



SYRTE



RENATER
CONNECTEUR DE SAVOIRS



Systemes de Référence Temps-Espace

LP2N



Frequency dissemination and comparison through a fiber network



E. Cantin, M. Tonnes, F. Frank, E. Bookjans,

P. Tuckey, A. Amy-Klein, O. Lopez,

P.-E. Pottie



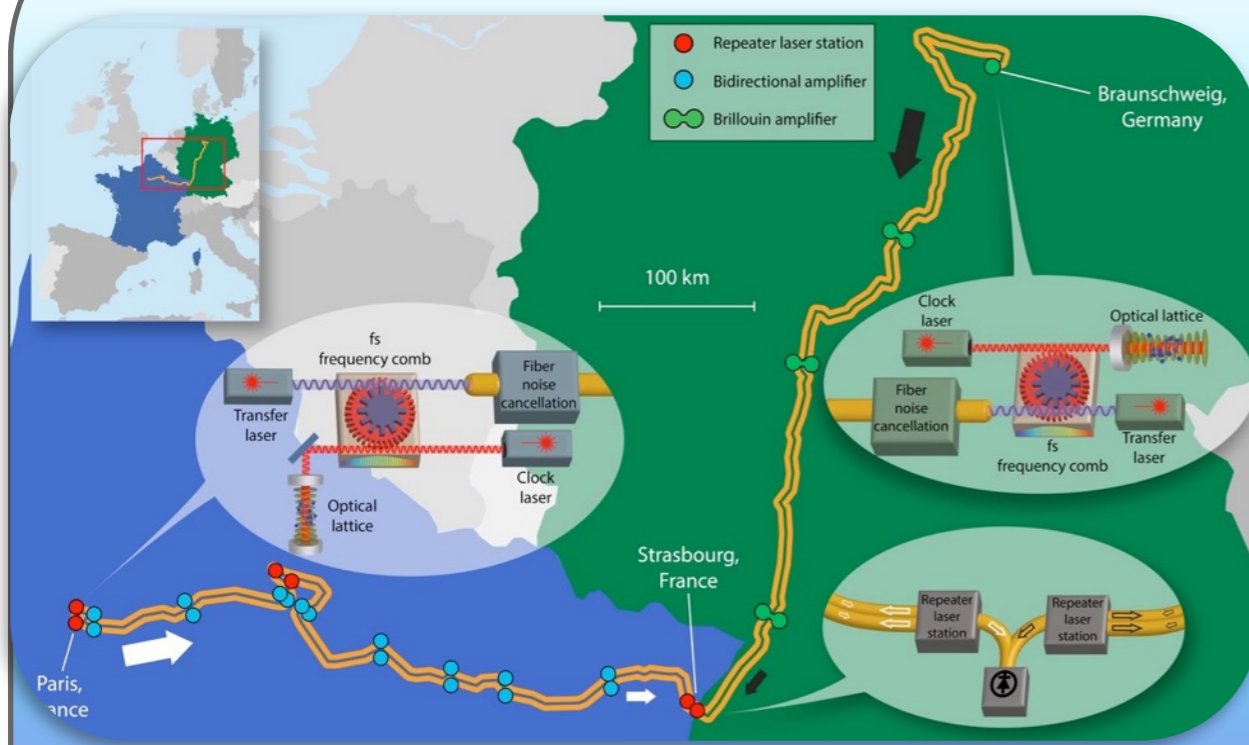
Contents

- **Fiber *link* technology**
- **Fiber *network*, towards a Research Infrastructure**

(CLONETS)
- **A clock network (OFTEN, ROCIT)**
- **The french fiber network (REFIMEVE+)**

Fiber network: Motivations

SI-s re definition



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

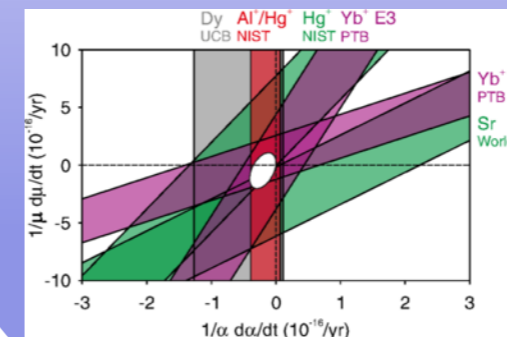
Fundamental physics Special relativity, LLI

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

Dark matter

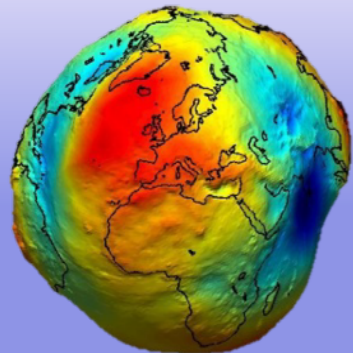
A. Hees and al. PRL **117** (21) 210802 (2016)

Temporal variations of α



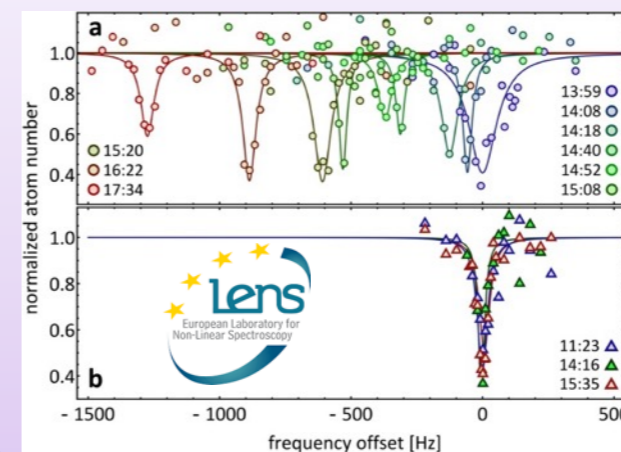
N. Huntemann
 and al.
 PRL **113** 21
 210802, (2014)

Chronometric geodesy



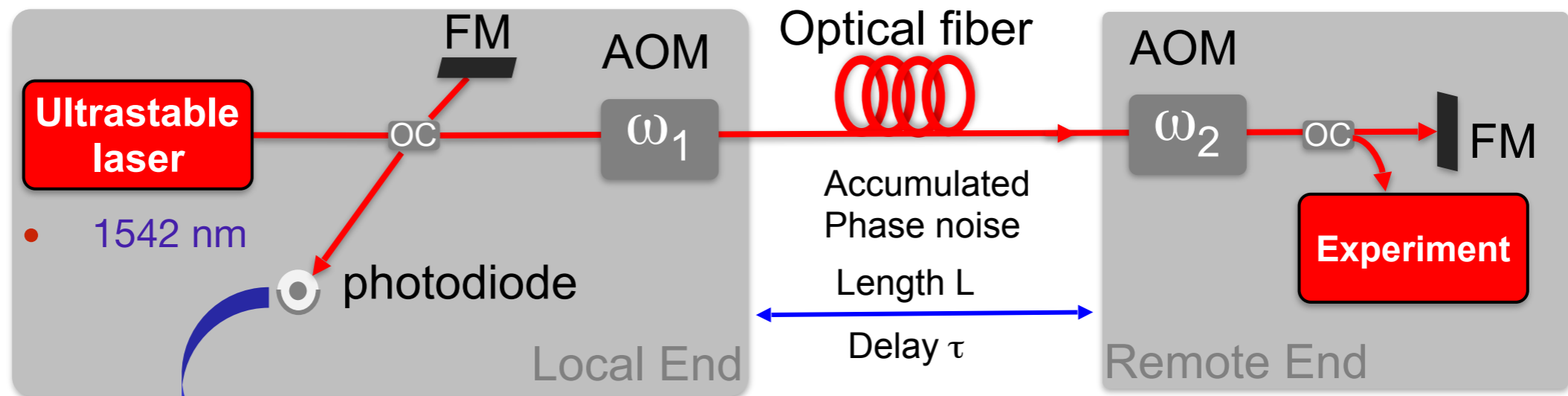
T. Takano et al.
 Nat. Phot. **10**, 10 (2016)
G. Lion et al.
 J Geod, **91** 6 (2017)

Spectroscopy



C. Clivati et al.,
 Opt. Expr., **24**, 11
 (2016)

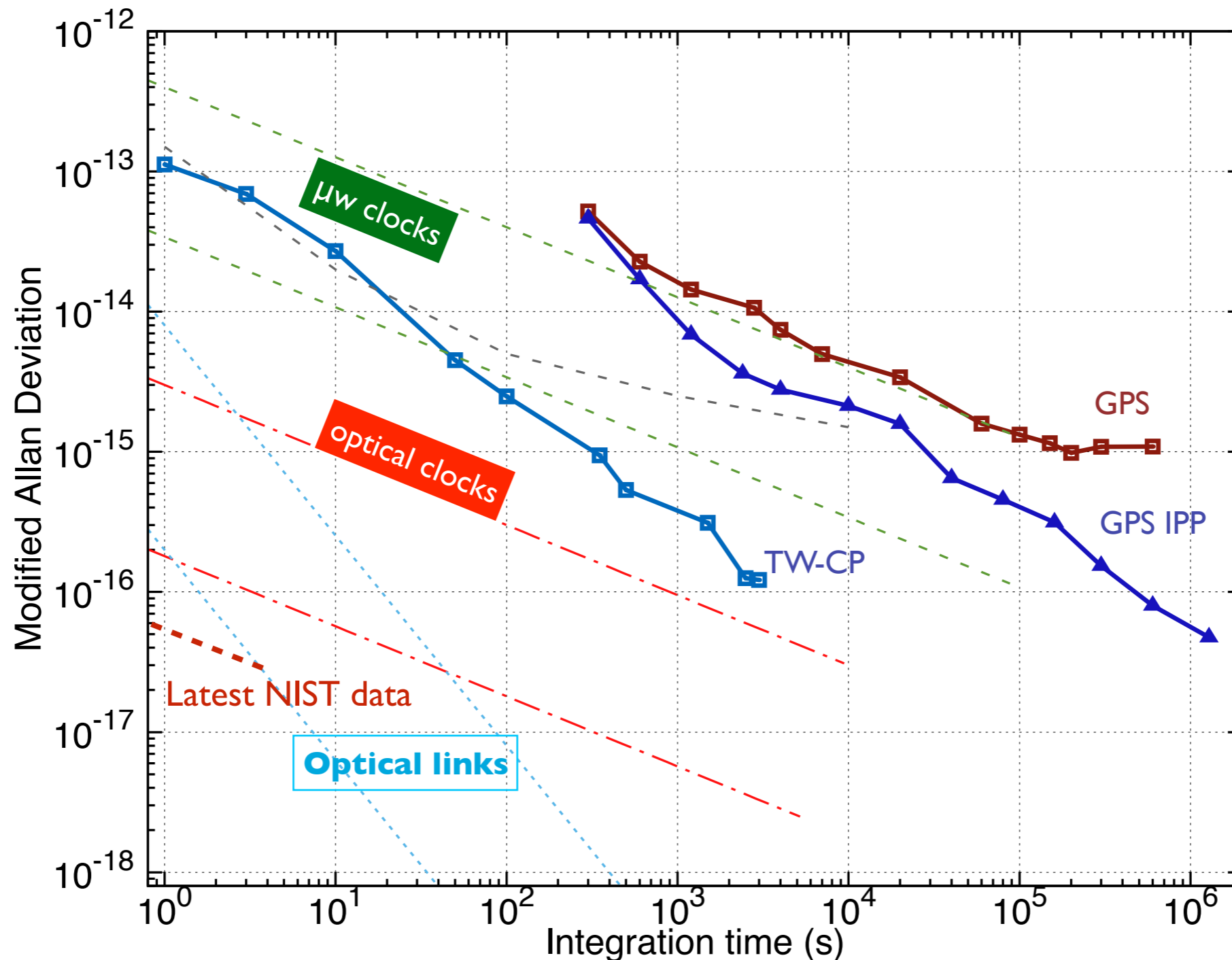
Basics on fiber links



- ✓ Round-trip fiber propagation noise
- ✓ + Laser autocorrelation noise $\phi_{laser}(t) - \phi_{laser}(t - 2\tau)$

- Fully bi-directional. A 2nd link transfers back the signal.
- Unbalanced Michelson interferometer
- Heterodyne detection: eliminates multipath
- Guided propagation: ensure paths reciprocity
 - Assumption : Forward noise = $\frac{1}{2}$ Round-trip noise
 - → corrects only reciprocal noise
- **Coherent regime** if coherence length $> 2L$: need ultra-stable laser !

Typical performances



O. Lopez et al., «F&T transfer for metrology and beyond (...)», Comptes Rendus Physique, 16 (5), pp. 459-586 (2015) (2015)

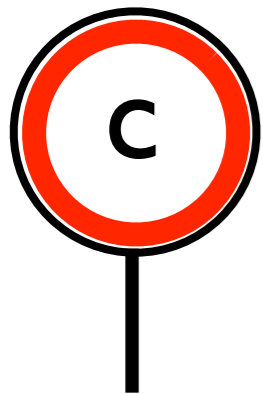
Challenges for long haul fiber links

- Fiber availability: money and partnership
- Attenuation: bi-directional amplification
- Accumulated noise: electronic, automatism, remote control
- Finite time of propagation: fundamental limit

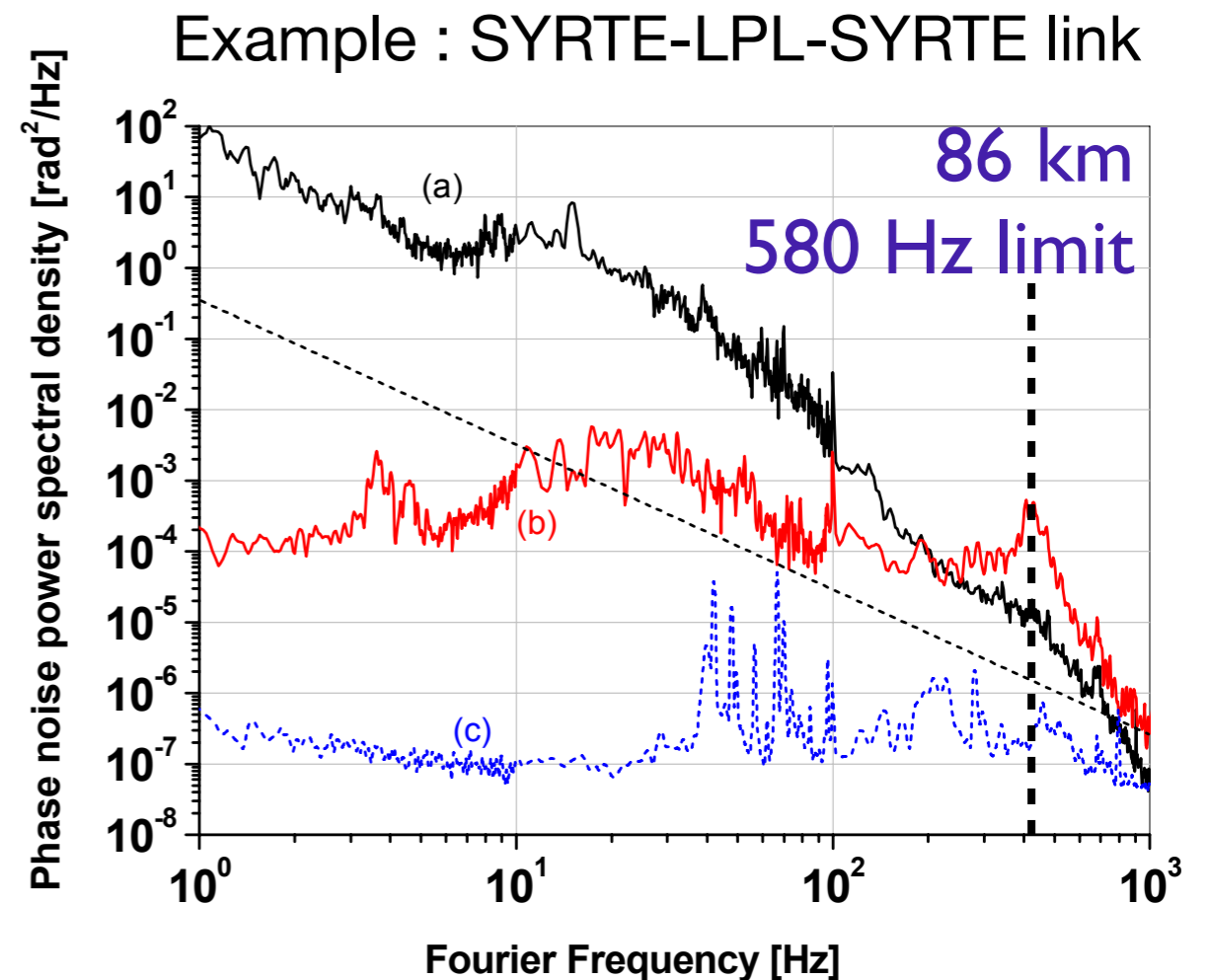
Noise scale as \sqrt{L}

More noise in urban area

20 to 45 dBc / Hz @ 1 Hz

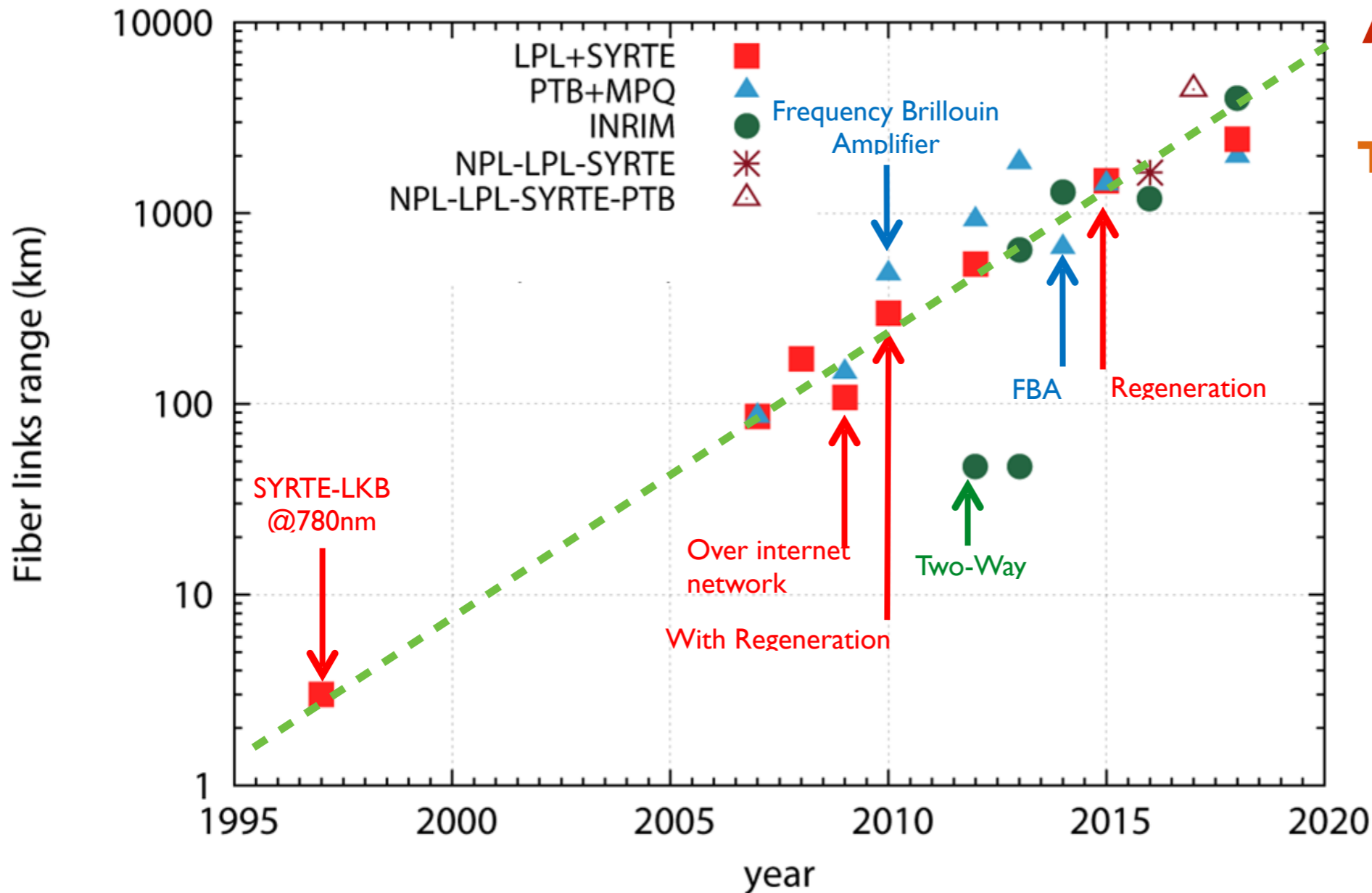


BW < 1 kHz
for $L > 50$ km



Range of fiber links in Europe

- Extend the range of fiber links
- Improve maturity (Technical readiness level)



At horizon 2020 :
8000 km

Towards a large research infrastructure ?

**RENATER, CESNET,
PSNC, GARR
JISC/JANET, DFN,
SURFNET,
NORDUNET...**





- Consortium of 16 partners : 1/3 academics, 1/3 Telecom Network, 1/3 Industrials
- **Expected outcomes :**
 - Review techniques and their evolutions, compatibility, needs for Research Infrastructures (NMIs, research labs, large research facilities as VLBI, accelerators...)
 - Survey potential application outside Research Infrastructure, economic and societal impact
 - Education and training
 - Define a strategic roadmap for RI
- **Mid-term goal :**
 - Secured accessed to the fiber network
 - Increase technical readiness level, offer « on the shelf » solutions and procedures to establish a fiber link

Project CLONETS involved 16 partners from 7 European countries. Partners represent 4 main areas:

- National Measurement Institutes: OBS PARIS (FR), NPL (UK), PTB (DE), INRIM (IT)
- National Research and Education Network: RENATER (FR), CESNET (CZ), PSNC (PL), GARR* (IT),
- Academic Laboratories: AGH (PL), UP13 (FR), UCL (UK), ISI (CZ), CNRS* (FR)
- Industrial: MUQUANS (FR), MENLO (DE), PIKTIME (PL), SEVEN SOL (SP), OPTOKON (CZ), TOP-IX* (IT)

* Third-party member

- 1 FRANCE**
 - OBSERVATOIRE DE PARIS
 - GIP RENATER
 - UNIVERSITE PARIS 13 - LPL
 - MUQUANS
 - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE
- 2 ITALY**
 - ISTITUTO NAZIONALE DI RICERCA METROLOGICA
 - CONSORTIUM GARR
 - CONSORZIO TOP-IX
- 3 GERMANY**
 - PHYSIKALISCH-TECHNISCHE BUNDESANSTALT
 - MENLO SYSTEMS GmbH
- 4 UNITED KINGDOM**
 - NPL MANAGEMENT LIMITED
 - UNIVERSITY COLLEGE LONDON
- 5 CZECH REPUBLIC**
 - CESNET, z.s.p.o.
 - USTAV PRISTROJOVE TECHNIKY AV CR, v.v.i.
 - OPTOKON
- 6 POLAND**
 - POZNANSKIE CENTRUM SUPERKOMPUTEROWO-SIECIOWE
 - PIKTIME SYSTEMS sp. z o. o.
 - AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZCZA W KRAKOWIE
- 7 SPAIN**
 - SEVEN SOLUTIONS S.L.



An EU-backbone to be designed

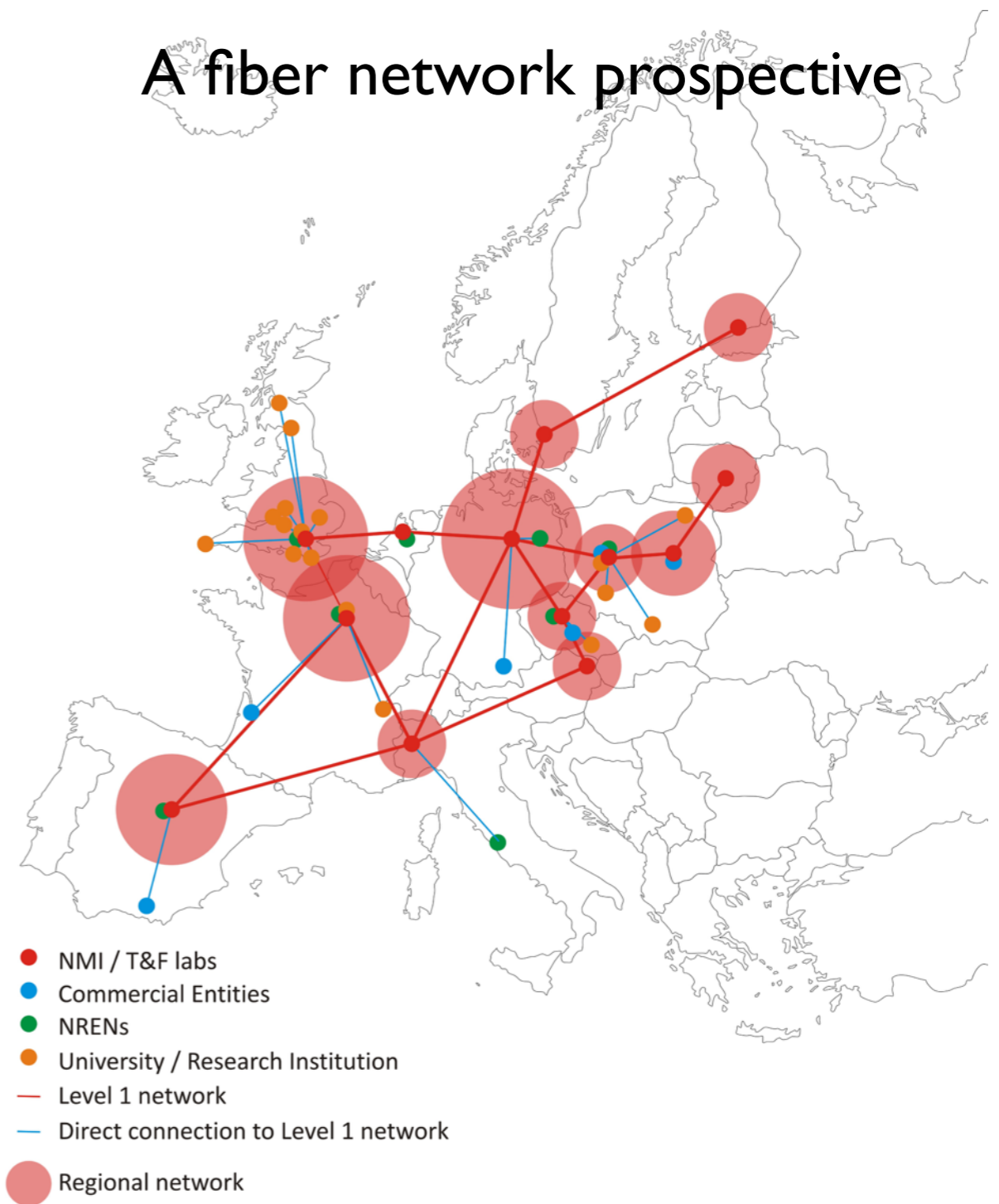
Sustainability

Long-term fiber network access

- REFIMEVE is extended to 2024
- Partnership with RENATER
- LIFT
- Partnership GARR, TOPIX
- OPTIME
- Partnership with PSNC
- CESNET
- NPL and PTB rent the fiber

<https://www.clonets.eu/>

A fiber network prospective



Networks interconnection

INRIM will be connected to NPL/SYRTE/PTB

- Paris-Grenoble (REFIMEVE, 900 km) :
- Grenoble-Modane (150km) :
 - Uni. Grenoble Alpes, +Région Auvergne-Rhône-Alpes
- REFIMEVE + LIFT + PTB + NPL:
 - about 2 x 4 650 km
- Clock comparisons: Yb, Cs



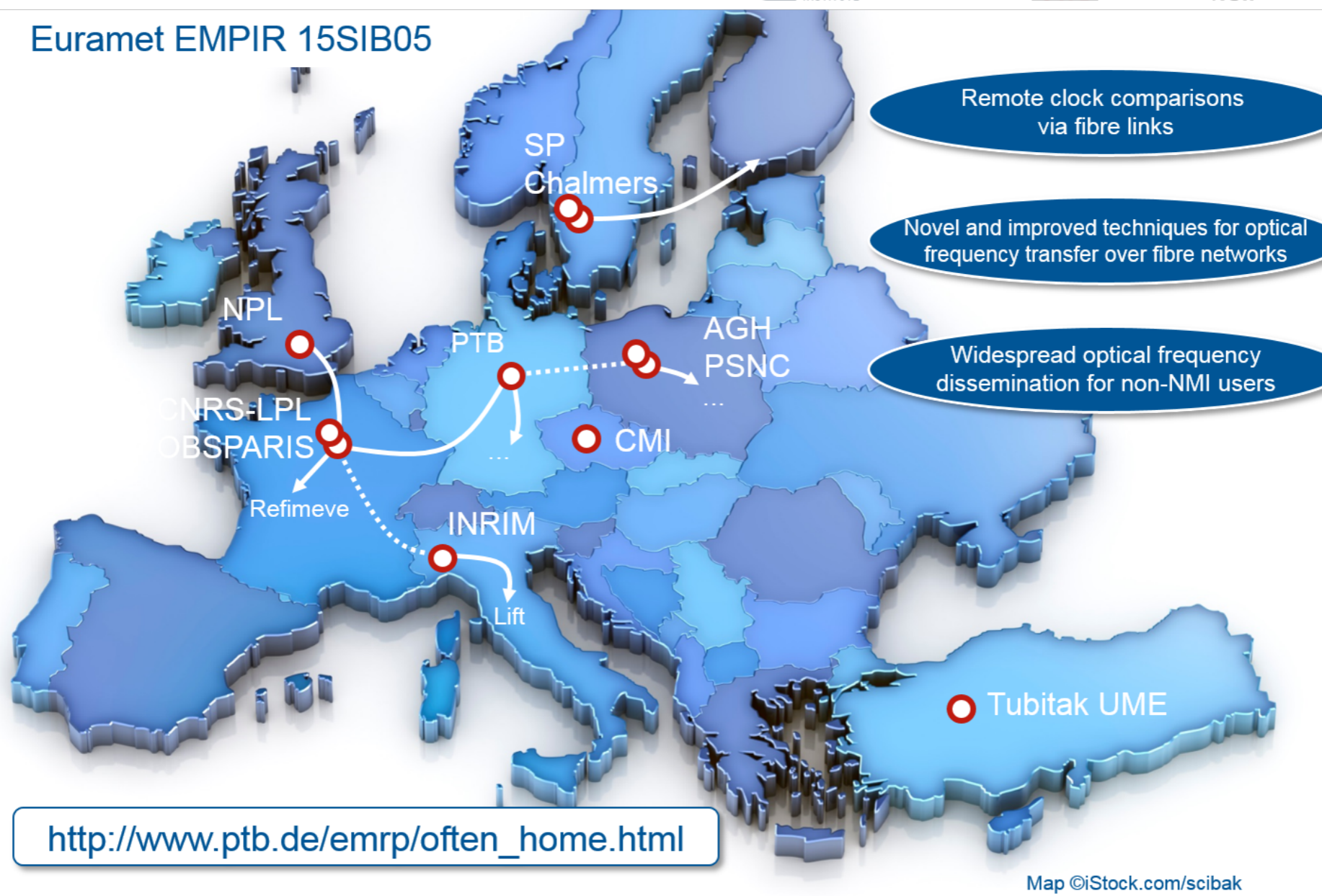
A suitable place for chronometric geodesy ?

European fiber network (OFTEN)

Optical Frequency Transfer – a European Network (OFTEN)



Euramet EMPIR 15SIB05

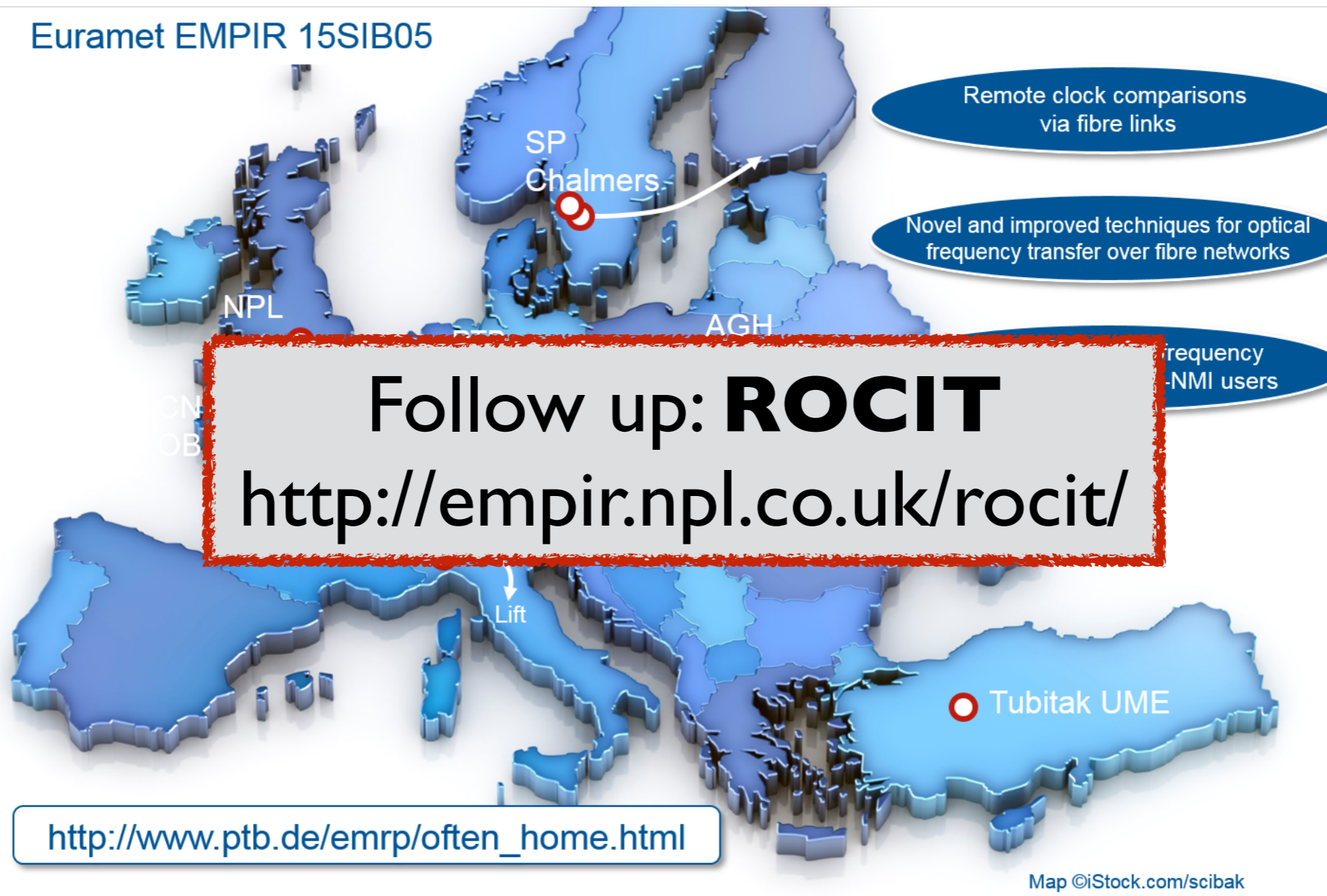


European fiber network (OFTEN)

Optical Frequency Transfer – a European Network (OFTEN)



Euramet EMPIR 15SIB05



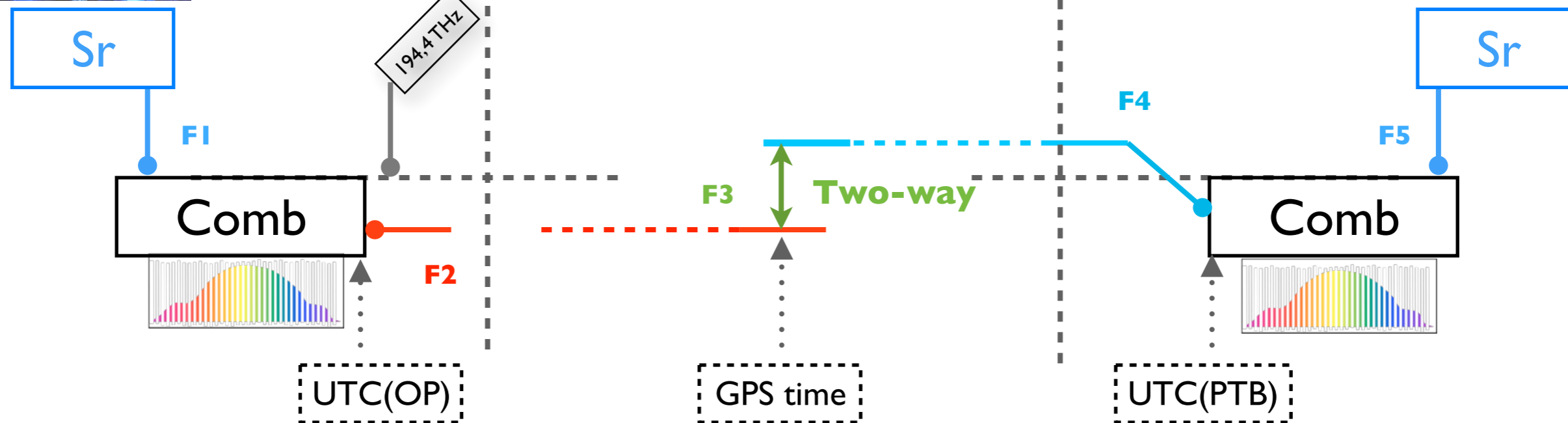
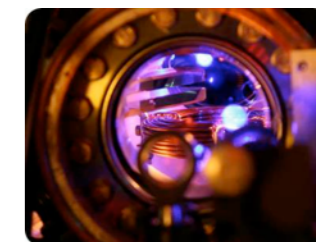
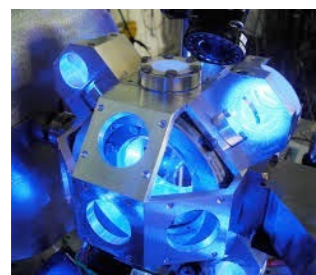
Optical clock comparisons

Paris

Strasbourg

Braunschweig

Counting the RF of the beat notes with the fs combs



Absolute frequency difference without SI-Hz

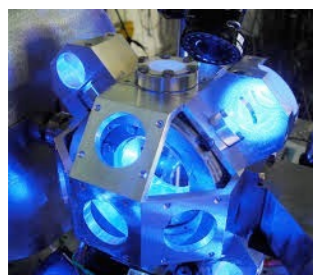
Optical clock comparisons

Paris

Villetaneuse

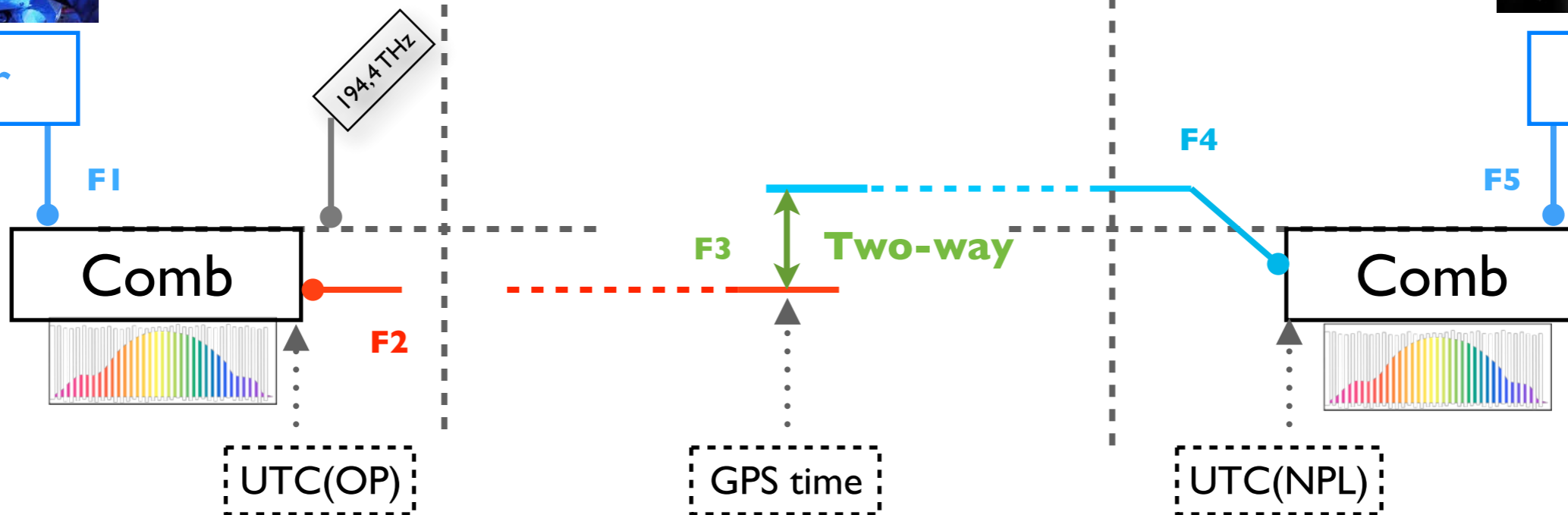
London

Counting the RF of the beat notes with the fs combs



Sr

Sr



Absolute frequency difference without SI-Hz

Clock comparisons within OFTEN

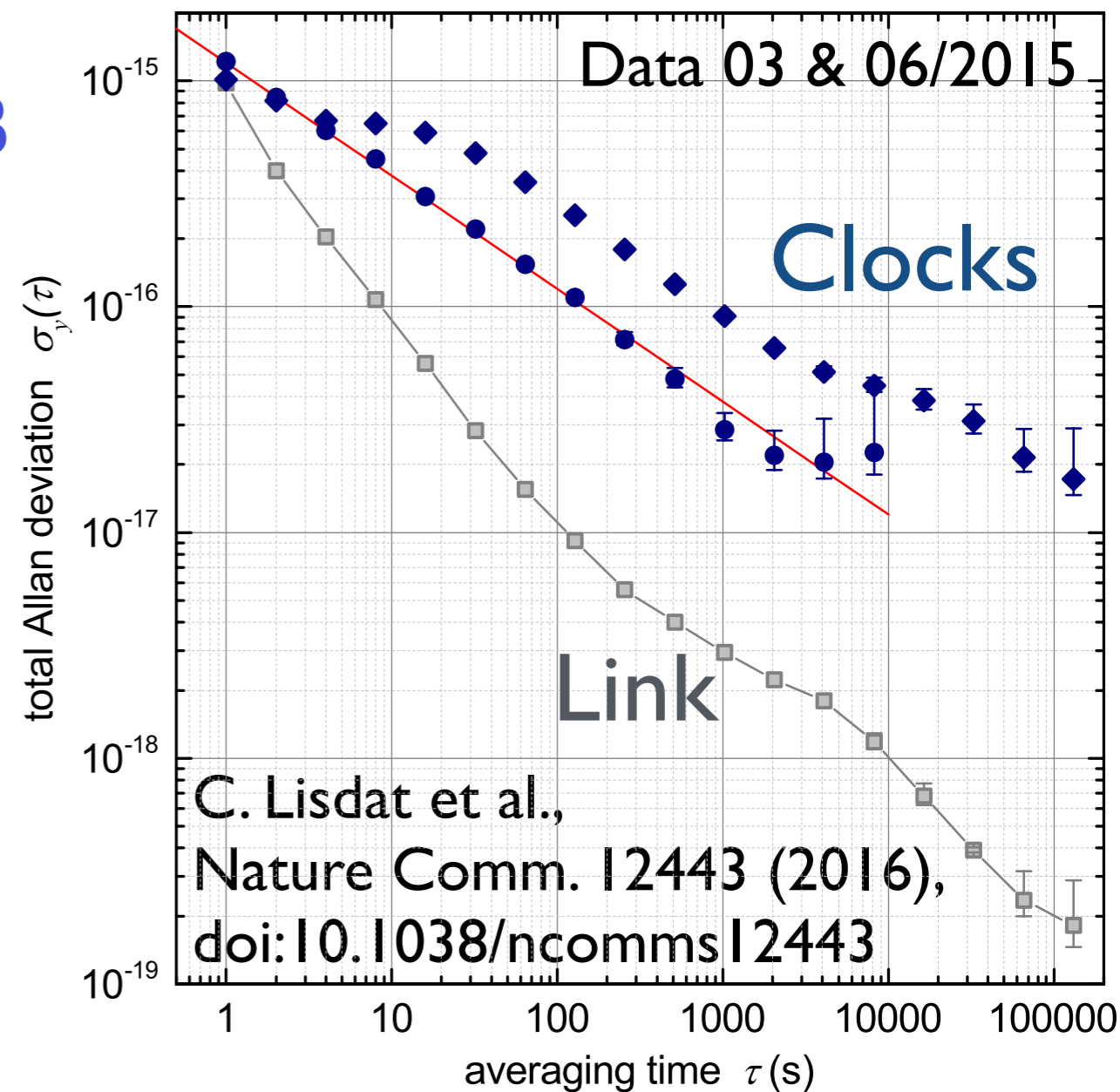
■ NPL-SYRTE + SYRTE-PTB

■ ~4 400 km

■ Sr, Yb+, Hg + Cs, Rb

■ 1 Transportable Sr (PTB)

■ 4 clock comparison campaigns 2016-2018



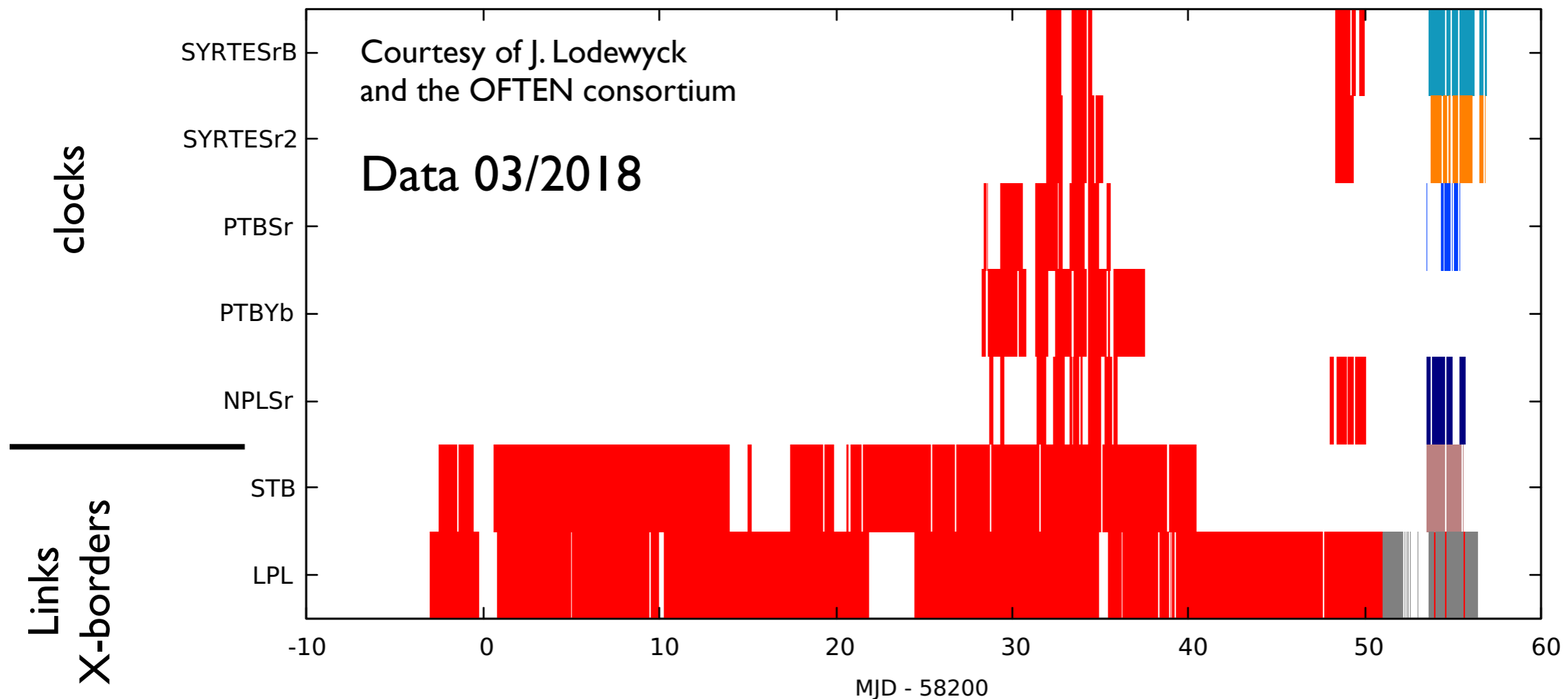
See also :

Test of Special Relativity Using a Fiber Network of Optical Clocks

Delva, P. et al.. Physical Review Letters 118, 221102 (2017).

Clock comparisons within OFTEN

Uptimes of 3-NMIs clock comparison

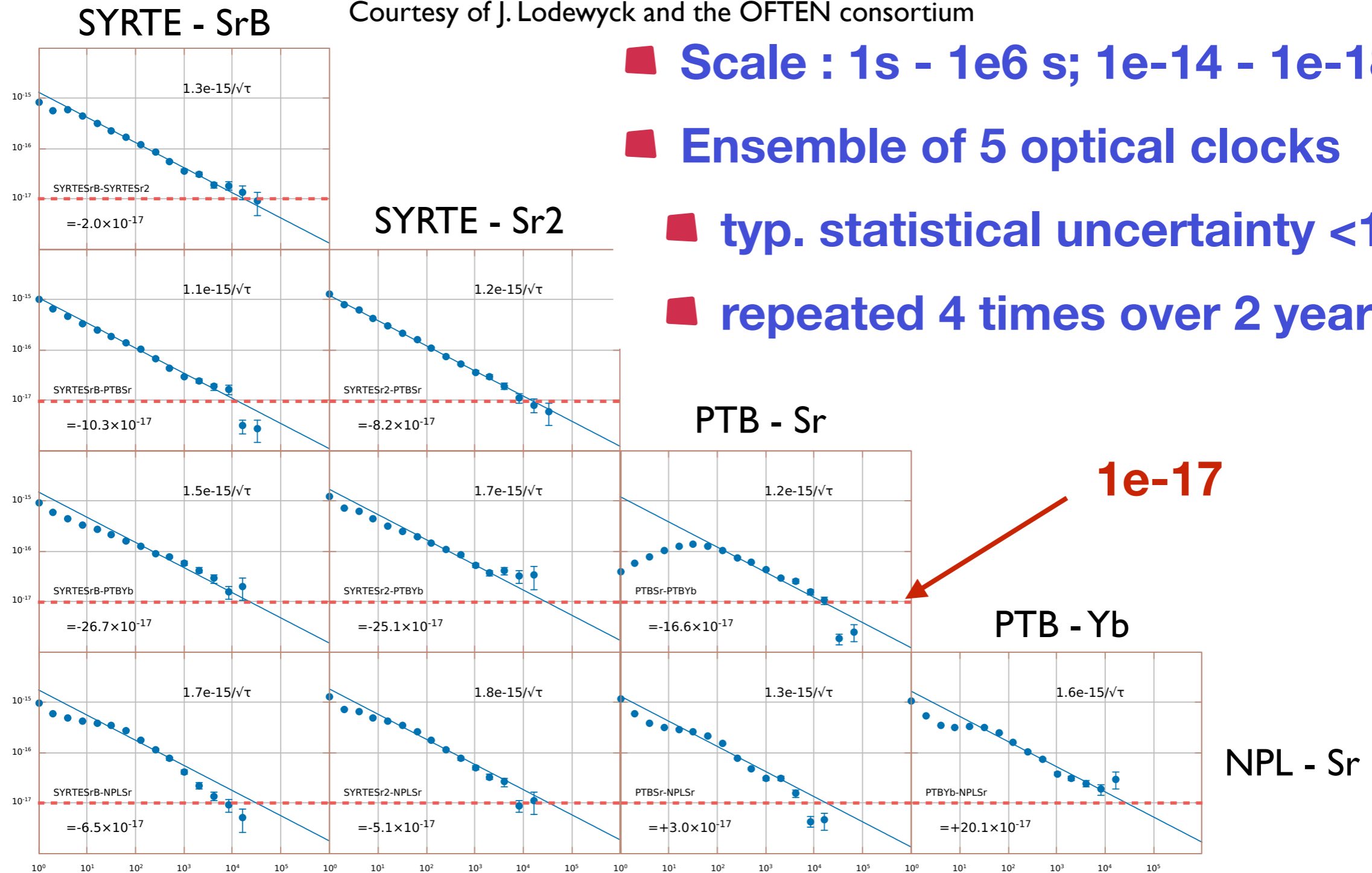


- Ensemble of independent OC : roadmap for SI-s redefinition
- Work on reliability, reproducibility
- Software and automated processing

Clock comparisons within OFTEN

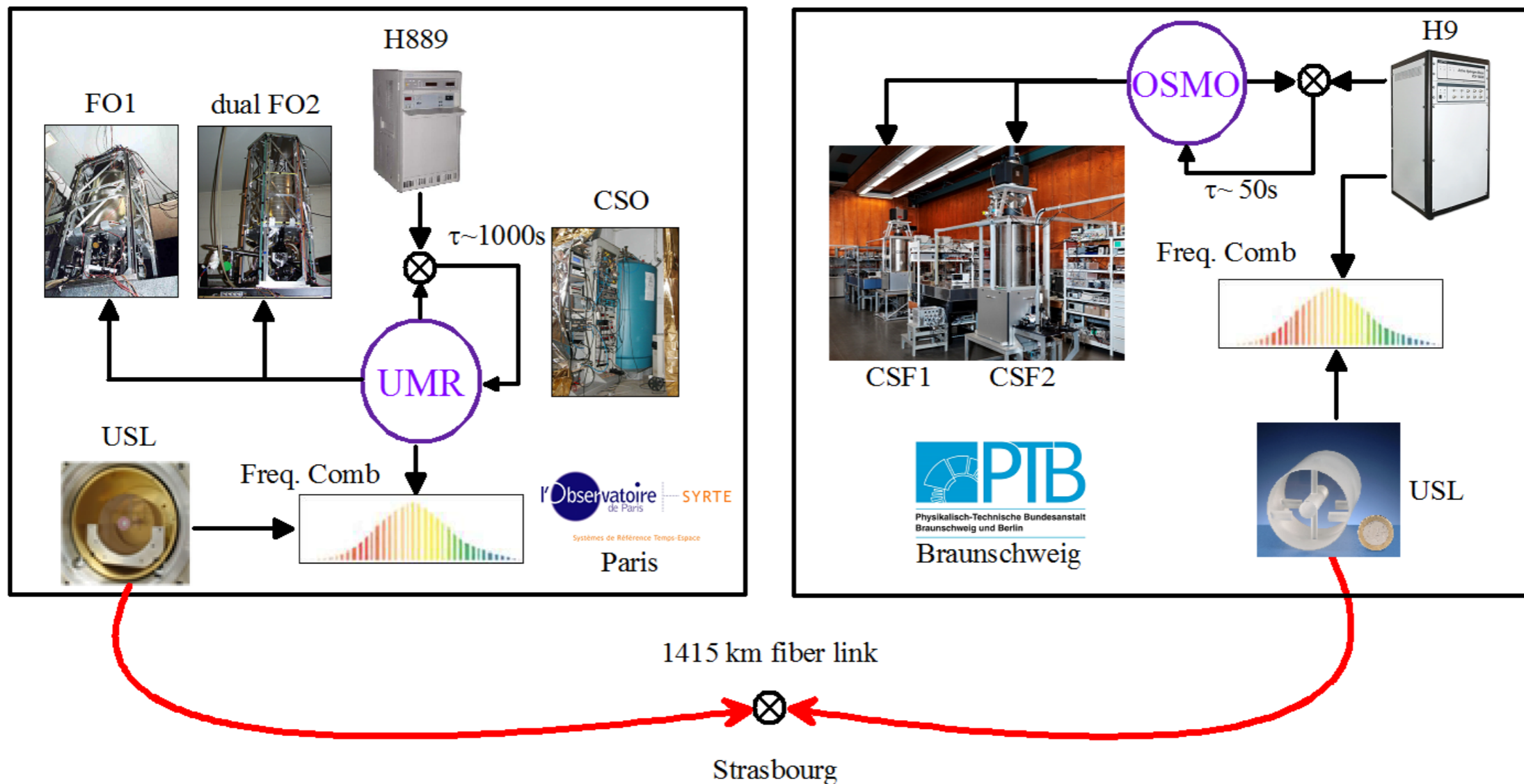
Courtesy of J. Lodewyck and the OFTEN consortium

- Scale : 1s - 1e6 s; 1e-14 - 1e-18
- Ensemble of 5 optical clocks
- typ. statistical uncertainty < 1e-17
- repeated 4 times over 2 years



Cs+Rb clocks comparison SYRTE-PTB

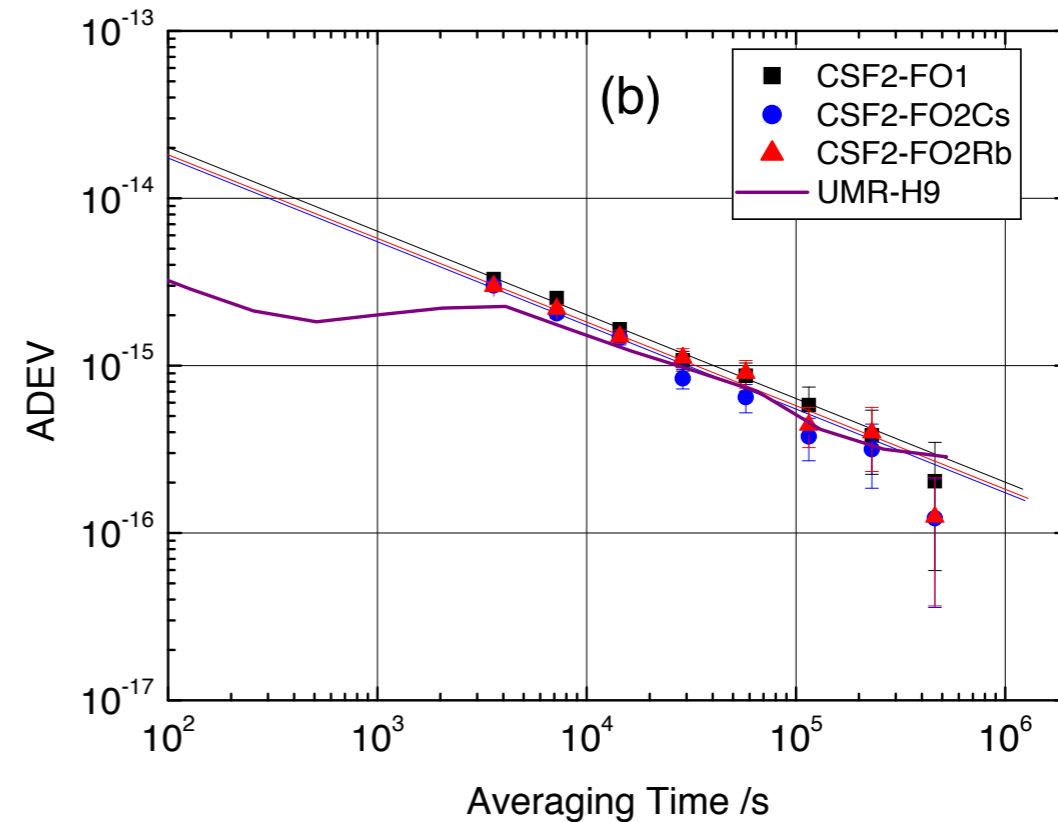
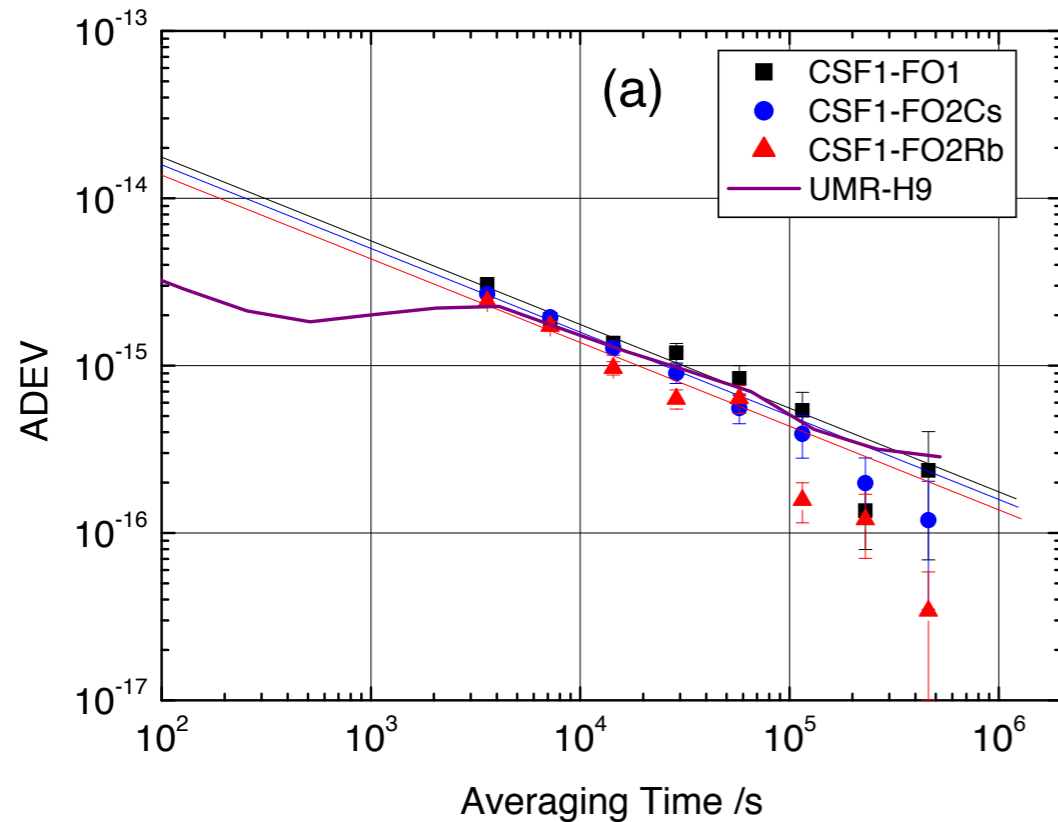
I. Guéna, J. et al. First international comparison of fountain primary frequency standards via a long distance optical fiber link. Metrologia 54, 348 (2017).



Cs+Rb clocks comparison SYRTE-PTB

Data 06/2015

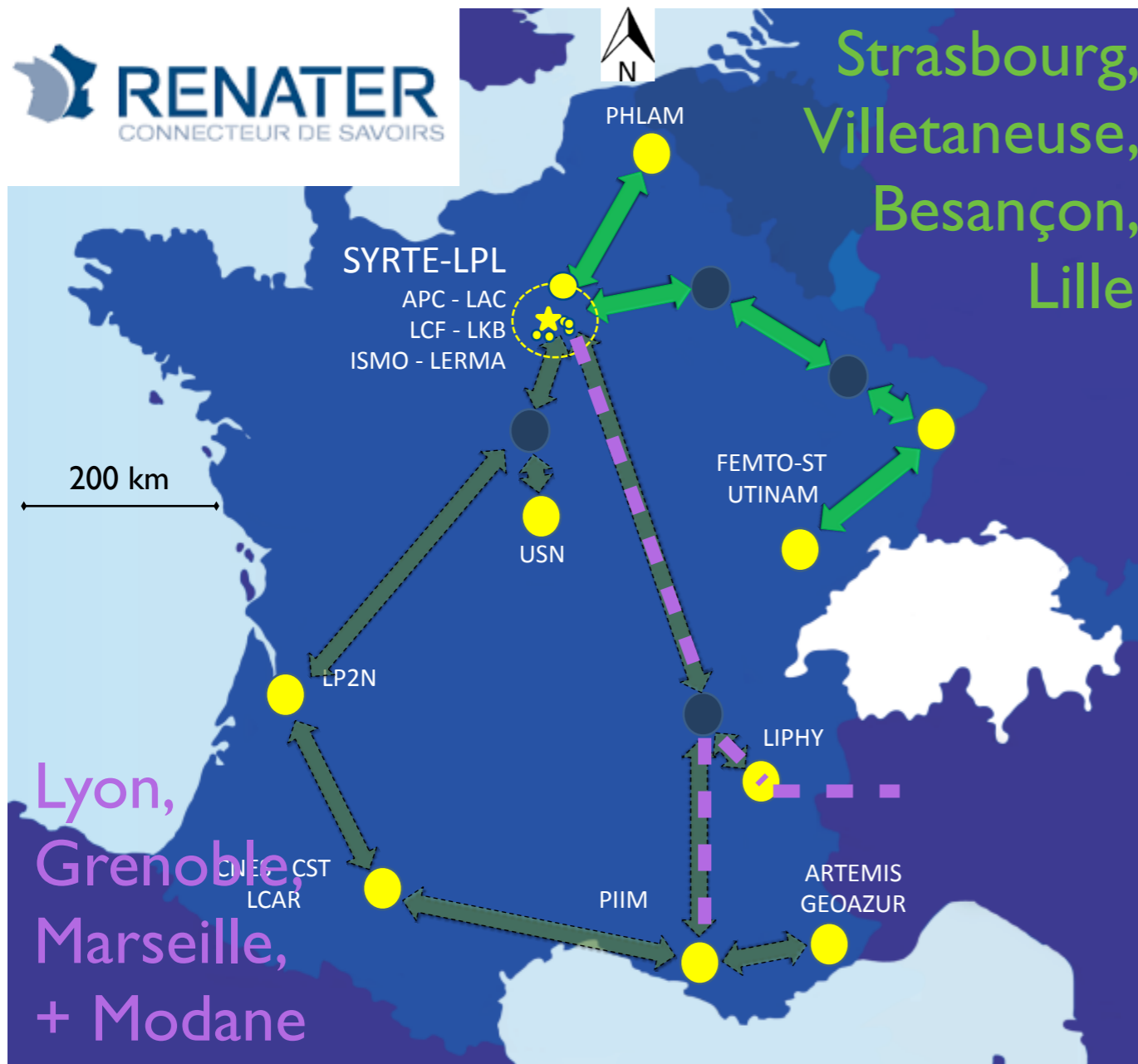
J. Guéna et al., Metrologia 54, 348 (2017).



- Improved relativistic gravitational redshift corrections
- Excellent agreement between fountains
- Compare Masers at PTB and SYRTE
 - Maser can be used as pivot oscillator with satellite means
- Accommodate with an arbitrary network architecture

REFIMEVE+ : a network in a nutshell

A Large Research Infrastructure



4000 km of fibers

Collaboration with RENATER

Signal in **parallel of data traffic**

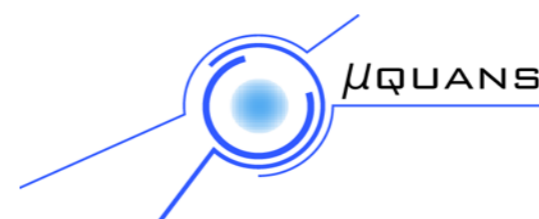
- **Sustainability**

- Dedicated Fiber \approx **200€ / km**
- Fiber sharing : \approx **cost / 10**
 - Supervision embedded in a **Network Operation Center**

- **20 partner laboratories as users**

- Network design : robustness, reliability, availability of the signal

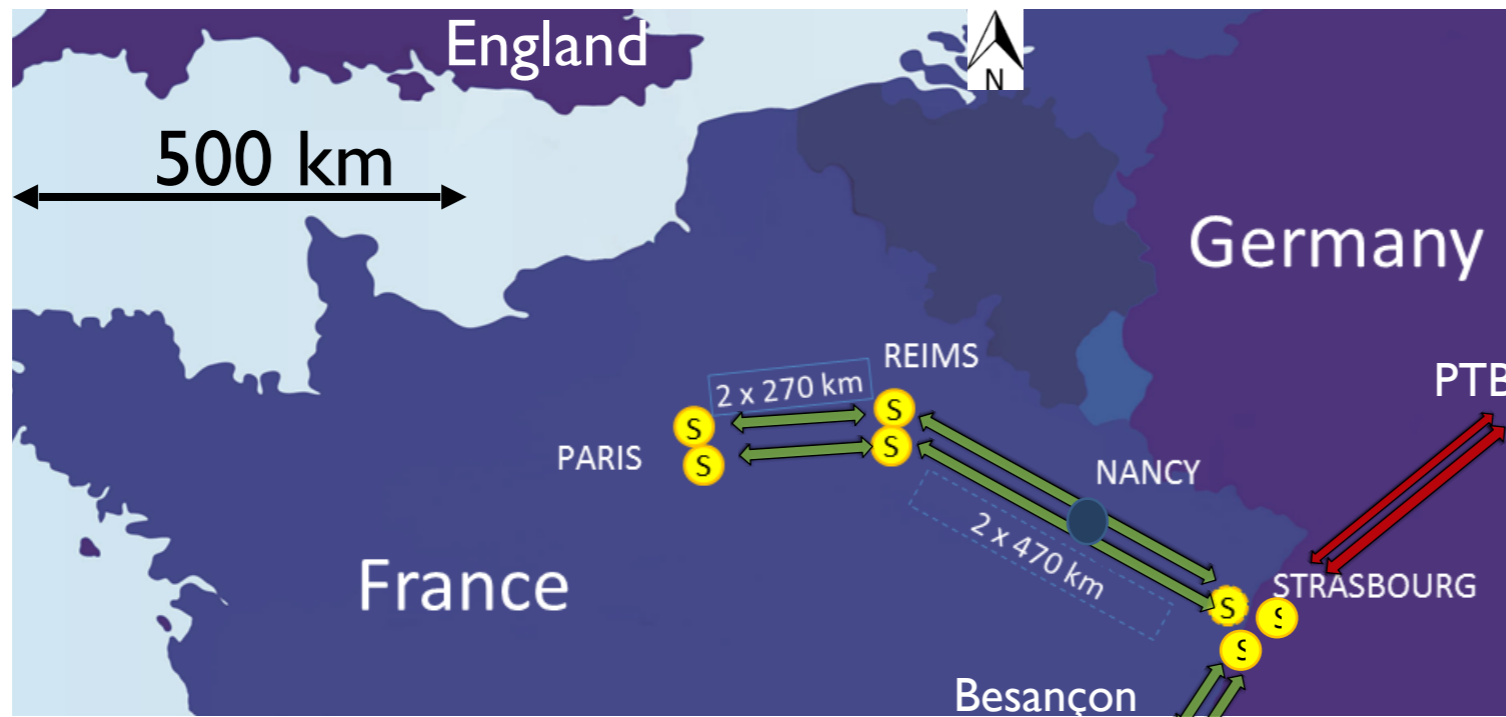
- **Knowledge transfer** : **TRL = 8**



Syrlinks

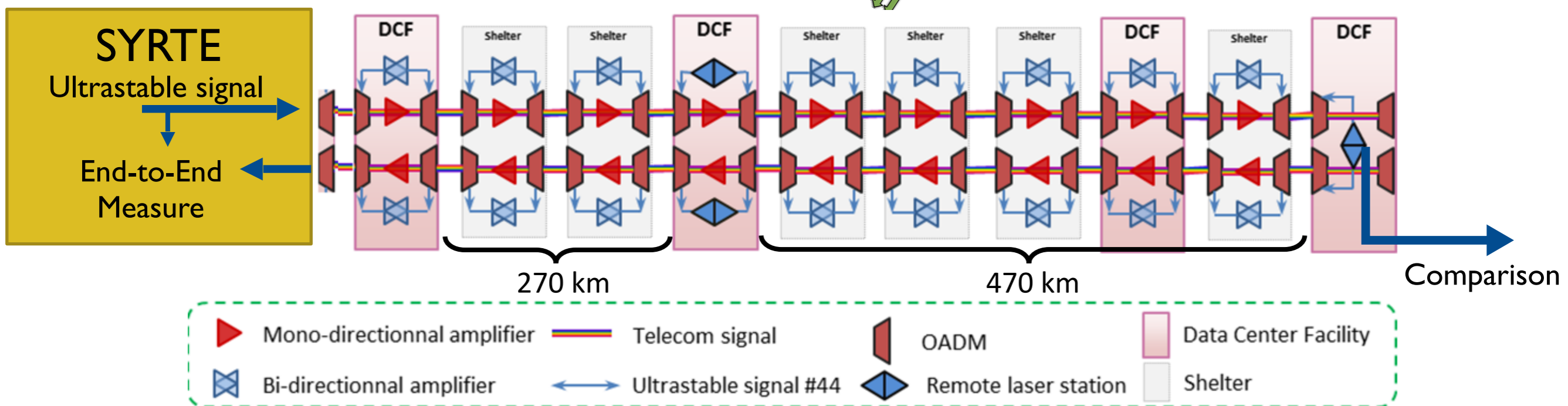
KEOPSYS
THE LIGHT TOUCH

Paris-Strasbourg-Paris link



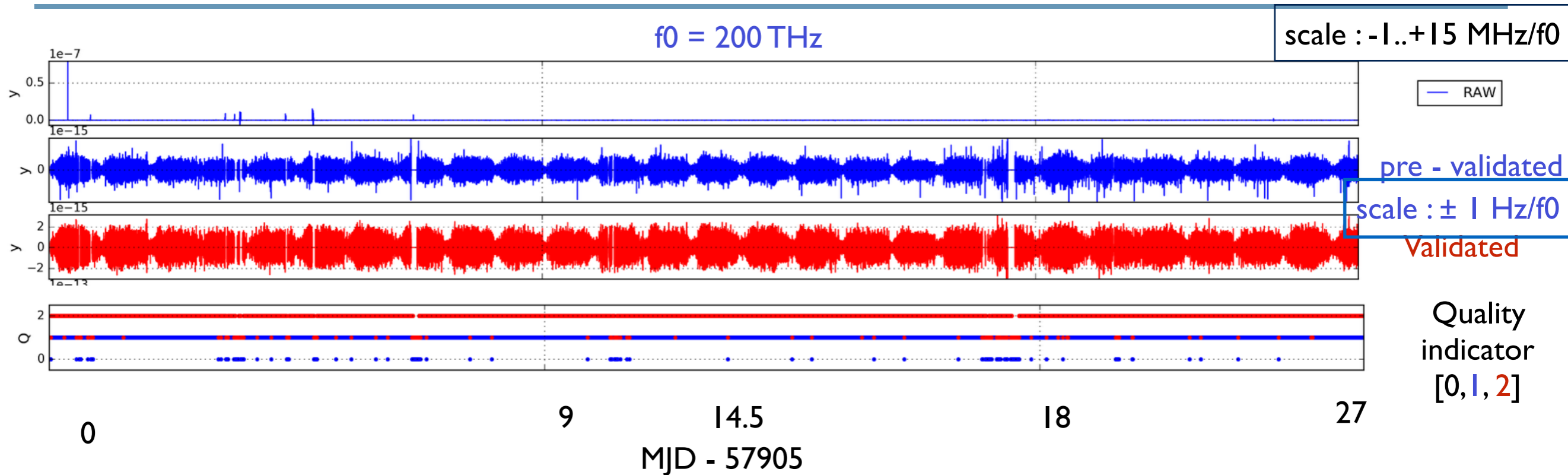
Link summary

- 2x205 dB attenuation
- Parallel data traffic
- 16 EDFA
- 32 OADM
- 5 Repeater laser stations
- ~ 1400 km



Chiodo, N. et al. Optics express 23, 33927–33937 (2015).

27 days during Clocks Comparison



Λ -counting

I-s gate time

up-time end-to-end @ Paris/ 27 days

Within 10 Hz filter : 99.30 %

Within validation procedure : 96.27 % (bad run removed)

Validated data for clock comparison : 96.20 %

(small outliers and cycle-slip removed)

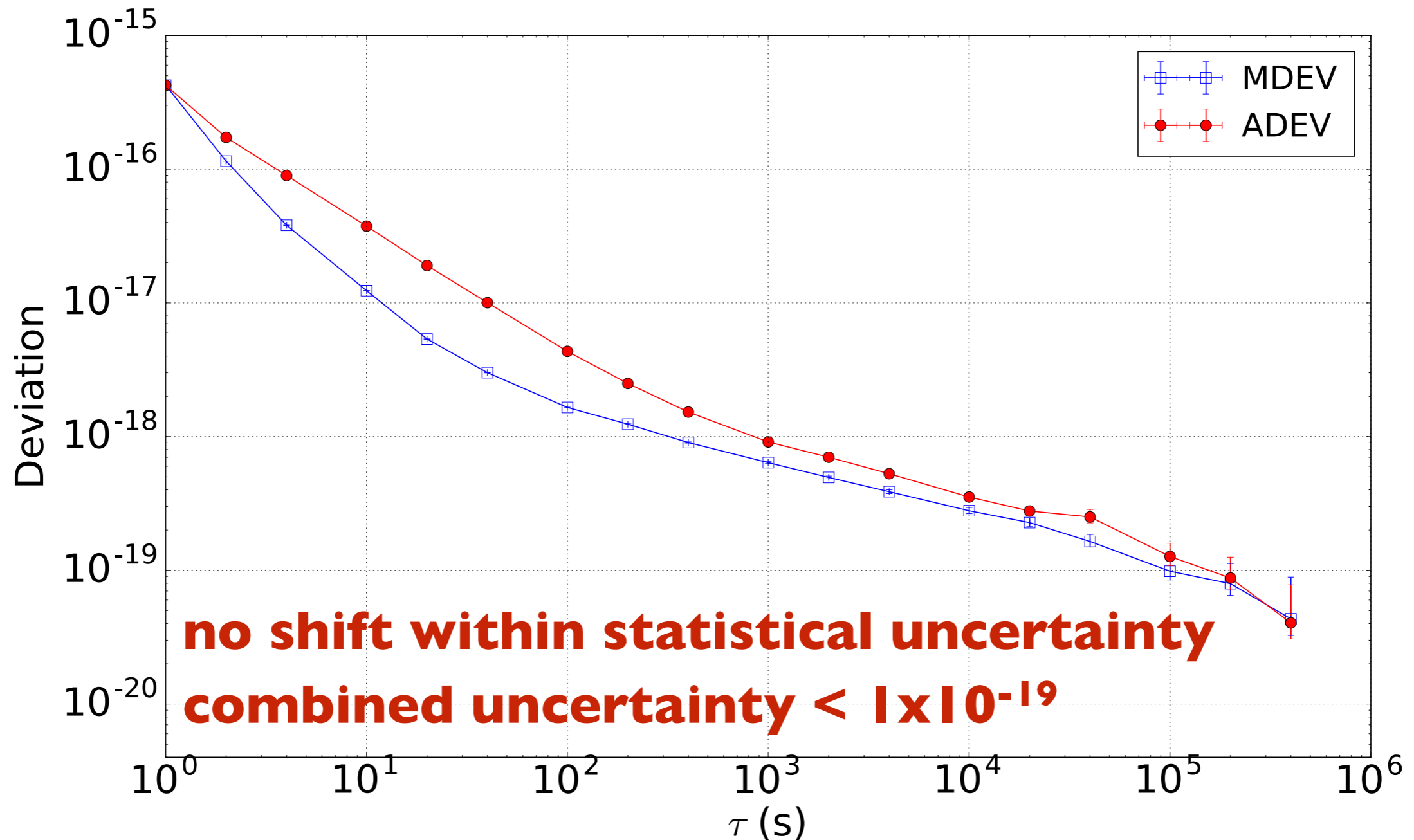
Xu, D. et al. IEEE TIM 1–6 (2019) doi:10.1109/TIM.2018.2886865.

validation procedure

Quantity tested	Looking for:
rolling mean	outliers
rolling standard	anomalous noise
'quality' stability	'rogue' points

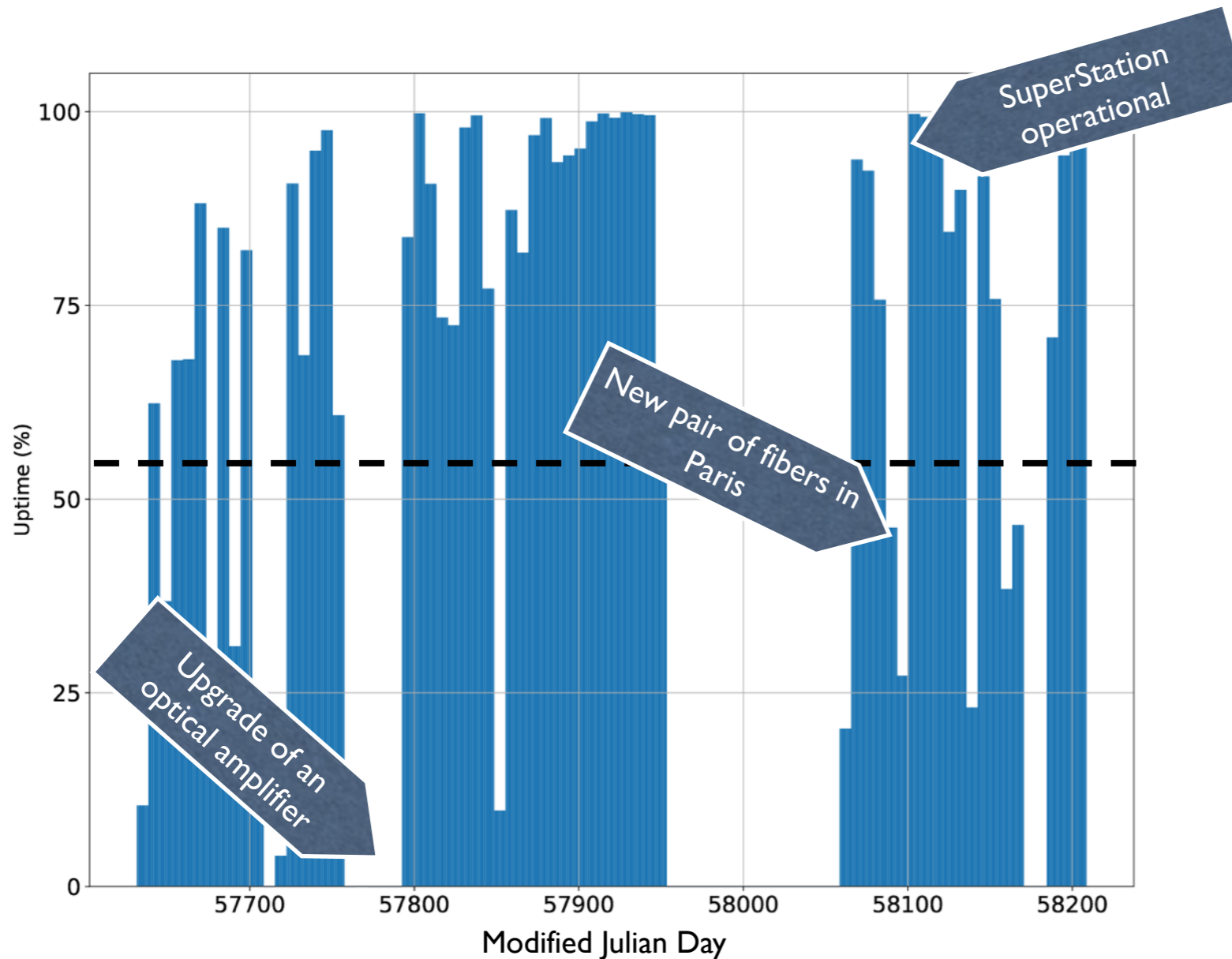
End-to-end stability (1400 km)

WholeSet_June_Lambda.txt



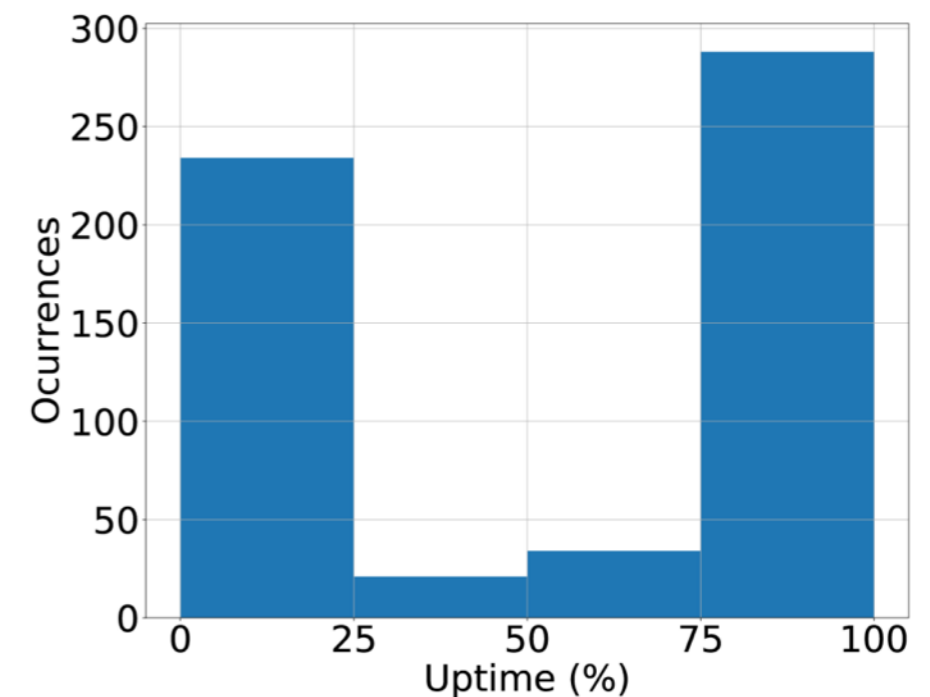
E. Cantin et al., EFTF'18

Operation of a link / 19 months



19 months = 576 days = 49'766'400s

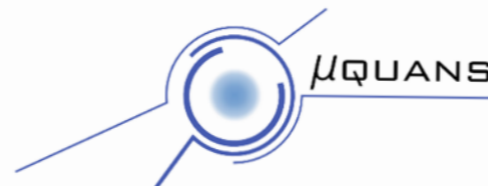
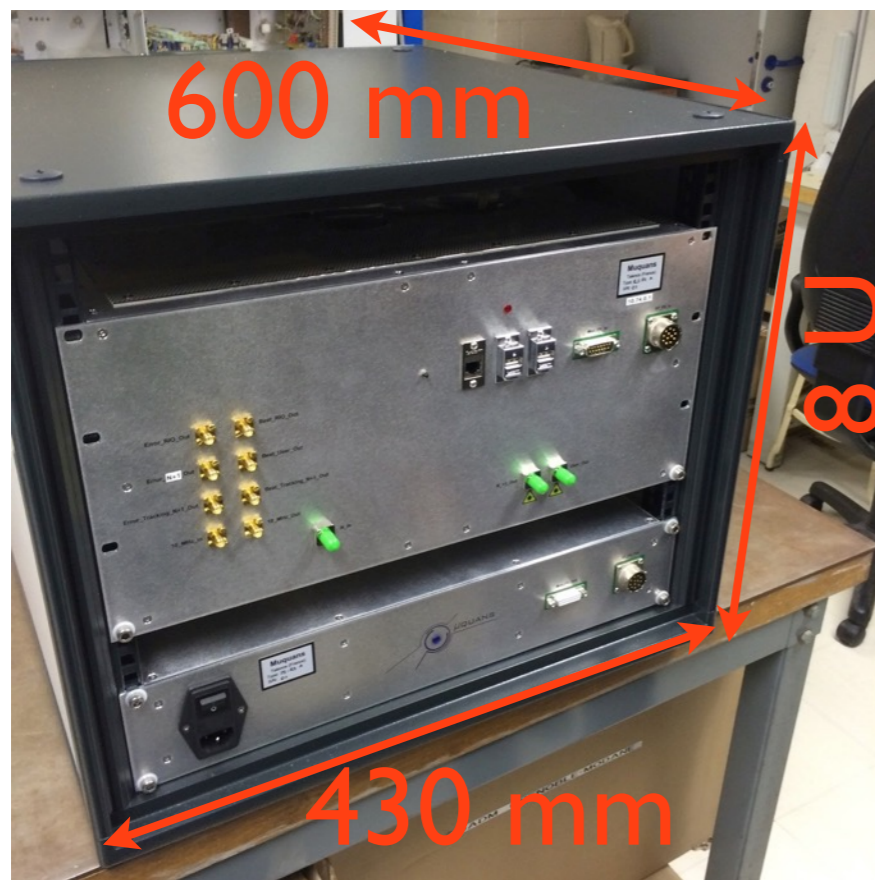
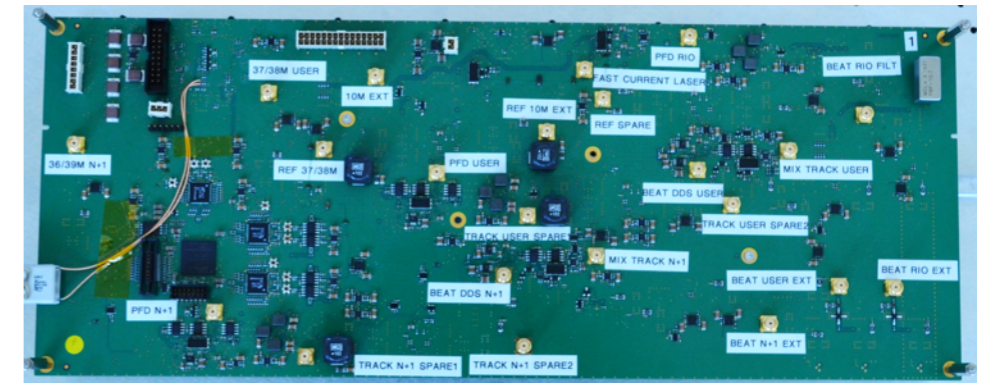
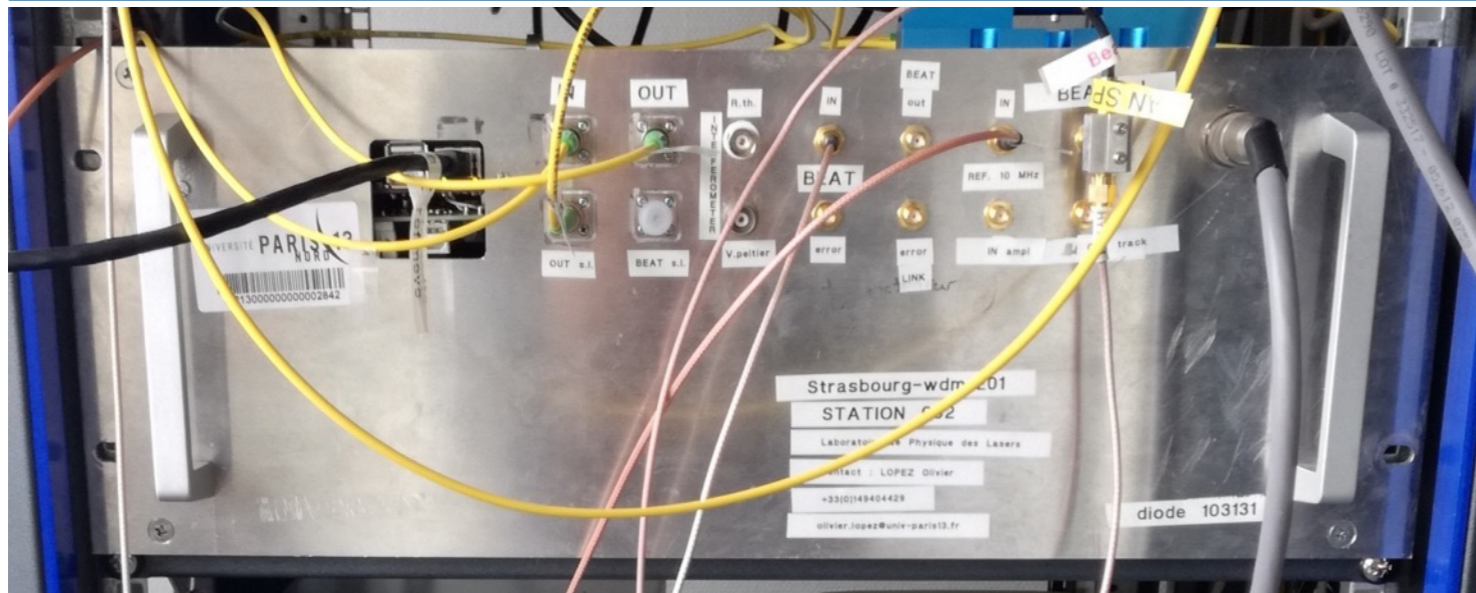
- Total Uptime = 54.5%
- Selection criterium
Frequency < 10 Hz = 5×10^{-14}
- All the system involved
(Ultra-stable Laser + Comb + Link)



link Paris-Strasbourg-Paris

E. Cantin et al., EFTF'18

Repeater laser station : pictures



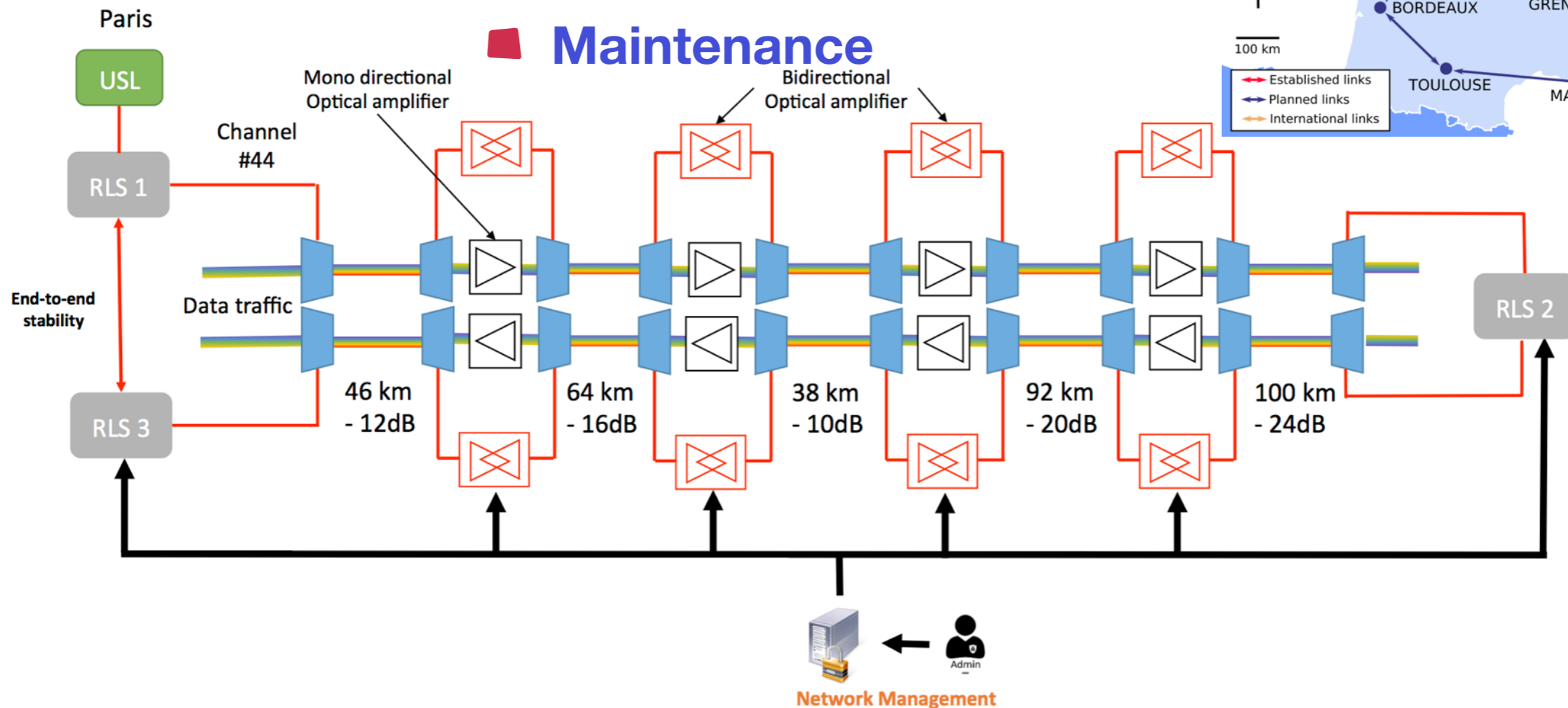
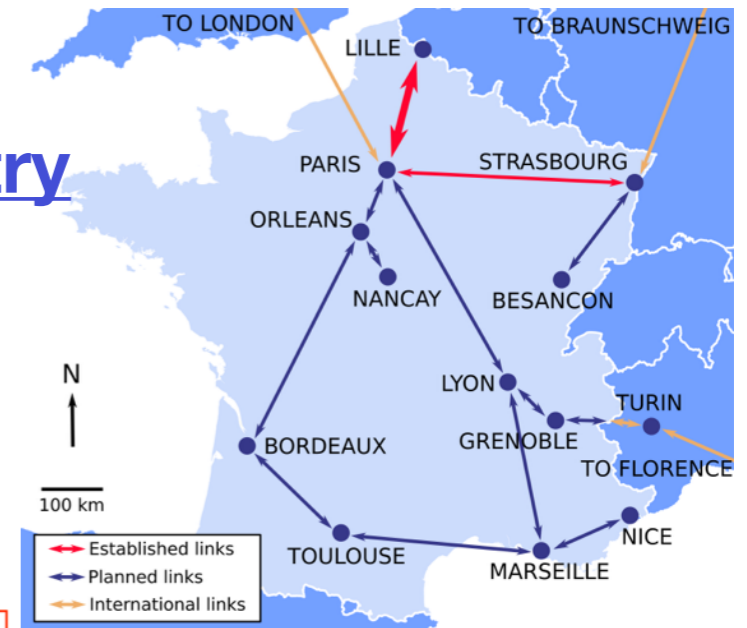
Industrial grade fiber links

F. Camargo et al., **57** (25), 2018, doi.org/10.1364/AO.57.007203

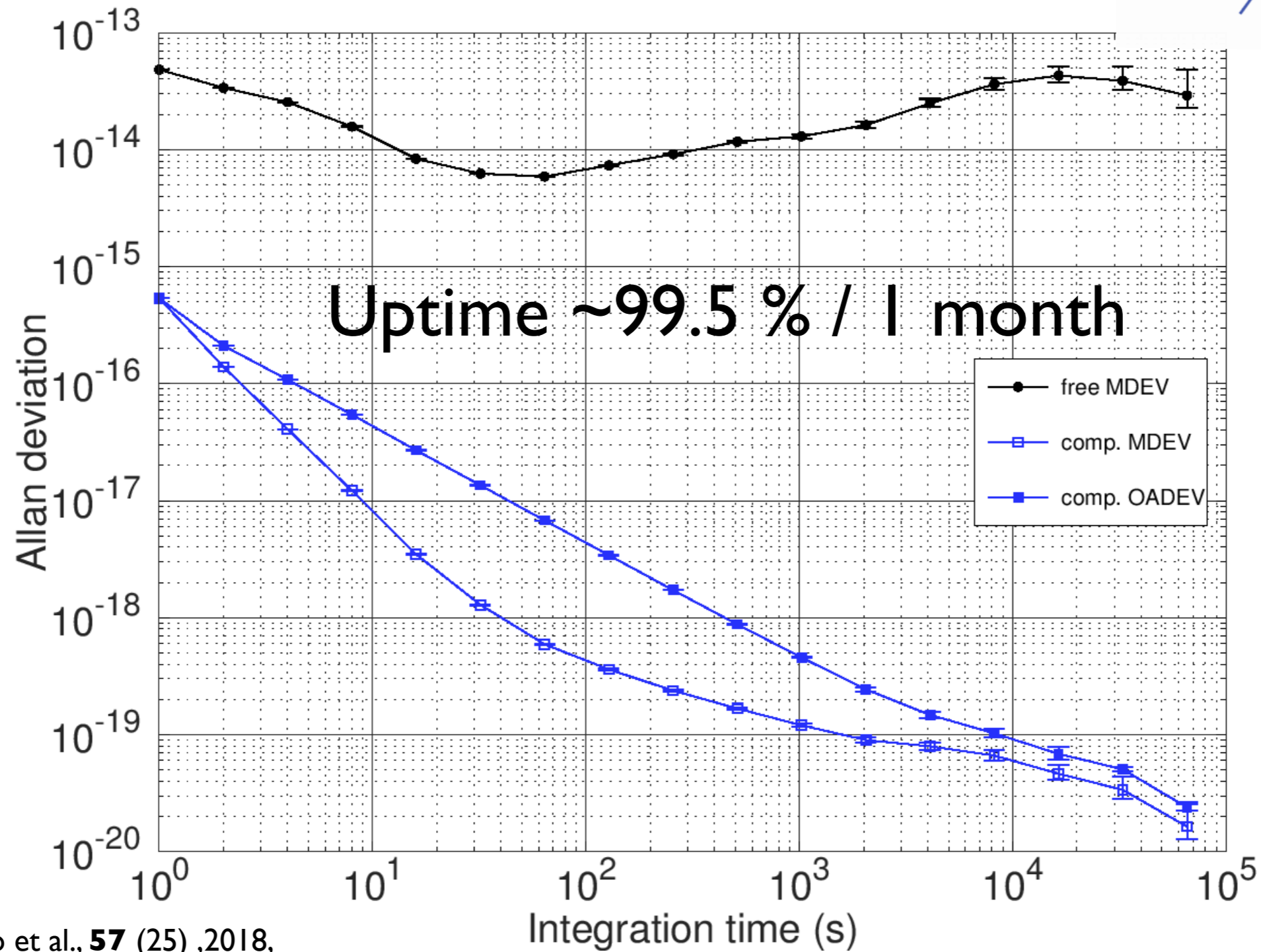
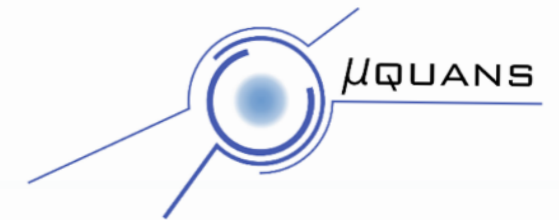


Knowledge transfer to industry

- **Equipment & System**
- **Deployment**
- **Maintenance**



Industrial grade fiber links



F. Camargo et al., **57** (25), 2018,
doi.org/10.1364/AO.57.007203

Repeater laser stations on the shelf

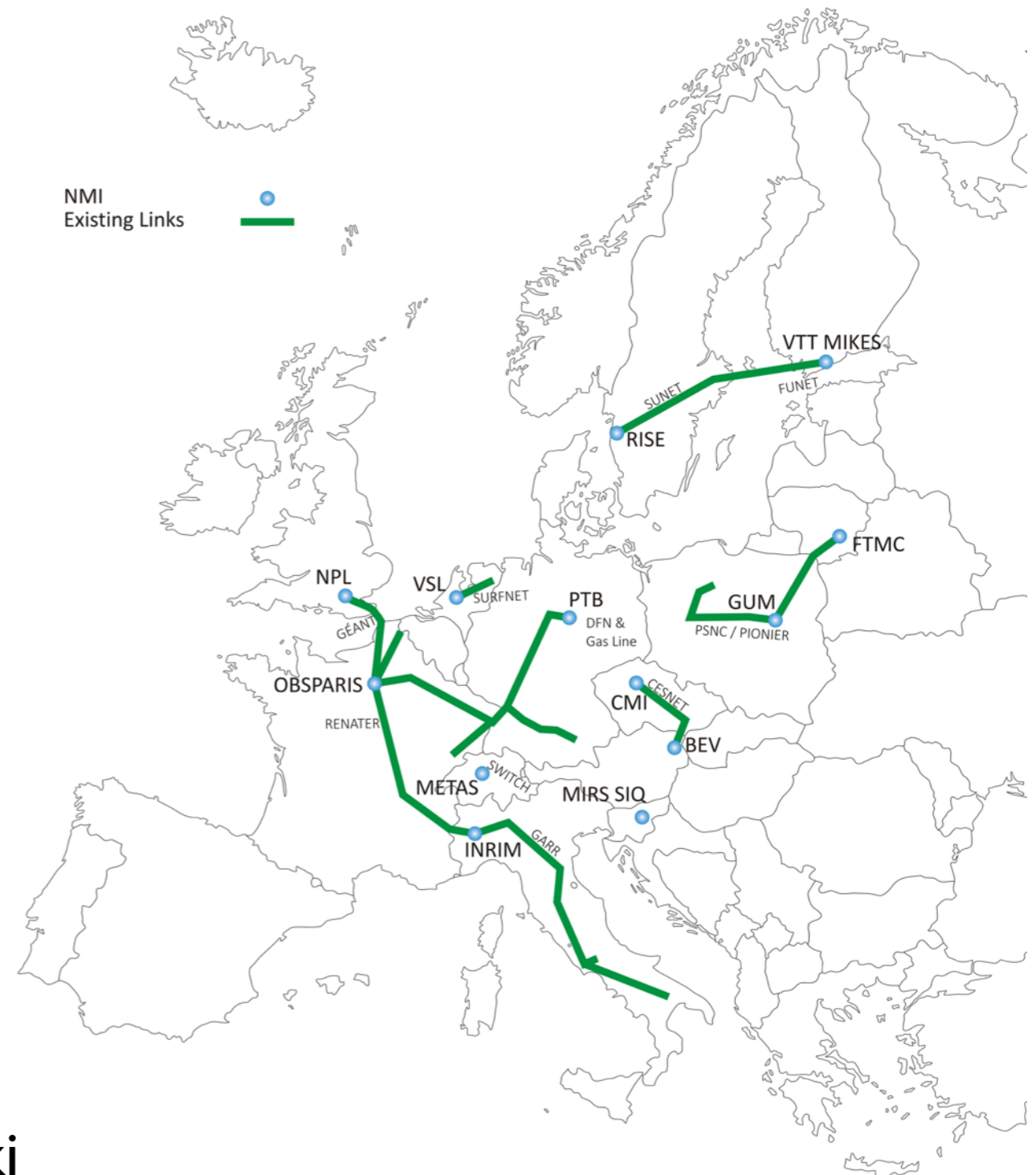


RLS stock at MuQuans before deployment

The European picture today

Next steps:

- Connection OPTIME-LIFT-REFIMEVE
- Connection to NORDUNET/(SURFNET)
- Amsterdam, Copenhaguen, Goteborg, Onsala...
- Connection to ROA (Spain)



CLONETS - Courtesy Wojbor Bogacki

Take away messages

■ CLONETS :

- Towards RI for a secured and long term access to the fiber
- Sustainable approach : partnership with NRENs, Spectral sharing / ITU#44

■ OFTEN :

- 4 comparisons, many improvements Clocks+Combs+Links
- Statistical uncertainty $< 4e-17$, for many of them $< 1e-17@2e4$ s

■ REFIMEVE

- **19 months** of operation with 54.5% uptime
- **>90% uptime** for several months, up to 99.5% over 1 month
- **Integration into RENATER network.**

Thank you for your attention !

>50 people

PTB

Sebastian Koke
Gesine Grosche
Erik Benkler
Harald Schnatz

NPL

Jochen Kronjaeger
Riley Ilieva

INRIM

Davide Calonico
Cecilia Clivati

LPL

Olivier Lopez
Anne Amy Klein

SYRTE

Rodolphe Le Targat
Jérôme Lodewyck
Frédéric Meynadier
Philip Tuckey

MuQuans

Fabiola Guillou-Camargo
Vincent Menoret
Bruno Desruelle

The young (linkers):
Alexander Kuhl
Thomas Waterholter

Etienne Cantin

Dan Xu

Eva Bookjans

Florian Frank

Mads Tonnes

Anna Tampellini

In memoriam Jocelyne Guéna



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<http://www.lkb.upmc.fr/>