- Light Waves and Matter Waves -
Atom Interferometers and Optical Clocks

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International Centre for Theoretical Physics
Winter College on Optics:
Light: a bridge between Earth and Space
Trieste, 9 - 20 February 2015

Lecture II: Optical Atomic Clocks

- Introduction to atomic clocks
- Basics
- Methods
- Optical clocks
- Experiments on Earth and in space

Main references

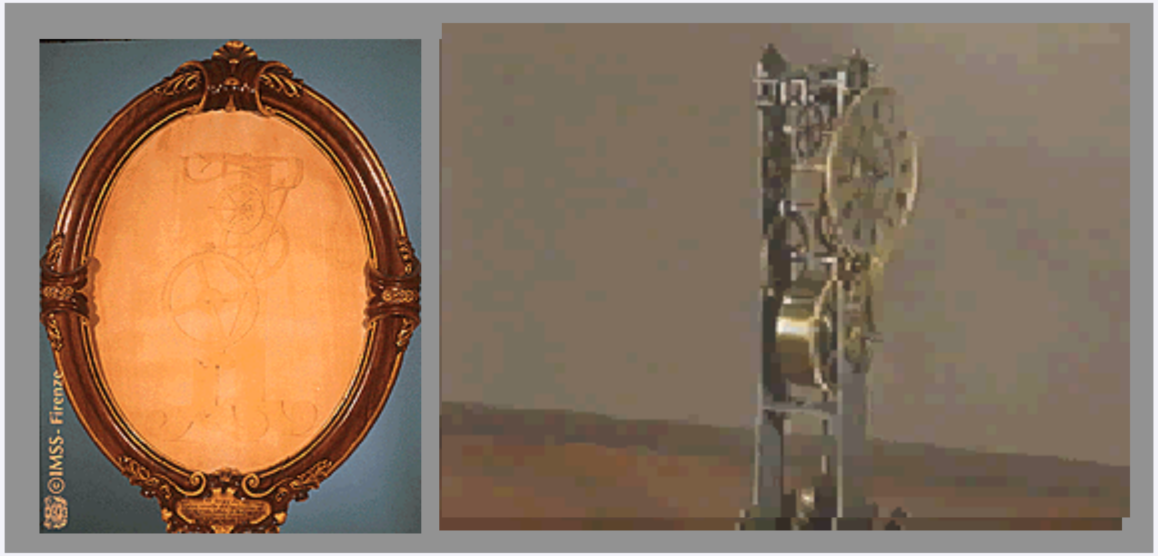
- J. L. Hall, *Nobel Lecture: Defining and measuring optical frequencies*, Rev. Mod. Phys. 78, 1279 (2006).

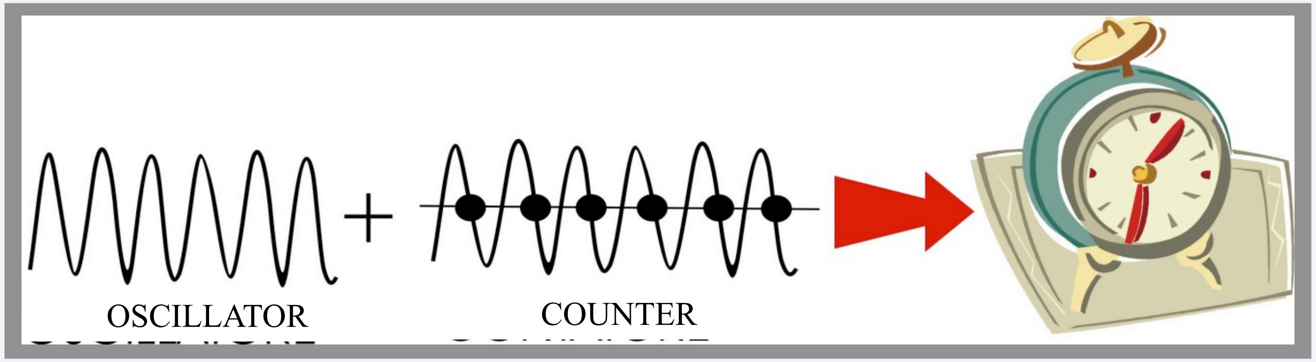
- T. W. Hänsch, *Nobel Lecture: Passion for precision,* Rev. Mod. Phys.78, 1297 (2006).

- D. J. Wineland, *Nobel Lecture: Superposition, entanglement, and raising Schrödinger's cat,* Rev. Mod. Phys., 85 1103 (2013).

- N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks*, Rivista del Nuovo Cimento 36, n. 12, 555 (2013).

The measurement of time

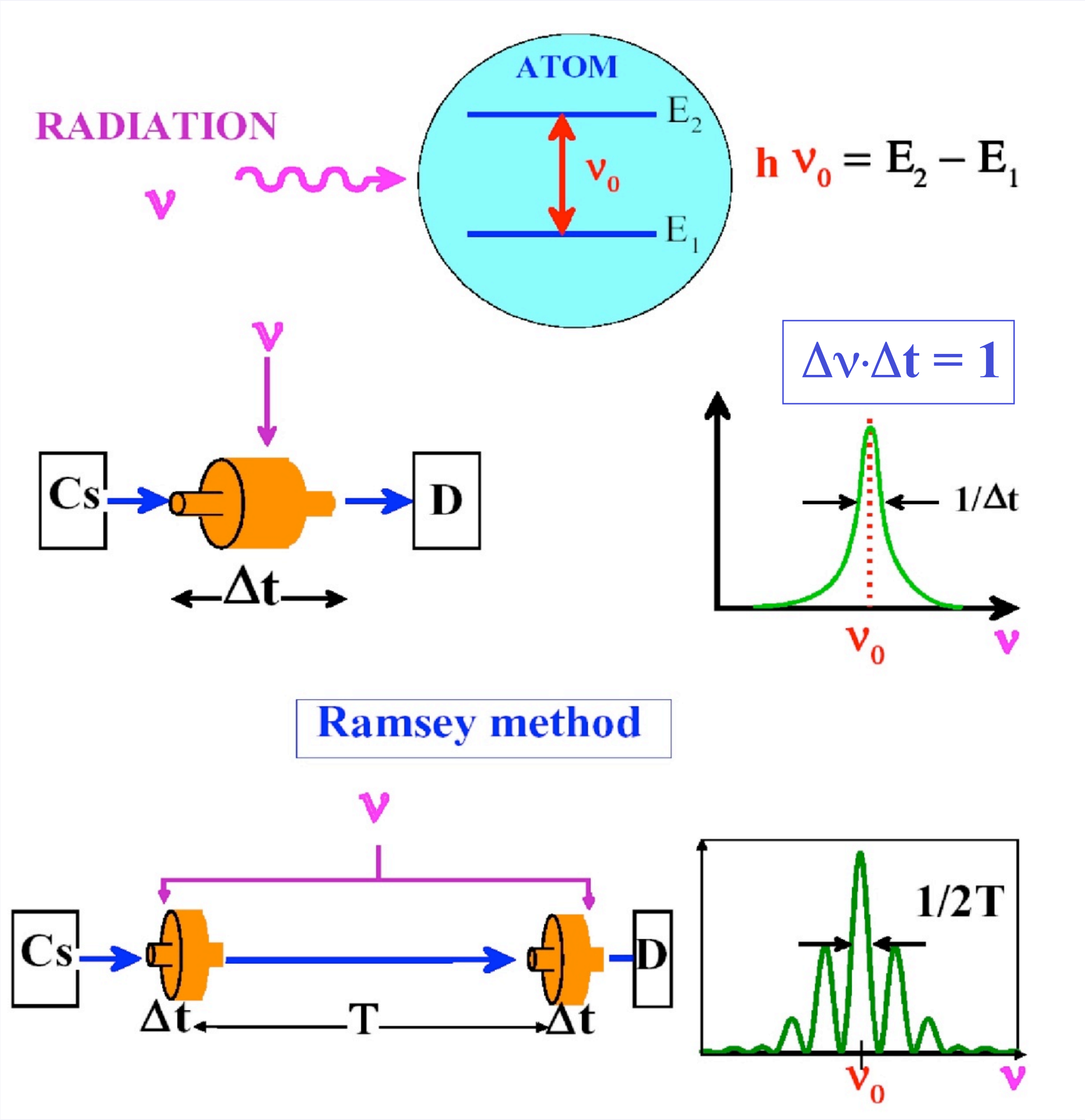




Accuracy → realization of the standard

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

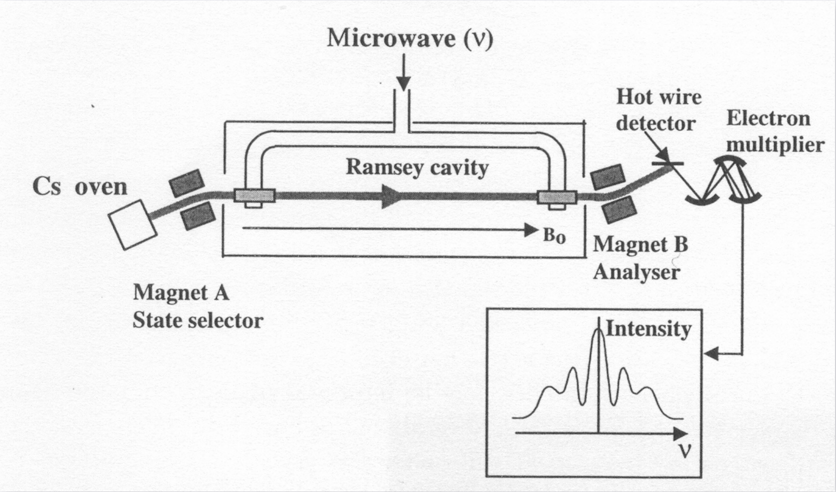
Atomic clocks



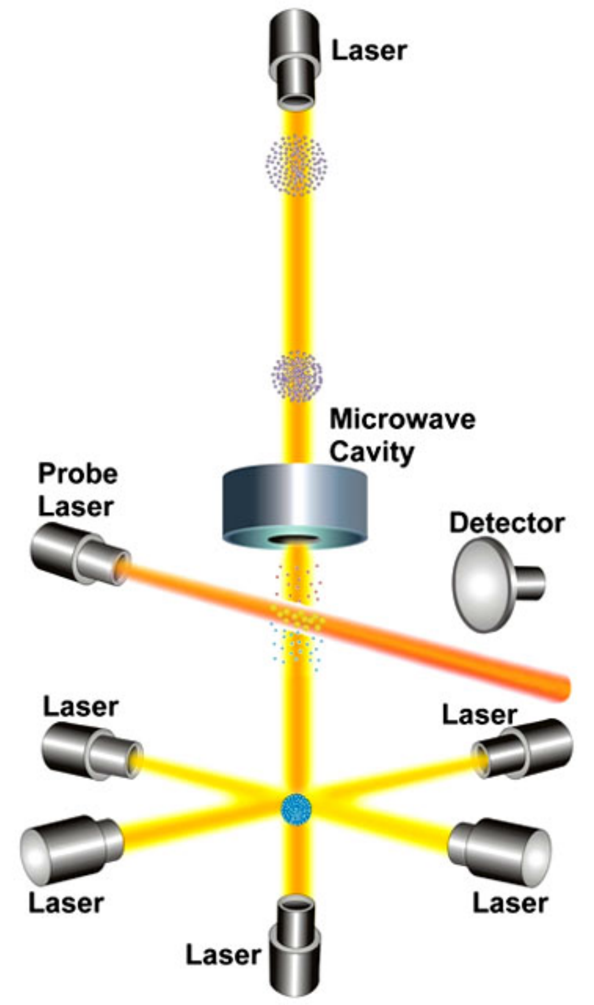
The definition of the second

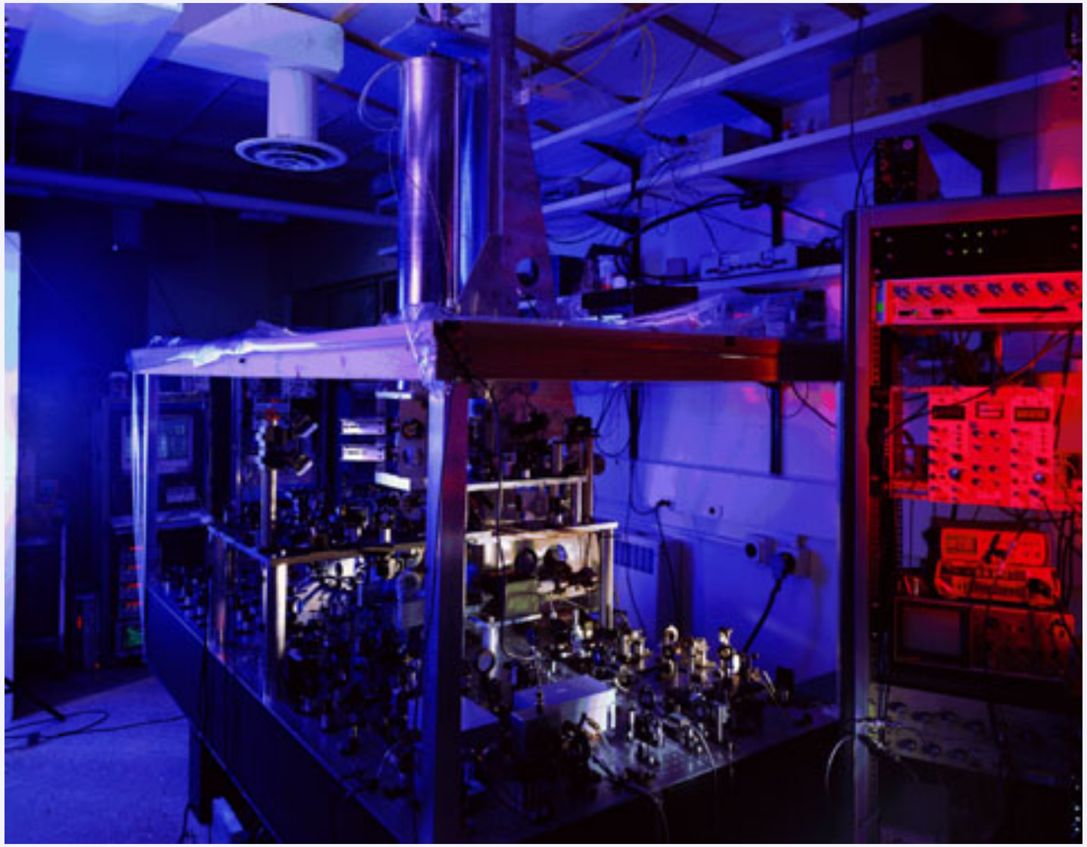
The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

(13th CGPM, 1967)



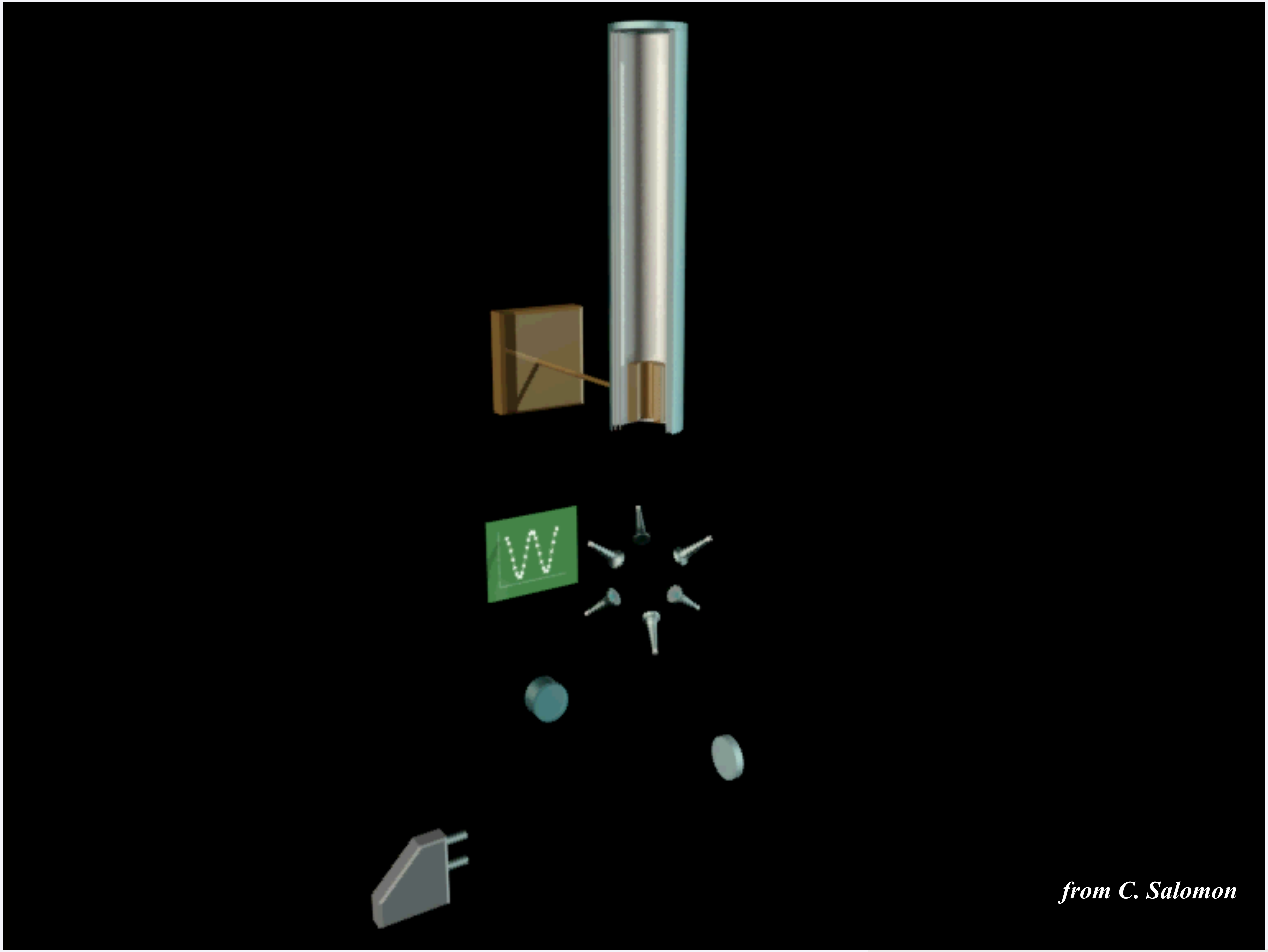
Atomic fountain clock





NIST-F1

Atomic fountain clock



from C. Salomon

Cronin, Schmiedmayer, and Pritchard: Optics and interferometry with atoms and molecules 1053

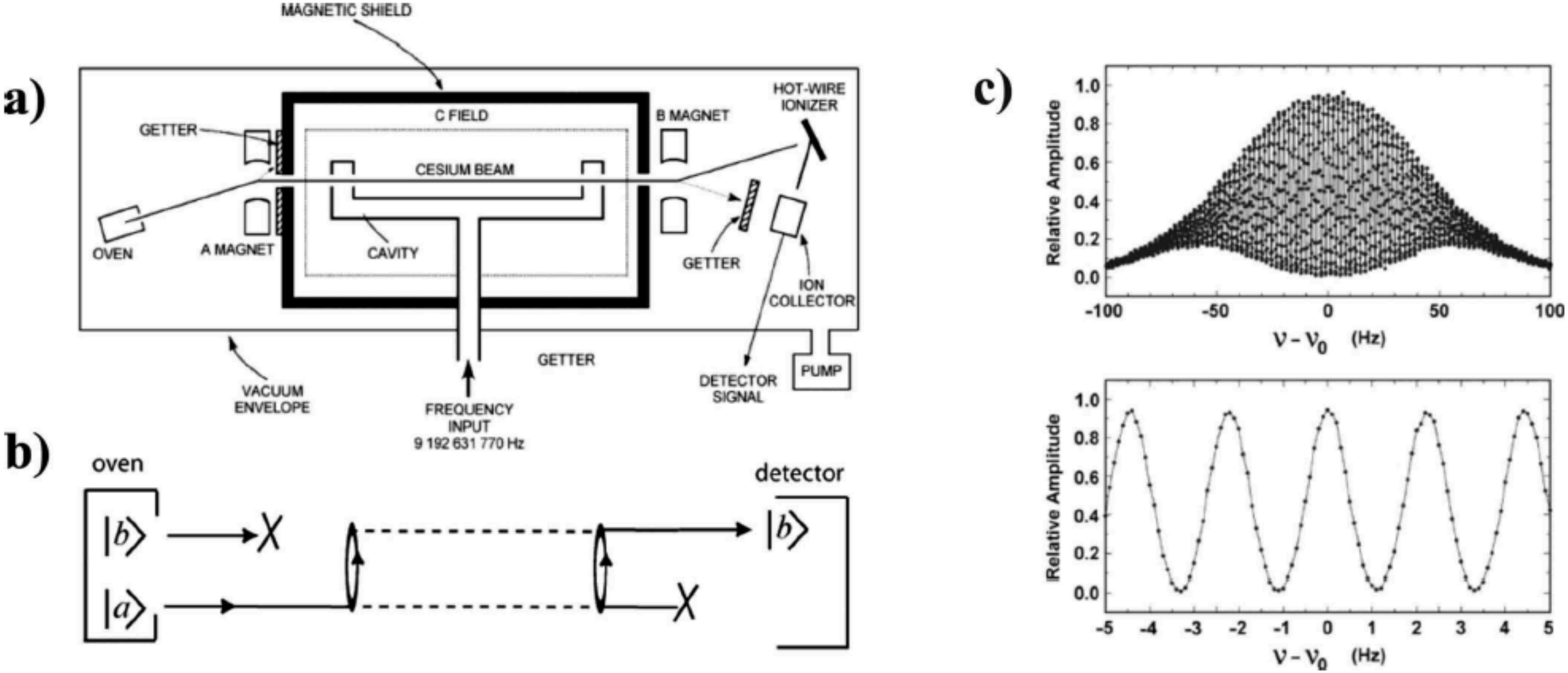
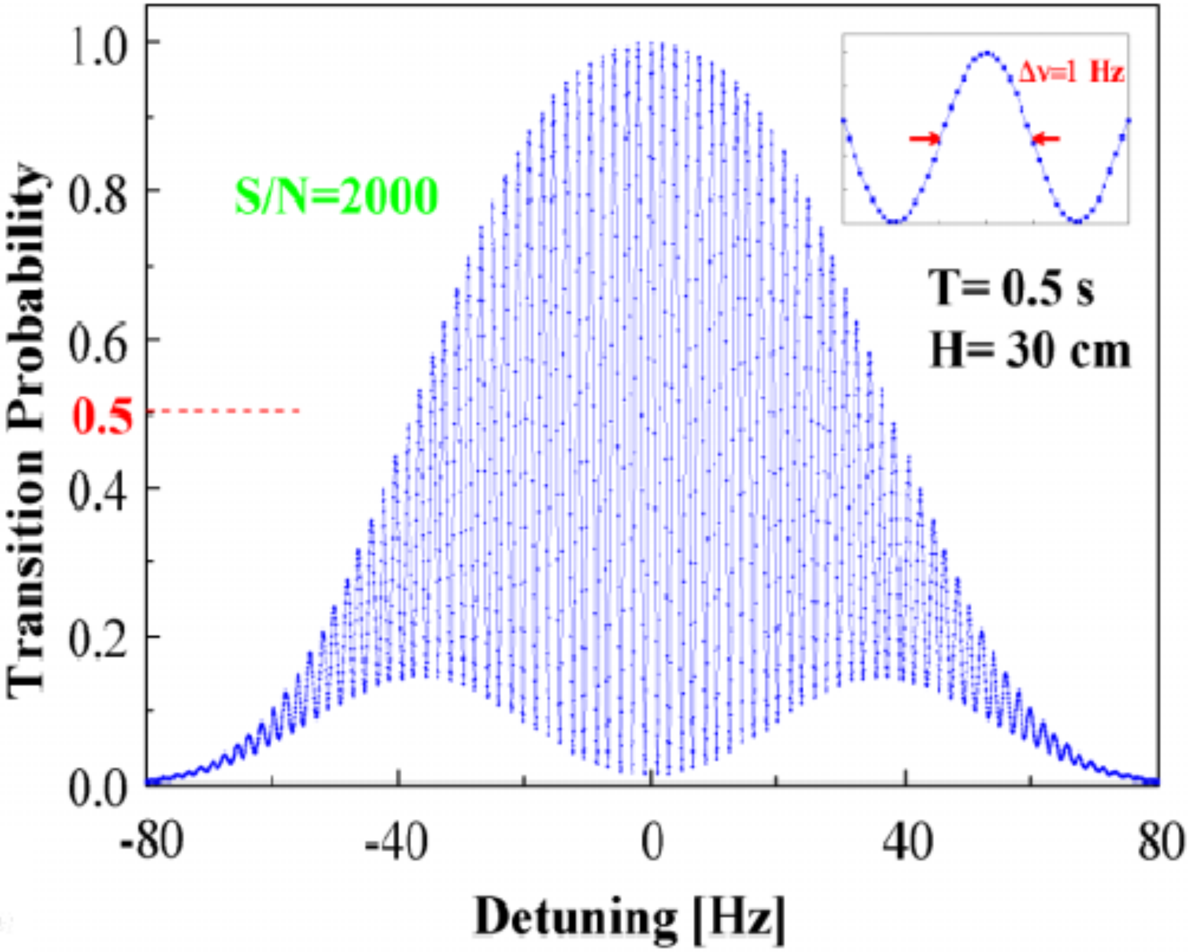


FIG. 1. Interferometry with internal quantum states of atoms. (a) Ramsey's separated oscillatory fields experiment. (b) The same experiment depicted as an interferometer for internal states. (c) The detected atom count rate exhibits interference fringes as a function of the applied rf frequency. These interference fringes, from the NIST-F1 fountain clock (Sullivan *et al.*, 2001), demonstrate the precision obtained with interference techniques. From Sullivan *et al.*, 2001.

Interference fringes



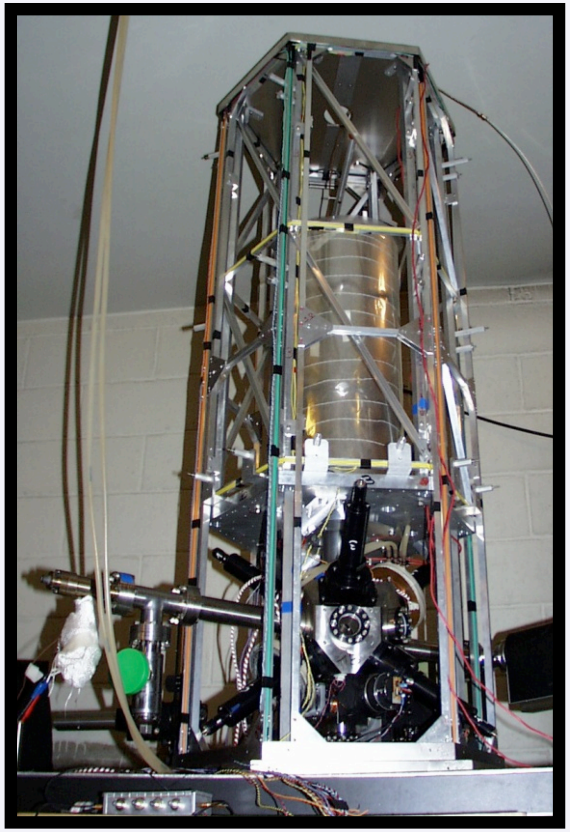
G. Santarelli et al., PRL 82, 4619 (1999)

Atomic Fountains

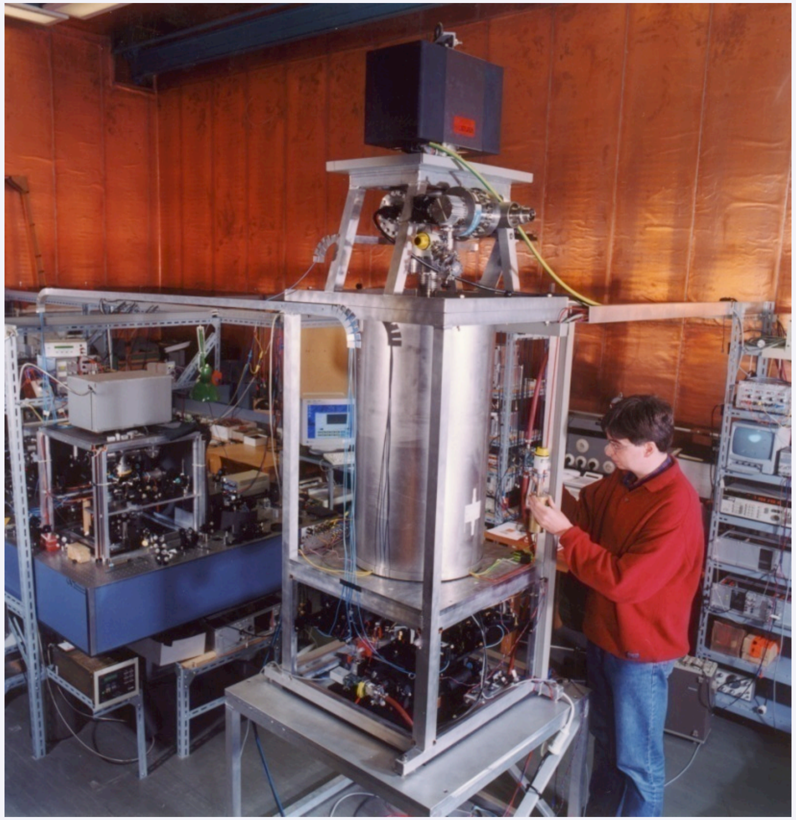
15 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, INRIM, NPL, METAS, JPL, NIM, NMIJ, NICT, Sao Carlos,….

~10 report to BIPM with accuracy of a few 1 10-16

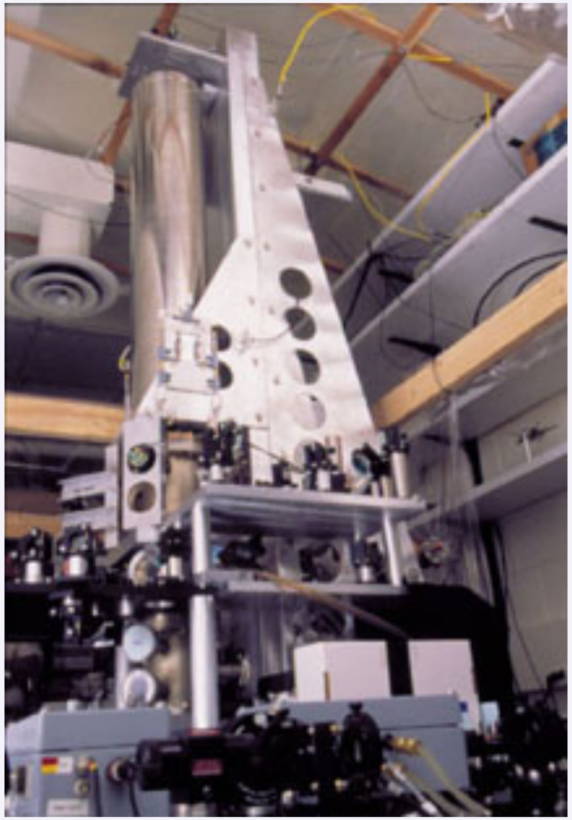
Realize the International Atomic Time, TAI



LNE-SYRTE, F



PTB, D



NIST, USA

from C. Salomon

Fountain Stability/Accuracy: State of the art

$\nu_{clock}(t) = \nu_{cesium}(1 + \varepsilon + y(t))$

Where ν_{cesium} is the transition frequency of a cesium atom at rest in absence of perturbation

ε : frequency shift, $\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \ldots.$

$y(t)$: frequency fluctuations with zero mean value.

Accuracy: ε

To what extent does the clock realizes the definition of the second?

Cesium and rubidium fountains: $\varepsilon \sim 6\ 10^{-16}$

Frequency stability

Measurement duration τ: $y(\tau)$

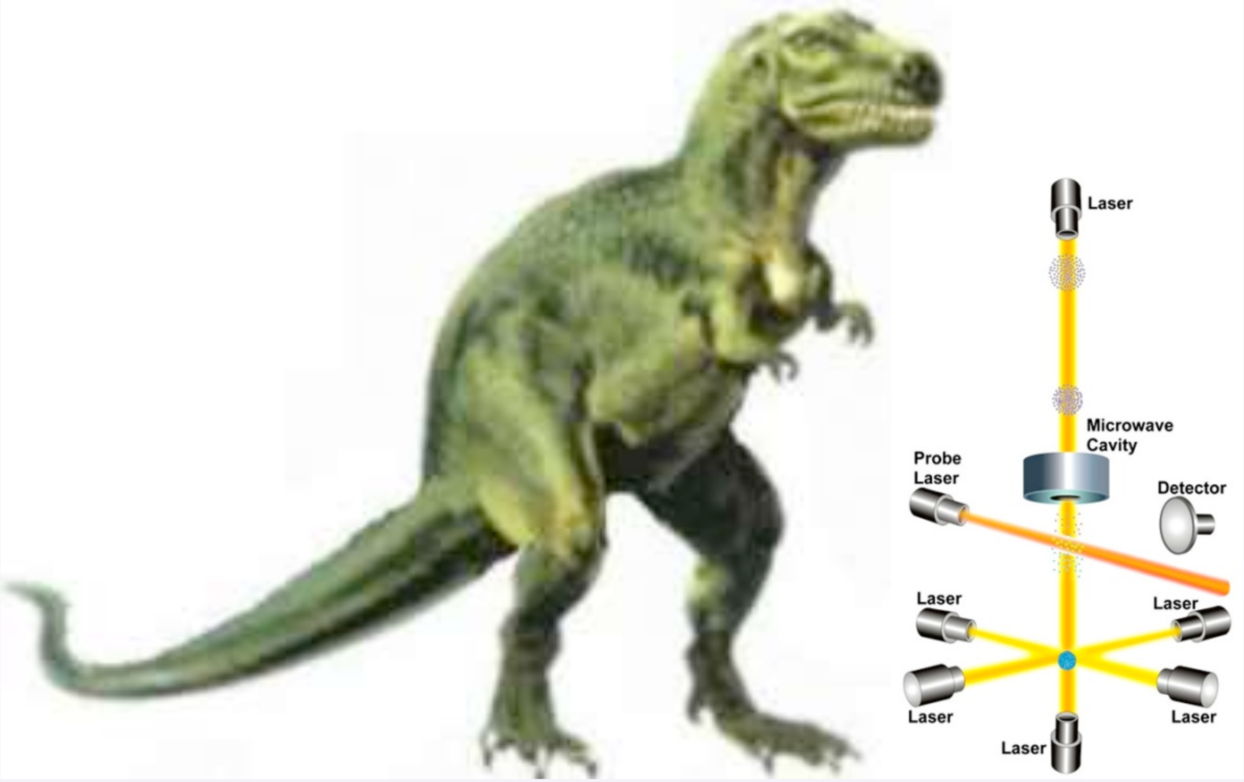
For $\tau = 1s$, $y(\tau) = 1.4\ 10^{-14}$ fundamental quantum limit

For $\tau = 50\,000$ s, $y(\tau) \sim 1.4 \times 10^{-16}$

from C. Salomon

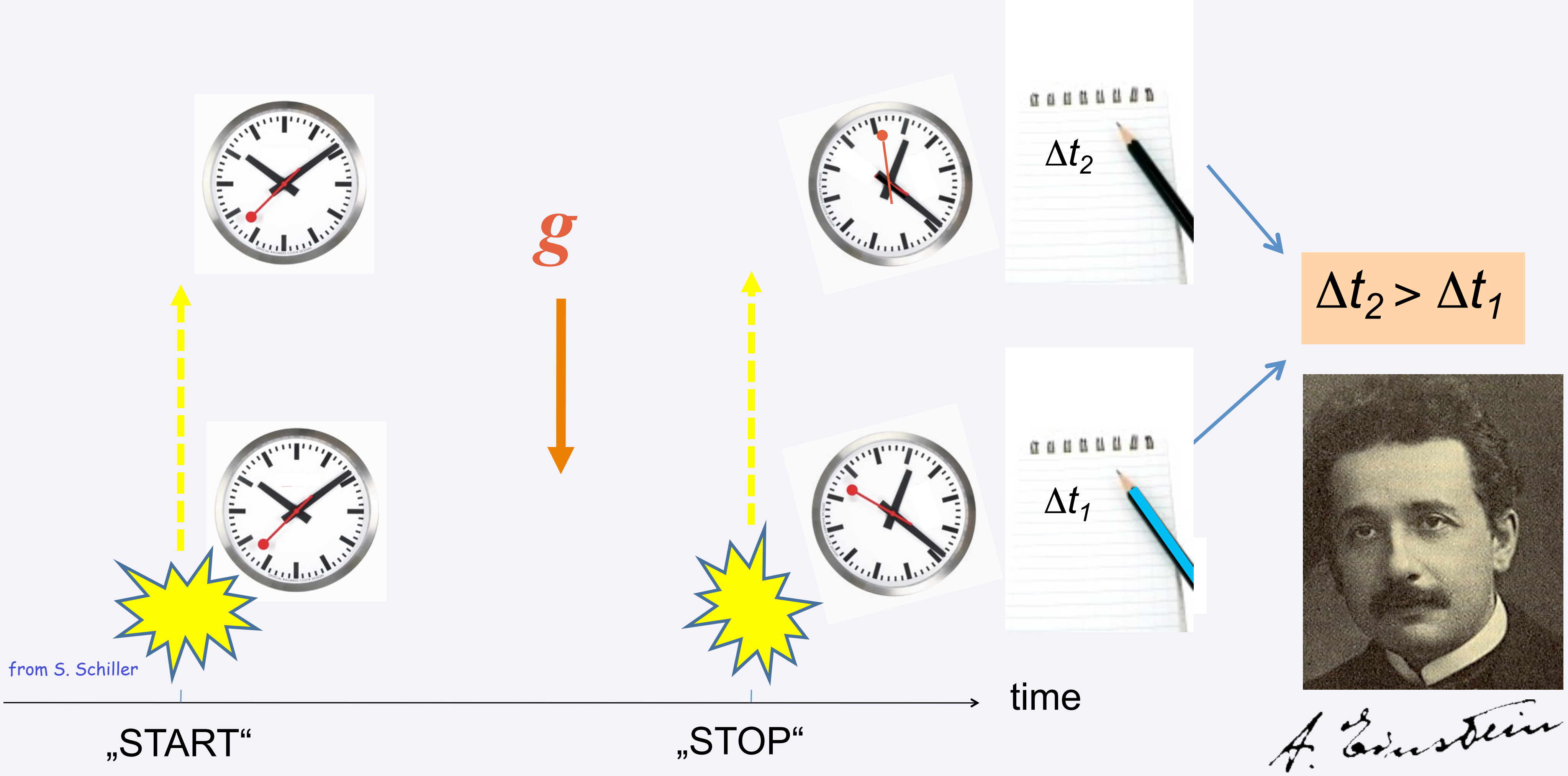
Dinosaurs and atomic clocks

$\sigma \approx 5 \times 10^{-16} \rightarrow$ 1 s every 2×10^{15} s (two million billion seconds)



60 millions years $\equiv 60 \times 10^{6}$ years x 365 d/y x 24 h/d x 3600 s/h $\approx 2 \times 10^{15}$ s

Gravitational time dilation

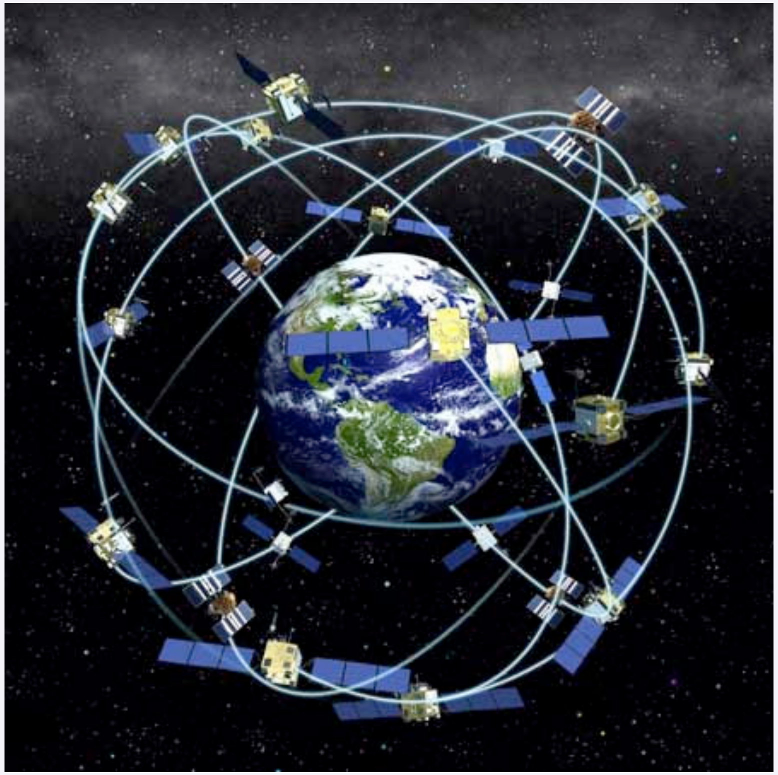


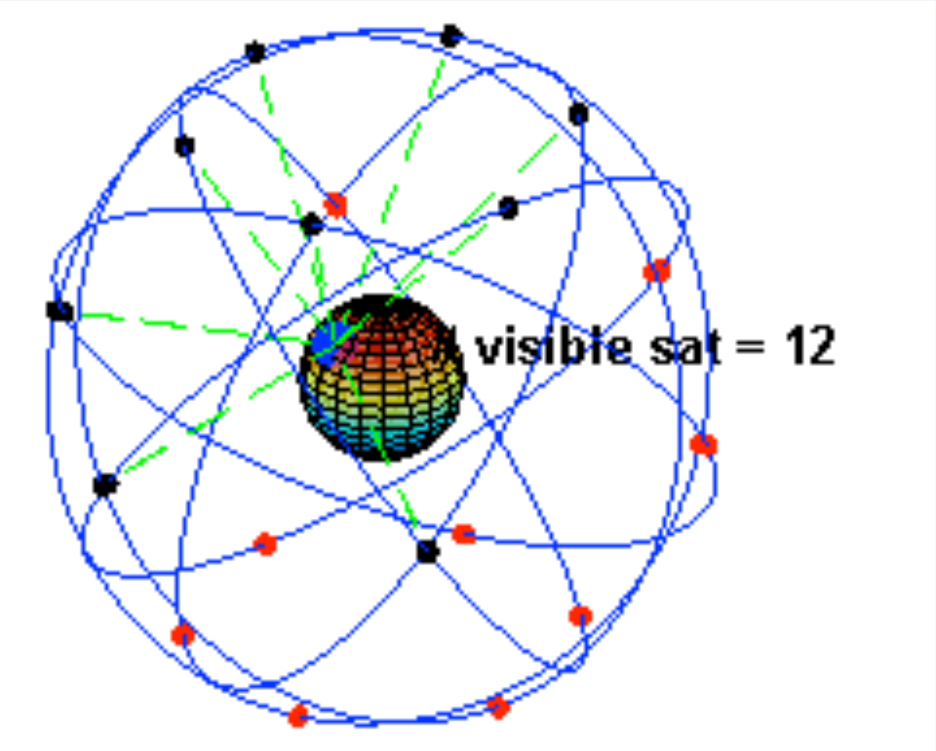
$$\frac{\nu - \nu_0}{\nu_0} = -\frac{GM}{c^2 r}$$

At a distance h from the surface of the Earth →

$$\frac{\nu_h - \nu_T}{\nu_T} = \frac{gh}{c^2} \cong 10^{-16} / m$$

Global Positioning System - GPS





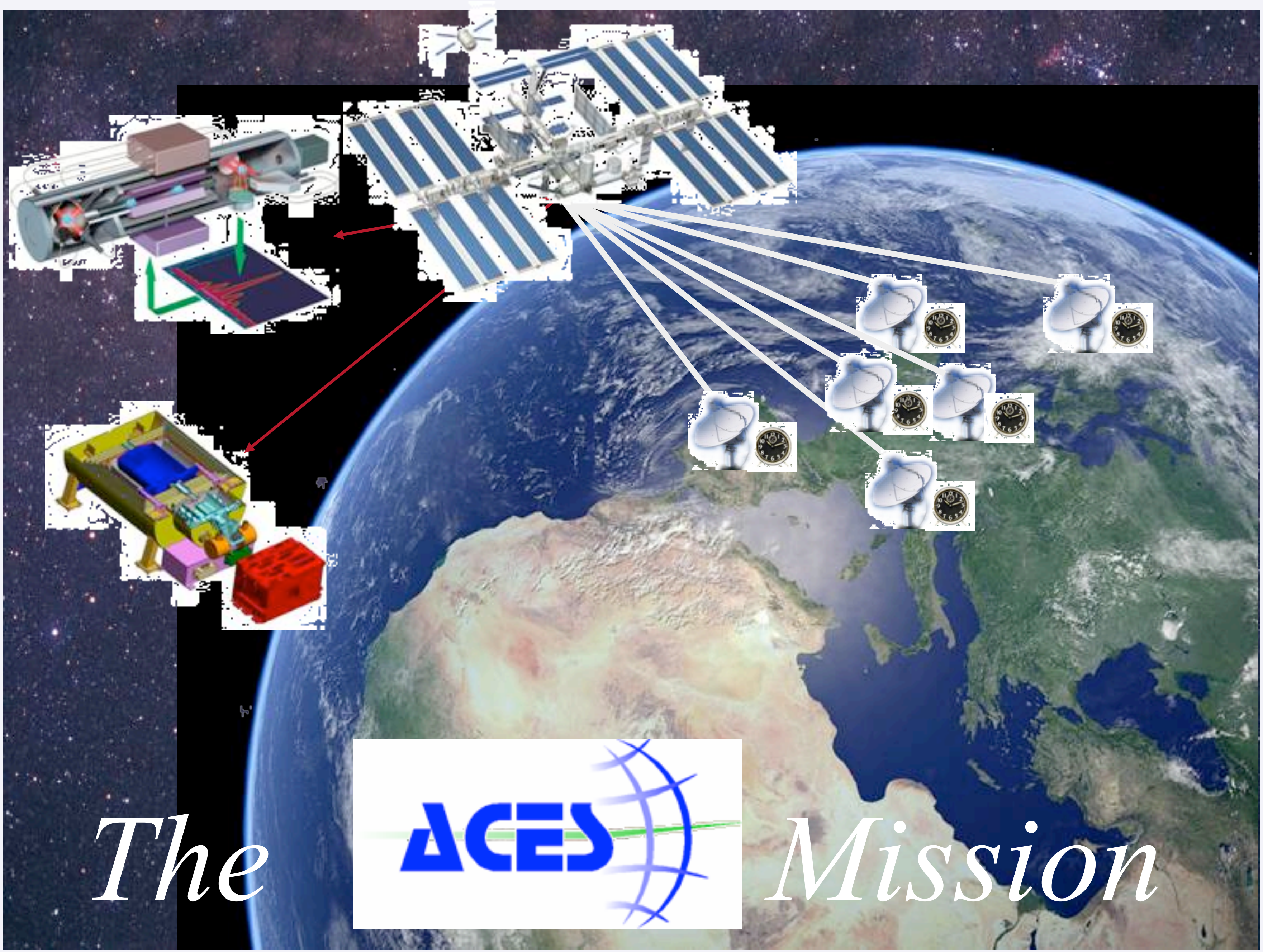
The current GPS configuration consists of a network of 24 satellites in high orbits around the Earth. Each satellite in the GPS constellation orbits at an altitude of about 20,000 km from the ground, and has an orbital speed of about 14,000 km/hour (the orbital period is roughly 12 hours). Each satellite carries with it an atomic clock.

Because an observer on the ground sees the satellites in motion relative to them, Special Relativity predicts that we should see their clocks ticking more slowly. Special Relativity predicts that the on-board atomic clocks on the satellites should fall behind clocks on the ground by about 7 microseconds per day because of the slower ticking rate due to the time dilation effect of their relative motion.

The satellites are in orbits high above the Earth, where the curvature of spacetime due to the Earth's mass is less than it is at the Earth's surface. As such, when viewed from the surface of the Earth, the clocks on the satellites appear to be ticking faster than identical clocks on the ground. A calculation using General Relativity predicts that the clocks in each GPS satellite should get ahead of ground-based clocks by 45 microseconds per day.

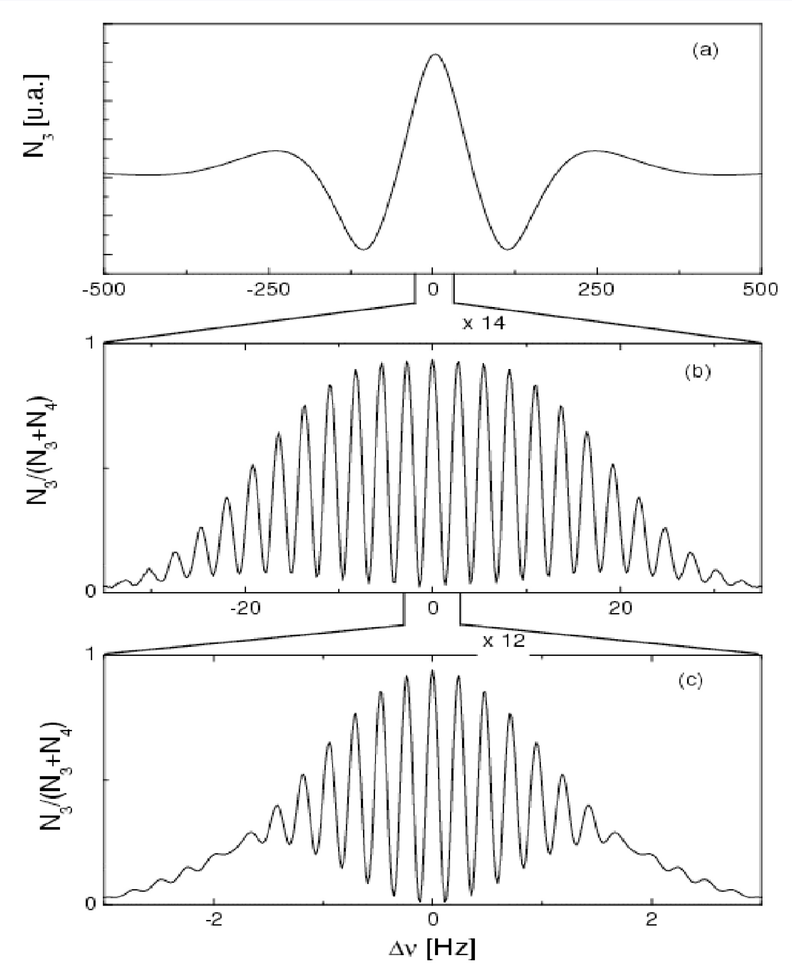
The combination of these two relativitic effects means that the clocks on-board each satellite should tick faster than identical clocks on the ground by about 38 microseconds per day

➡ **If these effects were not properly taken into account, errors in global positions would continue to accumulate at a rate of about 10 km/day.**



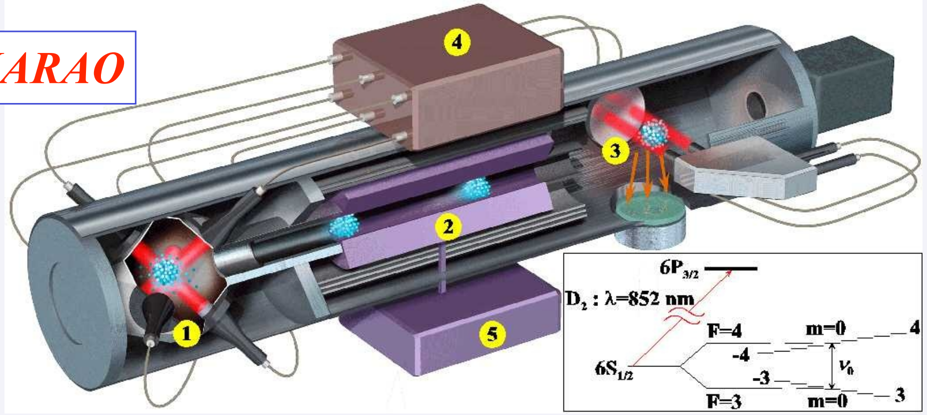
The ACES Mission

Cold Atoms Clocks in Space

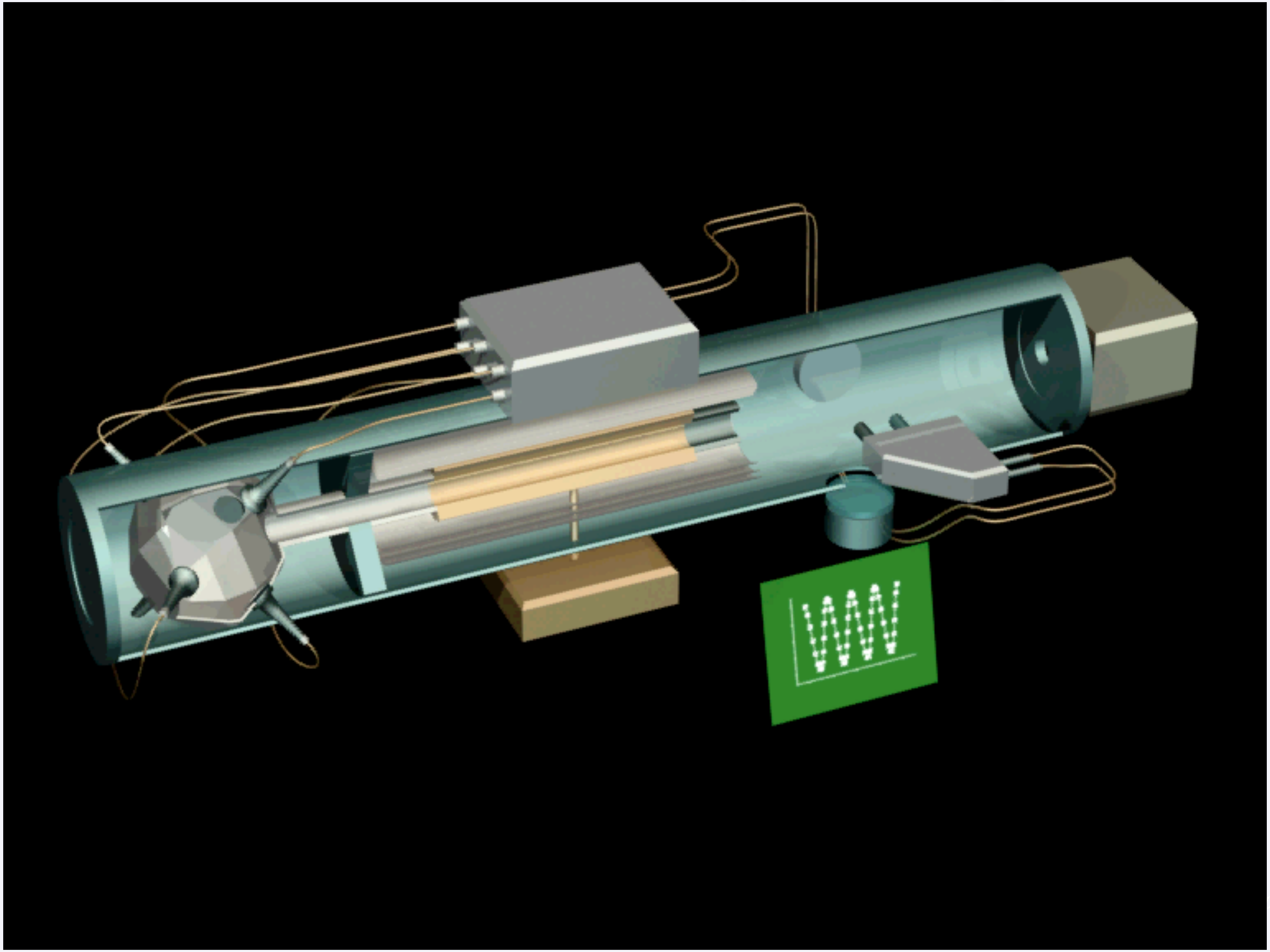


- Interrogate fast (hot) atoms over long distances → T = 10 ms
- Use laser cooled atoms, limitation due to the presence of gravity → T = 1 s
- Use laser cooled atoms in microgravity → T = 10 s

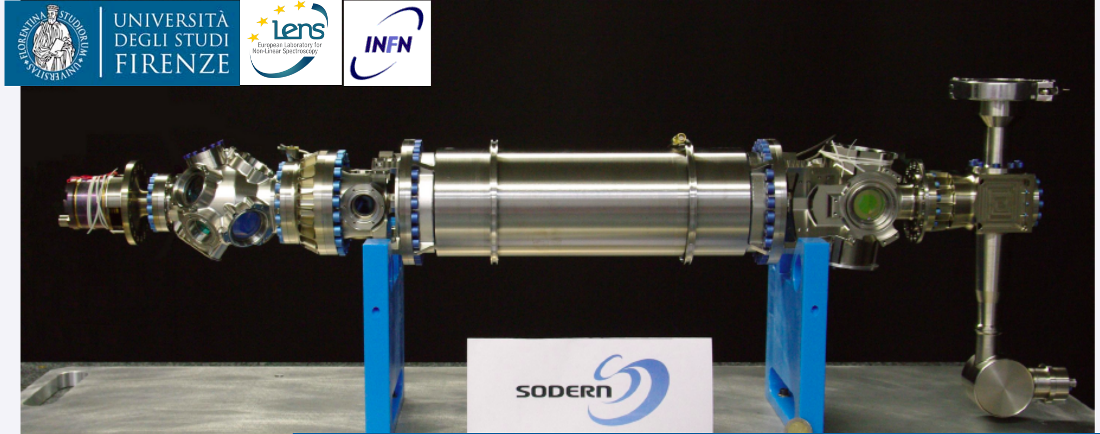
PHARAO

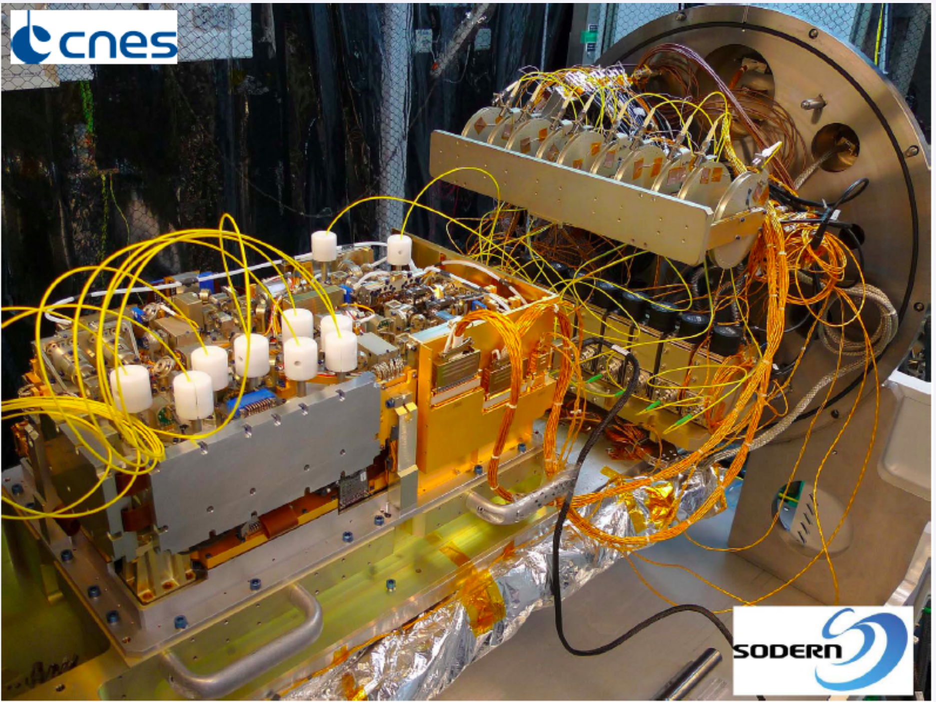


PHARAO: the cold atom clock for ACES space mission

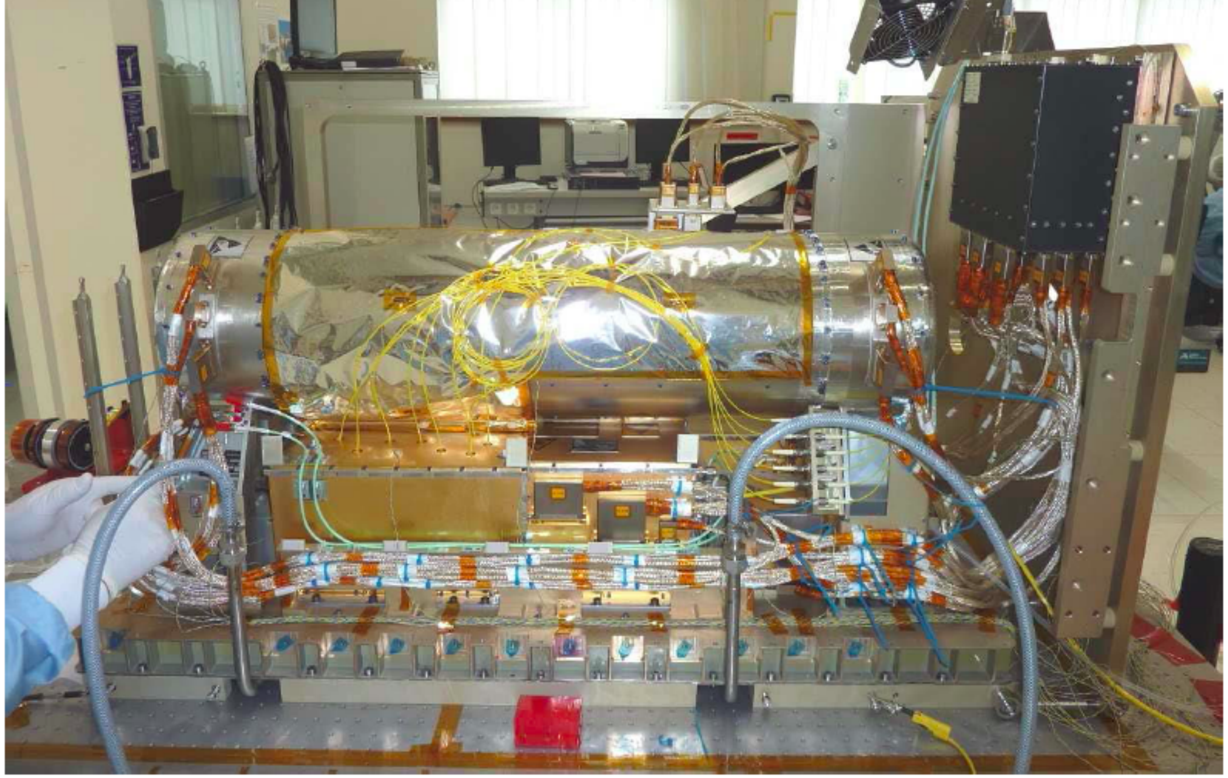


from C. Salomon





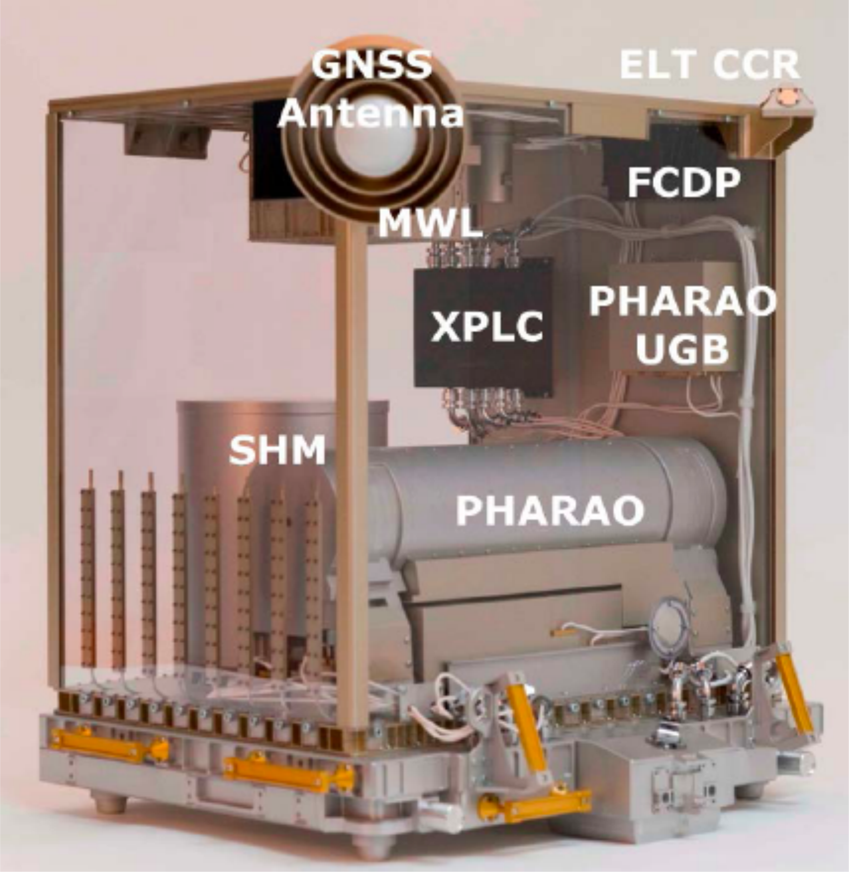
PHARAO FM Integration



from L. Cacciapuoti

The ACES Payload

- PHARAO (CNES): Atomic clock based on laser cooled Cs atoms
- SHM (ESA): Active hydrogen maser
- FCDP (ESA): Clocks comparison and distribution
- MWL (ESA): T&F transfer link
- GNSS receiver (ESA)
- ELT (ESA): Optical link
- Support subsystems (ESA)
  - XPLC: External PL computer
  - PDU: Power distribution unit,
  - Mechanical, thermal subsystems
  - CEPA: Columbus External PL Adapter (ESA-NASA)

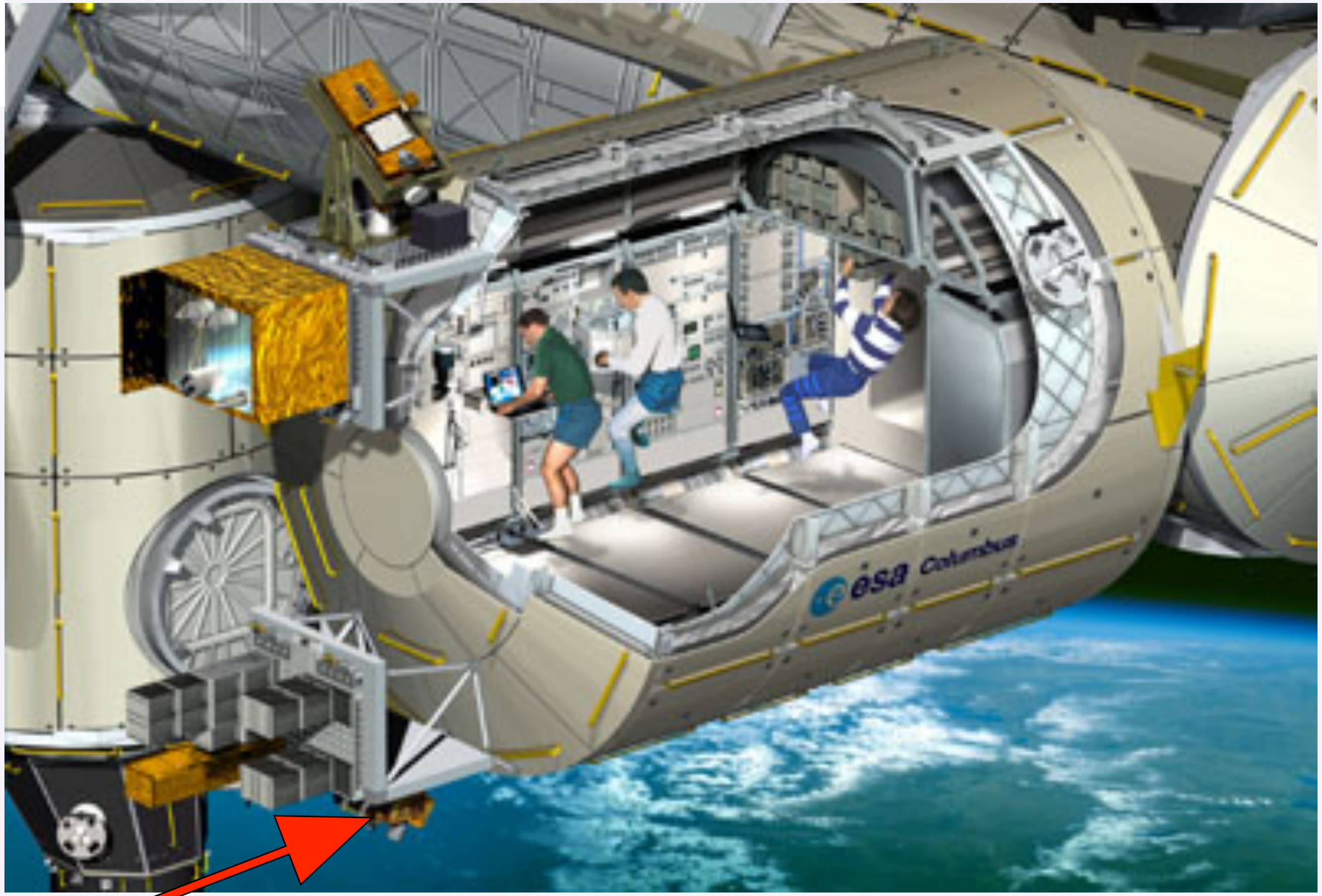


Volume: 1172x867x1246 mm^3
Mass: 227 kg
Power: 450 W

AIRBUS DEFENCE & SPACE

from L. Cacciapuoti

ACES ON COLUMBUS EXTERNAL PLATFORM



ACES

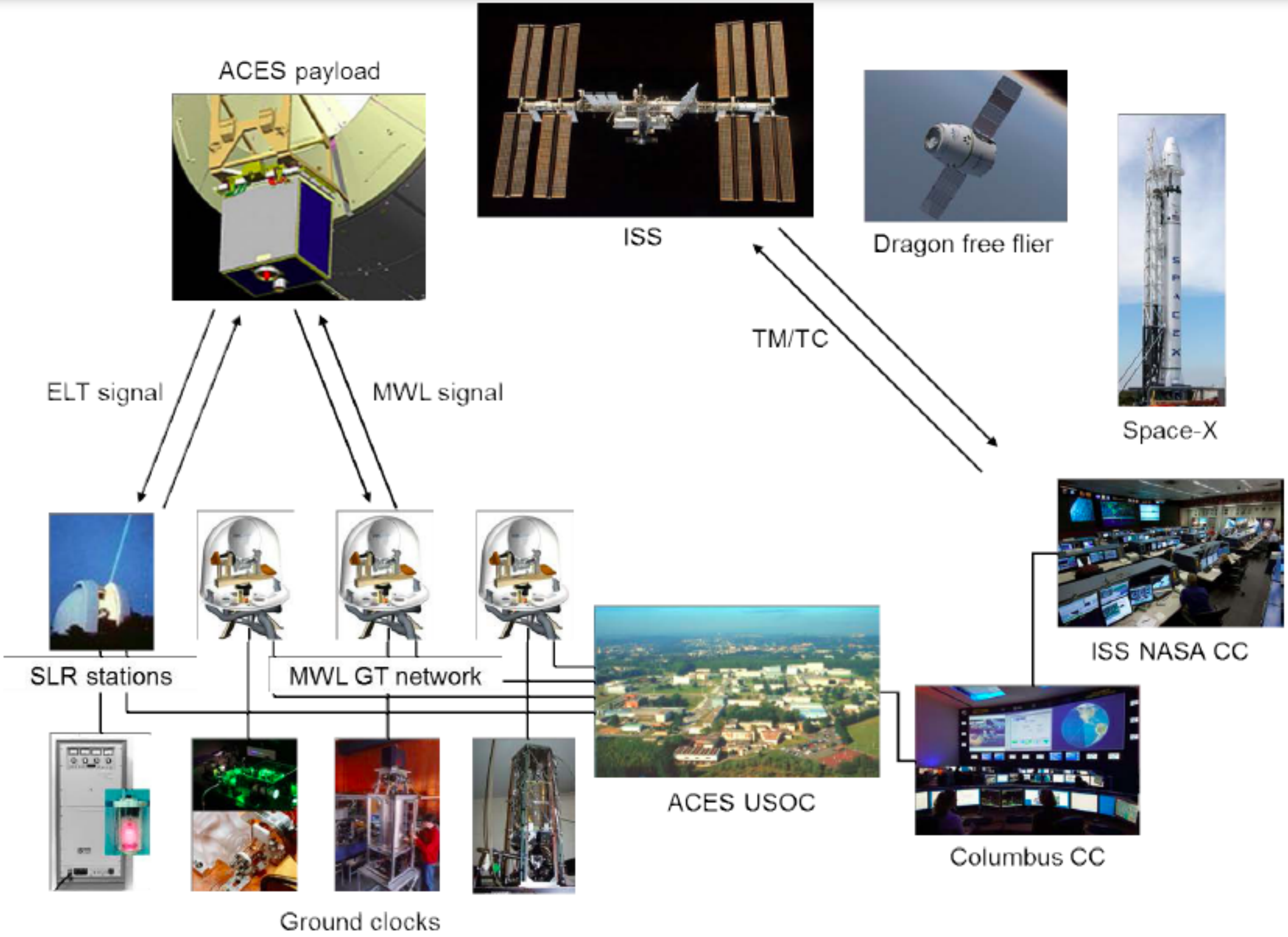
M = 227 kg P = 450 W

To be launched to ISS end 2016 by Space X Dragon capsule
Mission duration : 18 months to 3 years

The Columbus module

from L. Cacciapuoti

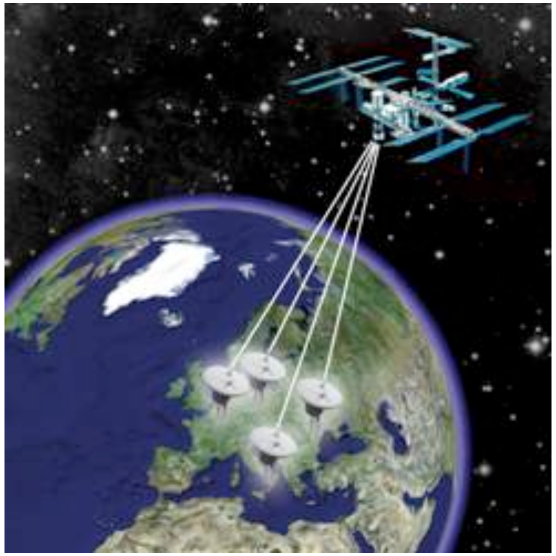
Atomic Clock Ensemble in Space



from L. Cacciapuoti

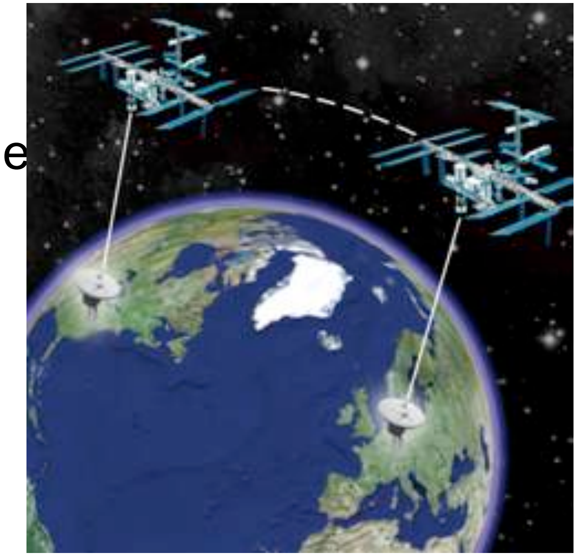
ACES Operational Scenario

- 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

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

ACES Mission Objectives I

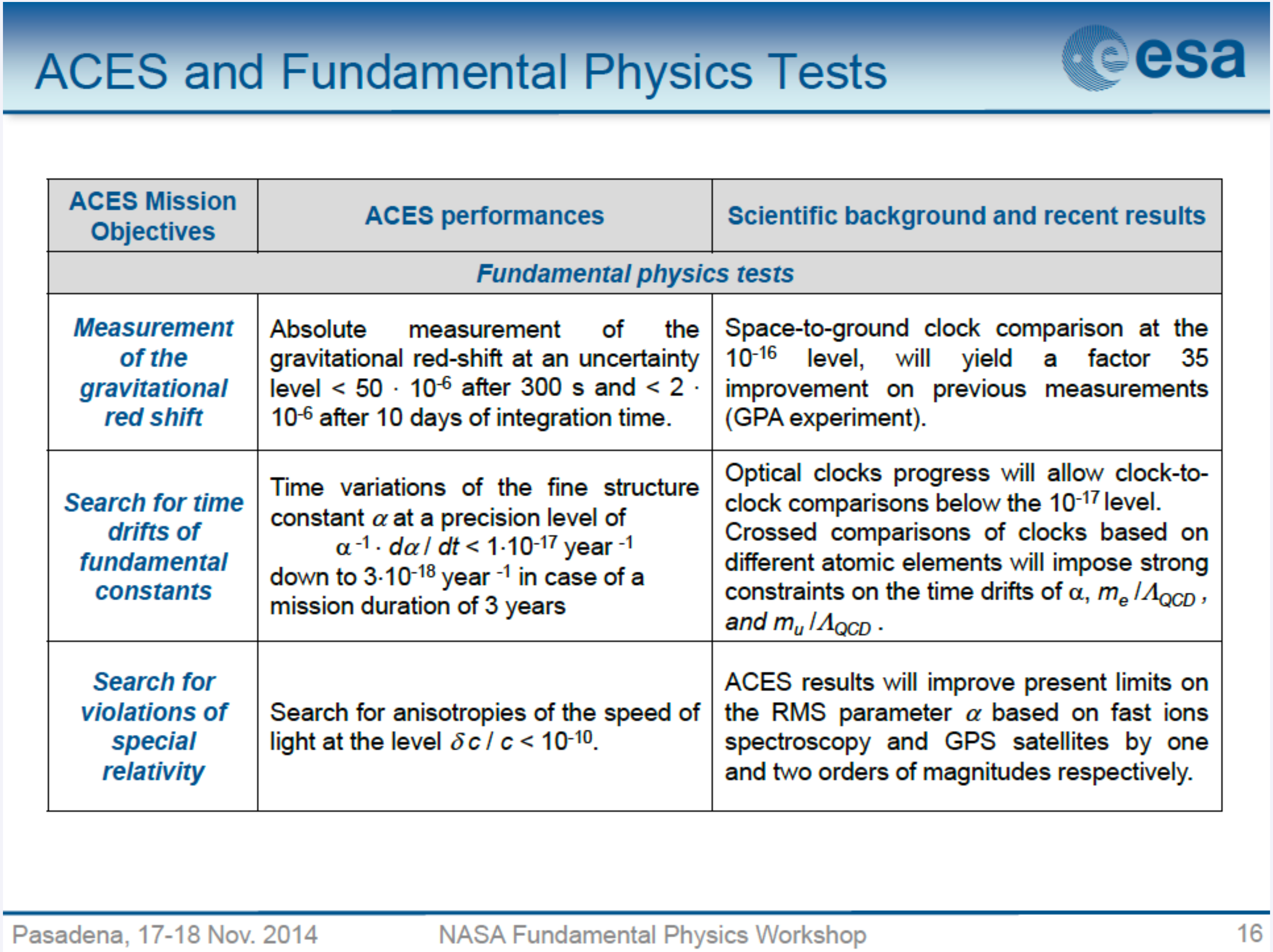
<table>
<tr><th>ACES Mission Objectives</th><th>ACES performances</th><th colspan="12">Scientific background and recent results</th></tr>
<tr><td colspan="14">*Test of a new generation of space clocks*</td></tr>
<tr><td>*Cold atoms in a micro-gravity environment*</td><td>Study of cold atom physics in microgravity.</td><td colspan="12">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 colspan="12">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 rowspan="4">*Test of the space hydrogen maser SHM*</td><td rowspan="4">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 colspan="12">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:</td></tr>
<tr><td colspan="4">Maser</td><td colspan="4">σ_y (1000 s)</td><td colspan="4">σ_y (10000 s)</td></tr>
<tr><td colspan="4">GALILEO</td><td colspan="4">$3.2\cdot10^{-14}$</td><td colspan="4">$1.0\cdot10^{-14}$</td></tr>
<tr><td colspan="4">EFOS C</td><td colspan="4">$2.0\cdot10^{-15}$</td><td colspan="4">$2.0\cdot10^{-15}$</td></tr>
<tr><td colspan="14">*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 colspan="12">At present, no time and frequency transfer link has performances comparable with MWL.</td></tr>
<tr><td rowspan="5">*Time and frequency comparisons between ground clocks*</td><td rowspan="5">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 colspan="3">Existing T&F links</td><td colspan="3">Time stability (1day)</td><td colspan="3">Time accuracy (1day)</td><td colspan="3">Frequency accuracy (1day)</td></tr>
<tr><td colspan="3">GPS-DB</td><td colspan="3">2 ns</td><td colspan="3">3-10 ns</td><td colspan="3">$4\cdot10^{-14}$</td></tr>
<tr><td colspan="3">GPS-CV</td><td colspan="3">1 ns</td><td colspan="3">1-5 ns</td><td colspan="3">$2\cdot10^{-14}$</td></tr>
<tr><td colspan="3">GPS-CP</td><td colspan="3">0.1 ns</td><td colspan="3">1-3 ns</td><td colspan="3">$2\cdot10^{-15}$</td></tr>
<tr><td colspan="3">TWSTFT</td><td colspan="3">0.1-0.2 ns</td><td colspan="3">1 ns</td><td colspan="3">$2\text{-}4\cdot10^{-15}$</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 35 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.

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

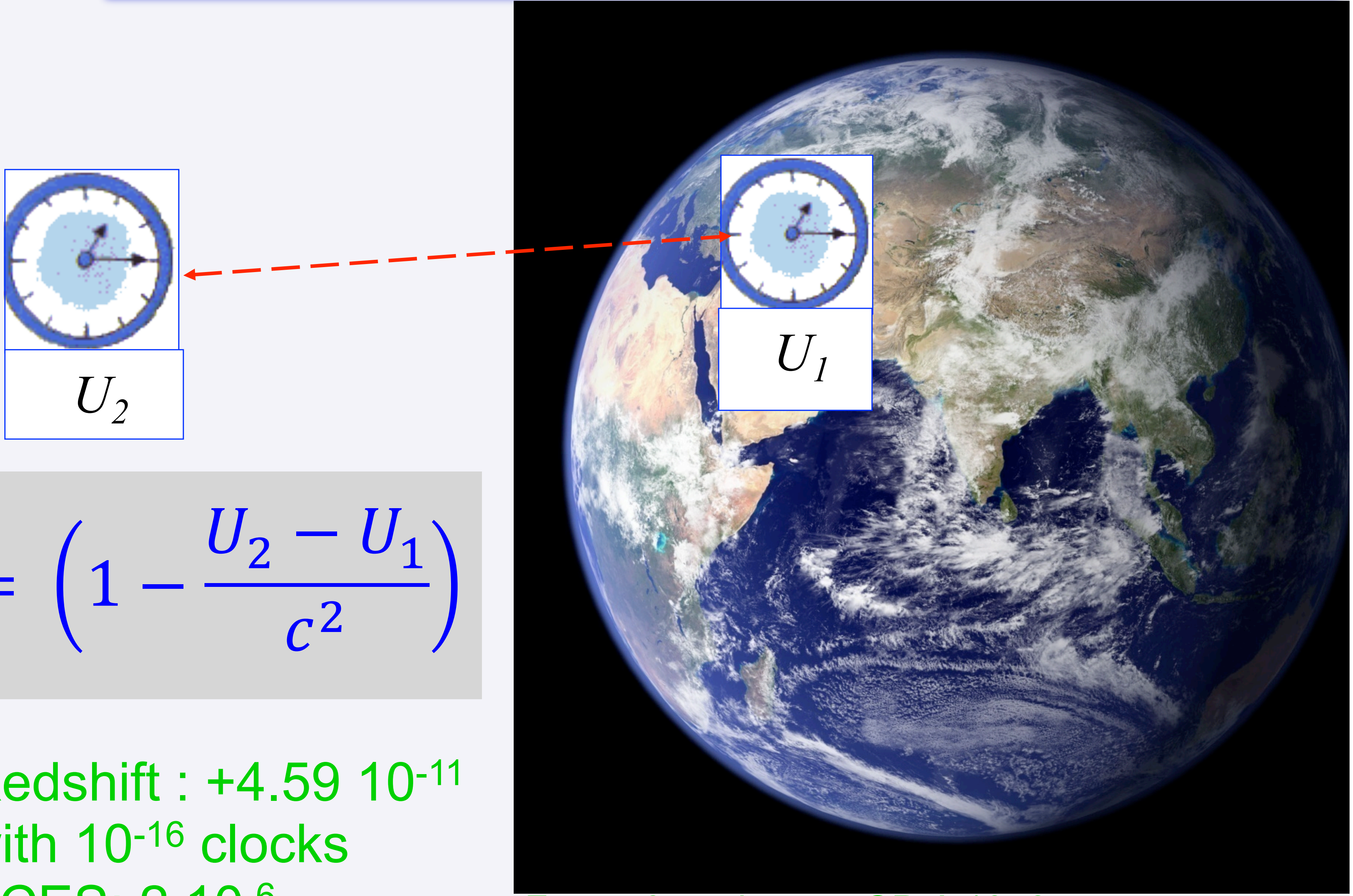


ACES and Fundamental Physics Tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
Fundamental physics tests		
Measurement of the gravitational red shift	Absolute measurement of the gravitational red-shift at an uncertainty level $< 50 \cdot 10^{-6}$ after 300 s and $< 2 \cdot 10^{-6}$ after 10 days of integration time.	Space-to-ground clock comparison at the 10^{-16} level, will yield a factor 35 improvement on previous measurements (GPA experiment).
Search for time drifts of fundamental constants	Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha / dt < 1 \cdot 10^{-17}$ year $^{-1}$ down to $3 \cdot 10^{-18}$ year $^{-1}$ in case of a mission duration of 3 years	Optical clocks progress will allow clock-to-clock comparisons below the 10^{-17} level. Crossed comparisons of clocks based on different atomic elements will impose strong constraints on the time drifts of α, m_e / Λ_{QCD}, and m_u / Λ_{QCD}.
Search for violations of special relativity	Search for anisotropies of the speed of light at the level $\delta c / c < 10^{-10}$.	ACES results will improve present limits on the RMS parameter α based on fast ions spectroscopy and GPS satellites by one and two orders of magnitudes respectively.

from L. Cacciapuoti

A Prediction of General Relativity
Einstein gravitational shift

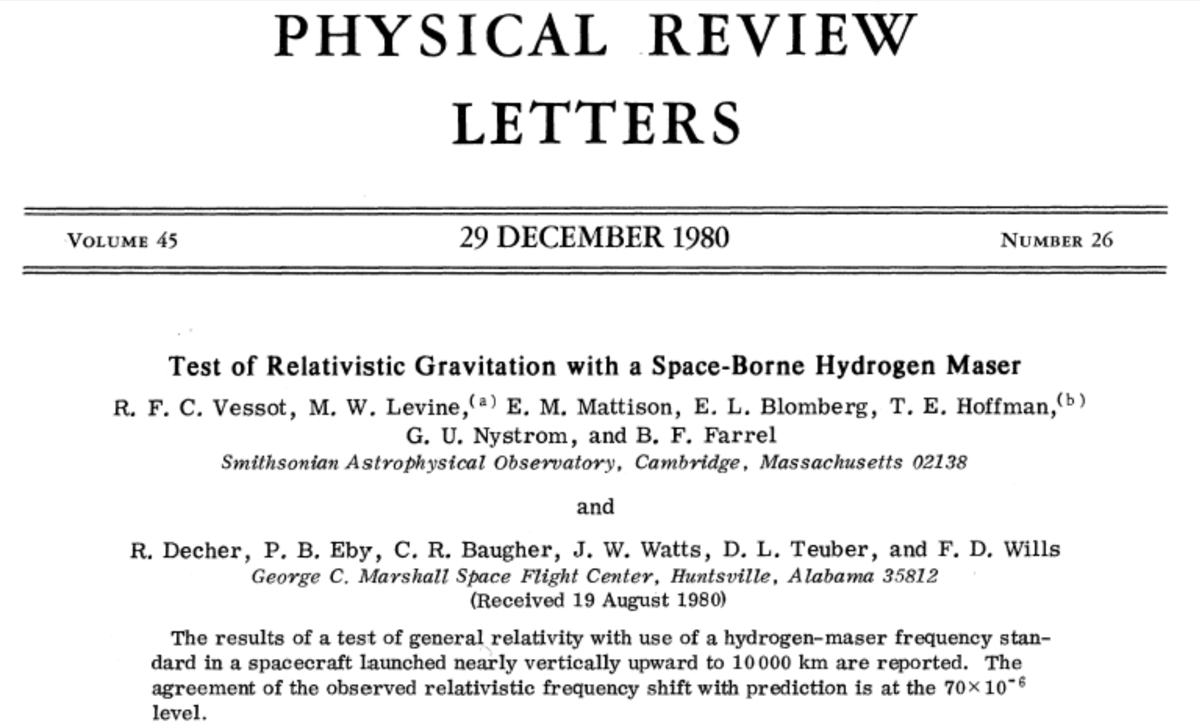


$$\frac{\nu_2}{\nu_1} = \left(1 - \frac{U_2 - U_1}{c^2}\right)$$

Redshift : +4.59 10^{-11}
with 10^{-16} clocks
ACES: 2 10^{-6}

Factor 35 gain over GP-A 1976

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.

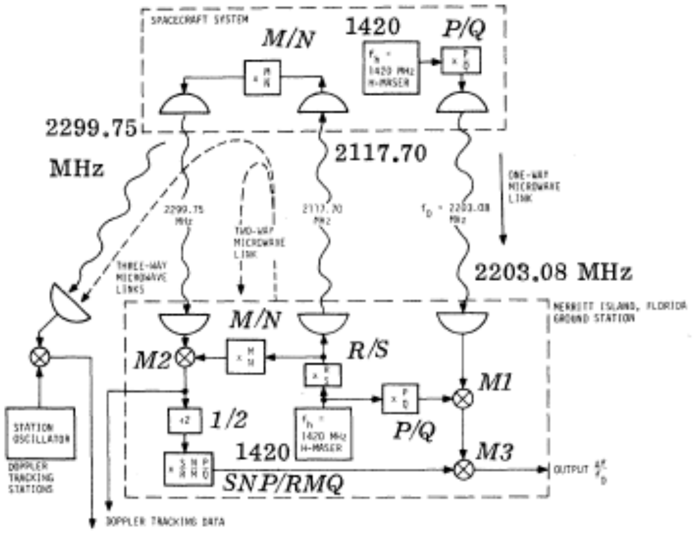


FIG. 1. Doppler cancellation and tracking system.

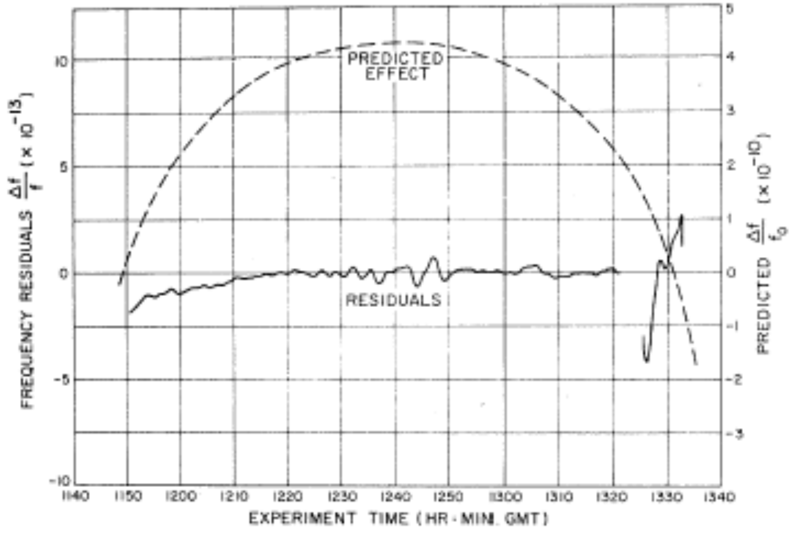


FIG. 3. Frequency residuals and predicted effect during mission.

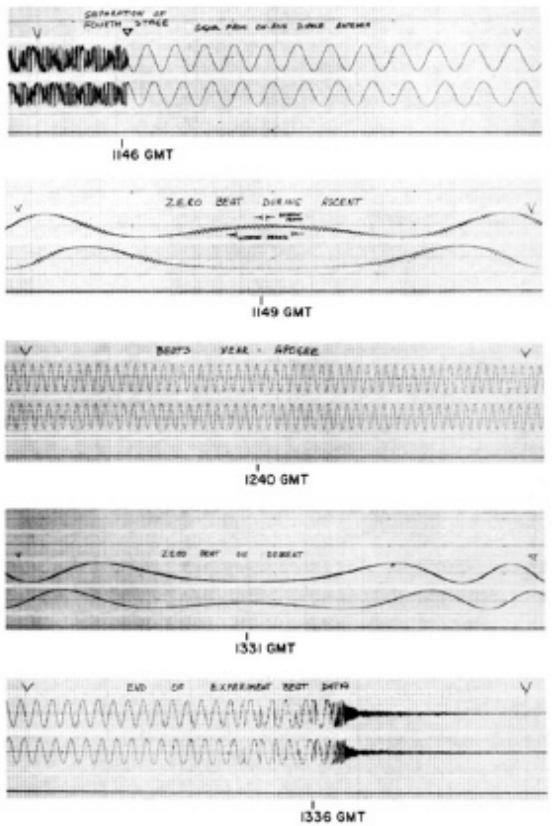


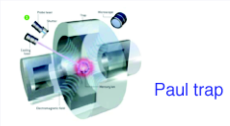
FIG. 2. Analog strip-chart recorder data at various times during the mission. (a) Signal from dipole antenna. The (inverted delta) markers indicate the time at which the fourth stage of the rocket separated. (b) Zero beat during ascent. The small interval indicated above the top trace is a rotation period;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

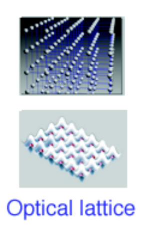
Optical clocks: Towards 10^{-18}

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

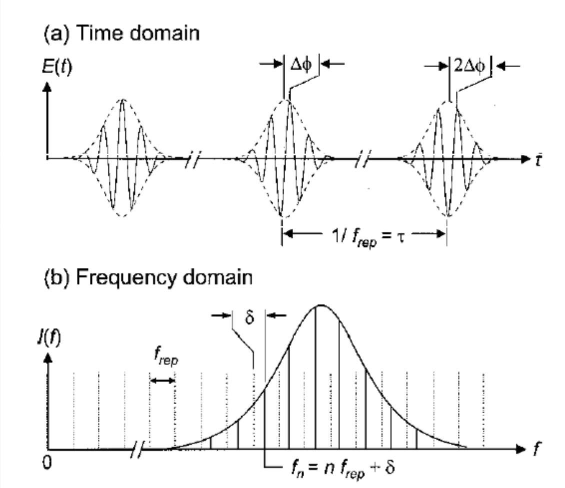
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atom}}} \sqrt{\frac{T_{\text{cycle}}}{2\tau_{\text{average}}}} \frac{1}{C_{\text{fringe}}}$$

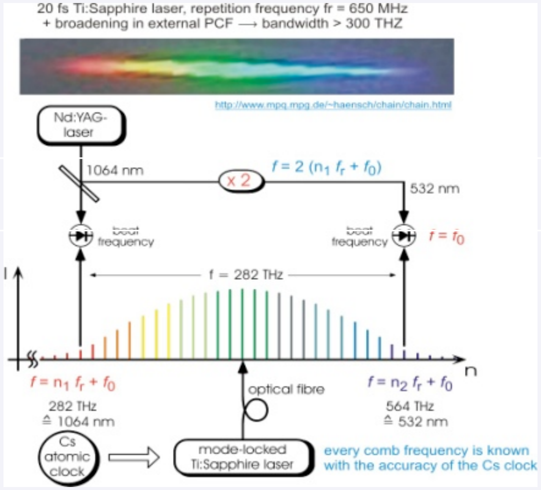
- **Candidate atoms** ⁄ **Trapped ions: Hg$^+$, In$^+$, Sr$^+$, Yb$^+$,…**
  ╲ **Cold neutral atoms: H, Ca, Sr, Yb,…**

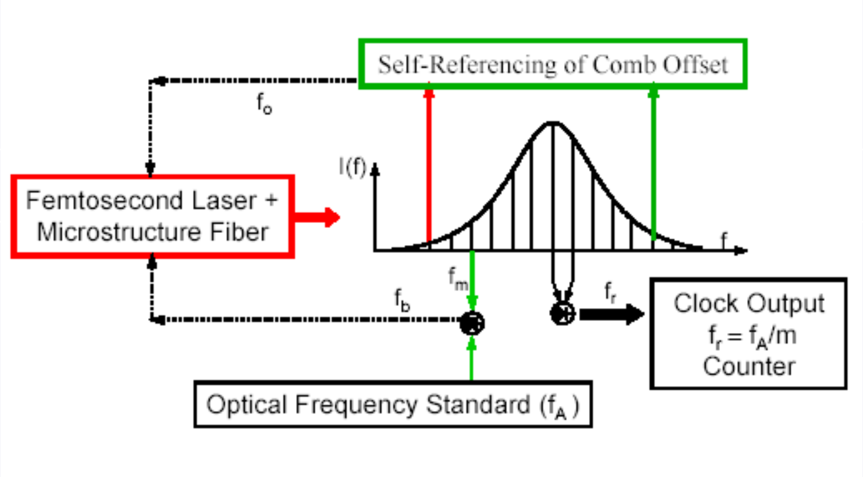




- **Direct optical-µwave connection by optical frequency comb**

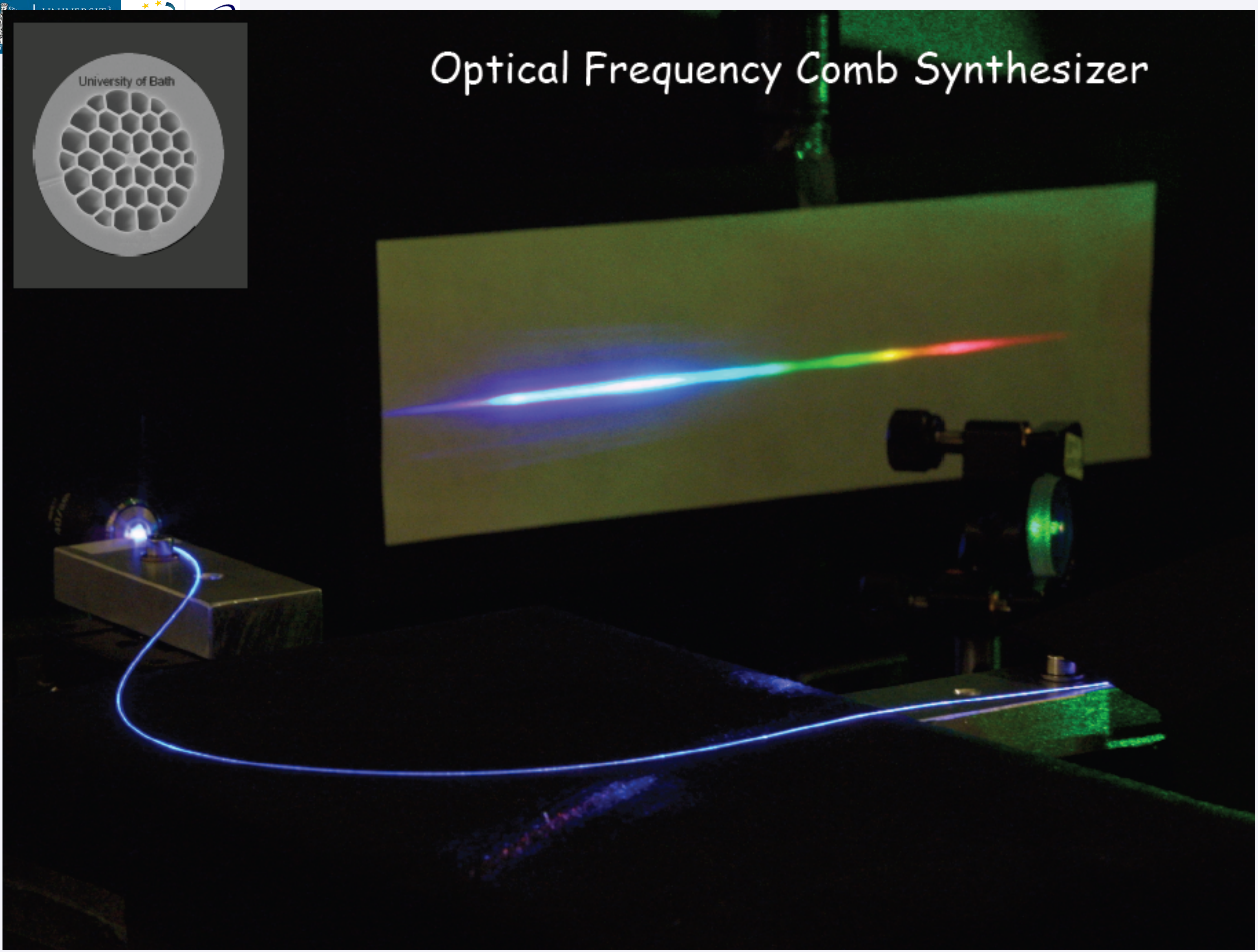




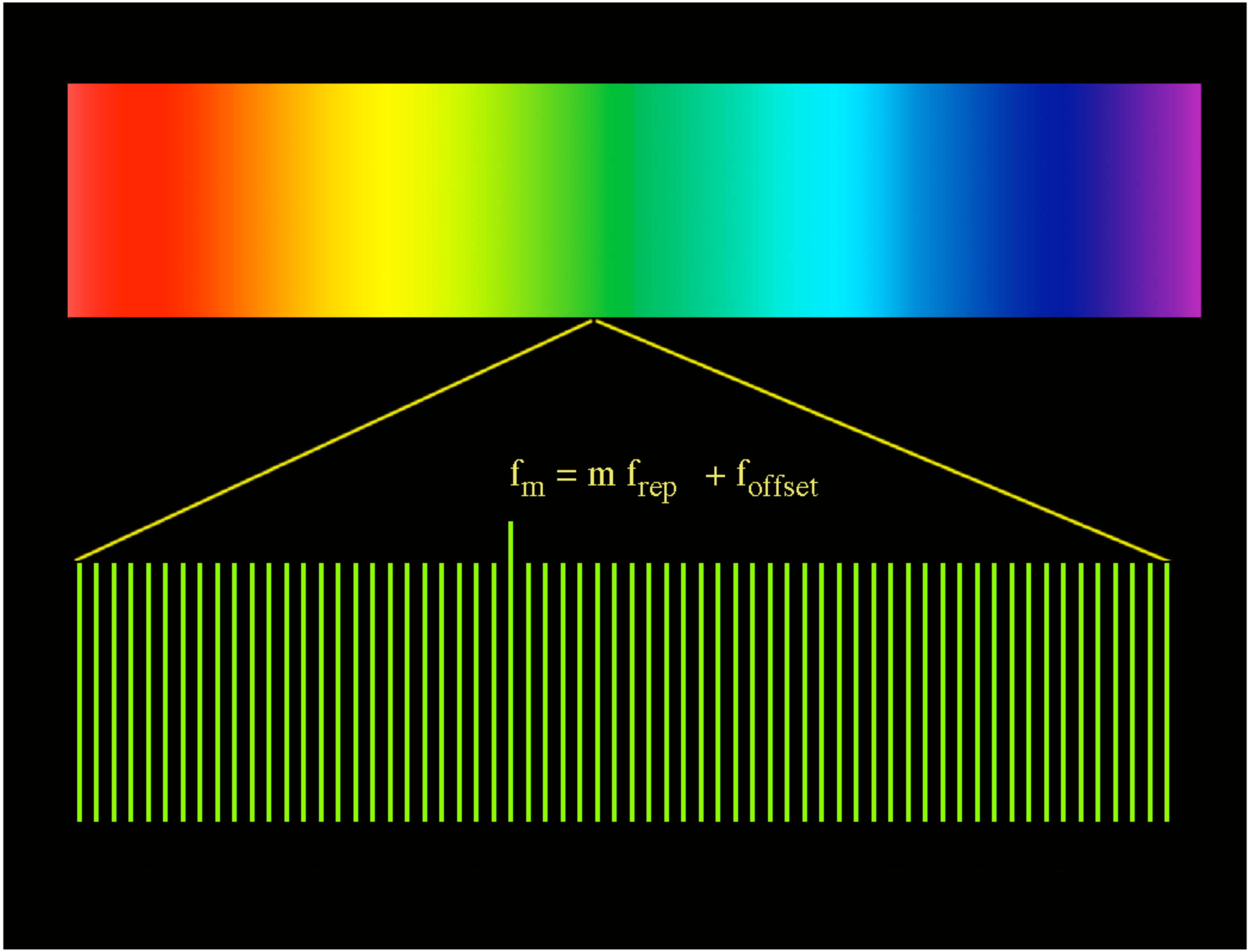


Th. Udem *et al.*, Nature 416 , 14 march 2002

Optical Frequency Comb Synthesizer



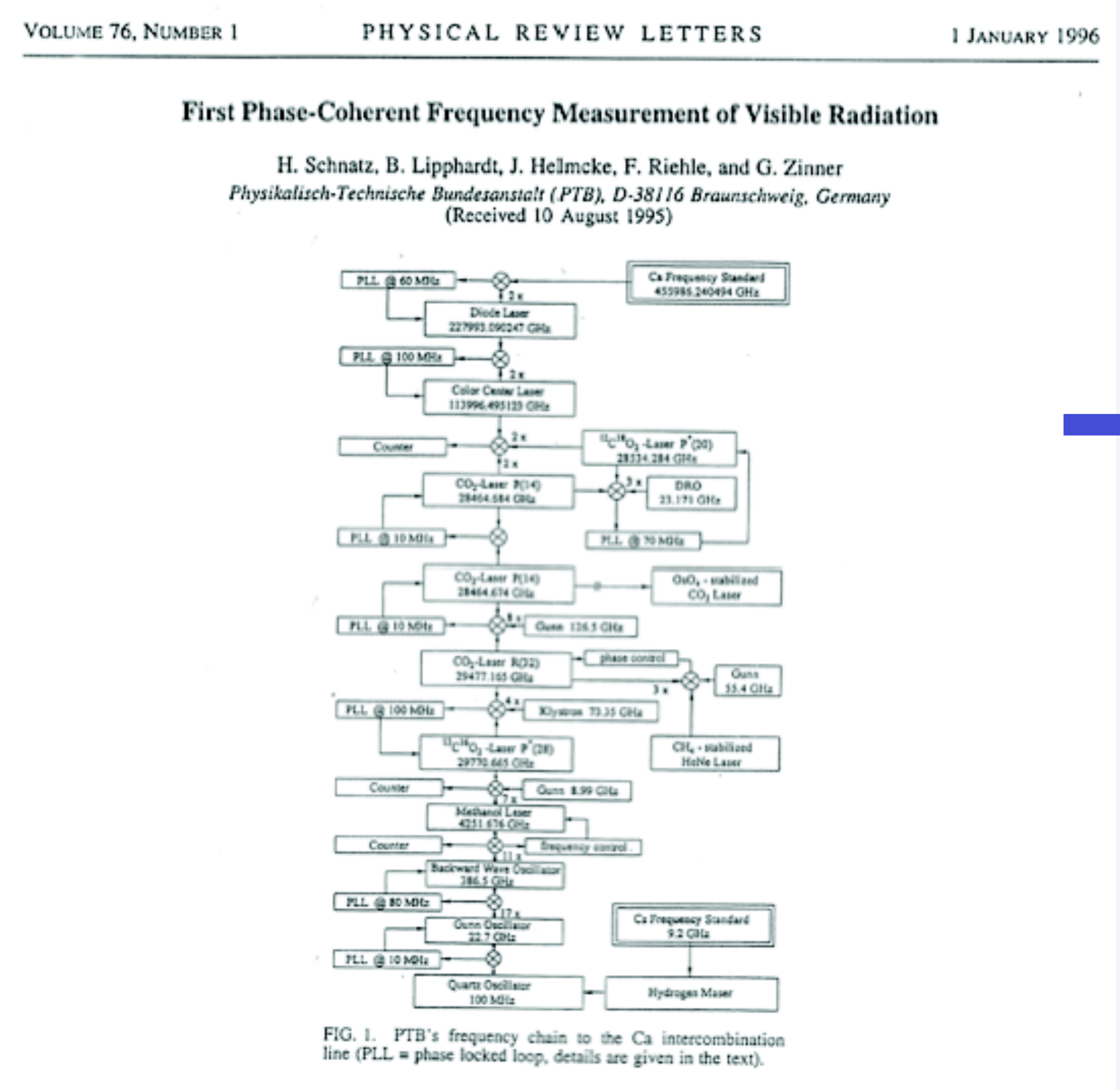
From T.W. Hänsch



$$f_m = m\, f_{rep} + f_{offset}$$

From T.W. Hänsch

Optical frequencies measurement



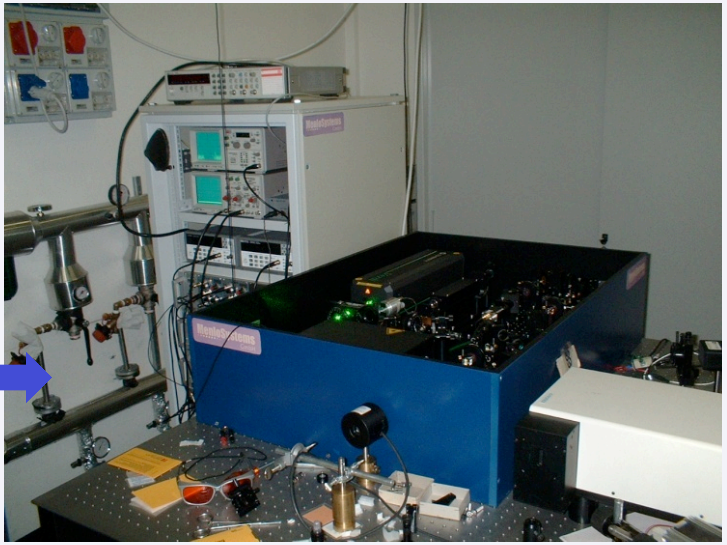
VOLUME 76, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1996

First Phase-Coherent Frequency Measurement of Visible Radiation

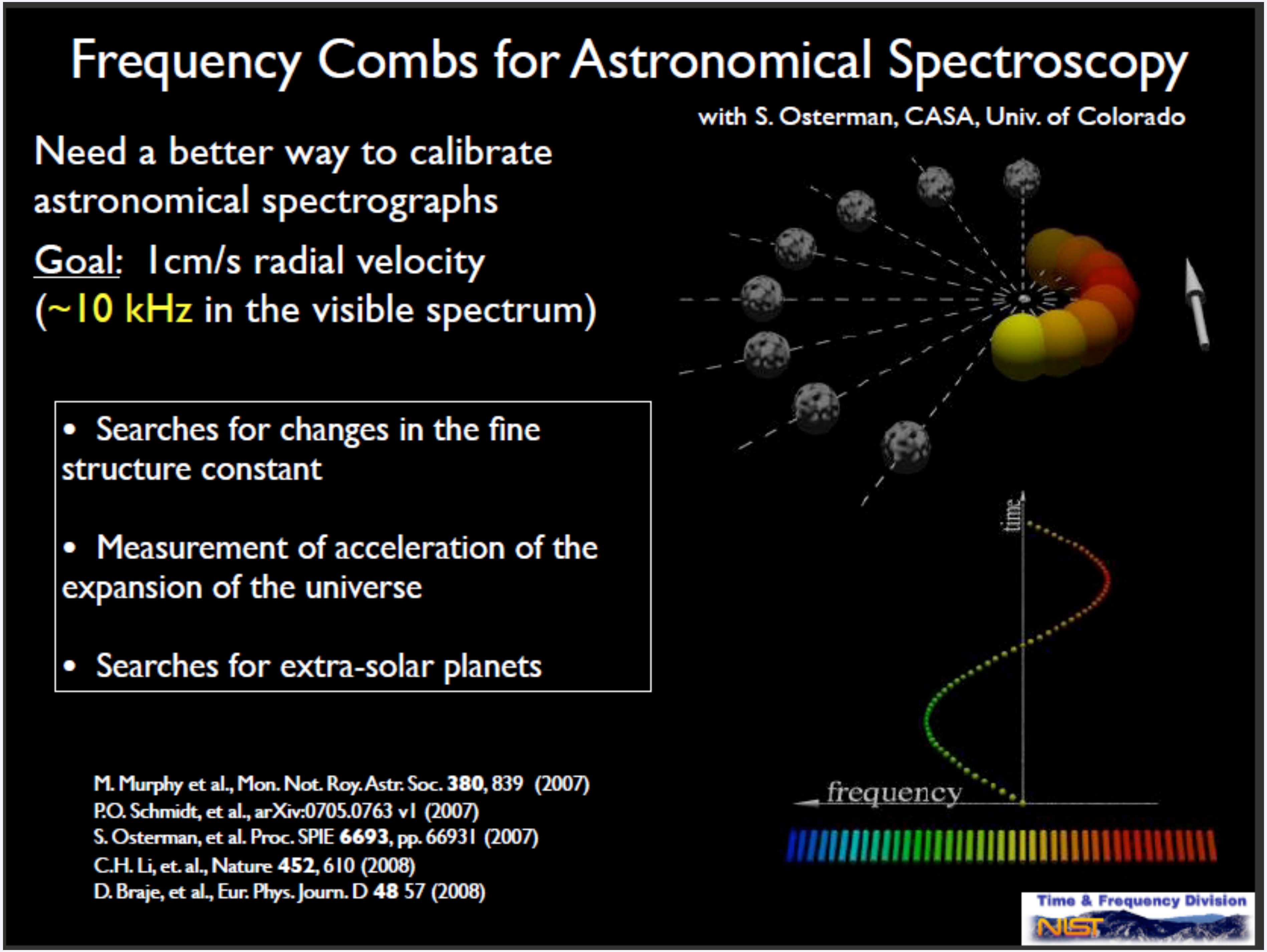
H. Schnatz, B. Lipphardt, J. Helmcke, F. Riehle, and G. Zinner
Physikalisch-Technische Bundesanstalt (PTB), D-38116 Braunschweig, Germany

(Received 10 August 1995)

FIG. 1. PTB's frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).



- Commercial system (MenloSystems)
- Repetition rate: 1 GHz



Frequency Combs for Astronomical Spectroscopy

with S. Osterman, CASA, Univ. of Colorado

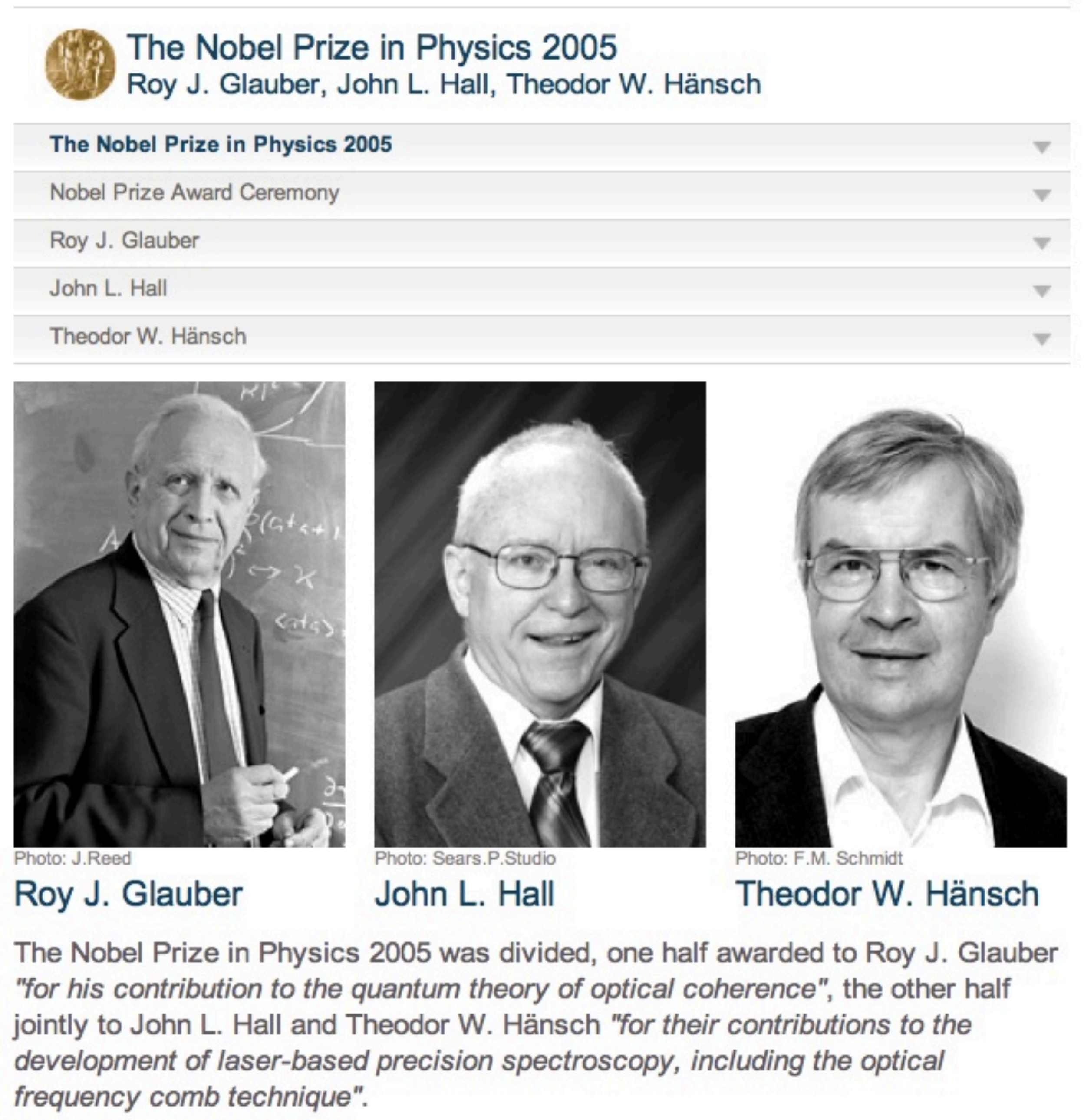
Need a better way to calibrate astronomical spectrographs

Goal: 1cm/s radial velocity
(~10 kHz in the visible spectrum)

- Searches for changes in the fine structure constant
- Measurement of acceleration of the expansion of the universe
- Searches for extra-solar planets

M. Murphy et al., Mon. Not. Roy. Astr. Soc. **380**, 839 (2007)
P.O. Schmidt, et al., arXiv:0705.0763 v1 (2007)
S. Osterman, et al. Proc. SPIE **6693**, pp. 66931 (2007)
C.H. Li, et. al., Nature **452**, 610 (2008)
D. Braje, et al., Eur. Phys. Journ. D **48** 57 (2008)

From S. Diddams, 2009



The Nobel Prize in Physics 2005

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

Photo: J.Reed

Roy J. Glauber

Photo: Sears.P.Studio

John L. Hall

Photo: F.M. Schmidt

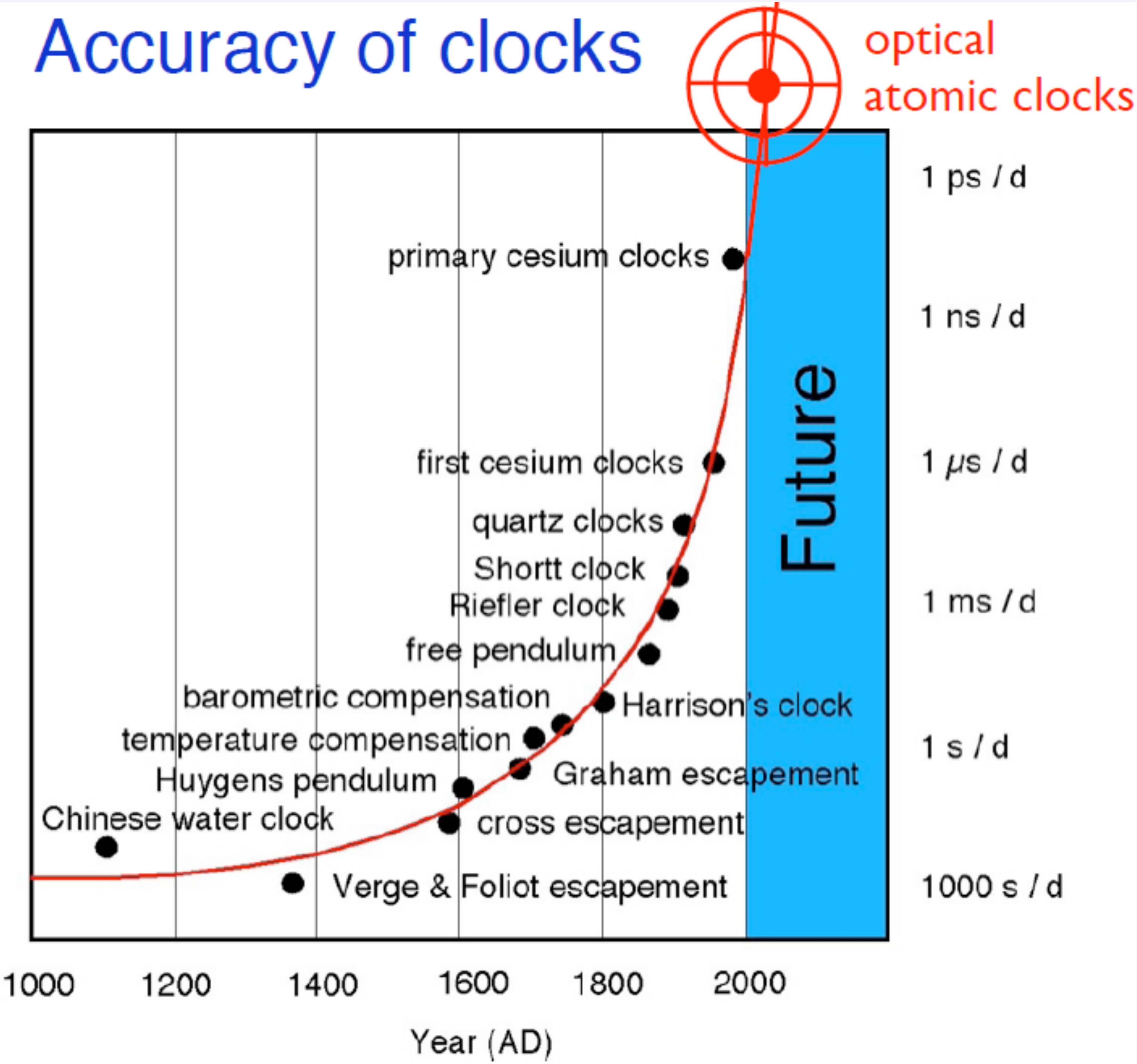
Theodor W. Hänsch

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

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

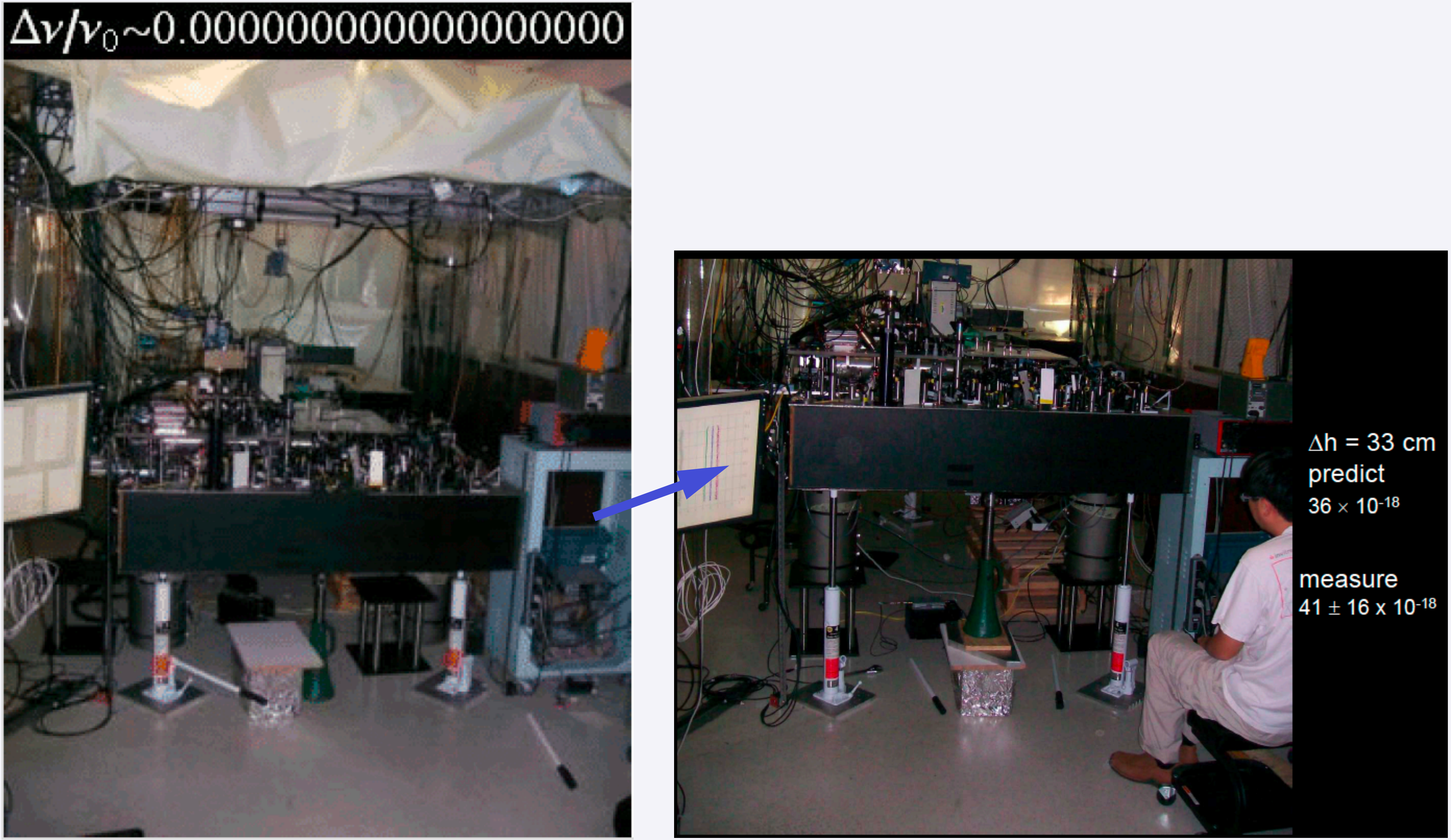
... The important contributions by John Hall and Theodor Hänsch have made it possible to measure frequencies with an accuracy of fifteen digits. Lasers with extremely sharp colours can now be constructed and with the frequency comb technique precise readings can be made of light of all colours. This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

Accuracy of clocks



From T.W. Hänsch

Measure gravitational red shift



Δh = 33 cm

predict

36×10^{-18}

measure

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

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

Measure gravitational red shift in the lab

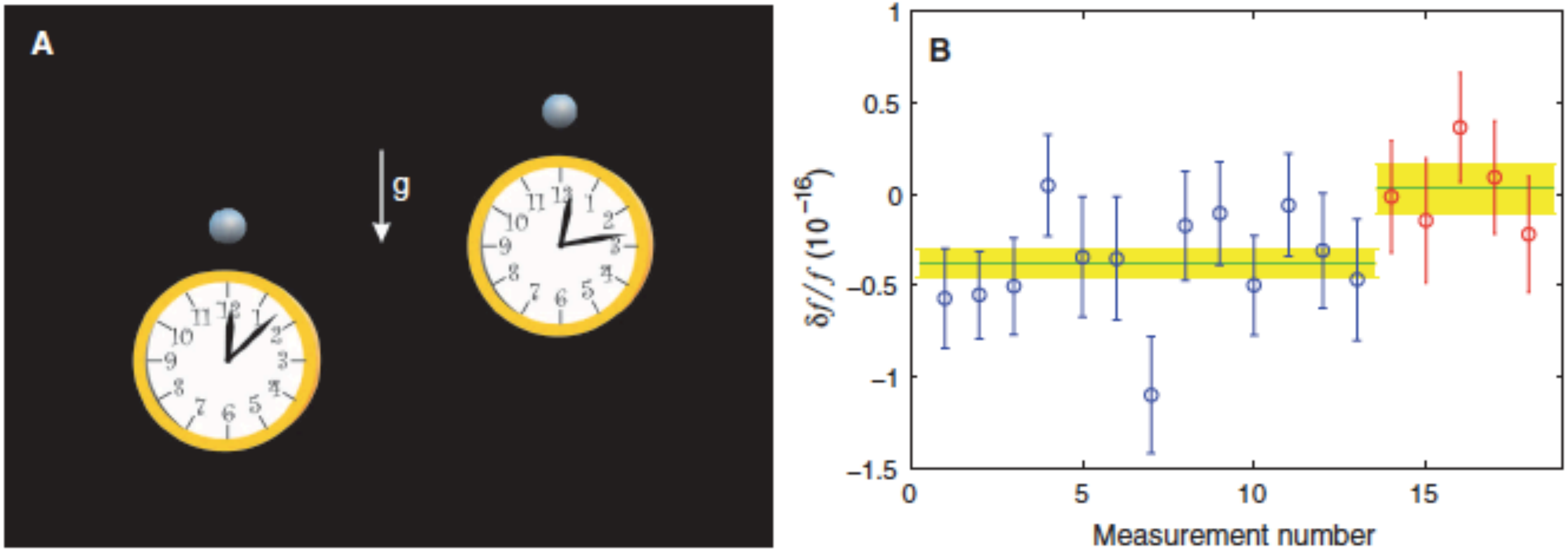
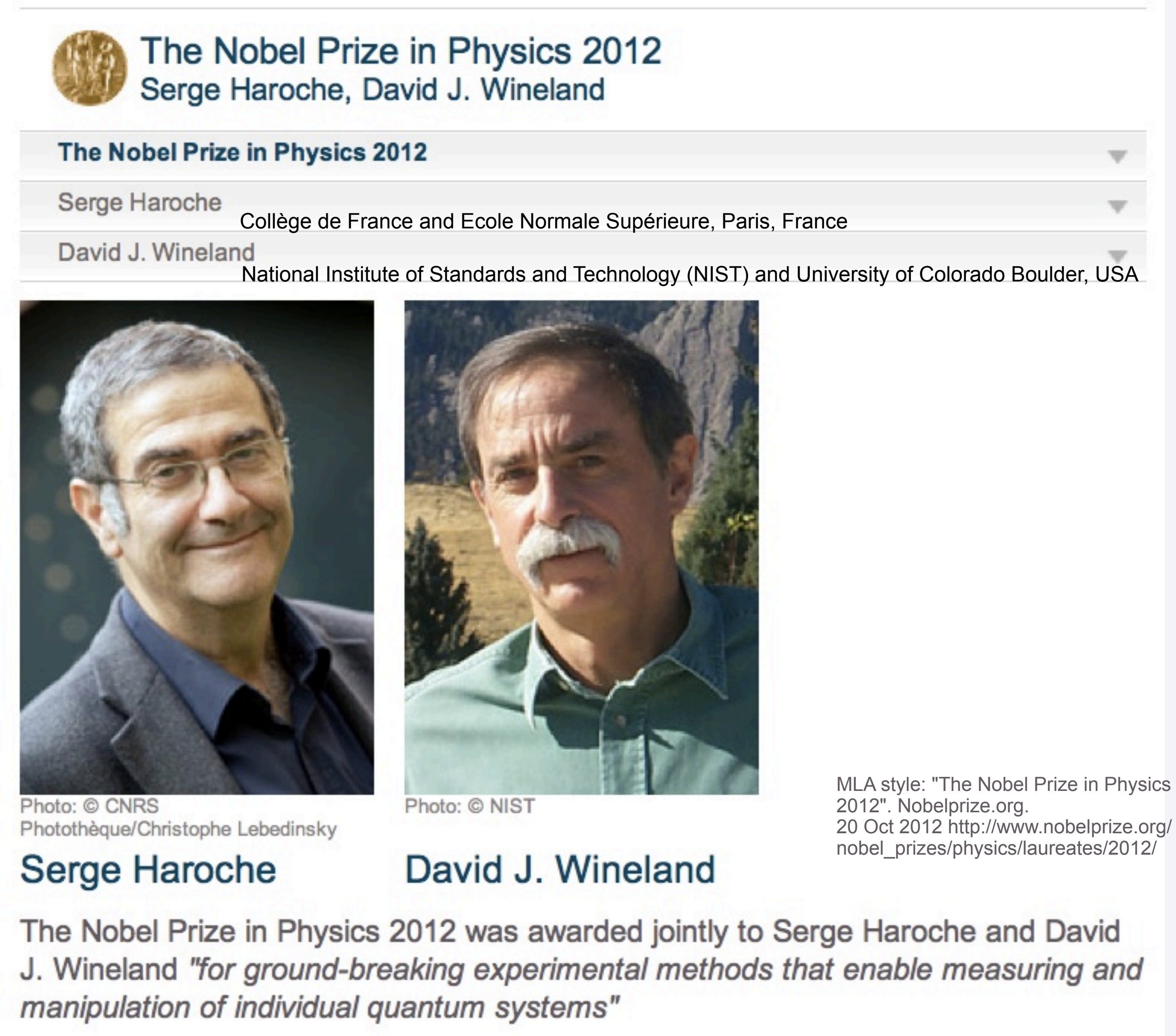


Fig. 3. Gravitational time dilation at the scale of daily life. (**A**) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (**B**) The fractional difference in frequency between two Al$^+$ optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be $(4.1 \pm 1.6) \times 10^{-17}$. The vertical error bars represent statistical uncertainties (reduced $\chi^2 = 0.87$). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

C. W. Chou, D. B. Hume, T. Rosenband and D. J. Wineland
Optical Clocks and Relativity, Science 329, 1630 (2010)



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

The Nobel Prize in Physics 2012

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

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

Photo: © CNRS Photothèque/Christophe Lebedinsky

Serge Haroche

Photo: © NIST

David J. Wineland

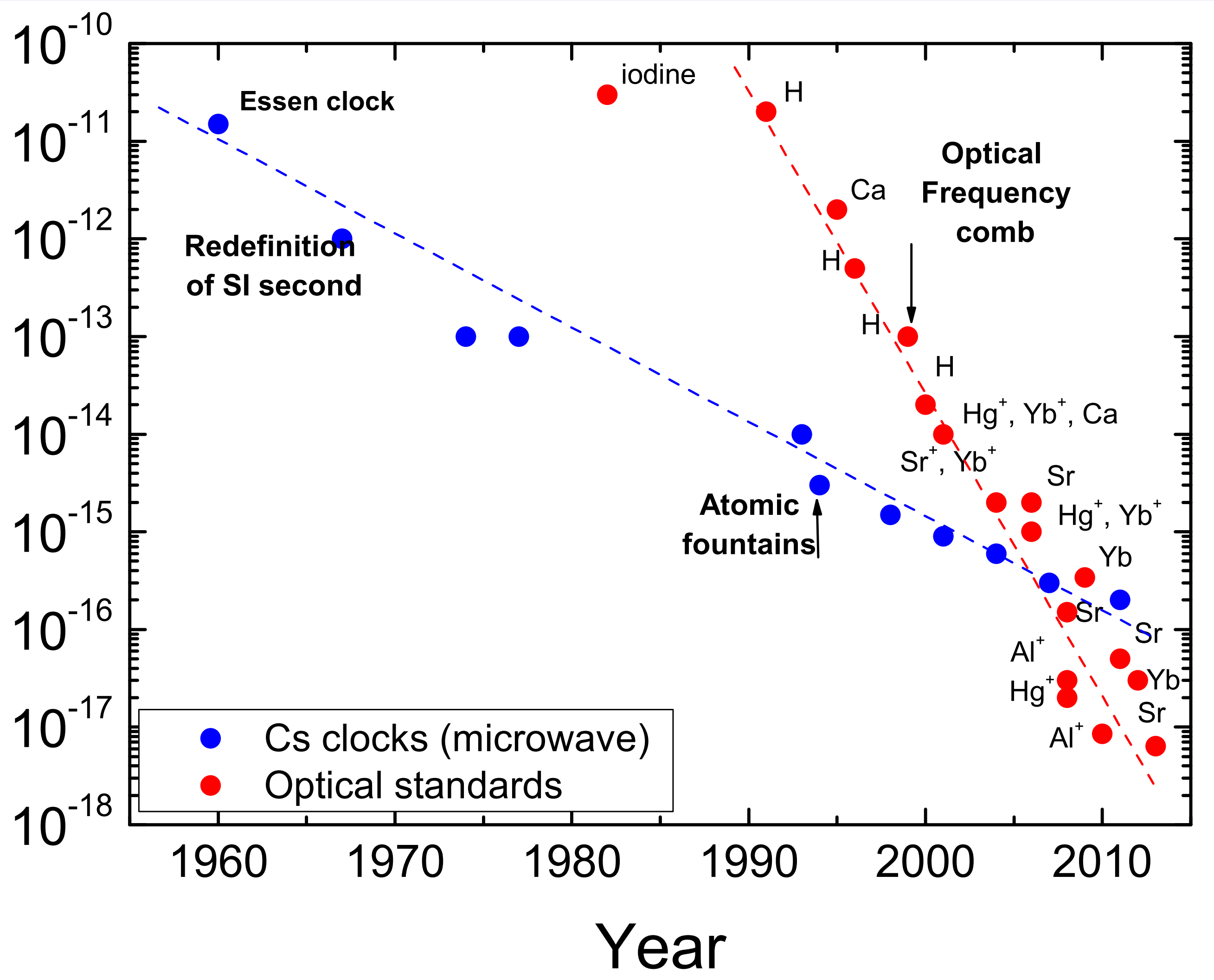
MLA style: "The Nobel Prize in Physics 2012". Nobelprize.org.
20 Oct 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/

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

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

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

Optical clocks: Towards 10^{-18}

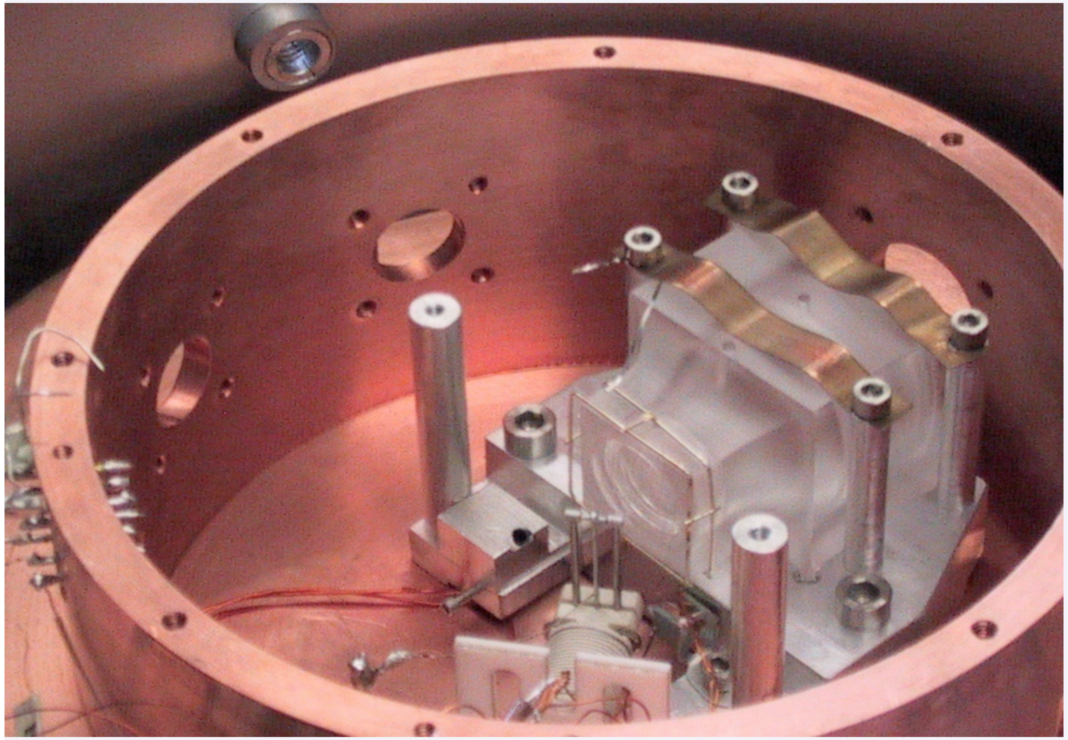


clock **stability** $\sigma_y(\tau) \approx 10^{-15}\tau^{-1/2}$

clock **accuracy** $\delta\nu/\nu < 10^{-17}$

N. Poli, C. W. Oates, P. Gill, G. M. Tino,
Optical Atomic Clocks, Rivista del Nuovo Cimento 36, n. 12, 555 (2013), arXiv:1401.2378

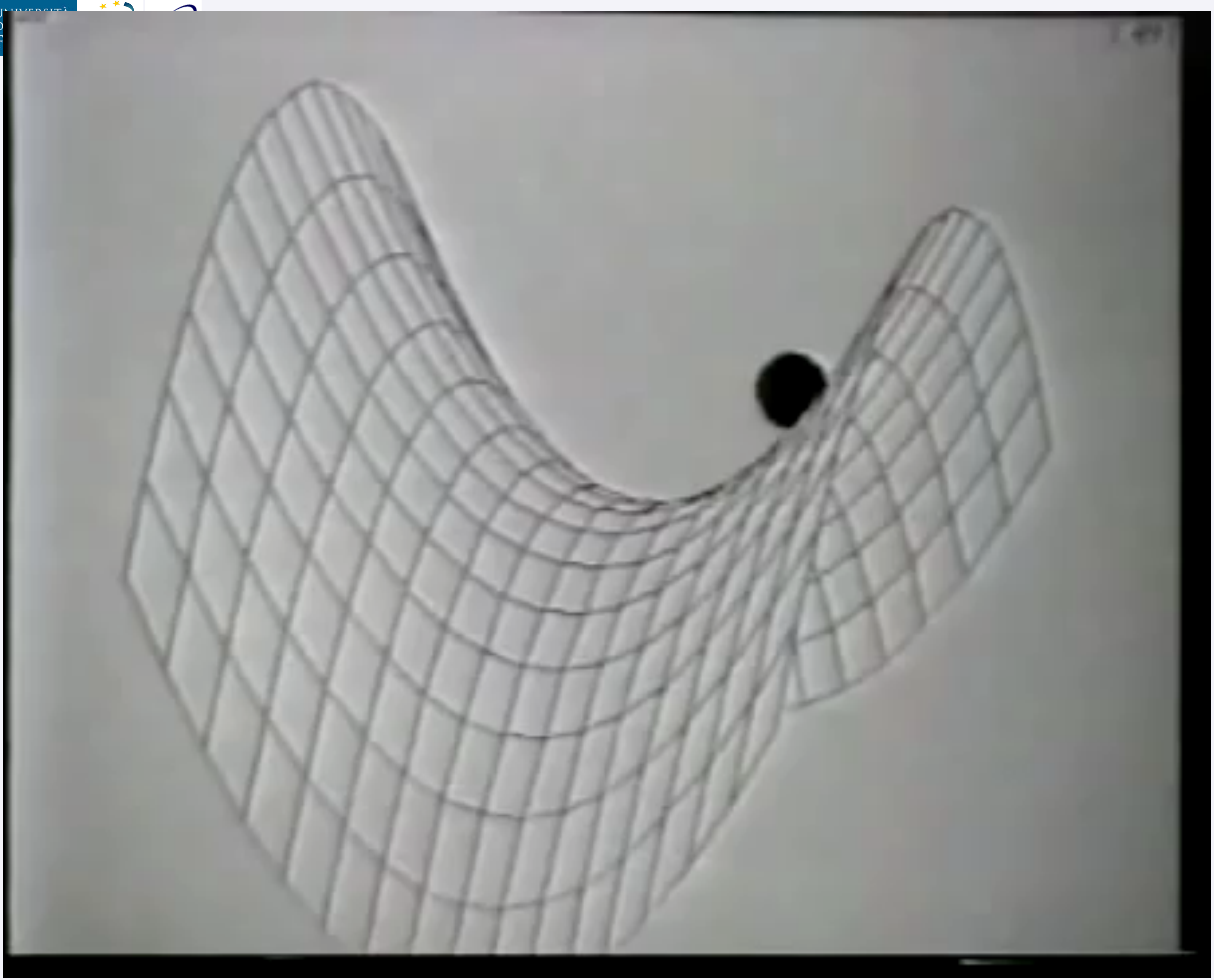
Single ion optical clocks



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

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

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



by T.W. Hänsch

by T.W. Hänsch

Trapped ions

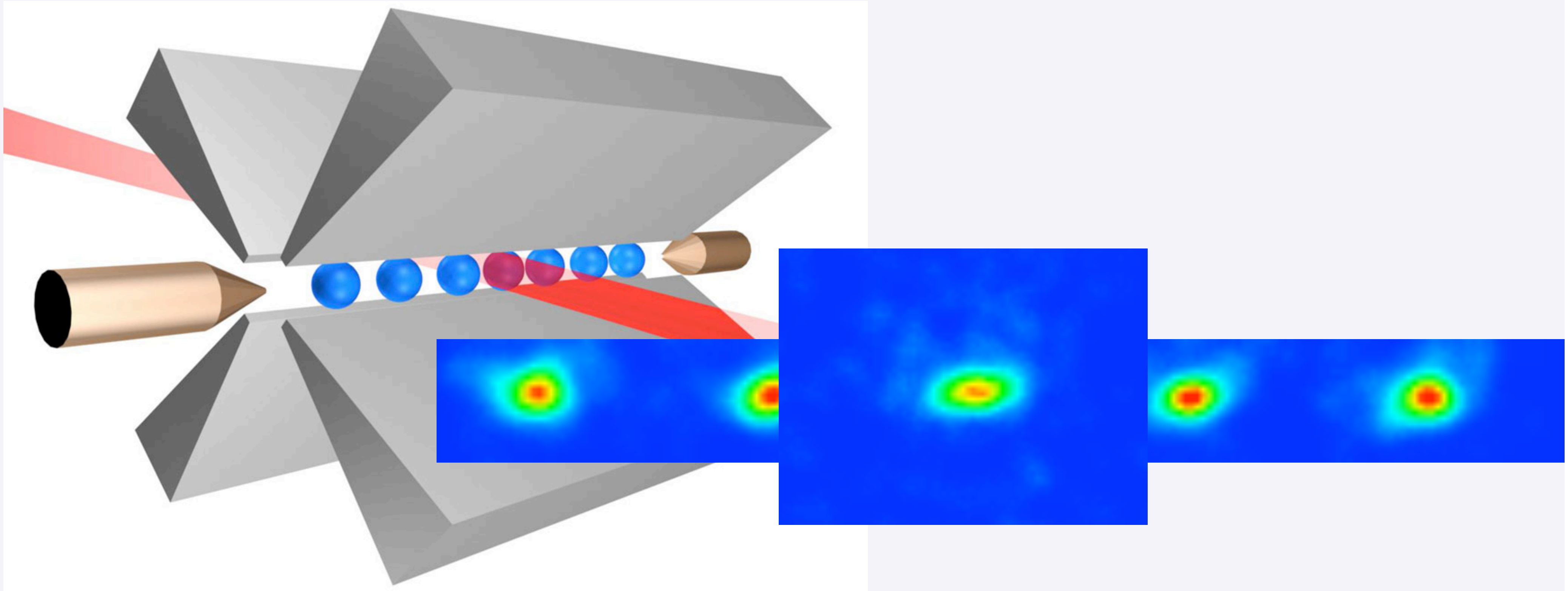


Figure and experimental data from Michael Drewsen

Sr optical clock

- **Method:**

Interrogate atoms in optical lattice without frequency shift

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

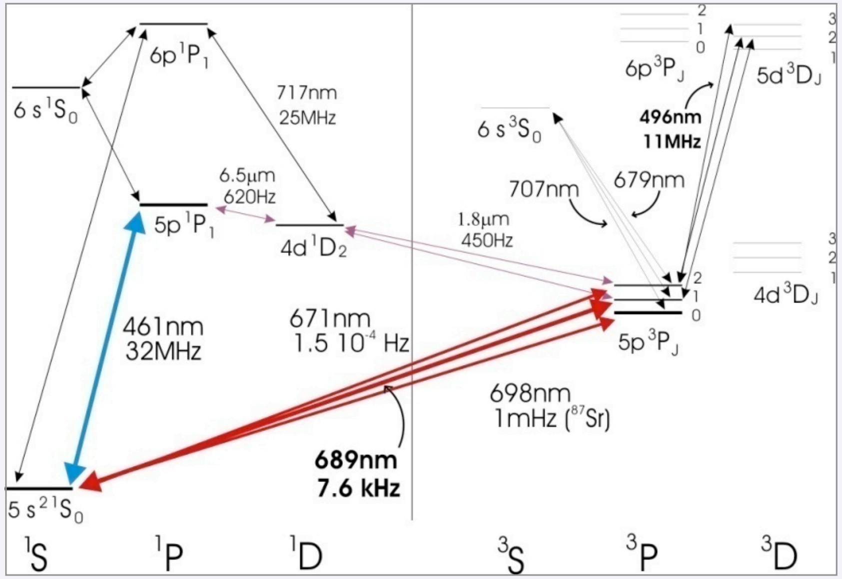
Excellent frequency stability

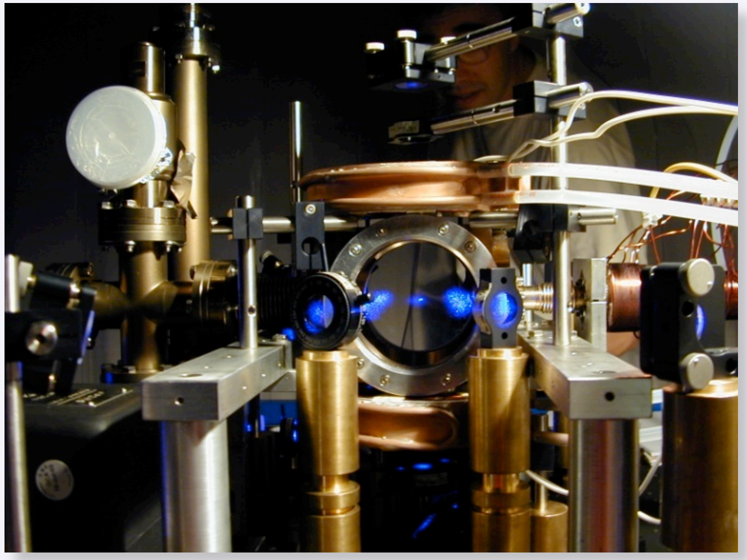
- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

Under development:

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

Ultracold Sr – The experiment in Firenze



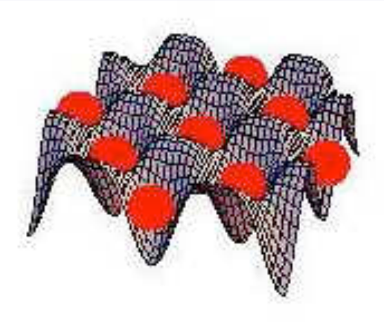


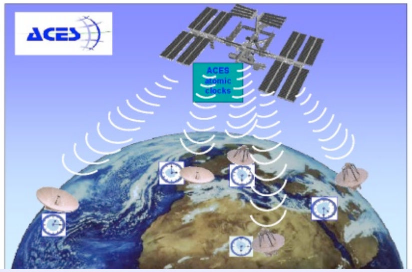
- Optical clocks using visible intercombination lines

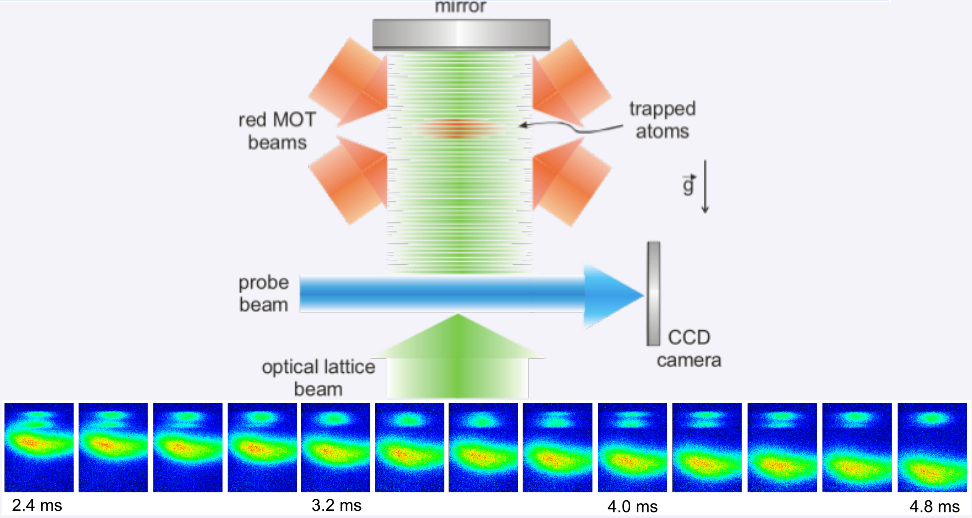
- New atomic sensors for fundamental physics tests

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

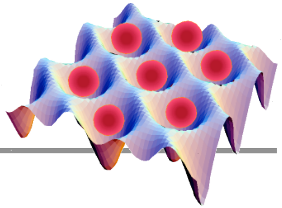






G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale, Phys. Rev. Lett. 97, 060402 (2006)



Space Optical Clocks - SOC

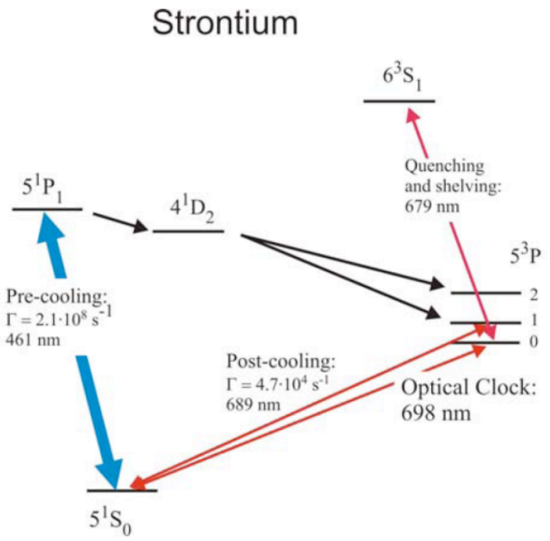
Space Optical Clocks: Pre-phase A study of an atomic clock ensemble in space based on the optical transitions of strontium and ytterbium atoms. Optical clocks will take advantage of the ACES heritage and will push stability and accuracy of atomic frequency standards down to the 10^{-18} regime.

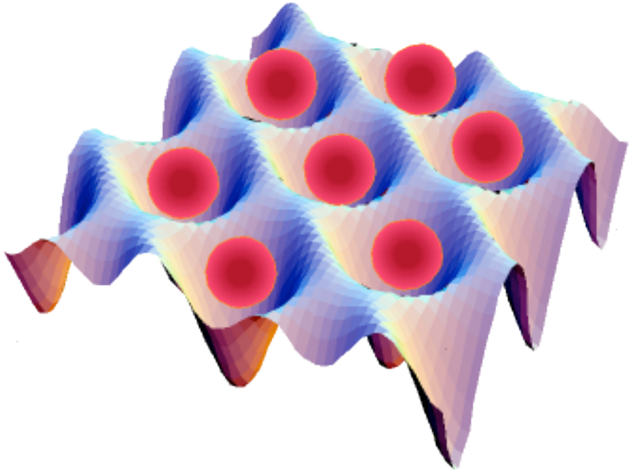
Team: Düsseldorf Univ. (D), LENS (I), SYRTE (F), ENS (F), PTB (D)

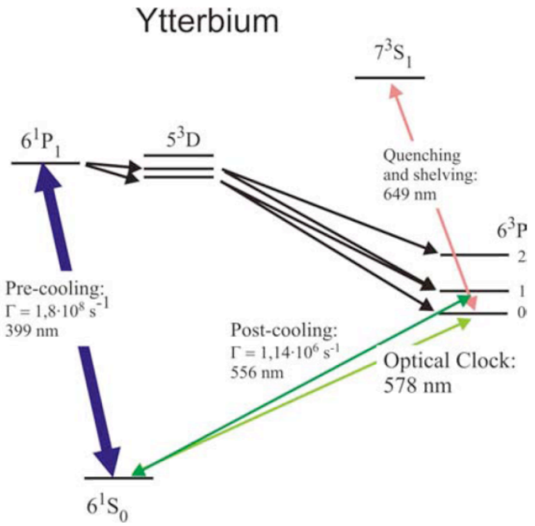
Objective: Ground based prototypes of atomic clocks based on Sr and Yb optical clocks

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding



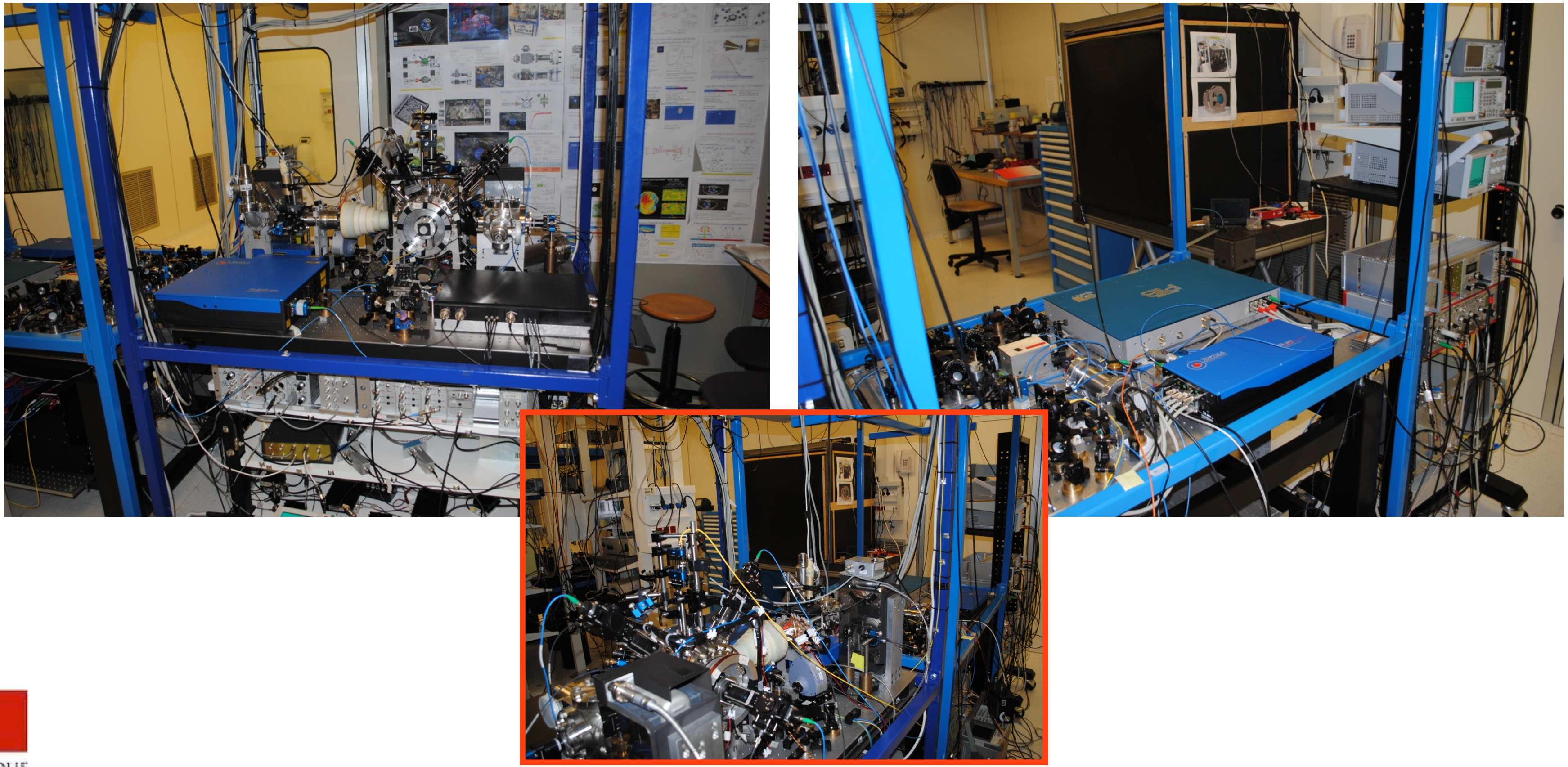




Integration of the compact laser-cooling strontium source (UNIFI) with the transportable clock laser (PTB)

Compact laser-cooling Sr source
(UNIFI)

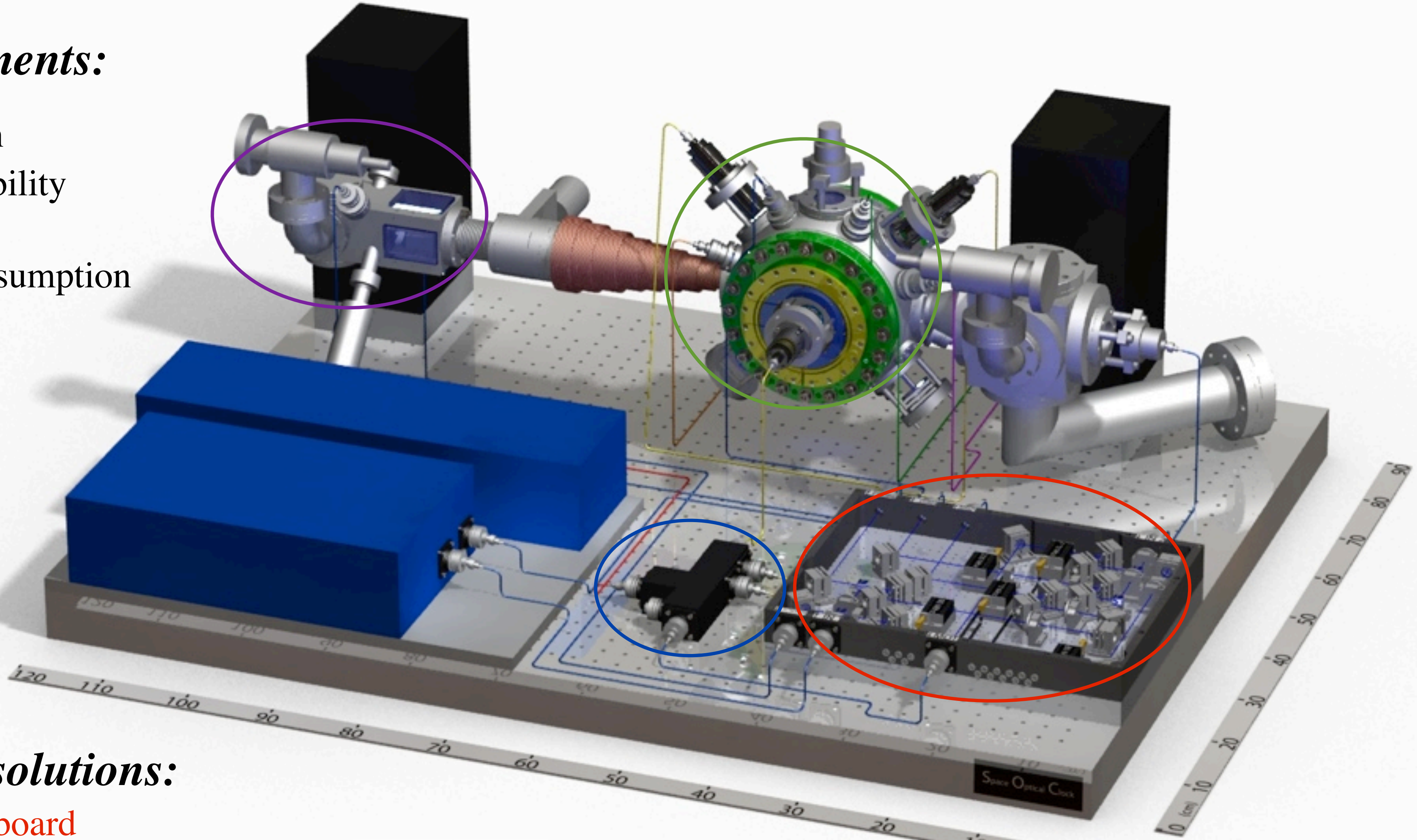
Transportable clock laser
(PTB)



Transportable cold Strontium Source (10^6 atoms @ 1mK)

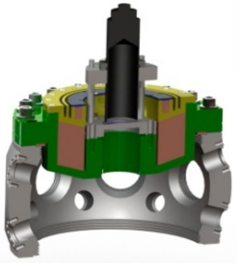
main requirements:

1. compact design
2. operation reliability
3. modularity
4. low power consumption



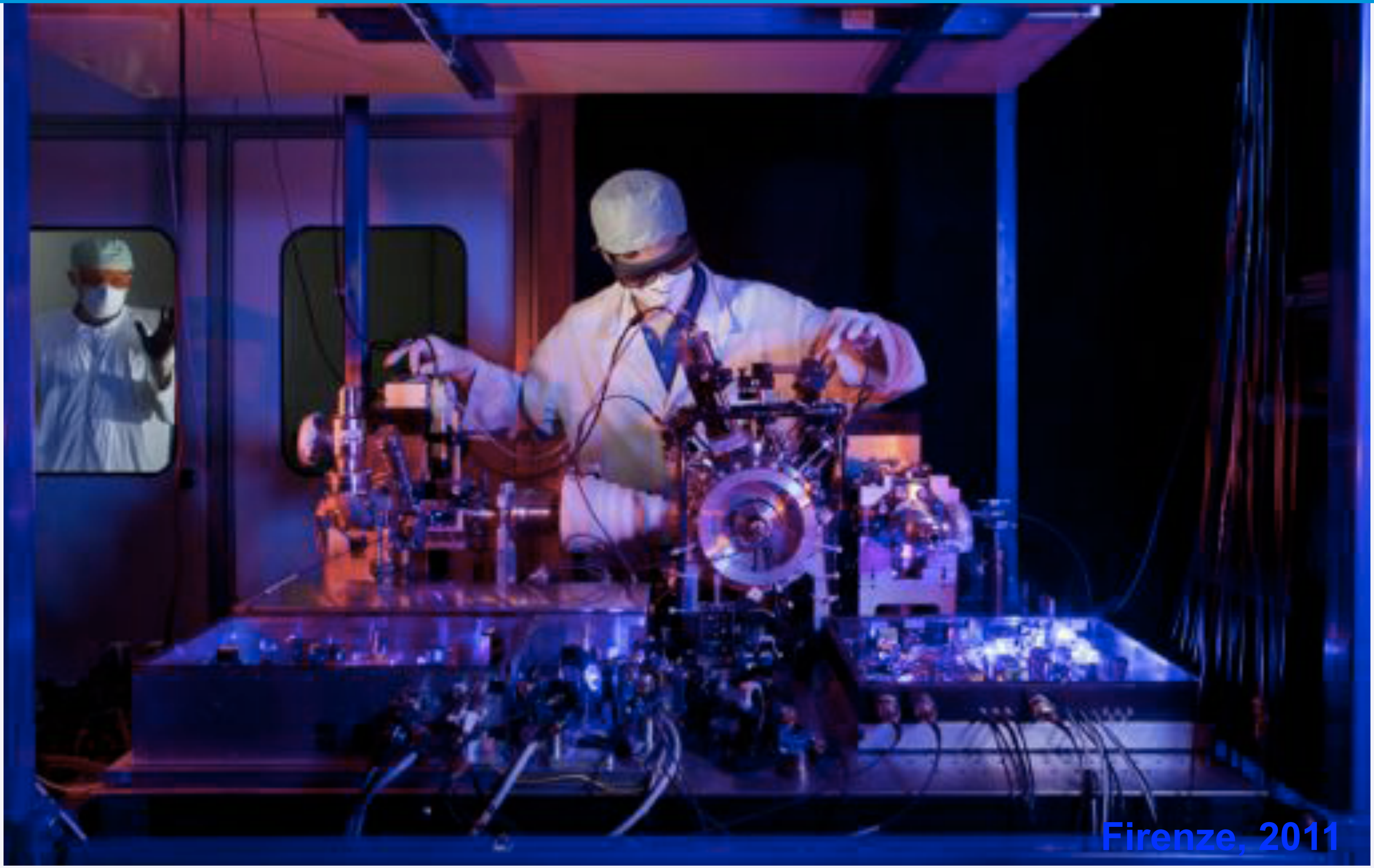
main design solutions:

1. compact breadboard for frequency production
2. all lights fiber delivered
3. custom flange holding MOT coils
4. new atomic oven with 2D cooling



- ***optical breadboard 120 cm x 90 cm***
- ***total power consumption 150 W***
- ***total weight 250 Kg***

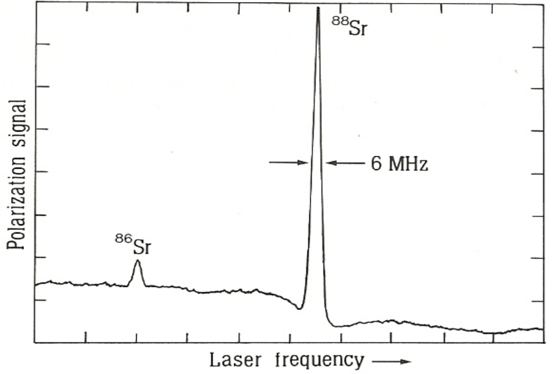
Space Optical Clock


Firenze, 2011

N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B 117, 1107 (2014) - arXiv:1409.4572v2

1992

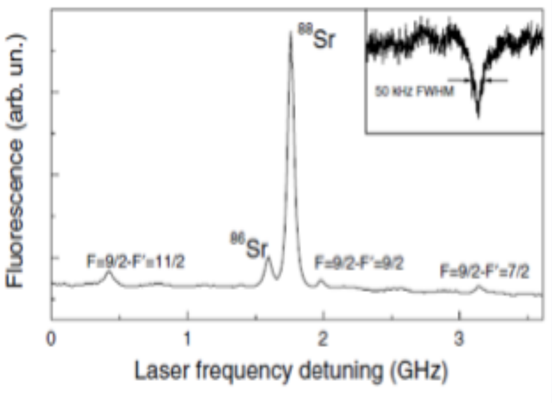
sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line



G.M. Tino, M. Barsanti, M. de Angelis, L. Gianfrani, M. Inguscio, *Spectroscopy of the 689 nm intercombination line of strontium using an extended cavity InGaP/InGaAlP diode laser*, Appl. Phys. B 55, 397 (1992)

2003

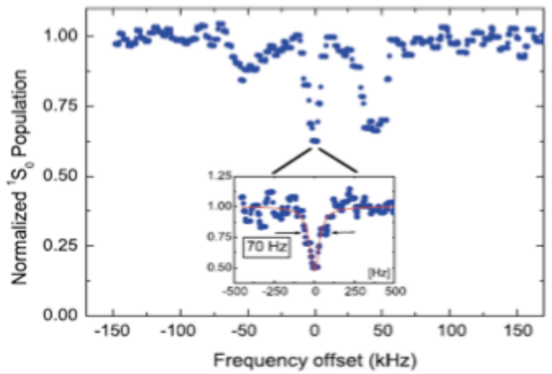
saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line



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

2009

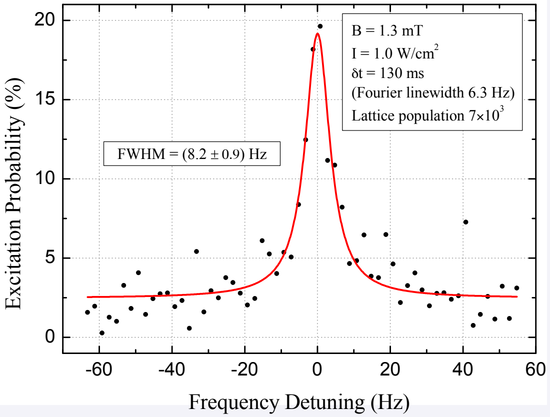
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



N. Poli, M.G. Tarallo, M. Schioppo, C.W. Oates, G.M. Tino, *A simplified optical lattice clock*, Appl. Phys. B 97, 27 (2009)

2012

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



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

N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks,* Rivista del Nuovo Cimento 36, n. 12, 555 (2013), arXiv:1401.2378

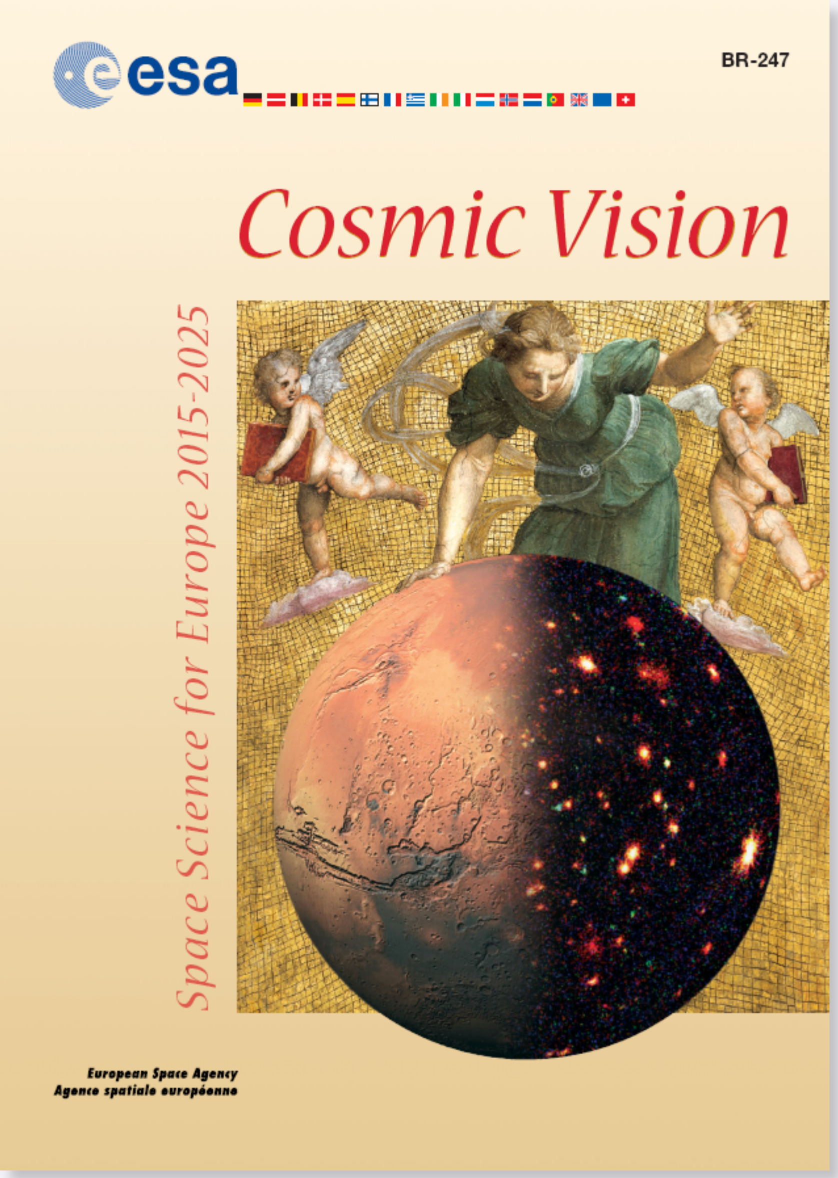
Clocks in Space

Optical clocks: $\sim 10^{-15} \cdot \tau^{-1/2}$ instability, $\sim 10^{-18}$ accuracy **Resonator clocks:** $\sim 10^{-17}$ 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)	$4 \cdot 10^{-10}$	$\sim 10^{4}$
Constancy of the speed of light - PRL **90**, 060402 (2003)	$7 \cdot 10^{-7}$	$>10^{3}$
Time dilation experiments - PRL 91, 190403 (2003)	$2 \cdot 10^{-7}$	$\sim 10^{3}$
Local Position Invariance		
Universality of the gravitational red-shift - PRD **65**, 081101 (2002)	$2 \cdot 10^{-5}$	$>10^{3}$
Time variations of fundamental constants - PRL **90**, 150801 (2003)	$7 \cdot 10^{-16}$	$>10^{2}$
Metric Theories of Gravity		
Gravitational red-shift - PRL **45**, 2081 (1980)	$7 \cdot 10^{-5}$	$>10^{3}$
Lense-Thirring effect – CQG **17**, 2369 (2000)	$3 \cdot 10^{-1}$	$\sim 10^{2}$
Gravitoelectric perigee advance - CQG **21**, 2139 (2004)	$3 \cdot 10^{-3}$	>10
1/r-Newton's law at long distances- PLA **298**, 315 (2002)	10^{-11}	>10

From L. Cacciapuoti, 2006

- STE-QUEST Space Mission-

Test of the gravitational red shift and equivalence principle



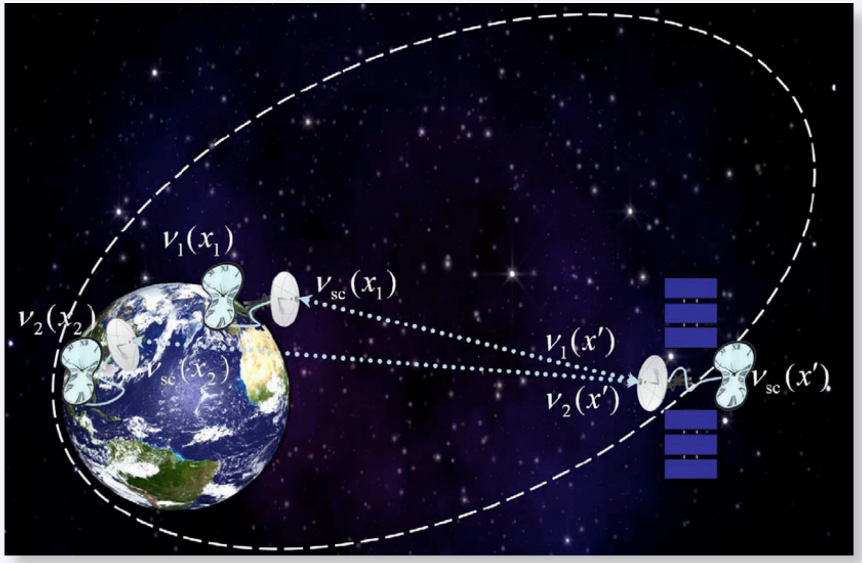
esa

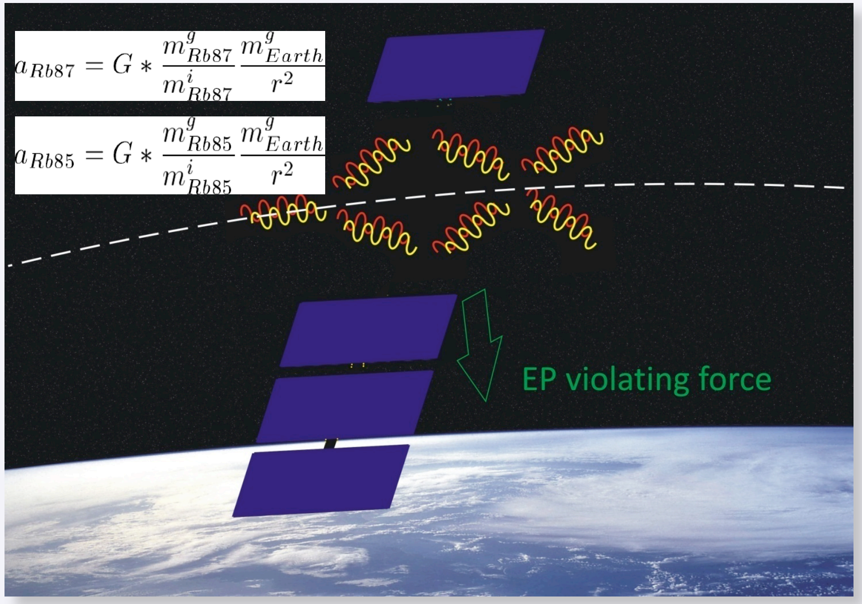
BR-247

Cosmic Vision

Space Science for Europe 2015-2025

European Space Agency
Agence spatiale européenne



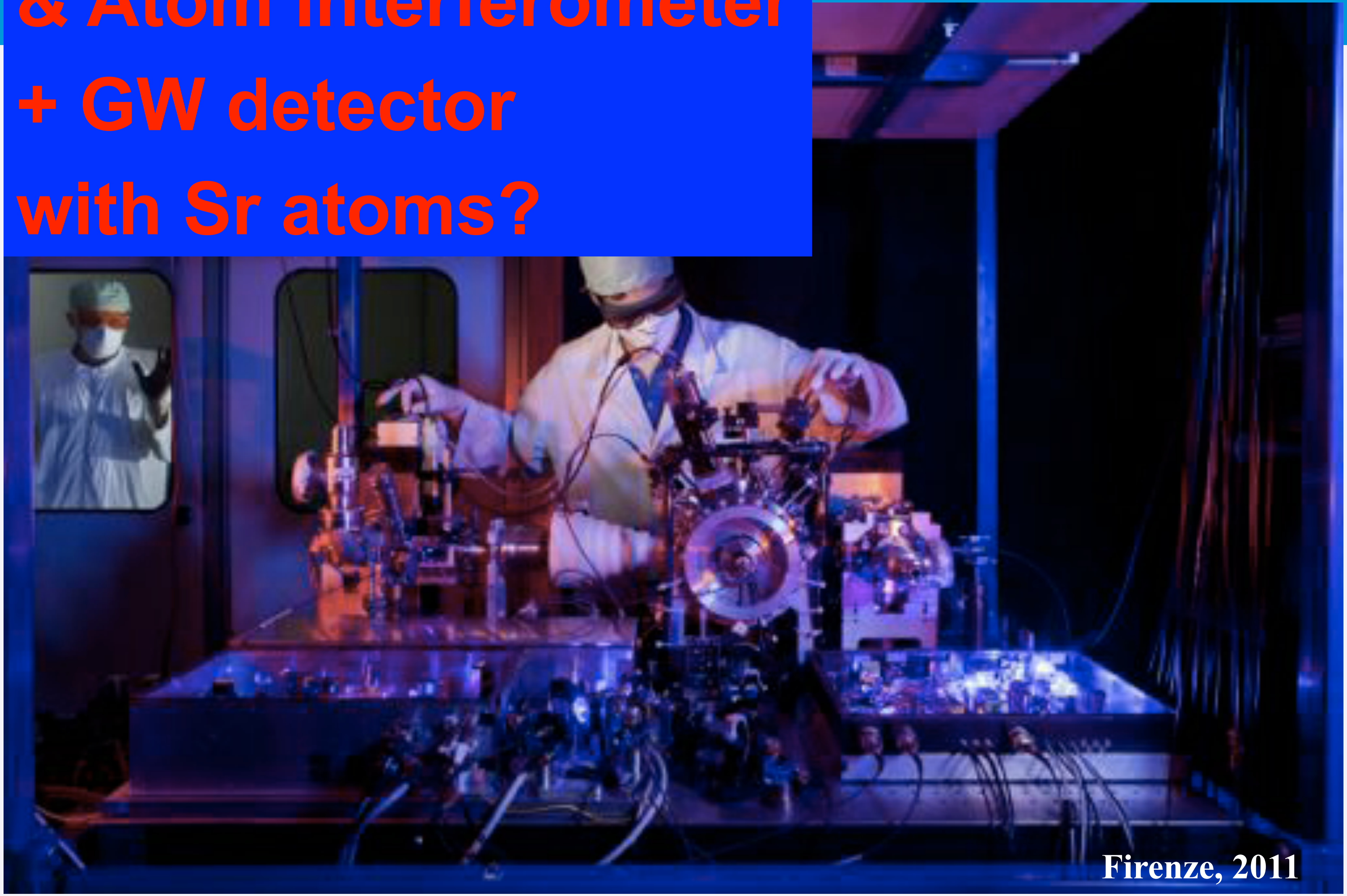


$$a_{Rb87} = G * \frac{m^g_{Rb87}}{m^i_{Rb87}} \frac{m^g_{Earth}}{r^2}$$

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

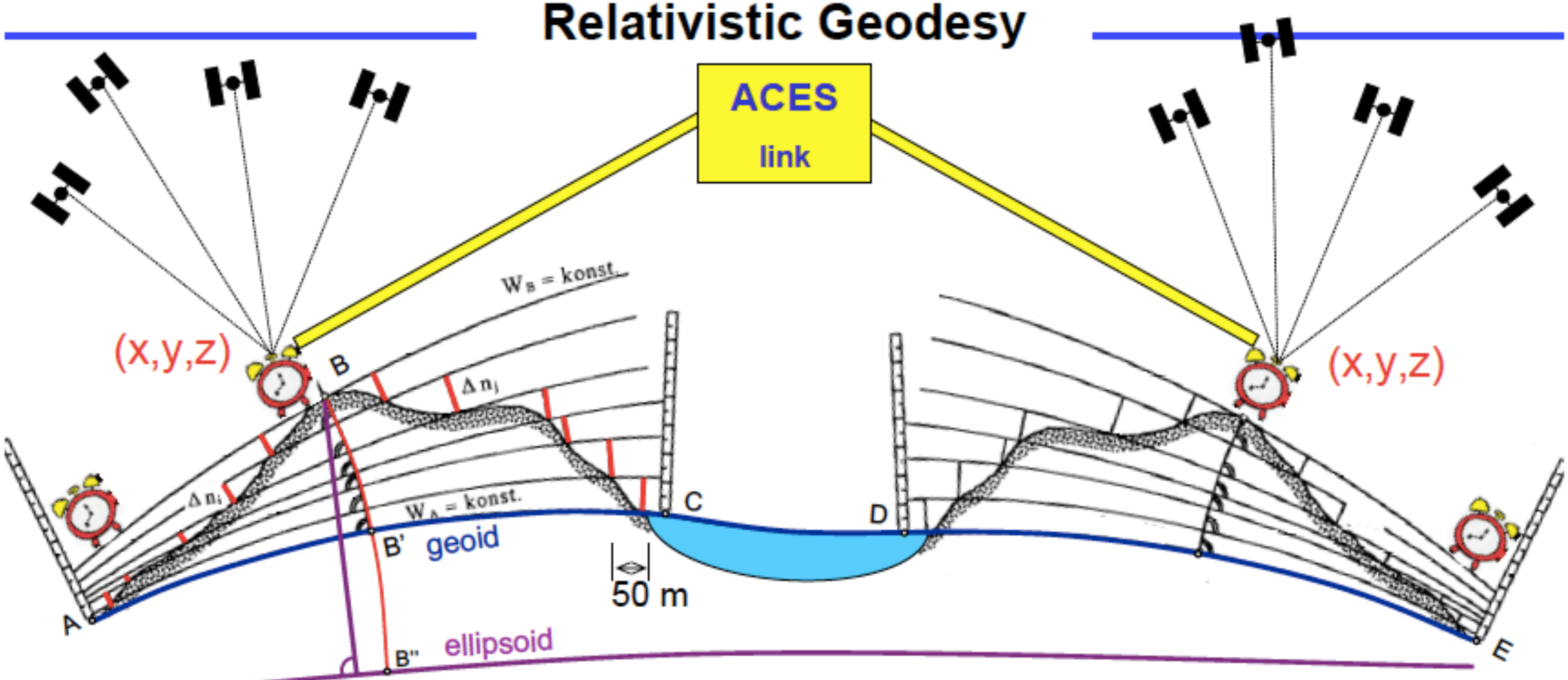
G. M. Tino et al., *Precision Gravity Tests with Atom Interferometry in Space*, Nuclear Physics B, 243–244, 203 (2013)

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


Firenze, 2011

G. M. Tino, in *Atom Interferometry*. Proc. International School of Physics 'Enrico Fermi', Course CLXXXVIII, Varenna 2013, SIF and IOS (2014)

Relativistic Geodesy



clock frequency

Gravitational potential

$$\nu_B/\nu_A = \Delta T_A/\Delta T_B = 1 + (V_B - V_A)/c^2$$

Geometry measured with GPS
Gravitational potential measured with optical clocks and ACES two-way links
Demonstrated accuracy of the ground optical clocks 2.6×10^{-17} (over only few hours)

Unification of the geometrical (GNSS) and gravitational positioning (optical clocks on the ground)

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

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Optical atomic clocks

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Conclusions

- New atomic clocks and atom interferometers are now available with unprecedented sensitivity using ultracold atoms and atom optics

- Applications: Fundamental physics, Earth science, Space research

- Well developed laboratory prototypes

- Work in progress for transportable/space-compatible systems