Comparaison des horloges Européennes

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Connecting European atomic clocks

Clock network

- 12+ optical clocks with 10^{-17} to 3×10^{-18} accuracy
- 6 microwave fountain clocks

Motivation

- Validation of the clocks accuracy
- Measurements of frequency ratios
- Tests of fundamental physics

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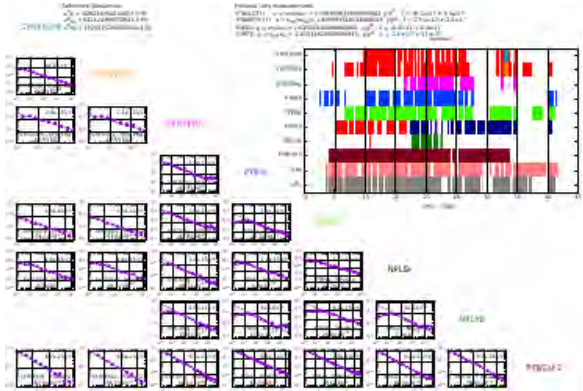
Challenge

- Large and diverse team (clocks, combs, links, cavities)
- All working together at a given time, for several weeks

Connecting European atomic clocks



Formalism to compare clocks

$$\rho_{\text{Sr SYRTE,Sr PTB}} = \rho_{\text{Sr SYRTE,IR Fr}} \times \rho_{\text{IR Fr,IR De}} \times \rho_{\text{IR De,Sr PTB}}$$

$$\rho_{n,0} = \rho_{n,n-1} \times \rho_{n-1,n-2} \times \ldots \times \rho_{2,1} \times \rho_{1,0}$$

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Idea 1: "Reduced frequency ratios"

$$\rho_{i,j} = \rho^0_{i,j}(1 + y_{i,j})$$

$$y_{n,0} = y_{n,n-1} + y_{n-1,n-2} + \ldots + y_{2,1} + y_{1,0}$$

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Idea 2: "Transfer beats"

$$f^T_{i,j} = \nu_i - \frac{m_i}{m_j}\nu_j$$

$\rho_{n,0}$ = affine combination of $f^T_{i,j}$

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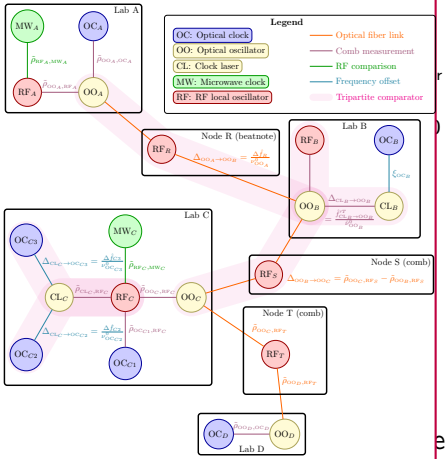
⚠ Physical significance, micro-wave clocks

Formalism to compare clocks

Universal formalism

- flexible
- abstract



Phys. Rev. Research 2, 043269 (2020)

Idea 1: “

$y_{n,0} = y_n,$

Idea 2: “

r PTB

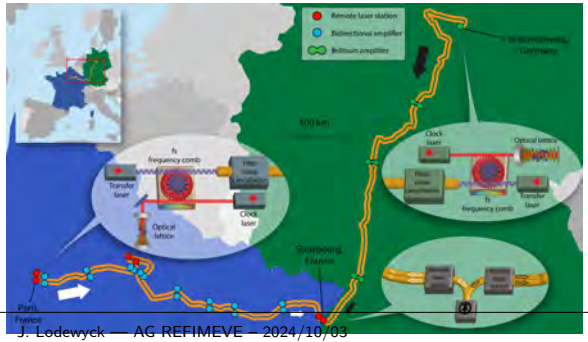
e clocks

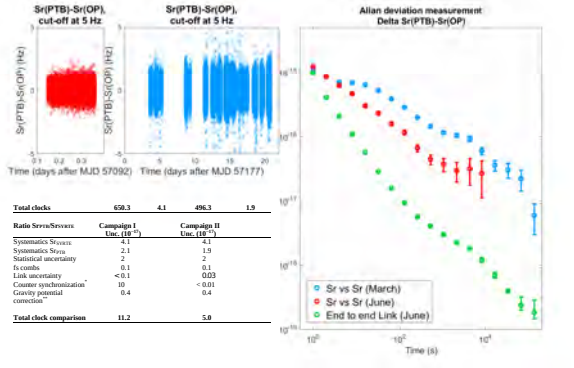
$\rho_{n,0}$ = affine combination of $f'_{i,j}$

Clock comparisons: first comparison

2015: Comparison Sr2 SYRTE vs. Sr PTB

- 1415 km long fiber link
  SYRTE – LPL – PTB
- first remote comparison of optical clocks below the SI:
  Sr_2 - $Sr_{PTB} = (-4.7 \pm 5.0) \times 10^{-17}$





Total clocks	**650.3**	**4.1**	**496.3**	**1.9**
Ratio Sr_{SYRTE}/Sr_{SYRTE}	**Campaign I Unc. (10^{-16})**		**Campaign II Unc. (10^{-16})**	
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**	

C. Lisdat *et al.*, Nat. Comm. **7** 12443 (2016)

Clock comparisons: tests of fundamental physics

2016: Comparison Sr2 SYRTE vs. SrB SYRTE vs. Sr NPL

- Sr_2 - $Sr_B = (2.3 \pm 7.1) \times 10^{-17}$
- $Sr_{NPL} \simeq 10^{-16}$ away

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- Fractional frequency shift on a clock $= \alpha \frac{\vec{v}^2_{clock/CMB}}{c^2}$
- $\Rightarrow$ In a frequency comparison between distant clocks A and B

$$\Delta_{LI} \simeq 2\alpha \frac{(\vec{v}_{A/Earth} - \vec{v}_{B/Earth}) \cdot \vec{v}_{Earth/CMB}}{c^2}$$

Result

Bayesianf fit of Δ_{LI} with the combined
SYRTE – PTB and SYRTE – NPL data (200 hours)
$\Rightarrow$ bound on $|\alpha| \lesssim 10^{-8}$

P. Delva *et al.*, Phys. Rev. Lett. **118** 221102 (2017)

Search for dark matter transients: New J. Phys. 22 093010 (2020), arXiv:2312.13723 (2023)

Clock comparisons: checking stability and accuracy

2017: Joint campaign SYRTE, NPL, PTB, Sr, Hg and Yb^+

- Sr_2 - $Sr_{PTB} = 10^{-16}$ to 10^{-15}

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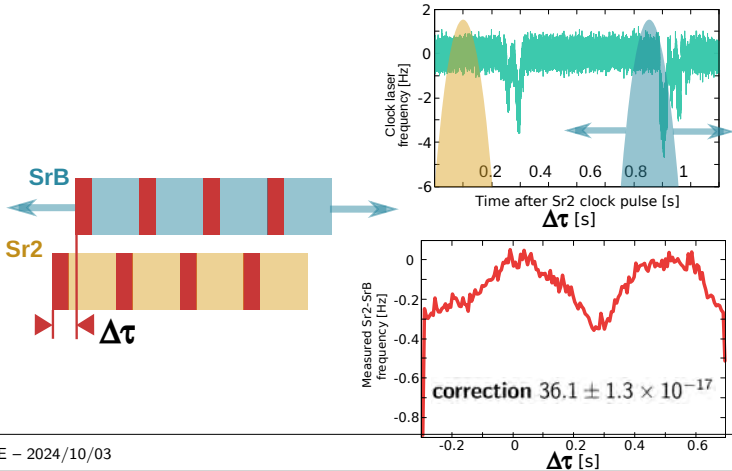
Technical systematic effect:



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Joint campaign SYRTE, NPL, PTB, Sr and Yb^+

- 2017: Sr_2 - $Sr_{PTB} = (0.8 \pm 3) \times 10^{-17}$
- 2018: Sr_2 - $Sr_{PTB} = (-1.5 \pm 2.5) \times 10^{-17}$

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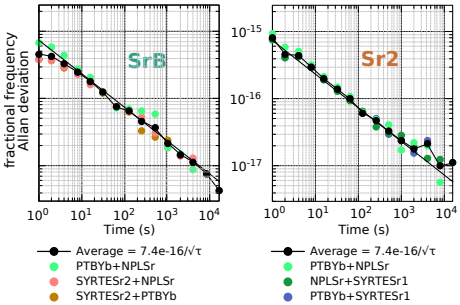
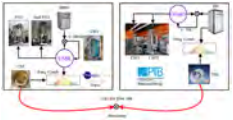
Frequency stability:



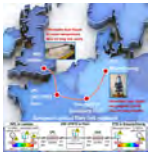
Clock comparisons: getting bigger

2017/2024: Comparison of microwave fountains



Metrologia **54** 348 (2017)

2022: Comparison of cavities



Nat. Comm. **13** 212 (2022)

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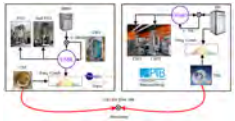

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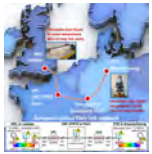
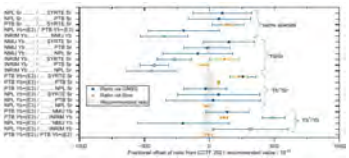
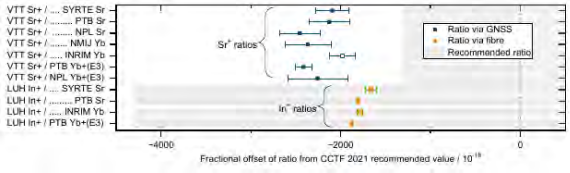


Nat. Comm. **13** 212 (2022)

2022: ROCIT project SYRTE, PTB, INRIM ; Sr, Yb, Yb^+ E_3, Yb^+, E_2, In^+, Sr^+ ; NPL, VTT, UMK by satellite.





2023/2024: ICON project comparison of RIKEN and PTB Sr transportable clocks at NPL and PTB ; SYRTE Hg clock data.

Conclusion

Clock comparisons by optical fibre links are an irreplaceable tool for:

- validating the clock systematic evaluation
- measuring frequency ratios
- tests of fundamental physics

What's next ?

- Roadmap for the redefinition of the SI second: confirm the frequency ratios, measure ratios closures.
- Promote agile comparisons ;
  exploit the excellent up-time of fibre links