Systèmes de Référence Temps-Espace

Fundamental Physics Tests using Rubidium and Cesium Fountains

F. Chapelet, S. Bize, P. Wolf, P. Rosenbusch, P. Laurent, G. Santarelli, M.E. Tobar, C. Salomon, A. Clairon

l'Observatoire de Paris – SYRTE

LNE – Le progrès, une passion à partager

CNRS – CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

IFRAF – Institut Francilien de Recherche sur les Atomes Froids

Workshop on "Advances on Precision Tests and Experimental Gravitation in Space"
September 28th 2006, Firenze, Italia

OUTLINES

- Introduction
- LLI test using a Cryogenic Sapphire Oscillator
- LLI test using a Cs fountain
- LPI test: Stability of fundamental constants
- Prospects

INTRODUCTION

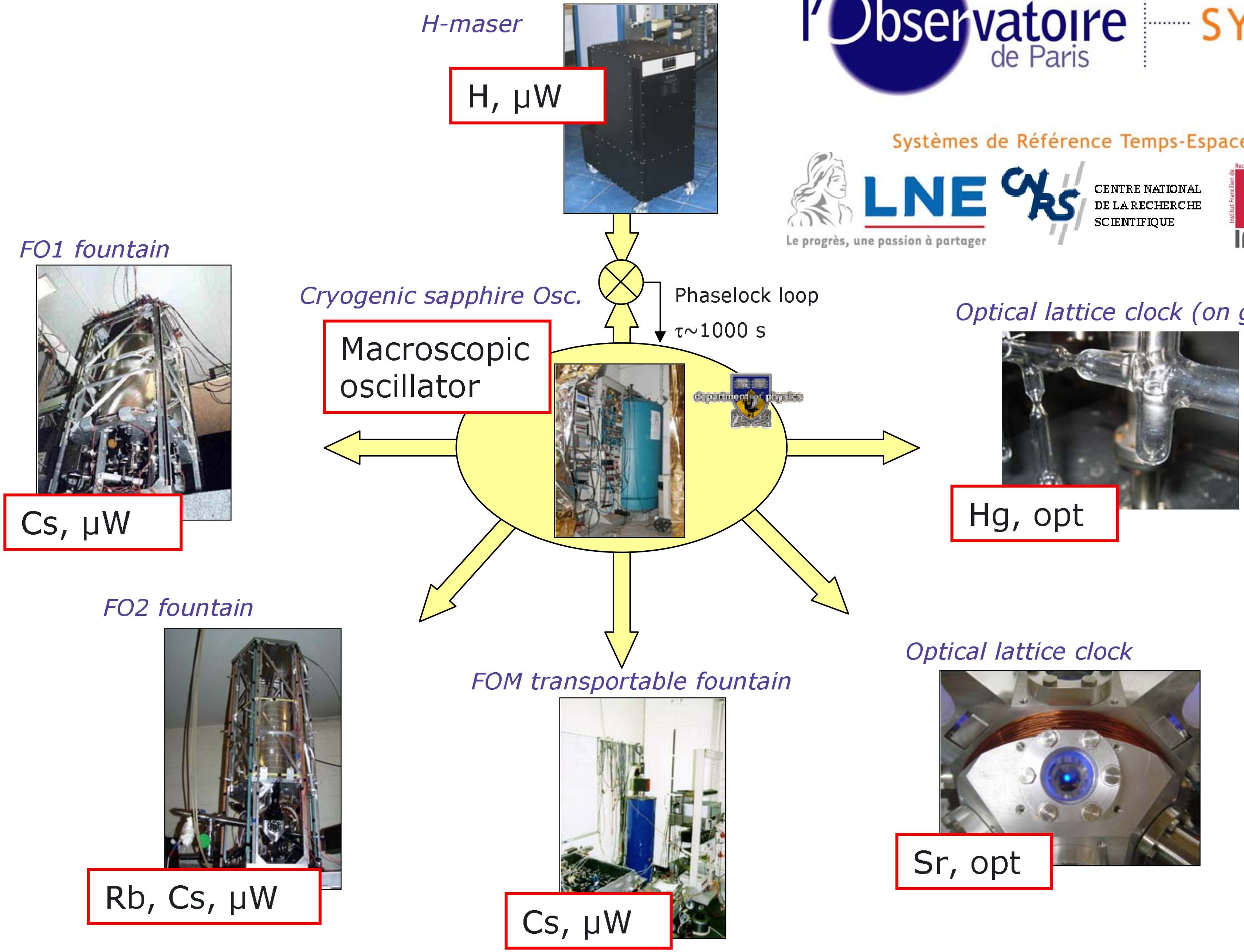
- Experimental tests of fundamental physical laws
  - Einstein Equivalence Principle
    - Focus on LLI and LPI
- Contribute to constraining unification theories
  - String theories, loop gravity,…
- LLI experiments analyzed within the SME framework
  - A general Lorentz violating extension of the Standard Model
  - Large number of parameters
  - Better insight of which part of the standard model is tested by a given experiment
  - Photon sector ⇔ Maxwell equations with modified coefficients, 19 parameters
  - Matter sector: 44 parameters per particle (p^+,e^-,n,…)

LNE-SYRTE CLOCK ENSEMBLE

l'Observatoire de Paris — SYRTE

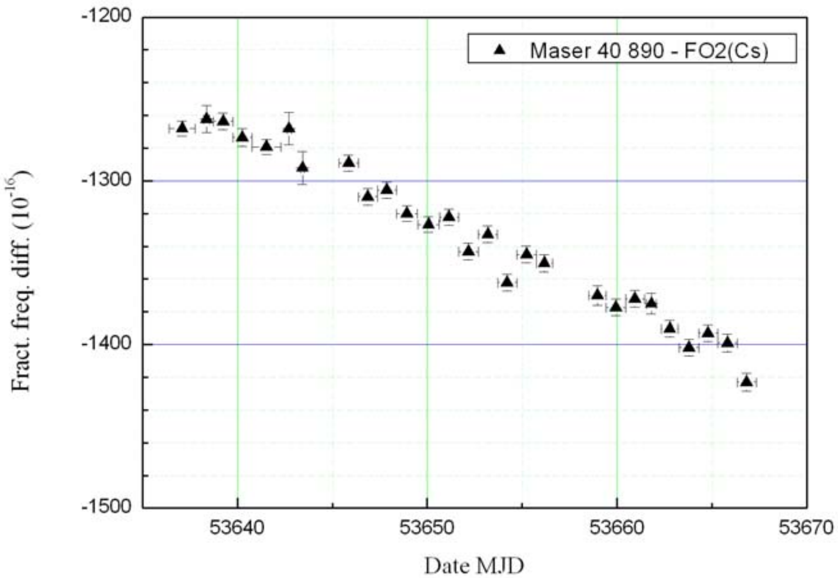
Systèmes de Référence Temps-Espace

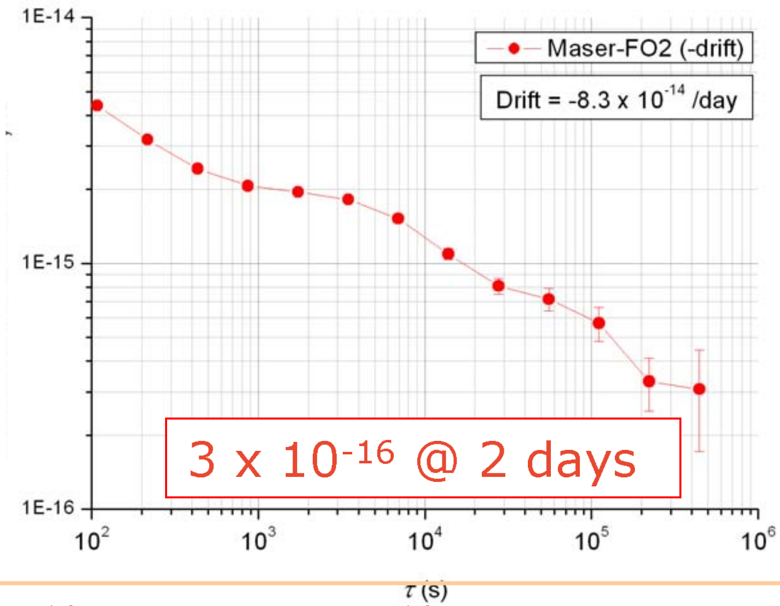
LNE Le progrès, une passion à partager — CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE — IFRAF



TIME AND FREQUENCY METROLOGY APPLICATIONS

- TAI calibration, more than 15 over the past 4 years





$u_B = 5.78 \times 10^{-16}$, $u_A = 0.71 \times 10^{-16}$, $u_{link/maser} = 1.43 \times 10^{-16}$

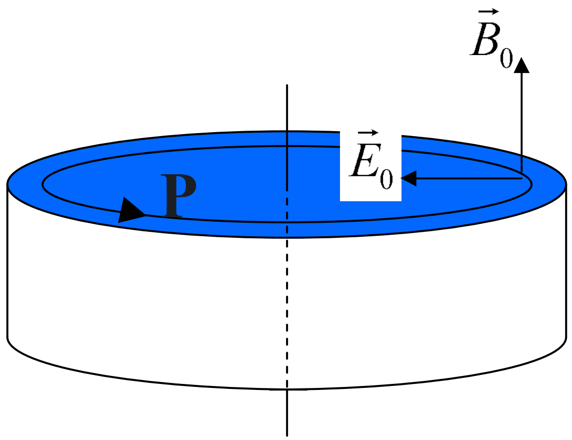
- Secondary representation of the SI second (2004)
  - Rb(hfs) $\nu_{\mathrm{Rb}}(2002) = 6\ 834\ 682\ 610.904\ 324(4)(7)$ Hz (1.3×10^{-15}) (CCTF: 3×10^{-15})
- Support to the development of PHARAO/ACES
  - Test of µW synthesizer IM, Ramsey cavity FM,…
  - **PHARAO EM is now operated as a clock, poster at this conference**

LLI test using a Cryogenic Sapphire Oscillator

P. Wolf, S. Bize, A. Clairon, A. Luiten, G. Santarelli, M. Tobar,
Phys. Rev. Lett. 90, 060402 (2003)
Gen. Rel. Grav. 36, 2351 (2004)
Phys. Rev. D70 051902(R) (2004)

SME ANALYSIS OF A MICROWAVE RESONATOR

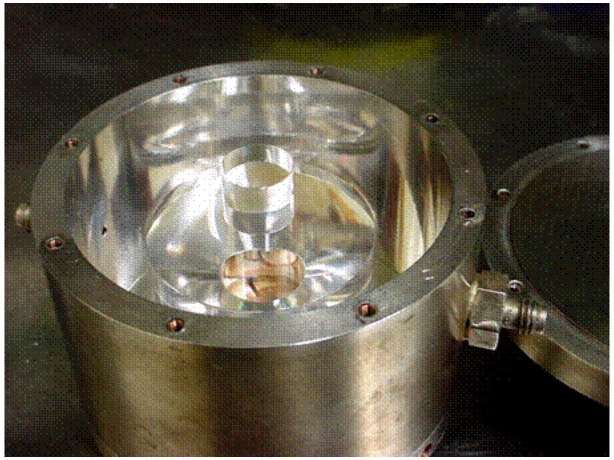
- The mode frequency is perturbed by a term involving 7 relevant SME coefficients
- Earth motion induces modulations of the SME term (SME coefficients are tensor components attached to a supposedly preferred frame)



$$\frac{\Delta f}{f}(t) = \sum_{\omega_i} \left(C_{\omega_i} \cos(\omega_i t) + S_{\omega_i} \sin(\omega_i t) \right)$$

with $\omega_i = \omega, 2\omega, \omega \pm \Omega, 2\omega \pm \Omega.$

(sidereal, semi-sidereal pulsations with orbital sidebands



- Detected wrt H-maser

SUMMARY OF DATA ANALYSIS AND RESULTS

- 222 days, spanning from Sept. 2002 to Jan. 2004
- Analysis accounted for
  - 2 different methods
  - Non-white noise
  - Contamination by diurnal modulation
  - Evaluation of systematic shifts

TABLE II. Contributions from systematic effects to the amplitudes A_i (parts in 10^{16}) at three frequencies ω_i.

Effect	$\omega_\oplus - \Omega_\oplus$	$\omega_\oplus$	$2\omega_\oplus$
H-maser	<5	<5	<5
Tilt	3	3	1
Gravity	0.3	0.3	0.3
B-field	<0.1	<0.1	<0.1
Temperature	<1	<1	<1
Atm. Pressure	2.3	0.3	0.4
Total	**6.4**	**5.9**	**5.2**

- Results
  - Improvement by a factor of 8 for three SME parameters
  - Non-zero at 2σ for 2 parameters but inconsistent with Müller *et al.* => *a* statistical coincidence, NOT a LLI violation

Müller et al. Phys. Rev. Lett. ***91****, 020401 (2003)*

  - Better measurements with rotating oscillators (factor ~10)

Stanwix et al. (2005), Herrman et al. (2005)

LLI test using a Cs fountain

P. Wolf, F. Chapelet, S. Bize, A. Clairon,
Phys. Rev. Lett. 96, 060801 (2006)

SME APPLIED TO CESIUM HFS

- SME shift of atomic energy levels in the local frame

$$\delta E(m_F,F)=\frac{m_F}{F}\sum_{e^-,p^+,n}\left(\beta_w\tilde{b}_3^w+\delta_w\tilde{d}_3^w+\kappa_w\tilde{g}_d^w\right)+\frac{3m_F^2-F(F+1)}{3F^2-F(F+1)}\sum_{e^-,p^+,n}\left(\gamma_w\tilde{c}_q^w+\lambda_w\tilde{g}_q^w\right)$$

  - $\beta_w,\delta_w,\kappa_w,\gamma_w,\lambda_w$ are specific to the atom and the particular state
  - The tilde coefficients are combinations of SME parameters
  - They are in general time dependent due to atom motion wrt supposedly preferred frame
- Cs hyperfine transition in the SME

|F=3, m_F> → |F=4, m_F> transition frequency:

$$\hbar\delta\omega=B_p\tilde{b}_3^p+D_p\tilde{d}_3^p+G_p\tilde{g}_d^p+C_p\tilde{c}_q^p+B_e\tilde{b}_3^e+D_e\tilde{d}_3^e+G_e\tilde{g}_d^e$$ ← SME part

$$+Z^{(1)}B+Z^{(2)}B^2$$ ← classical part: $Z^{(1)}B\approx m_F\,1400\text{Hz}$, $Z^{(2)}B^2\approx -2$ mHz

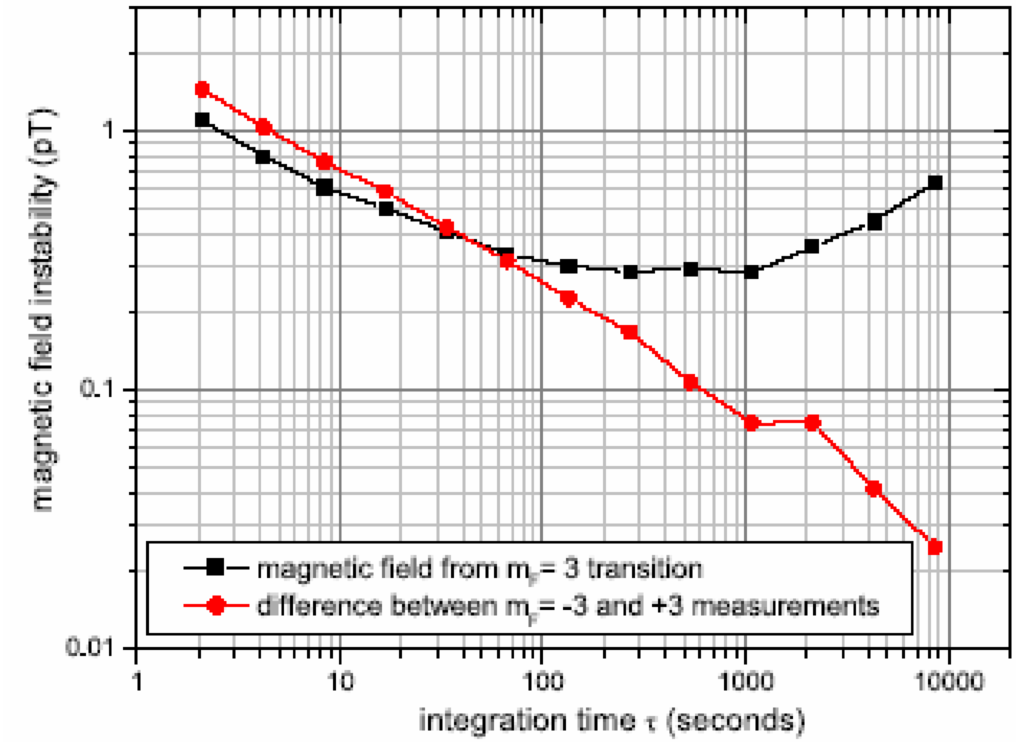
- An observable which free of 1st order Zeeman effect

$$\upsilon_{+3}+\upsilon_{-3}-2\upsilon_0=\frac{1}{7h}K_p\tilde{c}_q^p-\frac{9}{8}K_z^{(2)}B^2$$

$K_p\approx 10^{-2}$; $K_e\approx 10^{-5}$ (neglected)

EXPERIMENTAL STRATEGY

- Alternate $m_F = 3$ and $m_F = -3$ measurement every second (interleaved servo-loops).
- Measure $m_F = 0$ clock transition every 400 s (reference).
- Limited by stability of magnetic field at $\tau < 4$ s.
- Reduce launching height to optimize stability of observable.



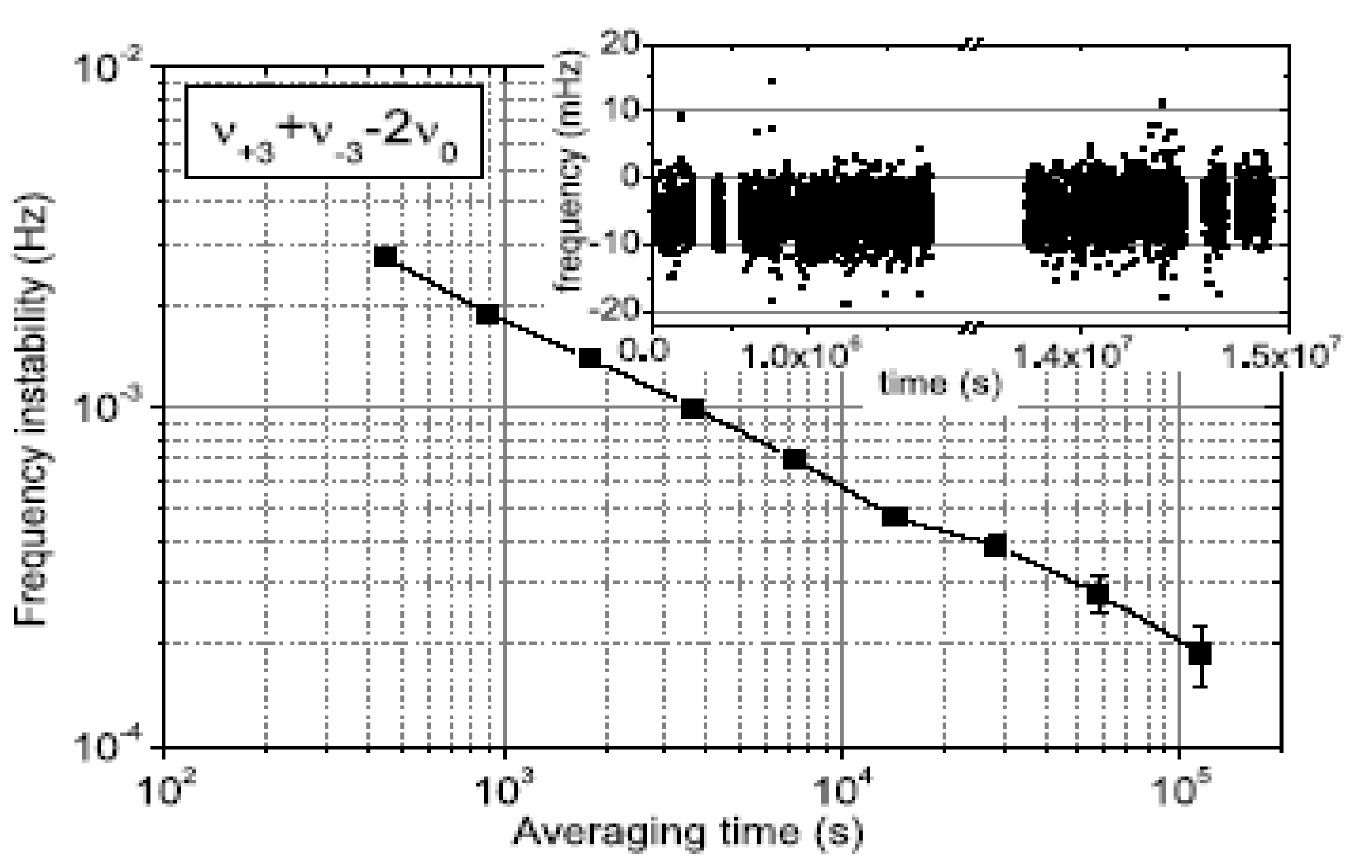
- Transforming to sun-frame SME parameters:

$$\tilde{c}_q^p = A + C_{\omega_\oplus}\cos(\omega_\oplus t) + S_{\omega_\oplus}\sin(\omega_\oplus t) + C_{2\omega_\oplus}\cos(2\omega_\oplus t) + S_{2\omega_\oplus}\sin(2\omega_\oplus t)$$

- A, C_i, S_i, are functions of the 8 proton components: $\tilde{c}_Q, \tilde{c}_X, \tilde{c}_Y, \tilde{c}_Z, \tilde{c}_-, \tilde{c}_{TX}, \tilde{c}_{TY}, \tilde{c}_{TZ}$
- 3 proton components ($\tilde{c}_{TX}, \tilde{c}_{TY}, \tilde{c}_{TZ}$) are suppressed by $v_\oplus/c \approx 10^{-4}$

- Search for offset, sidereal and semi-sidereal signatures in the observable

DATA AND STATISTICAL ANALYSIS



21 days of data in April 2005, 14 days in September 2005. Least squares fit:

$$A = -5.3(0.04);\ C_{\omega_\oplus} = 0.1(0.06);\quad S_{\omega_\oplus} = -0.03(0.06)$$

$$C_{2\omega_\oplus} = 0.04(0.06);\ S_{2\omega_\oplus} = 0.03(0.06)$$

in mHz

SYSTEMATICS: Residual 1st order Zeeman Shift

- Magnetic field gradients and non-identical trajectories of $m_F=+3$ and $m_F=-3$ atoms can lead to incomplete cancellation of $Z^{(1)}$.
- Confirmed by TOF difference ≈ 158 μs (→ 623 μm).
- Variation of *B* with launching height ≈ 0.02 pT/mm (at apogee).

  ⇒ MC simulation gives offset of only ≈ 6 μHz.

- Contrast as function of m_F: 0.94, 0.93, 0.87, 0.75
- MC simulation with only vertical *B* gradient cannot reproduce the contrast

  ⇒ horizontal *B* gradient of ≈ 6 pT/mm (≈ 2 pT/mm from tilt measurements).
- Complete MC simulation, assuming horizontal asymmetry between trajectories is same as vertical (worst case) gives offset ≈ 25 mHz.

- Fitting sidereal and semi-sidereal variations to the TOF difference and using the above gradients we obtain no significant effect within the statistical uncertainties (≈ 0.03 mHz at both frequencies). We take this as our upper limit of the time varying part of the residual first order Zeeman.

RESULTS

(in GeV)

8 proton parameters

$$\tilde{c}_Q = -0.3(2.2)\times10^{-22}$$
$$\tilde{c}_- = -1.8(2.8)\times10^{-25}$$
$$\tilde{c}_X = 0.6(1.2)\times10^{-25}$$
$$\tilde{c}_Y = -1.9(1.2)\times10^{-25}$$
$$\tilde{c}_Z = -1.4(2.8)\times10^{-25}$$

$$\tilde{c}_{TX} = -2.7(3.0)\times10^{-21}$$
$$\tilde{c}_{TY} = -0.2(3.0)\times10^{-21}$$
$$\tilde{c}_{TZ} = -0.4(2.0)\times10^{-21}$$

Parameter	p^+	n	e^-
$\tilde{b}_X, \tilde{b}_Y$	10^{-27}	10^{-31}	10^{-29}
$\tilde{b}_Z$	...	...	10^{-28}
$\tilde{b}_T, \tilde{g}_T, \tilde{H}_{JT}, \tilde{d}_\pm$	...	10^{-27}	...
$\tilde{d}_Q, \tilde{d}_{XY}, \tilde{d}_{YZ}$	...	10^{-27}	...
$\tilde{d}_X, \tilde{d}_Y$	10^{-25}	10^{-29}	10^{-22}
$\tilde{d}_{XZ}, \tilde{d}_Z$	...	...	...
$\tilde{g}_{DX}, \tilde{g}_{DY}$	10^{-25}	10^{-29}	10^{-22}
$\tilde{g}_{DZ}, \tilde{g}_{JK}$	...	...	...
$\tilde{g}_c$	...	10^{-27}	...
$\tilde{g}_-, \tilde{g}_Q, \tilde{g}_{TJ}$	...	...	...
$\tilde{c}_Q$	$\mathbf{10^{-22(-11)}}$	...	10^{-9}
$\tilde{c}_X, \tilde{c}_Y$	$\mathbf{10^{-25}}$	10^{-25}	10^{-19}
$\tilde{c}_Z, \tilde{c}_-$	$\mathbf{10^{-25}}$	10^{-27}	10^{-19}
$\tilde{c}_{TJ}$	$\mathbf{10^{-21(-8)}}$	...	10^{-6}

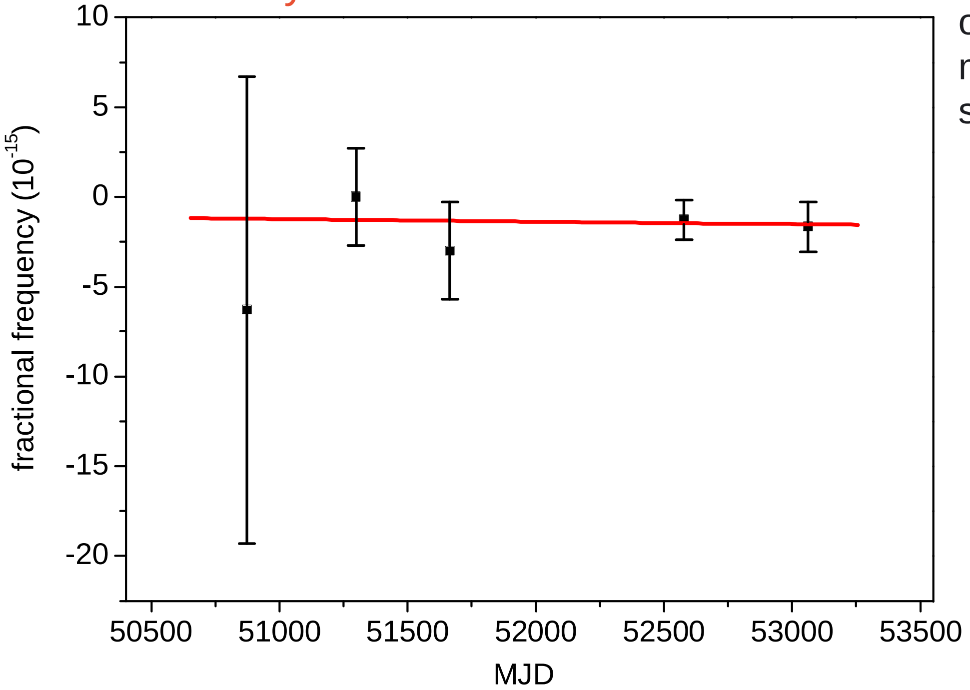
- Sensitivity to c_{TJ} reduced by a factor $v_\oplus/c$ ($\approx 10^{-4}$).
- Assuming no cancellation between c_{TJ} and others.
- First measurements of four components.
- Improvement by 11 and 13 orders of magnitude on previous limits (re-analysis of IS experiment, [Lane C., PRD 2005]).
- Dominated by statistical uncertainty (factor 2) except for c_Q.

LPI test: Stability of fundamental constants

S. Bize et al., J. Phys. B: At. Mol. Opt. Phys. ***38***, *S44 (2005)*
S. Bize et al., C.R. Physique ***5***, *829 (2004)*
M. Fischer et al., Phys. Rev. Lett. ***92***, *230802 (2004)*
H. Marion et al., Phys. Rev. Lett. ***90***, *150801 (2003)*
Y. Sortais et al., Phys. Scripta ***T95***, *50 (2001)*
M. Niering et al., Phys. Rev. Lett. ***84***, *5496 (2000)*
S. Bize et al., Europhys. Lett. ***45***, *558 (1999)*

COMPARISON OF Rb vs Cs HFS and H(1S-2S) vs Cs

Rb vs Cs over 6 years



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

$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{Rb}}}{\nu_{\mathrm{Cs}}}\right) = (-0.5 \pm 5.3) \times 10^{-16}\ \mathrm{yr}^{-1}$$

J. Prestage, et al., PRL (1995)

V. Dzuba, et al., PRL (1999)

$$\frac{d}{dt}\ln\left(\frac{g_{\mathrm{Cs}}}{g_{\mathrm{Rb}}}\alpha^{0.49}\right) = (0.5 \pm 5.3) \times 10^{-16}\ \mathrm{yr}^{-1}$$

With further theory, nuclear g-factors can be related to more fundamental parameters

V.V. Flambaum, et al., PRD (2004)

$$\frac{d}{dt}\ln\left(\alpha^{0.49}\left[m_q/\Lambda_{\mathrm{QCD}}\right]^{0.174}\left[m_s/\Lambda_{\mathrm{QCD}}\right]^{0.027}\right) = (0.5 \pm 5.3) \times 10^{-16}\ \mathrm{yr}^{-1}$$

H(1S-2S) vs Cs over ~3 years (with transportable fountain at MPQ Garching)

$$\frac{\partial}{\partial t}\ln\frac{\nu_{\mathrm{Cs}}}{\nu_{\mathrm{H}}} = \frac{\partial}{\partial t}\left(\ln\frac{\mu_{\mathrm{Cs}}}{\mu_B} + (2.0+0.8)\ln\alpha\right) = (3.2 \pm 6.3) \times 10^{-15}\ \mathrm{yr}^{-1}$$

Combined with Hg^+ vs Cs (NIST), Yb^+ vs Cs (PTB), these measurements independently constrain the stability of the electroweak interaction (α) and of the strong interaction at 2×10^{-15} per year

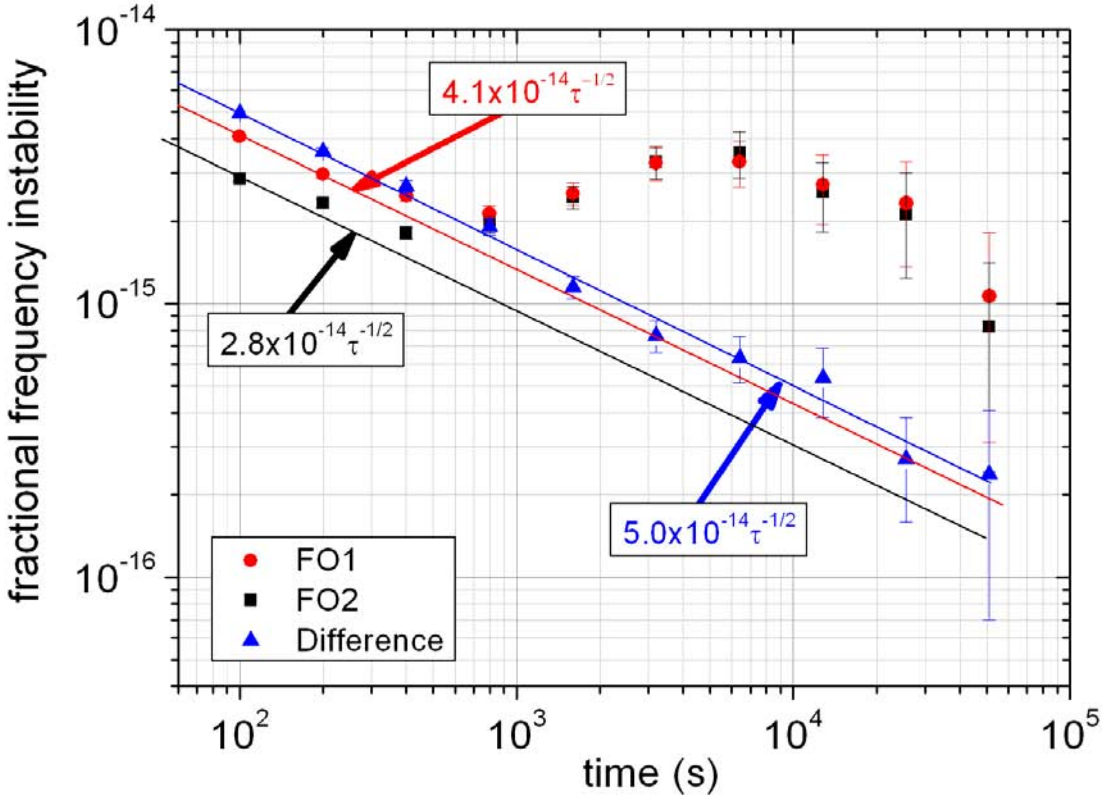
Current status and prospects in the development of LNE-SYRTE fountain ensemble

FREQUENCY COMPARISON AT THE 10^{-16} LEVEL

(2004)

S. Bize et al., C.R. Physique 5, 829 (2004)
C. Vian et al., IEEE Trans. Instrum. Meas. 54, 833 (2005)

Fractional frequency instability (Allan deviation) between FO1 and FO2 fountains & fractional frequency instability of **FO1** and **FO2** against the CSO locked to a hydrogen maser



$$\sigma_y(\tau = 50\,000\text{s}) = 2.2\times10^{-16}$$

1st comparison between primary standards in the low 10^{-16} range

Mean fractional frequency difference = 4 x 10^{-16}
fully compatible with the accuracy of each of the two clocks.

UNCERTAINTY BUDGET

(2004 and improvements since then)

Systematic fractional frequency shifts for FO1 and FO2 ^{133}Cs fountains

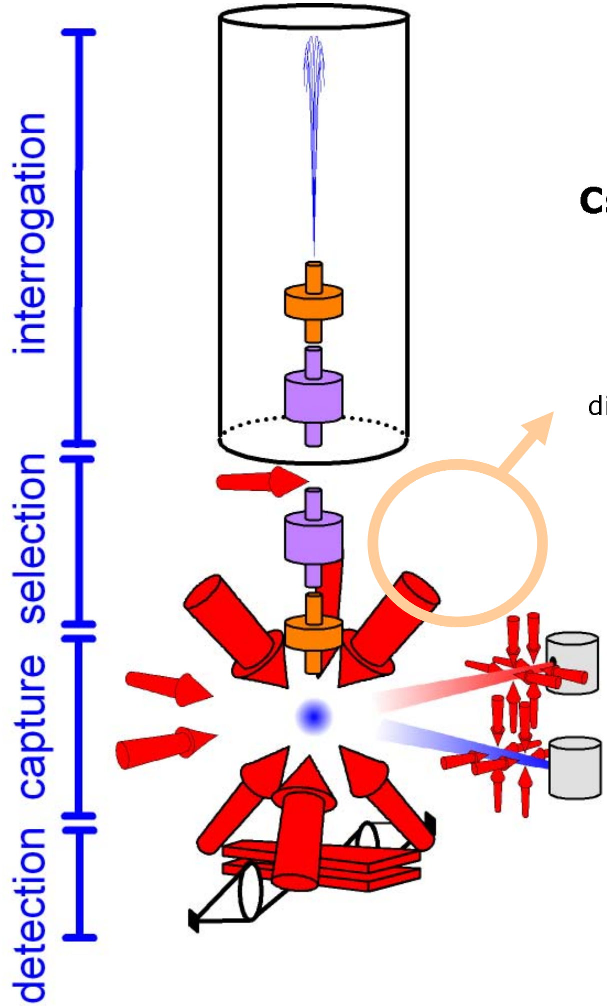
	FO1 ($\times 10^{16}$)	**FO2** ($\times 10^{16}$)	
Quadratic Zeeman effect	1199.7 ± 4.5	1927.3 ± 0.3	
Blackbody radiation	-162.8 ± 2.5	-168.2 ± 2.5	⇛±0.6
Collisions and cavity pulling	-197.9 ± 2.4	-357.5 ± 2.0	⇛±1.0
Microwave spectral purity & leakage	0.0 ± 3.3	0.0 ± 4.3	⇛±0.5
First order Doppler effect	< 3	< 3	⇛±??
Ramsey & Rabi pulling	< 1	< 1	
Microwave recoil	< 1.4	< 1.4	⇛<0.5
Second order Doppler effect	< 0.08	< 0.08	
Background collisions	< 1	< 1	
Total uncertainty	± 7.5	± 6.5	

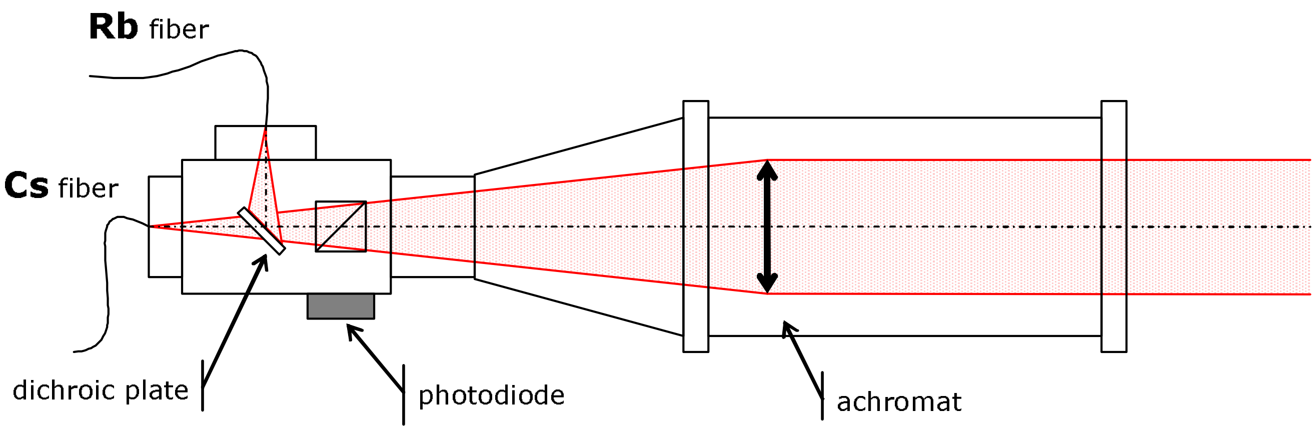
FO2 SOON OPERATED AS A DUAL FOUNTAIN

"Dichroic" collimators

Cs cooling: λ = 852 nm
Rb cooling: λ = 780 nm

6 collimators for the optical molasses
(+ 2 collimators for detection + 1 pusher beam)





[same focal length for both λ]

Optical adjustment by autocollimation

Mesured deviation: **< 0.1 mrad**

Centering: **< 1 mm**

⇒ Now attached to the FO2 fountain with Rb 2DMOT

FURTHER PROSPECTS

- Fountain accuracy of few 10^{-16}
- Stability of constants in the interesting 10^{-17} yr^{-1} range
- Improved SME tests with dual fountain

- Stability of constants using 2 µW clocks (Rb, Cs) and 2 optical lattice clocks (Sr, Hg)

- Towards PHARAO/ACES ground segment
  - Quasi-continuous operation of atomic fountain
  - Improved local timescale