Precision gravity measurements with cold atom interferometry

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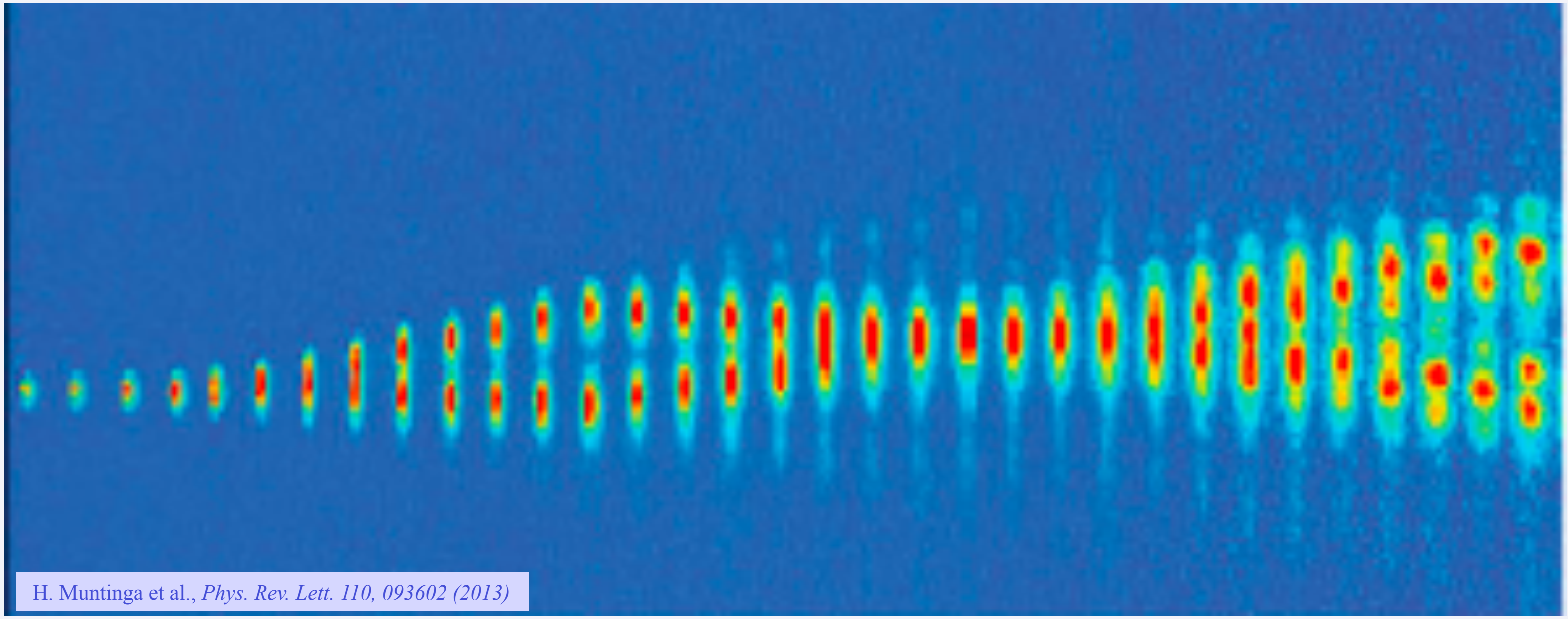
Colloquium - Dipartimento di Fisica dell'Università di Pisa, 4 November 2014

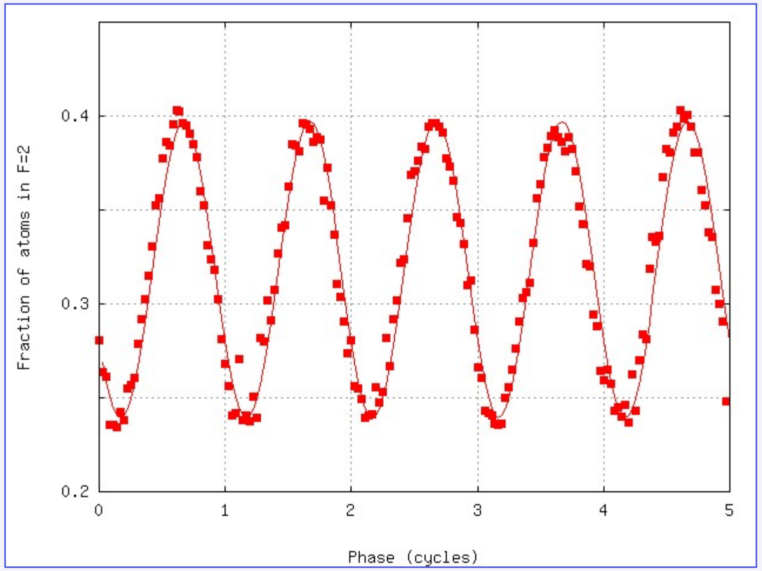
Outline

- *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*
- *Prospects*

Atom Interferometry



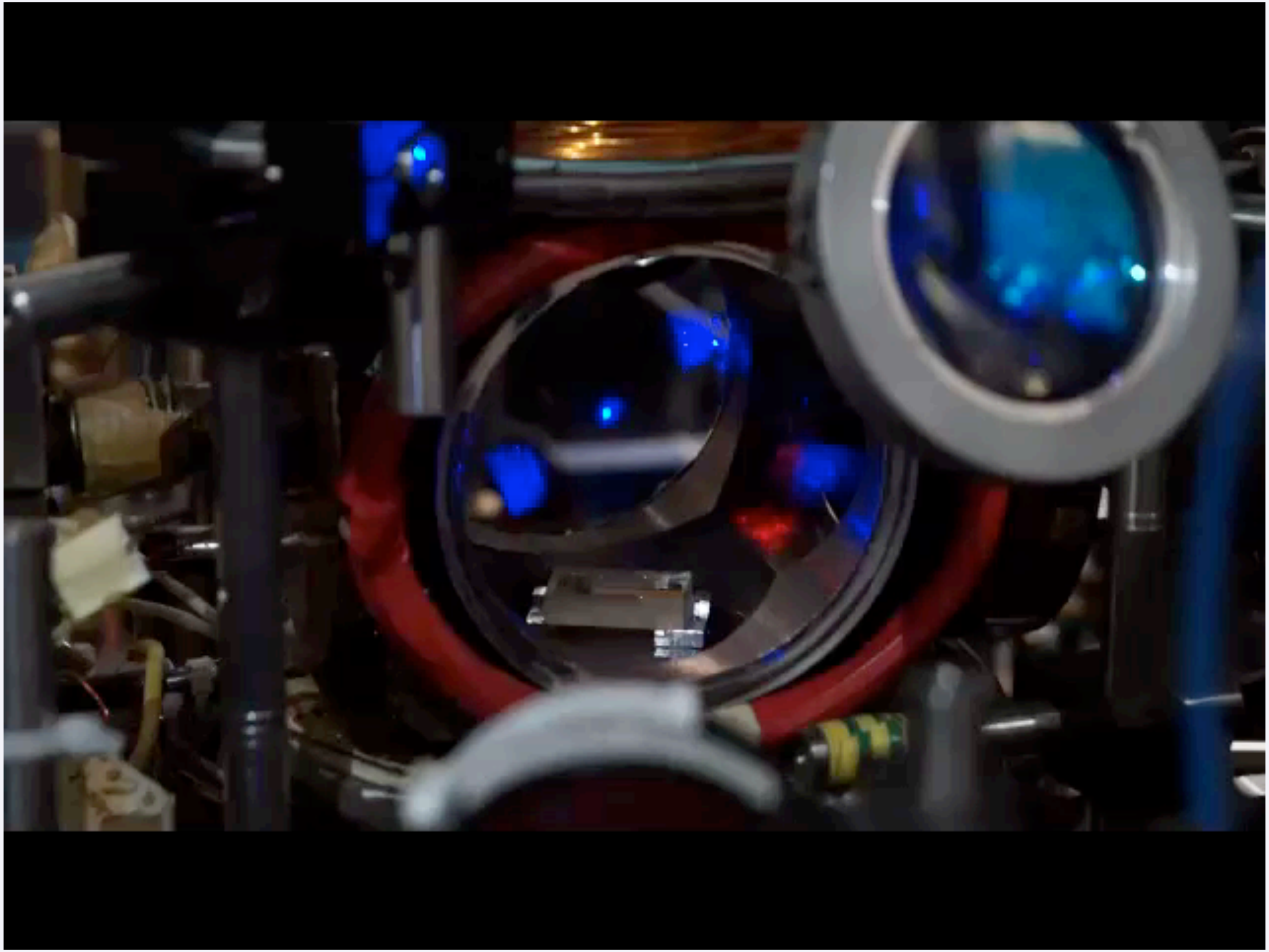
H. Muntinga et al., *Phys. Rev. Lett. 110, 093602 (2013)*



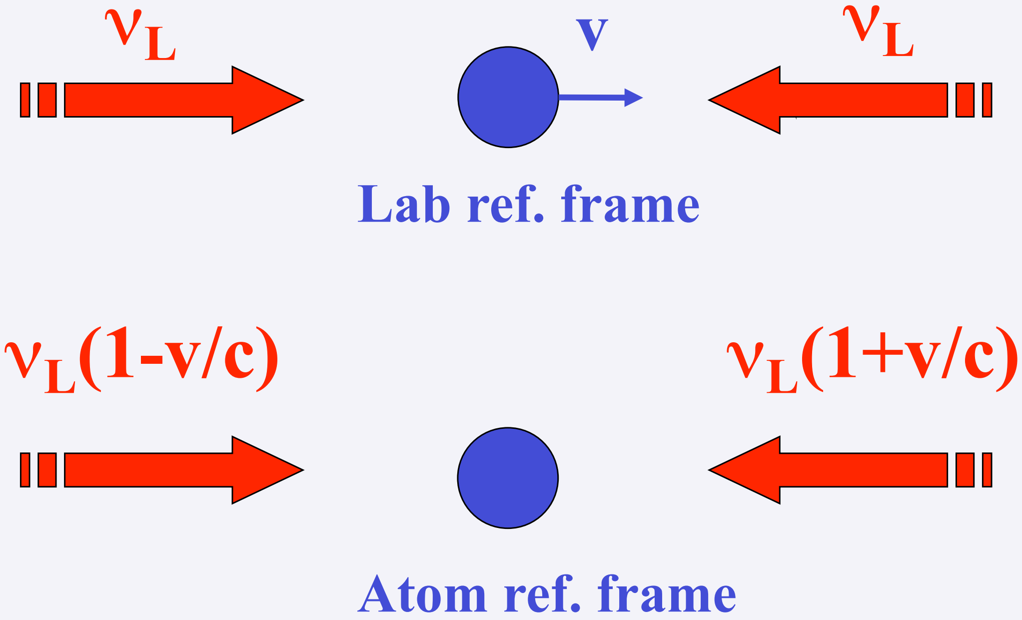
Interference fringes – Firenze 2006

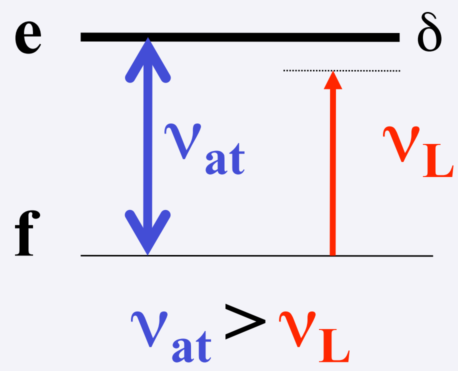
Sr Magneto-Optical Trap (MOT)

LENS - Firenze



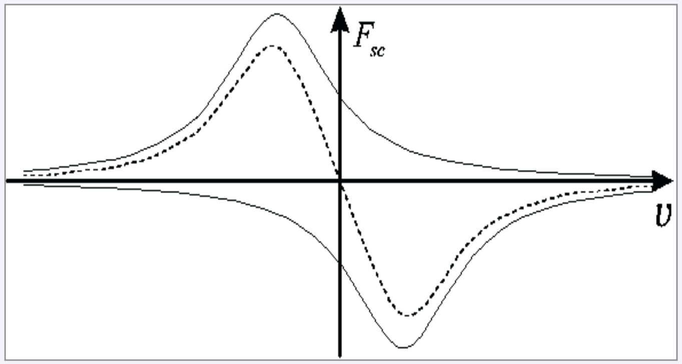
Laser cooling: Optical molasses





$(I/I_0 \ll 1)$

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



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

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

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

Laser cooling: Atomic temperatures

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

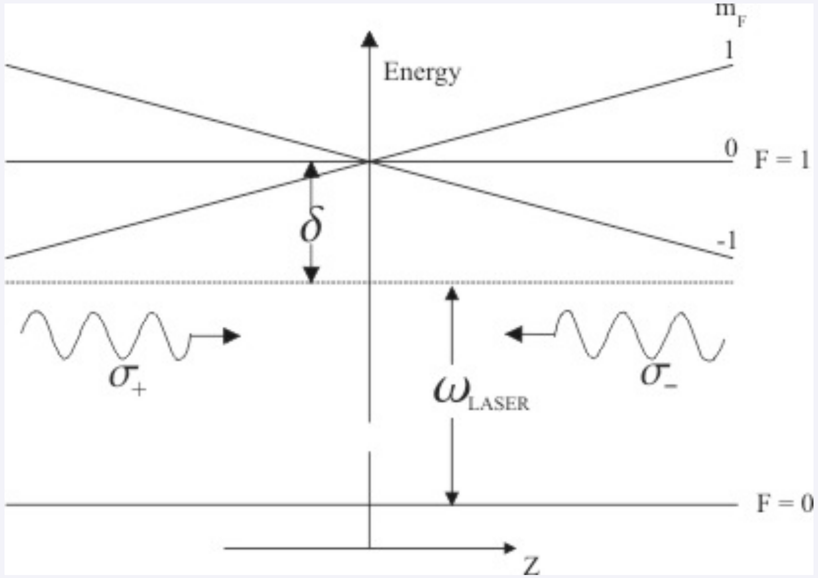
Minimum temperature for Doppler cooling: $k_B T_D = \frac{\hbar\Gamma}{2}$

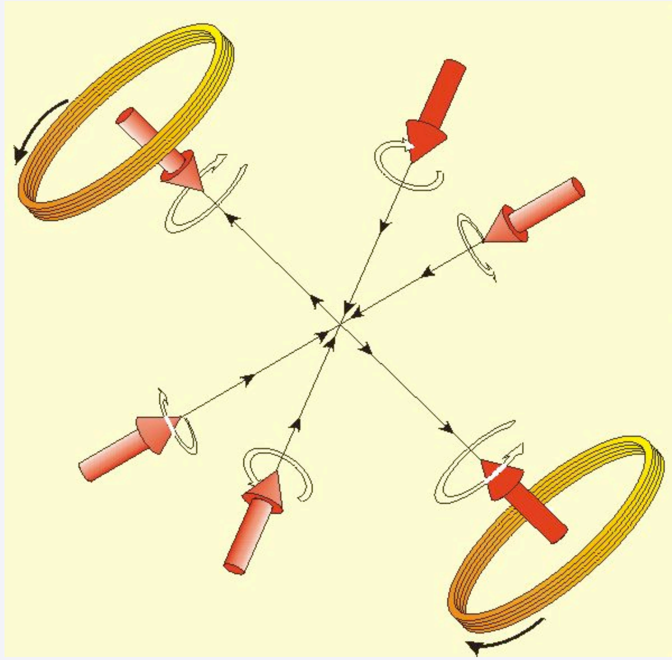
Single photon recoil temperature: $k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$

Examples:

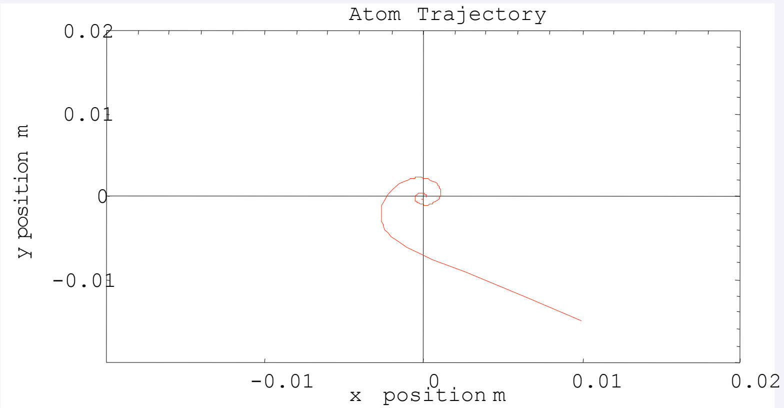
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK
Sr (**intercombination transition**)	180 nK	460 nK

Magneto-Optical Trap (MOT)





$$F(z,v) \simeq \frac{4hk}{\pi}\frac{I}{I_0}\frac{\delta}{\Gamma}\frac{kv+\beta z}{[1+(\frac{2\delta}{\Gamma})^2]^2}$$



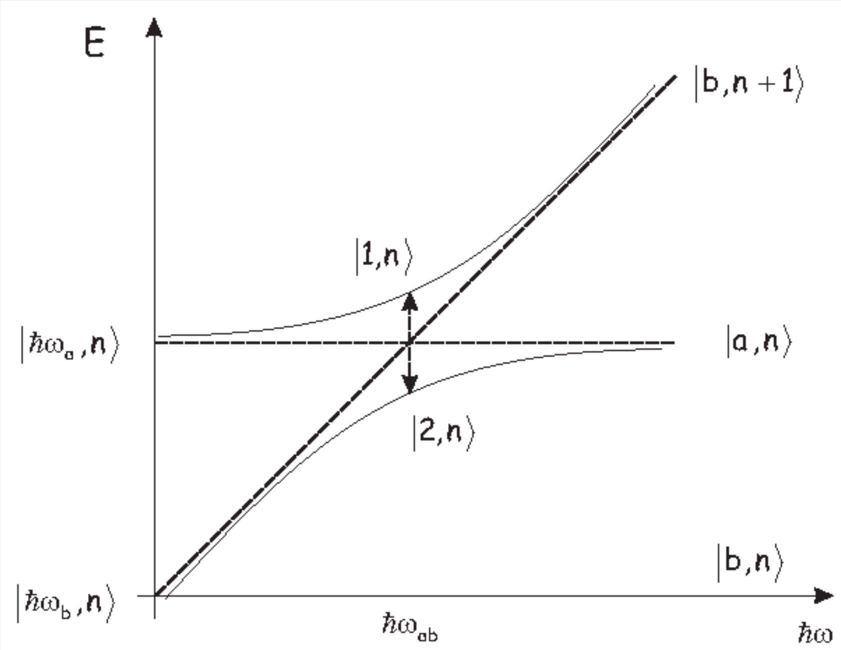
density n ≈ 10^{11} cm^{-3}

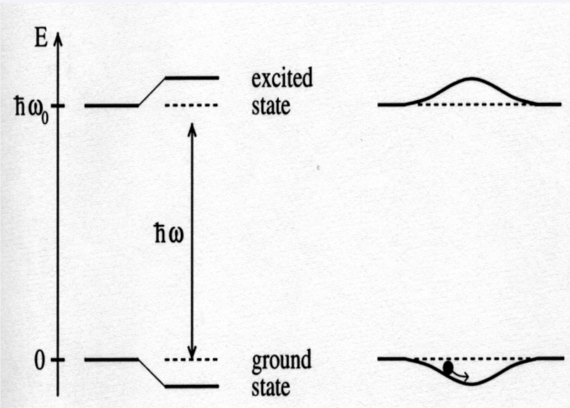
temperature T ≈ 100 μK

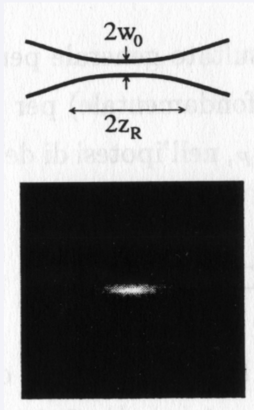
size Δx ≈ 1 mm

E. Raab *et al.*, Phys. Rev. Lett. 59, 2631 (1987)

Light shifts and optical traps



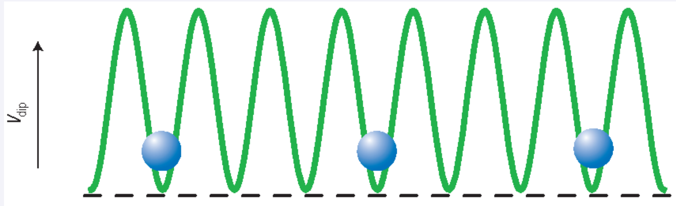




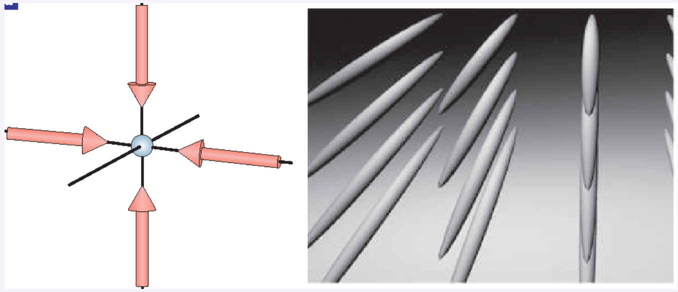
$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)|\mathbf{E}(\mathbf{r})|^2$$

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

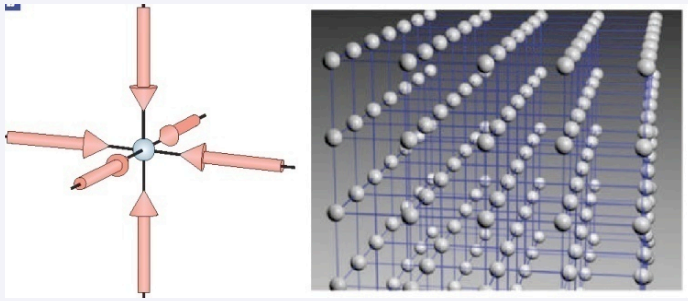
optical lattices



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



2 D optical lattice ⇒ array of 1D potential tubes



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

Review: **I. Bloch, 2005**

Cooling and trapping atoms with laser light
The Nobel Prize in Physics 1997

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▸LAUREATES ARTICLES EDUCATIONAL

Web Adapted Version of the Nobel Poster from the Royal Swedish Academy of Sciences

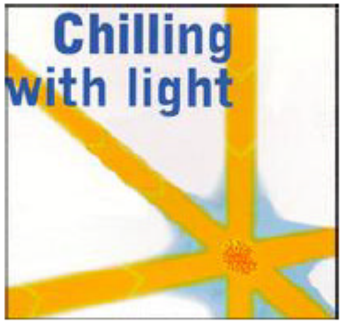
BACK

The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

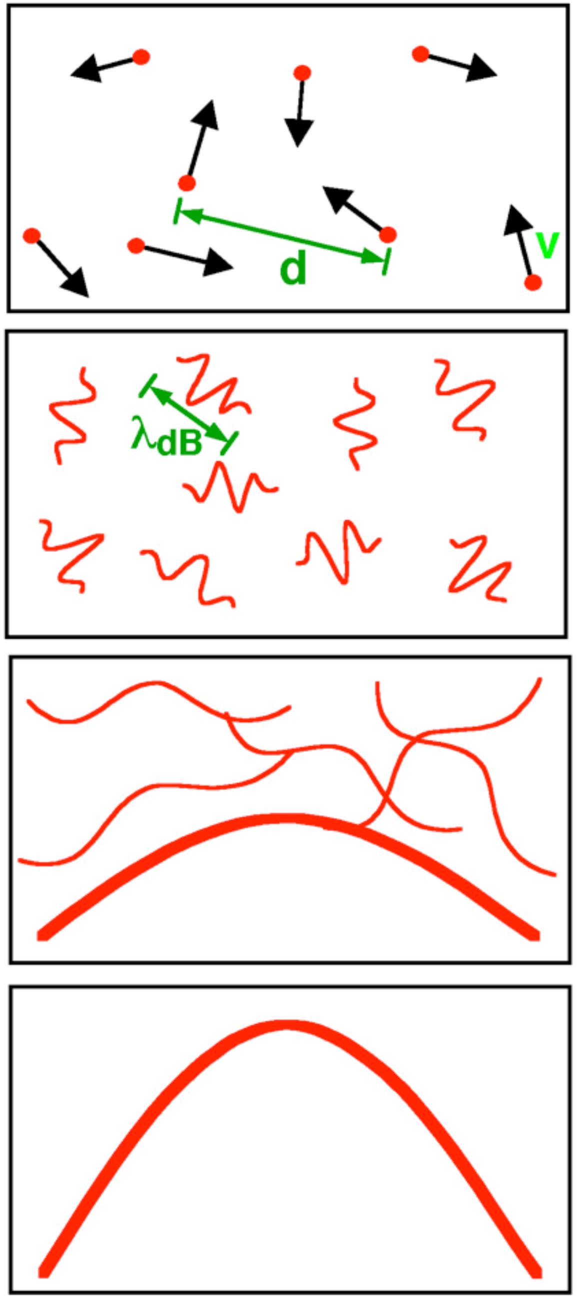
Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

for their developments of methods to cool and trap atoms with laser light.



This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

What is Bose-Einstein condensation (BEC)?



High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

"Wave packets"

$T=T_{crit}$:

Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0:

Pure Bose condensate

"Giant matter wave"

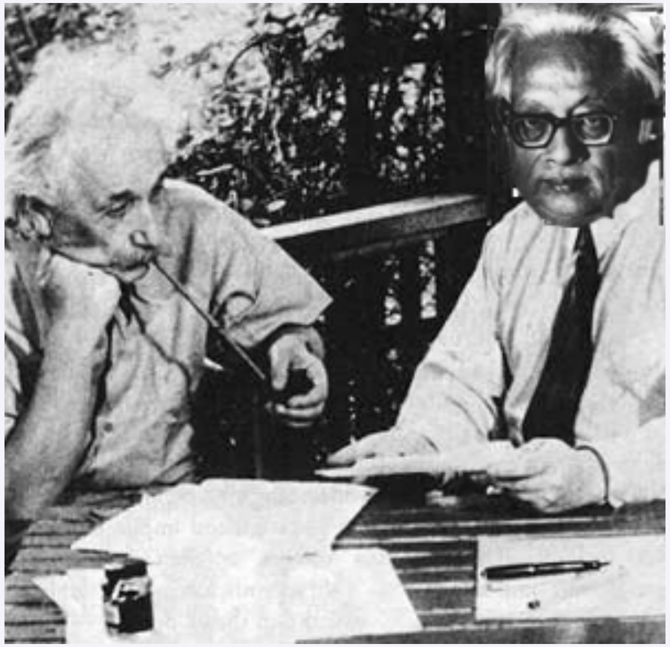
from W. Ketterle

Bose-Einstein condensation

The atoms with an even number of electrons + protons + neutrons at very low temperatures occupy all the ground state of the system.

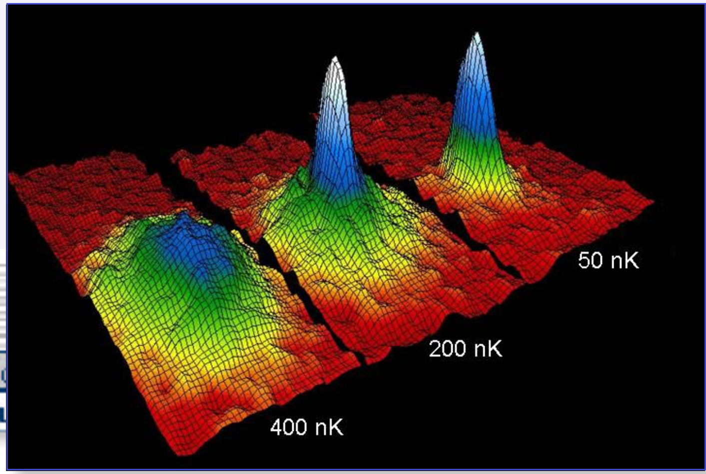
This new state of matter is called ***Bose-Einstein condensate***.

The atoms are called ***bosons***.



A. Einstein and S.N. Bose (1925)

Bose-Einstein condensation in dilute gases of atoms



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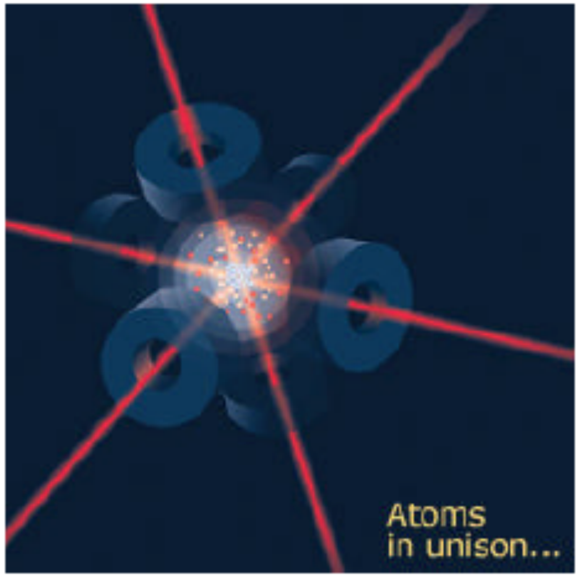
ABOUT SEARCH

PEACE ECONOMICS

BACK

The Nobel Prize in Physics 2001

The Royal Swedish Academy of Sciences has awarded the Nobel Prize in Physics for 2001 jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".



Eric A. Cornell JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.

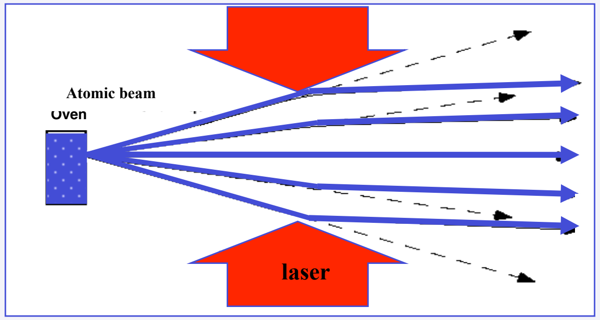
Carl E. Wieman JILA and University of Colorado, Boulder, Colorado, USA.

Wolfgang Ketterle Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

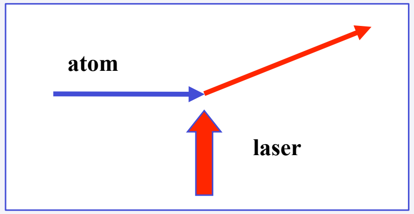
Contents:

Atom optics

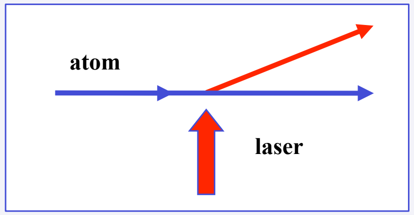
lenses



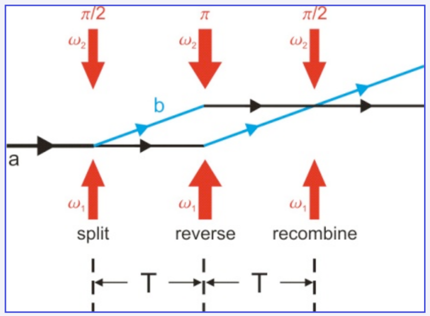
mirrors



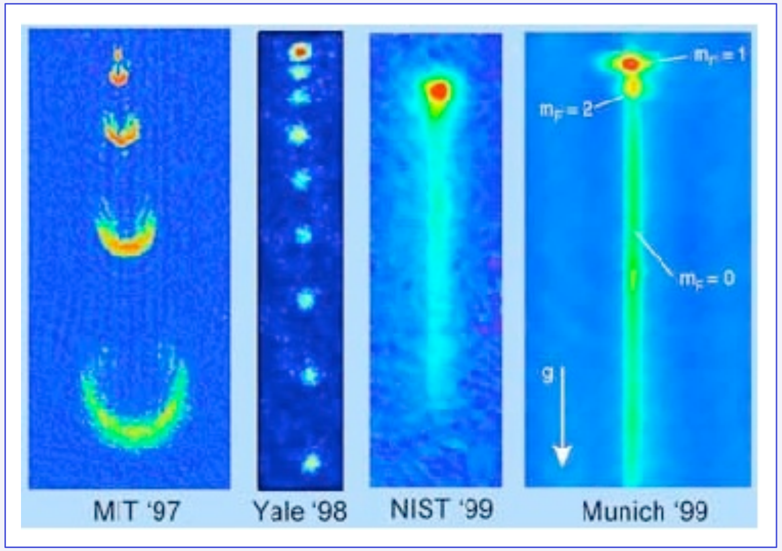
beam-splitters



interferometers



atom laser



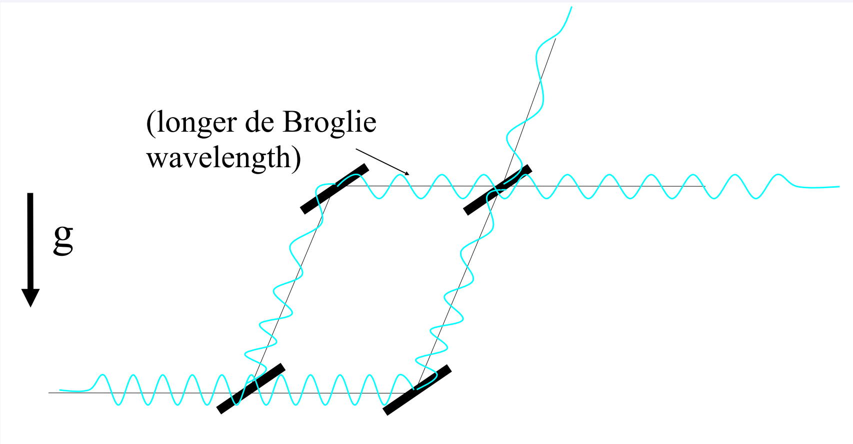
Atom interferometer force sensors

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

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

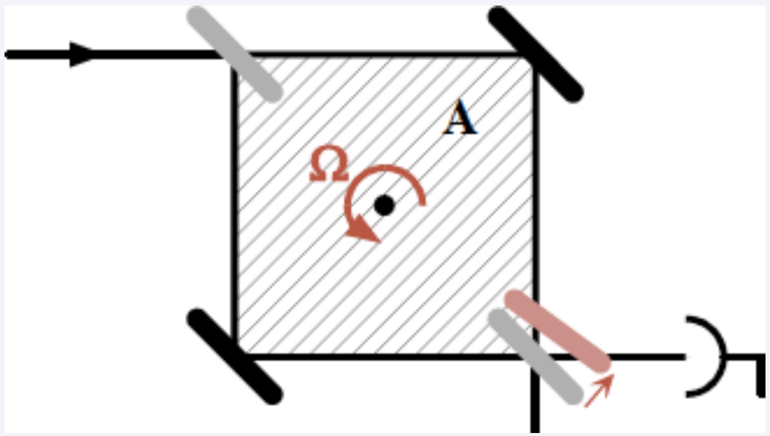
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



Rotations

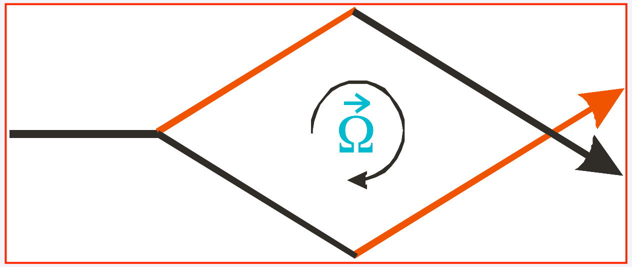
Rotations induce path length differences by shifting the positions of beam splitting optics



From M. Kasevich

Matter wave sensors

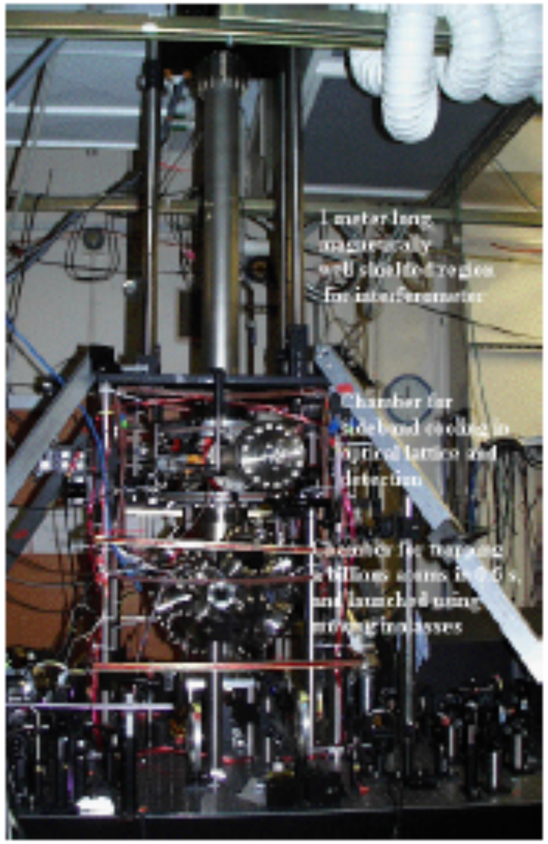
rotations:

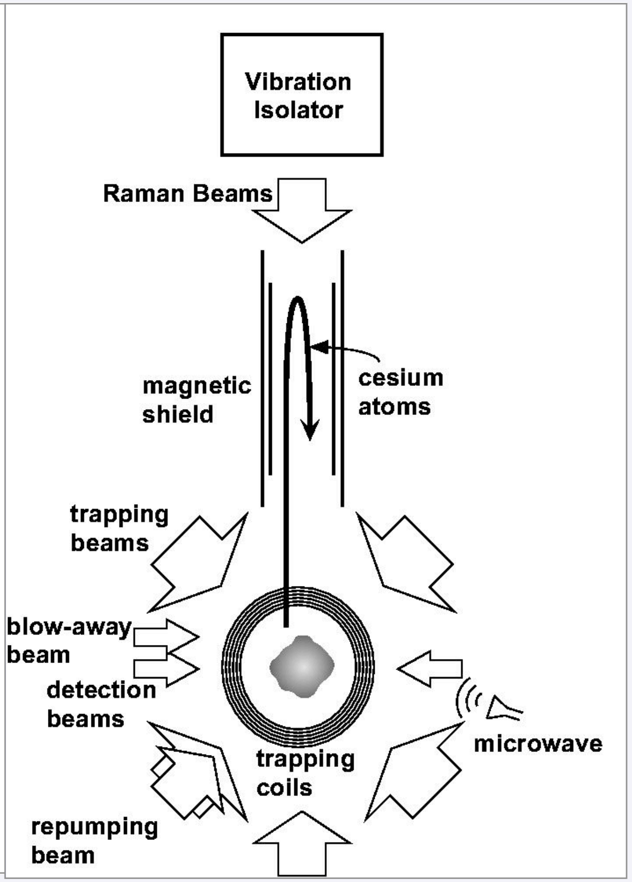


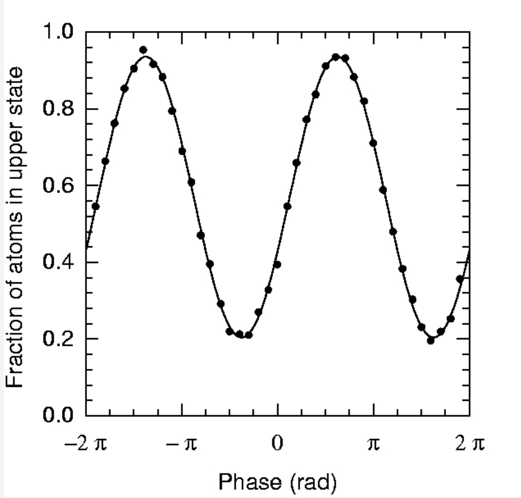
$$\Delta\Phi_{rot} = 2\pi \frac{2\, m_{at}}{h} A \times \Omega$$

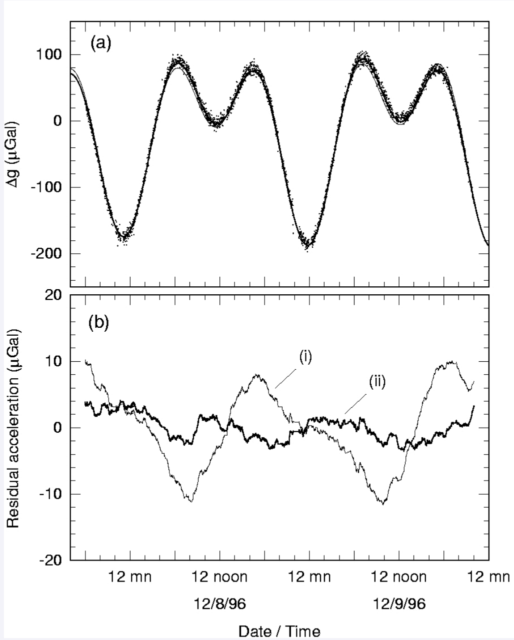
$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \frac{m_{at} \times \lambda \times c}{h} \approx 5 \times 10^{10}$$

Stanford atom gravimeter







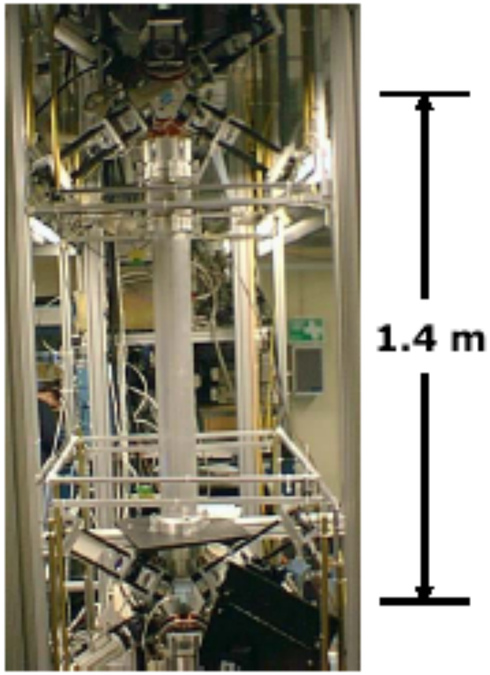


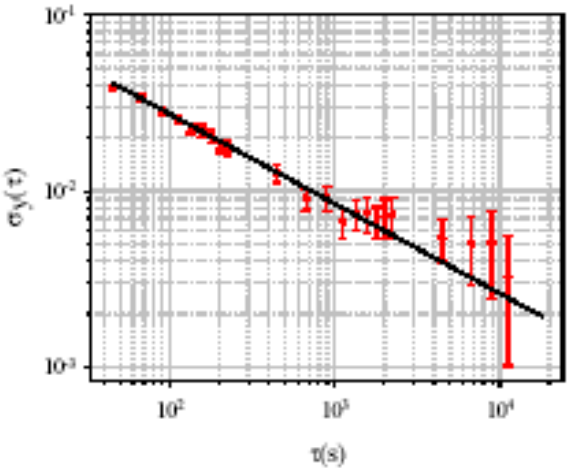
Resolution: $3\text{x}10^{-9}$ g after 1 minute

Absolute accuracy: $\Delta g/g<3\text{x}10^{-9}$

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

Stanford/Yale gravity gradiometer





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

Demonstrated diffential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

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

from M.A. Kasevich

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

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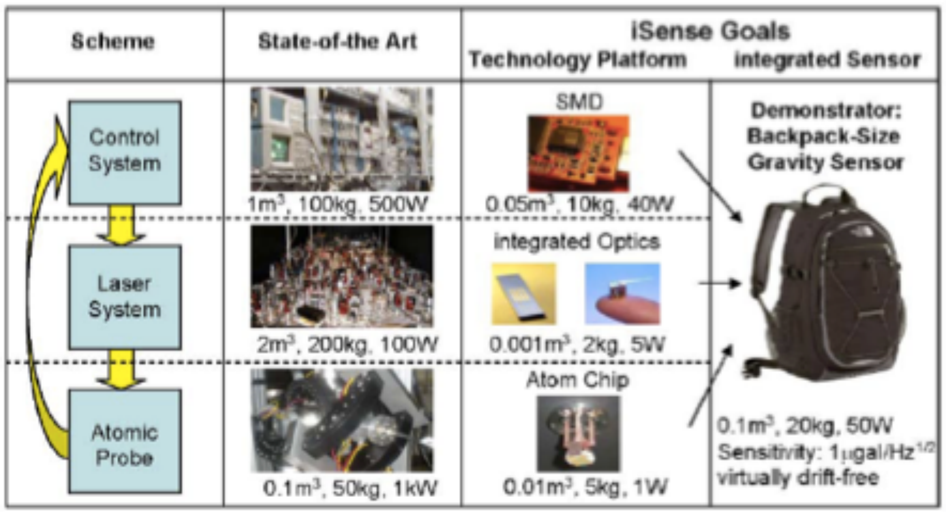
Future and Emerging Technologies (FET) - Open

iSense – Integrated Quantum Sensors

7th Framework Programme - Theme 3 "Information and Communication Technologies"

Call identifier: FP7-ICT-2009- C FET-Open



Participant no. *	Participant organisation name	Part. short name	Country
1 (Coordinator)	The University of Birmingham	Bham	UK
2	QinetiQ	QinetiQ	UK
3	University of Hamburg	UHH	D
4	Centre National de la Recherche Scientifique[1]	CNRS	F
5	University of Florence	UNIFI	I
6	Leibniz University Hannover	LUH	D
7	Institute for quantum optics and quantum information - Austrian Academy of Sciences	IQOQI-OEAW	A
8	Ferdinand-Braun-Institut für Höchstfrequenztechnik im Forschungsverbung Berlin e.V.	FBH	D
9	University of Nottingham	Nham	UK

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]

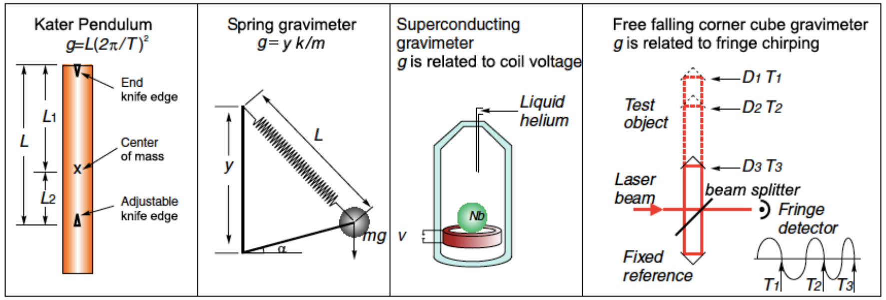


Table 1. Summary of error sources level and technical budgets for most used commercial gravimeters.

	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

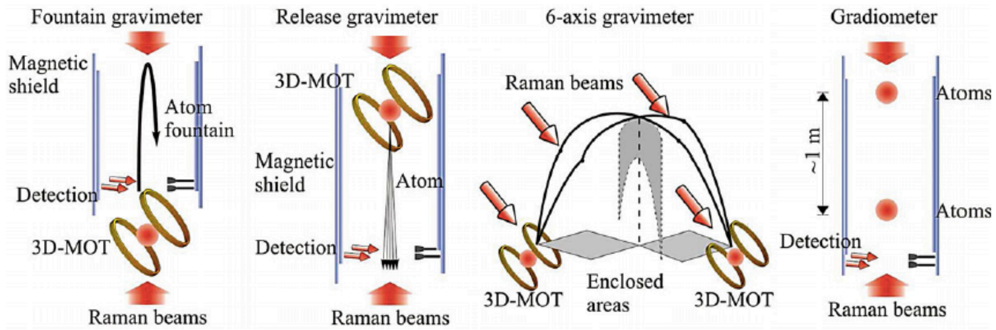


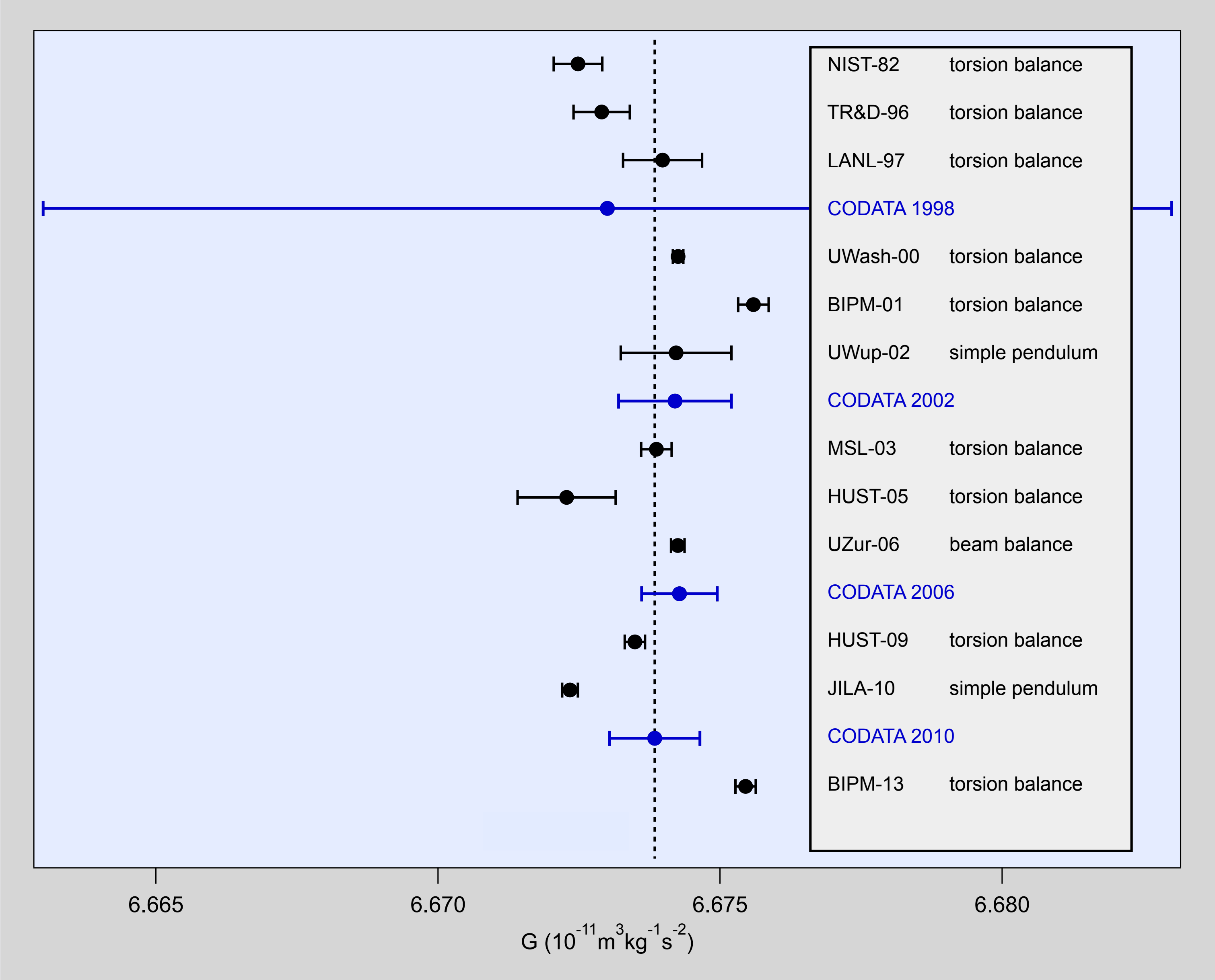
Figure 7. Scheme of gravity sensors based on atom interferometry: absolute measurement of g in a fountain configuration, a release configuration, a 6-axis configuration and a scheme of a gravity gradiometer. Their sensitivities and accuracy are given in table 2.

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

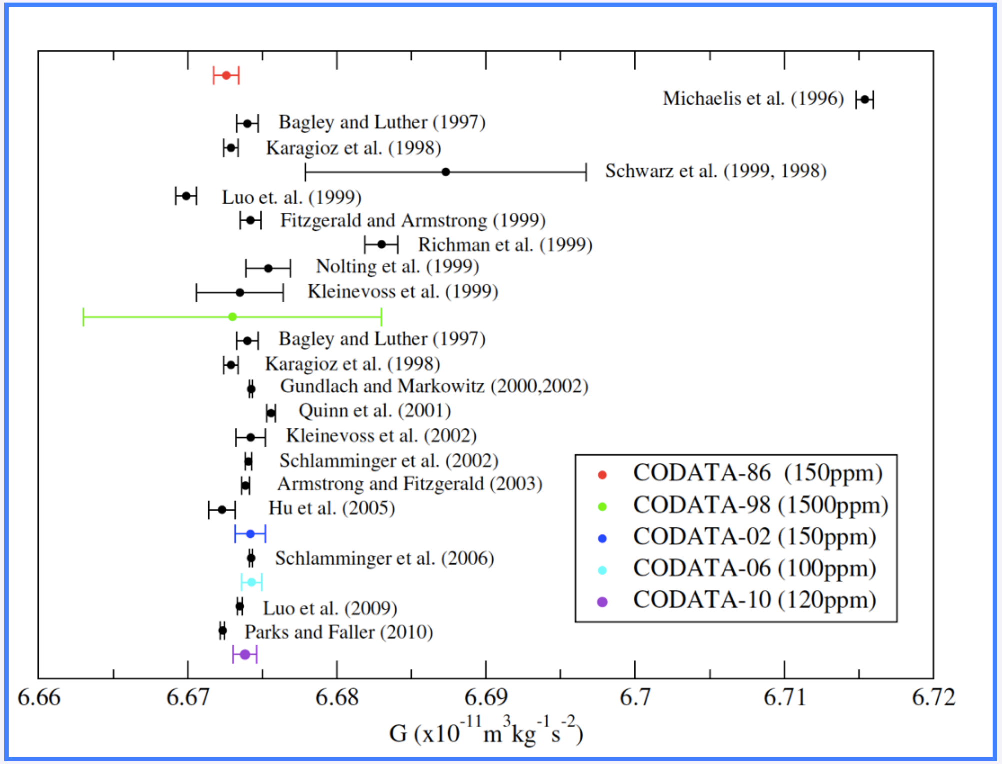
	Fountain [2, 3]	Release [82]	6-Axis sensor [83]	Gradiometer [5, 11]
Sensitivity	$1.1 \times 10^{-8} g/\sqrt{\mathrm{Hz}}$	$1.4 \times 10^{-8} g/\sqrt{\mathrm{Hz}}$	$1.5 \times 10^{-6} g/\sqrt{\mathrm{Hz}}$	$4 \times 10^{-9} (g/\mathrm{m})/\sqrt{\mathrm{Hz}}$
Accuracy	$3 \times 10^{-9} g$	–	–	–

Measurement of the gravitational constant G by atom interferometry

Measurements of the Newtonian gravitational constant G

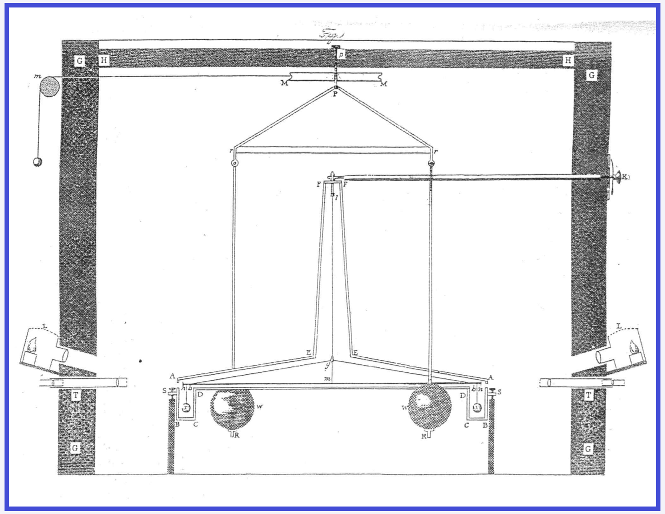


Measurements of the Newtonian gravitational constant G

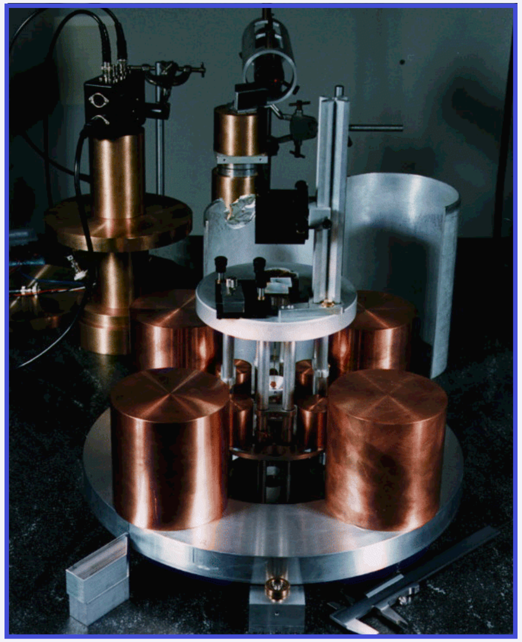


$G = 6.67384\,(80) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}s^{-2}}$
$[1.2\times10^{-4}]$

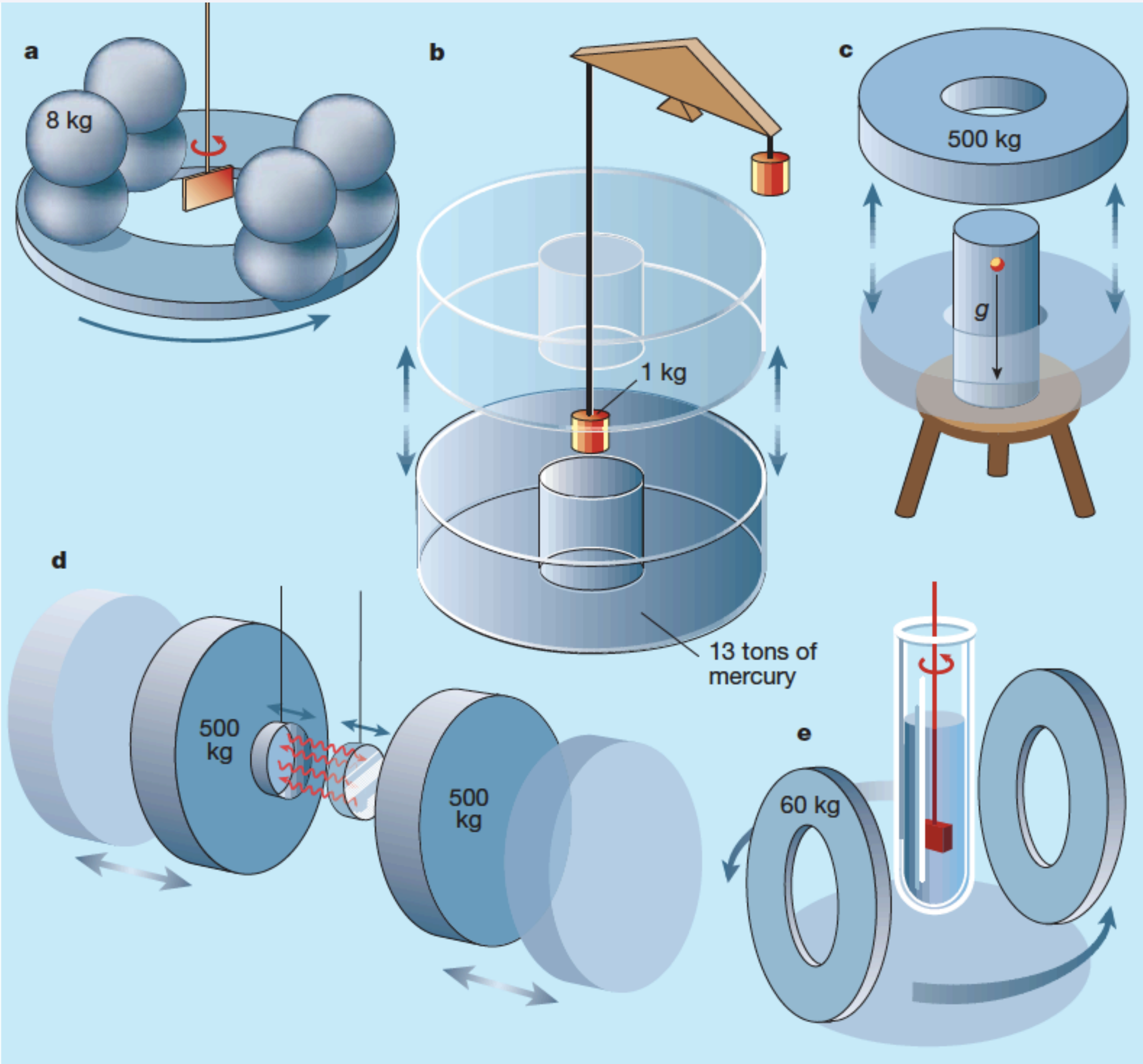
P.J. Mohr, B. N. Taylor, and D. B. Newell, *CODATA recommended values of the fundamental physical constants: 2010*, Rev. Mod. Phys., Vol. 84, No. 4, (2012)



Cavendish 1798



Quinn 2001

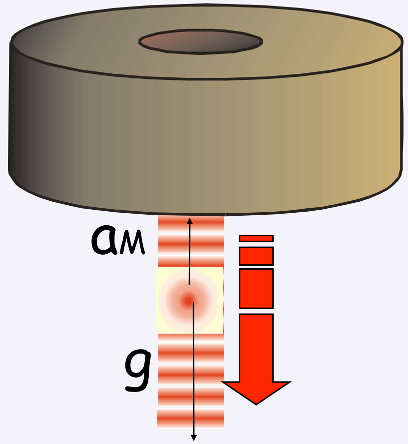


Terry Quinn. Measuring big G, NATURE|VOL 408 | 21/28 DECEMBER 2000

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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



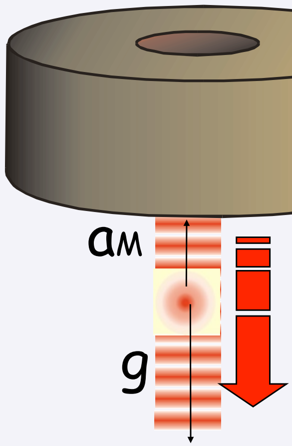
➢ ***Precision measurement of G***

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

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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



➢ ***Precision measurement of G***

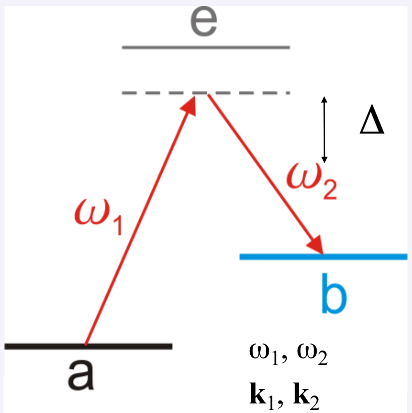
➢ ***Test of Newtonian law***

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

Why atoms?

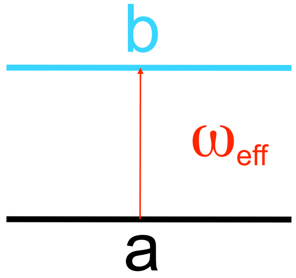
- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects
- Different states, isotopes,…

Raman pulse interferometer

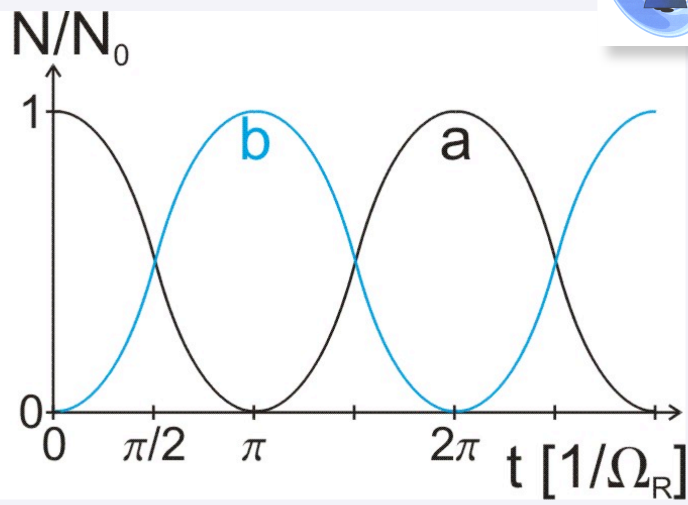


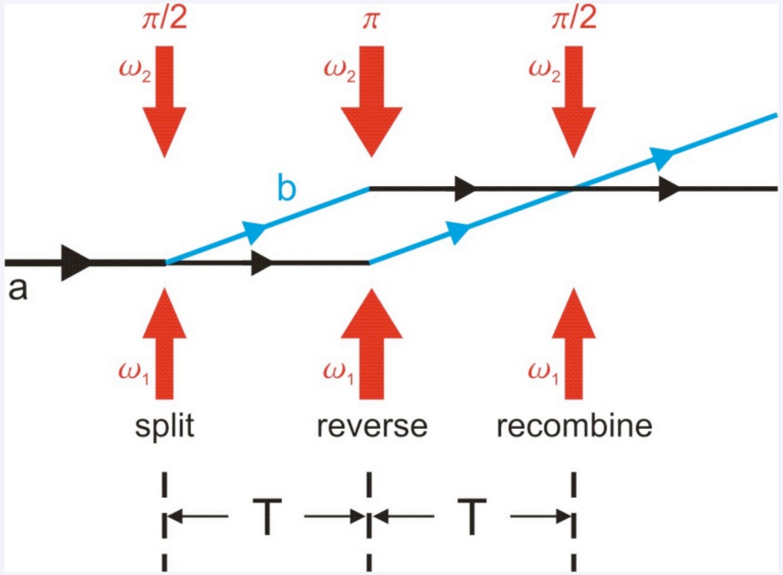
ω_1, ω_2
$\mathbf{k}_1$, $\mathbf{k}_2$
Ω_1, Ω_2
ϕ_1 , ϕ_2

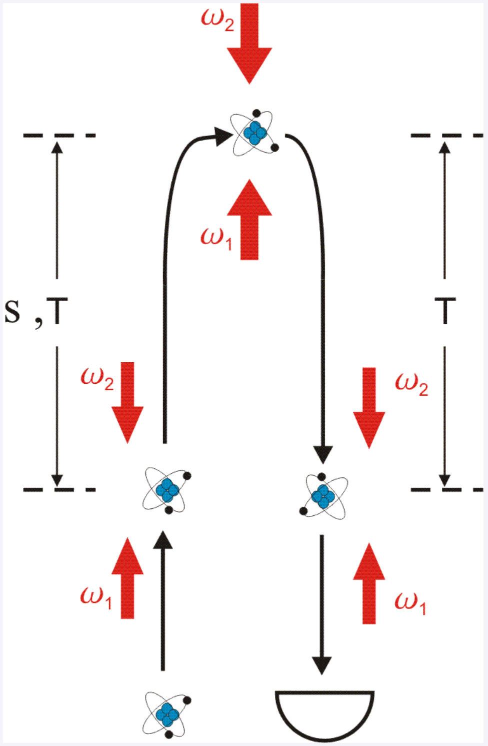
$\Longrightarrow$



$\omega_{eff} = \omega_1 - \omega_2$
$\mathbf{k}_{eff} = \mathbf{k}_1 - \mathbf{k}_2$
$\Omega_{eff} = \Omega_1\Omega_2/\Delta$
$\phi_{eff} = \phi_1 - \phi_2$



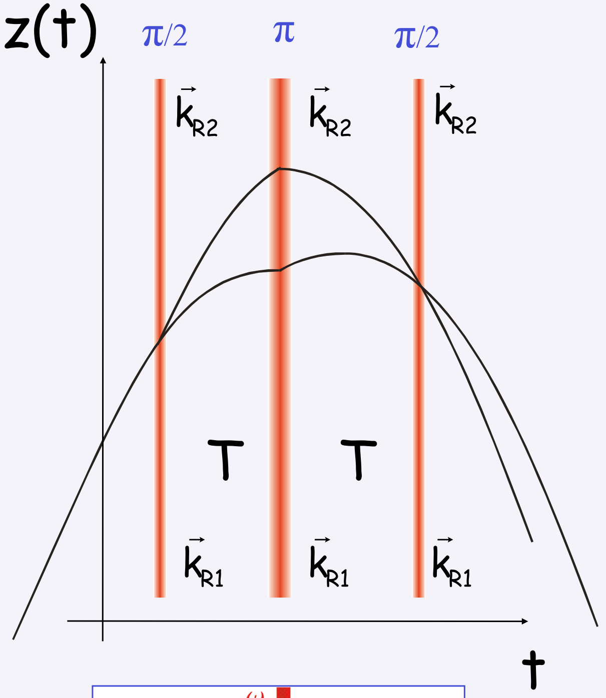




M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Raman interferometry in an atomic fountain

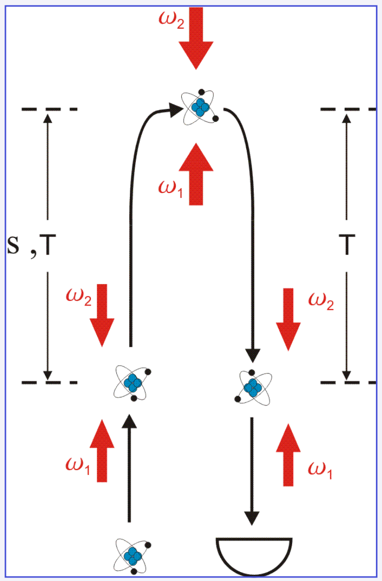


Phase difference between the paths:

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

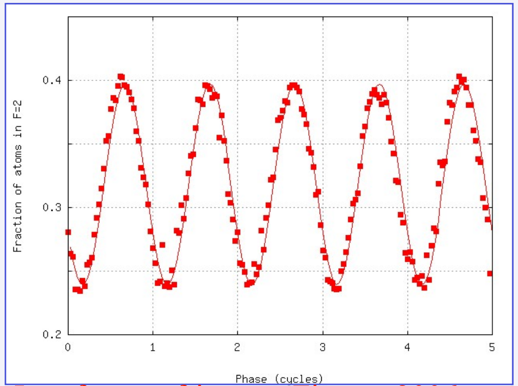
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Rightarrow \mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

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

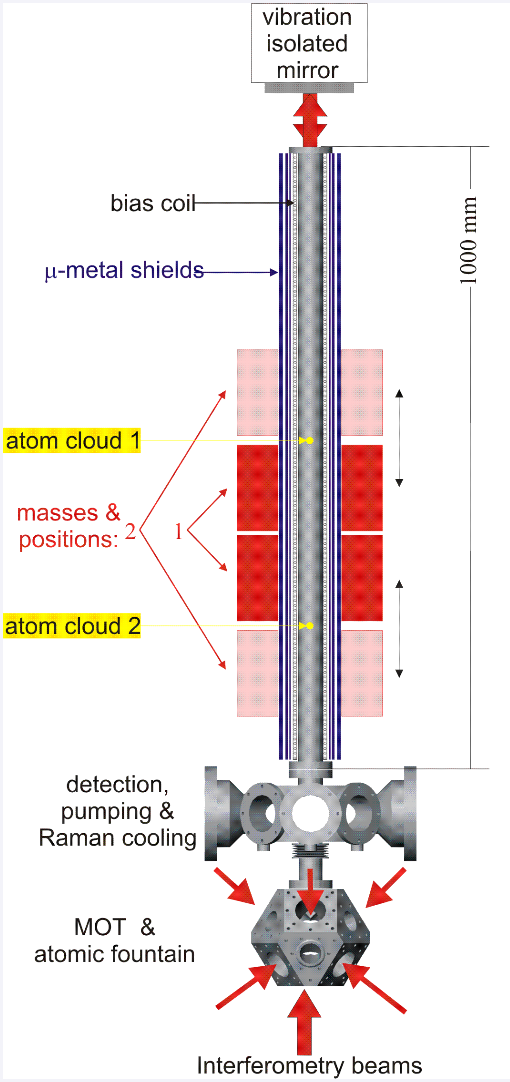
$S/N = 1000$

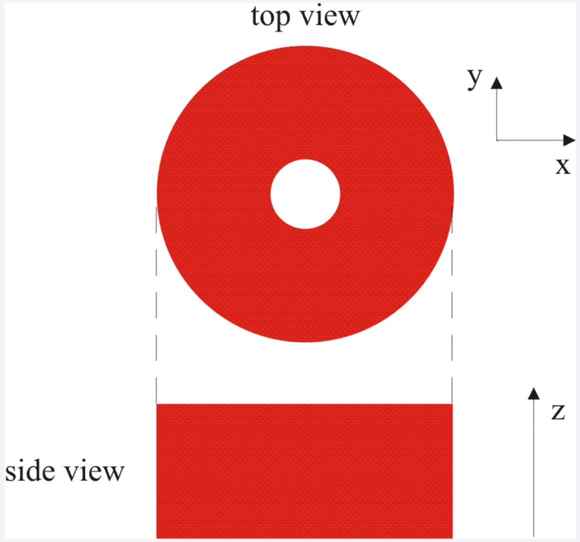
$\Rightarrow$ Sensitivity 10^{-9} g/shot

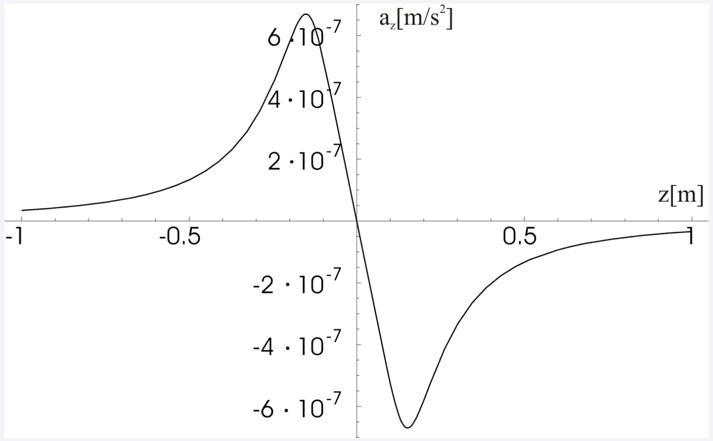
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

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

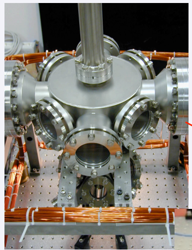
MAGIA apparatus

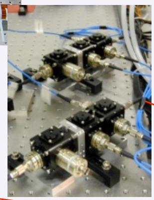
Cavendish 1798: “The apparatus is very simple”

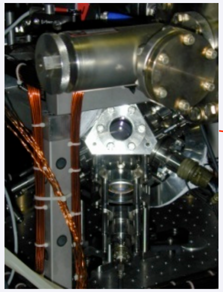
MAGIA apparatus is not very simple

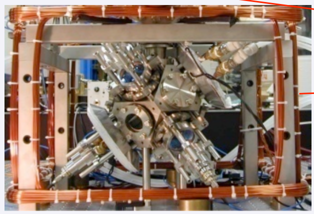
- Laser system
  - 6 frequency stabilized ECDL sources @ 780 nm (Reference, Cooling 2D-MOT, Cooling 3D-MOT, Repumper master, Raman master, Raman slave)
  - 3 optically injected diode lasers @ 780 nm (Repumper 2D-MOT, Repumper 3D-MOT, Probe)
  - 4 Tapered Amplifiers @ 780 nm (Cooling 2D-MOT, Cooling 3D-MOT, Raman master, Raman
  - ~20 AOMs
  - ~20 PM optical fibres
- Active stabilization loops
  - Intensity of 3D-MOT Cooling up and down laser beams, master and slave Raman laser beams and Probe laser
  - tilt of Raman retro-reflection mirror
  - Earth rotation compensation with tilt-tip Raman mirror
- Vacuum system
  - 2D-MOT chamber, steel, 10^{-7} torr Rb pressure
  - main chambers and interferometer tube, titanium, ~10^{-10} torr
- Electronic control system
  - real-time system for analog I/O and TTL signals, <5 μs jitter
  - ~20 shutter drivers
  - ~10 DDS for AOM and OPLL driving
  - 6 low-noise coil drivers
- Laboratory environment
  - temperature stability 0.1 °C
  - humidity stability 5%

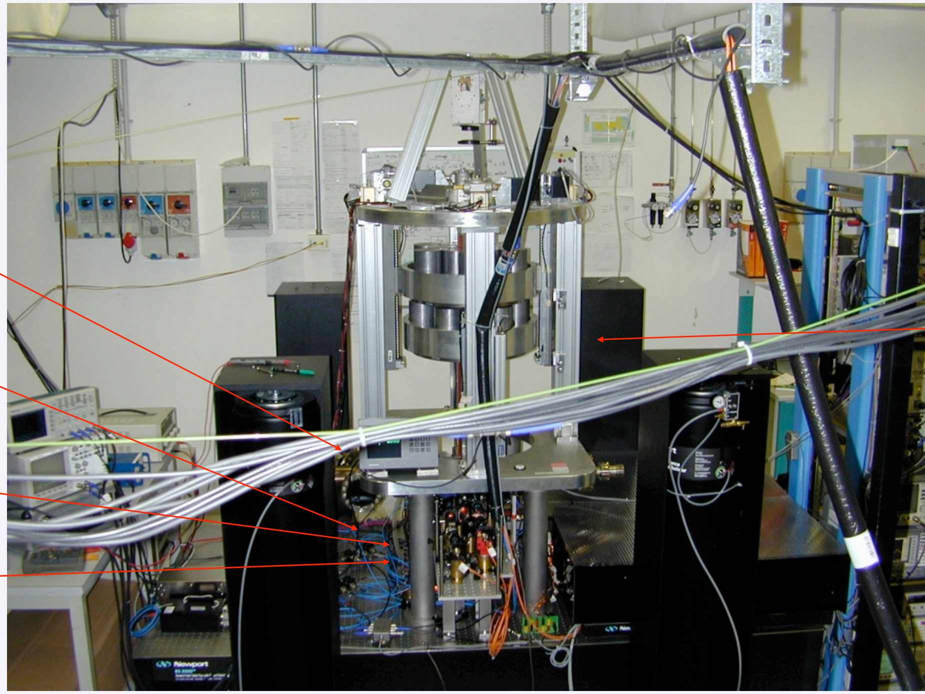
MAGIA apparatus







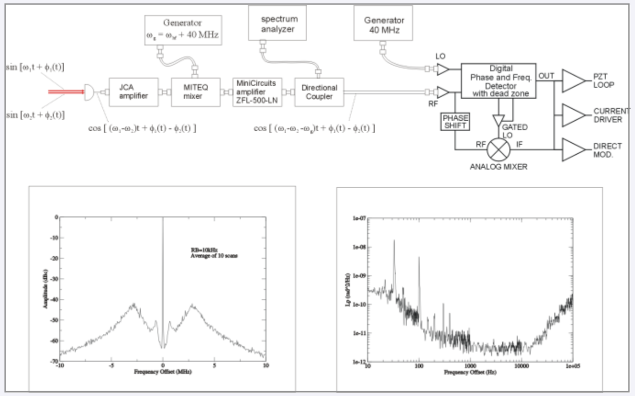




Source masses and support

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)**

Double launch and juggling

TRAPPING/COOLING

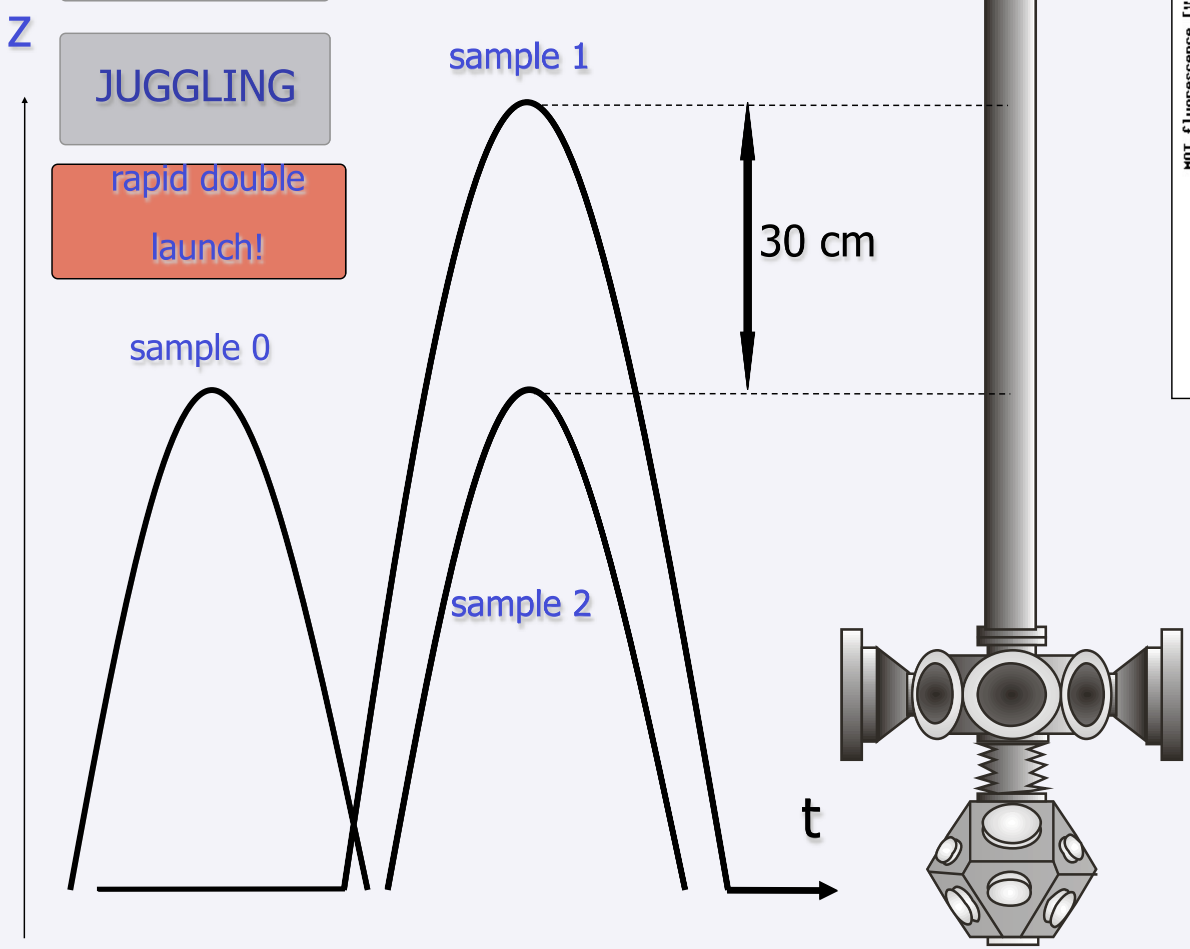
LAUNCH

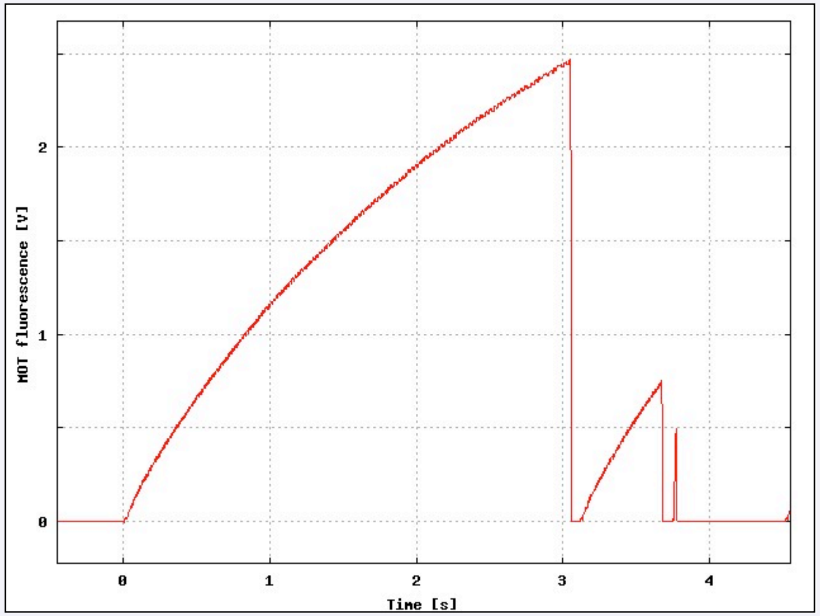
JUGGLING

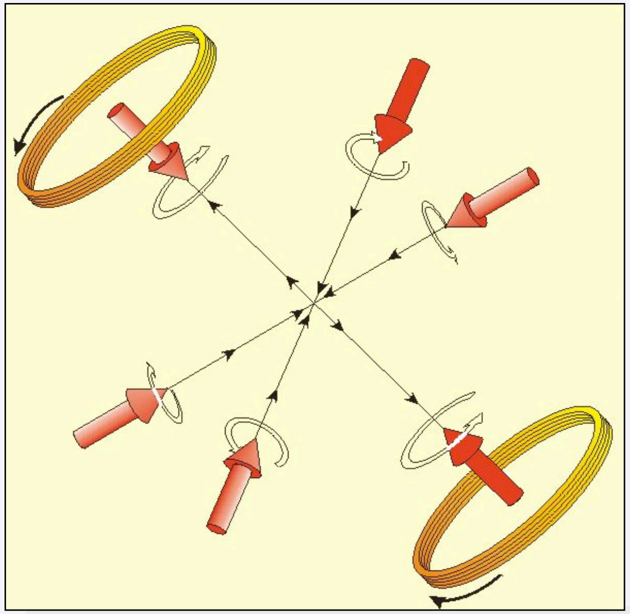
rapid double launch!

$N=5 \times 10^8$

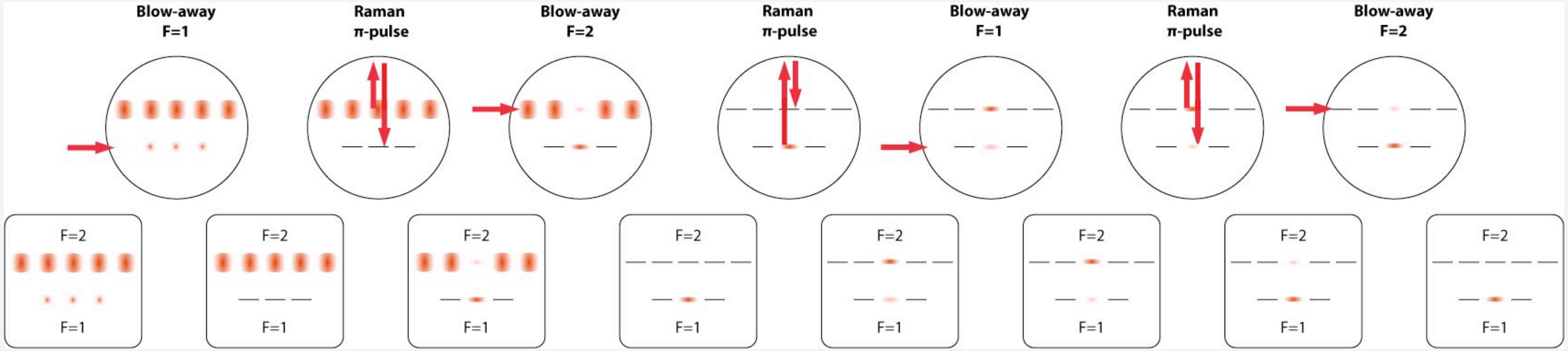
$T=2\ \mu K$







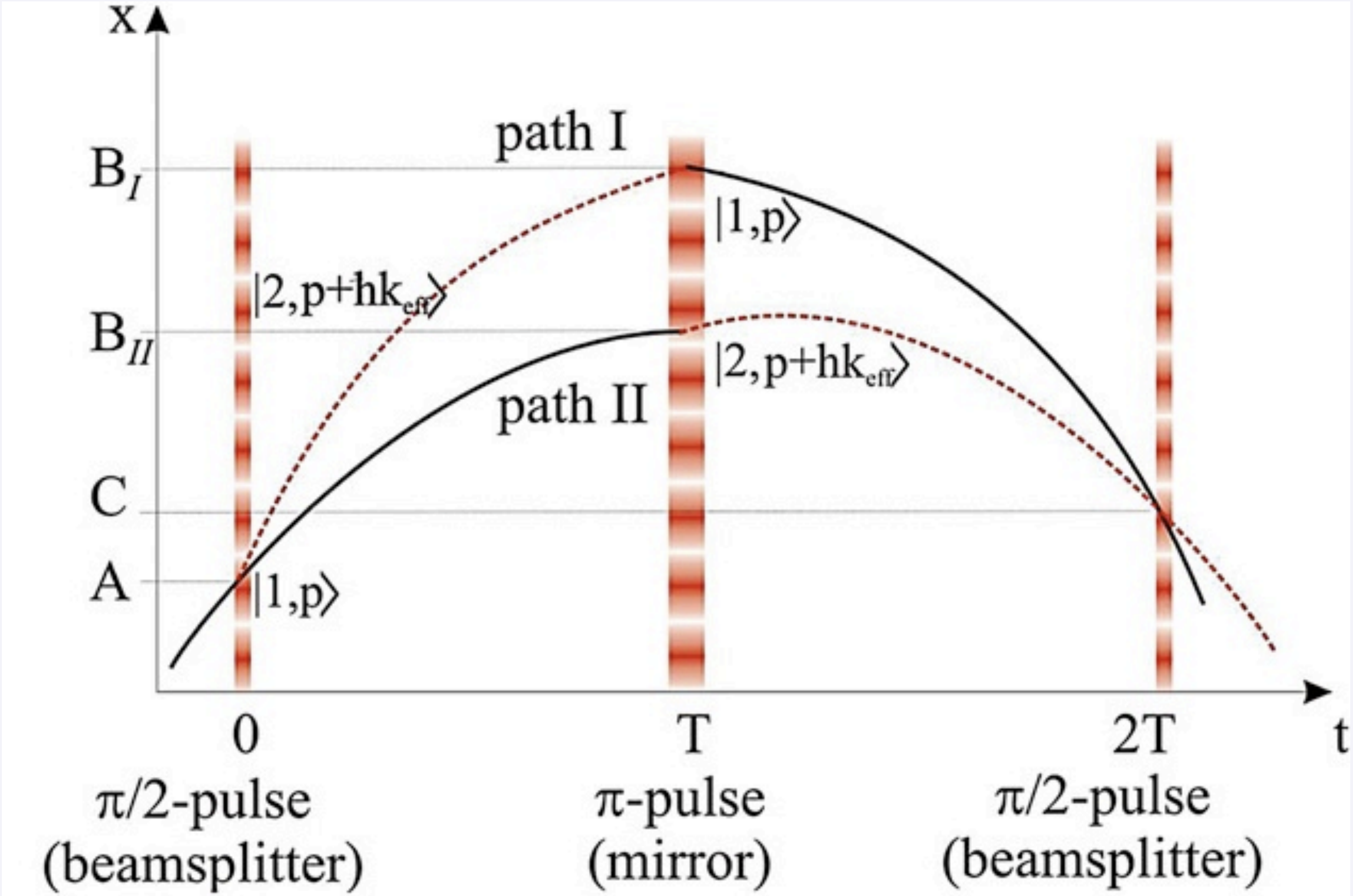
Triple velocity selection



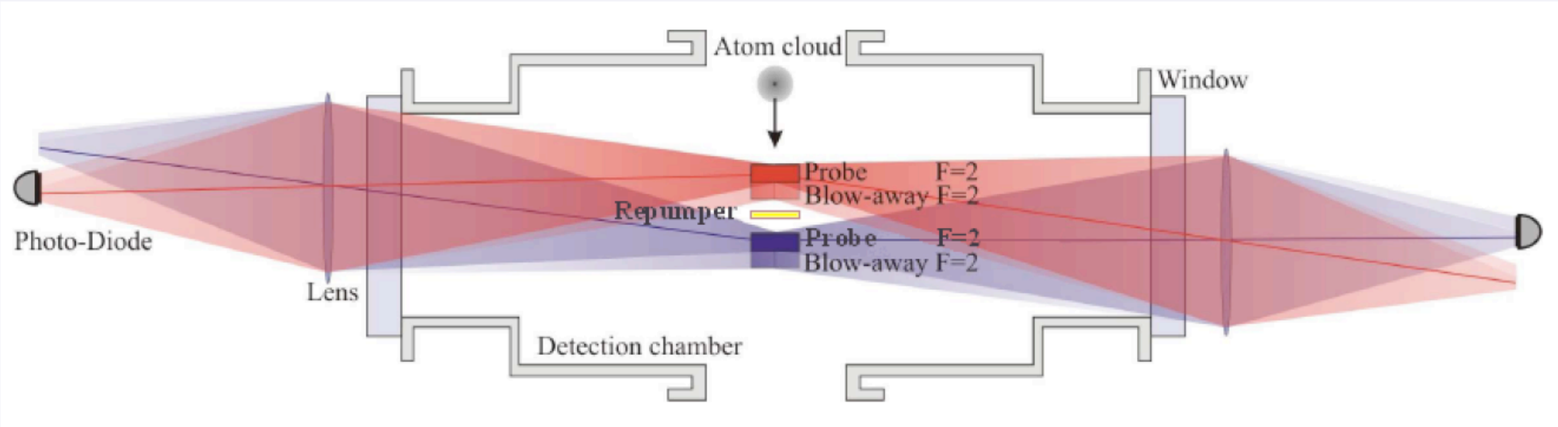
- Goal: reduce background of thermal atoms from off-resonant scattering during VS pulse

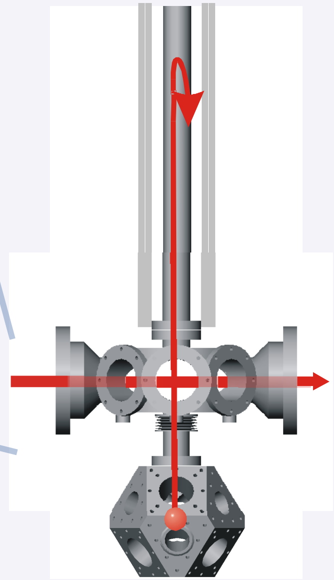
- Initial state after launch: F=2, unpolarized, 2.5 μK (3.5 v_{rec})
- Raman + blow-away pulses
- Final state: F=1, m_F=0, $\Delta v_z = v_{rec}/3$

Raman interferometry

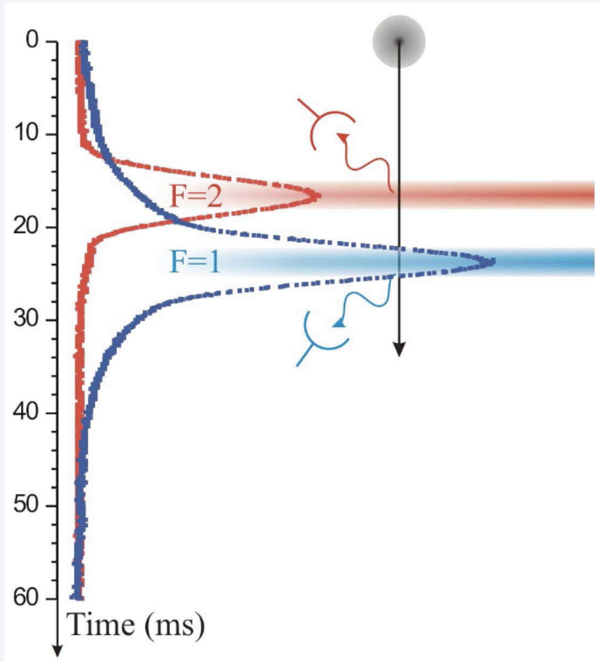


Detection

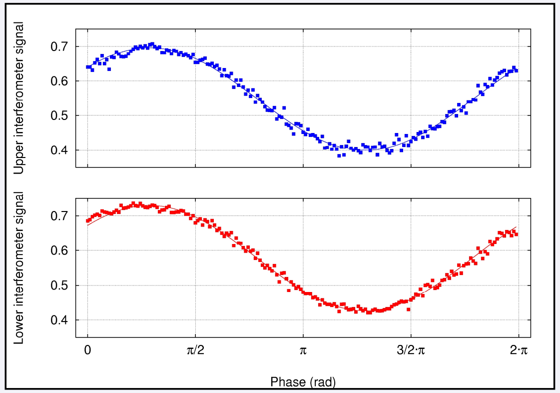




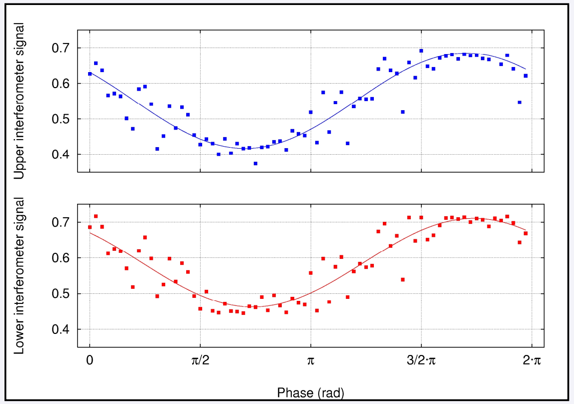
- In upper chamber, atoms interact with two horizontal laser beams resonant with the F=2—>F′=3 transition
  - rectangular shape, 15 mm width 4 mm height
  - intensity ~3.5 I_S
  - retro-reflected in upper half (blow-away in lower half)
- Additional F=1—>F′=2 laser beam in the middle to repump atoms in F=2
  - upper (lower) detector counts atom in F=2 (F=1)
- Fluorescence collected on two independent photodiodes
  - solid angle ~0.01 sterad
  - transimpedance 1 GOhm, conversion ~5 μV/atom



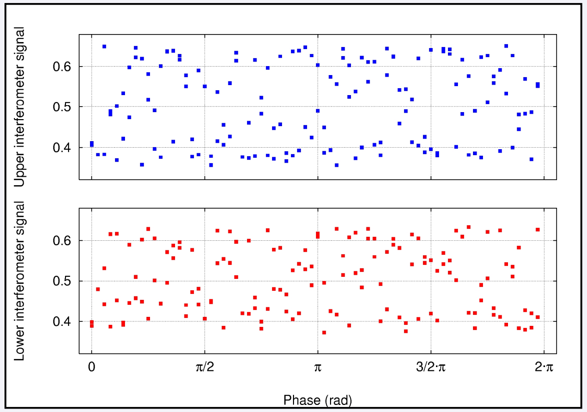
Gravity gradiometer



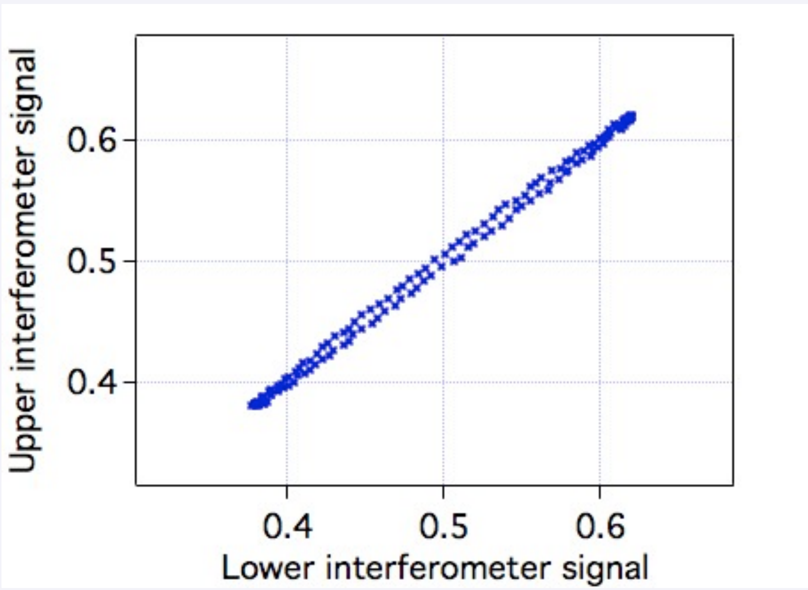
T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot



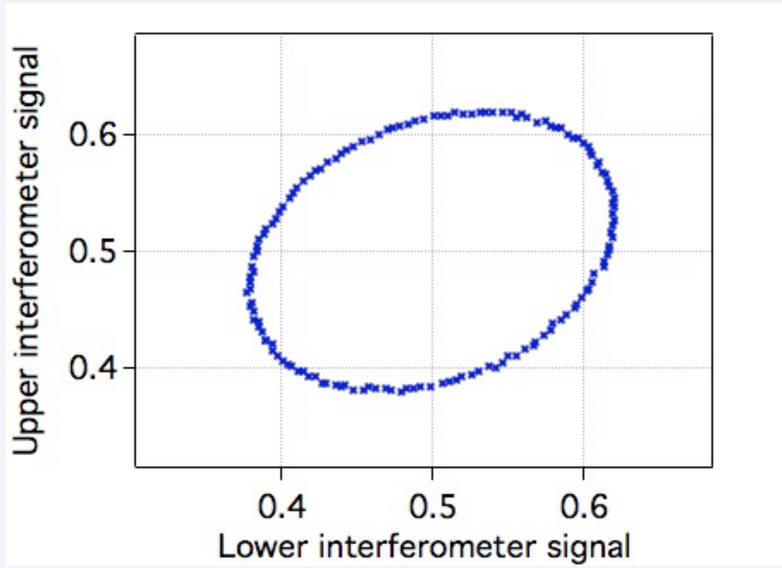
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot



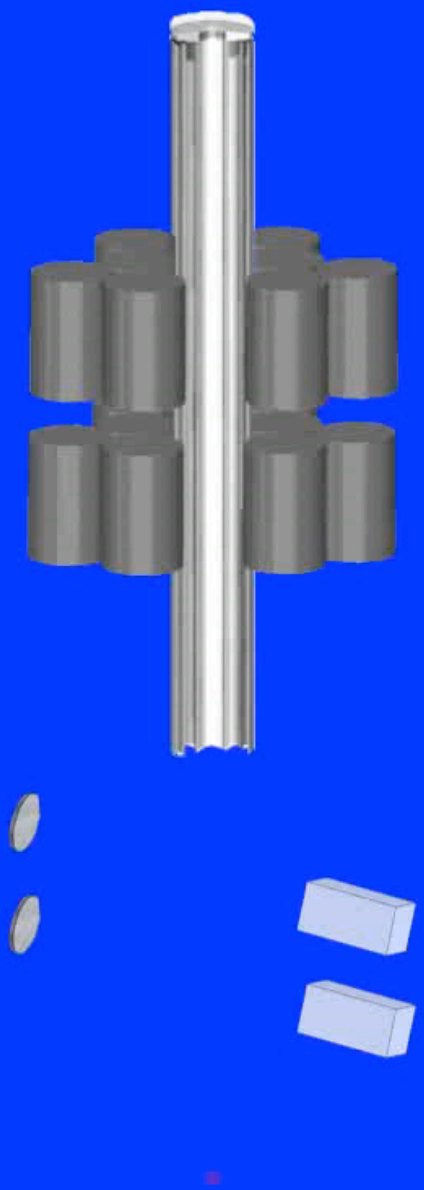
T=150 ms
resol. $= 3.2 \times 10^{-8}$g/shot

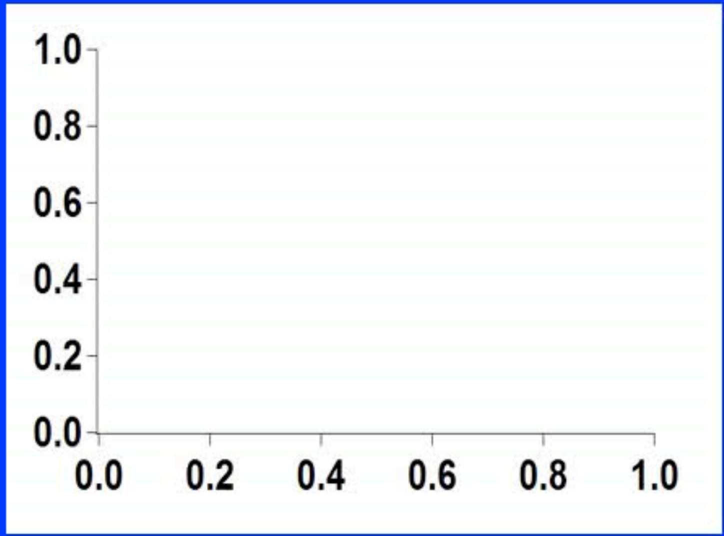


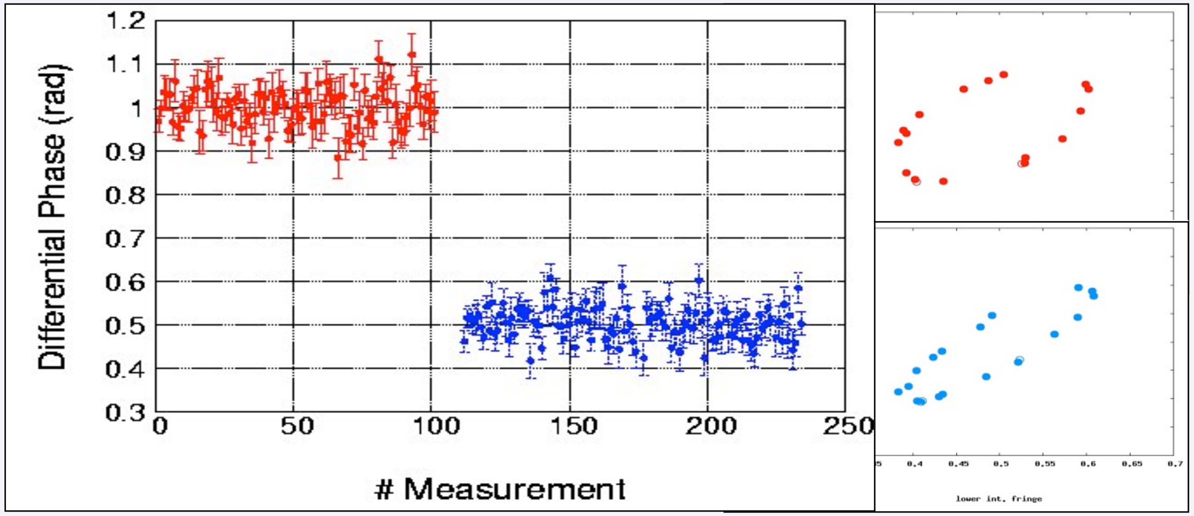
$$\Delta\Phi = k_e g T^2$$



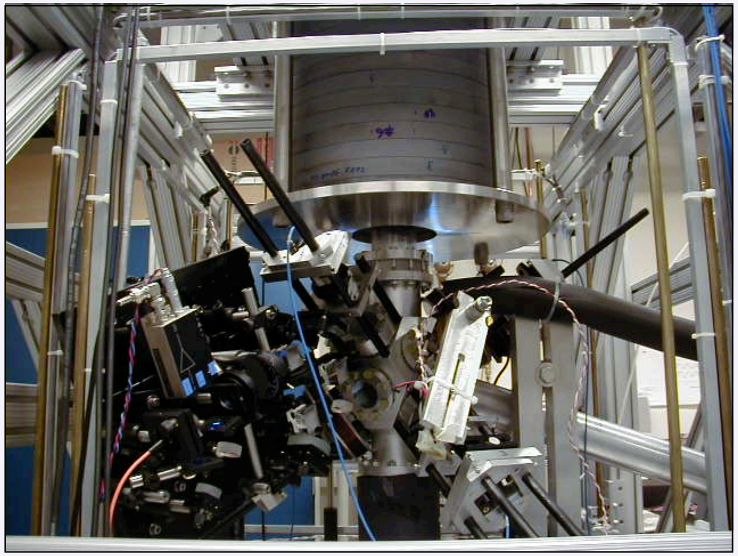
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

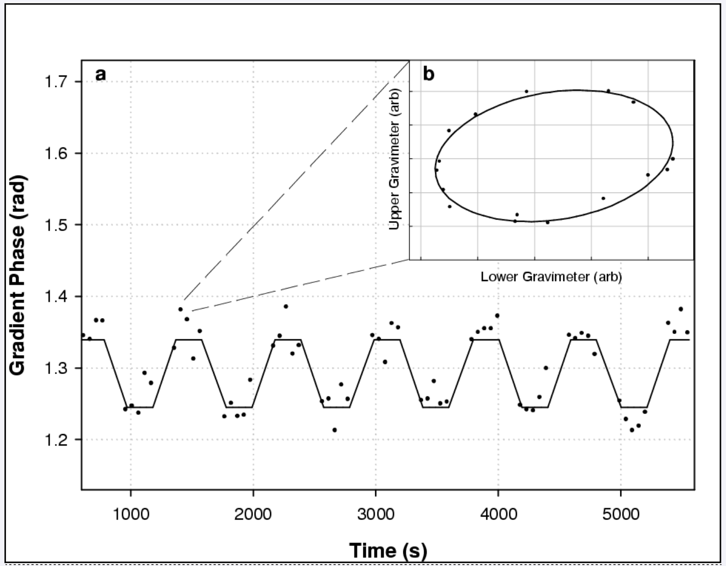



1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

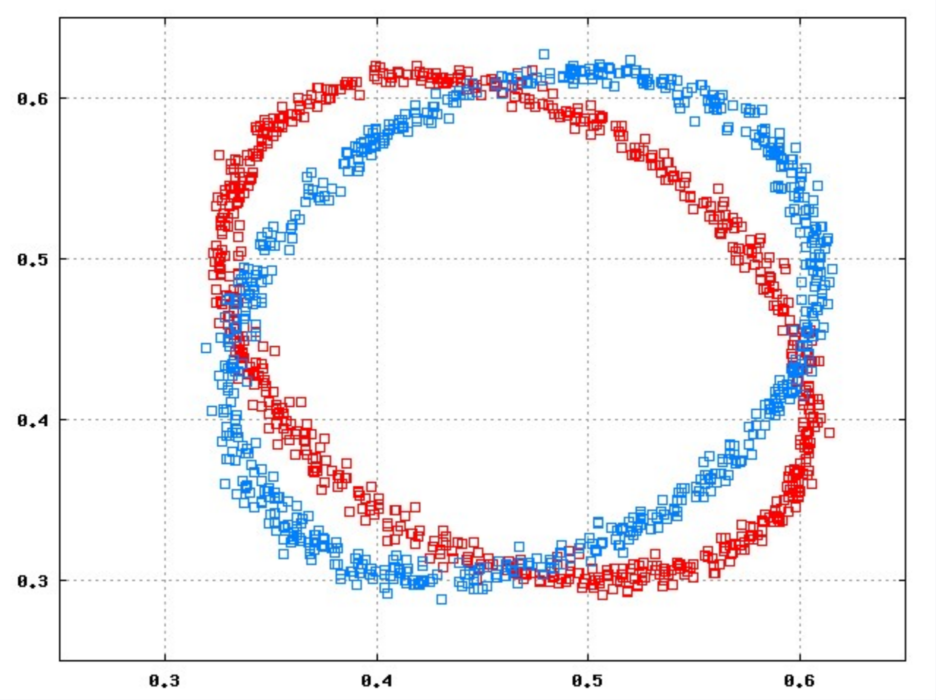


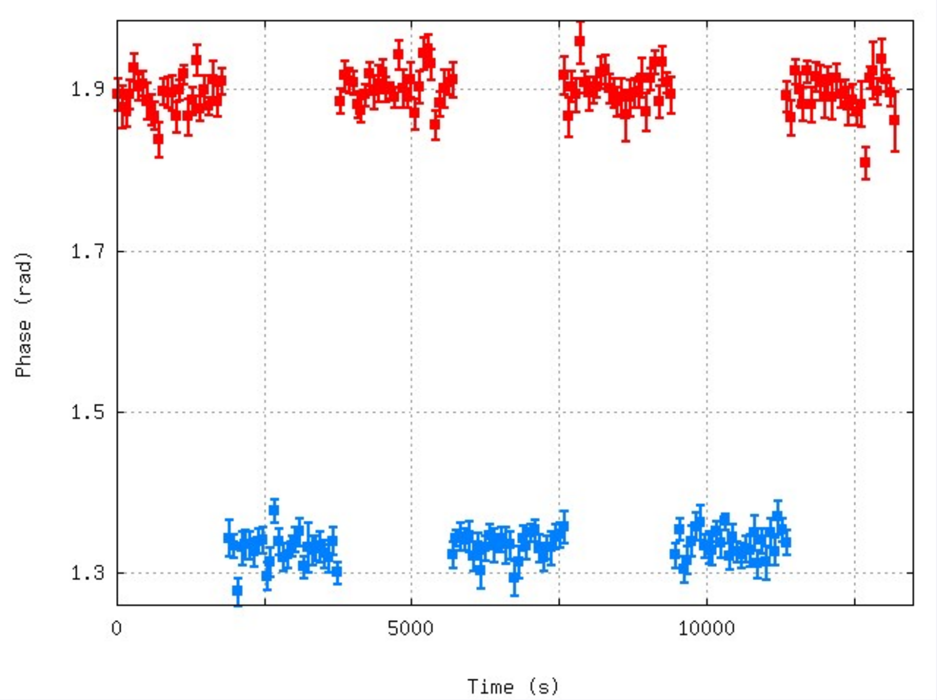
A. Bertoldi G.Lamporesi , L. Cacciapuoti, M. deAngelis, M.Fattori, T.Petelski, A. Peters, M. Prevedelli, J. Stuhler, G.M. Tino, *Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G*, Eur. Phys. J. D 40, 271 (2006)





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 Results from MAGIA

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

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

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

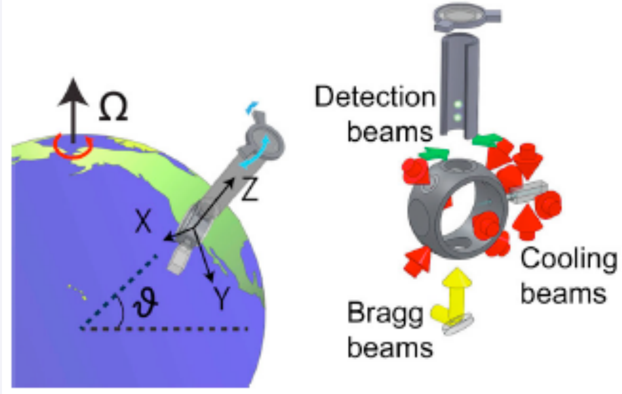
- Sensitivity
  - 15-fold improvement of the instrument sensitivity from 2008 to 2013
  - integration time for the target 100 ppm reduced by more than a factor 200
- Accuracy
  - systematic uncertainty reduced by a factor ~10 since 2008, mostly due to
    - better characterization of source masses
    - control & mitigation of Coriolis acceleration
    - excellent control of atomic trajectories
- Data analysis
  - we 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 are compared with a Montecarlo simulation

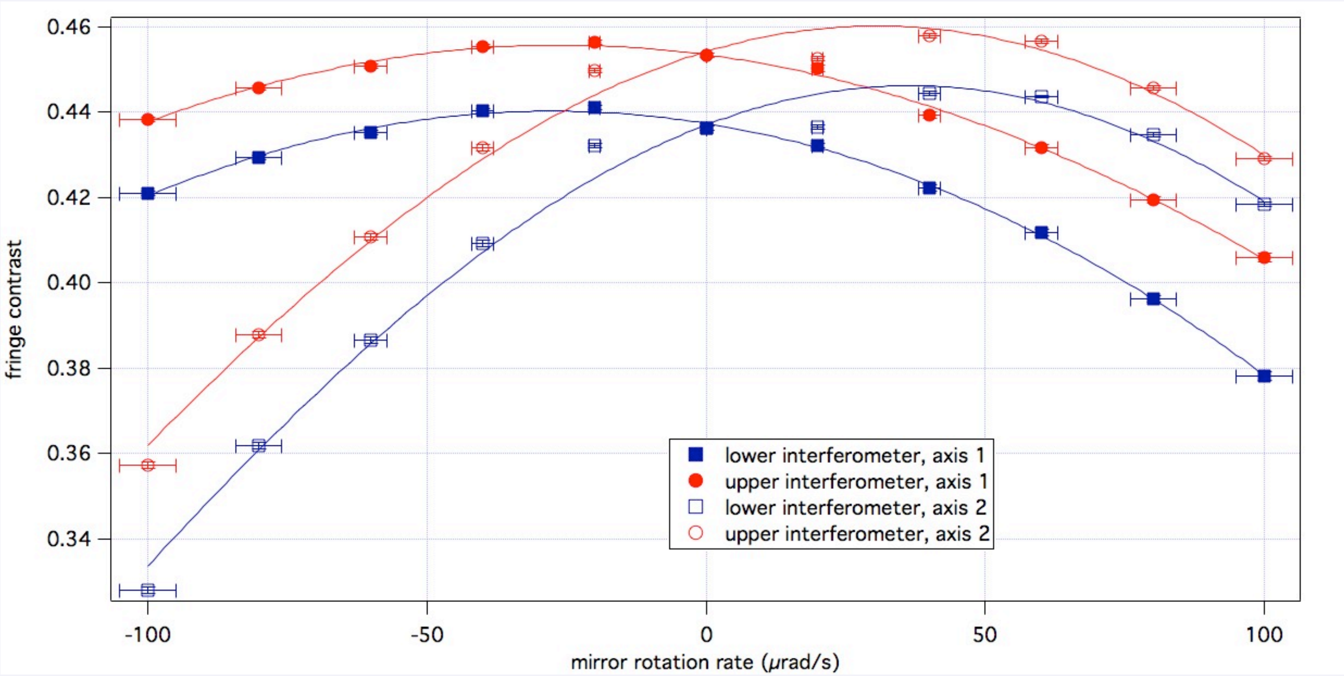
Improving the sensitivity

- 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
- ...

Coriolis effect compensation

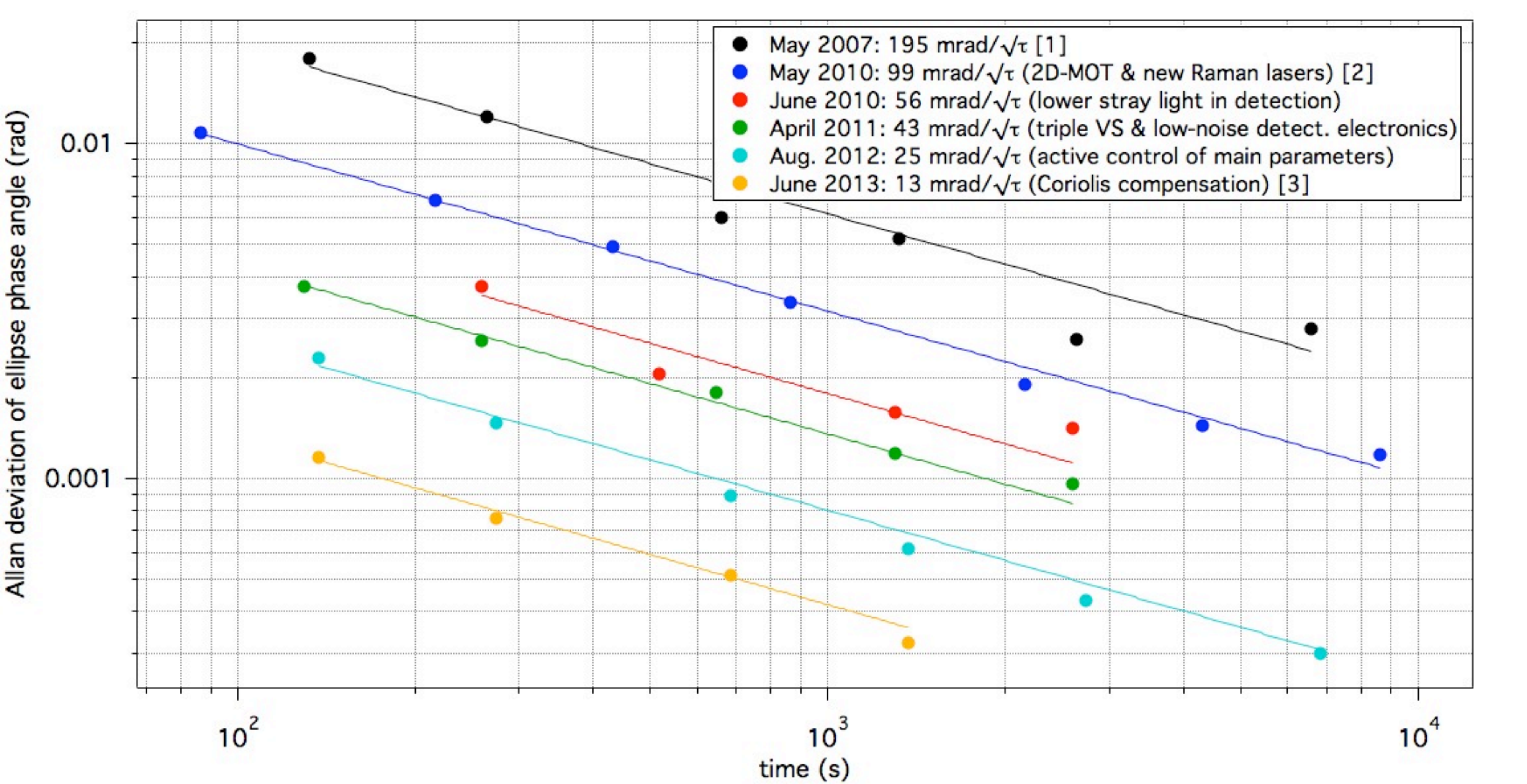
- Tip-tilt mirror steering the retro-reflected Raman beam to compensate for the Earth rotation
- Already shown to improve contrast in AI with LMT beam splitters
- In MAGIA, contrast drop due to Coriolis is minimal, but still detectable thanks to the large SNR





J. M. Hogan et al., Proc. Intern. School of Physics “Enrico Fermi” CLXVIII, 411 (2009)
S.-Y. Lan et al., PRL 108, 090402 (2012)
F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)

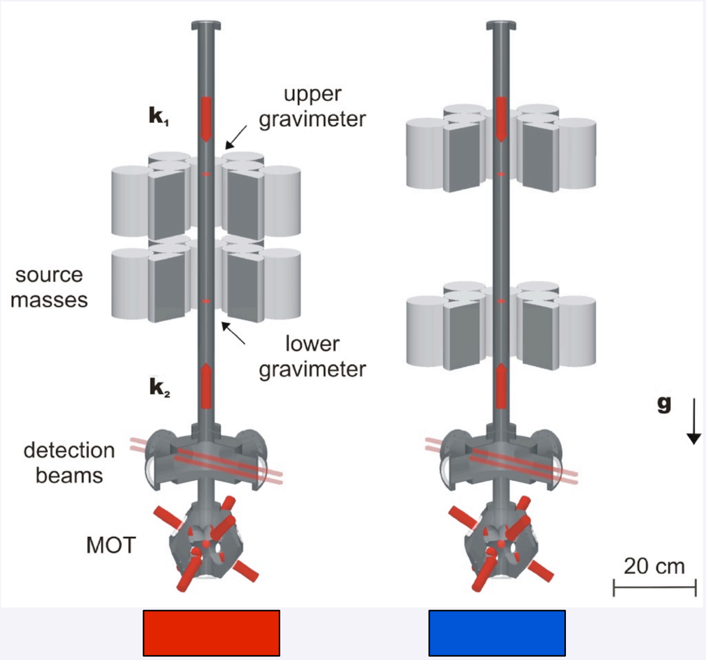
MAGIA: increasing sensitivity



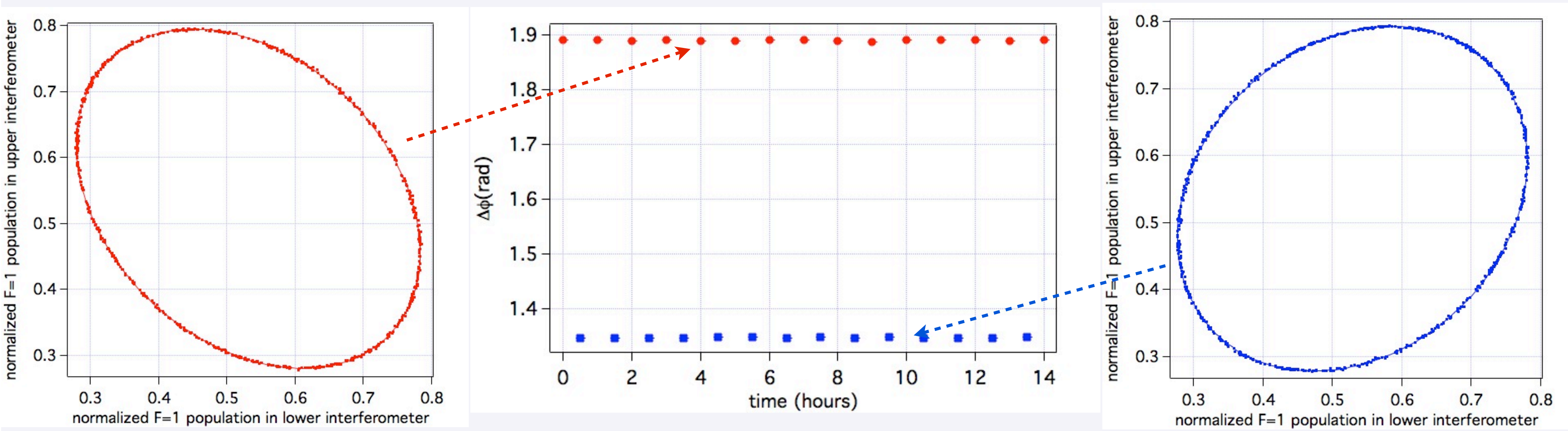
Current sensitivity to differential acceleration: 3×10^{-9} g @ 1s (=QPN for 4×10^5 atoms)

[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

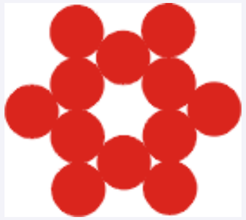
- Precise characterization of source masses (weight, density homogeneity, shape, position)
- Precise characterization of atomic trajectories
- Calibration of relative detection efficiency in the two interferometer outputs
- Removal of k-independent biases (Zeeman shift)
- Removal of k-dependent biases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

Source masses and support

INERMET 180K (95% W, 3.5% Ni, 1.5% Cu)
Hot isostatic pressing (1200 ^{o}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

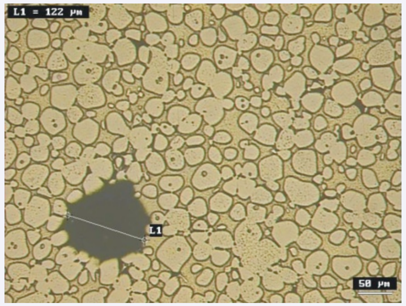
24 cylinders
External radius = 5 cm
Height = 15 cm
Cylinder mass = 20 kg
Total mass ~ 500 kg

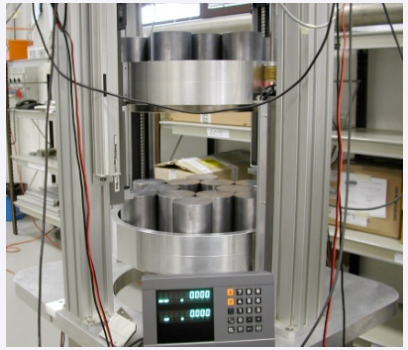


Hot Isostatic Pressing at 1200 C° and 1500 atm

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

Oscillation of cylinders on air cushion reveal radial inhomogeneities



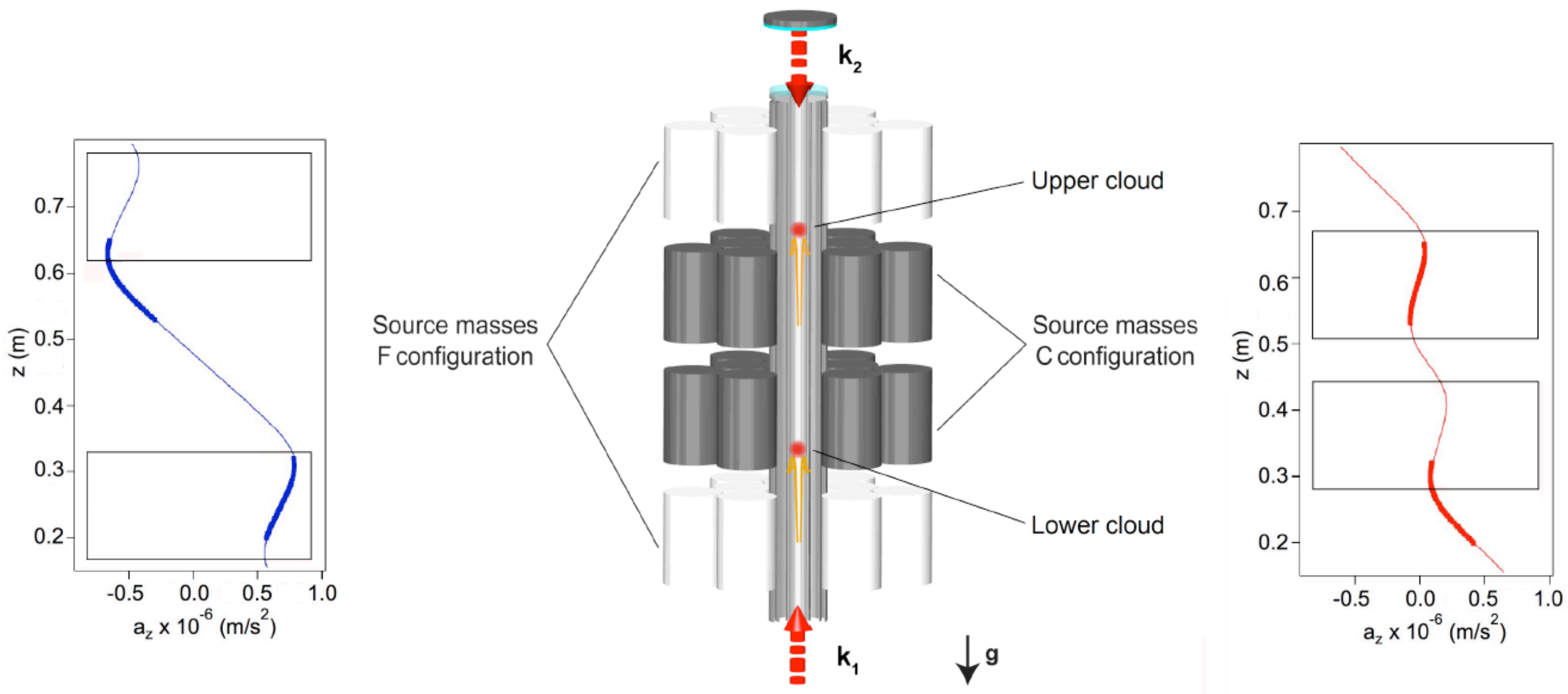


In collaboration with IMGC, Torino

In collaboration with LNF, Frascati

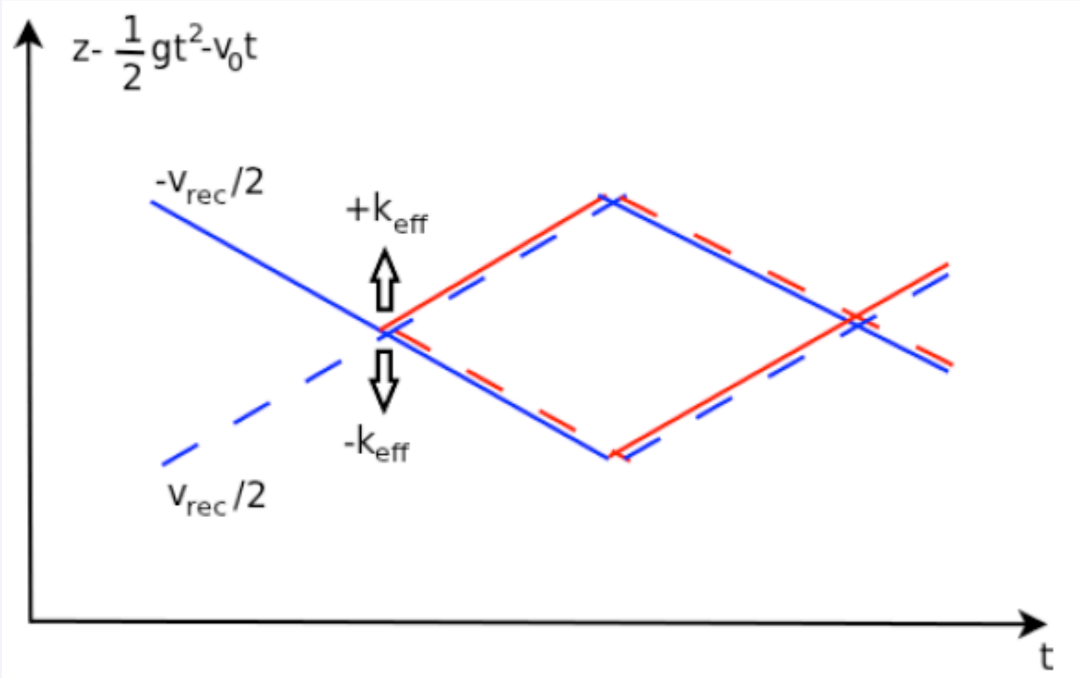
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G,* **Rev. Scient. Instr. 78, 075109 (2007)**

Optimized atomic trajectories



- In the presence of Earth's gravity gradient, the vertical position of the atoms would convert into phase shift of the atom interferometer as ~1 rad/m
- The high density of tungsten allows to compensate for the Earth's gravity gradient locally
- We first fix the C masses configuration, and vary the clouds apogees until the phase shift is stationary; then we adjust the F masses configuration to have a stationary phase again

Use of k-reversal to improve systematics



- Interferometer phase is affected by systematic shifts, which can be sorted into
  - k_{eff}-dependent: Coriolis (dominating), wave-front distortions, two-photon light shift (negligible in our case)
  - k_{eff}-independent: magnetic gradients, one-photon light shift
- Alternating measurements with k_{eff} directed upward and downwards allows to cancel out systematic errors from k_{eff}-independent terms; e.g. tiny changes in magnetic fields when moving the source masses
- Need good overlap of trajectories for direct-k_{eff} and reverse-k_{eff} interferometers

A. Louchet-Chauvet et al., *The influence of transverse motion within an atomic gravimeter,* **New J. Phys. 13, 065025 (2011)**

Measurement protocol

- Ellipse phase is the sum of gravitationally induced phase, the k_{eff}-independent spurious shift and the k_{eff}-dependent spurious phase shift:

$$\begin{cases} \Phi^{dir} = \Delta + \alpha + \beta \\ \Phi^{rev} = -\Delta + \alpha - \beta \end{cases}$$

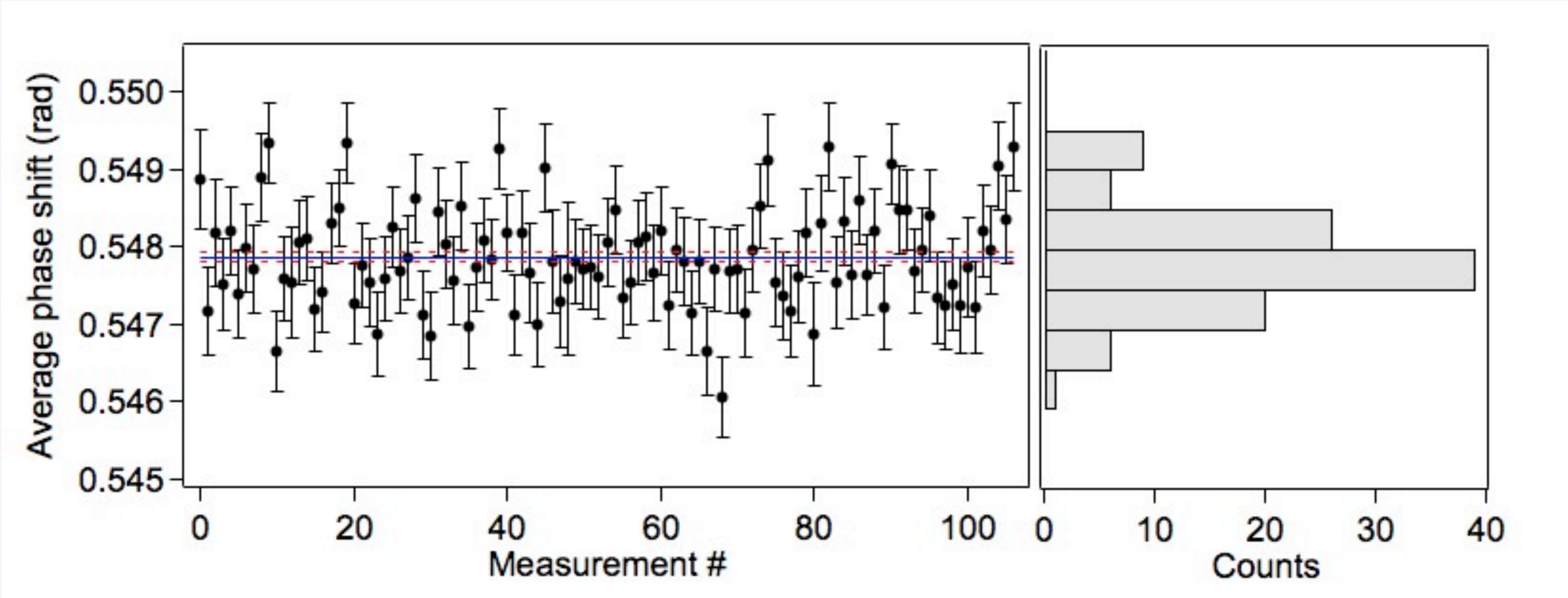
- For each configuration of source masses, we acquire two (interleaved) ellipses with direct and reversed k_{eff}
- We combine the four ellipse angles
  - the differential phase shift contains the gravitational effect of source masses plus twice the Close-Far change of k_{eff}-dependent terms

$$\Delta\Phi_{tot} = \Phi_C^{dir} - \Phi_F^{dir} - (\Phi_C^{rev} - \Phi_F^{rev}) = 2(\Delta_C - \Delta_F) + 2(\beta_C - \beta_F)$$

  - the other linear combination provides a measurement of twice the Close-Far change of independent phase shift

$$\Xi = \Phi_C^{dir} + \Phi_C^{rev} - (\Phi_F^{rev} + \Phi_F^{rev}) = 2(\alpha_C - \alpha_F)$$

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 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.

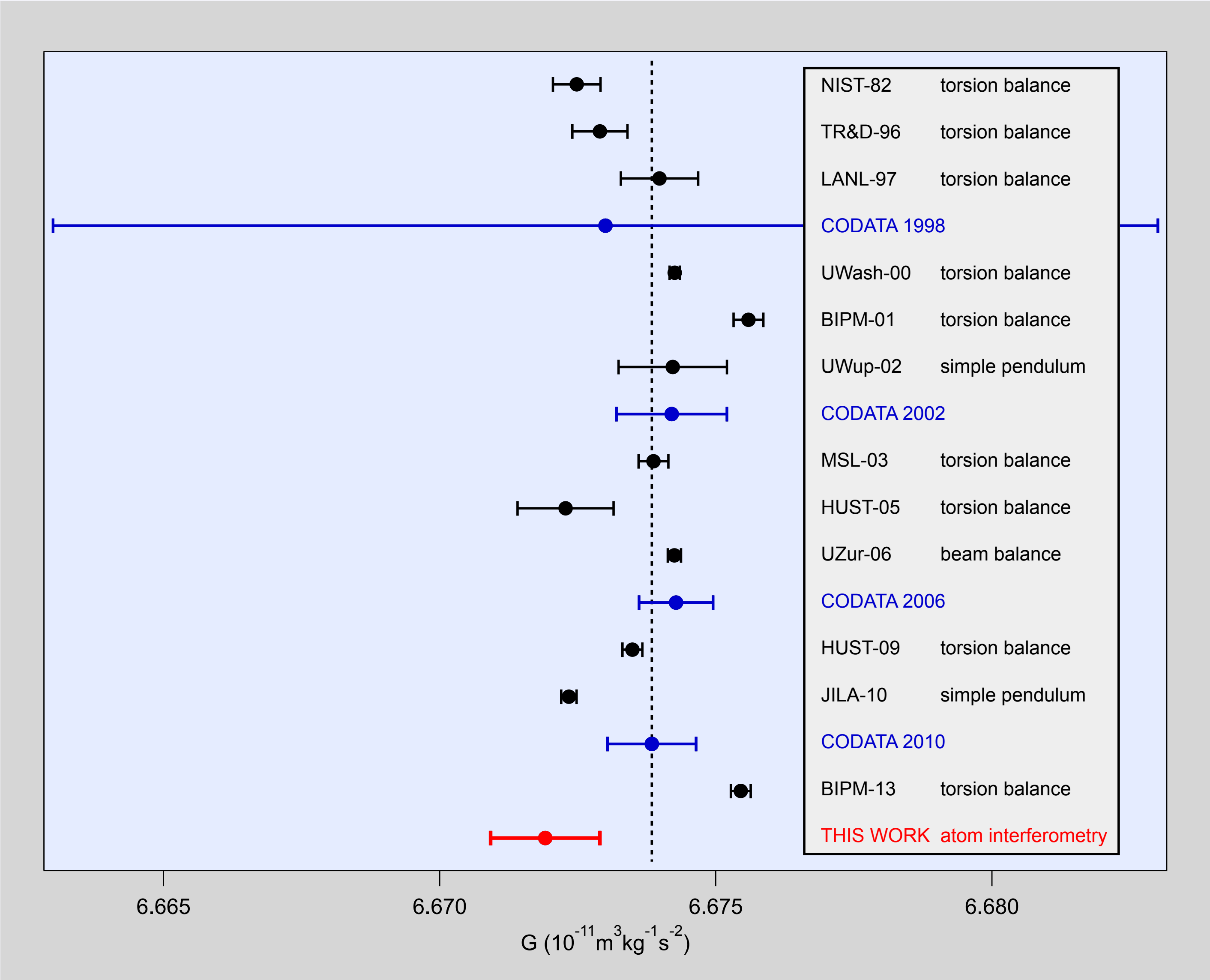
The atom interferometer is realized using light pulses to stimulate

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

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



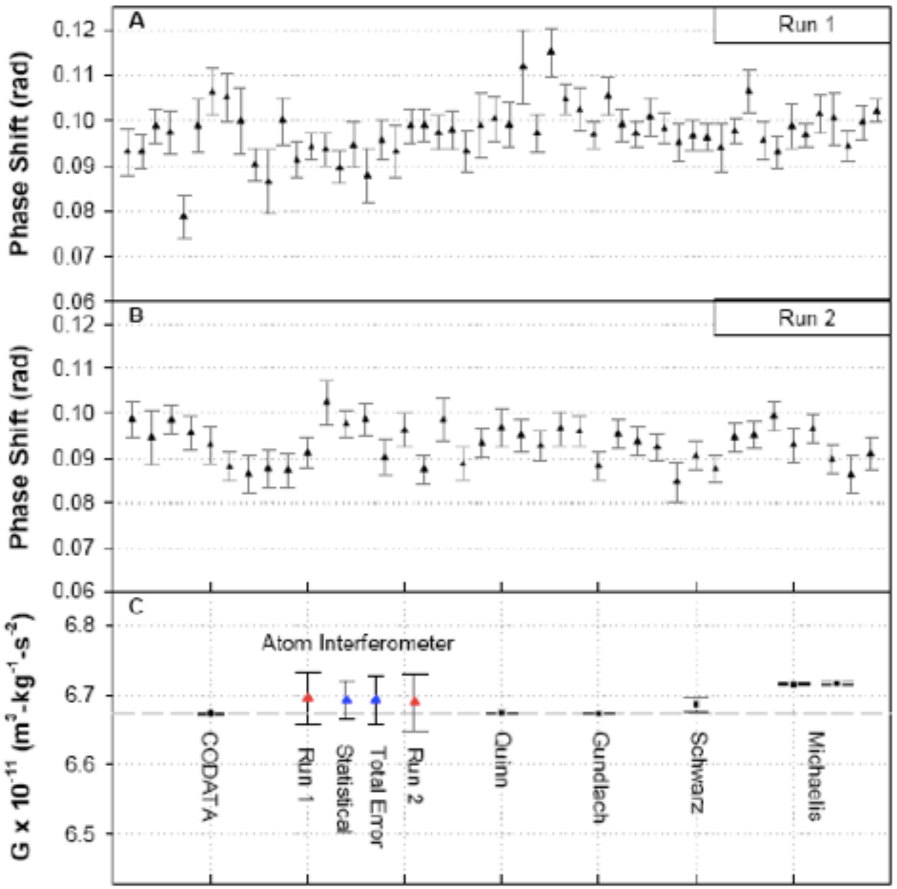
G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms
NATURE vol. 510, p. 518 (2014)

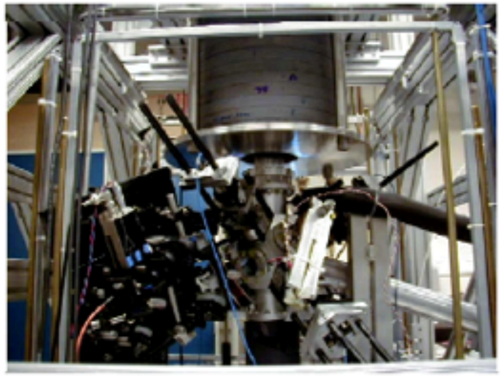
MAGIA error budget

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' Theme Issue of 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

Fixler, et al., Science, 2007.

Project of Measuring G with AI in HUST

HUST: Huazhong University of Science & Technology

Source masses：

24×10Kg spheres

Gravitational signal：

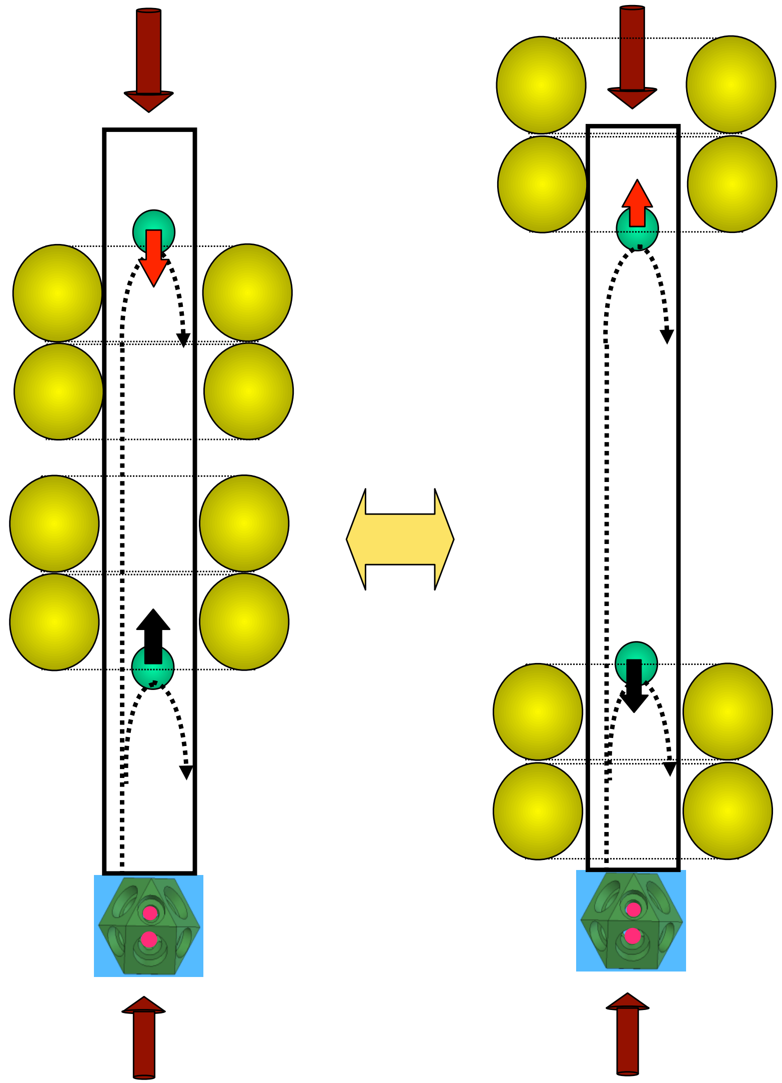
$$\Delta g = 120\mu Gal$$

Differential gravity sensitivity：

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

Project target

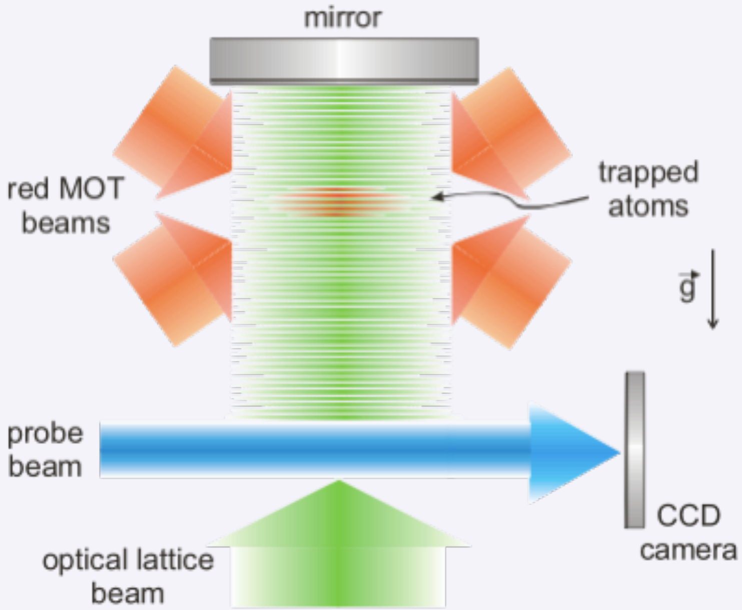
$$\delta G / G \sim 100\text{ppm}$$

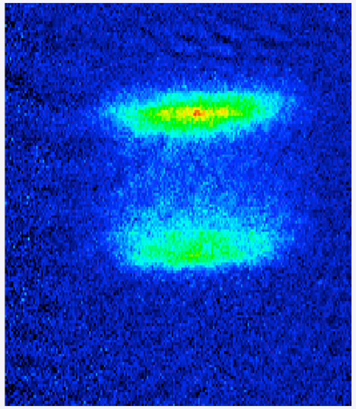


Future prospects to improve the measurement of G with atom interferometry

- 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





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

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

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

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)

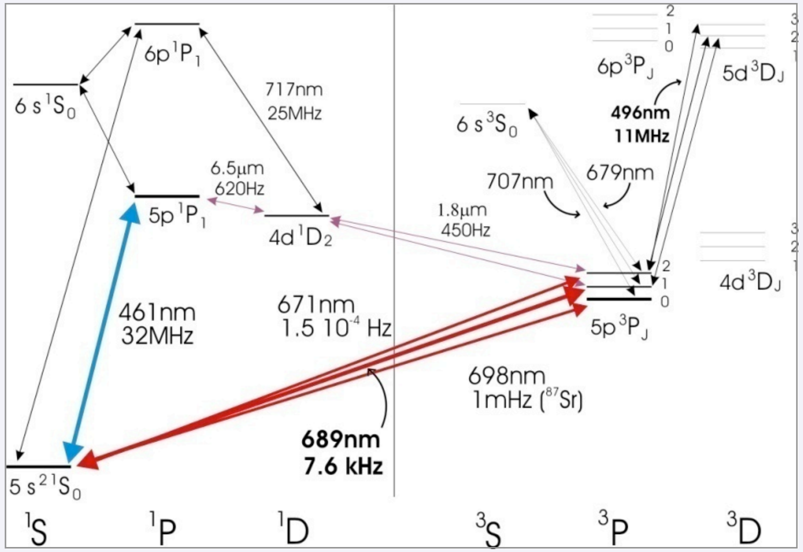
Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

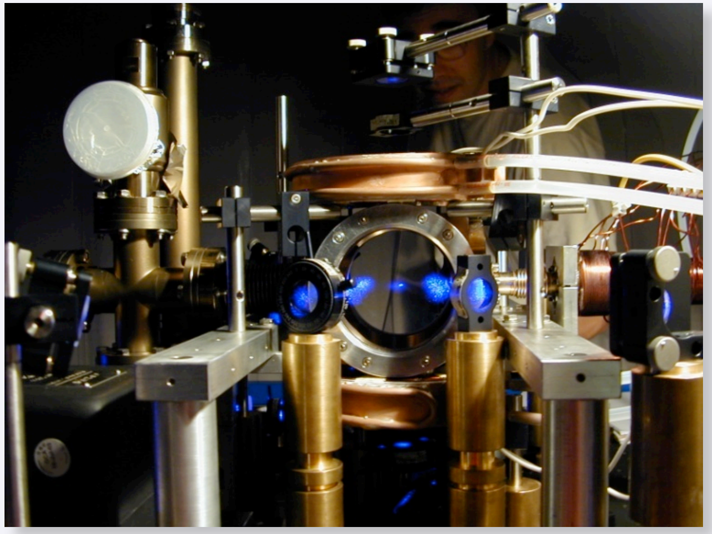
- **Small observed size of Einstein cosmological constant**

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

- **Experimental challenge**

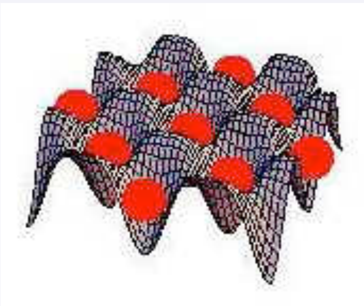
Ultracold Sr - Experiments in Firenze

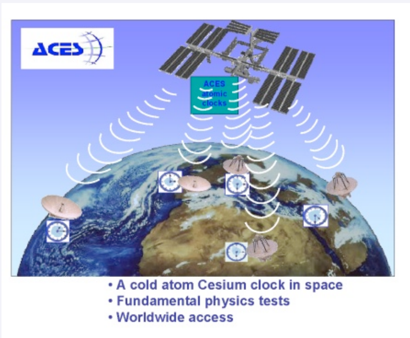


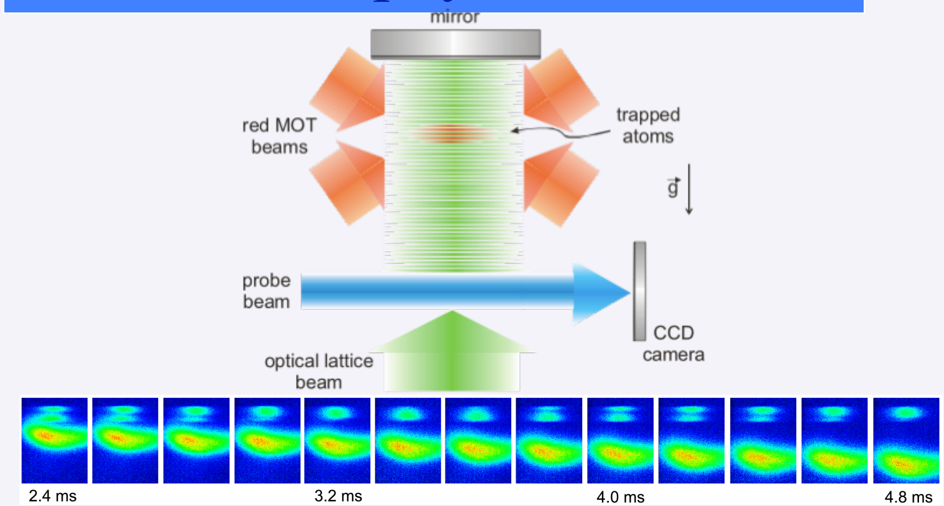


- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests





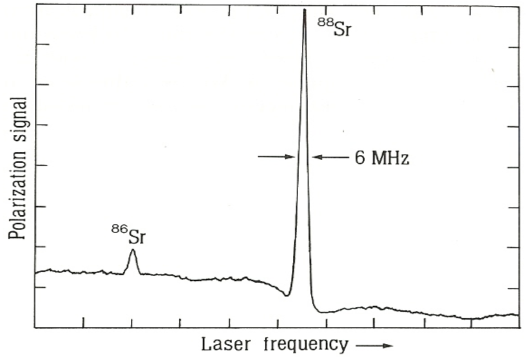


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

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

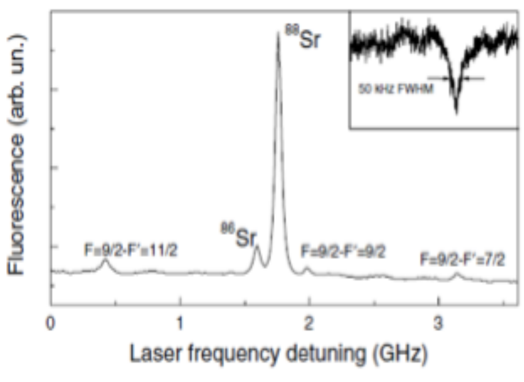
sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line



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

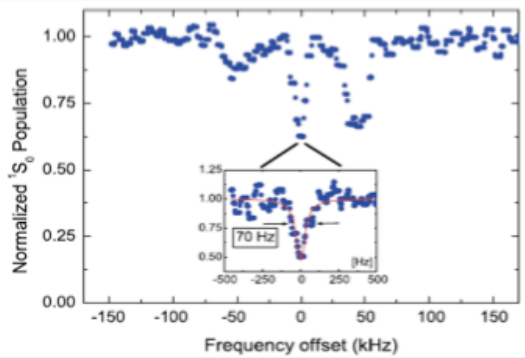
saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line



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

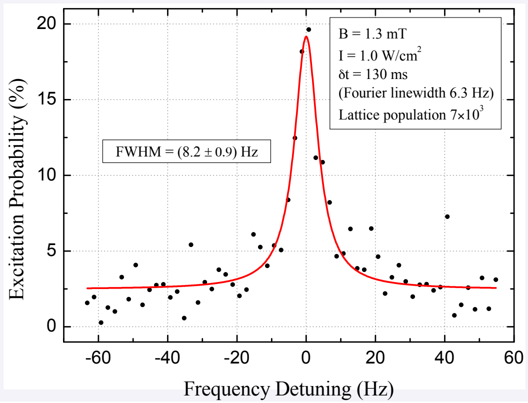
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



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

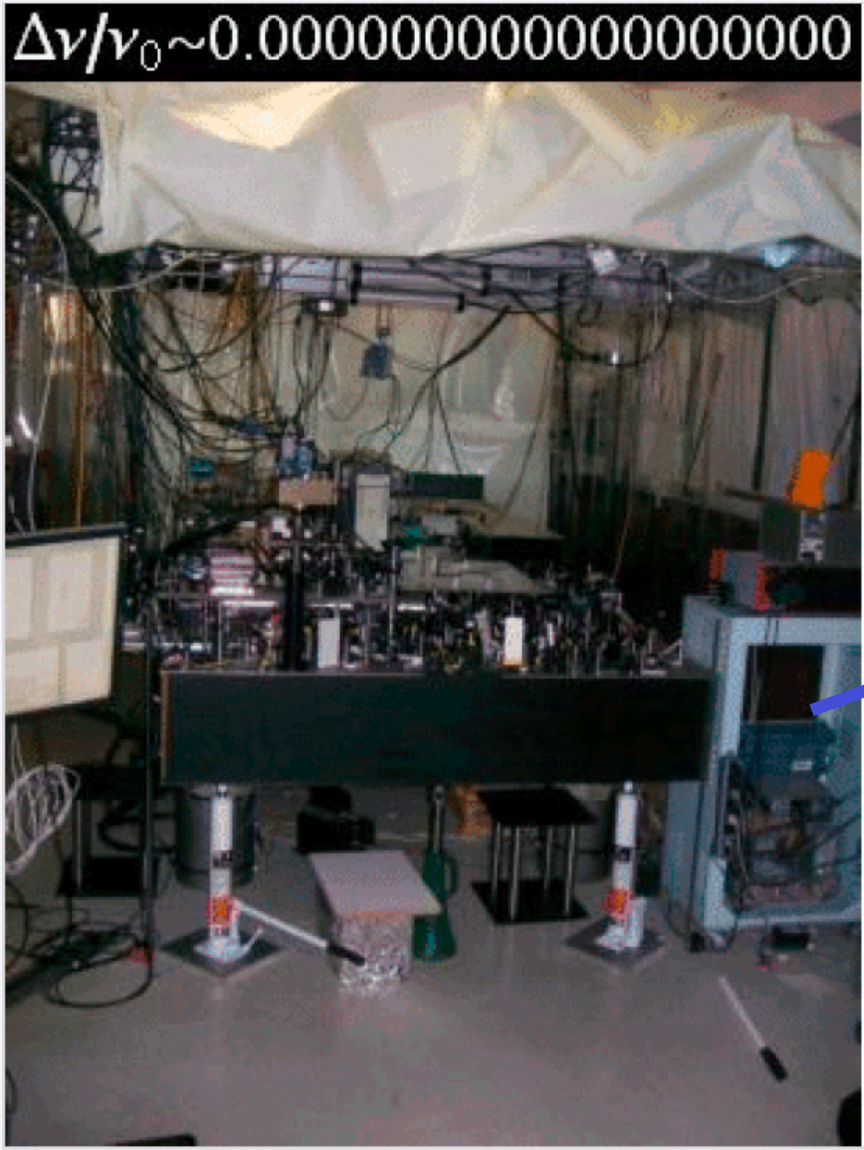
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line

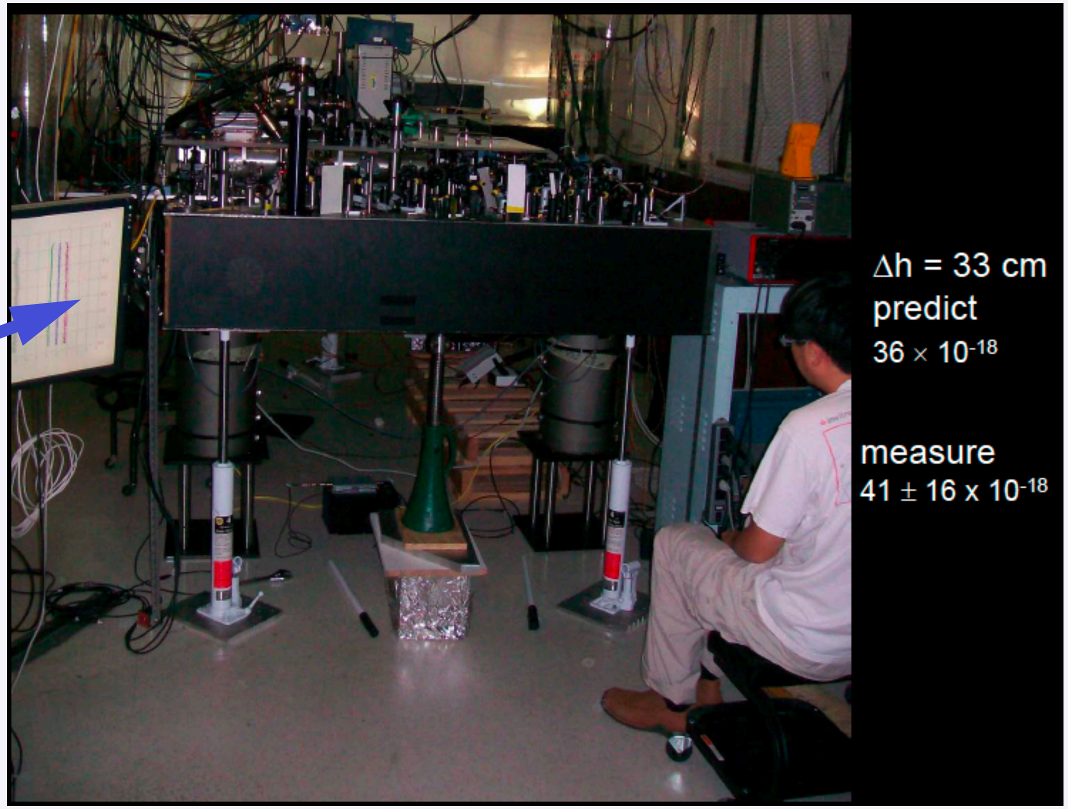


N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B (October 2014) DOI:10.1007/s00340-014-5932-9, arXiv:1409.4572v2

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

Measure gravitational red shift





"David J. Wineland - Nobel Lecture: Superposition, Entanglement, and Raising Schroedinger´s Cat". Nobelprize.org. 7 Feb 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/wineland-lecture.html

Measure gravitational red shift in the lab

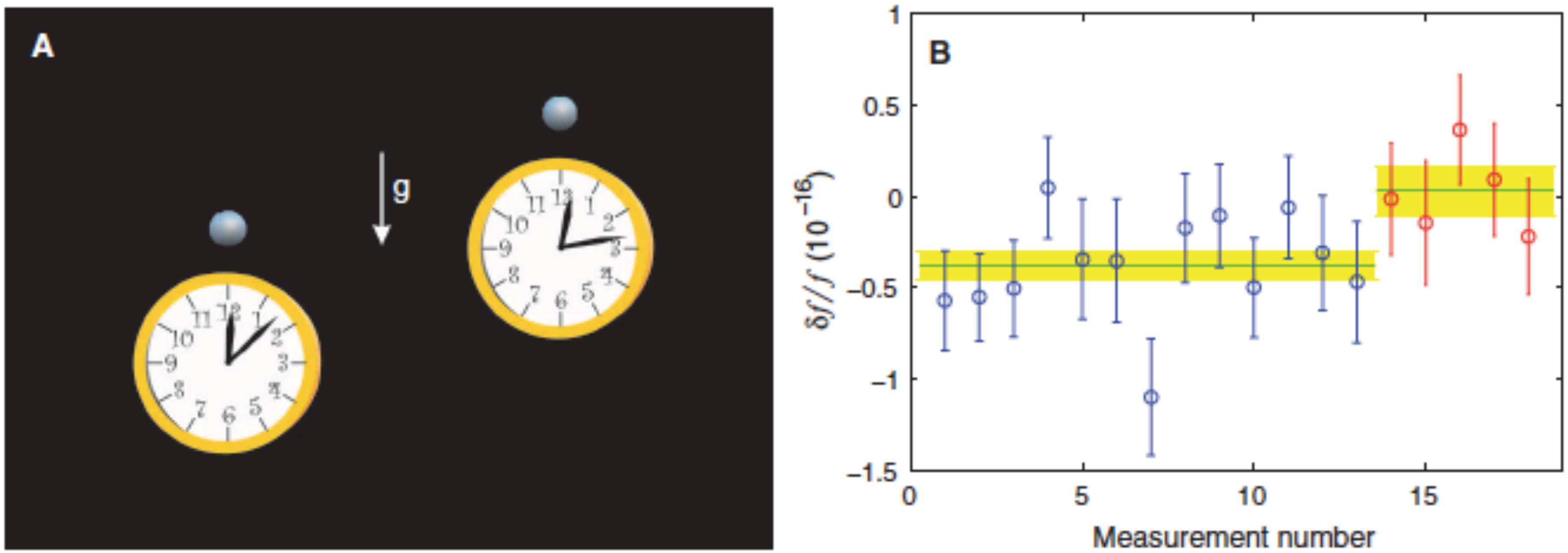


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg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

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

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) and University of Colorado Boulder, USA

Photo: © CNRS Photothèque/Christophe Lebedinsky

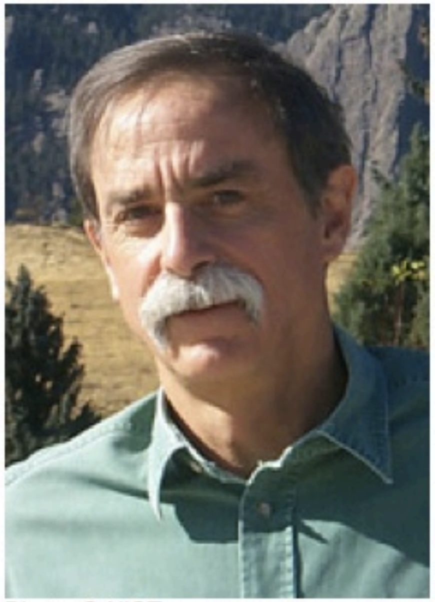


Photo: © NIST

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

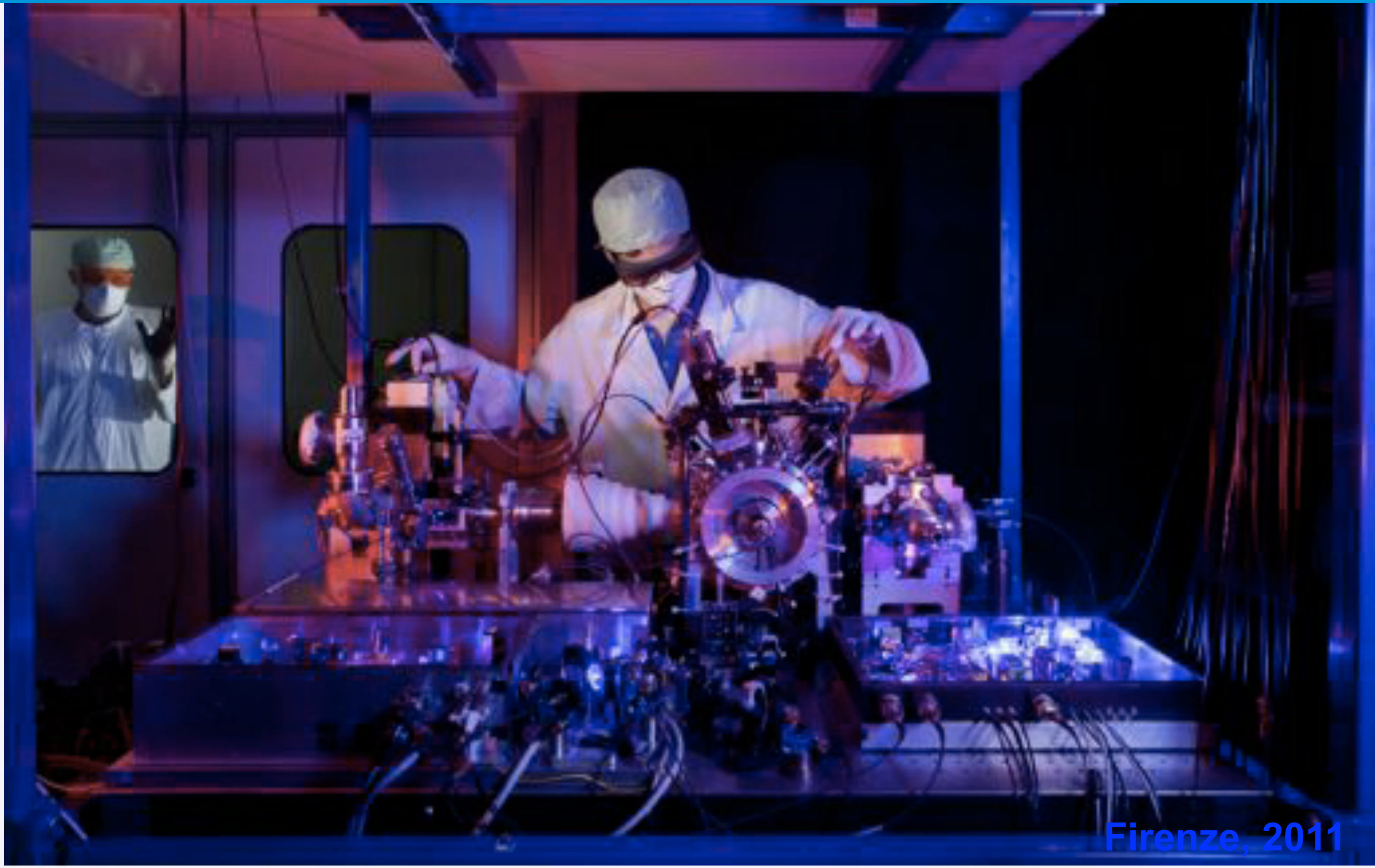
Serge Haroche   David J. Wineland

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.*

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 (October 2014) DOI: 10.1007/s00340-014-5932-9, arXiv:1409.4572v2

Laser cooling of ^{88}Sr

2000 ms:

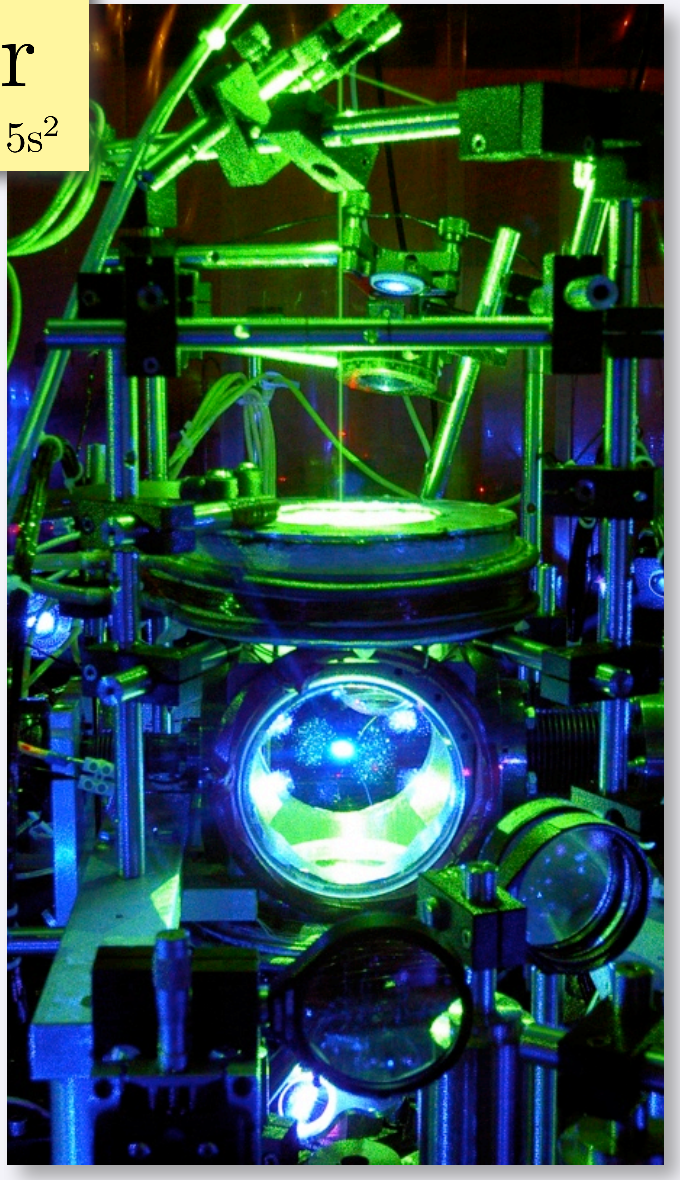
- 500 °C vapor from oven
- ↓
- Zeeman slower — Slow-down $a \sim 5 \times 10^5$ m/s^2
- ↓
- Blue MOT — $\lambda = 461$ nm (blue laser), $T \sim 1$ mK $\quad N \sim 5 \times 10^7$
- ↓

200 ms:

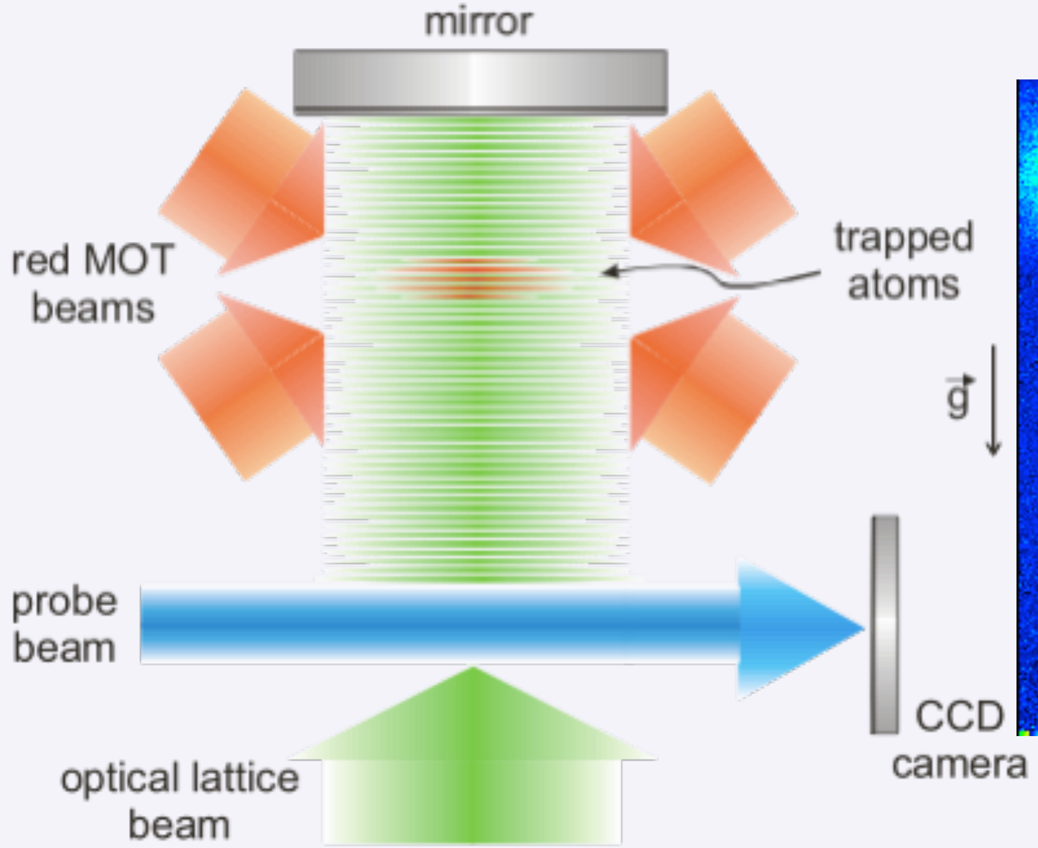
- Red MOT — $\lambda = 689$ nm (red laser), $T \sim 1\,\mu$K $\quad N \sim 2 \times 10^6$
- → Vertical optical lattice — $\lambda = 532$ nm (Nd:YVO_4 green laser), $T \sim 1\,\mu$K $\quad N \sim 10^5$

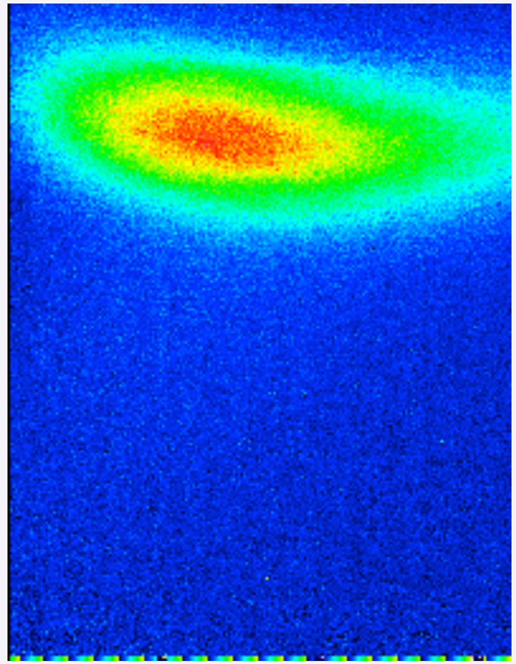
λ	T_R	T_D	I_s	a_{max}
461 nm	1 μK	760 μK	42 mW/cm^2	$10^5 \times g$
689 nm	460 nK	180 nK	3 μW/cm^2	$16 \times g$

88 38
Sr
[Kr]5s^2



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



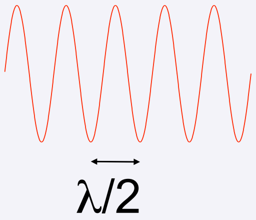


$$\nu = m\, g\, \lambda / 2\, h$$

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)**

Particle in a periodic potential: Bloch oscillations

periodic potential



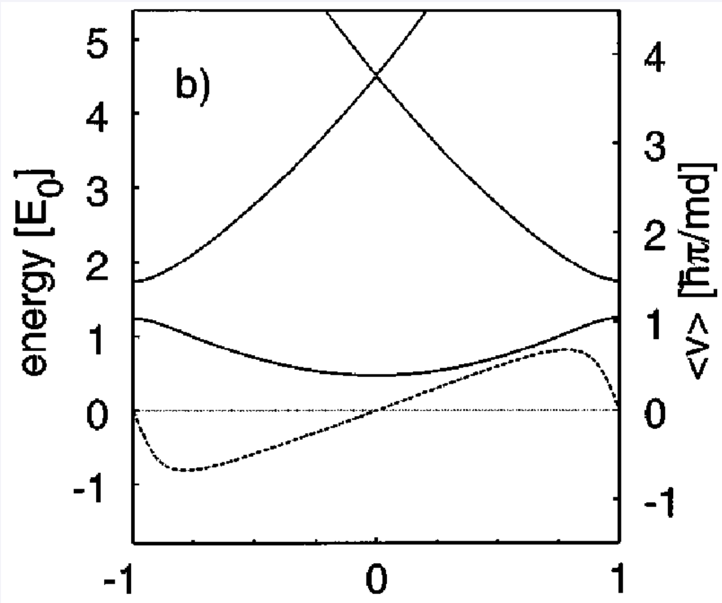
$V(z+\lambda/2) = V(z)$

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

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

Bloch's theorem

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



quasimomentum q [2π/λ]

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

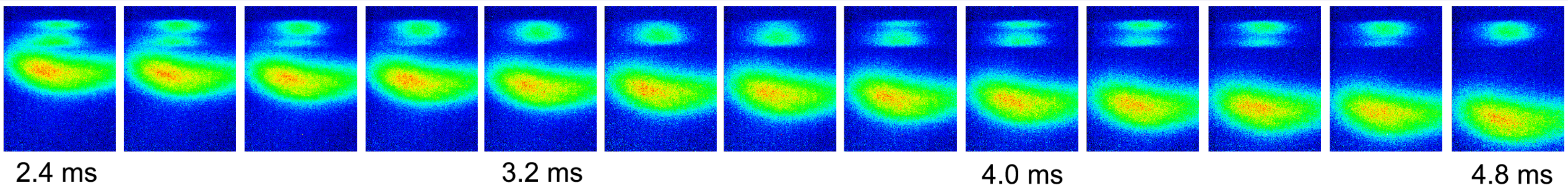
with a constant external force F

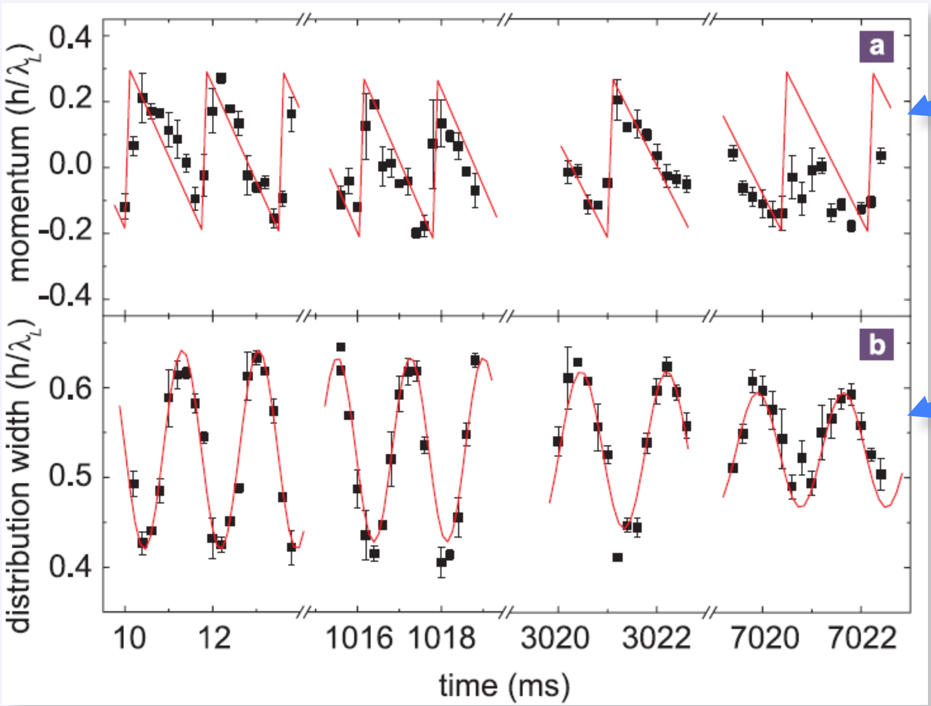
$$q(t) = q(0) + Ft/\hbar$$

Bloch oscillations

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

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency ν_B = 574.568(3) Hz

damping time τ = 12 s

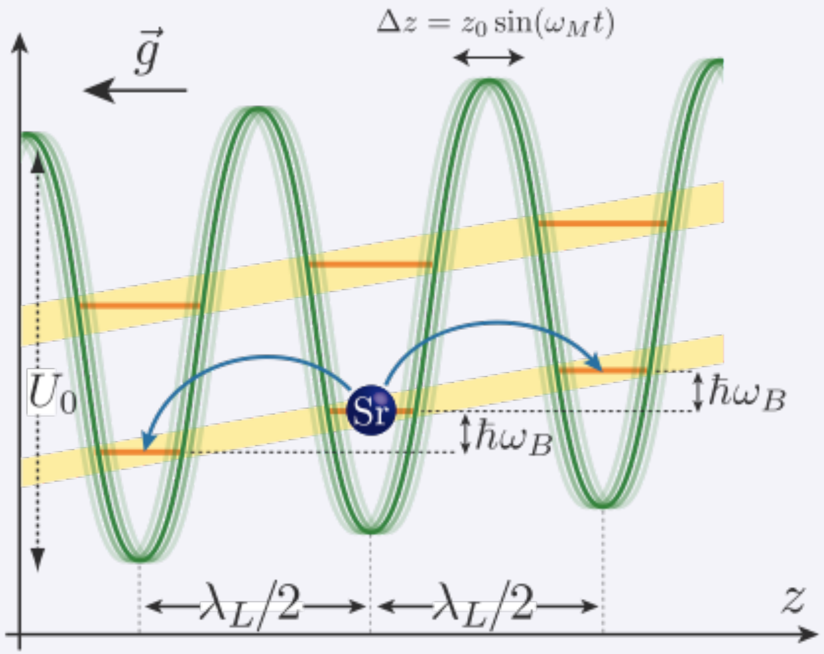
8000 photon recoils in 7s

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)**

Modulation of optical lattices

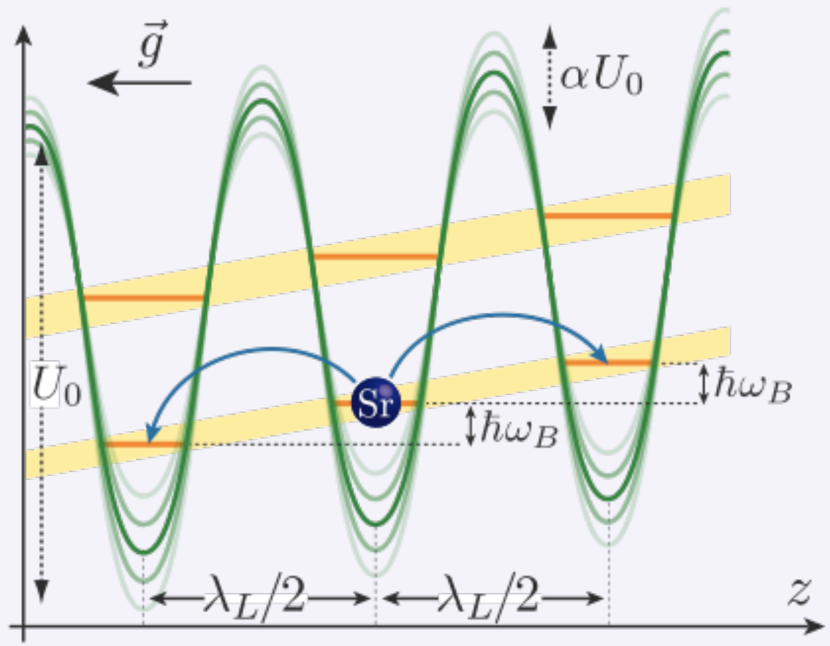
Phase modulation



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

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



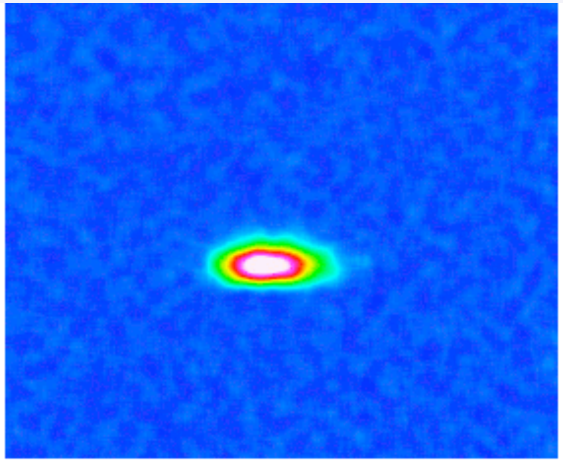
$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2}\cos(2k_L z)[1 + \alpha\,\sin(\omega_M t)] + mgz$$

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)**

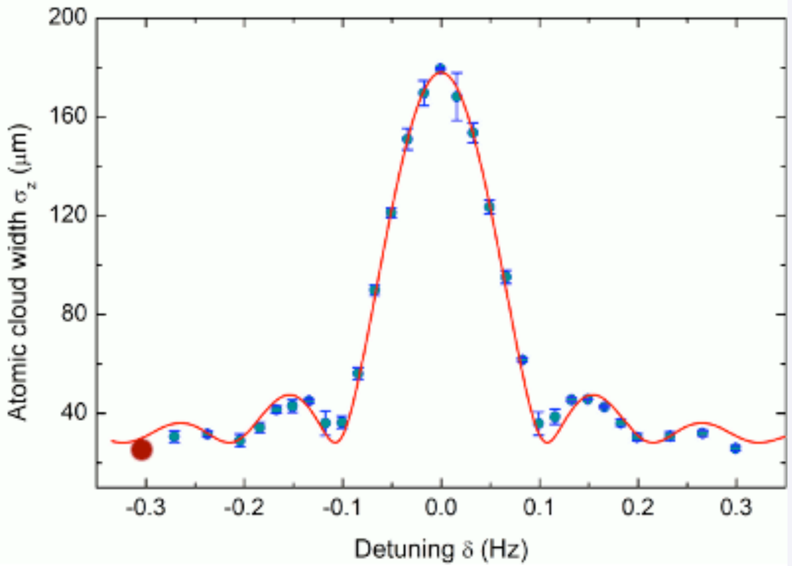
M. G. Tarallo, A. Alberti, N. Poli, M. L. Chiofalo, F.-Y. Wang, G. M. Tino, *Delocalization-enhanced Bloch oscillations and driven resonant tunneling in optical lattices or precision force measurements,* **Phys. Rev. A 86, 033615 (2012)**

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



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



- Direct measurement of ω_B by recording the atomic distribution broadening

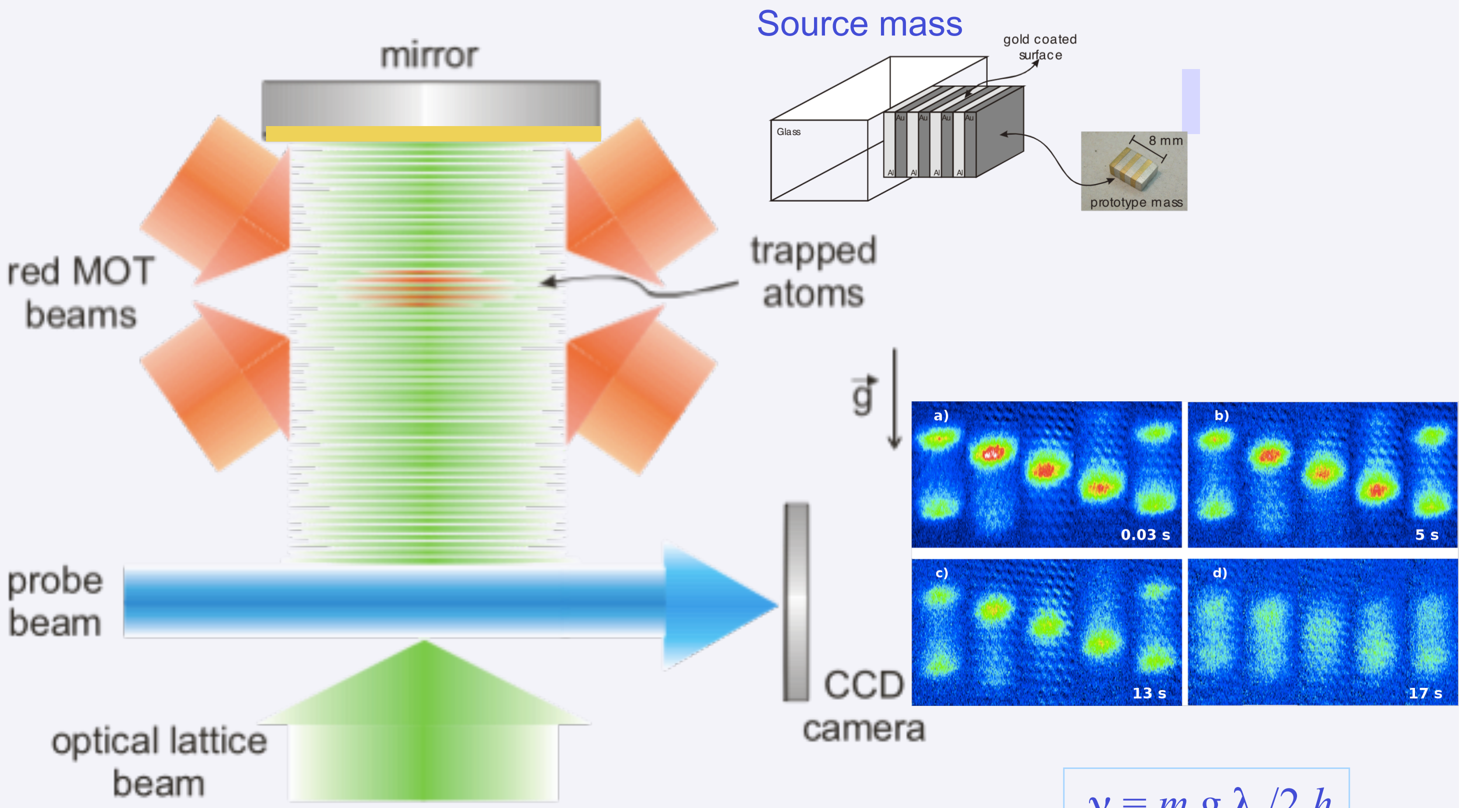
^{88}Sr

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

Poli *et al.*, Phys. Rev. Lett. 106, 038501 (2011)

Tarallo *et al.*, 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)**

Deviations from Newtonian gravity

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

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

- **Newton+Yukawa potential**

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

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

- **Modified power-law potential**

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

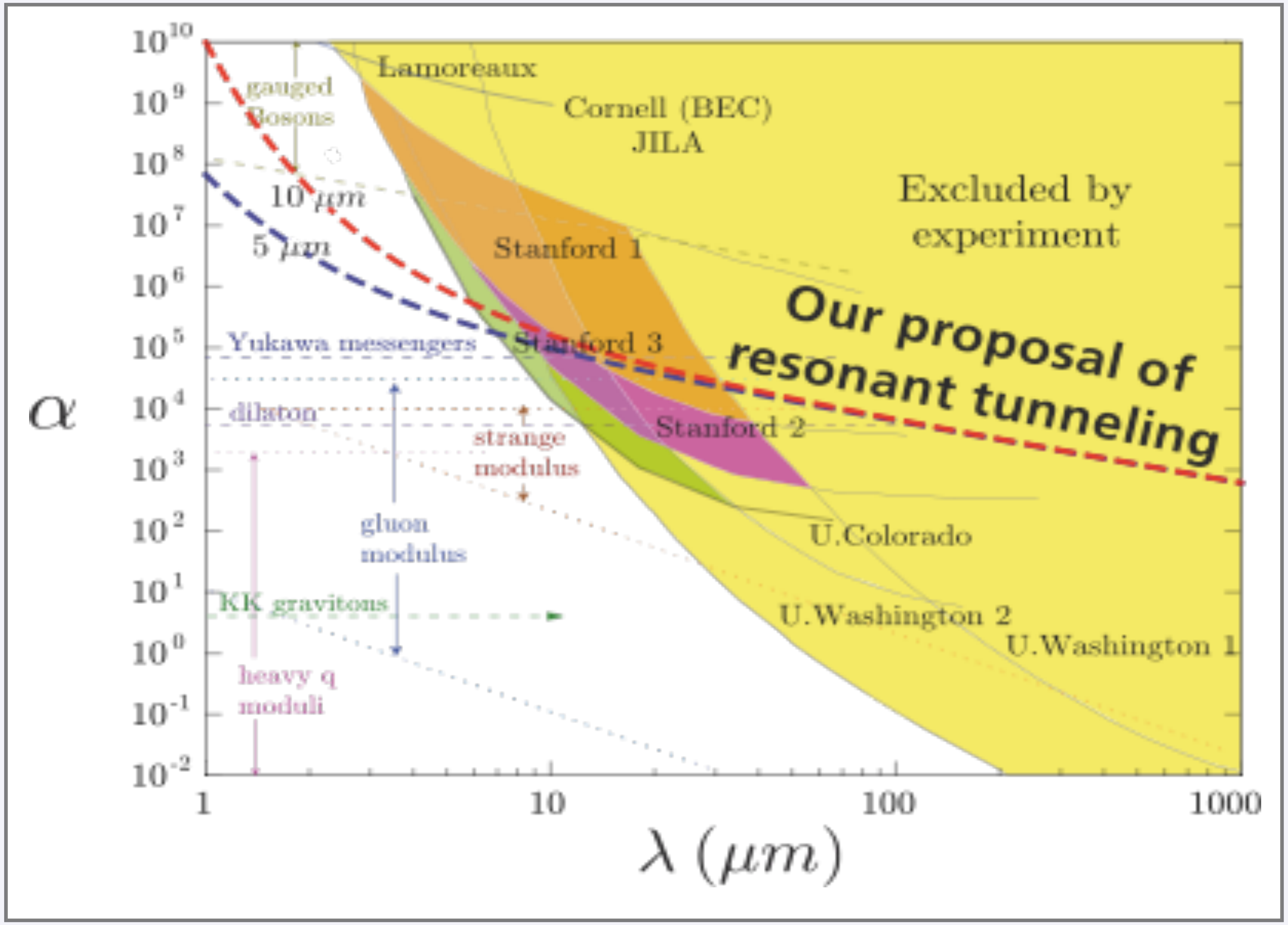
→ Exchange of 2 massless particles

Accessible region with atomic probes

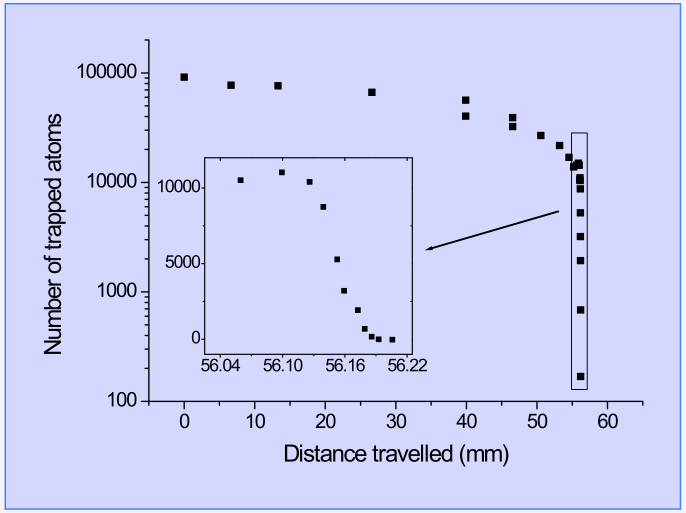
- **Newton+Yukawa potential**

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

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



Atom elevator

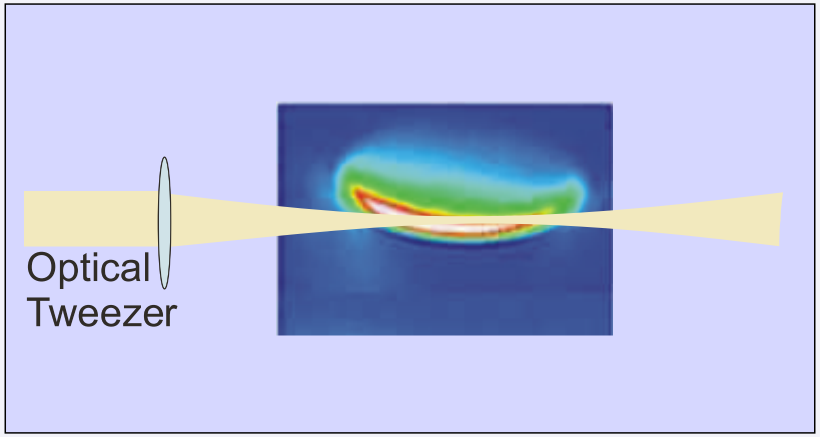


Vertical size of the atomic sample: 15 μm

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

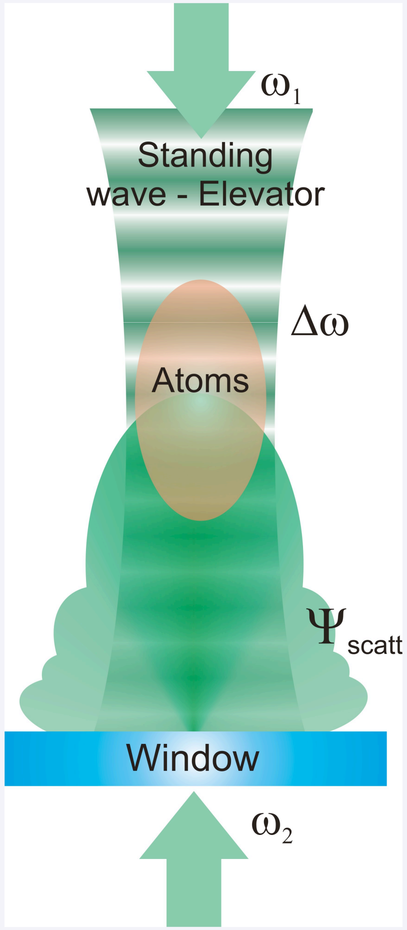
F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, **Phys. Rev. A 79, 013409 (2009)**

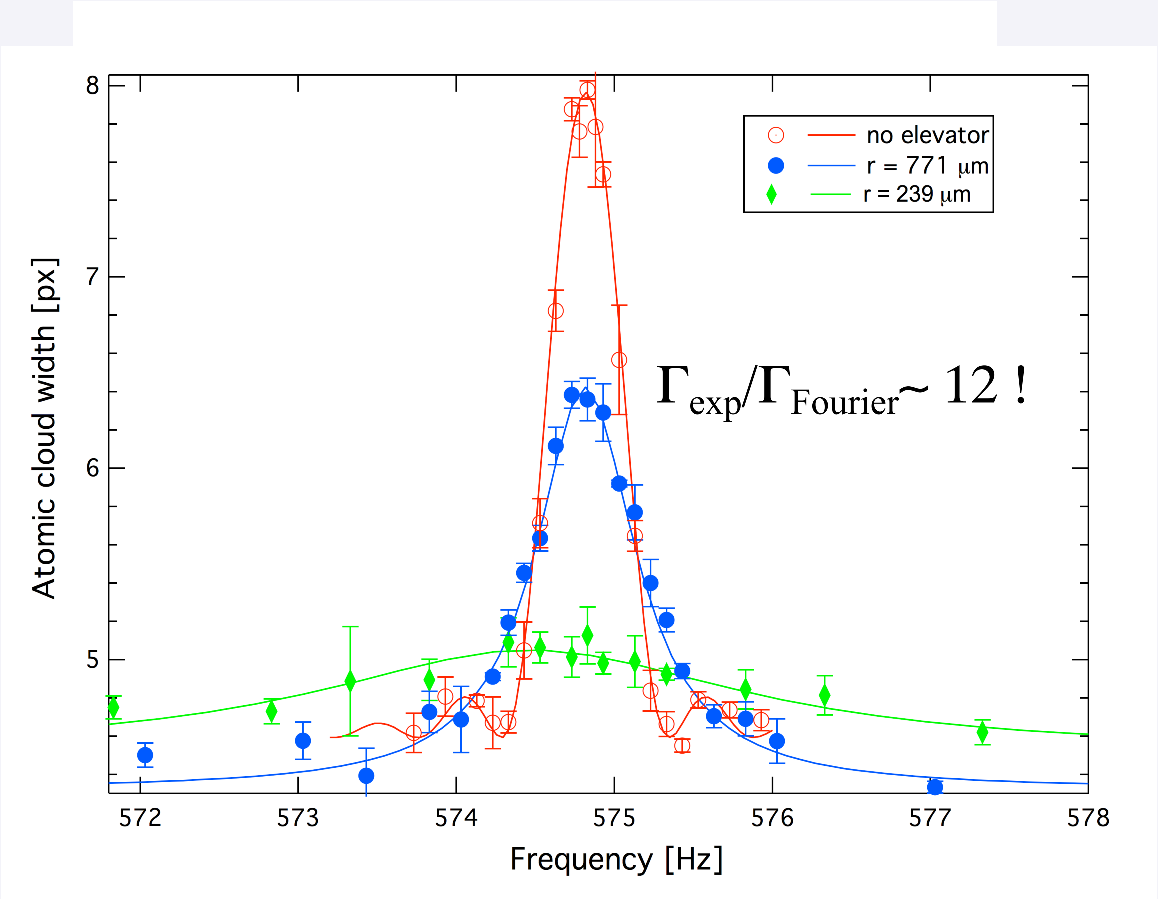
Short-distance measurements

- **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:





Experiment at SYRTE

Principle of the experiment

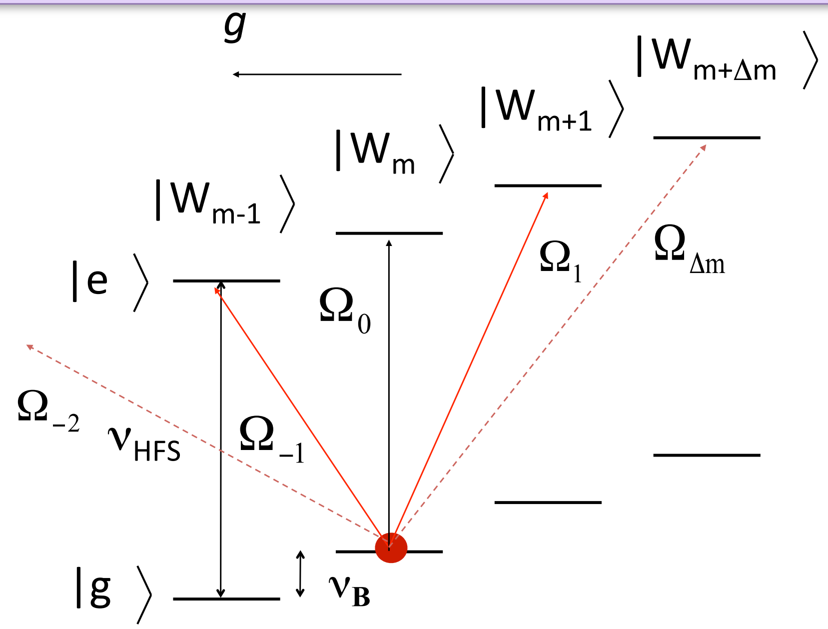
Induced tunneling

- Coupling in the same well:
  - Microwave
  - Co-propagating Raman impulsion
  - Or counter-propagating Raman impulsion

- Coupling between wells:
  - Contra-propagating Raman impulsion ($k_{eff} \sim 2k_{Ram}$)
  - Efficient when $k_{eff} \sim k_{lattice}$

- Resonance:
  - when Raman frequency is detuned by ν_B

$$\Delta\nu_{Raman} = \nu_{HFS} + \Delta m \cdot \nu_B$$



Coupling:
by translation operator in momentum space

$$\Omega_{\Delta m} = \Omega_{U_{lattice}=0} \left\langle W_m \middle| e^{ik_{eff}\hat{z}} \middle| W_{m+\Delta m} \right\rangle$$

with m: well index

G. Tackmann *et al.*, PRA 84, 063422 (2011)

The Equivalence Principle

Weak form of Einstein Equivalence Principle

→ Universality of Free Fall

The trajectory of a freely falling "test" body is independent of its internal structure and composition

- All bodies fall in the same way
- Inertial mass and gravitational mass are equivalent

(force) = (inertial mass) x (acceleration)

(force) = (gravitational mass) x (gravitational field)

$$\longrightarrow \text{(acceleration)} = \frac{\text{(gravitational mass)}}{\text{(inertial mass)}} \times \text{(gravitational field)}$$

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**

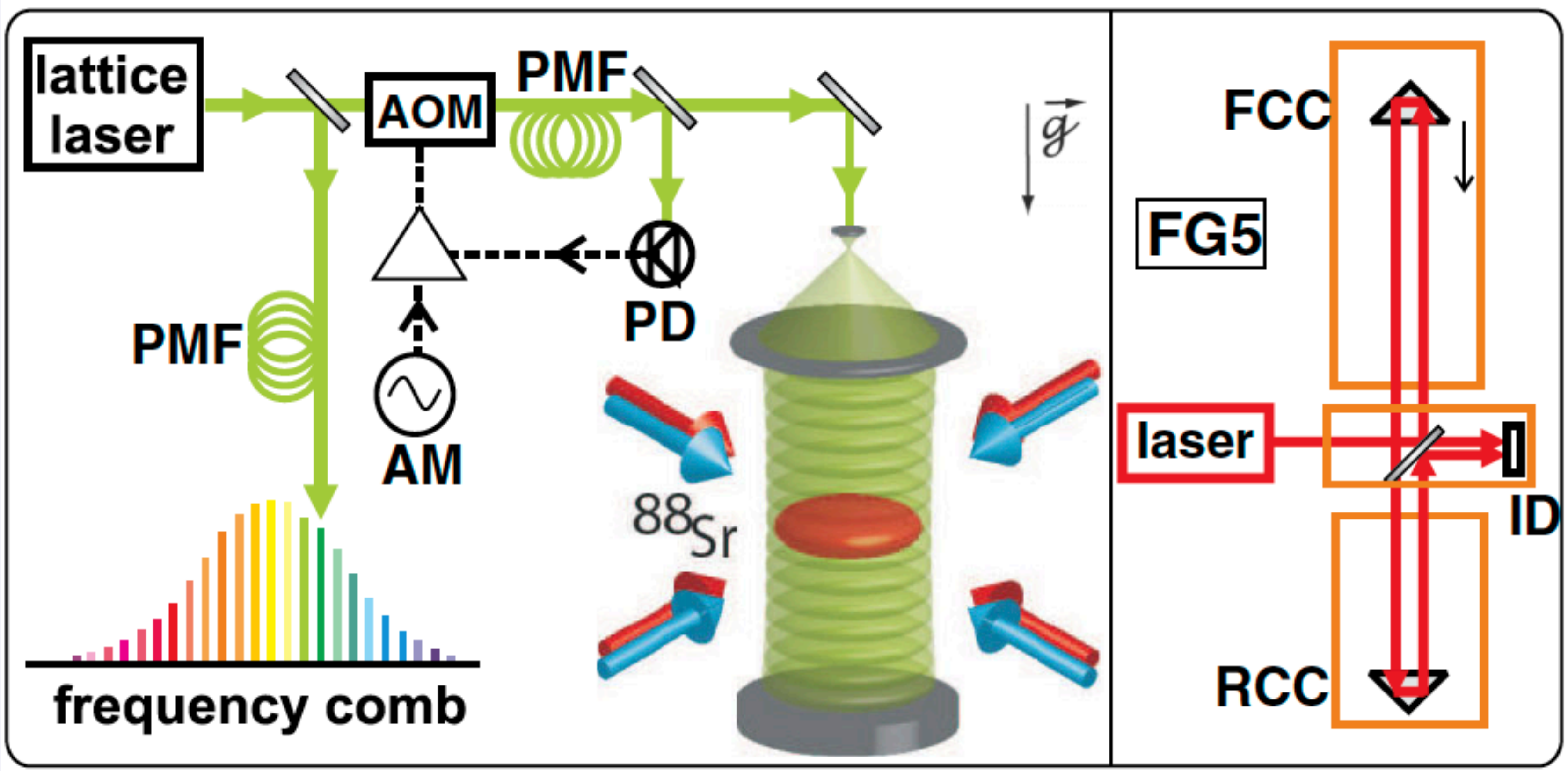
A. Kellerbauer, et al. (AEGIS collaboration), Nucl. Instr. Meth. Phys. Res. B 266, 351 (2008)

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

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

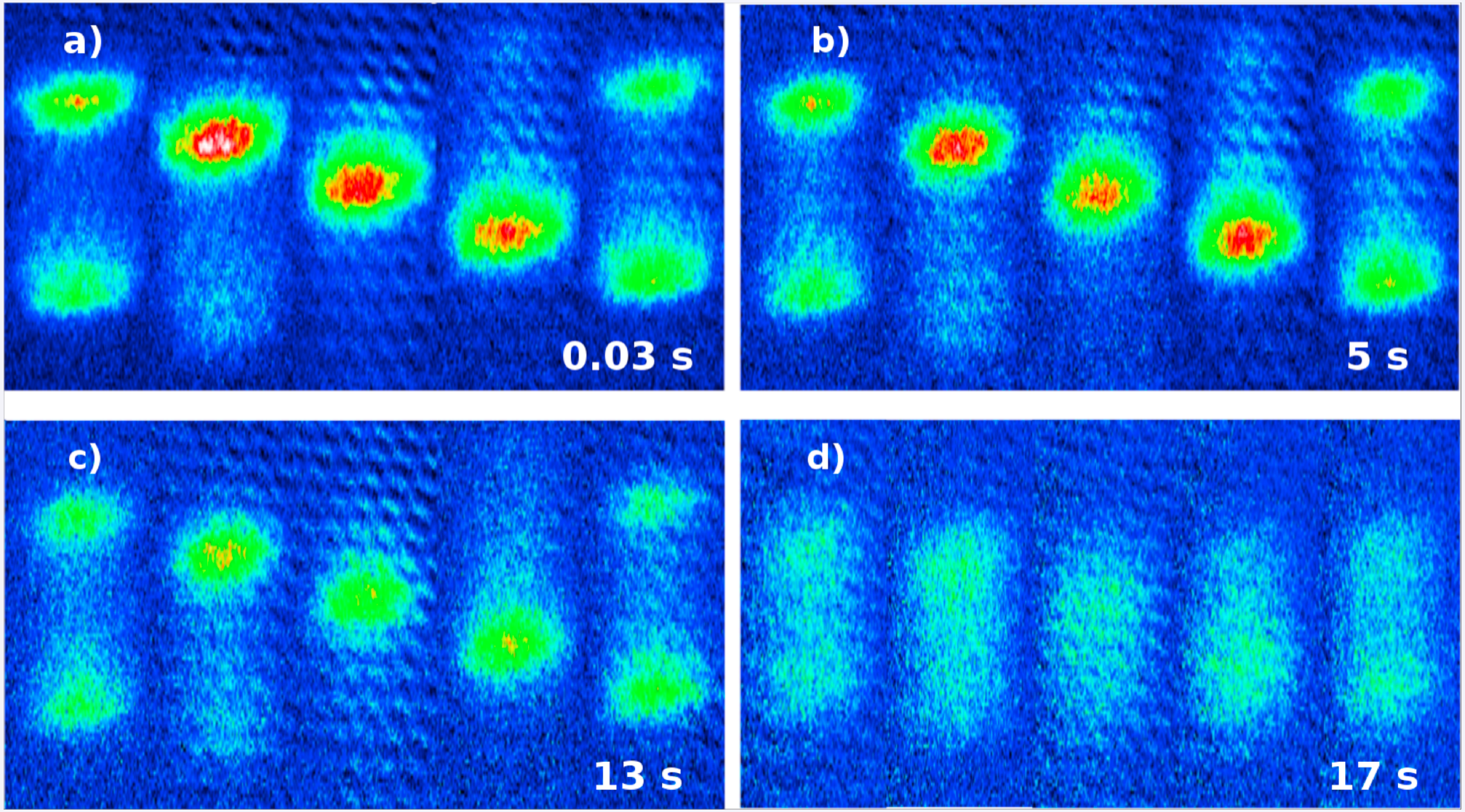
H vs anti-H

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



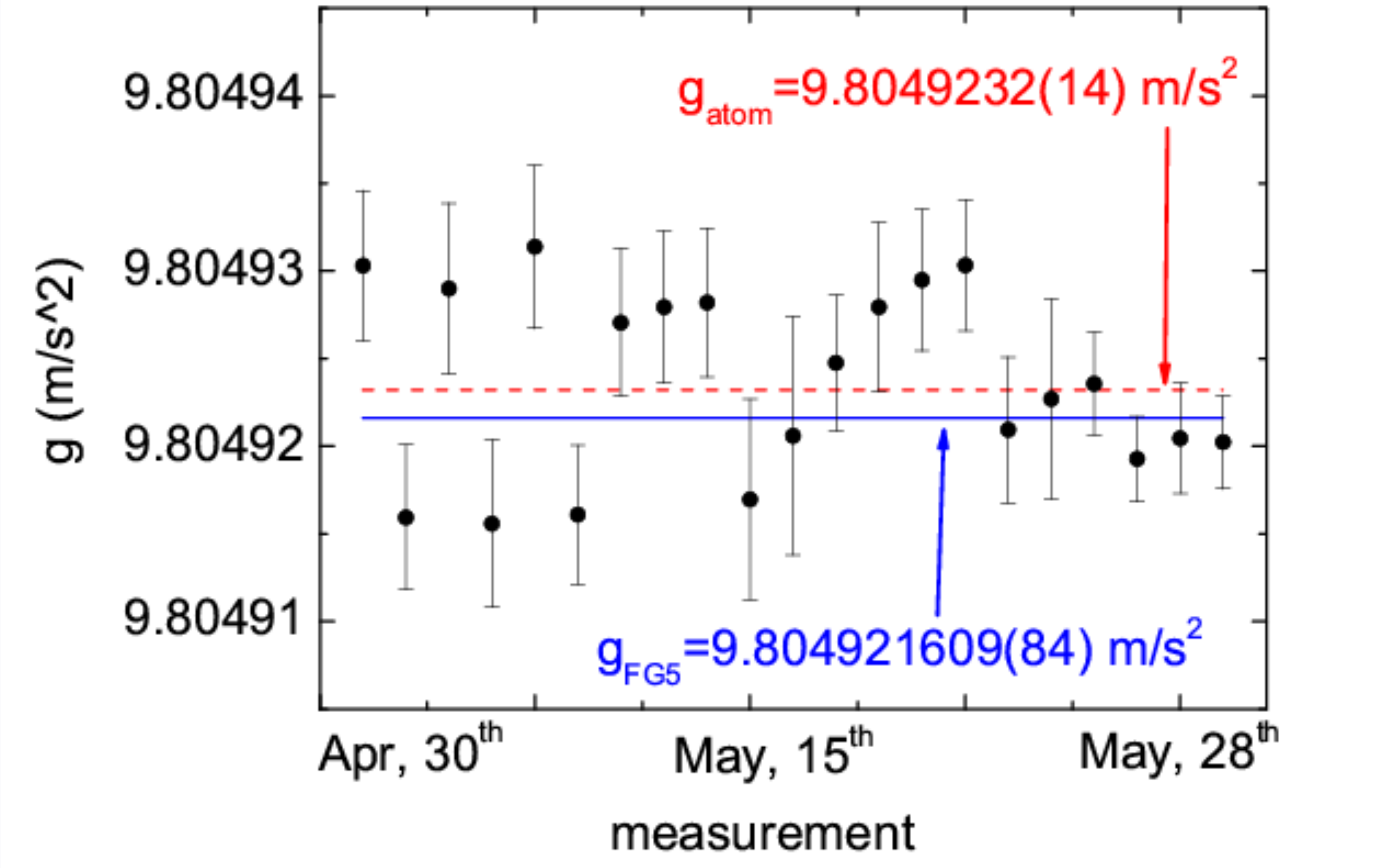
N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Phys. Rev. Lett. 106, 038501 (2011)

Bloch oscillations



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

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



140 ppb relative uncertainty

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

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

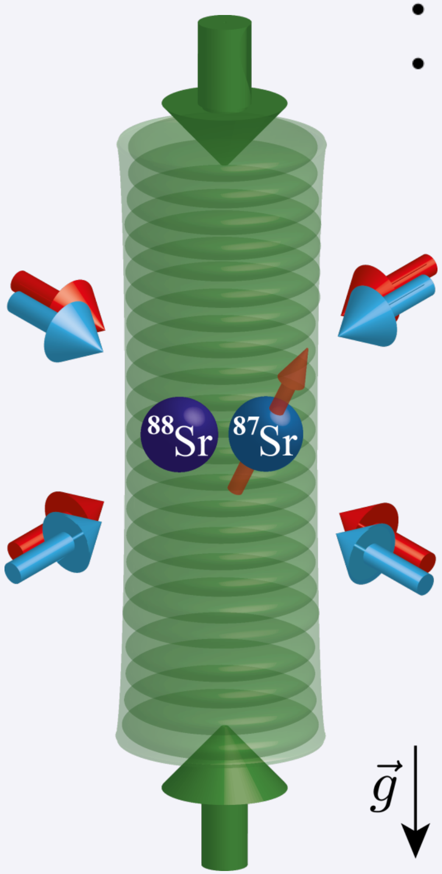
- General theoretical framework

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

- Spin-gravity coupling

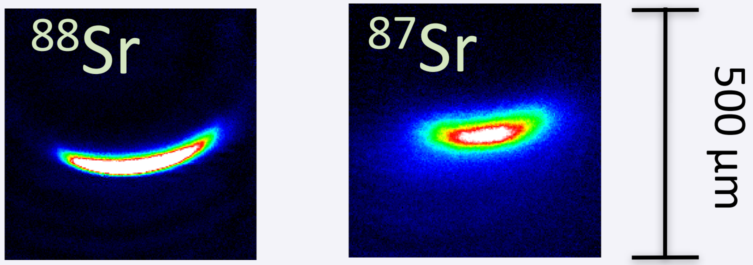
- J. Leitner and S. Okubo, Phys. Rev. 136 (1964) B1542.
- F.W. Hehl et al., Rev.Mod.Phys. 48 (1976) 393-416
- N.D. Hari Dass, Phys. Rev. Lett. 36 (1976) 393.
- S. Capozziello et al., Ann. Phys. 10 (2001) 713.
- D. Bini et al., Class. Quantum Grav. 21 (2004) 3893.
- B. Mashhoon, Lect. Notes Phys. 702 (2006) 112.
- 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



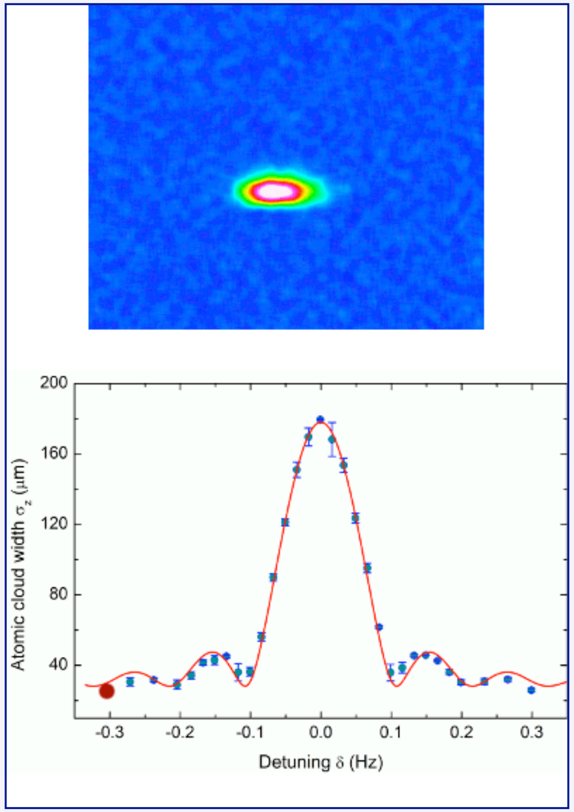
- Atomic beam from an oven at 430°C
- Zeeman-slowed down to 50 m/s
- Two cooling stages sequence in MOT
  - Broad transition 461 nm, $\gamma = 32$ MHz
  - Narrow transition 689 nm, $\gamma = 7$ kHz

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



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)**

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

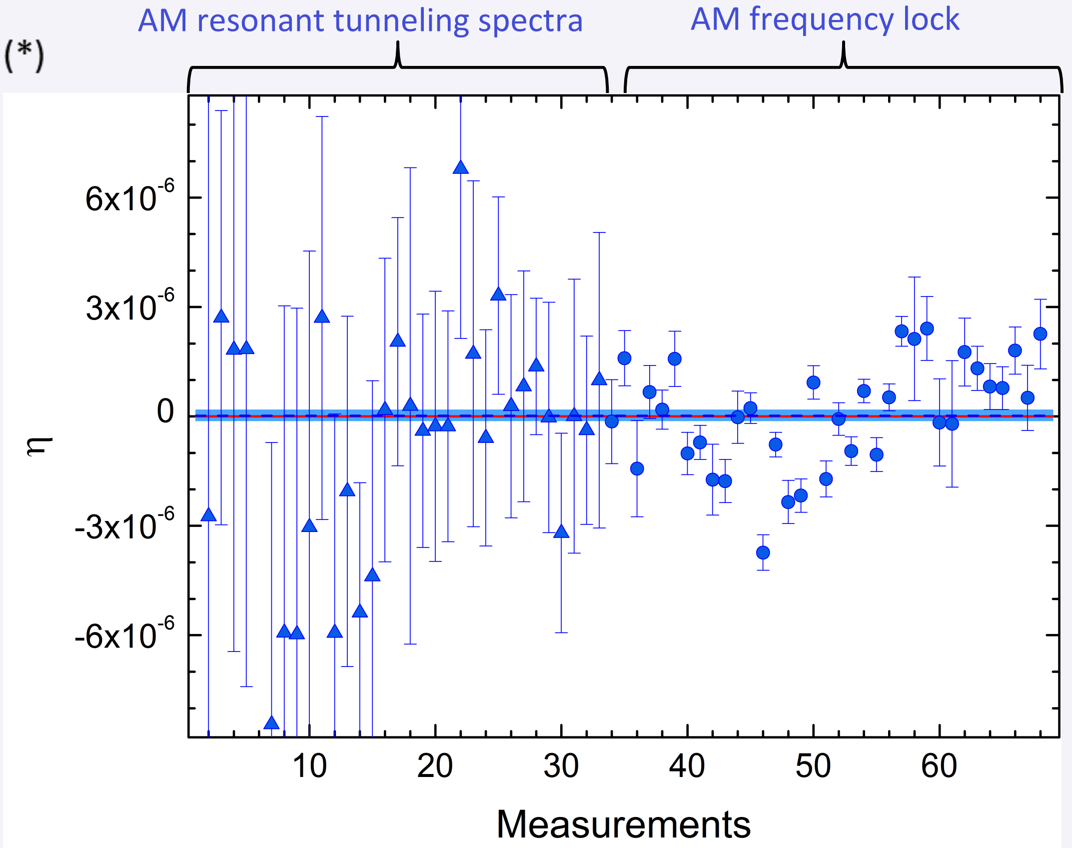
$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

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

W.-T. Ni, Rep. Prog. Phys. 73, 6901 (2010)
C. Lammerzahl, Class. Quantum Grav. 15, 13 (1998)

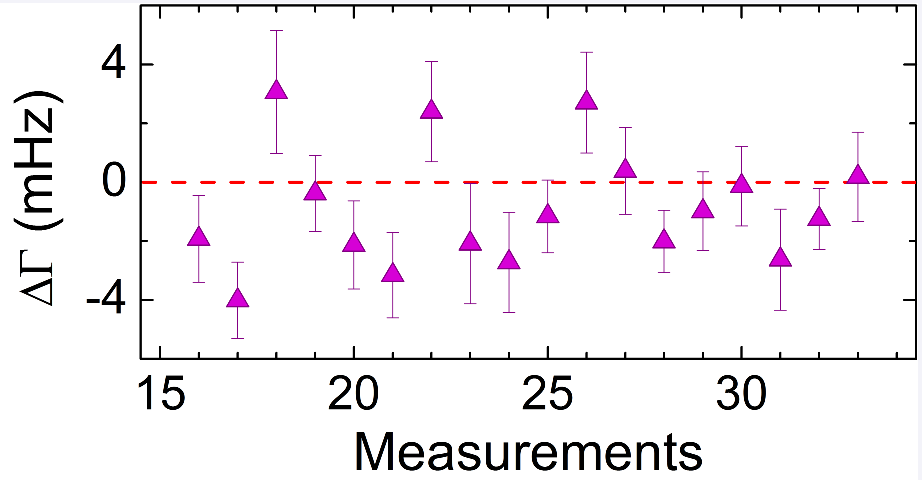
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

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

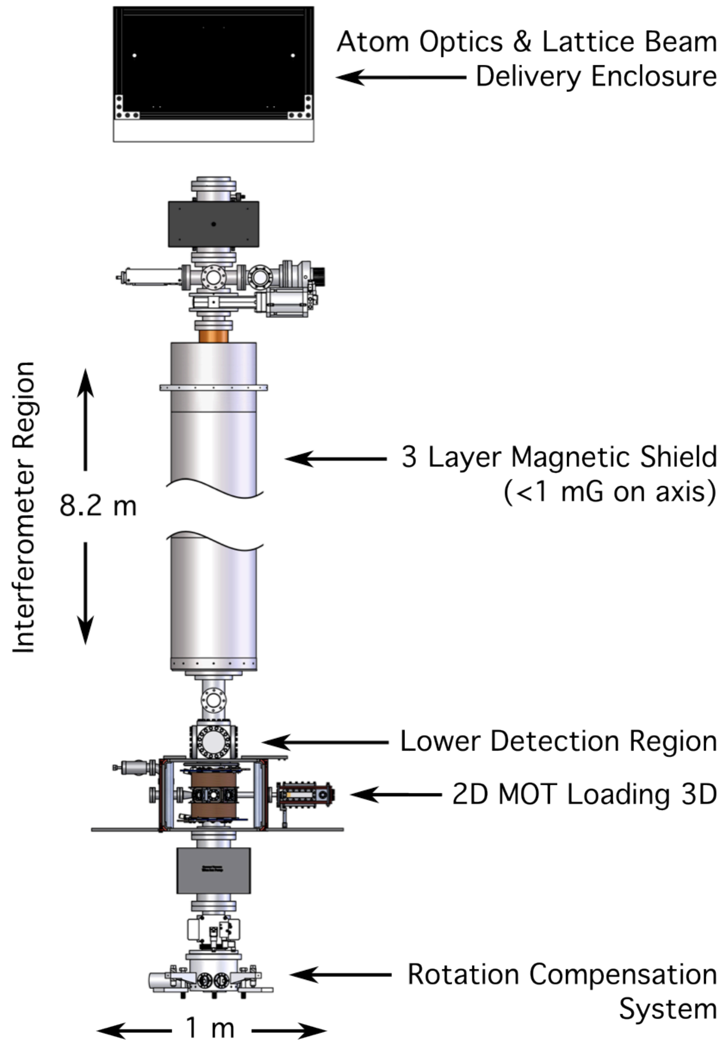
$$\Delta\Gamma = 2I_{87}kl\nu_{87}$$

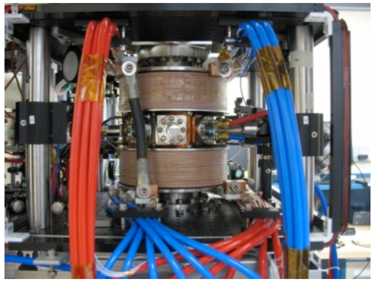
$$\Longrightarrow \quad k = (0.5 \pm 1.1) \times 10^{-7}$$



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)**

Apparatus





Ultracold atom source

$>10^6$ atoms at 50 nK

3e5 atoms at 1.6 nK

Optical Lattice Launch

13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry

2 cm $1/e^2$ radial waist

6 W total power

Dynamic nrad control of laser angle with precision piezo-actuated stage

Detection

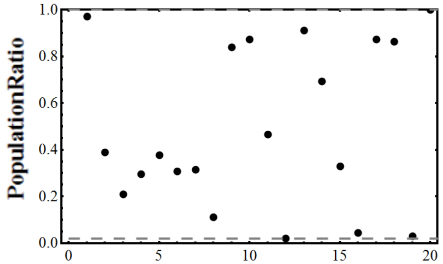
Spatially-resolved fluorescence imaging

Two CCD cameras on perpendicular lines of sight

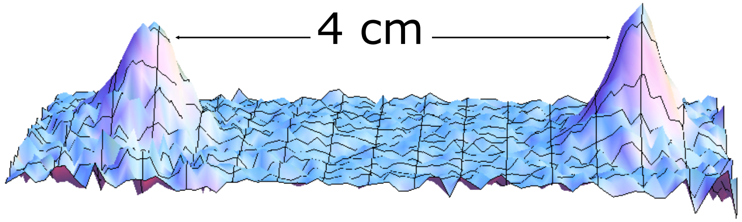
Current demonstrated statistical resolution, ~5e-13 g in 1 hr (87Rb)

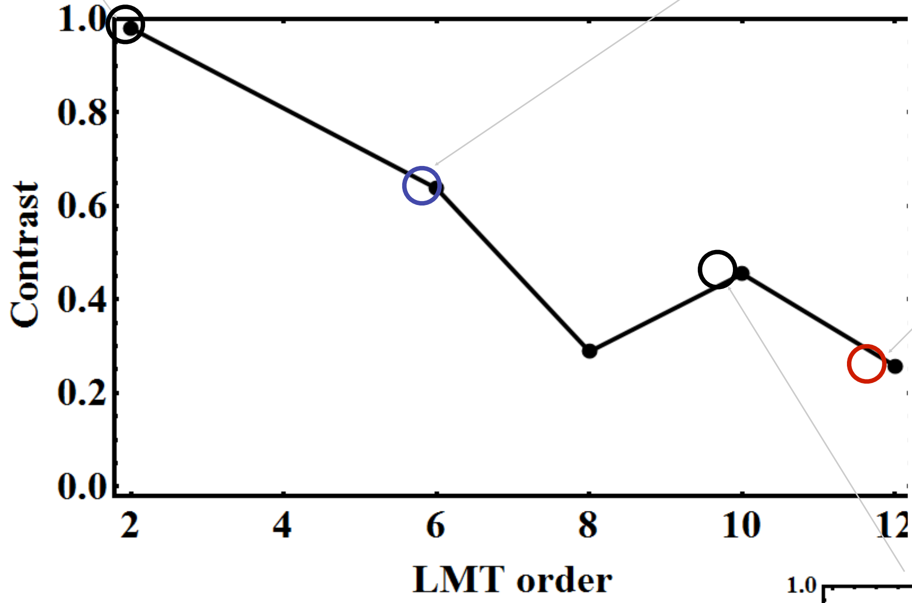
From M. Kasevich, ICAP 2014

Contrast vs. momentum recoil at 2T = 2.3 s

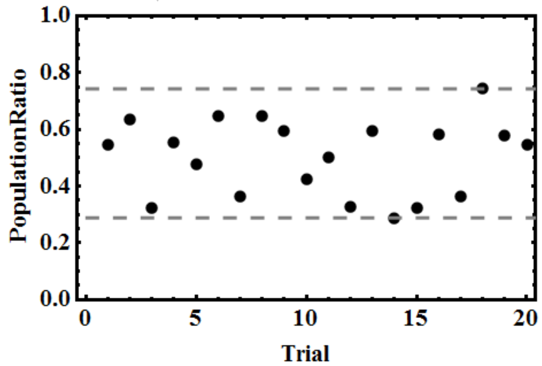


>98% contrast (!)





8 cm wavepacket separation (!!)



Large momentum transfer demonstration at 2T = 2.3 s (unpublished).

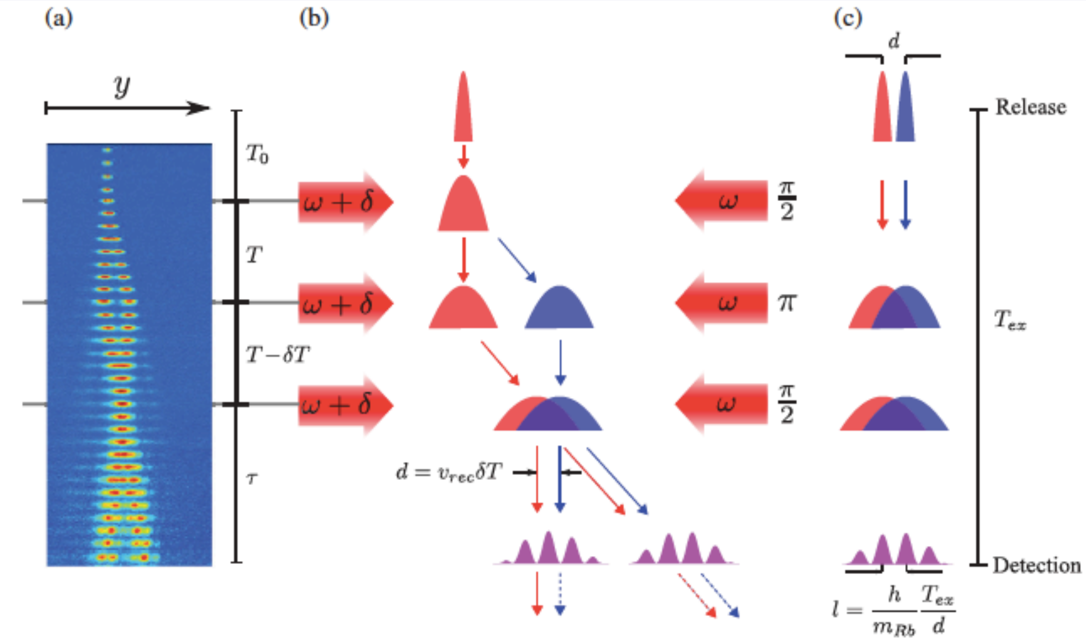
From M. Kasevich, ICAP 2014

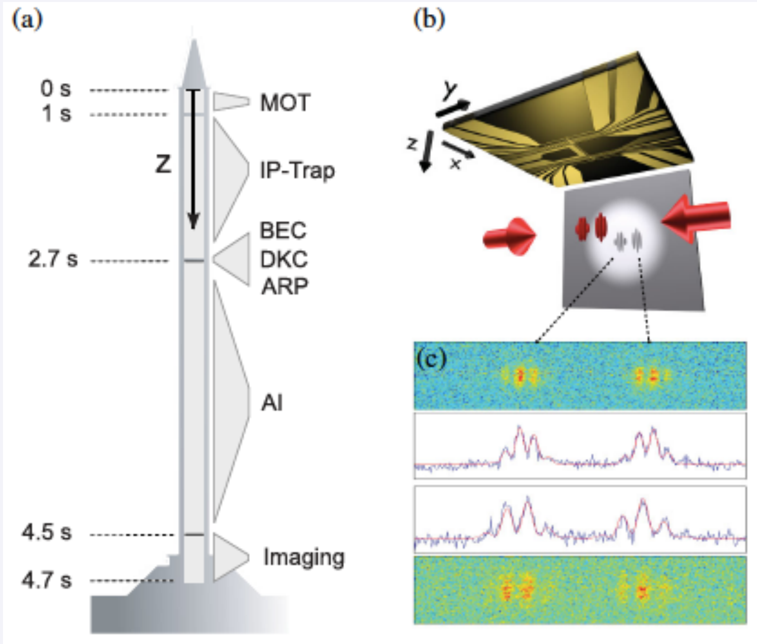
Selected for a Viewpoint in Physics
PRL 110, 093602 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

Interferometry with Bose-Einstein Condensates in Microgravity

H. Müntinga,[1] H. Ahlers,[2] M. Krutzik,[3] A. Wenzlawski,[4] S. Arnold,[5] D. Becker,[2] K. Bongs,[6] H. Dittus,[7] H. Duncker,[4] N. Gaaloul,[2] C. Gherasim,[8] E. Giese,[5] C. Grzeschik,[3] T. W. Hänsch,[9] O. Hellmig,[4] W. Herr,[2] S. Herrmann,[1] E. Kajari,[5,10] S. Kleinert,[5] C. Lämmerzahl,[1] W. Lewoczko-Adamczyk,[3] J. Malcolm,[6] N. Meyer,[6] R. Nolte,[8] A. Peters,[3,11] M. Popp,[2] J. Reichel,[12] A. Roura,[5] J. Rudolph,[2] M. Schiemangk,[3,11] M. Schneider,[8] S. T. Seidel,[2] K. Sengstock,[4] V. Tamma,[5] T. Valenzuela,[6] A. Vogel,[4] R. Walser,[8] T. Wendrich,[2] P. Windpassinger,[4] W. Zeller,[5] T. van Zoest,[7] W. Ertmer,[2] W. P. Schleich,[5] and E. M. Rasel[2,*]

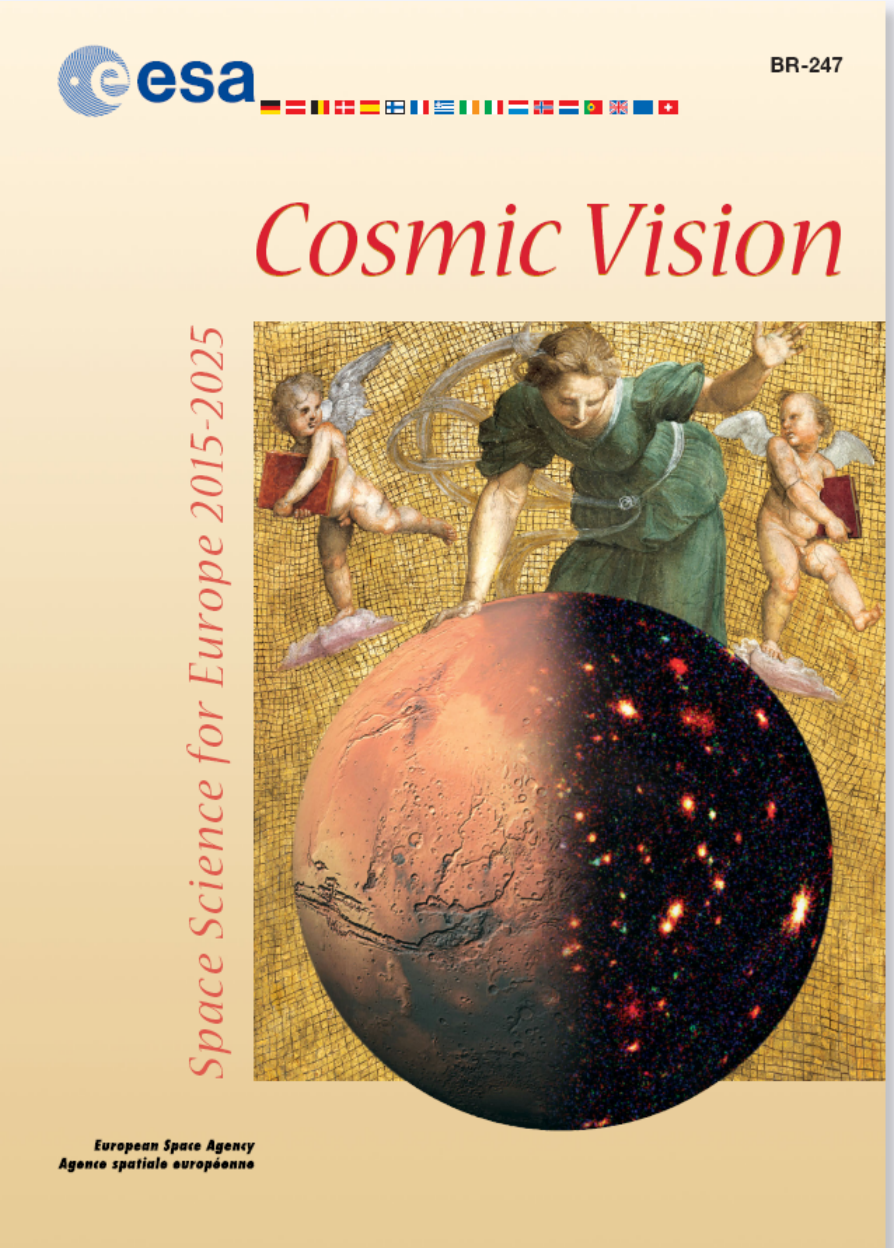
Atom interferometers covering macroscopic domains of space-time are a spectacular manifestation of the wave nature of matter. Because of their unique coherence properties, Bose-Einstein condensates are ideal sources for an atom interferometer in extended free fall. In this Letter we report on the realization of an asymmetric Mach-Zehnder interferometer operated with a Bose-Einstein condensate in microgravity. The resulting interference pattern is similar to the one in the far field of a double slit and shows a linear scaling with the time the wave packets expand. We employ delta-kick cooling in order to enhance the signal and extend our atom interferometer. Our experiments demonstrate the high potential of interferometers operated with quantum gases for probing the fundamental concepts of quantum mechanics and general relativity.

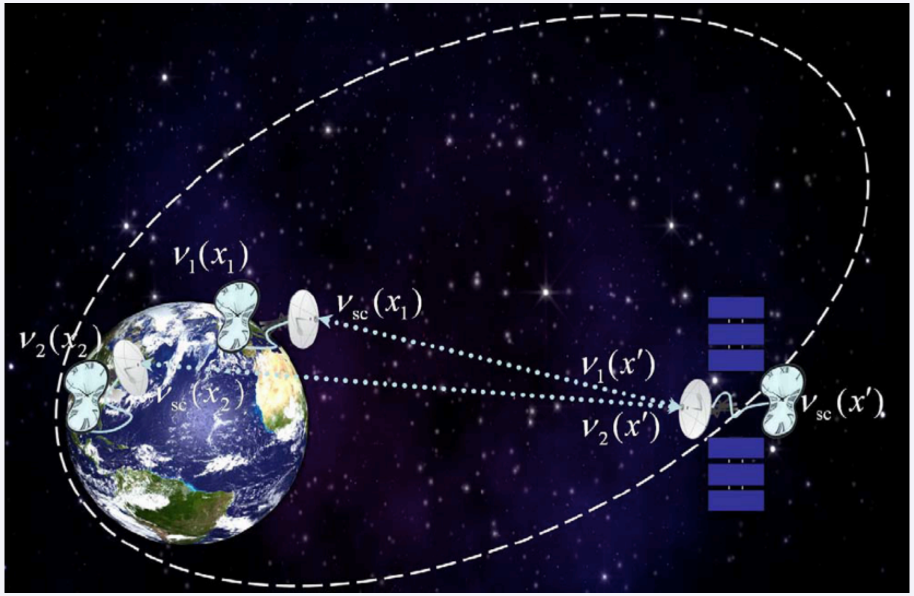


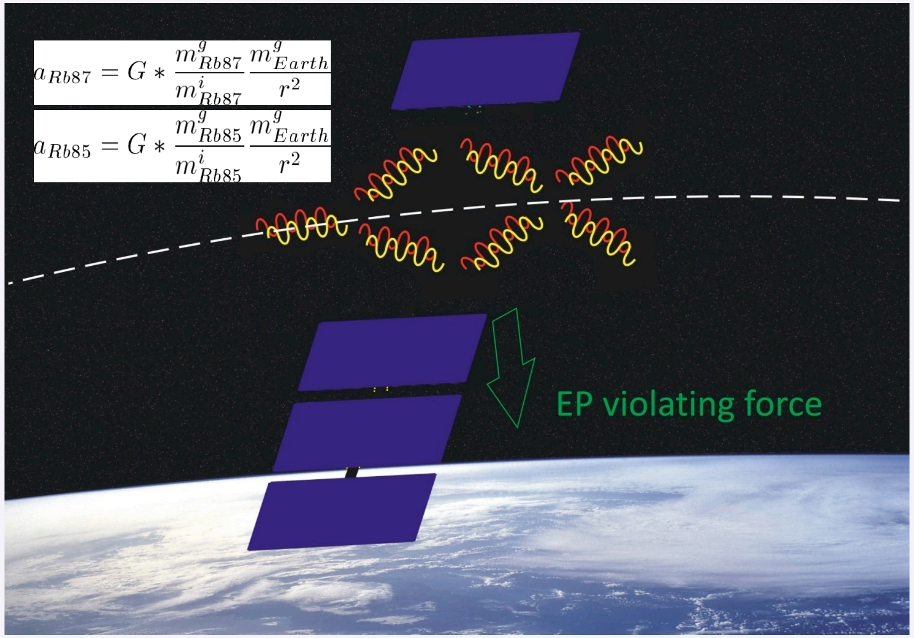


- STE-QUEST Mission -

Test of Gravitational Red Shift and Equivalence Principle







UNIVERSITÀ DEGLI STUDI FIRENZE

October 14, 2008

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Gravitational Waves Detection with Atom Interferometry

Conference

Apply | Schedule

Organizers:

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

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

Deadline: 15-01-2009

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

Abstract

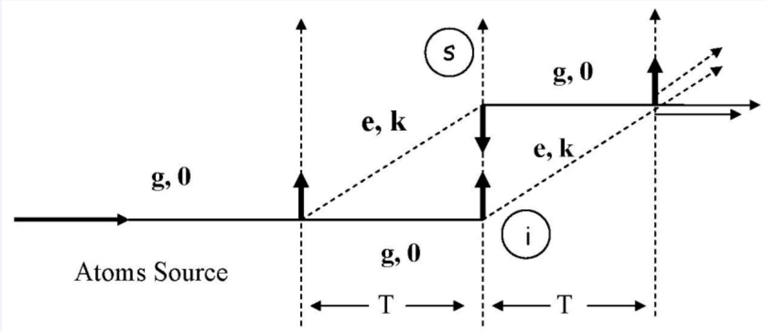
The possibility of using atom interferometers to detect gravitational waves is attracting increasing interest as an alternative to other detectors. Several papers were published discussing theoretical and experimental aspects. Although the results show that dedicated technological developments are still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

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

Two possible schemes

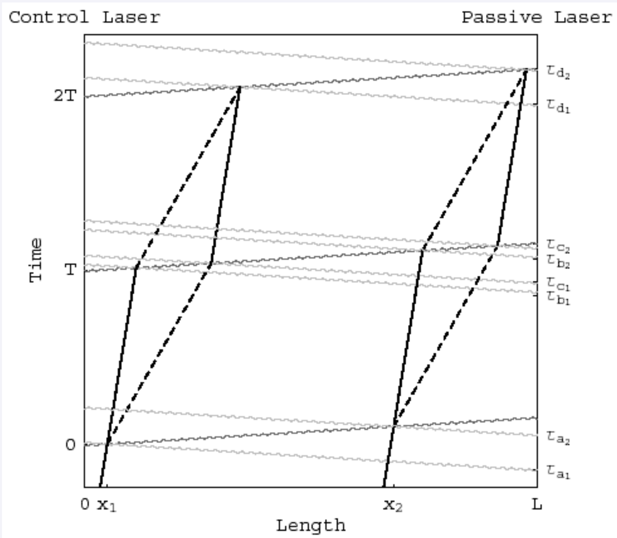
- *Single atom interferometer*

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

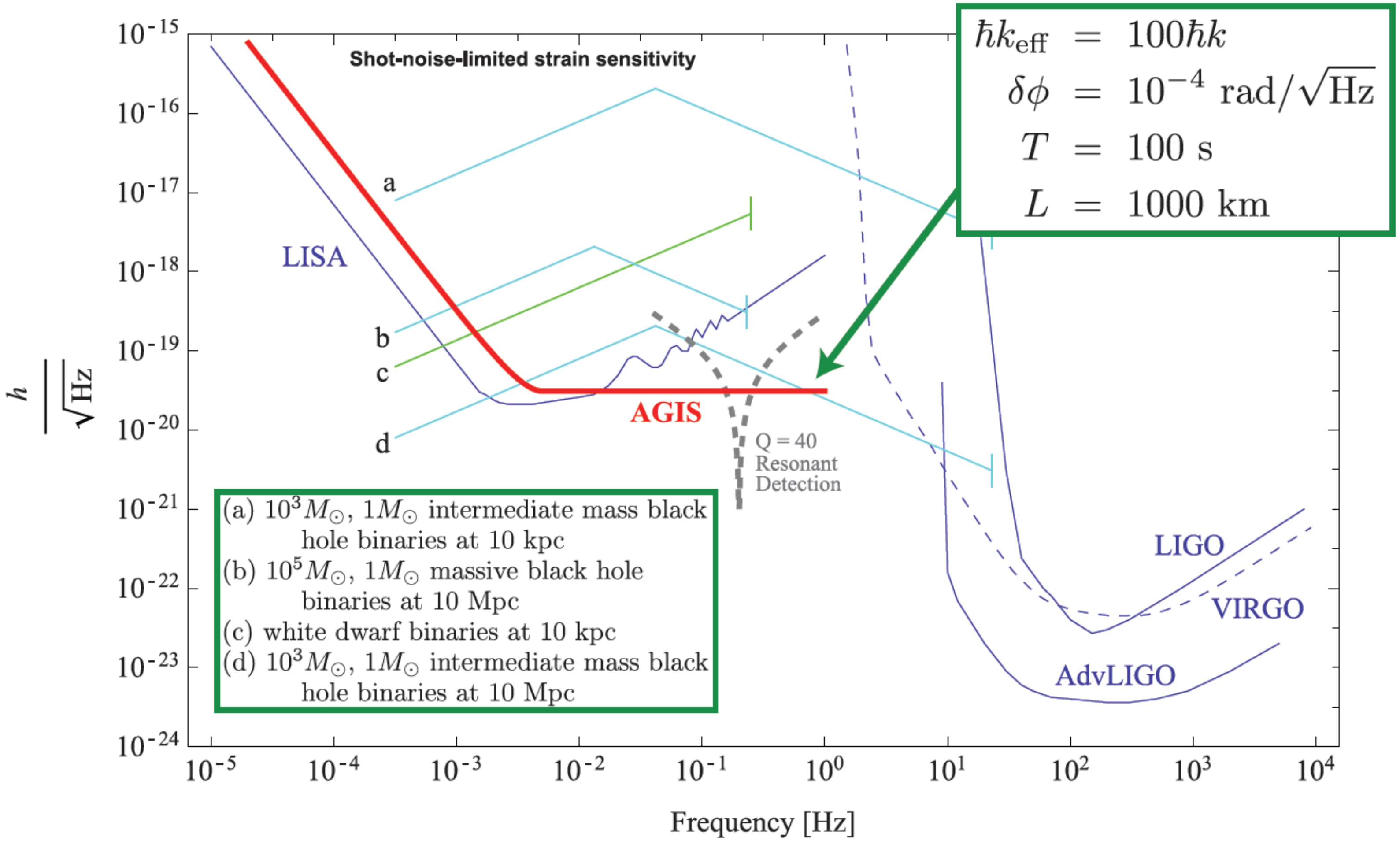


- *Differential scheme*

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

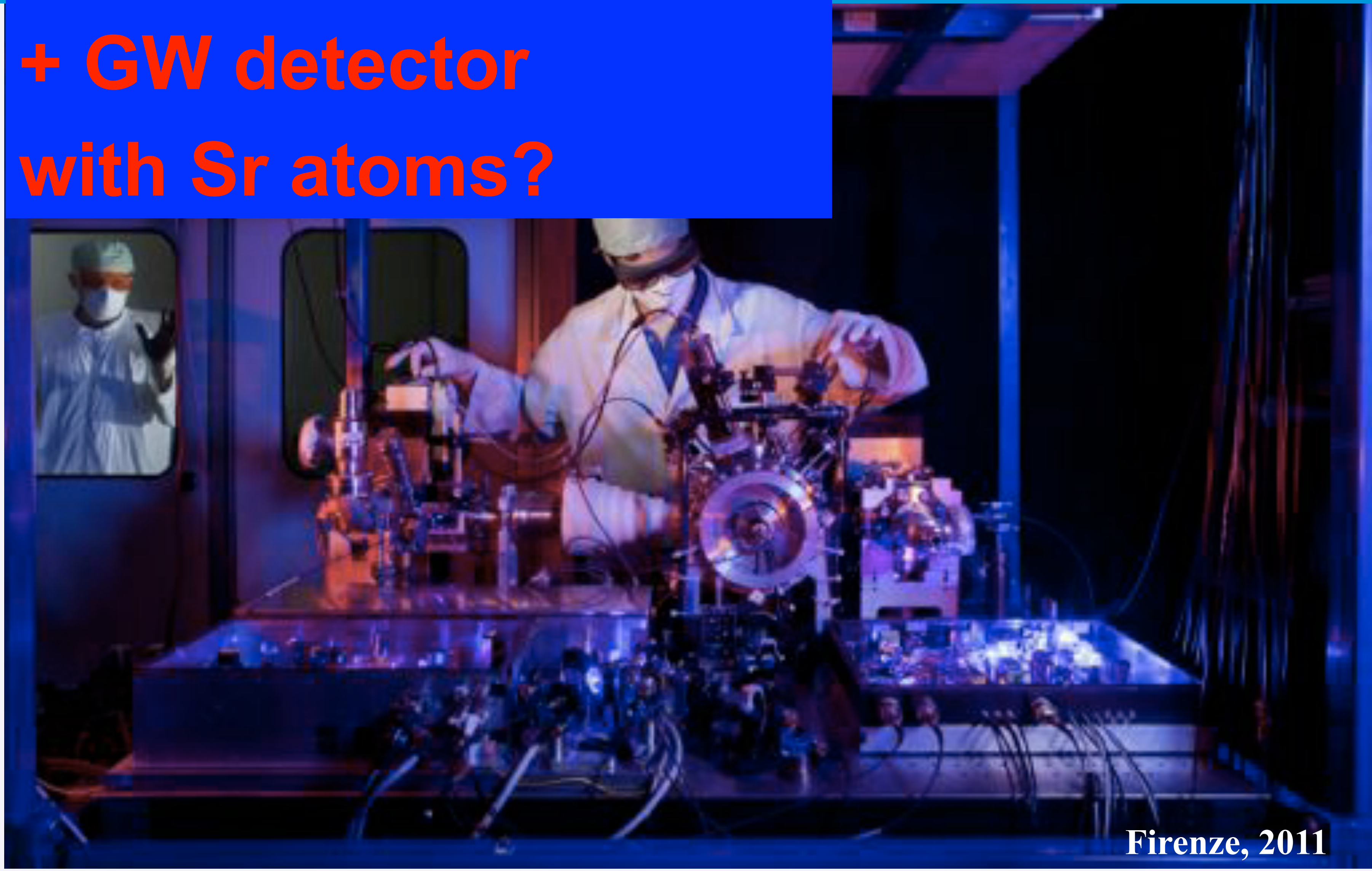


Application to Gravitational Wave Detection



P. Graham, et al., arXiv:1206.0818, PRL (2013).
J. Hogan, et al., GRG **43**, 7 (2011).

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]
[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 $|\xi_1| \sim 10^3$

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

Search for physics beyond the SM

PHYSICAL REVIEW A **89**, 052118 (2014)

Testing the a_μ anomaly in the electron sector through a precise measurement of h/M

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[1]*Department of Physics, University of Milano-Bicocca and INFN, Sezione di Milano-Bicocca, Milano, Italy*

[2]*Department of Physics and Astronomy and LENS Laboratory, University of Florence, INFN Sezione di Firenze, Sesto Fiorentino (FI), Italy*

(Received 13 April 2014; published 19 May 2014)

The persistent $a_\mu \equiv (g-2)/2$ anomaly in the muon sector could be due to new physics visible in the electron sector through a sub-ppb (parts per 10^9) measurement of the anomalous magnetic moment of the electron a_e. Driven by recent results on the electron mass [S. Sturm *et al.*, Nature **506**, 467 (2014)], we reconsider the sources of uncertainties that limit our knowledge of a_e including current advances in atom interferometry. We demonstrate that it is possible to attain the level of precision needed to test a_μ in the naive scaling hypothesis on a time scale similar to next-generation $g-2$ muon experiments at Fermilab and JPARC. In order to achieve this level of precision, knowledge of the quotient h/M, i.e., the ratio between the Planck constant and the mass of the atom employed in the interferometer, will play a crucial role. We identify the most favorable isotopes to achieve an overall relative precision below 10^{-10}.

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I. INTRODUCTION

In the last 40 years, the experimental accuracy of the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$ has been improved by more than five orders of magnitude [1]. The final results of the Fermilab E821 experiment [2] shows a clear discrepancy with respect to the Standard Model (SM) prediction, corresponding to an $\sim 3.5\sigma$ deviation. This puzzling outcome has boosted a vigorous experimental program, and new results from the E989 Fermilab [3] and g-2 JPARC [4] experiments are expected in a few years. If the origin of the muon discrepancy is due to physics beyond the SM, similar effects are expected in the electron sector too. In particular, corrections due to new physics [(NP); i.e., physics beyond the SM] should appear in the electron magnetic moment $a_e =$

the atom employed in the atomic interferometer (Sec. III D), and the ratio between the Planck constant and the atom mass (h/M; Sec. III E). For each of these observables we determine the best current accuracy and the improvements that are needed to reach the goal sensitivity. The sensitivity to the NP of a_e and the comparison with NP effects in the muon sector are discussed in Sec. IV.

II. THE a_μ ANOMALY AND ITS ELECTRON COUNTERPART

Precise measurement of the anomalous magnetic moment of the electron $a_e = (g-2)_e/2$ is one of the most brilliant tests of QED and a key metrological observable in fundamental

Applications of new quantum sensors based on atom interferometry

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


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