



Systemes de Référence Temps-Espace



# European connexions of REFIMEVE: a clock network and some applications

LPL, RENATER, SYRTE,

MuQuans

PTB, NPL, INRIM

Speaker : P.-E. Pottie



# People

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@PTB : S. Koke, A. Kuhl, T. Walterholter, S. Raupach, G. Grosche, H. Schnatz

@NPL : R. Ilieva, G. Marra, J. Kronjaeger

@INRIM : A. Mura, C. Clivati, D. Calonico

**+ OFTEN/ROCIT collaboration for the clocks and combs**

Grenoble-Modane :

**O. Charrier, G. Enderlé, R. Dorge, T. Zampieri, J. Bernier**

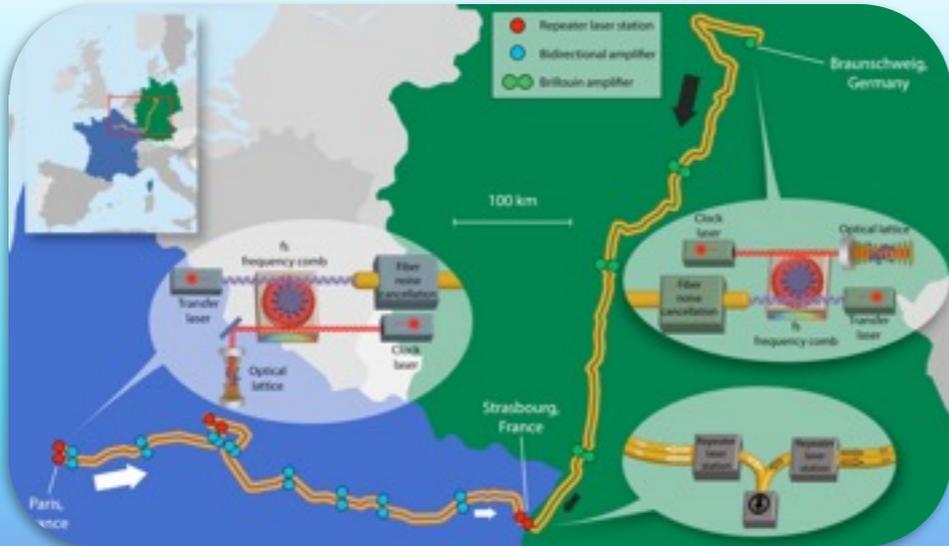
# Outline

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- REFIMEVE international connexions
  - Cross-border connection to Italy and LIFT T&F network
- Clock comparisons with a fiber network
  - Towards SI-second redefinition
  - Search for dark matter and transient of fine structure constant
  - Chronometric geodesy

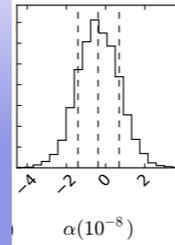
# Scientific context

## towards SI-s re definition



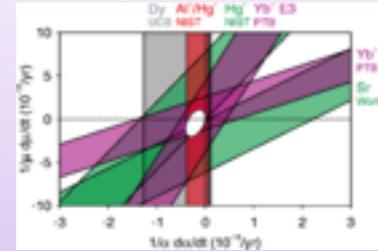
**C. Lisdat et al.**, Nat.Comm. **7** (2016)  
**Guéna et al.**, Metrologia, **54** 3 (2017)

## Special relativity Testing LLI

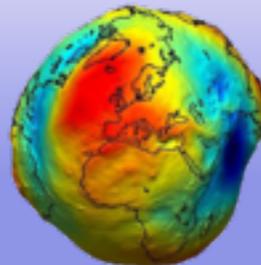


**P. Delva et al.**  
 PRL **118** 22 (2017)

## Temporal variations of $\alpha$

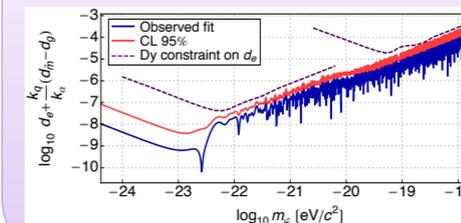


## Chronometric geodesy



**T. Takano et al.**  
 Nat. Phot. **10**,10 (2016)  
**G. Lion et al.**  
 J Geod, **91** 6 (2017)

## Dark matter



**A. Hees and al.**  
 PRL **117** (21)  
 210802 (2016)

# International connections of Refimeve

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- France-Germany:
  - Interconnection Strasbourg-Kehl
  - 3 km. Dark fiber pair, leased by SYRTE via RENATER since 2015.
  - Equipment on site +IP service hosted by RENATER / DSI University of Strasbourg
- France-United Kingdom:
  - Interconnection at LPL. Equipment hosted by LPL
  - 760 km NPL-LPL fiber links, leased by NPL since 2017. Started as EU project of GéANT (GN3+)
  - Home-made in band supervision channel SYRTE/NPL + IP through GéANT
- **NEW!** France-Italy
  - Interconnection at Laboratoire Souterrain de Modane (LSM/IN2P3/CNRS)
  - 140 km Grenoble-Modane dark channel on Amplifia network (Regional network from Région Rhone-Alpes-Auvergne)
  - 7 km dark channel on CNRS network (IN2P3) + IP service CNRS/Amplivia/RENATER
  - 155 km Modane-Torino, dark channels, on TOP-IX network (Piemont region)
  - IRU for 13 years by UGA. OPEX and CAPEX supported by SYRTE.

# Grenoble-Modane: a long story...

Thanks also to:  
 Emilie Camisard (RENATER)  
 Raoul DORGE (UGA)  
 Axel BELLUARD (COVAGE)  
 Michel Zampaolo (LSM)  
 Konstantin PROTASSOV (UGA)  
 Christophe SALOMON (LKB)



Nov 15, 2019  
 REFIMEVE runs  
 Paris-Grenoble

Jan 21, 2020  
 Grenoble-Modane  
 multiplexed

Feb 14, 2020  
 Interco  
 ITxFR



LIFT@Modane

« réforme territoriale »

Gaetan Enderlé



Fiber path  
 identification

Olivier Charrier



contractual phase



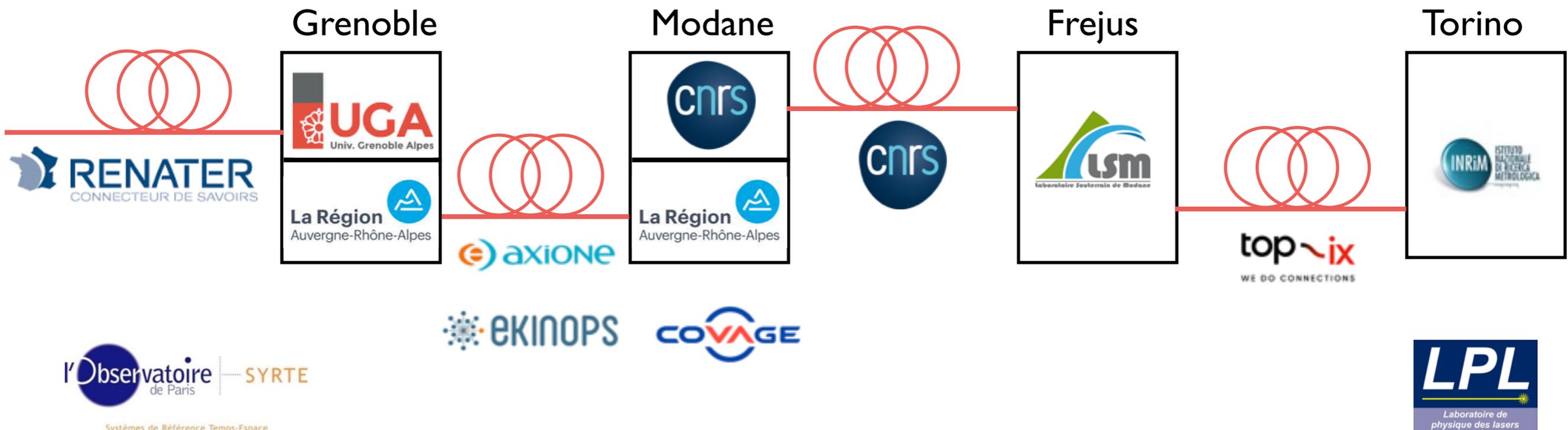
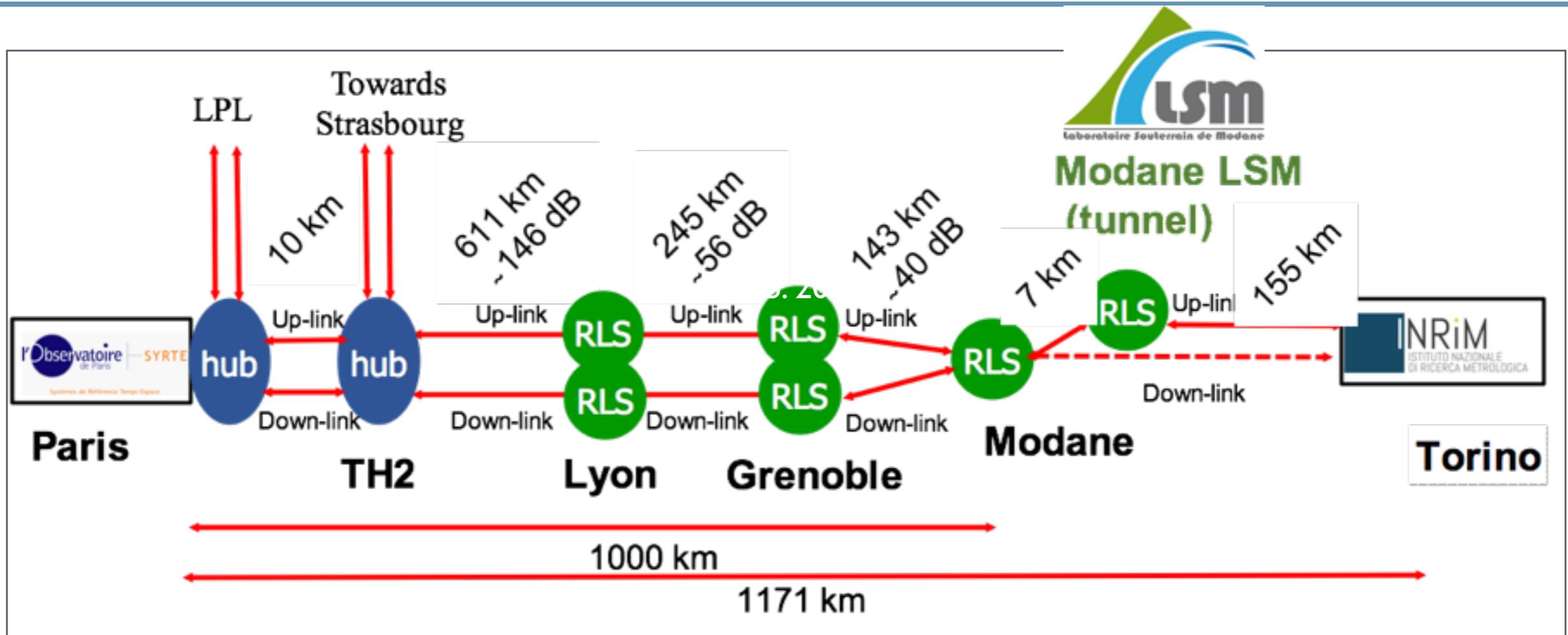
Agreement  
 SYRTE-UGA  
 undersigned



Etienne Cantin

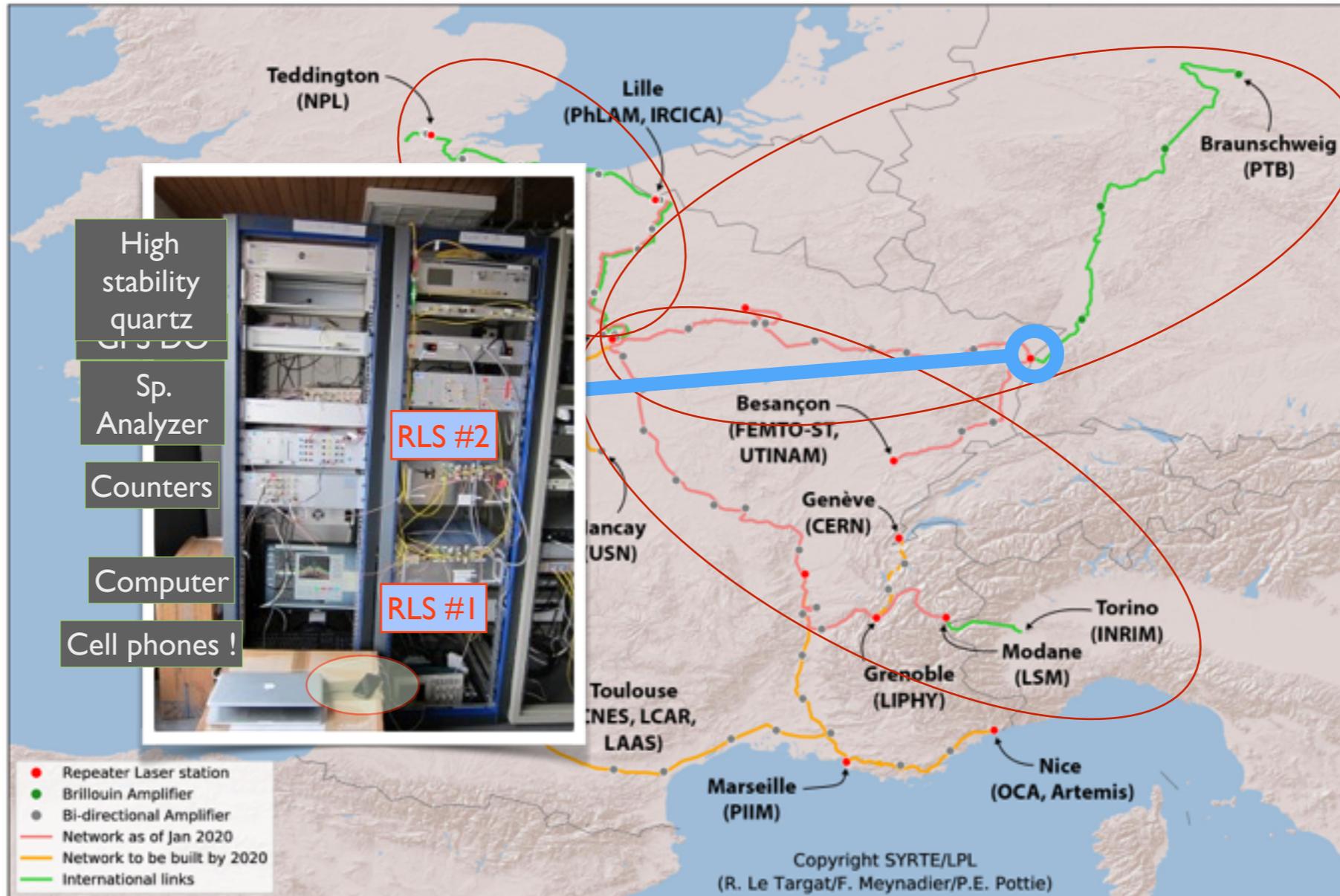


# Interconnection with ITALY



# Multi-domain optical links

REFIMEVE+ network and international links to NMIs



# OFTEN/ROCIT : a large collaboration

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- More than 50 people involved : 3x (clock(s) + comb + link)
- Coordination of effort mandatory
- Scheduling from 3 months to 2 weeks
- Best effort basis



# OFTEN/ROCIT : a large collaboration

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@ LPL: O. Lopez, **A. Amy-Klein**,

@RENATER: N. Quintin

@SYRTE: M. Tonnes, E. Cantin, D. Xu, P. Tuckey, F. Meynadier; **R. Le Targat**,  
H. Alvarez-Martinez, **J. Lodewyck**, S. Bilicki, E. Bookjans, C. Guo, J. Calvert,  
L. de Sarlo, C. Barentsen, M. Andia, Y. Foucault, B. Alves, W. Moreno, P.  
Delva, M. Abgrall, L. Lorini, J. Guéna, S. Bize, (...)

@PTB : **S. Koke**, T. Waterholter, A. Kuhl, G. Grosche, H. Schnatz; **Ch. Lisdat**,  
R. Lange, H. Shao, M. Abdel-Hafiz, S. Doerscher, T. Legero, S. Haefner, R.  
Schwarz, U. Sterr, **E. Benkler**, **N. Hunterman**, S. Weyers, B. Lipphardt, E.  
Peik, (...)

@NPL : R. Ilieva, **J. Kronjaeger**; I. Hill, R. Hobson, M. Schioppo, A. Silva, C.  
W. Bowden, J. Paterson, A. Vianello, G. Marra, **R. Godun**, **H. Margolis**, (...)

@INRIM : M. Pizzocaro, A. Mura, C. Clivati, D. Calonico, (...)

@UMK : S. Bilicki, M. Zawada, (...)

# Optical methodology

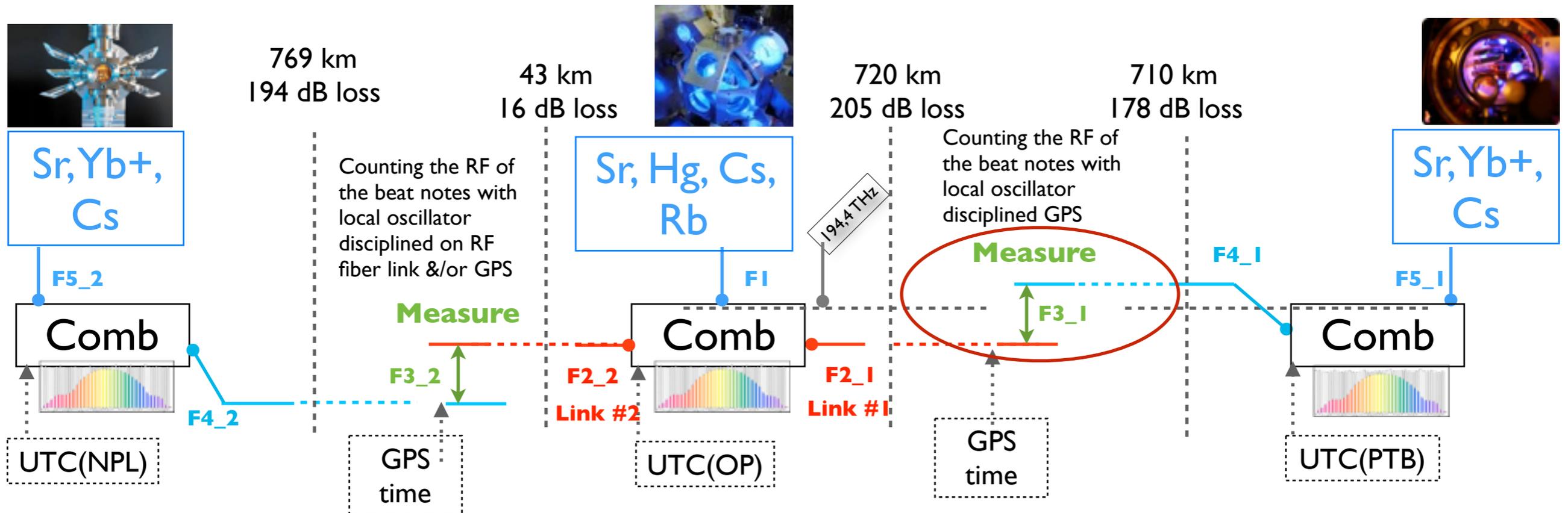
London

Villetaneuse

Paris

Strasbourg

Braunschweig



Counting the RF of the beat notes with the fs combs

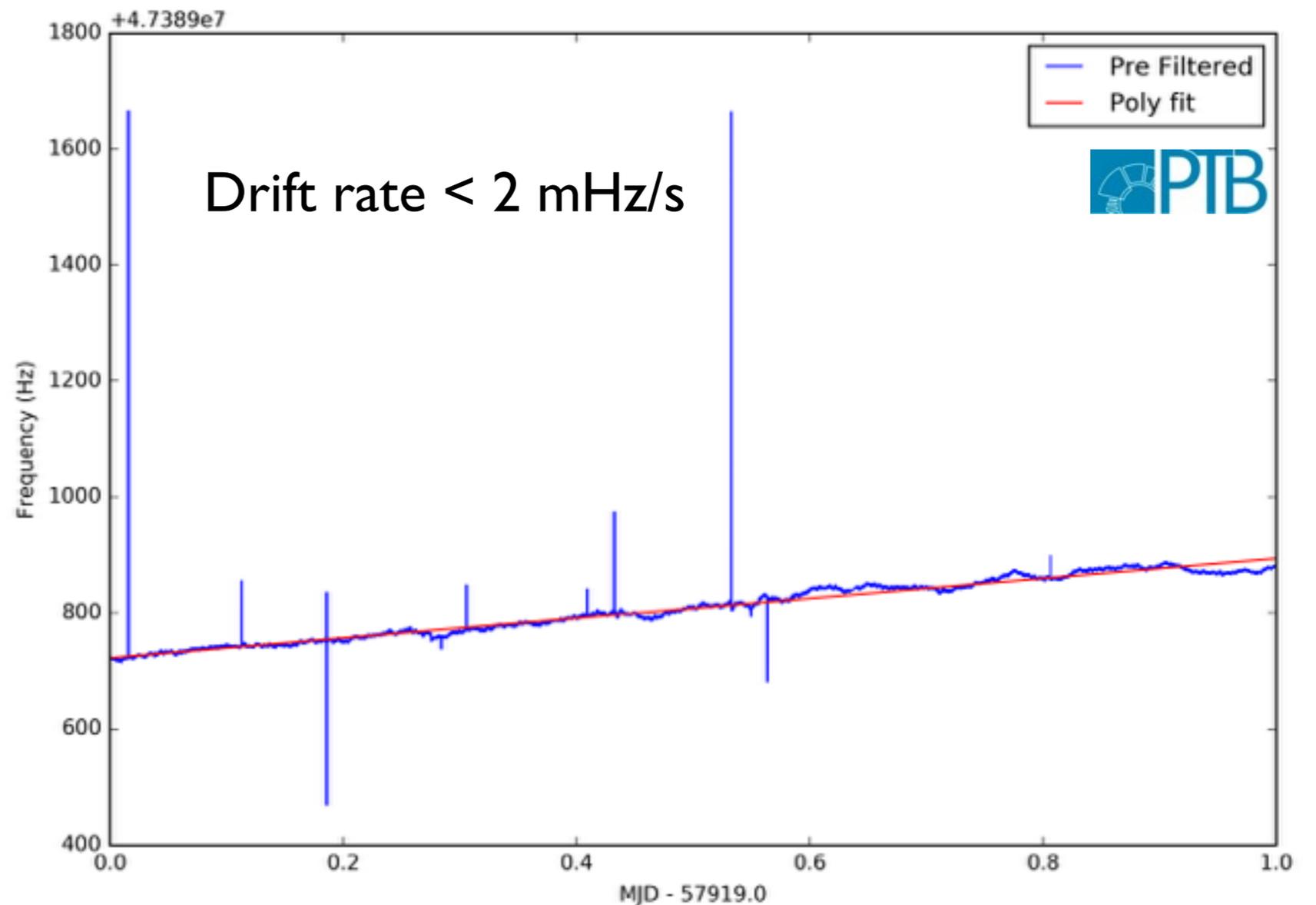
C. Lisdar et al., Nature Comm. (2016), 12443 (2016)  
 J. Guéna et al., Metrologia **54**, 3 (2017)  
 P. Delva et al., Phys. Rev. Lett. **118**, 221102 (2017)

# Optical frequency difference: remote measurement

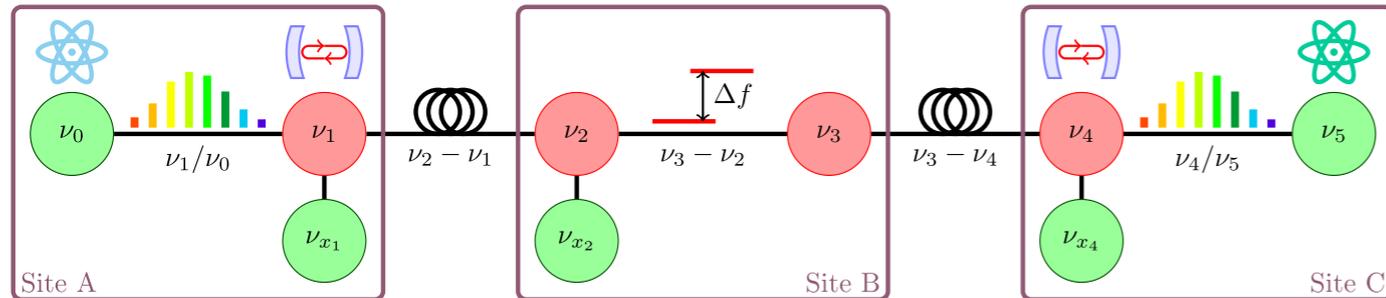
A look to the raw signal:

- Time tags counters disciplined on NTP
- Counters synchronized with GPS
- 10 MHz ultra-stable LO GPS-disciplined

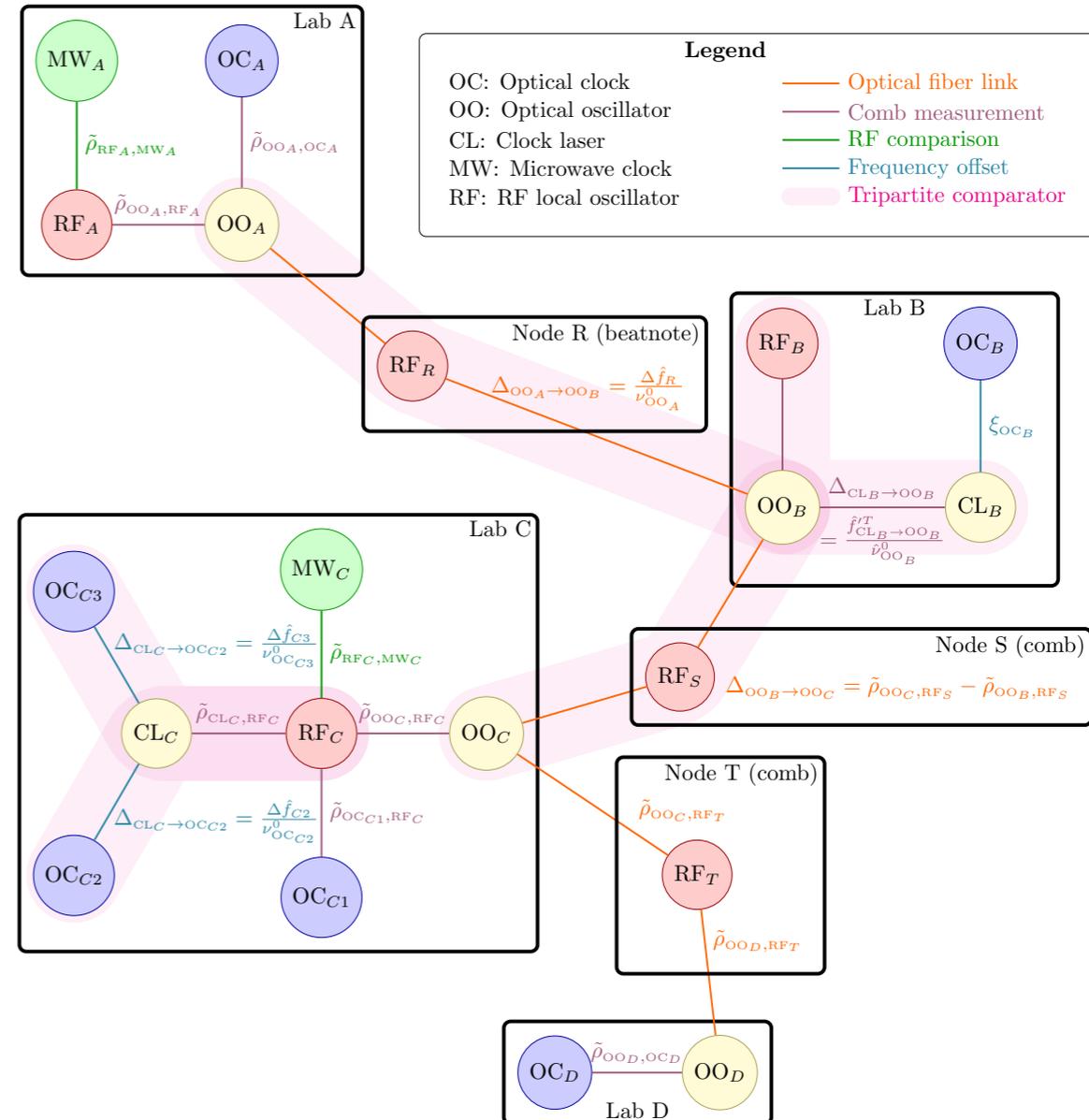
NIR lasers Beat @ Strasbourg



# Clock comparison formalism



- Green : clocks and RF references linked to accurate references
- Red : link lasers, inaccurate (Near-Infrared ultra-stable cavities)
- Comparator : Frequency ratios  $\rightarrow$  reduced frequency ratios.
- High precision if an a priori approximate value for these frequency ratios is available.
- data using only double precision floating point.
- requires only single and local quantity per measurement device within the network.



# Clock comparisons summary

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- duration from 3 days to ~1 month
  - $4 \times 10^{-17}$  to mid  $10^{-18}$  statistical uncertainty
- Ensemble of 10 optical clocks connected by 2020:
  - 6 Sr @ SYRTE, PTB, NPL, INRIM; UMK to join
  - 2 Yb+ @ PTB, NPL
  - 1 Hg @ SYRTE
  - 1 Yb @ INRIM (yet to be compared)
- Sr and Yb+ comparisons :
  - typ. statistical uncertainty  $< 1 \times 10^{-17}$
  - Most cases agreement between clocks down to  $1-2 \times 10^{-17}$ 
    - A few disagreement at  $1 \times 10^{-16}$  **See also : Dörscher, S. et al. Metrologia (2020) doi:10.1088/1681-7575/abc86f.**
  - repeated 8 times over 5 years

# SI-second redefinition

- Working group and task force set up at BIPM
  - More and more frequency ratios reported
  - Means of comparisons: needs fiber links on long term
    - REFIMEVE gives an important contribution
- Choice of a definition

On a definition of the SI second with a set of optical clock transitions:

**Lodewyck J.**, Metrologia 56, 055009 (2019).

Two-way satellite and GPS-IPPP, VLBI :

**Riedel, F. et al.**, Metrologia (2020) doi:10.1088/1681-7575/ab6745.

**McGrew, W. F. et al.**, Optica, OPTICA 6, 448–454 (2019).

**Pizzocaro, M. et al.**, Nature Physics 1–5 (2020) doi:10.1038/s41567-020-01038-6.

Local comparisons:

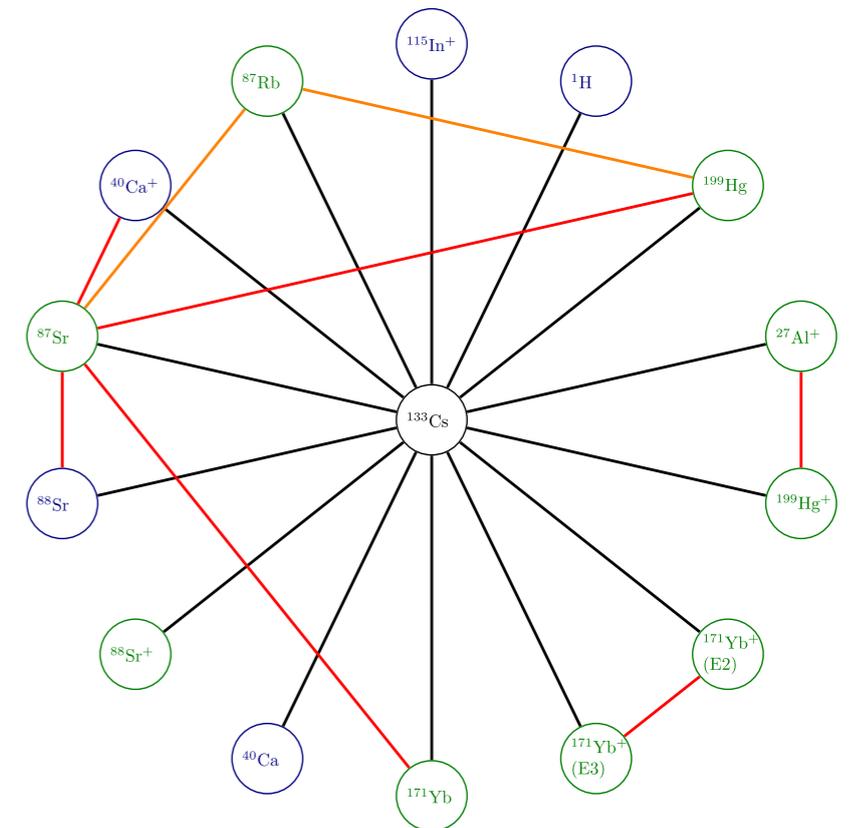
**Ohmae, N. et al.**, Optics Express (2020) doi:10.1364/OE.391602.

**Dörscher, S. et al.** Metrologia (2020) doi:10.1088/1681-7575/abc86f.

Optical free-space:

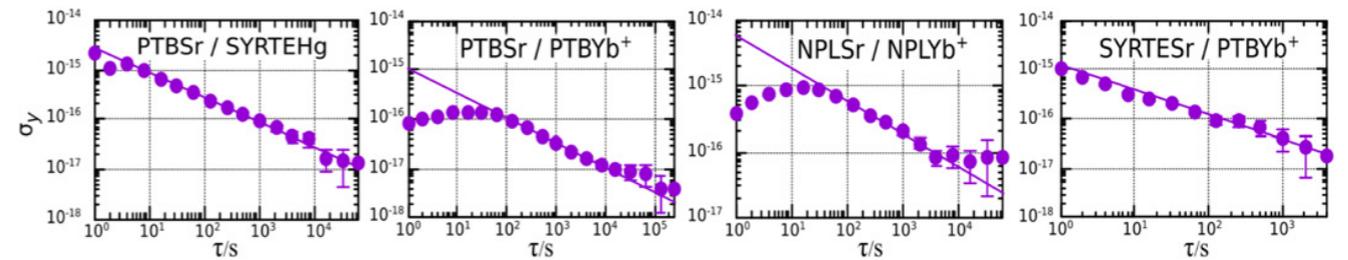
**Bodine, M. I. et al.** Phys. Rev. Research 2, 033395 (2020).

**Dix-Matthews, B. P. et al.** Point-to-Point Stabilised Optical Frequency Transfer with Active Optics. arXiv:2007.04985 [physics] (2020).

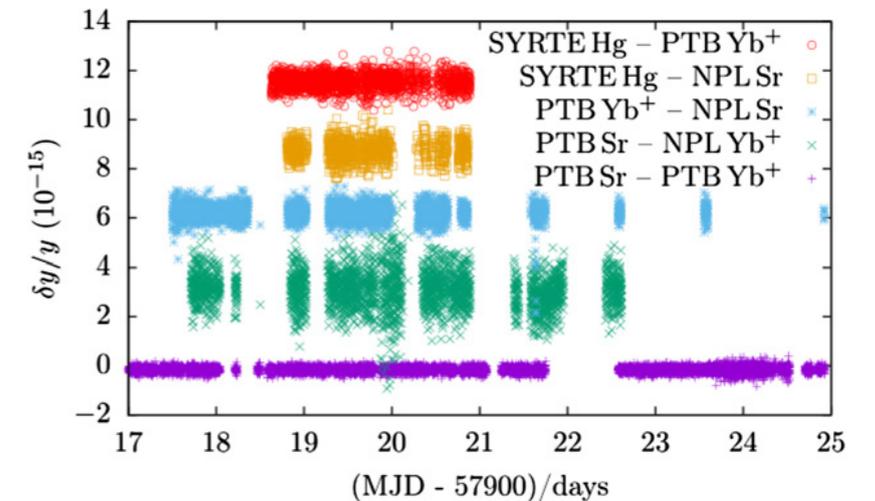


# Search for dark matter with the EU-clock network

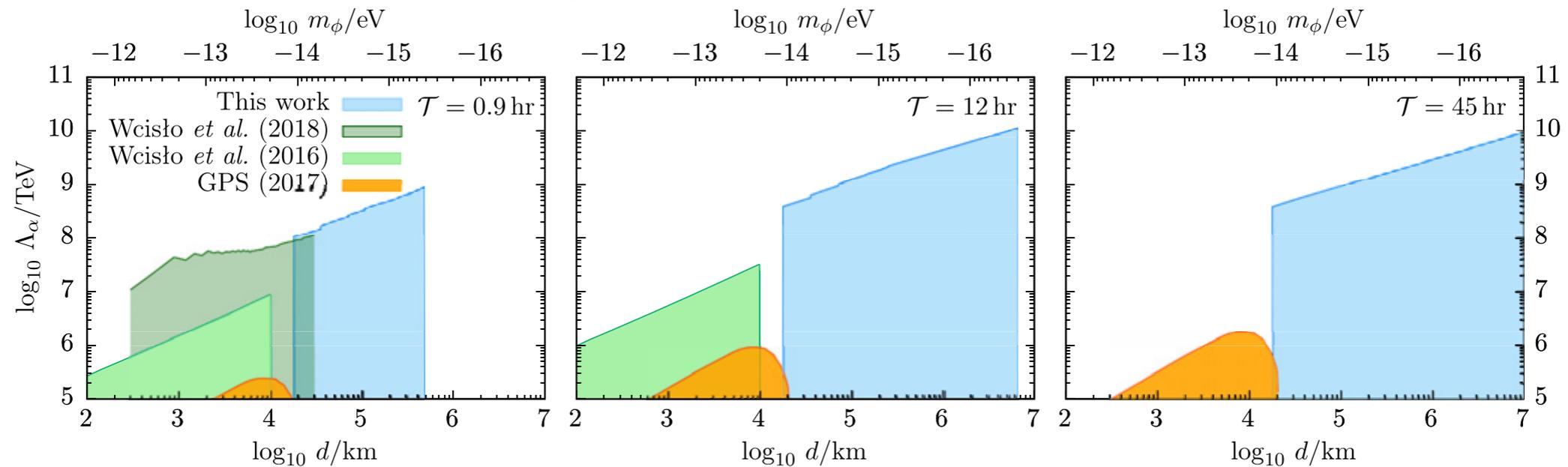
- Tests performed earlier with GPS and satellites
- Improved by fiber network
  - Test of transient of fine structure constant
  - Topological defect dark matter:



June 2017



Roberts, B. M. et al., New J. Phys. 22, 093010 (2020).



see also :

Wcisło, P. et al., Nature Astronomy 1, 1–6 (2016).

Hees, A. et al., Phys. Rev. D 98, 064051 (2018).

Wcisło, P. et al., Science Advances 4, eaau4869 (2018).

# Chronometric levelling

- Clock rate, when compared to coordinate time, depends on the velocity of the clock and on the space-time metric (which depends on the mass/energy distribution).
- Accuracy of optical clocks starts to be competitive with classical methods: up to a few centimeters for the static potential at high spatial resolution
- Possibilities for technical realization of a system for measuring potential differences over intercontinental distances using clock comparisons

Gravitational shift  $\sim 10^{-16}$  /m

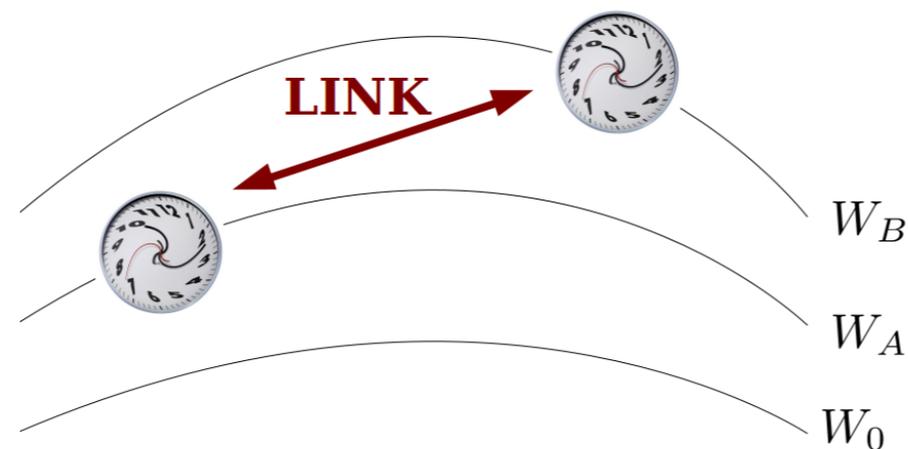


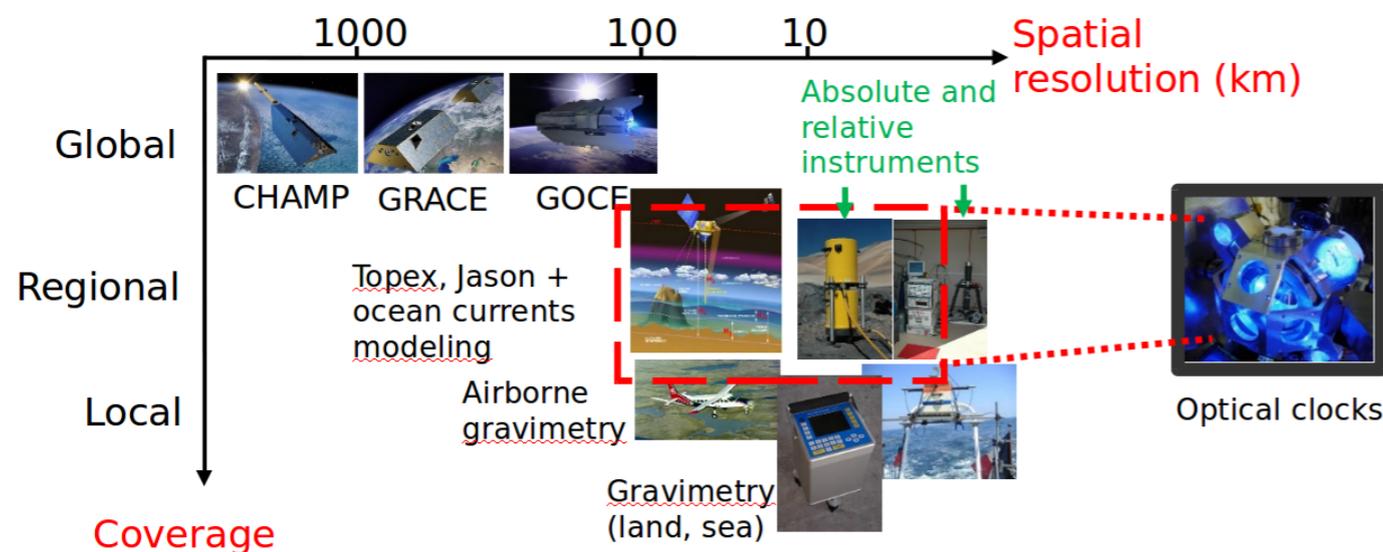
Illustration: Courtesy G. Lion, P. Delva

Vermeer, M. (1983). Chronometric Levelling. Finnish Geodetic Institute, Helsinki.

Bjerhammar, A. (1985). Bull. Geodesique 59.3, pp. 207–220. doi: 10.1007/BF02520327.

# Chronometric geodesy with REFIMEVE

- Classical methods to measure the gravitational potential of the Earth :
  - Satellites data or on classical levelling combined with gravimetric data
  - Performance limited in mountainous or coastal areas,
  - Suffers from long distances biases
- An atomic clock measures directly the gravitational potential (gravitational time dilation predicted by Einstein): there is no classical equivalent to this quantum sensor!



Courtesy G. Lion

- ANR ROYMAGE, PI R. Le Targat
- Mobile Ytterbium Optical Clock Applied to Geodesic Exploration
- Goal: exploit the most relevant of the ~60 outputs of REFIMEVE in France to remotely compare the clock to the ~12 existing European optical clocks



See also: Oelker, E. et al. Nature Photonics 13, 714–719 (2019).

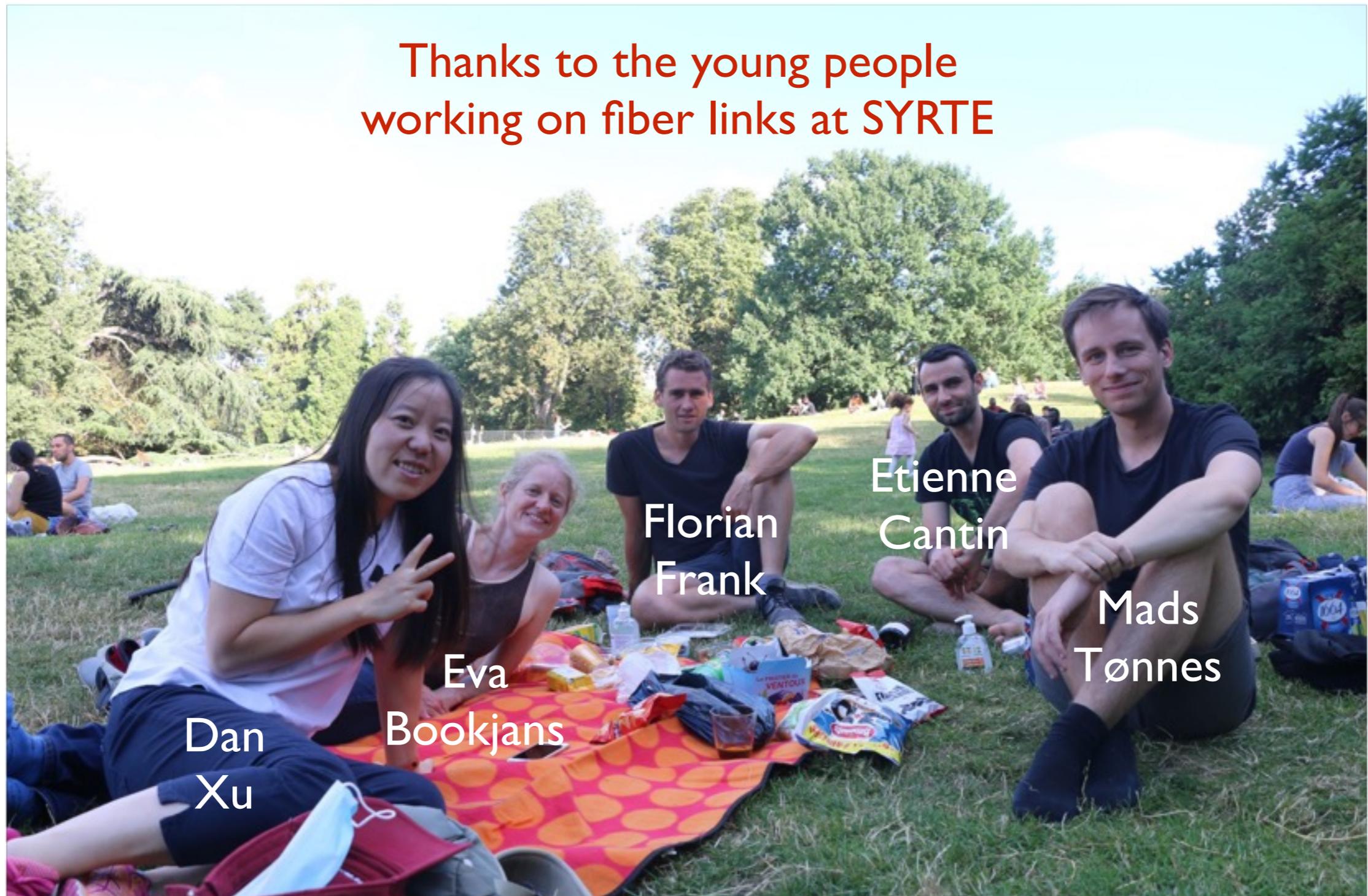
# Outlook

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- REFIMEVE: 3 international connexions to Germany, UK and Italy
- Clock comparisons over 5 years
  - Show good agreement between clocks but... not always
  - Clock network is useful to improve clocks
  - Test of special relativity
- A clock network impacts:
  - SI-second redefinition
  - Search for dark matter and transient of fine structure constant
  - Chronometric geodesy
- Future (T-REFIMEVE ?) for clock comparisons:
  - More international connexion: Torun in Poland, (...)
  - Chronometric geodesy, VLBI and reference frames
- Time transfer, optical time scale comparisons

# Thank you for your attention !

Thanks to the young people  
working on fiber links at SYRTE



Dan  
Xu

Eva  
Bookjans

Florian  
Frank

Etienne  
Cantin

Mads  
Tønnes

Credit photo : Dan Xu