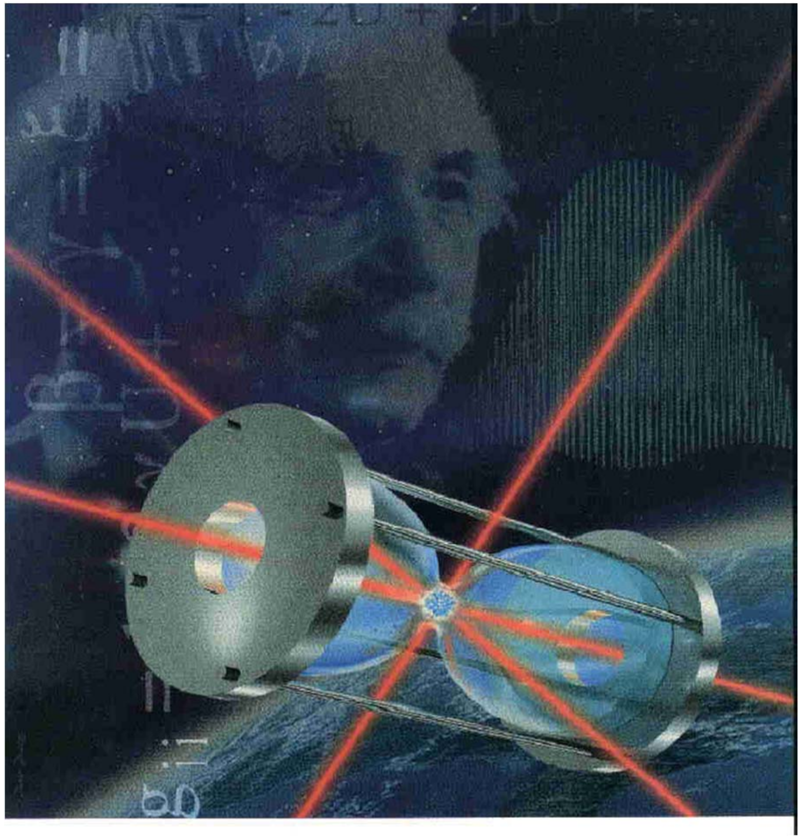
Atomic Quantum Sensors in Space and Fundamental Tests



C. Salomon

Laboratoire Kastler Brossel, Ecole Normale Supérieure, Paris

ISS Symposium, May 2-4, 2012, Berlin

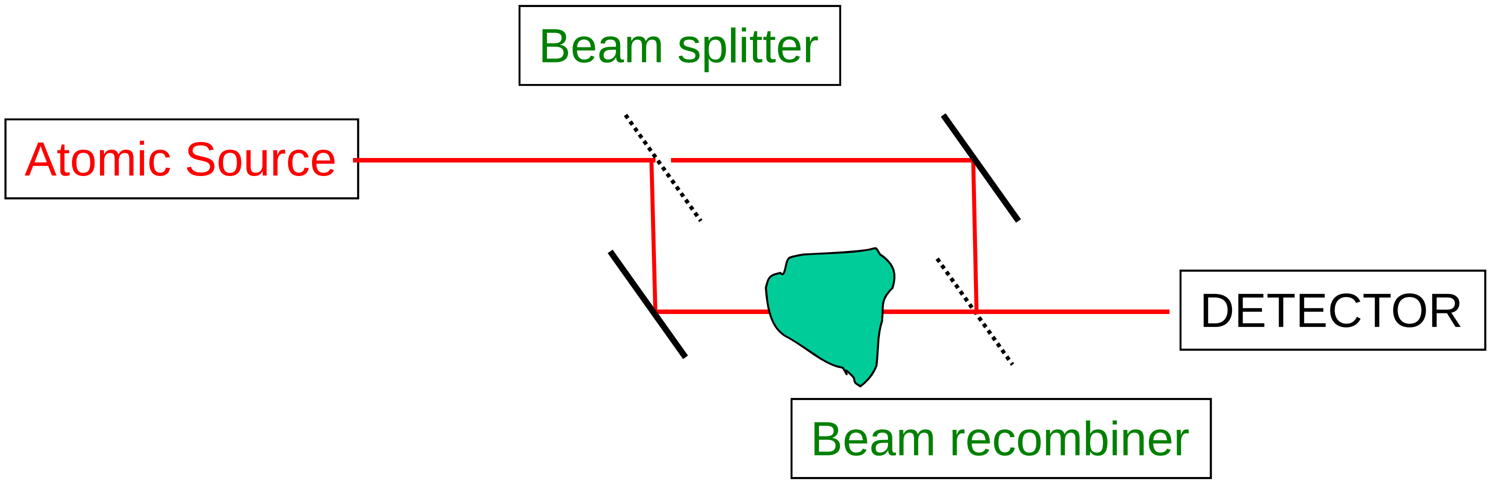
Slide 1

CS1 I would like to thank you for the very int visit. It is my 3 visit to Heidelberg.....
I would lke to describe the recent progress in col datom clocks and precision measureemnt. The fact that you can cool atom to tempeature of a few hunderd nanK enables to observe them for very long times and thus make precision measuremnts.
Christophe Salomon, 22/11/2007

Atomic Quantum Sensors

1) Use quantum interference in atoms for precision measurements
Matter-wave interferometers and clocks as old as Quantum Mech.

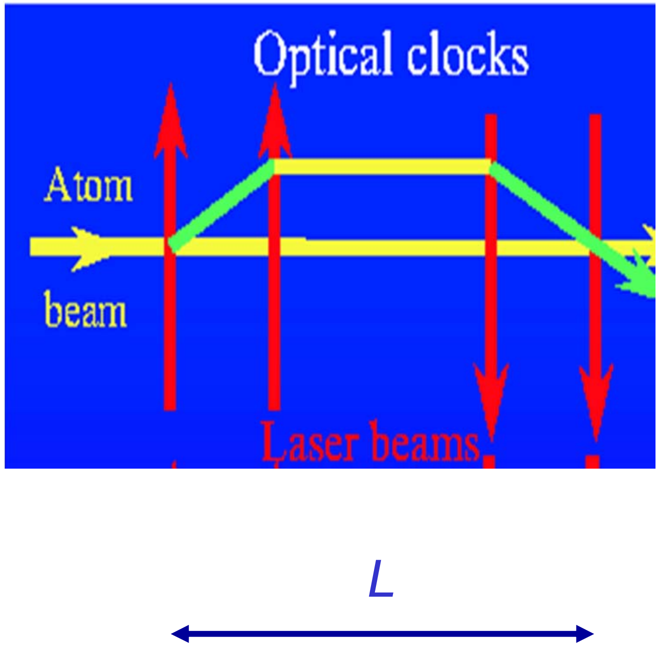
2) Space: cold atoms, microgravity, quietness, World coverage
New opportunities with large de Broglie wavelength $\lambda = h / Mv$



Atom interferometry and clocks → Atomic source, Beam splitters: lasers, Detectors

Matter-wave sensors and precision measurements

Clocks and Interferometers



T : interaction time with ELM field
Slow atoms: *T* large; atomic fountain or microgravity
Trapped atoms: *T* large
Clocks: gain prop. to *T*

Inertial sensors:
Accelerometers: gain as T^2
Sagnac gyrometers : gain as *L T*

Current sensitivity:
Acceleration: $\delta g/g = 1.4\ 10^{-8}$ in 1s
Rotation: $\Omega = 6\ 10^{-10}$ rad s^{-1} in 1 s

Clocks:
Frequency stability: $\delta\nu/\nu = 2\ 10^{-15}$ in 1s
Accuracy: $= 8.6\ 10^{-18}$

1989 Nobel Prize in Physics
N. Ramsey, H. Dehmelt, W. Paul

separated oscillatory fields method
for atomic clocks, ion trap techniques

1997 Nobel prize in physics
S. Chu, C. Cohen-Tannoudji, W. Phillips
Laser manipulation of atoms

2005 Nobel prize in physics
J. Hall, T. Haensch, R. Glauber
Laser precision spectroscopy
Optical frequency comb
Quantum optics

Fundamental Questions

1) **Missing mass in the Universe**

   Dark matter and dark energy represent 95% of the mass of the Universe but have unknown origin !

   New particles and/or change of the laws of gravity ?

2) **Atomic Sensors can tests fundamental laws with exquisite precision**

   Einstein's equivalence principle and Universality of Free Fall

   Tests of gravity in Earth orbit or at solar system scale

   Precision redshift measurement

   Variability of fundamental constants

3) **Quantum sensors have societal applications**

   Accelerometry, Gravimetry, Navigation, GPS, GALILEO, Geodesy, Earth monitoring,…

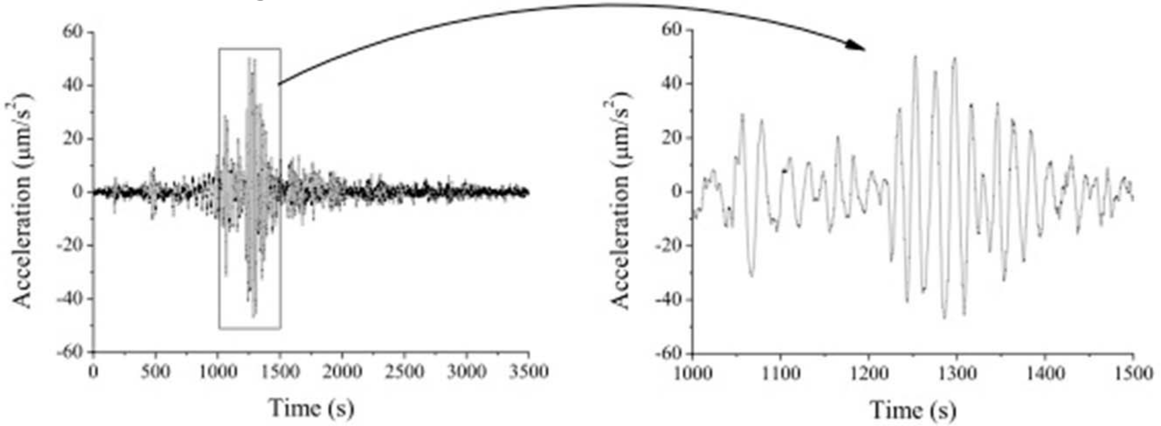
Complementarity to ground based research: example: cold atom gravimeter

$$\delta\phi = -k_{eff} a T^2 = -k_{eff} g T^2 = -2k_L g T^2$$

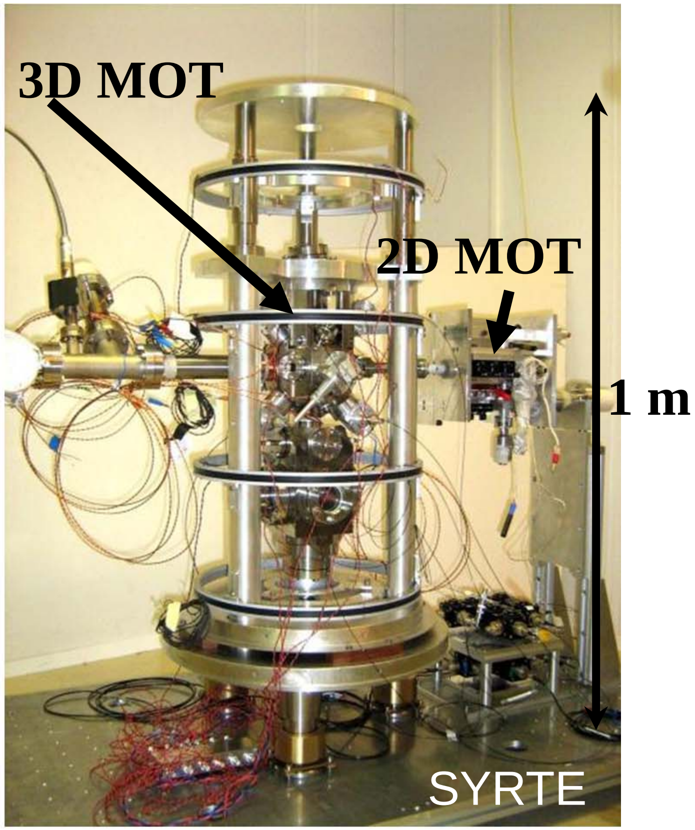
Ground sensitivity: $\sigma_g \sim 10^{-7}$ m.s^{-2} at 1s
with interrogation time 100 ms

Extrapolation to space: $<10^{-10}$ m.s^{-2} at 1s
with interrogation time 2 s

With ultra-cold atoms: $\sim 10^{-11}$ m.s^{-2} at 1s
with interrogation time 10 s



Earthquake in China, March 20th 2008 (magnitude 7,7)



Space Projects:
Q-WEP, SAI, ICE
Start-up company: MuQuans
Field applications

BEC in microgravity: QUANTUS

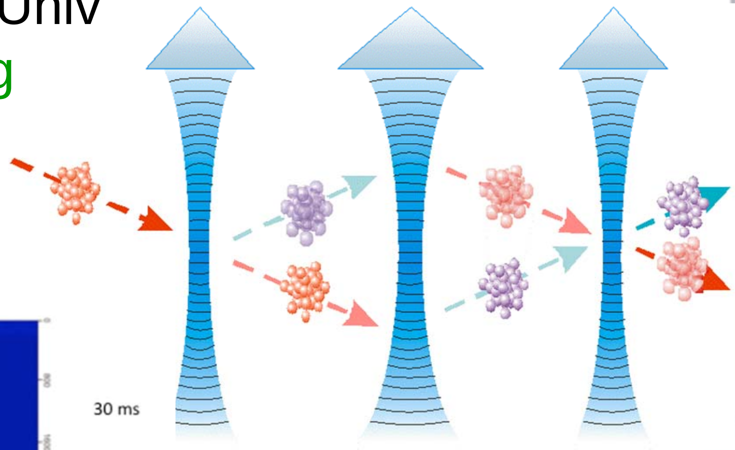
Exploring coherent matter waves at lowest energy scales, for:

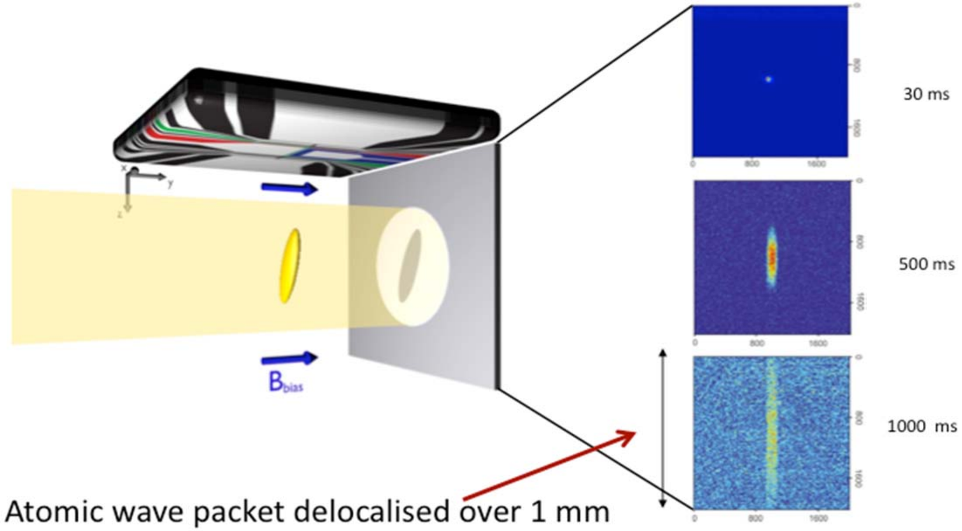
- Precision inertial sensing
- Quantum test of the Equivalence Principle at 1 part in 10^{15}

Coordinator: E. Rasel, Hannover Univ

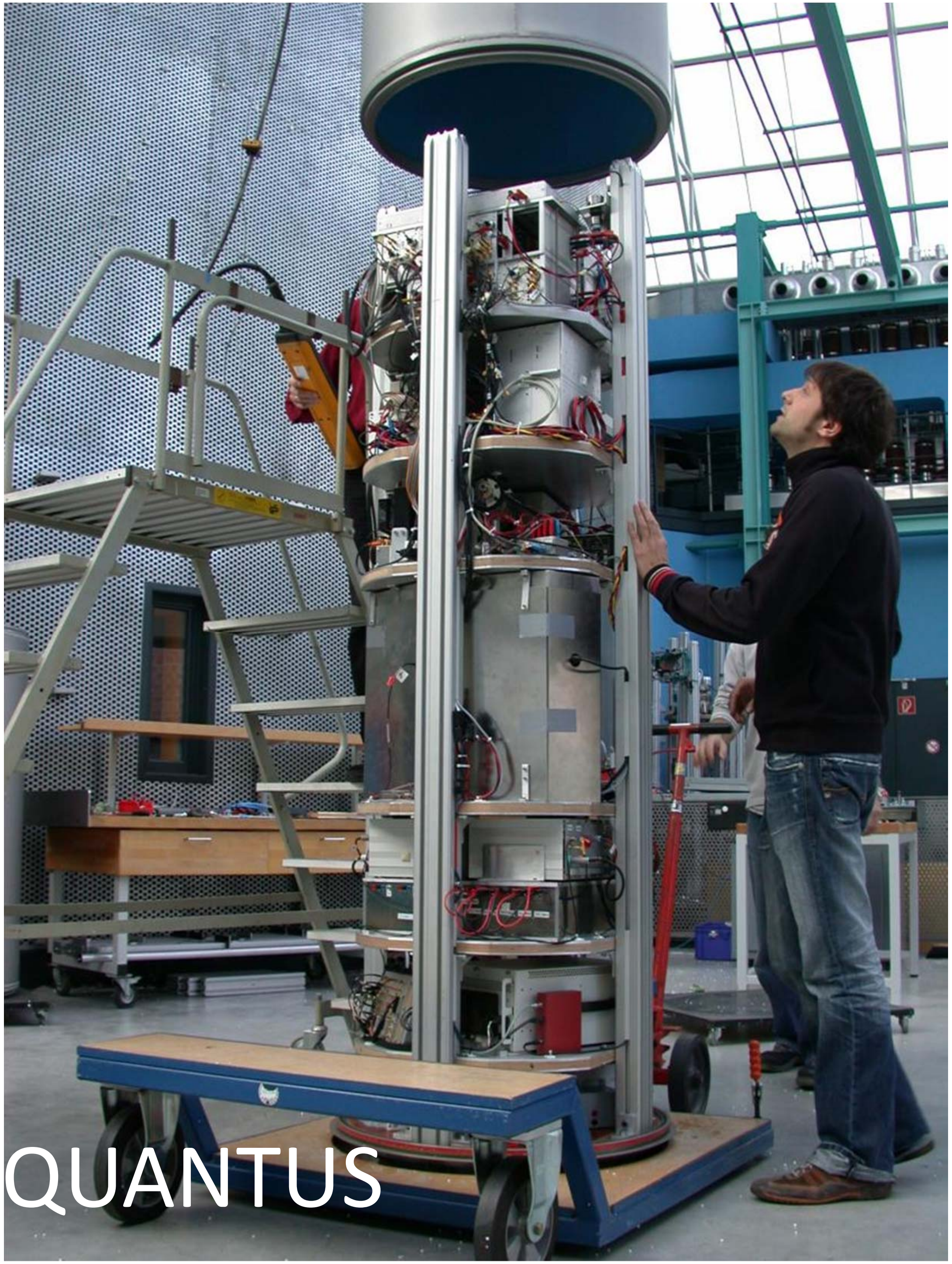
Bose-Einstein Condensation in μg

Science, June 16, 2010





DLR



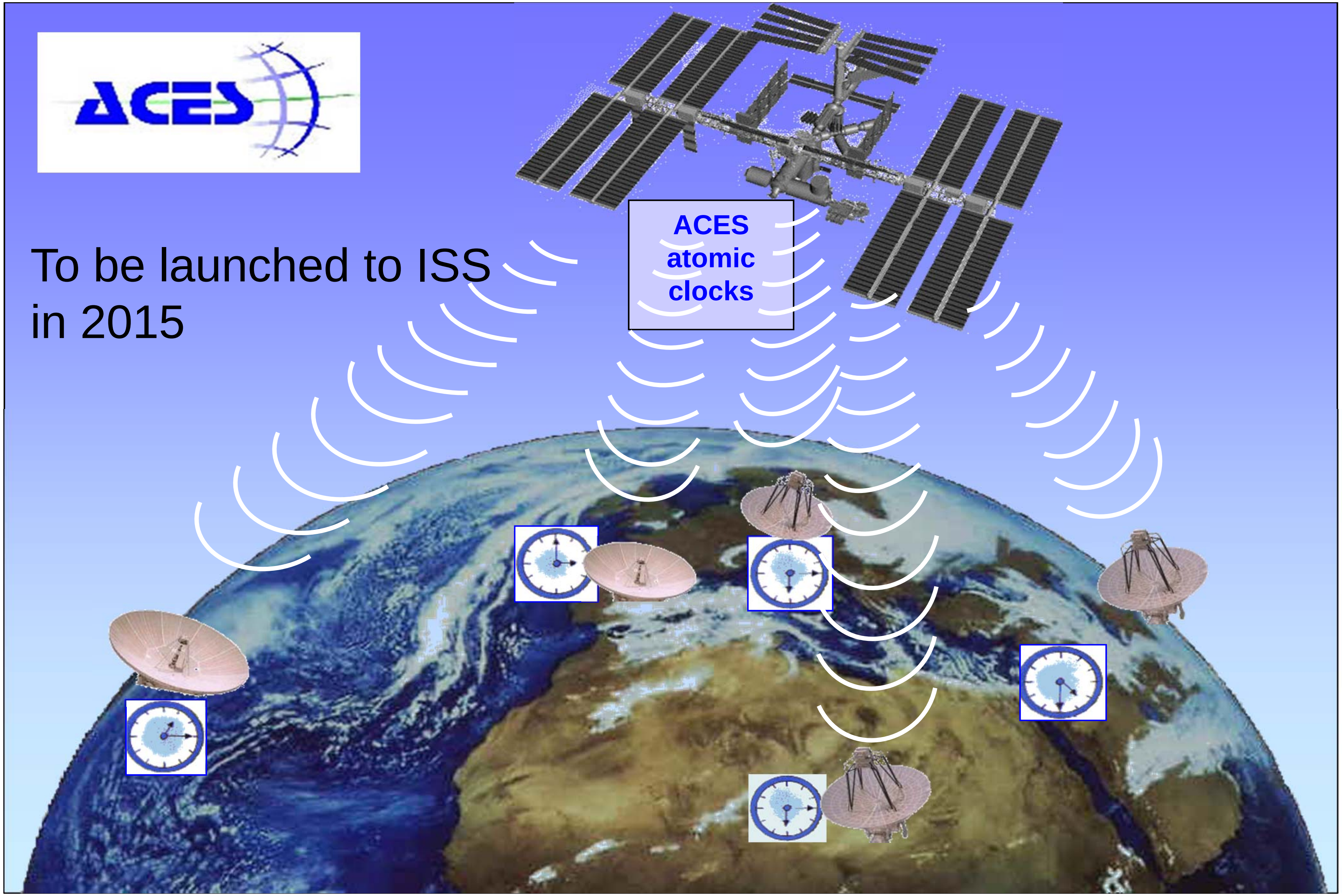
Achievements:

- Interferometry in free fall
- Robust alignment
- > 170 drops, 3 drops per day
- Study of Evolution & control of condensates

Goals:

- Test of chip-based and all-optical atom lasers for precision inertial sensing
- Atom interferometry with coherent matter waves
- Test of free fall of isotopes of potassium and rubidium
- STE-QUEST

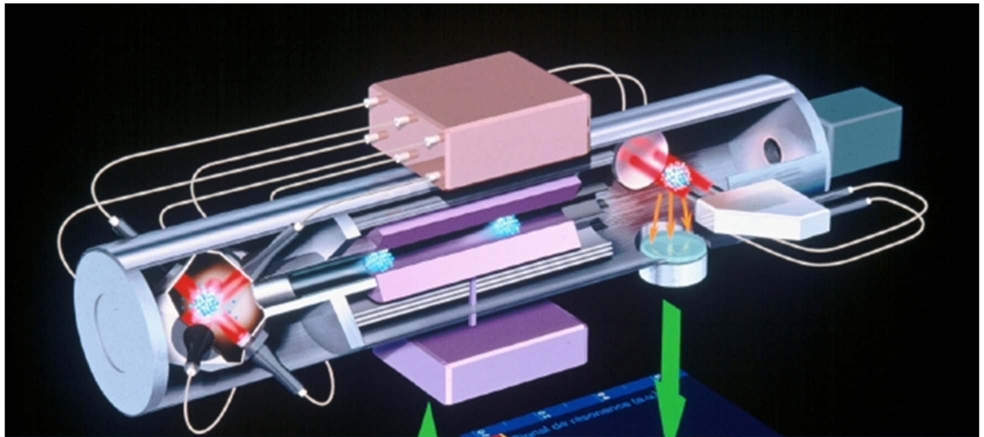
Atomic Clocks in Space: the ACES Mission on the ISS

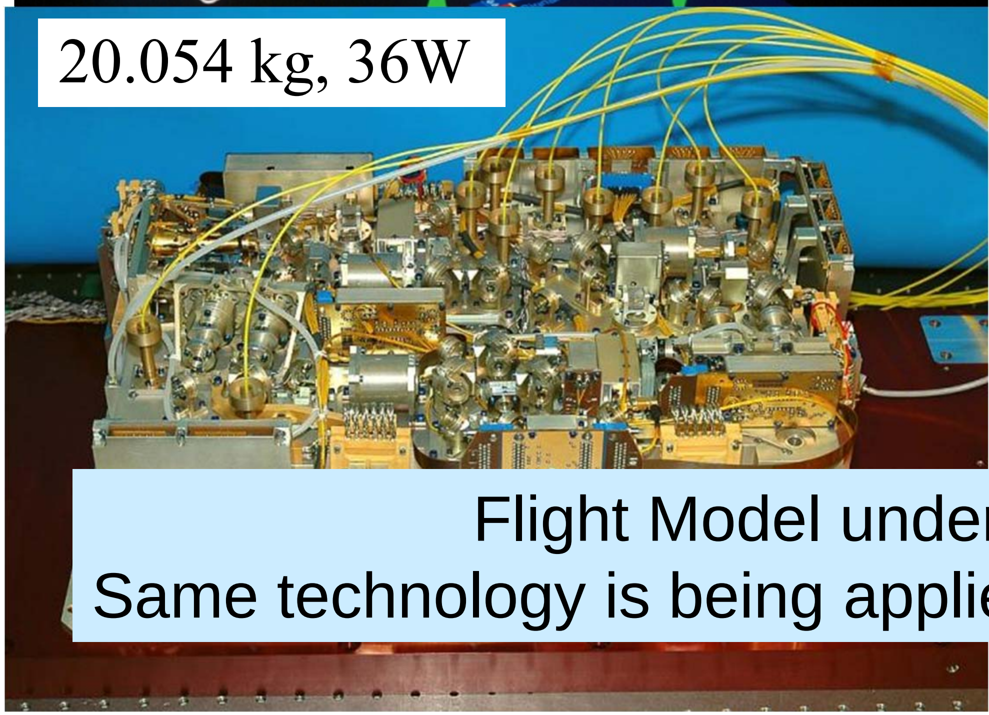


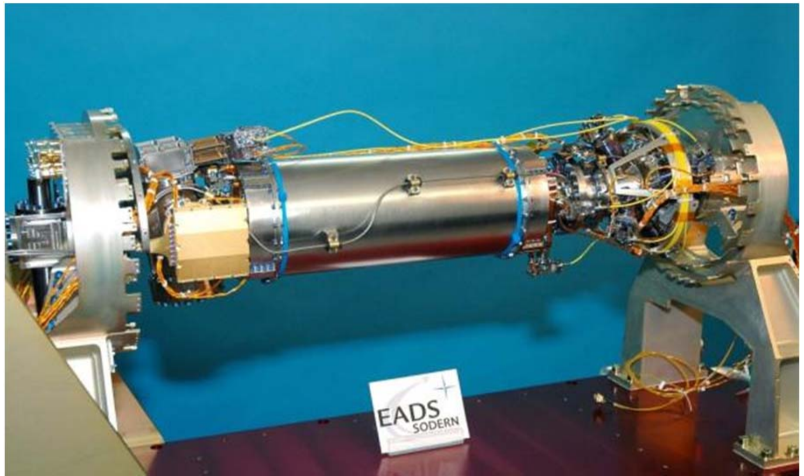
- A cold atom Cesium clock in space
- Fundamental physics tests
- Worldwide access

CENTRE NATIONAL D'ETUDES SPATIALES

Cold Atom Clock
in μ-gravity : PHARAO/ACES





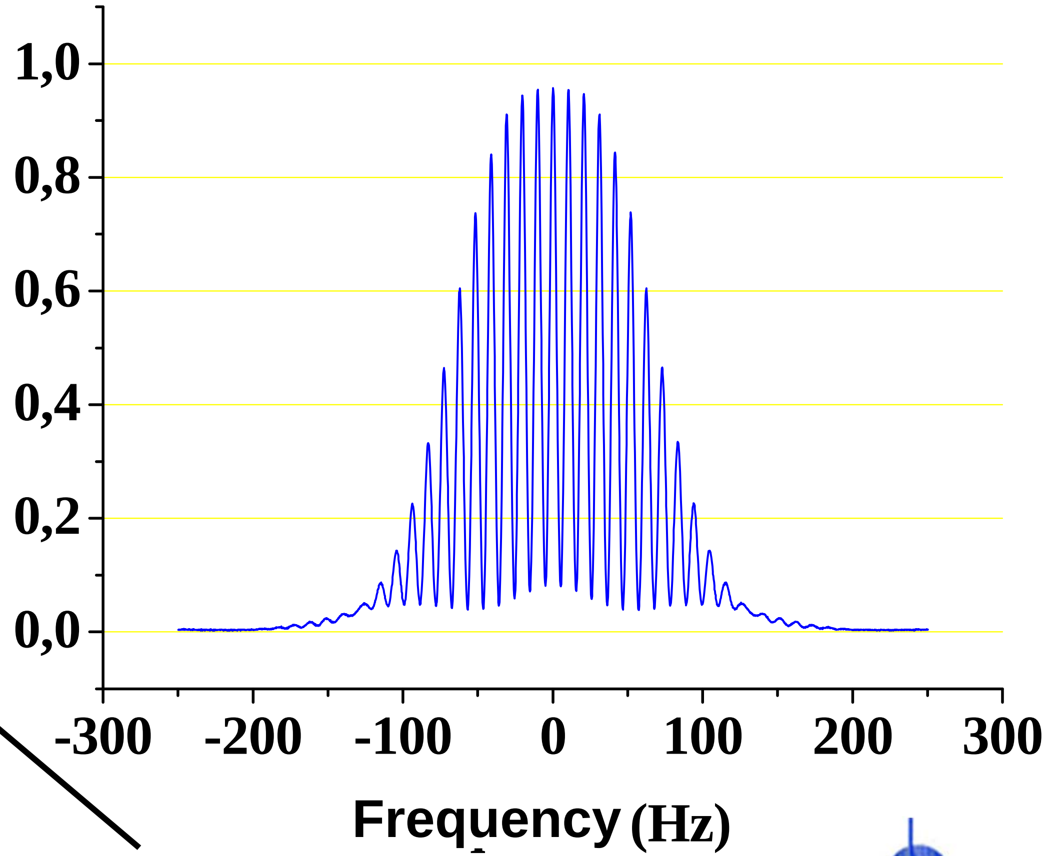


Flight Model under construction

Same technology is being applied to matter wave sensors

PHARAO Space Clock

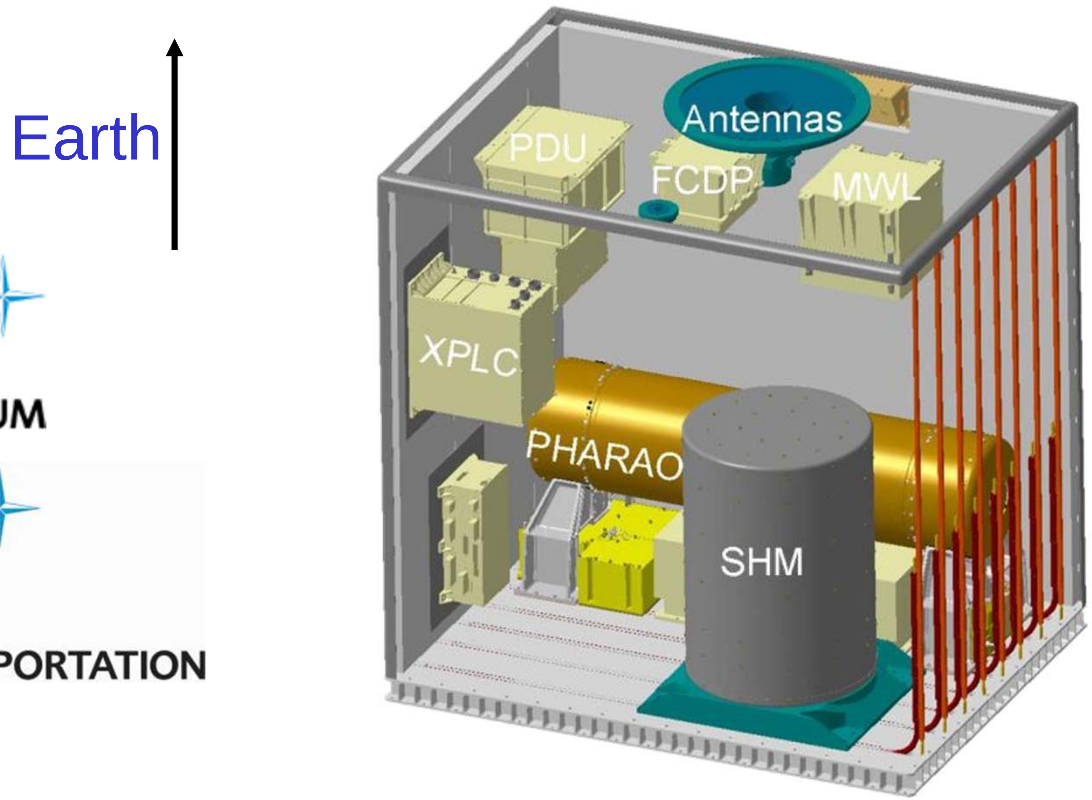
Laser source



Cesium tube

EM performance tests completed
Flight model under construction
Delivery: end of 2012

ACES General View



Mass: 227 kg, Power 450 W
Challenge: thermo-mechanical stability
Three year operation

ACES on Columbus external platform

ACES

Current launch date : 2015

Mission duration : 18 months to 3 years

Do fundamental physical constants vary with time ?

Motivation: unification theories, string theory,…
Damour, Polyakov, Marciano,….

α_{elm}, m_e / m_p…

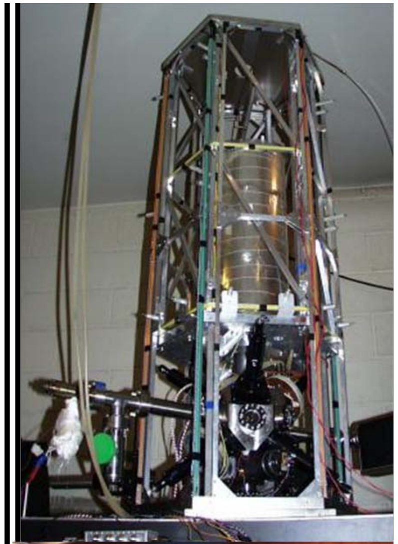
Principle : Compare two or several clocks of different nature as a function of time

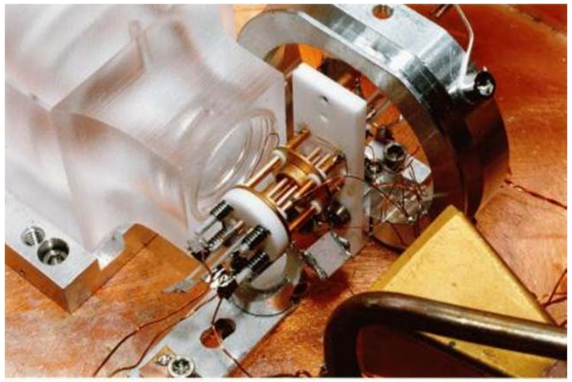
Microwave clock/Microwave clock: α, m_e/m_p, $g^{(i)}$

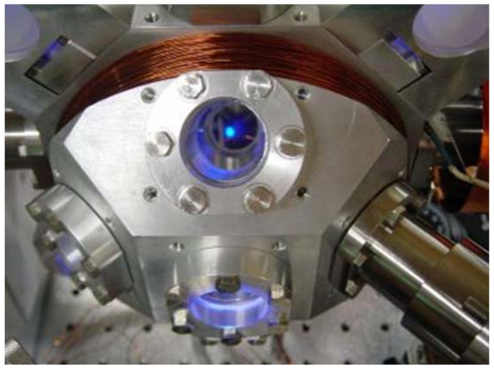
rubidium and cesium

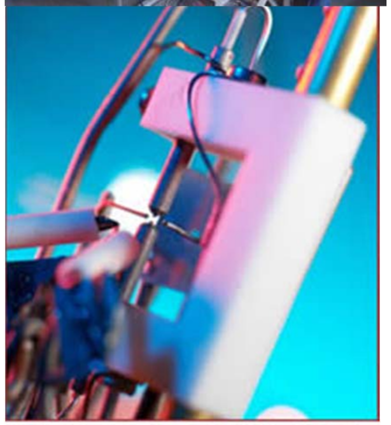
Microwave/Optical clock : α, m_e/m_p, $g^{(i)}$

Optical Clock / Optical clock: α

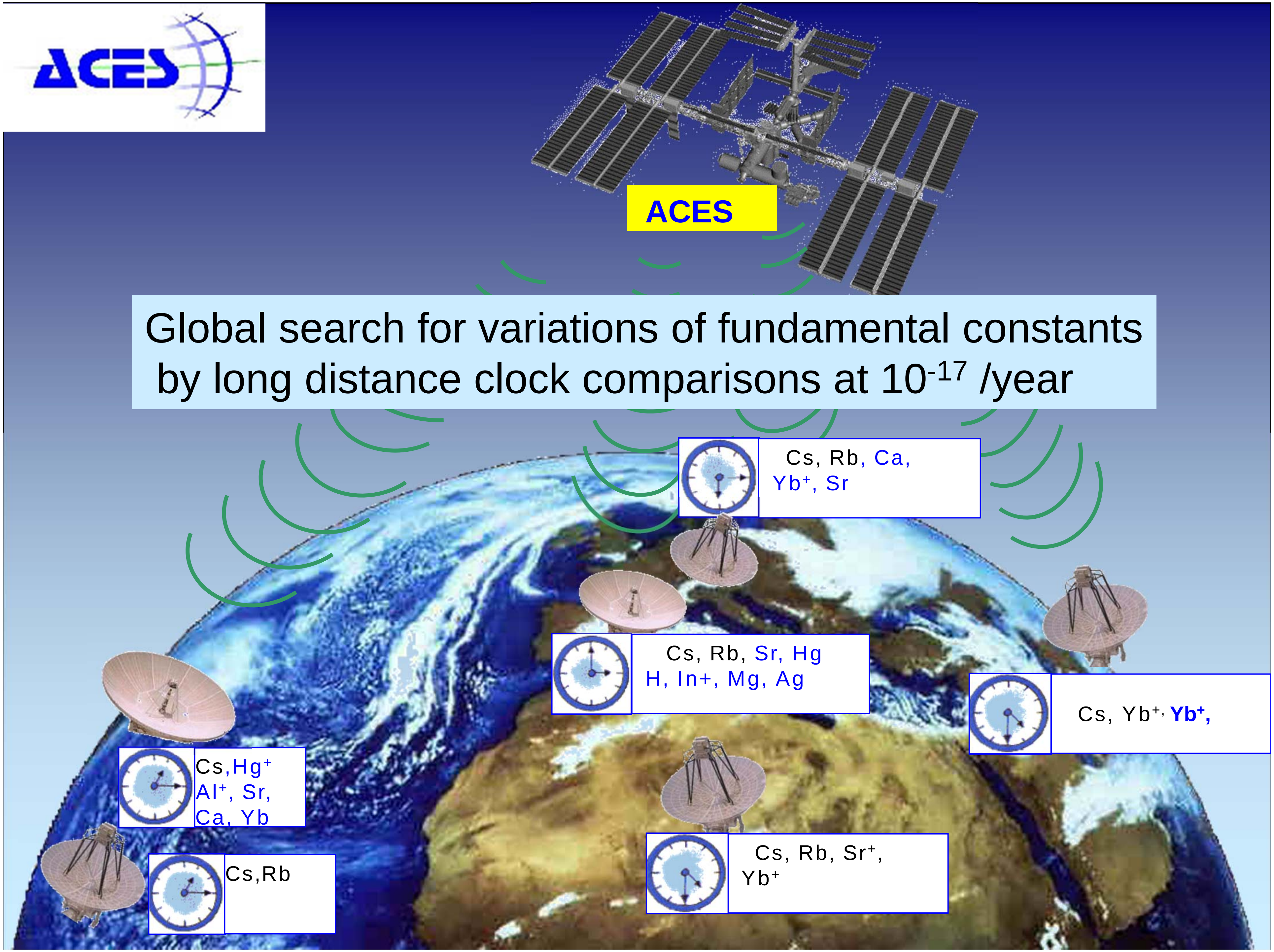




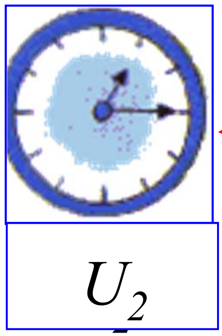


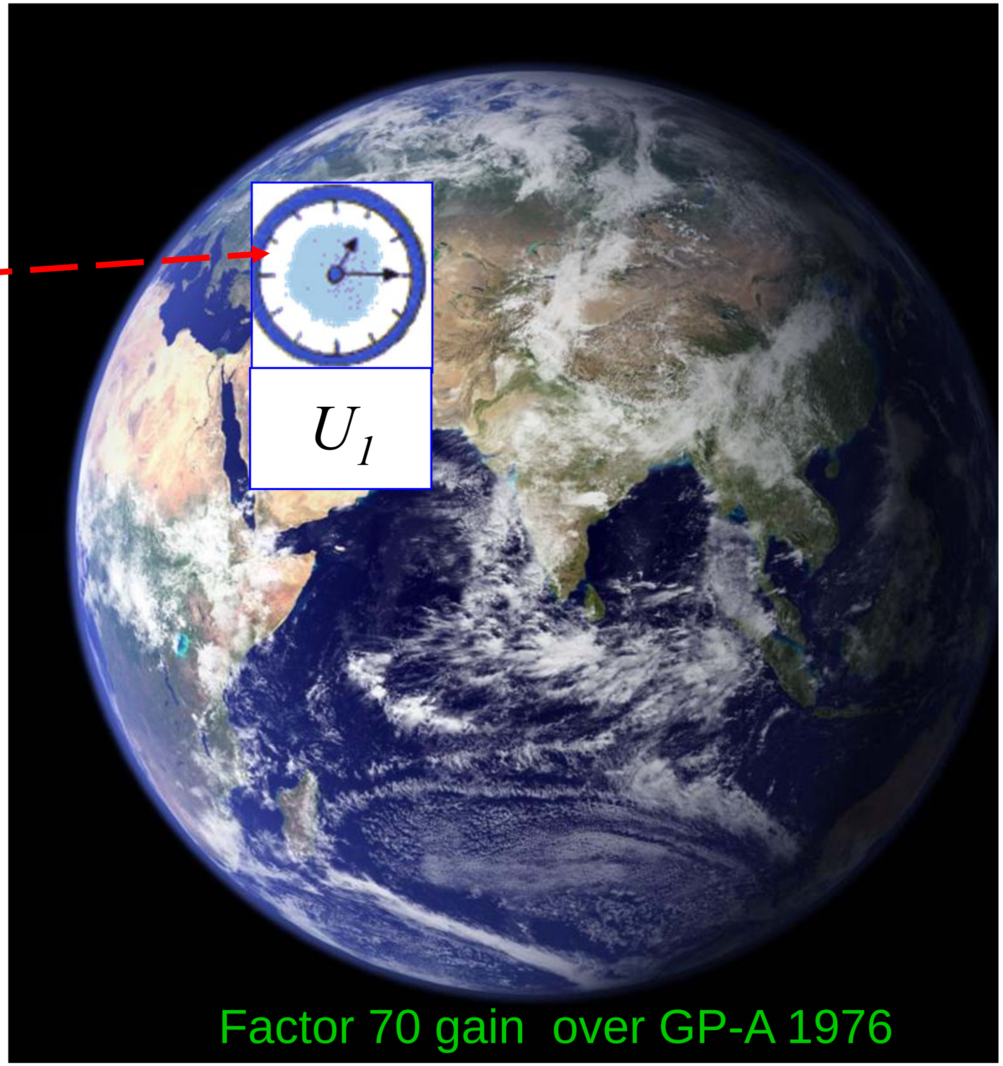


The ovens and electrodes of the NPL strontium ion end-cap trap.


ACES
ACES
Global search for variations of fundamental constants
by long distance clock comparisons at 10^-17 /year
Cs, Rb, Ca,
Yb+, Sr
Cs, Rb, Sr, Hg
H, In+, Mg, Ag
Cs, Yb+, Yb+,
Cs,Hg+
Al+, Sr,
Ca, Yb
Cs,Rb
Cs, Rb, Sr+,
Yb+

A Prediction of General Relativity: the gravitational redshift



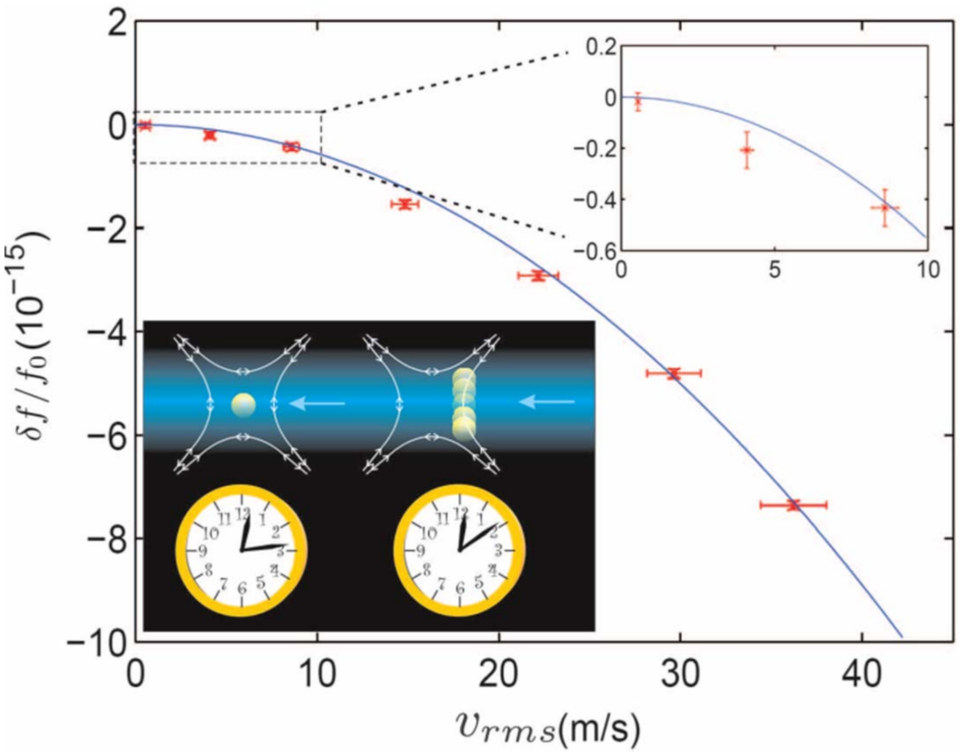


$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

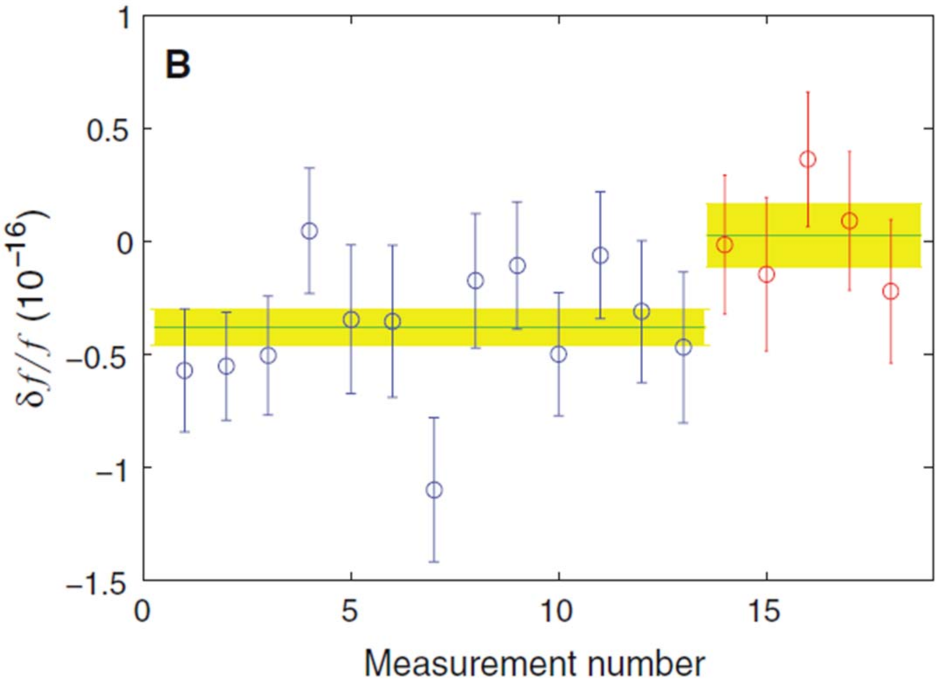
Redshift : 4.59 10^{-11}
With 10^{-16} clock
ACES: ~2 10^{-6}

Relativity with Optical Clocks at 30 cm level

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland, Science 329, 1630, (2010)



Time dilation

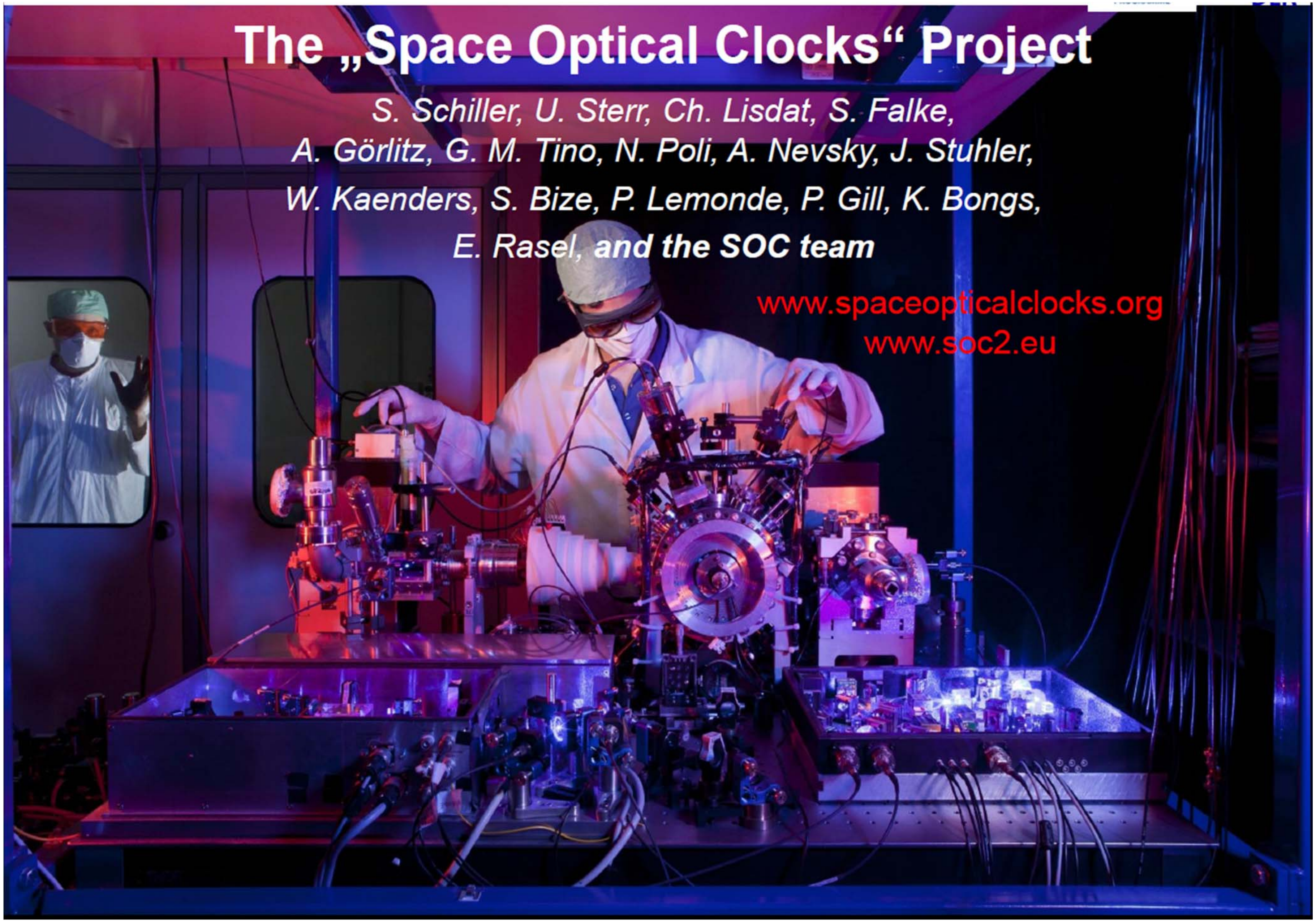


Gravitational shift

Clock B is lifted up by 33 cm

its rate is increased by 3. 4 10^{-17}

Optical Clocks for Space

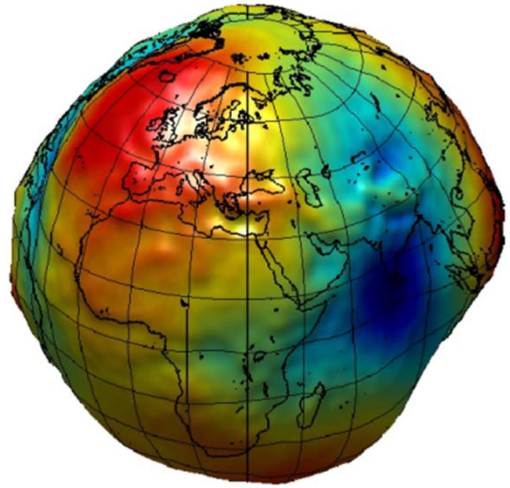


Relativistic Geodesy

The clock frequency depends on the Earth gravitational potential

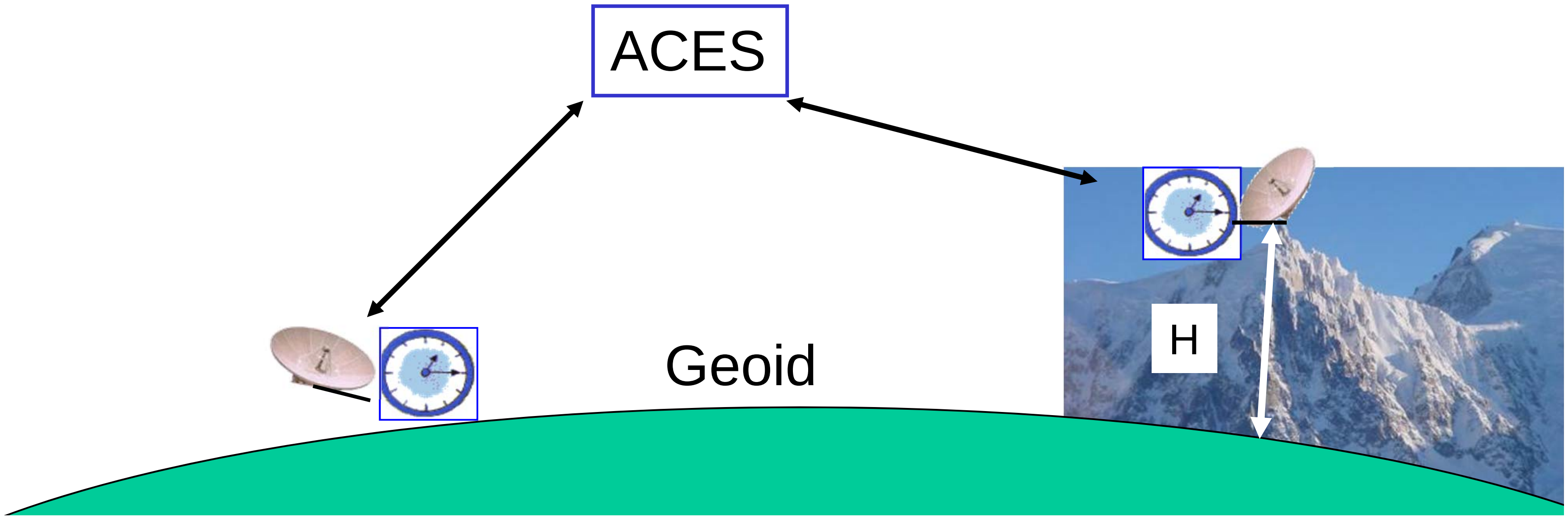
10^{-16} per meter

Best ground clocks have accuracy of 9 10^{-18} and will improve ! (NIST '10)



Competitive with satellite + levelling techniques at ~ 20 cm level

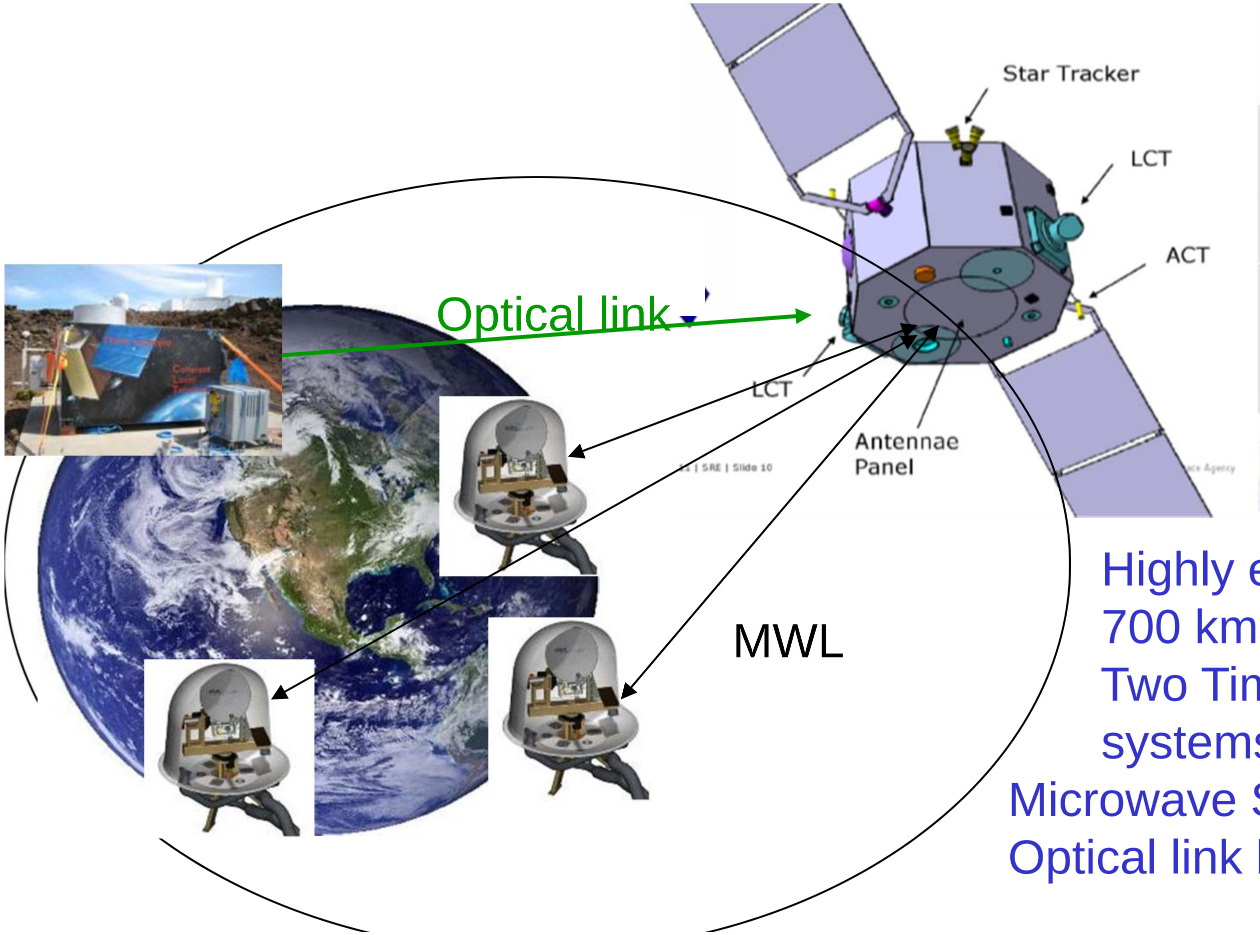
Possibility to measure the **potential difference** between the two clock locations at 10^{-17} level ie 10 cm

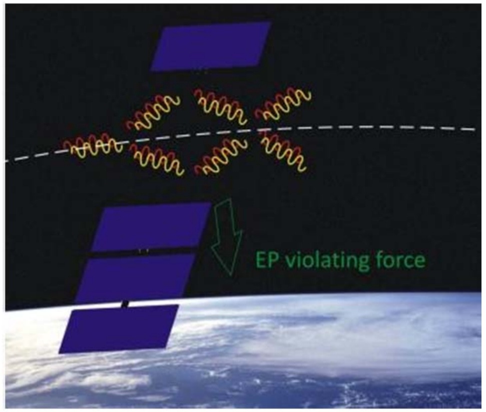


STE-QUEST

Space-Time Explorer and Quantum Equivalence Principle Space Test
Currently one of the 4 candidate missions to Cosmic Vision Medium class size

- Earth gravitational red shift at 0.17ppm (x 700 over GPA, x10 beyond ACES)
- Test of the EP at 10^{-15} with quantum objects, vs Microscope with classical masses





Highly elliptical Earth orbit
700 kms to 55 000 kms
Two Time and Frequency Transfer
systems with 10^{-18} stability
Microwave S and Ka bands 2-26 GHz
Optical link based on TESAT laser comm.

Future Time Definition from Space

1) The Earth gravitational potential fluctuations will limit the precision of time on the ground at 10^{-18}-10^{-19} (ie: cm to mm level)
2) The only Solution: set the reference clocks in space where potential fluctuations are vastly reduced
3) Improved Navigation, Earth Monitoring and Geodesy
4) Interesting for fundamental physics Tests

Summary

Matter-wave interferometers and cold atom clocks have entered into high precision measurement phase

Technology has progressed fast with routinely working instruments
Clocks reach stabilities and accuracies in the sub 10^{-17} range

Impressive efforts for miniaturization and reliability for space and ground
Compact laser sources and atom chips
quantum gases sources: BEC in microgravity and atom lasers

ACES on the ISS (2015-2017); new relativity tests

Optical Clocks with 10^{-17} frequency stability in 2020 on the ISS or satellite
Test of Equivalence Principle in Space with quantum objects beyond 10^{-15}
Precise accelerometry demonstration

High precision quantum sensors will bring tests of the laws of gravitation to a new level of precision esa

PTB

Leibniz Universität Hannover

Atom-Chip

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

cnrs

FBH

quest

Robust & Compact Laser

Fermionic Source

DLR

Ens

ONERA
THE FRENCH AEROSPACE LAB

INSTITUT d'OPTIQUE GRADUATE SCHOOL

UHH

TECHNISCHE UNIVERSITÄT DARMSTADT

Theory

l'Observatoire de Paris — BNM-SYRTE
Bureau National de Métrologie - Systèmes de Référence Temps-Espace

ECOLE NORMALE SUPERIEURE

ZARM

DLR

Drop Tower & Space Integration

EADS SODERN

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

PHARAO

THALES

INRIM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

UNIVERSITY OF BIRMINGHAM

NPL
National Physical Laboratory

TOPTICA PHOTONICS

KAYSER-THREDE
Ein Unternehmen der OHB Technology AG

EADS astrium

MenloSystems GmbH

KAYSER ITALIA

LTF Université de Neuchâtel unine

LENS
EUROPEAN LABORATORY FOR NON-LINEAR SPECTROSCOPY

csem
centre suisse d'électronique et de microtechnique

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Thank you for your attention !