Atom interferometers and optical clocks

New quantum sensors for fundamental physics and applications in earth laboratories and in space.

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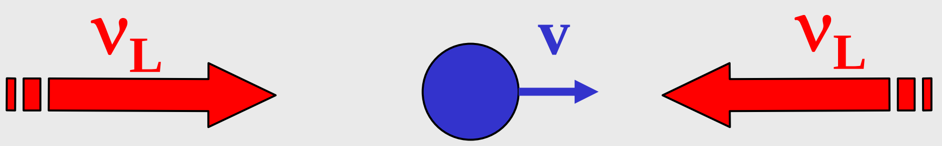
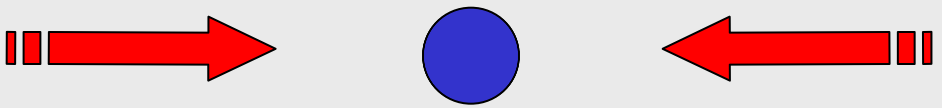
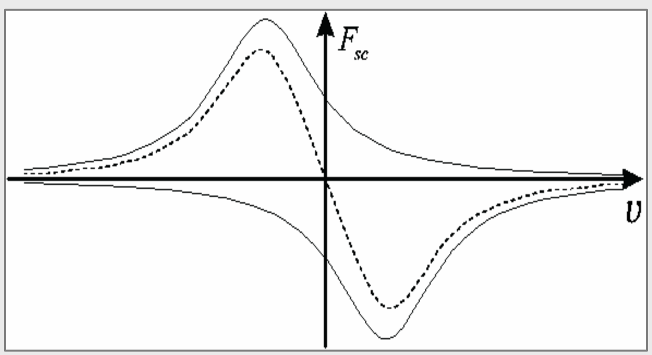
Università degli Studi di Firenze - Dipartimento di Fisica, LENS
Istituto Nazionale di Fisica Nucleare - Sezione di Firenze

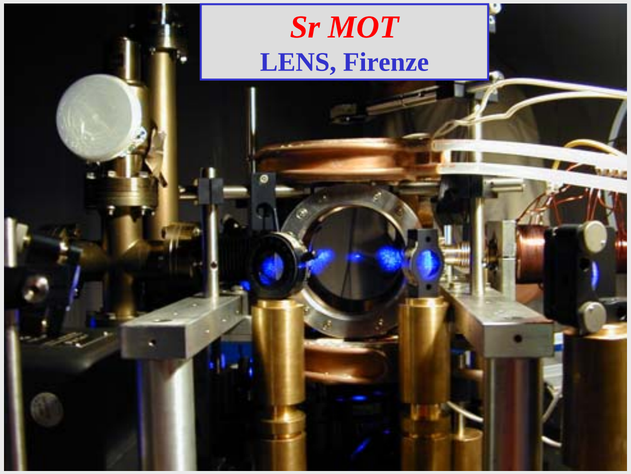
Laser cooling of atoms



Idea:
T.W. Hänsch, A. Schawlow, 1975
Exp. demonstration:
S. Chu et al., 1985







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

Laser cooling: temperatures

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

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

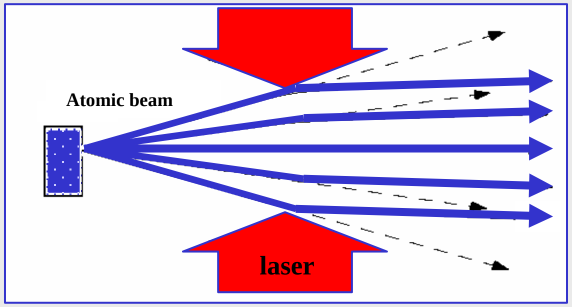
Single photon recoil temperature: $k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$

Examples:

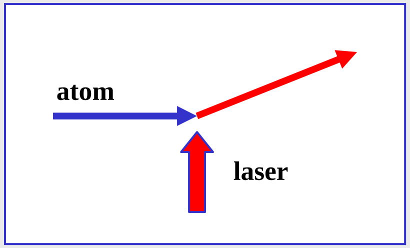
	T_D	T_r
Na	240 µK	2.4 µK
Rb	120 µK	360 nK
Cs	120 µK	200 nK

Atom optics

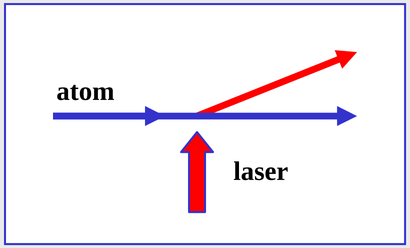
lenses



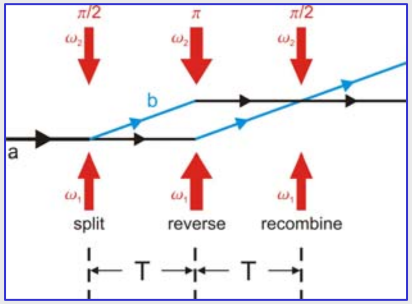
mirrors



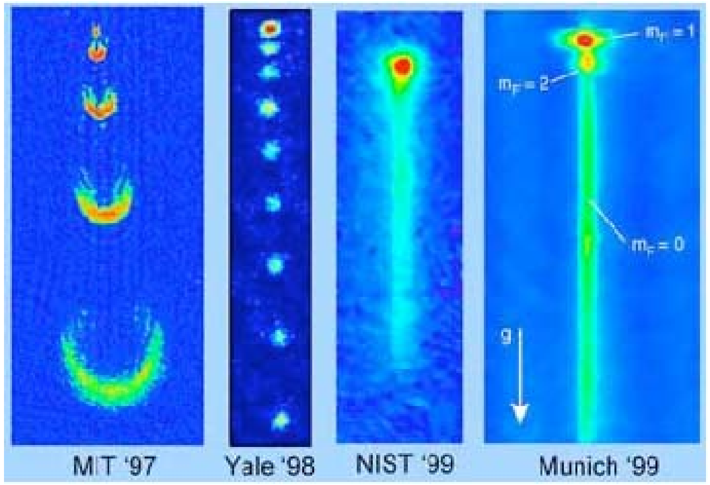
beam-splitters



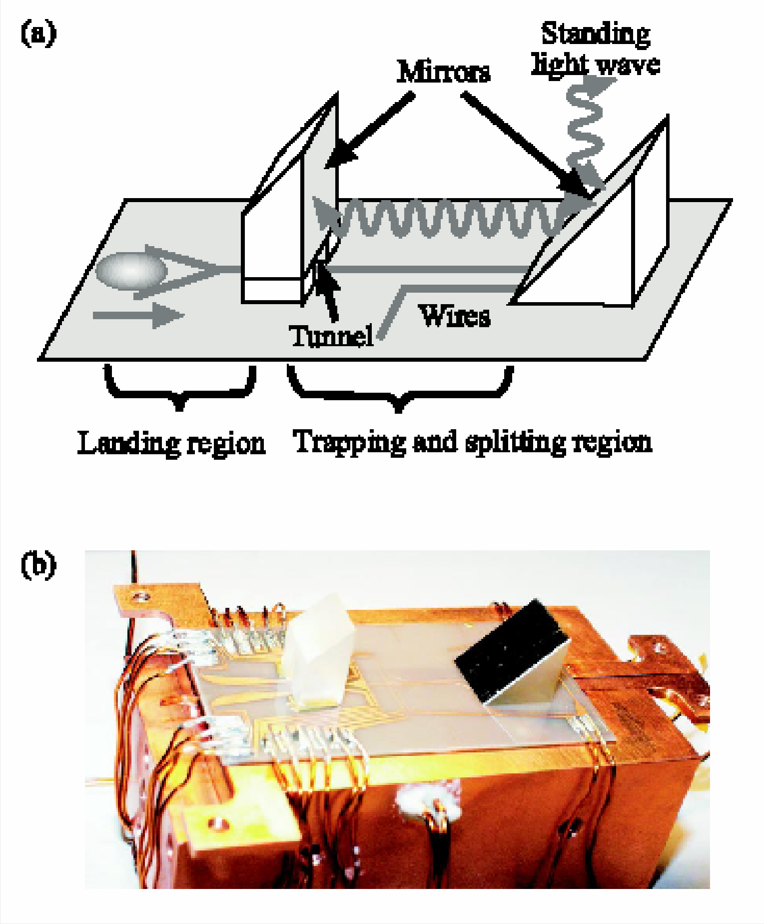
interferometers

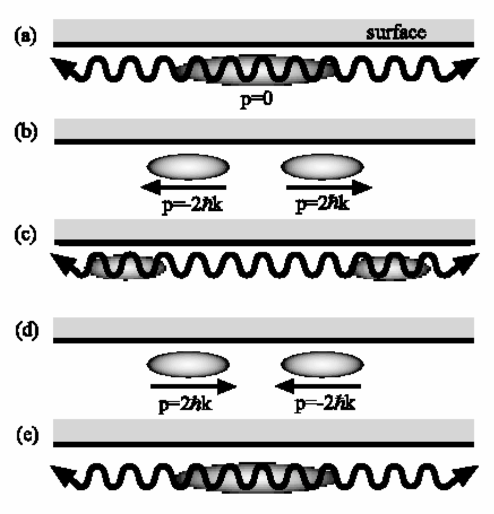


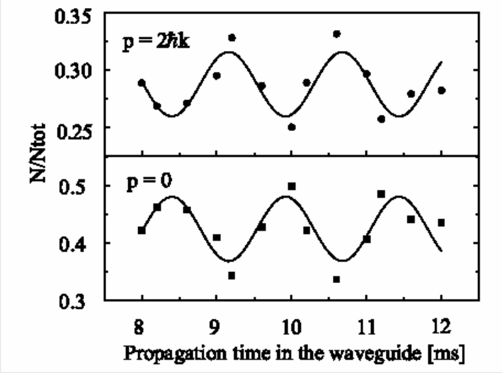
atom laser



Atom Michelson Interferometer on a Chip Using a Bose-Einstein Condensate







Ying-Ju Wang, Dana Z. Anderson, Victor M. Bright, Eric A. Cornell, Quentin Diot, Tetsuo Kishimoto, Mara Prentiss, R. A. Saravanan, Stephen R. Segal, Saijun Wu, Phys. Rev. Lett. **94,** 090405 (2005)

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

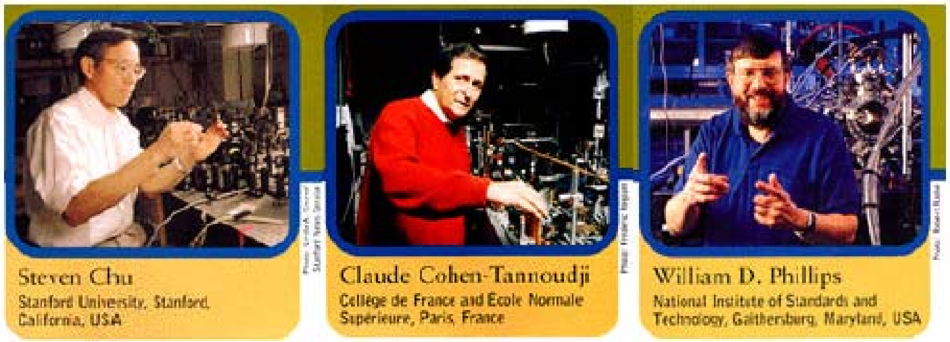
BACK

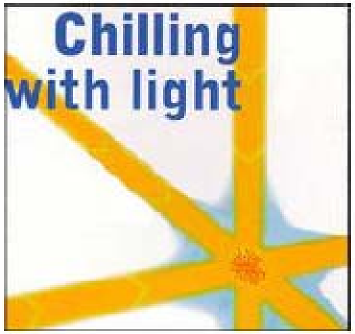
The Nobel Prize in Physics 1997

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**

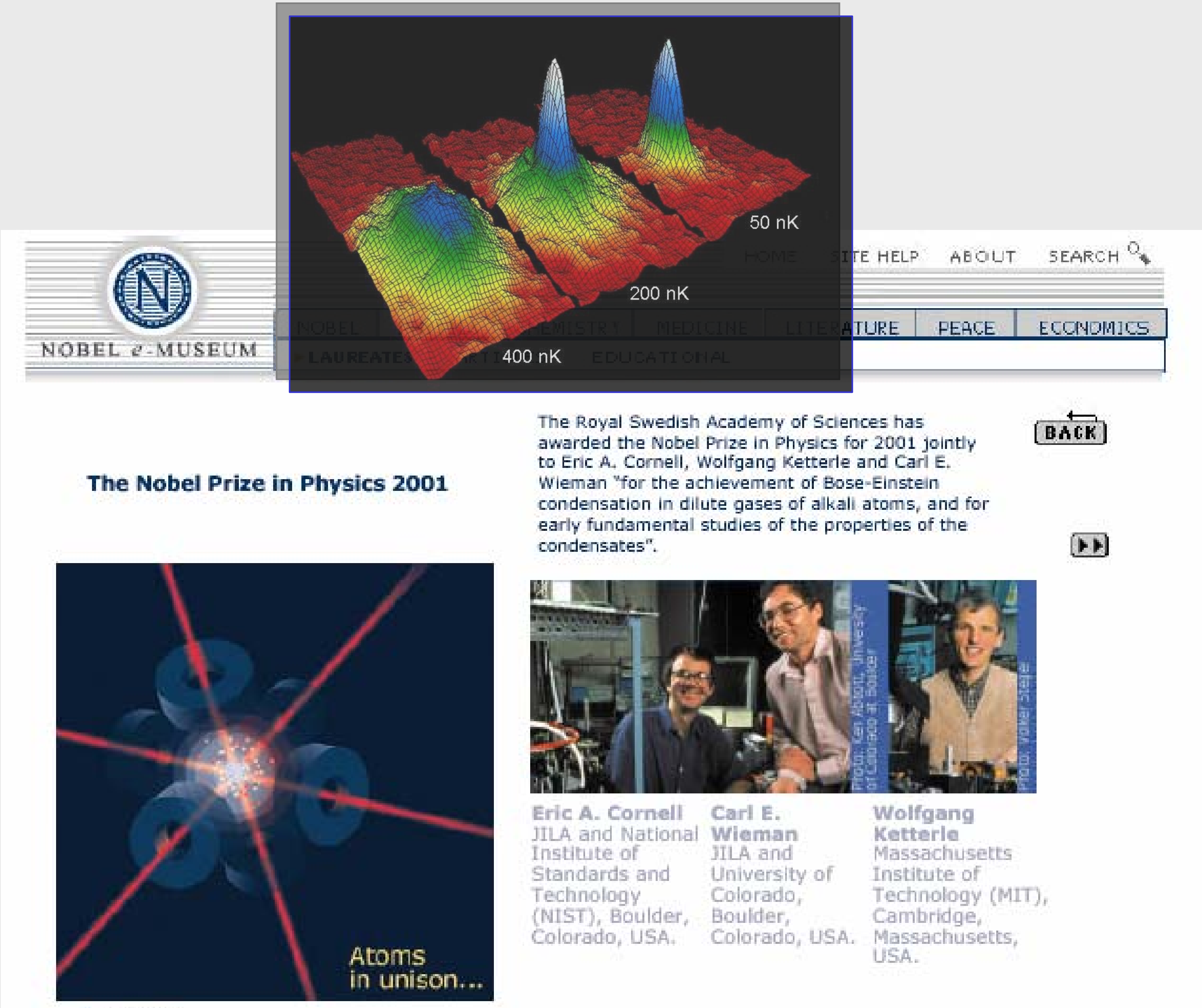
for their developments of methods to cool and trap atoms with laser light.





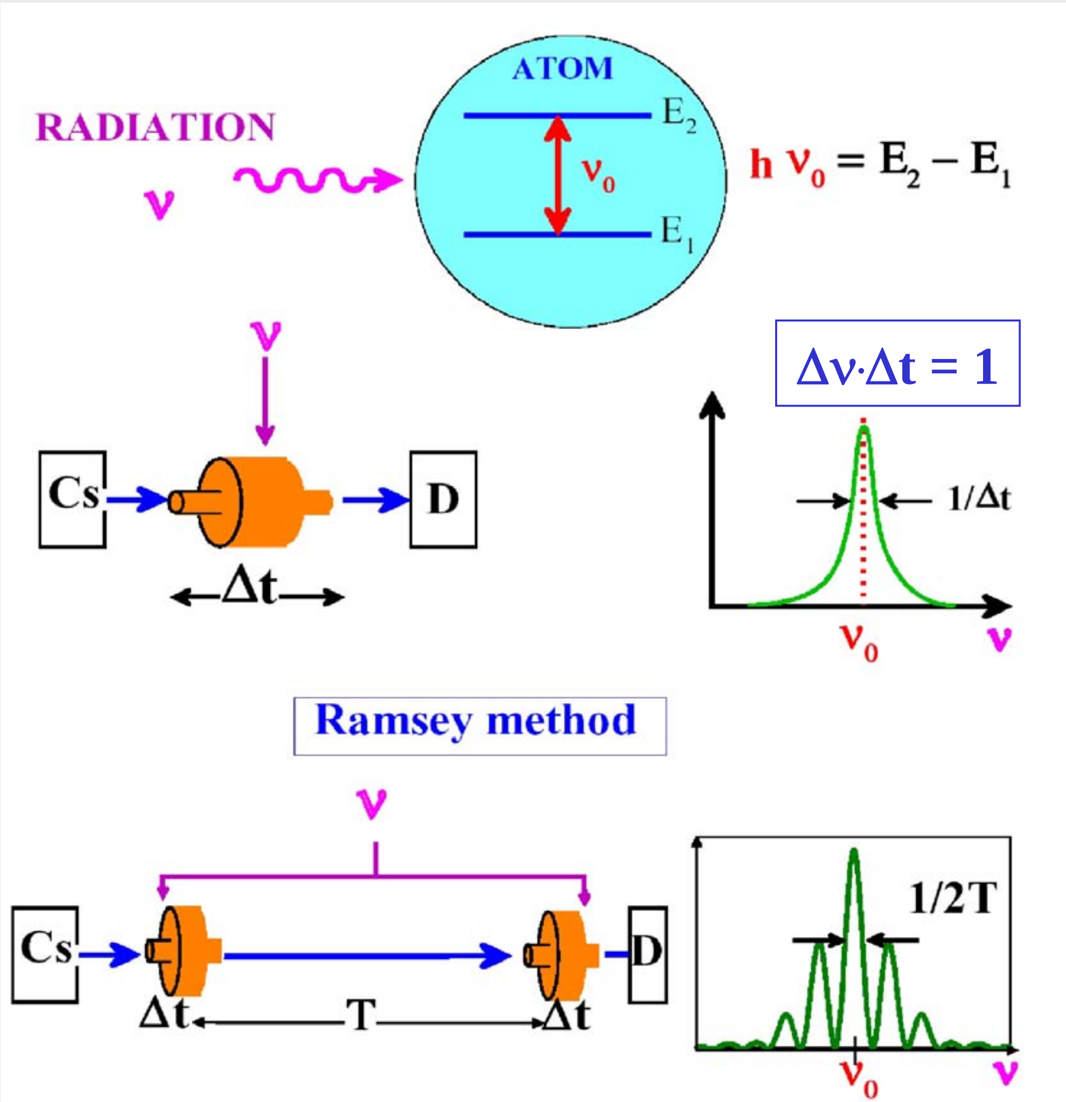
This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

The Nobel Prize in Physics 2001



Atomic clocks

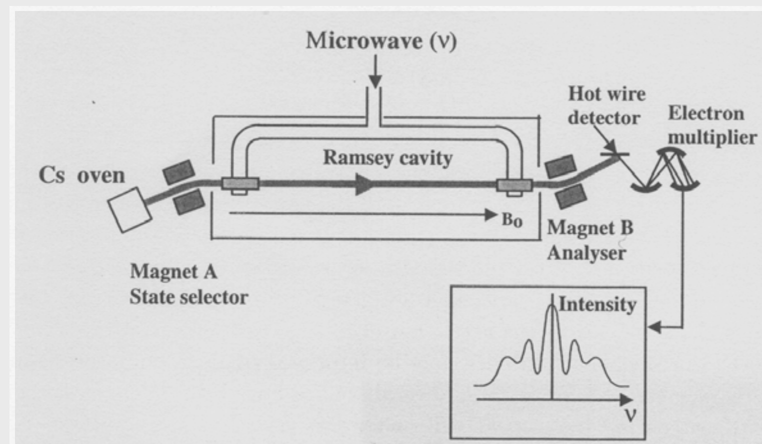
Atomic clocks



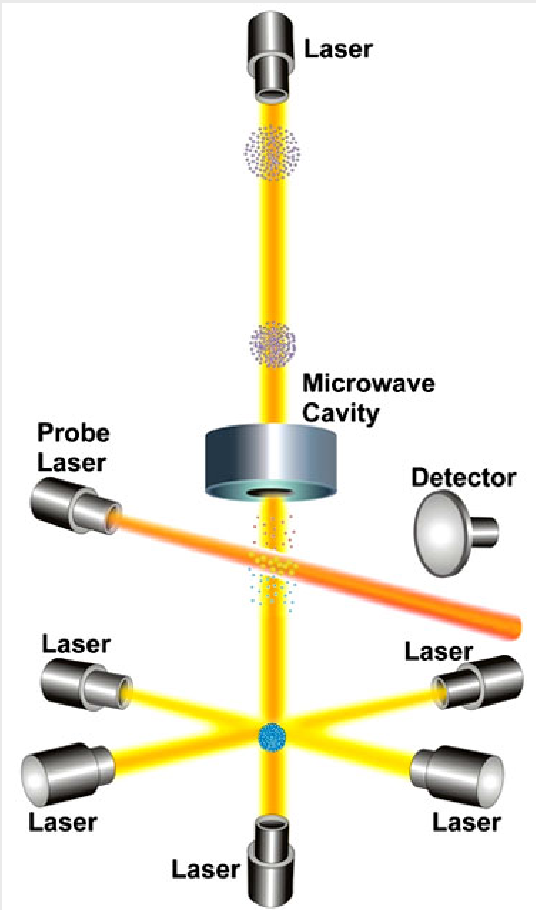
The definition of the second

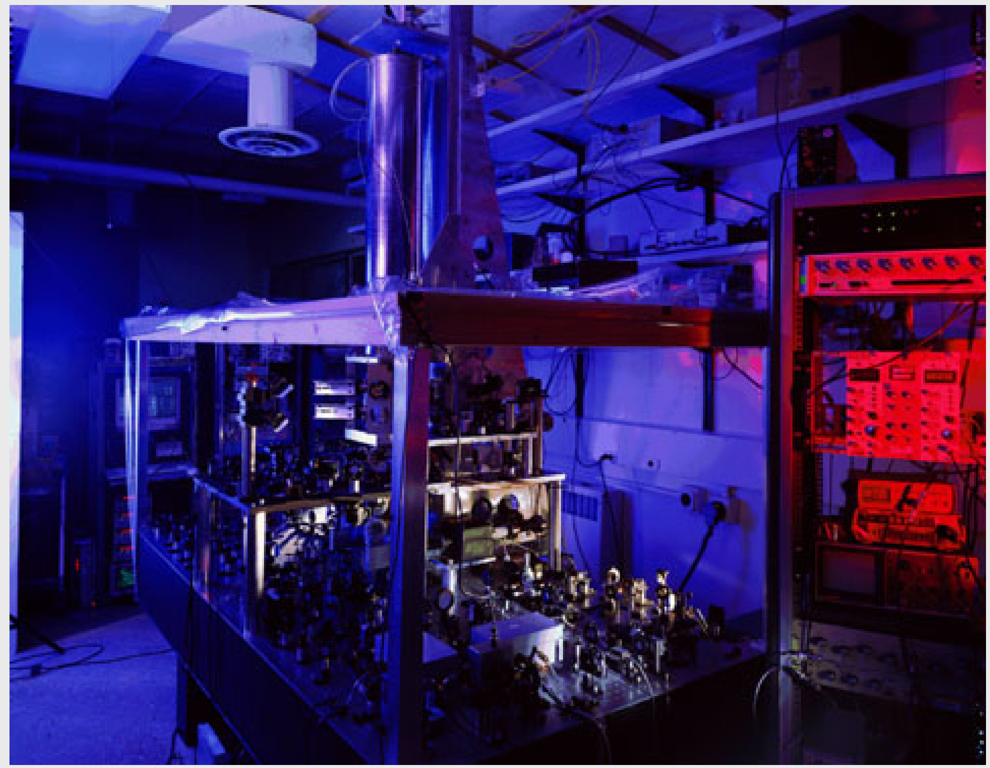
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

(13th CGPM, 1967)



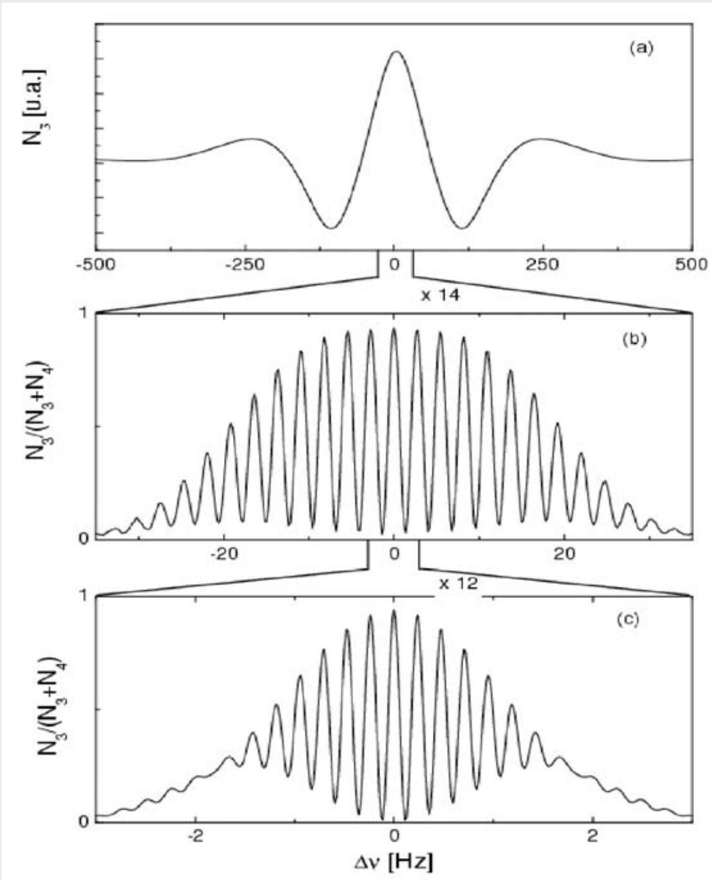
Atomic fountain clock





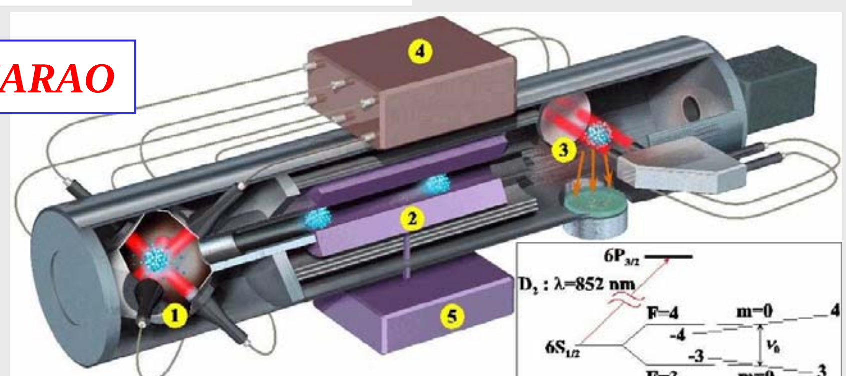
NIST-F1

Cold Atoms Clocks in Space



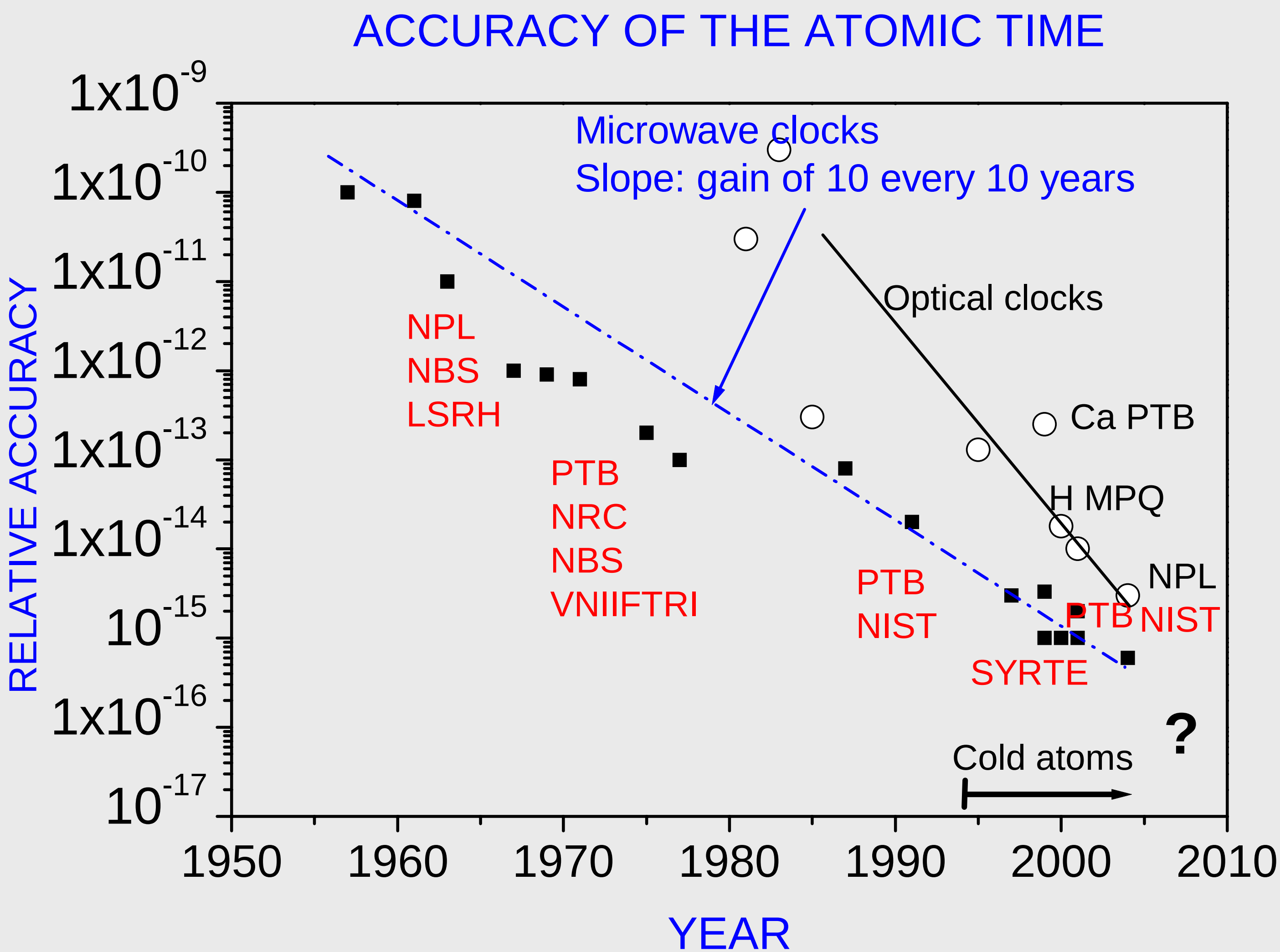
- Interrogate fast (hot) atoms over long distances → T = 10 ms
- Use laser cooled atoms, limitation due to the presence of gravity → T = 1 s
- Use laser cooled atoms in microgravity → T = 10 s

PHARAO



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

Accuracy of the atomic time



from C. Salomon

Optical clocks: Towards 10^{-18}-10^{-19}

- **Narrow optical transitions**

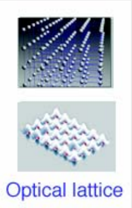
$\delta\nu_o \sim 1$ Hz, $\nu_0 \sim 10^{15}$ Hz

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

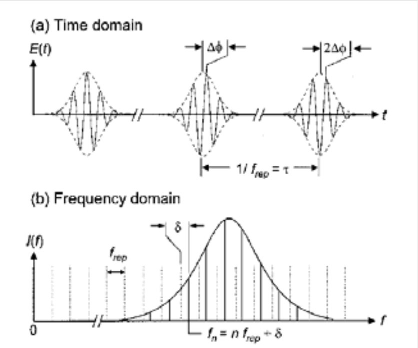
- **Candidate atoms**

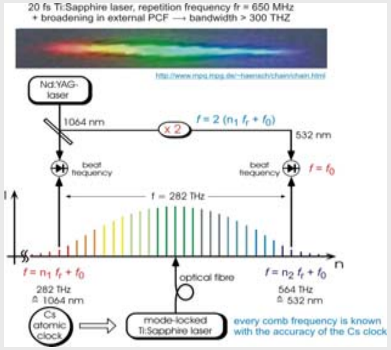
Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…

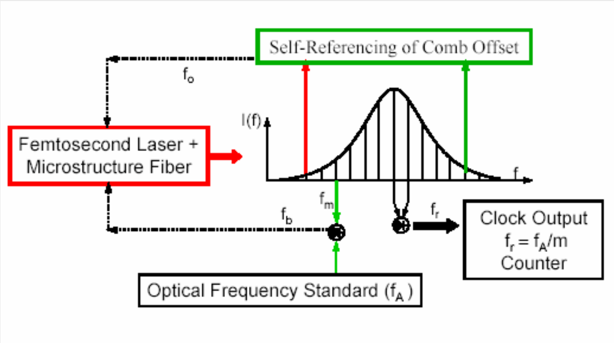
Cold neutral atoms: H, Ca, Sr, Yb,…
(Fermions?)



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







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

HOM

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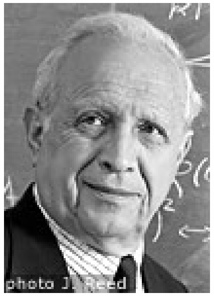
The Nobel Prize in Physics 2005

"for his contribution to the quantum theory of optical coherence"

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"



Roy J. Glauber	John L. Hall	Theodor W. Hänsch
1/2 of the prize	1/4 of the prize	1/4 of the prize
USA	USA	Germany
Harvard University Cambridge, MA, USA	University of Colorado, JILA; National Institute of Standards and Technology Boulder, CO, USA	Max-Planck-Institut für Quantenoptik Garching, Germany; Ludwig-Maximilians-Universität Munich, Germany
b. 1925	b. 1934	b. 1941

The Nobel Prize in Physics 2005
Prize Announcement
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Roy J. Glauber
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Interview
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John L. Hall
Nobel Lecture
Interview
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Theodor W. Hänsch
Nobel Lecture
Interview
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2004

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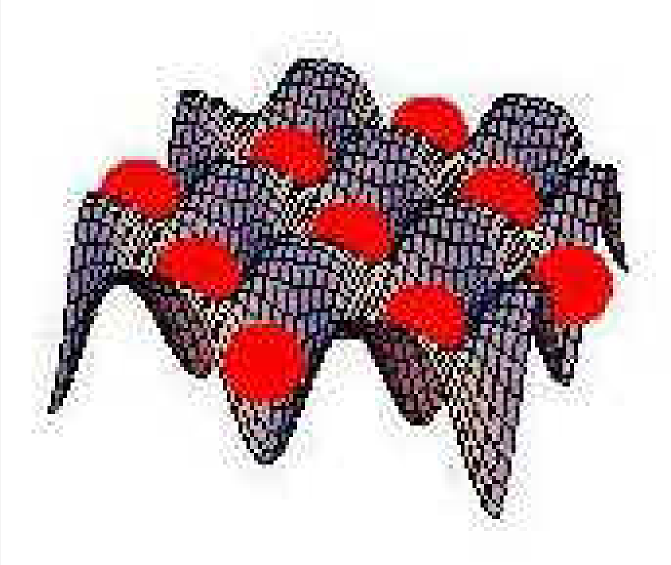
^{87}Sr optical clock

- **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



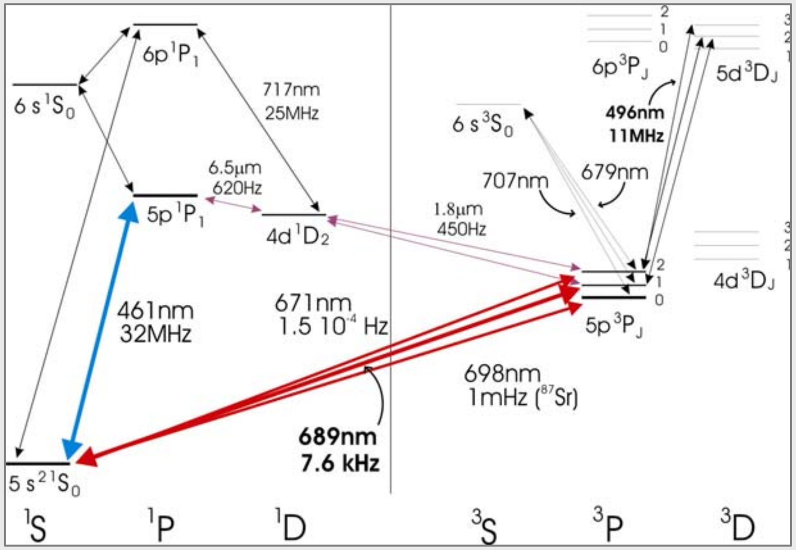
- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

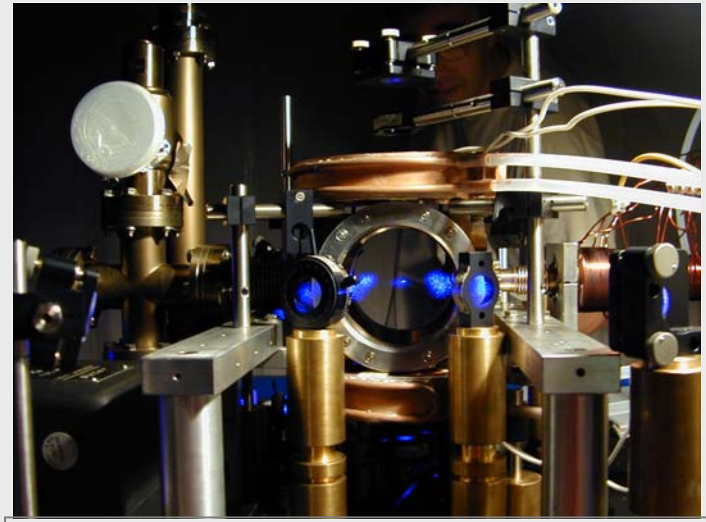
Under development:

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

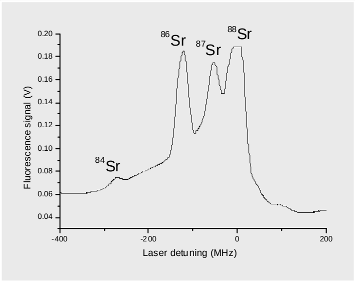
Yb (Kyoto, NIST, Düsseldorf)

Towards a Sr clock – The experiment in Firenze





Firenze 2003, Magneto-optical trapping of all Sr isotopes



- Optical clocks using visible intercombination lines

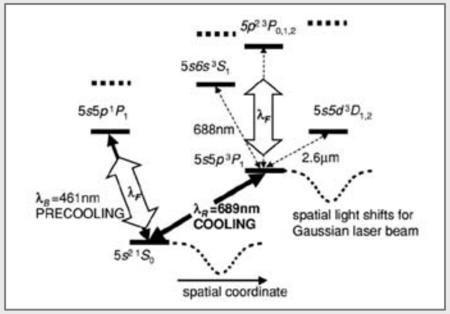
$^1S_0$ - $^3P_1$ (7.5 kHz)

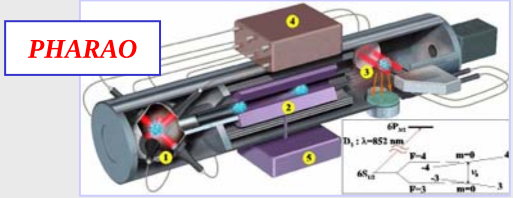
$^1S_0$ - $^3P_0$ (1 mHz, ^{87}Sr)

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

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

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

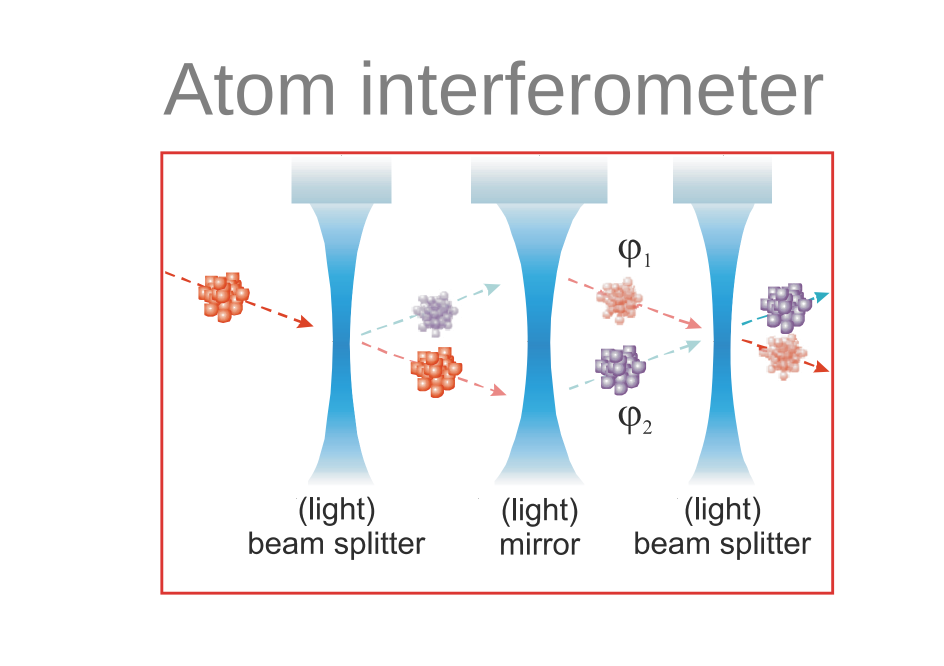


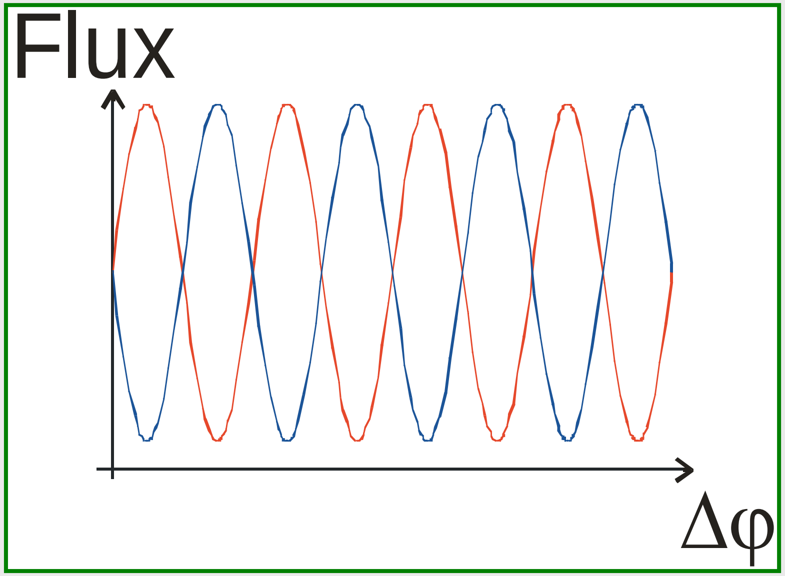


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli and G.M. Tino, Phys. Rev. Lett. 91, 243002 (2003)

Atom Interferometers

Atom Interferometry





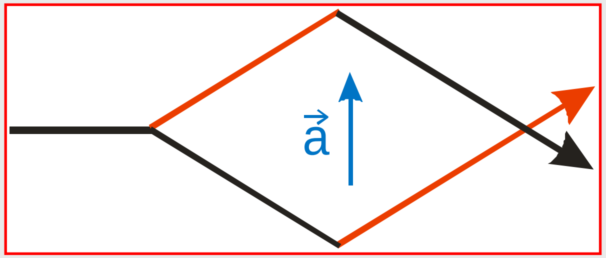
atomic flux at **exit** port **1**
at **exit** port **2**

Phase difference

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

Matter wave sensors

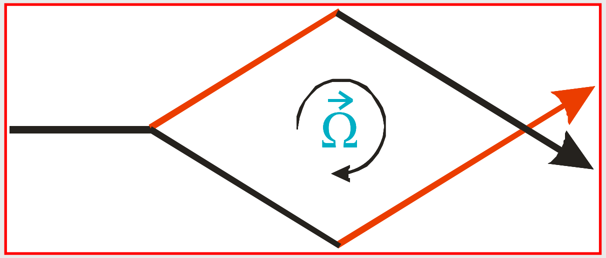
accelerations:



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

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

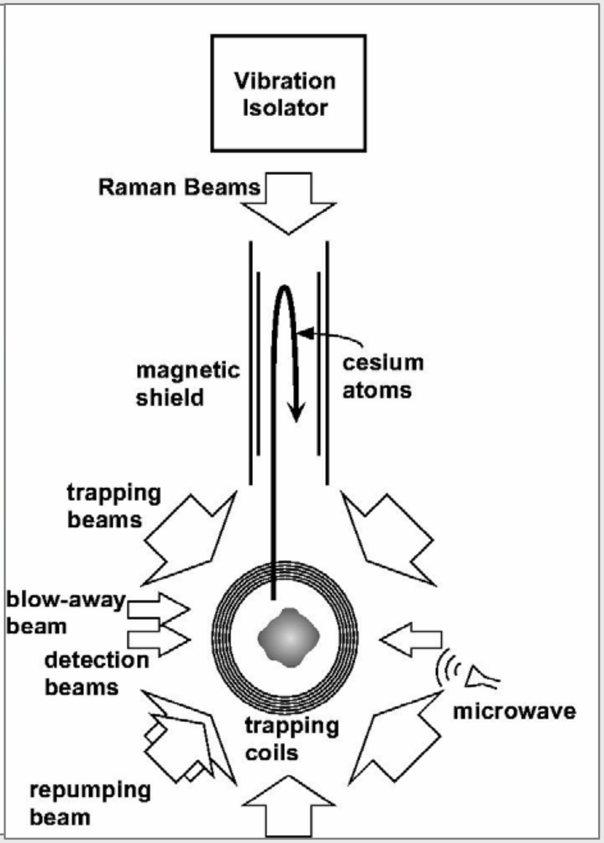
rotations:

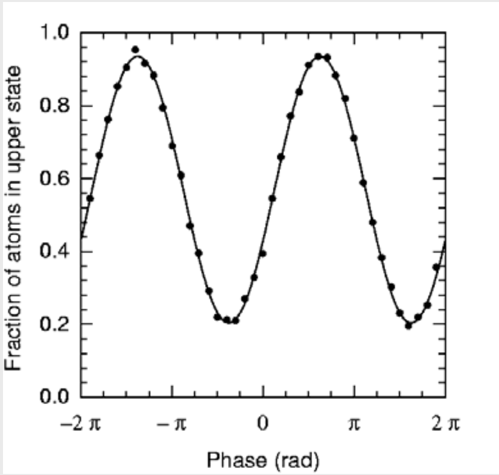


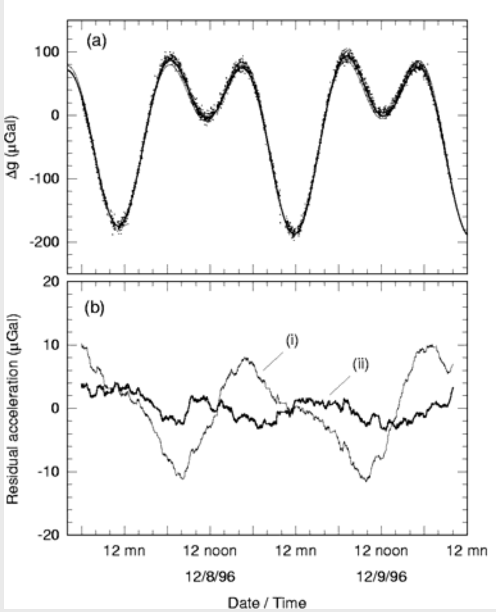
$$\Delta\Phi_{rot} = 2\pi \frac{2\,m_{at}}{h} A \cdot \Omega$$

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

Stanford atom gravimeter





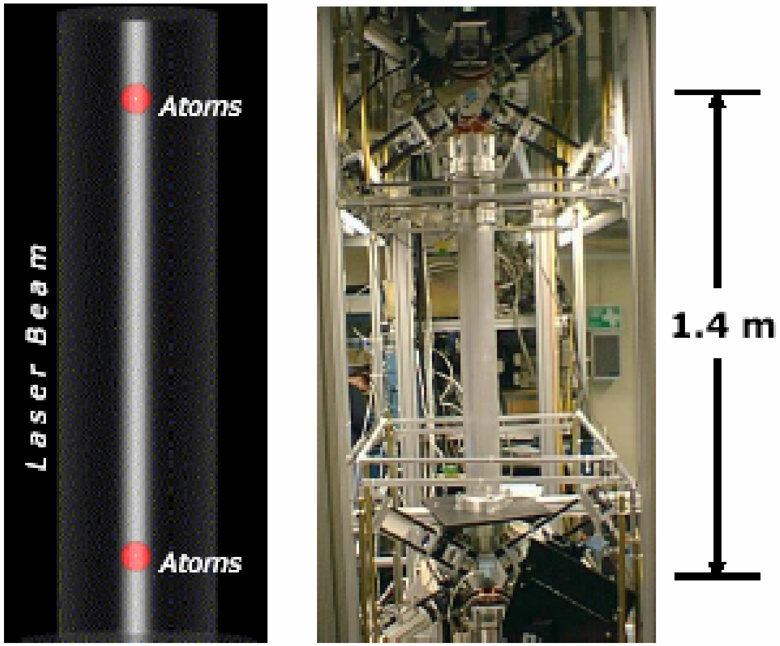


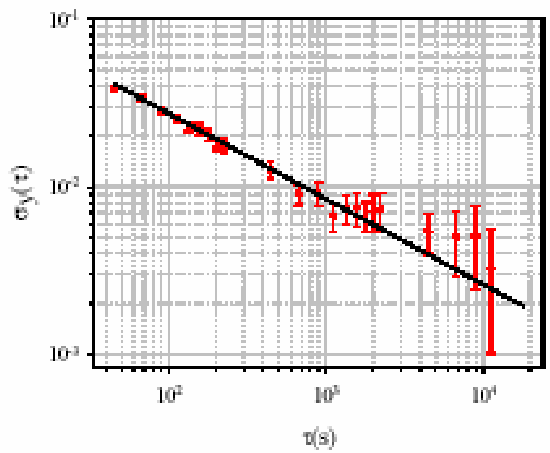
Resolution: $3x10^{-9}$ g after 1 minute

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

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

Stanford/Yale gravity gradiometer





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

Demonstrated diffential acceleration sensitivity:

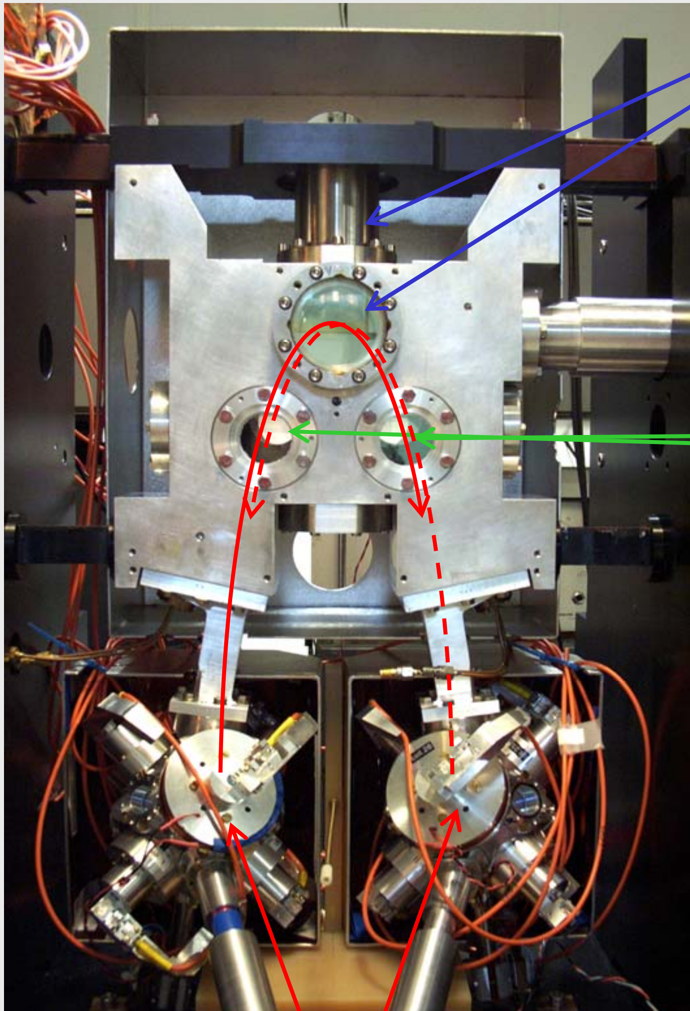
4×10^{-9} g/Hz$^{1/2}$

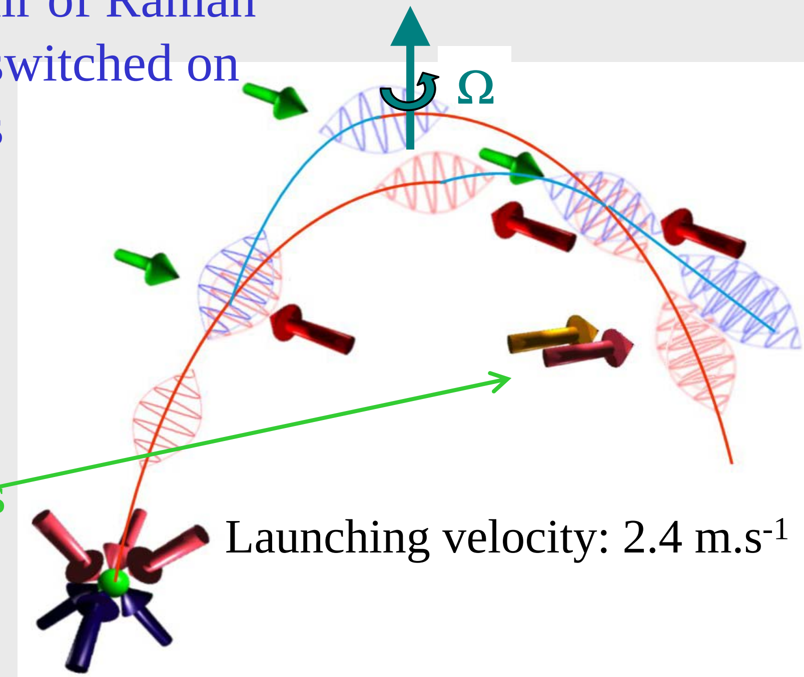
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

from M.A. Kasevich

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

SYRTE cold atom gyroscope





Maximum interaction time : 90 ms

3 rotation axes

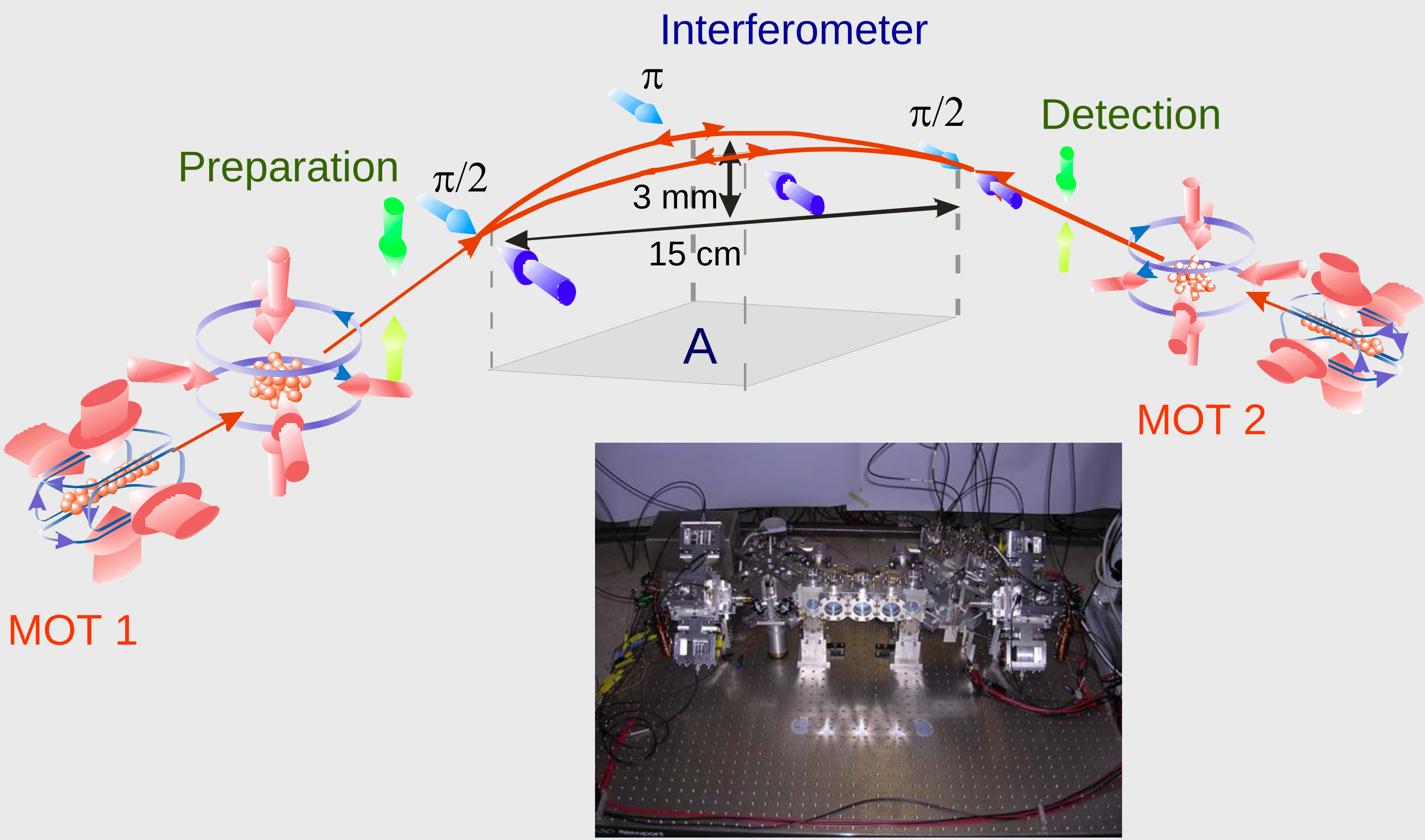
2 acceleration axes

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}.$Hz^{-1/2}$

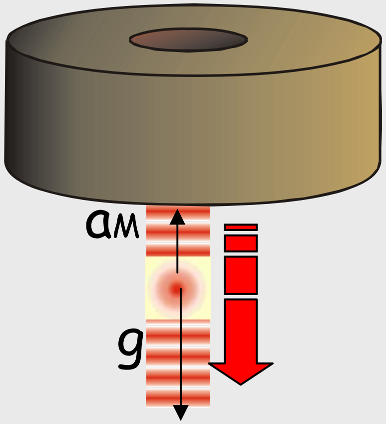
IQO Cold Atom Sagnac Interferometer



C. Jentsch, T. Müller, E. Rasel, and W. Ertmer, Gen. Rel. Grav, 36, 2197 (2004)
& Adv. At. Mol. Physics

MAGIA

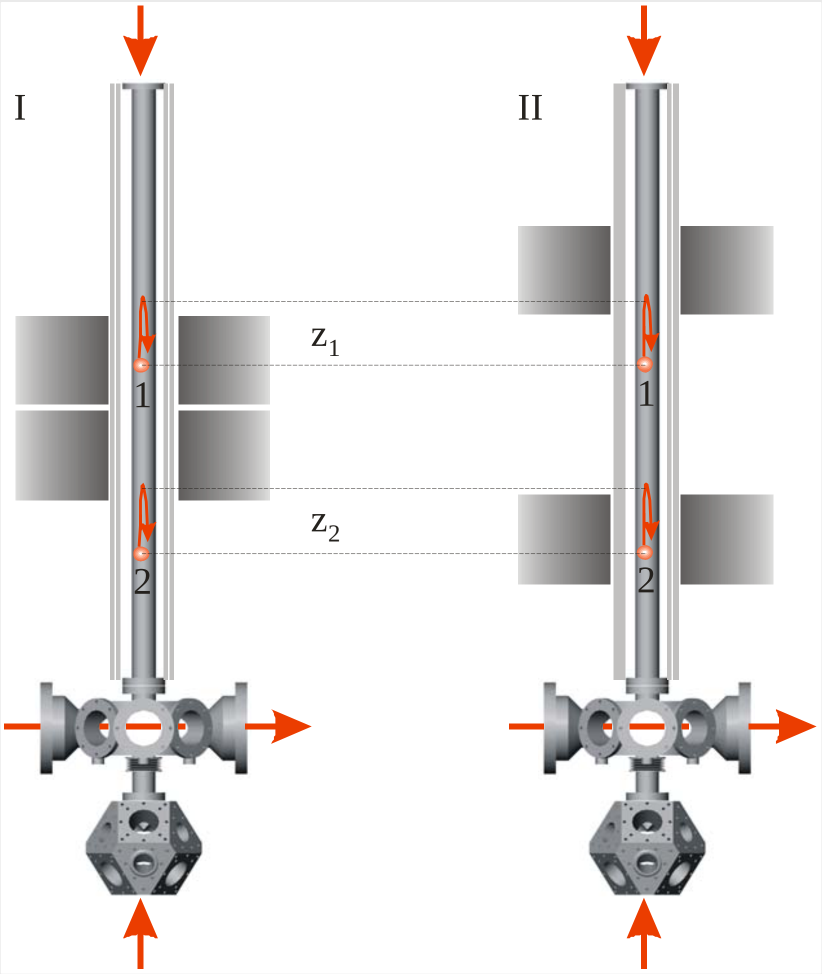
- Measure g by atom interferometry
- Add source masses
- Measure change of g



- *Precision measurement of G*
- *Measurement of gravity at sub-mm distances*

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

MAGIA: Experimental procedure



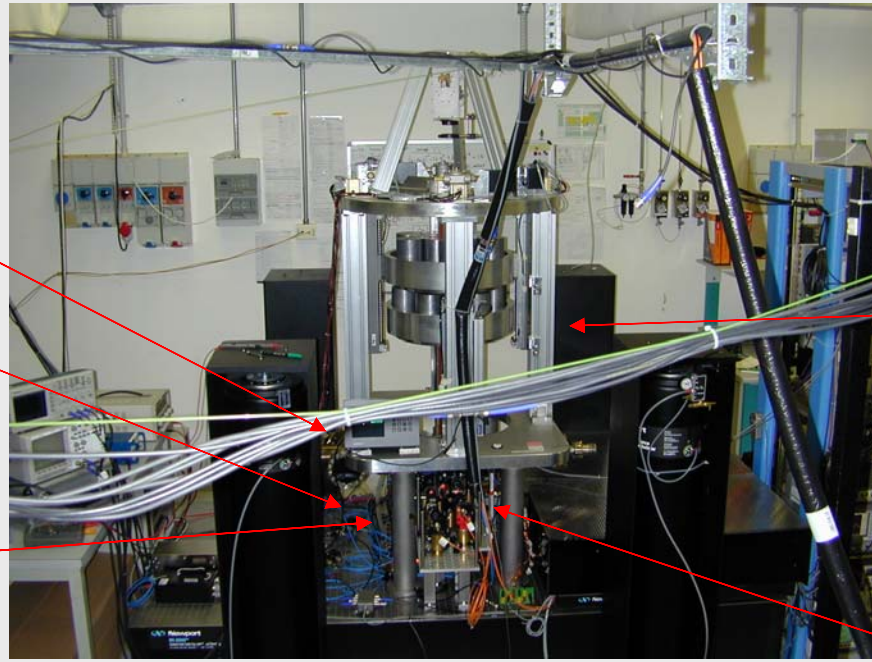
- trap, cool and launch 2 clouds of Rb atoms
- apply Raman light pulses
  masses in position 1
- detect atoms state selectively
- repeat several times
- plot N_a/N and fit the differential phase shift $\Delta\Phi_g$ between the clouds
- move masses to position 2
  repeat all procedure
- subtract the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

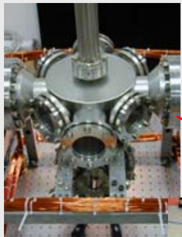
$$\phi_1^I - \phi_2^I = \phi_g(z_1) + \phi_{SM} + \phi_{Sys}(z_1, t_I) - \left(\phi_g(z_2) - \phi_{SM} + \phi_{Sys}(z_2, t_I)\right)$$

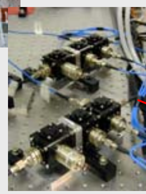
$$\phi_1^{II} - \phi_2^{II} = \phi_g(z_1) - \phi_{SM} + \phi_{Sys}(z_1, t_{II}) - \left(\phi_g(z_2) + \phi_{SM} + \phi_{Sys}(z_2, t_{II})\right)$$

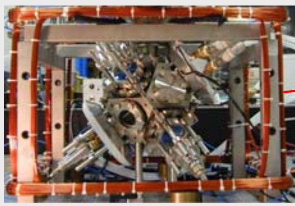
$$\Rightarrow (\phi_1^I - \phi_2^I) - (\phi_1^{II} - \phi_2^{II}) = 4\phi_{SM} + \phi_{Sys}(\Delta z, \Delta t)$$

Atom gravity gradiometer apparatus

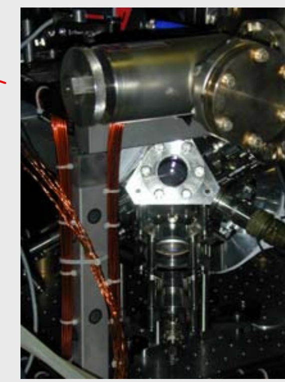




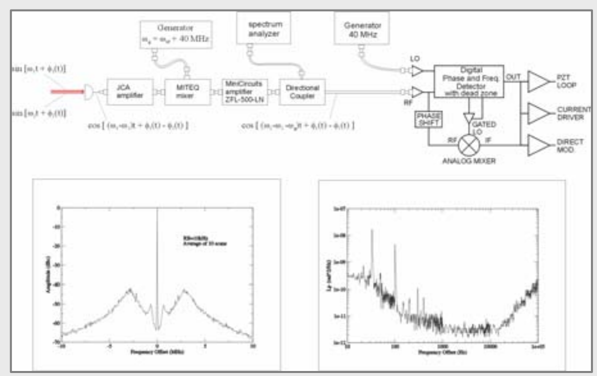




Source masses and support

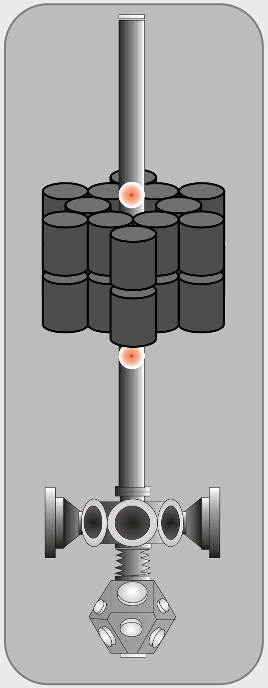


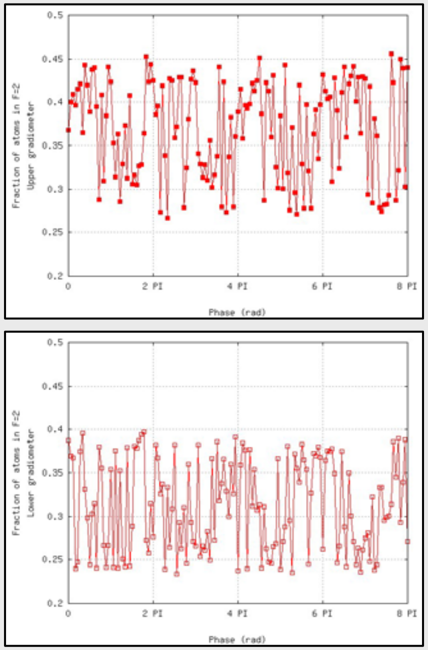
Laser and optical system

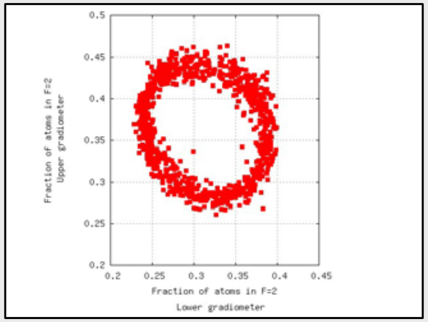


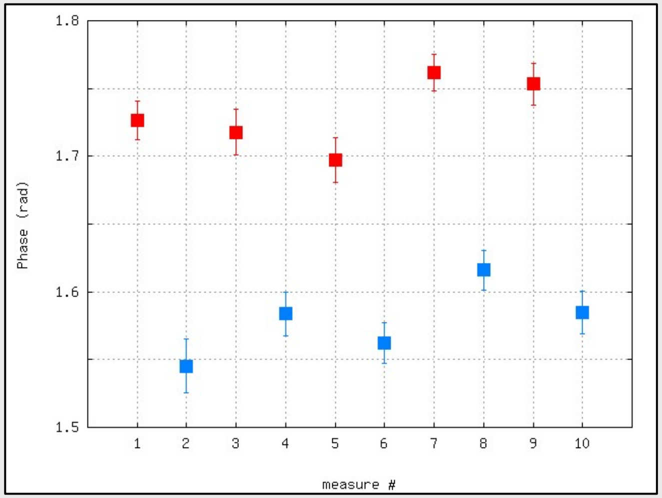
L. Cacciapuoti, M.de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M.Prevedelli, J. Stuhler, G.M. Tino, ***Analog+digital phase and frequency detector for phase locking of diode lasers,*** **Rev. Scient. Instr. 76, 053111 (2005)**

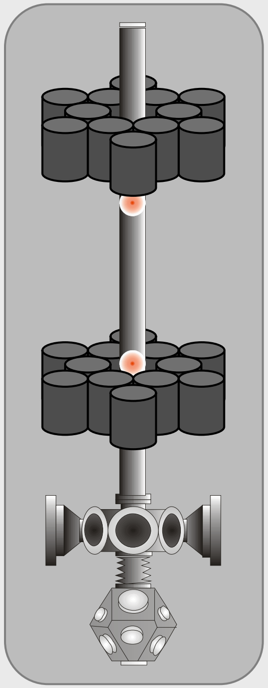
MAGIA: first results

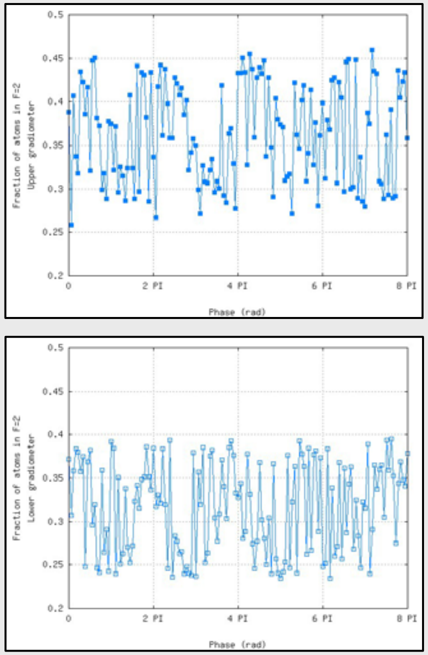


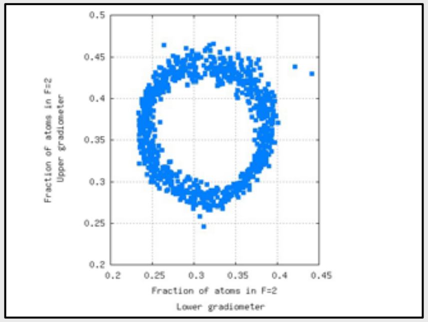












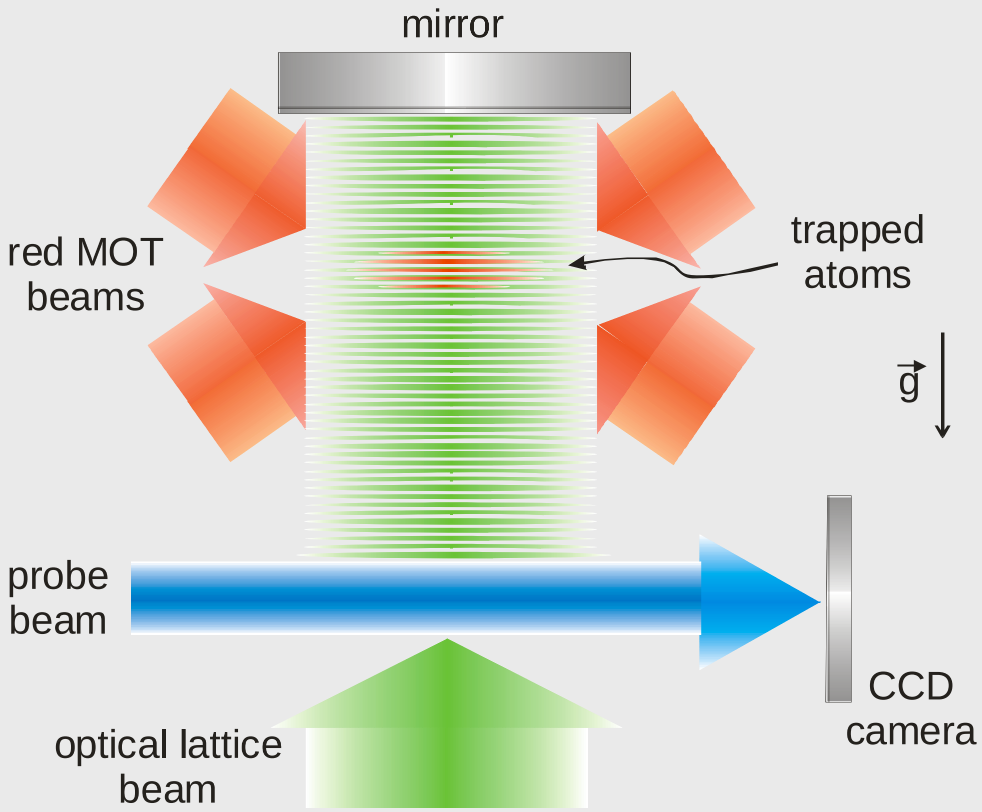
MAGIA – Relevant numbers

- 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

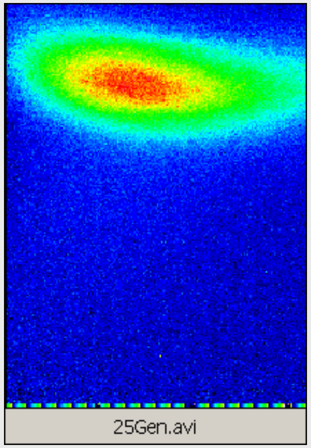
$\Downarrow$

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

Precision Measurement of Gravity at Micrometer Scale using Ultracold Sr Atoms

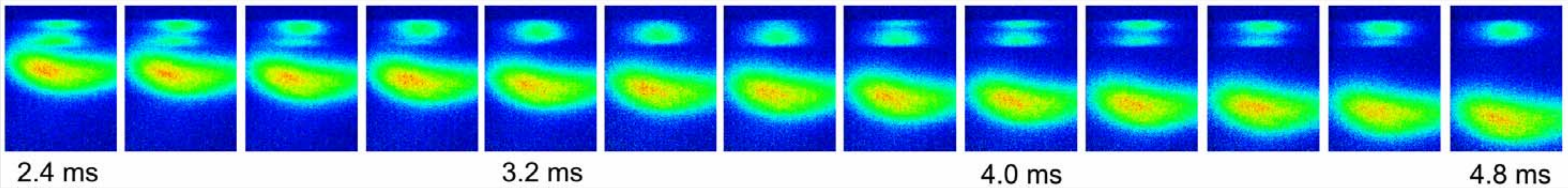


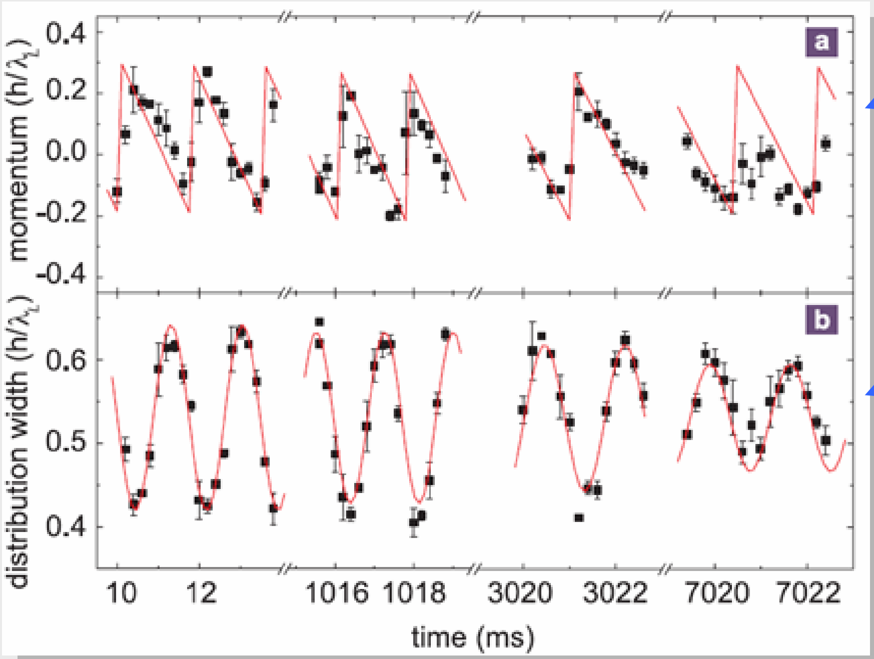
$\nu = m\, g\, \lambda\, /2\, h$



- **G. Ferrari et al., 2006, to be published**

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency ν_B = 574.568(3) Hz

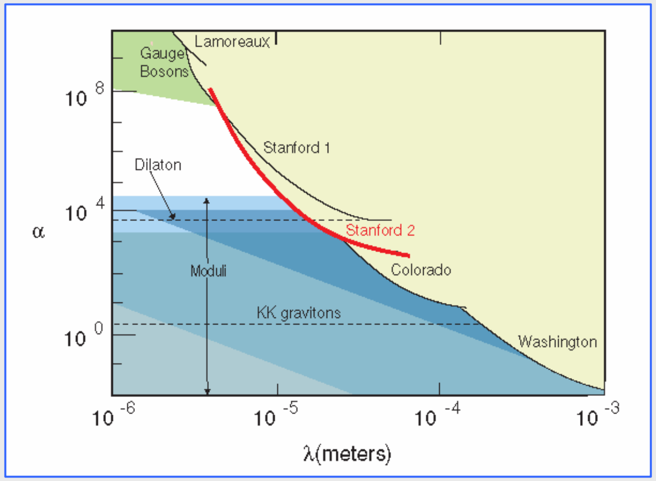
damping time τ = 12 s

8000 photon recoils in 7s

g_{meas} = 9.80012(5) ms^{-2}

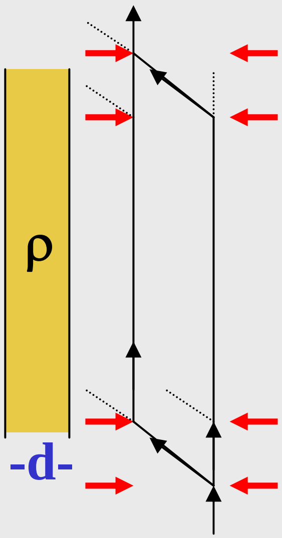
G. M. Ferrari, N. Poli, F. Sorrentino & G. M. Tino, *Precision gravity measurement at micrometer scale with laser-cooled Sr atoms in an optical lattice,* 2006, to be published

Test of the gravitational $1/r^2$ law in the sub-mm range with atom interferometry sensors (Casimir?)



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 S. J. Smullin et al., 2005)

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

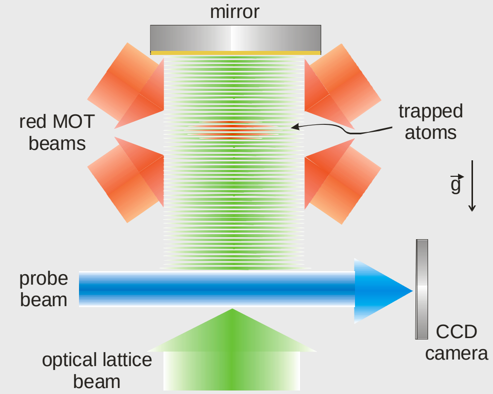


$a = 2\pi G\rho d$

Example:

ρ_{Au} ~19 g/cm^3
d ~ 200 μm

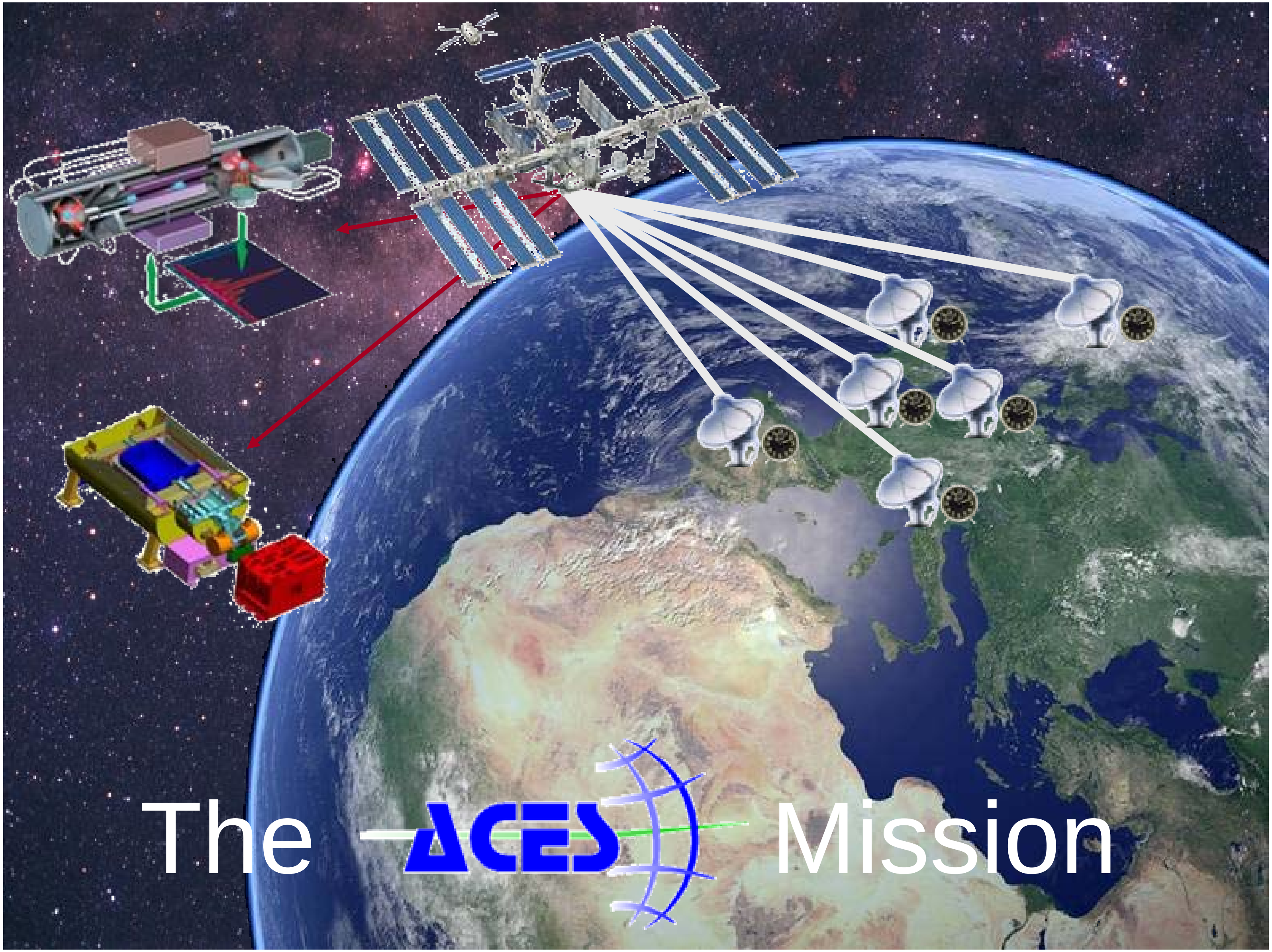
$a \sim 2 \times 10^{-9}$ ms^{-2}



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

- **G.M. Tino, *in "2001: A Relativistic Spacetime Odyssey", Firenze, 2001,* World Scientific (2003)**
- **G.M. Tino, Nucl. Phys. B 113, 289 (2002)**
- **G. Ferrari et al., 2006, to be published**

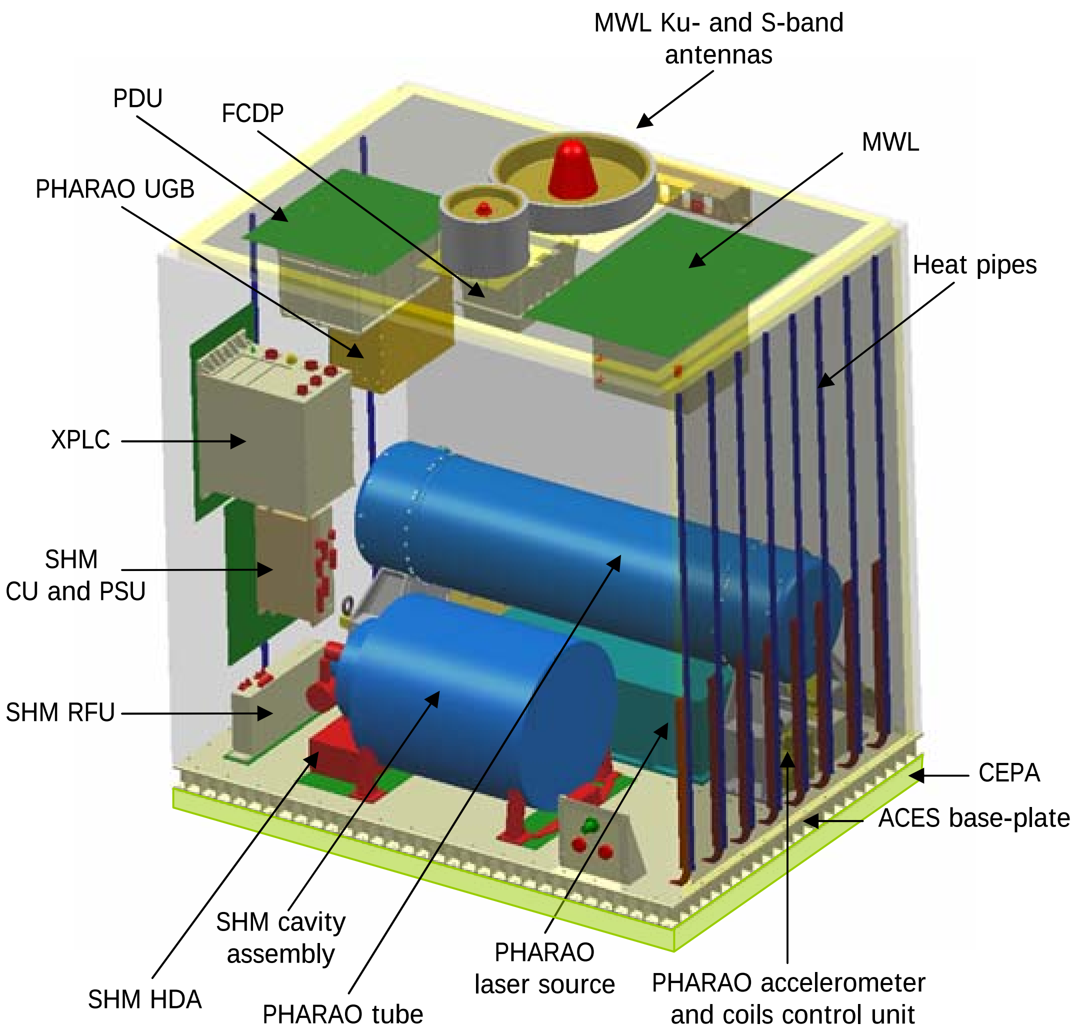
From Earth Laboratories to Space

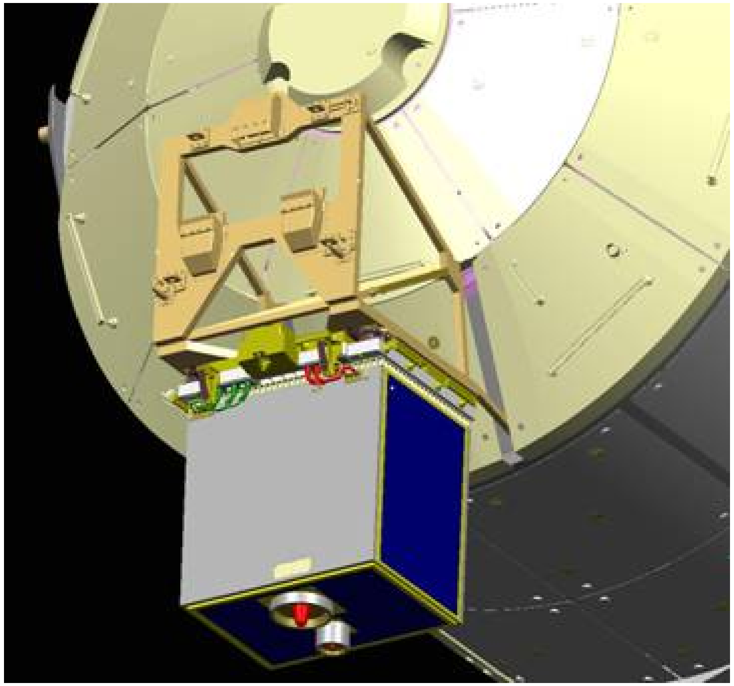


From L. Cacciapuoti, FPS 06, Frascati, 20-22 March 2006

See Poster

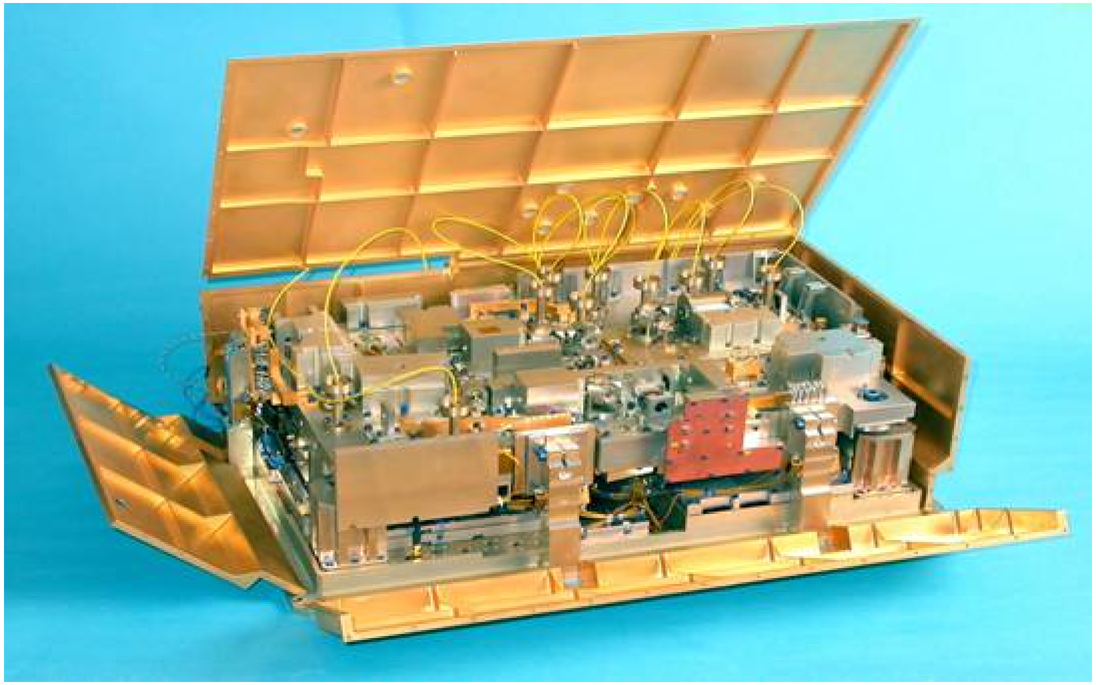
The ACES Payload





Volume: 1172x867x1246 mm^3
Total mass: 227 kg
Power: 450 W

PHARAO Optical System

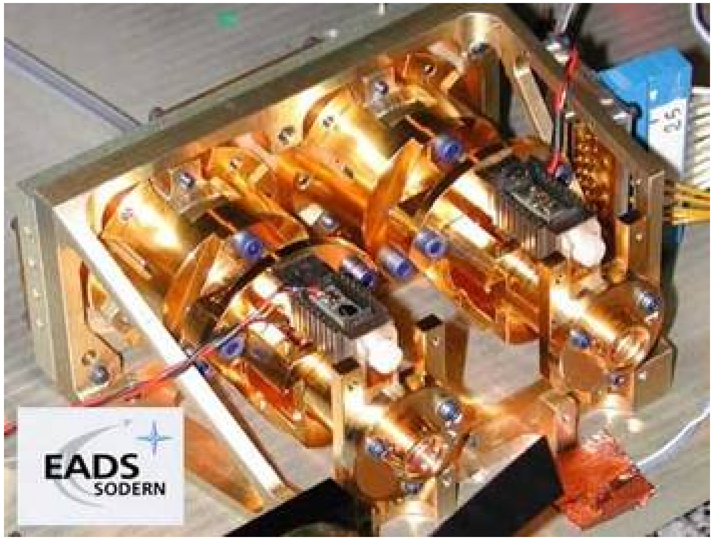


Detection system

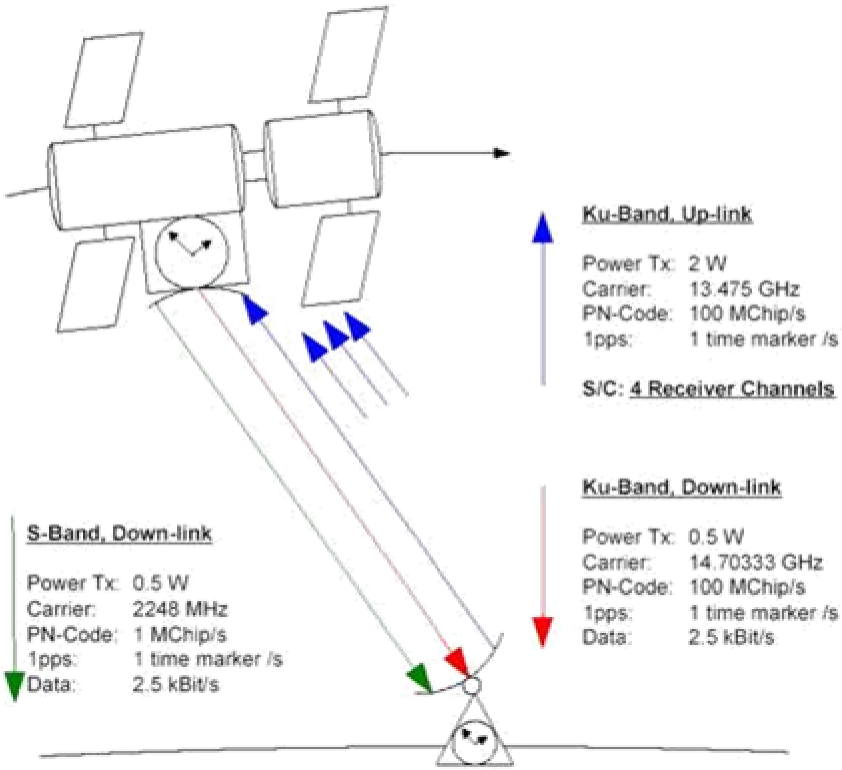
- Standing wave (F=4)
- Pushing beam (F=4)
- Pumping beam (F=3)
- Standing wave (F=4)

Power of the cooling laser at the fibers output

- Capture 3 x 14 mW + 3 x 12 mW
- Relative phase noise between the 6 cooling beams: ~0.25 mrad rms (100 Hz - 100 kHz)



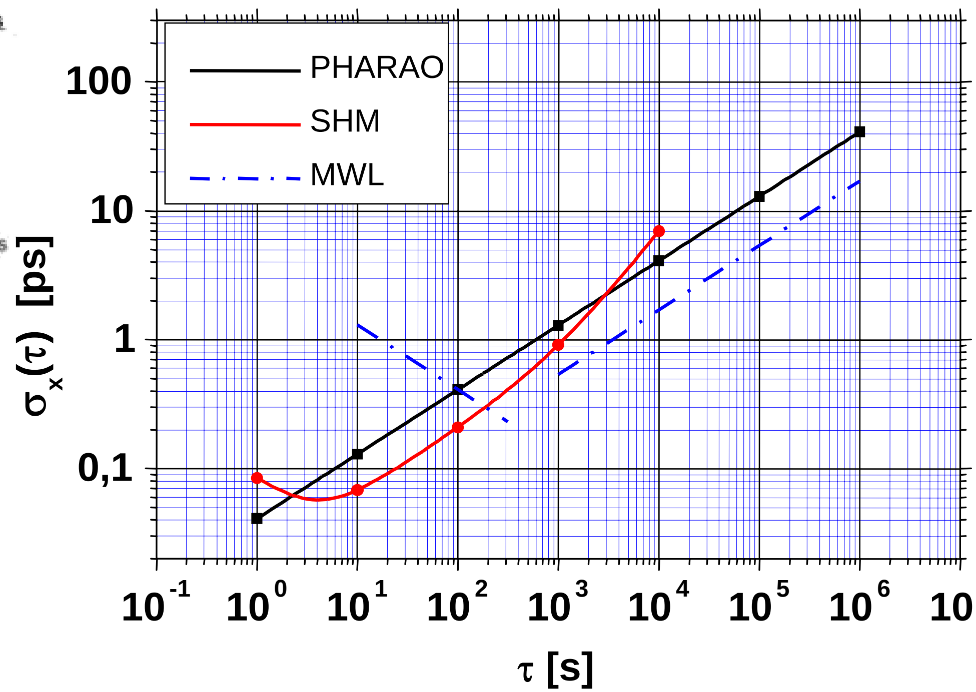
ACES Microwave Link



Time stability

- 0.3 ps over 300 s
- 6 ps over 1 day
- 23 ps over 10 days

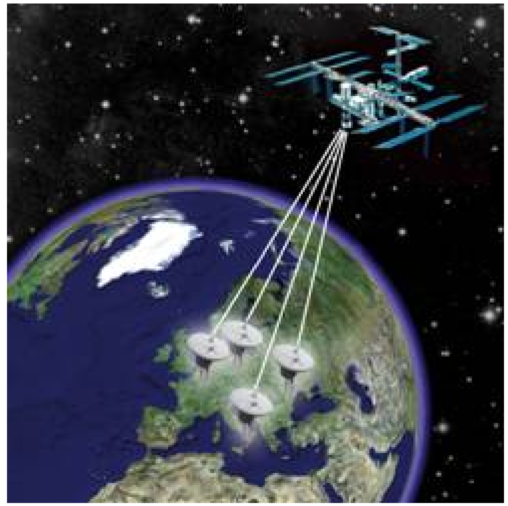
Clock comparisons at the 10^{-17} level on an integration time of 1 day possible

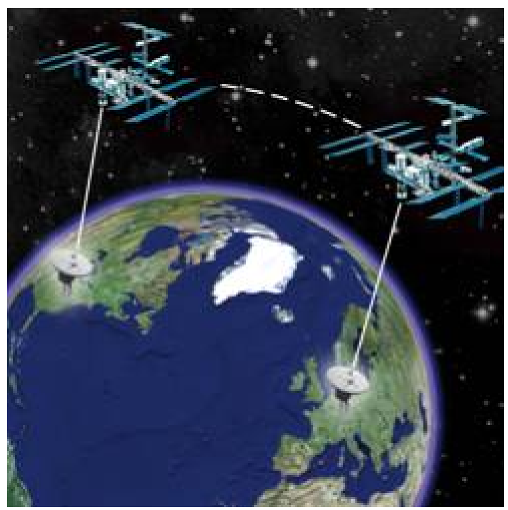


EADS SPACE TRANSPORTATION TIMETECH KAYSER-THREDE

ACES Operational Scenario

- Mission Duration: 1.5 years up to 3 years
- ISS Orbit Parameters:
  – Altitude: ~ 400 km
  – Inclination: ~ 51.6°
  – Period: 90 min
- Link According to Orbit Characteristics:
  – Link duration: up to 400 seconds
  – Useful ISS passes: at least one per day
- MWL Ground Terminals
  – Located at ground clock sites
  – Distributed worldwide





Common View Comparisons

– Comparison of up to 4 ground clocks simultaneously

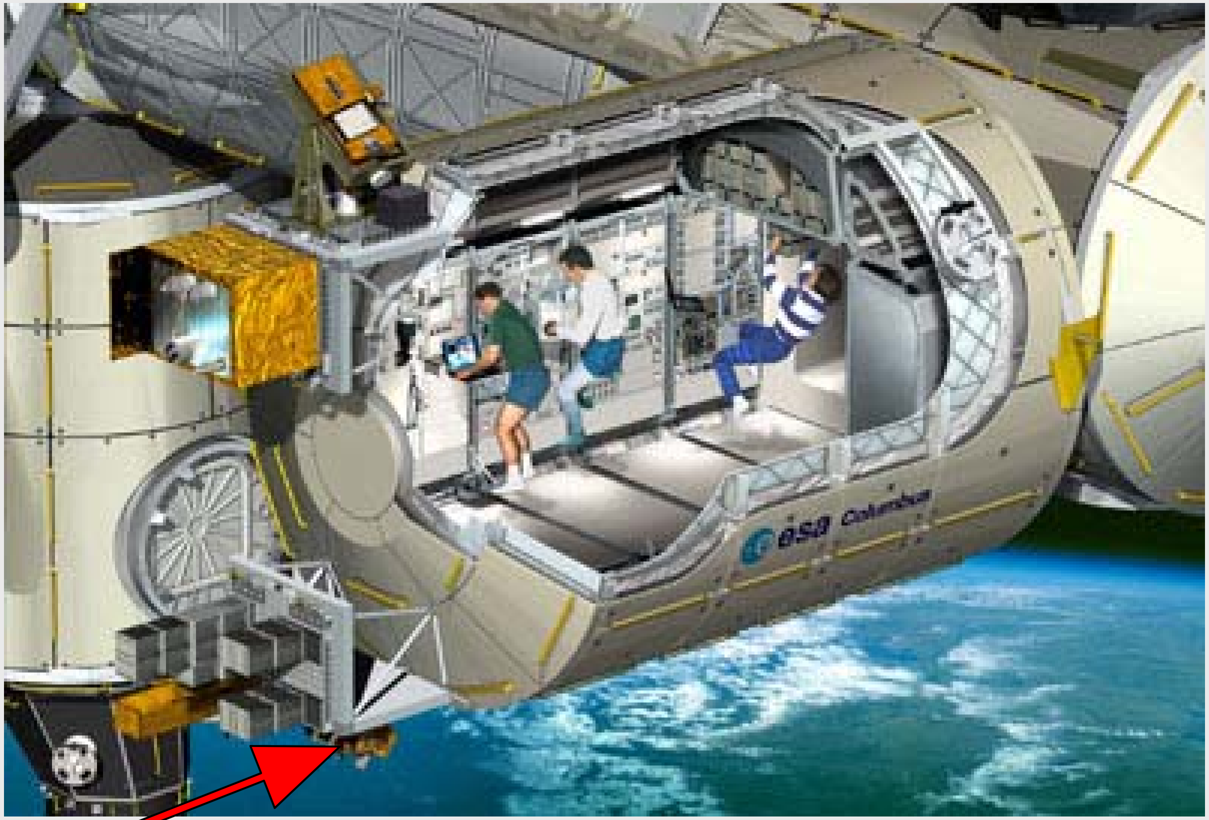
– Uncertainty below 1 ps per ISS pass (~ 300 s)

Non-Common View Comparisons:

– ACES clocks as *fly wheel*

– Uncertainty below 2 ps over 1000 s and 20 ps over 1 day

ACES ON COLUMBUS EXTERNAL PLATFORM



ACES

M = 227 kg **P = 450 W**

Launch date : 2010
Mission duration : 18 months

ACES Mission Objectives I

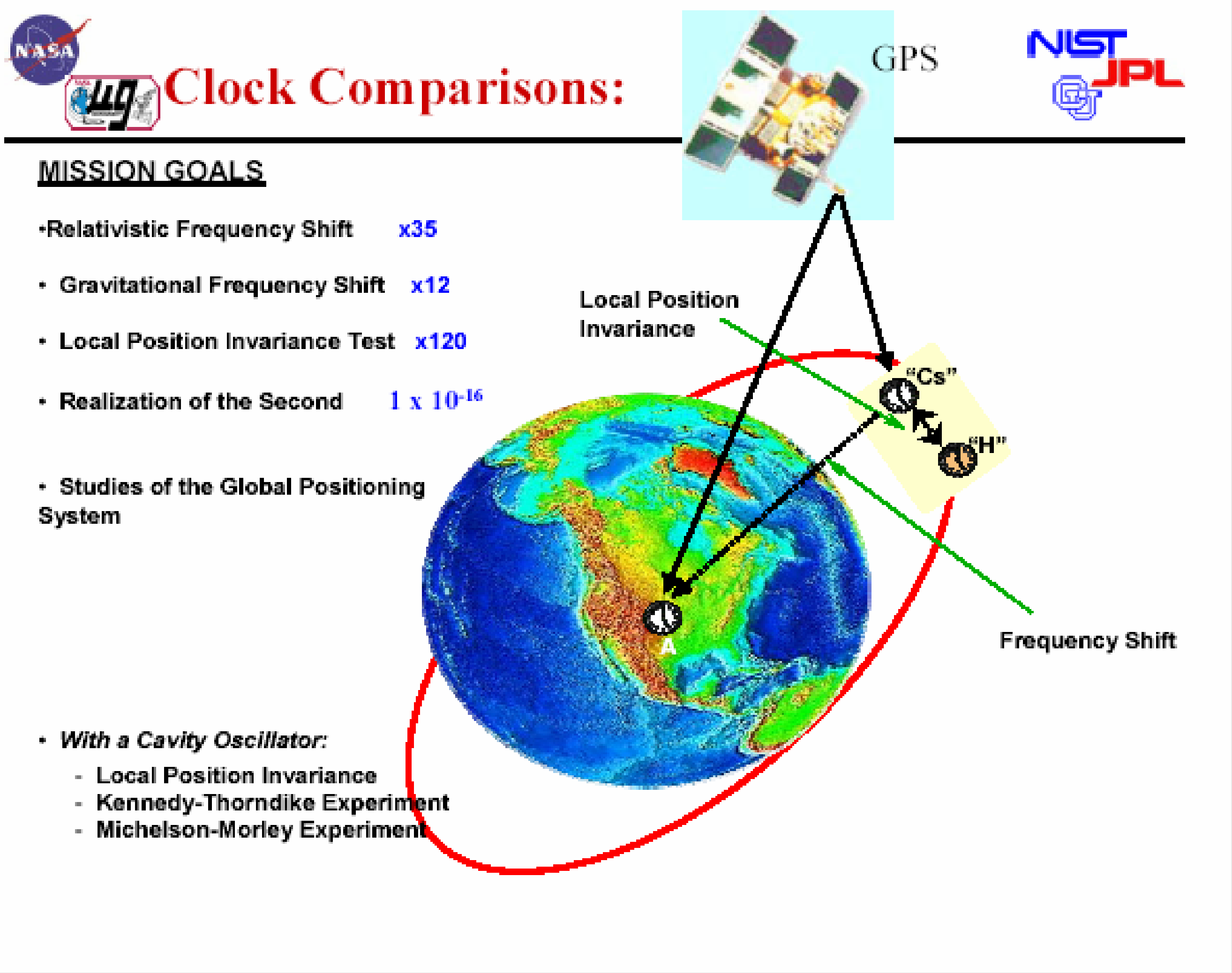
<table>
<tr><th>ACES Mission Objectives</th><th>ACES performances</th><th>Scientific background and recent results</th></tr>
<tr><td colspan="3">Test of a new generation of space clocks</td></tr>
<tr><td>Cold atoms in a micro-gravity environment</td><td>Study of cold atom physics in microgravity.</td><td>Such studies will be essential for the development of atomic quantum sensors for space applications (optical clocks, atom interferometers, atom lasers).</td></tr>
<tr><td>Test of the space cold atom clock PHARAO</td><td>PHARAO performances: frequency instability lower than $3\cdot10^{-16}$ at one day and inaccuracy at the 10^{-16} level.
The short term frequency instability will be evaluated by direct comparison to SHM. The long term instability and the systematic frequency shifts will be measured by comparison to ultra-stable ground clocks.</td><td>Frequency instability: optical clocks show better performances; their frequency instability can be one or more orders of magnitude better than PHARAO, but their accuracy is still around the 10^{-15} level.
Inaccuracy: at present, cesium fountain clocks are the most accurate frequency standards.</td></tr>
<tr><td>Test of the space hydrogen maser SHM</td><td>SHM performances: frequency instability lower than $2.1\cdot10^{-15}$ at 1000 s and $1.5\cdot10^{-15}$ at 10000 s.
The medium term frequency instability will be evaluated by direct comparison to ultra-stable ground clocks. The long term instability will be determined by the on-board comparison to PHARAO in FCDP.</td><td>SHM performances are extremely competitive compared to state-of-the-art as the passive H-maser developed for GALILEO or the ground H-maser EFOS C developed by the Neuchâtel Observatory:
<table>
<tr><td>Maser</td><td>σ_y (1000 s)</td><td>σ_y (10000 s)</td></tr>
<tr><td>GALILEO</td><td>$3.2\cdot10^{-14}$</td><td>$1.0\cdot10^{-14}$</td></tr>
<tr><td>EFOS C</td><td>$2.0\cdot10^{-15}$</td><td>$2.0\cdot10^{-15}$</td></tr>
</table></td></tr>
<tr><td colspan="3">Precise and accurate time and frequency transfer</td></tr>
<tr><td>Test of the time and frequency link MWL</td><td>Time transfer stability will be better than 0.3 ps over one ISS pass, 7 ps over 1day, and 23 ps over 10 days.</td><td>At present, no time and frequency transfer link has performances comparable with MWL.</td></tr>
<tr><td>Time and frequency comparisons between ground clocks</td><td>Common view comparisons will reach an uncertainty level below 1 ps per ISS pass.
Non common view comparisons will be possible at an uncertainty level of
• 2 ps for τ=1000 s
• 5 ps for τ=10000 s
• 20 ps for τ=1 day</td><td>
<table>
<tr><td>Existing T&F links</td><td>Time stability (1day)</td><td>Time accuracy (1day)</td><td>Frequency accuracy (1day)</td></tr>
<tr><td>GPS-DB</td><td>2 ns</td><td>3-10 ns</td><td>$4\cdot10^{-14}$</td></tr>
<tr><td>GPS-CV</td><td>1 ns</td><td>1-5 ns</td><td>$2\cdot10^{-14}$</td></tr>
<tr><td>GPS-CP</td><td>0.1 ns</td><td>1-3 ns</td><td>$2\cdot10^{-15}$</td></tr>
<tr><td>TWSTFT</td><td>0.1-0.2 ns</td><td>1 ns</td><td>$2\text{-}4\cdot10^{-15}$</td></tr>
</table></td></tr>
</table>

From L. Cacciapuoti, FPS 06, Frascati, 20-22 March 2006

ACES Mission Objectives II

ACES Mission Objectives	ACES performances	Scientific background and recent results
Precise and accurate time and frequency transfer		
Absolute synchronization of ground clocks	Absolute synchronization of ground clock time scales with an uncertainty of 100 ps.	These performances will allow time and frequency transfer at an unprecedented level of stability and accuracy. The development of such links is mandatory for space experiments based on high accuracy frequency standards.
Contribution to atomic time scales	Comparison of primary frequency standards with accuracy at the 10^{-16} level.	
Fundamental physics tests		
Measurement of the gravitational red shift	The uncertainty on the gravitational red-shift measurement will be below $50 \cdot 10^{-6}$ for an integration time corresponding to one ISS pass (~ 300 s). With PHARAO full accuracy, uncertainty will reach the $2 \cdot 10^{-6}$ level.	The ACES measurement of the gravitational red shift will improve existing results (Gravity Probe A experiment and measurements based on the Mössbauer effect). Space-to-ground clock comparisons at the 10^{-16} level, will yield a factor 25 improvement on previous measurements.
Search for a drift of the fine structure constant	Time variations of the fine structure constant α ca be measured at the level of precision $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-16}$ year $^{-1}$. The measurement requires comparisons of ground clocks operating with different atoms	Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of fundamental constants improving existing results.
Search for Lorentz transformation violations and test of the SME	Measurements can reach a precision level of $\delta c / c \sim 10^{-10}$ in the search for anisotropies of the speed of light. These measurements rely on the time stability of SHM, PHARAO, MWL, and ground clocks over one ISS pass.	ACES results will improve previous measurements (GPS-based measurements, Gravity Probe A experiment, measurements based on the Mössbauer effect) by a factor 10 or more.

PARCS
Primary Atomic Reference Clock in Space



ESA-AO-2004

Life and Physical Sciences and Applied Research Projects

Life and Physical Sciences and Applied Research Projects

Coordinator: **S. Schiller, Universität Düsseldorf, Germany**

Team members: P. Lemonde (SYRTE Paris), C. Salomon (ENS Paris), U. Sterr (PTB Braunschweig), A. Görlitz (Universität Düsseldorf), G. Tino (Universita di Firenze)

Proposal Title: Space Optical Clocks

Abstract

Prepare a brief description of the application stating the broad, long-term objectives and specific aims of the proposed work. Describe concisely the research design and methods for achieving these objectives and aims. This abstract is meant to serve as a succinct and accurate description of the proposed work when separated from this application. Limit abstract to 300 words or fewer.

Optical atomic clocks based on ensembles of ultracold neutral atoms stored in periodic potentials generated by standing-wave light fields will lead to the next leap in accuracy and stability in clock technology. The expected improvement is by a factor of 100 compared to microwave cold atom clocks now in operation in several national metrology laboratories worldwide and under deployment for the ISS within the ACES project. Space represents the best environment for such ultrastable clocks because the well-defined location and the microgravity environment maximize accuracy and stability.

The goal of this project is to demonstrate operation and characterize the performance of an optical clock ensemble in a space environment, with an expected accuracy 10 times higher than ACES. Time transfer to earth will be demonstrated with 10^-17 accuracy. An adequate carrier is the ISS, but tests on the FOTON carrier are desirable.

The aim of the first funding period (three years) is to implement several optical clock laboratory demonstrator systems using Strontium and Ytterbium as atomic systems, to characterize and compare them, to test and validate different operational procedures and specifications required for operation in space. Subcomponents of the clock demonstrator with the added specification of transportability and using techniques that are suitable for later space use, such as all-solid-state lasers, low power consumption, and small volume, will be developed and validated.

At the end of the 3-year project, the specifications for a space clock will be finalized, enabling the start of Phase B.

The clock development will be based on the experience that the team members have acquired in the field of precision optical measurements and quantum optics, in particular on their successful laboratory microwave and optical clock developments based on cold atoms, which have resulted in the space clock PHARAO.

ESA Rating OUTSTANDING

See Poster

Clocks in Space

Optical clocks: ~$10^{-15}\cdot\tau^{-1/2}$ instability, ~10^{-18} accuracy **Resonator clocks:** ~10^{-17} instability floor level **T&F transfer link:** not degrading space clocks performances **SLR:** single-shot range <1cm	**Uncertainty level**	
	Present	**Improvement in space**
Local Lorentz Invariance		
Isotropy of the speed of light - PRA **71**, 050101 (2005)	$4\cdot10^{-10}$	~10^4
Constancy of the speed of light - PRL **90**, 060402 (2003)	$7\cdot10^{-7}$	>10^3
Time dilation experiments - PRL 91, 190403 (2003)	$2\cdot10^{-7}$	~10^3
Local Position Invariance		
Universality of the gravitational red-shift - PRD **65**, 081101 (2002)	$2\cdot10^{-5}$	>10^3
Time variations of fundamental constants - PRL **90**, 150801 (2003)	$7\cdot10^{-16}$	>10^2
Metric Theories of Gravity		
Gravitational red-shift - PRL **45**, 2081 (1980)	$7\cdot10^{-5}$	>10^3
Lense-Thirring effect – CQG **17**, 2369 (2000)	$3\cdot10^{-1}$	~ 10^2
Gravitoelectric perigee advance - CQG **21**, 2139 (2004)	$3\cdot10^{-3}$	>10
1/r-Newton's law at long distances- PLA **298**, 315 (2002)	10^{-11}	>10

ESA-AO-2004
Atom Interferometry Sensors for Space Applications
September 2005

Atom Interferometry Sensors for Space Applications

Proposal coordinator: ***Prof. Guglielmo M. Tino***
Dipartimento di Fisica/LENS
Università di Firenze, Italy

Participants

Academic Teams

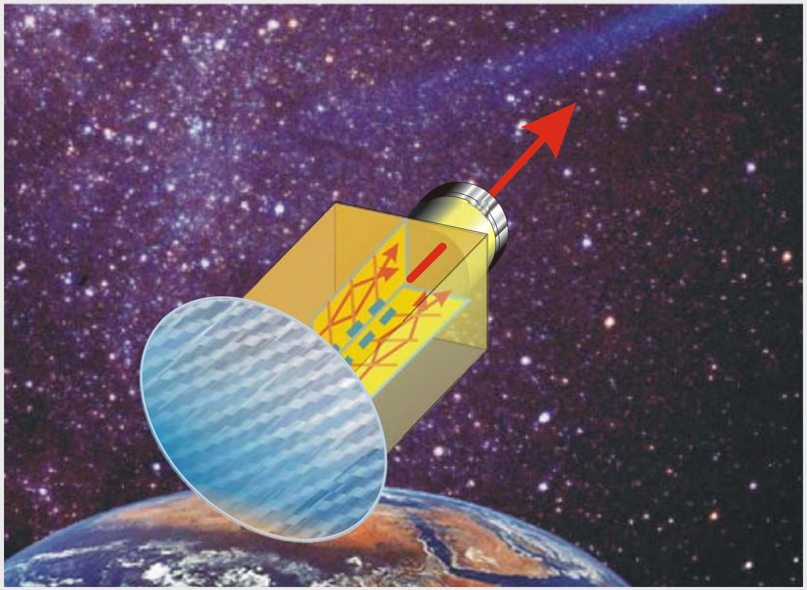
• Dipartimento di Fisica, Università di Firenze	I	(UNIFI)
• Institut d'Optique, Orsay (+ ONERA)	F	(IOTA)
• Institut für Quantenoptik, Universität Hannover	D	(IQO)
• Universität Hamburg	D	(UH)
• Institut für Physik, Humboldt-Universität zu Berlin	D	(HUB)
• SYRTE, Observatoire de Paris	F	(SYRTE)
• LENS, Firenze	I	(LENS)
• Universität Ulm	D	(ULM)
• ZARM, University of Bremen	D	(ZARM)

Industrial Partners

• Carlo Gavazzi Space	I
• EADS Astrium	D
• Galileo Avionica	I
• Techno System	I
• TOPTICA	D
• THALES	F
• IXSEA	F

ESA Rating
OUTSTANDING

HYPER

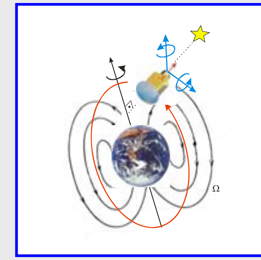


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

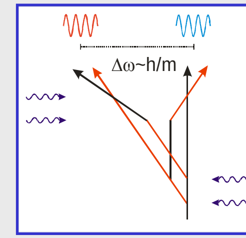
Resolution: 3×10^{-12} rad/s /√Hz

- Expected Overall Performance: 3×10^{-16} rad/s over one year of integration i.e. a S/N~100 at twice the orbital frequency

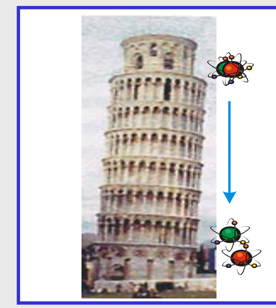
Mapping Lense-Thirring effect close to the Earth



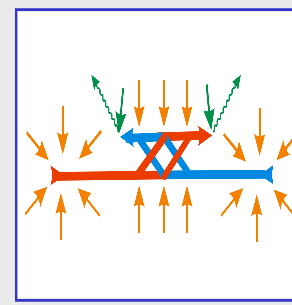
Improving knowledge of fine-structure constant



Testing EP with microscopic bodies



Atomic gyroscope control of a satellite



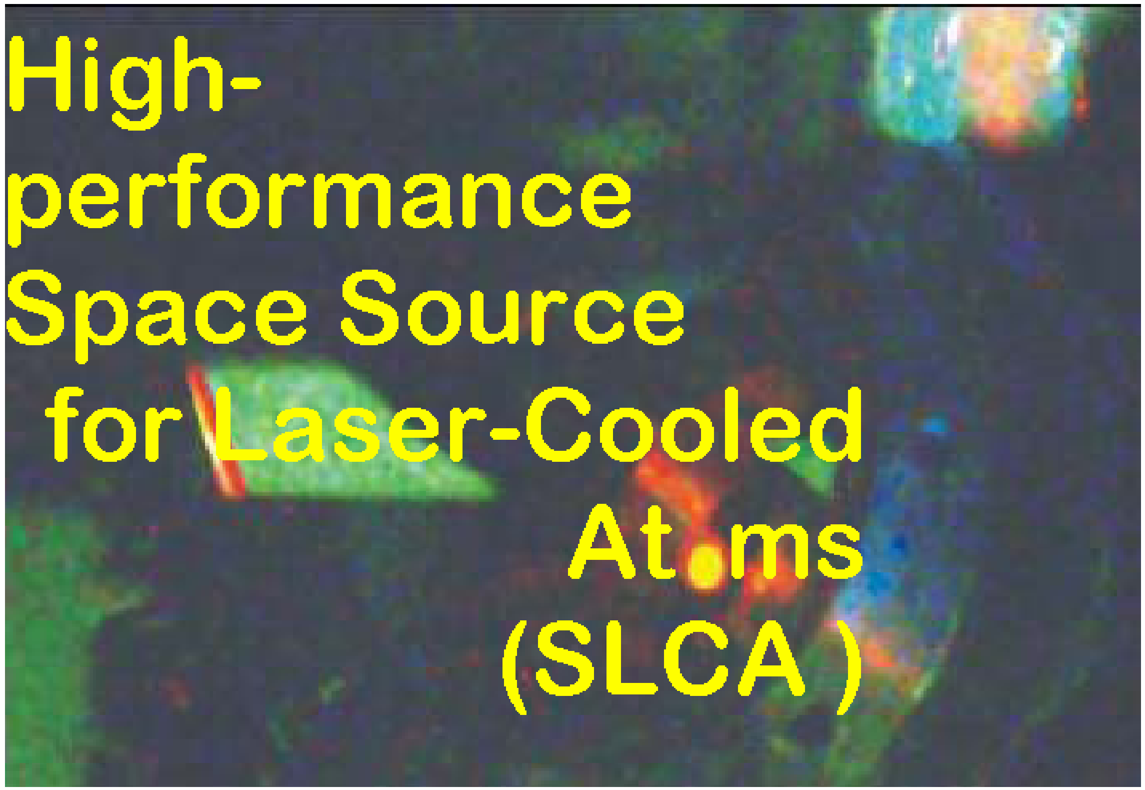
http://sci.esa.int/home/hyper/index.cfm

Laser Cooled Atom (LCA) Sensor

for Ultra-High-Accuracy Gravitational Acceleration

and Rotation Measurements

ESA Project 4477



Jet Propulsion Laboratory
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Quantum Sciences and Technology Group

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- QUANTUM OPTICS AND PHOTONICS
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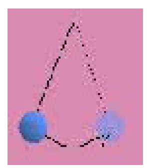
- PUBLICATIONS
- PEOPLE

Atom Interferometry

- **Gravity gradiometer**

Progresses in laser cooling and manipulation of atoms have made it possible to utilize atom interferometry for practical applications. At JPL, we are developing the atom interferometer technology and inertial sensing instruments for applications such as planetery gravity field mapping, underground structure detection, autonomous inertial navigation, and precision measurements of fundamental physics.

- **Atom interferometer for EEP**



The Quantum Interferometer Test of the Equivalence Principle (QuITE) is a proposed space mission concept that promises to test the Einstein Equivalence Principle at a new and interesting level. The experiment employs two co-located atom interferometers of different atomic species and measures the absolute single axis differential acceleration. JPL is part of the PI team as well as responsible for the technology development for the mission.

- **Atom interferometer on a chip**

This project aims to develop guided atomic interferometer technology, based on micro-wire structures fabricated on an insulated chip. Running currents through the micro-wires generates strong magnetic potentials near the chips surface. We can utilize particular wire geometries to produce strong 2-D and 3-D confinement for cold neutral atoms. We are investigating various designs that will yield atom-wave interferometry with Rubidium atoms. This technology can be used in sensor applications, including atomic gyroscopes.

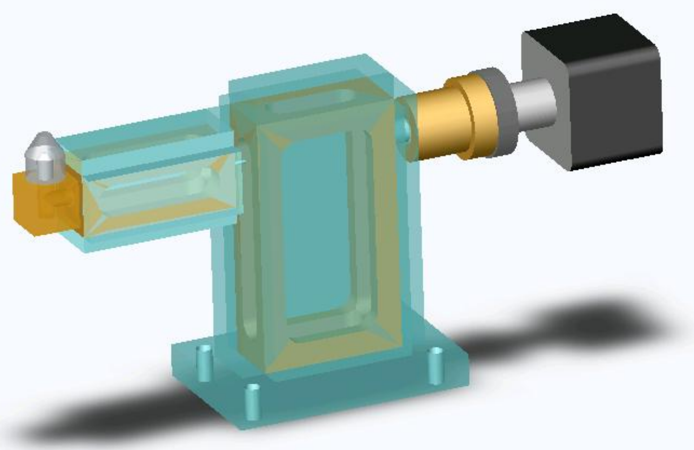
FIRSTGOV Your First Click to the U.S. Government

Webmaster: Phuong Reder

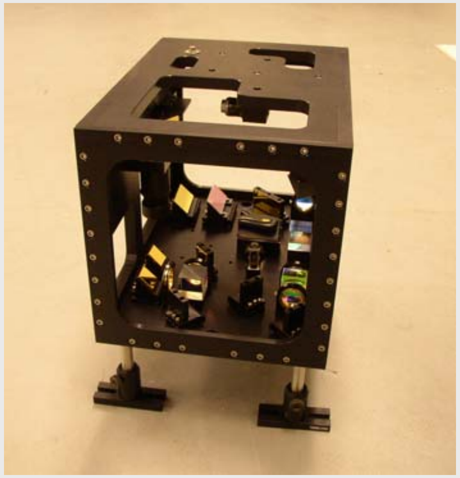
http://horology.jpl.nasa.gov/quantum/atominterferometry.html

Prototype field ready sensor

W.W. Hansen Experimental Physics Laboratory, Stanford, CA 94305



Sensor head



Sensor optomechanics

Laser system

From M. Kasevich talk at
SpacePart '03 Conference
Washington D.C., December 10th - 12th, 2003.

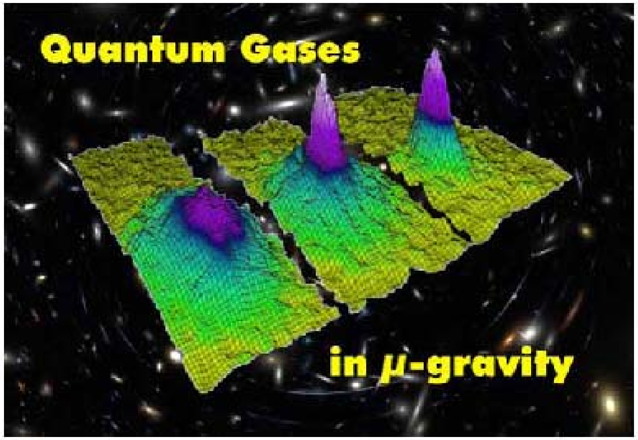
Quantum Gases / BEC in SPACE

-

A research proposal

on reply to the

AO - Life and Physical Sciences and Applied Research Projects 2004

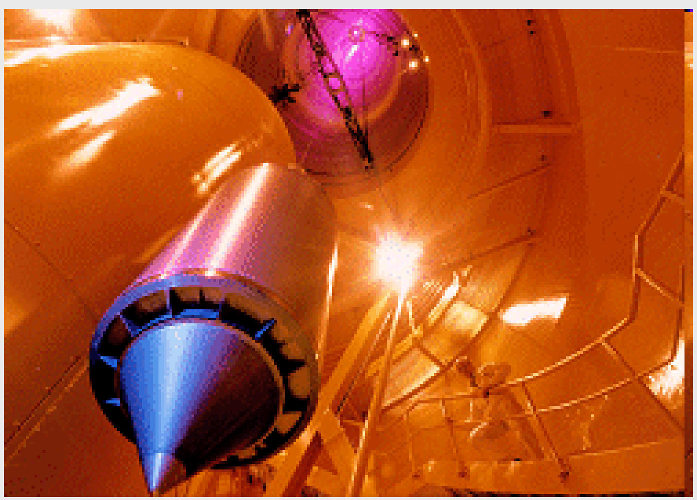


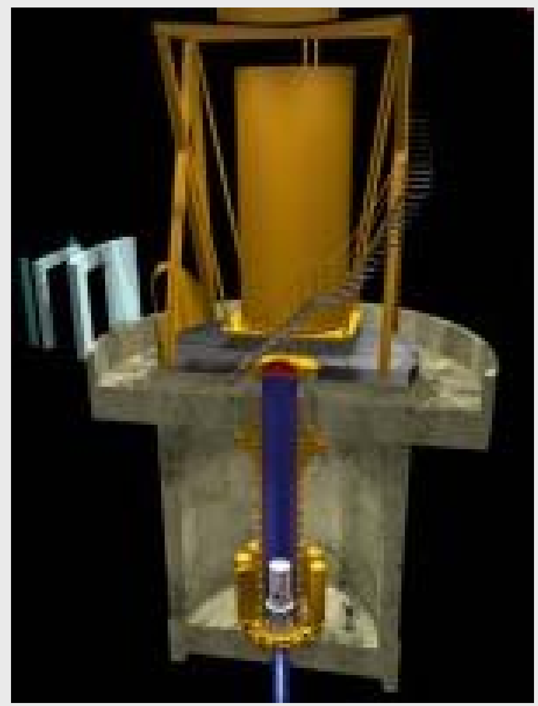
ESA Rating OUTSTANDING

Implementation (From E. Rasel, 2006)

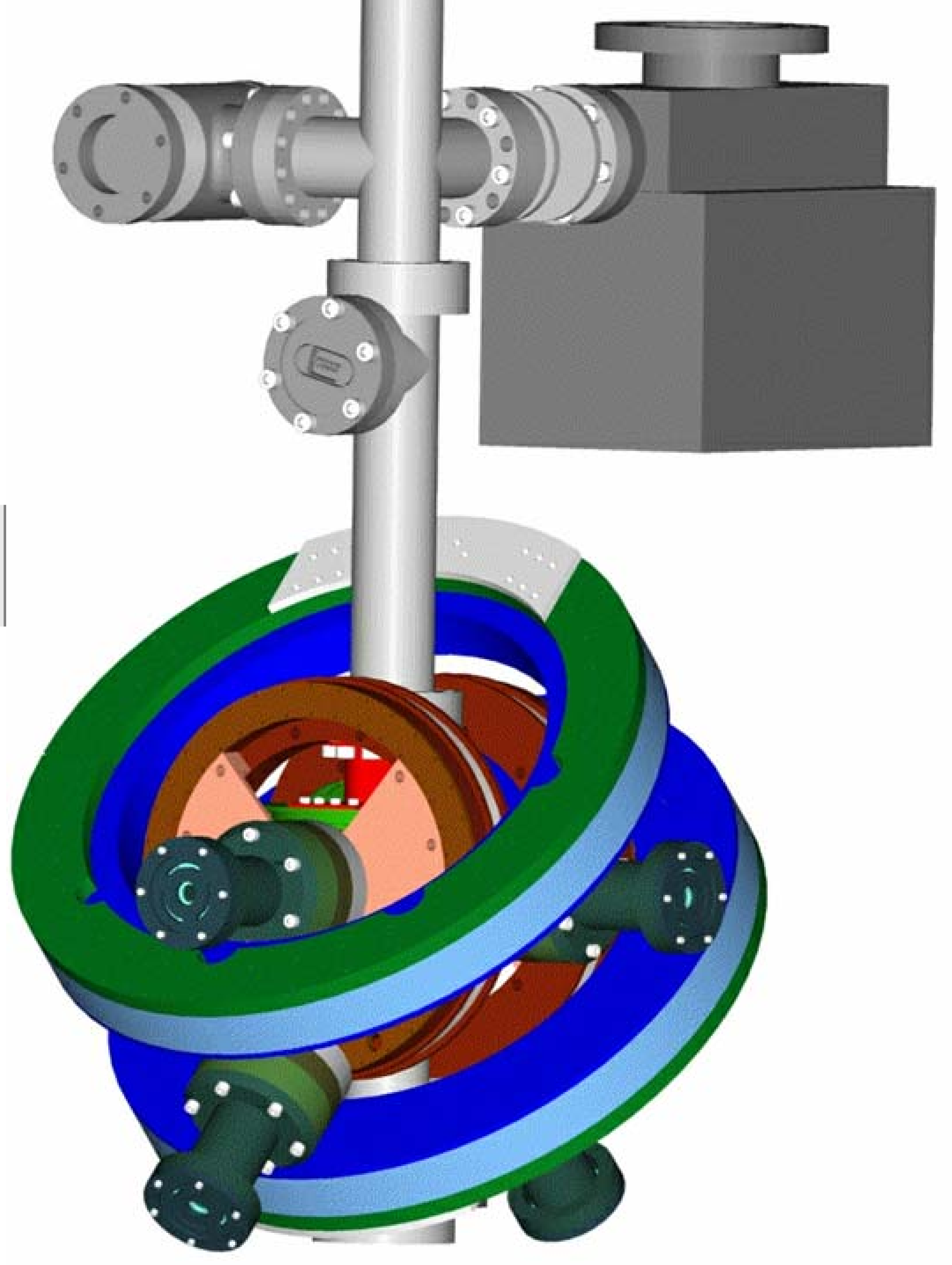
See Poster

- Free Fall: up to 9 sec
- Duration > 1 BEC-Experiment
- 3 flights per day
- Test of a robust BEC Facilities
  Dimensions < 0.7 ∅ x 1.5 m
- Height 110 m





Status after 24 months (From E. Rasel, 2006)



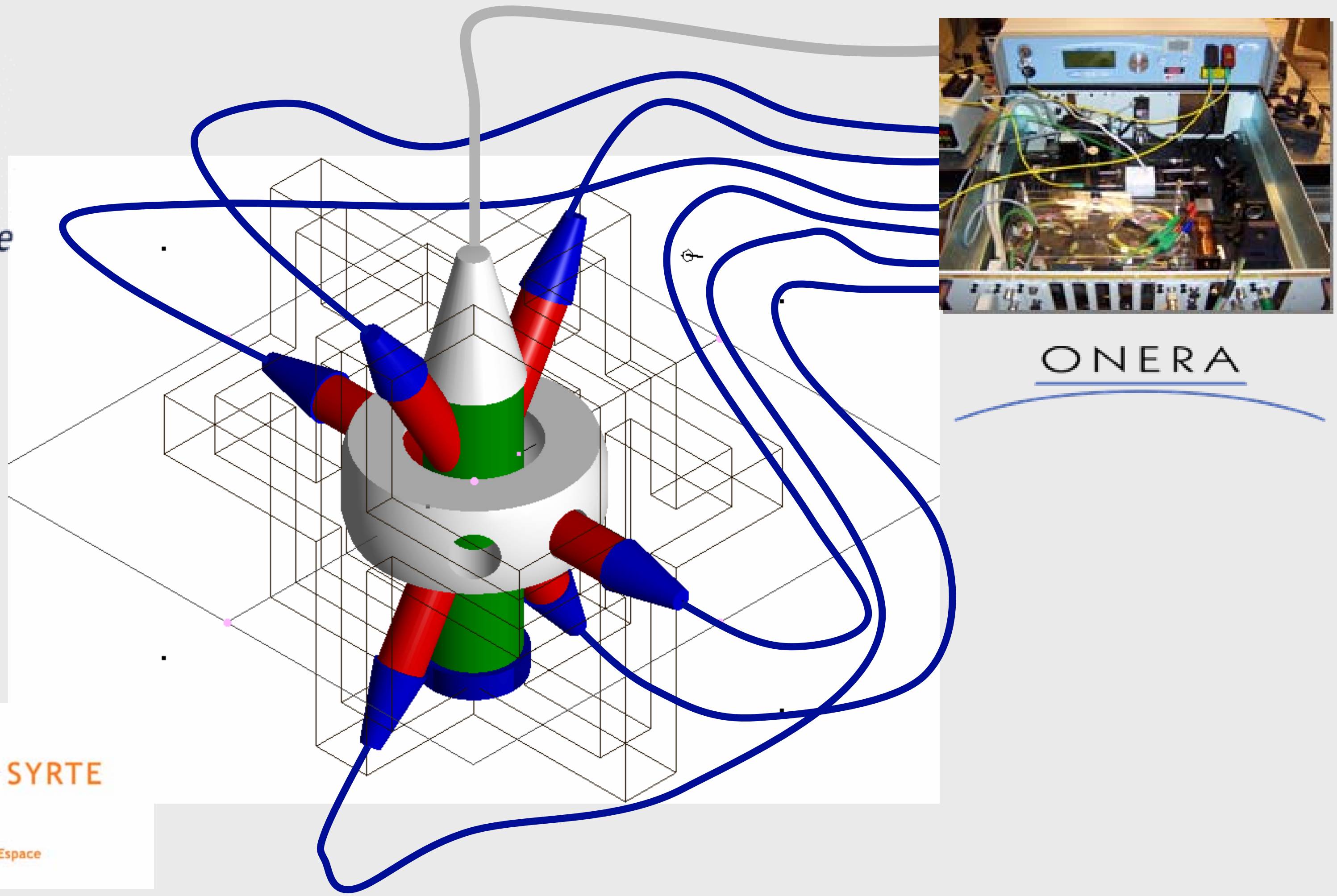
elding

ack

G.M

ICE : interferometry in 0-g

Institut d'Optique



ONERA

l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

Future Inertial Atomic Quantum Sensors

FINAQS

Date of preparation: 13.09.2004

A Specific Targeted Research Project (STREP)

FULL Proposal

for

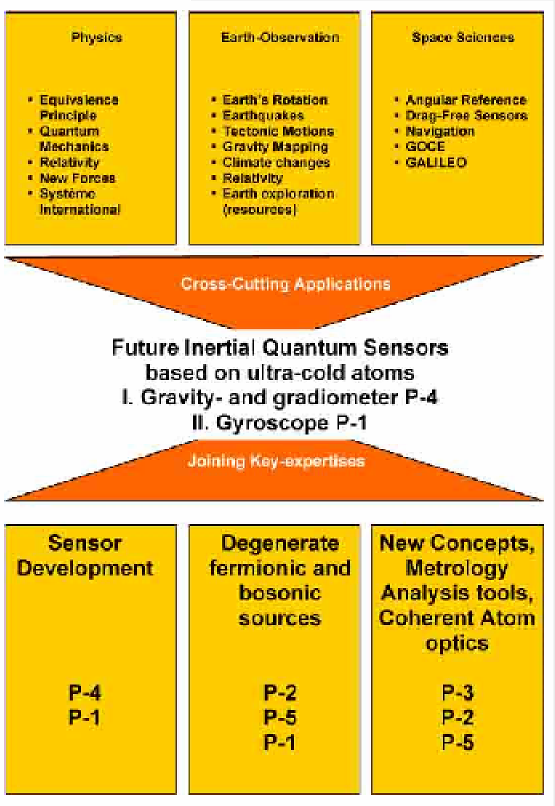
NEST-2003-1 ADVENTURE

Duration: 3 years

Co-ordinator: Prof. Dr. Wolfgang Ertmer
Contact: Email: ertmer@iqo.uni-hannover.de
Phone: +49 511 762-3242
Fax : +49 511 762-2211

Participants

Nr	Organisation name	Abbrev.	Town	
1	Institut für Quantenoptik, Universität Hannover	IQ	HANNOVER	D
2	Laboratoire Charles Fabry de l'Institut d'Optique	IOTA	ORSAY	F
3	Système de Références Temps – Espace, Observatoire de Paris	BNM/SYRTE	PARIS	F
4	AG Optische Metrologie / Institut für Physik Humboldt-Universität zu Berlin	HUB	BERLIN	D
5	Dipartimento di Fisica, Università di Firenze	UNIFI	FIRENZE	I



Applications of new quantum sensors based on atom interferometry

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

Future prospects: Atomic clocks

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

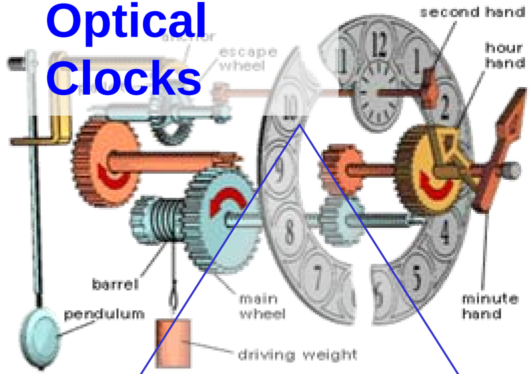
Conclusions

- New atomic quantum devices can be developped with unprecedented sensitivity using ultracold atoms and atom optics

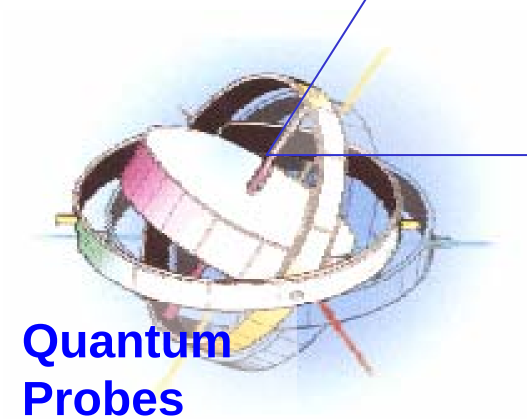
- Applications: Fundamental physics, Earth science, Space research, Commercial

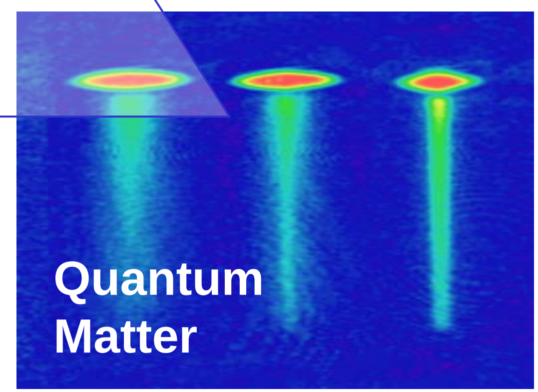
- Well developped laboratory prototypes

- Work in progress for transportable/space-compatible systems

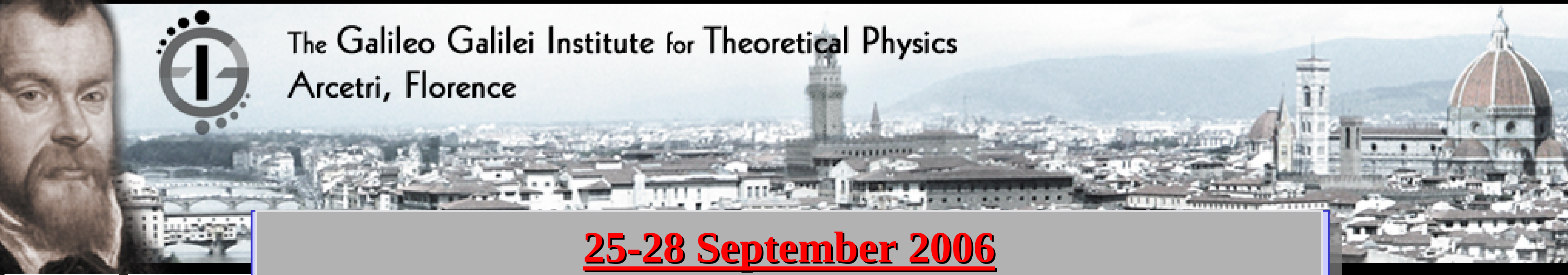


ENOUGH SPACE FOR EXCITING EXPERIMENTS





(From E. Rasel)



25-28 September 2006

SIGRAV School

EXPERIMENTAL GRAVITATION in SPACE

Directors: L. Iess, G. M. Tino

28-30 September 2006

International Workshop

ADVANCES IN PRECISION TESTS
and
EXPERIMENTAL GRAVITATION IN SPACE

Supported by ESA, GREX, SIGRAV

Organizers: L. Cacciapuoti, W. Ertmer, C. Salomon, G. M. Tino

http://www.fi.infn.it/GGI/