REFIMEVE: Etat d'avancement et quelques cas d'applications

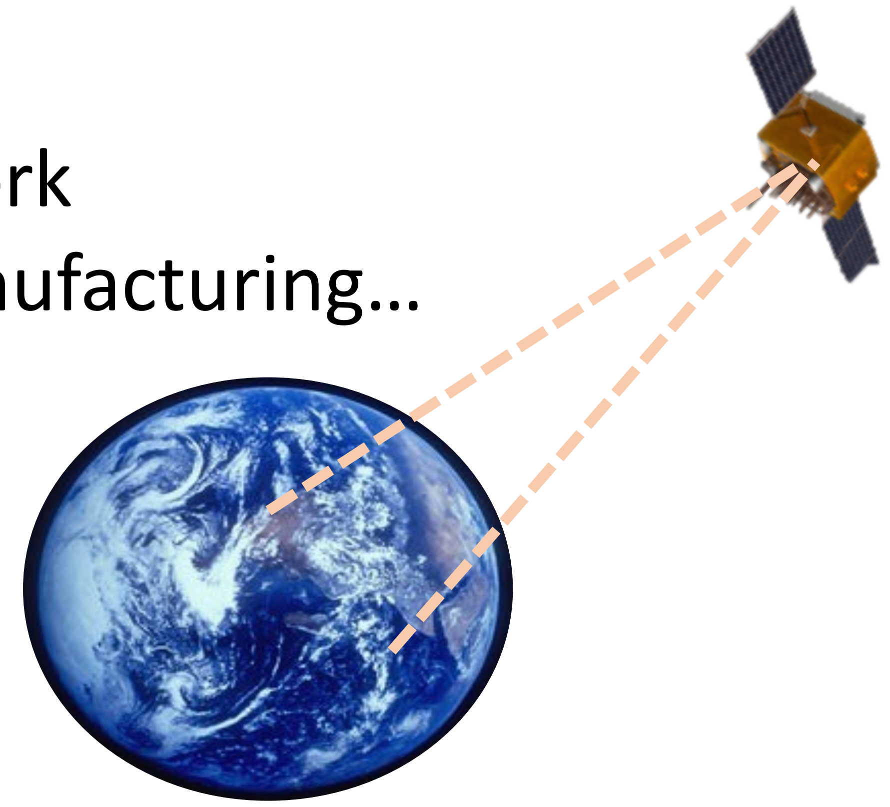
Paul-Eric Pottie, Etienne Cantin, Mads Tønnes, Maxime Mazouth-Laurol, Benjamin Pointard, Rodolphe Le Targat, Olivier Lopez, Christian Chardonnet, Anne Amy-Klein

Outline

- Motivations
- Introduction to fiber links
- From fiber links to fiber networks
  - update of the REFIMEVE fiber network
- Optical clocks network
- On-going projects and outlook

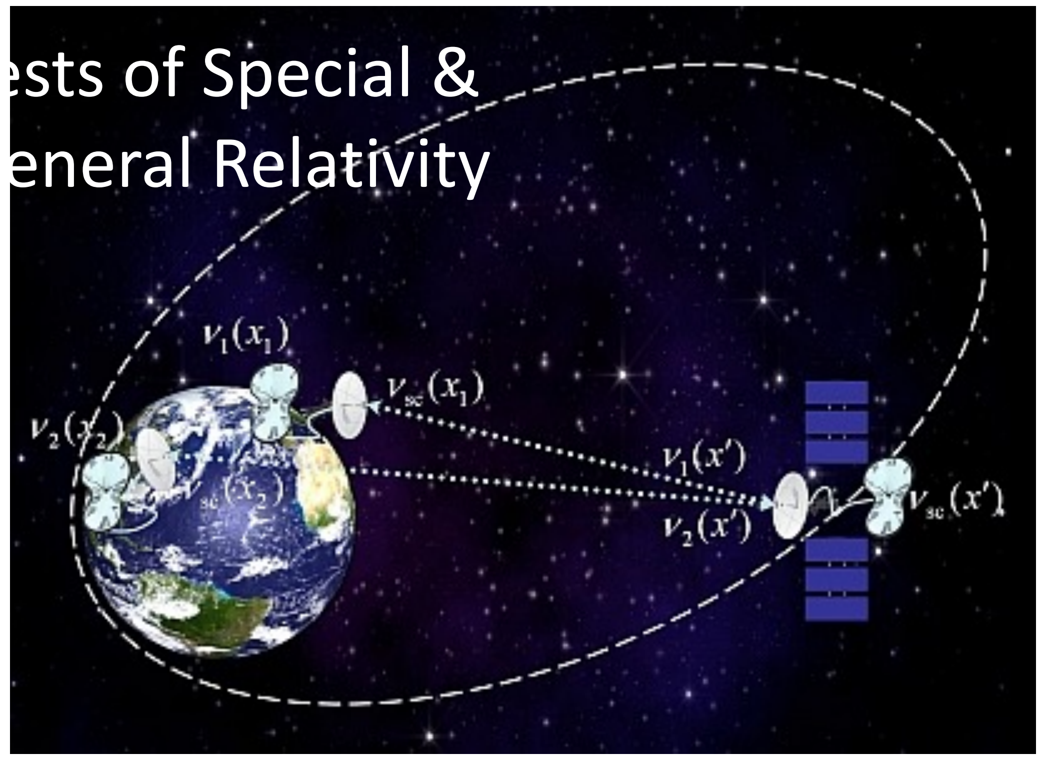
Motivations for time and frequency dissemination

Dissemination of Time and Frequency from standards (atomic clocks, timescales)
for industry / society : Telecom and network synchronisation, smart grids, finance, manufacturing…

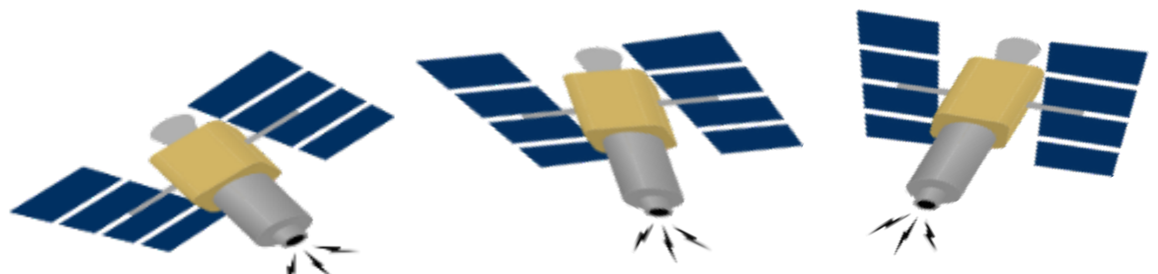


Timing+syntonisation:
ms-ns, 1e-11-1e-15
Traceability

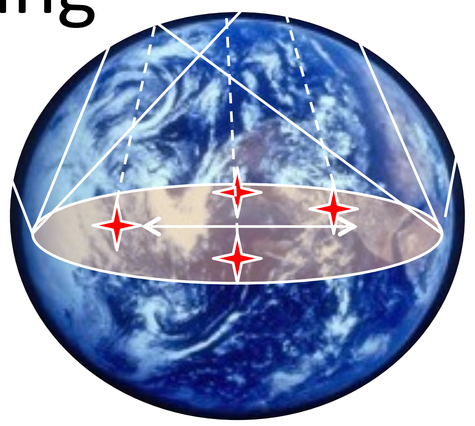
Fundamental Scientific Applications
Definition & Variations in fundamental constants



Sensing/Defense:
Positioning, Navigation and Timing

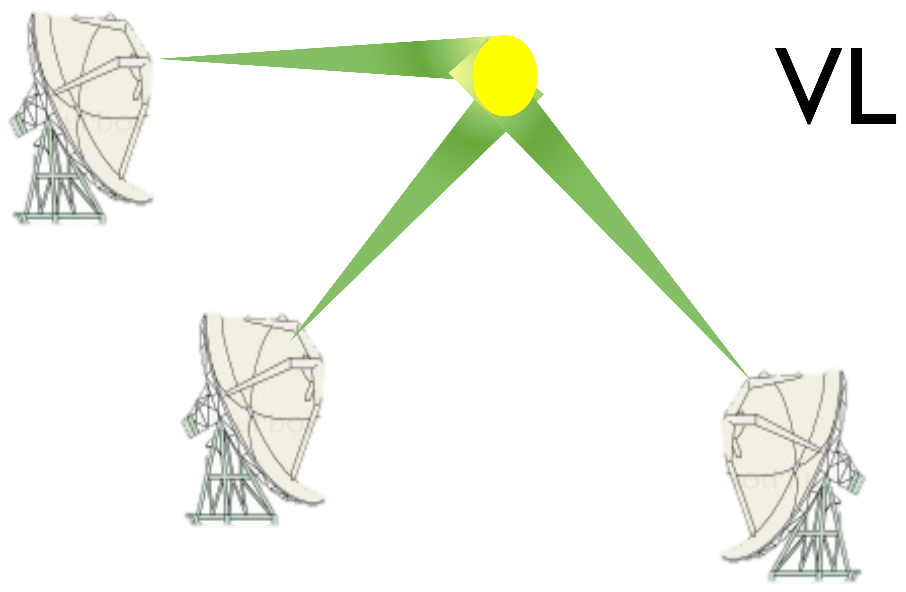


synthetic aperture
global imaging



Timing+syntonisation:
ns, 1e-13-1e-16
Resiliency

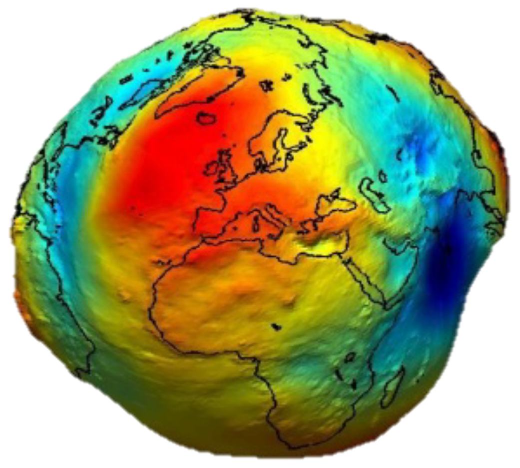
Large instruments, array of detectors
astronomy, astro particle, geoscience
multi-messenger astronomy

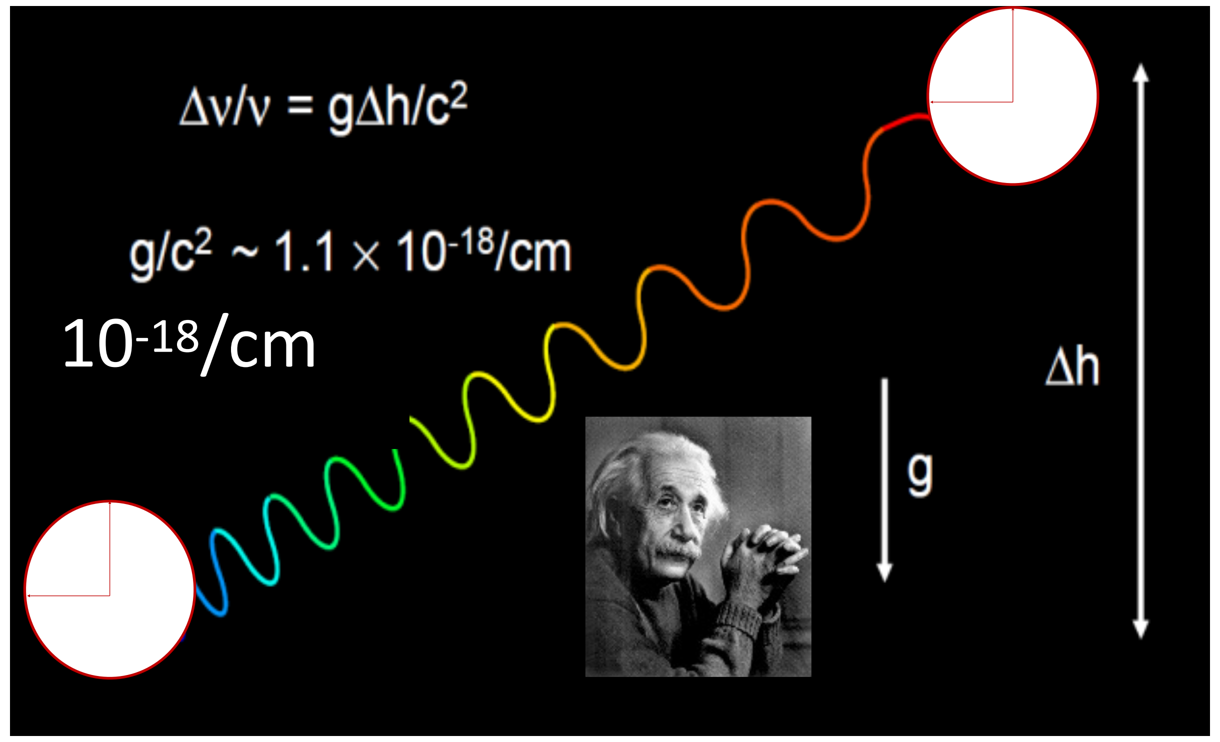


VLBI…

Timing+syntonisation:
ns-ps, 1e-16
Comparisons

Earth Science and climate change
geodesy, chronometric leveling





Timing+syntonistion:
ps, 1e-18 and better!
Comparisons

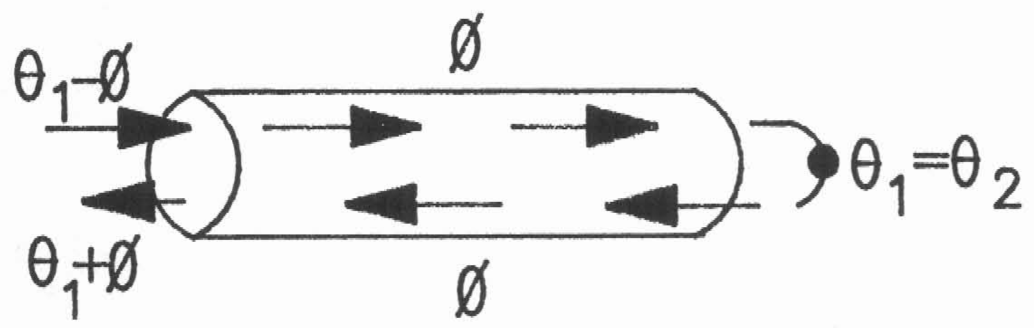
Illustrations: courtesy N . Newbury, NIST

Fiber links : seminal works (Primas et al., 1988)

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

Lori E. Primas
George F. Lutes
Richard L. Sydnor
Jet Propulsion Laboratory
Pasadena, California 91109

Passive stabilization of fiber optic transmission links, such as burial of the cable, is not sufficient for maintaining stabilities in the range required for many applications. When stabilities higher than a part in 10^{15} are required the link must be actively stabilized.



$$\theta_2 = (\theta_1 - \emptyset) + \frac{(\theta_1 + \emptyset) - (\theta_1 - \emptyset)}{2} = \theta_1$$

FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

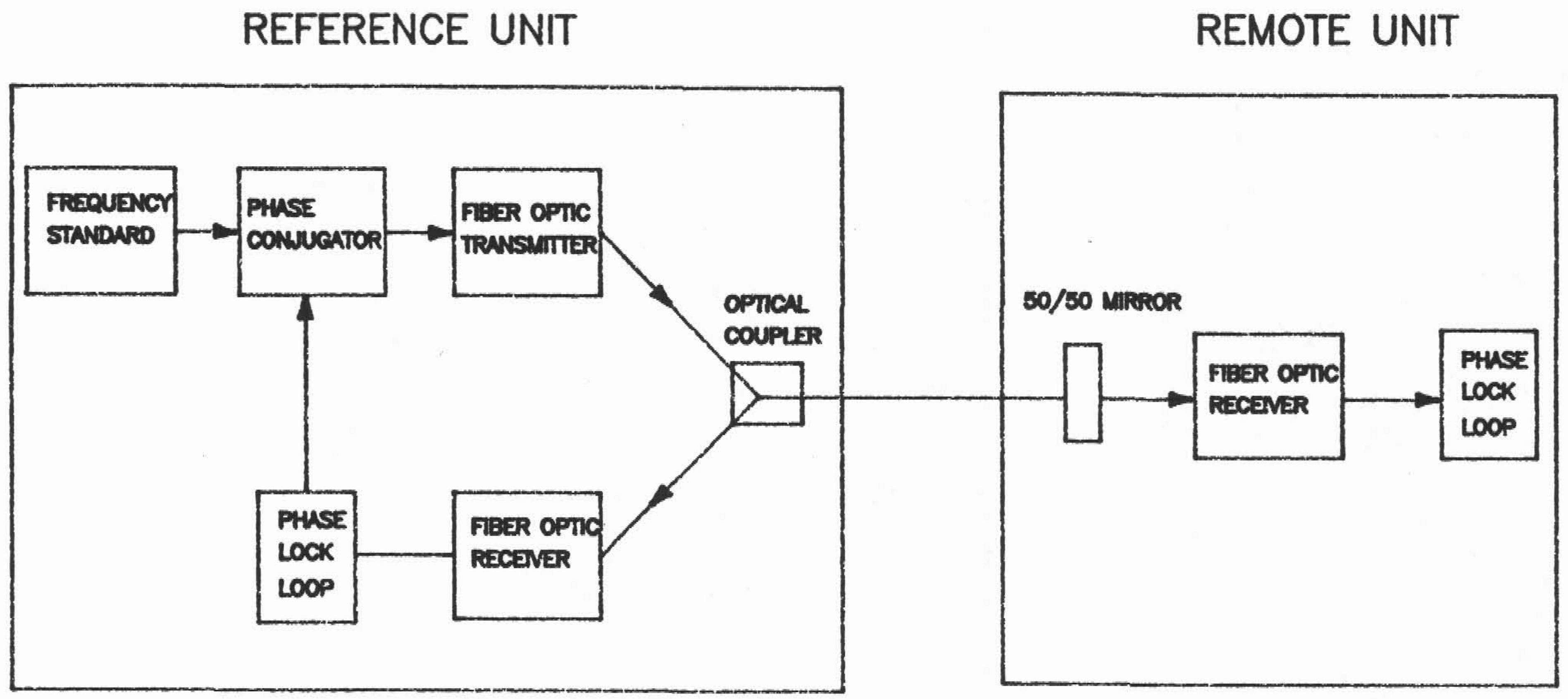


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988 (1988)

Fiber links : seminal works (Primas et al., 1988)

STABILIZED FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM*

Lori E. Primas

- Active noise compensation after one round-trip
- Strong hypothesis : noise forth and back are the same
- 2 ends at the same place (for link stability measurements)
- RF, hF or optical signals

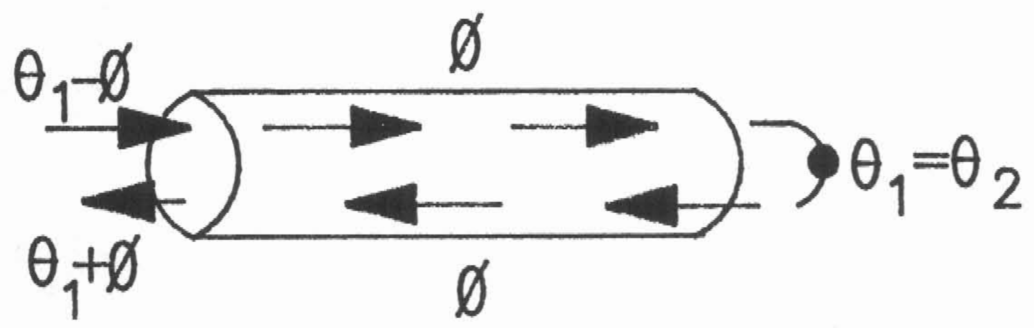


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FIGURE 1. PHASE CONJUGATION AT INPUT TO OPTICAL FIBER

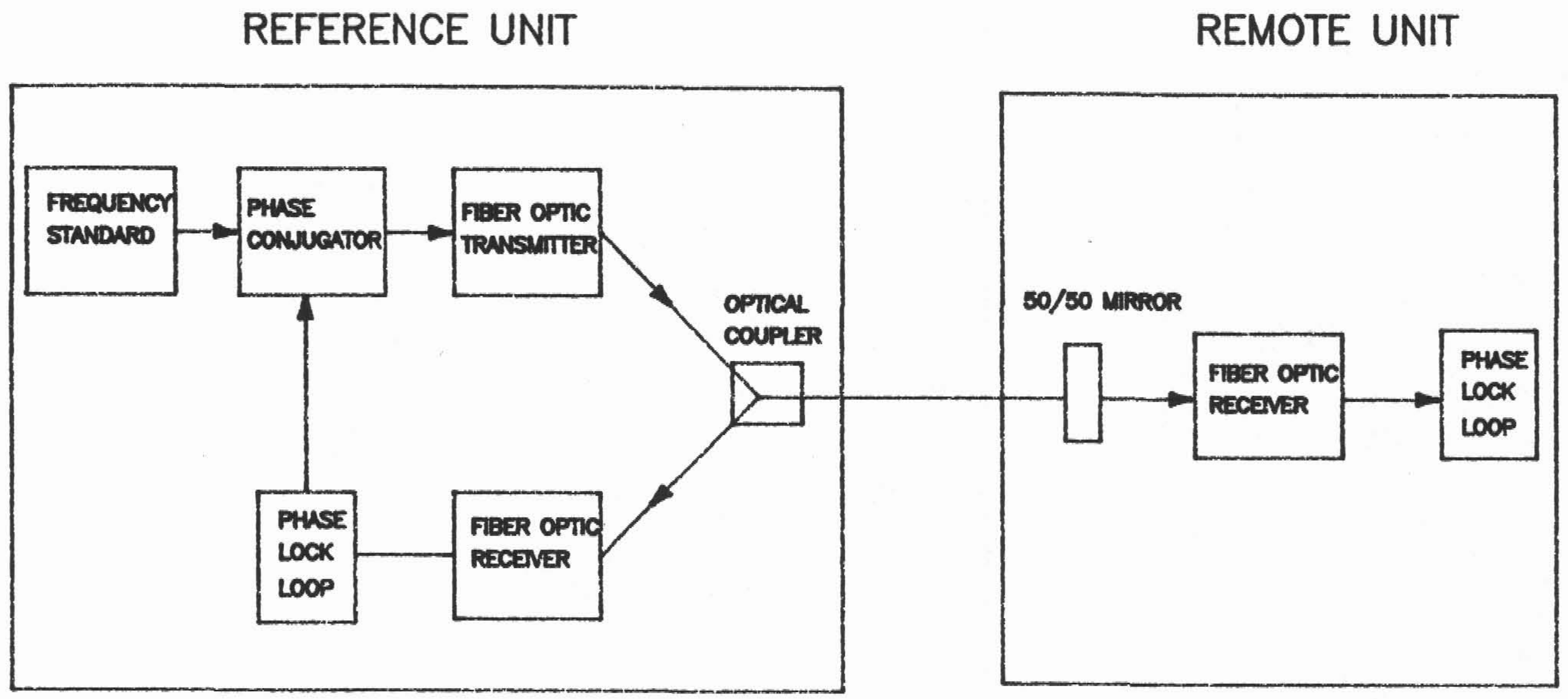
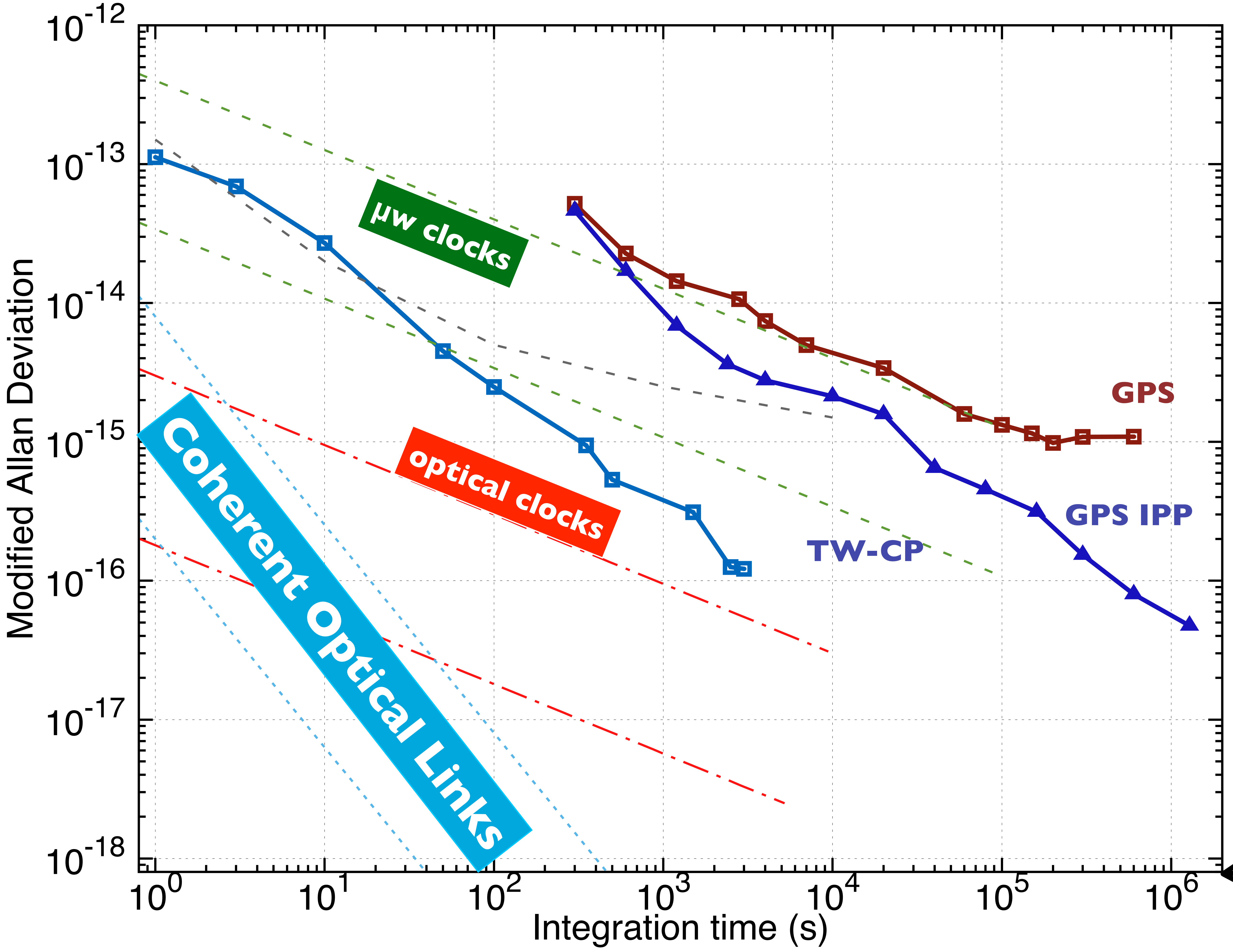


FIGURE 3. FIBER OPTIC FREQUENCY DISTRIBUTION SYSTEM

L. E. Primas *et al.*, Proc. 20th PTTI, Vienna, VA, 29 Nov - 1 Dec 1988 (1988)

Coherent optical fiber links



Fiber links: pro and contra

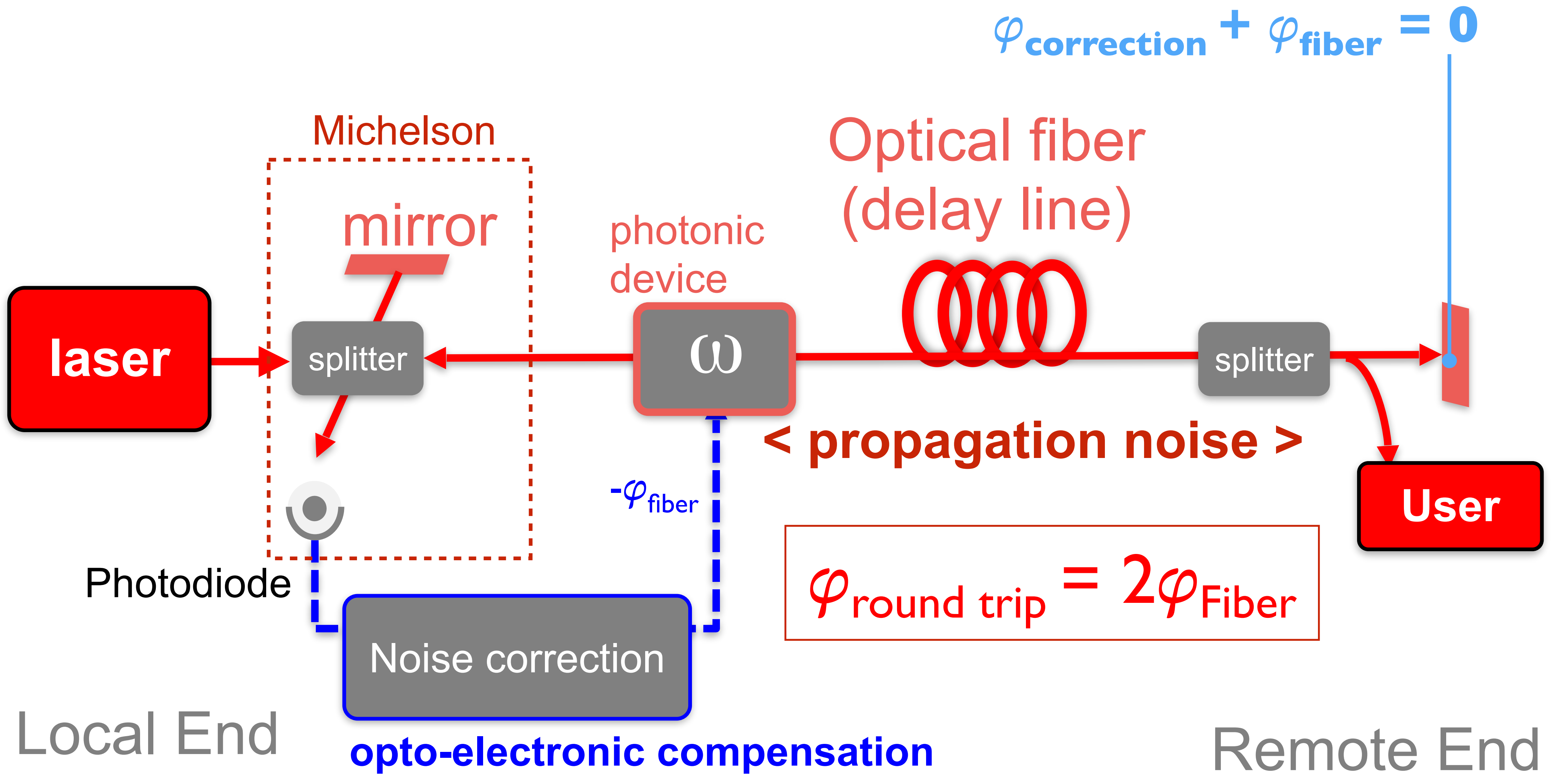
- Guided propagation:
  - Low noise
  - No interferences
  - Low optical losses
  - Excellent reciprocity
- Major drawback
  - Point to point

Goal for SI-s re-definition

Coherent optical links are the only technique to date to enable optical clocks comparisons at continental scale

see review: O. Lopez *et al.*, CRAS, 16 (5), pp. 459-586 (2015) (2015)
CCTF task force at BIPM for the redefinition of the SI-s:
https://www.bipm.org/documents/20126/52354676/CCTF_2020_Task_force_Introduction_Finale.pdf/62bb4dc1-a662-a07e-dd9c-d9ed17829d70

Optical frequency transfer : key elements



- Unbalanced Michelson interferometer
- Heterodyne detection: eliminates mutli-path
- Fully bi-directional. A 2nd link transfers back the signal
- Guided propagation: ensure paths reciprocity
- Assumption : Forward noise = ½ Round-trip noise
- → corrects only reciprocal noise
- Coherent regime if coherence length > 2L (need ultra-stable laser !)
- Fundamental limits set at short term by the finite velocity of light in media

A second set-up on a second fiber transfers back the signal: « End-to-end » measurement, out of loop.

Multi-segment approach

- Shorter delay, larger bandwidth
- Signal regeneration with a narrow laser (a few kHz at 1 Hz bandwidth, free running)

O. Lopez, *et al.*. OE **18**, 16849–16857 (2010).

Repeater laser station (RLS) functionalities :

- sends back signal to station N-1,
- corrects the noise of next link N,
- provides a user output

Multi-branches Laser Station (Hub station) can correct the noise of several (~5) links

E.Cantin *et al.* New J. Phys. **23**, 053027 (2021).

Optical frequency transfer : noise floor

Design of low-temperature sensitivity multi-branches Michelson interferometers

RLS : 3-branches > 2 input/output (back, next) and one user output

MLS : 2x6 input/output to seed up to 6 branches and their link back for traceability

<u>temperature sensitivity:</u>

1st lab prototypes: 7fs / K

RLS industrial grade: < 1 fs / K

MLS industrial grade: < .04 fs / K

3 designs :

MLS1 : Free-space, starting point design

MLS2 : Free-space, man-in-the-middle design

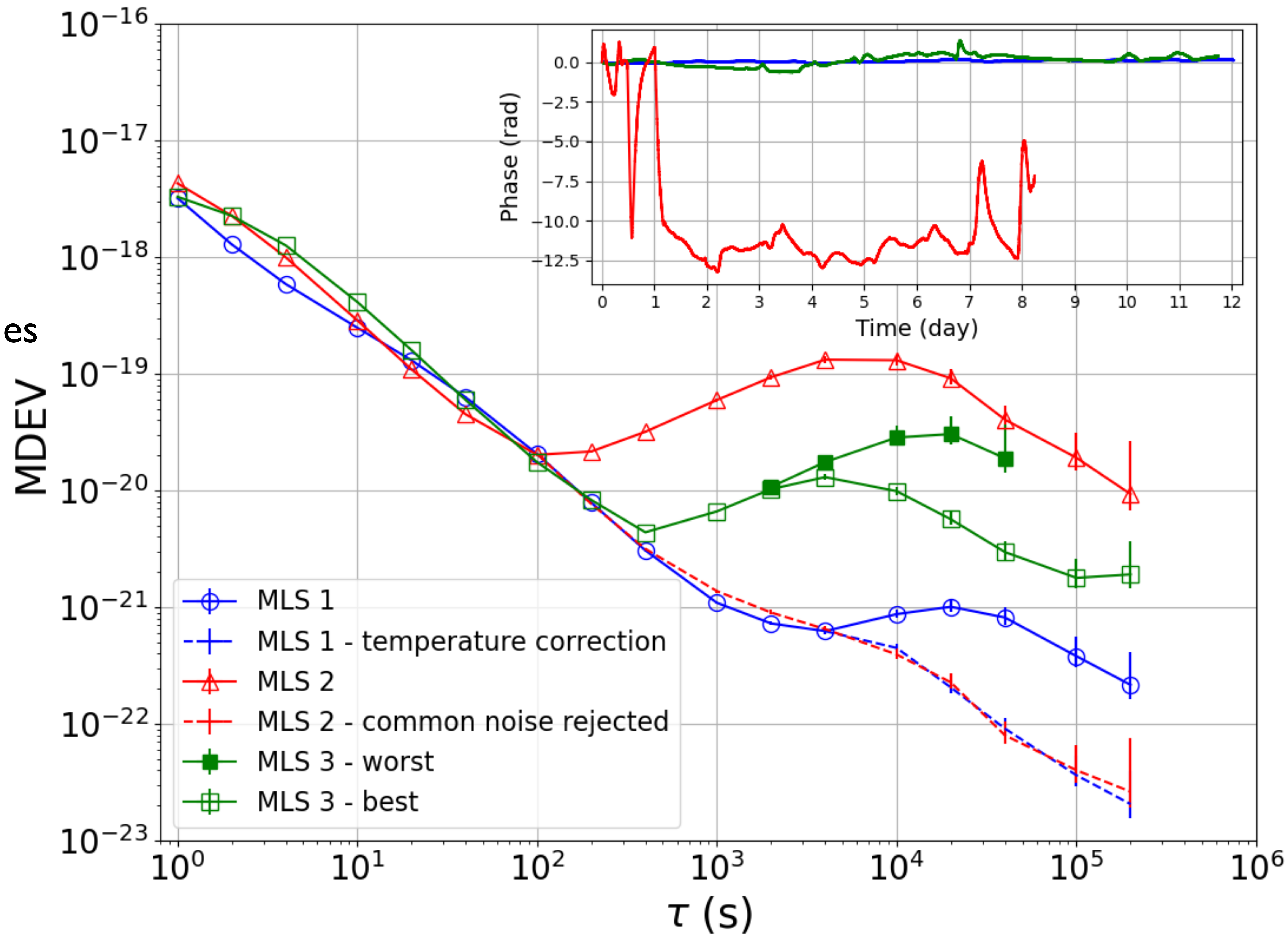
MLS3 : Fibered, end-point design

see also work on spools and mid-haul fiber links:

F. Stefani *et al.*, JOSA. B **32** (2015), doi: 10.1364/JOSAB.32.000787.

D. Xu *et al.*, OE **29**, (2021) doi: 10.1364/OE.420661.

D. Xu, *et al.* OE **27** (2019), doi: 10.1364/OE.27.036965.



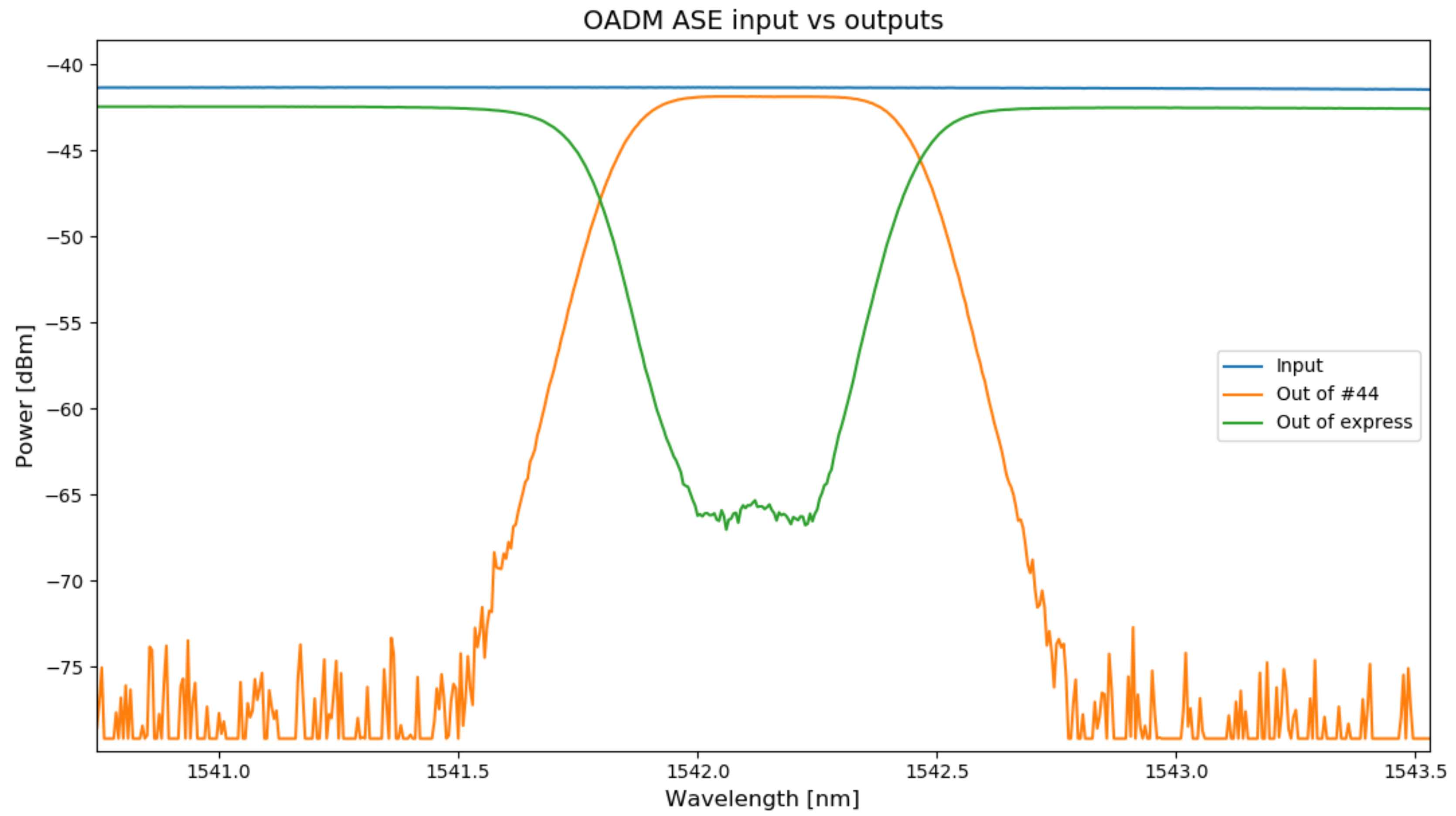
<u>E.Cantin *et al.* New J. Phys. **23**, 053027 (2021).</u>

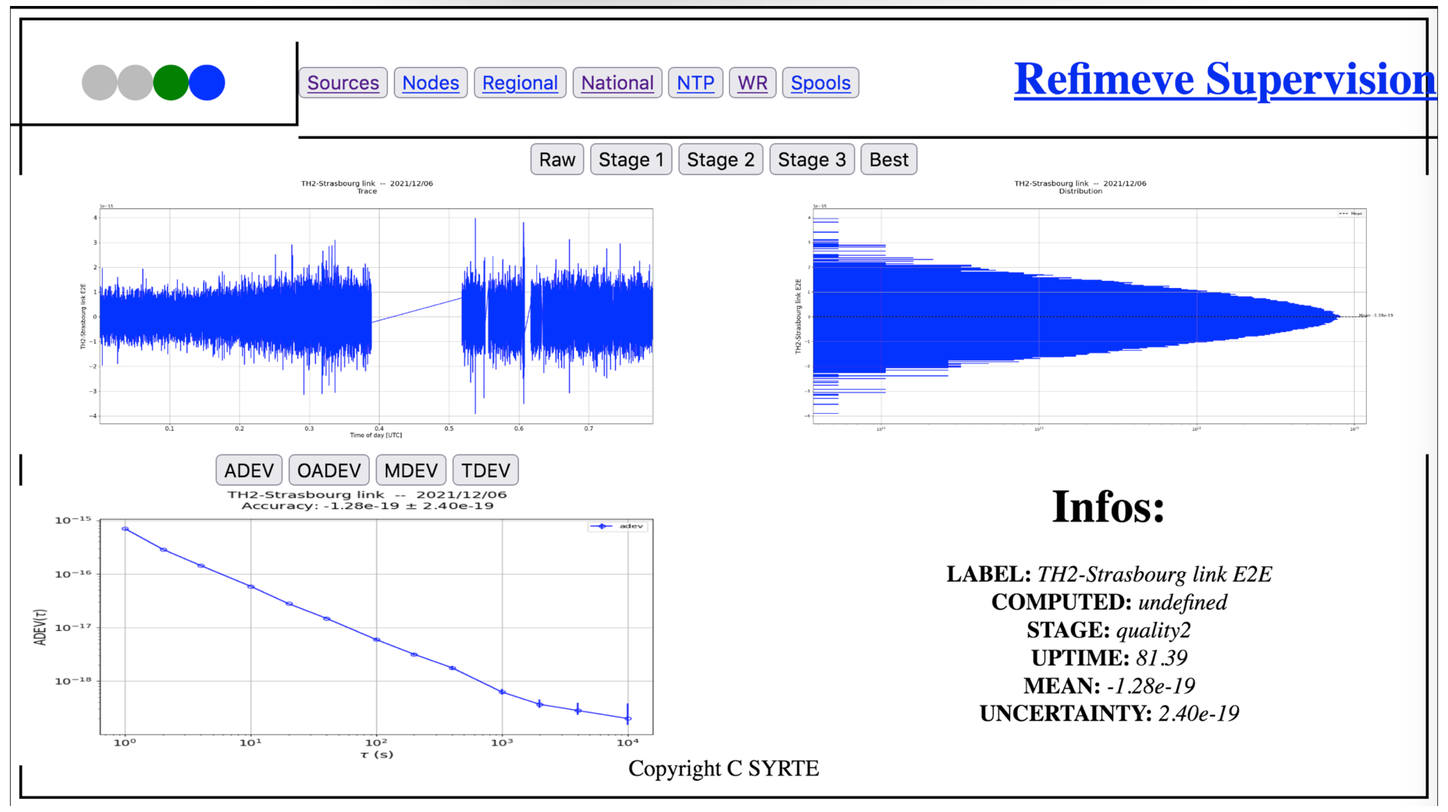
REFIMEVE metrological fiber network

- **Aim**
  - Wide dissemination to academic labs, that covers wide scientific applications
  - Link between National Metrological Institutes (in Europe)
- **Technical issues**
  - Signal generation
  - Remote control (for installation in telecom hubs)
  - Compatibility with non-metrological environment (no stable RF, no GPS…)
  - Robustness
  - Assessment of the accuracy and stability of the disseminated signal

From fiber links to a metrological network

- **Availability of the fiber**
  - Dedicated frequency channel aka "dark channel": parallel transmission of ultra-stable signal and data traffic in the same fiber on different frequency channels using dense wavelength division multiplexing (DWDM)
- **Knowledge transfers**:
  - System vision, production, installation, & operation
- **Network supervision:** operational + scientific
- **Data** availability & usability (FAIR), documentation, archives, live monitoring, community management…





REFIMEVE

<u>Built with 2 large investment programs</u>
REFIMEVE+ ~7M€ (2012-2024)
T-REFIMEVE ~10 M€ (2021-2029)
Acknowledged as
national research infrastructure by 2021

MINISTÈRE
DE L'ENSEIGNEMENT SUPÉRIEUR,
DE LA RECHERCHE
ET DE L'INNOVATION

Key concepts

- Mutualisation
  - Time and frequency reference systems
  - Fiber networks (national, regional,…) for education and research
- T/F as a service
  - To date : ~30 academic research laboratories. 19 physically connected as of 10/2023
    - 6 research infrastructures: SOLEIL, ESRF, IRAM, LOFAR, LSM, + CERN
  - Industrial partnership & societal impact
  - Open access (FAIR)

Partnership

Refimeve+ Réseau fibré métrologique à vocation européenne

Kernel

LPL (USPN, CNRS)

SYRTE (OP-PSL, CNRS, SU, LNE)

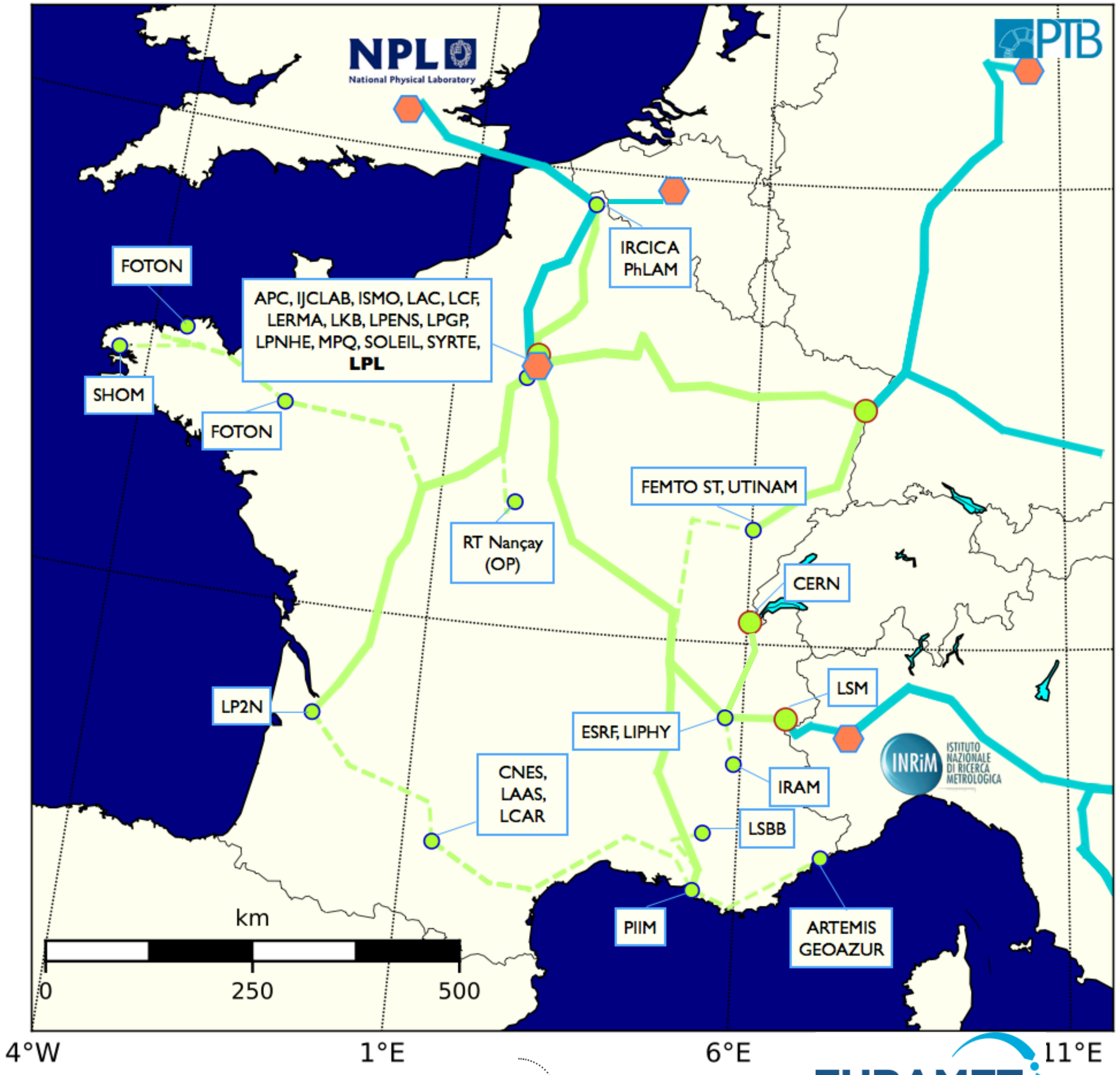
RENATER

Industrials

30 Users

Refimeve network map (2023)

- 3 international connections (DE, UK, IT)
  - New: CERN connected March 2023
  - New: Belgium-France cross-connection planned
- Clocks (microwave and optical) at INRIM, PTB, NPL, and SYRTE are connected with fiber network
- REFIMEVE connects, by 10/2023: PhLAM, IRCICA, FEMTO-ST, UTINAM, LIPHY, LSM, PIIM, APC, IJCLAB, ISMO, LAC, LERMA, LKB, LPGP, LPNHE, MPQ, LP2N, SYRTE, LPL
- FIRST-TF (Research federation) acts for the scientific animation of the French users connected by the fiber network
- EURAMET: 5 EU projects to develop technology, + run optical clock comparisons,…



The signal source + network monitoring and supervision

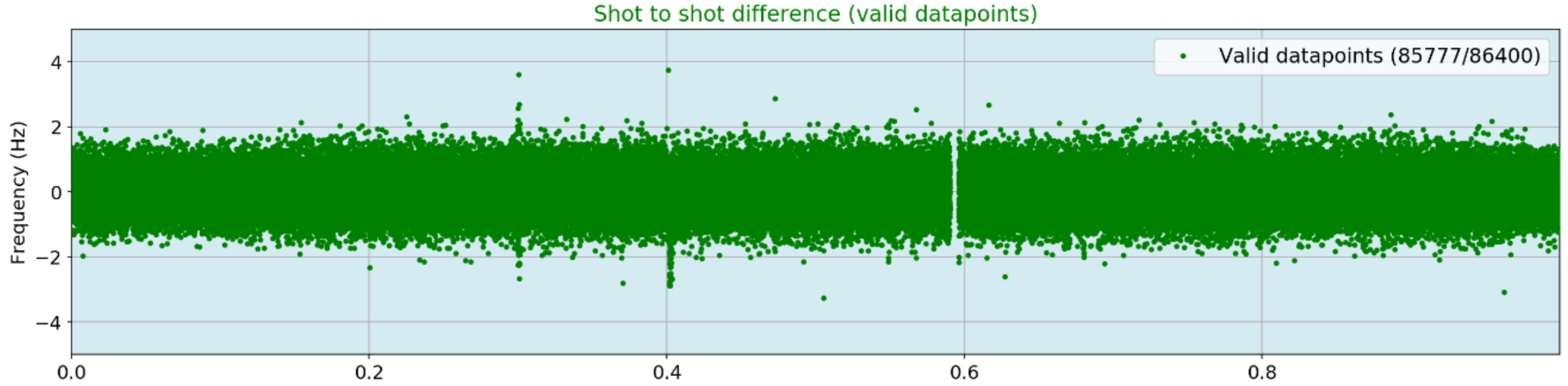
- Optical and microwave sources are compared with an optical comb (femto-second laser)
- REFIMEVE signal copies the stability of the laser at short term, and the one of the (flywheel) maser at long term.
- Enable comparisons with satellites links (GNSS, TWSTF, ACES…)
- Source uptime since Dec. 2019 : 95 %
- REFIMEVE signal frequency:

  194 400 121 000 000 +/- 2 Hz

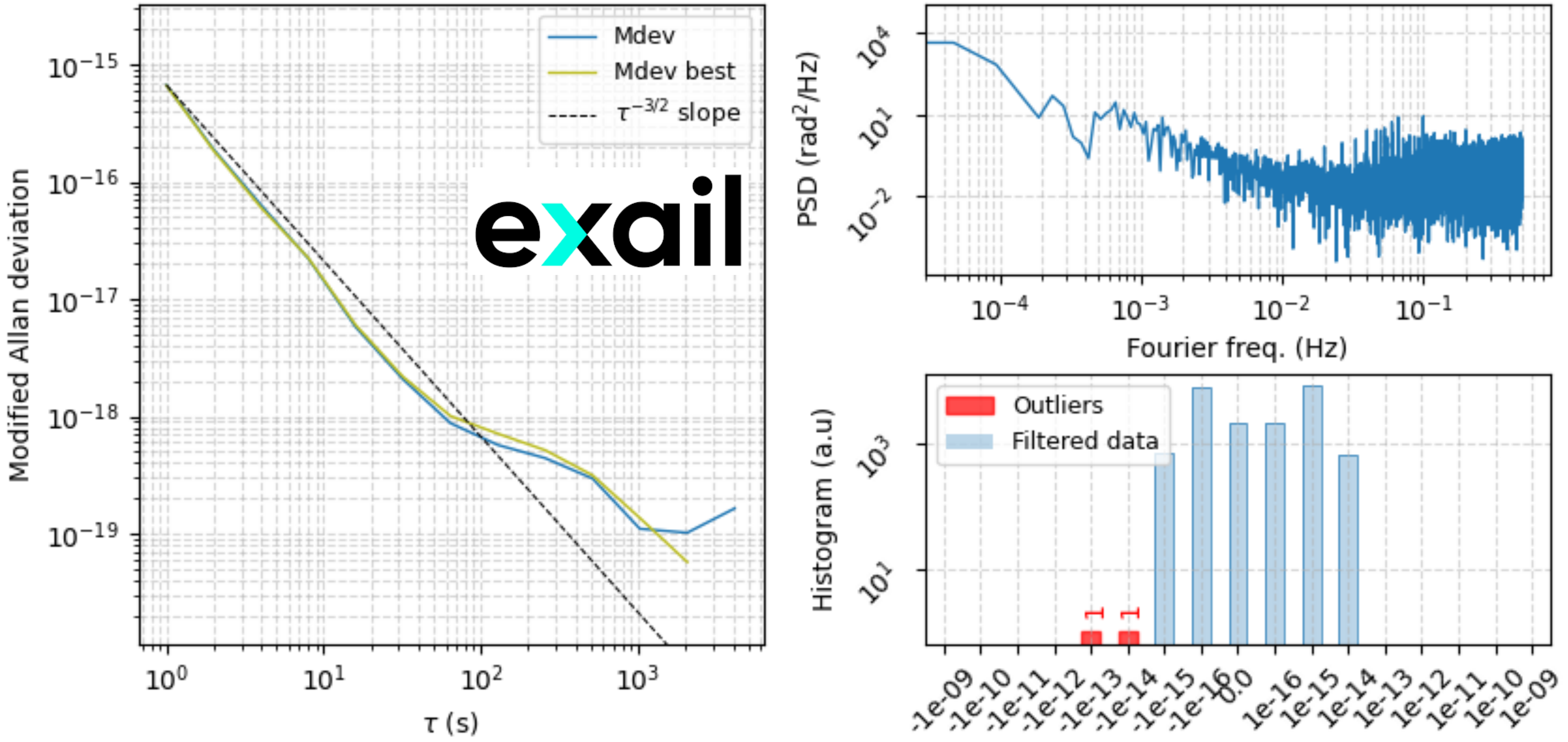
  No He > stop cryogenic oscillator

  194 400 121 000 000 +/- 25 Hz

- Signal generation monitoring example:



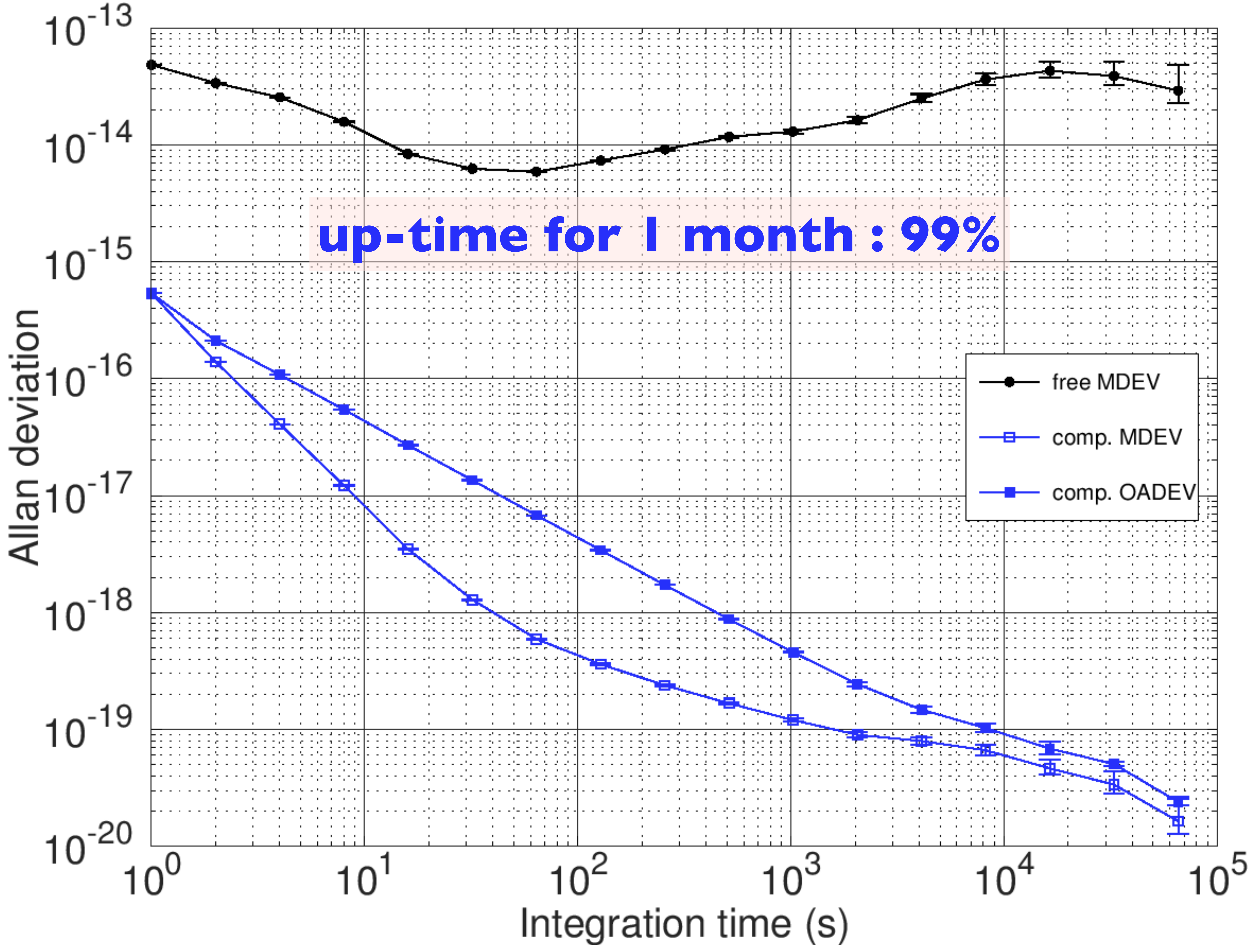
- Link performance monitoring example:



Exail (ex-iXblue, ex-MuQuans)'s supervision

Industrial grade fiber links

Tech. readiness level: from 5 in 2012 to 8-9 by 2018



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

First industrial link:
Paris - Lille - Paris (2x 330 km)

Optical amplifiers:

KEOPSYS

LUMIBIRD
MORE THAN LASERS

Repeater laser stations

μQUANS

iXblue
exail

https://www.muquans.com/products/time-and-frequency-transfer/
https://www.keopsys.com/portfolio/bi-directional-fiber-amplifier/

Towards a highly available signal

Relative frequency fluctuations vs time (days)

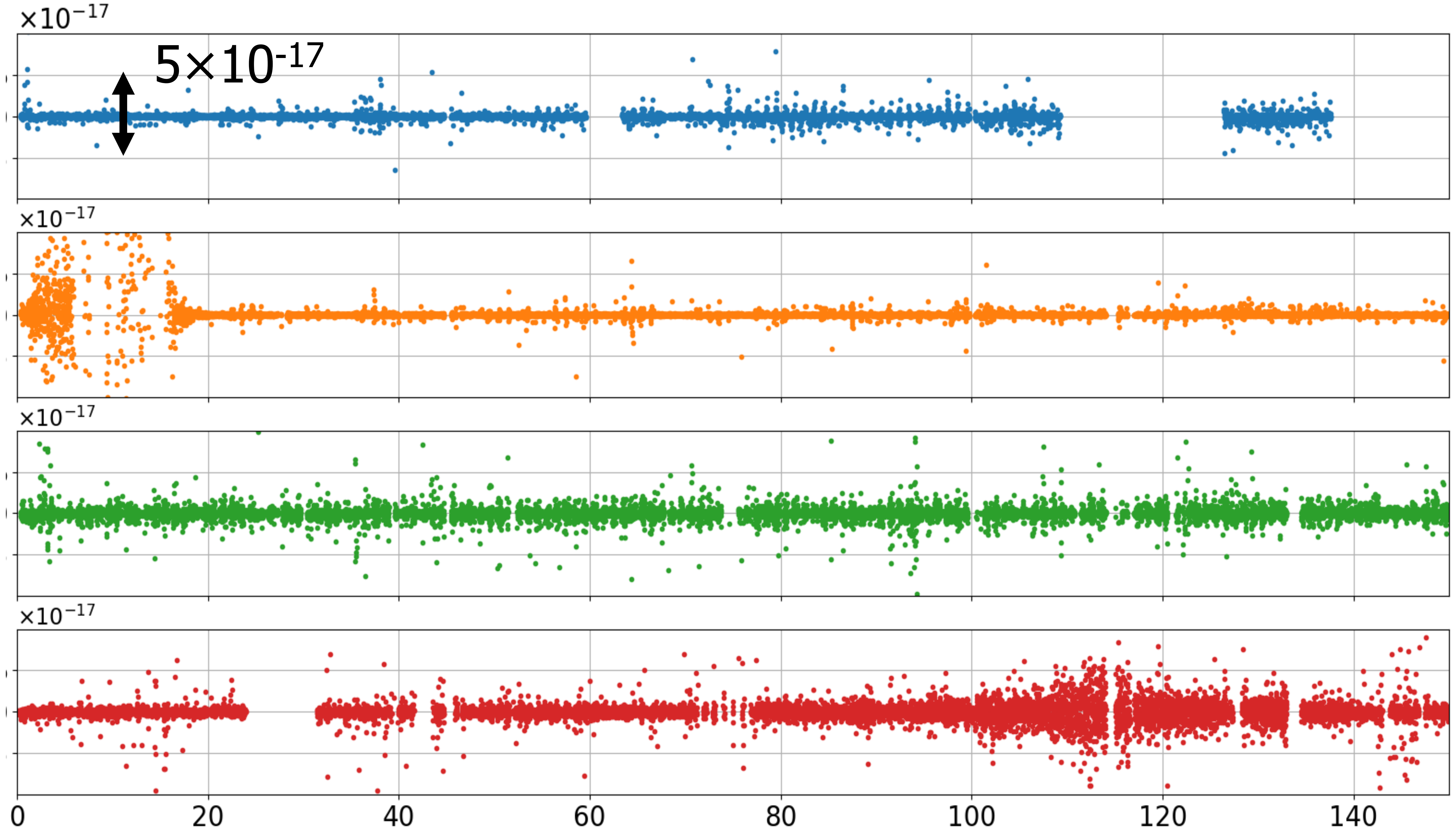
1000 s / point

Paris-Lille-Paris (2 x 340 km) — Uptime 71%

Paris-Strasbourg-Paris (2x650 km) — Uptime 85%

Paris-Lyon-Modane-Lyon-Paris (2x900 km) — Uptime 81%

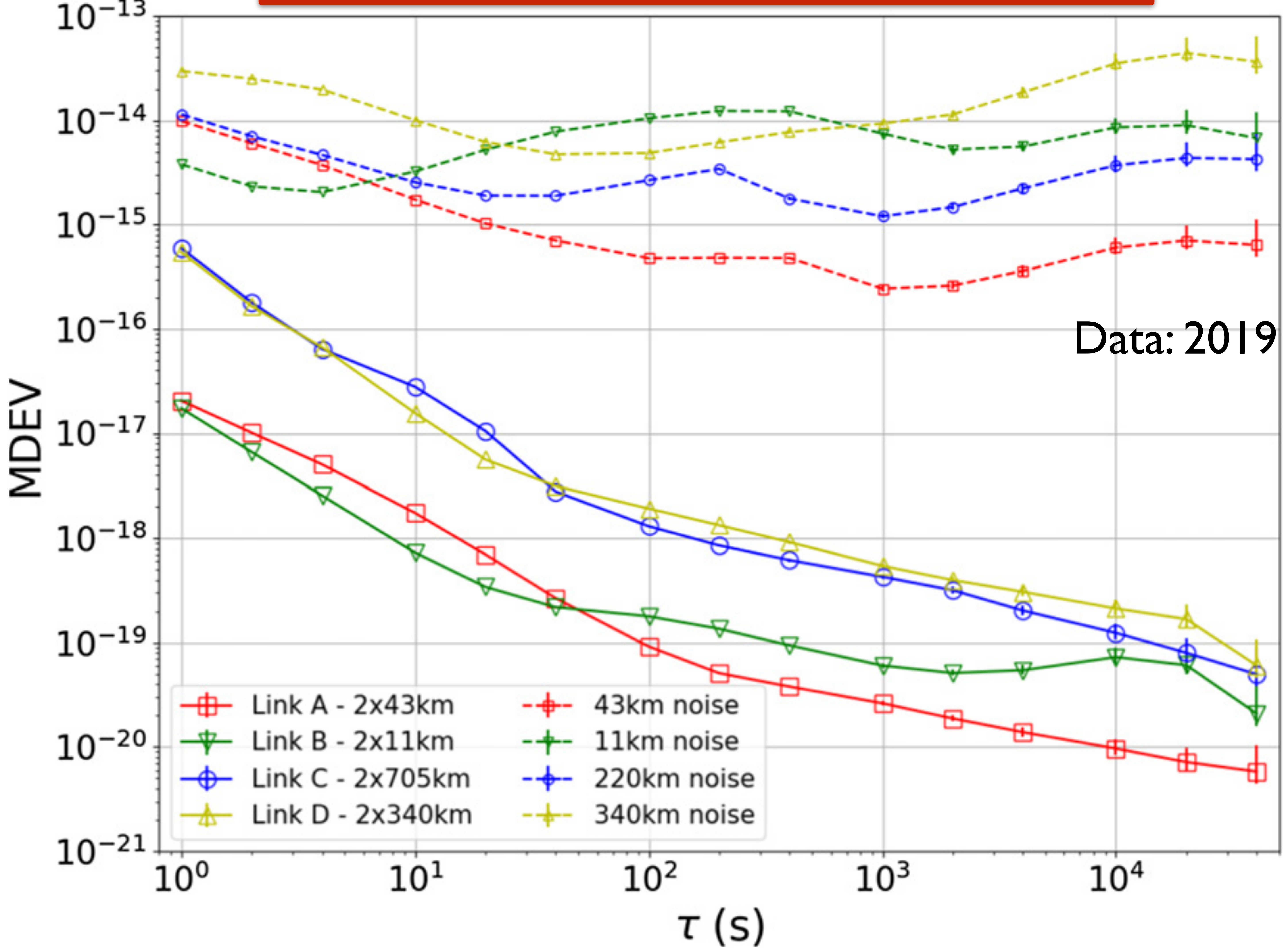
Lyon-Marseille-Lyon (2x440 km) — Uptime 85%



4 links: {340,650,900,440} km x2 = 2x2330 km
>70% / 1/2 year (2022)
>90% uptime for several months
<u>next objective: 90 % / year</u>

Simultaneous optical frequency transfer to several users

unique capacity of REFIMEVE



E.Cantin *et al.*, New J. Phys. 23, 053027 (2021).

- 4 simultaneous transfer (links A to D)
  - Central node in Paris (11 km)
  - Villetaneuse (43 km)
  - Lille (340 km)
  - Strasbourg (705 km)
- Relative frequency instability
  - < 1e-18 after a few 100 s
- 2200-km stabilized fiber link in total

By 2023 :

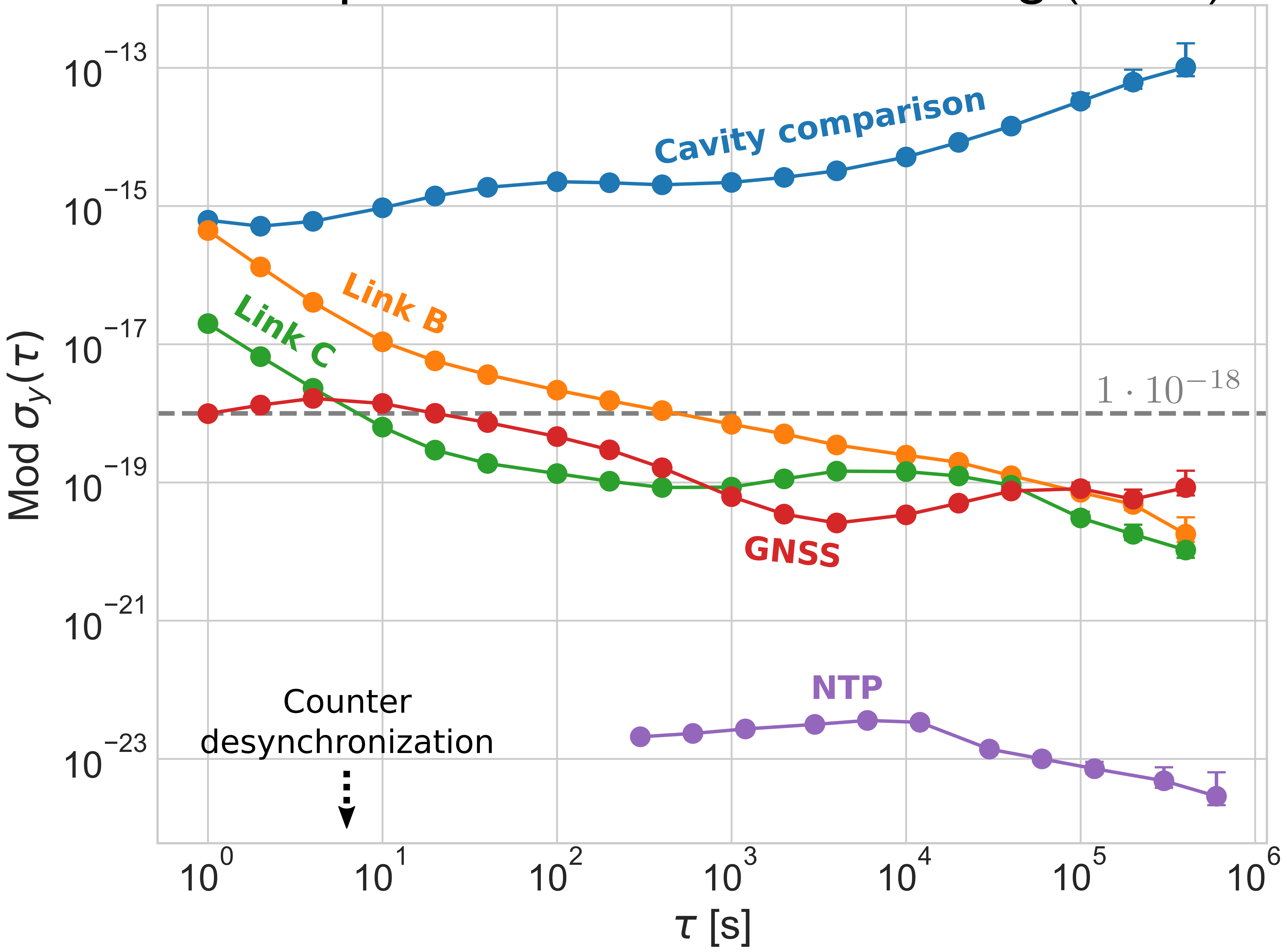
- 7 links operated in parallel
- 2x3800 km
- Data analysis over years meas. time

M. Tønnes *et al.*, Metrologia, **59** 065004, (2022), doi: 10.1088/1681-7575/ac938e.

Accuracy of the optical frequency transfer

Statistical contributions

Example link SYRTE-Uni Strasbourg (>PTB)



Note: scaling factor Optical / GNSS ~ 1e6

Systematic contributions

Sources of systematic error:

- Inaccuracy of the 10 MHz signal provided to the counter by GNSS
- Desynchronisation of the measurement
- Time error of the data time stamps (> NTP)
- Mean offset of the stabilized link

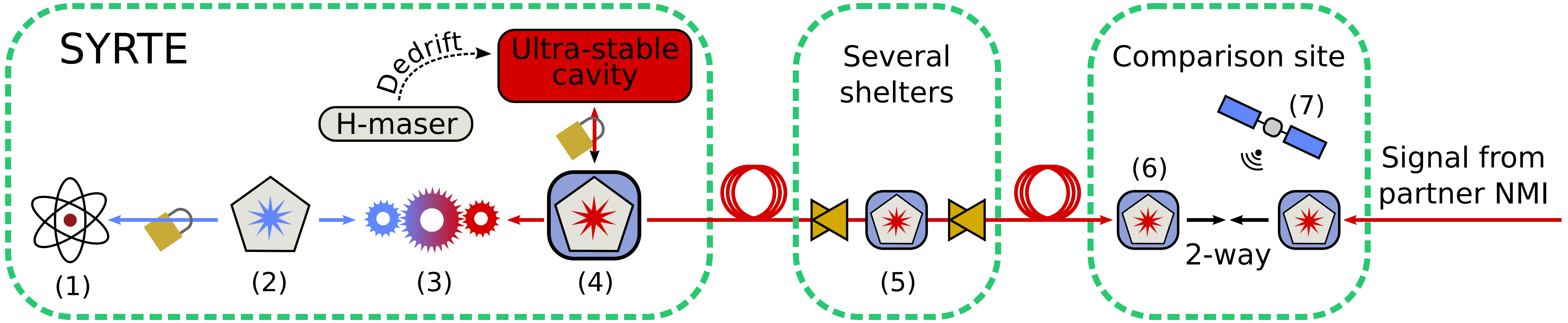
	shift (x 10^{-18})	statistical (x 10^{-18})	systematic (x 10^{-18})
Remote RF frequency reference at comparison point	1.7	.1	-
Instruments desynchronisation	2.9 x 10^{-4}	2.6 x 10^{-12}	
Data timestamping	2.4 x 10^{-6}	3.6 x 10^{-6}	3.7 x 10^{-4}
Optical frequency transfer, 705-km link	.17	.45	< .1
Optical frequency transfer, 10-km link	.11	.14	< .1
Total	1.7	1.1	<.14

M. Tønnes PhD Thesis , https://hal.science/tel-03984045https://hal.science/tel-03984045.

On data processing with missing data: **M. Tønnes** *et al.*, Metrologia, **59** 065004, (2022), doi: 10.1088/1681-7575/ac938e.

Optical clock comparisons : peer-2-peer comparisons

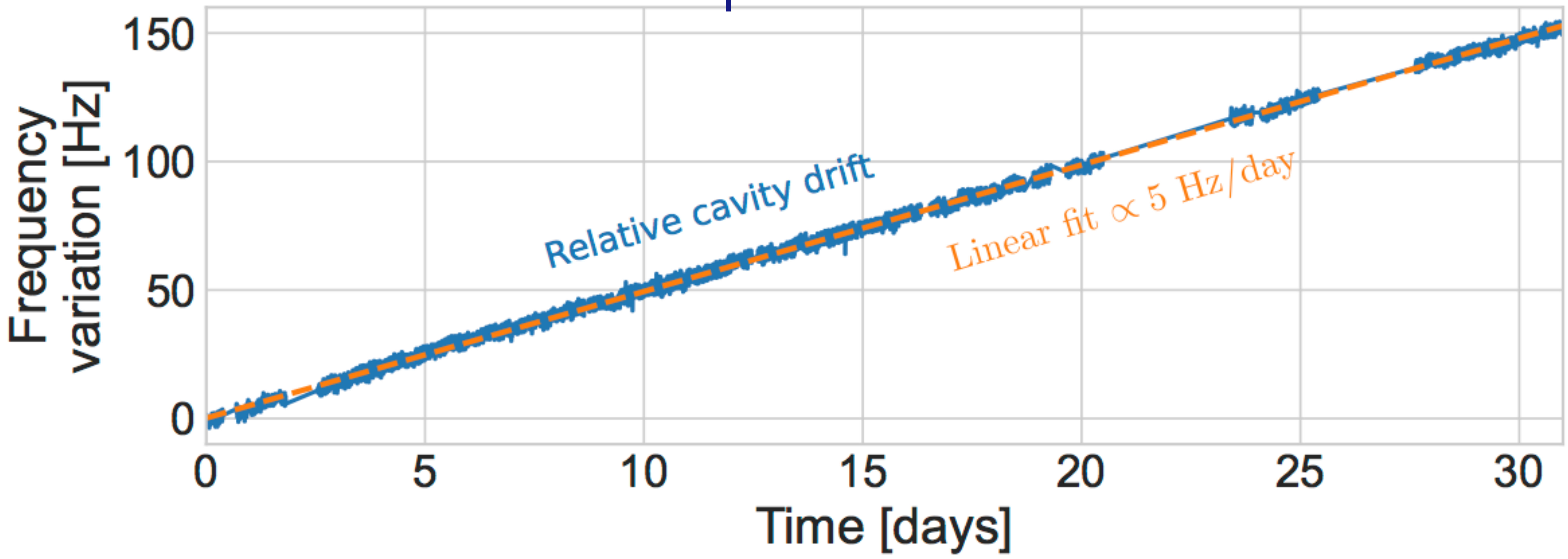
Sketch of the experiment



Links lengths:

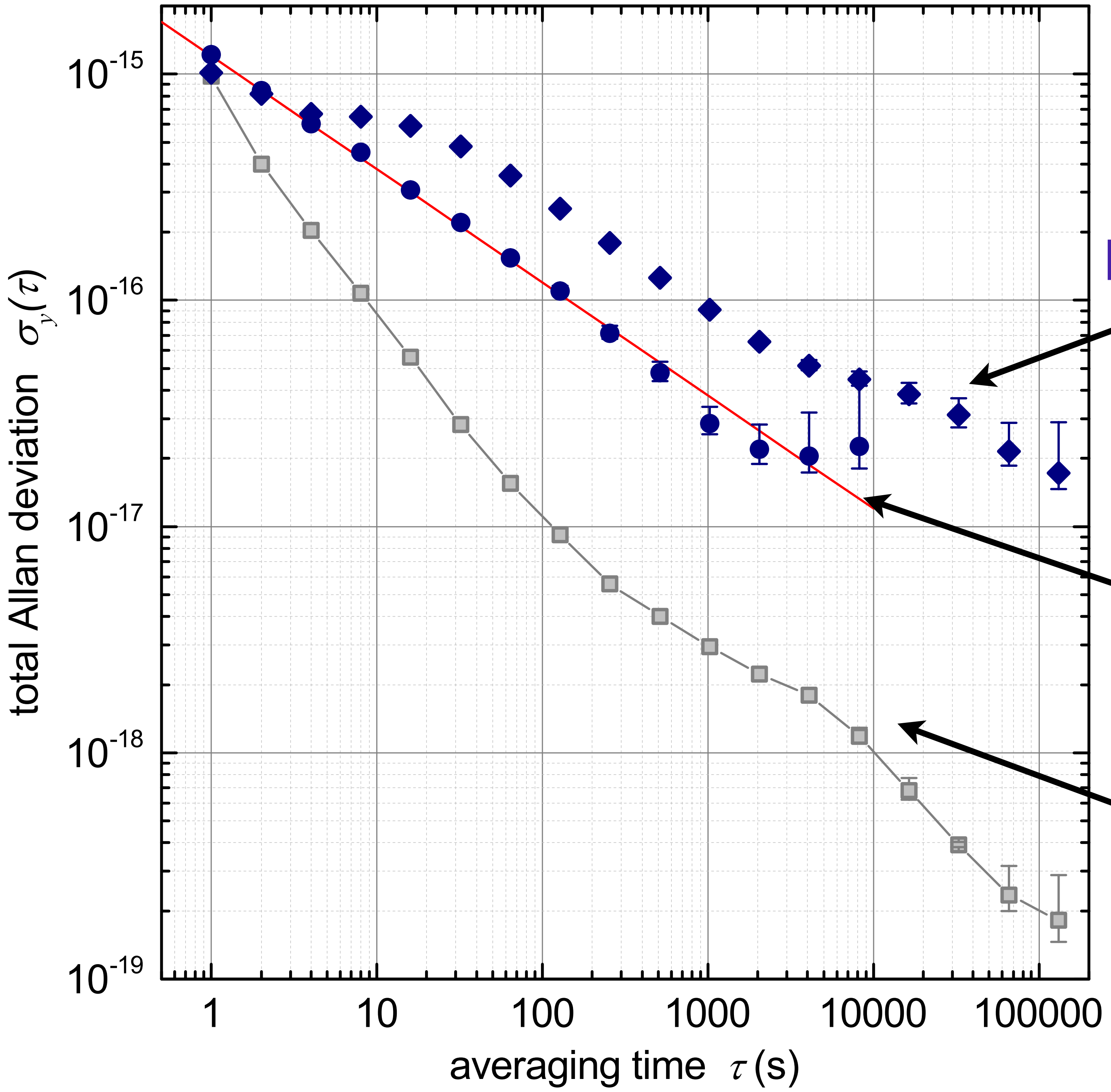
To Germany: ~1400 km
To UK: ~900 km
To Italy: ~1200 km
(in total)

Real-time ultra-stable laser comparisons: example SYRTE-PTB



M. Tønnes PhD Thesis ,
https://hal.science/tel-03984045https://hal.science/tel-03984045.

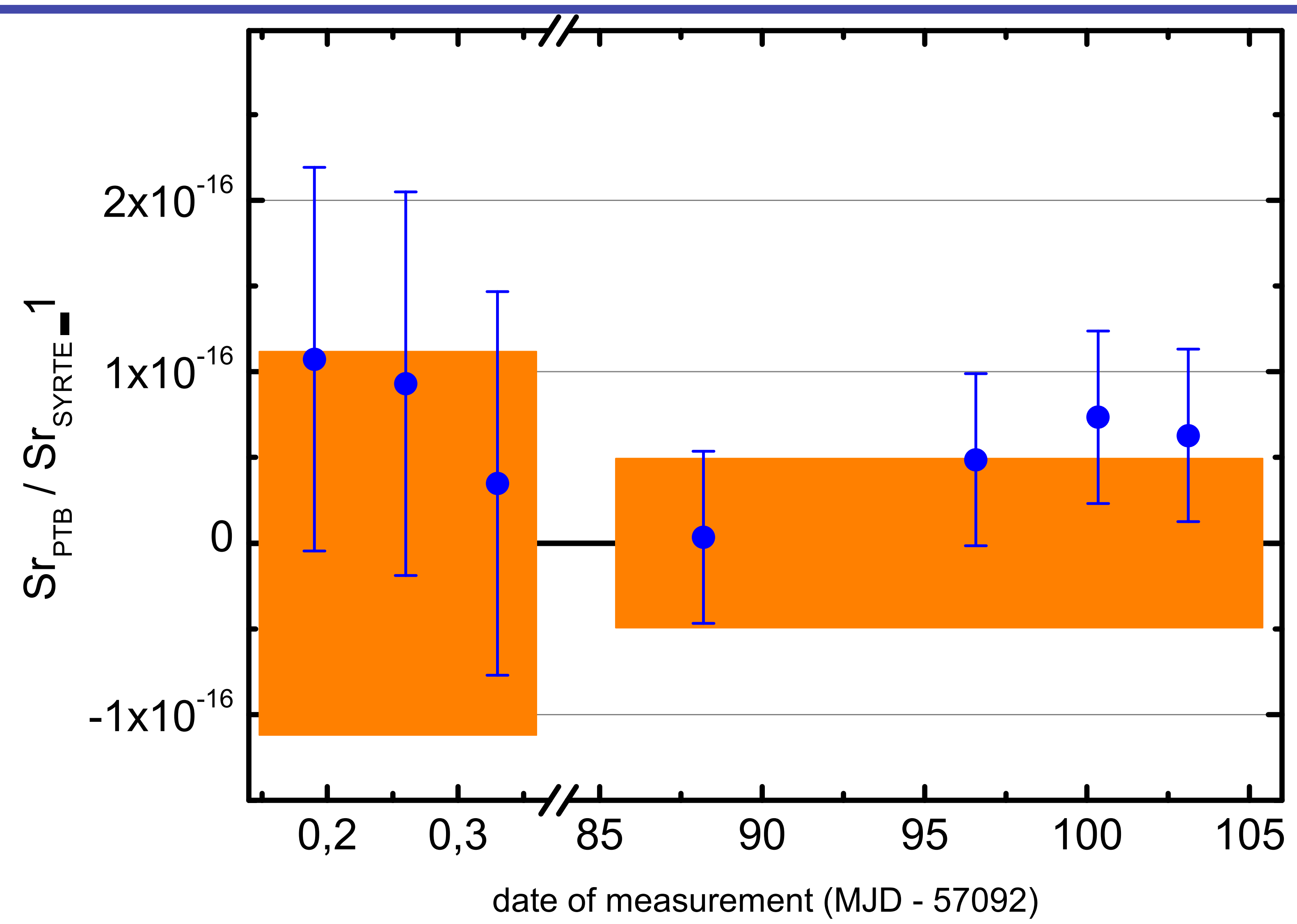
International clock comparisons: a world first in 2015



Run II : June 2015

Run I : March 2015

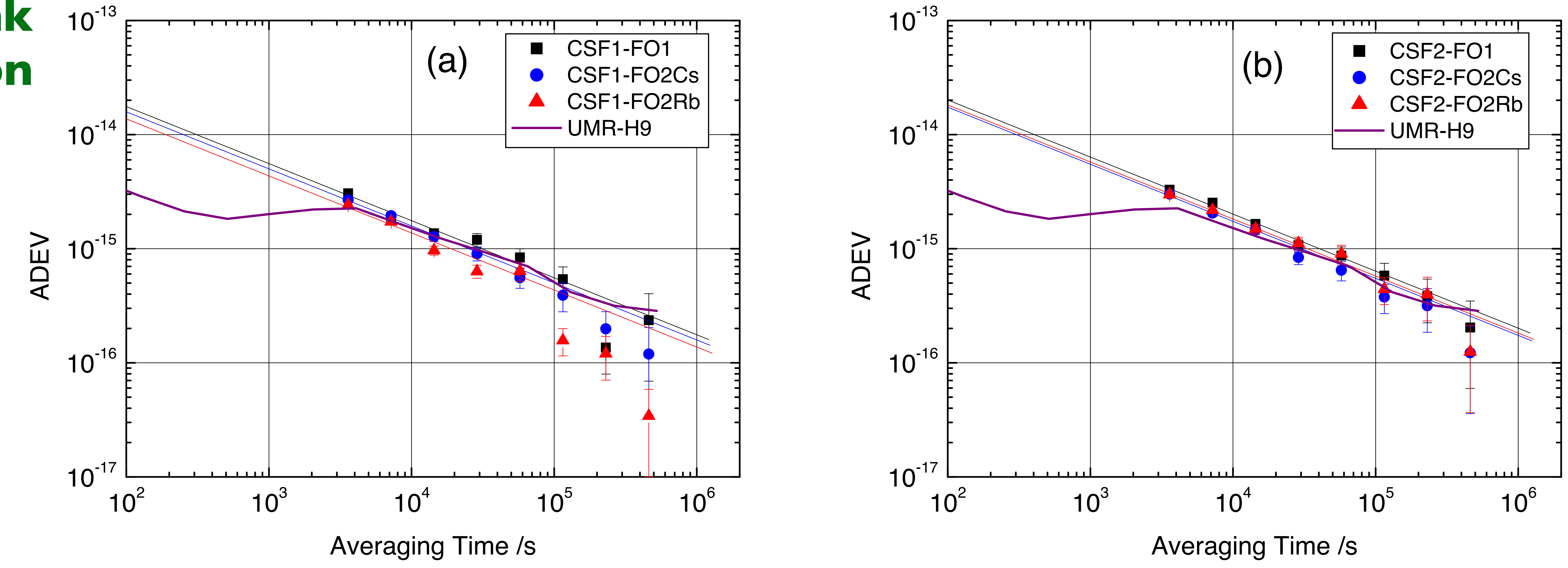
Combined link contribution



Red shift ~10^{-16} / m
Comparisons require precise clock levelling to take into account the clock height difference !

- **Frequency instability Sr^{PTB}-Sr^{SYRTE}**
  $2x10^{-17}$ (@5000 and 50,000 s)
- **Accuracy : Sr^{PTB}-Sr^{SYRTE} agreement**
  $(4.7±5)x10^{-17}$

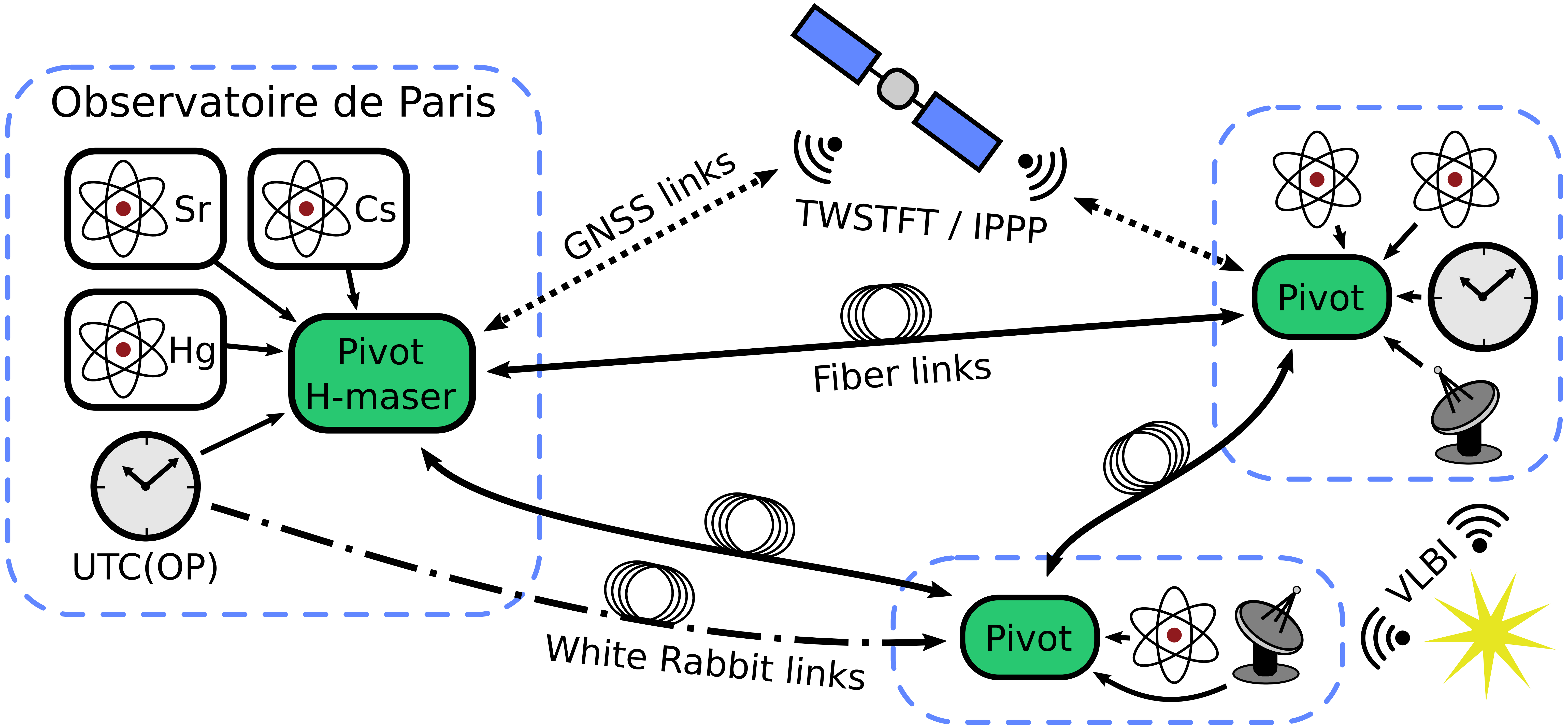
- **Fountains (Rb and Cs) comparison**

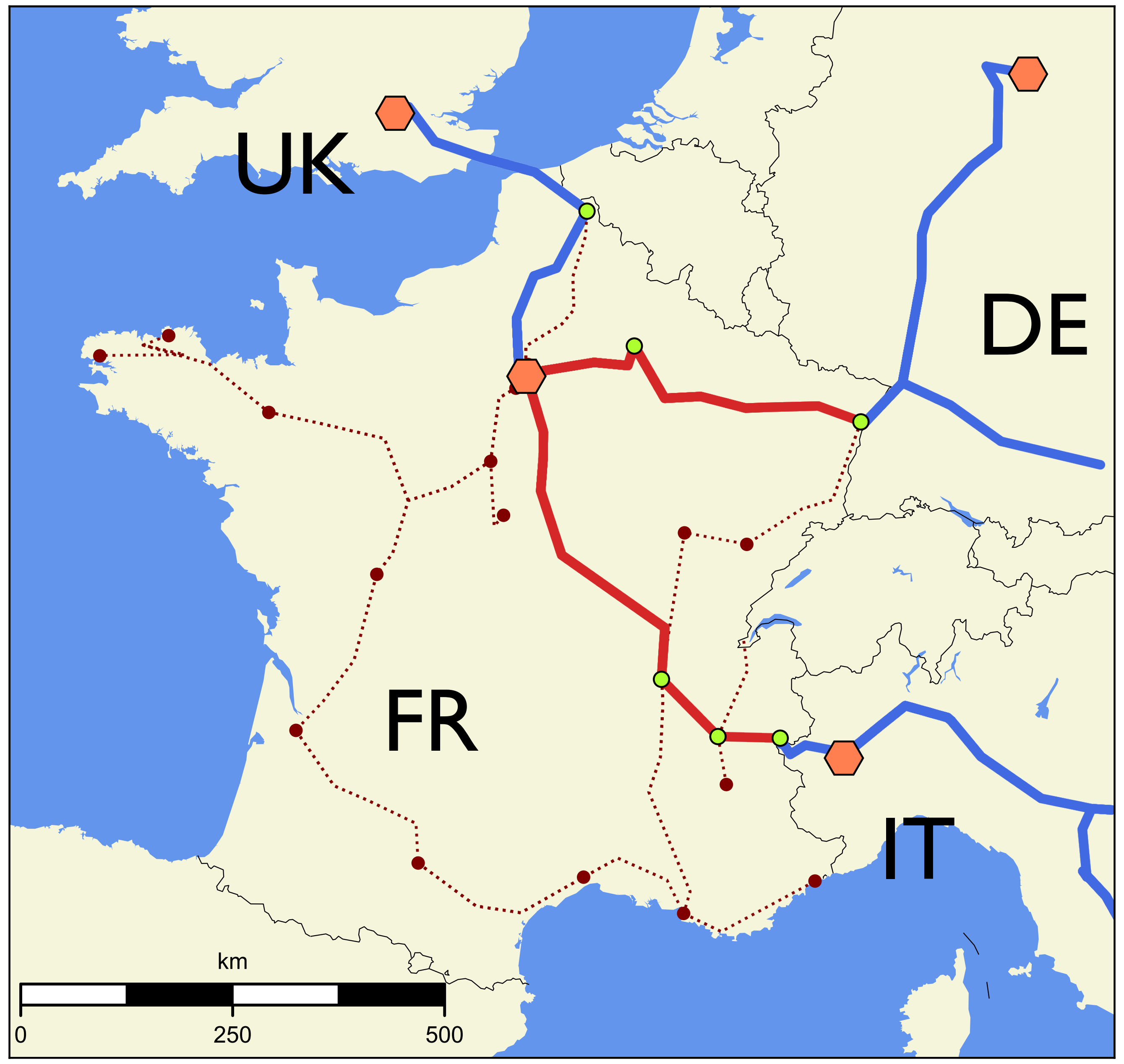


C. Lisdat et al., Nature Comm. (2016), 12443 (2016); J. Guéna et al., Metrologia **54**, 3 (2017)

Optical clock comparisons : clock network

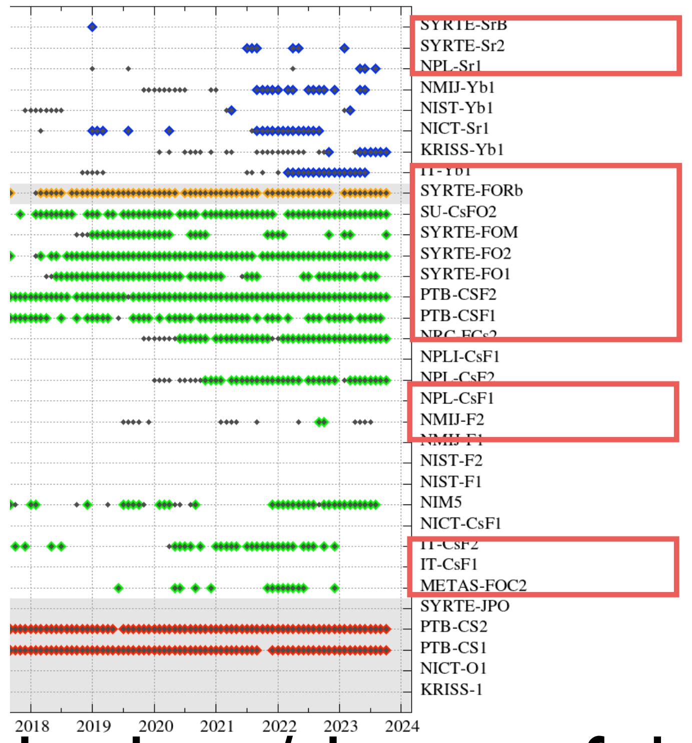
Comparison of an ensemble of clocks (microwave and optical) by several means





Optical clocks (12):
SYRTE: Sr2, SrB, Hg
PTB :Yb+, Sr (static), Sr (transportable), In+
NPL:Yb+, Sr+, Sr
INRIM :Yb, Sr

Microwave clocks (9):
SYRTE: FO1, FO2-Cs, FO2-Rb, FOM
PTB : CSF1, CSF2
NPL: Cs-F1, Cs-F2
INRIM : CsF2

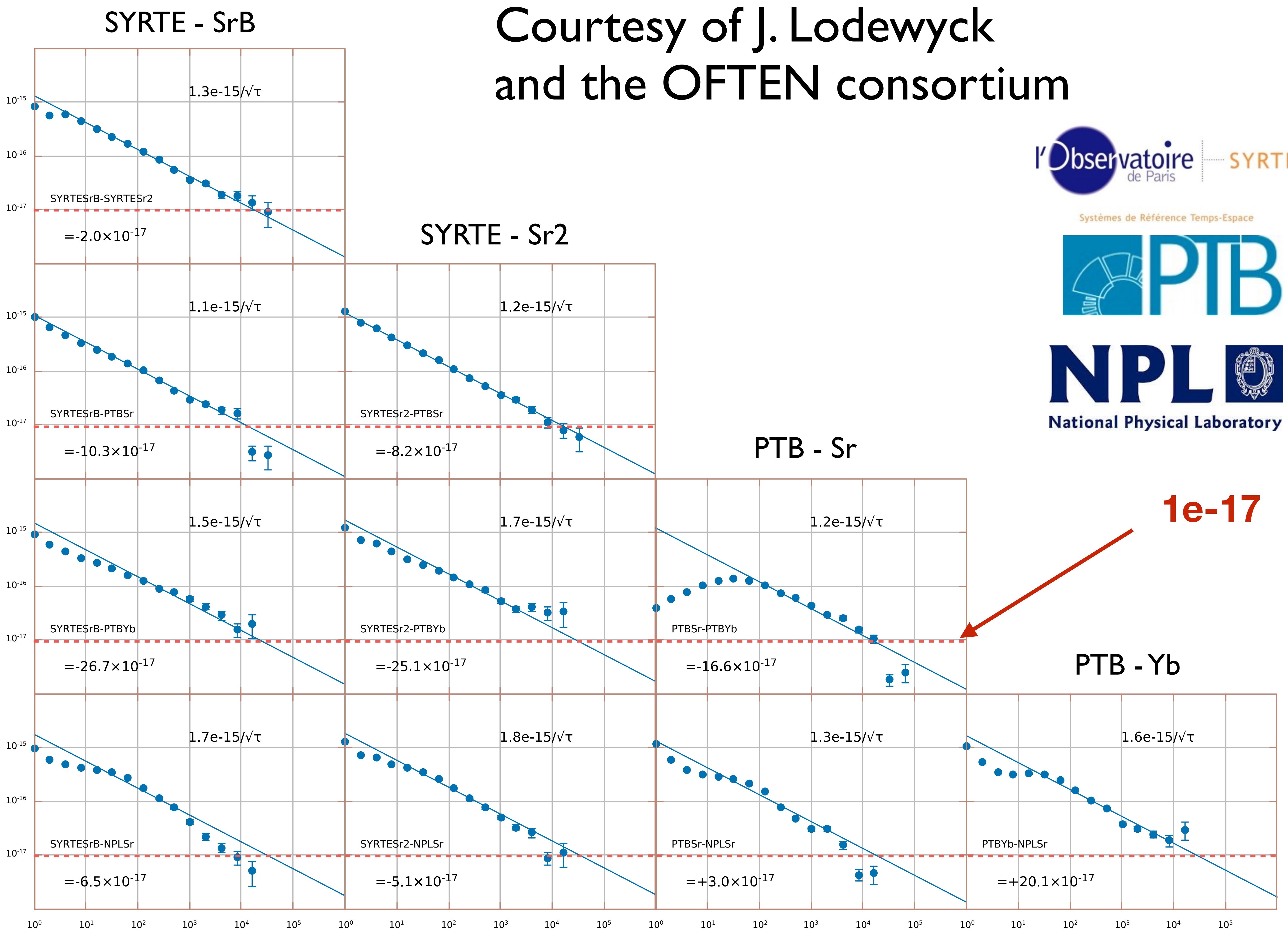


REFIMEVE connects many clocks contributing to TAI

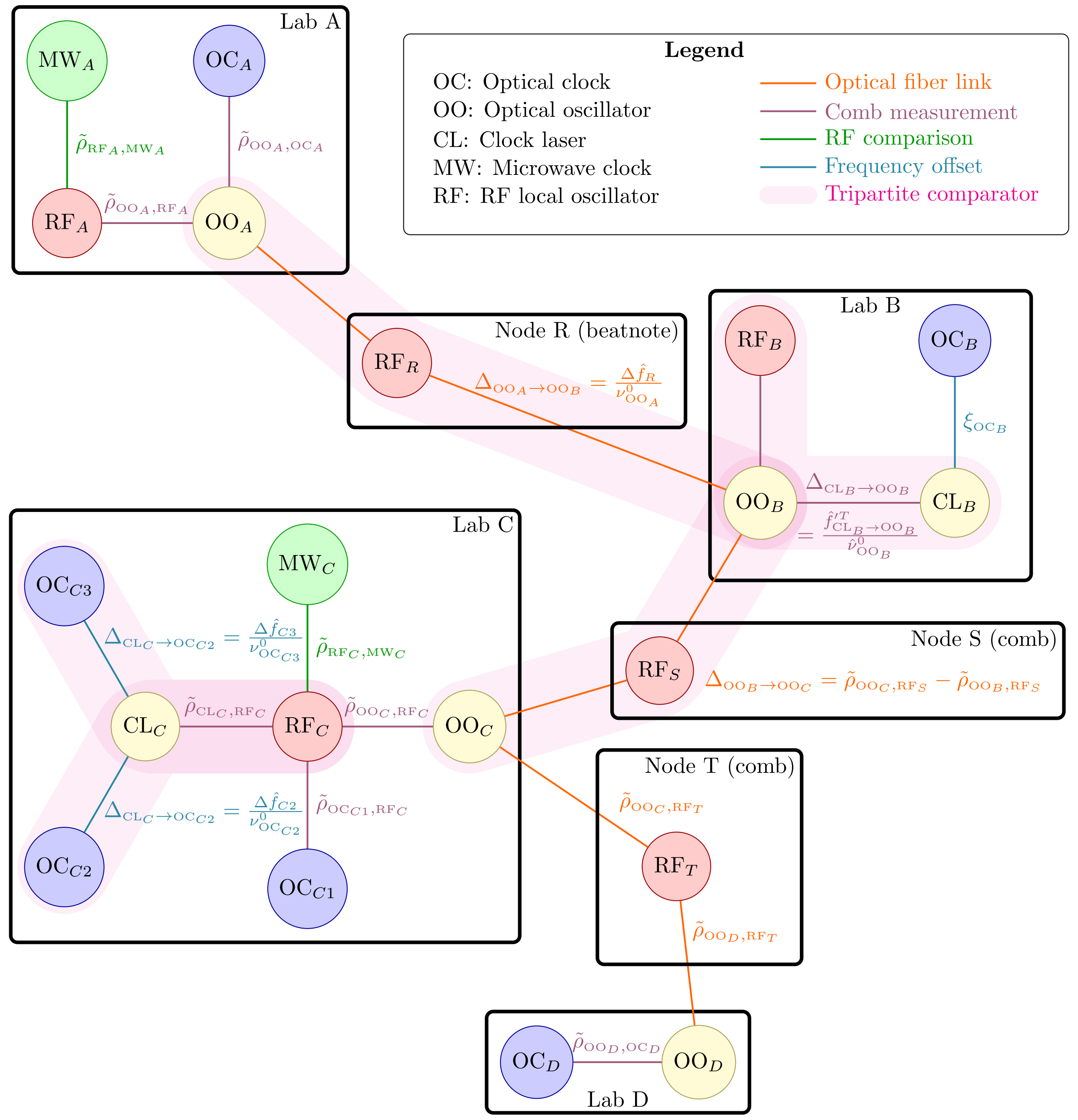
https://webtai.bipm.org/database/show_psfs.html

An optical clock network

Courtesy of J. Lodewyck and the OFTEN consortium



NPL -



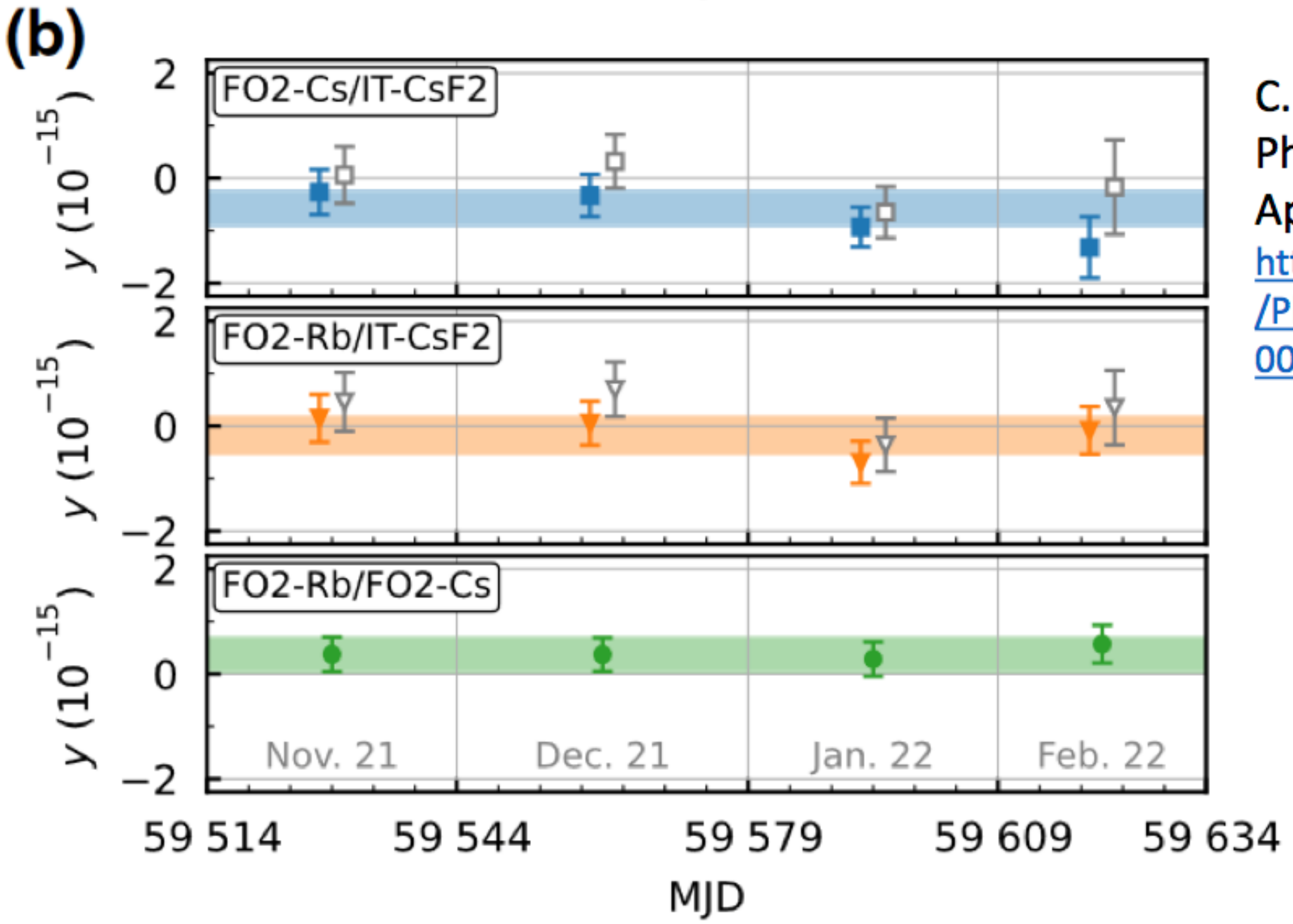
example OFTEN campaign SYRTE-PTB-NPL

- Scale : 1s - 1e6 s; 1e-14 - 1e-18
- Ensemble of 4 optical clocks
  - typ. statistical uncertainty <1e-17
- Repeated 10 times over 7 years
- Major step towards the SI-s re definition

Lodewyck *et al.*, Phys. Rev. Research 2, 043269 (2020).
Search for dark matter : **B. M. Roberts *et al.*** New J. Phys. 22 (2020).
Test of LLI : **P. Delva et al.**, Phys. Rev. Lett. 118, 221102 (2017)

Recent clock comparisons campaign: 4 months-long comparisons

First clock comparison



C. Clivati et al., Physical Review Applied (2022) https://doi.org/10.1103/PhysRevApplied.18.054009

Parallel operation of GNSS links
→ „Common-clock GNSS“

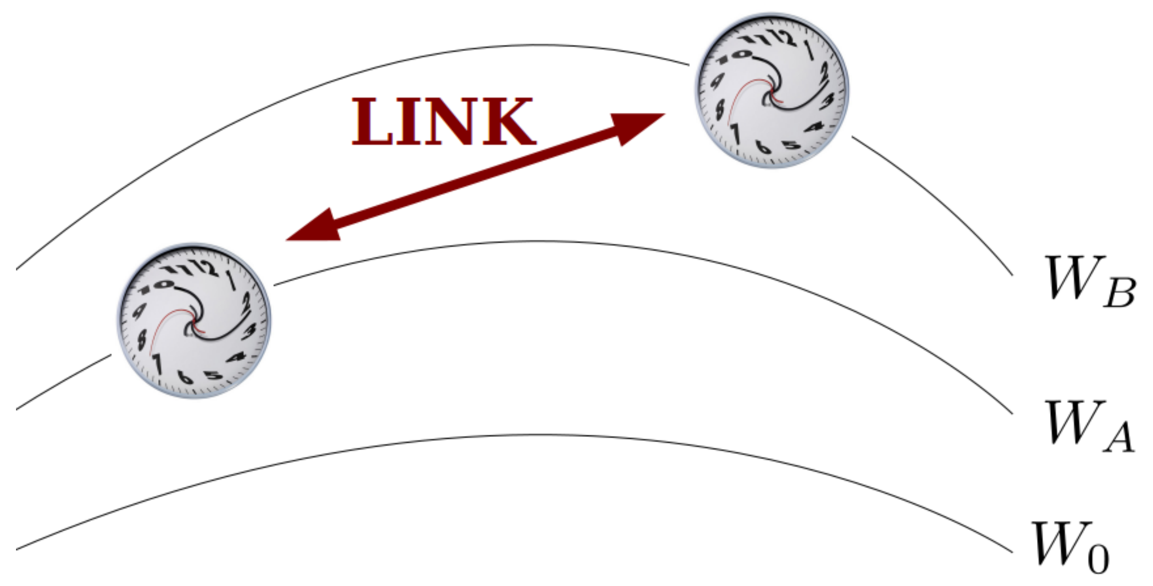
unpublished

Call for more work to compare means of comparisons

Application: Chronometric geodesy

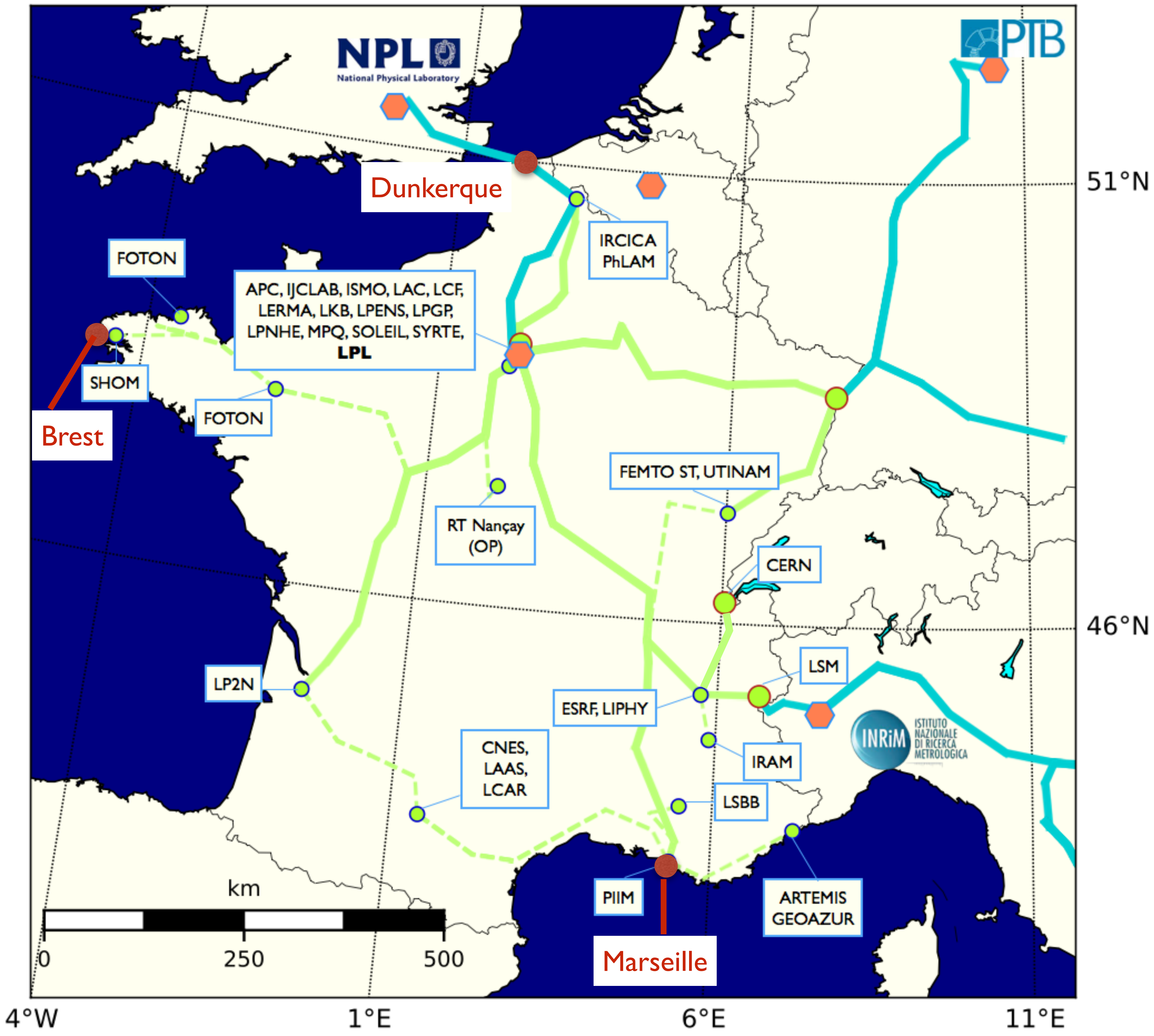
Gravitational (red) shift ~10^{-16} /m

Vermeer, M. (1983),
Bjerhammar, A. (1985).
doi: 10.1007/BF02520327.



G. Lion *et al.*, J Geod 115 (2017)

- Adding ~30 clocks are sufficient to obtain centimeter-level standard deviations and **1-2 order of magnitude improvements in the bias.**
- Clocks can also contribute to the unification of height systems realizations
- **3 tide gauges in France can be connected to REFIMEVE**
- On going projects (ROYMAGE) :
  - Evaluating the contribution of optical clocks for the determination of the geopotential at high spatial resolution
  - Find the best locations to put optical clocks to improve the determination of the geopotential
- Need complementary optical frequency transfer in free-space



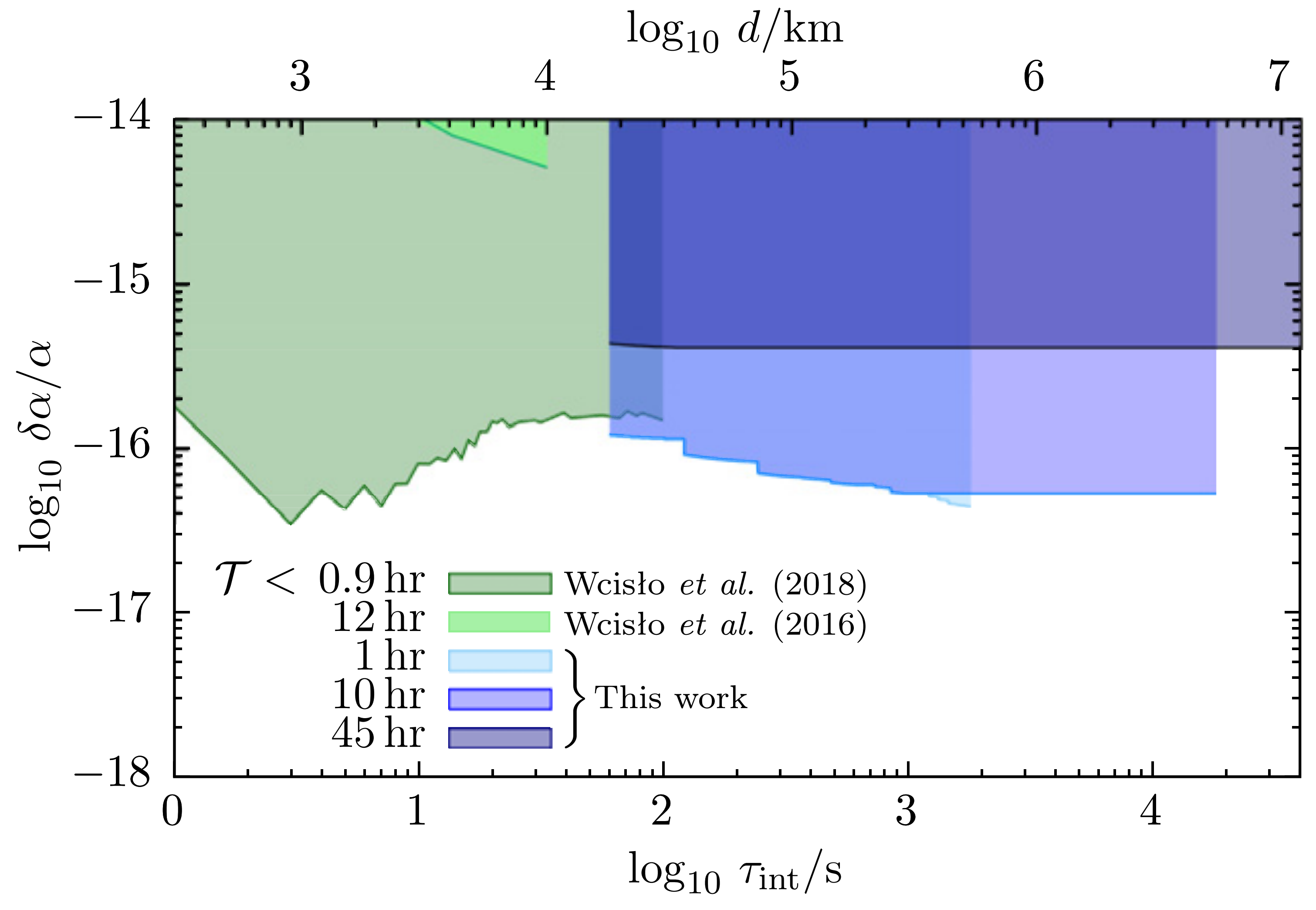
see also :
T. E. Mehlstäubler et al.,Rep. Progr. in Phys. **81**, 064401 (2018).
A. Yamaguchi *et al.* Applied Physics Express 4, 082203 (2011), T. Takano *et al.*, Nat. Photonics **10** (2016), J.Grotti *et al.*, Nature Physics 1 (2018)., E. Oelker *et al.*, Nat. Photonics **13**, 714–719 (2019).

A wide fields of applications

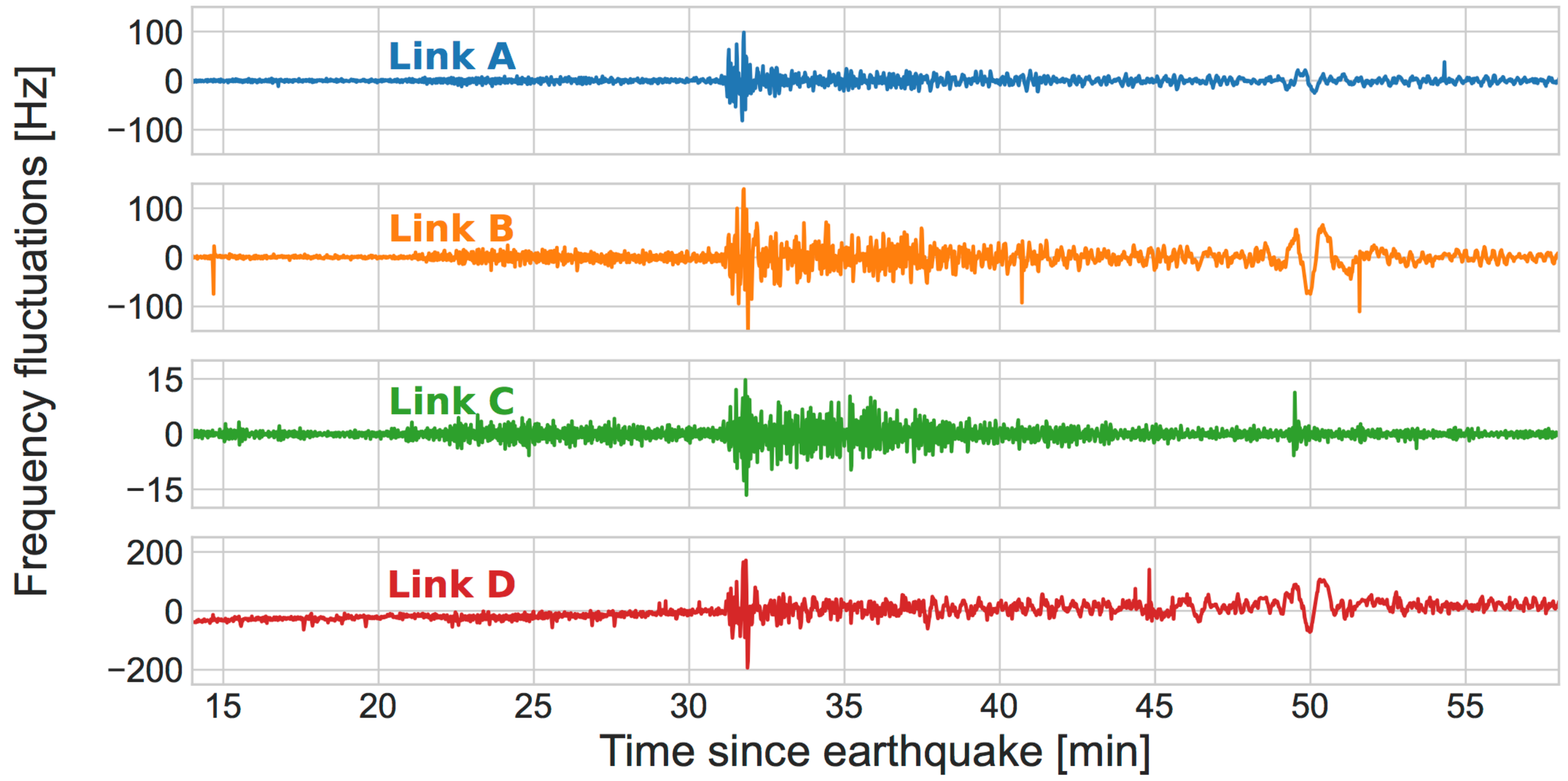
- Clocks and cavities comparisons
  - C. Lisdat *et al.*, Nat. Comm., **7**, (2016),
  - Guéna *et al.*, Metrologia, **54**, 3, (2017)
  - Lodewyck *et al.*, Phys. Rev R. **2**, 4 (2020)
  - Schioppo *et al.*, Nat. Comm **13**, 1(2022)
- Test of general relativity
  - P. Delva et al., Phys. Rev. Lett., **118**, 22 (2017)
- Chronometric geodesy
  - G. Lion et al., J Geod, **91**, 6, (2017)
- Search for Dark Matter
  - B. M. Roberts *et al*. New J. Phys. **22** (2020).
- High-precision atomic and molecular spectroscopy
  - B. Argence, *et al.*, Nat. Phot. **9** (2015).
  - R. Santagata *et al.*, R. *et al.* Optica **6** (2019).
  - F. Du Burck et al., JOSA B (2021) doi: 10.1364/JOSAB.442302.
  - O. Votava *et al.* Phys. Chem. Chem. Phys.(2022), doi: 10.1039/D1CP04989E.
- VLBI, GW, QKD, Seismic sensing…

see also
VLBI: C. Clivati et al., Optica (2020), doi: 10.1364/OPTICA.393356.
M. Pizzocaro et al., Nature Physics (2021) doi: 10.1038/s41567-020-01038-6.
QKD : C. Clivati et al., Nat Commun (2022) doi: 10.1038/s41467-021-27808-1.
GW : S. Kolkowitz, PRD **94** (2016), doi: 10.1103/PhysRevD.94.124043.

Dark matter



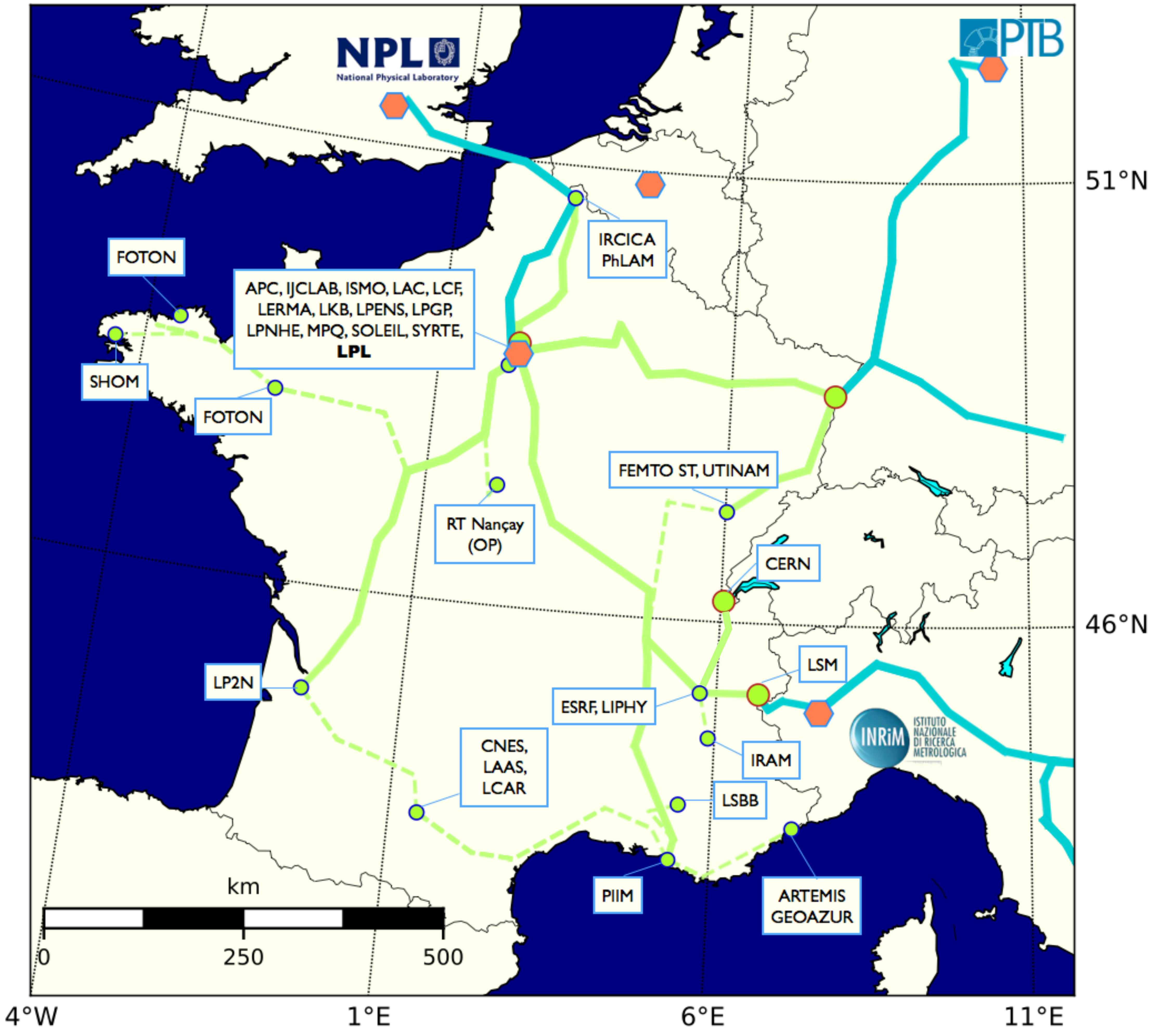
Seismic detection by a fiber network



M.Tønnes et al., in prep

T- REFIMEVE (2021-2029)

- Extension to Brest, IRAM, CERN; +14 new users
- RF (1GHz) and time signal on the optical carrier (bi-directional, highest performance)
- WR: 10 MHz and time signal, additional channel, mono-directional
- Mobile platform:
  - A test facility for the REFIMEVE users and exploration of chronometric geodesy
    - Extraction of the REFIMEVE signal
    - Transportable shelter with ultra-stable cavity, comb, and room to host a transportable clock or a transportable quantum sensor



Fundings

LIOM, REMIF, REFIMEVE+, T-REFIMEVE, FIRST-FT

LOFIC

JRP: NEAT FT, OFTEN, WRiTE, TIFOON
ITOC, ROCIT (clock comparisons)
H2020: ICOF

INSU
GRAM

ROME, LICORNE, TORTUE, (…)

EU Research infrastructure

CLONETS
CLONETS-DS

TOCUP, ONSEPA, (…)

Thank you for your attention