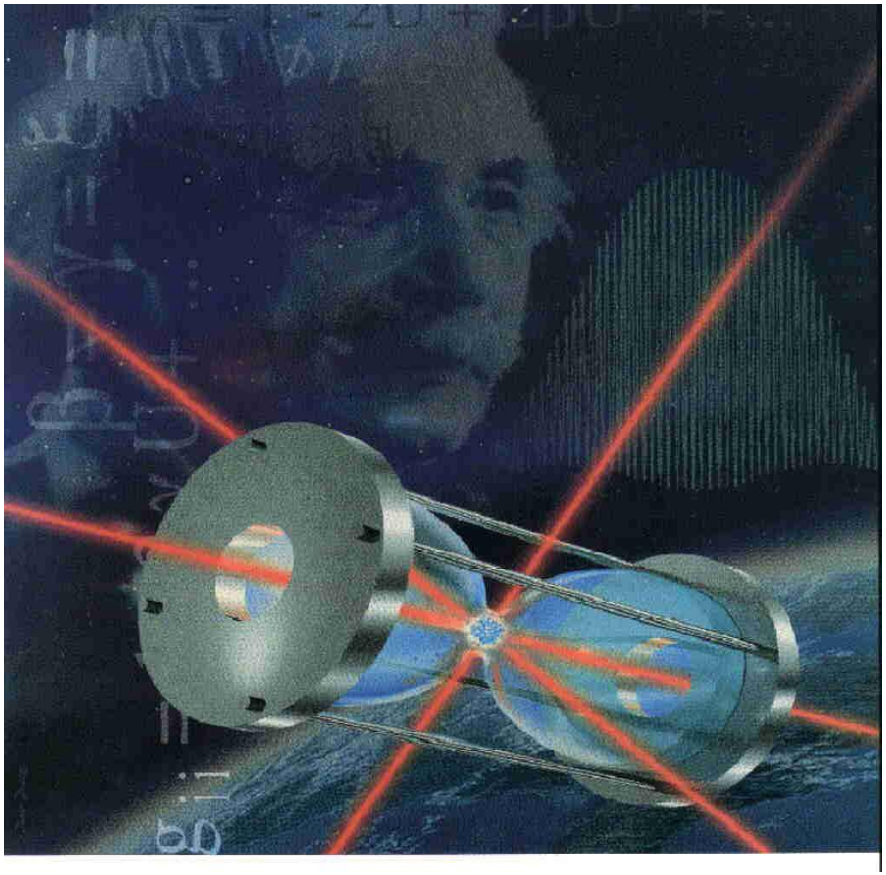
Fundamental Tests with Ultrastable Clocks



ESF-PORTO
March 29, 2008

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http://www.lkb.ens.fr/recherche/atfroids/welcome
http://www.lkb.ens.fr/%7esalomon/

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Discussions with T. Damour and J. P. Uzan

Fundamental Physics Tests using ultra-stable clocks

Search for variation of fundamental constants with Laboratory clocks

Tests present values of fundamental constants (z=0)

Complementary to astrophysical observations such as quasar absorption spectra or OKLO nuclear reactor
See Paolo Molaro's talk

Modern clocks have ~10^{-16} /year sensitivity
Quasar spectra have ~10^{-6} resol. x 10^{10} years ~ 10^{-16}/year

Summary

1) What is an atomic clock ?

Frequency stability,

Accuracy

2) Fundamental tests

Search for drift of fundamental constants

Precision redshift measurement

4) Perspectives

Space clocks, PHARAO/ACES

Time measurement

Find a periodic phenomenon:

1) Nature:

observation: Earth rotation, moon rotation, orbit of pulsars,..

2) Human realization: egyptian sandstone, Galileo pendulum….

simple phenomenon described by a
small number of parameters

The faster the pendulum,
The better is time resolution

$$T = 2\pi\sqrt{l/g}$$

Time measurement (2)

Electromagnetic field:

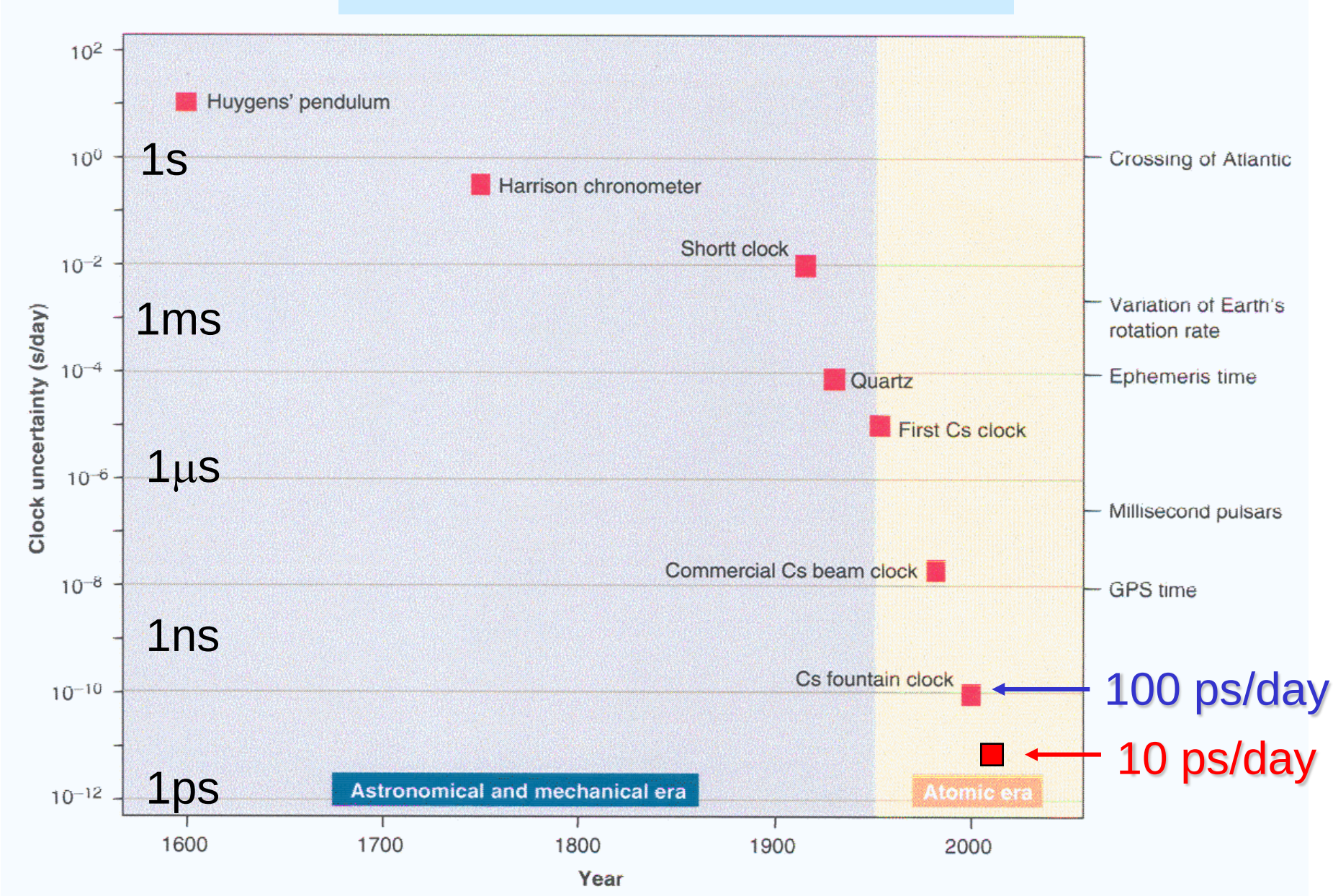
Quartz oscillator,… vibration of crystal coupled to an electrical circuit

Atomic Clock:

Intrinsic stability of energy levels (Quantum Mechanics)
Control of atomic motion
Laser cooling: low velocities : 1 cm/s

→ Long measurement time:
→ Narrow atomic resonance
→ Better clock

Precision of Time

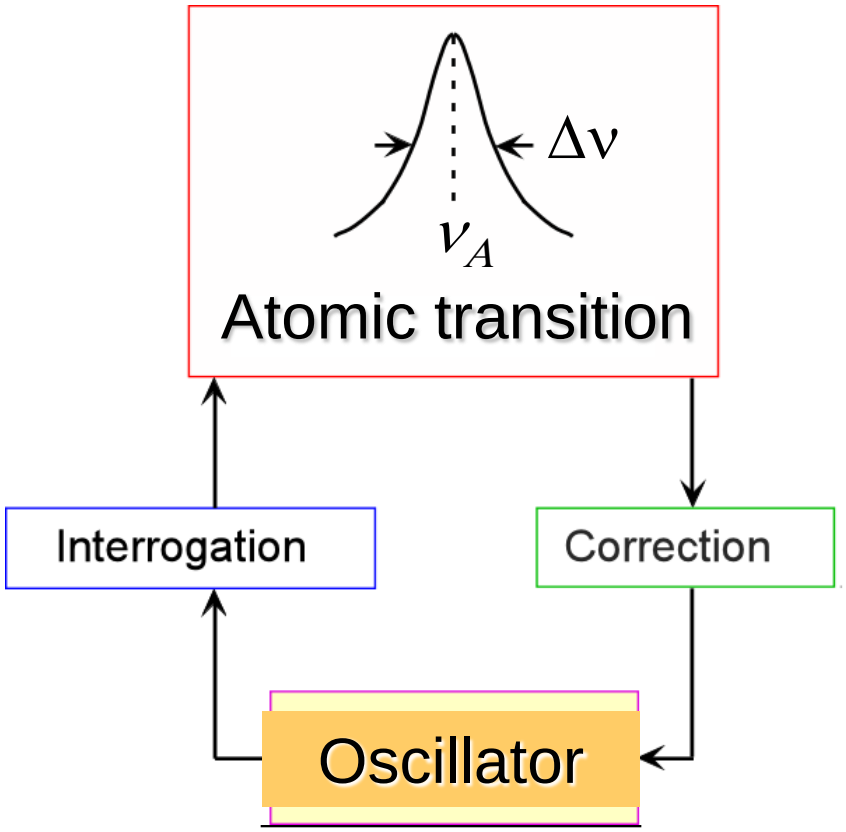


Atomic Clock

An oscillator of frequency ν produces an electromagnetic wave which excites une transition a - b

The transition probability a→b as a function of ν has the shape of a resonance curve centred in $\nu_A = (E_b - E_a) / h$ and of width $\Delta\nu$

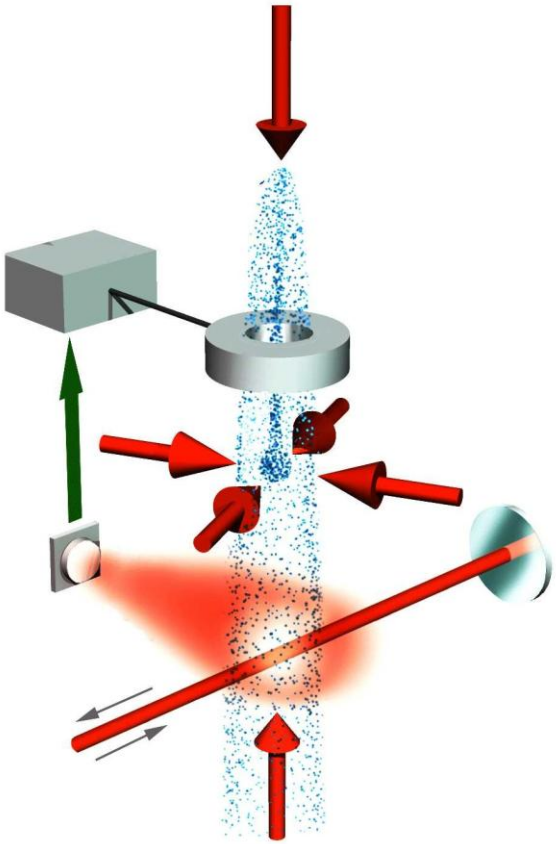
A servo system forces ν to stay equal to the atomic frequency ν_A



An atomic clock is an oscillator whose frequency is locked to that of an atomic transition

The smaller $\Delta\nu$, the better is the precision of the lock system

Atomic clock



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 electronic state of cesium 133

Intrinsic stability of atomic energy levels

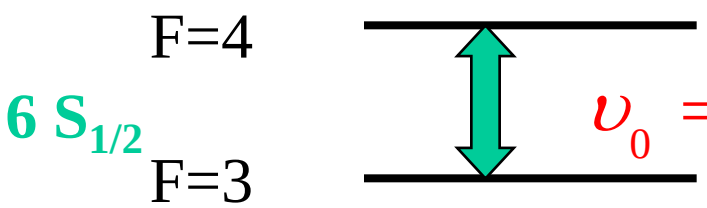
Laser cooling to 1 µK

Corresponding to rms velocity of 7mm/s

1) Fountain geometry

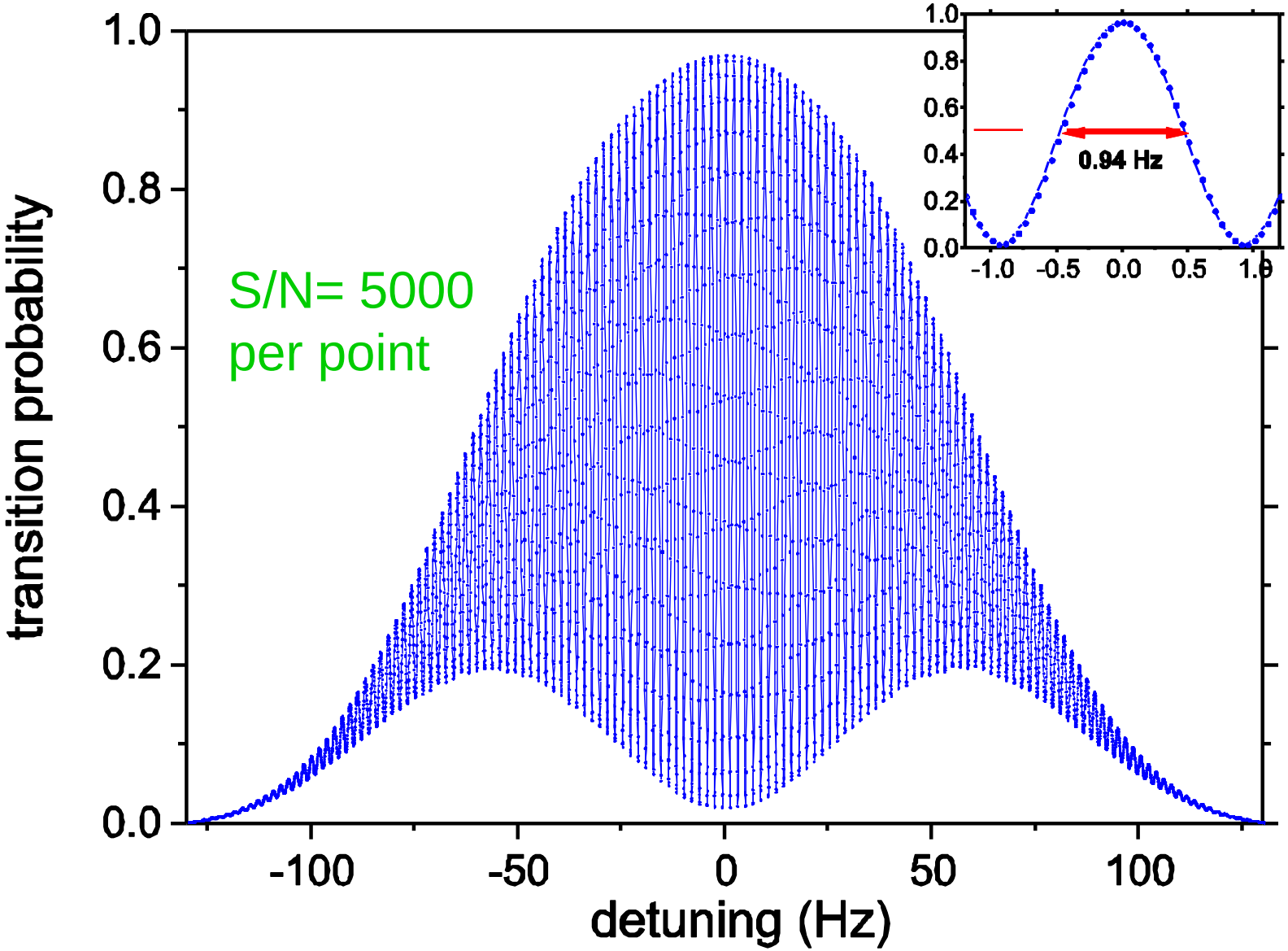
2) Microgravity environment

1. **Stability**
2. **Accuracy**



$\upsilon_0 = 9\ 192\ 631\ 770$ **Hz**

Ramsey fringes in atomic 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 realize the definition of the second?

Cesium fountains: $\varepsilon \sim 4\ 10^{-16}$; Al+ and Hg+ : $2\ 10^{-17}$

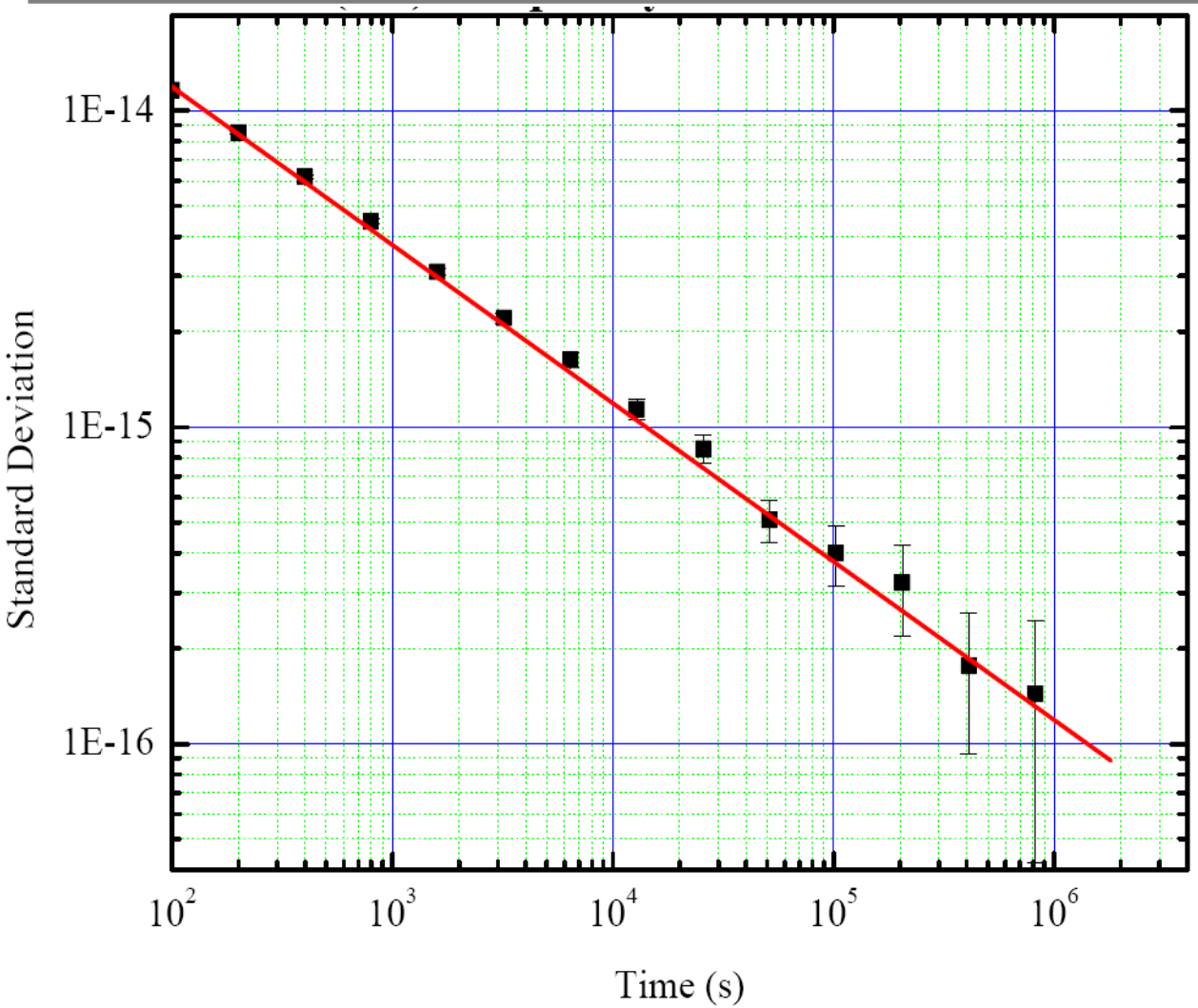
Frequency stability

Measurement duration τ: $y(\tau)$ averaged frequency instability

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

For τ= 50 000 s to 10^6 s, $y(\tau) \sim 1 \times 10^{-16}$

Comparison between two Fountains FOM and FO2-Rb (Paris Observatory)

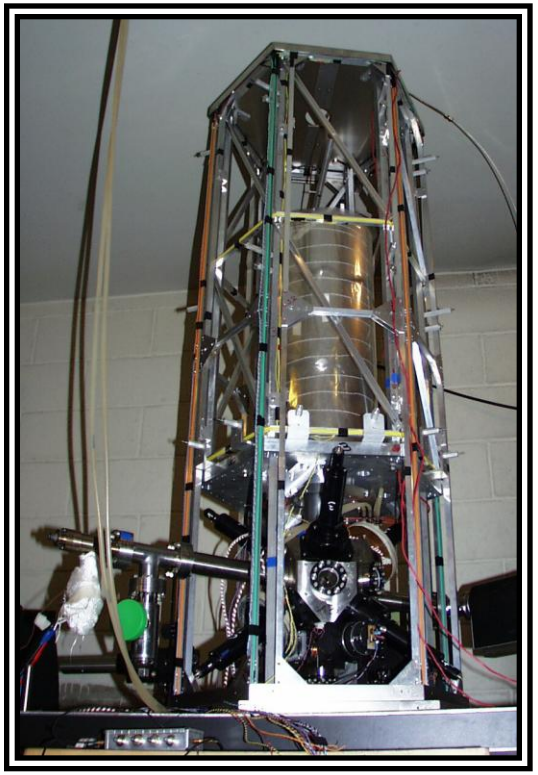


S. Bize
et al.
J. Phys. B 2005
and to be published
SYRTE

Best measured stability for fountains !
Factor 5 /Hydrogen Maser

Atomic Fountains

14 fountains in operation at SYRTE, PTB, NIST, USNO, Penn St, IEN, NPL, ON. 6 with accuracy at 1 10^{-15} . More than 10 under construction.



LNE-SYRTE, FR

PTB, D

NIST, USA

Optical Clocks
Trapped Ions and Neutral Atoms

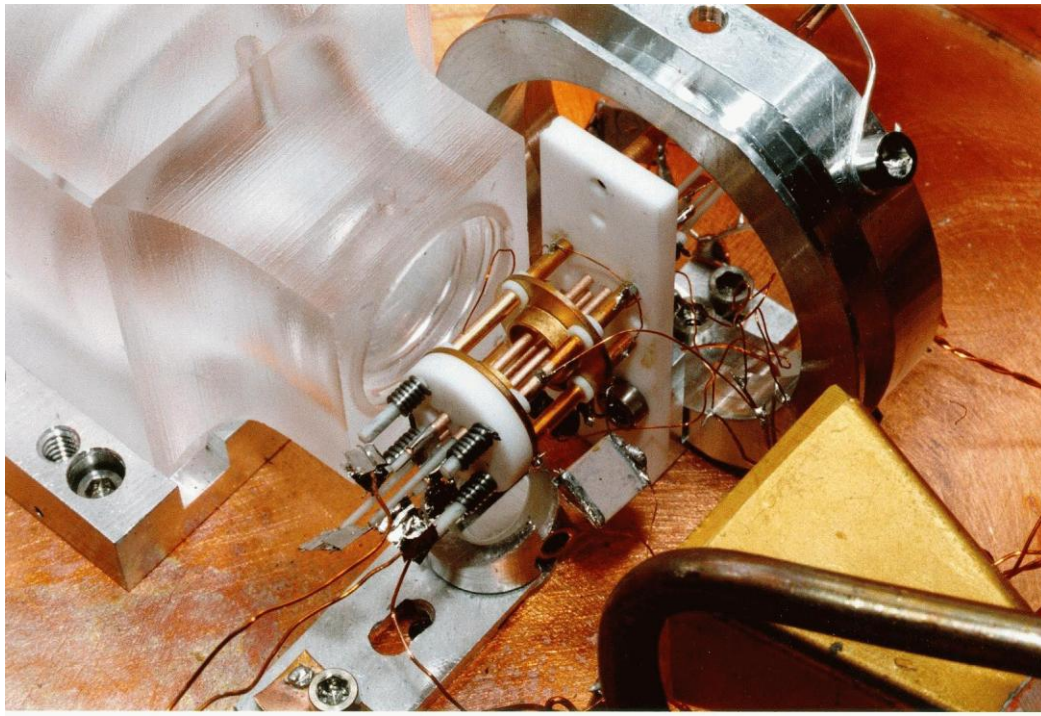
- Quality of the clock: $\nu/\Delta\nu$ x S/N = 2 ν T x S/N
- Increase the frequency, increase T, increase S/N
- <u>Trapped ions :</u> T very long but only one ion in the trap.
- Neutral atoms: T long and large numbers: improved stability

NIST : Bergquist et al.

- Hg^+:optical transition
- stability: $4\ 10^{-15}\ \tau^{-1/2}$
- Accuracy: $1.9\ 10^{-17}$
- Al^+: $2.3\ 10^{-17}$

A factor of 10 beyond the cesium accuracy !

- Neutral Sr at JILA:
- 10^{-16} accuracy, J. Ye et al.



Applications of atomic clocks

- **Navigation, Positioning**

  GPS, GLONASS, deep space probes
- **Geodesy**
- **Datation of millisecond pulsars**
- **VLBI**
- **Synchronisation of distant clocks**

  TAI
- **Fundamental physics tests** Ex : general relativity

Einstein effect, gravitational red-shift : $10^{-4} \longrightarrow 10^{-6}$

Shapiro delay : $3\ 10^{-5} \longrightarrow 10^{-7}$

Search for a drift of fundamental constants such as the fine structure constant α : $\alpha^{-1} d\alpha / dt$ at 10^{-17}/ year

Search for variations of fundamental constants and Einstein Equivalence Principle

In any free falling local reference frame, the result of a non gravitational measurement should not depend upon when it is performed and where it is performed.

EEP ensures the universality of the definition of the second

It implies the stability of fundamental constants: $\alpha = e^2/4\pi\varepsilon_0\hbar c$, m_e, m_p,…

In particular: the ratio of the transition frequencies in different atoms and molecules should not vary with space and time

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

EEP revisited by modern theories: $g_{\mu\nu} \Rightarrow g_{\mu\nu}, \varphi, \ldots$

Fundamental constants may depend upon local value of φ : $\alpha(\varphi)$, $m(\varphi)$,

Violations of EEP are expected at some level !!

For instance: T. Damour, G. Veneziano, PRL 2002

Do fundamental physical constants vary with time ?

G, α_{elm}, m_e / m_p…

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

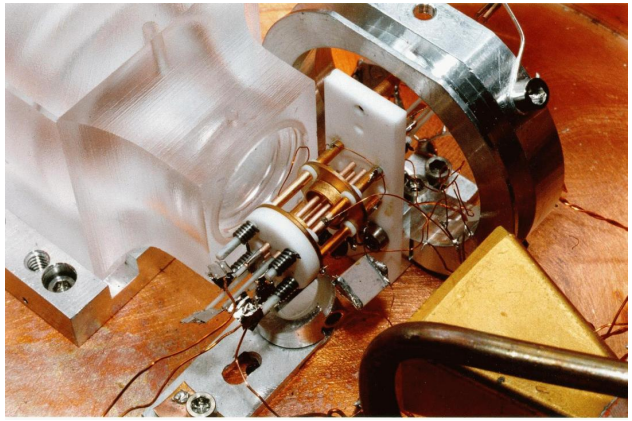
ex:

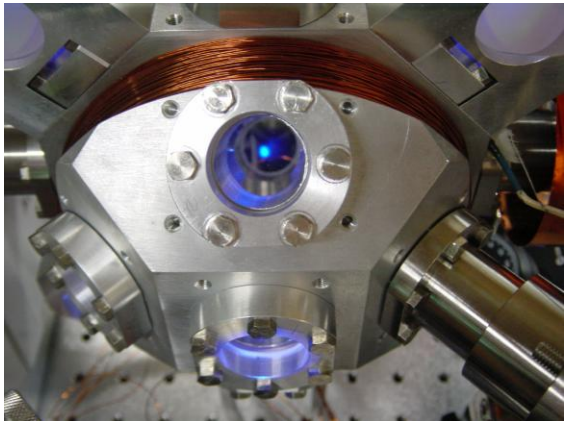
Microwave clock/Microwave clock

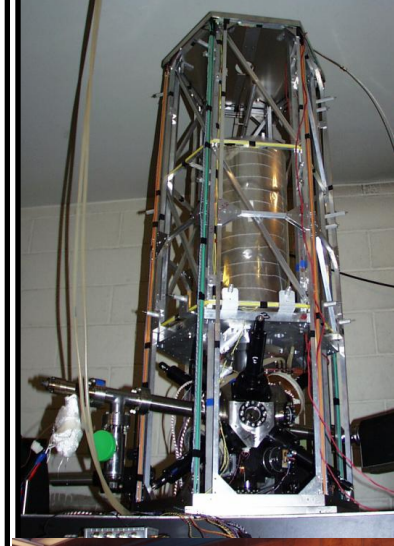
rubidium and cesium

Microwave/Optical clock

Optical Clock/Optical clock







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

Fundamental constants and atomic transitions

Hyperfine transition:

$$\nu_{\rm hfs}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\rm hfs}^{(i)} \times g^{(i)} \left(\frac{m_e}{m_p}\right) \alpha^2 F_{\rm hfs}^{(i)}(\alpha),$$

Electronic transition:

$$\nu_{\rm elec}^{(i)} \simeq R_\infty c \times \mathcal{A}_{\rm elec}^{(i)} \times F_{\rm elec}^{(i)}(\alpha).$$

Actual measurements: frequency ratios

$$\frac{\nu_{\rm elec}^{(ii)}}{\nu_{\rm elec}^{(i)}} \propto \frac{F_{\rm elec}^{(ii)}(\alpha)}{F_{\rm elec}^{(i)}(\alpha)}$$

$$\frac{\nu_{\rm hfs}^{(ii)}}{\nu_{\rm elec}^{(i)}} \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F_{\rm hfs}^{(ii)}(\alpha)}{F_{\rm elec}^{(i)}(\alpha)}$$

$$\frac{\nu_{\rm hfs}^{(ii)}}{\nu_{\rm hfs}^{(i)}} \propto \frac{g^{(ii)}}{g^{(i)}} \frac{F_{\rm hfs}^{(ii)}(\alpha)}{F_{\rm hfs}^{(i)}(\alpha)}.$$

Electronic transitions sensitive to alpha only
Hyperfine and molecular transitions are also sensitive to strong interaction.

Fundamental constants and atomic transitions (2)

Magnetic moments and m_p are not fundamental parameters of the Standard Model, but can be related to:

$$m_q/\Lambda_{QCD},\ m_s/\Lambda_{QCD},\ m_q=(m_u+m_d)/2$$

V. Flambaum, 2004, and PR C 73, 2006

Any atomic transition of species (i) can be expressed as a function of only 3 parameters $(\alpha,\ m_e/\Lambda_{QCD},\ m_q/\Lambda_{QCD})$

$$\delta \ln\left(\frac{\nu^{(i)}}{R_\infty c}\right) \simeq K_\alpha^{(i)} \times \frac{\delta\alpha}{\alpha} + K_q^{(i)} \times \frac{\delta(m_q/\Lambda_{\rm QCD})}{(m_q/\Lambda_{\rm QCD})} + K_e^{(i)} \times \frac{\delta(m_e/\Lambda_{\rm QCD})}{(m_e/\Lambda_{\rm QCD})}$$

With calculable coefficients: $K_\alpha^{(i)}$ $K_q^{(i)}$ $K_e^{(i)}$

Example of atomic transitions

	κ_α	κ_q	κ_e
Rb hfs	2.34	-0.064	1
Cs hfs	2.83	-0.039	1
H opt	0	0	0
Yb^+ opt	0.88	0	0
Hg^+ opt	-3.2	0	0
Dy comb.	$1.5\ 10^7$	0	0

K_α, K_e : accuracy at the percent level or better

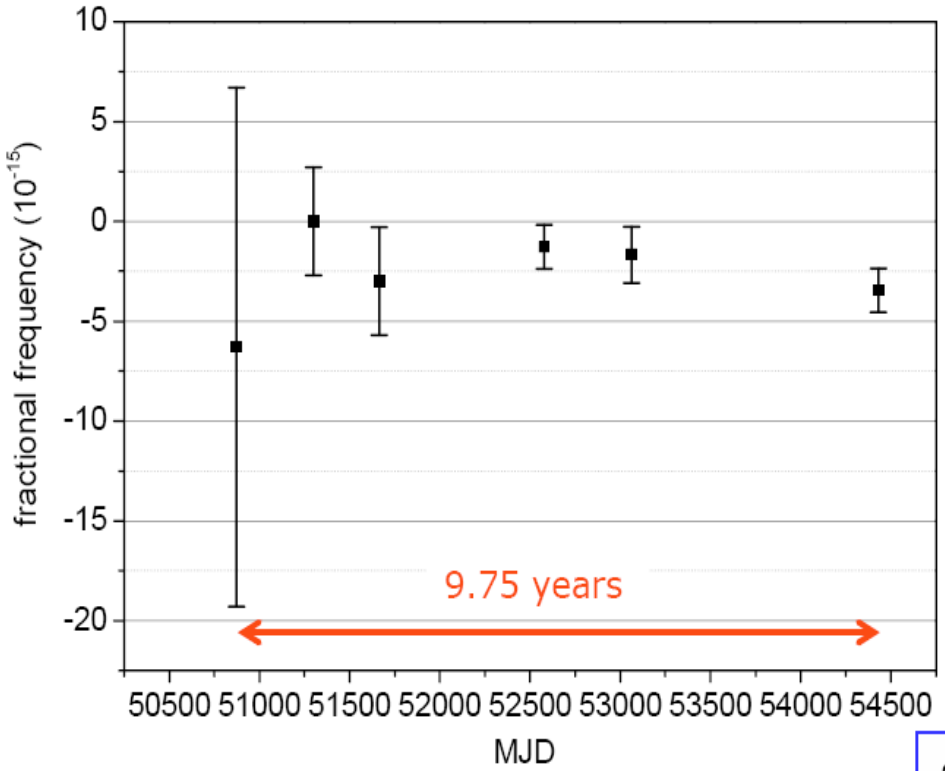
K_q : accuracy ?

Atom	^{87}Rb	^{133}Cs
Method A	−0.074	0.127
Method B	−0.056	0.044
Method C	−0.016	0.009

*PR **C73**, 055501 (2006)*

Note: accidental degeneracy in Dy atom,
as well as in some diatomic molecules, where HF and rotational structures have level crossing

SYRTE Comparison between Rubidium and Cesium Hyperfine Structure over ~10 years



one data point ⇔ ~1 to 2 months of measurements, with many checks of systematic shifts

Weighted least squares fit gives:

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

$$\frac{d}{dt}\ln\left(\frac{g_{\mathrm{Rb}}}{g_{\mathrm{Cs}}}\alpha^{-0.49}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

With further theory, nuclear g-factors can be related to m_q/Λ_{QCD}:

$$\frac{d}{dt}\ln\left(\alpha^{-0.49}\left[m_q/\Lambda_{\mathrm{QCD}}\right]^{-0.025}\right) = (-3.2 \pm 2.3) \times 10^{-16}\,\mathrm{yr}^{-1}$$

New limit on alpha stability

- Aluminium-Mercury optical transitions
- Over 2006-2007: observed linear rate of change

$d(\nu_{Al+}/\nu_{Hg+})/dt = (-5.3 +- 7.9) \times 10^{-17}$/year

is consistent with zero.

Hg+ sensitivity: -3.19 $\delta\alpha/\alpha$

Al+ sensitivity: +0.008 $\delta\alpha/\alpha$

We obtain:

$d\alpha/\alpha dt = (-1.6 +- 2.4) \times 10^{-17}$/year

Best current limit on alpha drift

T. Rosenband et al., Science Express, March 2008, NIST group

Recent limits with atomic clocks

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-3.2\pm2.3)\times10^{-16}\,\mathrm{yr}^{-1} = -0.49\frac{d}{dt}\ln(\alpha) - 0.025\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}})$$

LNE-SYRTE, JPB (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Hg+}}}{\nu_{\mathrm{Cs}}}\right) = (3.7\pm3.9)\times10^{-16}\,\mathrm{yr}^{-1} = -6.03\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

NIST, PRL (2007)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Yb+}}}{\nu_{\mathrm{Cs}}}\right) = (-7.8\pm14)\times10^{-16}\,\mathrm{yr}^{-1} = -1.95\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

PTB, arXiv (2006)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{H}}}{\nu_{\mathrm{Cs}}}\right) = (-32\pm63)\times10^{-16}\,\mathrm{yr}^{-1} = -2.83\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

MPQ
+ LNE-SYRTE
PRL (2004)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Dy}}}{\nu_{\mathrm{Cs}}}\right) = (-4\pm3.9)\times10^{-8}\,\mathrm{yr}^{-1} = 1.5\times10^{7}\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

Berkley,
PRL (2007)

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Sr}}}{\nu_{\mathrm{Cs}}}\right) = (-7\pm18)\times10^{-16}\,\mathrm{yr}^{-1} = -2.77\frac{d}{dt}\ln(\alpha) + 0.039\frac{d}{dt}\ln(m_q/\Lambda_{\mathrm{QCD}}) - \frac{d}{dt}\ln(m_e/\Lambda_{\mathrm{QCD}})$$

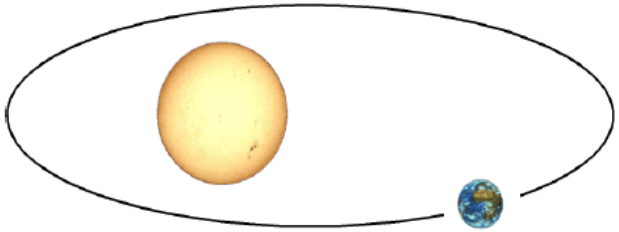
Tokyo
JILA
LNE-SYRTE
arXiv (2008)

$$\frac{d}{dt}\ln\left(\frac{\nu_{Al+}}{\nu_{Hg+}}\right) = (-5.3\pm7.9)\,10^{-17}\ yr^{-1} = 3.20\frac{d}{dt}\ln(\alpha)$$

Without reference to cesium !

Couplings of fundamental constants to gravity

Annual modulation of the Sun gravitation potential at the Earth :



$$\frac{\Delta U(t)}{c^2} = -\underbrace{\frac{GM_S}{c^2 a}}_{\sim 1.6\ 10^{-10}} \epsilon \cos \phi(t).$$

Correlations with varying potential are searched in atomic clock data. Sensitivity of atomic transitions to α, m_q/Λ_{QCD} and m_e/Λ_{QCD} are as before.

Putative sensitivities of α, m_q/Λ_{QCD} and m_e/Λ_{QCD} to $\Delta U/c^2$ are defined: $\frac{\delta\alpha}{\alpha} = k_\alpha \frac{\Delta U(t)}{c^2}$.

*PR A **76**, 062104 (2007)*
Dy/Cs (Berkley)
Hg^+/Cs (NIST)
Cs/H(hfs) (NIST, SYRTE, PTB)

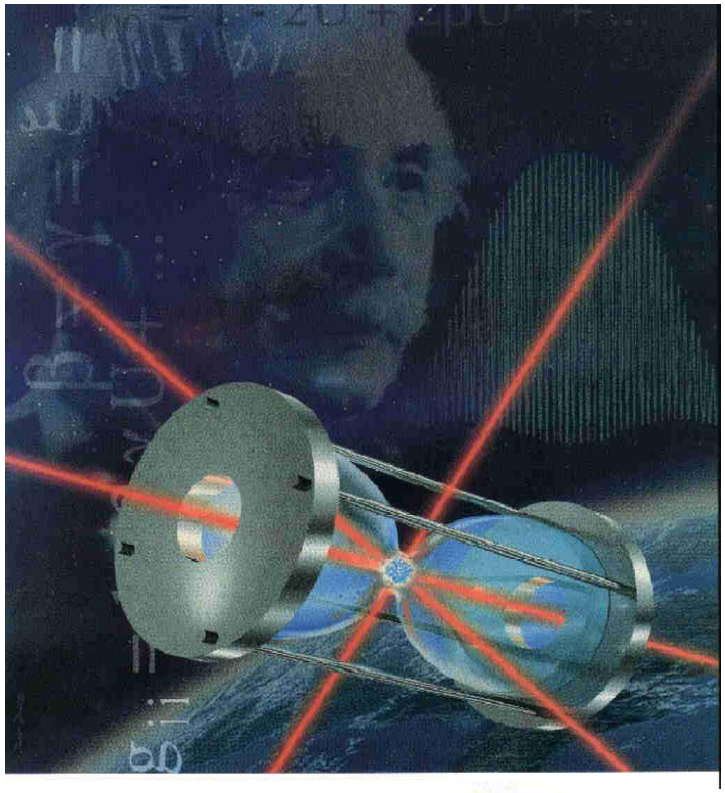
Parameter	Constraint
$k_\alpha + 0.17 k_e$	$(-3.5 \pm 6) \times 10^{-7}$
$\lvert k_\alpha + 0.13 k_q \rvert$	$< 2.5 \times 10^{-5}$
$k_\alpha + 0.13 k_q$	$(-1 \pm 17) \times 10^{-7}$
k_α	$(-8.7 \pm 6.6) \times 10^{-6}$
k_e	$(4.9 \pm 3.9) \times 10^{-5}$
k_q	$(6.6 \pm 5.2) \times 10^{-5}$

arxiv:0801.1874 (2008)
Sr/Cs (SYRTE,Tokyo,JILA)
Hg^+/Cs (NIST)
Cs/H(hfs) (NIST, SYRTE, PTB)

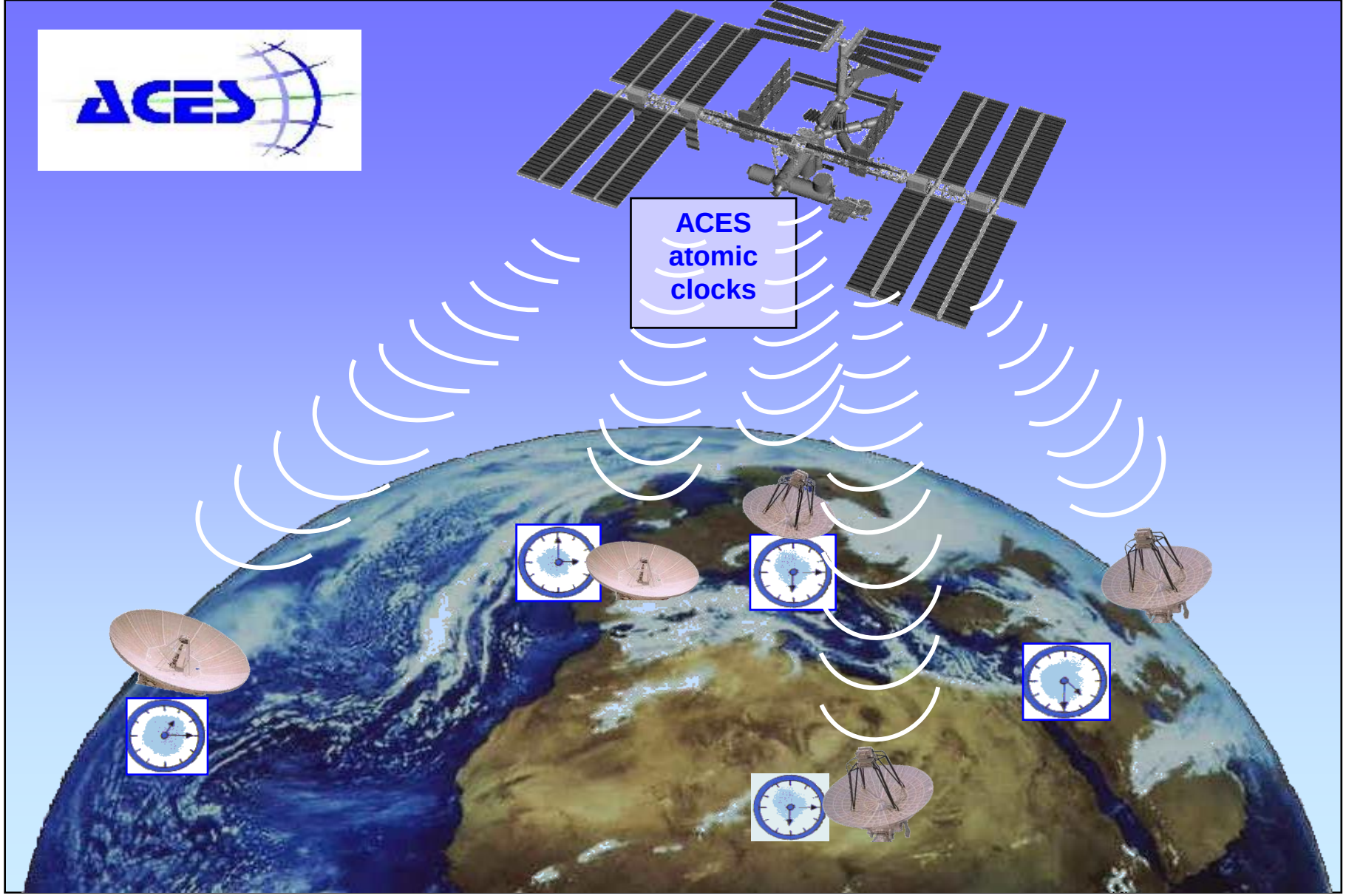
$$k_\alpha = (-2.3 \pm 3.1) \times 10^{-6}$$
$$k_\mu = (1.1 \pm 1.7) \times 10^{-5}$$
$$k_q = (1.7 \pm 2.7) \times 10^{-5}.$$

Fundamental physics tests with space clocks

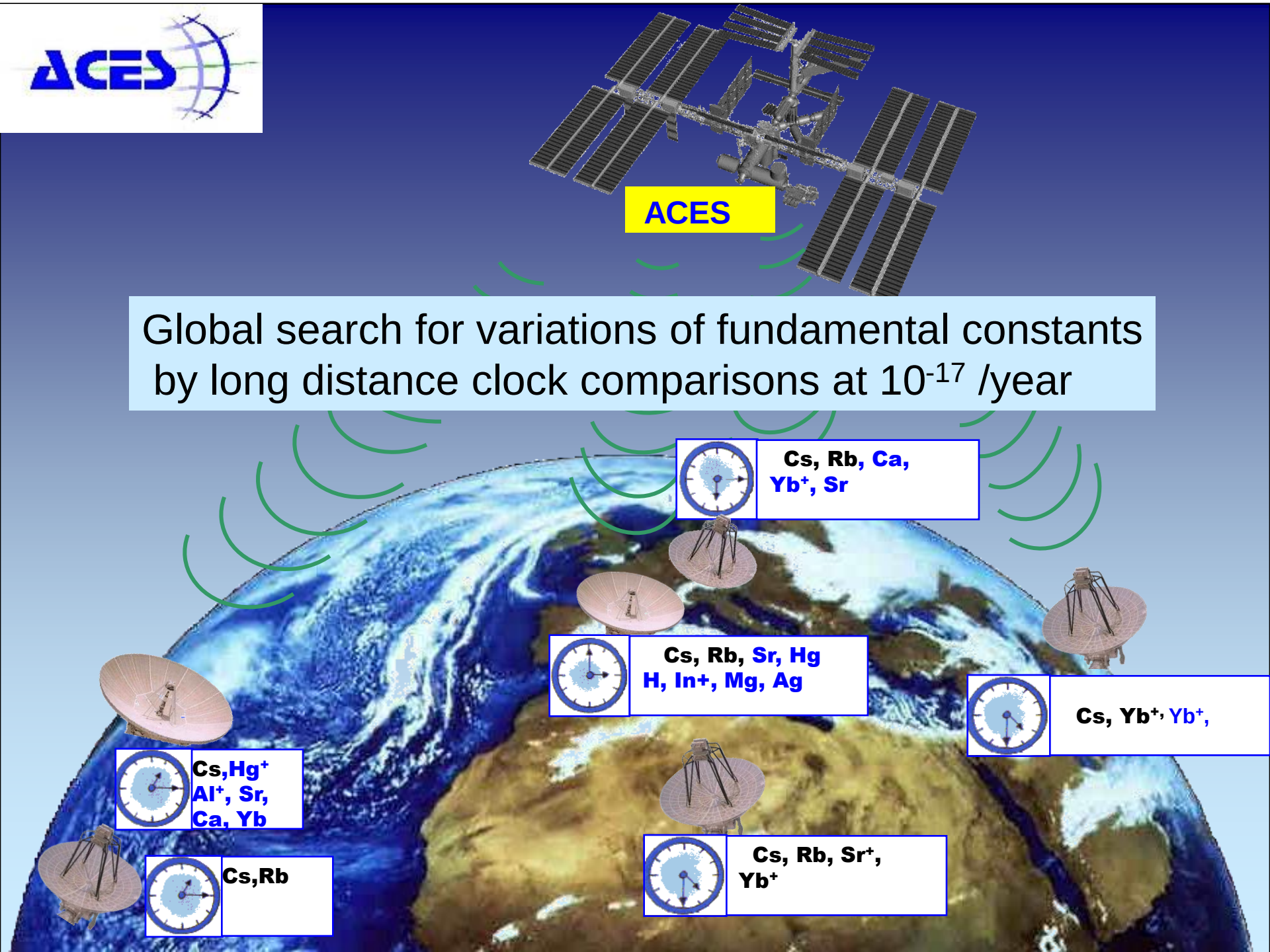
1997



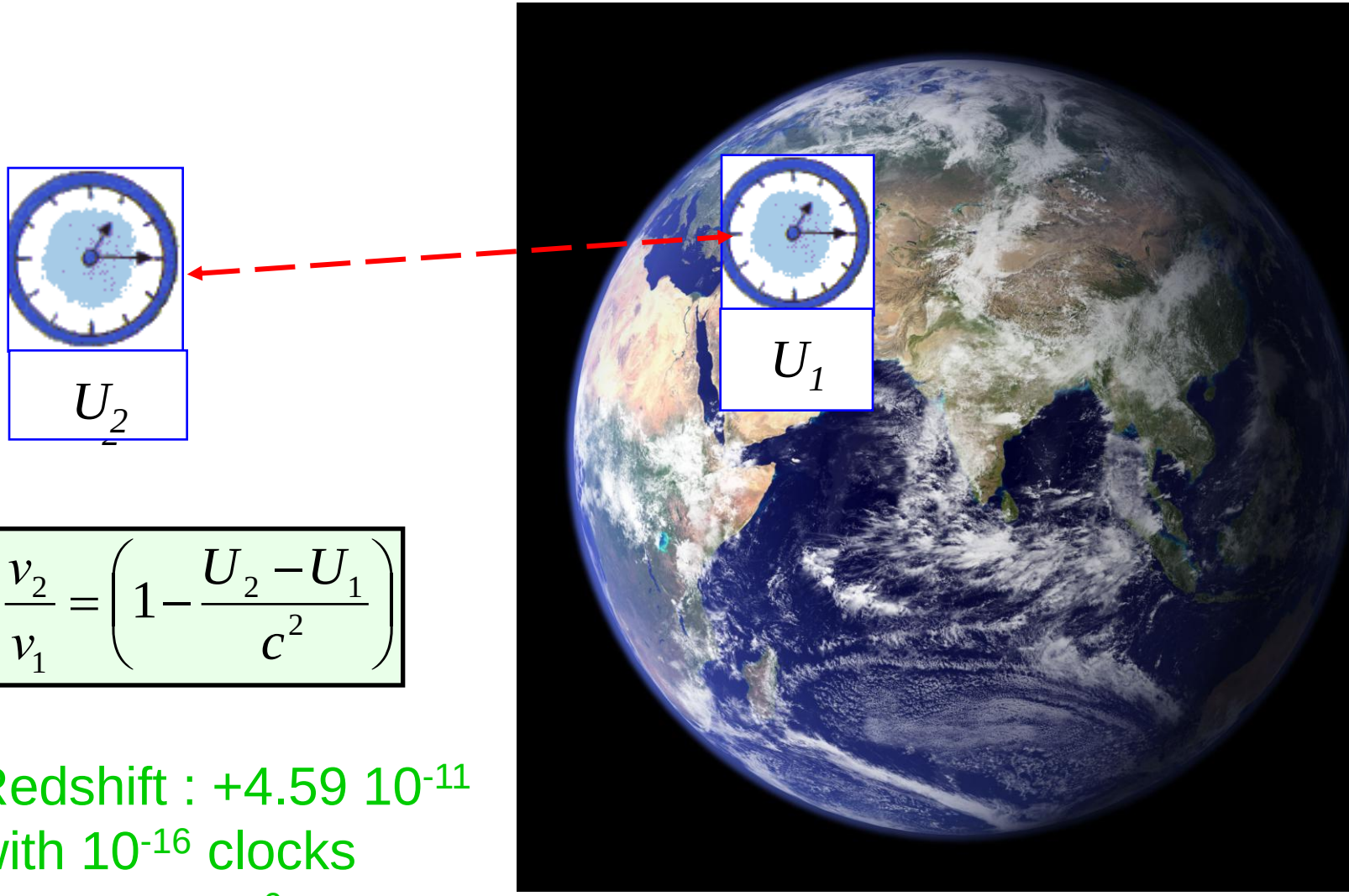
CENTRE NATIONAL D'ETUDES SPATIALES



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


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^+

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

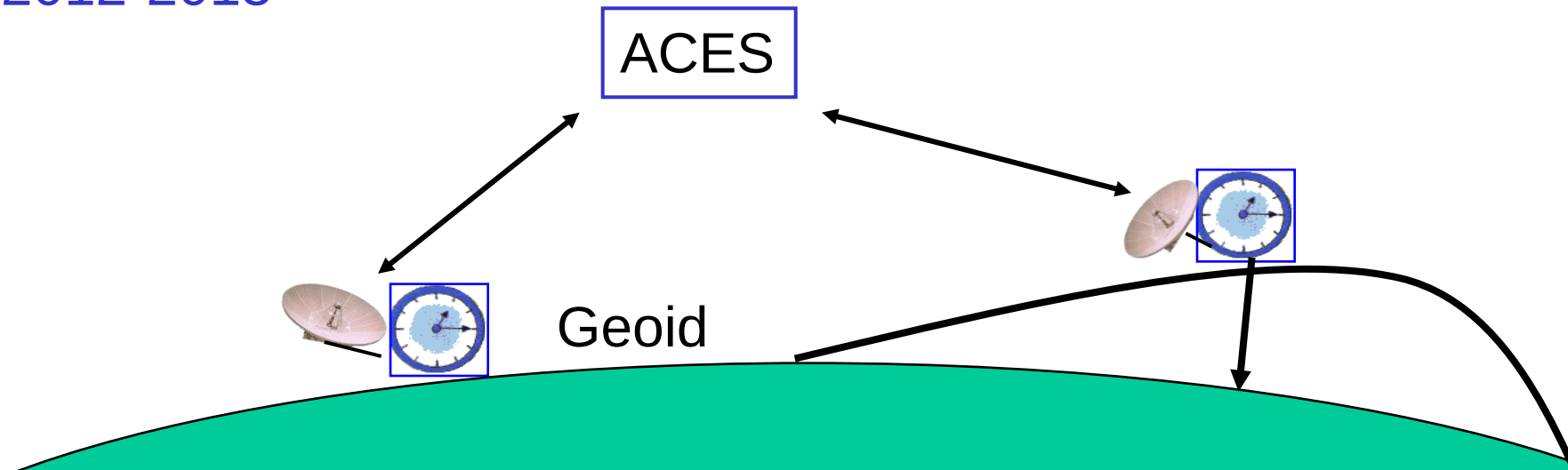
Limits on Ground: Relativistic Geodesy

The clock frequency depends on the Earth gravitational potential 10^{-16} per meter

Best ground clocks have today an accuracy of 2 10^{-17} and will improve !

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

In 2012-2015



ACES ON COLUMBUS EXTERNAL PLATFORM

Current launch date : end of 2012

Mission duration : 18 months to 3 years

Summary

Microwave clocks:

stability 10^{-16} per day, accuracy: ~ 1 10^{-16} on Earth and in Space

Optical clocks:

4 10^{-17} today and towards 10^{-18} range

Towards a redefinition of the SI second

Clocks with quantum correlated atoms

ACES (2012)

Comparisons between distant clocks at 10^{-17}

Large improvements on relativity tests

and on limits for variations of α, g_p, M_e/M_p

Applications to GPS & GALILEO monitoring and in Earth Science

Clocks at 10^{-17} or below will probe time-dependent Earth potential

future: EGE, dedicated satellites for global time dissemination without Earth potential variations

Probe of gravity at solar system scale: SAGAS proposal to ESA.