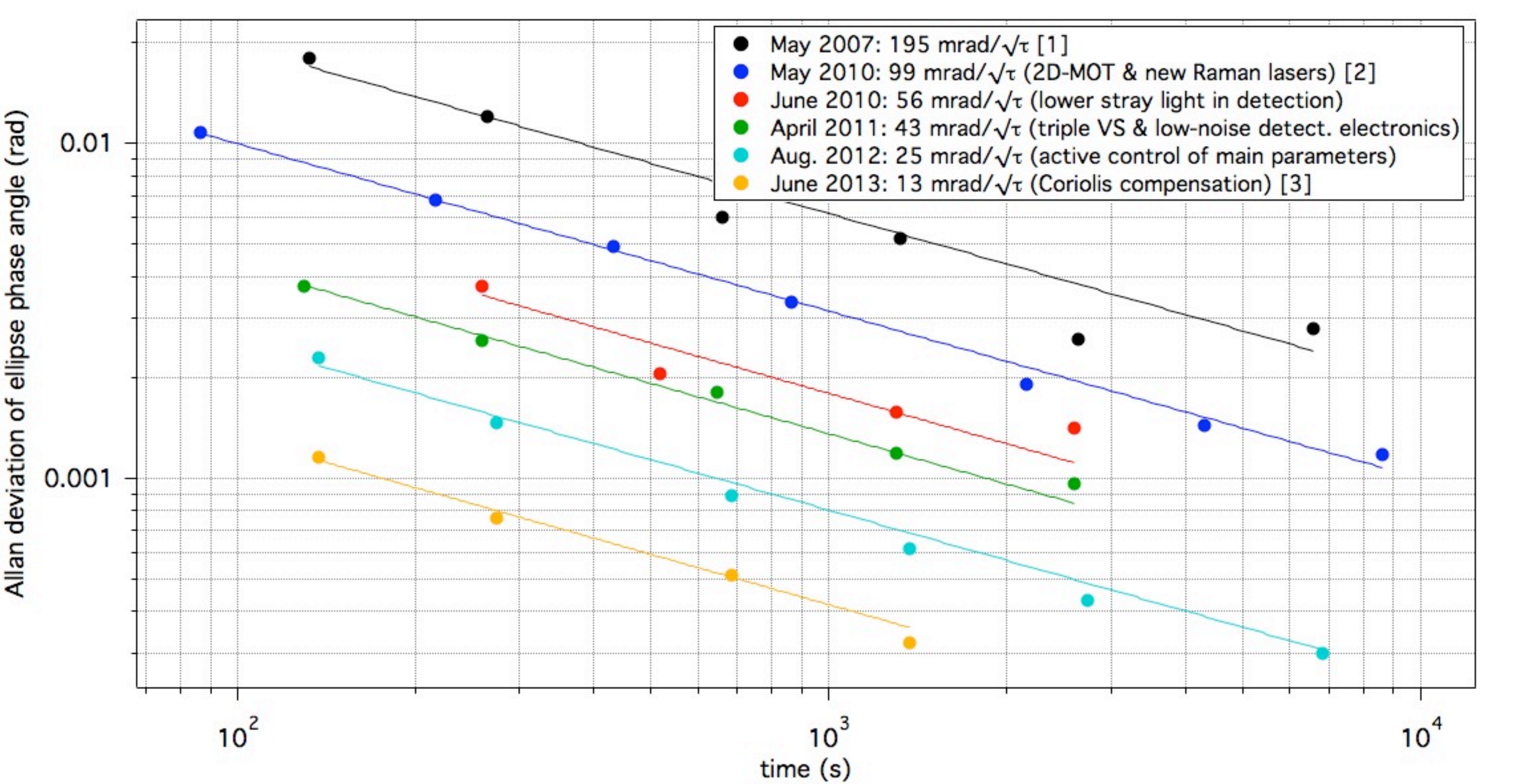


J. B. Fixler, G. T. Foster, J. M. McGuirk and M. A. Kasevich,
Atom Interferometer Measurement of the Newtonian Constant of Gravity,
Science 315, 74 (2007)

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

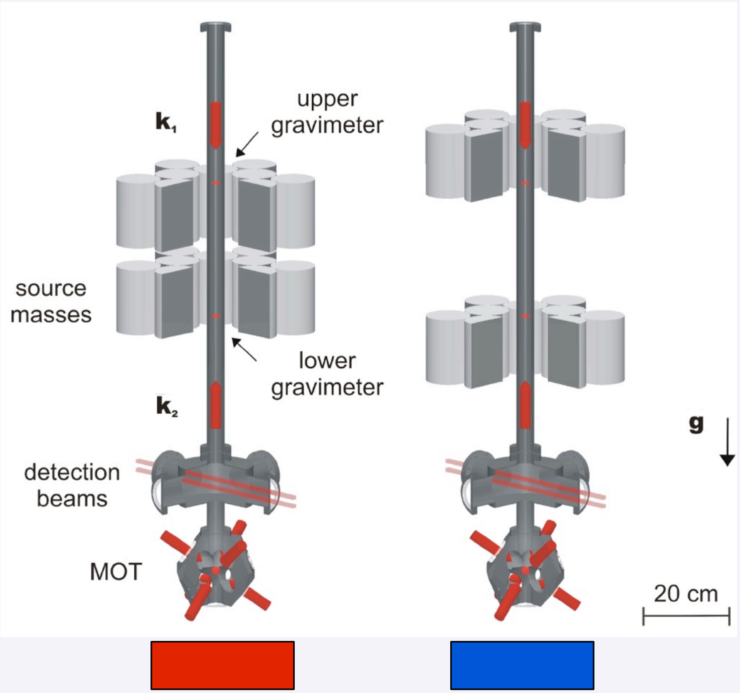
MAGIA: increasing sensitivity



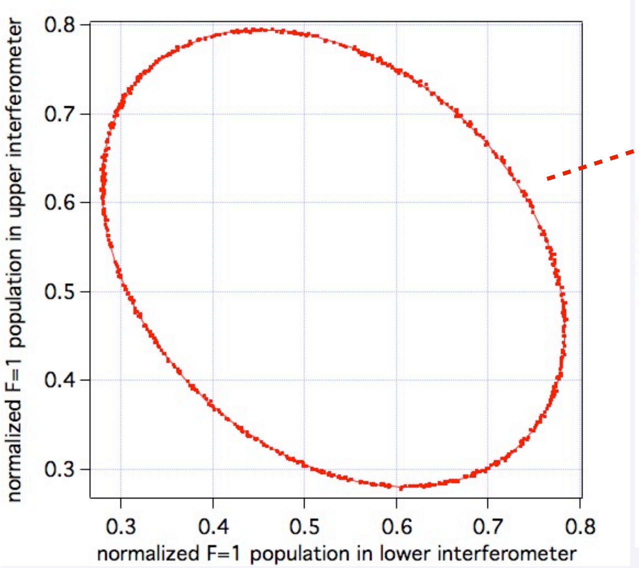
Current sensitivity to differential acceleration: 3×10^{-9} g @ 1s (=QPN for 4×10^{5} atoms)

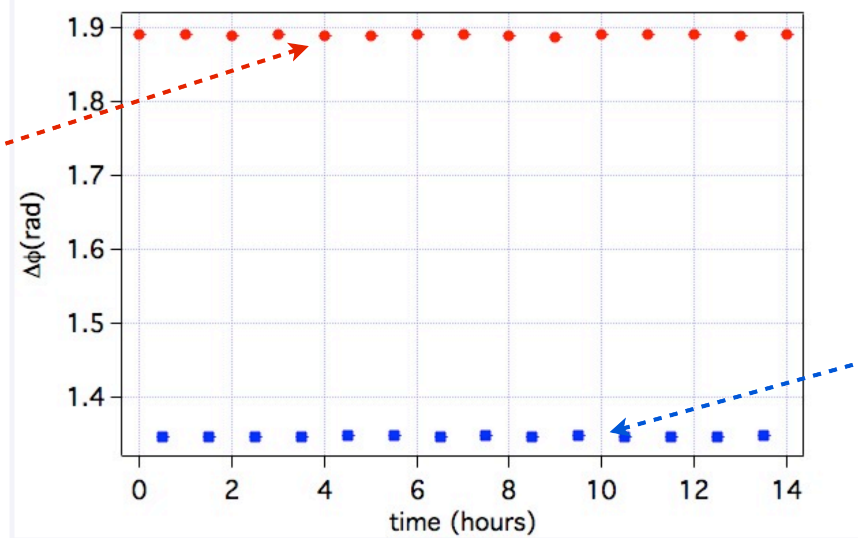
[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)
[2] F. Sorrentino et al., New J. Phys. 12, 095009 (2010)
[3] F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)

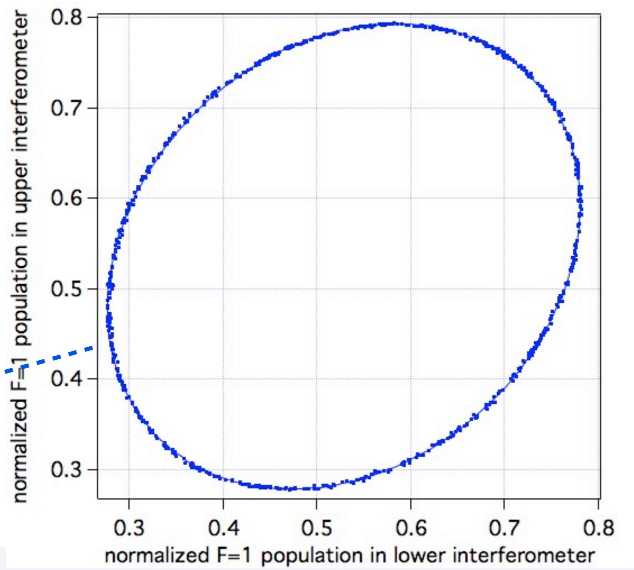
MAGIA: Final sensitivity



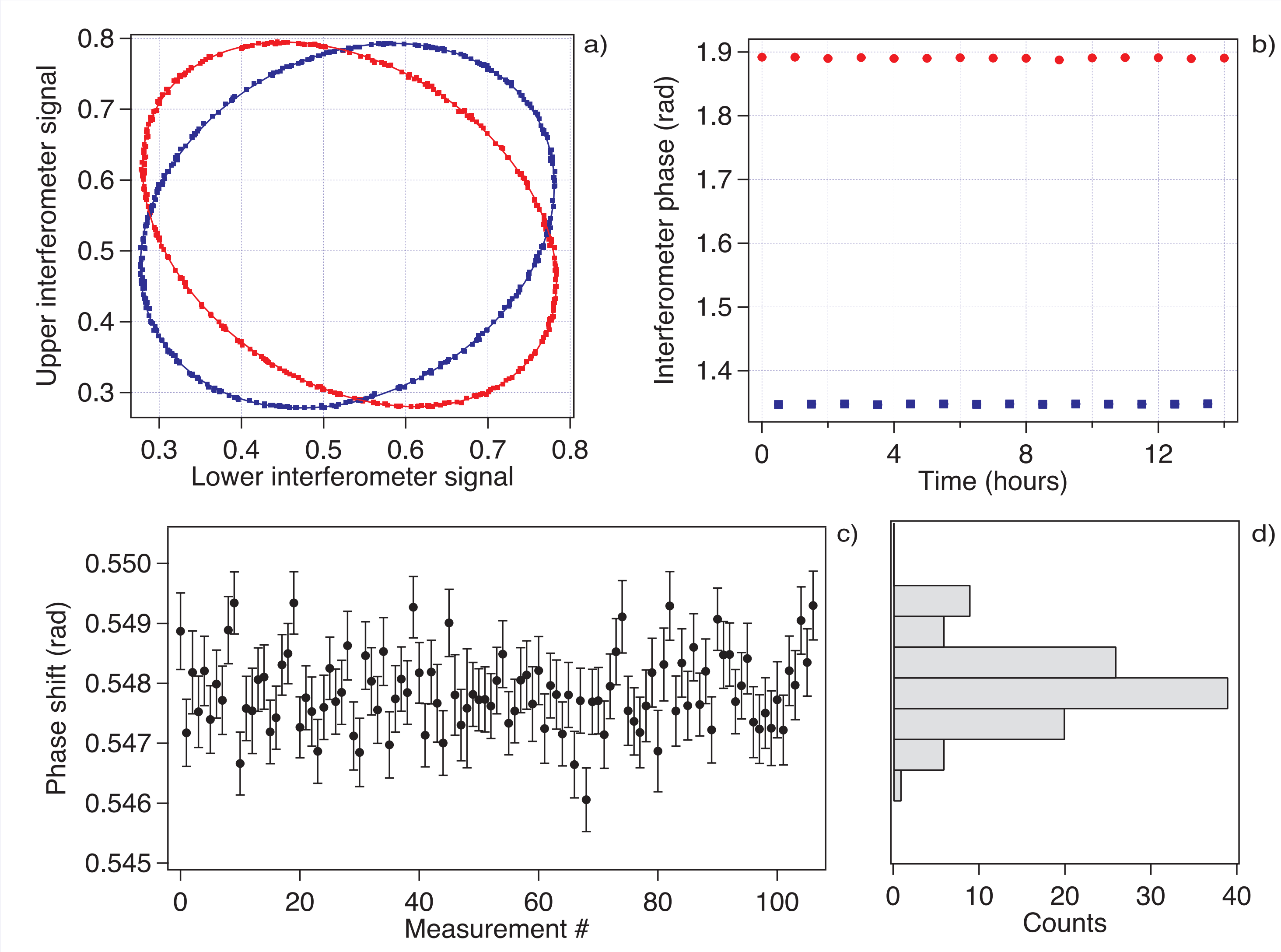
- Repetition period of experimental cycle: 1.9 s
- Number of points per ellipse: 720 (23 min)
- Number of launched atoms: ~10^9 per cloud
- Number of detected atoms: ~$4x10^5$ per cloud
- Sensitivity to ellipse angle: ~ 9 mrad/shot
- Sensitivity to differential gravity: $3x10^{-9}$ g /√Hz
- Sensitivity in *G* measurements: $5.7x10^{-2}$/√Hz
- Integration time to *G* at 10^{-4}: 100 hours







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 $G = 6.67191(99) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$ with a relative uncertainty of 150 parts per million (the combined standard

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.

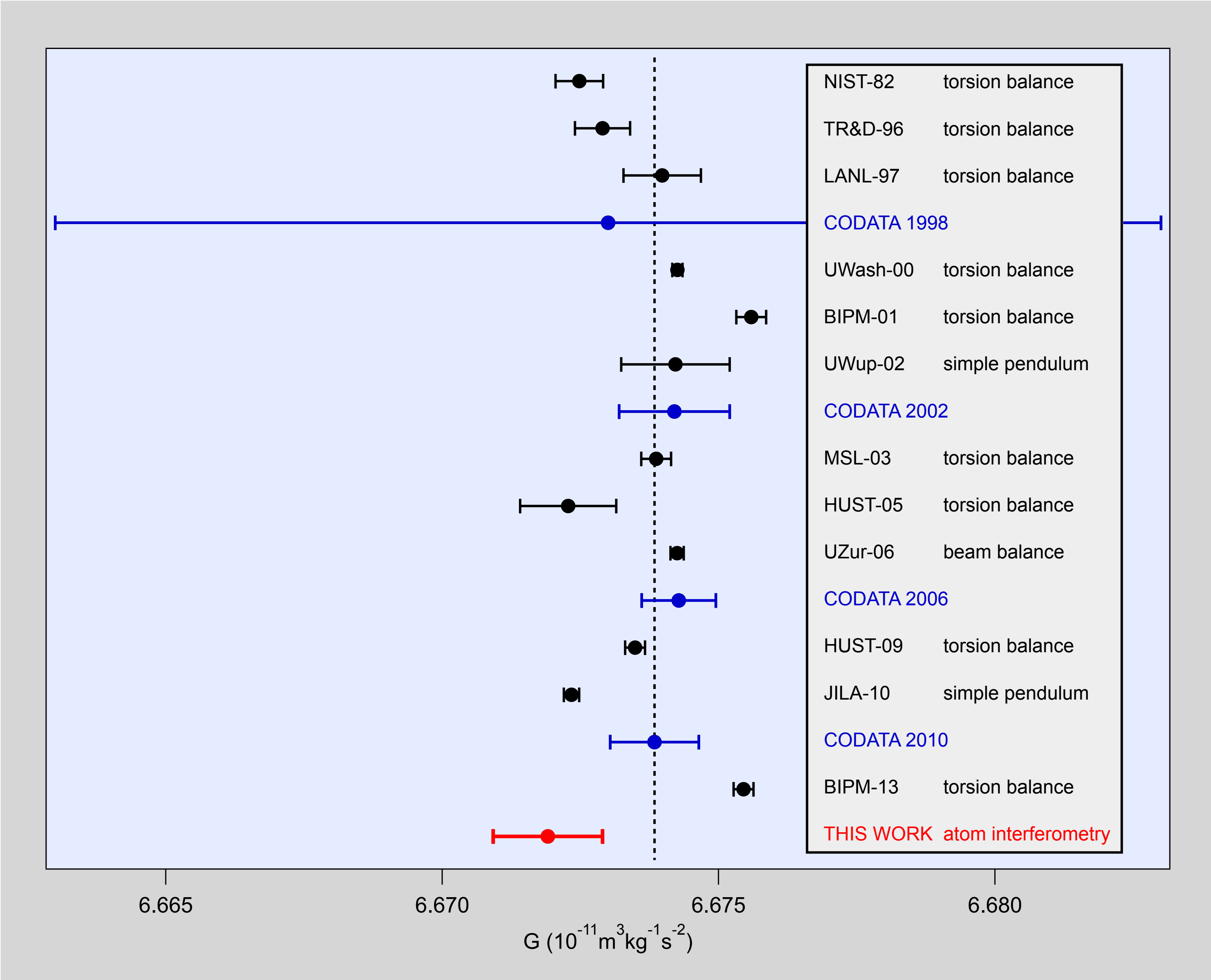
The atom interferometer is realized using light pulses to stimulate ^{87}Rb atoms at the two-photon Raman transition between the hyperfine

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

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



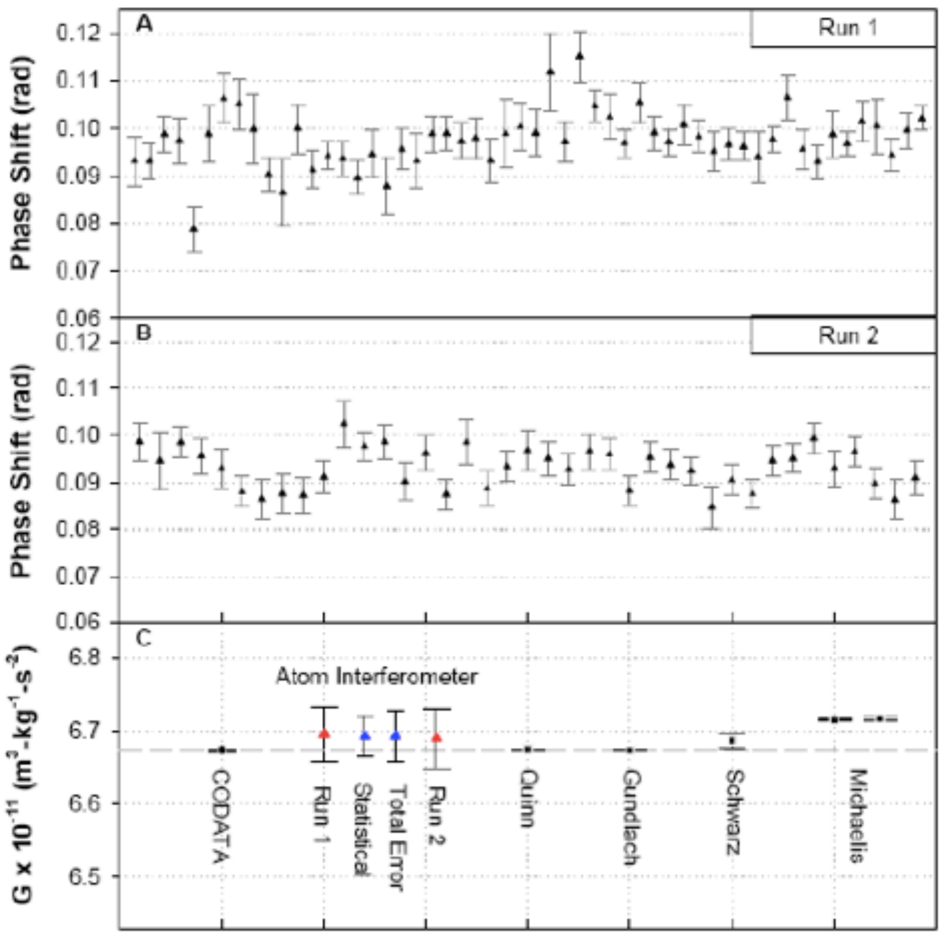
G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms
NATURE vol. 510, p. 518 (2014)

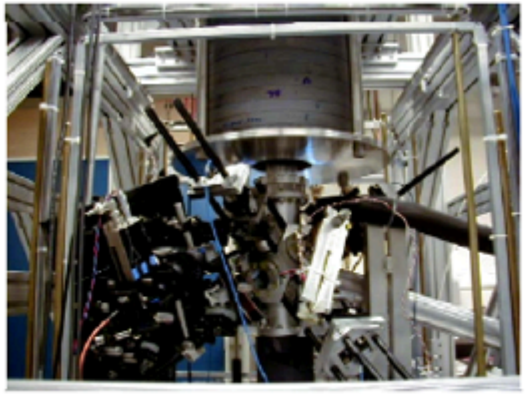
MAGIA error budget

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)**

Measurement of G





Systematic	$\delta G/G$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

Systematic error sources dominated by initial position/velocity of atomic clouds. $\delta G/G \sim 0.3\%$.

Next Generation: <1e-4, exp't in progress at AOSense, Inc. in colloboration with LLNL.

STANFORD UNIVERSITY

From M. Kasevich

G. W. Biedermann et al., *Testing Gravity with Cold-Atom Interferometers*, arXiv:1412.3210 (2014)

Project of Measuring G with AI in HUST

HUST: Huazhong University of Science & Technology

Source masses:

24×10Kg spheres

Gravitational signal:

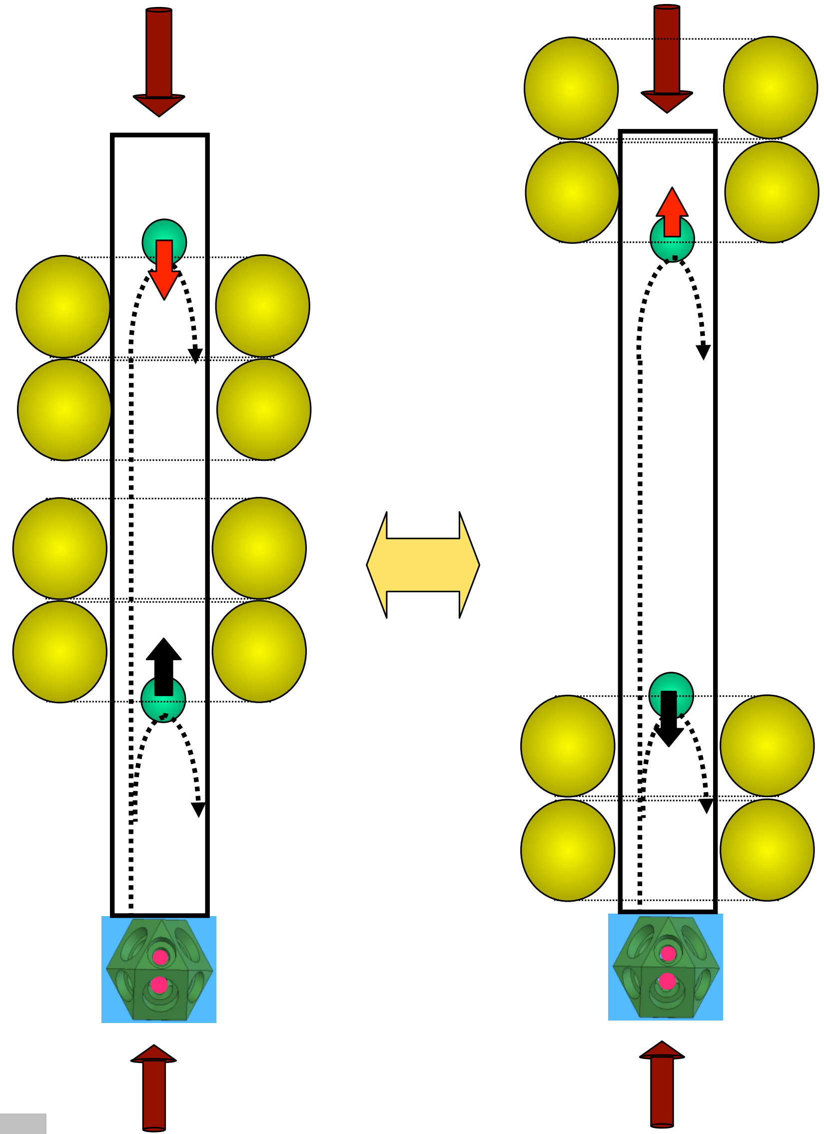
$$\Delta g = 120\,\mu Gal$$

Differential gravity sensitivity:

$$\sigma_{\Delta g} = 0.01\,\mu Gal\,@\,10^4\,s$$

Project target

$$\delta G / G \sim 100\text{ppm}$$

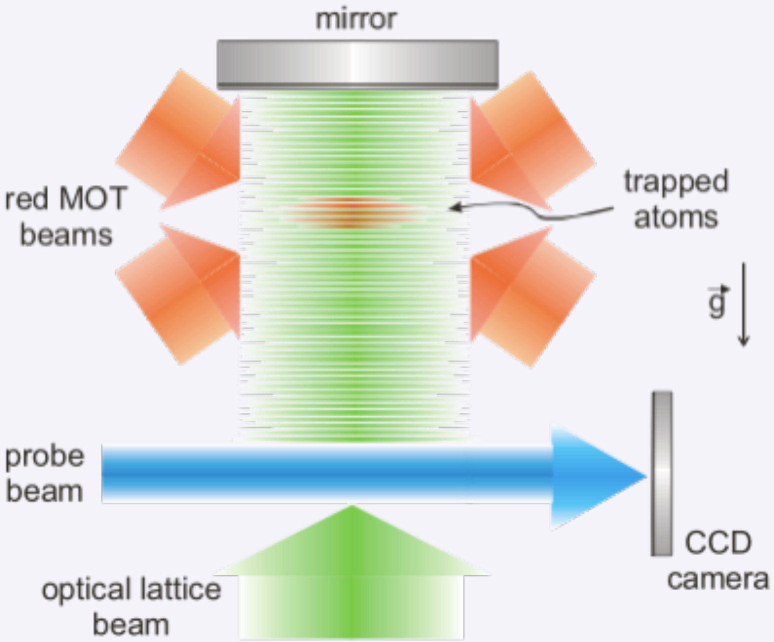


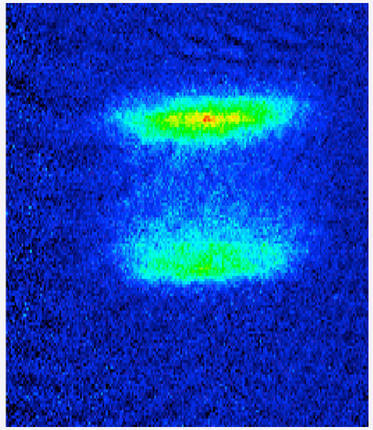
Xiao-Chun Duan et al., *Operating an atom-interferometry-based gravity gradiometer by the dual-fringe-locking method*, Phys. Rev. A 90, 023617 (2014)

Future prospects to improve the measurement of G with atom interferometry

- Highly homogeneous (lower-density, e.g. silicon) source mass
- Higher sensitivity atom interferometer
- Different scheme with better definition of atomic velocities
- Smaller size of the atomic sensor
- Atom with lower sensitivity to magnetic fields

Possible scheme for MAGIA Advanced
Ultracold Sr atoms in optical lattice



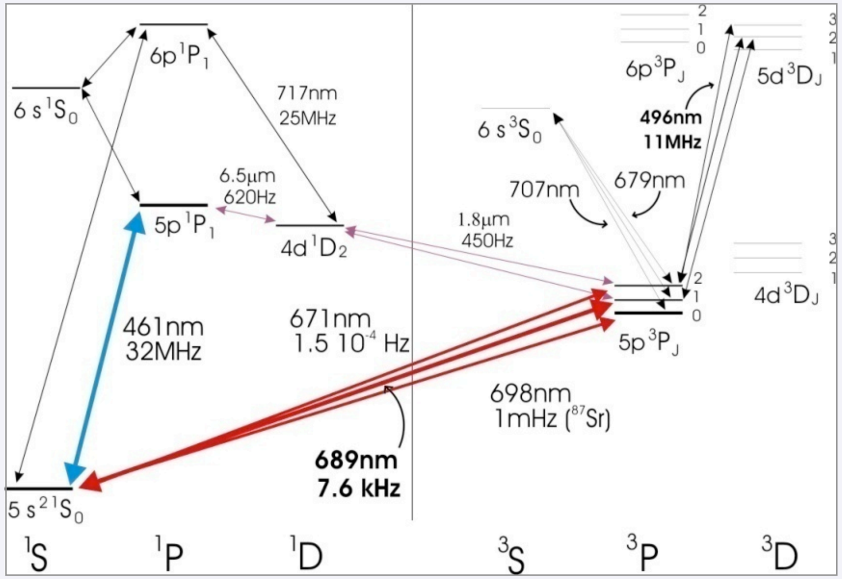


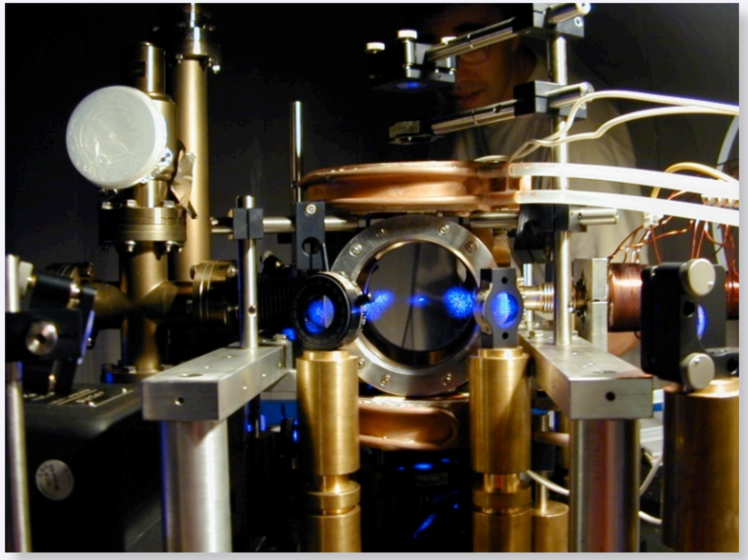
$\nu = m\, g\, \lambda / 2\, h$

$$\Delta G/G \approx 10^{-5}$$

$$\Delta G/G \approx 10^{-6}\ ?$$

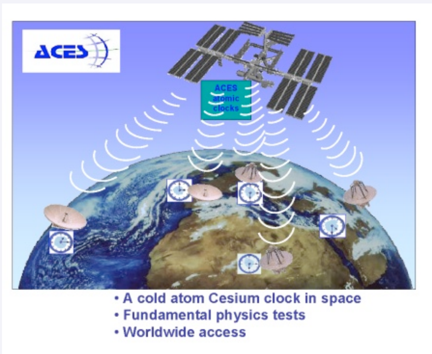
Ultracold Sr - Experiments in Firenze

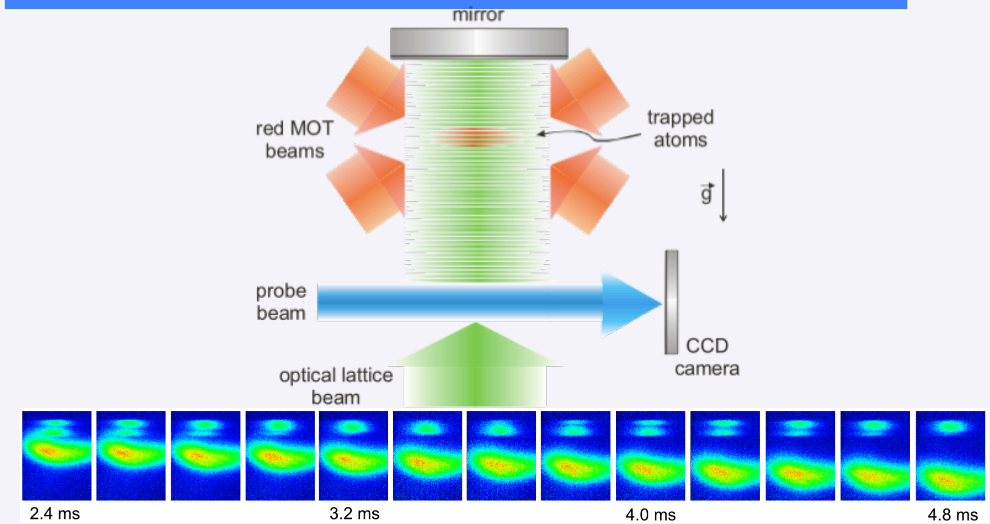




- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests



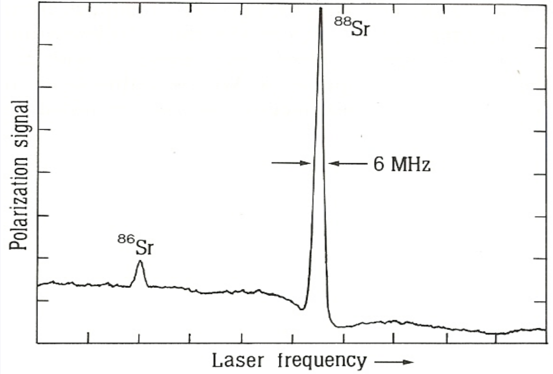


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

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)

1992

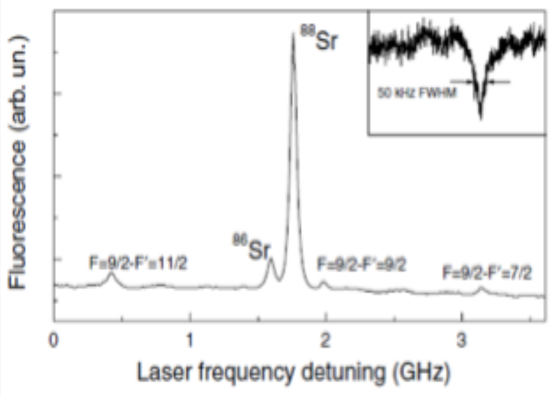
sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line



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

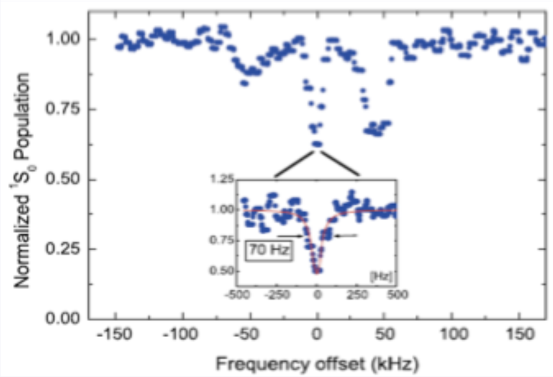
saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line



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
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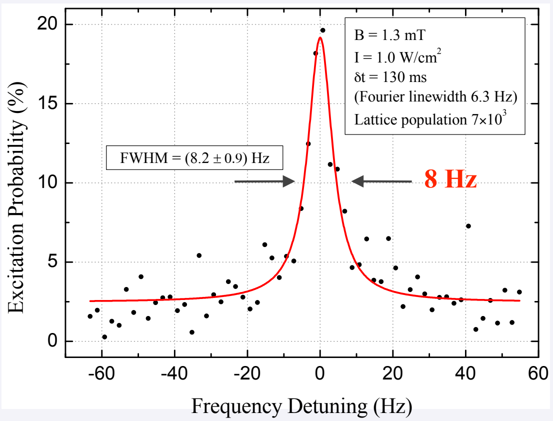
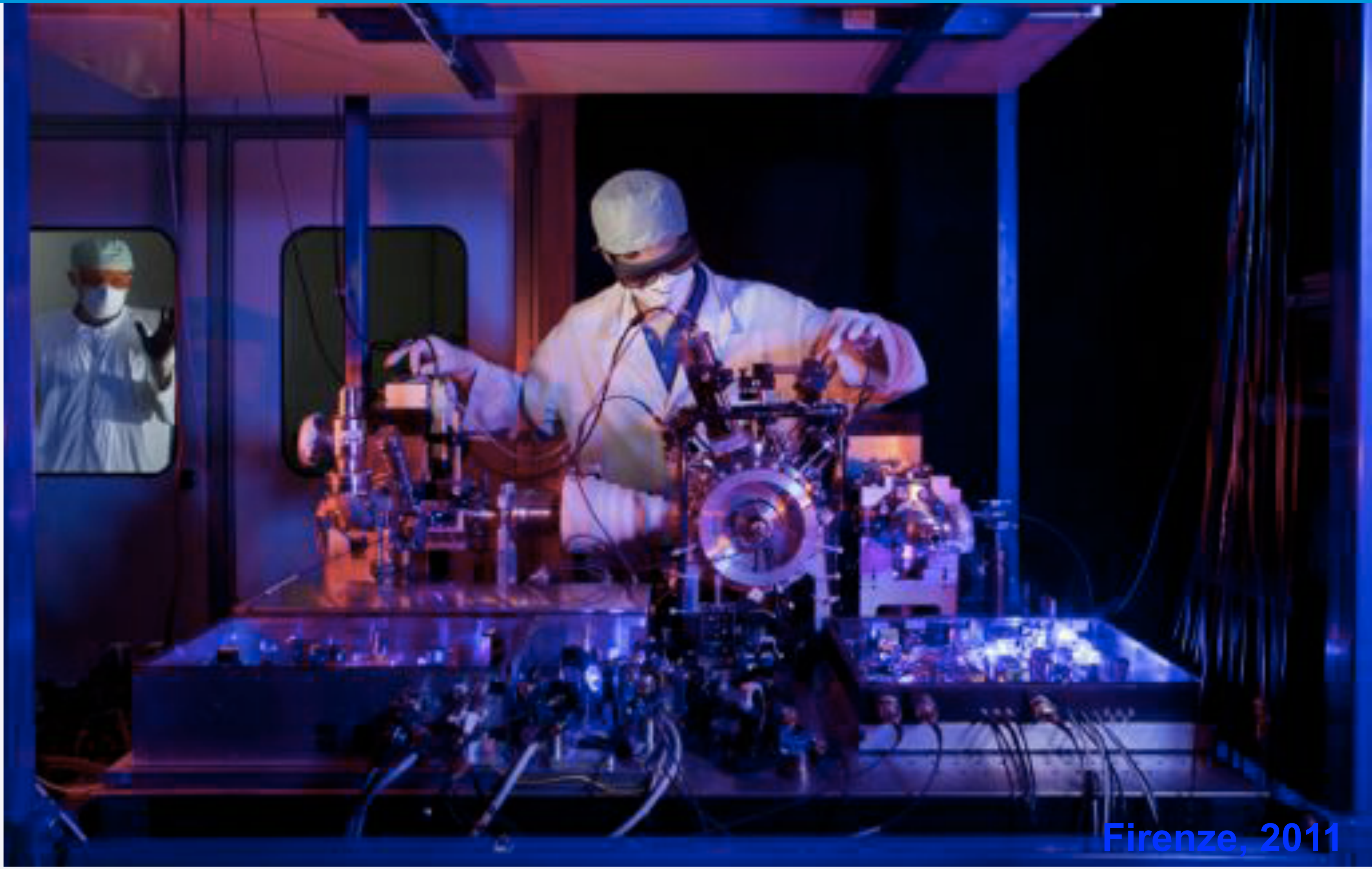
0 -> 0 intercombination line



N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B 117, 1107 (2014)

Space Optical Clock



N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino,
A transportable strontium optical lattice clock, Appl. Phys. B 117, 1107 (2014)

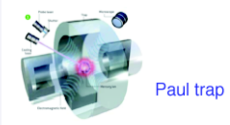
N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks,*
Rivista del Nuovo Cimento 36, n.12 (2013), arXiv:1401.2378

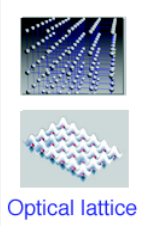
Optical clocks: Towards 10^{-18}

- **Narrow optical transitions**
  $\delta\nu_o \sim$ 1-100 Hz, $\nu_0 \sim 10^{14}$-10^{15} Hz

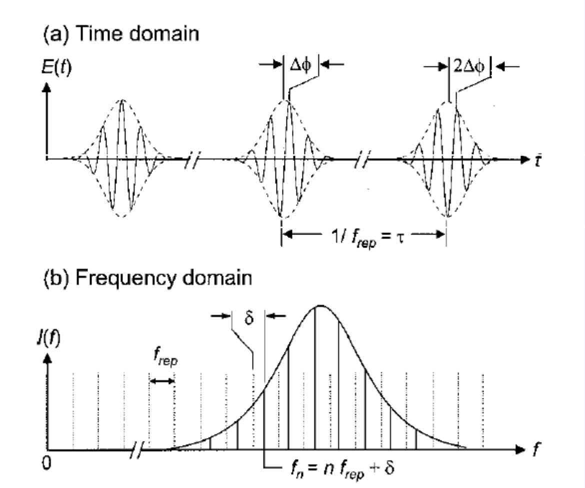
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atom}}} \sqrt{\frac{T_{cycle}}{2\tau_{average}}} \frac{1}{C_{fringe}}$$

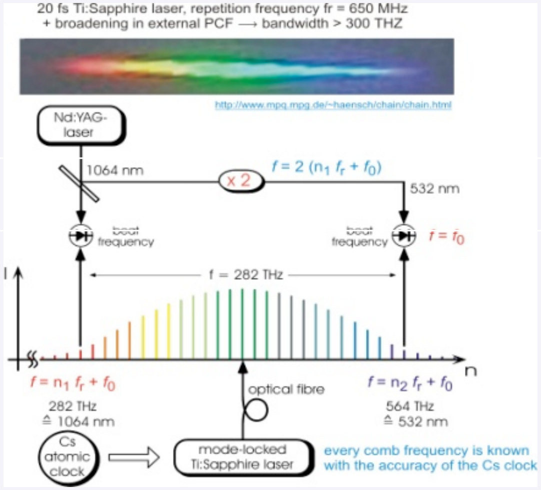
- **Candidate atoms**
  - **Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…**
  - **Cold neutral atoms: H, Ca, Sr, Yb,…**

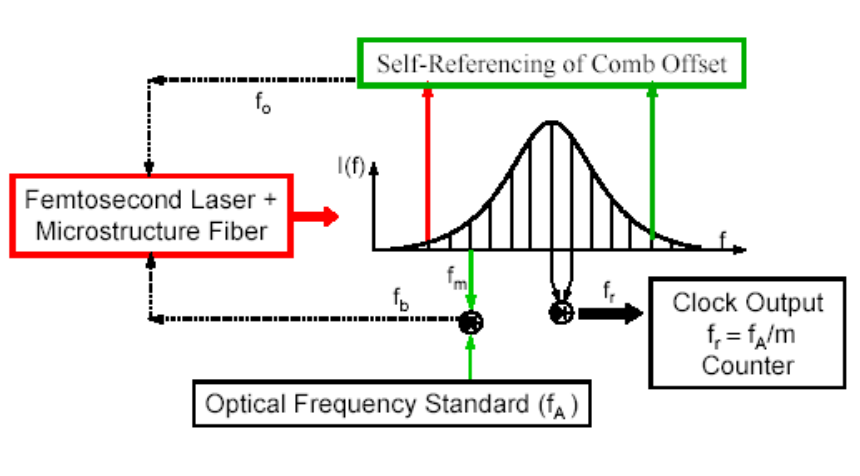




- **Direct optical-μwave connection by optical frequency comb**







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

UNIVERSITÀ DEGLI STUDI FIRENZE

The Nobel Prize in Physics 2005

Roy J. Glauber, John L. Hall, Theodor W. Hänsch

The Nobel Prize in Physics 2005

Nobel Prize Award Ceremony

Roy J. Glauber

John L. Hall

Theodor W. Hänsch

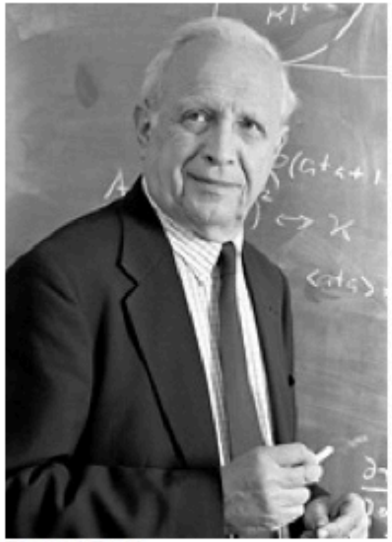


Photo: J.Reed	Photo: Sears.P.Studio	Photo: F.M. Schmidt
Roy J. Glauber	John L. Hall	Theodor W. Hänsch

The Nobel Prize in Physics 2005 was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*, the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

MLA style: "The Nobel Prize in Physics 2005". Nobelprize.org. 20 Oct 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/

... The important contributions by John Hall and Theodor Hänsch have made it possible to measure frequencies with an accuracy of fifteen digits. Lasers with extremely sharp colours can now be constructed and with the frequency comb technique precise readings can be made of light of all colours. This technique makes it possible to carry out studies of, for example, the stability of the constants of nature over time and to develop extremely accurate clocks and improved GPS technology.

Measure gravitational red shift in the lab

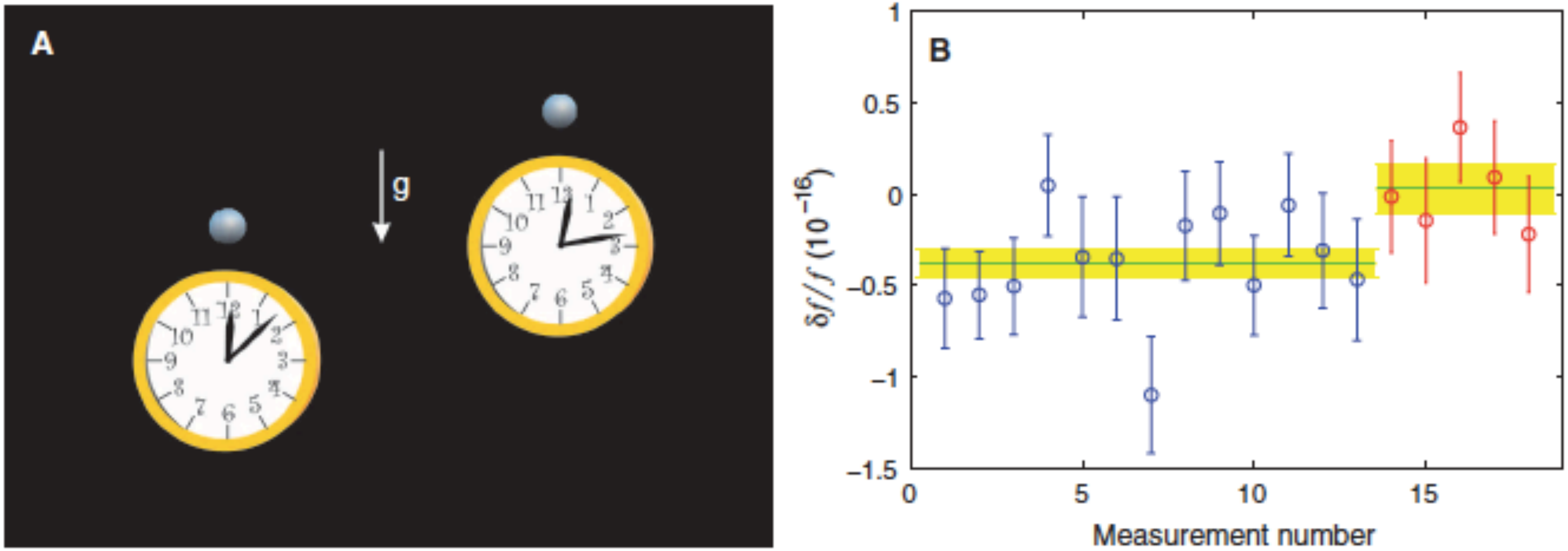


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg 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.

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

UNIVERSITÀ DEGLI STUDI FIRENZE

The Nobel Prize in Physics 2012
Serge Haroche, David J. Wineland

The Nobel Prize in Physics 2012

Serge Haroche Collège de France and Ecole Normale Supérieure, Paris, France

David J. Wineland National Institute of Standards and Technology (NIST), University of Colorado Boulder, USA

Photo: © CNRS Photothèque/Christophe Lebedinsky

Serge Haroche

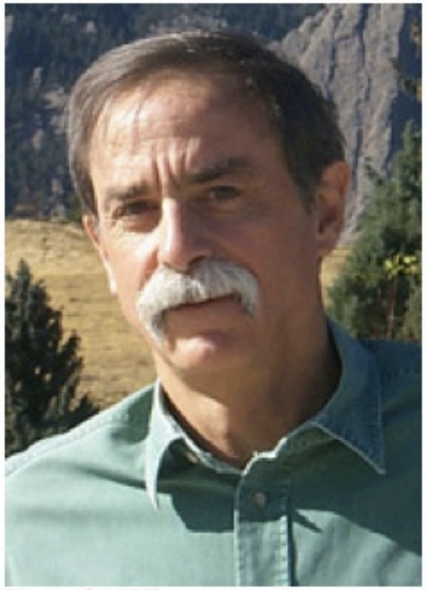


Photo: © NIST

David J. Wineland

MLA style: "The Nobel Prize in Physics 2012". Nobelprize.org.
20 Oct 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

... Both Laureates work in the field of quantum optics studying the fundamental interaction between light and matter, a field which has seen considerable progress since the mid-1980s.

... The research has also ***led to the construction of extremely precise clocks*** *that could become the future basis for a new standard of time, with more than hundred-fold greater precision than present-day caesium clocks.*

Laser cooling of ^{88}Sr

2000 ms:

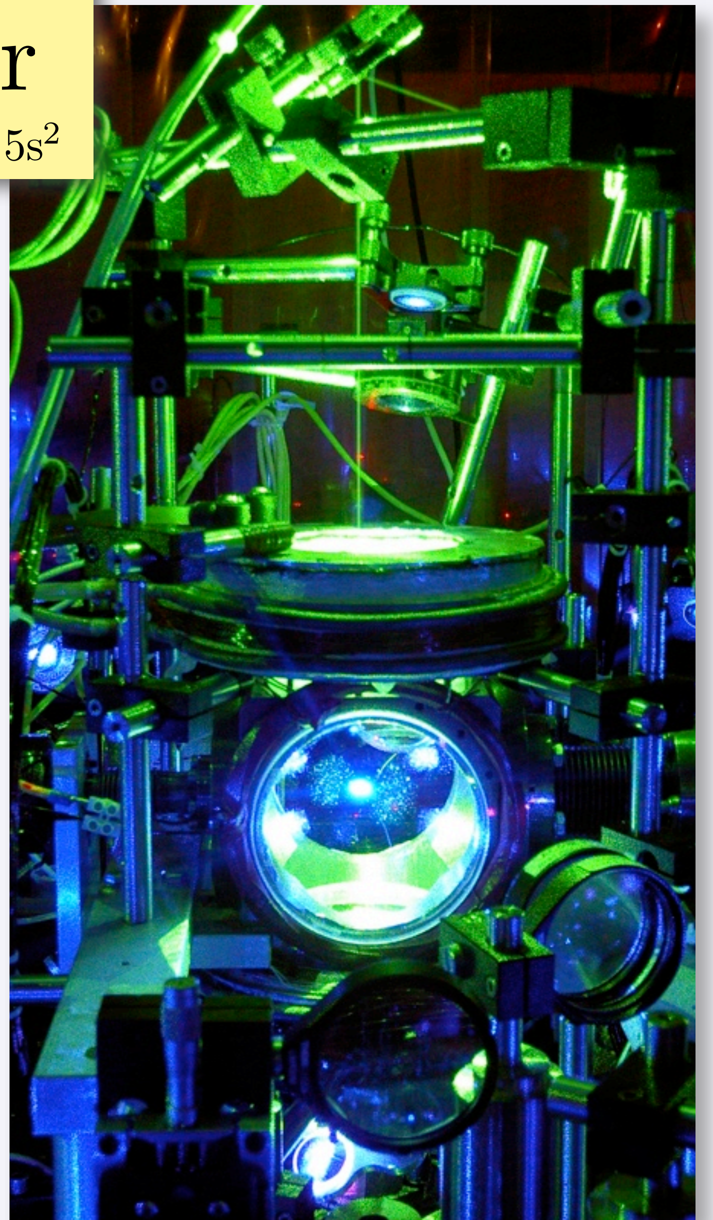
- 500 °C vapor from oven
- ↓
- Zeeman slower — Slow-down, $a \sim 5 \times 10^5$ m/s^2
- ↓
- Blue MOT — $\lambda = 461$ nm (blue laser), $T \sim 1$ mK, $N \sim 5 \times 10^7$
- ↓

200 ms:

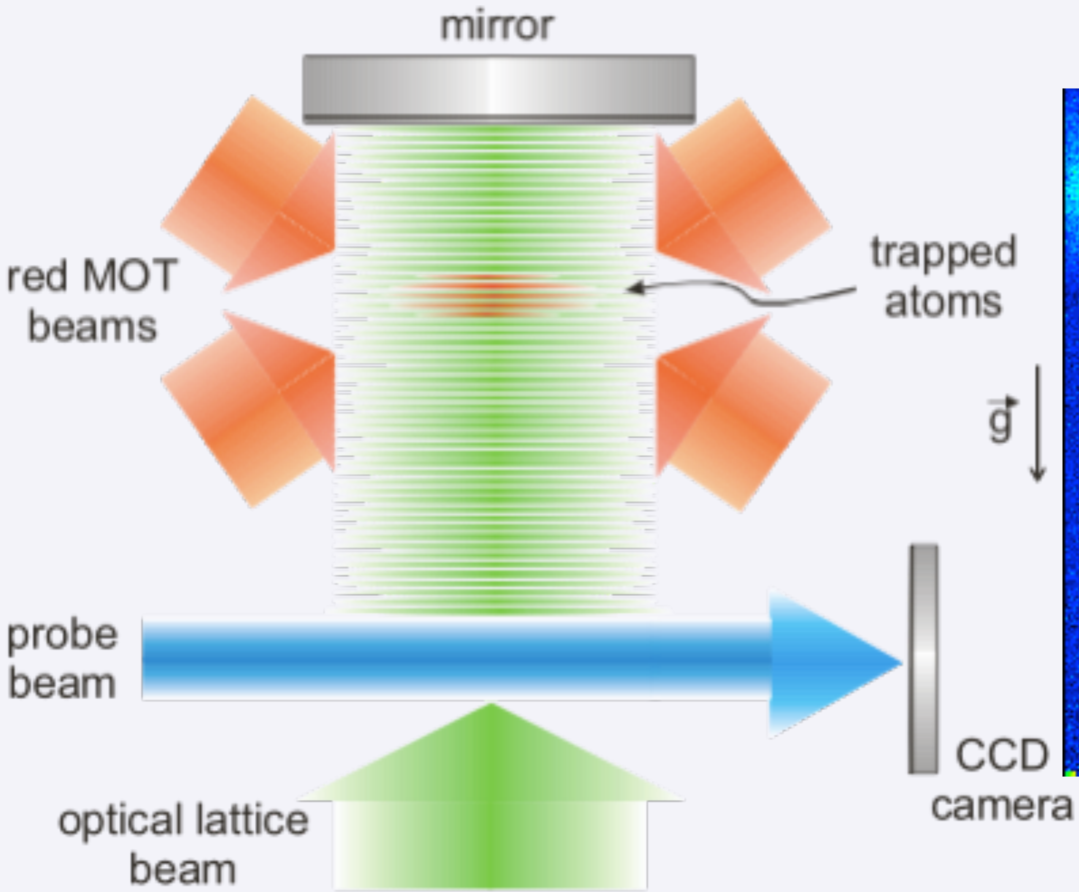
- Red MOT — $\lambda = 689$ nm (red laser), $T \sim 1\,\mu$K, $N \sim 2 \times 10^6$
- → Vertical optical lattice — $\lambda = 532$ nm ($Nd{:}YVO_4$ green laser), $T \sim 1\,\mu$K, $N \sim 10^5$

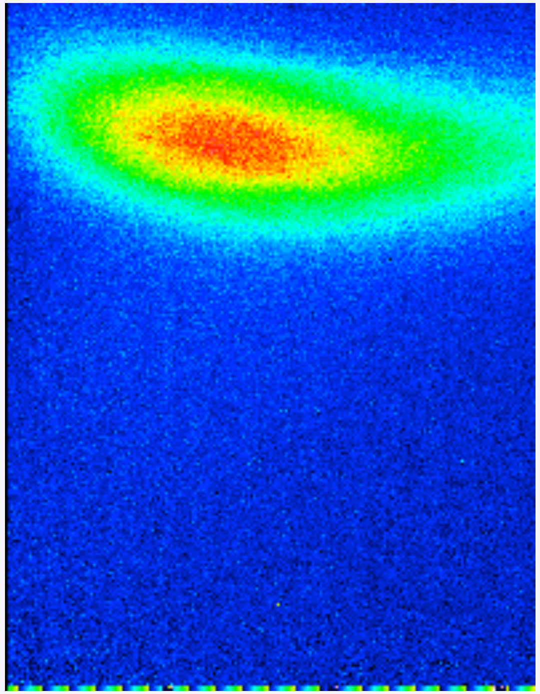
λ	T_R	T_D	I_s	a_{max}
461 nm	1 μK	760 μK	42 mW/cm^2	$10^5 \times g$
689 nm	460 nK	180 nK	3 μW/cm^2	$16 \times g$

88 38
Sr
[Kr]5s^2



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

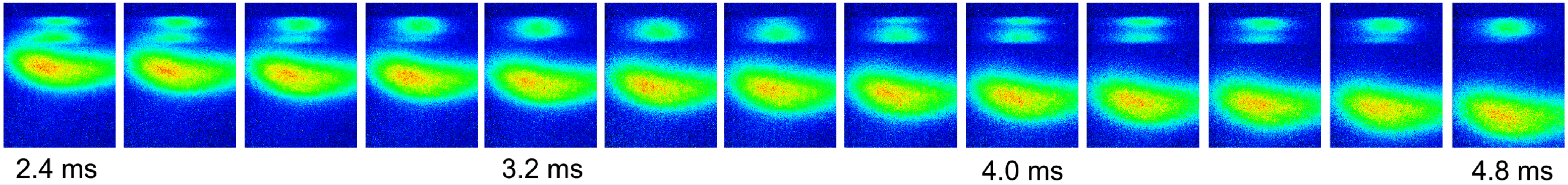


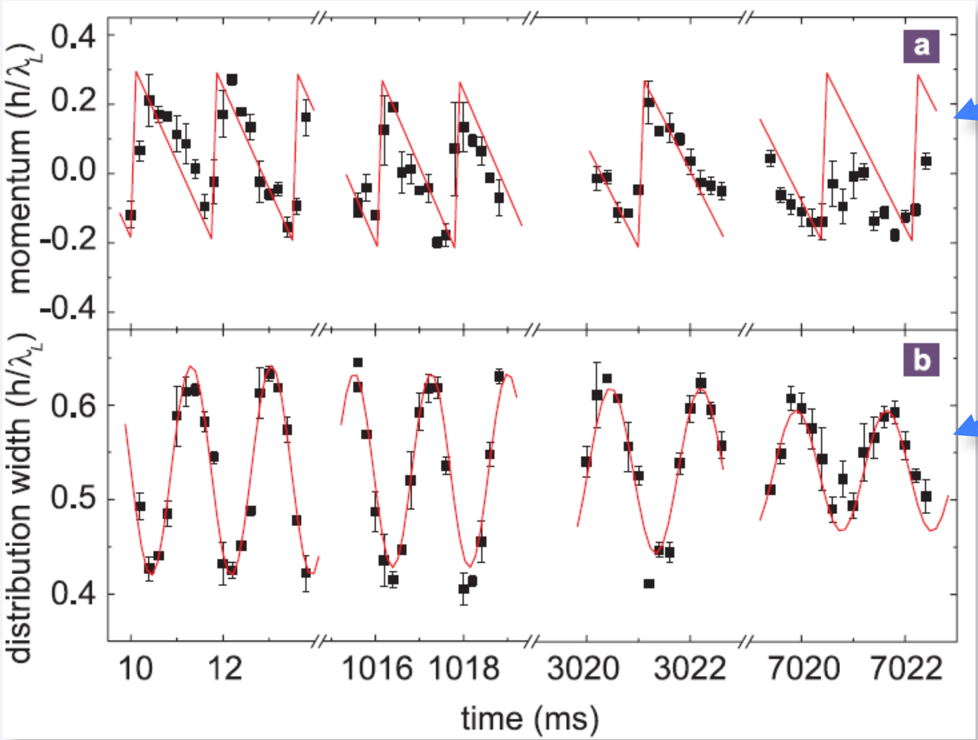


$\nu = m\, g\, \lambda / 2\, h$

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)**

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency ν_B = 574.568(3) Hz

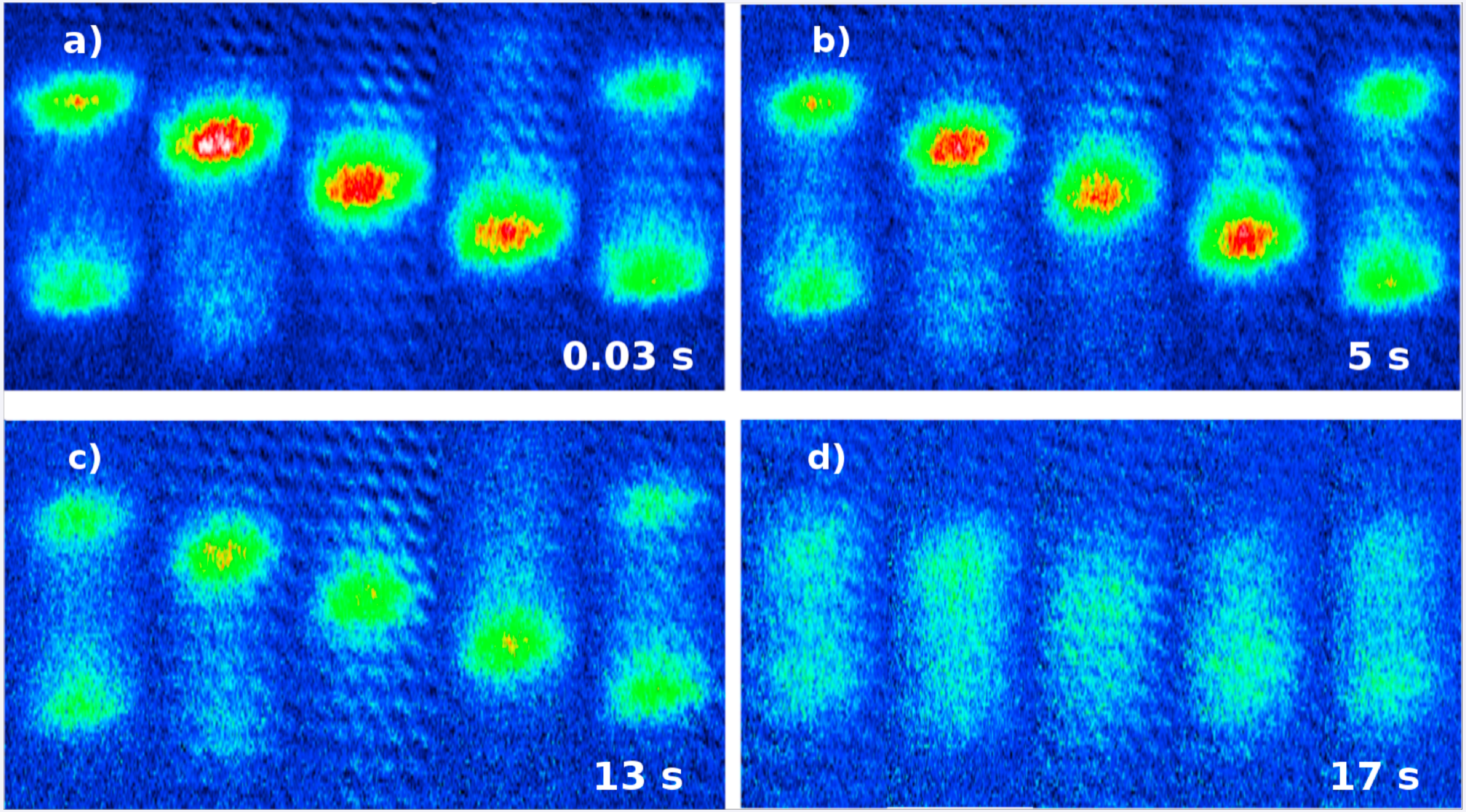
damping time τ = 12 s

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)**

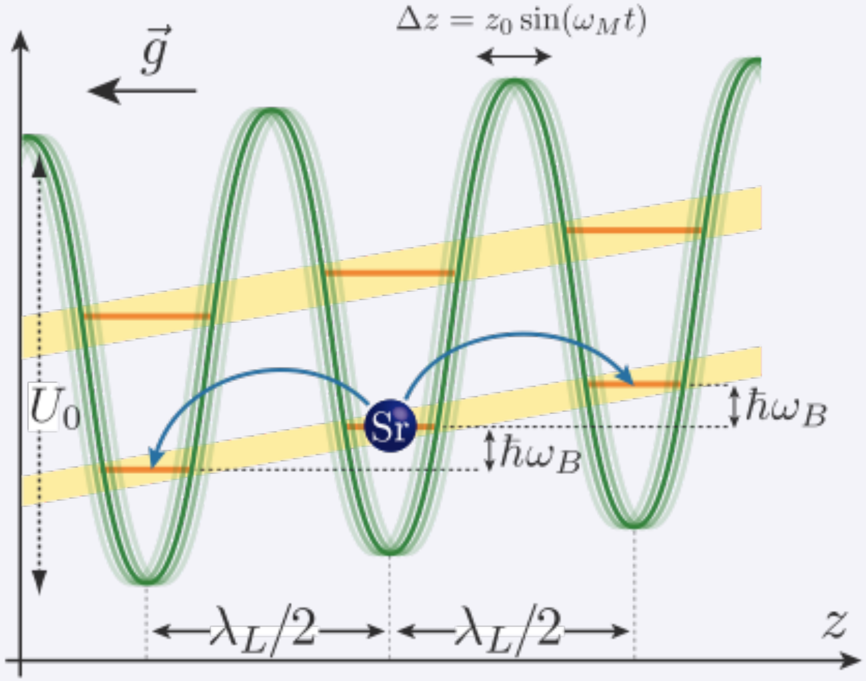
Bloch oscillations



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)

Modulation of optical lattices

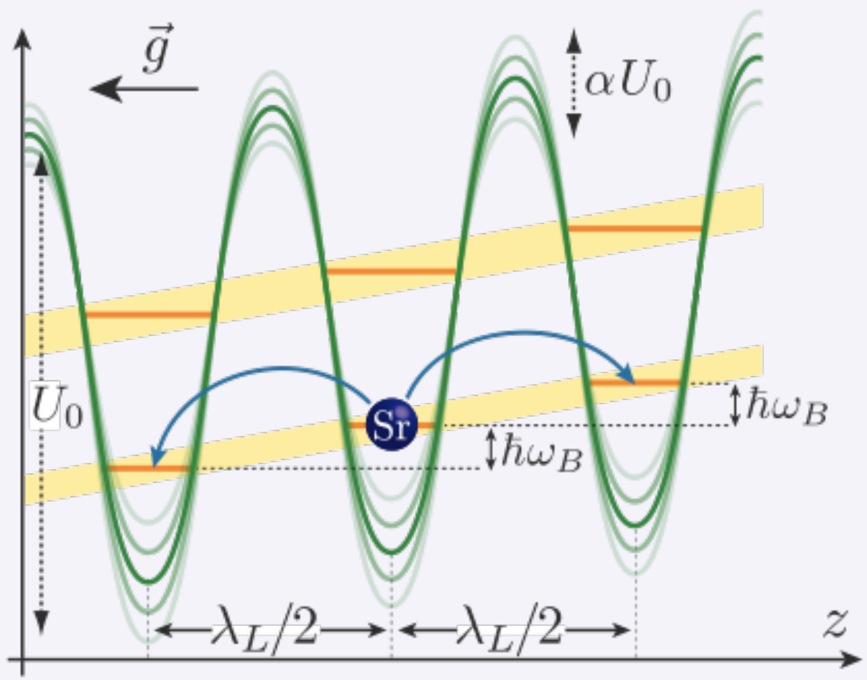
Phase modulation



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

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

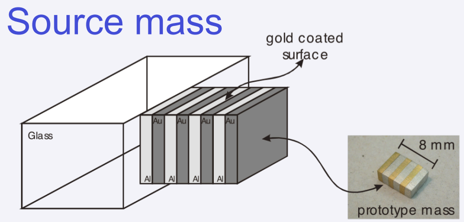


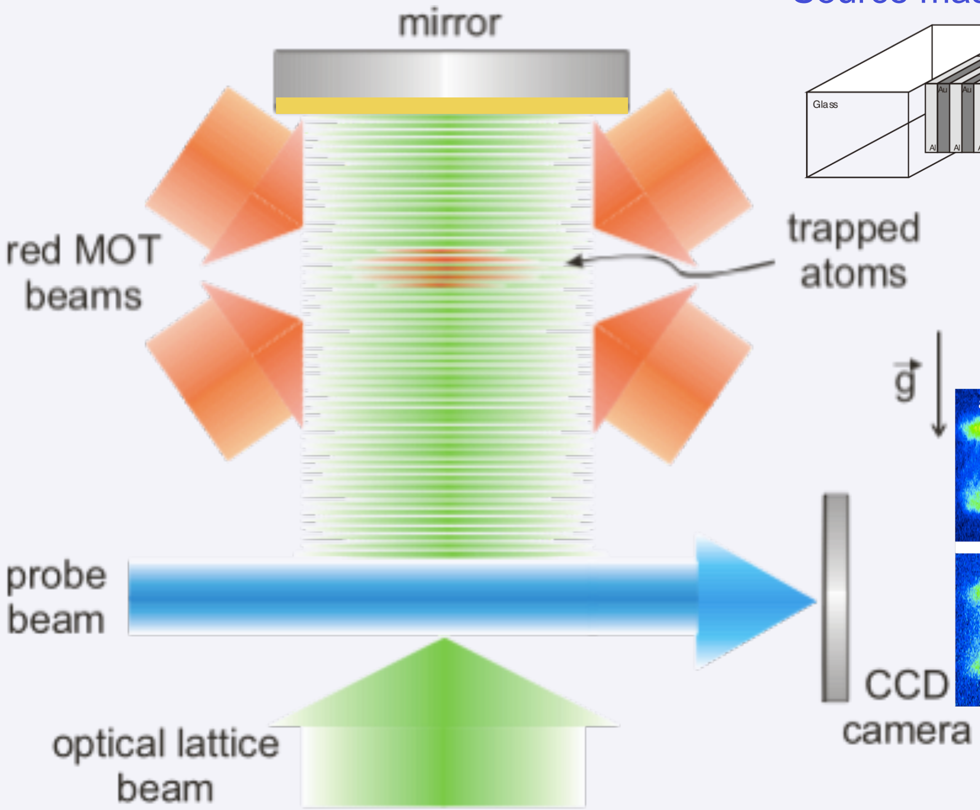
$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2}\cos(2k_L z)[1 + \alpha\,\sin(\omega_M t)] + mgz$$

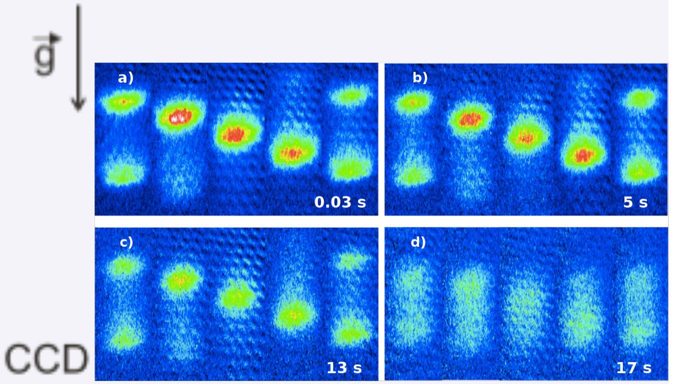
A. Alberti, G. Ferrari, V.V. Ivanov, M. L. Chiofalo, G. M. Tino, *Atomic wave packets in amplitude-modulated vertical optical lattices* **New Journal of Physics 12, 065037 (2010)**

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)**

Scheme for the measurement of small distance forces







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

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

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

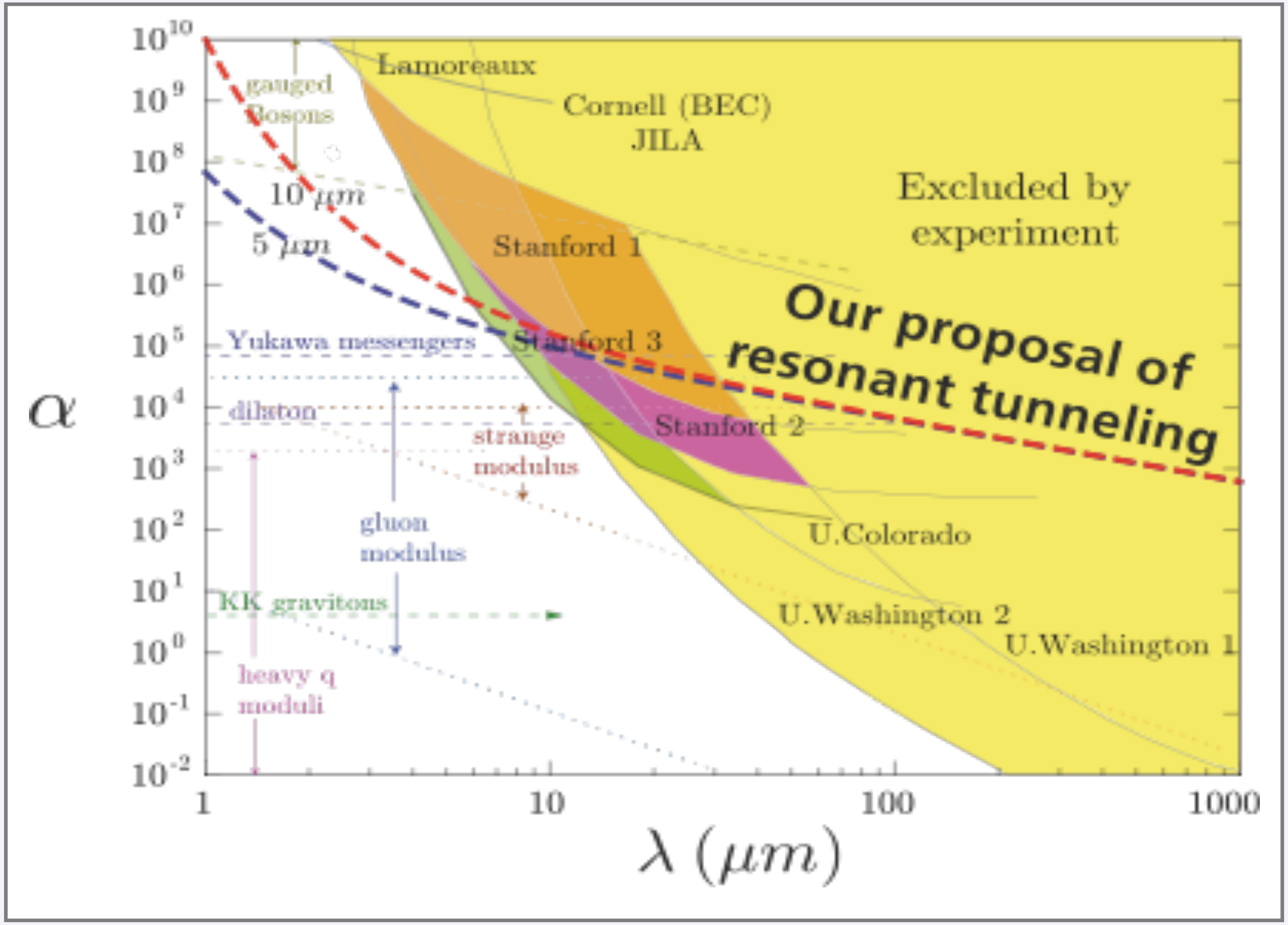
F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, **Phys. Rev. A 79, 013409 (2009)**

Accessible region with atomic probes

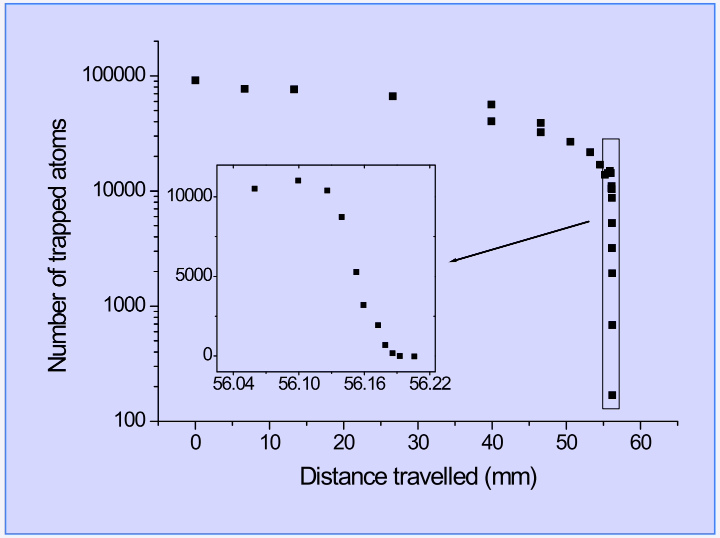
- **Newton+Yukawa potential**

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

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



Atom elevator

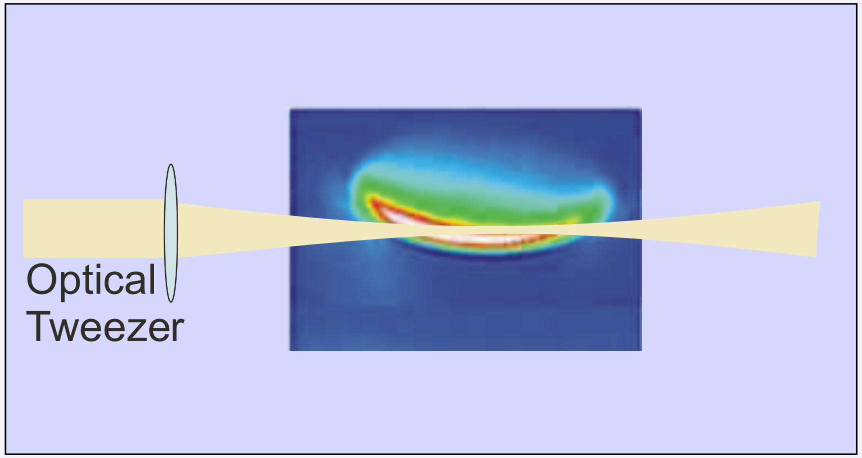


Vertical size of the atomic sample: 15 μm

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



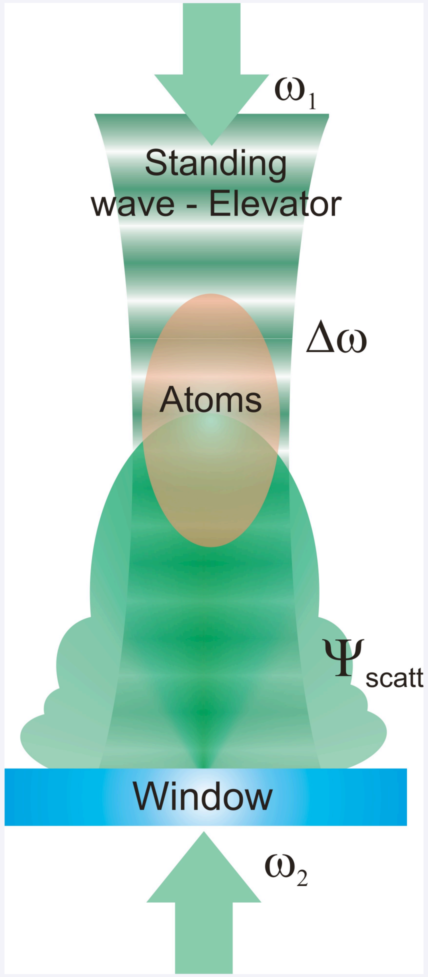
•Vertical size reduced to 4 μm with an optical tweezer

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)**

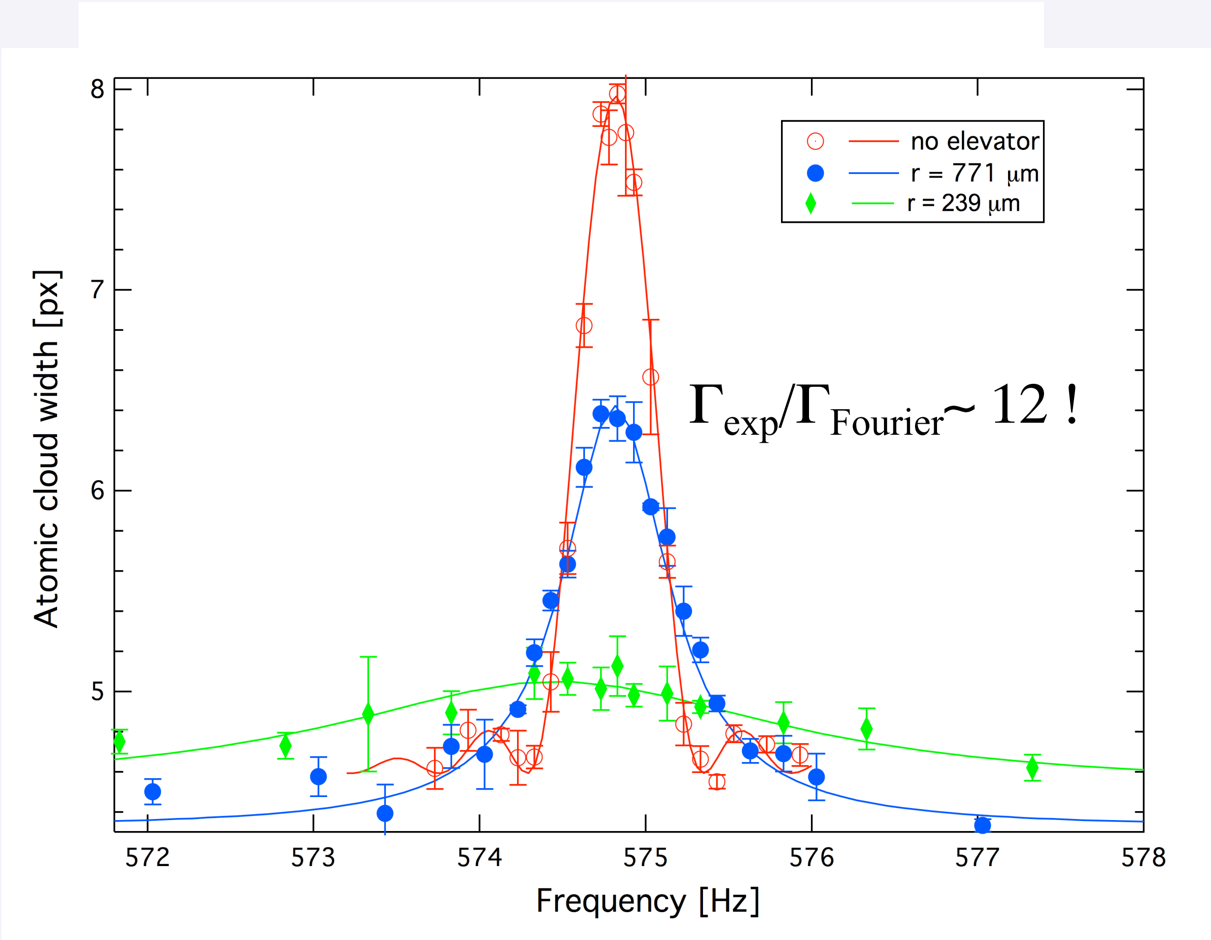
Short-distance measurements

- **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**

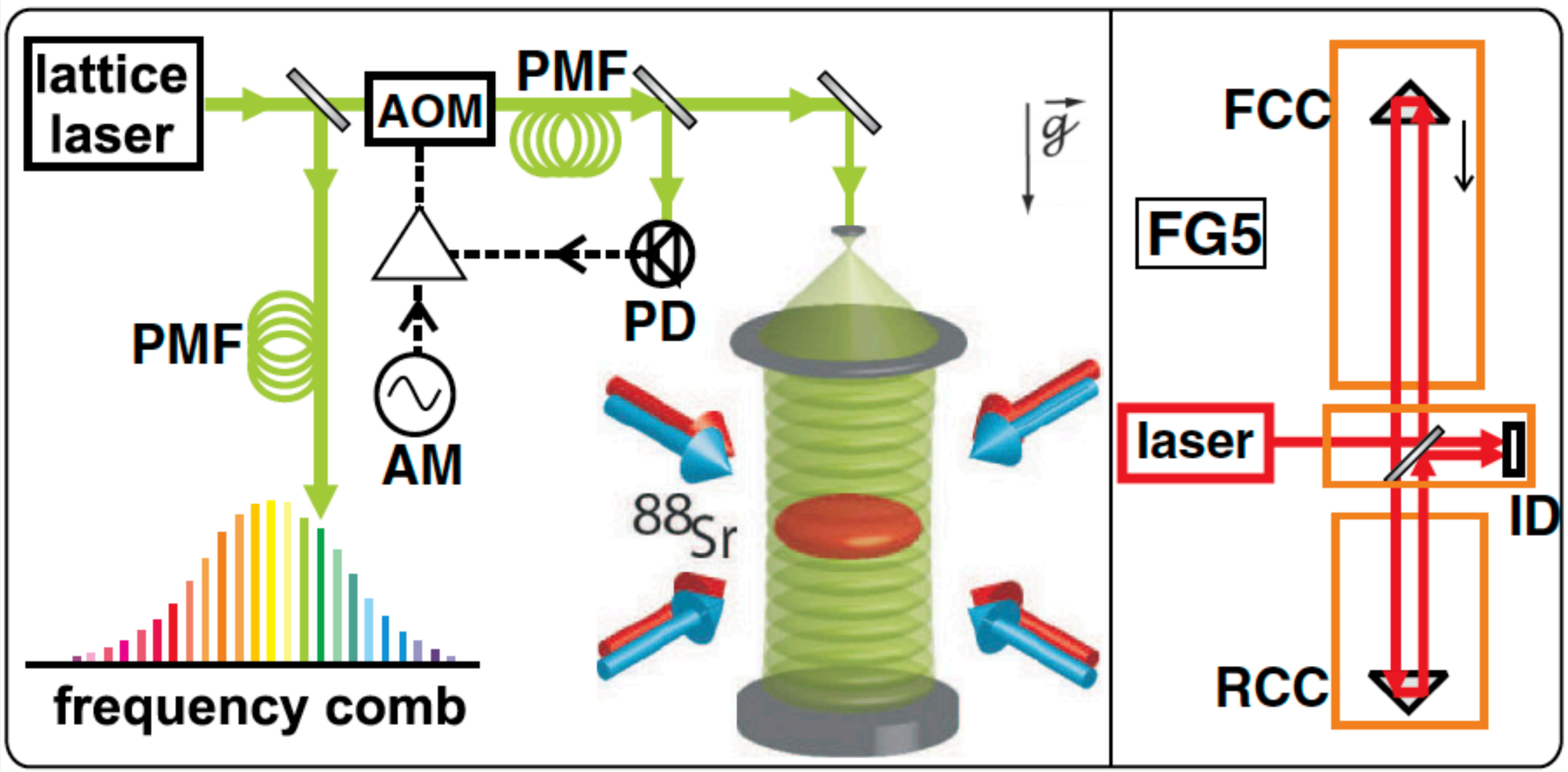
A. Kellerbauer, et al. (AEGIS collaboration), Nucl. Instr. Meth. Phys. Res. B 266, 351 (2008)

A.E. Charman, et al. (ALPHA collaboration), Nat. Commun. 4, 1785 (2013)

P. Hamilton, et al, Phys. Rev. Lett. 112, 121102 (2014)

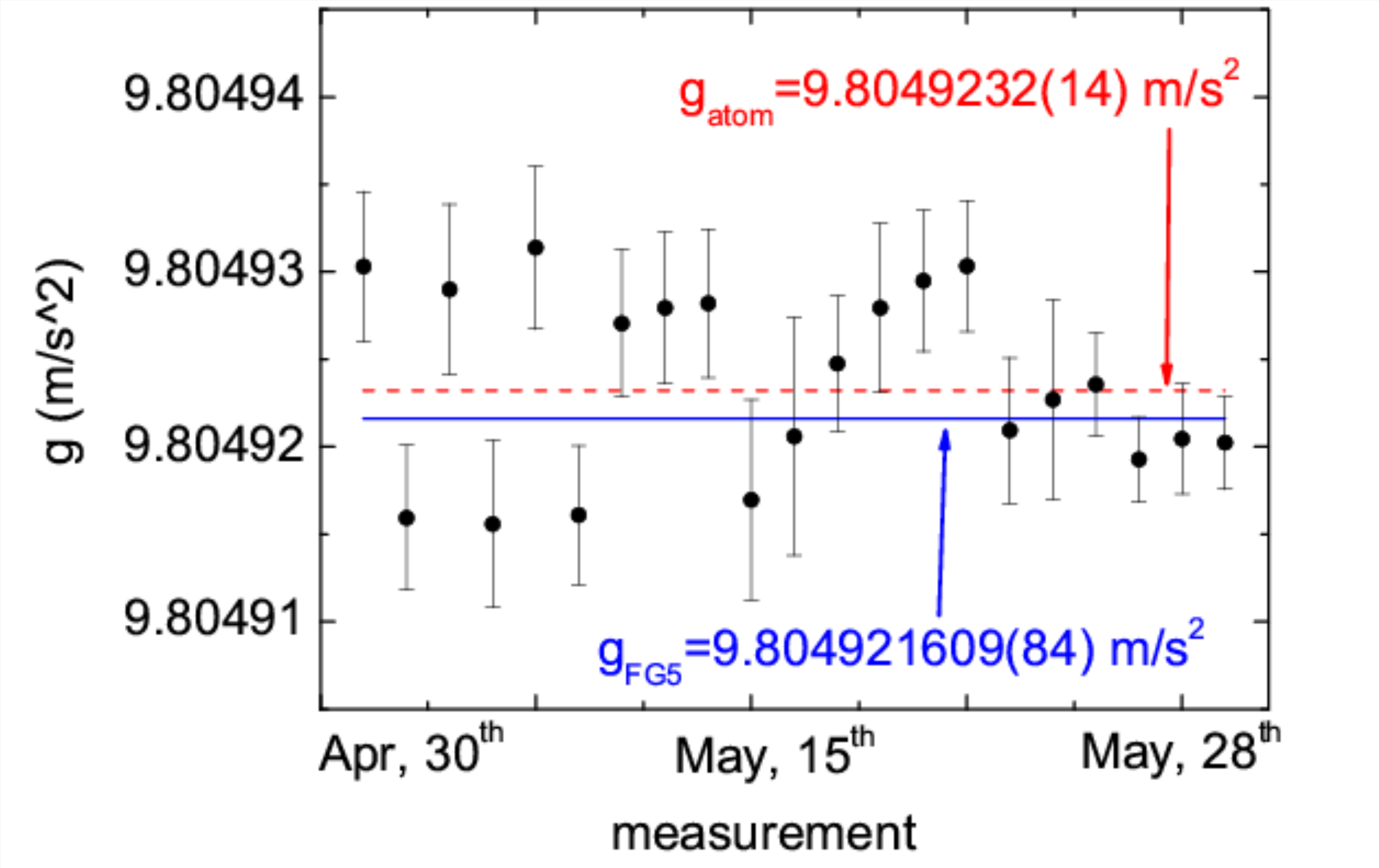
H vs anti-H

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

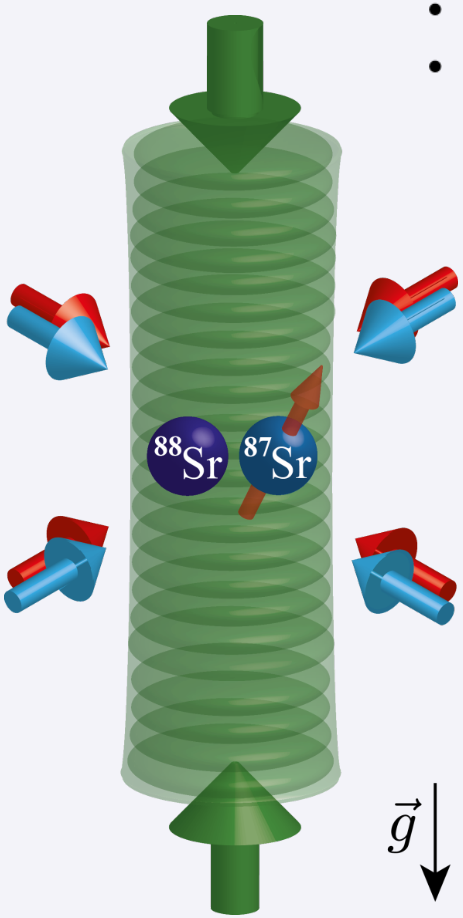
Comparison of the acceleration of ^{88}Sr and ^{87}Sr under the effect of gravity by measuring the respective Bloch frequencies in a vertical optical lattice

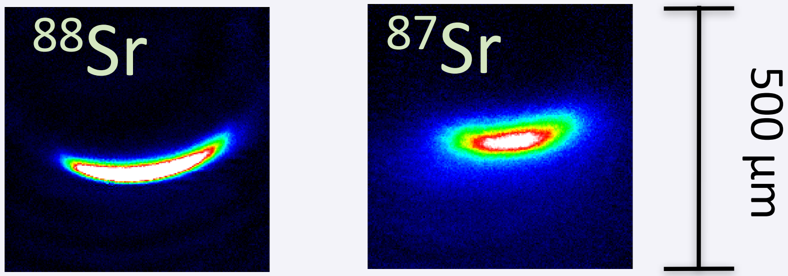
Suitable system to search for EP violations due to spin-gravity coupling effects

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

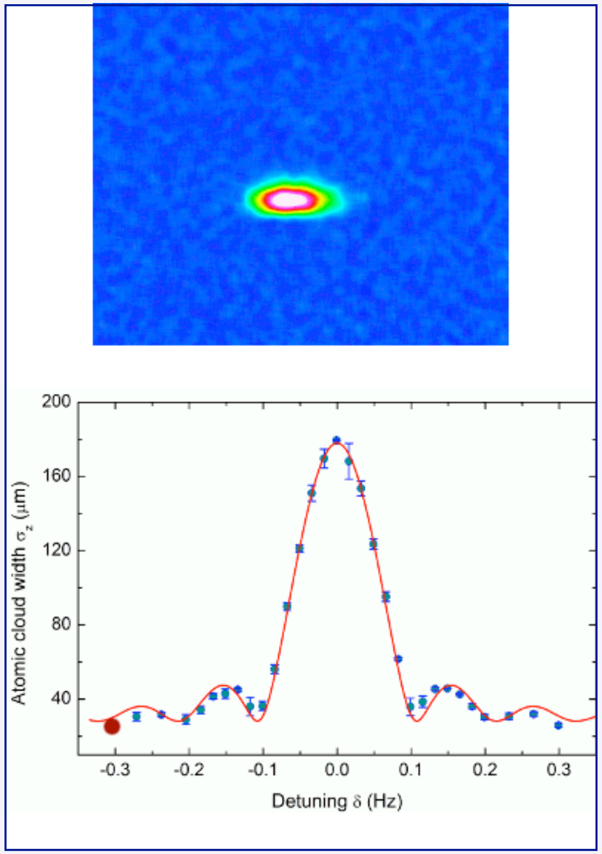
Loaded alternately in a vertical OL @ 532 nm
- waist 300 µm
- $U_0 = 6E_R$
- lifetime >10 s





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 $R_m = \frac{m_{88}}{m_{87}}$ (*)

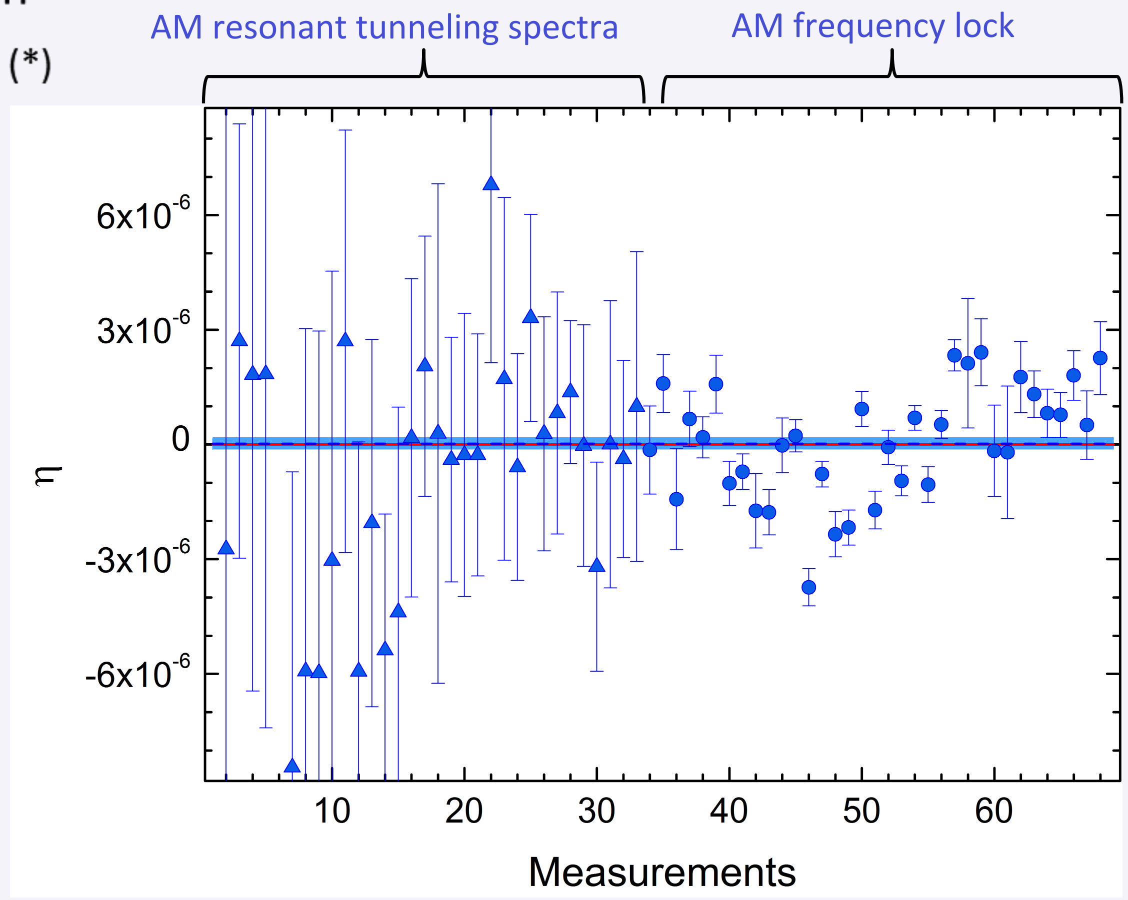
$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

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

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

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

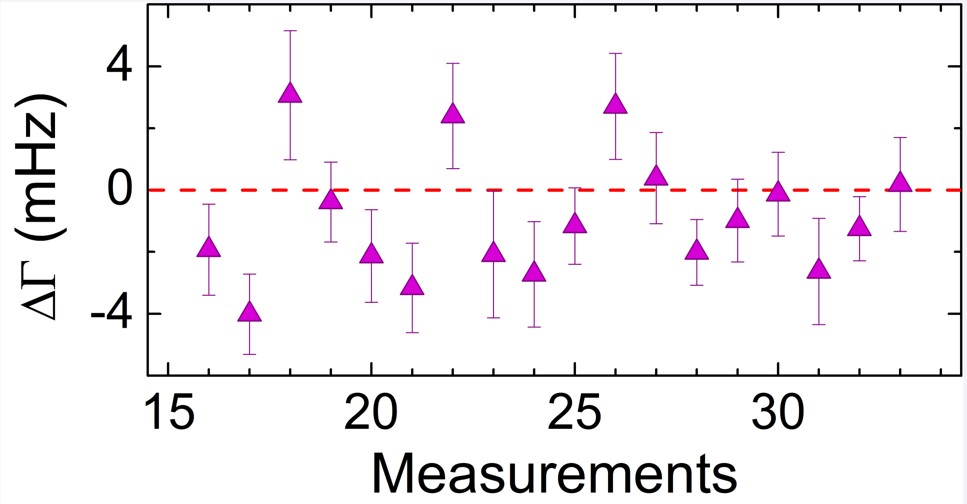
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

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

$$\Delta\Gamma = 2I_{87} k l \nu_{87}$$

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

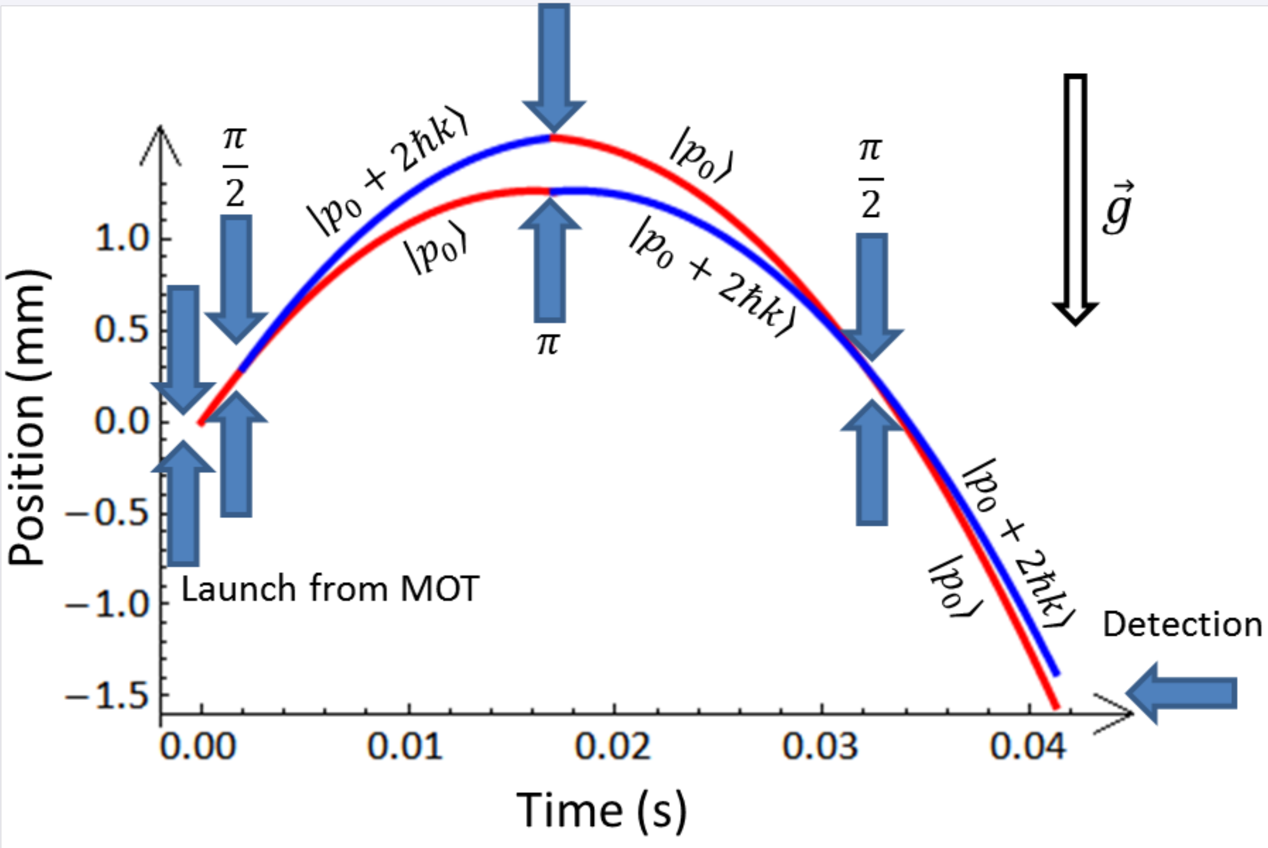


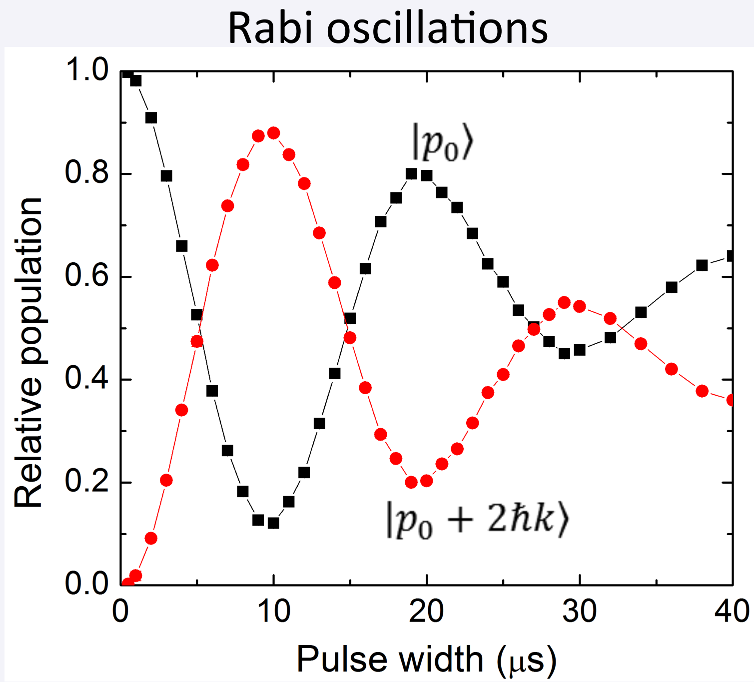
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

Sr Bragg interferometer

^{88}Sr free falling Mach-Zehnder interferometer with Bragg pulses

- Single ground state: Raman transitions are not present
- Bragg laser detuned 8 GHz from allowed 461 nm line
- Direct launch from MOT with high efficiency Bragg pulses





Simultaneous detection of the two output ports with absorption imaging or fluorescence detection

Sr Bragg gravimeter

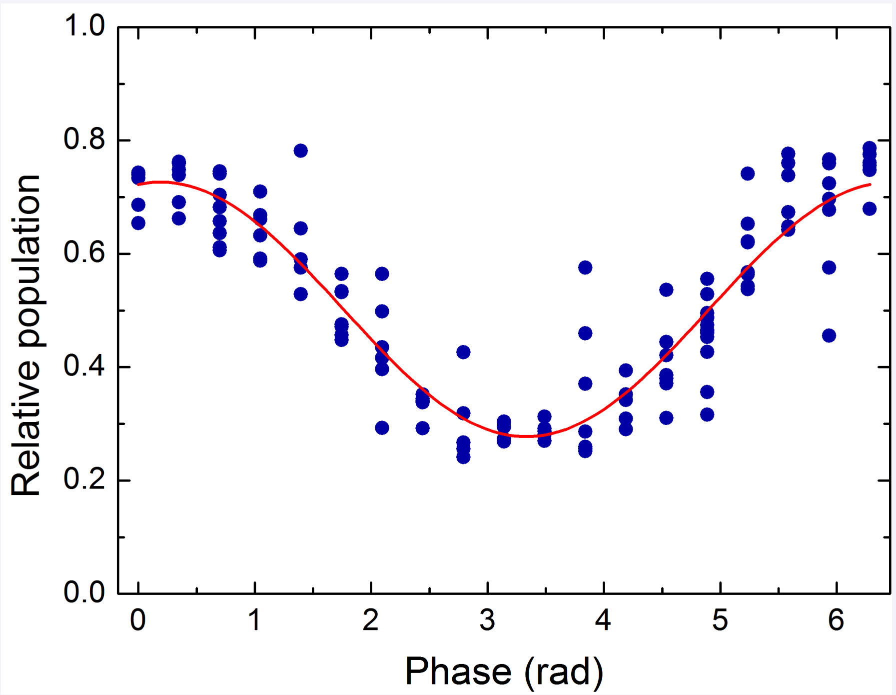
Gravimeter best performances so far achieved with:

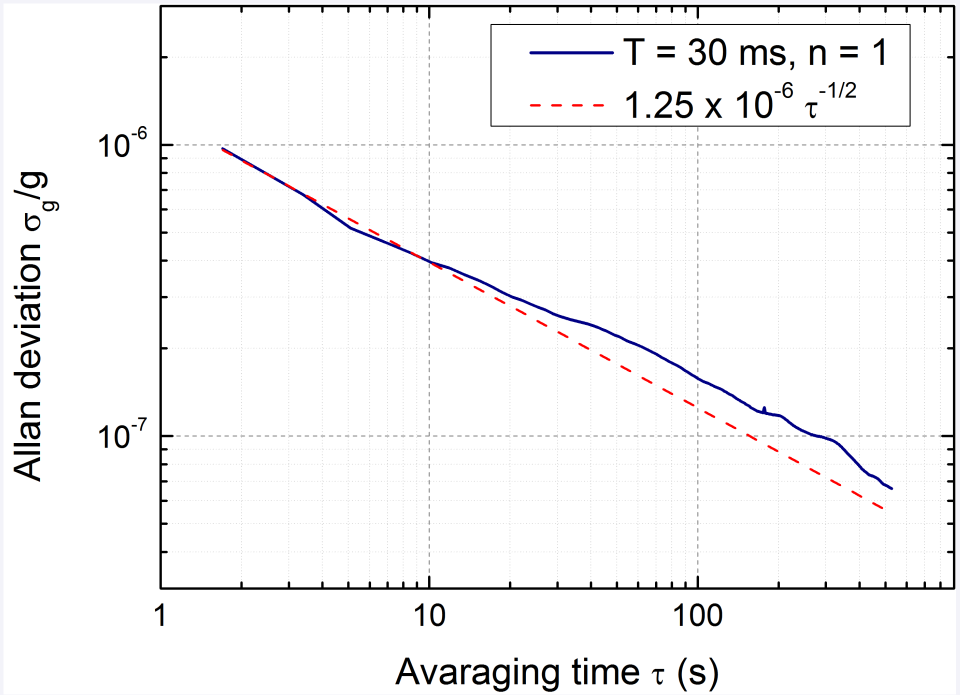
- T = 30 ms
- $n = 1$

- Phase noise limited by vibrations of the retroreflecting mirror

$$\frac{\Delta g}{g} \sim 6 \times 10^{-8} \quad @ \ 500\ \mathrm{s}$$

Contrast around 50 %





Large Momentum Transfer Bragg interferometer

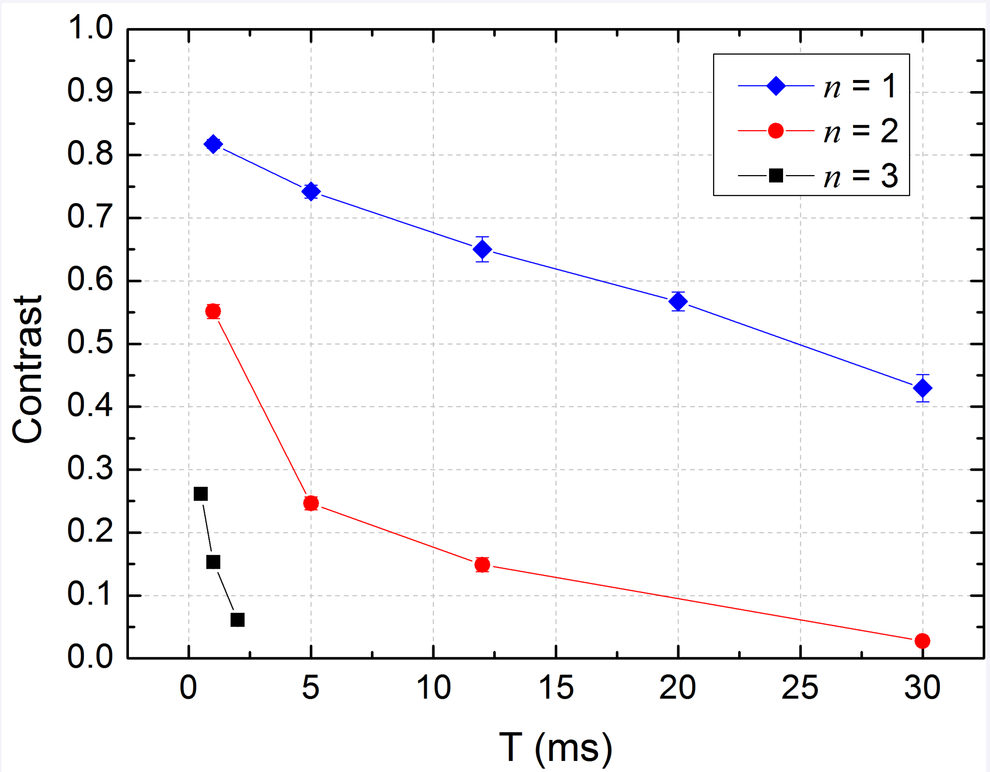
Phase of the Mach-Zehnder interferometer

$$\phi = n(k_{eff} \cdot g - 2\pi\alpha)T^2 + n\phi_L$$

Phase sensitivity

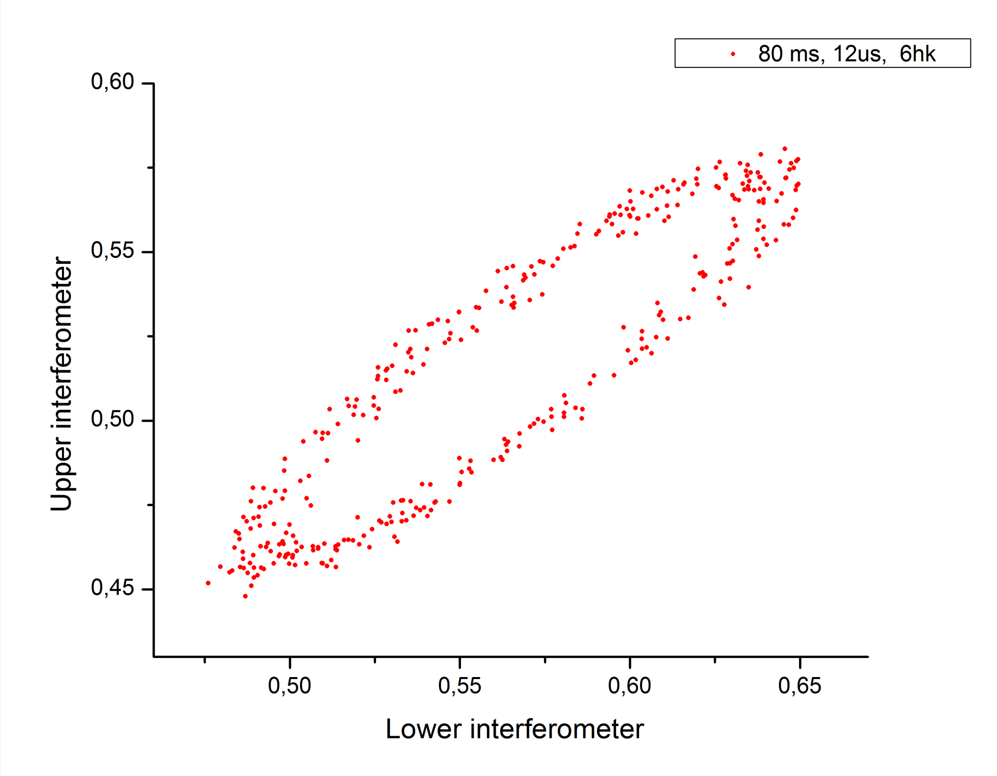
- Scales quadratically with interferometer time T
- Sensitivity scales linearly with order of Bragg diffraction *n* corresponding to *2nħk* transferred momentum

- Main limitation to contrast coming from beam intensity inhomogeneity and atomic transvers velocity
- The effect is stronger for higher orders



Rb LMT atom gradiometer

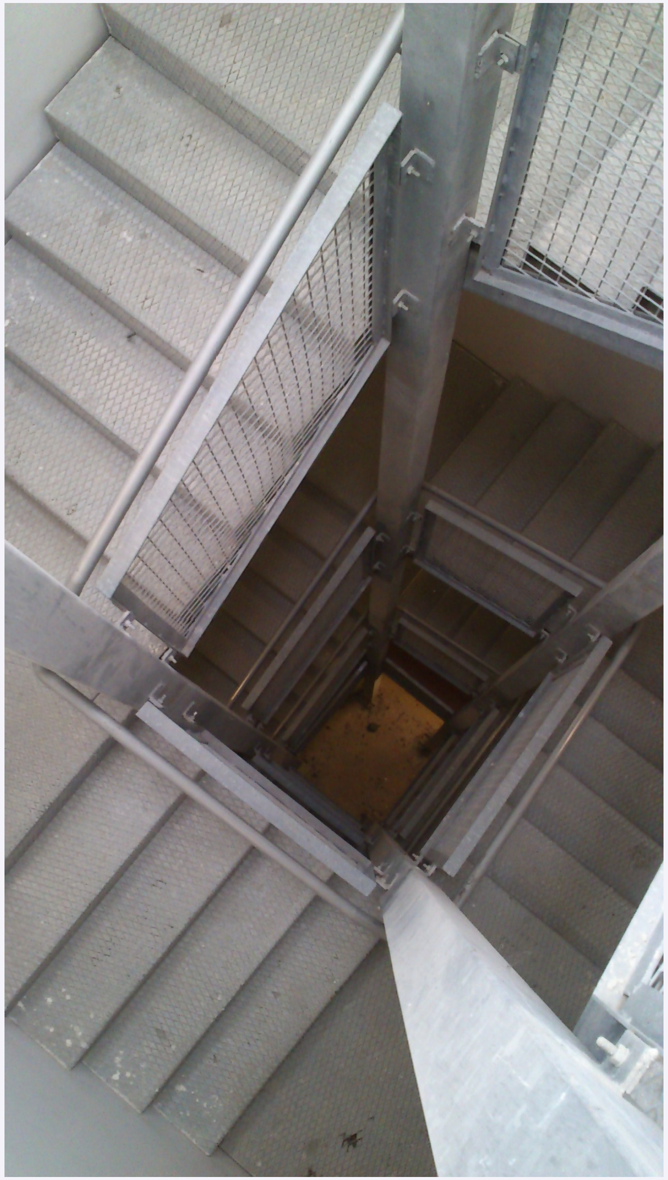
- Experimental condition: **3° Bragg order**, **T=80 ms**, state F=1, detuning 4.8 GHz, Gaussian pulses (sigma=12 us), vertical velocity spread 0.15 hk, peak intensity 0.2 W/cm^2

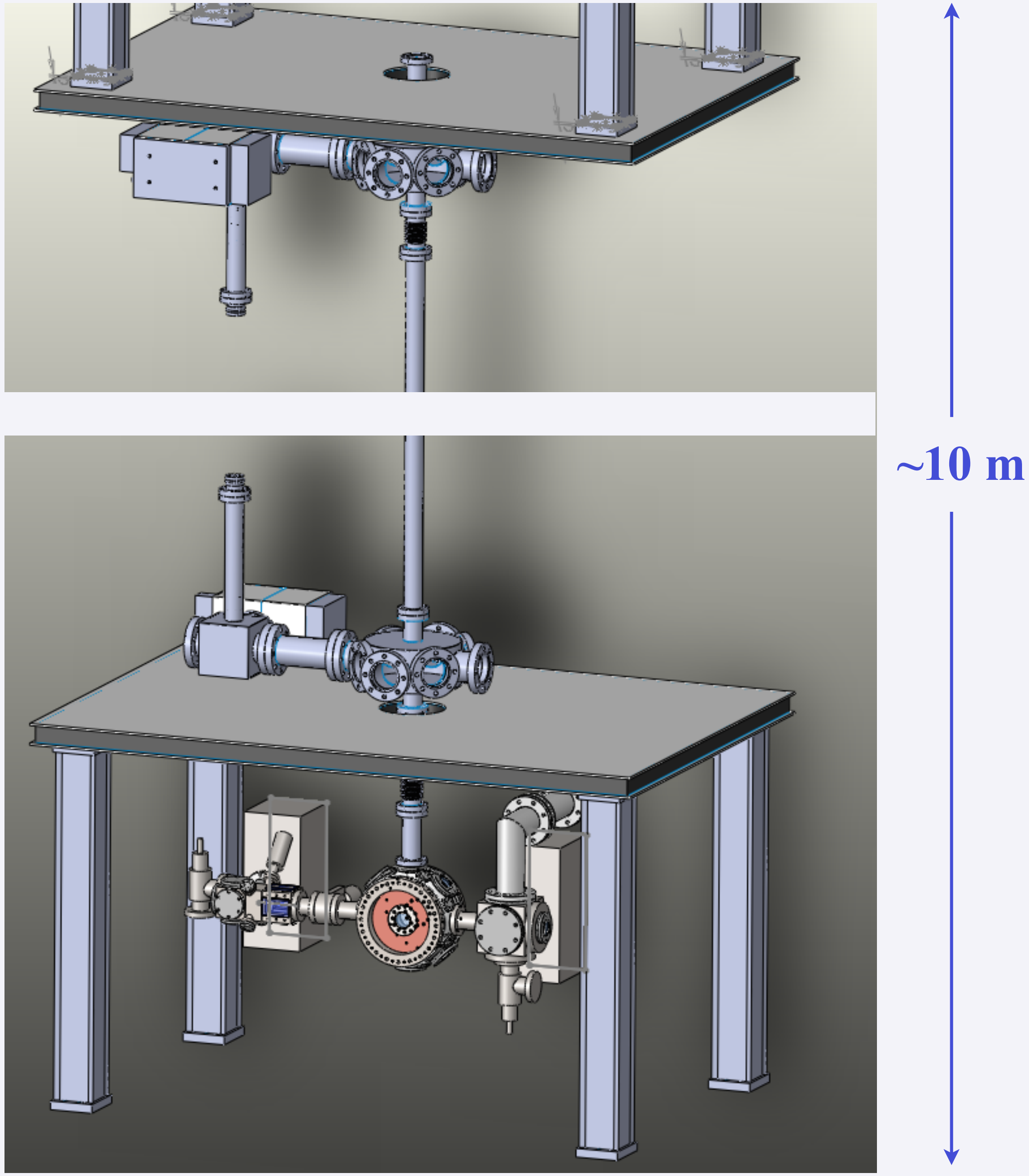


Problems to address:

- Increasing the order n => losing in contrast at large T
- Bragg transitions need narrow vertical (0.1 hk) momentum spread => severe velocity selection => low atomic flux
- Same internal state at the interferometer output => fluorescence detection makes difficult to distinguish between interferometer outputs

New large-scale atomic fountain apparatus



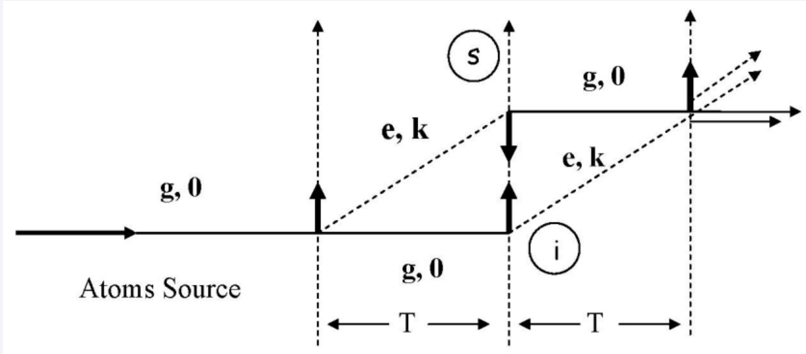


EP Tests, GW detection, ...

Gravitational waves detection with atom interferometry

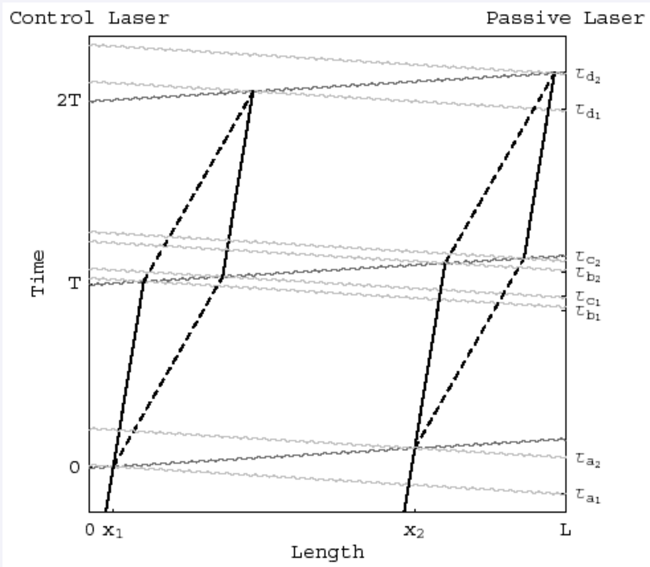
- *Single atom interferometer*

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)



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

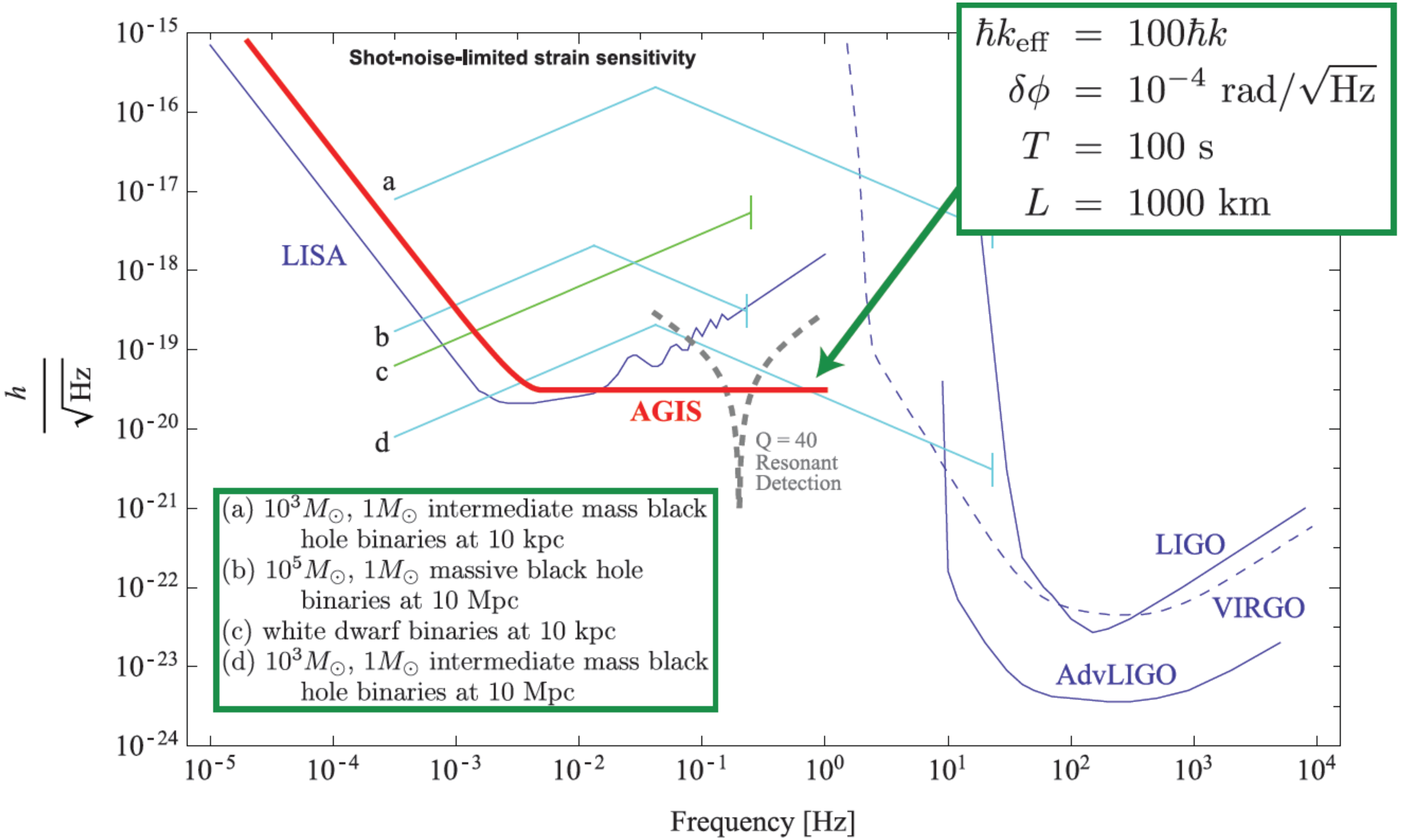
Note: The number of participants is limited to 50 The participation fee for the Workshop is 150 Euros including registration, coffee-breaks, lunches and the social dinner. The fee should be paid cash on arrival at the registration desk

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, newschemes 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)

Application to Gravitational Wave Detection

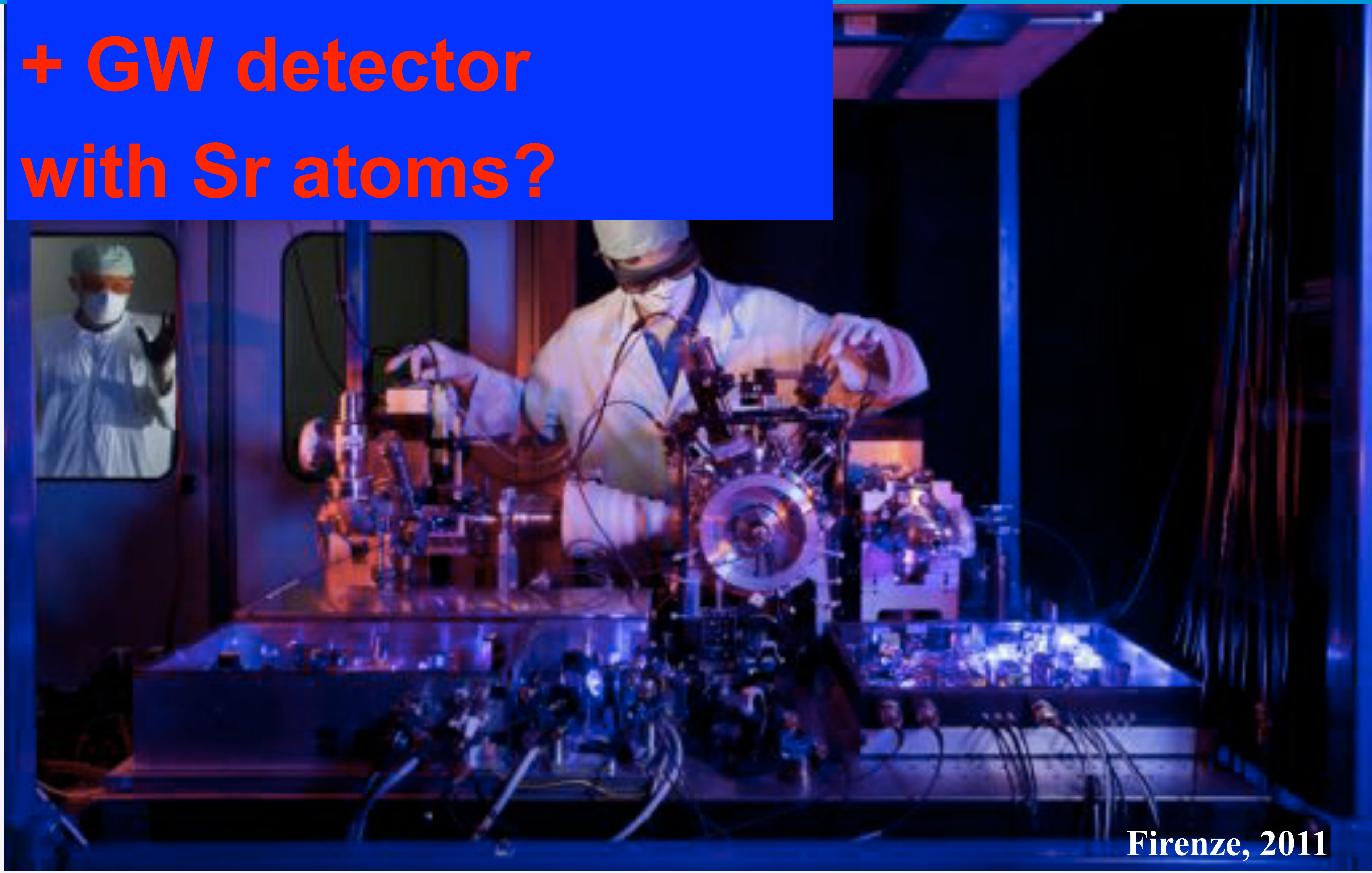


P. Graham, et al., arXiv:1206.0818, PRL (2013).

J. Hogan, et al., GRG **43**, 7 (2011).

From M. Kasevich, ICAP 2014

Space Optical Clock & Atom Interferometer + GW detector with Sr atoms?



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]
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(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.

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

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

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

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


Fourteenth Marcel Grossmann Meeting - MG14
University of Rome "La Sapienza" - Rome, July 12-18, 2015
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Precision Tests
PT1 Tests of gravity with atom interferometers and clocks (Guglielmo Tino)
PT2 Theory of light propagation in gravitational fields (Perlick Volker)
PT3 Experimental Gravitation (Claus Lämmerzahl, Angela Di Virgilio)
PT4 Variation of Fundamental Constants (Victor Flambaum, Julian Berengut)
PT5 GR in the Solar System (Roberto Peron, Agnes Fienga)
PT6 Dynamics of extended test objects -- equations of motion and their solution (Eva Hackmann, Dirk Puetzfeld)

G. Tino team members	**Nicola Poli**	Researcher, Università di Firenze
	Fiodor Sorrentino	Post-doc, LENS (now at INFN - Genova)
	Gabriele Rosi	Post-doc, Università di Firenze
	Quentin Bodart	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 (now at PTB)
	Marco Marchetti	Diploma student, Università di Firenze
	Marco Menchetti	Diploma student, Università di Bologna (now at NPL)
Collaborators	**Luigi Cacciapuoti**	Long term guest, ESA-Noordwijk
	Marella de Angelis	Long term guest, CNR
	Marco Prevedelli	Long term guest, Università di Bologna

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 Schioppo, Post-doc, LENS
Juergen Stuhler, Post-doc
Denis Sutyrin, Post-doc
Fu-Yuan Wang, Post-doc

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- ✓ **European Laboratory for Non-linear Spectroscopy (LENS)**
- ✓ **Ente Cassa di Risparmio di Firenze (CRF)**
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- ✓ **Agenzia Spaziale Italiana (ASI)**
- ✓ **Istituto Nazionale per la Fisica della Materia (INFM)**
- ✓ **Istituto Nazionale Geofisica e Vulcanologia (INGV)**

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