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PSL Research University

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Systèmes de Référence Temps-Espace

SYRTE

Searching for variations of fundamental constants and dark matter using an atomic clock ensemble

J. Guéna, M. Abgrall, A. Hees, R. Le Targat, J. Lodewyck, L. De Sarlo, Y. Le Coq, P. Wolf, and S. Bize

Varcosmofun'16
September 13rd, 2016
Szczecin, Poland

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Outline

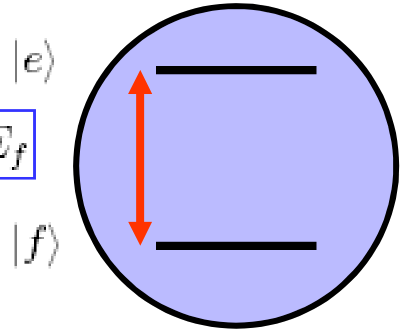
- ► Atomic clocks and fundamental constants
- ► Rb vs Cs in atomic fountain clocks
- ► Some measurements with optical clocks
- ► Constraints to variation of constants with time and gravitation potential
- ► Prospects

Principles of atomic clocks

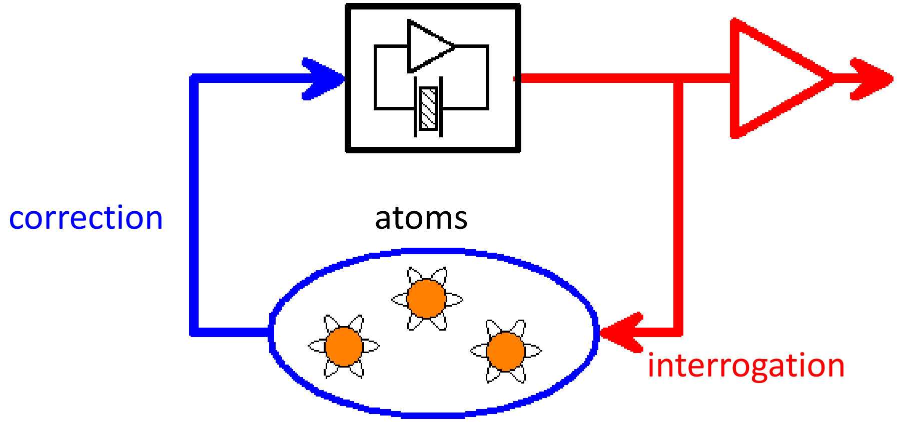
- Goal
  - Deliver a signal with stable and universal frequency

- Atoms can help
  - Bohr frequencies of unperturbed atoms are thought to be "perfectly" stable and universal

$$\hbar\omega_{ef} = h\nu_{ef} = E_e - E_f$$



- Building blocks of an atomic clock



Output = "macroscopic" practically usable signal tightly connected to the atomic transition

$$\omega(t) = \omega_{ef} \times (1 + \varepsilon + y(t))$$

Motivations for tests with clocks

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- A pending question in modern physics
  - Unification of gravity with the electroweak and strong interactions in a consistent theory

- Unification theories often allow or even predict violations of Einstein's Equivalence Principle
  - Could manifest themselves by variations of what we call natural constants

- Laboratory experiments with accurate atomic clocks can search for such variations
  - Constrain unification theories independently of cosmological models
  - Search for physics beyond GR and the Standard Model
  - Complement tests over cosmological timescales, e.g. tests based on atomic absorption lines in the spectra of quasars

Atomic transitions and natural constants

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- Leading term in the frequency of atomic transitions
  - Electronic transition

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

  - Hyperfine transition

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

  - Molecular vibration and rotation

$$\nu^{(i)}_{vib} \simeq R_\infty c \times \mathcal{A}^{(i)}_{vib} \times \left(\frac{m_e}{m_p}\right)^{1/2}$$

$$\nu^{(i)}_{rot} \simeq R_\infty c \times \mathcal{A}^{(i)}_{rot} \times \left(\frac{m_e}{m_p}\right)$$

- Actual measurements : dimensionless frequency ratios

$$\frac{\nu^{(ii)}_{\rm elec}}{\nu^{(i)}_{\rm elec}} \propto \frac{F^{(ii)}_{\rm elec}(\alpha)}{F^{(i)}_{\rm elec}(\alpha)}$$

$$\frac{\nu^{(ii)}_{\rm hfs}}{\nu^{(i)}_{\rm elec}} \propto g^{(ii)} \frac{m_e}{m_p} \alpha^2 \frac{F^{(ii)}_{\rm hfs}(\alpha)}{F^{(i)}_{\rm elec}(\alpha)}$$

$$\frac{\nu^{(ii)}_{\rm hfs}}{\nu^{(i)}_{\rm hfs}} \propto \frac{g^{(ii)}}{g^{(i)}} \frac{F^{(ii)}_{\rm hfs}(\alpha)}{F^{(i)}_{\rm hfs}(\alpha)}.$$

- Possibility to test electroweak and strong interactions
  - Electronic transitions: sensitivity to α → electroweak int.
  - Hyperfine and molecular transitions: sensitivity to the strong interaction via g-factors and m_e/m_p

Sensitivity coefficients

- m_p and g-factors $g^{(i)}$ are not fundamental parameters of the Standard Model
  - They can be related to the light quark mass: m_q/Λ_{QCD}

V. V. Flambaum et al., PRD 69, 115006 (2004)
V. V. Flambaum and A. F. Tedesco, PRC 73, 055501 (2006)

- Any atomic (or molecular) transition is sensitive to 3 dimensionless fundamental constants
  - α , $\mu = m_e/m_p$, m_q/Λ_{QCD}

$$\delta \ln\left(\frac{\nu^{(i)}}{R_\infty c}\right) \simeq k_\alpha^{(i)} \times \frac{\delta\alpha}{\alpha} + k_\mu^{(i)} \times \frac{\delta\mu}{\mu} + k_q^{(i)} \times \frac{\delta(m_q/\Lambda_{\mathrm{QCD}})}{(m_q/\Lambda_{\mathrm{QCD}})}$$

- Generally, sensitivity coefficients can be computed with reasonable uncertainty with QED + QCD
  - k_α << 1%
  - k_μ < 1% to 10%
  - k_q ?

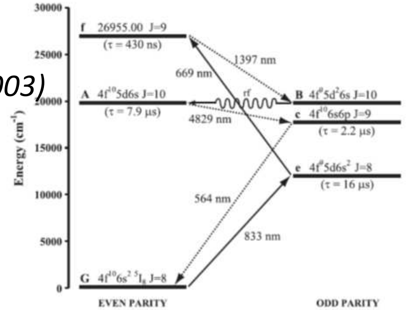
Alternatively: α , m_e/Λ_{QCD} , m_q/Λ_{QCD}
k_α , k_e , k_q
$d \ln(\mu) = d \ln(m_e/\Lambda_{QCD}) - 0.048\, d \ln(m_q/\Lambda_{QCD})$

Values of sensitivity coefficients

	k_α	k_μ	k_q
Rb hfs	2.34	1	-0.019
Cs hfs	2.83	1	0.002
H hfs	2	1	-0.100
H opt	~0	0	0
Yb^+ E2 opt	1.0	0	0
Yb^+ E3 opt	-6.0	0	0
Hg^+ opt	-2.94	0	0
Sr opt	0.06	0	0
Al^+ opt	0.008	0	0
Dy rf	1.7×10^7	0	0

- Diversity of atomic systems is essential
  - To separate electroweak and strong interactions
  - To provide redundancy and signatures
- Huge sensitivity of Dy
  - RF transition between 2 accidentally degenerated electronic states of different parity

Dzuba et al., Phys. Rev. A 68, 022506 (2003)



- Other systems with large sensitivities
  - Diatomic molecules: coincidences between hyperfine and rotational energies give 10^2-10^3 enhancement

Flambaum, PRA 73, 034101 (2006)

  - Highly charged ions

Flambaum, PRL 105, 120801 (2010)

  - ^{229}Th: M1 nuclear transition in the optical domain (163nm) between 2 nearly degenerated nuclear states

E. Peik and Chr. Tamm, Europhys. Lett. 61, 181 (2003)

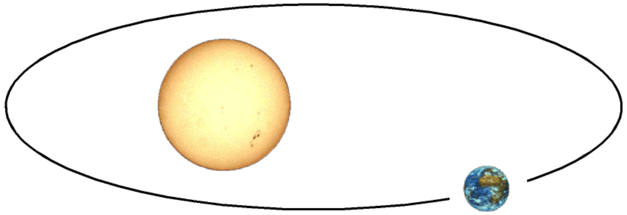
3 types of search

- Variation with time
  - Repeated measurements between clock A and clock B over few years

$$\frac{d}{dt}\ln\left(\frac{\nu^{(A)}}{\nu^{(B)}}\right) = k_\alpha^{(AB)} \times \frac{d}{dt}\ln(\alpha) + k_\mu^{(AB)} \times \frac{d}{dt}\ln(\mu) + k_q^{(AB)} \times \frac{d}{dt}\ln(m_q/\Lambda_{QCD})$$

- Variation with gravitational potential

Annual modulation of the Sun gravitation potential at the Earth :



$$\Delta u(t) = \frac{\Delta U(t)}{c^2} \simeq -\underbrace{\frac{GM_\odot}{c^2 a}\epsilon}_{\sim 1.6\ 10^{-10}} \cos[\Omega(t - t_{perihelion})]$$

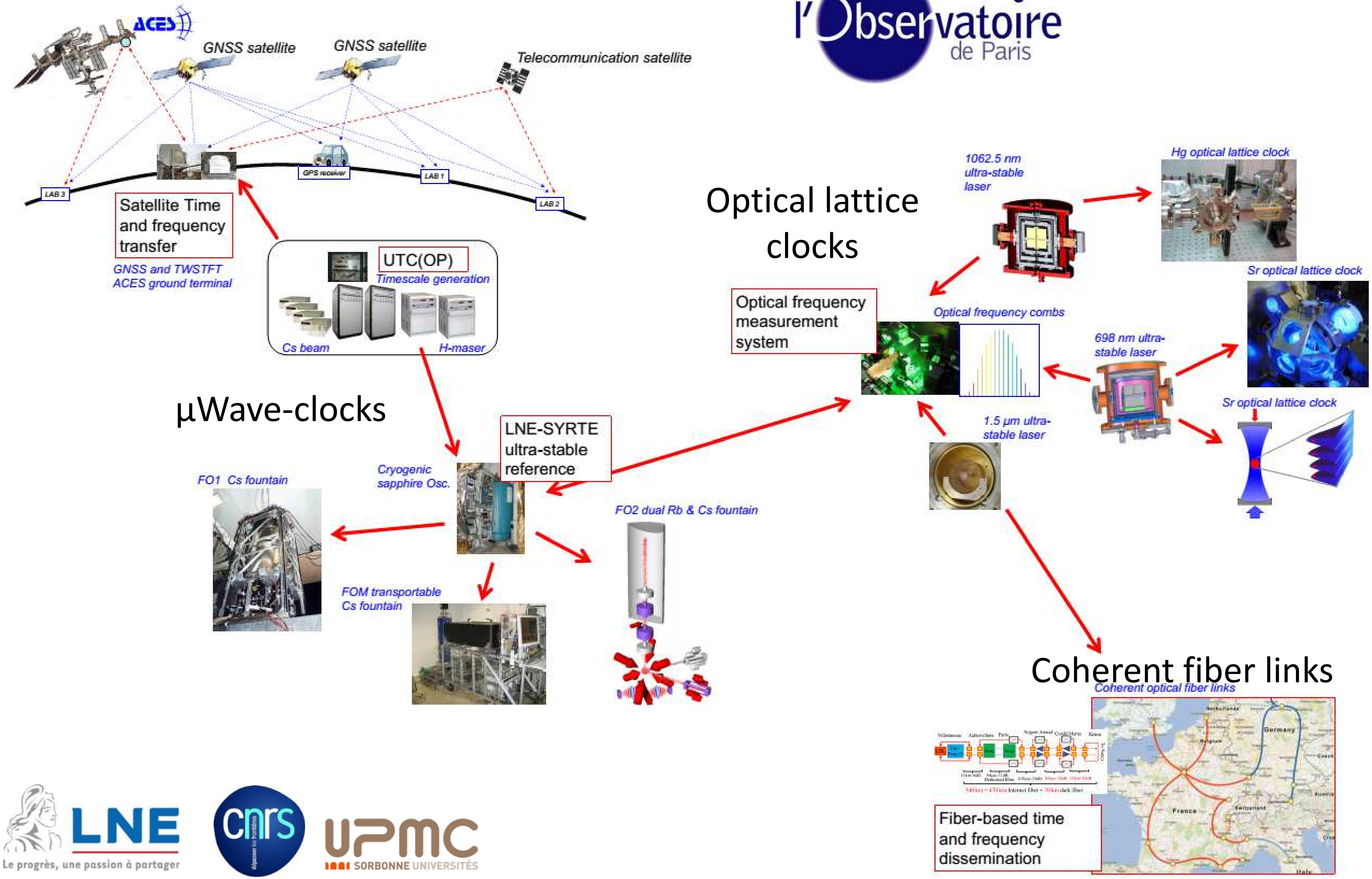
  - Several measurements per year, search for a modulation with annual period and phase origin at the perihelion

$$\frac{d}{du}\ln\left(\frac{\nu^{(A)}}{\nu^{(B)}}\right) = k_\alpha^{(AB)} \times \frac{d}{du}\ln(\alpha) + k_\mu^{(AB)} \times \frac{d}{du}\ln(\mu) + k_q^{(AB)} \times \frac{d}{du}\ln(m_q/\Lambda_{QCD})$$

- Variation with space
  - Several measurements per year, search modulation with annual period and arbitrary phase $x(t) \simeq a\cos\Omega t, \quad y(t) \simeq a\sin\Omega t, \quad a \simeq 1.496 \times 10^{11}\mathrm{m}$
  - Time variation interpreted as spatial variation probed by the motion of the Solar system wrt the CMB at 369 $\mathrm{km.s^{-1}}$ or $1.2\mathrm{x}10^{-3}$ $\mathrm{lyr.yr^{-1}}$

Berengut and Flambaum, Europhys Lett 97, 20006 (2012)

LNE-SYRTE atomic clock ensemble



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Applications of LNE-SYRTE clock ensemble

- Time and frequency metrology
  - Realization of highly stable timescale: UTC(OP)
  - Calibration of the international atomic time TAI
  - Develop optical clocks and optical frequency metrology for a redefinition of the SI second

- Technology development
  - ACES space mission, space clocks, satellite and fiber T&F dissemination, oscillators, etc.

- Local Lorentz Invariance tests
  - In the photon sector: CSO vs H-maser over > 10 years

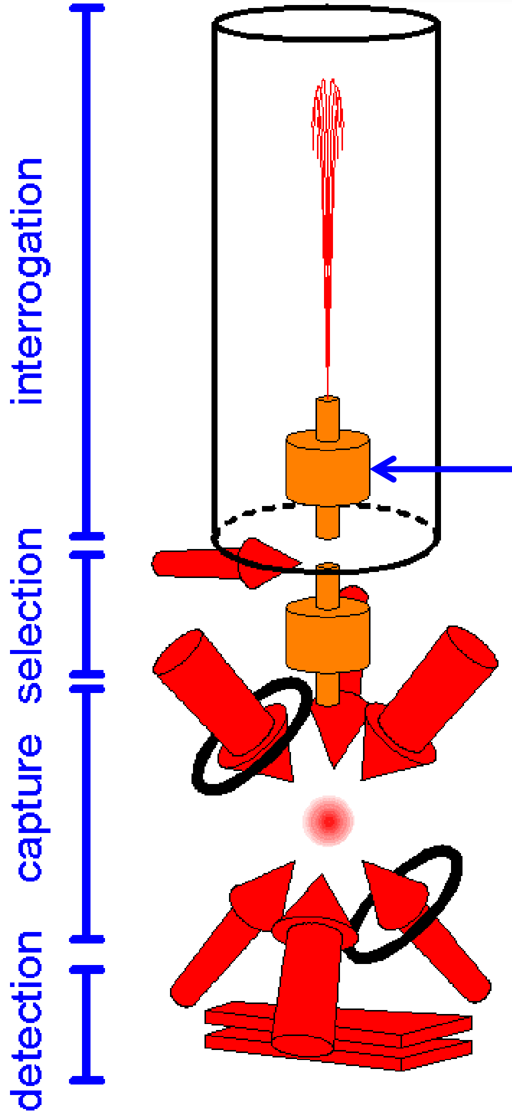
    most stringent Kennedy-Thorndike test by a factor of ~500

    P. Wolf et al., Phys. Rev. Lett. 90, 060402 (2003), P. Wolf et al., Gen. Rel. Grav. 36, 2351 (2004)
    P. Wolf et al., Phys. Rev. D 70, 051902(R) (2004), M. Tobar et al., Phys. Rev. D. 81, 022003 (2010)

  - In the matter sector: with Zeeman transitions in Cs fountain, interpreted within the SME framework

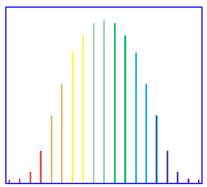
    P. Wolf et al., Phys. Rev. Lett. 96, 060801 (2006)

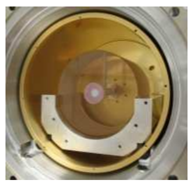
Atomic fountain clocks

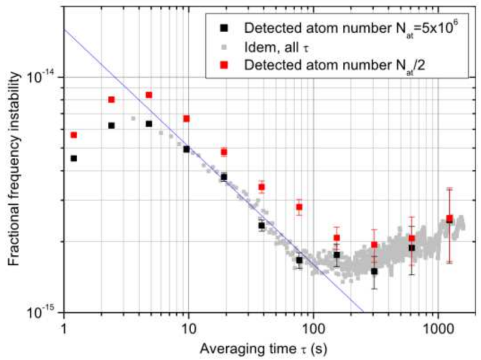


Cryogenic Sapphire Ocillator

µW from laser stabilized comb

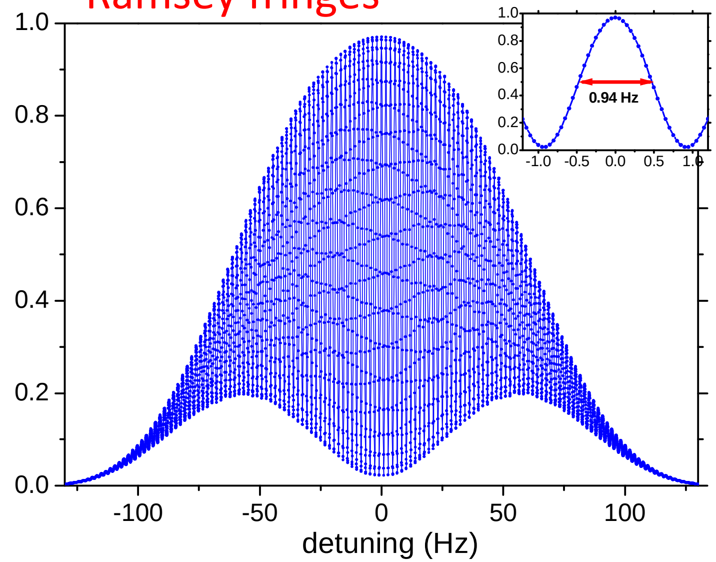






J. Guéna et al., IEEE TUFFC 59, 391 (2012)

Ramsey fringes



Atomic quality factor:

$$Q_{at} = \nu_{ef}/\Delta\nu \simeq 9.8 \times 10^9$$

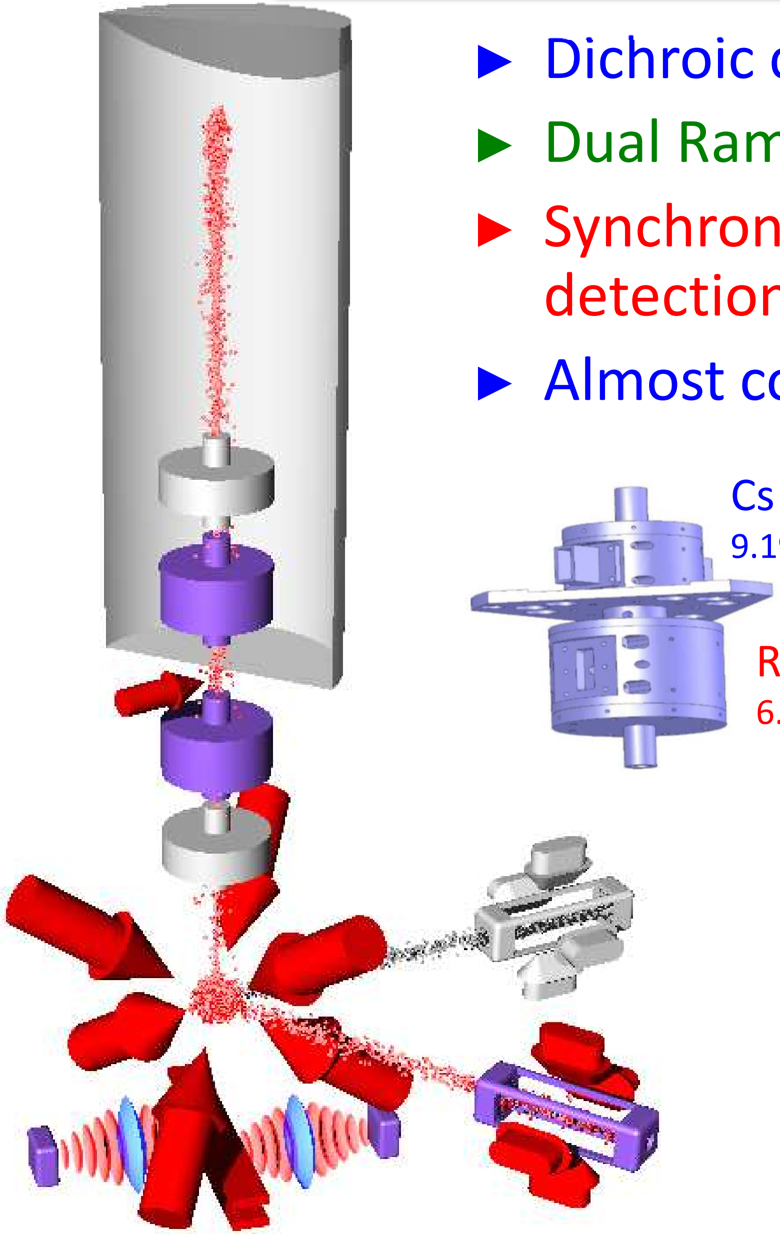
Best frequency stability (Quantum Projection Noise limited): 1.6×10^{-14} @1s

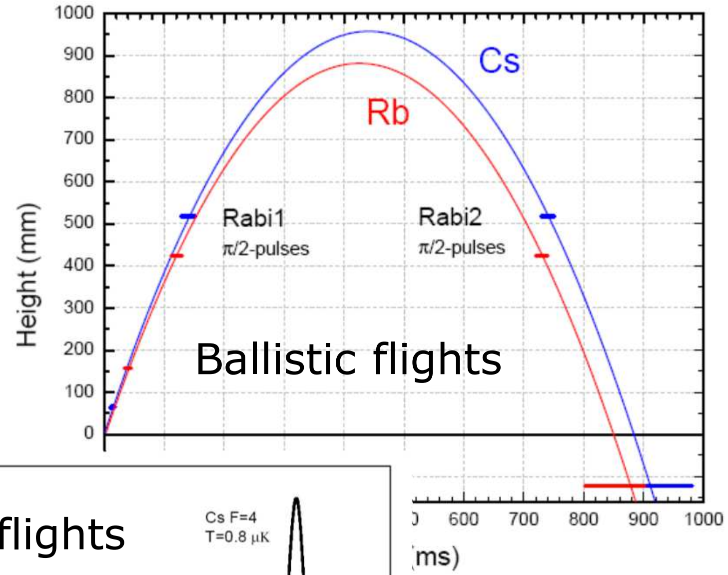
⇔ $\sigma_{\delta P}$ ~ 2×10^{-4} is a single measurement (~ 1.6 s)

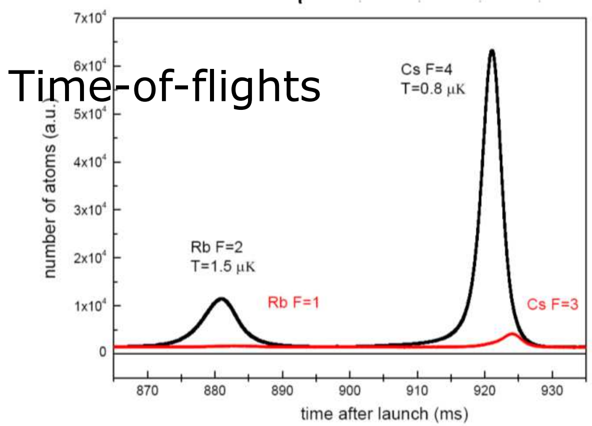
Best accuracy: $(2\text{-}3)\times10^{-16}$

LNE-SYRTE FO2: a dual Rb & Cs fountain

- Dichroic collimators ➔co-located optical molasses
- Dual Ramsey microwave cavity
- Synchronized control systems and time-resolved detections of Rb and Cs
- Almost continuous dual clock operation since 2009

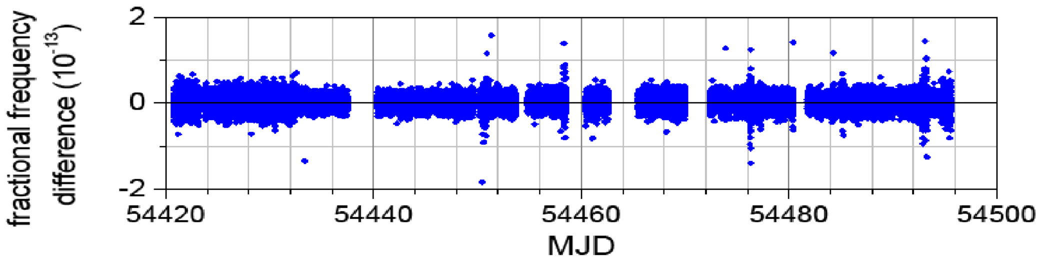




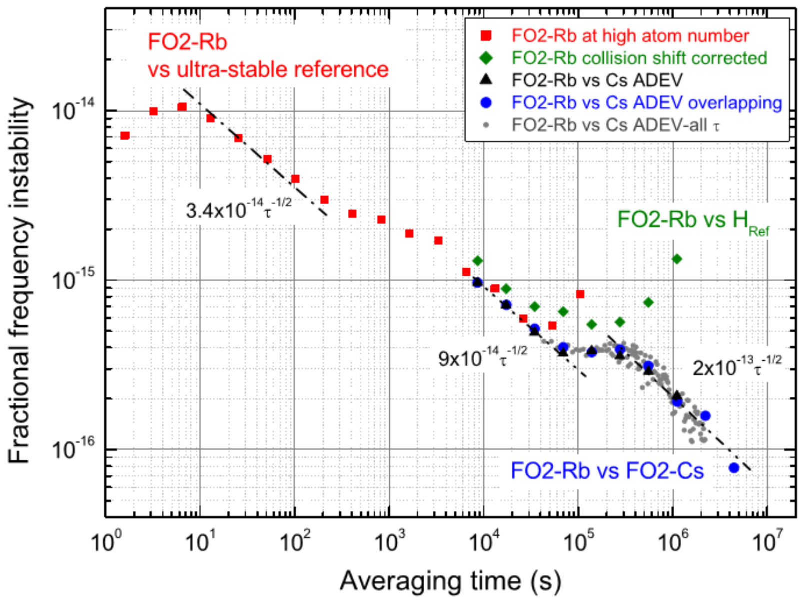


J. Guéna et al., IEEE Trans. on UFFC 57, 647 (2010)

Rb/Cs measurements



- Feb. to Aug. 2012 measurement
  6 834 682 610.904 312(3) Hz (4.4x10^{-16})
- Since 2012, FO2-Rb contributes to the calibration of TAI and steering of the SI second.



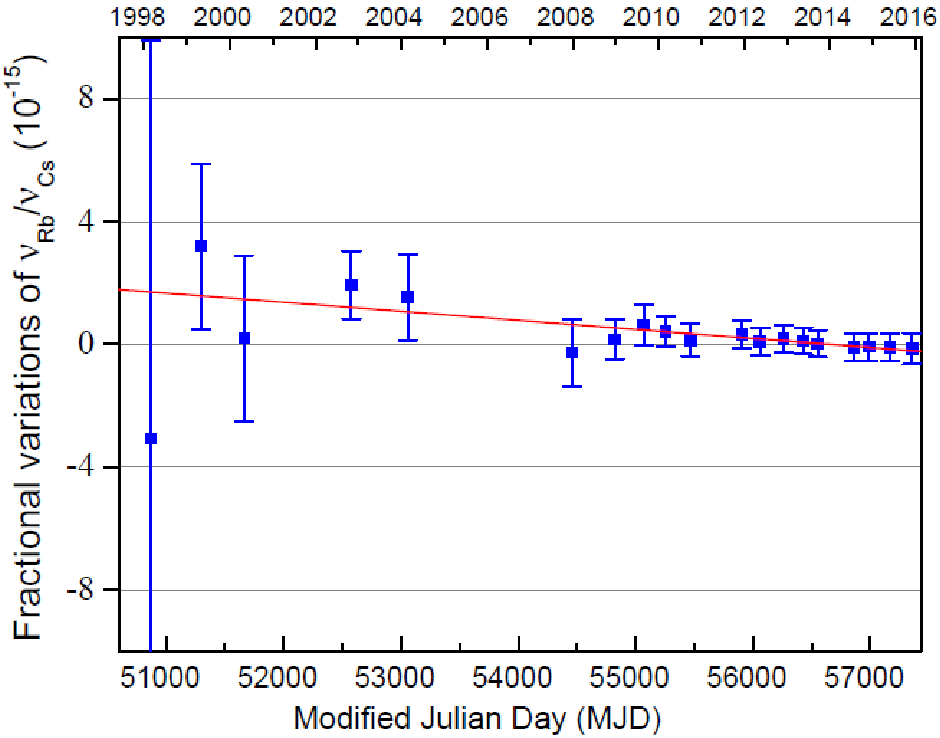
J. Guéna et al., Metrologia 51, 108 (2014)

Fountain accuracy budgets (10^{-16})

	FO1	FO2-Cs	FOM	FO2-Rb
Quadratic Zeeman shift	-1274.5 ± 0.4	-1915.9 ± 0.3	-305.6 ± 1.2	-3465.5 ± 0.7
Blackbody radiation	172.6 ± 0.6	168.0 ± 0.6	165.6 ± 0.6	122.8 ± 1.3
Collisions and cavity pulling	70.5 ± 1.4	112.0 ± 1.2	28.6 ± 5.0	2.0 ± 2.5
Distributed cavity phase shift	-1.0 ± 2.7	-0.9 ± 0.9	-0.7 ± 1.6	0.4 ± 1.0
Spectral purity and leakage	<1.0	<0.5	<4.0	<0.5
Ramsey and Rabi pulling	<1.0	<0.1	<0.1	<0.1
Microwave lensing	-0.7 ± 0.7	-0.7 ± 0.7	-0.9 ± 0.9	-0.7 ± 0.7
Second-order Doppler shift	<0.1	<0.1	<0.1	<0.1
Background collisions	<0.3	<1.0	<1.0	<1.0
Total	-1033.1 ± 3.5	-1637.5 ± 2.1	-113.0 ± 6.9	-3341.0 ± 3.3
Prior to 2011*	-1031.4 ± 4.1	-1635.9 ± 3.8	-111.4 ± 8.1	-3340.7 ± 4.2

- DCP shift
  Phys. Rev. Lett. 106, 130801 (2011)
- µW lensing
  arXiv:0403194v1
  Phys. Rev. Lett. 97, 073002 (2006)
  Metrologia 48, 283 (2011)
- Background collisions
  Phys. Rev. Lett. 110, 180802 (2013)

Rb/Cs: search for time variation



J. Guéna et al., Phys. Rev. Lett. 109,080801 (2012)
Updated to 2016

Weighted least-squares fit to a line

$$\frac{d}{dt}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-10.7 \pm 4.9)\times 10^{-17}\, yr^{-1}$$

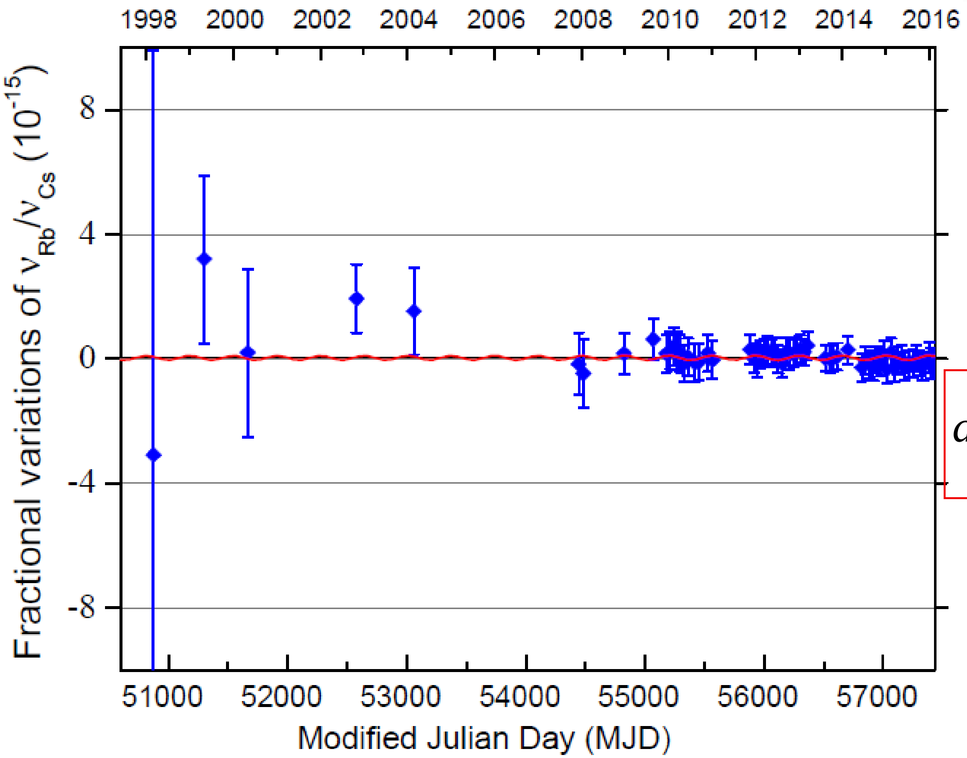
⇒ With QED calculations: *J. Prestage et al., PRL (1995), V. Dzuba, et al., PRA (1999)*

$$\frac{d}{dt}\ln\left(\frac{g_{Rb}}{g_{Cs}}\alpha^{-0.49}\right) = (-10.7 \pm 4.9)\times 10^{-17}\, yr^{-1}$$

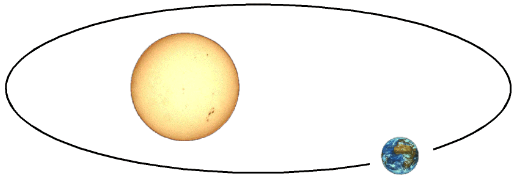
⇒ With QCD calculations: *T.H. Dinh, et al., PRA79 (2009)*

$$\frac{d}{dt}\ln\left[\alpha^{-0.49}(m_q/\Lambda_{QCD})^{-0.021}\right] = (-10.7 \pm 4.9)\times 10^{-17}\, yr^{-1}$$

Rb/Cs: search for annual variations



Phys. Rev. Lett. 109,080801 (2012)



$$\frac{\Delta U(t)}{c^2} \simeq -\frac{GM_\odot}{c^2 a}\epsilon \cos[\Omega(t - t_{perihelion})]$$

$$d\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = C + (0.8 \pm 0.9)\times 10^{-16}\cos[\Omega_\oplus(t - t_{perihelion})]$$

$$c^2\frac{d}{dU}\ln\left(\frac{\nu_{Rb}}{\nu_{Cs}}\right) = (-4.7 \pm 5.3)\times 10^{-7}$$

- Differential redshift test

$$d\nu/\nu = (1+\beta)dU/c^2$$

$$\beta(^{87}Rb) - \beta(^{133}Cs) = (-4.7 \pm 5.3)\times 10^{-7}$$

- Variation of constants with gravity

$$c^2\frac{d}{dU}\ln\left(\frac{g_{Rb}}{g_{Cs}}\alpha^{-0.49}\right) = (-4.7 \pm 5.3)\times 10^{-7}$$

$$c^2\frac{d}{dU}\ln\left(\alpha^{-0.49}(m_q/\Lambda_{QCD})^{-0.021}\right) = (-4.7 \pm 5.3)\times 10^{-7}$$

Searching for Dark matter candidates

•Modified gravitational theories contain long range <u>scalar</u> fields φ. If <u>massive</u> and <u>pressureless</u> : DM candidates. Under quite general assumptions they will oscillate at the Compton frequency

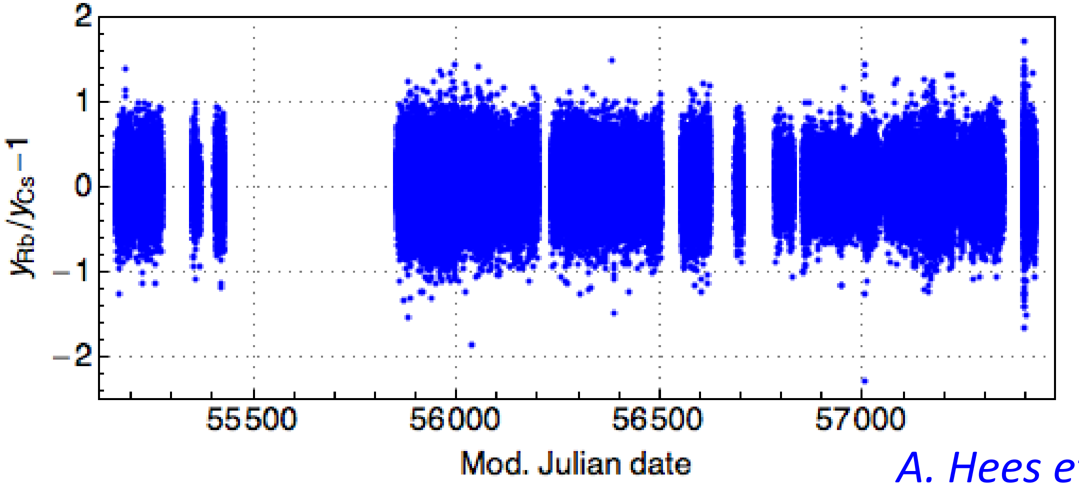
$$f = m_\varphi c^2/h.$$

Damour & Donoghue, PRD 82, 084033,2010
Stadnik & Flambaum 2014,2015

•Scalar fields φ might be non-minimally coupled to SM-fields, leading to violations of EEP, e.g. space-time variations of (α, m_i, Λ_3) if φ varies

$$\alpha(\varphi) = \alpha(1 + d_e\varphi)$$
$$m_i(\varphi) = m_i(1 + d_{mi}\varphi)$$
$$\Lambda_3(\varphi) = \Lambda_3(1 + d_g\varphi)$$

We look for oscillation in the Rb/Cs hyperfine frequency ratio:



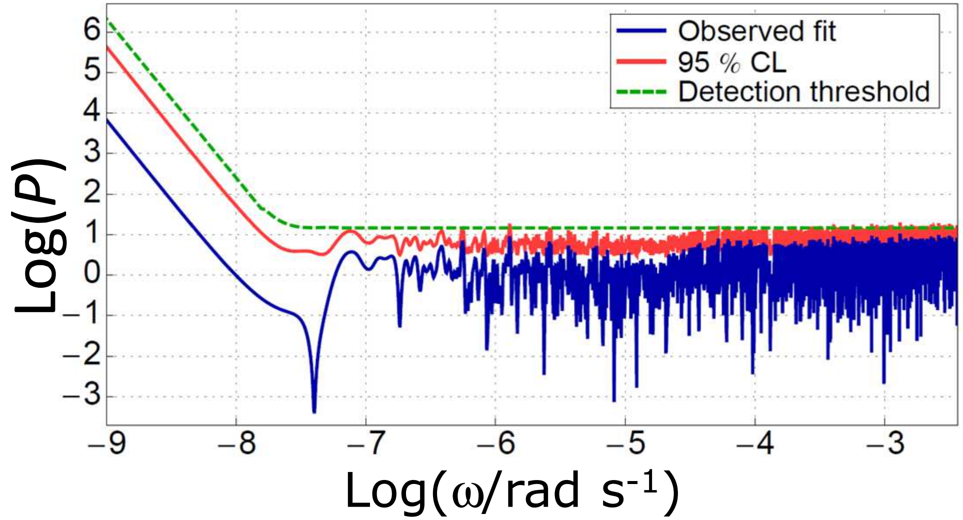
- Nov 2009 – Feb 2016
- Averaged to 100 points/day
- 100814 points in total
- ≈ 45% duty cycle with gaps due to maintenance and investigation of systematics
- Standard deviation = 3×10^{-15}

A. Hees et al., arXiv:1604.8514, to appear in PRL

Analysing 6 years of Rb vs. Cs

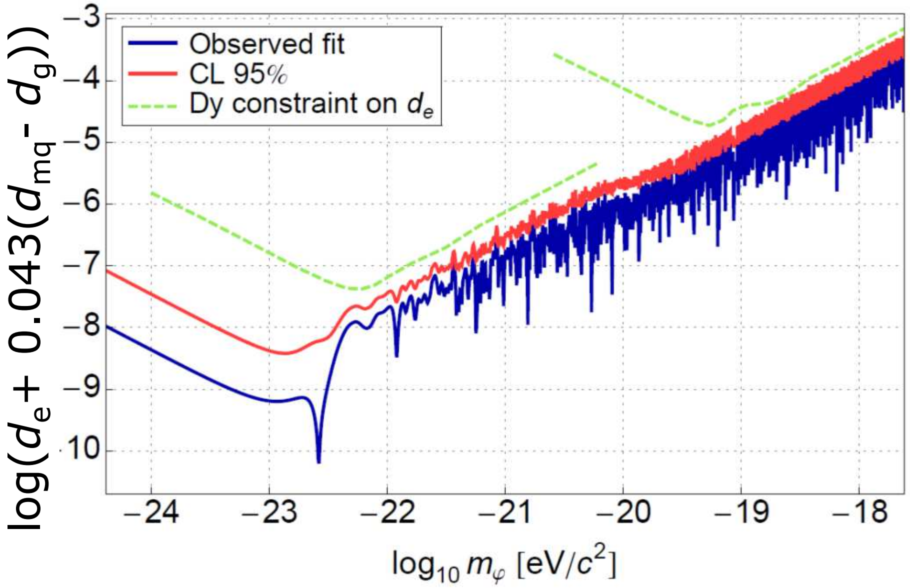
We look for oscillation in the Rb/Cs frequency ratio:

arXiv:1604.8514, PRL



- Fit $A + C_\omega \cos(\omega t) + S_\omega \sin(\omega t)$ to data for each independent ω.
- Search for a peak in normalized power $P_\omega = \frac{N}{4\sigma^2}(C_\omega^2 + S_\omega^2)$.
- Determine confidence limits (LSQ + MC, Bayesian MCMC)

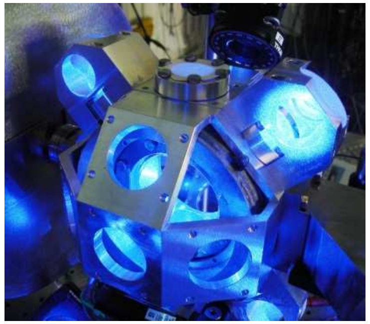
No detection, but limit to coupling $d_e+0.043(d_{mq}- d_g)$ as function of mass

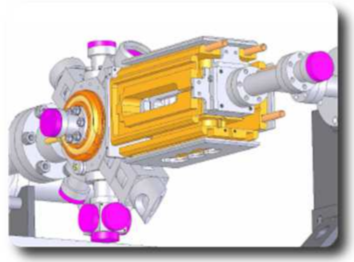


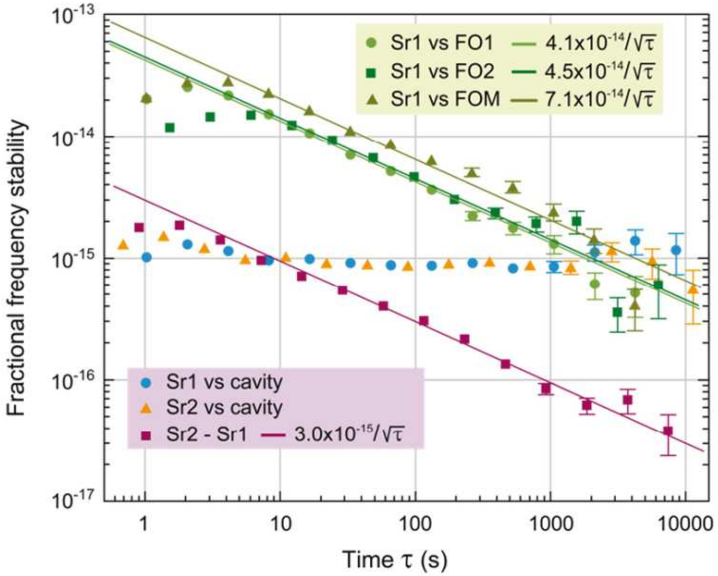
- Complementary to previous searches (Dy) that are sensitive to d_e only.
- When assuming only $d_e \neq 0$, improve Dy limits significantly.
- Also complementary to WEP tests

*Van Tilburg et al., PRL **115**, 011802 (2015)*
*Arvanitaki,et al. PRL **116**, 031102 (2016)*

Optical lattice clocks







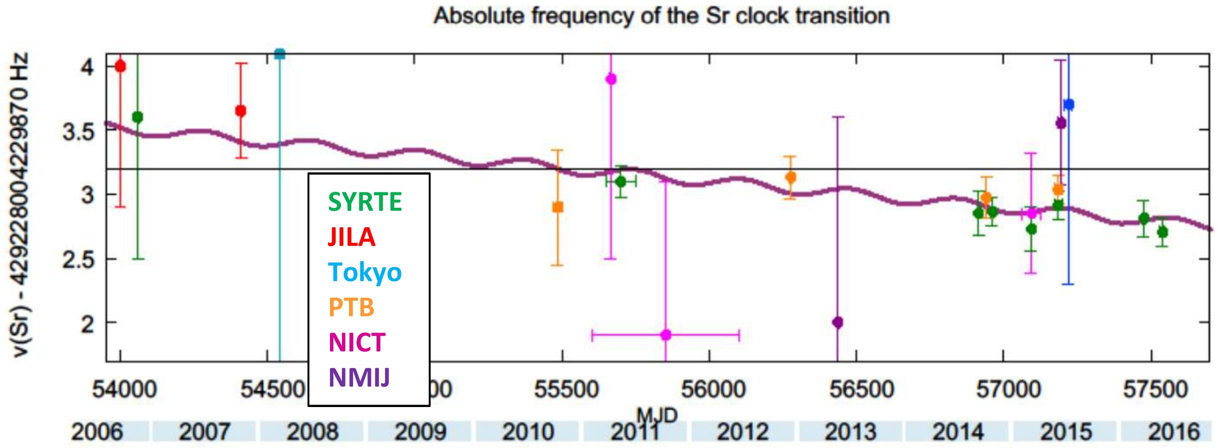
- 2 Sr optical lattice clocks: accuracy of 4-5x10^{-17}, frequency stability of 10^{-15} at 1s between the two clocks -> low 10^{-17} resolution after a few hours
- 1 Hg OLC

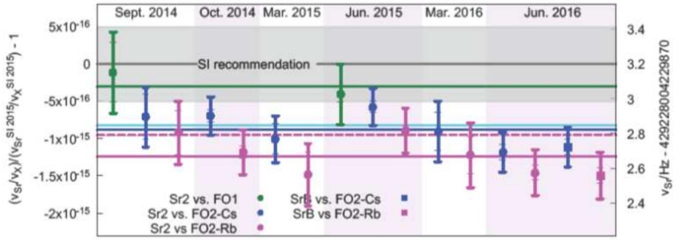
Le Targat et al., Nat. Commun. 4, 2109 (2013)

Main achievements:

- First comparison between 2 OLCs with an uncertainty beyond the Cs primary standard -> confirm the accuracy budget
- Quasi-continuous operation over periods of 1 to 3 weeks *Metrologia 53, 1123* (2016) -> calibration of international time scales with optical clocks now possible
- Frequency ratio measurement of Sr/Hg with 1.7x10^{-16} uncertainty *arXiv:1603.02026, to appear in NJP* -> excellent agreement with RIKEN

Local optical-to-microwave comparisons





Metrologia 53,1123,2016
arXiv:1605.03878,

- Excellent reproducibility over time for SYRTE's Sr vs fountains (Cs&Rb), and also at the international level
- Agreement between the two best measurements at a few 10^{-16} from two independent laboratories (PTB and SYRTE) *New J. Phys. 16, 073023 (2014)*

> 10 years of measurements : Possible to fit a linear drift + coupling to the solar gravitational potential

$$\frac{d}{dt}\ln\left(\frac{\nu_{Sr}}{\nu_{Cs}}\right) = (-18 \pm 5.5)\times 10^{-17}\, yr^{-1}$$

$$c^2 \frac{d}{dU}\ln\left(\frac{\nu_{Sr}}{\nu_{Cs}}\right) = (-0.99 \pm 1.5)\times 10^{-6}$$

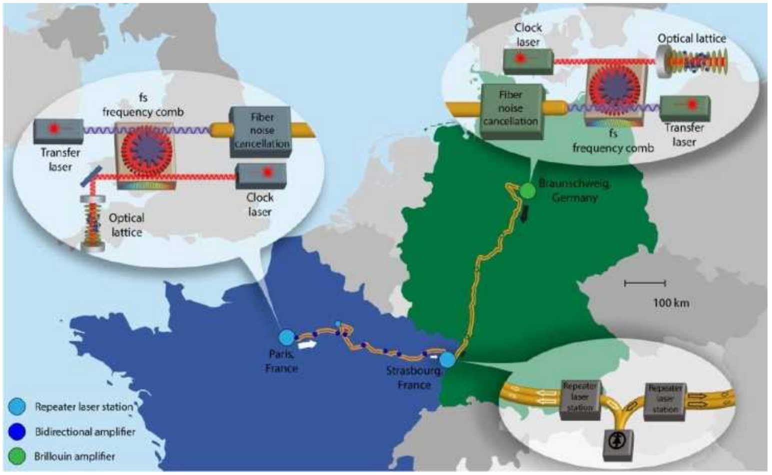
QED + QCD

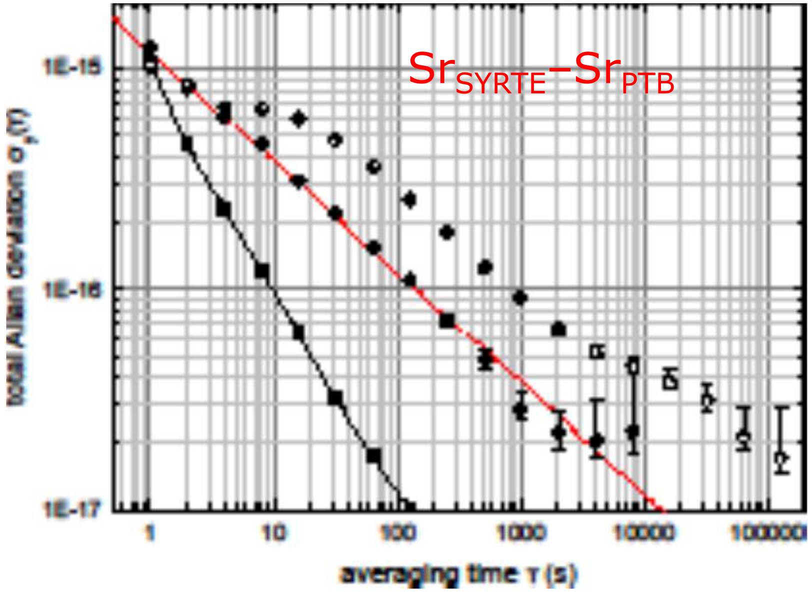
$$d\ln\left(\frac{\nu_{\mathrm{Sr}}}{\nu_{\mathrm{Cs}}}\right) \Rightarrow d\ln\left(\alpha^{-2.77}\mu^{-1}\left(\frac{m_q}{\Lambda_{\mathrm{QCD}}}\right)^{-0.002}\right)$$

limited by the accuracy of atomic fountains

All-optical remote comparison of lattice clocks

SYRTE, LPL, PTB collaboration





- First long distance or international clock comparison with a fibre link

- 10 times better resolution, and orders of magnitude faster than satellite comparison (2×10^{-17} resolution after a few 1000 s)

- record agreement between distant clocks: $Sr_{SYRTE} - Sr_{PTB} = (4\pm5)\times10^{-17}$

- First links of a backbone of fibre links in France/Europe

Global analysis of variation with time

SYRTE

$$d \ln(\nu_1/\nu_2)/dt \approx \Delta k_\alpha \, d \ln(\alpha)/dt + \Delta k_\mu \, d \ln(\mu)/dt + \Delta k_q \, d \ln(m_q/\Lambda_{QCD})/dt$$

ν_1/ν_2	Δk_α	Δk_μ	Δk_q	$d \ln(\nu_1/\nu_2)/dt$ (10^{-16} yr^{-1})	
Rb/Cs	-0.49	0	-0.021	-1.07 ± 0.49	SYRTE (PRL 109, 2012 + update)
H(1S-2S)/Cs	-2.83	-1	-0.002	-32 ± 63	MPQ + SYRTE (PRL92, 2004)
Yb^+ E2/Cs	-1.83	-1	-0.002	0.5 ± 1.9	PTB (PRL 113, 2014)
Yb^+ E3/Cs	-8.83	-1	-0.002	0.2 ± 4.1	PTB (PRL 113, 2014)
Hg^+/Cs	-5.77	-1	-0.002	3.7 ± 3.9	NIST (PRL 98, 2007)
Sr/Cs	-2.77	-1	-0.002	-1.8 ± 0.55	Tokyo, JILA, SYRTE, PTB (+NICT, NMIJ)
(^{162}Dy-^{163}Dy)/Cs	1.7×10^7	-1	-0.002	$(-4.0\pm 4.1)\times10^8$	Berkeley (PRL 2007)
(^{162}Dy-^{164}Dy)/Cs	4×10^6	-1	-0.002	$(-2.4\pm 2.8)\times10^6$	Berkeley (PRL 2013)
Al^+/Hg^+	2.95	0	0	-0.53± 0.79	NIST (Science 2008)

To be added: ^{88}Sr+/Cs (NPL, NRC)

Least square fit ➔

$d \ln(\alpha)/dt = (-2.6 \pm 2.3)\times10^{-17}$ yr^{-1} — mainly determined by Al^+/Hg^+

$d \ln(\mu)/dt = (21.2 \pm 8.3)\times10^{-17}$ yr^{-1} — mainly determined by Opt/Cs

$d \ln(m_q/\Lambda_{QCD})/dt = (5.7 \pm 2.4)\times10^{-15}$ yr^{-1} — mainly determined with Rb/Cs

➔ multiply by ~833 yr.lyr^{-1} for spatial variation

<u>INDEPENDENT OF COSMOLOGICAL MODELS</u>

Global analysis of variation with gravity

SYRTE

$$d\ln(\nu_1/\nu_2)/dU \approx \Delta k_\alpha\, d\ln(\alpha)/dU + \Delta k_\mu\, d\ln(\mu)/dU + \Delta k_q\, d\ln(m_q/\Lambda_{QCD})/dU$$

ν_1/ν_2	Δk_α	Δk_μ	Δk_q	$c^2\, d\ln(\nu_1/\nu_2)/dU$ (10^{-6})
Rb/Cs	-0.49	0	-0.021	0.47 ± 0.53 SYRTE
Rb/Cs	-0.49	0	-0.021	-1.6± 1.3 USNO (PRA87, 2013)
H^{hf}/Cs	-0.83	0	-0.102	|0.1± 1.40| NIST, SYRTE, PTB, INRIM (PRL98, 2007)
H^{hf}/Cs	-0.83	0	-0.102	-0.7± 1.1 USNO (PRA87, 2013)
H^{hf}/Cs	-0.83	0	-0.102	0.0± 4.8 SYRTE (with UWA, PRD 87, 2013)
Rb/H^{hf}	0.34	0	0.081	0.0± 10 SYRTE (with UWA, PRD 87, 2013)
Rb/H^{hf}	0.34	0	0.081	-0.27± 0.49 USNO (PRA87, 2013)
Hg^+/Cs	-5.77	-1	-0.002	2.0± 3.5 NIST (PRL 98, 2007)
Sr/Cs	-2.77	-1	-0.002	0.66 ± 0.91 Tokyo, JILA, SYRTE, PTB (+NICT, NMIJ)
(^{162}Dy-^{163}Dy)/Cs	1.7×10^7	-1	-0.002	$(1.34\pm 1.04)\times10^8$ Berkeley (PRL 2007)
(^{164}Dy-^{162}Dy)/Cs	4×10^6	-1	-0.002	$(2.2\pm 2.1)\times10^6$ Berkeley (PRL 2013)

Least square fit ➡

$c^2\, d\ln(\alpha)/dU = (0.38 \pm 0.45)\times10^{-6}$

$c^2\, d\ln(\mu)/dU = (-0.24 \pm 2.0)\times10^{-6}$

$c^2\, d\ln(m_q/\Lambda_{QCD})/dU = (-3.1 \pm 5.6)\times10^{-6}$

INDEPENDENT OF COSMOLOGICAL MODELS

Summary and Prospects

- Atomic clocks provide high sensitivity measurements of present day variation of constants
  - Clock tests are independent of any cosmological model
  - Complement tests at higher redshift (geological and cosmological time scale)
  - ➔ Inputs for developing unified theories
- Clock data exploited to search for dark matter
  - Constraint to the coupling of light scalar field to SM matter *arXiv:1604.8514*
  - In prospect: Search for the passage of topological defects

    Derevianko & Popelov, Nat. Phys. 10, 933, 2014
- In the future: improvements from
  - Improvement of clocks: towards low 10^{-18}
  - Exploiting advanced remote comparison methods

    - ACES/PHARAO: mid-10^{-17} for ground-to-ground

      L. Cacciapuotia, Nuclear Physics B166 (2007) 303

    - Coherent optical fiber links: $<10^{-18}$

      (2×10^{-17} resolution after a few 1000 s)

Science 336, 441 (2012)
Opt. Express 20, 23518 (2012)