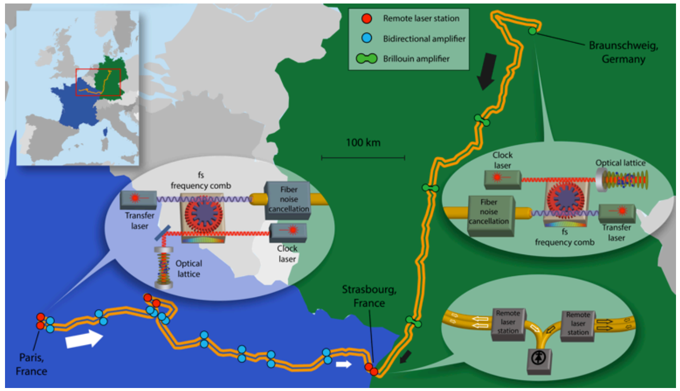
l'Observatoire de Paris | SYRTE

Systèmes de Référence Temps-Espace

STRONTIUM OPTICAL LATTICE CLOCKS

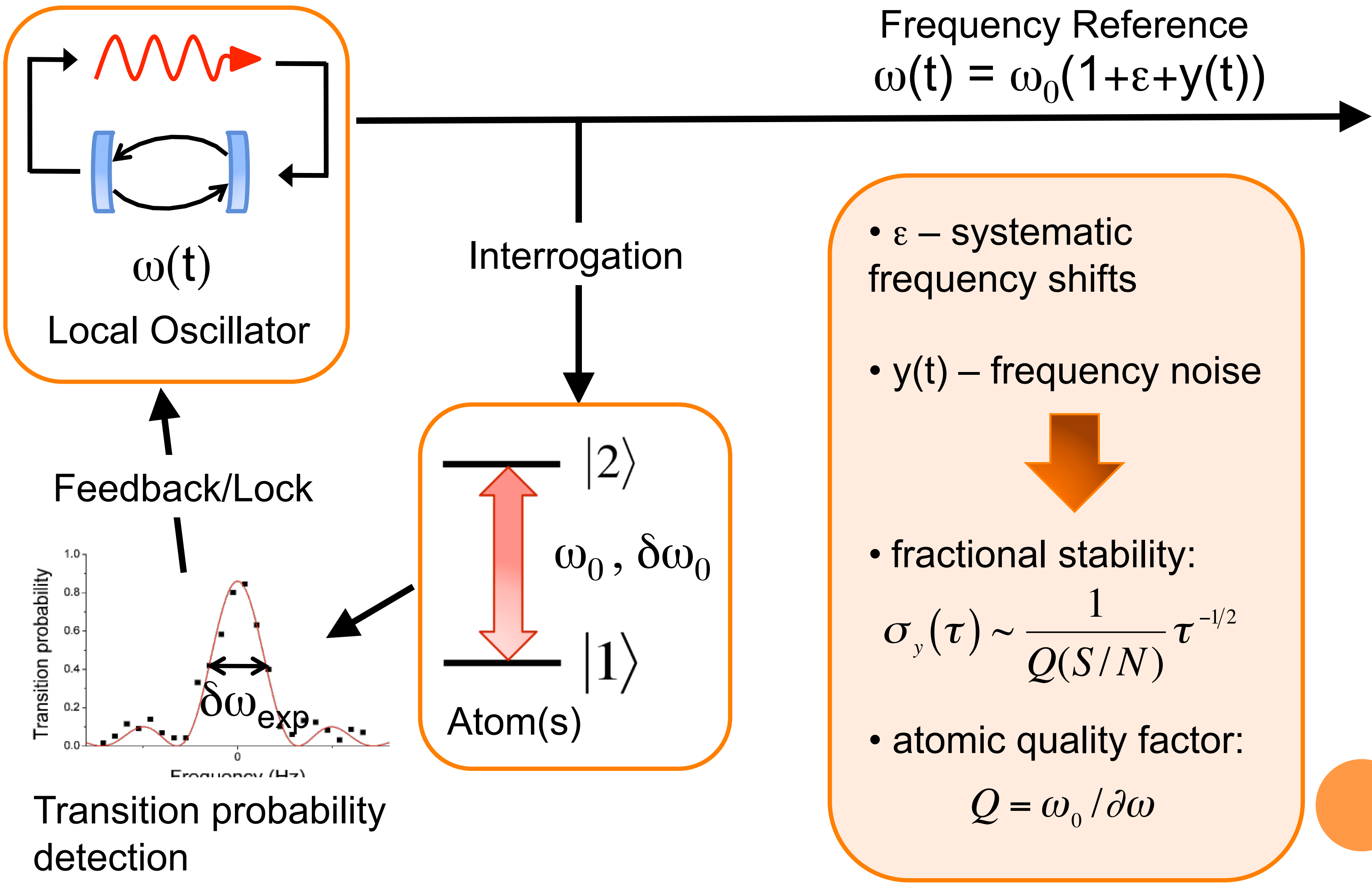
Eva Bookjans

GPHYS, July 6th 2016

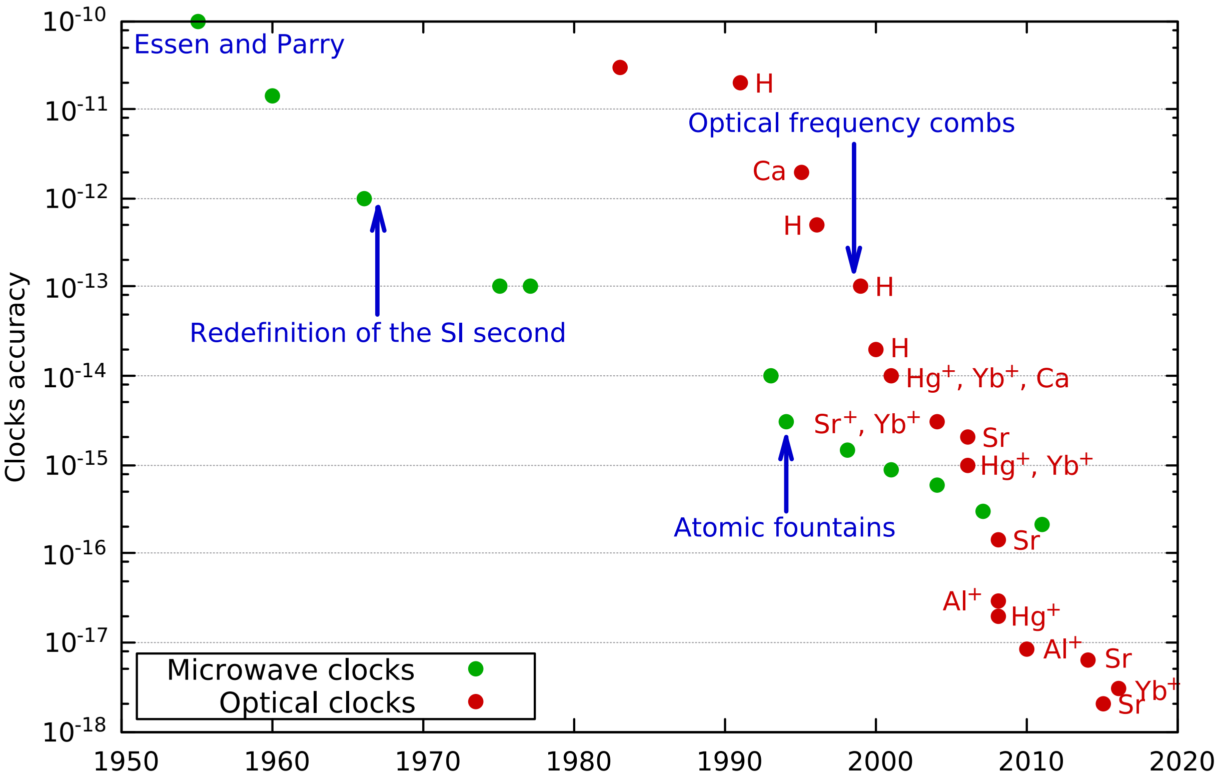


LNE Le progrès, une passion à partager · cnrs dépasser les frontières · UPMC PARIS UNIVERSITAS · LPL Laboratoire de physique des lasers · PTB Messen · Forschen · Wissen

Atomic clocks



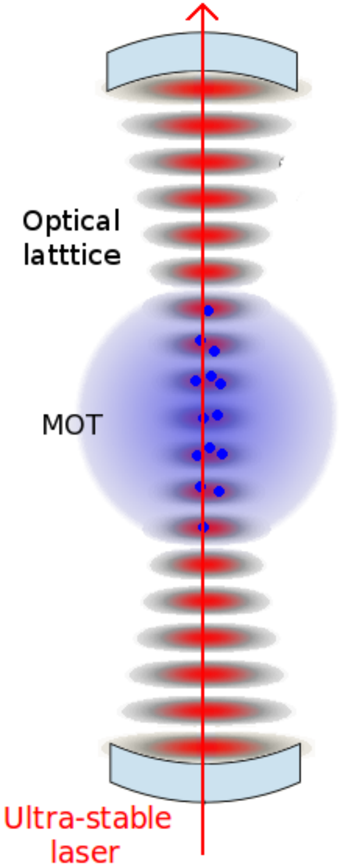
History of atomic clock accuracy



- Microwave clocks:
  $\omega_0/2\pi \cong 10^{10}\,\mathrm{Hz}$
  $\Rightarrow Q \cong 10^{10}$
- Optical clocks:
  $\omega_0/2\pi \cong 10^{15}\,\mathrm{Hz}$
  $\Rightarrow Q \cong 10^{15}$

- Optical clocks improve both the accuracy and the frequency stability

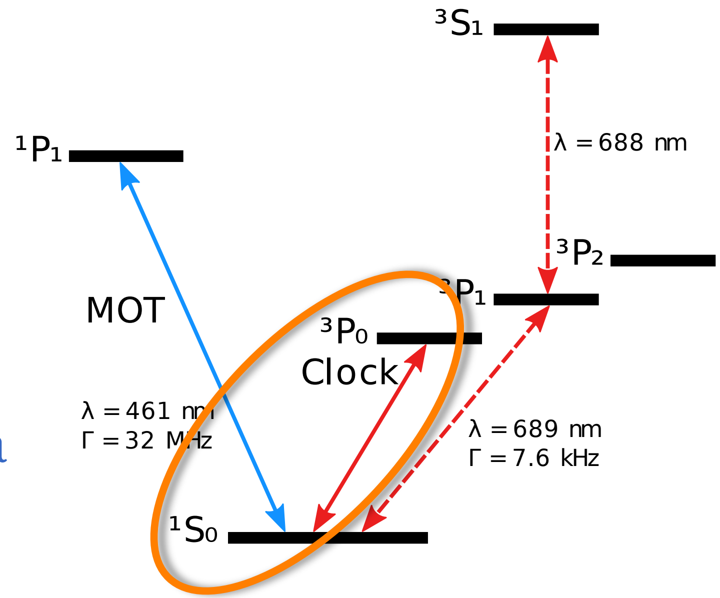
Optical lattice clocks



- Probe on a narrow optical resonance with an ultra-stable "clock" laser (high Q)
- Trap atoms in an optical lattice potential
  - Lamb-Dicke regime: insensitive to motional effects
  - trap light at magic wavelength: minimal light-shift effects
  - Large number of interrogated atoms (unlike with ion traps): high SNR
- Record stability: a few $10^{-16} / \tau^{1/2}$
- Record accuracy: a few 10^{-18}

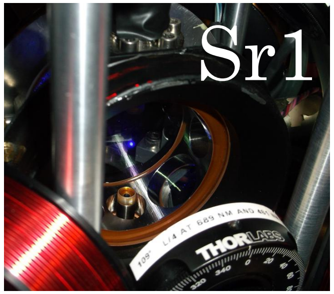
Different optical lattice clock species at LNE-SYRTE

- Sr lattice clock
  - required laser sources are accessible with semi-conductor technology: transportable clocks
  - implemented in many laboratories: good candidate for a new SI second



- Hg lattice clock
  - requires UV lasers: technically challenging
  - low sensitivity to BBR: excellent ultimate accuracy

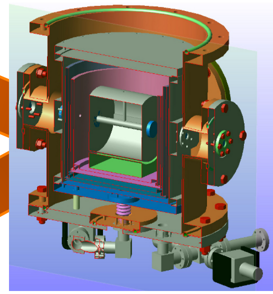
TWO STRONTIUM OPTICAL LATTICE CLOCKS



- Accuracy : 4-5 × 10^{-17}
- New vacuum system

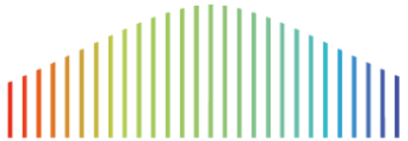
Lock

Clock laser



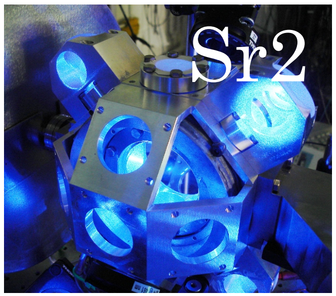
- Ultra-stable cavity
  - 10 cm ULE spacer and silica mirrors
  - thermal shielding
- Residual drift of a few 10s of mHz/s

Optical frequency comb



Comparisons with other clocks

Lock



- Accuracy : 4.1 × 10^{-17}
- Operational measurements

ACCURACY BUDGET (SR2)

Main contributions in 10^{-18} :

Effect	Correction	Uncertainty
Blackbody radiation shift	5208	20
Quadratic Zeeman shift	1317	12
Lattice light shift	-30	20
Lattice spectrum	0	1
Density shift	0	8
Line pulling	0	20
Probe light-shift	0.4	0.4
AOM phase chirp	-8	8
Servo error	0	3
Static charges	0	1.5
Blackbody radiation oven	0	10
Background collisions	0	8
Total	**6487.4**	**41**

Remains the most important contribution

Otherwise limited by statistics

Other groups

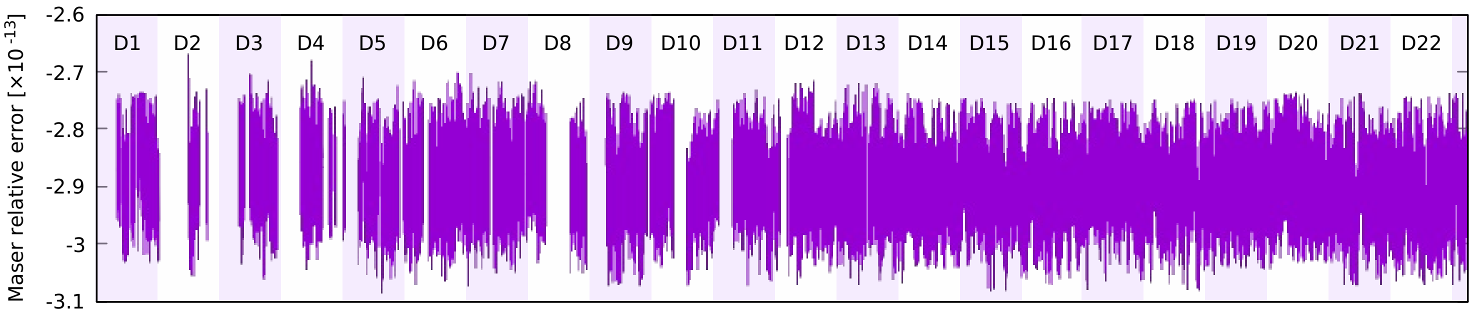
- JILA: Sr optical lattice clock with 2×10^{-18} accuracy
- NIST: Stability down to 1.6×10^{-18} after 7h of integration between two Yb clocks
- PTB: Sr optical lattice clock with 1.9×10^{-17} accuracy and an ultra-stable laser with a 8×10^{-17} noise floor
- Riken: Comparison between two cryogenic Sr clocks with 7.2×10^{-18} accuracy
- NPL (Sr), NMIJ (Sr,Yb), NICT (Sr), NMI (Sr),…

OPERATIONAL OPTICAL CLOCKS

- Improvement of statistical resolution
  - allow for characterization of systematic effects
- Clock comparisons
- Space clocks, e.g. Pharao/ACES space mission
- Establishment of time scales with optical clocks

- **Goal:** reach a level of maturity equivalent to the Cs based clock architecture

Jun. 2015: Unattended operation of 31 days, 83% uptime (ITOC JRP)



Clock comparisons

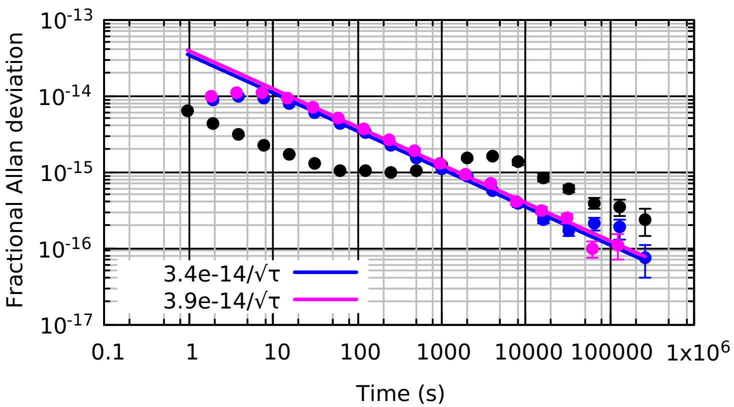
- Test the reproducibility of optical lattice clocks
- Creation of a network of optical lattice clocks
  - eventual establishment of time scales with optical clocks
- Determine and track frequency ratios between different atomic species
  - probe of fundamental physics
- Measure offsets and variations of the geo-potential
  - applications in geophysics

Means of comparison

- Local/on-site comparisons
  - through shared LOs (e.g. clock laser), fiber links, cables
- Stabilized optical fiber links
  - allows for direct optical-to-optical frequency comparisons
  - limited to intercontinental scales
- Satellite links (GPS/TWSFTF)
  - allows worldwide comparisons of clocks
  - limited resolution (sufficient for microwave clocks but not for optical clocks)
- Pharao/ACES space clock on board the ISS (2018)
  - time limited mission (3-5 years?)

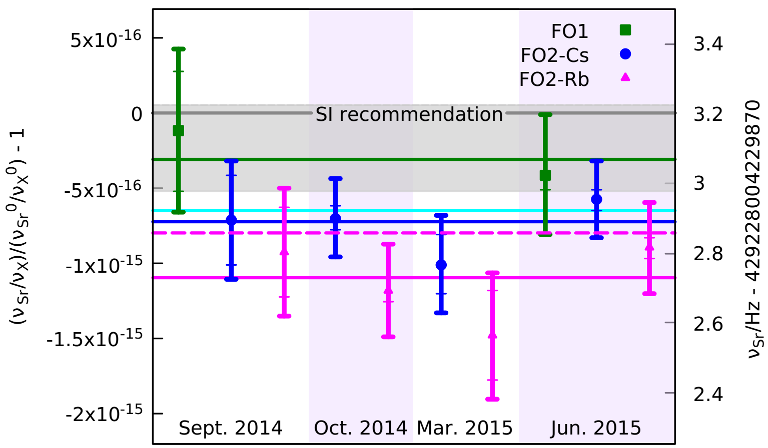
LOCAL COMPARISONS AT LNE-SYRTE
SR CLOCK VS. MICROWAVE CLOCKS

Stability



- limited by QPN of the microwave fountains
- 10^{-16} resolution after 12h
- mid 10^{-17} resolution after 7 days

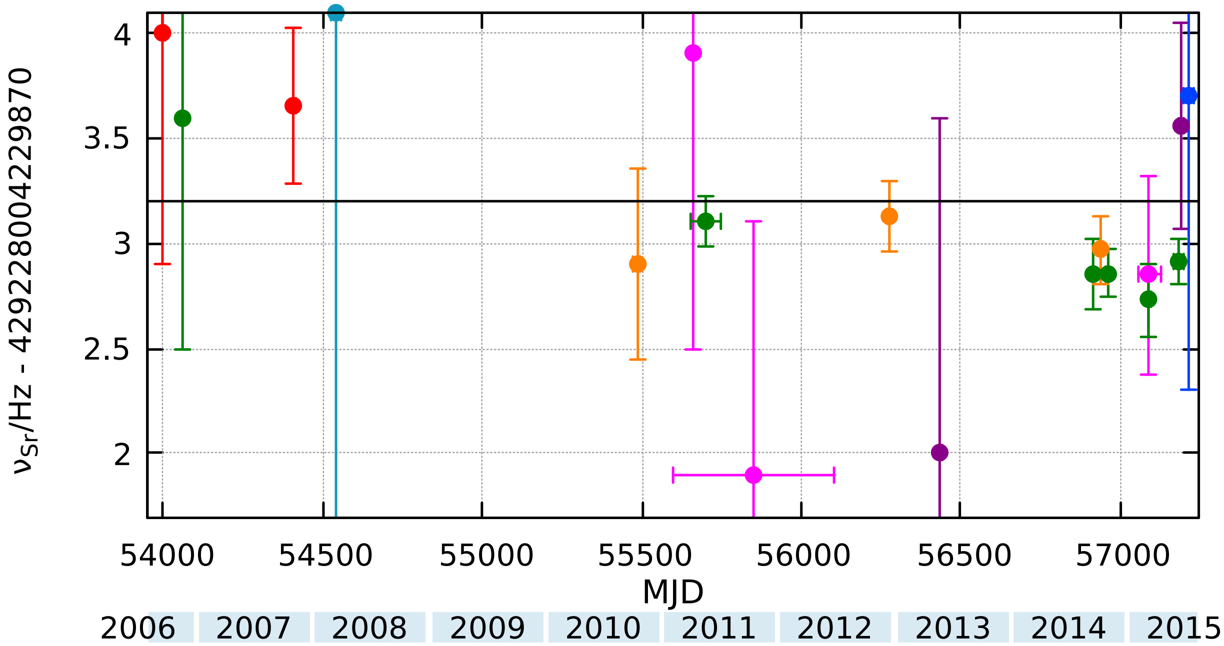
Accuracy



- limited by accuracy of the fountains
- international agreement

J.Lodewyck *et al.*, Metrologia (2016), arXiv:1605.03878

Absolute frequency of the Sr clock transition



- SYRTE, PTB, JILA, Tokyo University, NICT, NMIJ, NIM
- Track potential variations of fundamental constants:

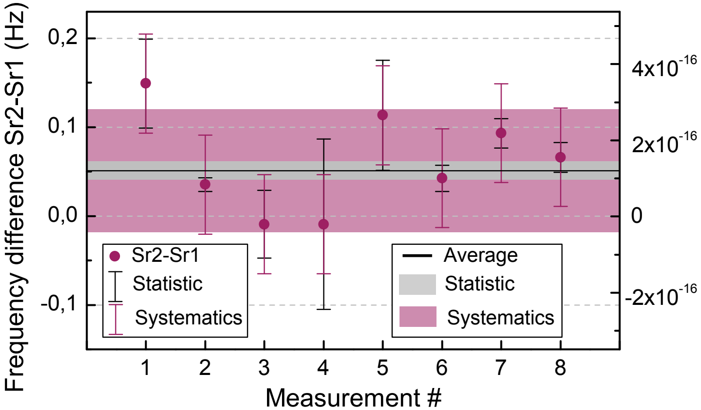
$$\frac{d\ln(\upsilon_{Sr}/\upsilon_{Cs})}{dt} = -1.6\times10^{-16} \pm 6.5\times10^{-17}\,/\,\text{year}$$

Annual variation of $\upsilon_{Sr}/\upsilon_{Cs}$ with relative amplitude: $5.5\times10^{-17} \pm 1.8\times10^{-16}$

LOCAL COMPARISONS AT LNE-SYRTE
OPTICAL VS. OPTICAL

Sr vs. Sr

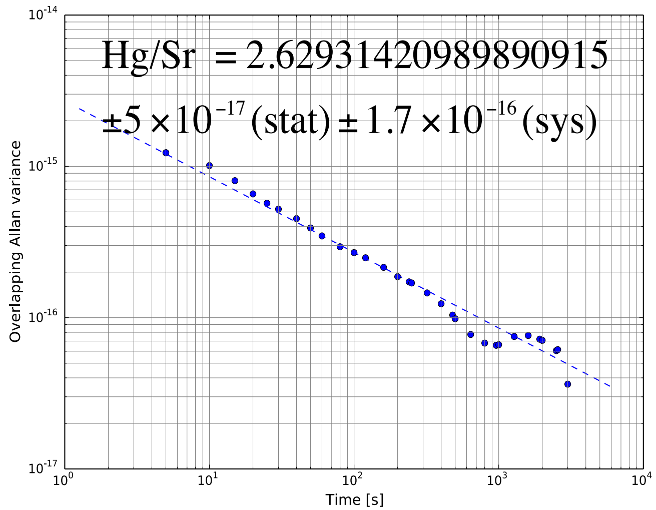
$$1.1\times10^{-16} \pm 2\times10^{-17}\,(\text{stat}) \pm 1.6\times10^{-16}\,(\text{sys})$$



- First agreement between OLCs
- Detection and characterization of several systematic effects

R. Le Targat *et al.*, Nat. Commun. (2013)

Sr vs. Hg

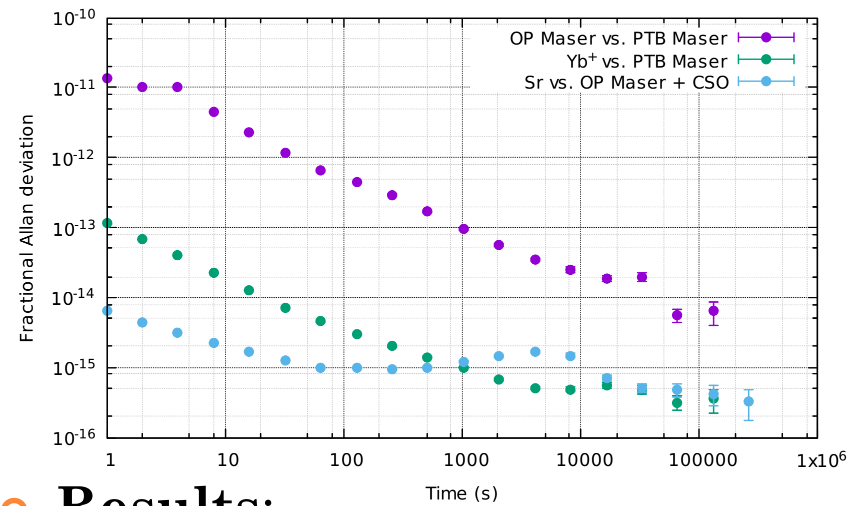


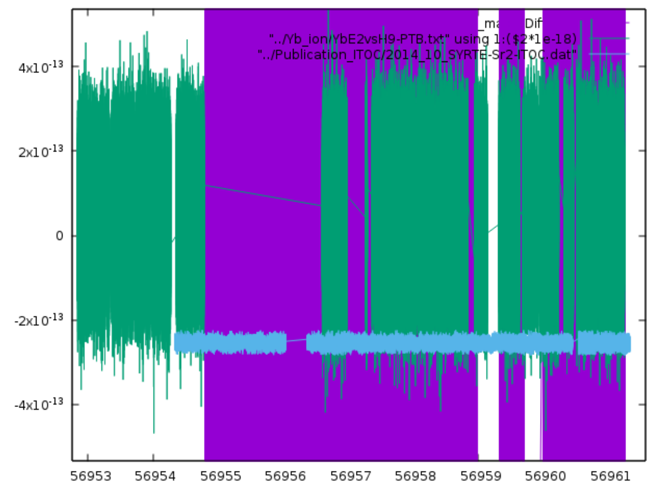
- Direct optical-to-optical frequency measurement (via fiber comb)
- Best reproduced frequency ratio (with RIKEN, Tokyo)

R. Tyumenev *et al.*, arXiv:1603.02026

INTERNATIONAL CLOCK COMPARISONS VIA TWSTFT

- Comparison of Sr vs. Yb+ (PTB, NPL) via TWSTFT (ITOC JRP project)





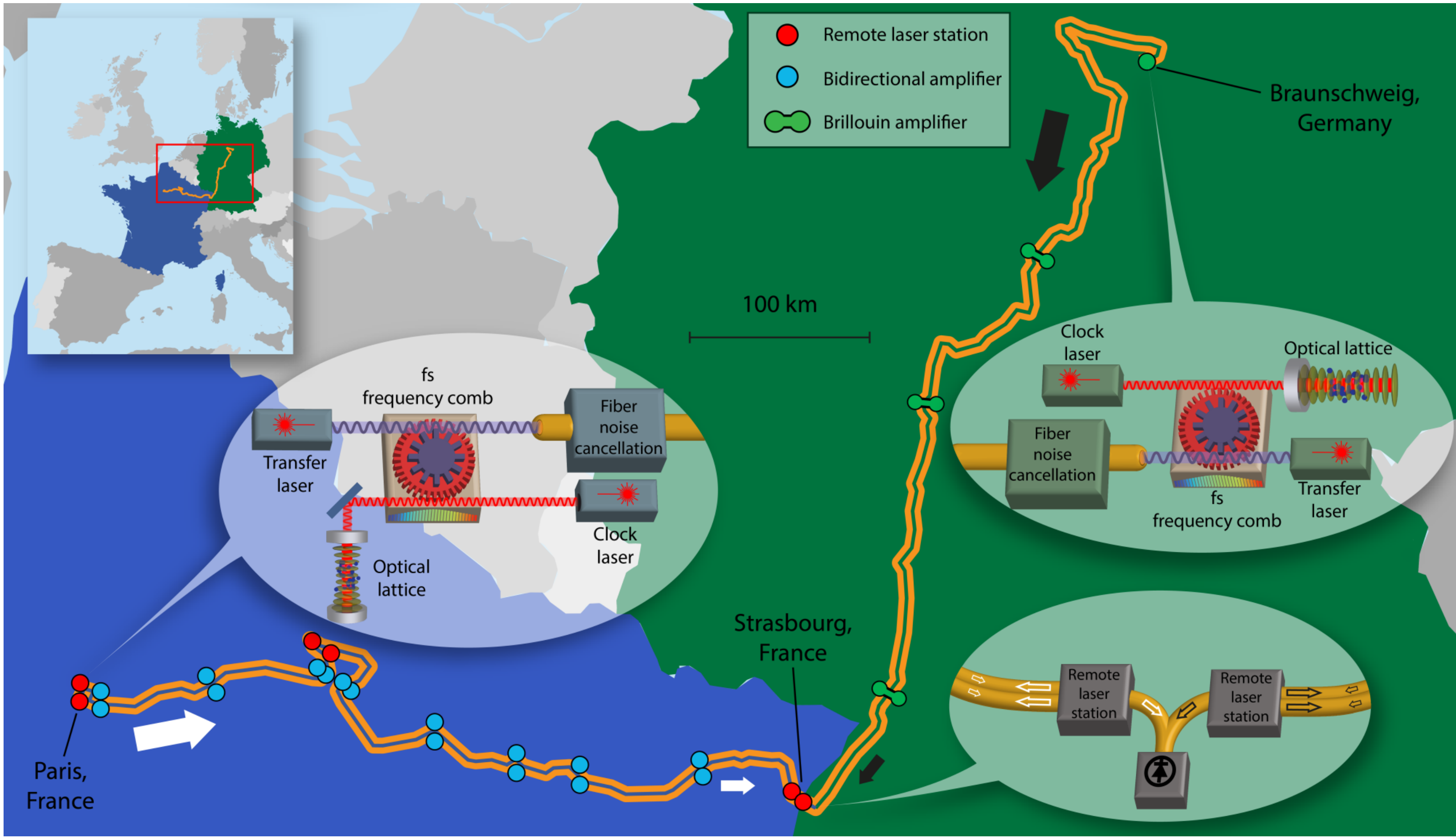
- **Results**:
  - Statistical resolution only in the mid 10^{-16} even after 7 days of measurements
    - limited by the link
  - Frequency ratio compatible with independent local measurements
  - 3 weeks comparison achieved in June 2015 with many more clocks!

International clock comparisons via fiber links

- **Goal: high resolution comparison:**
  - Direct comparison of optical clocks over a continental scale
  - Pure optical comparison, not limited by
    - Microwave transfer methods
    - Microwave oscillators
  - Preservation of the frequency stability over long distances
- **Implementation:**
  - Disseminate an IR (1542 nm) "vector" narrow laser through phase-compensated optical fibers
  - Optical frequency combs to measure $\upsilon_{IR}/\upsilon_{clock}$ on both sides
- **Challenges**:
  - Fiber attenuation (e.g. 450 dB for 1500 km) – need amplifiers
  - Availability of fibers (dark channel or dark fibers)
  - Propagation delays (cascaded links)
  - Power limits (non-linear effects, disturbance of telecom networks)

SYRTE – PTB LINK VIA LPL

PTB, LPL and SYRTE established a 1415 km long optical fiber link and performed in 2015 the first direct comparison of optical clocks on a continental scale.

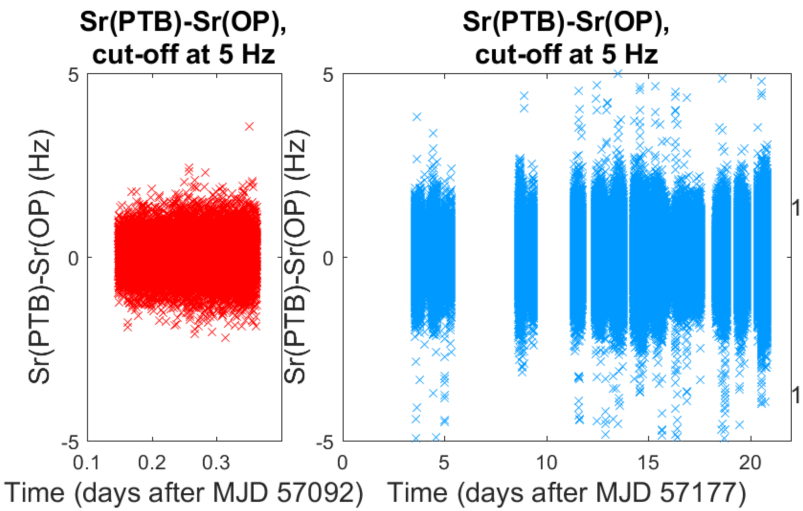


Comparison of two remote and completely independent clocks

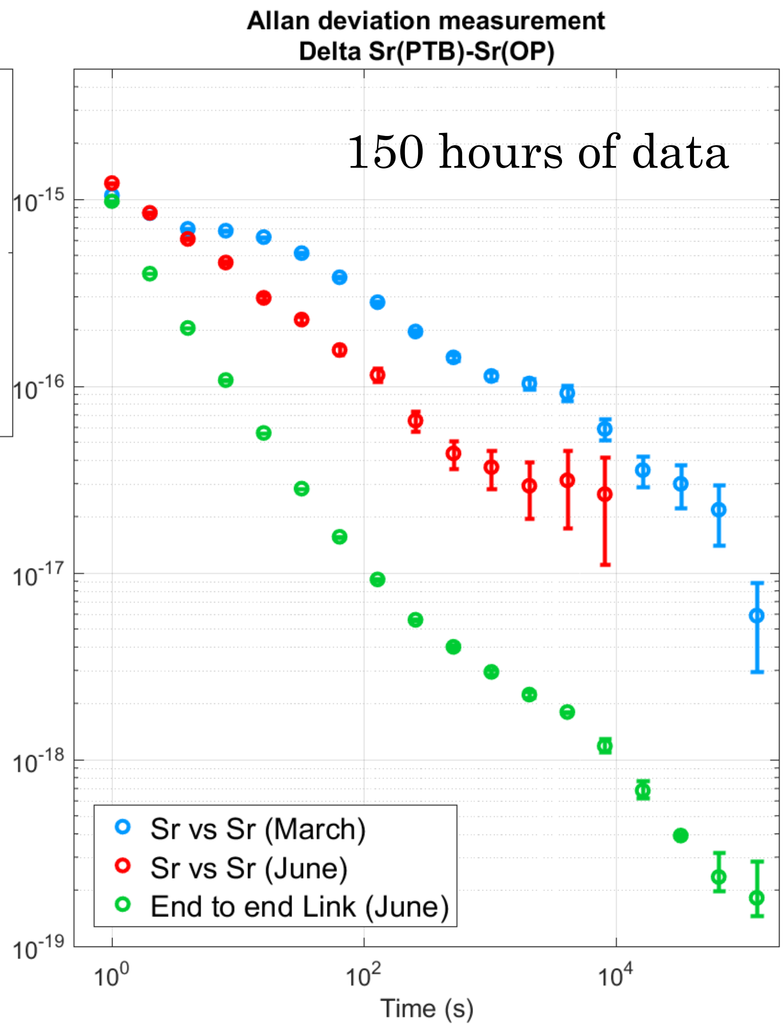
	PTB	SYRTE
Loading of the atoms	Blue MOT-Red MOT	Blue+atomic drain
Lattice light	TiSa pumped by a multimode pump	TiSa pumped by a monomode pump
BBR Shield from oven	No direct line of sight	Deflected atomic beam
Lattice orientation	Horizontal	Vertical
Lattice effect	Retroreflected light	Cavity-formed + PDH lock
Clock laser	48 cm long cavity, flickering at 8×10^{-17}	10 cm long cavity, flickering at 5×10^{-16}
Density of atoms	1-2 atoms/site	5-10 atoms/site
Coils	In-vacuum MOT coils	MOT coils outside of vacuum
Gravitational redshift	$-247.4\ (\pm0.4)\times10^{-17}$	
Uncertainty budgets	**1.9×10^{-17}**	**4.1×10^{-17}**

- Only agreement between completely independent optical clocks
- Second to best comparison of optical lattice clocks

2 Measurement campaigns



Total clocks	650.3	4.1	496.3	1.9
Ratio Sr_{PTB}/Sr_{SYRTE}	**Campaign I Unc. (10^{-17})**		**Campaign II Unc. (10^{-17})**	
Systematics Sr_{SYRTE}	4.1		4.1	
Systematics Sr_{PTB}	2.1		1.9	
Statistical uncertainty	2		2	
fs combs	0.1		0.1	
Link uncertainty	< 0.1		0.03	
Counter synchronization*	10		< 0.01	
Gravity potential correction**	0.4		0.4	
Total clock comparison	**11.2**		**5.0**	



Statistical uncertainty: 2×10^{-17} after 1 hour

SrPTB/SrSYRTE - 1 = $(4.7 \pm 5.0) \times 10^{-17}$

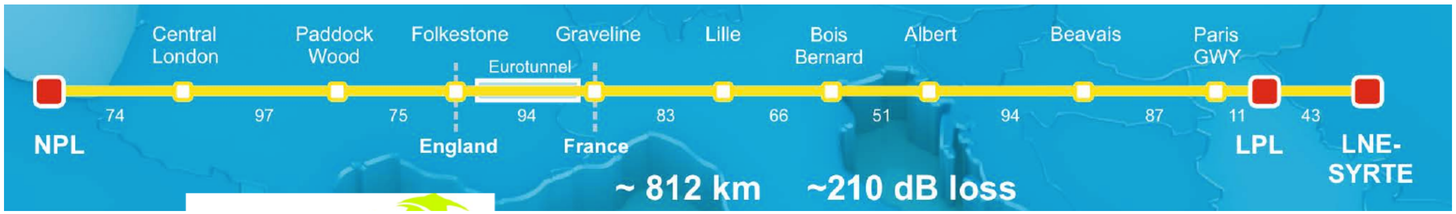
C. Lisdat *et al.*, Nat. Commun. (2016)

Applications:

- **Gravitation:**
  - Correction for the gravitational redshift:
    - $(-247.4 \pm 0.4) \times 10^{-17}$ corresponding to a 4 cm uncertainty of the (geodetic) height of the clocks
  - The next generation of remote clocks comparison will improve our knowledge of the gravitational potential of the Earth
- **Fundamental Sciences:**
  - Precise measurement of frequency ratios
  - Search for variation of fundamental constants, detection of dark matter

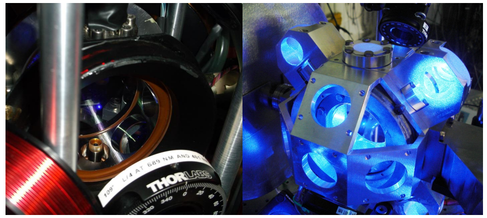
PERSPECTIVES

- Improved stability and accuracy of OLCs
  - 10^{-19} feasible
- Contribution of optical clocks to international time-scales
  - redefinition of the SI second
- Extension of the European fiber network for comparison of optical clocks
  - e.g. link between SYRTE and NPL (already established)

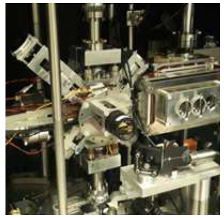


Clock ensemble at LNE-SYRTE

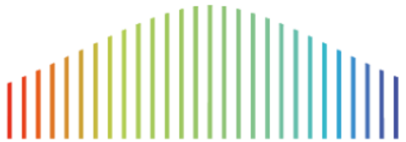
- 2 Strontium OLCs
  - **J. Lodewyck, R. Le Targat**, S. Bilicki, E Bookjans, G. Vallet



- 1 Mercury OLC
  - **S. Bize, L. De Sarlo**, M. Favier, R. Tyumenev

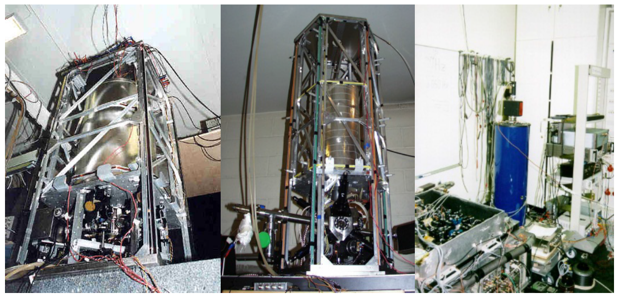


- Frequency combs
  - **Y. Lecoq, R. Le Targat**, D. Nicolodi



- 3 atomic fountains

  Cs, Cs/Rb, and Cs (mobile)
  - **J. Guena, P. Rosenbusch, M.Abgrall, D. Rovera, S. Bize, P. Laurent**



Fiber link comparison

- LPL
  - N. Quintin, F. Wiotte, E. Camisard, C. Chardonnet, A. Amy-Klein, O. Lopez
- SYRTE
  - C. Shi, F. Stefani, J.-L. Robyr, N. Chiodo, P.Delva, F. Meynadier, M. Lours, G. Santarelli, P.-E. Pottie
- PTB
  - C. Lisdat, G. Grosche, S.M.F. Raupach, C. Grebing, A. Al-Masoudi, S. D orscher, S. H afner, A. Koczwara, S. Koke, A. Kuhl, T. Legero, H. Schnatz, U. Sterr
- LUH
  - H. Denker, L. Timmen, C. Voigt