# Optical clocks and fibre links

Jérôme Lodewyck

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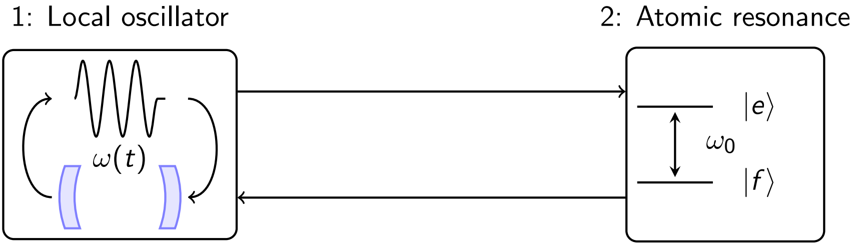
## Atomic clock:




Linewidth $\delta\omega \simeq 2\pi \times 1$ Hz

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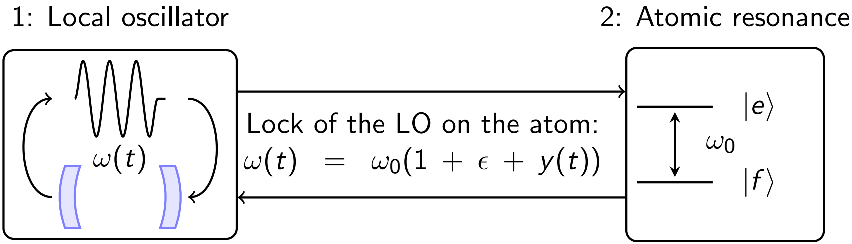


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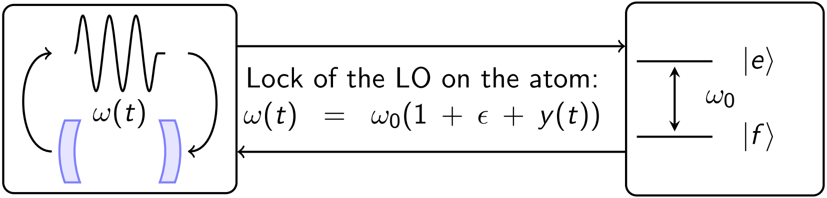
# A quick overview of atomic clocks

## Atomic clock:

1: Local oscillator

2: Atomic resonance



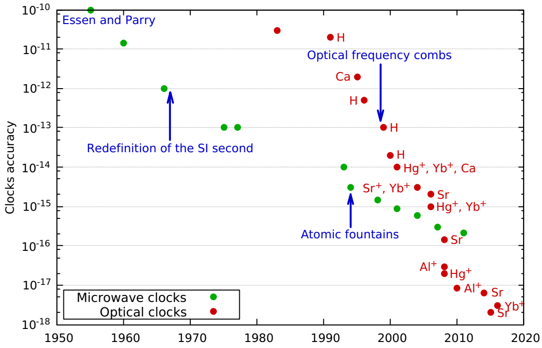

Linewidth $\delta\omega \simeq 2\pi \times 1$ Hz

## Optical vs. microwave

- Microwave clocks:
  $\omega_0/2\pi \simeq 10^{10}$ Hz $\Rightarrow Q = \omega_0/\delta\omega \simeq 10^{10}$
- Optical clocks:
  $\omega_0/2\pi \simeq 10^{14}$ to $10^{15}$ Hz $\Rightarrow Q = \omega_0/\delta\omega \simeq 10^{15}$

$\Rightarrow$ Optical clocks improves both the accuracy and the frequency stability

# History of atomic clocks accuracy




- Microwave clocks: 1 order of magnitude every 10 years since 1950
- Optical clocks: 2 orders of magnitude every 10 years since 1990

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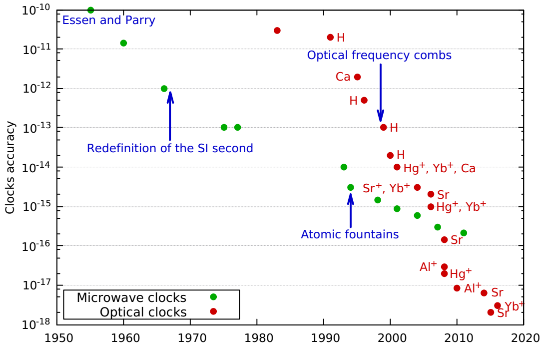


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| | Microwave | Optical |
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| Neutral | low Q, $10^6$ atoms | high Q, $10^4$ atoms |

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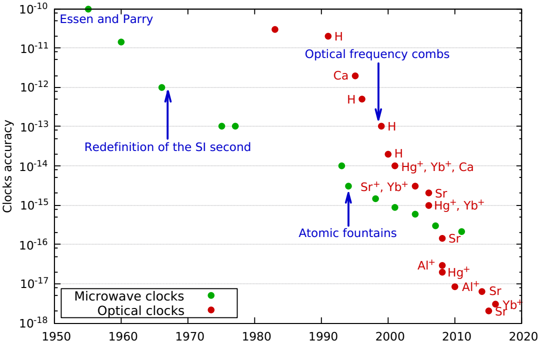


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Optical lattice clocks

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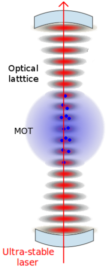
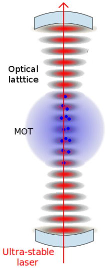
# Optical lattice clocks




- Atoms loaded from a MOT to an optical lattice formed by a 1D standing wave
- Probing a narrow optical resonance with an ultra-stable "clock" laser
- Stabilize the clock laser on the narrow resonance

# Optical lattice clocks

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## Combine several advantages:

- Optical clock
- Large number of atoms
- Lamb-Dicke regime
  insensitive to motional effects

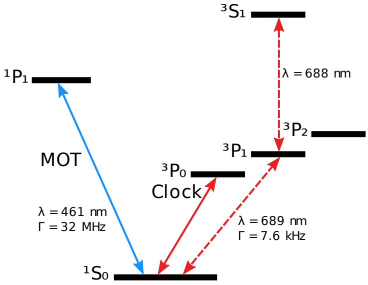
$\Rightarrow$

- Record frequency stability : a few $10^{-16}/\sqrt{\tau}$
- Record accuracy : a few $10^{-18}$

# Which atom for an optical lattice clocks?

## Sr lattice clock

- Wavelengths accessible with semi-conductor sources
- Magic wavelength at 813 nm
- Implemented in many laboratories
  $\Rightarrow$ good candidate for a new SI second



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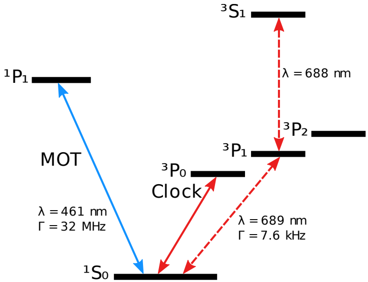


## Hg lattice clock

- Developed at LNE-SYRTE
- Low sensitivity to BBR ⇒ excellent ultimate accuracy
- Requires UV lasers

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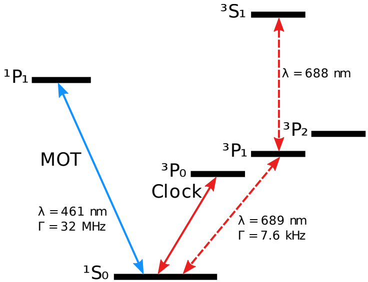


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## Other candidates

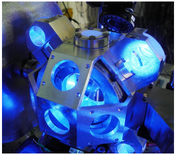
- Yb: mostly equivalent to Sr
- Mg, Cd

# Two strontium optical lattice clocks

### Sr1


- Accuracy : $1.1 \times 10^{-16}$
- New vacuum system

### Sr2



- Accuracy : $4.1 \times 10^{-17}$
- Operational measurements

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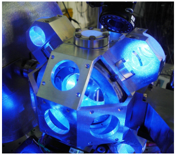
## Sr2



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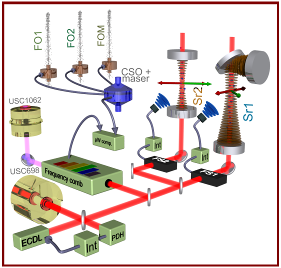
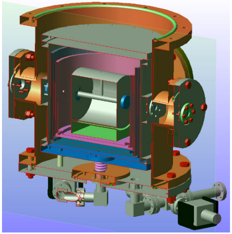
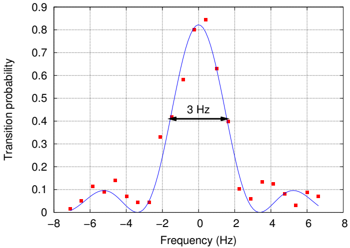


# Sr clock laser



- 10 cm horizontal ULE spacer and silica mirrors
- Not at inversion of CTE $\Rightarrow$ 3 layers of thermal shielding
  (short term temperature fluctuations in the nK range, $\tau = 4$ days)
- Residual drift of a few 10s of mHz/s (feed forward compensation below 1mHz/s)

# Locking the clock laser to the atomic transition




Resonance of the clock transition

- Fourier limited at 3 Hz (250 ms)
- Laser noise dominating

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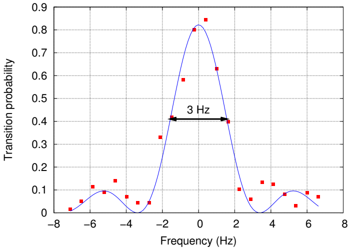


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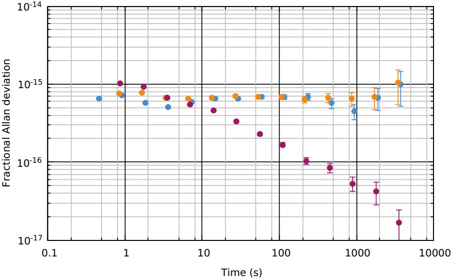


- Atoms vs cavity
  - $< 5$ s : limited by the atoms (Dick effect) $1 \times 10^{-15}/\sqrt{\tau}$
  - $> 5$ s : limited by the thermal noise of the cavity $6.5 \times 10^{-16}$
- Clock comparison
  - $1.5 \times 10^{-15}/\sqrt{\tau}$
  - resolution in the low $10^{-17}$

# Accuracy budget for the Sr clocks

## Main contributions: (Sr 2), in $10^{-18}$

| Effect | Correction | Uncertainty |
|---|---|---|
| Black-body 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 |
| Black-body radiation oven | 0 | 10 |
| Background collisions | 0 | 8 |
| **Total** | **6487.4** | **41** |

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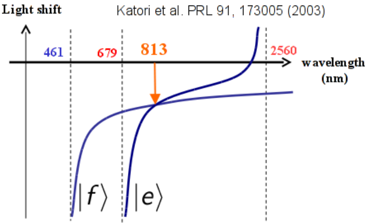
- The black-body shift remains the most important contribution
- Other effects mainly limited by statistics
- Particularity of our clocks:
  - Low level of cold collisions.
  - characterization of the static Stark effect
  - Accurate determination of lattice light-shift

# Magic wavelength

## Light-shift

- Intense trapping laser
  ⇒ light-shift of several MHz
- At the magic wavelength, this huge light-shift is cancelled



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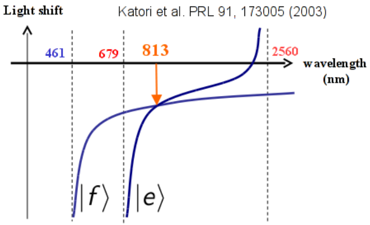


## Looking closer. . .

- Polarization dependent 1st order light-shifts (vector and tensor shifts)
  Mostly cancelled for a $J = 0 \rightarrow J = 0$ transition.
- Hyperpolarizability (2 photon transitions)
- Multipolar effects (E2/M1)

$\Rightarrow$ Need to pay attention to achieve high accuracy

P. Westergaard *et al.*, PRL **106** 210801 (2011)

# Other groups

## Rapid progress for optical lattice clocks

- JILA: Sr optical lattice clock with $2 \times 10^{-18}$ accuracy
- NIST: Stability down to $1.6 \times 10^{-18}$ after 7 h between 2 Yb clocks
- PTB: Sr optical lattice clock with $1.9 \times 10^{-17}$ accuracy
  ultra-stable laser with $8 \times 10^{-17}$ noise floor
- Riken: Comparison between to cryogenic Sr clocks with $7.2 \times 10^{-18}$ accuracy.

# Improving the clock reliability

## Motivation: Need for operational optical clocks

- Enhancing the statistical resolution
  $\Rightarrow$ better characterization of systematic effects
- Enabling clock comparisons
- Participating to the Pharao/ACES space mission
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Reach a level of maturity equivalent to the Cs based clock architecture

⇒ possible redefinition of the SI second

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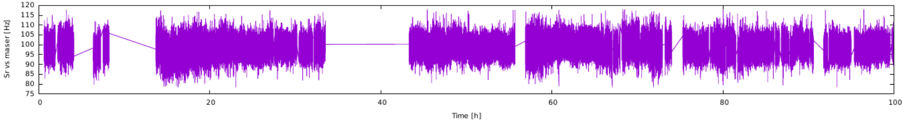
## Results:

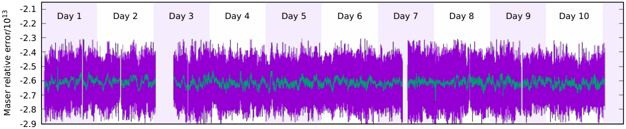
- Accumulation of 3 long operations of the Sr2 clock
- More and more autonomous

# Operation of the full metrological chain

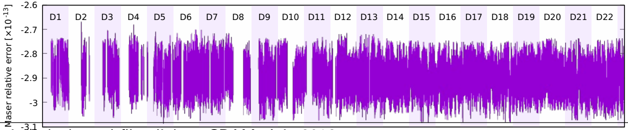
Feb. 2014 Attended operation of 5 days, 87% uptime




Oct. 2014 Unattended operation of 10 days, 92% uptime (ITOC JRP)




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



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# Clock comparisons: why and how ?

## Objectives of clock comparisons

- Prove the reproducibility of optical lattice clocks
- Determine and track frequency ratios between different atomic species
- Measure offsets and variations of the geo-potential at country/continental scales
- Probe fundamental physics
- Use optical clocks to define international time scales

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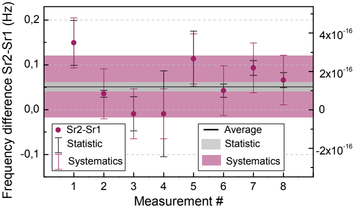
## Means of comparison

- Local or local area comparisons
  $\Rightarrow$ limited range
- Satellite comparisons (GPS/TWSTFT)
  $\Rightarrow$ limited resolution (fine for microwave clocks, but not optical)
- Stabilized optical fibre links
  $\Rightarrow$ limited to continental scales and connected places
- Pharao/ACES space clock on board the ISS (2017)
  $\Rightarrow$ limited in time

# Local optical to optical comparison

## Sr vs. Sr



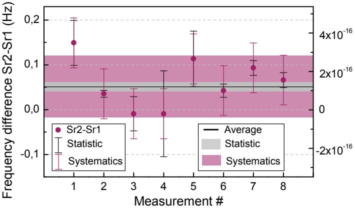

$Sr_2$ - $Sr_1$ $= 1.1 \times 10^{-16} \pm 2 \times 10^{-17}$(stat) $\pm 1.6 \times 10^{-16}$(sys)

- First agreement between OLCs
- Enabled the detection of several systematic effects

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

# Local optical to optical comparison

## Sr vs. Sr

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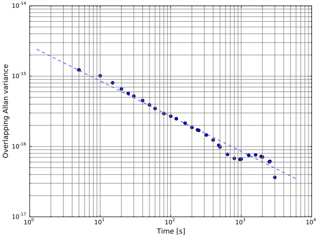
## Sr vs. Hg




$\text{Hg/Sr} = 2.62931420989890915 \pm 5 \times 10^{-17}(\text{stat}) \pm 1.7 \times 10^{-16}(\text{sys})$

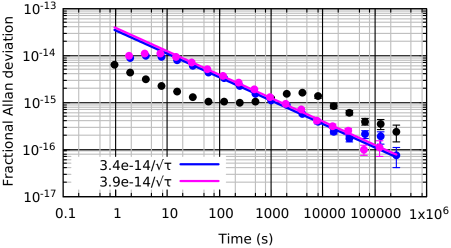
- Optical to optical frequency measurement
- Best reproduced frequency ratio (with RIKEN, Tokyo)

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

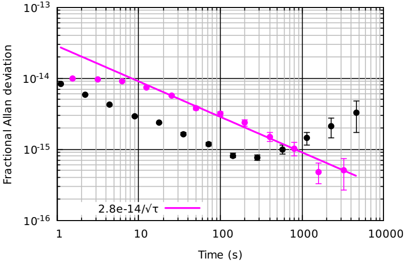
# Sr vs microwave atomic fountains: stability

## Absolute frequency measurements

Sr vs Cs and Rb

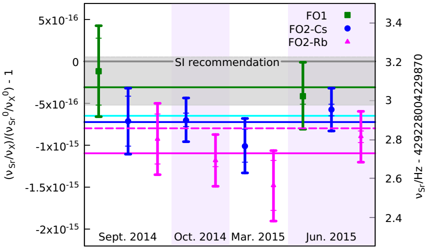


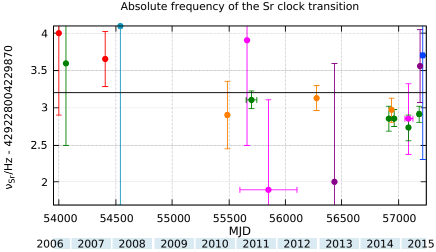

Sr vs Rb
(best $\mu$Wave vs optical stability)




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

# Sr vs microwave atomic fountains: accuracy




- International agreement, limited by the accuracy of the fountains
  SYRTE, PTB, JILA, Tokyo University, NICT, NMIJ, NIM
- Track variations of fundamental constants:

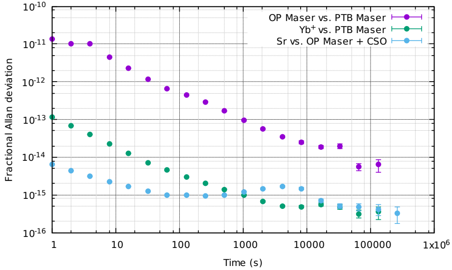
$$\frac{d\ln(\nu_{Sr}/\nu_{Cs})}{dt} = -1.6 \times 10^{-16} \pm 6.5 \times 10^{-17} \text{ /year}$$

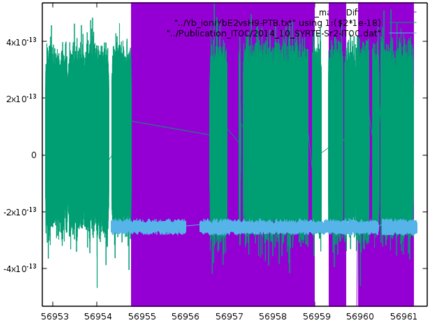
Annual variation of $\nu_{Sr}/\nu_{Cs}$ with relative amplitude: $5.5 \times 10^{-17} \pm 1.8 \times 10^{-16}$

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

# INTERNATIONAL CLOCK COMPARISONS: TWSTFT

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




## RESULTS

- Statistical resolution in the mid $10^{-16}$ after 7 days of measurement
- Frequency ratio compatible with independent local measurements
- 3 weeks comparison achieved in June 2015 with many more clocks !

# Content

# International clock comparisons: fibre links

## Goal: high resolution comparison

- Direct comparison of optical clocks over continental scale
- Pure optical comparison, not limited by
  - Microwave transfer methods
  - Microwave oscillators
- Preserve the frequency stability over long distances

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## Implementation

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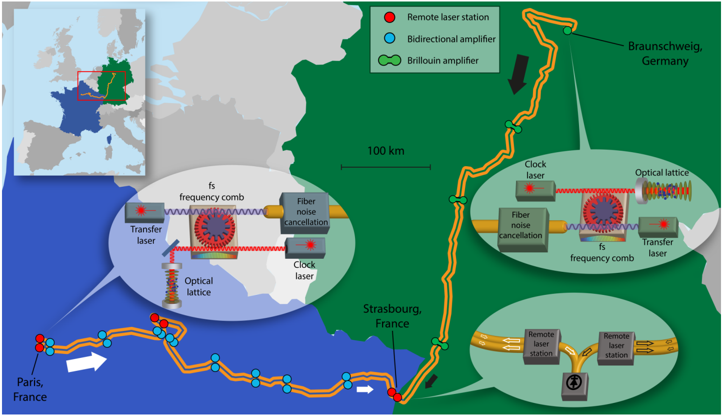
## Challenges

- Fibre attenuation (e.g. 450 dB for 1500 km)
- Availability of fibres (dark channel or dark fibre)
- Propagation delays (cascaded links)
- Power limits (non-linear effects, disturbance of telecom networks)

# SYRTE – PTB link, via LPL

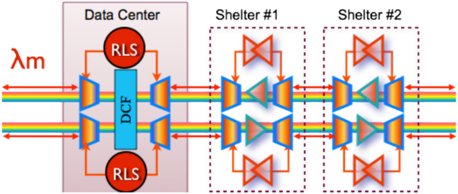



**PTB, LPL and SYRTE established a 1415 km long optical fibre link and performed in 2015 the first direct comparison of optical clocks at continental scale**

# Challenge 1: Amplification and signal regeneration

## Paris ↔ Strasbourg

- Signal along internet traffic (RENATER)
- Bidirectional amplifiers
- Regeneration stations




Poster by A. Amy-Klein

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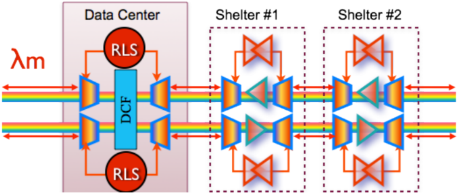
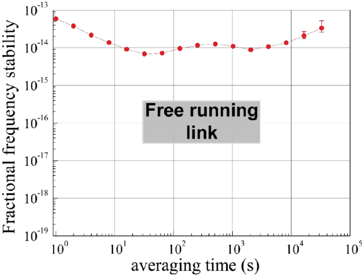



Poster by A. Amy-Klein

## Braunschweig ↔ Strasbourg

- Dark fibre
- Fibre Brillouin amplification

# Challenge 2: Fibre noise compensation



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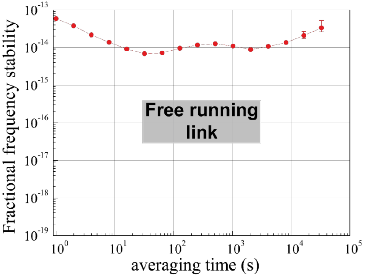


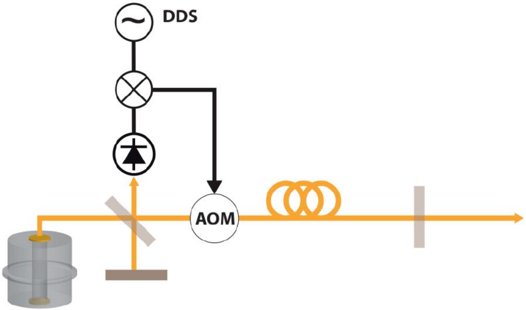

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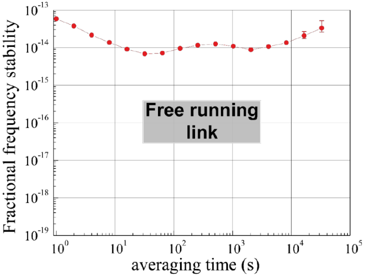


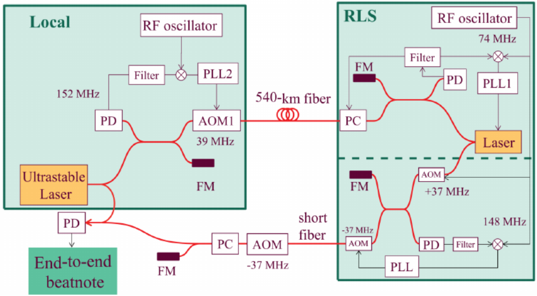

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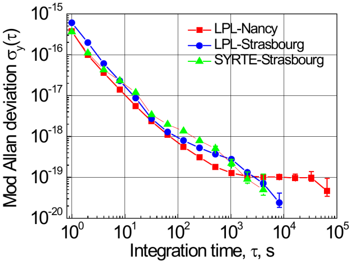
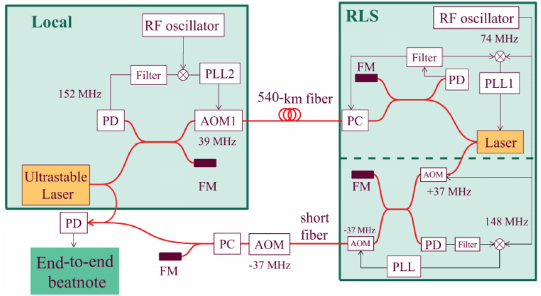


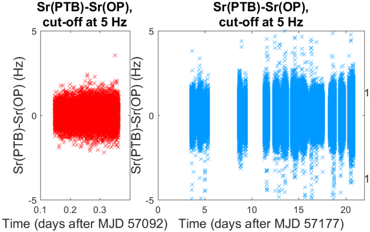
# Comparing remote optical clocks

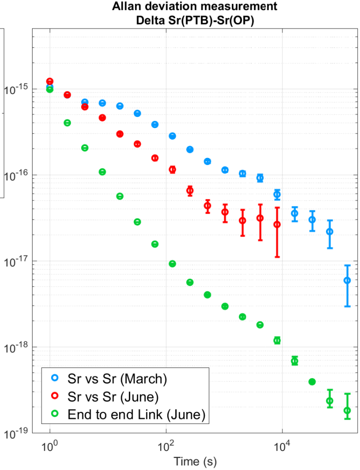
## Completely independent Sr clocks:

| | 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 $8 \times 10^{-17}$ | 10 cm long cavity, flickering at $5 \times 10^{-16}$ |
| Density of atoms | 1-2 atoms/site | 5-10 atoms/site |
| Coils | In-vacuum MOT coils | MOT coils outside of vacuum |
| Gravitational redshift | $-247.4\ (\pm 0.4) \times 10^{-17}$ | |
| **Uncertainty budgets** | **$1.9 \times 10^{-17}$** | **$4.1 \times 10^{-17}$** |

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

## 2 Measurement campaigns

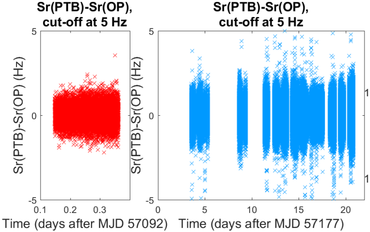


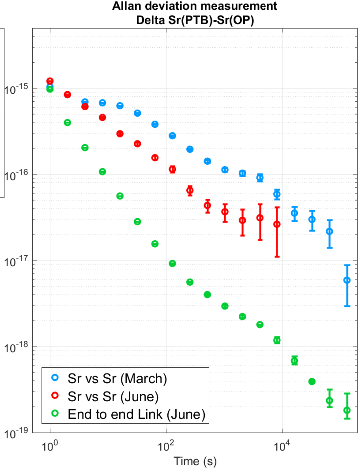




| | | | | |
|---|---|---|---|---|
| **Total clocks** | **650.3** | **4.1** | **496.3** | **1.9** |

| **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** |

## 2 MEASUREMENT CAMPAIGNS




| | | | | |
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Statistical uncertainty $2 \times 10^{-17}$ after $\simeq 1$ hour

150 hours of data

$$Sr_{PTB}/Sr_{SYRTE} - 1 = (4.7 \pm 5.0) \times 10^{-17}$$

C. Lisdat *et al.*, arXiv:1511.07735

# Applications

## Gravitation

- Correction for the gravitational redshift: $(-247.4 \pm 0.4) \times 10^{-17}$
  $\Leftrightarrow$ 4 mm uncertainty of the (geodetic) height of the clocks

  Work by P. Delva (SYRTE), H. Denker (LUH)

- The next generation of remote clocks comparison will improve our knowledge of the gravitational potential of the Earth

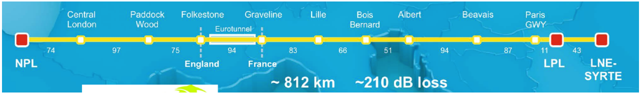
Presentation by P. Delva

## Fundamental sciences

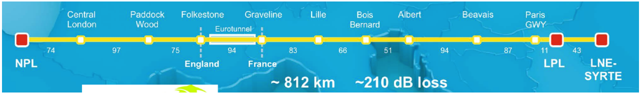
- Precise measurement of frequency ratios
- Search for variation of fundamental constant, detection of dark matter

# Extensions of the fibre networks

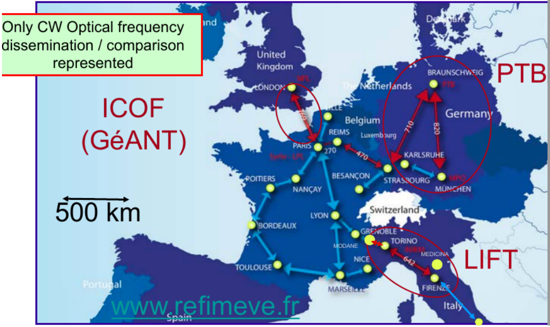
## Link SYRTE ↔ NPL

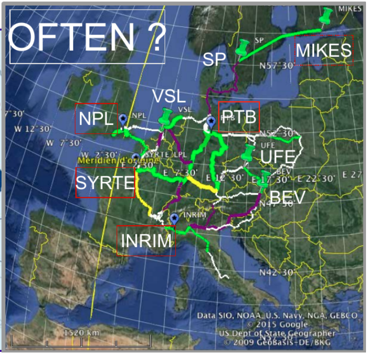


## LINK SYRTE ↔ NPL



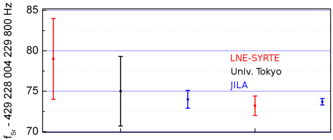

## NATIONAL AND INTERNATIONAL FIBRE NETWORKS



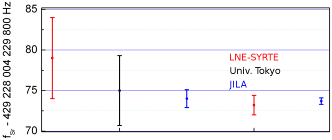
# Conclusion

GRAM 2010: "Horloges optiques" local Sr/Cs comparisons at $10^{-15}$



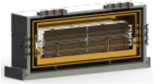
# Conclusion

GRAM 2010: "Horloges optiques" local Sr/Cs comparisons at $10^{-15}$



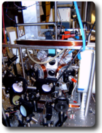

## Perspectives

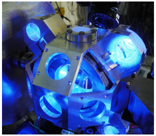
- Improved stability and accuracy of OLCs → $10^{-19}$ feasible

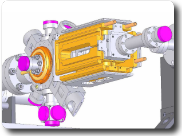


- Contribution of optical clocks to international time-scales
  ⇒ redefinition of the SI second
- Complete European fibre network for comparison of optical clocks

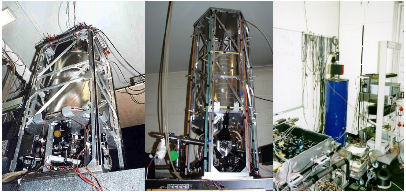
# Clock ensemble at SYRTE







- **2 strontium lattice clocks**
  **J. Lodewyck, R. Le Targat**,
  S. Bilicki, E Bookjans, G. Vallet
- **1 mercury lattice clock**
  **S. Bize, L. De Sarlo**,
  M. Favier, R. Tyumenev
- **Frequency combs** (Ti-Sa, fiber)
  **Y. Lecoq, R. Le Targat**, D. Nicolodi
- **3 atomic fountains**
  (1 Cs, 1 Cs mobile, 1 Cs/Rb)
  **J. Guéna, P. Rosenbusch, M. Abgrall, D. Rovera, S. Bize, P. Laurent**



# Comparison with fiber links

- **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. Dörscher, S. Häfner, A. Koczwara, S. Koke, A. Kuhl, T. Legero, H. Schnatz, U. Sterr
- **LUH**
  H. Denker, L. Timmen, C. Voigt