Esperimenti sulla gravità:
da Galileo Galilei ai sensori quantistici con atomi ultrafreddi

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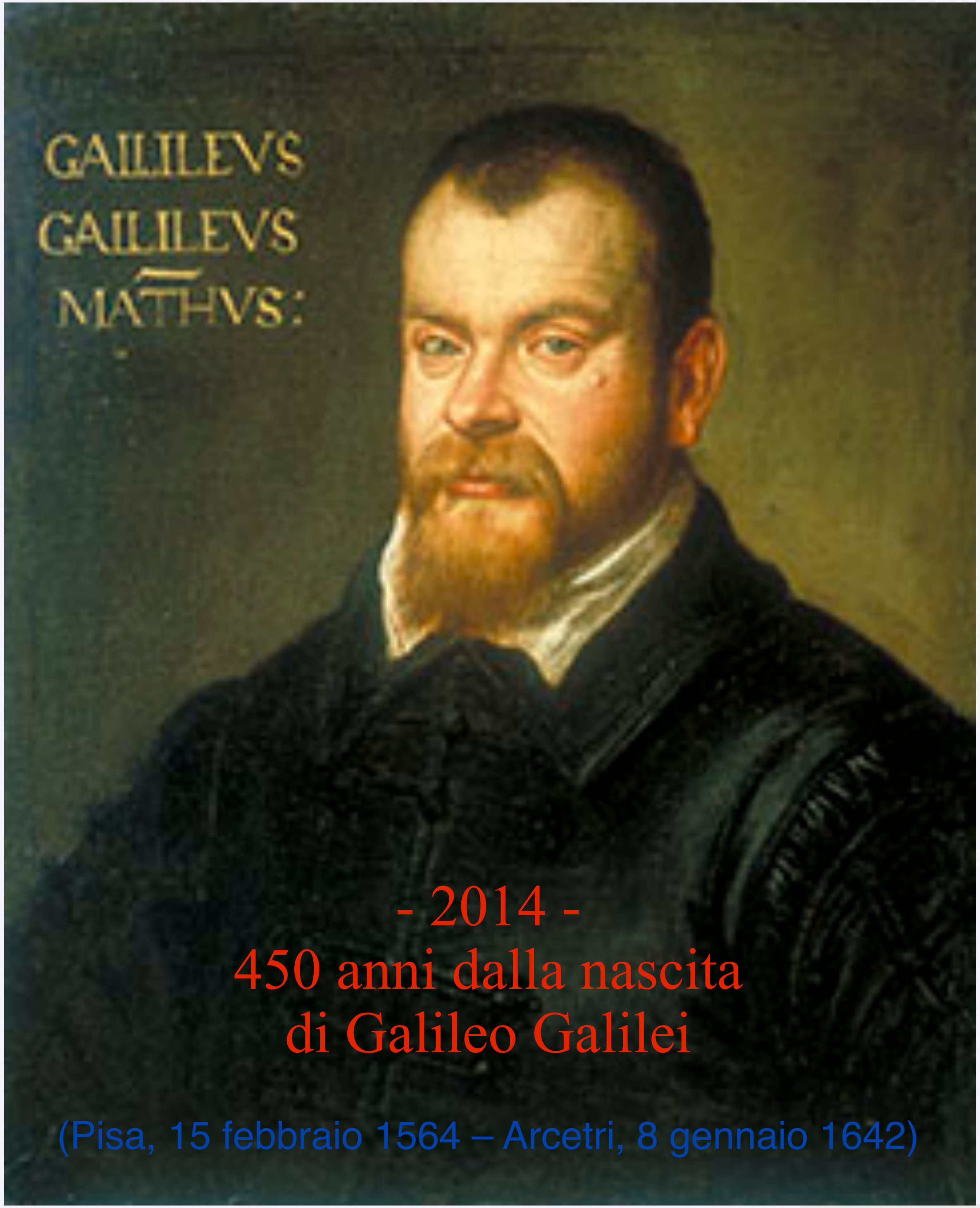
http://coldatoms.lens.unifi.it/

Polo Scientifico, Sesto Fiorentino, 23 Settembre 2014



- 2014 -
450 anni dalla nascita di Galileo Galilei

(Pisa, 15 febbraio 1564 – Arcetri, 8 gennaio 1642)

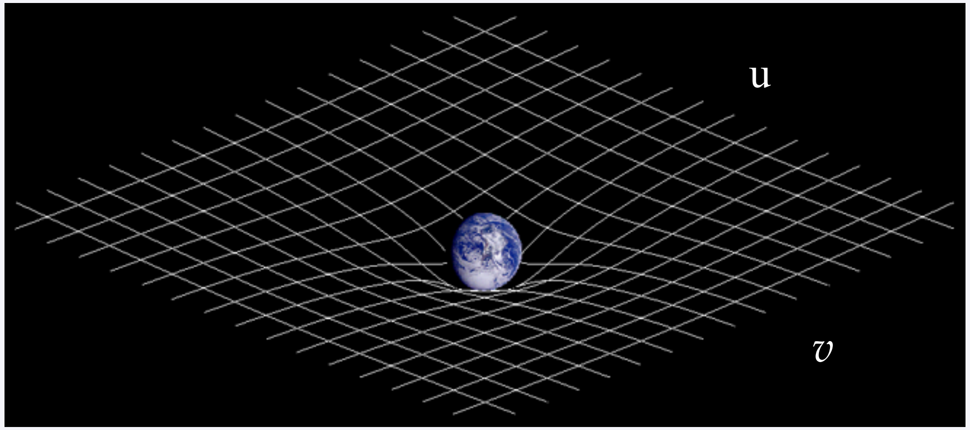
IL SAGGIATORE
Nel quale
Con bilancia eſquiſita e giuſta
ſi ponderano le coſe contenute
nella
LIBRA ASTRONOMICA E FILOSOFICA
DI LOTARIO SARSI SIGENSANO
Scritto in forma di lettera
All'Ill^{mo} et Reuer^{mo} Mons^{re} D.
VIRGINIO CESARINI
Acc^{o} Linceo M^{o} di Camera di N.S.
Dal Sig^{r}
GALILEO GALILEI
Acc^{o} Linceo Nobile Fiorentino
Filoſofo e Matematico Primario
del
Ser^{mo} Gran Duca di Toſcana
IN ROMA MDCXXIII
Appreſſo Giacomo Maſcardi

La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi a gli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intender la lingua, e conoscer i caratteri, ne' quali è scritto. Egli è scritto in lingua matematica, e i caratteri son triangoli, cerchi, ed altre figure geometriche, senza i quali mezi è impossibile a intenderne umanamente parola; senza questi è un aggirarsi vanamente per un oscuro laberinto.

La Relatività Generale

Descrizione della gravità come una proprietà geometrica dello spazio-tempo

- Geometria non euclidea
- Spazio a 4 dimensioni descritto da coordinate curvilinee (gaussiane) e da una metrica $g_{\alpha\beta}(x)$



$$ds^2 = g_{11}du^2 + 2g_{12}du\,dv + g_{22}dv^2$$

Equazioni di Einstein

$$G_{\mu\nu} \equiv R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

La Relatività Generale
Albert Einstein (1916)

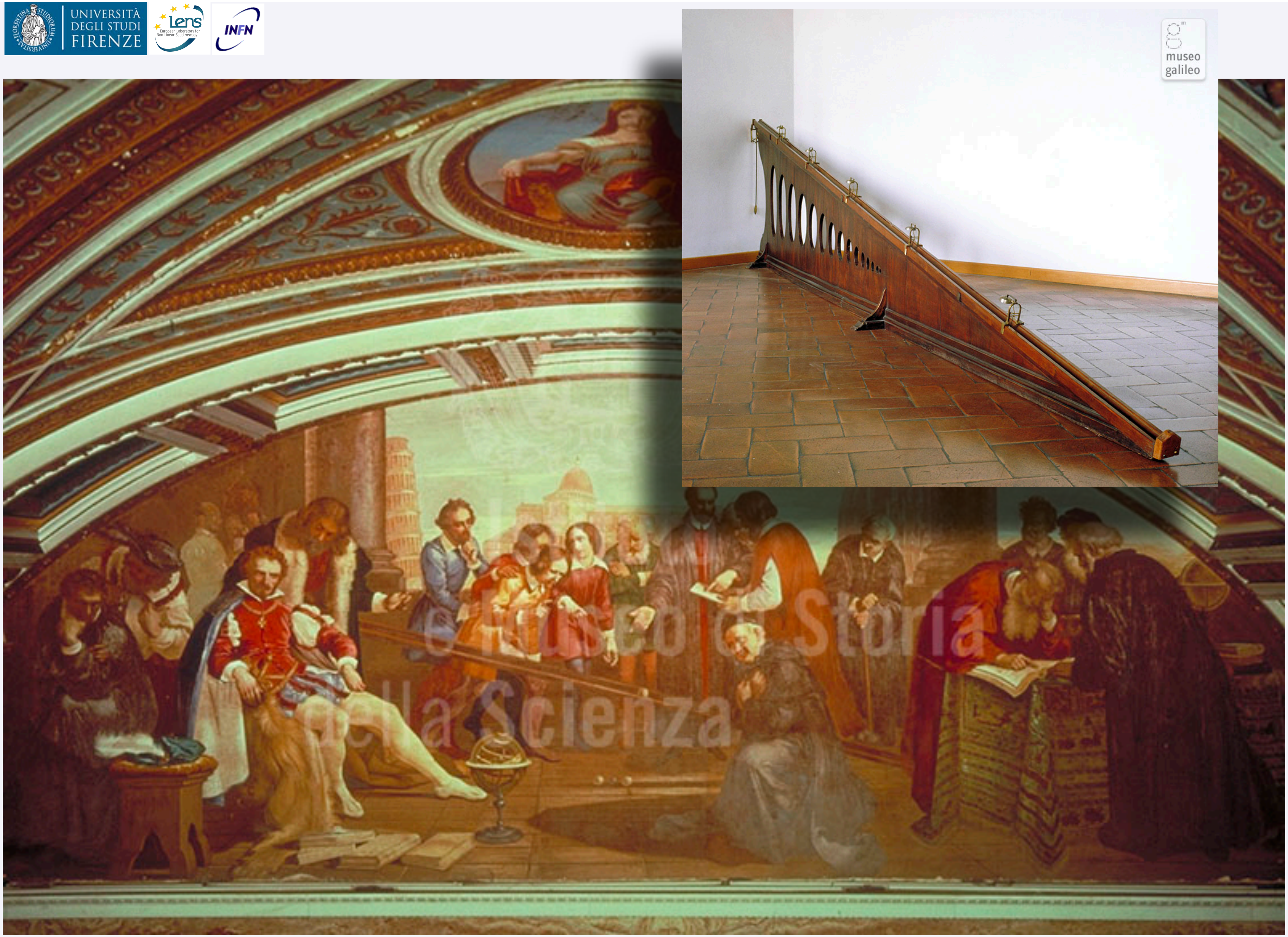
I was sitting on a chair in my
patent office in Bern.
Suddenly, a thought struck me:
If a man falls freely,
he would not feel his weight.
I was taken aback.
This simple thought experiment
made a deep impression on me.
This led to the theory of gravity.

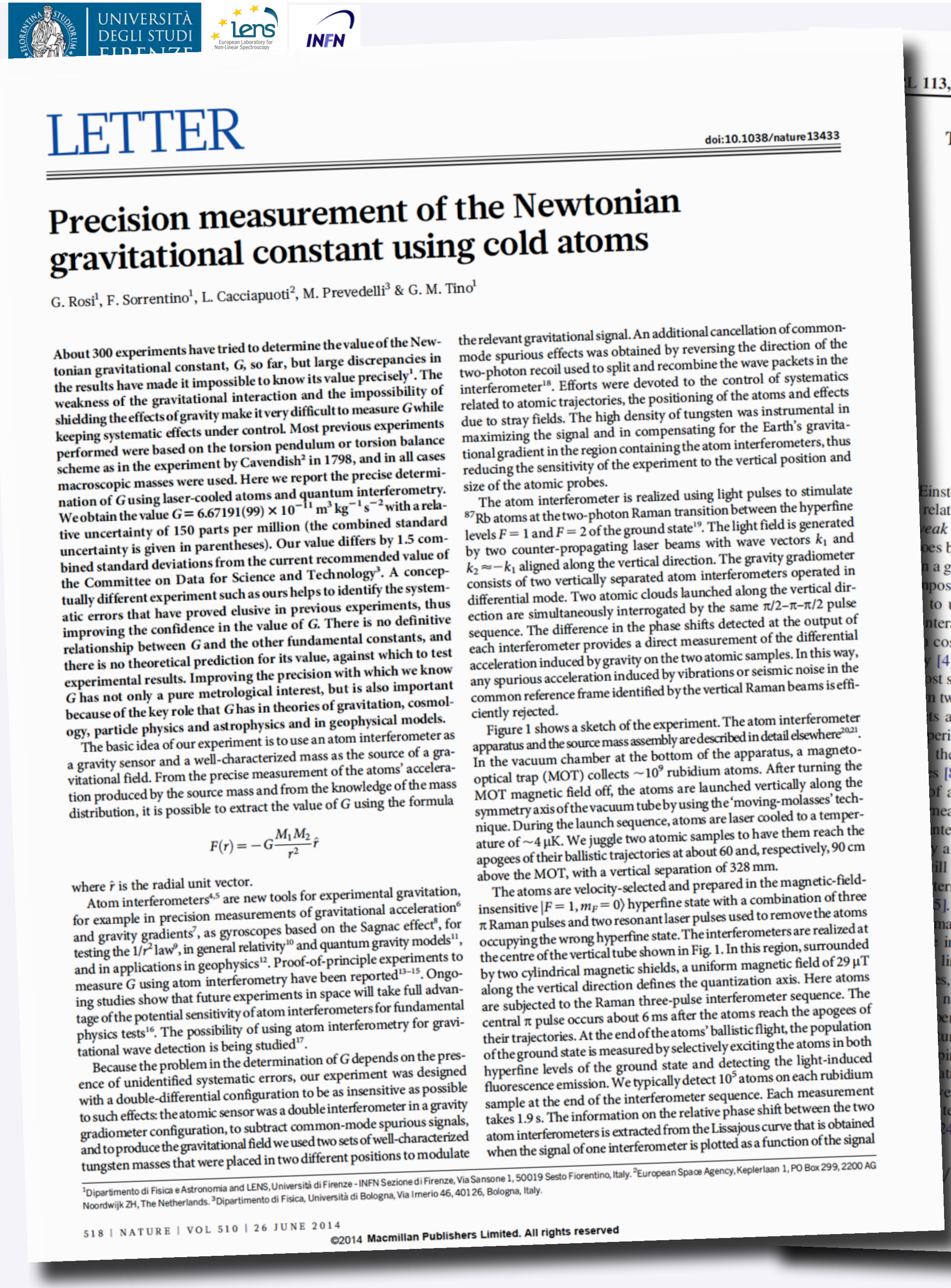
A. Einstein, How I created the theory of relativity,
Trad.: Ono Y. A., Physics Today, 35, 45 (1982)

La Relatività Galileiana

« Riserratevi con qualche amico nella maggiore stanza che sia sotto coverta di alcun gran navilio, e quivi fate d'aver mosche, farfalle e simili animaletti volanti; siavi anco un gran vaso d'acqua, e dentrovi de' pescetti; sospendasi anco in alto qualche secchiello, che a goccia a goccia vadia versando dell'acqua in un altro vaso di angusta bocca, che sia posto a basso: e stando ferma la nave, osservate diligentemente come quelli animaletti volanti con pari velocità vanno verso tutte le parti della stanza; i pesci si vedranno andar notando indifferentemente per tutti i versi; le stille cadenti entreranno tutte nel vaso sottoposto; e voi, gettando all'amico alcuna cosa, non piú gagliardamente la dovrete gettare verso quella parte che verso questa, quando le lontananze sieno eguali; e saltando voi, come si dice, a piè giunti, eguali spazii passerete verso tutte le parti. Osservate che avrete diligentemente tutte queste cose, benché niun dubbio ci sia che mentre il vassello sta fermo non debbano succeder cosí, ***fate muover la nave con quanta si voglia velocità; ché (pur che il moto sia uniforme e non fluttuante in qua e in là) voi non riconoscerete una minima mutazione in tutti li nominati effetti, né da alcuno di quelli potrete comprender se la nave cammina o pure sta ferma****: voi saltando passerete nel tavolato i medesimi spazii che prima né, perché la nave si muova velocissimamente, farete maggior salti verso la poppa che verso la prua, benché, nel tempo che voi state in aria, il tavolato sottopostovi scorra verso la parte contraria al vostro salto; e gettando alcuna cosa al compagno, non con piú forza bisognerà tirarla, per arrivarlo, se egli sarà verso la prua e voi verso poppa, che se voi fuste situati per l'opposito; le gocciole cadranno come prima nel vaso inferiore, senza caderne pur una verso poppa, benché, mentre la gocciola è per aria, la nave scorra molti palmi; i pesci nella lor acqua non con piú fatica noteranno verso la precedente che verso la sussequente parte del vaso, ma con pari agevolezza verranno al cibo posto su qualsivoglia luogo dell'orlo del vaso; e finalmente le farfalle e le mosche continueranno i lor voli indifferentemente verso tutte le parti, né mai accaderà che si riduchino verso la parete che riguarda la poppa, quasi che fussero stracche in tener dietro al veloce corso della nave, dalla quale per lungo tempo, trattenendosi per aria, saranno state separate… »*

Giornata Seconda del « Dialogo sui Massimi Sistemi del Mondo », (1623)





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 $G = 6.67191(99)\times10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ with a relative uncertainty of 150 parts per million (the combined standard uncertainty is given in parentheses). Our value differs by 1.5 combined standard deviations from the current recommended value of the Committee on Data for Science and Technology[3]. A conceptually different experiment such as ours helps to identify the systematic errors that have proved elusive in previous experiments, thus improving the confidence in the value of *G*. There is no definitive relationship between *G* and the other fundamental constants, and there is no theoretical prediction for its value, against which to test experimental results. Improving the precision with which we know *G* has not only a pure metrological interest, but is also important because of the key role that *G* has in theories of gravitation, cosmology, particle physics and astrophysics and in geophysical models.

The basic idea of our experiment is to use an atom interferometer as a gravity sensor and a well-characterized mass as the source of a gravitational field. From the precise measurement of the atoms' acceleration produced by the source mass and from the knowledge of the mass distribution, it is possible to extract the value of G using the formula

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

where $\hat{r}$ is the radial unit vector.

Atom interferometers[4,5] are new tools for experimental gravitation, for example in precision measurements of gravitational acceleration[6] and gravity gradients[7], as gyroscopes based on the Sagnac effect[8], for testing the $1/r^2$ law[9], in general relativity[10] and quantum gravity models[11], and in applications in geophysics[12]. Proof-of-principle experiments to measure G using atom interferometry have been reported[13–15]. Ongoing studies show that future experiments in space will take full advantage of the potential sensitivity of atom interferometers for fundamental physics tests[16]. The possibility of using atom interferometry for gravitational wave detection is being studied[17].

Because the problem in the determination of G depends on the presence of unidentified systematic errors, our experiment was designed with a double-differential configuration to be as insensitive as possible to such effects: the atomic sensor was a double interferometer in a gravity gradiometer configuration, to subtract common-mode spurious signals, and to produce the gravitational field we used two sets of well-characterized tungsten masses that were placed in two different positions to modulate 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 levels $F=1$ and $F=2$ of the ground state[19]. The light field is generated by two counter-propagating laser beams with wave vectors k_1 and $k_2 \approx -k_1$ aligned along the vertical direction. The gravity gradiometer consists of two vertically separated atom interferometers operated in differential mode. Two atomic clouds launched along the vertical direction are simultaneously interrogated by the same $\pi/2$–π–$\pi/2$ pulse sequence. The difference in the phase shifts detected at the output of each interferometer provides a direct measurement of the differential acceleration induced by gravity on the two atomic samples. In this way, any spurious acceleration induced by vibrations or seismic noise in the common reference frame identified by the vertical Raman beams is efficiently rejected.

Figure 1 shows a sketch of the experiment. The atom interferometer apparatus and the source mass assembly are described in detail elsewhere[20,21]. In the vacuum chamber at the bottom of the apparatus, a magneto-optical trap (MOT) collects ~10^9 rubidium atoms. After turning the MOT magnetic field off, the atoms are launched vertically along the symmetry axis of the vacuum tube by using the 'moving-molasses' technique. During the launch sequence, atoms are laser cooled to a temperature of ~4 μK. We juggle two atomic samples to have them reach the apogees of their ballistic trajectories at about 60 and, respectively, 90 cm above the MOT, with a vertical separation of 328 mm.

The atoms are velocity-selected and prepared in the magnetic-field-insensitive $|F=1, m_F=0\rangle$ hyperfine state with a combination of three π Raman pulses and two resonant laser pulses used to remove the atoms occupying the wrong hyperfine state. The interferometers are realized at the centre of the vertical tube shown in Fig. 1. In this region, surrounded by two cylindrical magnetic shields, a uniform magnetic field of 29 μT along the vertical direction defines the quantization axis. Here atoms are subjected to the Raman three-pulse interferometer sequence. The central π pulse occurs about 6 ms after the atoms reach the apogees of their trajectories. At the end of the atoms' ballistic flight, the population of the ground state is measured by selectively exciting the atoms in both hyperfine levels of the ground state and detecting the light-induced fluorescence emission. We typically detect 10^5 atoms on each rubidium sample at the end of the interferometer sequence. Each measurement takes 1.9 s. The information on the relative phase shift between the two atom interferometers is extracted from the Lissajous curve that is obtained when the signal of one interferometer is plotted as a function of the signal

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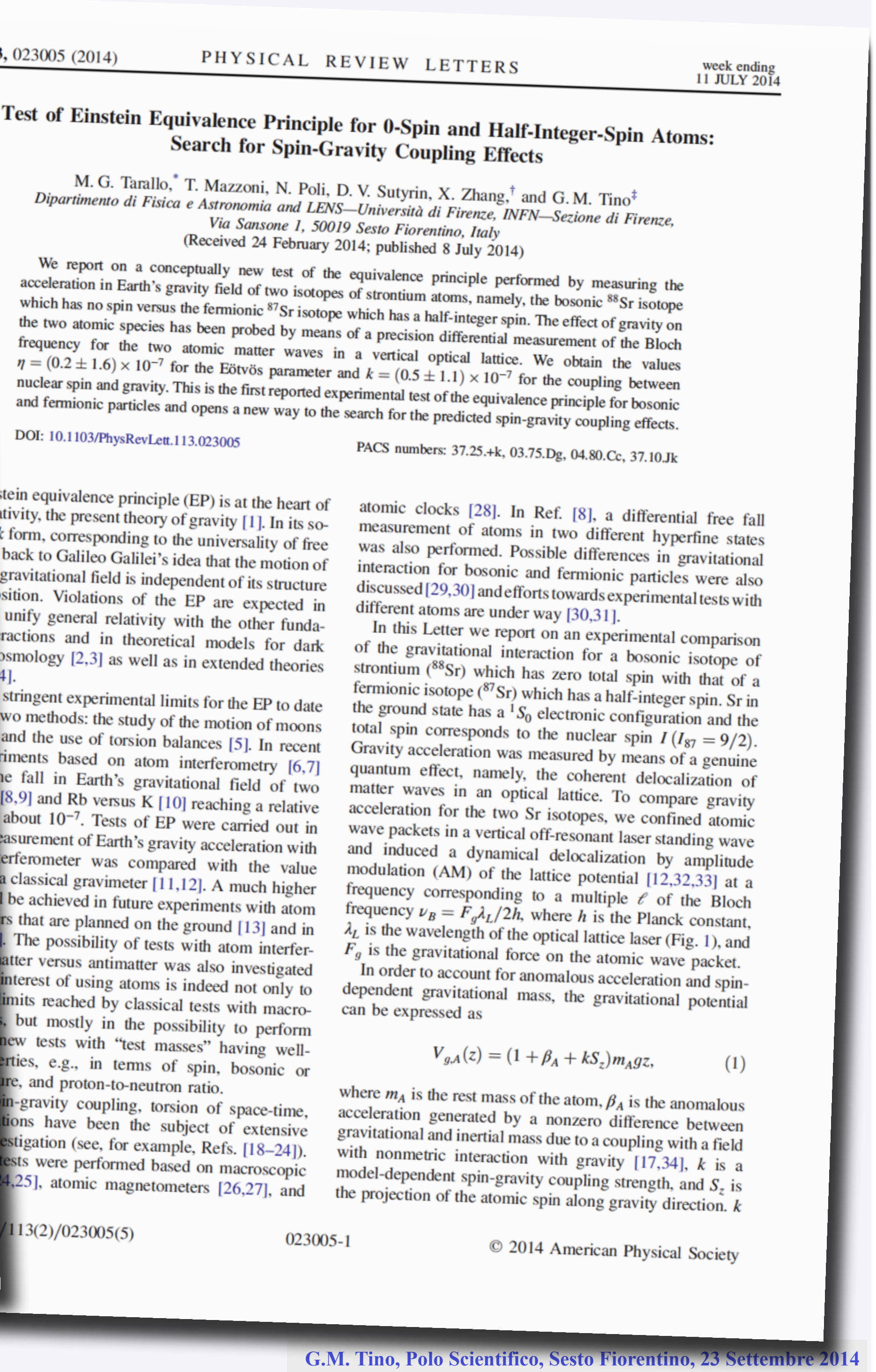

L 113, 023005 (2014) PHYSICAL REVIEW LETTERS week ending 11 JULY 2014

Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms: Search for Spin-Gravity Coupling Effects

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We report on a conceptually new test of the equivalence principle performed by measuring the acceleration in Earth's gravity field of two isotopes of strontium atoms, namely, the bosonic ^{88}Sr isotope which has no spin versus the fermionic ^{87}Sr isotope which has a half-integer spin. The effect of gravity on the two atomic species has been probed by means of a precision differential measurement of the Bloch frequency for the two atomic matter waves in a vertical optical lattice. We obtain the values $\eta = (0.2 \pm 1.6)\times10^{-7}$ for the Eötvös parameter and $k = (0.5 \pm 1.1)\times10^{-7}$ for the coupling between nuclear spin and gravity. This is the first reported experimental test of the equivalence principle for bosonic and fermionic particles and opens a new way to the search for the predicted spin-gravity coupling effects.

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PACS numbers: 37.25.+k, 03.75.Dg, 04.80.Cc, 37.10.Jk

Einstein equivalence principle (EP) is at the heart of relativity, the present theory of gravity [1]. In its so- *eak* form, corresponding to the universality of free oes back to Galileo Galilei's idea that the motion of n a gravitational field is independent of its structure nposition. Violations of the EP are expected in to unify general relativity with the other funda- nteractions and in theoretical models for dark cosmology [2,3] as well as in extended theories [4].

ost stringent experimental limits for the EP to date n two methods: the study of the motion of moons ts and the use of torsion balances [5]. In recent periments based on atom interferometry [6,7] the fall in Earth's gravitational field of two s [8,9] and Rb versus K [10] reaching a relative of about 10^{-7}. Tests of EP were carried out in neasurement of Earth's gravity acceleration with nterferometer was compared with the value a classical gravimeter [11,12]. A much higher ill be achieved in future experiments with atom ters that are planned on the ground [13] and in 5]. The possibility of tests with atom interfer- matter versus antimatter was also investigated interest of using atoms is indeed not only to limits reached by classical tests with macro- s, but mostly in the possibility to perform new tests with “test masses” having well- perties, e.g., in terms of spin, bosonic or ure, and proton-to-neutron ratio.

pin-gravity coupling, torsion of space-time, ations have been the subject of extensive estigation (see, for example, Refs. [18–24]). tests were performed based on macroscopic 4,25], atomic magnetometers [26,27], and atomic clocks [28]. In Ref. [8], a differential free fall measurement of atoms in two different hyperfine states was also performed. Possible differences in gravitational interaction for bosonic and fermionic particles were also discussed [29,30] and efforts towards experimental tests with different atoms are under way [30,31].

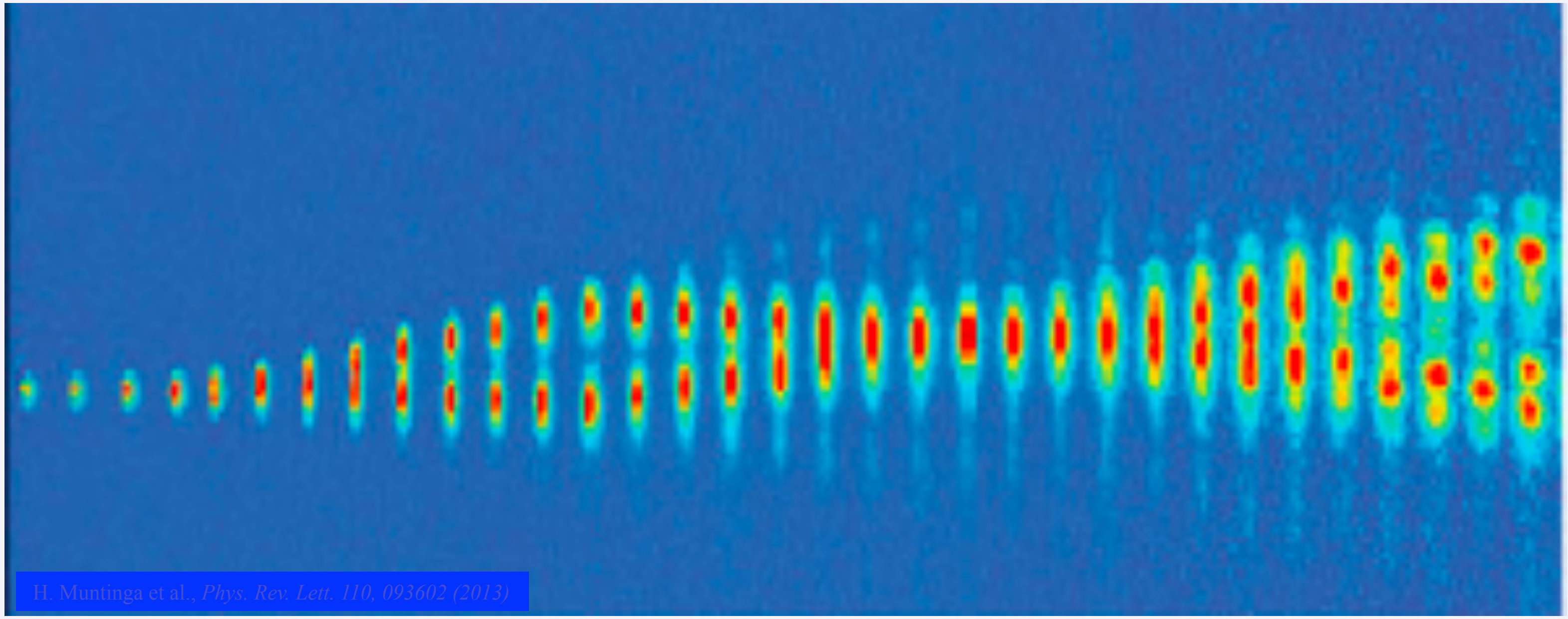
In this Letter we report on an experimental comparison of the gravitational interaction for a bosonic isotope of strontium (^{88}Sr) which has zero total spin with that of a fermionic isotope (^{87}Sr) which has a half-integer spin. Sr in the ground state has a $^1S_0$ electronic configuration and the total spin corresponds to the nuclear spin I ($I_{87} = 9/2$). Gravity acceleration was measured by means of a genuine quantum effect, namely, the coherent delocalization of matter waves in an optical lattice. To compare gravity acceleration for the two Sr isotopes, we confined atomic wave packets in a vertical off-resonant laser standing wave and induced a dynamical delocalization by amplitude modulation (AM) of the lattice potential [12,32,33] at a frequency corresponding to a multiple ℓ of the Bloch frequency $\nu_B = F_g\lambda_L/2h$, where h is the Planck constant, λ_L is the wavelength of the optical lattice laser (Fig. 1), and F_g is the gravitational force on the atomic wave packet.

In order to account for anomalous acceleration and spin-dependent gravitational mass, the gravitational potential can be expressed as

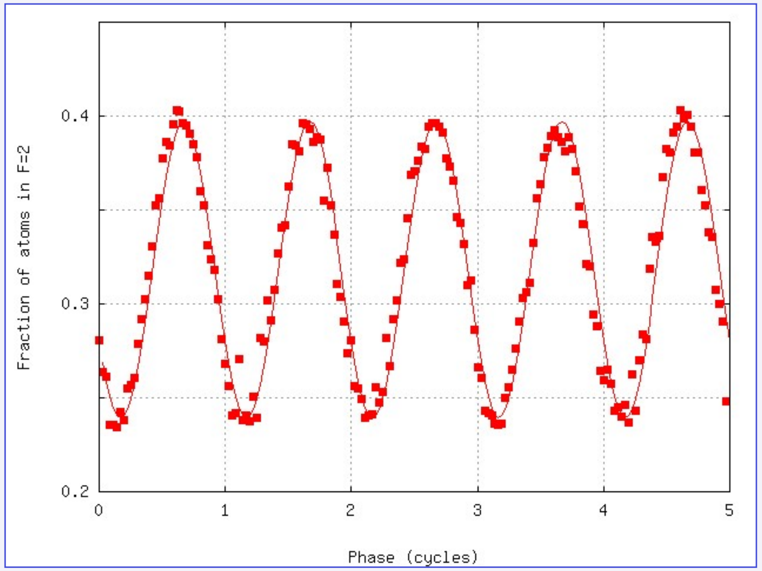
$$V_{g,A}(z) = (1 + \beta_A + kS_z)m_A g z, \tag{1}$$

where m_A is the rest mass of the atom, β_A is the anomalous acceleration generated by a nonzero difference between gravitational and inertial mass due to a coupling with a field with nonmetric interaction with gravity [17,34], k is a model-dependent spin-gravity coupling strength, and S_z is the projection of the atomic spin along gravity direction. k

Interferometria Atomica



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



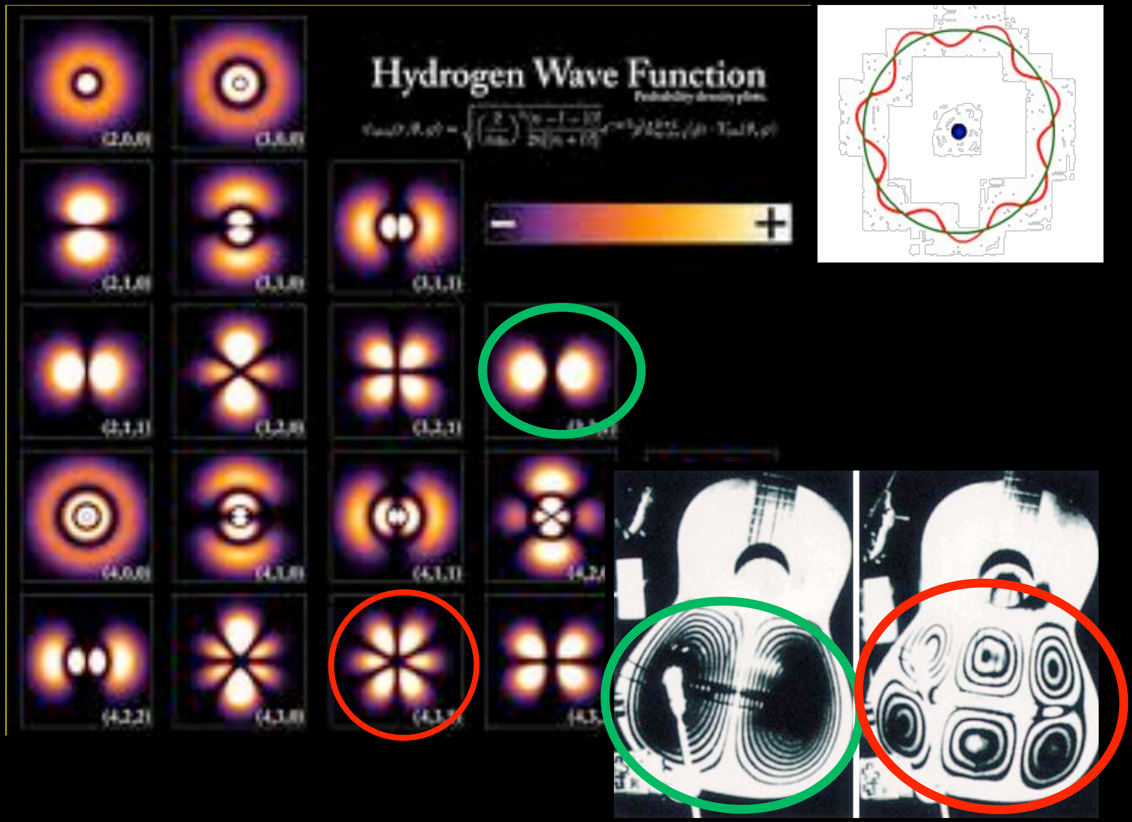
Frange d’interferenza atomica – Firenze 2006

Meccanica Quantistica
Modello di Bohr dell’atomo d’idrogeno (1913)

Meccanica Quantistica
Equazione di Schrödinger per la funzione d'onda

Erwin Schrödinger
(1887 -1961)

$$i\hbar \frac{d}{dt}\Psi(\vec{r},t) = \left[-\frac{\hbar^2}{2m}\Delta + V(\vec{r})\right]\Psi(\vec{r},t)$$



da Klaus Mölmer
AARHUS
UNIVERSITET

SCIENCE AND TECHNOLOGY

Matter Waves

Luis de-Broglie 1924:

Particles with rest-mass $m_0>0$ (electrons, neutrons, atoms, molecules) are elementary quanta of a wave field $\Psi(x,t)$

relativistic:

$$\hbar\omega = E = mc^2 = \gamma m_0 c^2$$

$$\hbar|\vec{k}| = \frac{h}{\lambda} = |\vec{p}| = mv = \gamma m_0 v$$

non - relativistic:

$$\lambda_{dB} = \frac{h}{mv} \qquad \hbar k = mv$$

Optics with
Matter Waves:
Some numbers

Particle	Energy	Velocity	Wave length
Neutron	0.025 eV	2200 m/s	2.2 A
Electron	100 eV	$6\ 10^6$ m/s	1.2 A
Na (atomic beam)	0.11 eV	1000 m/s	0.17 A
Cs (laser cooled)	$7\ 10^{-11}$ eV	1 cm/s	3000 A

from J. Schmiedmayer, E. Fermi School on "Atom Interferometry", Varenna 2013

Interferenza quantistica

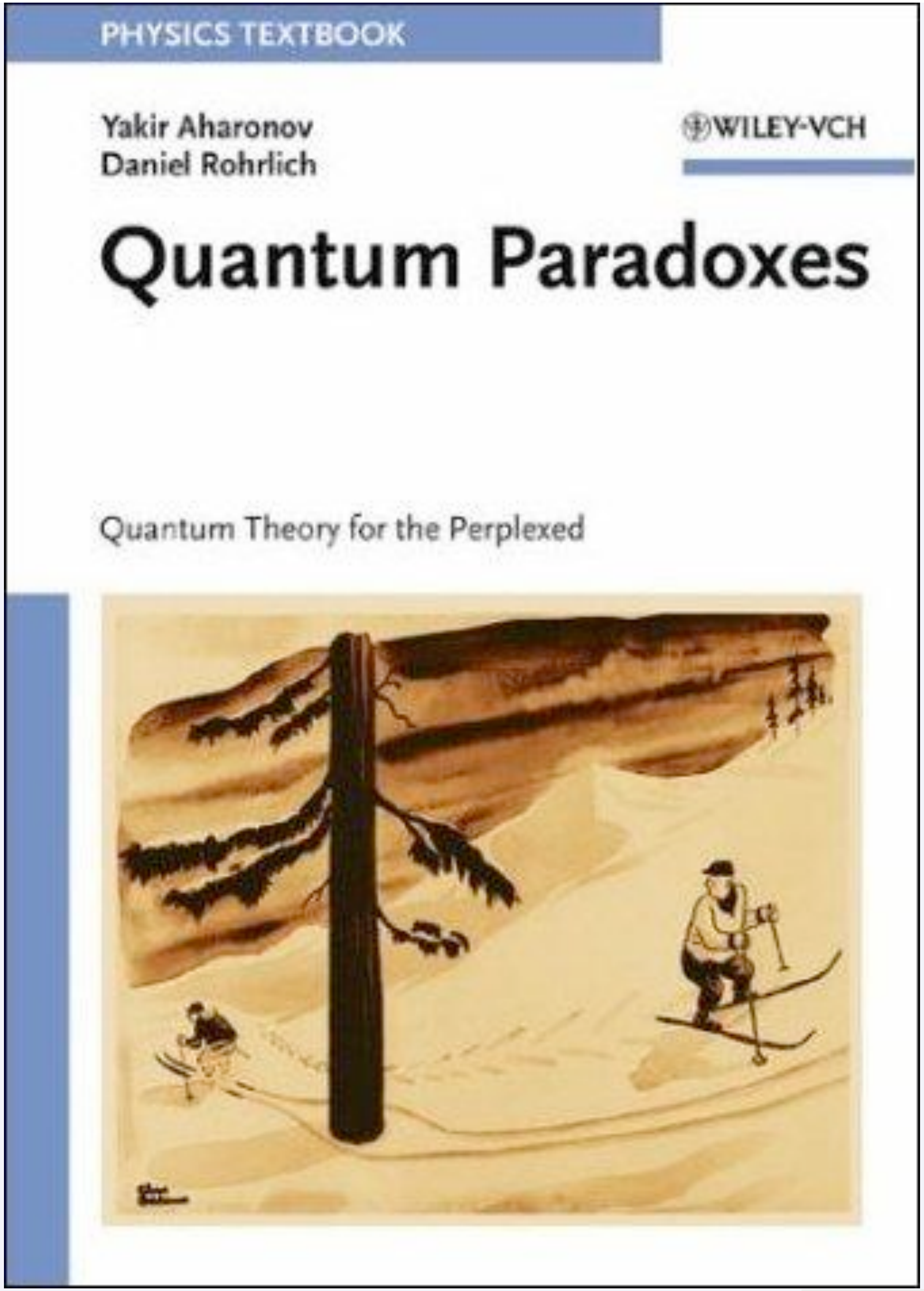
Fisica classica: una particella può viaggiare lungo il cammino A **o** lungo il cammino B

Fisica quantistica: una particella può viaggiare lungo il cammino A **e** lungo il cammino B **contemporaneamente**

La particella si trova in uno stato di sovrapposizione delle due traiettorie.

La **funzione d'onda** che caratterizza il sistema si scrive

$$\boxed{\begin{gathered}|\phi_A\rangle + |\phi_B\rangle = \\ |\text{particella sul percorso A}\rangle + |\text{particella sul percorso B}\rangle\end{gathered}}$$



PHYSICS TEXTBOOK

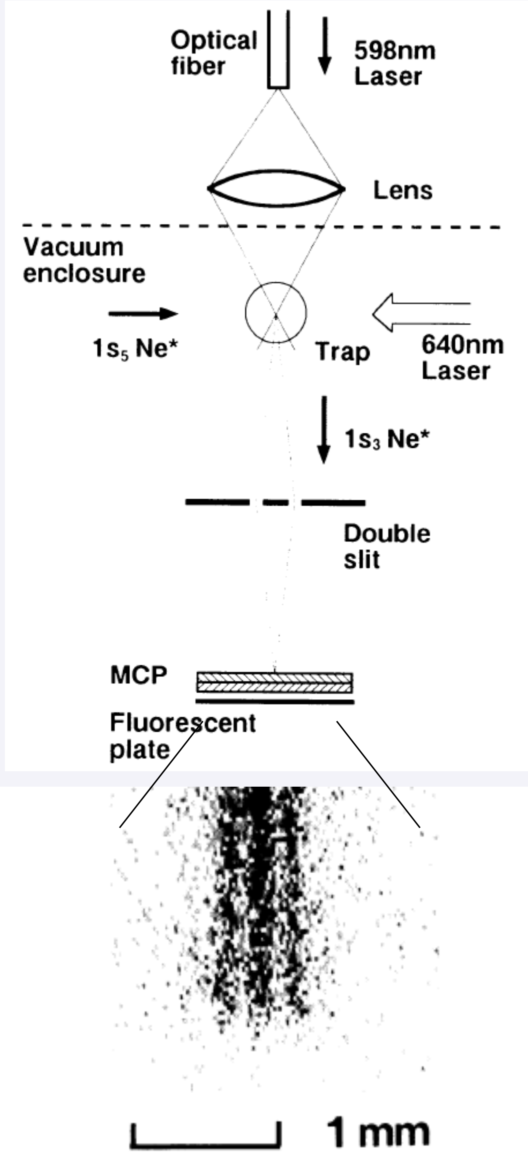
Yakir Aharonov
Daniel Rohrlich

WILEY-VCH

Quantum Paradoxes

Quantum Theory for the Perplexed

Atoms are particles or waves?
Wave-Particle Duality in QM



Cold atom source
→ large λ_{dB}
→ large fringe spacing

Metastable atoms
→ single atom detection
→ wave/particle duality for atoms

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

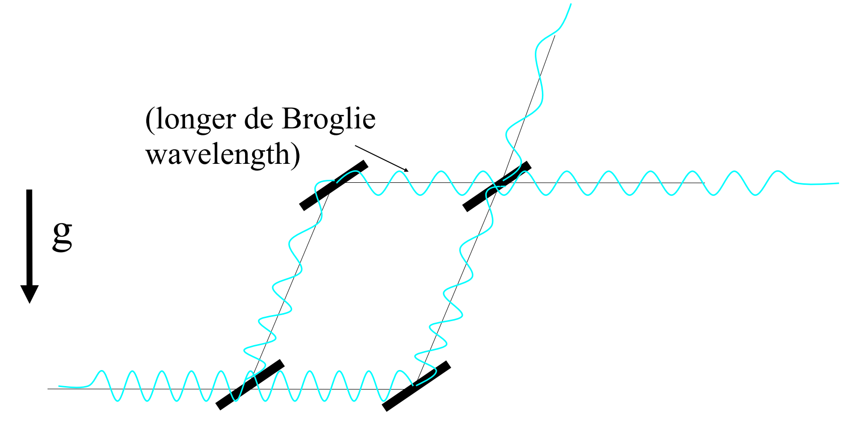
Atom interferometer force sensors

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

$$\boxed{\lambda_{dB} = \frac{h}{Mv}}$$

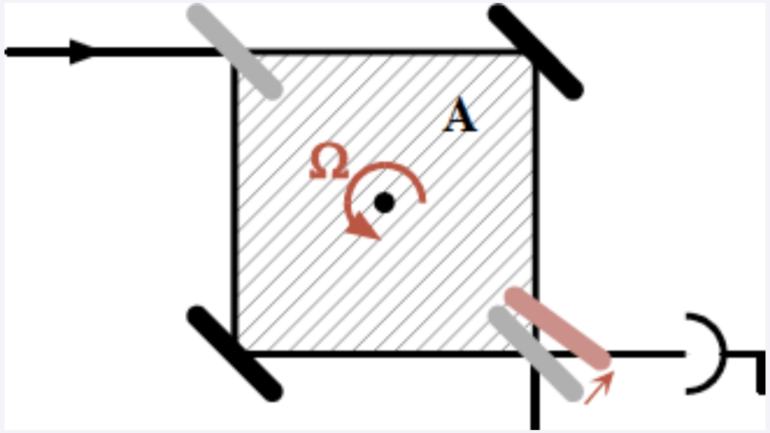
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



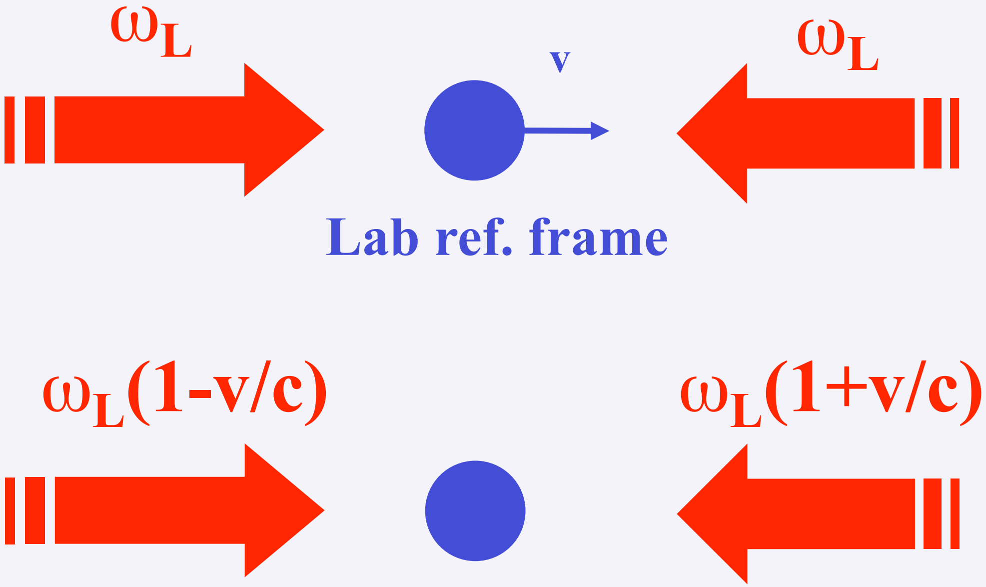
Rotations

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



From M. Kasevich

Laser Cooling of Atoms



ω_L v ω_L

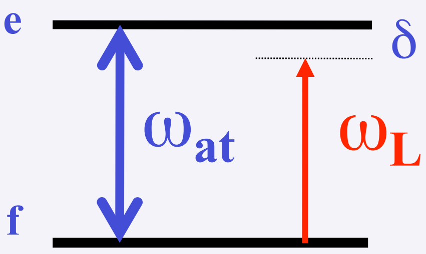
Lab ref. frame

$\omega_L(1\text{-}v/c)$ $\omega_L(1+v/c)$

Atom ref. frame

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

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



$\omega_{at} > \omega_L$

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

Laser cooling: atomic temperatures

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

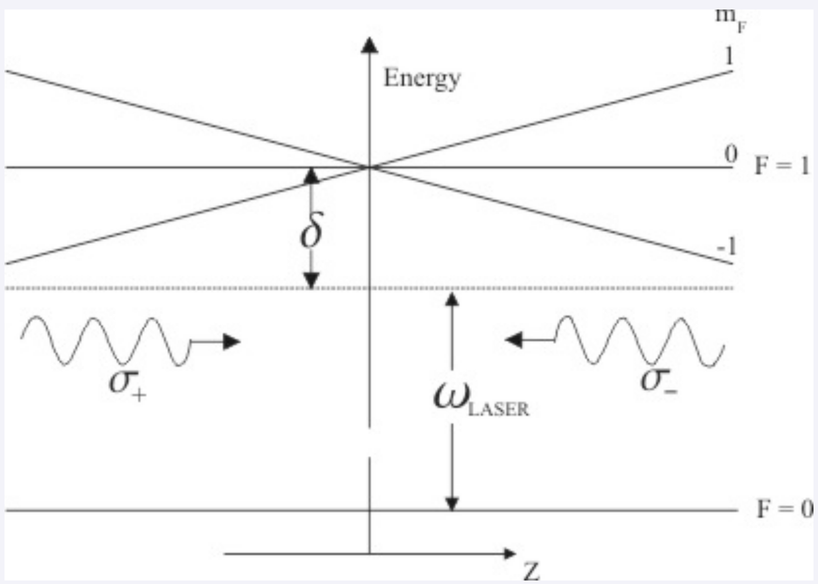
Minimum temperature for Doppler cooling: $\boxed{k_B T_D = \frac{h\Gamma}{2}}$

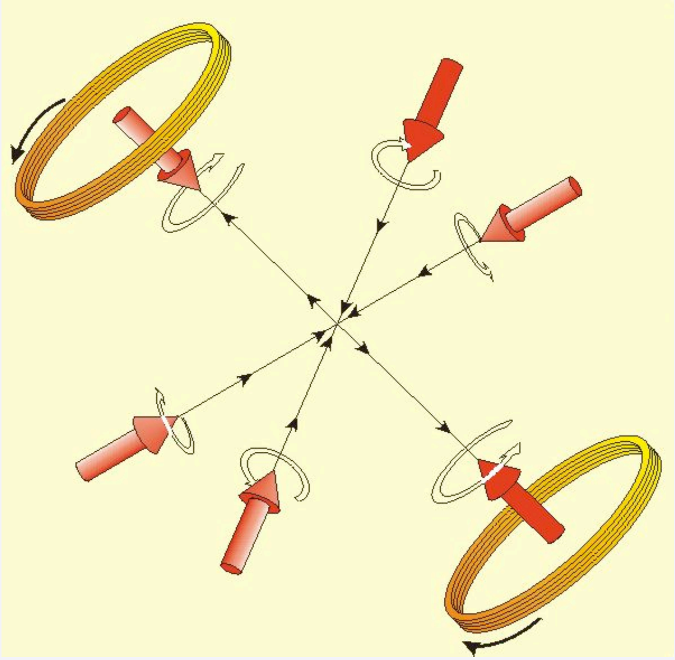
Single photon recoil temperature: $\boxed{k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2}$

Examples:

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

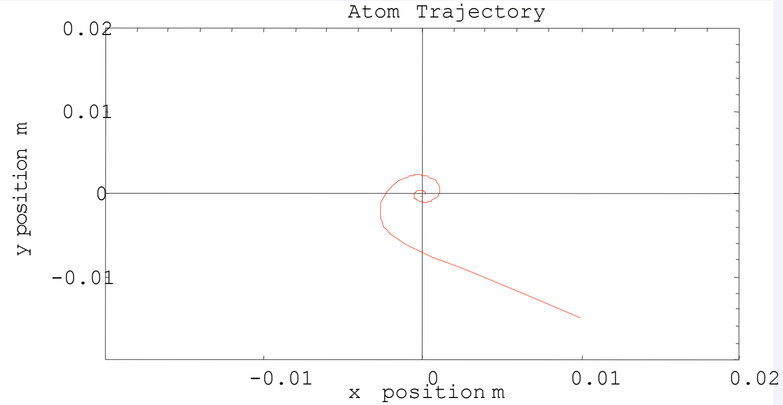
Magneto-Optical Trap (MOT)





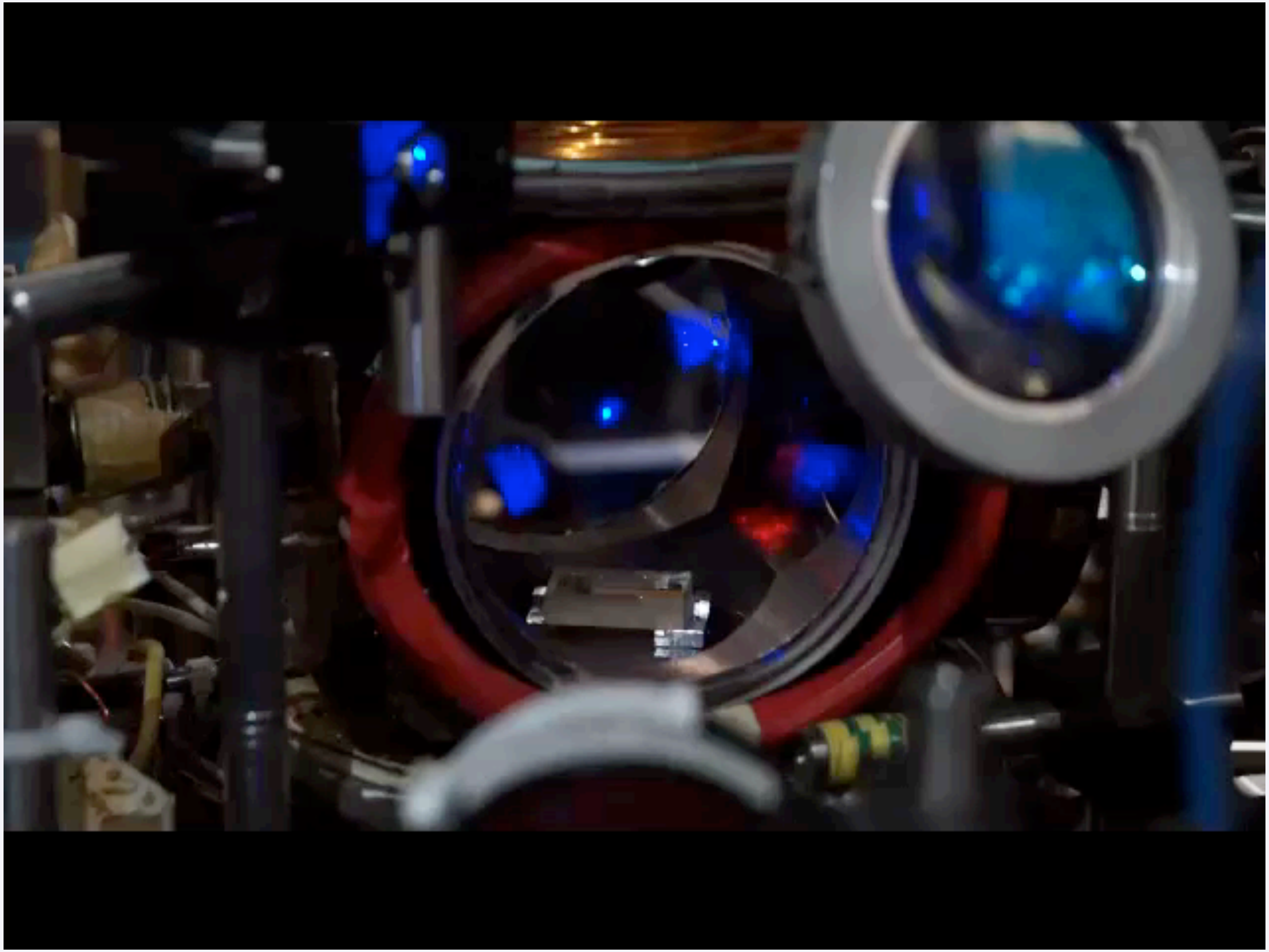
$$F(z,v) \simeq \frac{4hk}{\pi}\frac{I}{I_0}\frac{\delta}{\Gamma}\frac{kv+\beta z}{[1+(\frac{2\delta}{\Gamma})^2]^2}$$

density n $\approx 10^{11}$ cm^{-3}
temperature T ≈ 100 μK
size Δx ≈ 1 mm



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

Sr Magneto-Optical Trap (MOT)
LENS - Firenze



Nobel Prize in Physics 1997

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.

Steven Chu
Stanford University, Stanford, California, USA

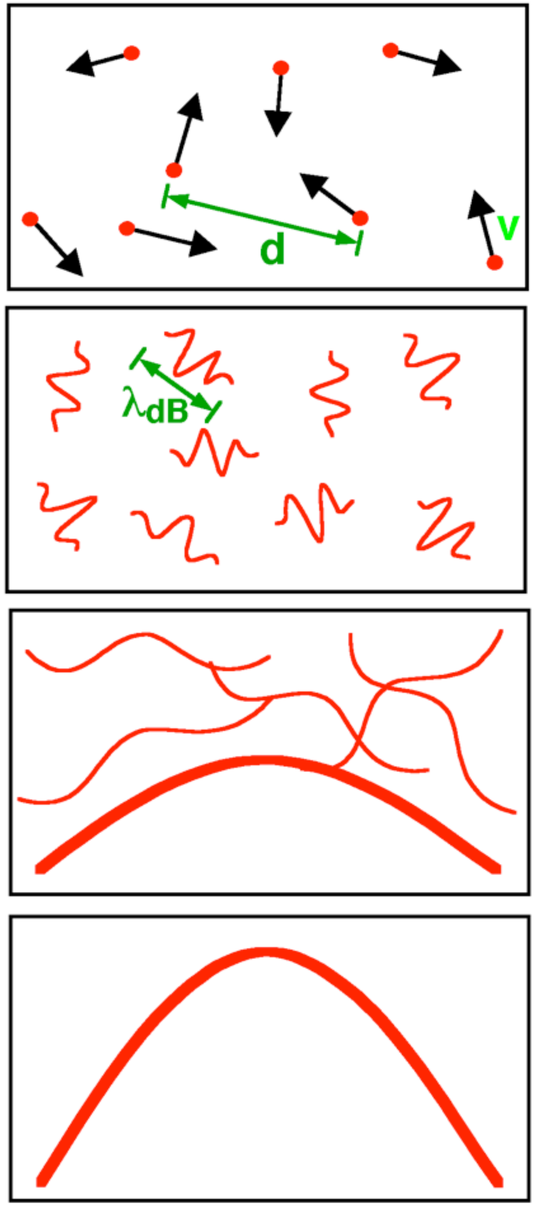
Claude Cohen-Tannoudji
Collège de France and École Normale Supérieure, Paris, France

William D. Phillips
National Institute of Standards and Technology, Gaithersburg, Maryland, USA

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.

Bose-Einstein Condensation

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"

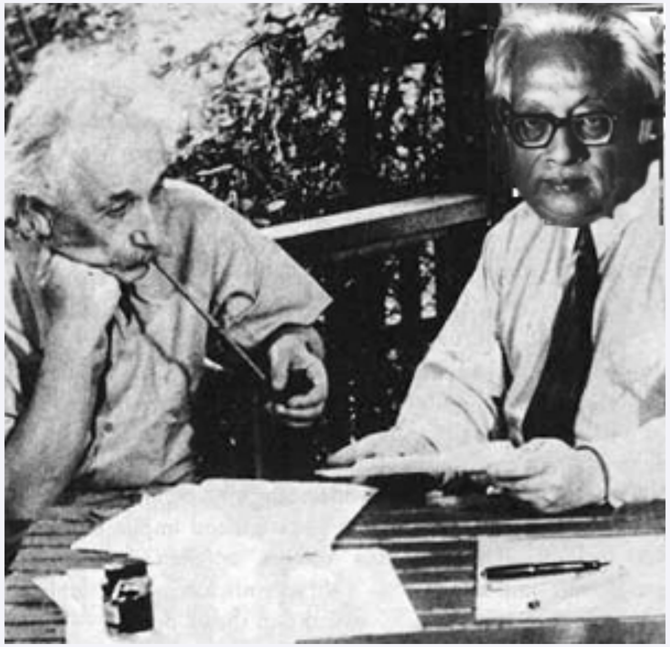
from W. Ketterle

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***.

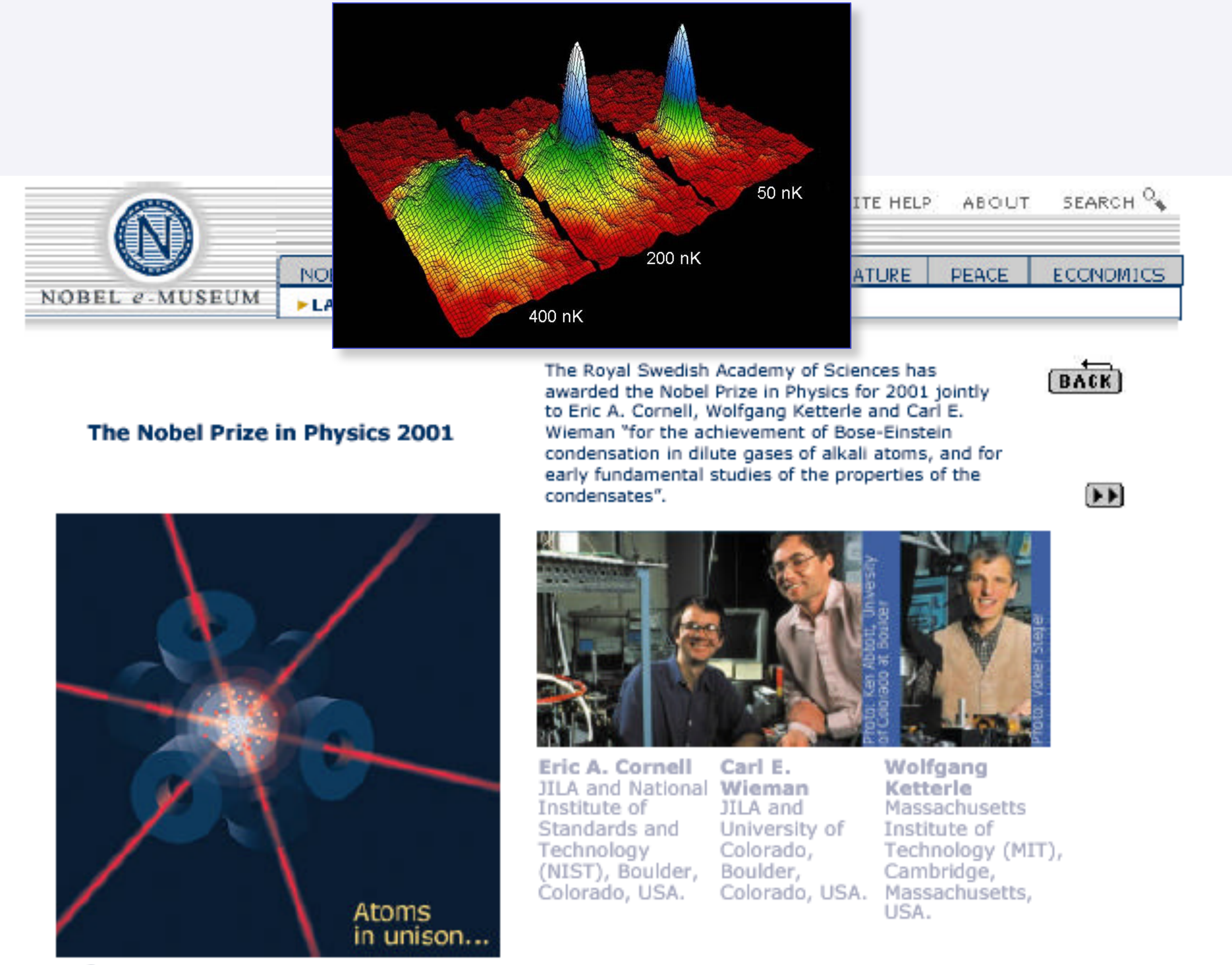
The atoms are called ***bosons***.



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

LENS - Arcetri, 1998

Nobel Prize in Physics 2001



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".

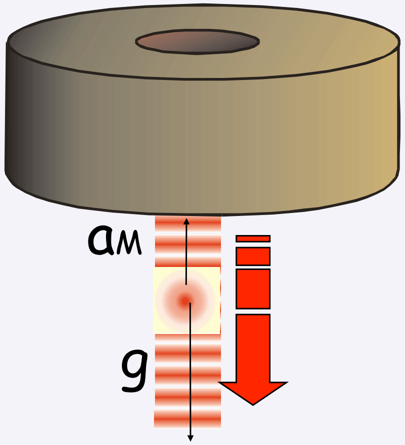
Eric A. Cornell	Carl E. Wieman	Wolfgang Ketterle
JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.	JILA and University of Colorado, Boulder, Colorado, USA.	Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Contents:

MAGIA

(*Misura Accurata di G mediante Interferometria Atomica*)

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

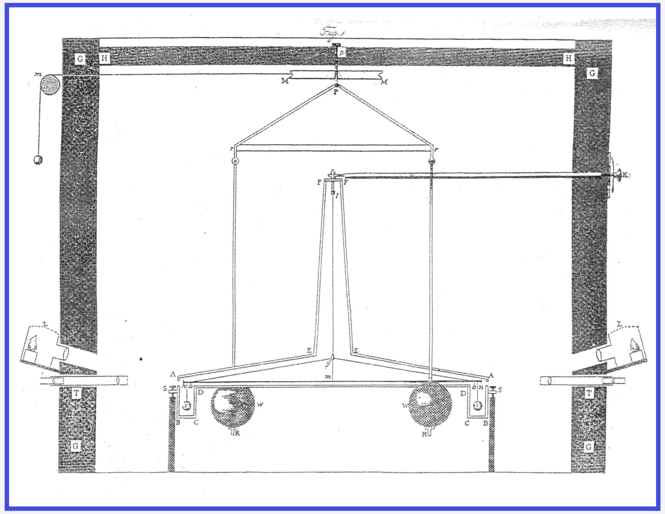


↓

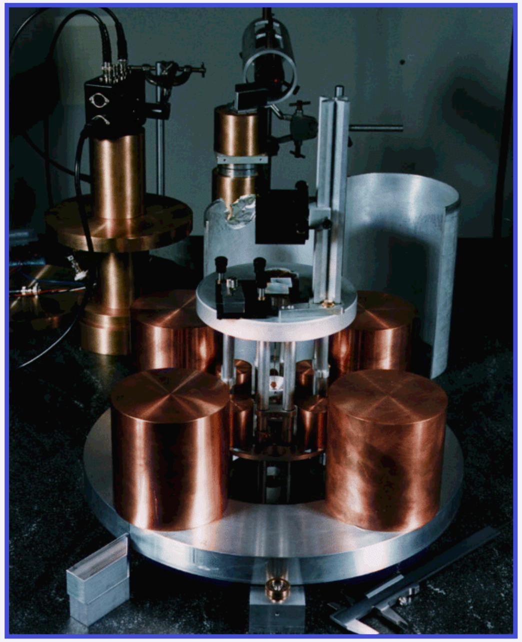
➢ ***Precision measurement of G***

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

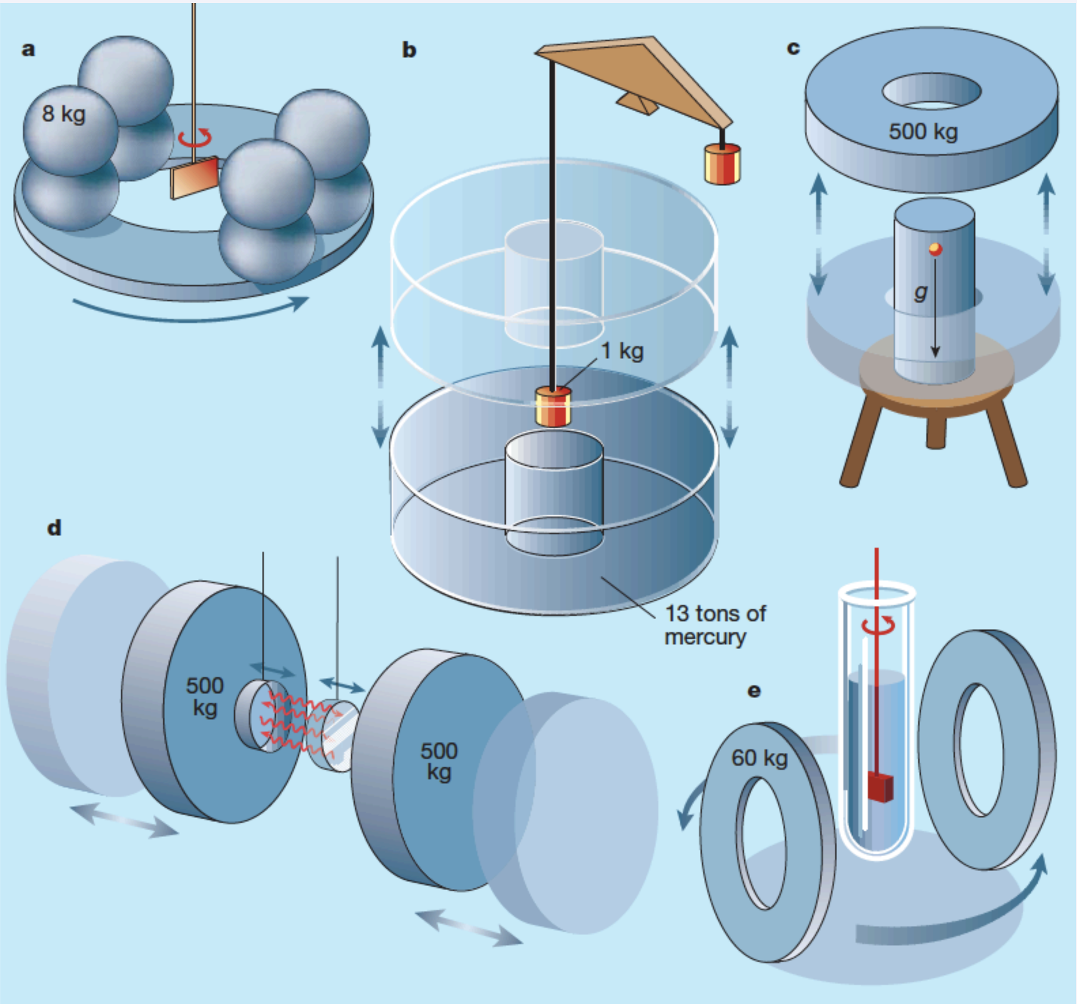
Measurements of the Newtonian gravitational constant G



Cavendish 1798

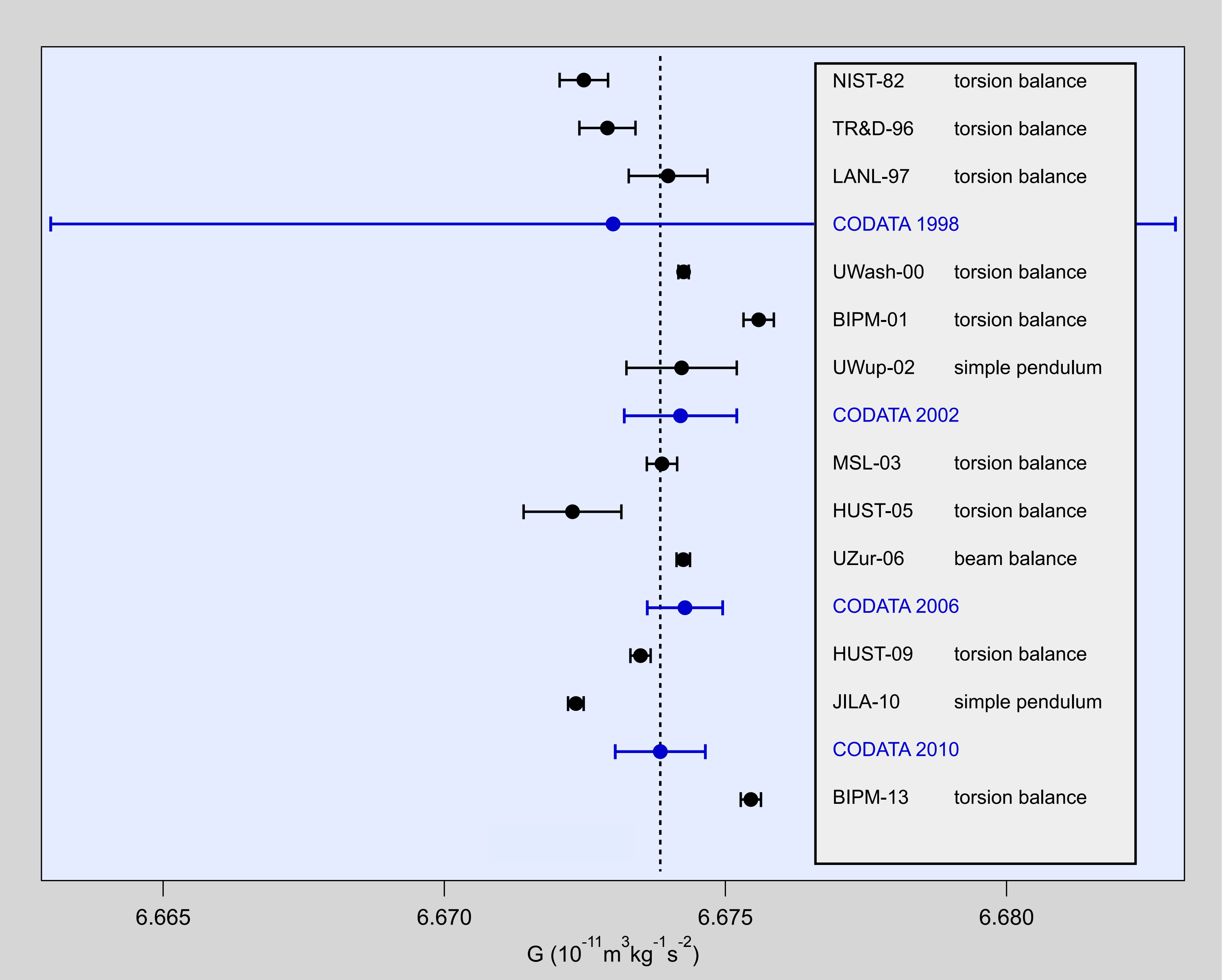


Quinn 2001

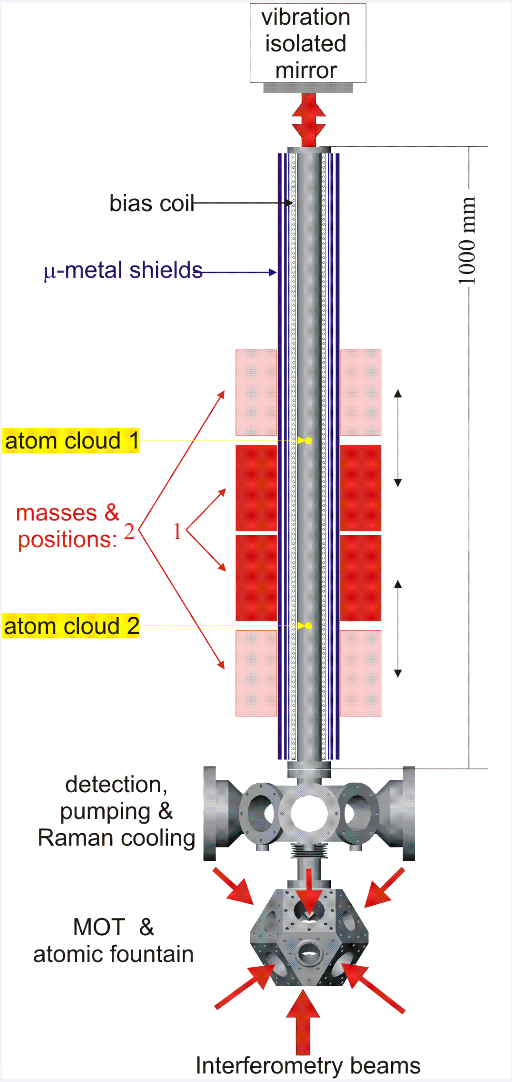


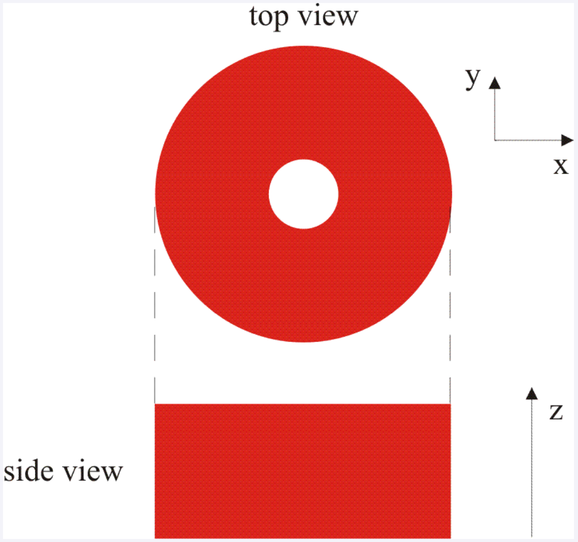
Terry Quinn. Measuring big G, NATURE|VOL 408 | 21/28 DECEMBER 2000

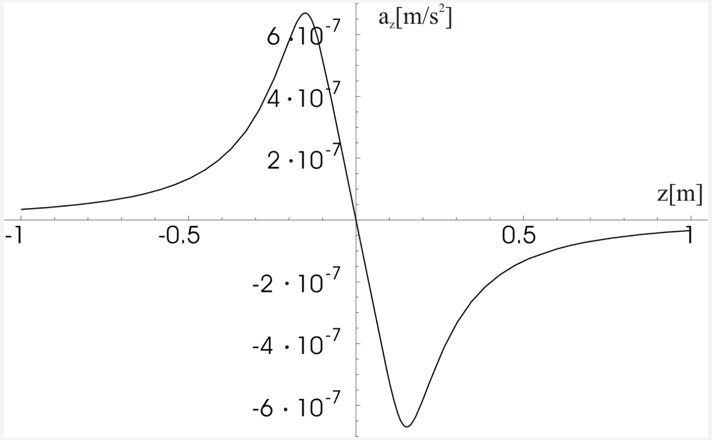
Measurements of the Newtonian gravitational constant G



MAGIA: atom gravimeter + source mass







500 kg tungsten mass

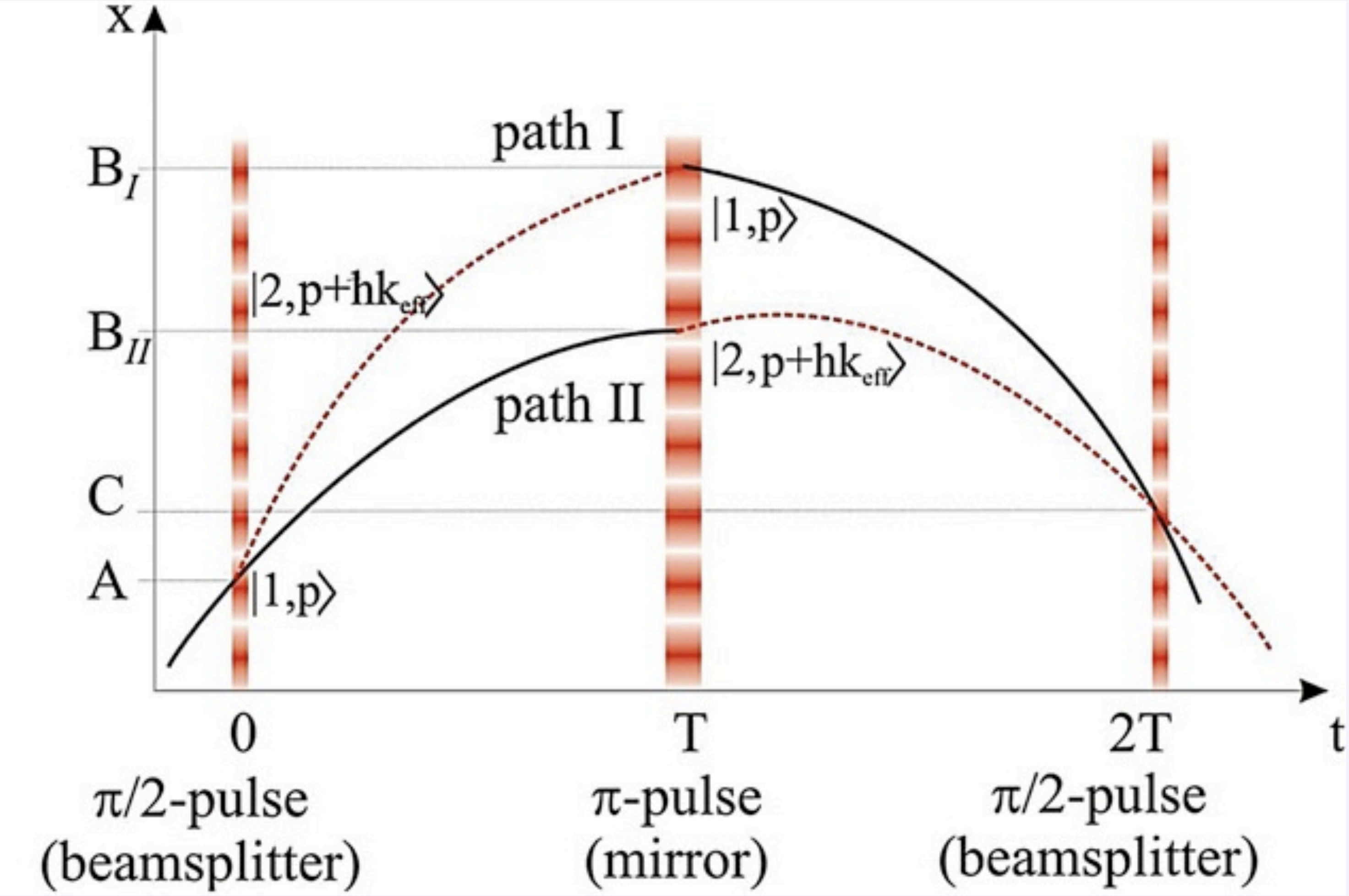
Sensitivity 10^{-9}g/shot

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

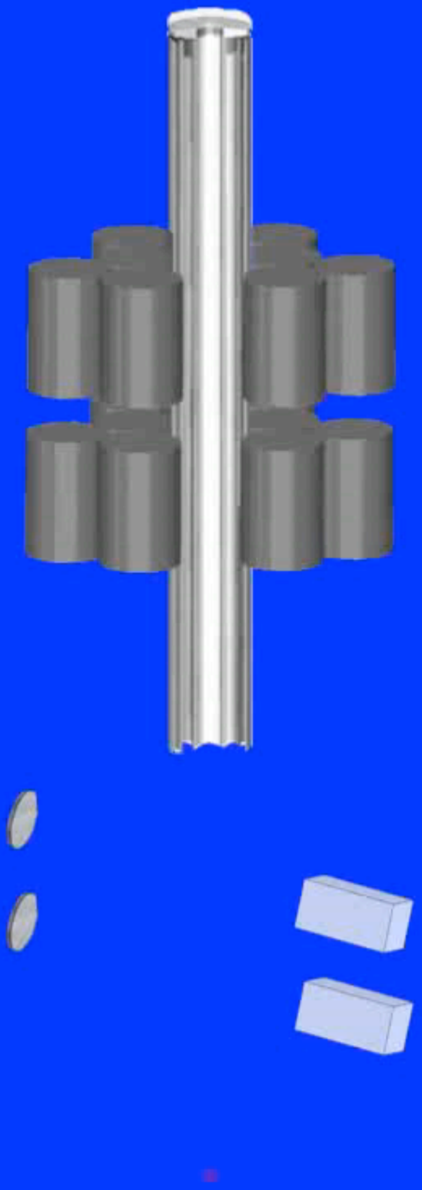
one shot ⇒ $\Delta G/G \approx 10^{-2}$

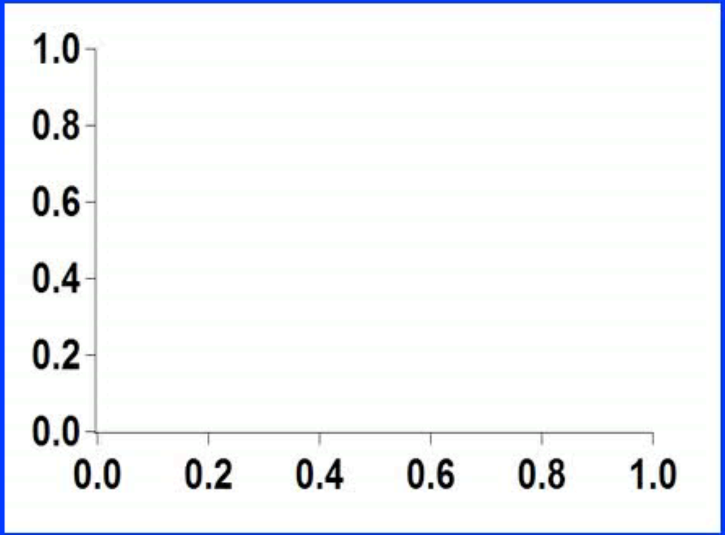
10000 shots ⇒ $\boldsymbol{\Delta G/G \approx 10^{-4}}$

Raman atom interferometry

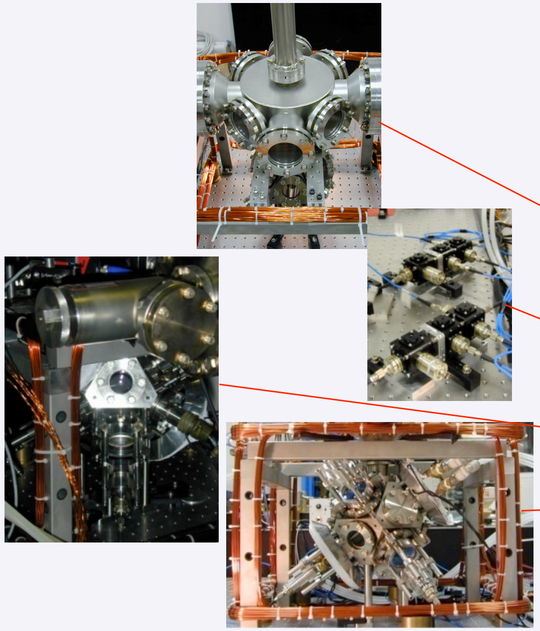


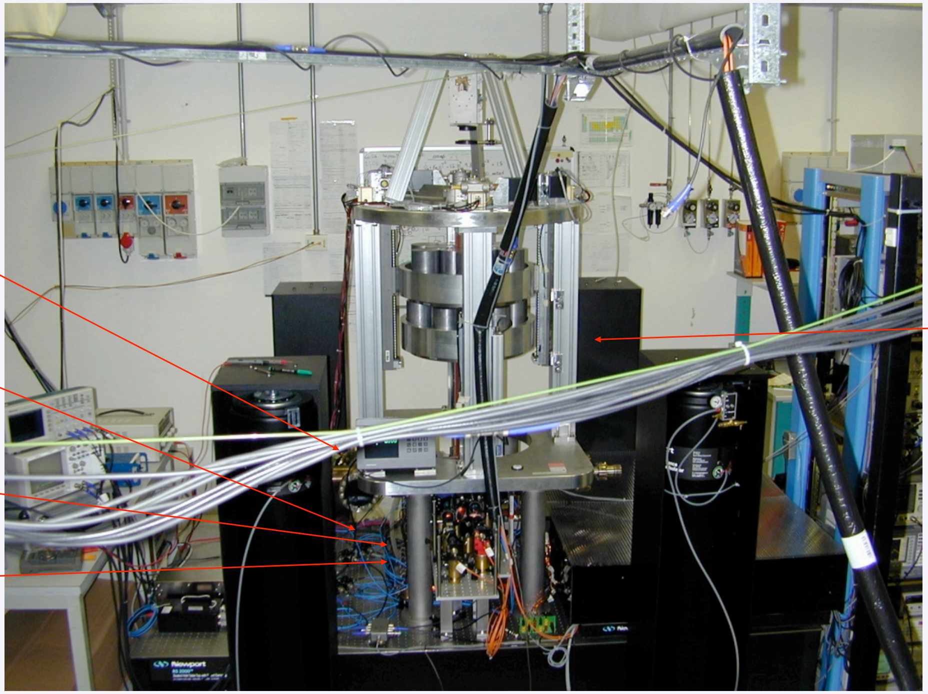
MAGIA





MAGIA apparatus

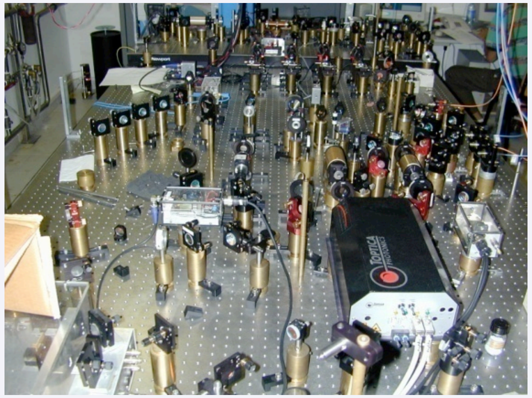


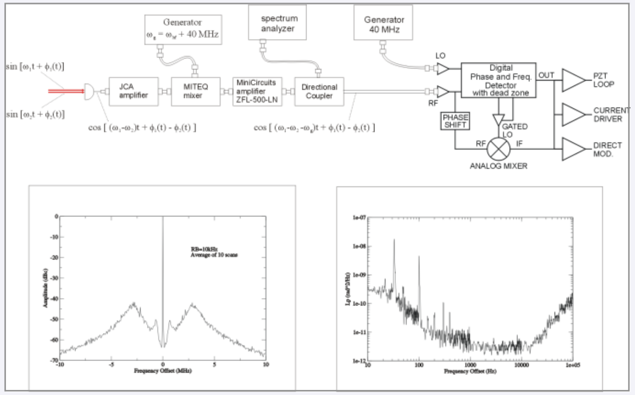


Source masses and support

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)**

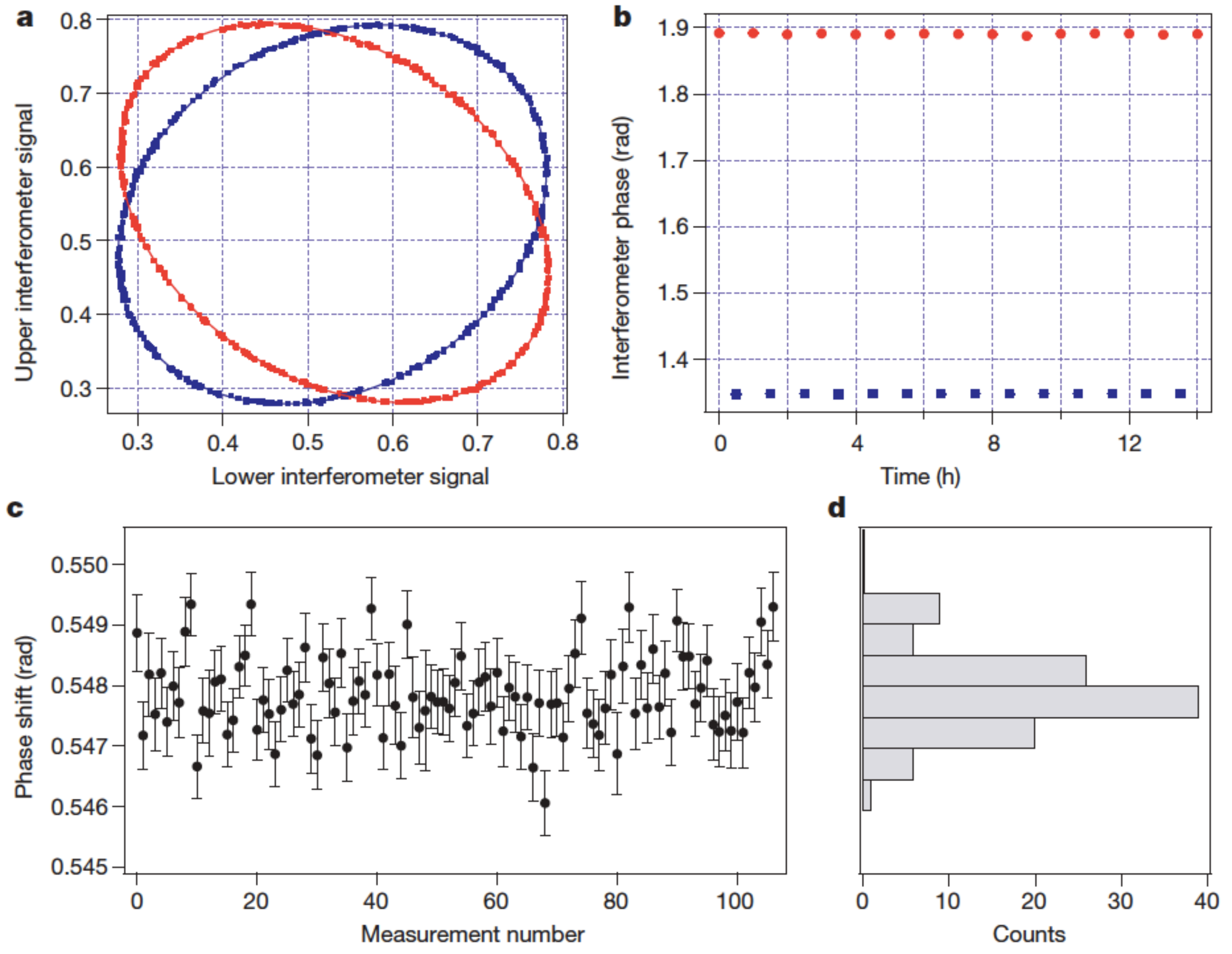
Laser and optical system





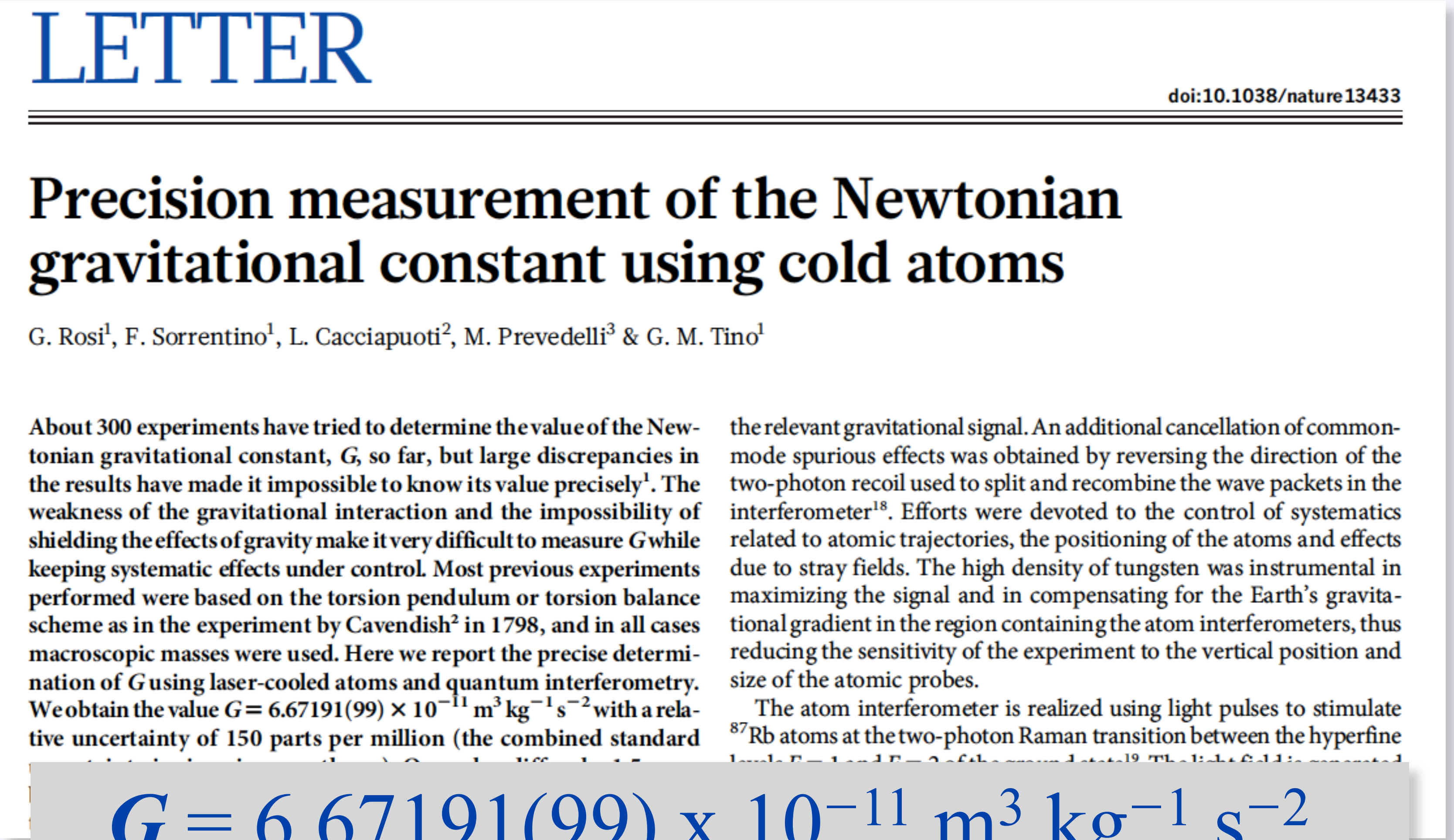
L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* **Rev. Scient. Instr. 76, 053111 (2005)**

Measurement of G



(July 2013)

Relative uncertainty ~ 116 ppm (statistical)



LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

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

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

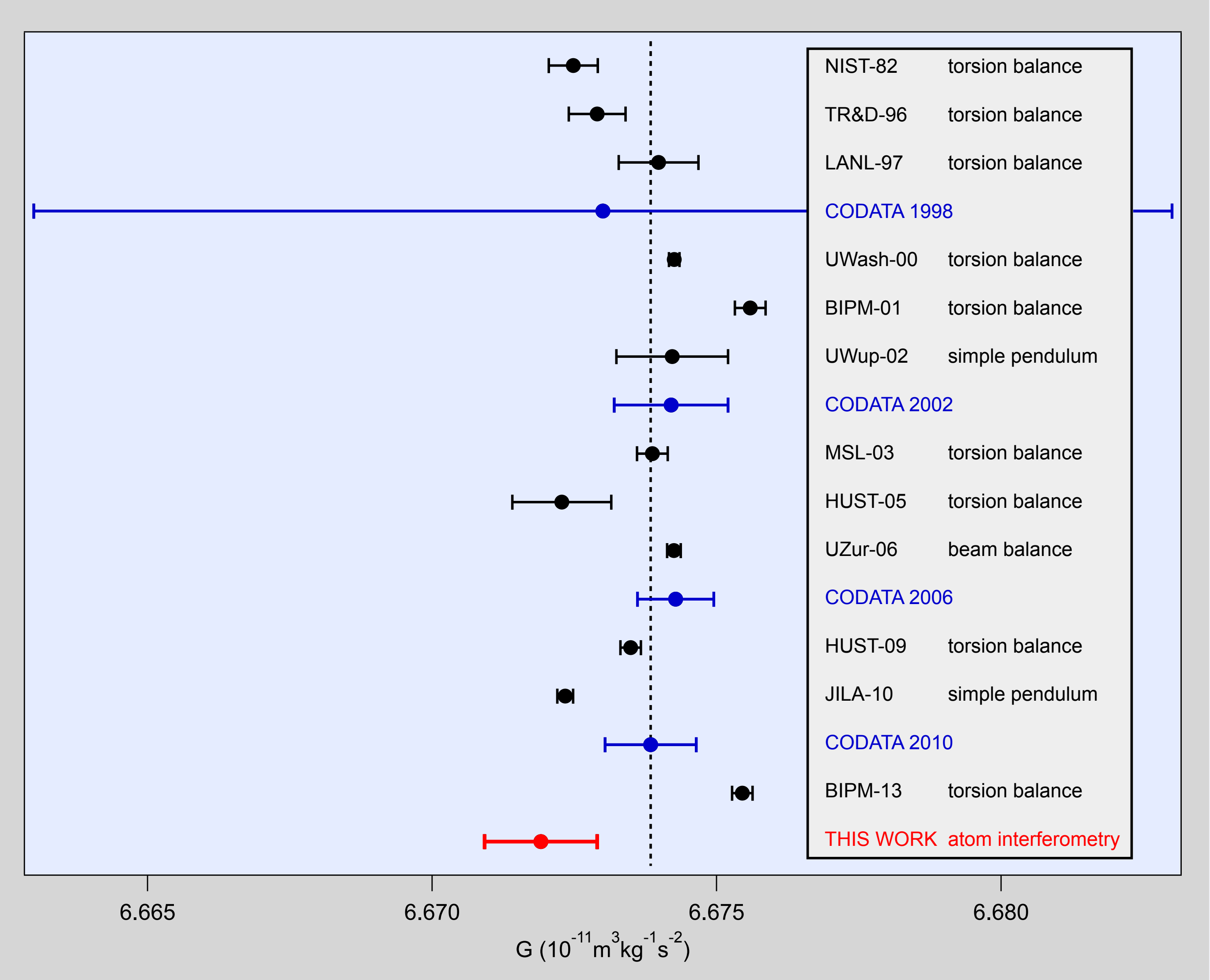
The atom interferometer is realized using light pulses to stimulate ^{87}Rb atoms at the two-photon Raman transition between the hyperfine

$$G = 6.67191(99) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$$

Relative uncertainty: 150 ppm

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

Measurements 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)

Test of the Equivalence Principle of General Relativity

Einstein Equivalence Principle
→ Universality of the Free Fall

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

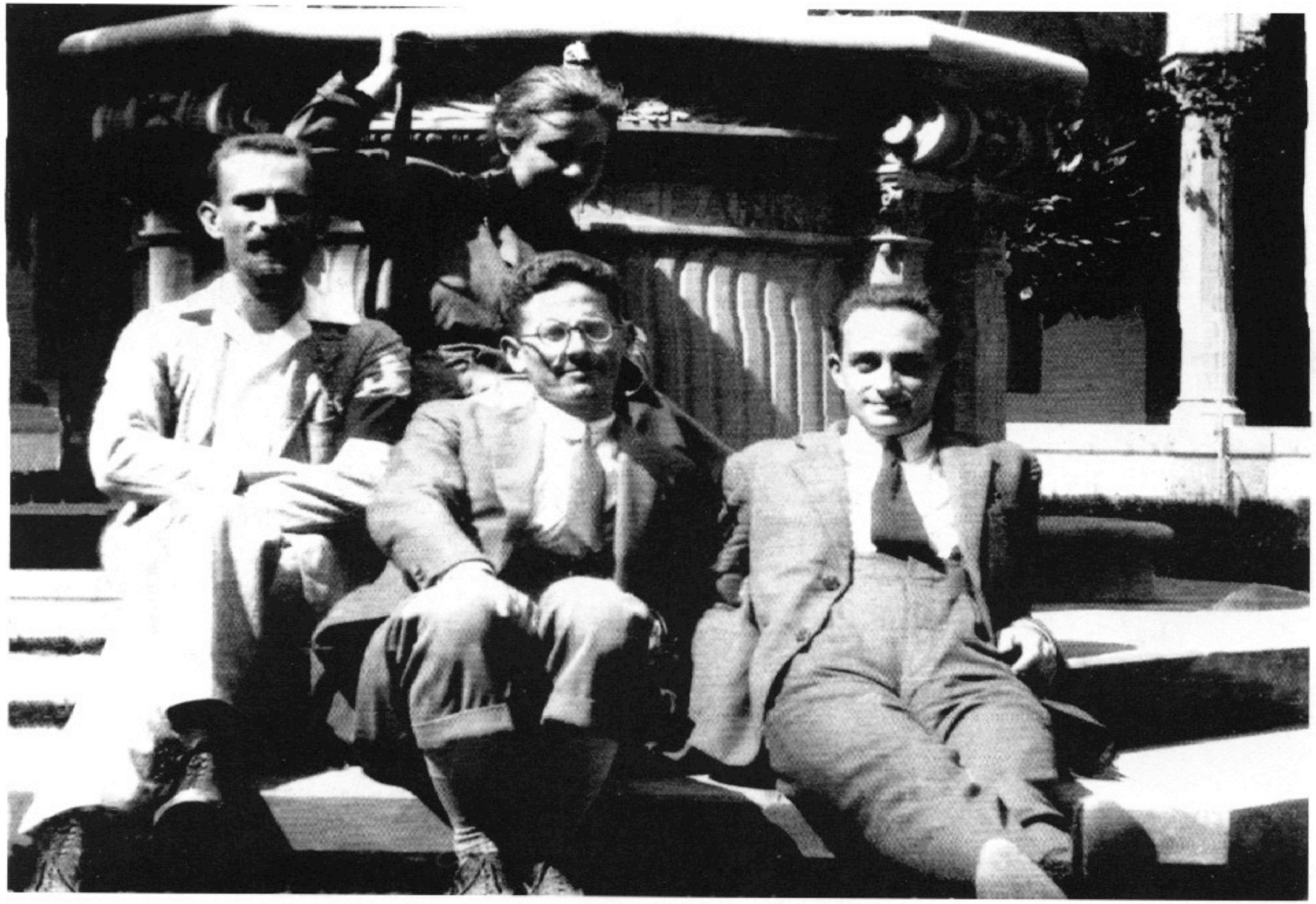
Test of EP with two isotopes of strontium atom:

^{88}Sr	**^{87}Sr**
•Boson	•Fermion
•Zero total spin	•Total spin equal to nuclear spin I = 9/2

EP test by comparing the acceleration of ^{88}Sr and ^{87}Sr under the effect of gravity by measuring the respective **Bloch frequencies** in a driven **vertical optical lattice**

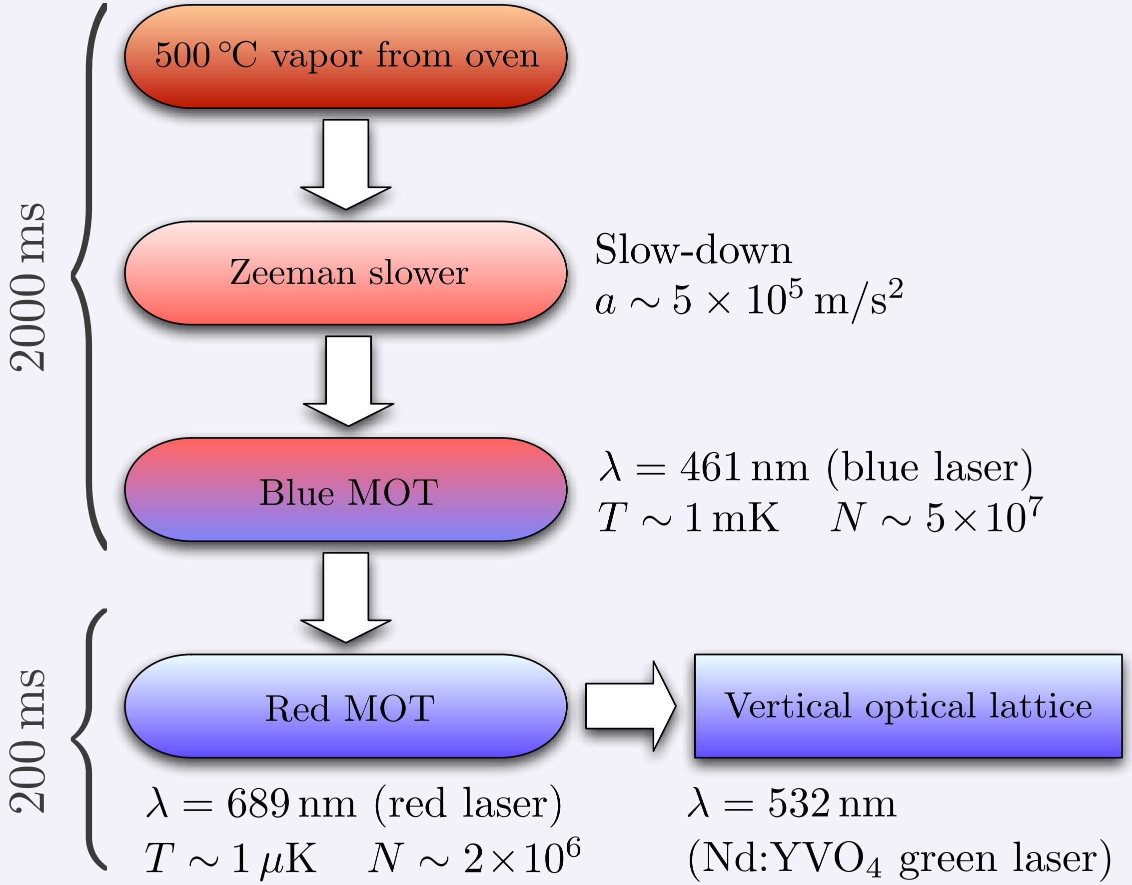
Suitable system for looking at EP violations due to spin-gravity coupling effects

Enrico Fermi a Firenze



Ad Arcetri nel 1925: Franco Rasetti, Fermi e Nello Carrara con Rita Brunetti

Laser cooling of ^{88}Sr



500 °C vapor from oven

Zeeman slower

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

Blue MOT

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

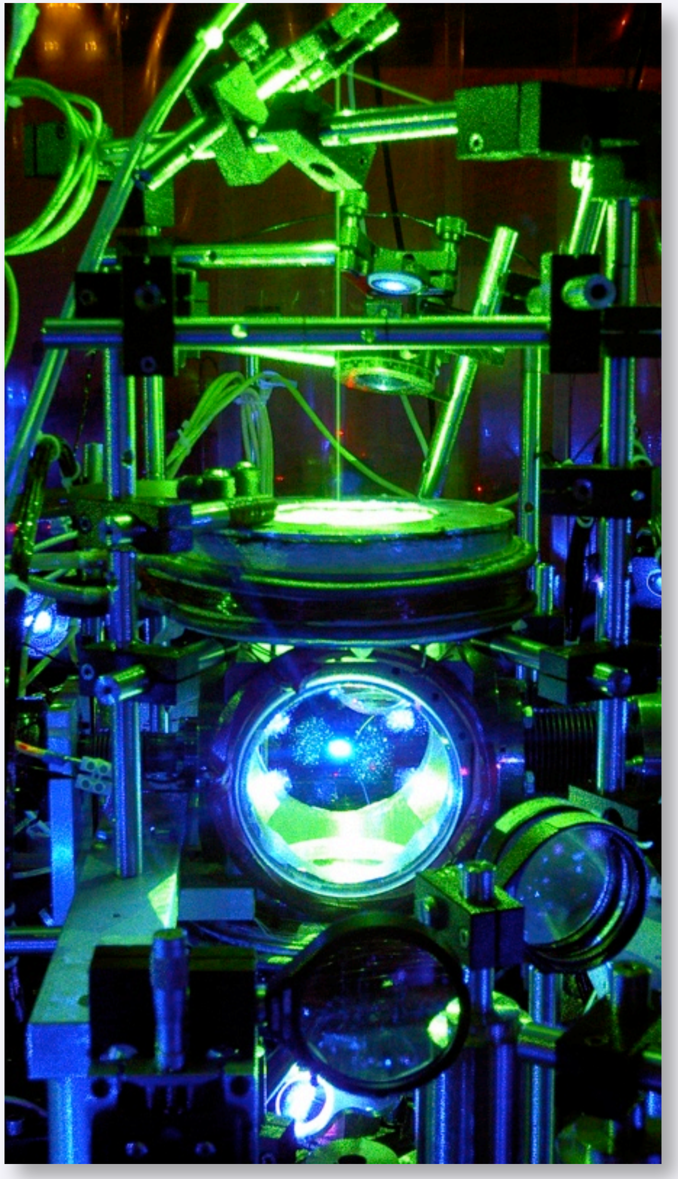
Red MOT

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

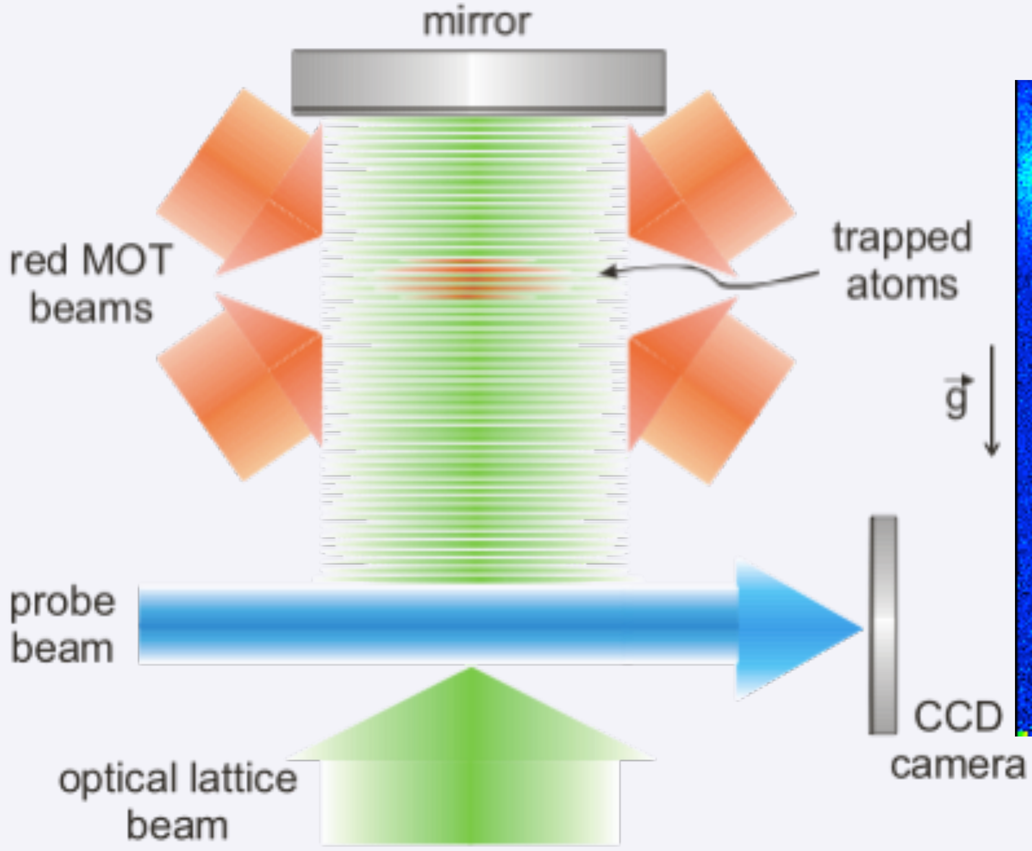
Vertical optical lattice

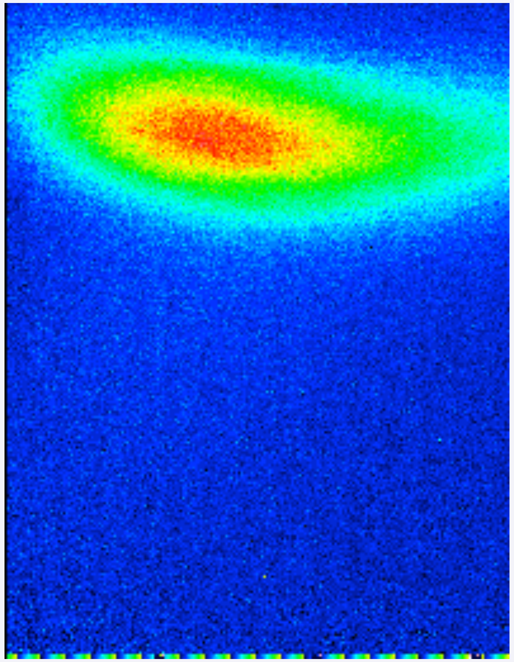
$\lambda = 532\,\text{nm}$
(Nd:YVO$_4$ green laser)
$T \sim 1\,\mu\text{K} \quad N \sim 10^5$

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	$16 \times g$



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



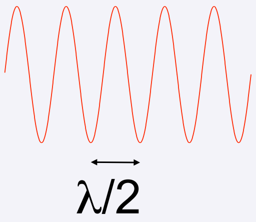


$$\nu = m\, g\, \lambda / 2\, h$$

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



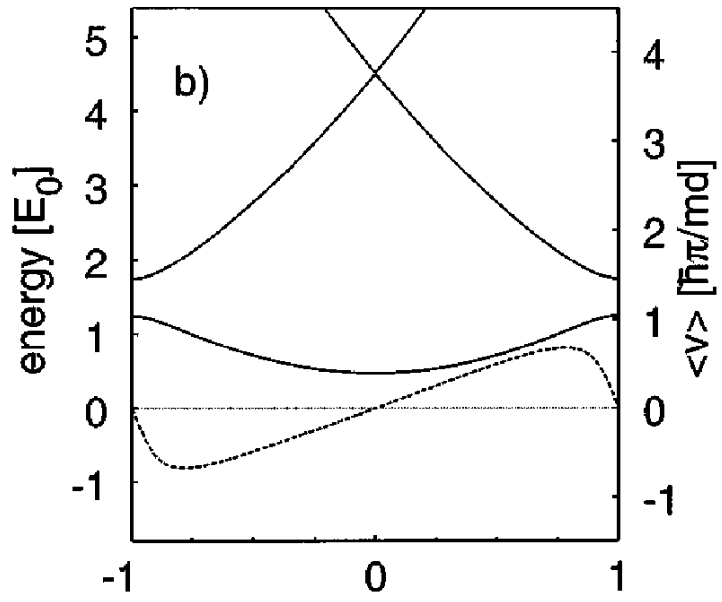
$V(z+\lambda/2) = V(z)$

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

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

Bloch’s theorem

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



quasimomentum q [2π/λ]

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

with a constant external force F

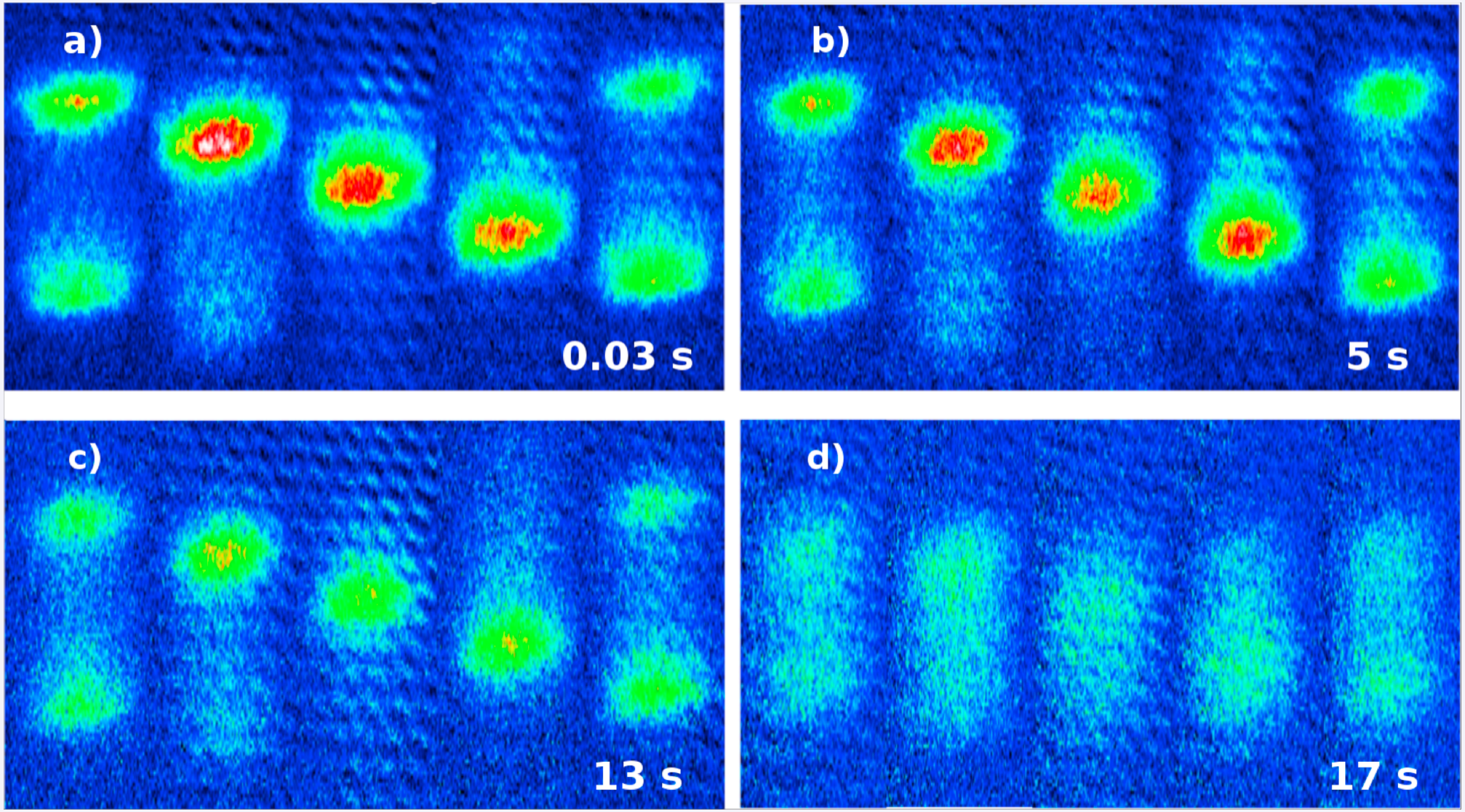
$$q(t) = q(0) + Ft/\hbar$$

⬇

Bloch oscillations

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

Bloch Oscillations

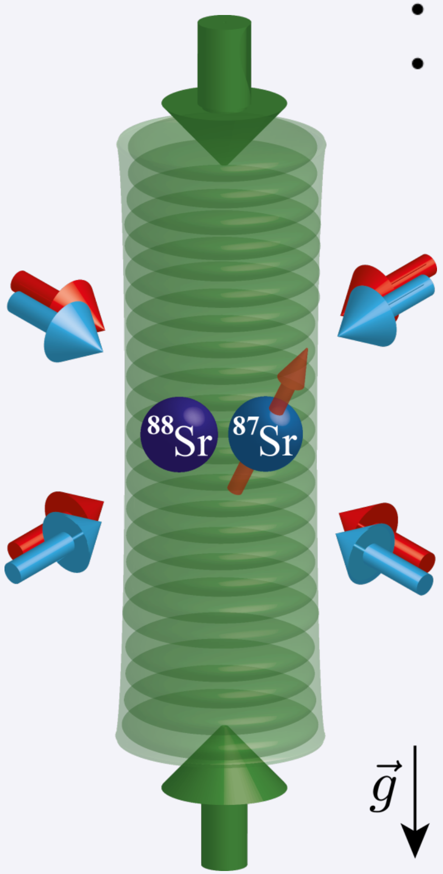


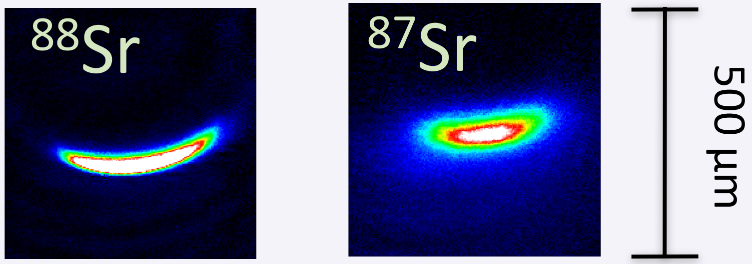
N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,
Phys. Rev. Lett. 106, 038501 (2011)

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





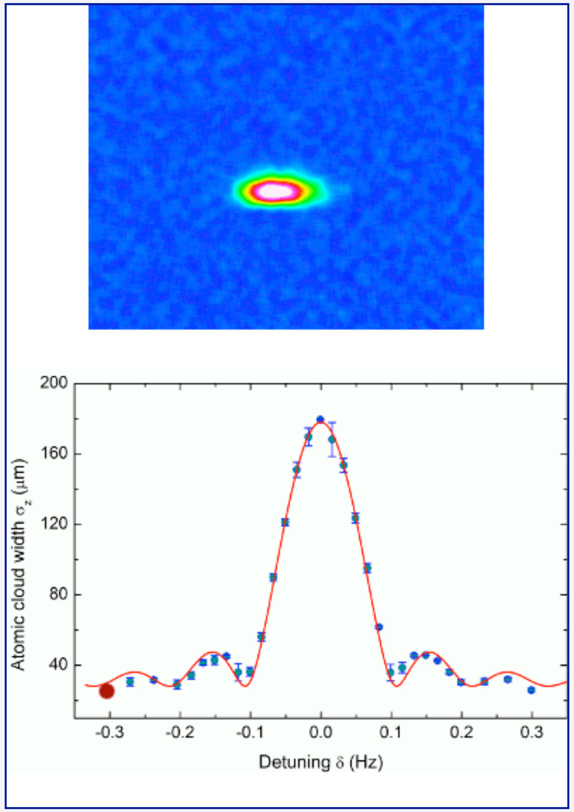
8×10^6 atoms
T: 1 μK

1×10^6 atoms
T: 1.4 μK

$\vec{g}\downarrow$

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

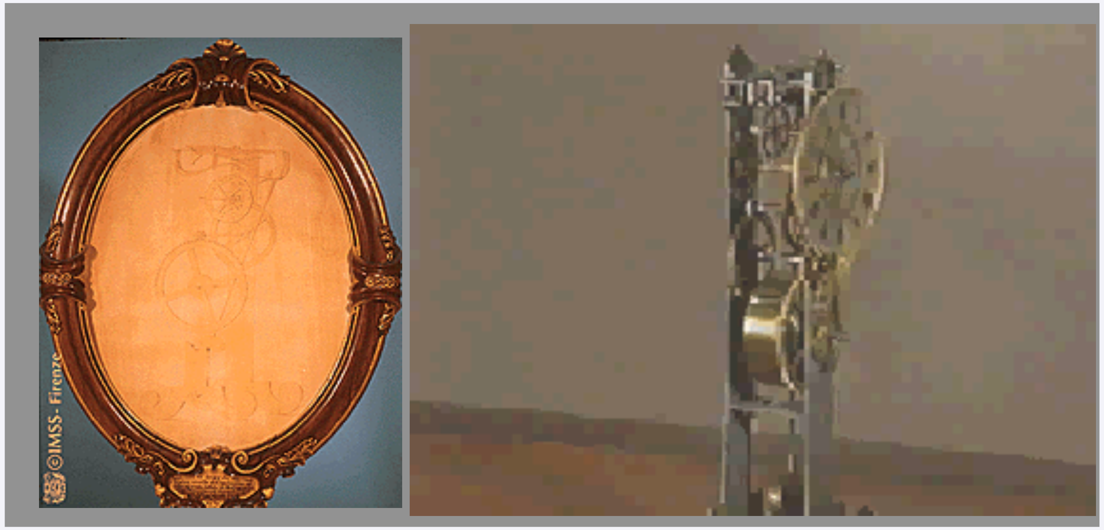
$$\Longrightarrow \qquad k = (0.5 \pm 1.1) \times 10^{-7}$$



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)**

Orologi Atomici

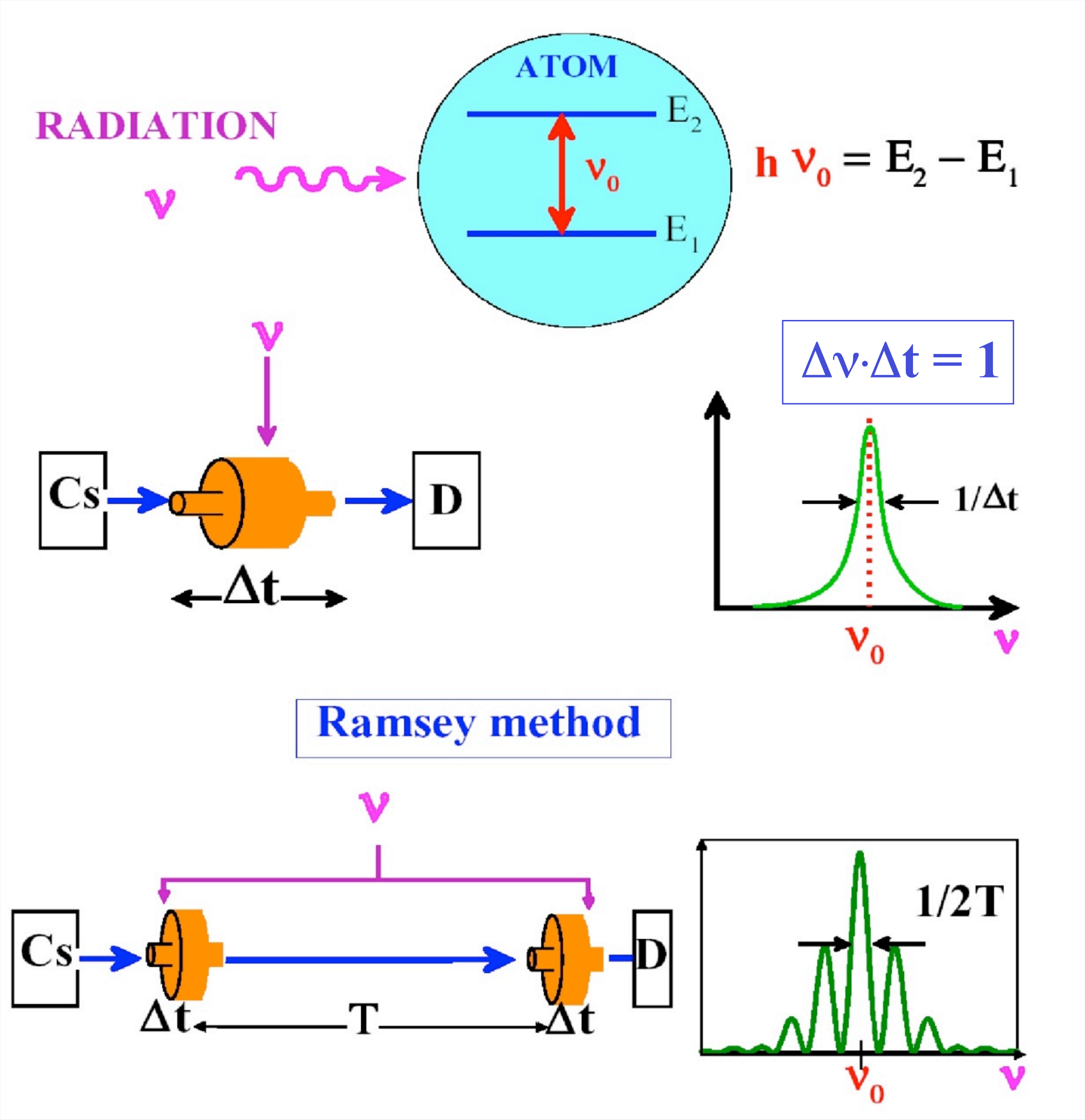
La misura del tempo



Accuratezza → capacità di un orologio di realizzare lo standard definito.

Stabilità → capacità di un orologio di riprodurre una frequenza costante nel tempo; dipende da $\frac{\Delta\nu_0}{\nu_0}$ della transizione

Orologi atomici

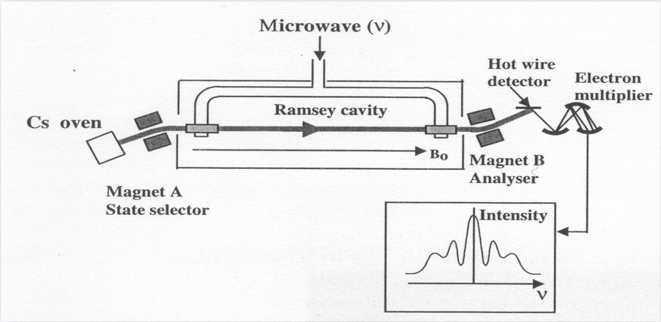


The definition of the second

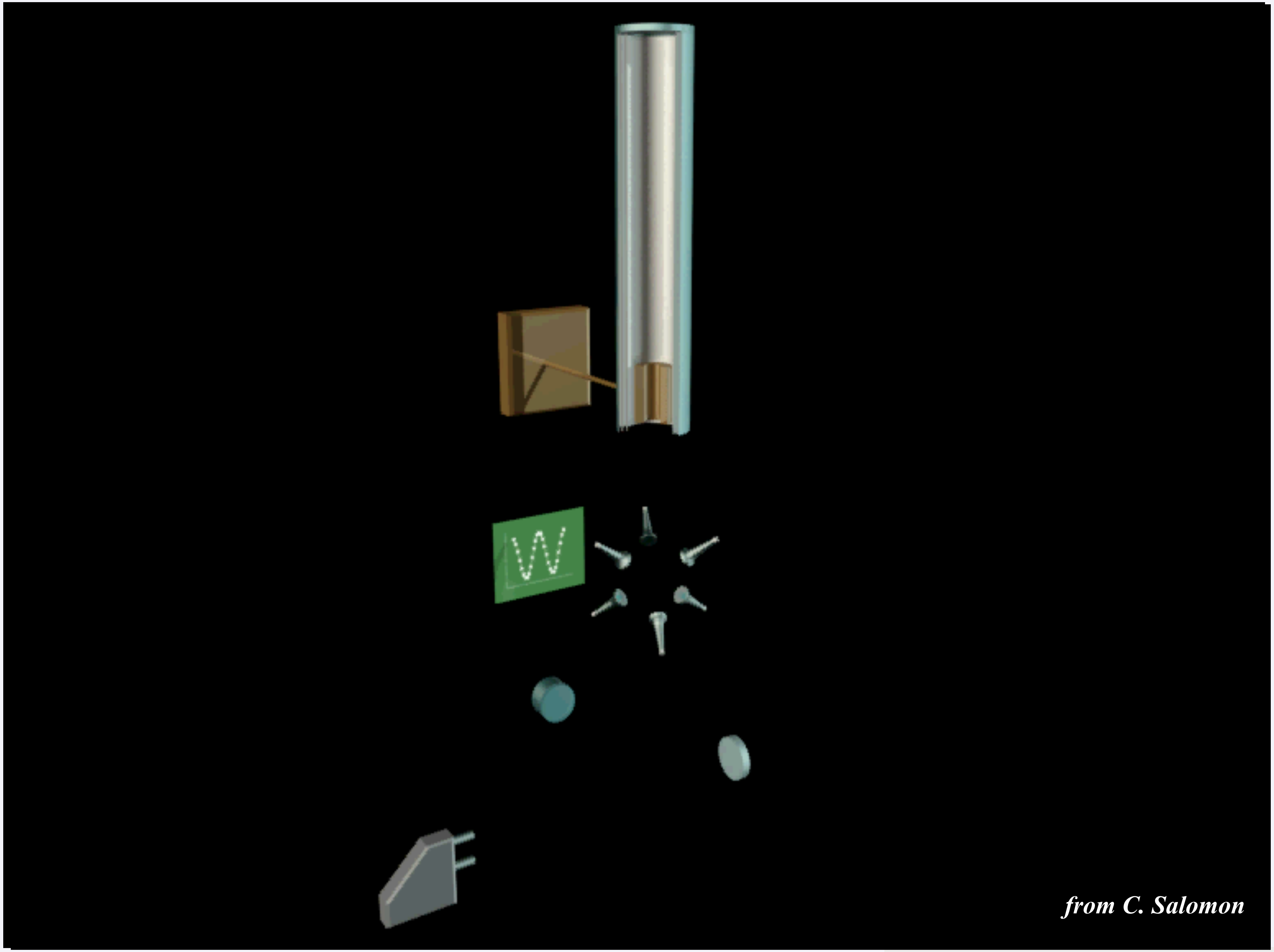
Il secondo è la durata di 9 192 631 770 cicli della radiazione corrispondente alla transizione tra i livelli iperfini (F=3, M_F=0) e (F=4, M_F=0) dello stato fondamentale dell’atomo ^{133}Cs

(13th CGPM, 1967)

$$\boxed{\Delta\nu \cdot \Delta t = 1}$$



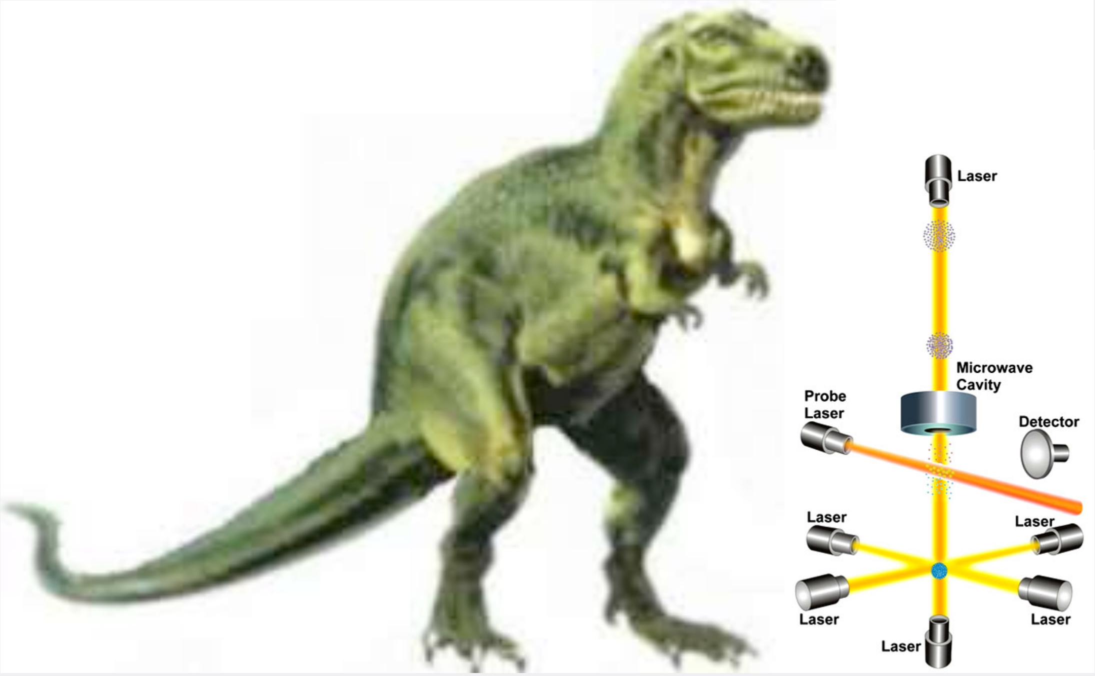
Atomic fountain clock



from C. Salomon

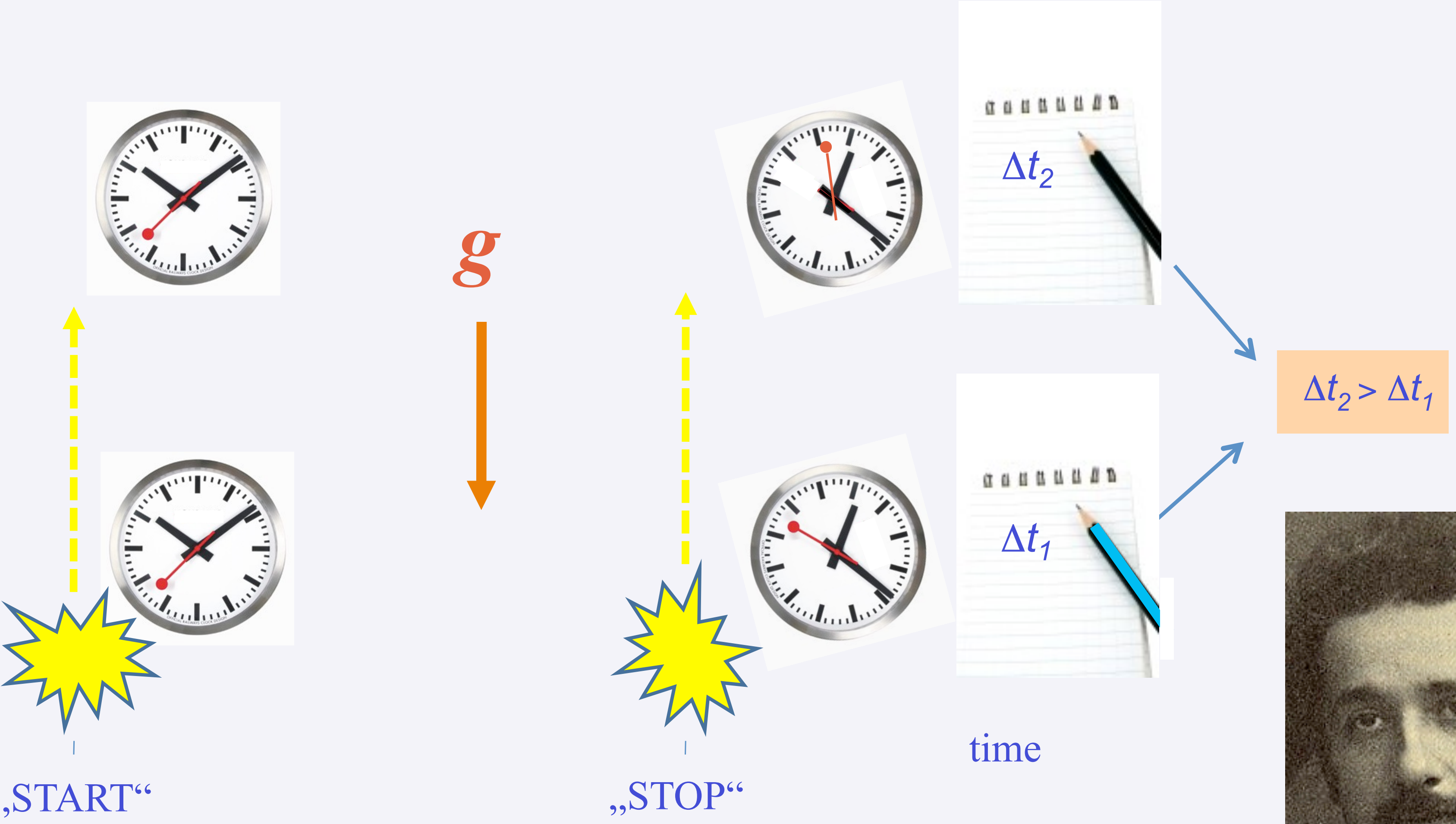
Dinosauri e orologi

$\sigma \approx 5 \times 10^{-16} \rightarrow$ 1 s ogni 2×10^{15} s (due milioni di miliardi di secondi)



60 milioni di anni ≡ 60×10^{6} anni x 365 g/anno x 24 ore/g x 3600 s/ora $\approx 2 \times 10^{15}$ s

Dilatazione del tempo in un campo gravitazionale



$\boldsymbol{g}$

Δt_2

Δt_1

$\Delta t_2 > \Delta t_1$

„START“

„STOP“

time

A. Einstein

1911

from S. Schiller

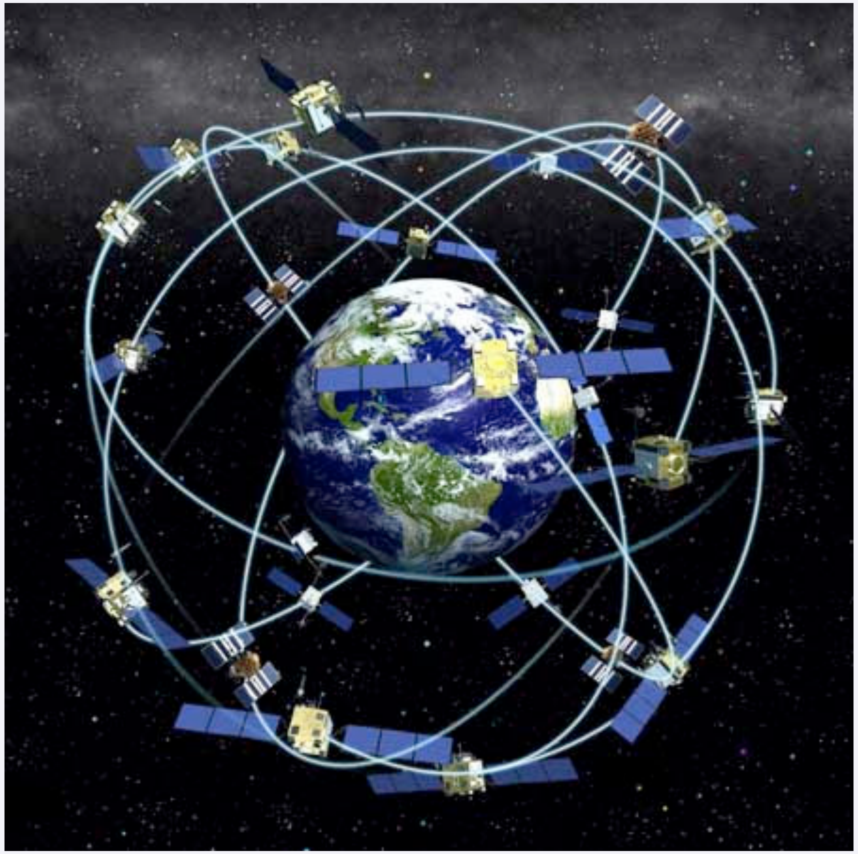
Red shift gravitazionale

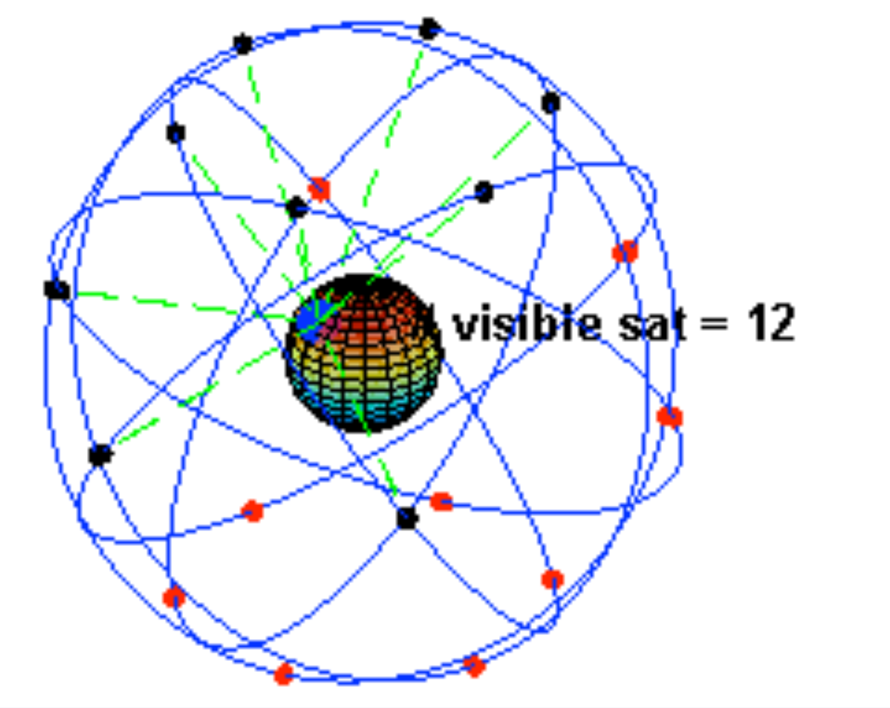
Un orologio è più lento in prossimità di una massa M

$$\frac{\nu - \nu_0}{\nu_0} = -\frac{GM}{c^2 r}$$

In prossimità della Terra →
$$\frac{\nu_h - \nu_T}{\nu_T} = \frac{gh}{c^2} \cong 10^{-16} / m$$

GPS (→ GALILEO)





Gli orologi satellitari sono affetti dalle conseguenze della teoria della relatività. Infatti, a causa degli effetti combinati della velocità relativa, che rallenta il tempo sul satellite di circa 7 microsecondi al giorno, e della minore curvatura dello spazio-tempo a livello dell'orbita del satellite, che lo accelera di 45 microsecondi, il tempo sul satellite scorre ad un ritmo leggermente più veloce che a terra, causando un anticipo di circa 38 microsecondi al giorno, e rendendo necessaria una correzione automatica da parte dell'elettronica di bordo.

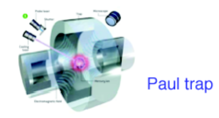
Se non si tenesse conto di questi effetti relativistici, si accumulerebbe un errore di 10 km al giorno nella determinazione della posizione.

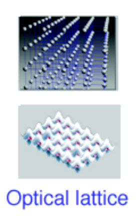
Optical clocks: Towards 10^{-18}

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

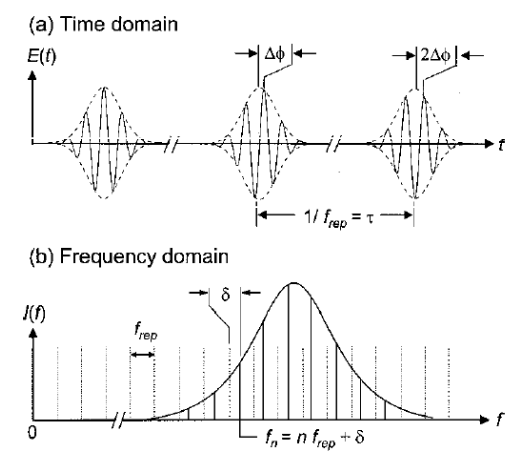
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atom}}} \sqrt{\frac{T_{cycle}}{2\tau_{average}}} \frac{1}{C_{fringe}}$$

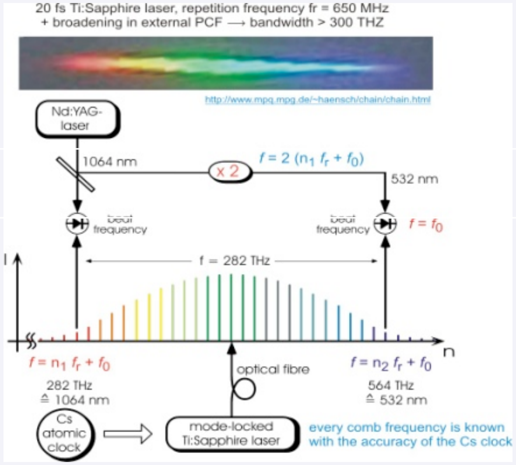
- **Candidate atoms**
  - **Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…**
  - **Cold neutral atoms: H, Ca, Sr, Yb,…**


Paul trap

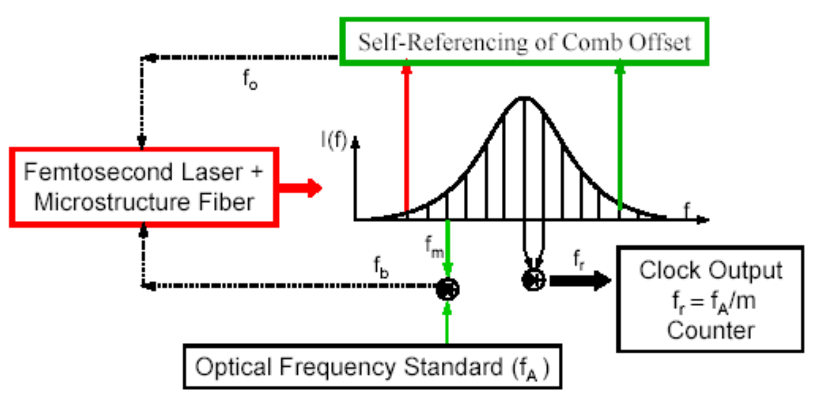

Optical lattice

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



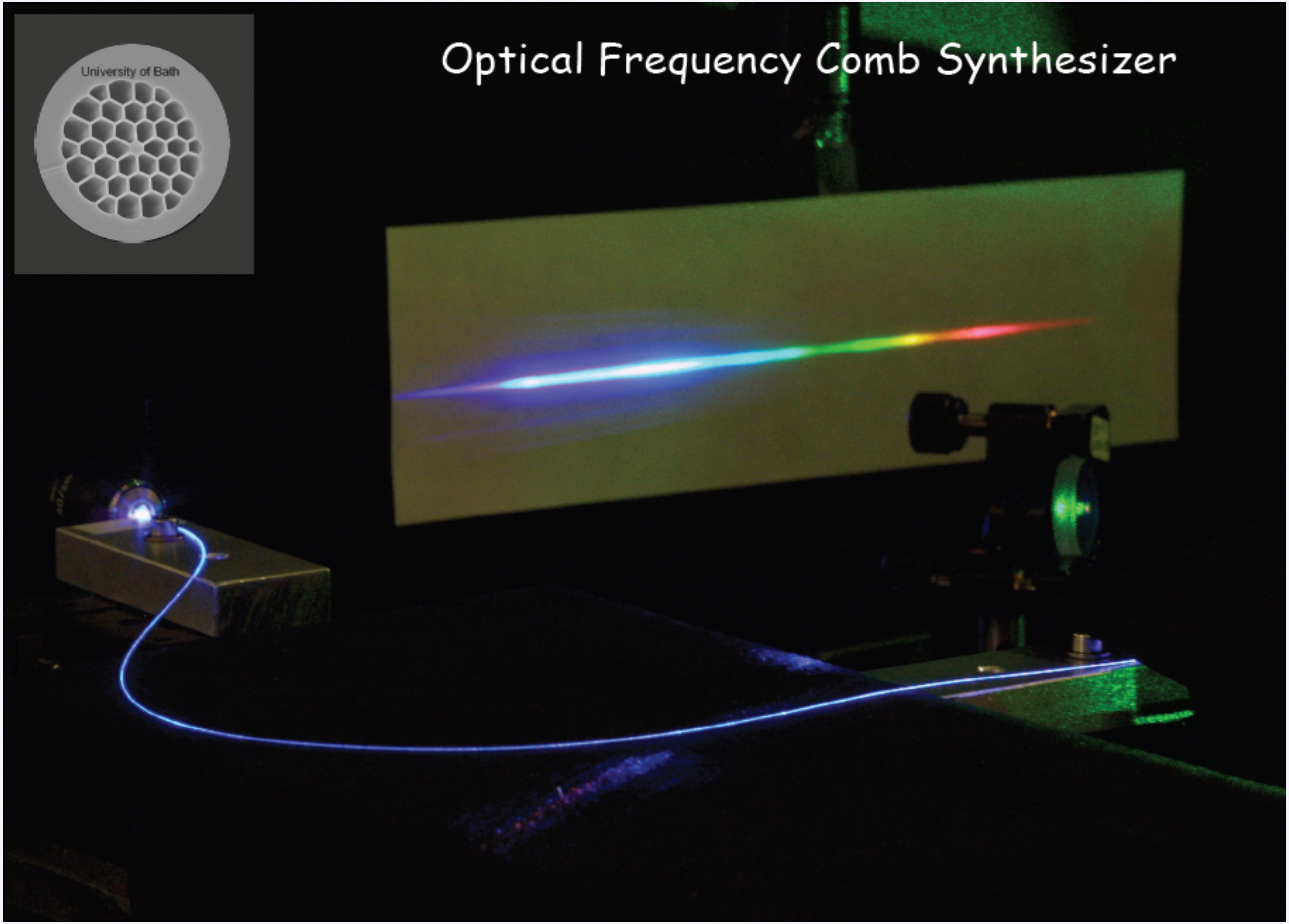

20 fs Ti:Sapphire laser, repetition frequency fr = 650 MHz
+ broadening in external PCF ⟶ bandwidth > 300 THZ

http://www.mpq.mpg.de/~haensch/chain/chain.html

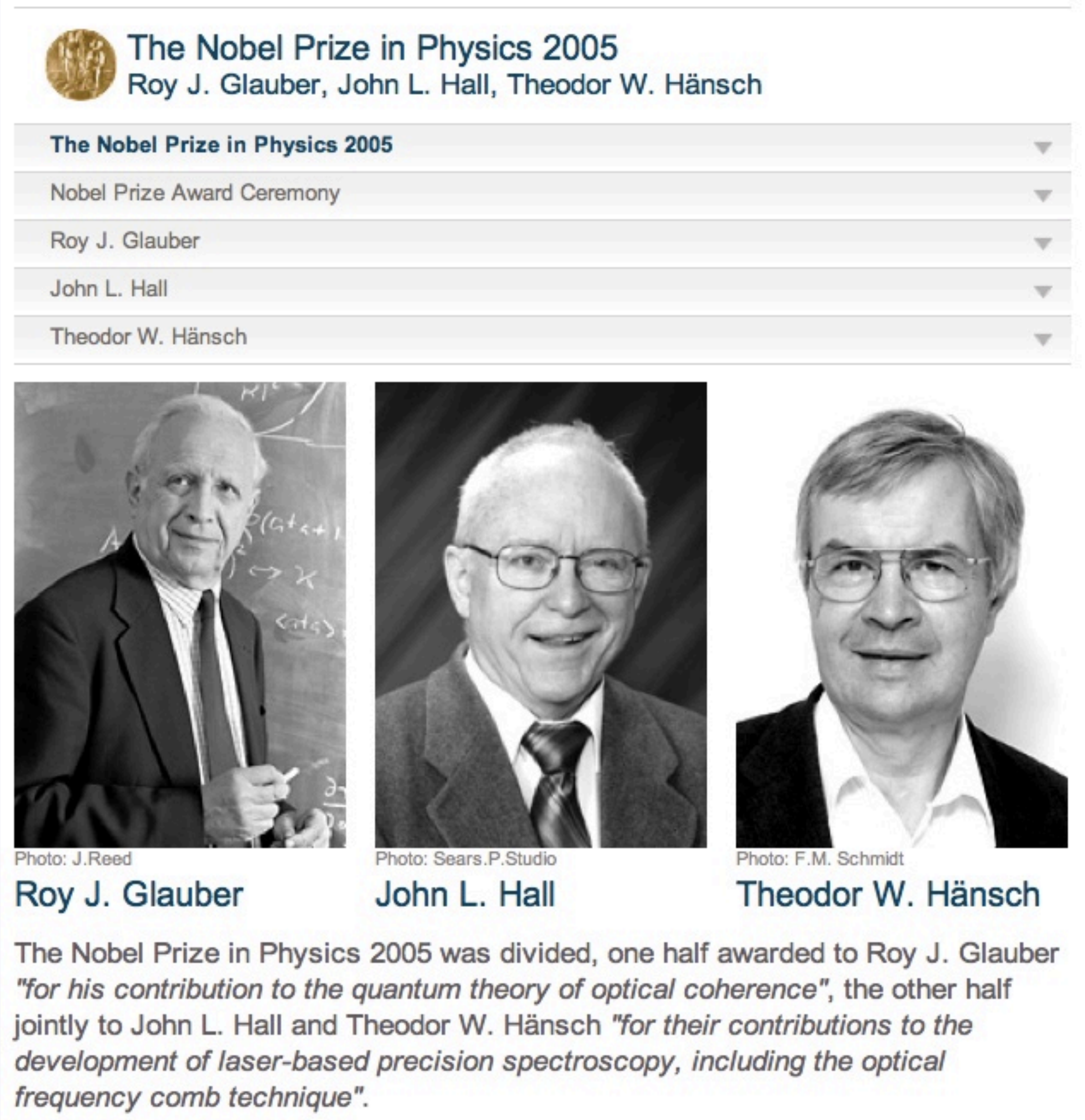


Th. Udem *et al.*, Nature 416 , 14 march 2002

Optical Frequency Comb Synthesizer



From T.W. Hänsch



The Nobel Prize in Physics 2005
Roy J. Glauber, John L. Hall, Theodor W. Hänsch

Photo: J.Reed
Roy J. Glauber

Photo: Sears.P.Studio
John L. Hall

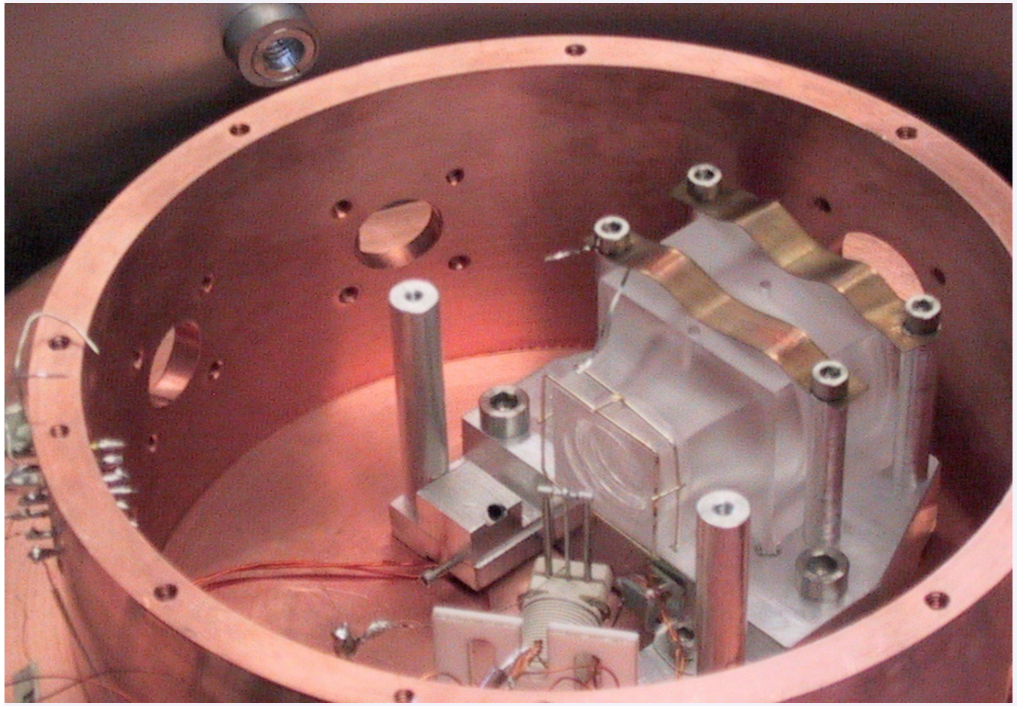
Photo: F.M. Schmidt
Theodor W. Hänsch

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.*

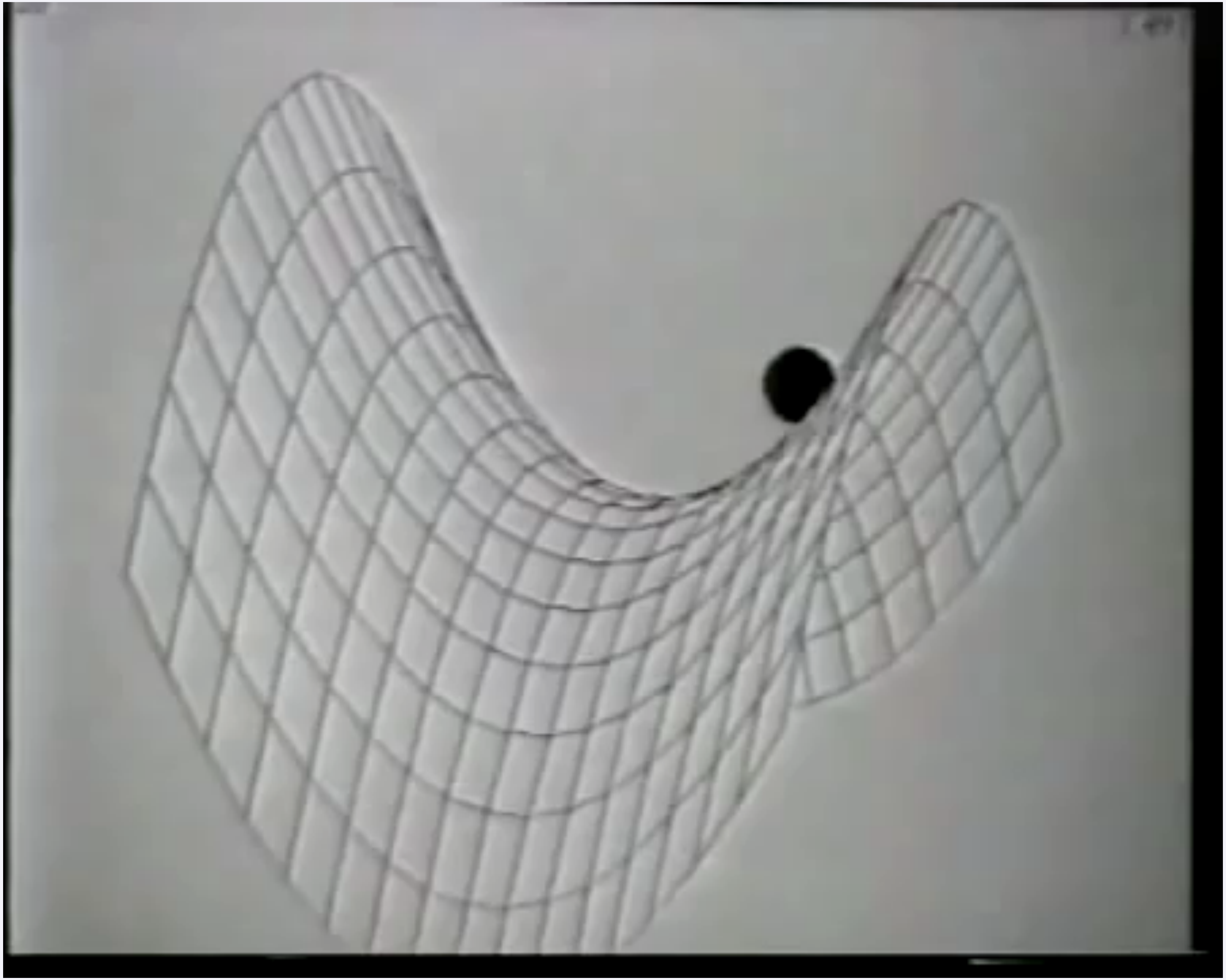
Single ion Optical clock



Hg+, Al+, NIST (Bergquist et al.)

Yb+, PTB (Tamm, Peik...)

Other experiments: NPL : Yb$^+$, Sr$^+$, NRC : Sr$^+$,
MPQ : In$^+$…, Innsbruck: Ca+, ….



by T.W. Hänsch

by T.W. Hänsch

Trapped ions

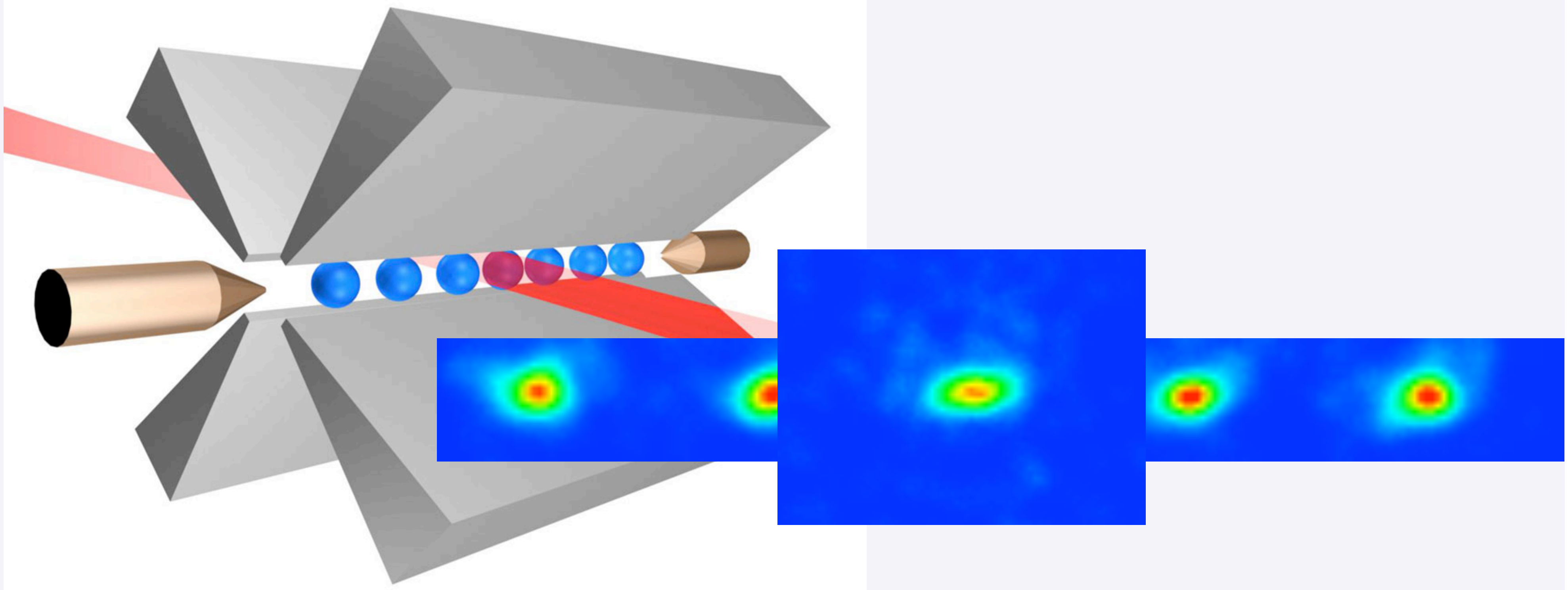
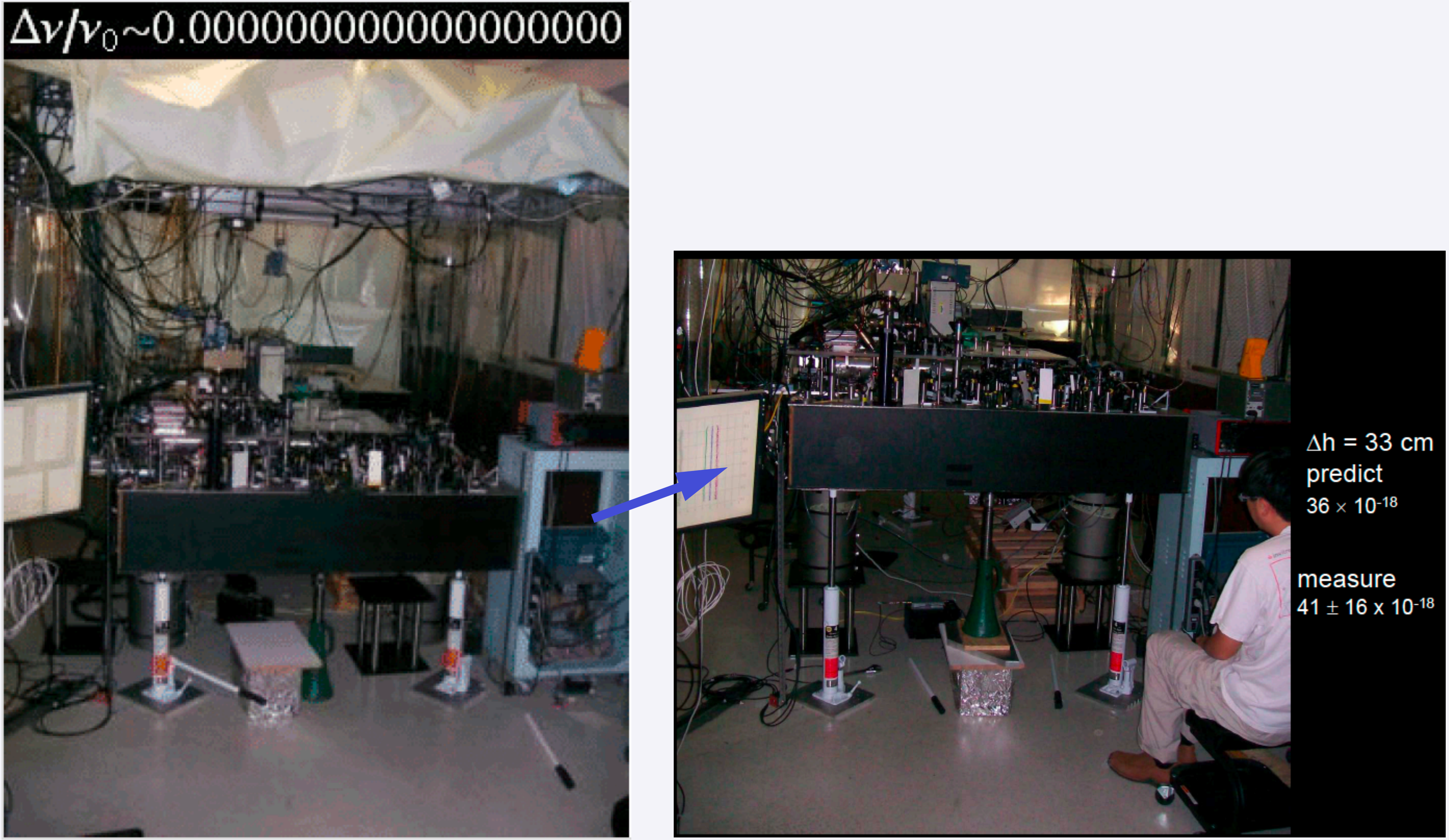


Figure and experimental data from Michael Drewsen

Measure gravitational red shift in the lab



$\Delta\nu/\nu_0 \sim 0.000000000000000000$

$\Delta h = 33$ cm

predict

36×10^{-18}

measure

$41 \pm 16 \times 10^{-18}$

"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

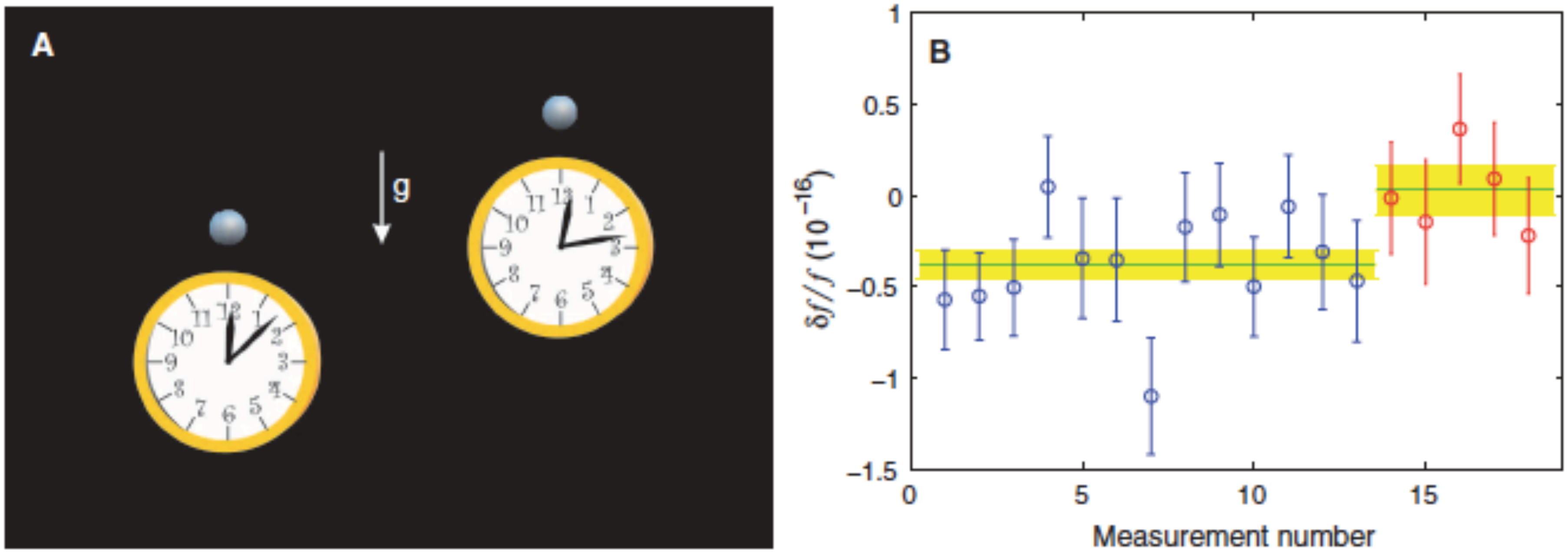
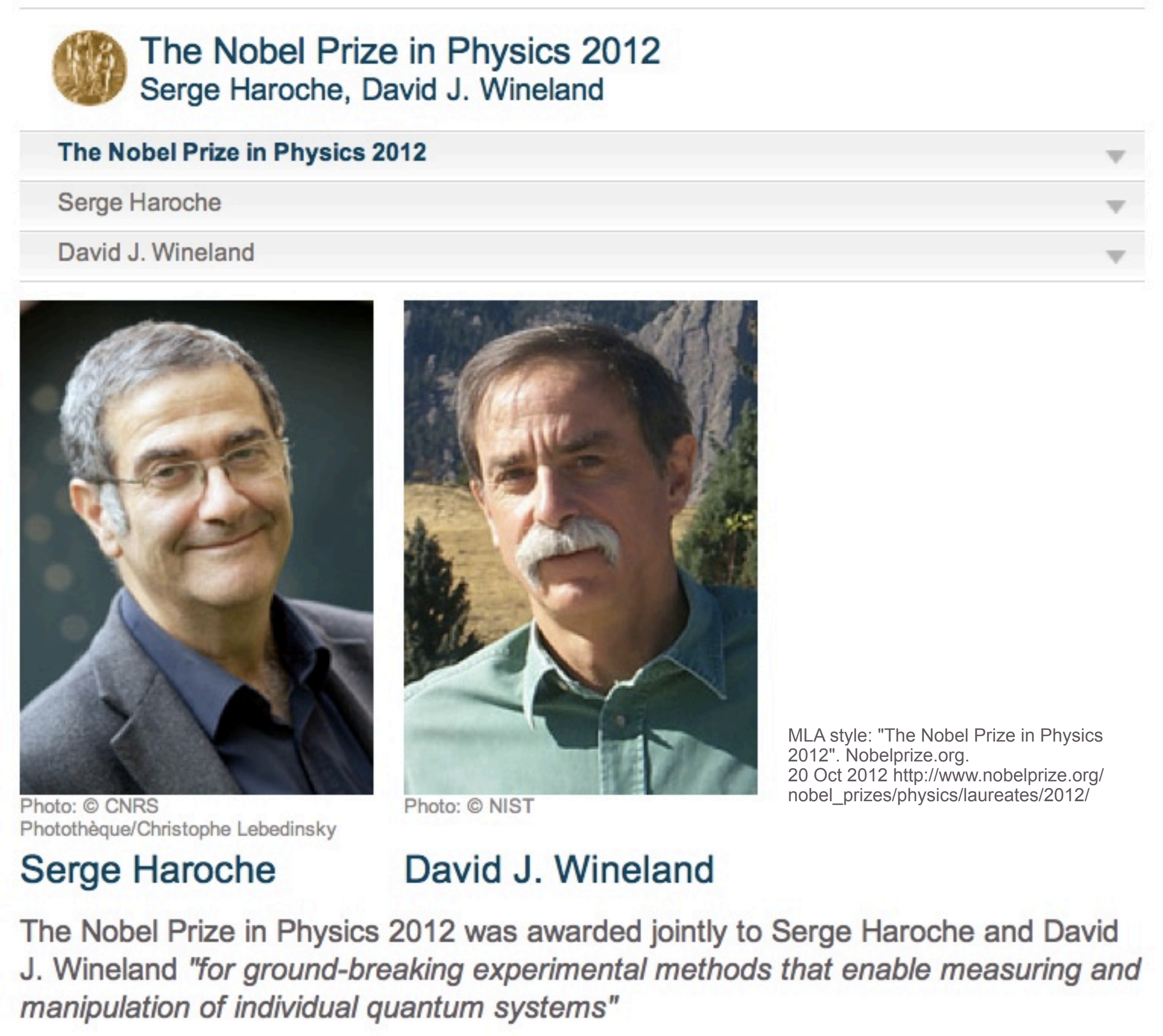


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg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

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



The Nobel Prize in Physics 2012

Serge Haroche, David J. Wineland

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.*

Sr optical clock

- **Method:**

Interrogate atoms in optical lattice without frequency shift

  - Long interaction time
  - Large atom number (10^8)
  - Lamb-Dicke regime

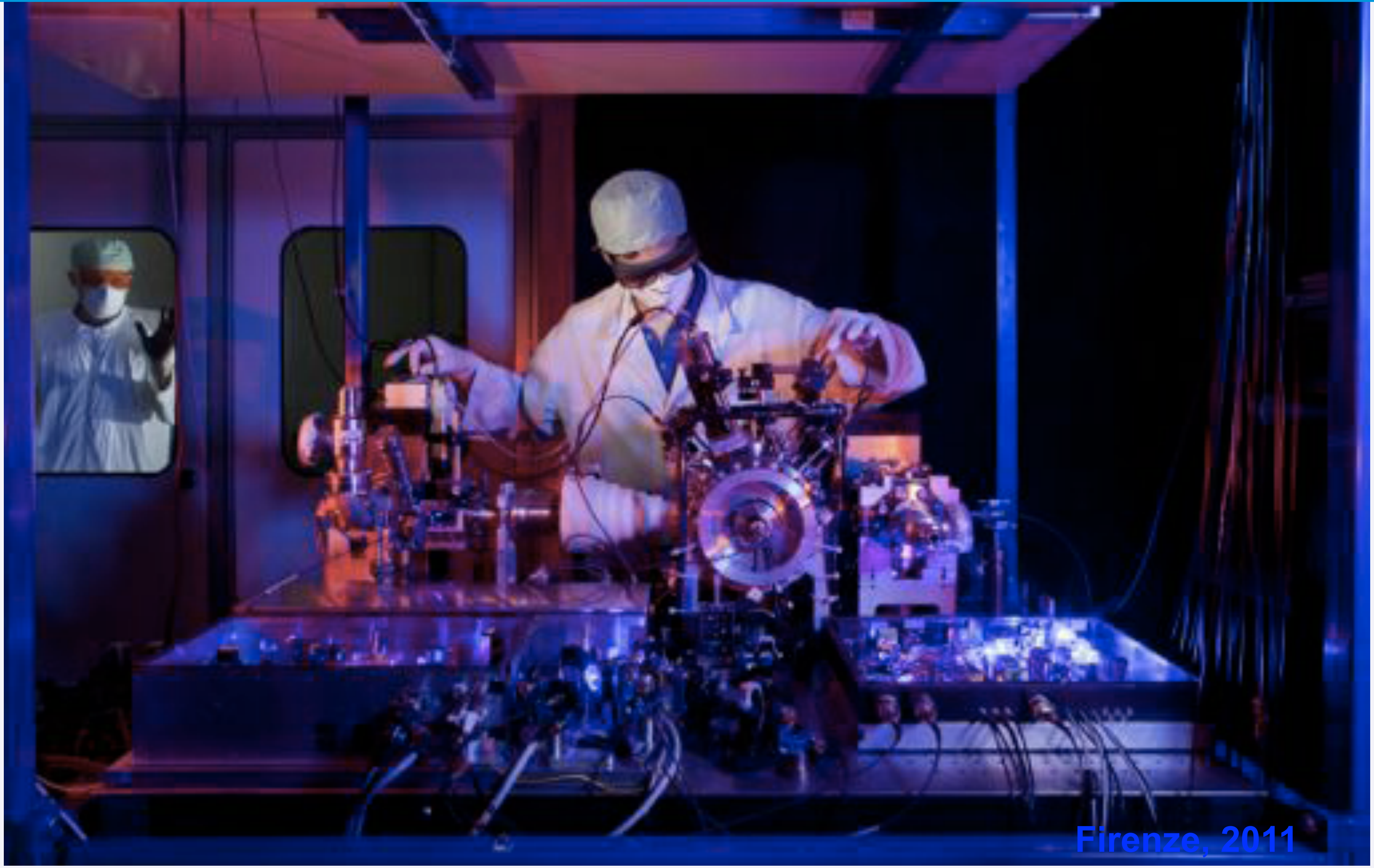
Excellent frequency stability

- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

Under development:

Sr (Tokyo, JILA, PTB, SYRTE, Firenze)

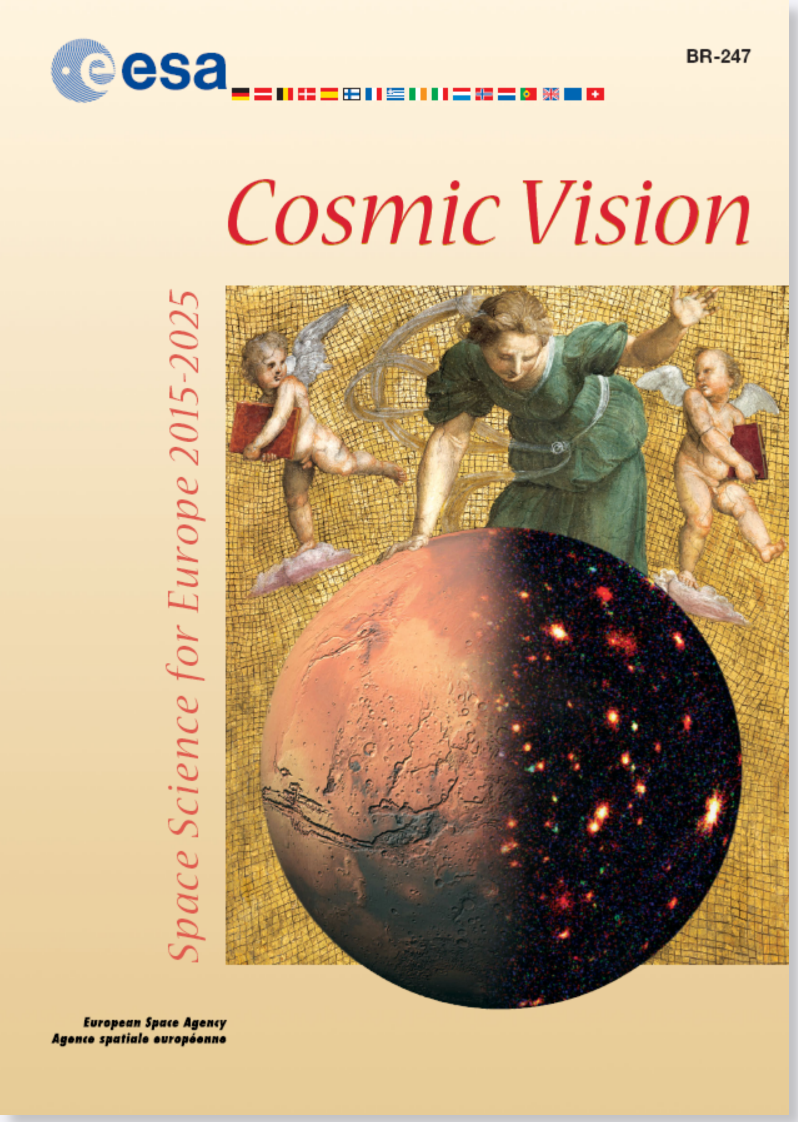
Space Optical Clock

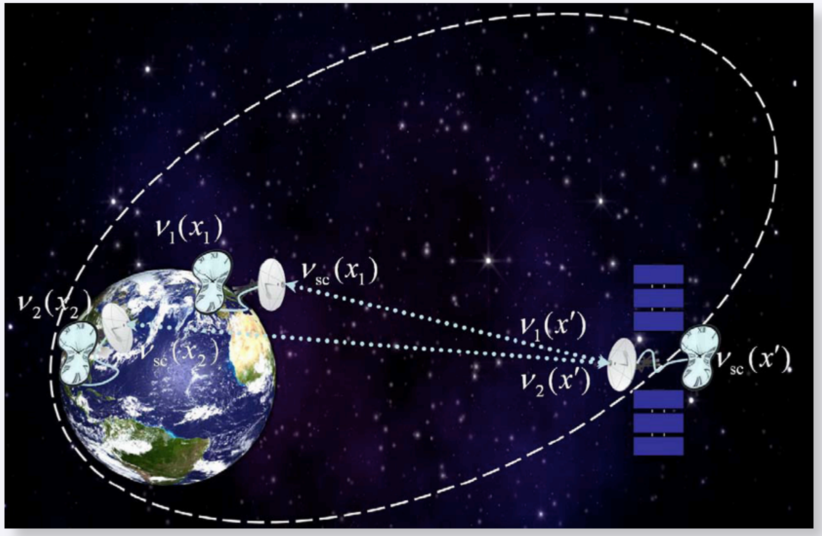


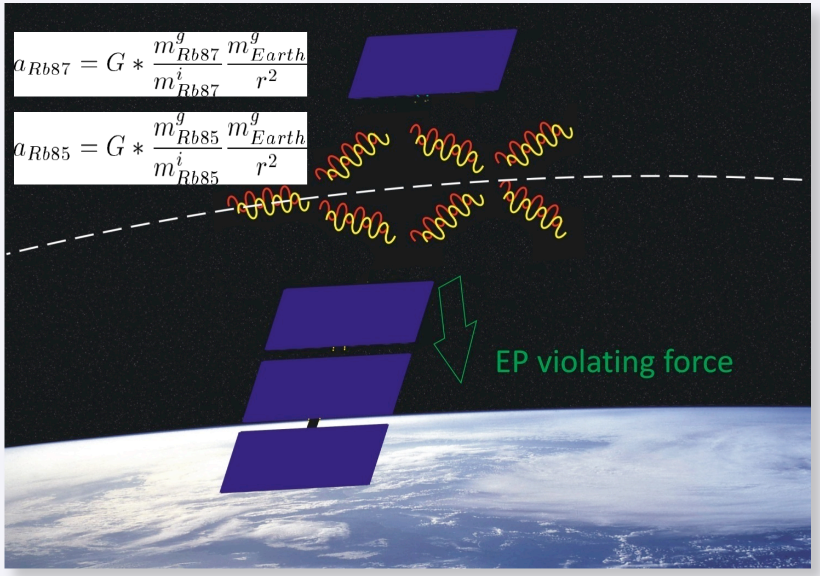
N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino,
A transportable strontium optical lattice clock, Appl. Phys. B, in press (2014)

- Missione STE-QUEST -

Test del red shift gravitazionale e del principio di equivalenza





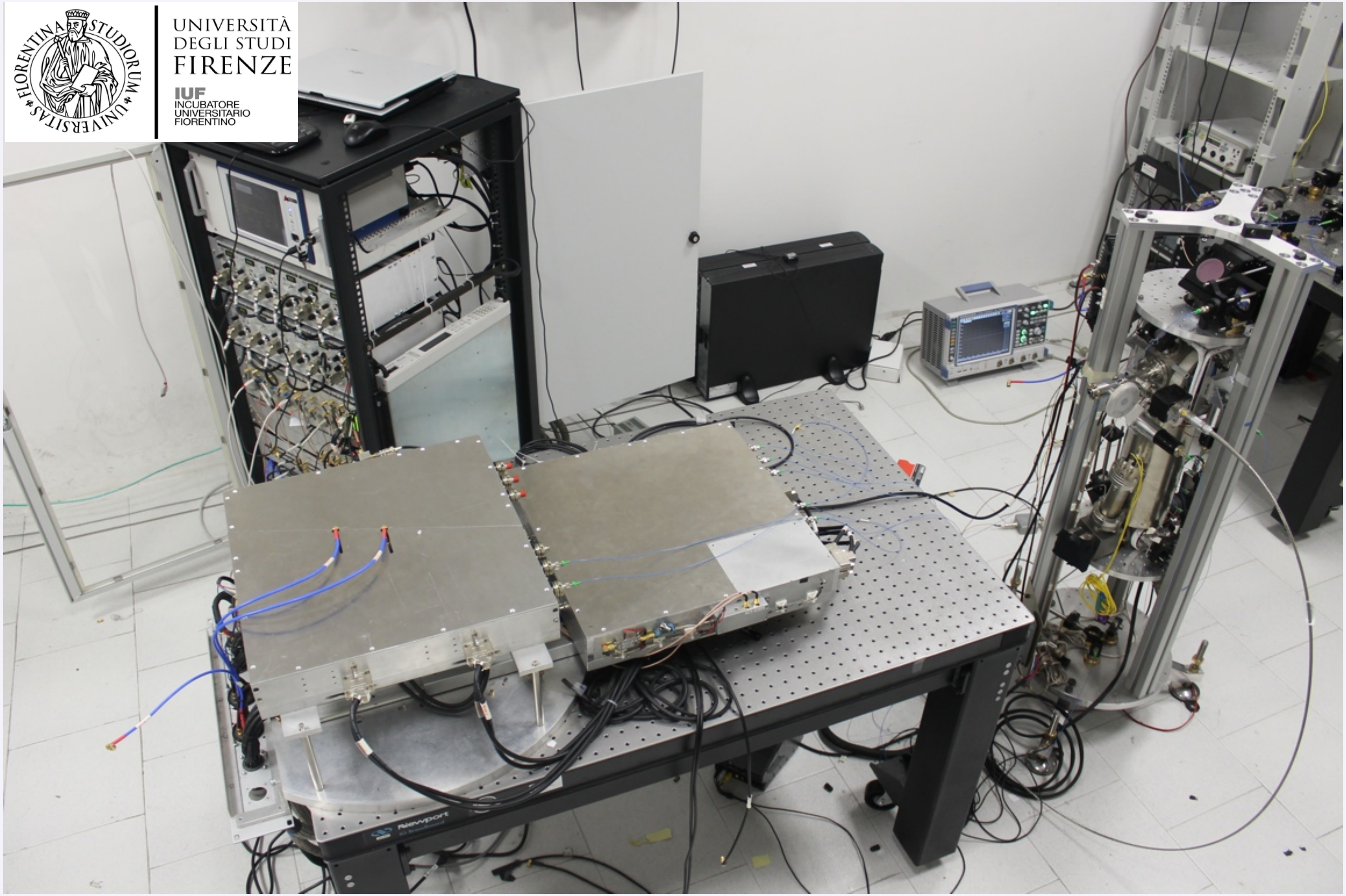


$$a_{Rb87} = G * \frac{m^g_{Rb87}}{m^i_{Rb87}} \frac{m^g_{Earth}}{r^2}$$

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

G. M. Tino et al., *Precision Gravity Tests with Atom Interferometry in Space*, Nuclear Physics B, 243–244, 203 (2013)

Spin-Off - Atom Sensors



G. Tino team members

Nicola Poli	Researcher, Università di Firenze
Fiodor Sorrentino	Post-doc, LENS
Quentin Bodart	Post-doc, Università di Firenze
Marco Tarallo	Post-doc, LENS
Gabriele Rosi	Post-doc, Università di Firenze
Denis Sutyrin	Post-doc, Università di Firenze
Xian Zhang	Post-doc, LENS/ICTP
Tommaso Mazzoni	PhD student, LENS
Jacopo Grotti	Diploma student, Università di Firenze
Marco Menchetti	Diploma student, Università di Bologna
Leonardo Salvi	Diploma student, Università di Firenze
Luigi Cacciapuoti	Long term guest, ESA-Noordwijk
Marella de Angelis	Long term guest, CNR
Marco Prevedelli	Long term guest, Università di Bologna
Elisa Tonelli	Secretary

Previous members and visitors

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

Support

- ✓ **Istituto Nazionale di Fisica Nucleare (INFN)**
- ✓ **European Commission (EC)**
- ✓ **ENI**
- ✓ **Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)**
- ✓ **European Laboratory for Non-linear Spectroscopy (LENS)**
- ✓ **Ente Cassa di Risparmio di Firenze (CRF)**
- ✓ **European Space Agency (ESA)**
- ✓ **Agenzia Spaziale Italiana (ASI)**
- ✓ **Istituto Nazionale per la Fisica della Materia (INFM)**
- ✓ **Istituto Nazionale Geofisica e Vulcanologia (INGV)**

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