Orologi e interferometri atomici

nuovi sensori ad atomi ultrafreddi per misure di fisica fondamentale e applicazioni in laboratori terrestri e nello spazio

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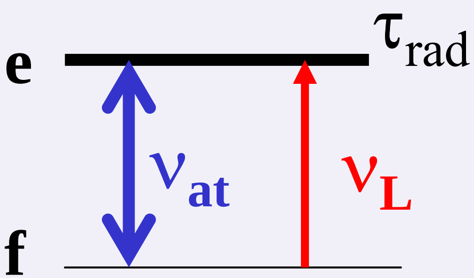
INFN, Sezione di Firenze

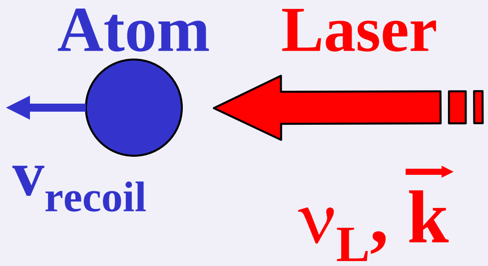
Outline

- ***Cooling and manipulation of atoms***
- ***Atomic fountains and clocks***
- ***Matter-wave interferometry***
- ***Experiments and future prospects***

Laser cooling and manipulation of atoms

Radiation pressure





Momentum conservation $\rightarrow$ $\vec{v}_{recoil} = \hbar\vec{k}/M$

Isotropic emission $\rightarrow$ $\langle\vec{v}_{em}\rangle = 0$

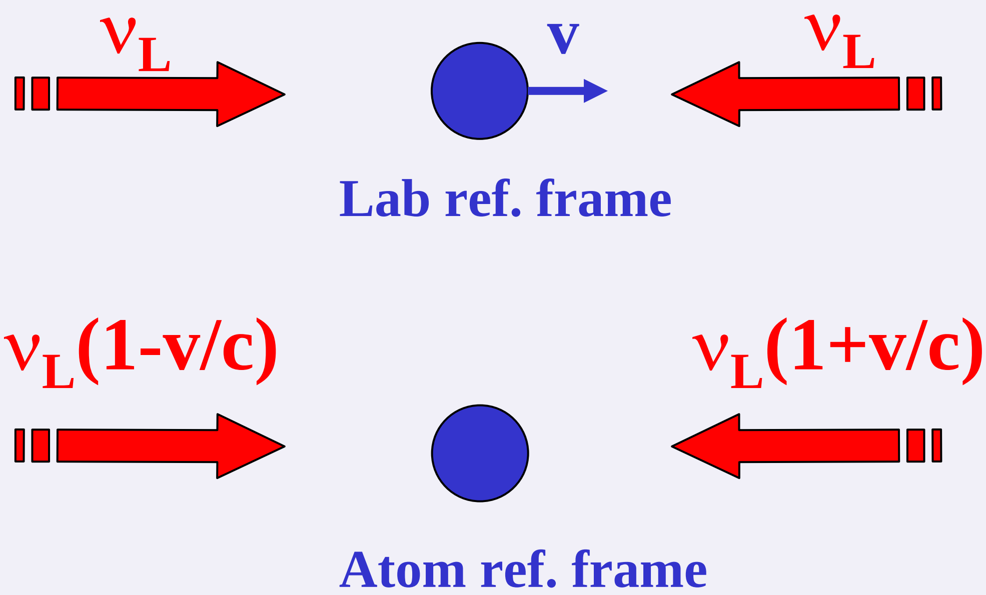
$\rightarrow$**Radiation pressure force:** $\vec{F} = \hbar\vec{k}/2\tau_{rad} = M\vec{a}$ $\rightarrow$ $a = \hbar k/2\tau_{rad}$

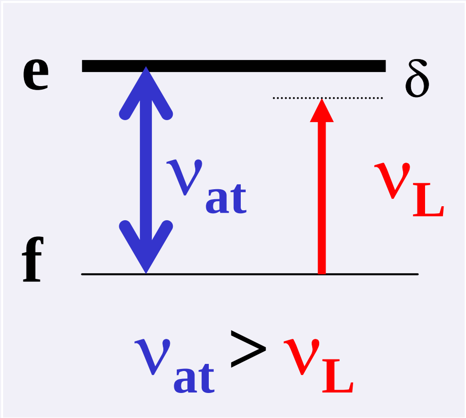
Example, Na atom : $\lambda \approx 589$ nm, M= 23 a.m.u., $\tau_{rad} \approx 16$ ns

$\rightarrow$ $v_{recoil} \approx 3$ cm/s, $a \approx 10^6$ m/s$^2 \approx 10^5$ g

$t_{stop} = v_{in}/a \approx 1$ ms, $L_{stop} = v_{in}^2/2a \approx 0.5$ m

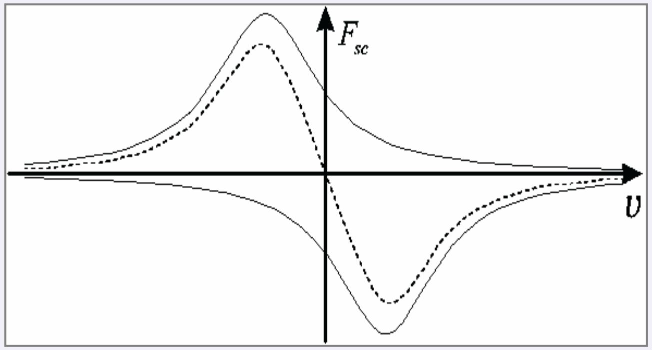
Optical molasses





$(I/I_0 \ll 1) \rightarrow$

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



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

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

Laser cooling: temperatures

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

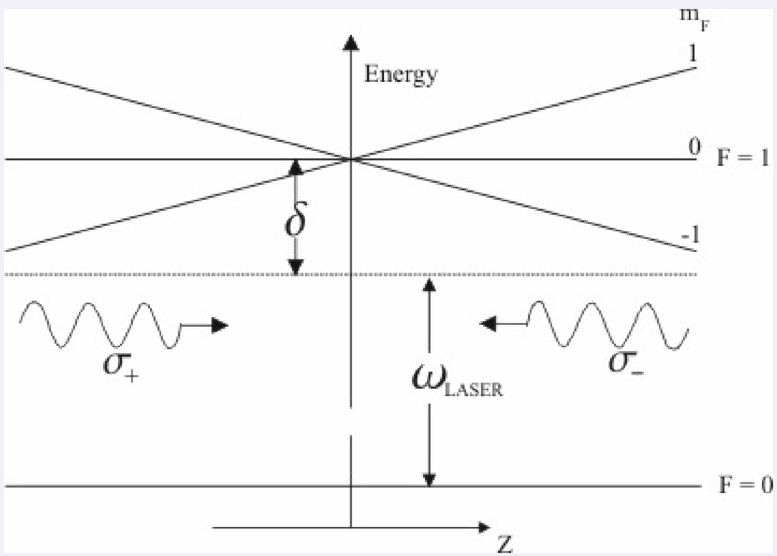
Minimum temperature for Doppler cooling: $$k_B T_D = \frac{h\Gamma}{2}$$

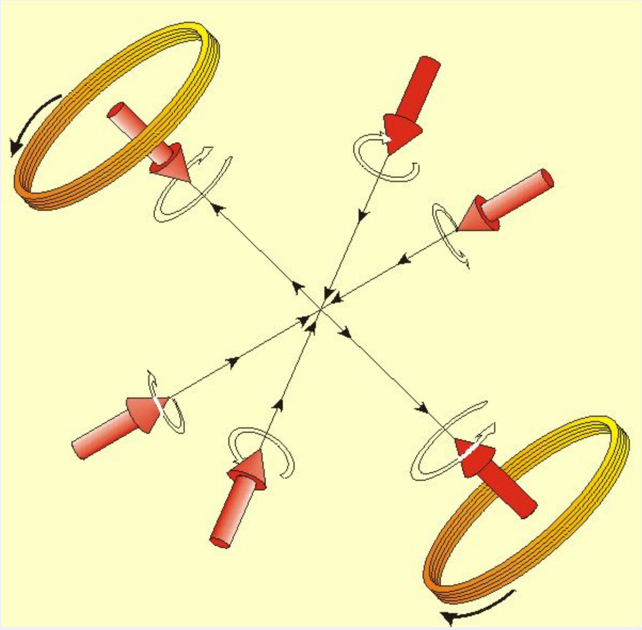
Single photon recoil temperature: $$k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$$

Examples:

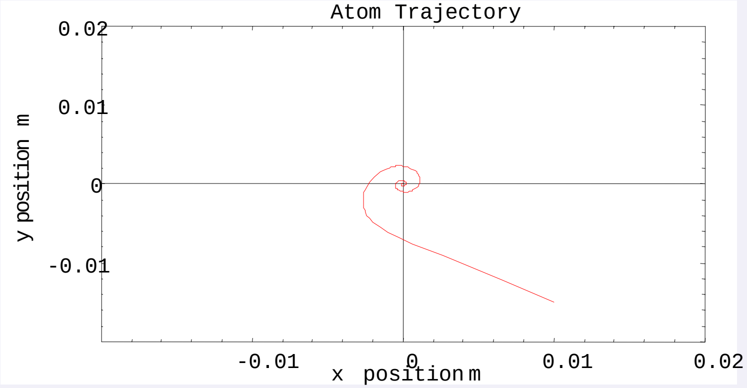
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK

Magneto-Optical Trap (MOT)





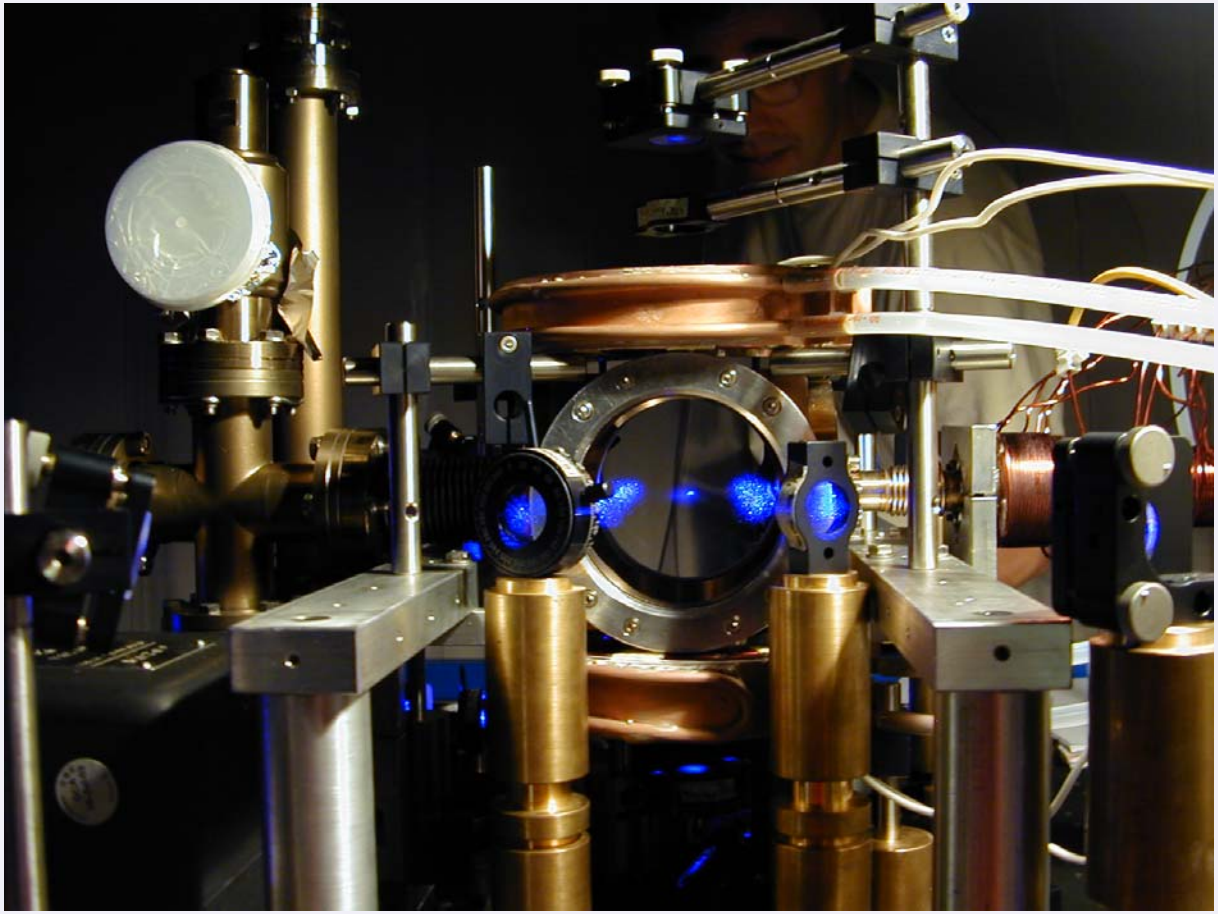
$$F(z,v) \simeq \frac{4hk}{\pi}\frac{I}{I_0}\frac{\delta}{\Gamma}\frac{kv+\beta z}{[1+(\frac{2\delta}{\Gamma})^2]^2}$$



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

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

Sr MOT picture



LENS, Firenze

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

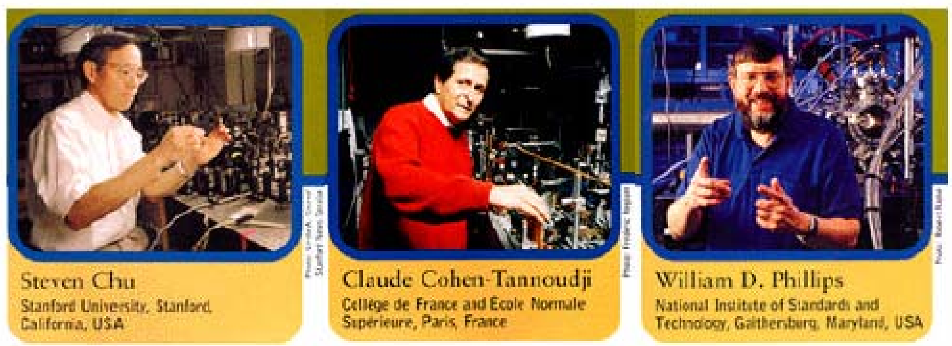
BACK

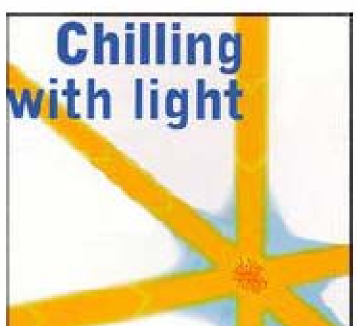
The Nobel Prize in Physics 1997

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**

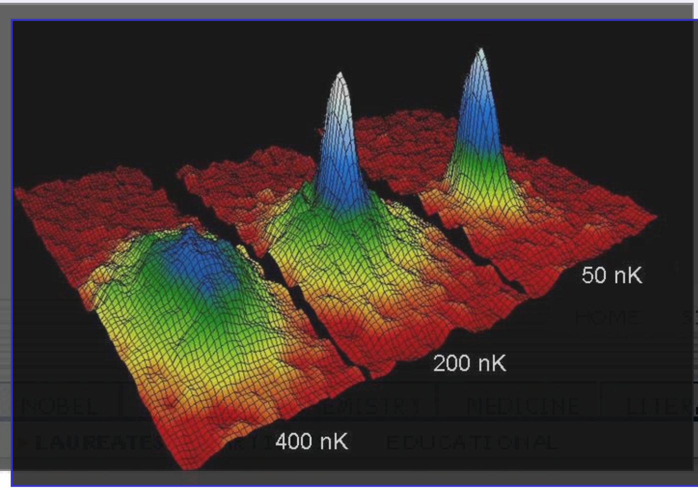
for their developments of methods to cool and trap atoms with laser light.





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.

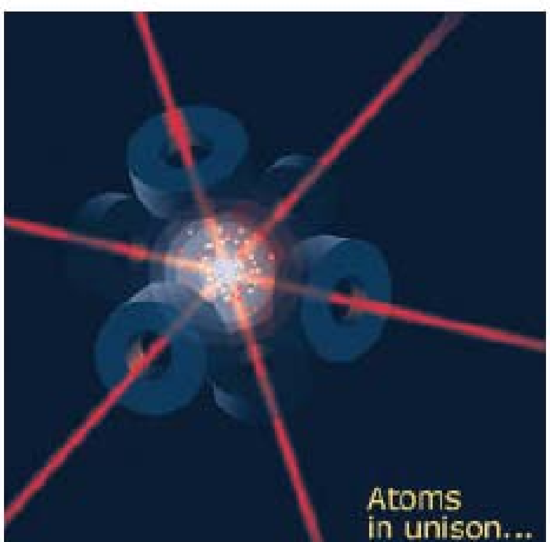
The Nobel Prize in Physics 2001

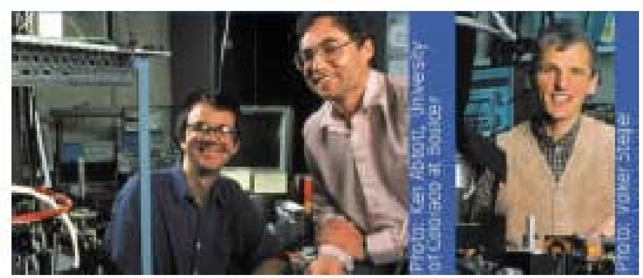


The Nobel Prize in Physics 2001

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".

BACK





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

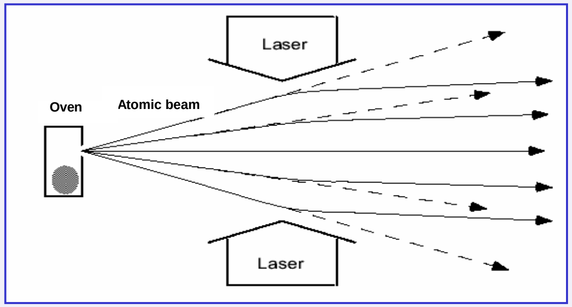
Carl E. Wieman
JILA and University of Colorado, Boulder, Colorado, USA.

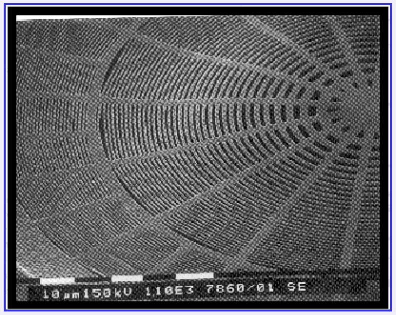
Wolfgang Ketterle
Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Contents:

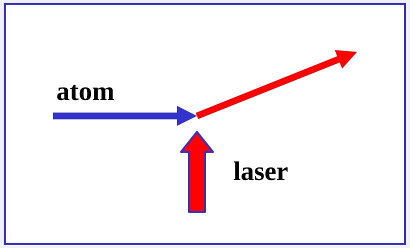
Atom optics

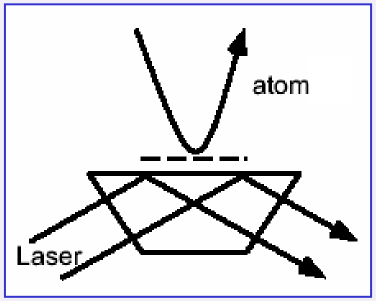
lenses



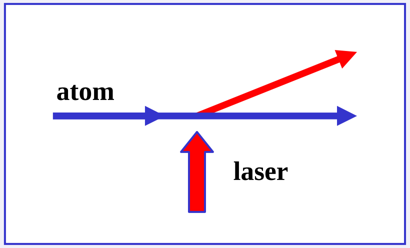


mirrors

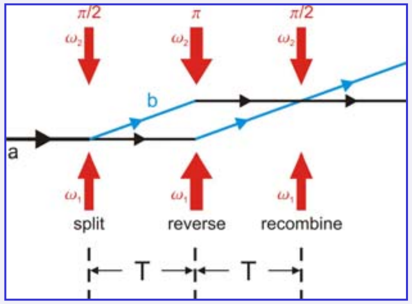




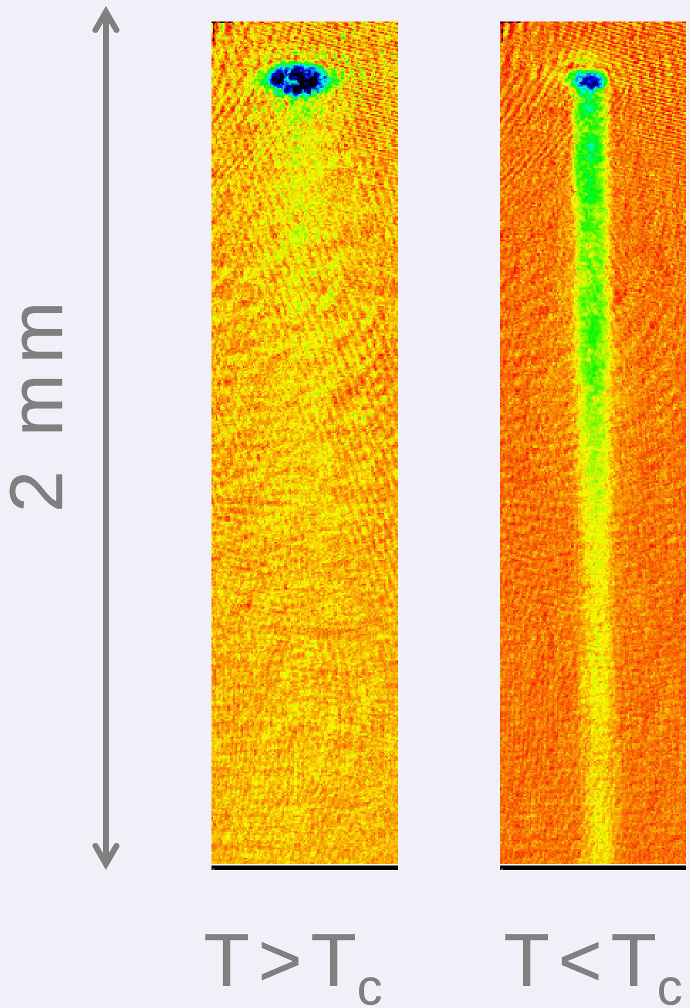
beam-splitters



interferometers



Atom Laser

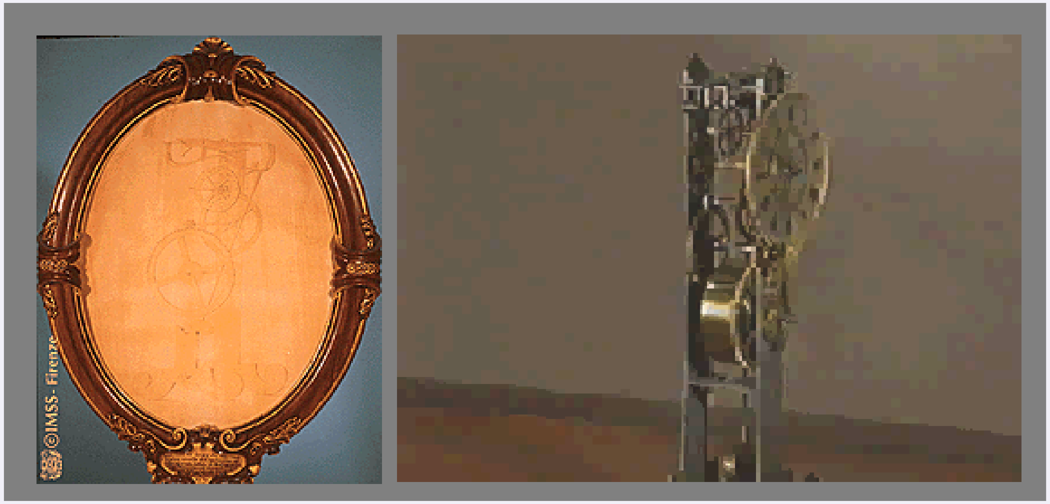


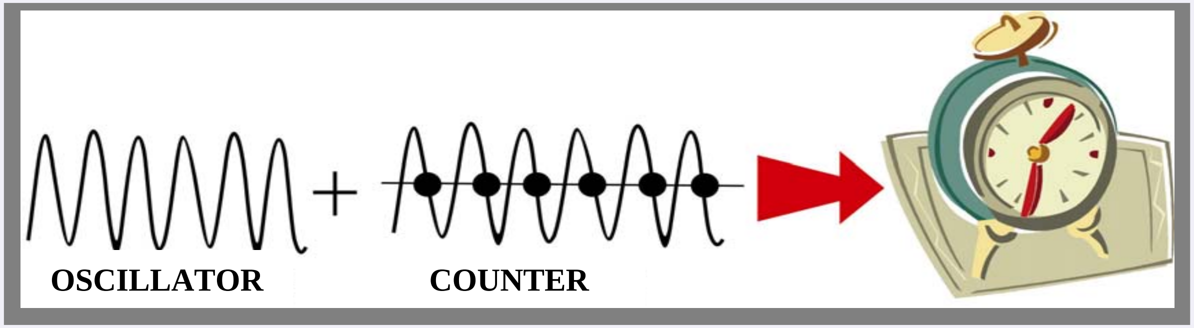
Physics and applications of ultracold atoms

- **BEC, degenerate Fermi gases, collective quantum effects**
- **Ultracold interactions and collision dynamics**
- **Ultracold molecules**
- **Surface physics and quantum reflection**
- **Entanglement and quantum information**
- **Precision spectroscopy**
- **Ultrasensitive isotope trace analysis**
- **Atom optics and atom laser**
- **Atom lithography**
- **Atomic clocks**
- **Atom interferometers**

Atomic clocks

The measurement of time

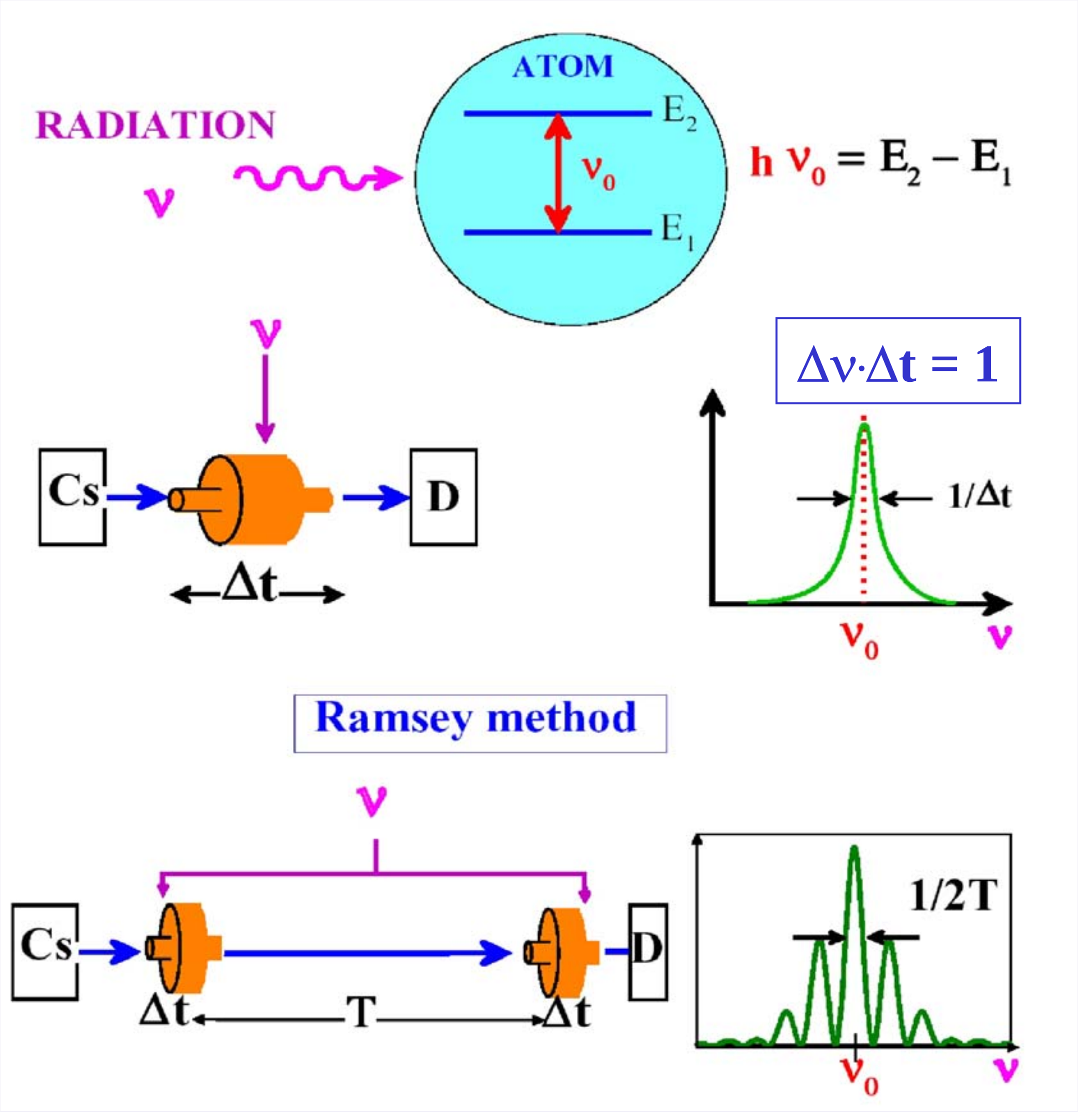




Accuracy → realization of the standard

Precision → stability of the frequency: depends on $\frac{\Delta\nu_0}{\nu_0}$ of the oscillator

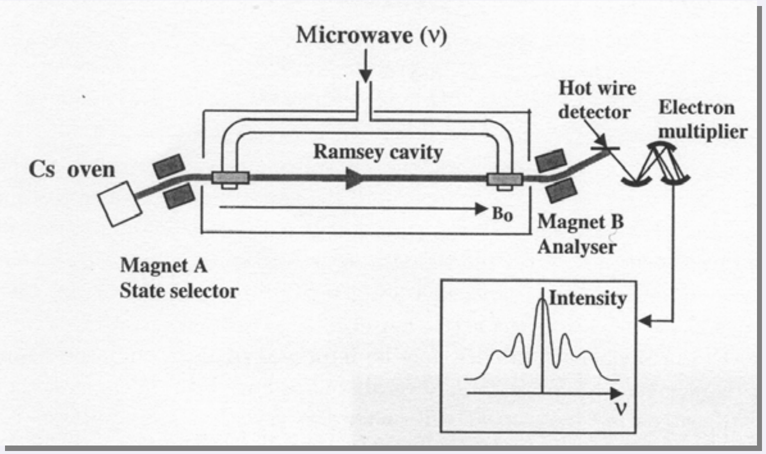
Atomic clocks



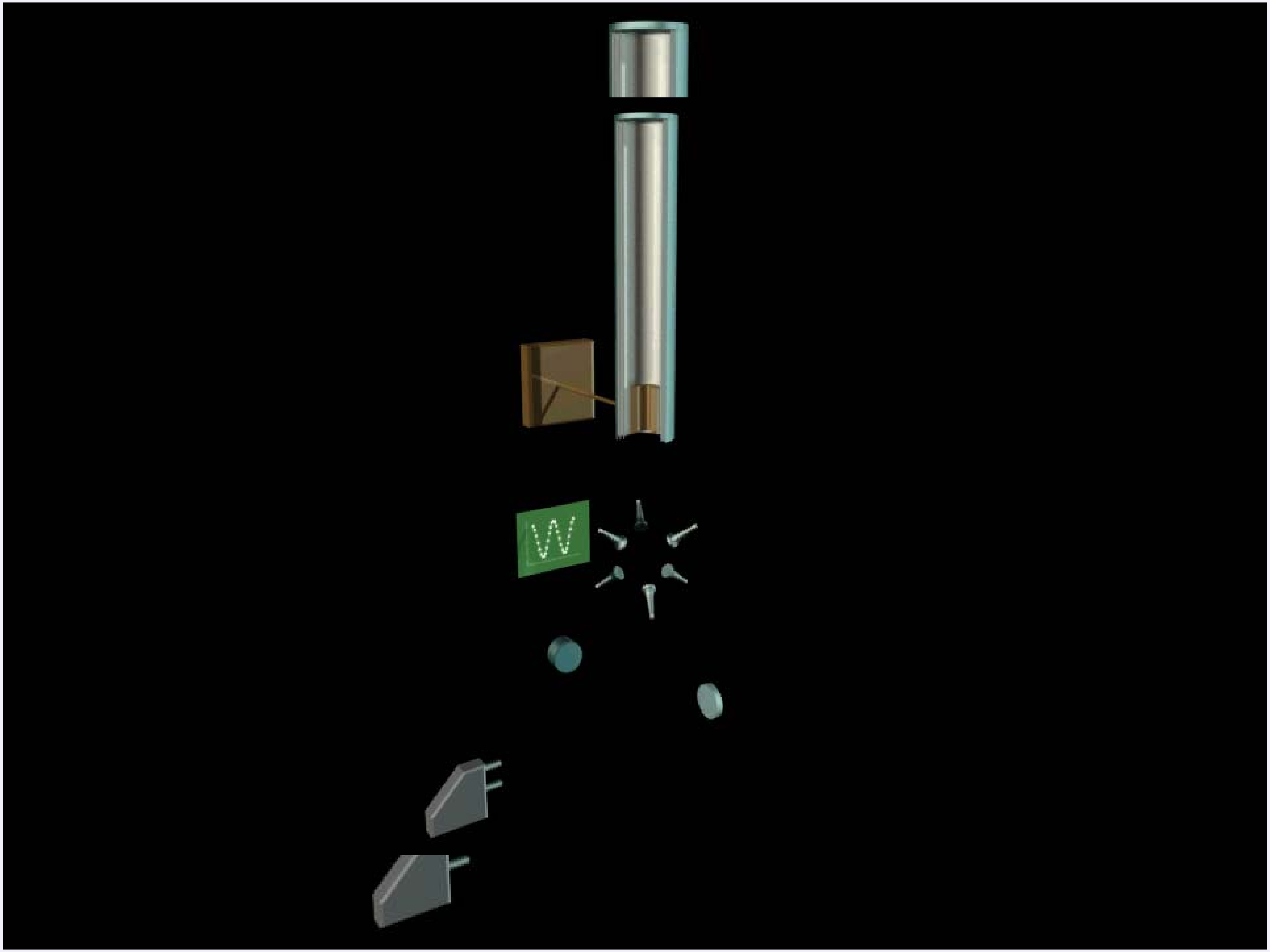
The definition of the second

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

(13th CGPM, 1967)

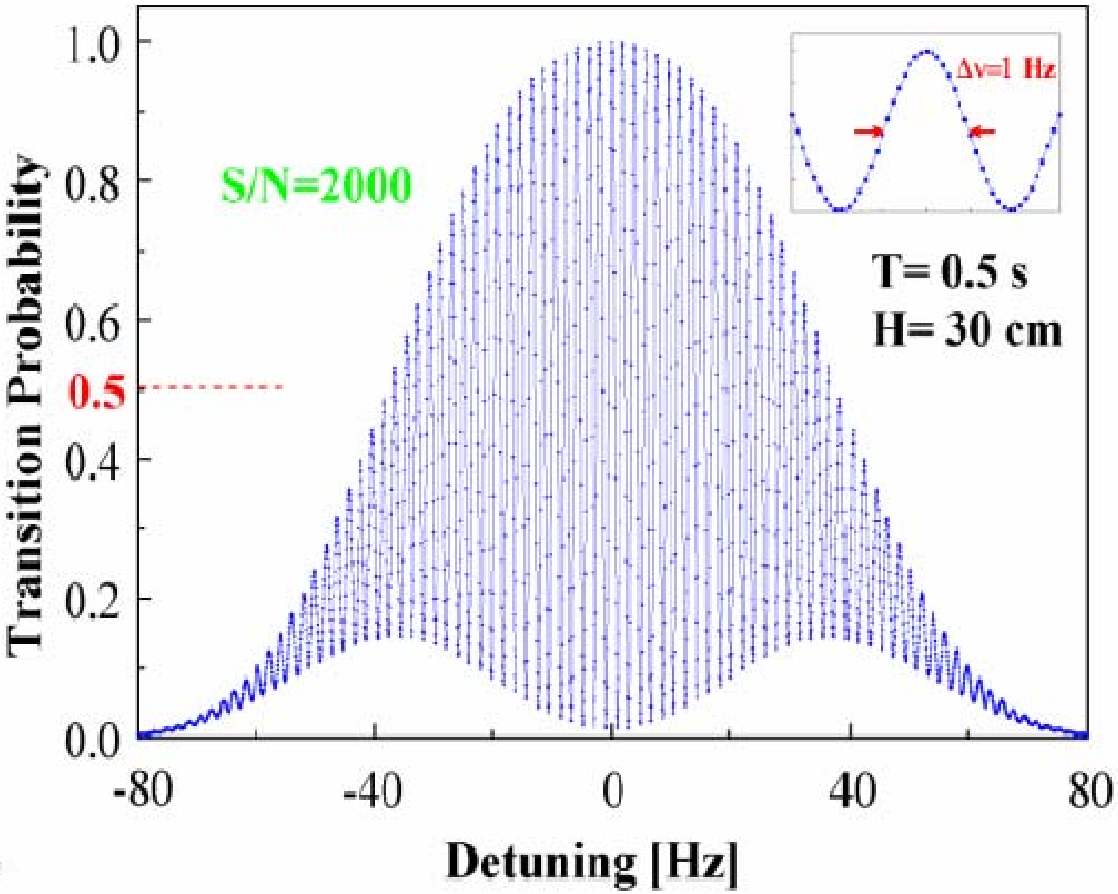


Atomic fountain clock



from C. Salomon

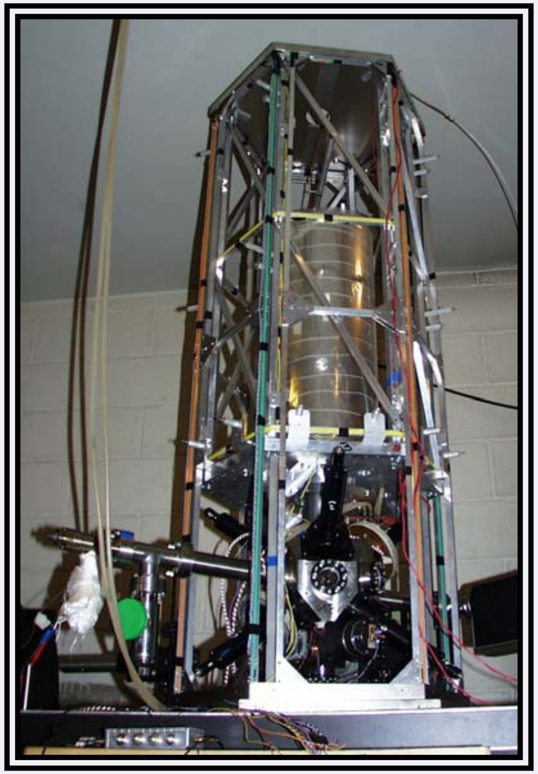
Interference fringes



G. Santarelli et al., PRL 82, 4619 (1999)

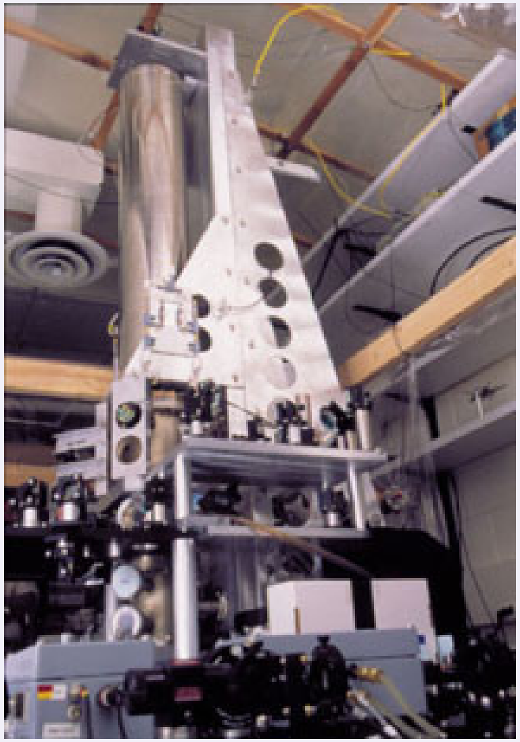
Atomic Fountains

8 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN, NPL, ON. 5 with accuracy at $1\ 10^{-15}$. More than 15 under construction.



BNM-SYRTE, FR

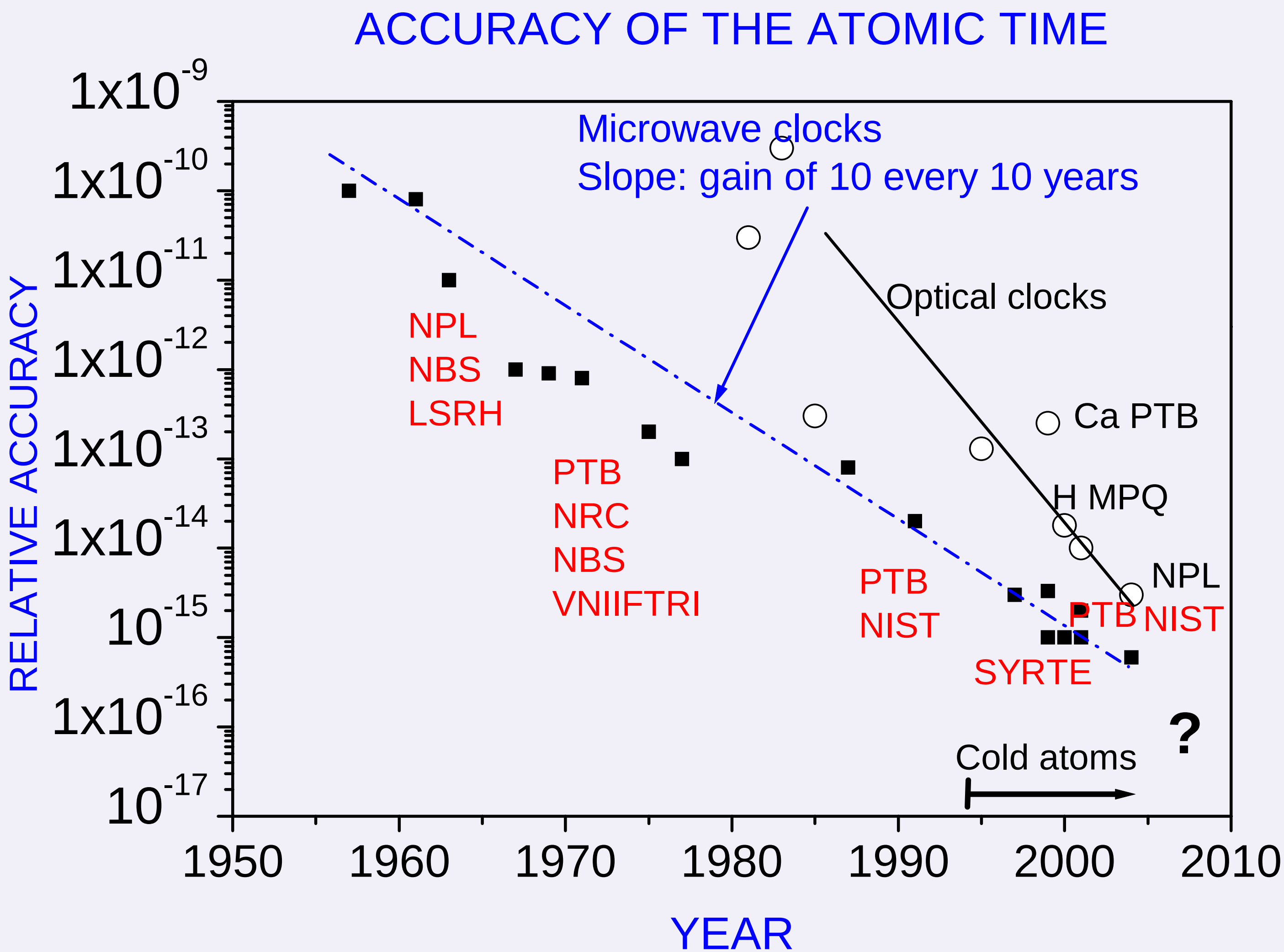
PTB, D



NIST, USA

from C. Salomon

Accuracy of the atomic time



from C. Salomon

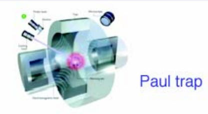
Optical clocks: Towards 10^{-18}

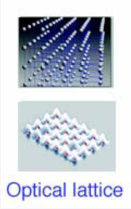
- **Narrow optical transitions**

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

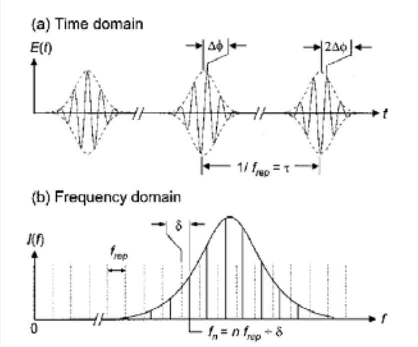
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N_{atom}}}\sqrt{\frac{T_{cycle}}{2\tau_{average}}}\frac{1}{C_{fringe}}$$

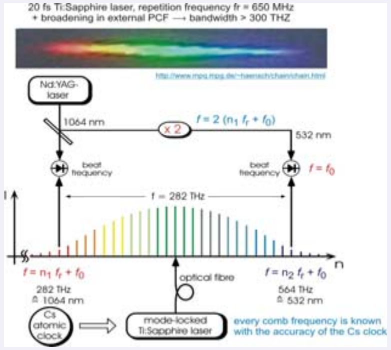
- **Candidate atoms**
  - **Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…**
  - **Cold neutral atoms: H, Ca, Sr, Yb,… (Fermions?)**

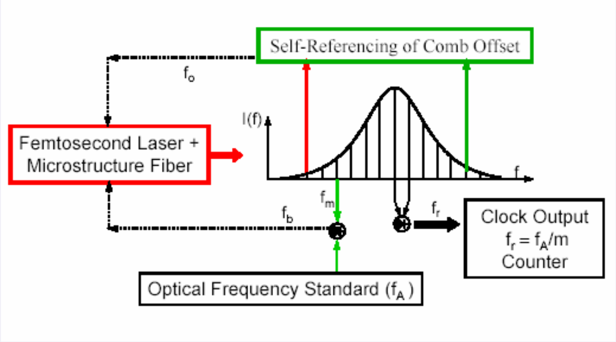




- **Direct optical-μwave connection by optical frequency comb**







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

Ca clock example

Cold atom Optical Clocks

The fractional frequency instability: (Allan deviation)

$$\sigma_y \simeq \frac{Noise}{\pi Q^* (Signal)} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atoms}}} \sqrt{\frac{T_{cycle}}{2\tau}} \frac{1}{C}$$

T_{cycle} = time to measure both sides of atomic resonance

Q = line quality factor $Q = \frac{\nu_0}{\Delta\nu}$ C = fringe contrast

τ = averaging time

N_{atom} = # of atoms detected in T_{cycle}

Eg. What should be possible w/ **Calcium**

λ = 657 nm, 456 THz clock transition

$\Delta\nu$ = 400 Hz C = 30 %

$\nu_0 = 456 \times 10^{15}$ Hz $N_A = 10^7$

$\sigma_y = 3\times10^{-16}$ in 1 ms ! $T_{cycle} = 2\, T_{Ramsey}$

$$\sigma_y(\tau) = 3\times10^{-17}\,\tau^{-1/2}$$

Other optical transitions?

w/ 1Hz wide line

$$\sigma_y(\tau) = 1\times10^{-19}\,\tau^{-1/2} \text{ ?}$$

From L. Hollberg, Hyper symposium 2002

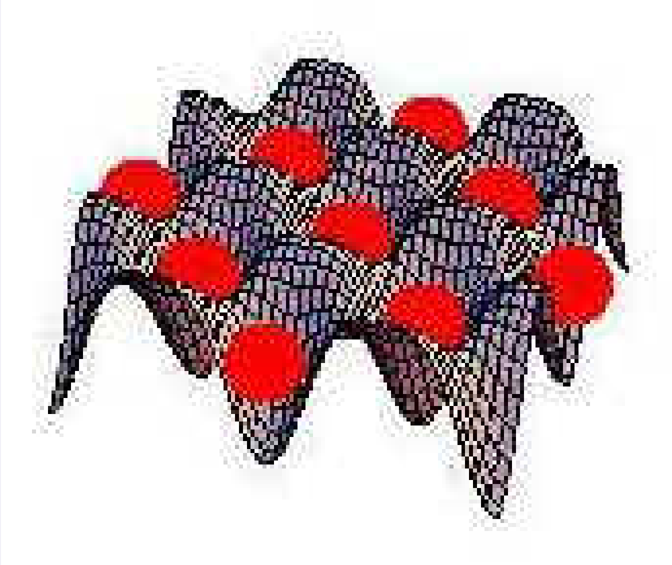
^{87}Sr optical clock

- **Method:** (H. Katori)

Interrogate atoms in optical lattice without frequency shift

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

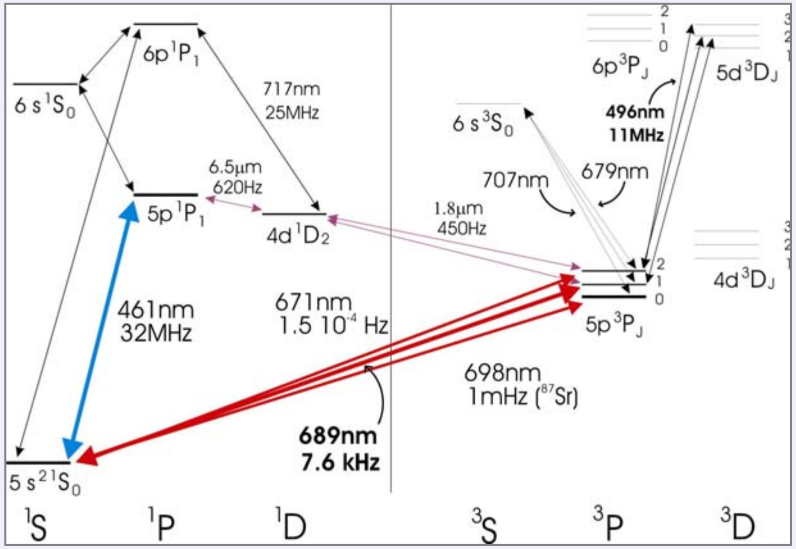
Excellent frequency stability

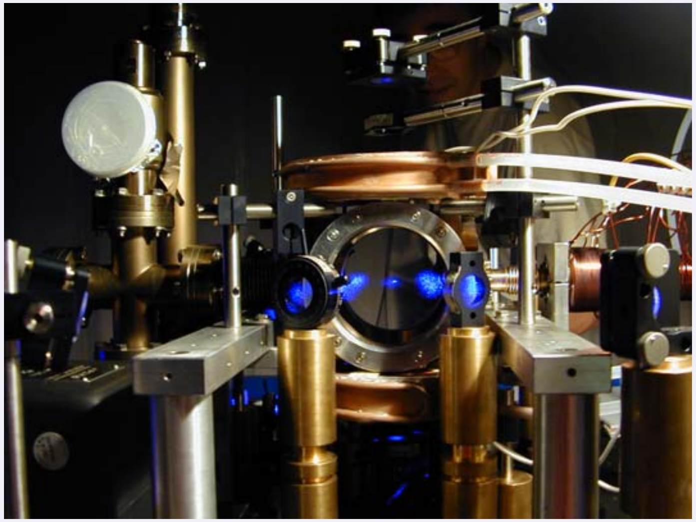


- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

2004: current linewidth: 80 Hz; stability at 1s: 3 10^{-14} !

Towards a Sr clock – The experiment in Firenze





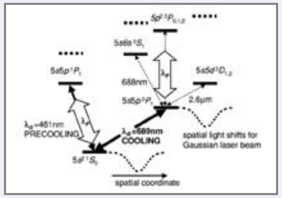
Firenze 2003, Magneto-optical trapping of all Sr isotopes

- Optical clocks using visible intercombination lines

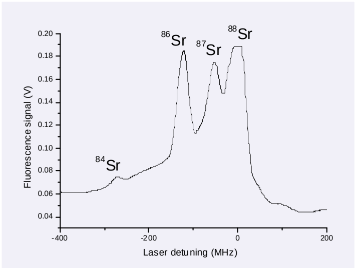
$^1S_0$ - $^3P_1$ (7.5 kHz)

$^1S_0$ - $^3P_0$ (1 mHz, ^{87}Sr)

$^1S_0$ - $^3P_2$ (0.15 mHz)

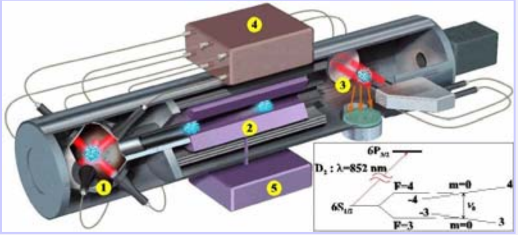


Optical trapping in Lamb-Dicke regime with negligible change of clock frequency



	Abundance
^{88}Sr	82.6%
^{86}Sr	9.9%
^{87}Sr	7.0%
^{84}Sr	0.6%

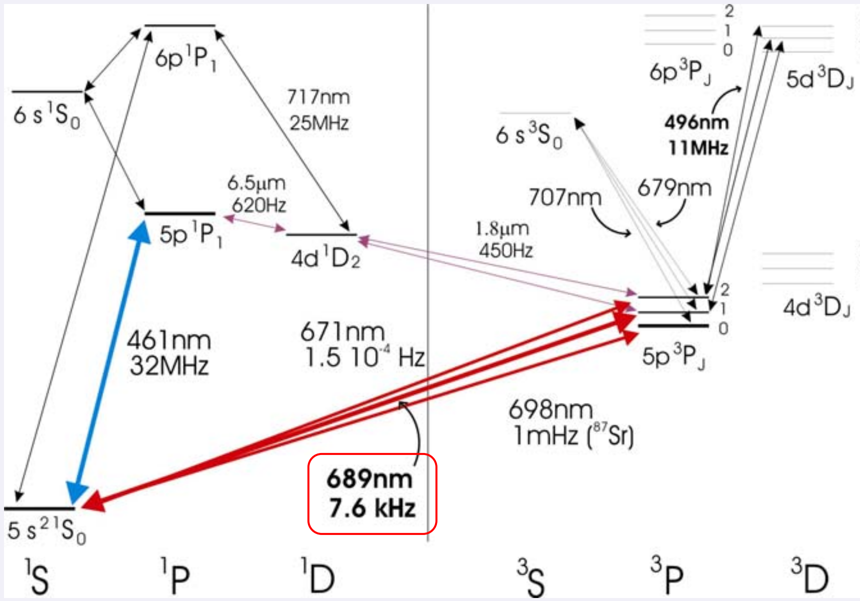
Comparison with different ultra-stable clocks (PHARAO/ACES)

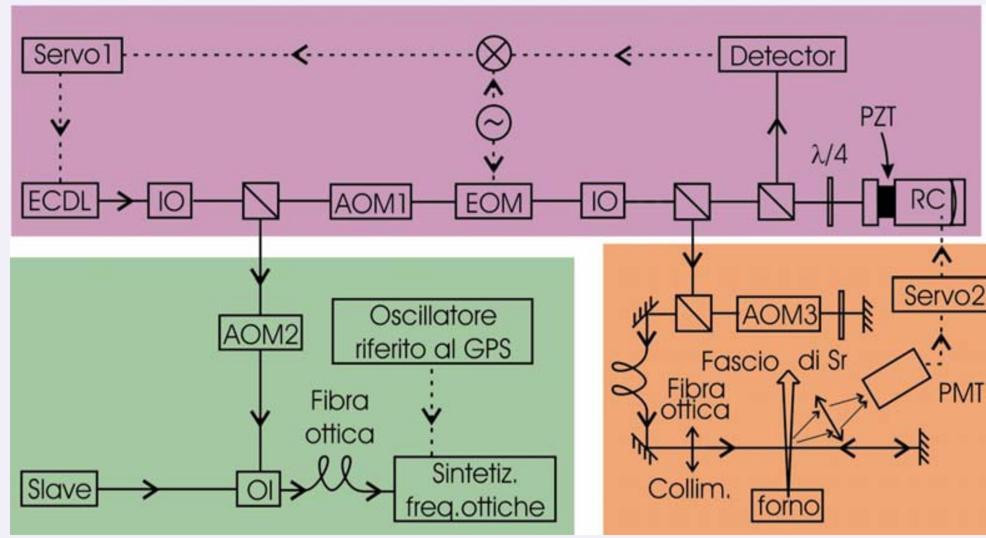


Isotope	I	transition	lifetime	λ	t_{int}	$\sigma_y\ t^{-1/2}$	abundance
^{88}Sr	0	$^1S_0$-$^3P_1$	20 µs	689 nm	10 µs	2 10^{-13}	83%
^{87}Sr	9/2	$^1S_0$-$^3P_0$	200 s	698 nm	0.5 s	10^{-17}	7%

http://www.lens.unifi.it/poli/

Precision frequency measurement of visible intercombination lines of strontium





- **Final value 434 829 121 311 (10) kHz**
- ≡ **Relative accuracy: 2 x 10^{-11}**
- ≡ **> 4 orders of magnitude better than previous data**

G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli and G.M. Tino, Phys. Rev. Lett. **91**, 243002 (2003)

Applications of atomic clocks

- Location finding
- Precision navigation and navigation in outer space
- Variability of Earth's rotation rate and other periodic phenomena
- Earth's crustal dynamics
- Secure telecommunications

- Very Long Baseline Interferometry (VLBI)
- Spectroscopy
- Expression of other physical quantities in terms of time
- Tests of constancy of fundamental constants
- Tests of the special and general theories of relativity

General relativity test: gravitational red shift

PHYSICAL REVIEW LETTERS

VOLUME 45 | 29 DECEMBER 1980 | NUMBER 26

Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser

R. F. C. Vessot, M. W. Levine,[a] E. M. Mattison, E. L. Blomberg, T. E. Hoffman,[b] G. U. Nystrom, and B. F. Farrel

Smithsonian Astrophysical Observatory, Cambridge, Massachusetts 02138

and

R. Decher, P. B. Eby, C. R. Baugher, J. W. Watts, D. L. Teuber, and F. D. Wills

George C. Marshall Space Flight Center, Huntsville, Alabama 35812

(Received 19 August 1980)

The results of a test of general relativity with use of a hydrogen-maser frequency standard in a spacecraft launched nearly vertically upward to 10 000 km are reported. The agreement of the observed relativistic frequency shift with prediction is at the 70×10^{-6} level.

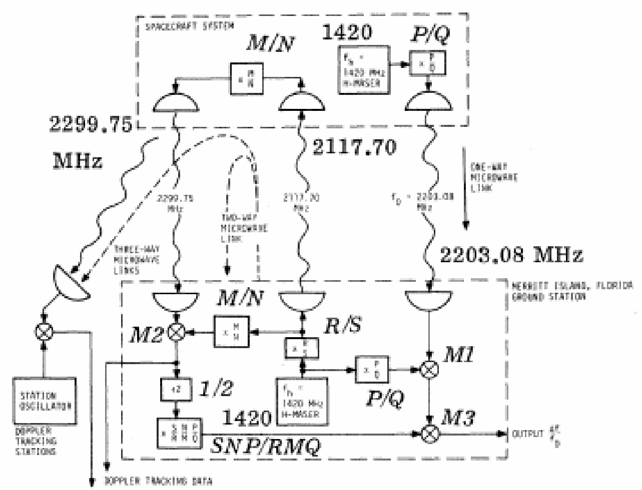


FIG. 1. Doppler cancellation and tracking system.

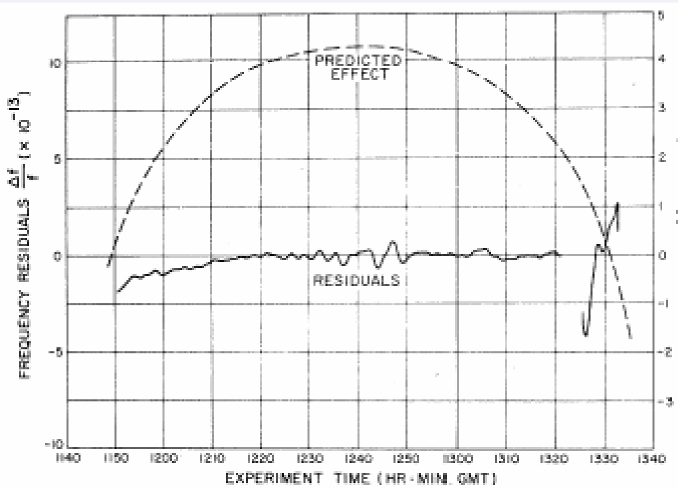


FIG. 3. Frequency residuals and predicted effect during mission.

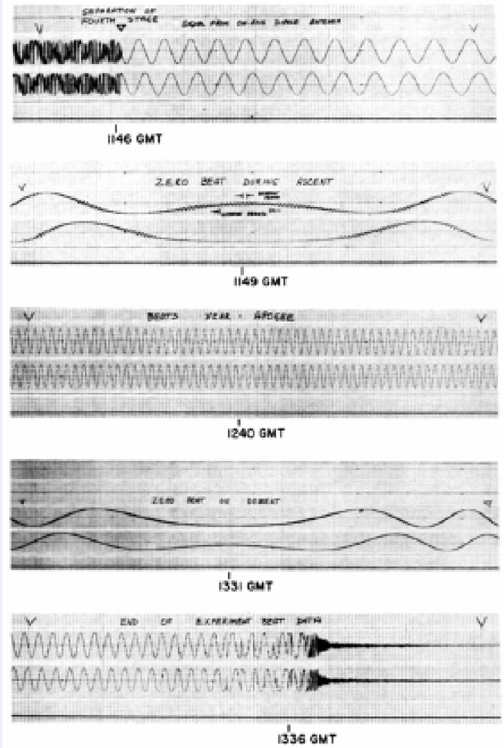
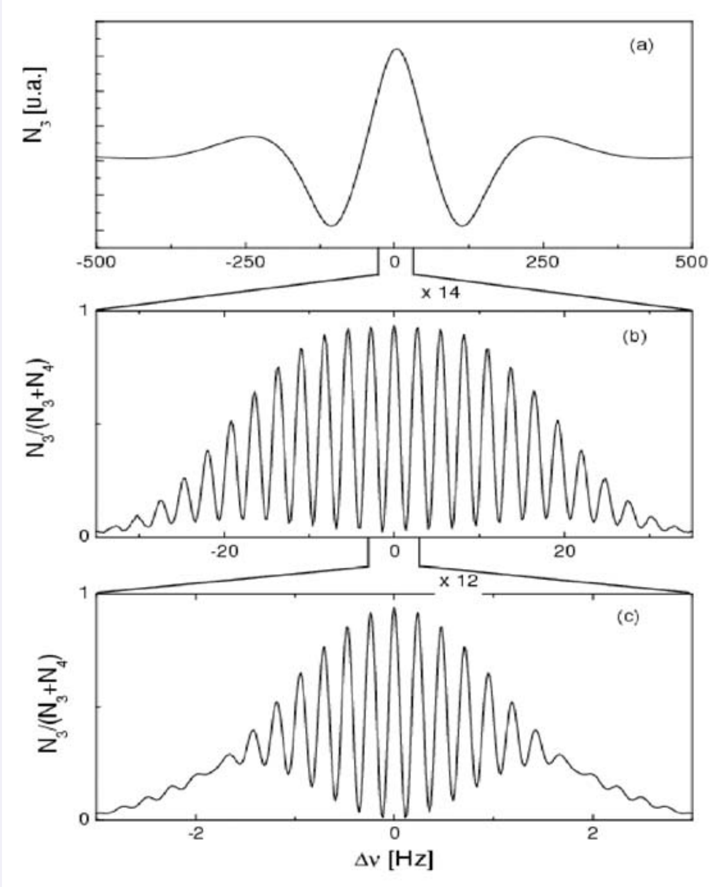


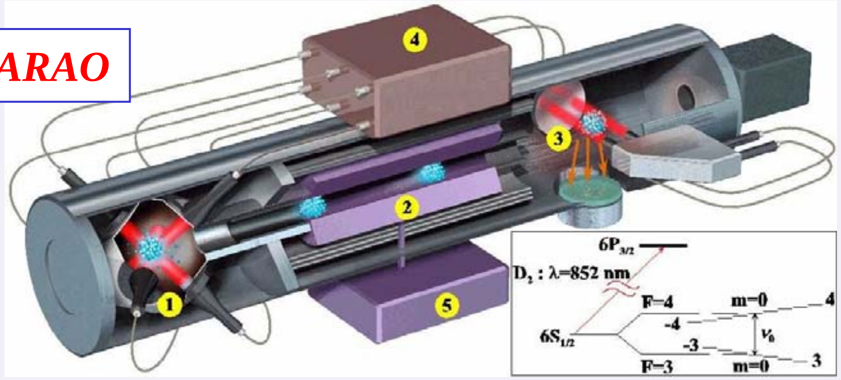
FIG. 2. Analog strip-chart recorder data at various times during the mission. (a) Signal from dipole antenna. The (inverted delta) markers indicate the time at which the fourth stage of the rocket separated. (b) Zero beat during ascent. The small interval indicated above the top trace is a rotation period; the longer interval below is a nutation period. (c) Beats near apogee. (d) Zero beat on descent. (e) End of experimental beat data.

Cold Atoms Clocks in Space



- Interrogate fast (hot) atoms over long distances → T = 10 ms
- Use laser cooled atoms, limitation due to the presence of gravity → T = 1 s
- Use laser cooled atoms in microgravity → T = 10 s

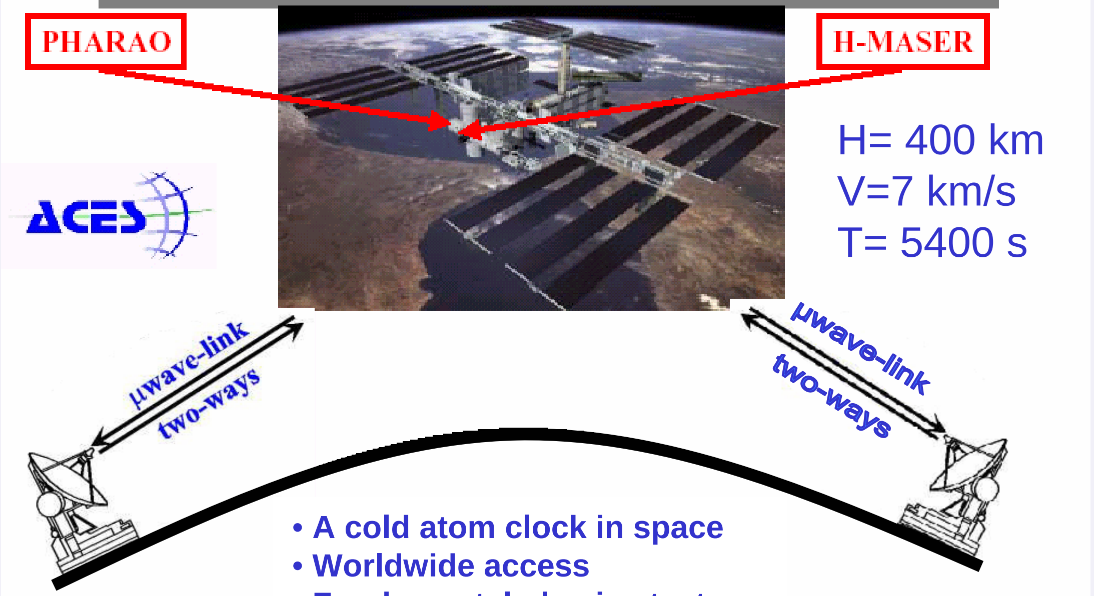
PHARAO



C. Salomon et al., C.R. Acad. Sci. 2, 1313 (2001)

Atomic Clock Ensemble in Space

ACES : New clocks on board the ISS



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

PHARAO : Cold Atom Clock in Space. CNES (France)

A. Clairon, P. Laurent, P. Lemonde, M. Abgrall, S. Zhang, C. Mandache, F. Allard, M. Maximovic, F. Pereira, G. Santarelli, Y. Sortais, S. Bize, H. Marion, D. Calonico, (BNM-LPTF), N. Dimarcq (LHA), C. Salomon (ENS)

SHM : Space Hydrogen Maser. ON (Switzerland)

L. Jornod, D. Goujon, L.G. Bernier, P. Thomann, G. Busca

MWL : Microwave link. Kayser-Threde-Timetech (Germany)

W. Schaefer, S. Bedrich

ACES is open to any interested scientific user

W. Knabe, P. Wolf, L. Blanchet, P. Teyssandier, P. Uhrich, A. Spallici

New members :

2001: UWA (Australia), A. Luiten, M. Tobar, J. Hartnett, R. Kovacich

2002: LENS (Italy), G.M. Tino, G. Ferrari, L. Cacciapuoti

ESA: MSM

Stephen Feltham

CNES:

C. Sirmain + team of 20 engineers at CST, Toulouse

Support: ESA, CNES, BNM, CNRS

ACES objectives

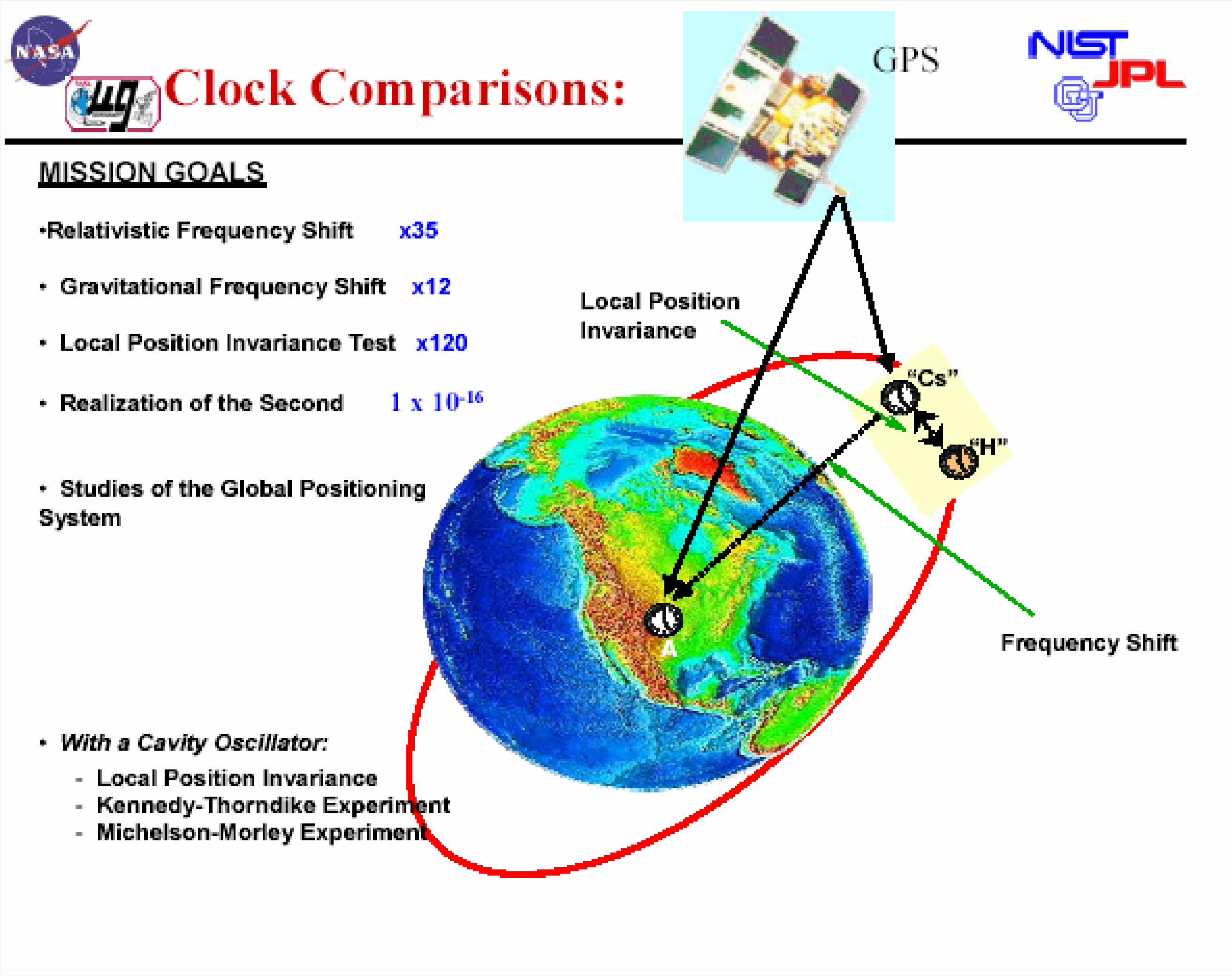
1. Operate a cold atom clock in microgravity :
   - A linewidth of 50 milliHertz
   - A frequency stability of : $\sigma_y(\tau)$ $< 10^{-13}\,\tau^{-1/2}$

     $< 3\ 10^{-16}$/day
2. Study the ultimate stability and accuracy in space :
   - Accuracy : $\sim 10^{-16}$
   - Compromise stability-accuracy
3. Ultra-stable time-scale comparisons on a worldwide basis :
   - 30 ps accuracy
   - Clock synchronisation (10^{-16} accuracy)
   - Contribution to TAI
4. Test General Relativity :
   - Red shift : x25 sensitivity improvement
   - Search for a possible drift of the fine structure constant

     α : 10^{-16} / year (x100)
   - Search for an anisotropy of speed of light (x10)

L. Blanchet, C. Salomon, P. Teyssandier, and P. Wolf, A&A 370, 320 (2001)

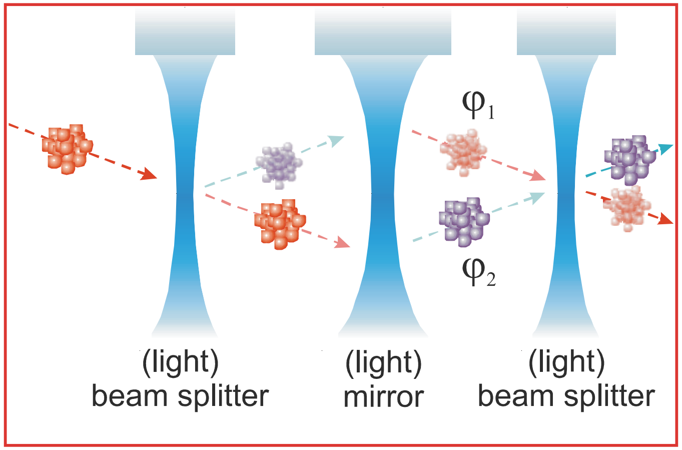
PARCS
Primary Atomic Reference Clock in Space



Atom Interferometry

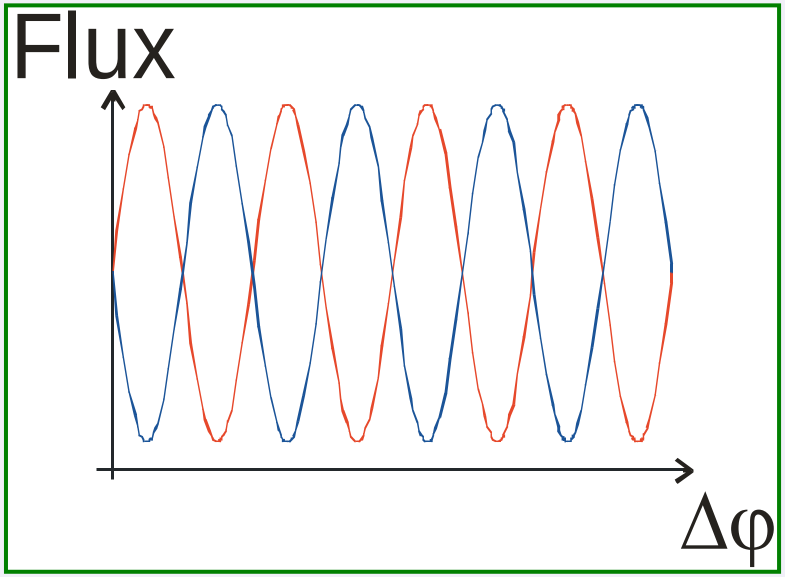
Matter wave interferometry

Atom interferometer



Phase difference

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

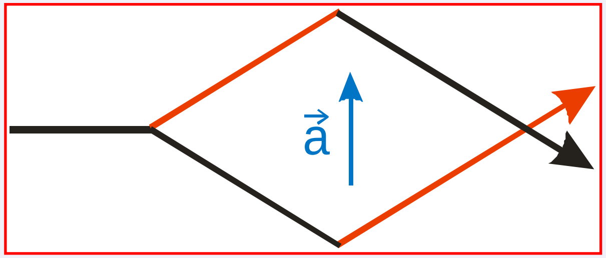


atomic flux at **exit** port **1**

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

Matter wave sensors

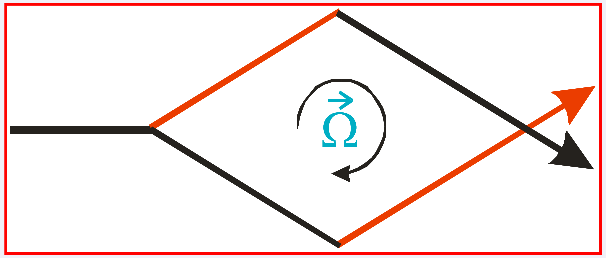
accelerations:



$$\Delta\Phi_{acc} = k\, T_{drift}^2 \cdot a$$

$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \left(\frac{c}{v_{at}}\right)^2 \approx 10^{11} - 10^{17}$$

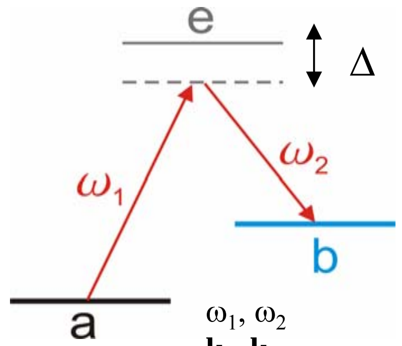
rotations:



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

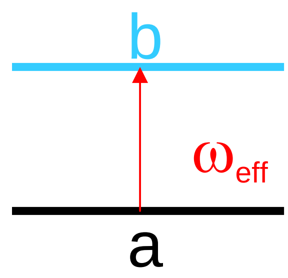
$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \frac{m_{at} \cdot \lambda \cdot c}{h} \approx 5 \cdot 10^{10}$$

Raman pulse interferometer

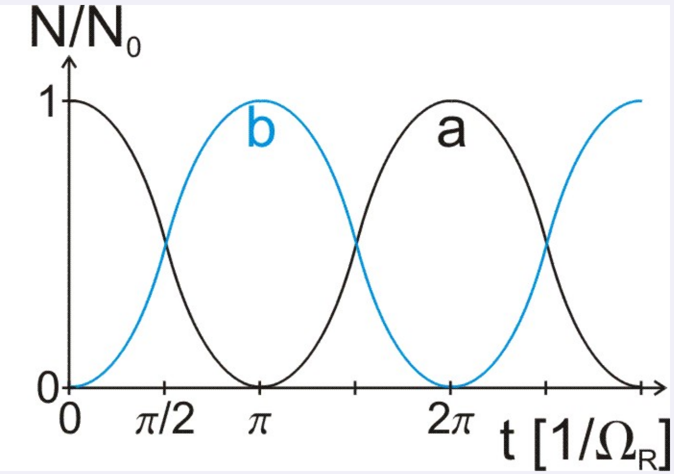


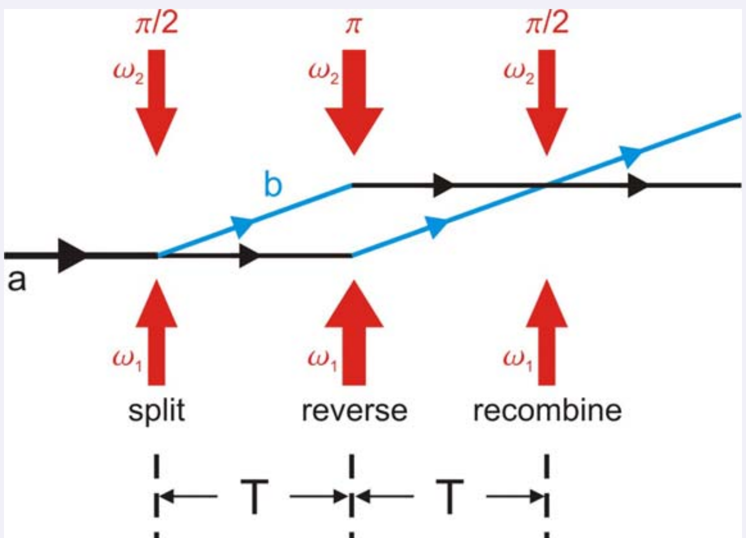
ω_1, ω_2
$\mathbf{k}_1$, $\mathbf{k}_2$
Ω_1, Ω_2
ϕ_1 , ϕ_2

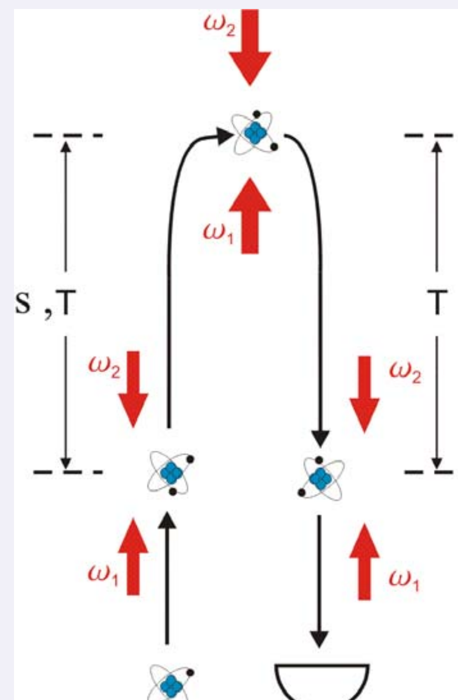
$\Longrightarrow$



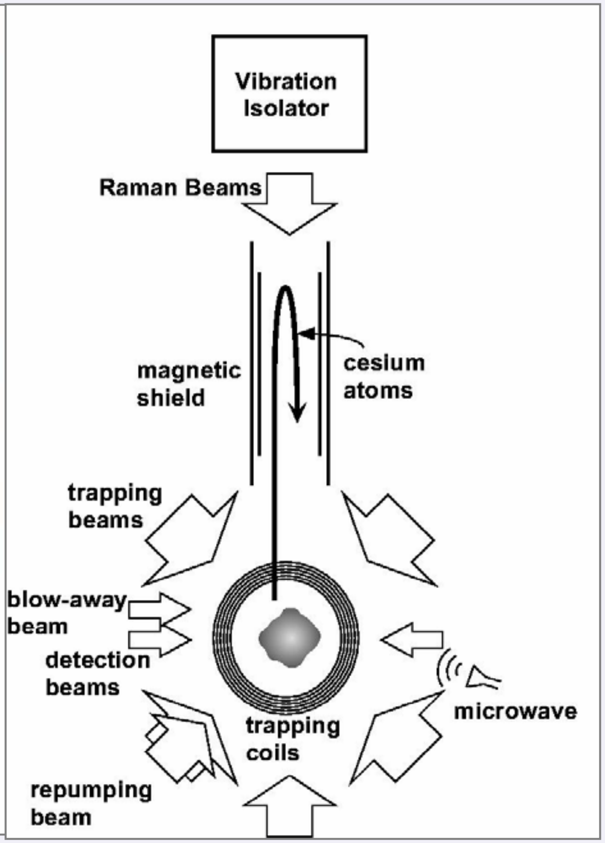
$\omega_{eff} = \omega_1 - \omega_2$
$\mathbf{k}_{eff} = \mathbf{k}_1 - \mathbf{k}_2$
$\Omega_{eff} = \Omega_1\Omega_2/\Delta$
$\phi_{eff} = \phi_1 - \phi_2$

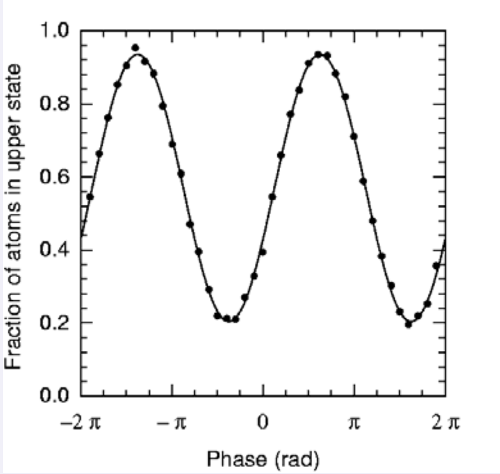


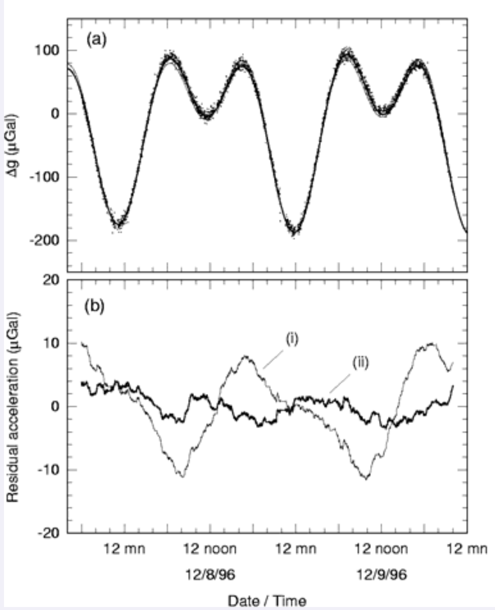




Stanford atom gravimeter





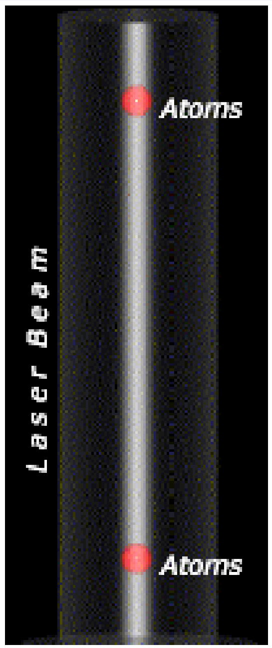


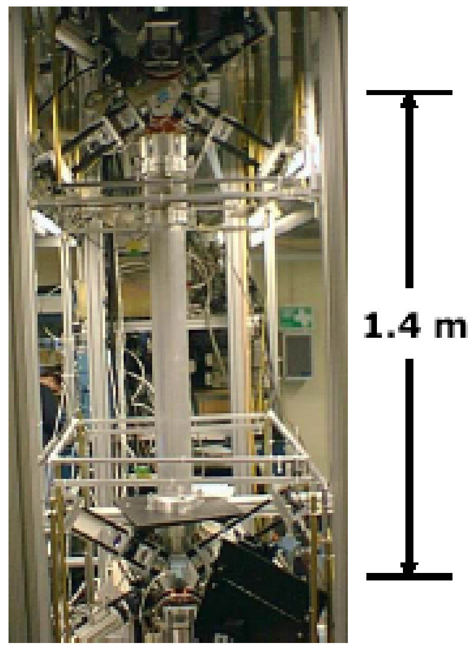
Resolution: 3×10^{-9} g after 1 minute

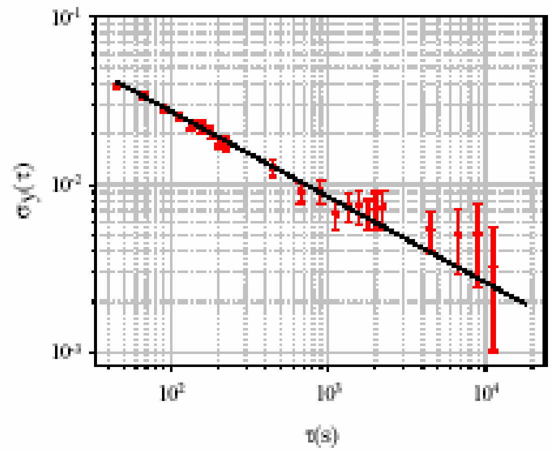
Absolute accuracy: $\Delta g/g<3\times10^{-9}$

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:

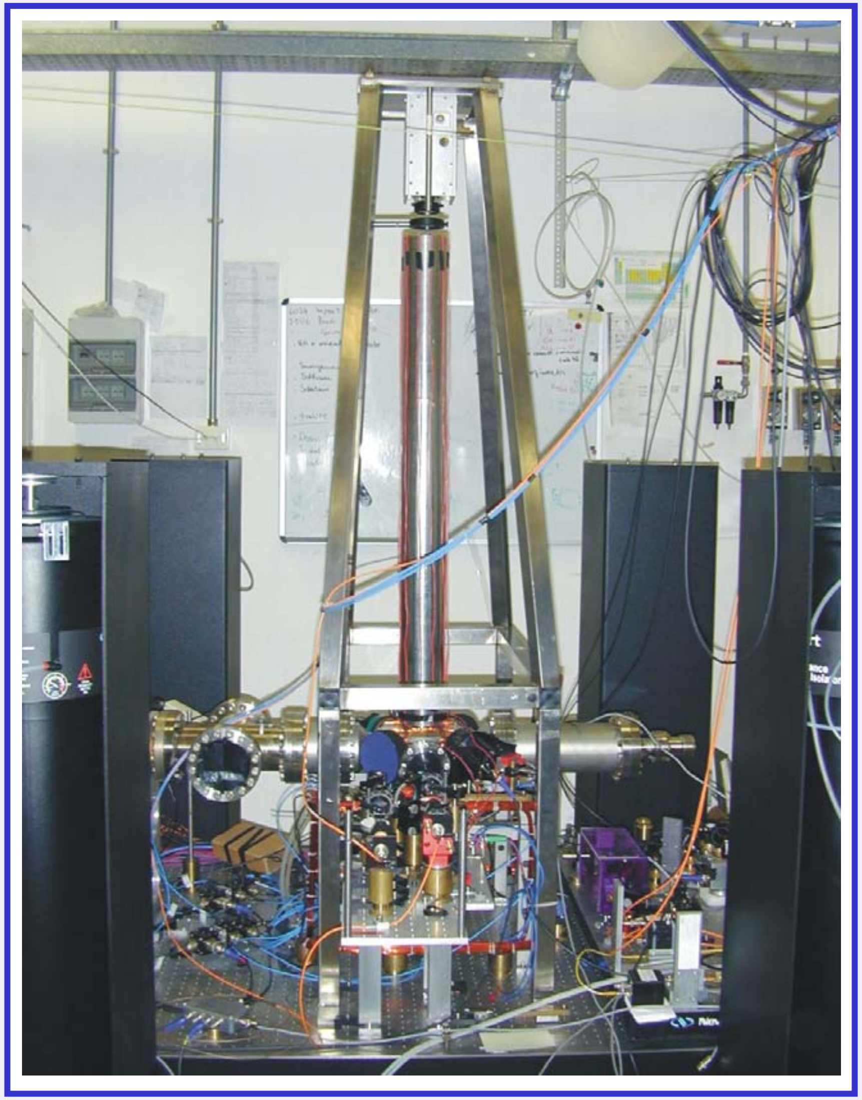
4×10^{-9} g/Hz$^{1/2}$

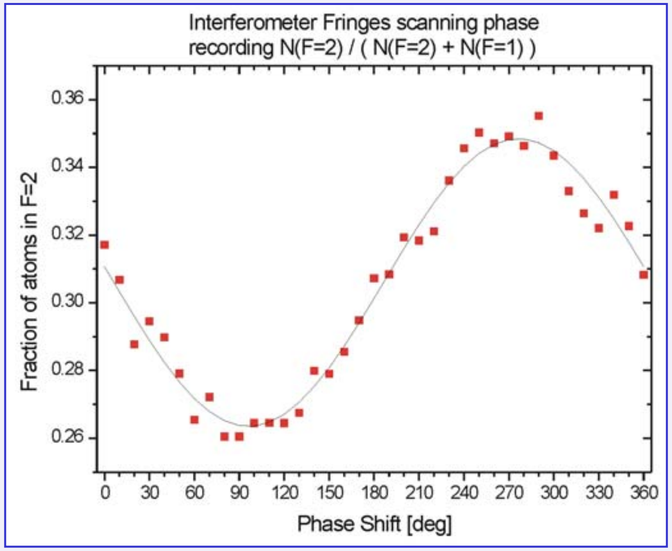
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

from M.A. Kasevich

M.J. Snadden et al., Phys. Rev. Lett. <u>81</u>, 971 (1998)

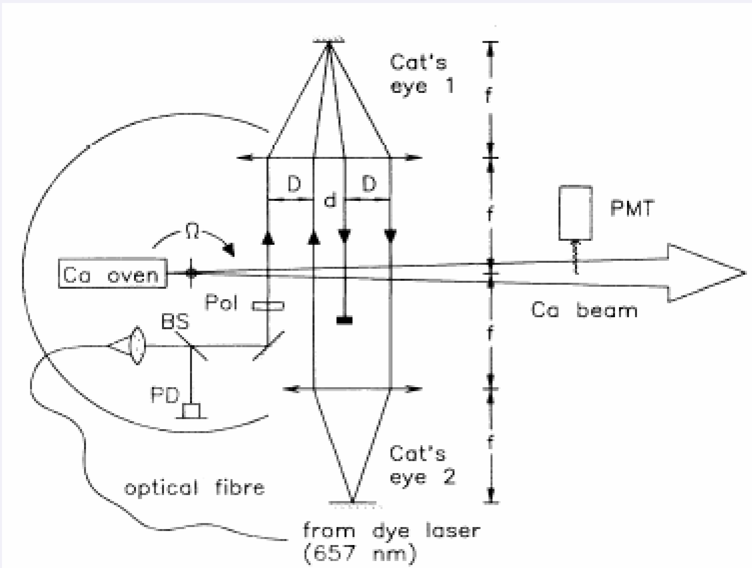
Atom gravimeter/gradiometer in Firenze

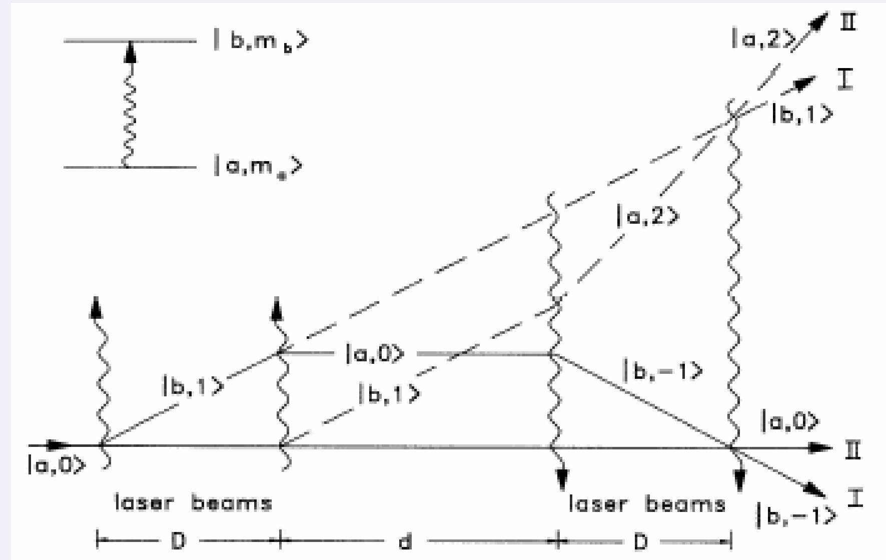


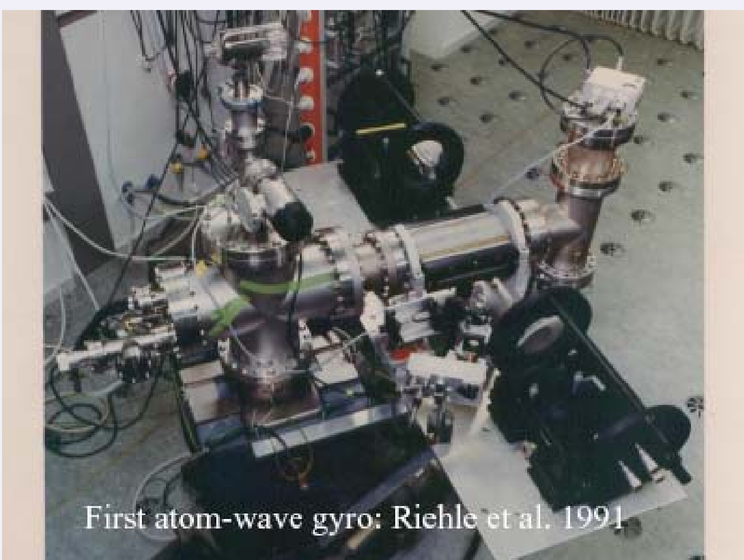


$$\Rightarrow \Delta g/g = 8.6 \cdot 10^{-6} \frac{1}{\sqrt{\text{Hz}}} = 9.1 \cdot 10^{-7} \ \text{ in } 90\,\text{s}$$

Atom gyroscope



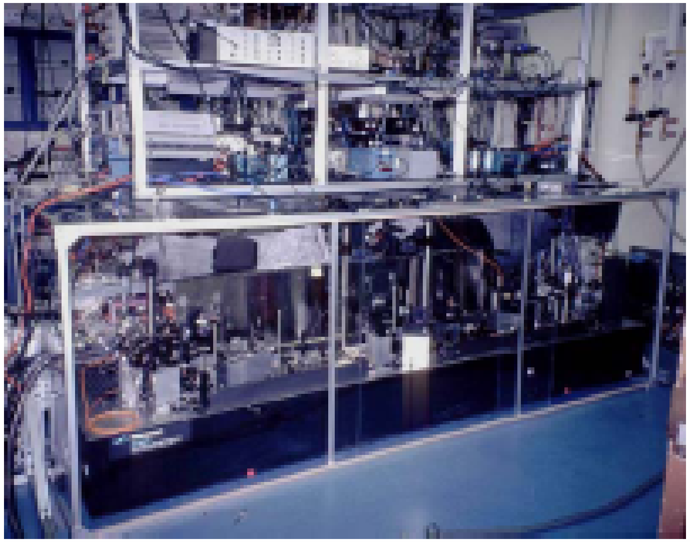


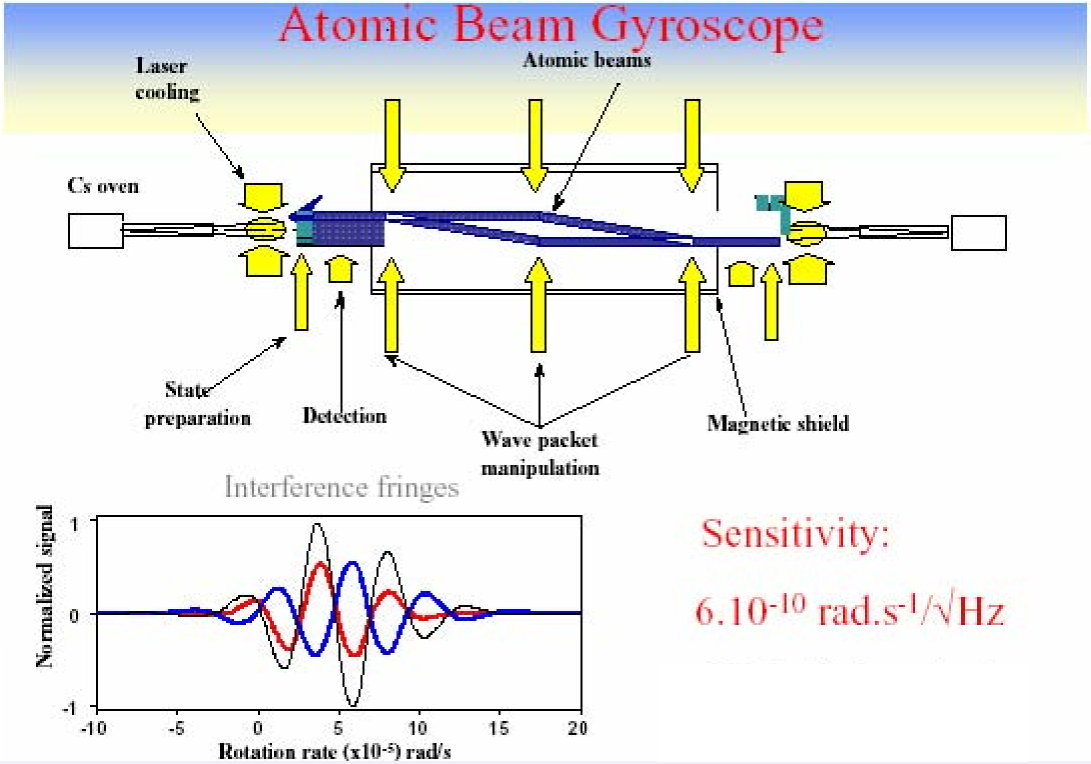

First atom-wave gyro: Riehle et al. 1991

with light: Sagnac (1913)
with neutrons: Werner et al.(1979)
with atoms: Riehle et al. (1991)

F. Riehle, Th. Kisters, A. Witte, J. Helmcke, Ch. J. Bordé, Phys. Rev. Lett. 67, 177 (1991)

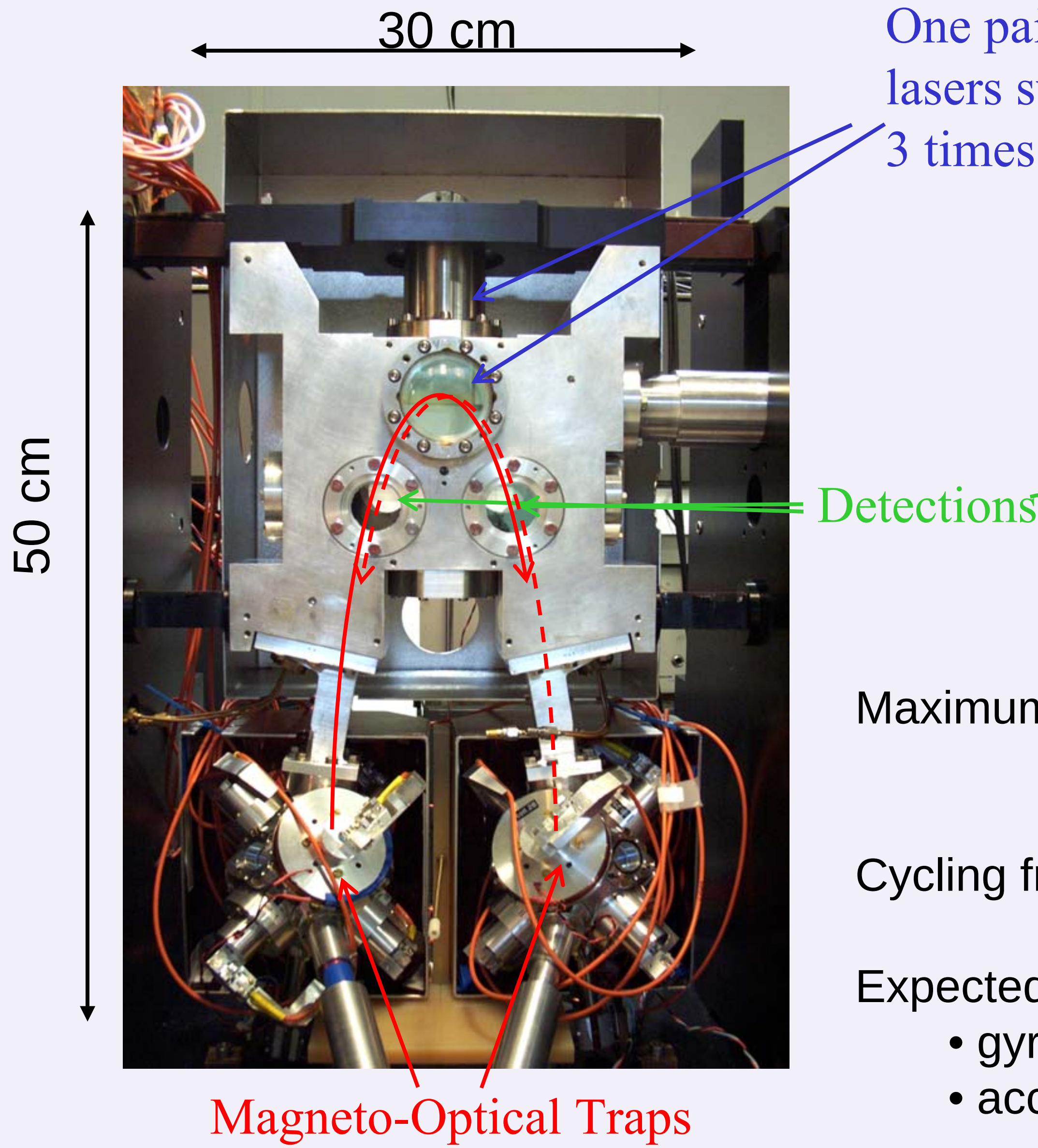
Stanford/Yale gyroscope

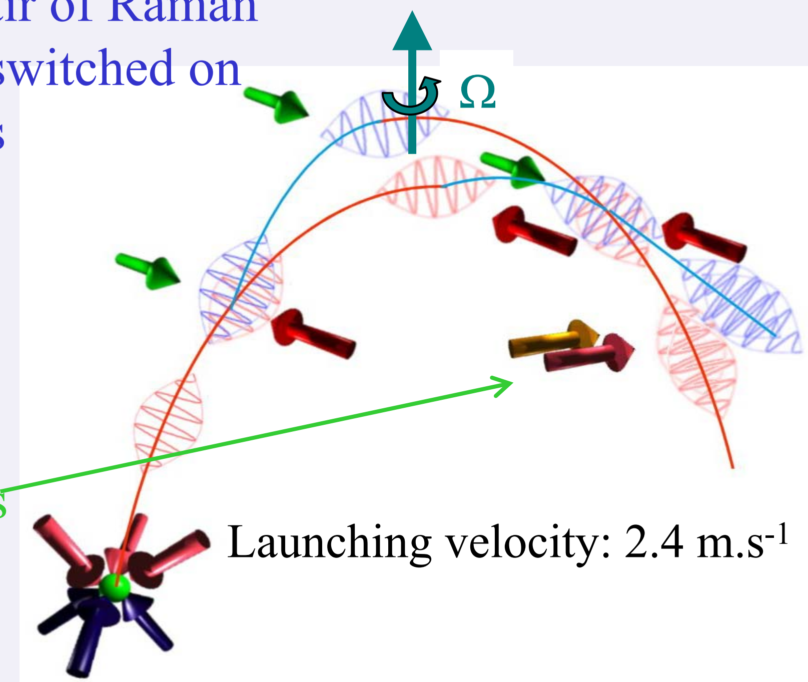




T.L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)

SYRTE cold atom gyroscope





Maximum interaction time : 90 ms
3 rotation axes
2 acceleration axes
Cycling frequency 2Hz

Expected sensitivity (10^6 at):

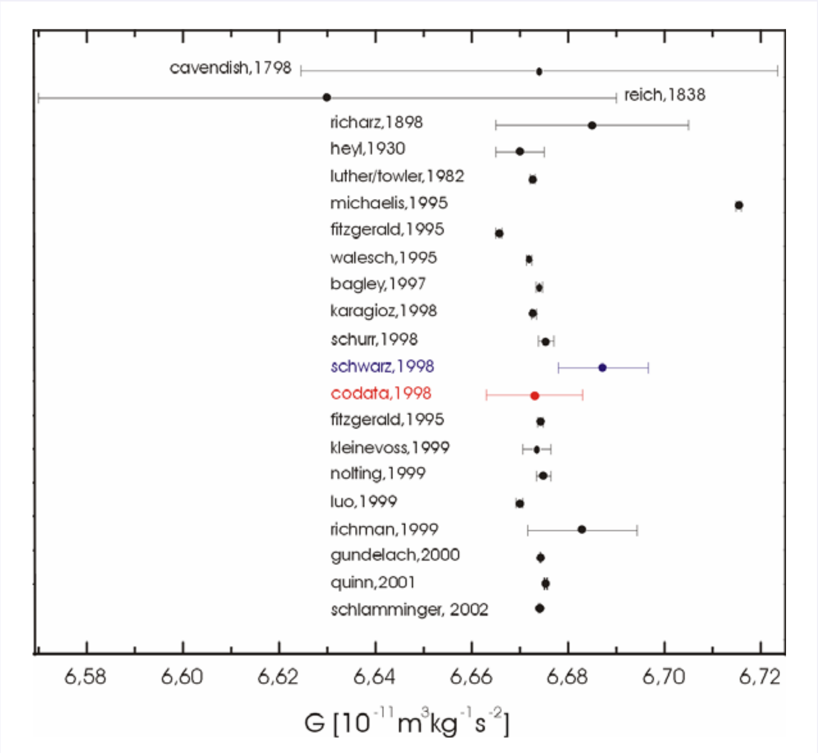
- gyroscope : $4\ 10^{-8}$ rad.s^{-1}.Hz$^{-1/2}$
- accelerometer : $3\ 10^{-8}$ m.s^{-2}.Hz$^{-1/2}$

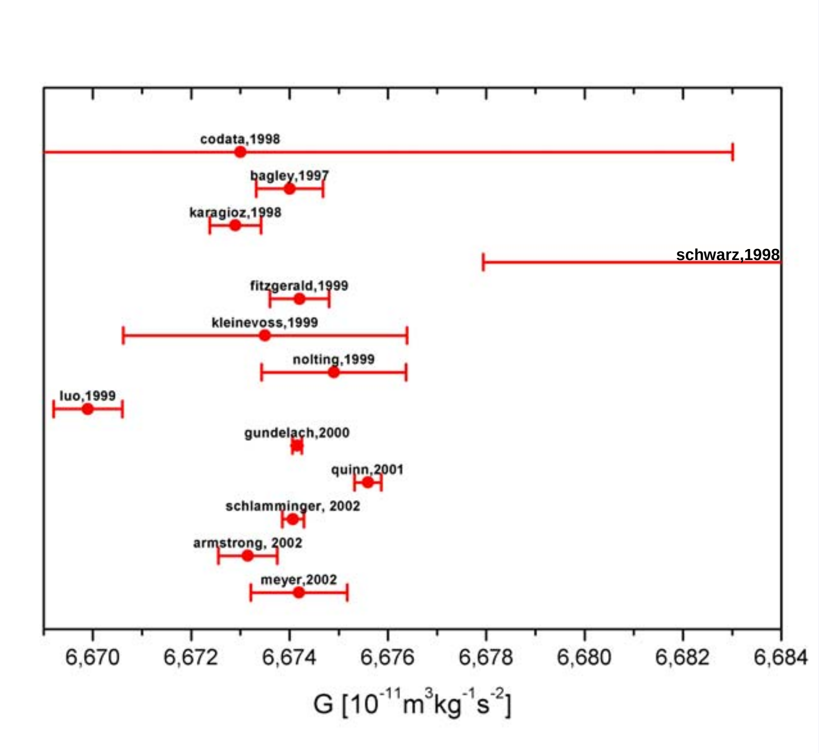
MAGIA

Misura Accurata di G mediante Interferometria Atomica

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Measurements of G



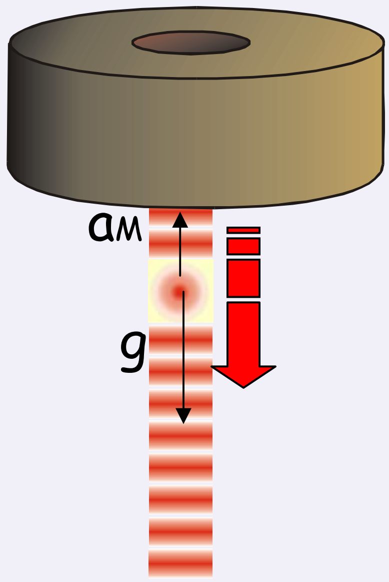


- 1986 CODATA $G = 6.672\,59\ (85) \times 10^{-11}\ m^3\,kg^{-1}s^{-2}$ $[1.3\times10^{-4}]$
- 1998 CODATA $G = 6.673\ (10) \times 10^{-11}\ m^3\,kg^{-1}s^{-2}$ $[1.5\times10^{-3}]$
- New "2002 CODATA recommended value" $G = 6.6742\ (10) \times 10^{-11}\ m^3\,kg^{-1}s^{-2}$ $[1.5\times10^{-4}]$

MAGIA – The idea

- **Measure g using free falling atoms and atom interferometry**
- **Add known source masses**
- **Measure change of g**

→ Determine *G*

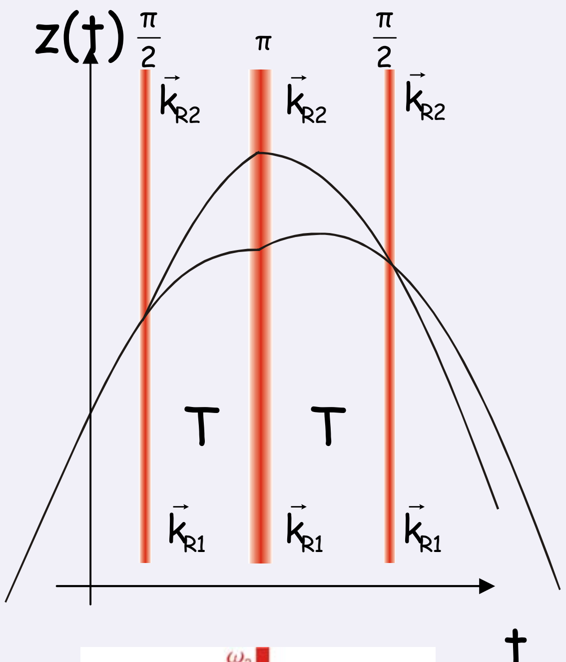


G.M. Tino, *in "2001: A Relativistic Spacetime Odyssey"*, World Scientific (2003)

J. Stuhler, M. Fattori, T. Petelski, G.M. Tino, *J. Opt. B* 5, S75 (2003)

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Vertical interferometer sensitivity

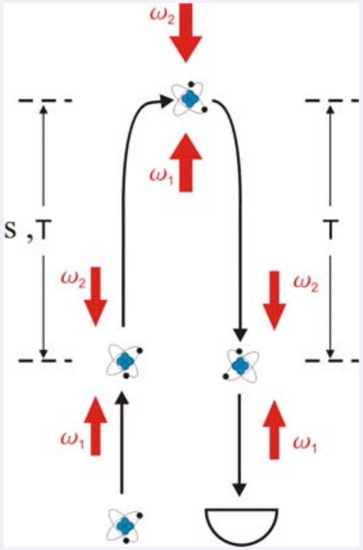


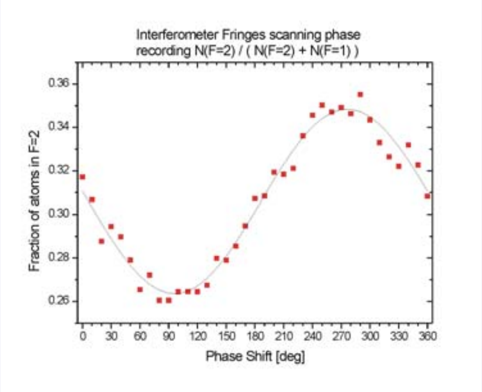
Phase difference between the paths:

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

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:

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

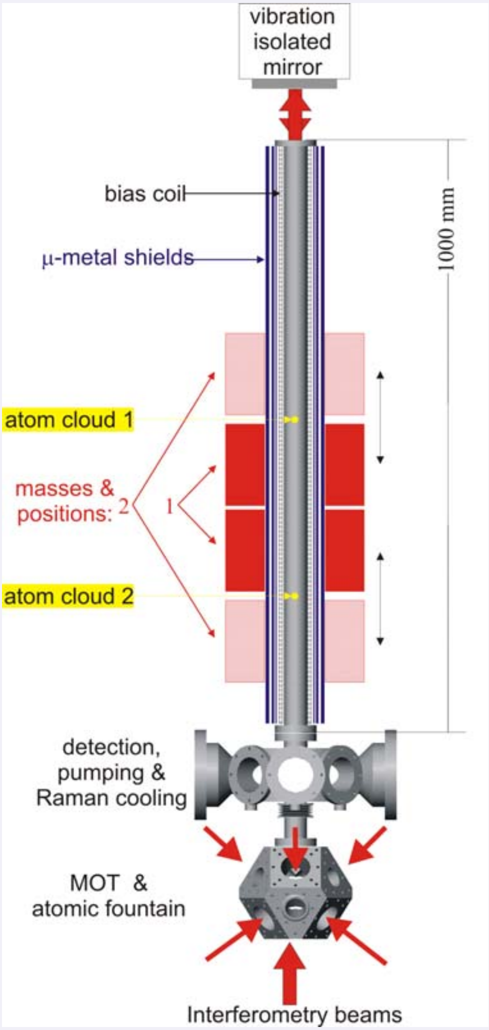
$T = 150$ ms $\Rightarrow 2\pi = 10^{-6}g$

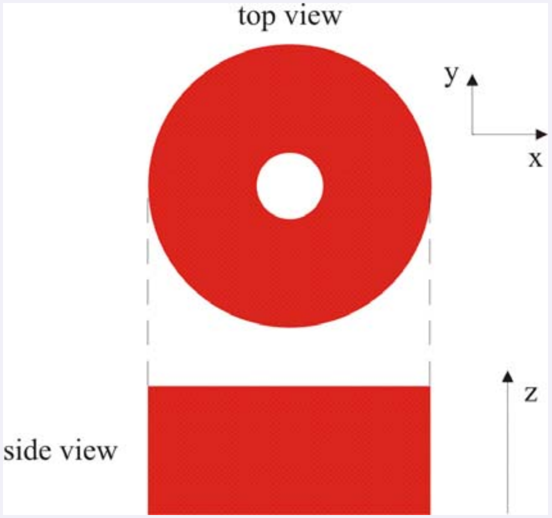
$S/N = 1000$

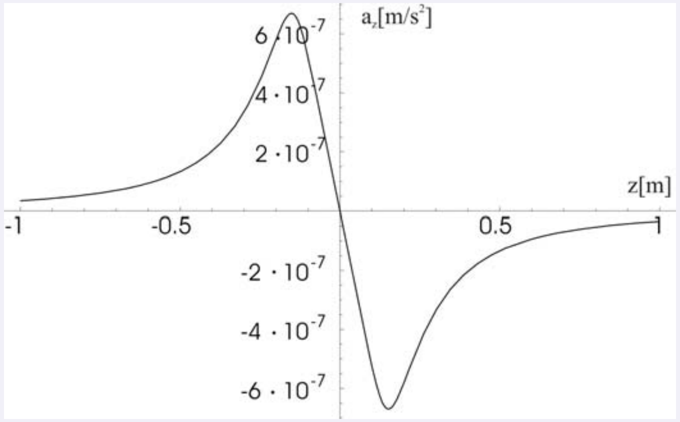
$\Rightarrow$ Sensitivity 10^{-9} g/shot

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

MAGIA: atom gravimeter + source mass







500 kg tungsten mass

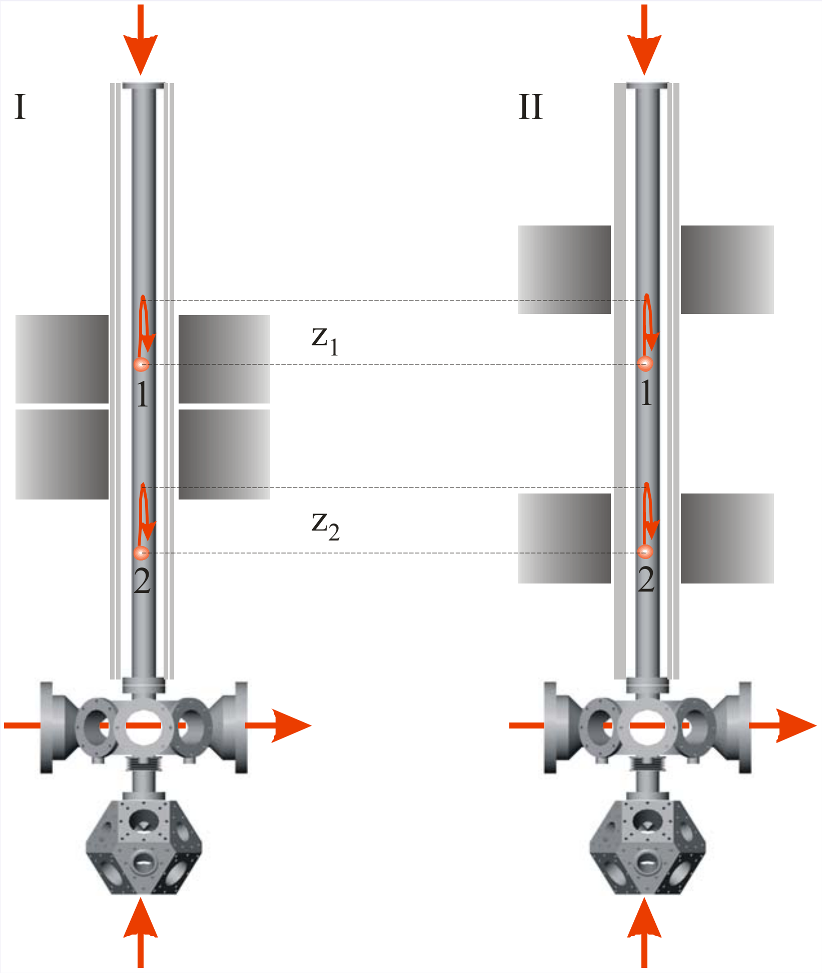
Sensitivity 10^{-9}g/shot

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

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

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

Experimental procedure



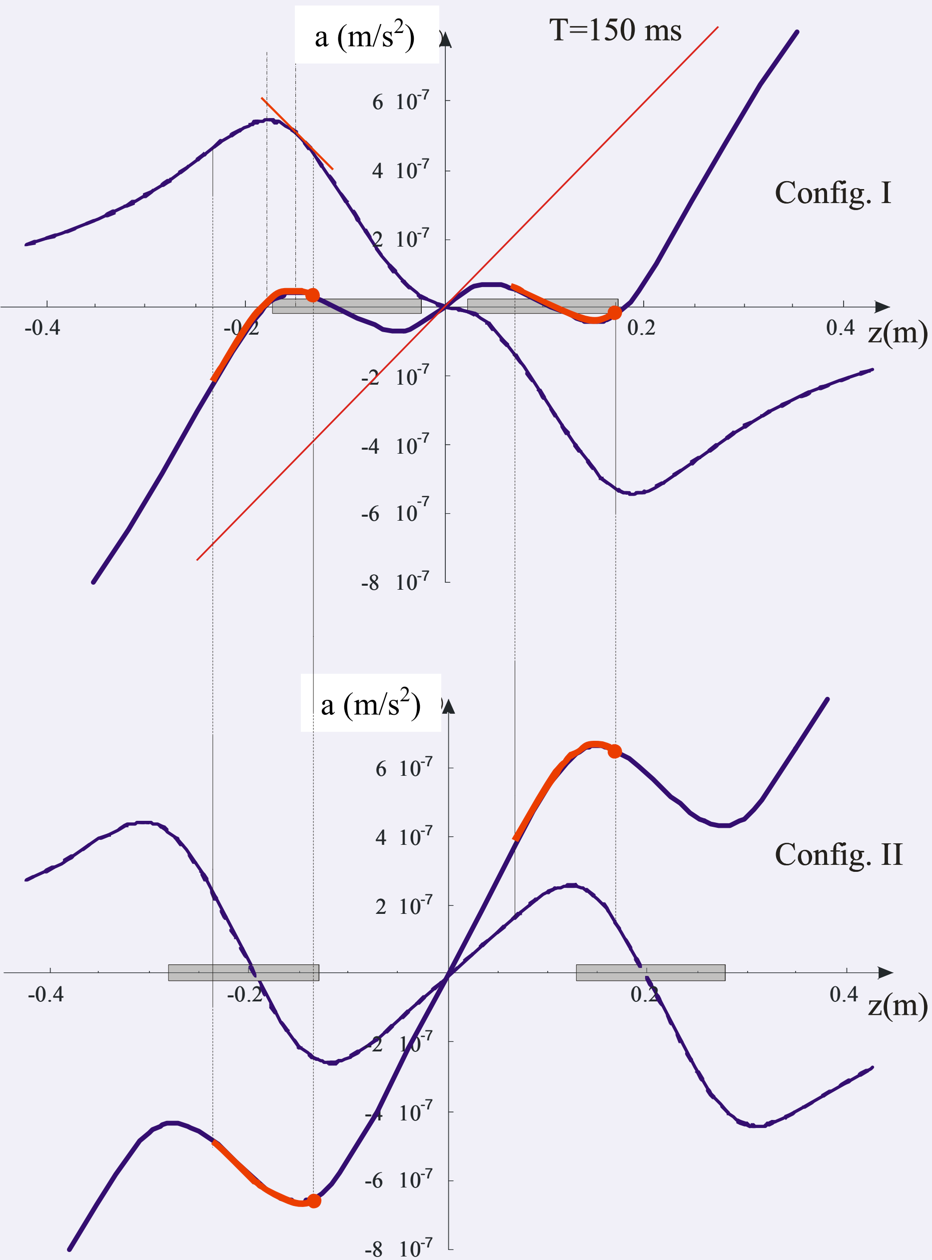
- trap, cool and launch 2 clouds of Rb atoms
- apply Raman light pulses
  masses in position 1
- detect atoms state selectively
- repeat several times
- plot N_a/N and fit the differential phase shift $\Delta\Phi_g$ between the clouds
- move masses to position 2
  repeat all procedure
- subtract the differential phase shifts for the two mass positions

$$\phi_1^I - \phi_2^I = \phi_g(z_1) + \phi_{SM} + \phi_{Sys}(z_1, t_I) - \left(\phi_g(z_2) - \phi_{SM} + \phi_{Sys}(z_2, t_I)\right)$$

$$\phi_1^{II} - \phi_2^{II} = \phi_g(z_1) - \phi_{SM} + \phi_{Sys}(z_1, t_{II}) - \left(\phi_g(z_2) + \phi_{SM} + \phi_{Sys}(z_2, t_{II})\right)$$

$$\Rightarrow (\phi_1^I - \phi_2^I) - (\phi_1^{II} - \phi_2^{II}) = 4\phi_{SM} + \phi_{Sys}(\Delta z, \Delta t)$$

Earth gradient compensation



Gravity gradient γ:

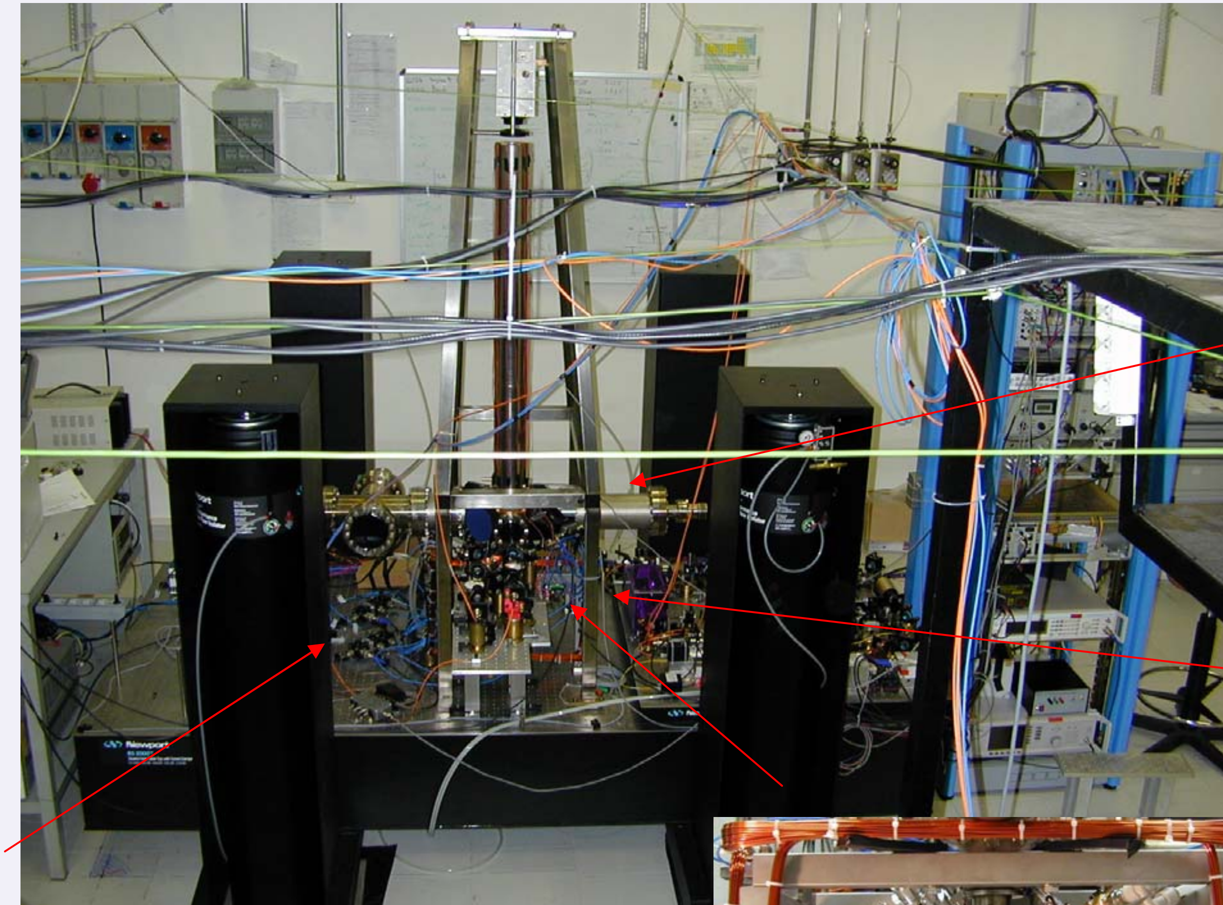
Compensate $\gamma \Rightarrow$ heavy, dense SM

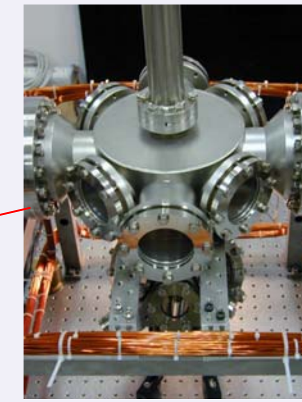
Optimize trajectories:

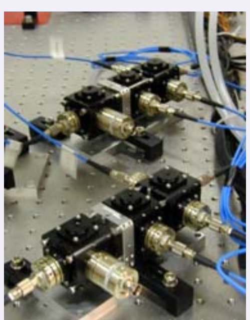
- Same atom positions in I and II
- Around extremum
- Close to a_{max}

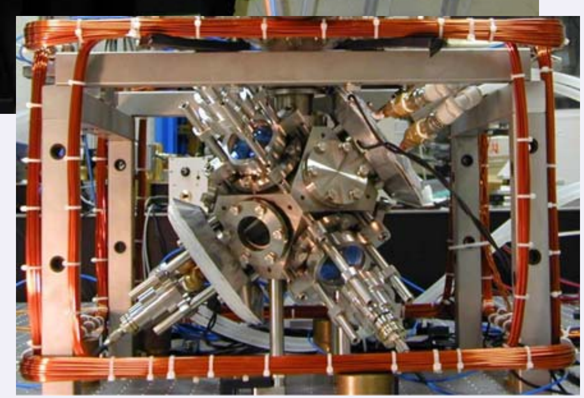
Tolerance in position > 1 mm
with velocity uncertainty 1 v_{rec}

Fountain set up









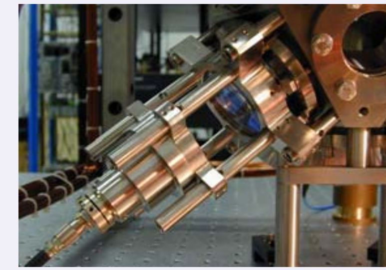
Laser and optical system

Diode lasers

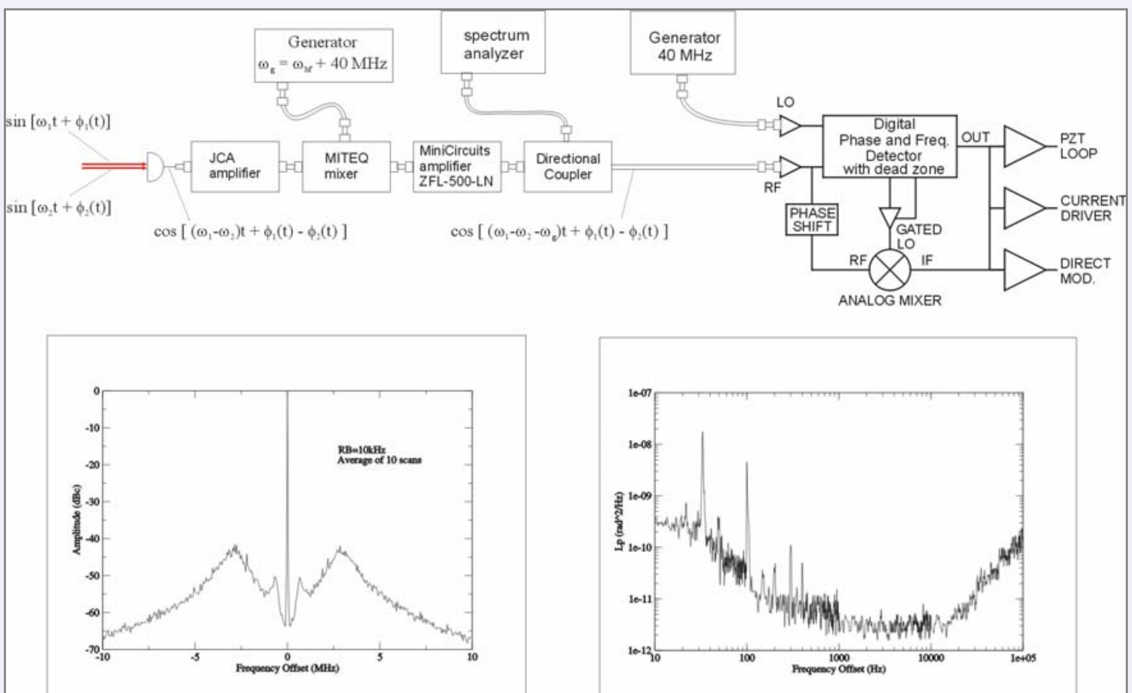
Tapered amplifiers

AOM for frequency and amplitude control

PM fibers

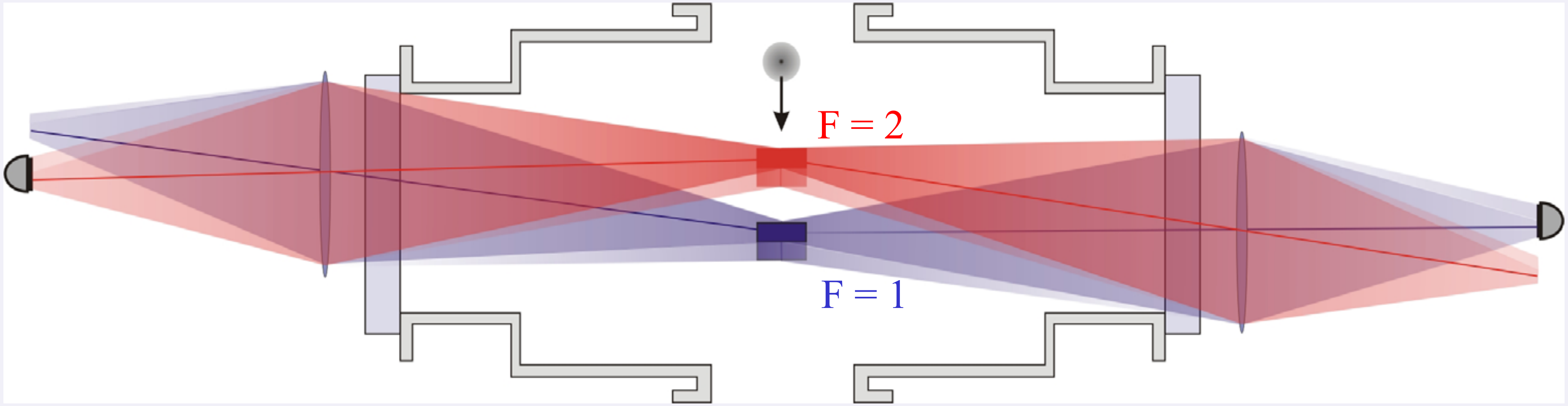


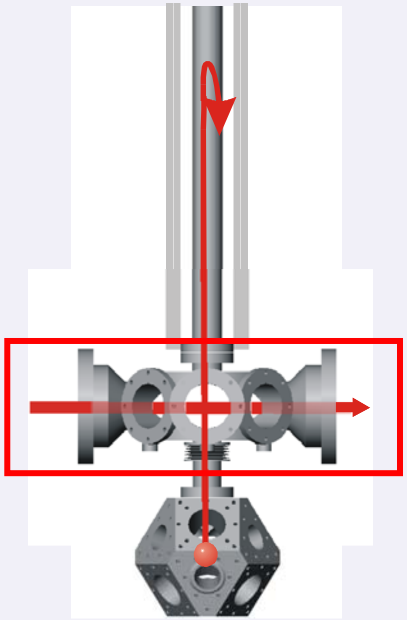
Stable connection to vacuum chamber

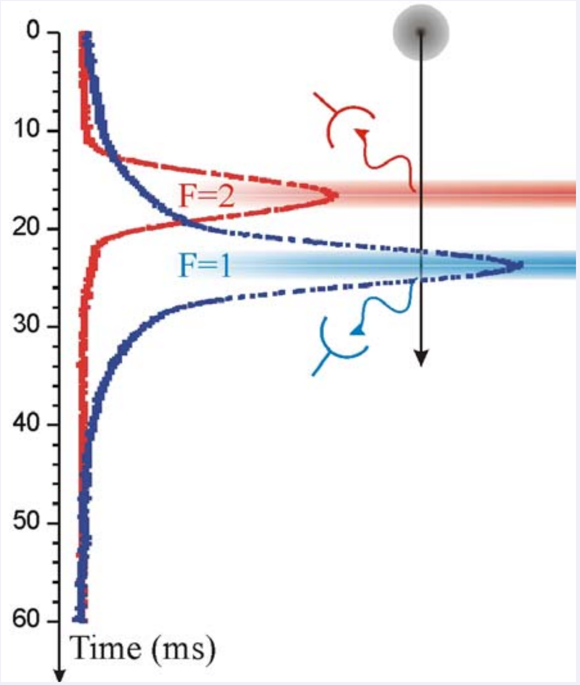


Phase locked lasers for Raman transitions

Detection



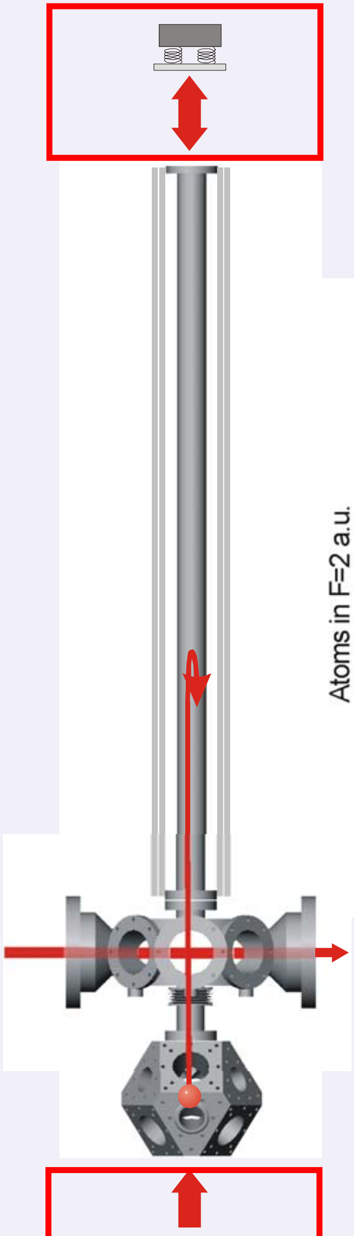




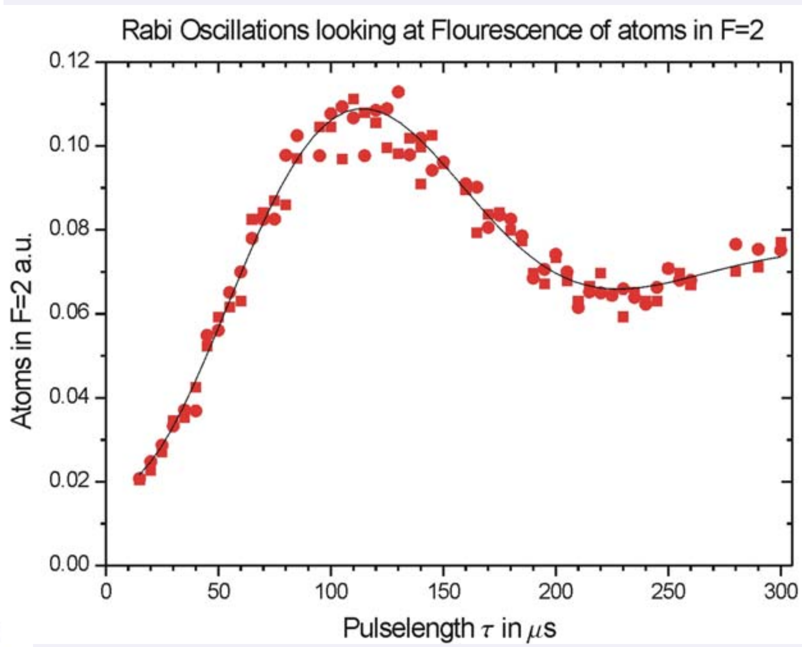
$$\frac{N_a}{N_a + N_b} = \frac{1}{2}\left(1 + \cos\Delta\phi\right)$$

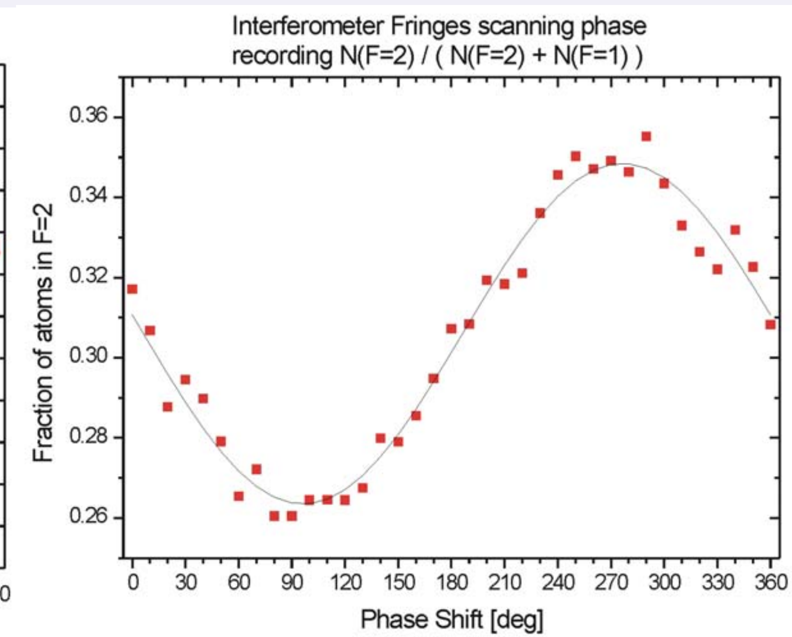
$$\Delta\phi = \frac{1}{2} k_{eff} g T^2$$

Interferometer



- Apply Raman pulse on velocity selected atoms all in one state
- Sequence of three Raman pulses



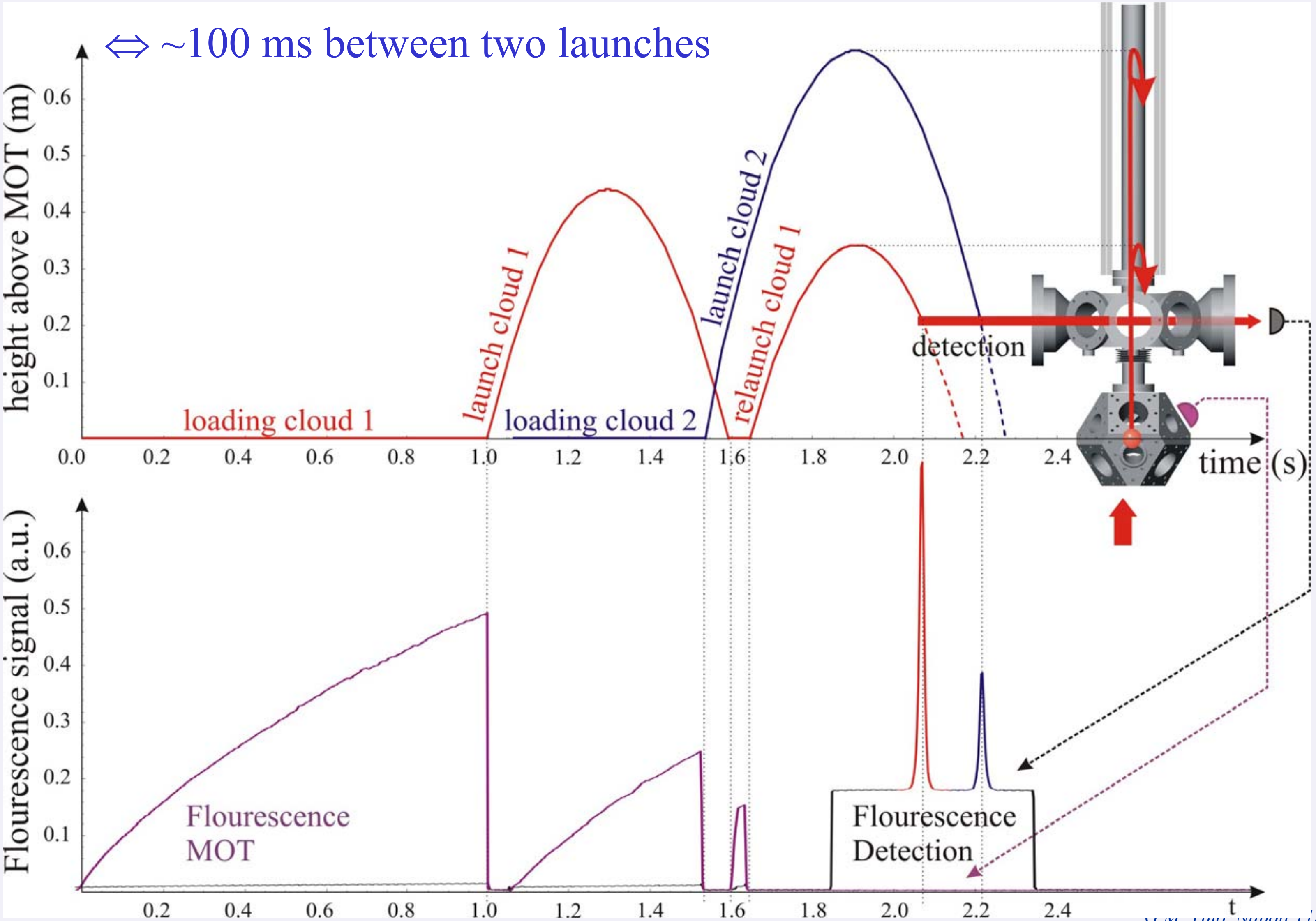


$$\Rightarrow \Delta g/g = 8.6 \cdot 10^{-6} \frac{1}{\sqrt{\text{Hz}}} = 9.1 \cdot 10^{-7} \text{ in } 90\,\text{s}$$

Juggling

Goal: Prepare 2 clouds with same velocity at distance of ≈ 35 cm

⇔ ~100 ms between two launches

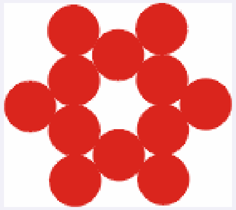


Source masses and support

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

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

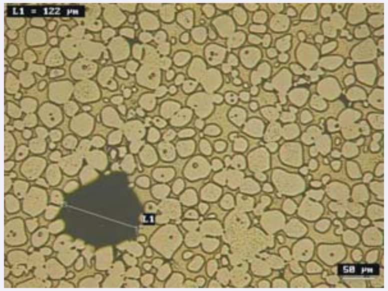
24 cylinders
External radius = 5 cm
Height = 15 cm
Cylinder mass = 20 kg
Total mass ~ 500 kg



Hot Isostatic Pressing at 1200 C° and 1500 atm

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

Oscillation of cylinders on air cushion reveal radial inhomogeneities



In collaboration with IMGC, Torino

In collaboration with LNF, Frascati

MAGIA – Relevant numbers

- **time separation between pulses T=150 ms**
- **10^6 atoms**
- **shot noise limited detection**
- **launch accuracy: 1 mm e $\Delta v \sim 5$ mm/s**
- **knowledge of the masses dimensions and relative positions: 10 μm**
- **10000 measurements**

$$\Downarrow$$

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

Future prospects

Future prospects: Atomic clocks

- New optical clocks with fractional stability ~ 10^{-17}-10^{-19}
- Search for variation of fundamental constants
- Tests of SR and GR in Earth orbit (ACES, PARCS, RACE, OPTIS)
- Improved tests of GR in solar orbit: Shapiro delay, red shift, …
- mm-scale positioning and long-distance clock syncronization
- Very large baseline interferometry (VLBI) and geodesy

Future prospects: Atom interferometers

- Development of transportable atom interferometers → geophysics, → space
  EC-STREP "FINAQS": BEC or Fermionic Source?
- Test of Newton's law at short distances
- Test of equivalence principle
- New definition of kg
- Accurate measurement of h/m and α
- Search for electron-proton charge inequality
- Test of equivalence principle for anti-matter (?)
- New detectors for gravitational waves (?)

People

• G. Lamporesi	PhD student, Università di Firenze
• T. Petelski	PhD student, LENS
• N. Poli	PhD student, Università di Firenze
• M. Fattori	Post-doc, Università di Firenze
• F. Sorrentino	Post-doc, LENS
• J. Stuhler	Post-doc, LENS (now in Stuttgart)
• L. Cacciapuoti	Researcher, (now at ESA)
• G. Ferrari	Researcher, INFM
• M. de Angelis	Visitor, CNR
• R. Drullinger	Visitor, Università di Firenze
• M. Prevedelli	Visitor, Università di Bologna

Collaborations

IEN, Torino
IMGC, Torino
Istituto Nazionale di Ottica Applicata, Firenze
Humboldt-Universitaet zu Berlin
IQO, Hannover
ENS, SYRTE, Paris

Support and funding

Istituto Nazionale di Fisica Nucleare (INFN)
European Commission (EC)
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)

Fine

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  - 1997 Nobel lectures, Rev. Mod. Physics 70, 685 (1997)

- **Frequency metrology and optical clocks**
  - J.C. Bergquist *et al.*, Physics Today (March, 2001), p. 37
  - Th. Udem *et al.*, Nature 416, 233 (2002)

- **Atom interferometry and MAGIA**
  - "Atom Interferometry", P.R. Berman ed., Academic Press (1997)
  - J. Stuhler *et al.*, J. Opt. B 5, S75 (2003)

- **Cold atoms in space**
  - C. Salomon *et al.*, C.R. Acad. Sci. Paris 2, 1313 (2001)
  - G.M. Tino, Nuclear Phys. B 113, 289 (2002)

ACES: Relativity tests

1. **Red shift**
   Comparaison of absolute frequencies of space clock V_S and ground clock V_E

$$\frac{\nu_S - \nu_E}{\nu_E} = \frac{\Delta\nu}{\nu_E} = (1+\alpha)\frac{\Delta U}{c^2} = (1+\alpha)\frac{gH}{c^2}$$

Einstein : $\alpha = 0$ at 7 10^{-5} (Vessot, Levine 76)
At $H = 450$kms : $\Delta V / V = + 4.59\ 10^{-11}$

With clock accuracy of 10^{-16}, the red-shift can be measured at 3 10^{-6}

Factor 25 improvement

Second order Doppler: $-1/2\ v^2 / c^2 = 3\ 10^{-10}$

2. **Isotropy of speed of light**
   $\delta c/c = 2\text{-}5\ 10^{-9}$ (Vessot 79, Riis 87, Wolf 97)

ISSA : 2 10^{-10} (gain : 10)

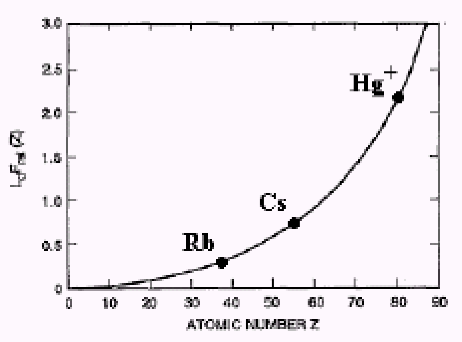
Search for variation of α

Relativistic corrections : the energy levels of the frequencies of two different alkalis depend on α and Z_1, Z_2

– The ratio of the hyperfine energies of different atomic species explicitely depends on $\alpha = e^2/\hbar c$

$$\frac{d}{dt}\ln\left(\frac{\upsilon_2}{\upsilon_1}\right) = \left[L_d F_{rel}(\alpha, Z_2) - L_d F_{rel}(\alpha, Z_1)\right] \times \frac{\dot{\alpha}}{\alpha} = K_{21} \times \frac{\dot{\alpha}}{\alpha}$$

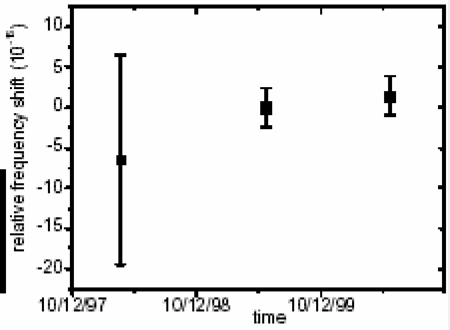
– Hg+ vs H : Prestage *et al.*, PRL **74**, 3511 (1995)



$$\left|\dot{\alpha}/\alpha\right| \leq 3.7 \times 10^{-14}\, yr^{-1}$$

– LPTF (Paris) Cs vs Rb

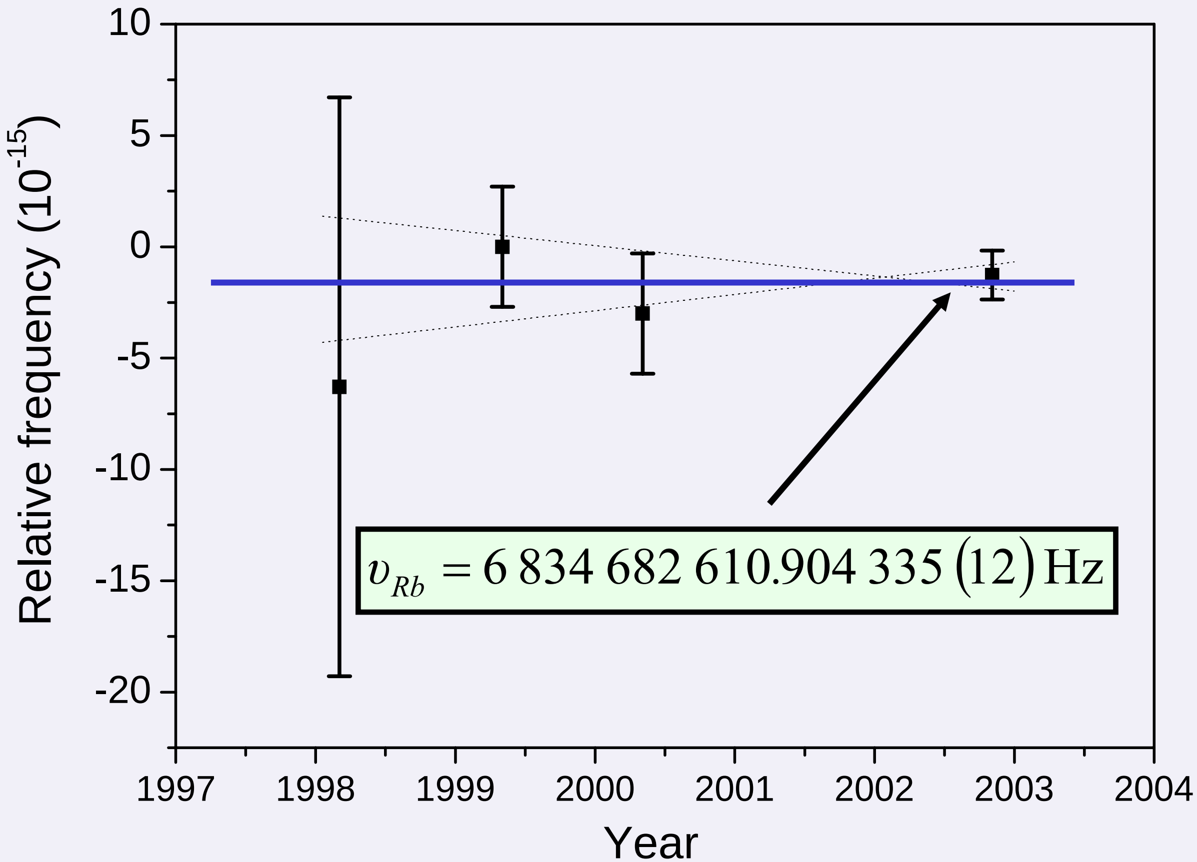
$$\frac{d}{dt}\ln\left(\frac{\upsilon_{Rb}}{\upsilon_{Cs}}\right) = (1.9 \pm 3.1) \times 10^{-15}\, yr^{-1}$$



– Within Prestage *et al.* theoretical framework :

$$\left|\dot{\alpha}/\alpha\right| = (4.2 \pm 6.9) \times 10^{-15}\, yr^{-1}$$

^{87}Rb - ^{133}Cs Comparison over 6 years



$$\frac{d}{dt}\ln\left(\frac{\upsilon_{Rb}}{\upsilon_{Cs}}\right) = (-0.5 \pm 5.3) \times 10^{-16} \,/\, year$$

H. Marion et al., PRL (2003), Bize 2004

Within Prestage *et al*. theoretical framework :

$$\frac{\dot{\alpha}}{\alpha} = (1.0 \pm 12) \times 10^{-16} \,/\, year$$

Search for variation of α

Einstein Equivalence Principle

The ratio of the hyperfine energies of different atomic species should not vary with time

- The EEP can be tested by high resolution frequency measurements regardless of any theoretical assumption

Present non laboratory tests of α variations

- **Oklo test** : geochemical analysis of the natural fossil fission reactor in Oklo (Gabon, 1.8×10^{9} yr ago) :

$$\left|\alpha_{now}-\alpha_{Oklo}\right|\leq 1\times10^{-7} \qquad \left|\dot{\alpha}/\alpha\right|\leq 5\times10^{-17}\ yr^{-1}$$

Damour, Poliakov, Nucl. Phys. B **480**, 37 (1996)

- Absorption spectroscopy from quasars:

$$\left|\Delta\alpha/\alpha\right|=(-0.72\pm0.18)\times10^{-5}\ (0.5<z<3.5)$$

J. Webb *et al.*, PRL **87**, 091301 (2001)

Caratteristiche dei principali standard atomici

TABLE I. – *Important characteristics of the classical atomic frequency standards. The Cs fountain and the linear trap are included for comparison.*

Type of clock	Frequency stability: Short term: $\sigma(\tau)$	Frequency stability: Drift (per month)	Accuracy	Volume	Main characteristic of interest
Hydrogen maser active	$3.2 \times 10^{-14}\,\tau^{-1/2}$ $10\,\mathrm{s} < \tau < 4000\,\mathrm{s}$	$\sim 10^{-14}$	2×10^{-12}	Large: 100 to 1000 l	Best stability below 10^4 s
Hydrogen maser passive	$2 \times 10^{-12}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^5\,\mathrm{s}$	$\sim 10^{-14}$	2×10^{-12}	Large but smaller than active maser	Trade off stability for size
Cesium beam: magnetic deflection (laboratory)	$3 \times 10^{-12}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^5\,\mathrm{s}$	$< 10^{-14}$	1×10^{-14}	Large: 500 to 1000 l	Accuracy, primary standard
Cesium beam: optical pumping (laboratory)	$8 \times 10^{-13}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^4\,\mathrm{s}$	$< 10^{-14}$	7×10^{-15}	Large: 500 to 1000 l	Accuracy, primary standard
Cesium beam: magnetic deflection (industrial)	$5 \times 10^{-12}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^6\,\mathrm{s}$	$< 10^{-13}$	1×10^{-12}	Small: 20 l	Long-term stability and small size
Cesium fountain	$1.5 \times 10^{-13}\,\tau^{-1/2}$ $10\,\mathrm{s} < \tau < 10^4\,\mathrm{s}$	*	2×10^{-15}	Large: 500 l	Stability, best accuracy, primary standard
Rubidium cell	$2 \times 10^{-11}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^4\,\mathrm{s}$	$< 10^{-11}$	**	Very small: 0.25 to 1 l	Very small size and good stability
Mercury ion trap	$2 \times 10^{-12}\,\tau^{-1/2}$ $1\,\mathrm{s} < \tau < 10^5\,\mathrm{s}$	*	1×10^{-14}	Medium size; a few liters	Accuracy, stability and relatively small

* Unknown. ** Does not apply.

Tests of weak equivalence principle

Best tests so far: EOT-Wash group (Adelberger, Gundlach),
See "http://www.npl.washington.edu/eotwash/"
Long range EP tested at the level of $\mathbf{10^{-13}}$

Prospects

Space: MICROSCOPE $\rightarrow$ $\mathbf{10^{-15}}$

STEP $\rightarrow$ $\mathbf{10^{-18}}$

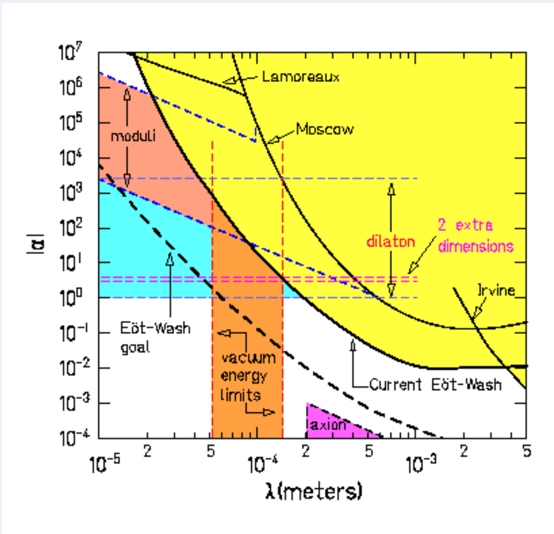
Atoms:

- different isotopes, e.g. ^{85}Rb vs ^{87}Rb (Fray S, et al. PRL. 93, 240404 (2004) **$\Delta g/g=(0.4+/-1.2)x10^{-7}$**)
- different atoms, e.g. Rb vs Cs
- bosons vs fermions, e.g. Rb vs ^{40}K
- different spins

…

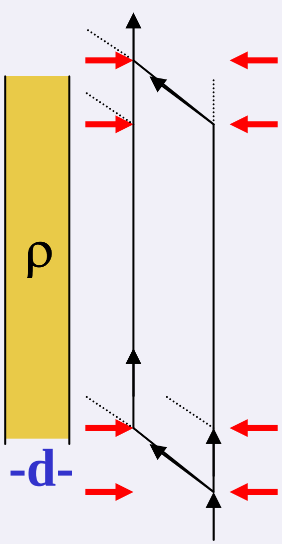
$\rightarrow$ $\mathbf{10^{-12} - 10^{-13}}$

Possible test of the gravitational law in the sub-mm range



95% confidence level constraints on a Yukawa violation of the gravitational inverse-square law. The vertical axis represents the strength of a deviation relative to that of Newtonian gravity while the horizontal axis designates its characteristic range. The yellow region has been excluded (From E.G. Adelberger, 2001)

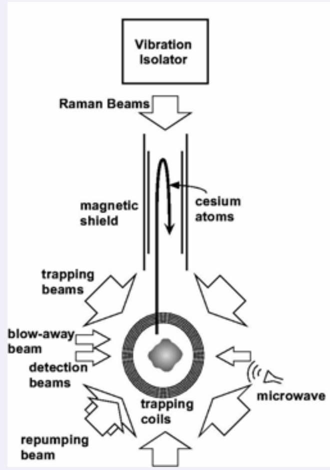
$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

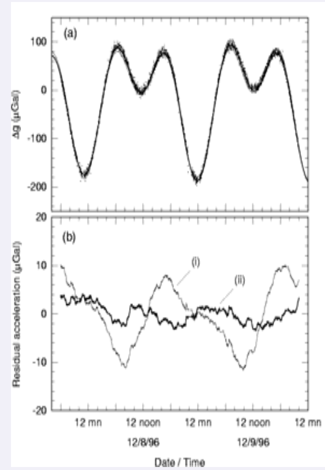


$$a = 2\pi G\rho d$$

Example: ρ_{Au} **~19 g/cm^3**
d ~ 200 μm ⇒ $a \sim 2 \times 10^{-9}\ ms^{-2}$

Gravimeters





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

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

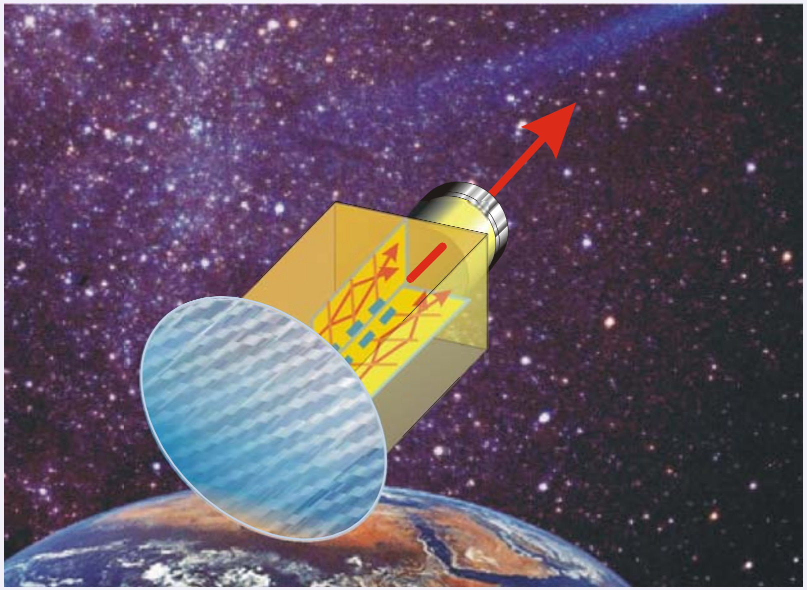
Absolute accuracy: $\Delta g/g<3x10^{-9}$

Comparison between instruments

	Spring gravimeter[1]	Optical interferometry dropping gravimeter[2,3]	Superconducting gravimeter[3,4]	Atom interferometry gravimeter[5]
Resolution $\Delta g/g$	5×10^{-9} only for short periods and distances	$1 \times 10^{-8}/\sqrt{Hz}$	$1 \times 10^{-8}/\sqrt{Hz}$	2×10^{-8} in 1.3 s
Accuracy $\Delta g/g$ Or Repeatibility	0.5×10^{-6} only for short periods and distances	4×10^{-9}	1×10^{-9}	1×10^{-9}
Measurement	Relative	Absolute	Relative	Absolute
Size and Weight	21.5 x 22 x 31 cm 9 kg	1.5 m^3 320 kg	No field operation	estimated 1 m^3 250 kg
Error sources	temperature and random drift Clibration varies in time and with position	magnetic and electrostatic effects	thermal drift magnetic and electrostatic effects	?

(1) www.LaCosteRomberg.com
(2) www.microgsolutions.com
(3)O. Francis, T.M. Niebauer, G. Sasagawa, F. Klopping, and G. Gschwind, "Calibration of a superconducting gravimeter by comparison with an absolute gravimeter FG5 in Boulder", Geoph. Res. Lett.25 (1998) 1075-1078.
(4) J.M. Goodkind "The superconducting gravimeter", Rev. Scient. Instr., 70 (1999) 4131-4152.
(5) A. Peters, K.Y. Chung, and S. Chu "Measurement of gravitational acceleration by dropping atoms", 400 (1999) 849-852.

HYPER

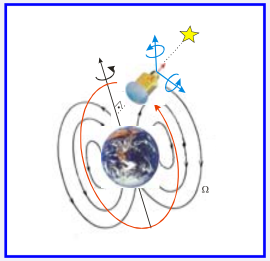


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

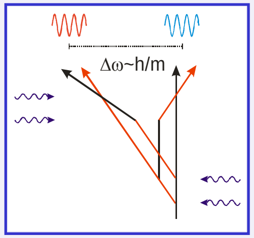
Resolution: $3x10^{-12}$rad/s /√Hz

- Expected Overall Performance: $3x10^{-16}$rad/s over one year of integration i.e. a S/N~100 at twice the orbital frequency

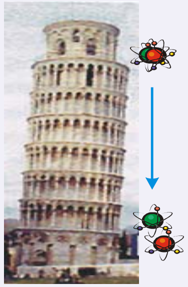
Mapping Lense-Thirring effect close to the Earth



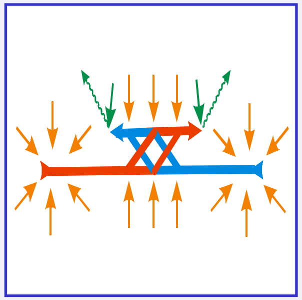
Improving knowledge of fine-structure constant



Testing EP with microscopic bodies



Atomic gyroscope control of a satellite



Unit of mass

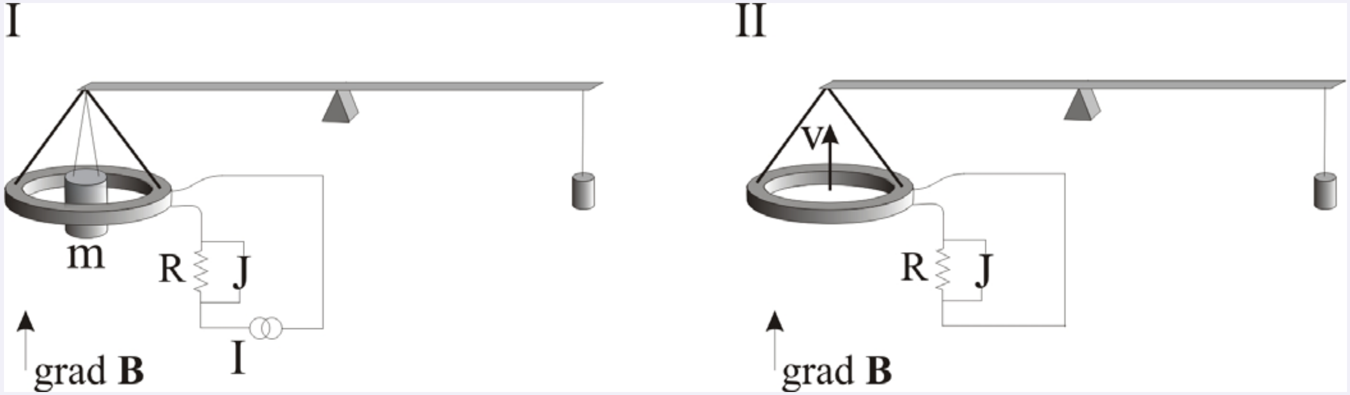
The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram (1st CGPM, 1889)

Goal: Redefinition of kg on microscopic quantities with accuracy better than 10^{-8}

Idea: Watt-balance compares electrical and mechanical realization of Watt

$$UI = m\mathbf{g}\,\mathrm{v}$$

Watt balance groups working at NPL (UK), NIST (USA), METAS (Switzerland), BNM (France)

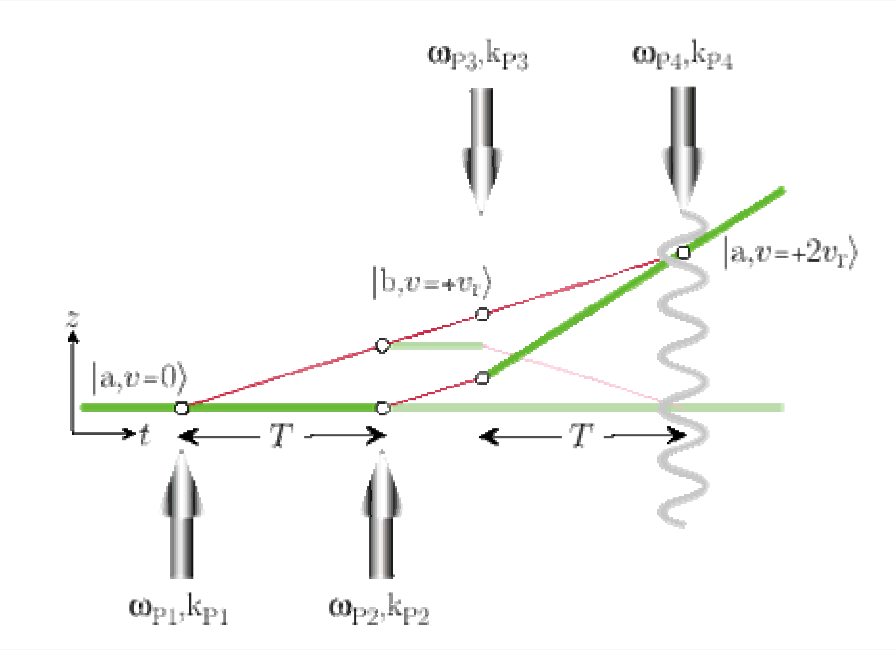


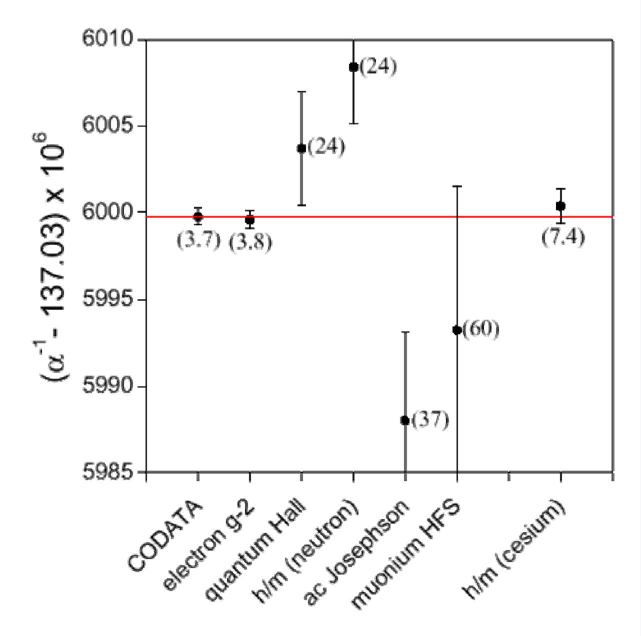
$$-I\frac{\partial\Phi}{\partial z} = -mg$$

$$U = \frac{\partial\Phi}{\partial t} = -\mathrm{v}\frac{\partial\Phi}{\partial z}$$

h/m and fine structure constant

fine-structure constant $\alpha = e^2/4\pi\epsilon_0\hbar c$	
Value	$7.297\ 352\ 568 \times 10^{-3}$
Standard uncertainty	$0.000\ 000\ 024 \times 10^{-3}$
Relative standard uncertainty	3.3×10^{-9}
Concise form	$7.297\ 352\ 568(24) \times 10^{-3}$



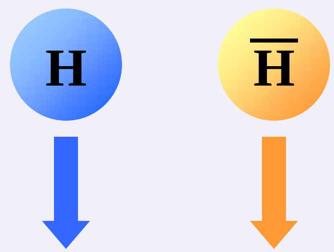


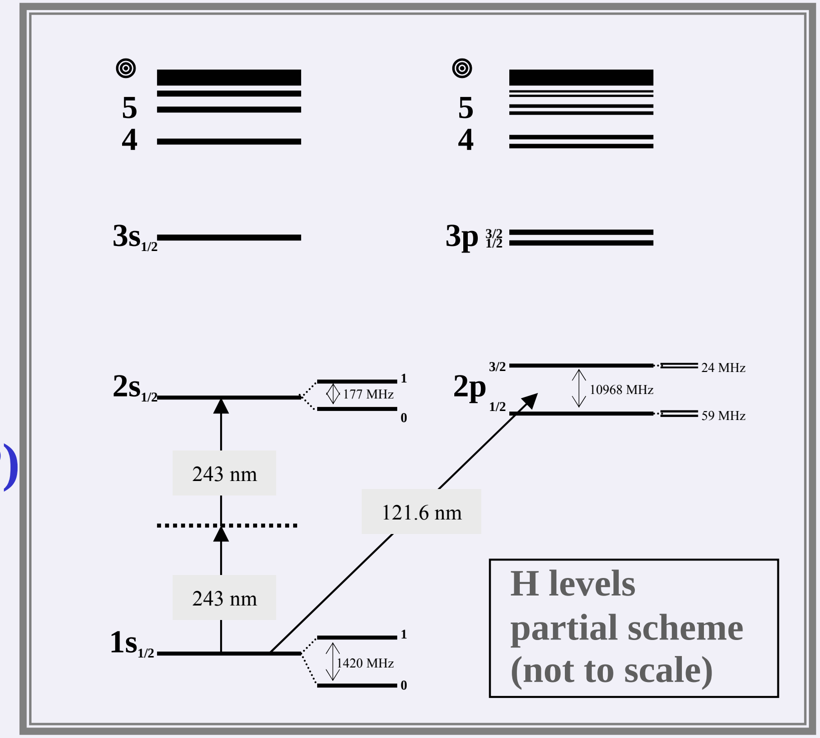
$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_p}{m_e}\frac{m_{Cs}}{m_p}\frac{h}{m_{Cs}}$$

S. Chu et al., 2002

Test of equivalence principle for anti-matter

- **Compare g**





- **Steps:**

→ anti-H production (ATHENA, ATRAP)

→ anti-H selective state population

→ anti-H cooling

→ anti-H trapping

→ g measurement:

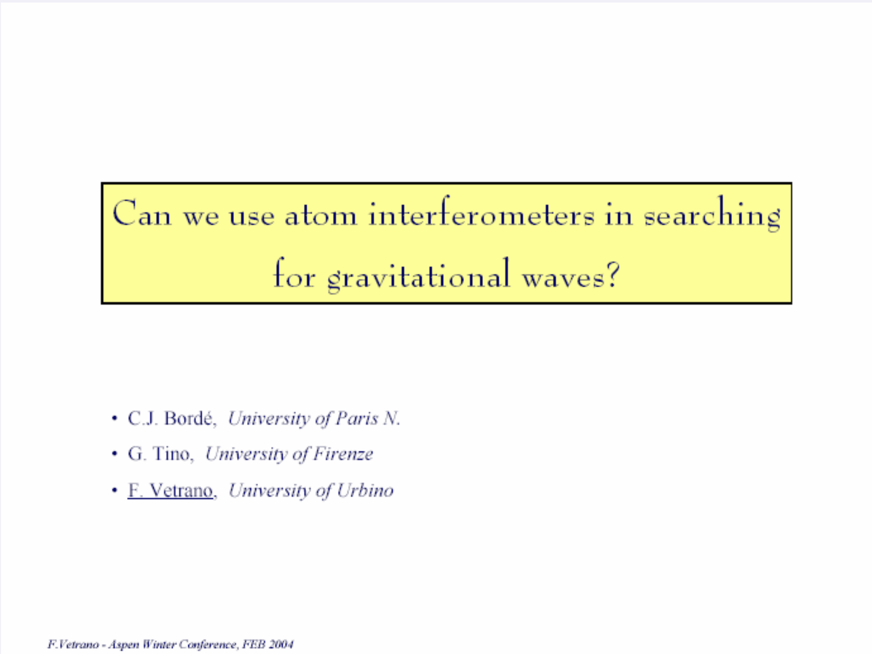
- Time of flight $\Delta g/g \rightarrow 10^{-3}$?

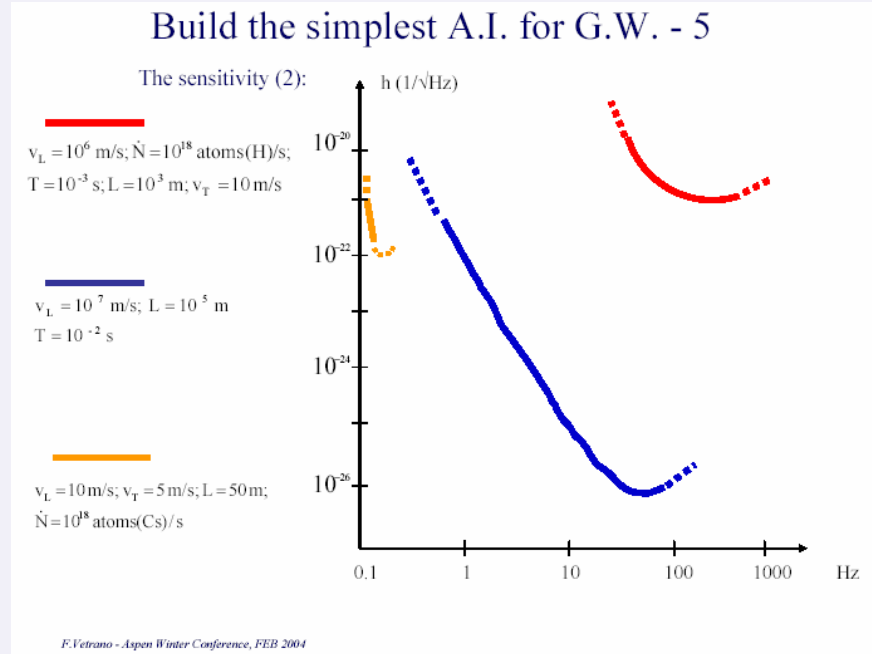
- Atom interferometry

- **Raman transitions between 2S HFS sublevels**
- **2S→high-P levels transitions**
  (T. Heupel *et al.*, Europhys. Lett. 57, 158 (2002))

$\Delta g/g \rightarrow 10^{-9}$?

Gravitational wave detection by atom interferometry





Presentation at 2004 Aspen Winter College on Gravitational Waves:
See http://www.ligo.caltech.edu/LIGO_web/Aspen2004/pdf/vetrano.pdf

See also:
Chiao RY, Speliotopoulos AD, J. Mod. Opt. 51, 861 (2004)
A. Roura, D.R. Brill, B.L. Hu, C.W. Misner, gr-qc/0409002