REFIMEVE optical fiber network
for time and frequency dissemination and applications

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Tuckey, Michel Abgrall, Rodolphe Le Targat, **Paul-Eric Pottie**
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Martin Rabault, Grégoire Coget, Peter Rosenbusch, Vincent Ménoret,
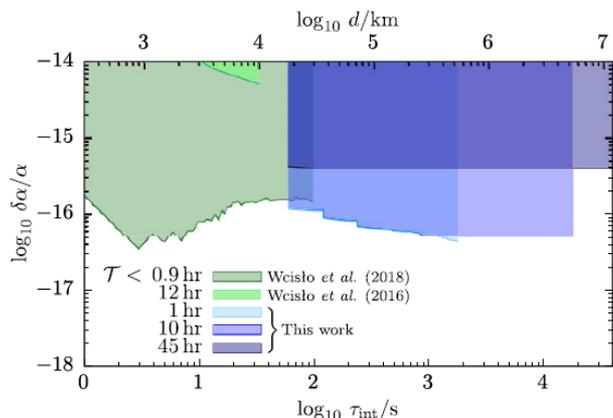**Exail Quantum Sensors (formerly Muquans)**, Talence, France

Nicolas Quintin, **RENATER**, Paris, France

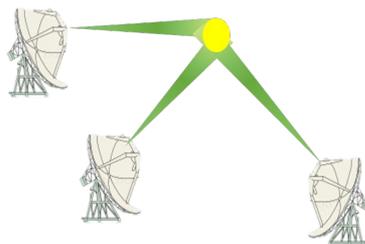# Motivation for time/frequency dissemination

Fundamental Science
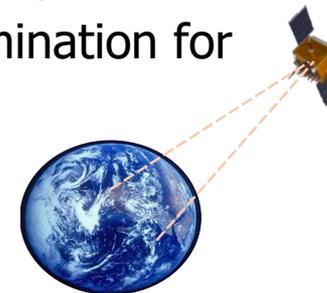Search for dark matter

Roberts et al, NJP2020

Astrophysics
Large instruments, array of detectors

Quantum technologies
Long-distance communications

Clivati et al, Nature Comm 2022

Time-frequency metrology
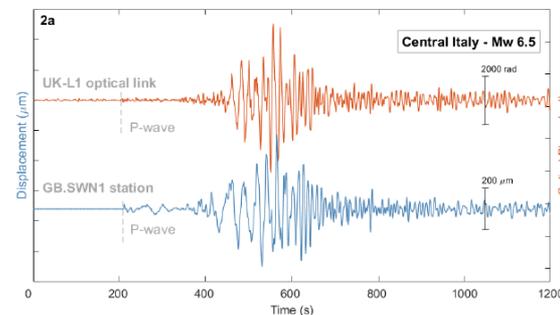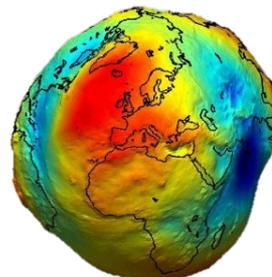Redefinition of the s, Dissemination for science and industry

Sensing – Defense
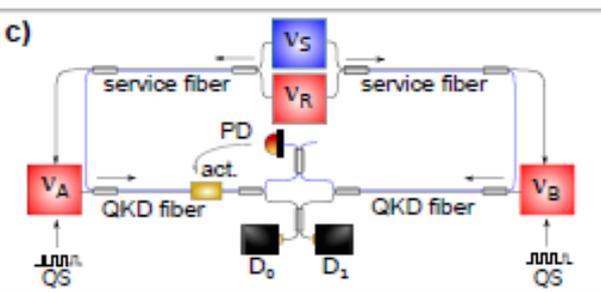Positioning, navigation, timing

Earth observation – Geodesy
Climate change – Sismology - Spectroscopy and atmospheric chemistry

Takano et al., Nat. Phot 2016
Lion et al., J Geod, 2017

Marra et al, Science 2019
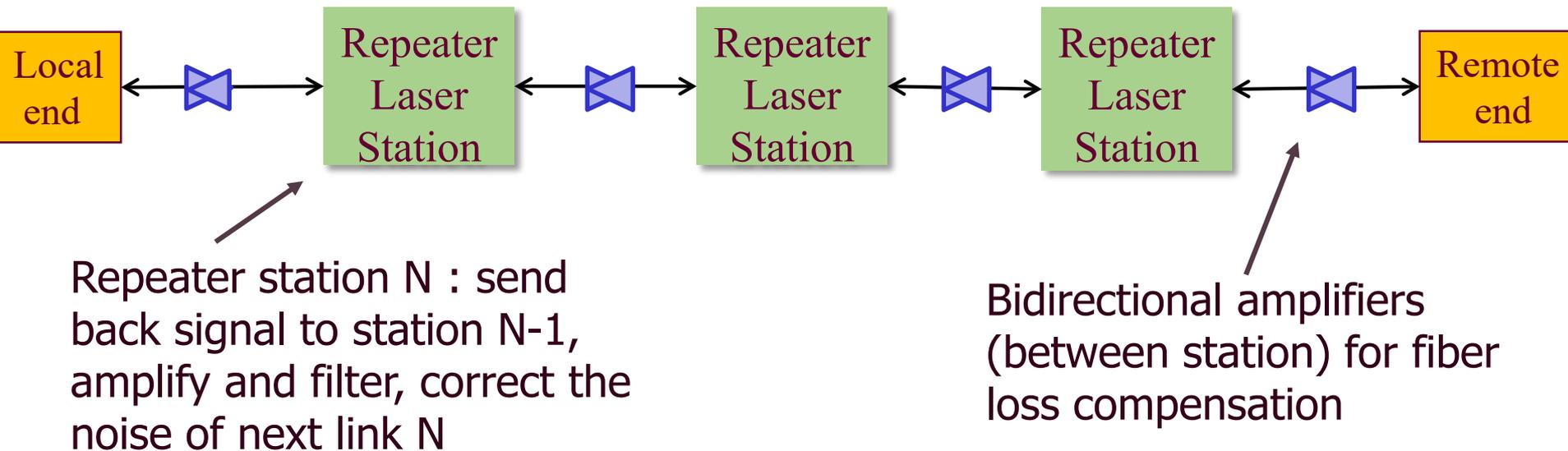
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Outline

I.   REFIMEVE network
   – Quick reminder on active noise compensation
   – REFIMEVE equipment
   – Network development
   – Results and performance

II. A few applications
   – International clocks comparison
   – High resolution molecular spectroscopy
   – Earthquakes sensing

Quick reminder about optical links

- Transferred signal: the frequency of an ultrastable laser
- Round-trip propagation noise detected with a strongly unbalanced Michelson interferometer
- → Doppler noise compensation or active noise compensation

- Assumption : Forward noise = ½ Round-trip noise
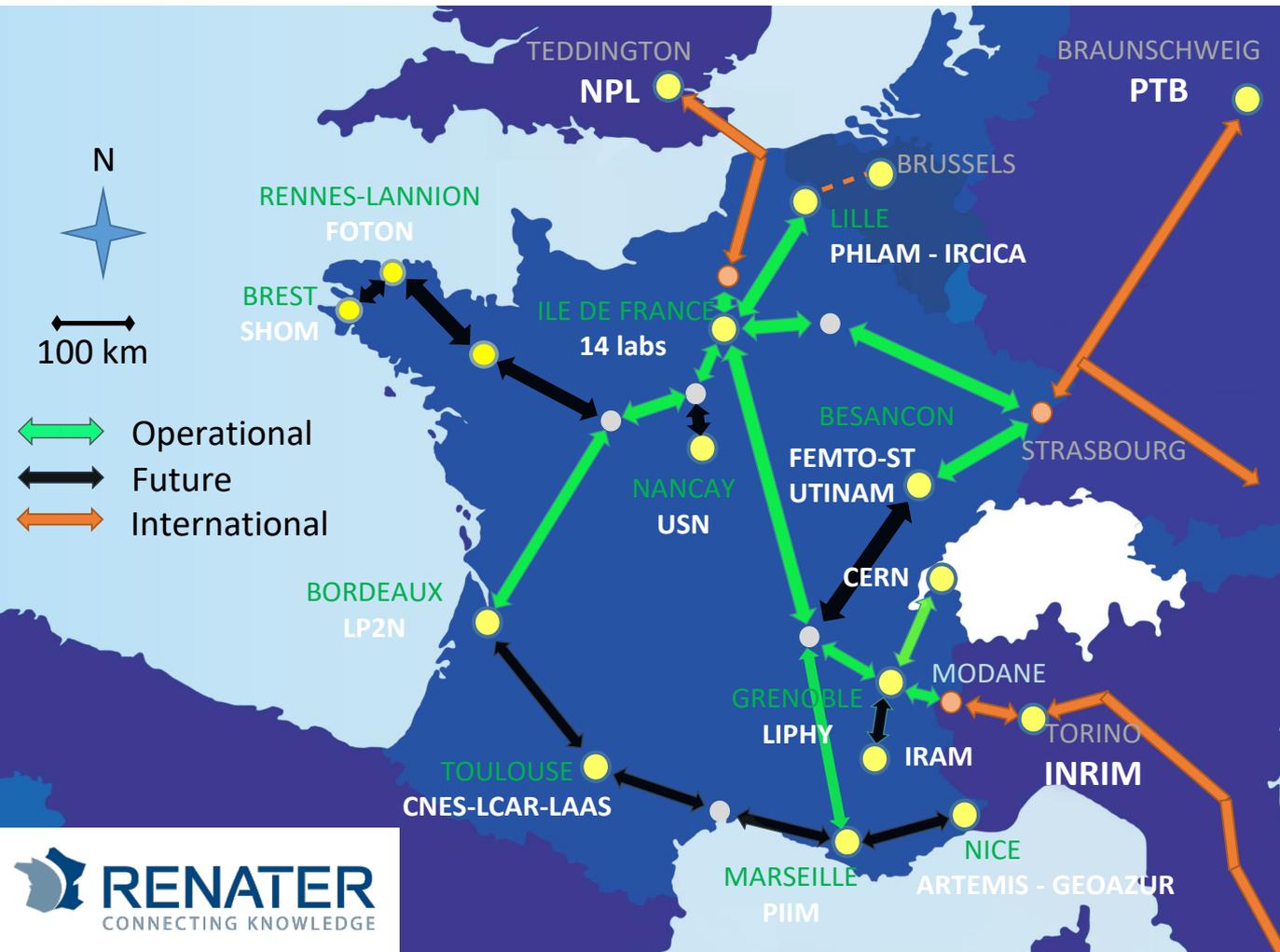 - → corrects only reciprocal noise   See Newbury OL 2007

Long-distance optical links

- Fiber noise power increases: $\propto L$ with large variations depending on fiber location (factor>100) (see for instance Clivati, Optica 2018)

- Attenuation due to fiber loss and connectors

  ➢ bidirectional optical amplifiers

  ➢ and/or signal regeneration

  → Link is divided into a few segments → cascaded link

  → shorter delay and better noise rejection

Repeater station N : send back signal to station N-1, amplify and filter, correct the noise of next link N

Bidirectional amplifiers (between station) for fiber loss compensation

See Lopez, Opt Exp 2010; Chiodo, Opt Exp 2015; Akatsuka, Opt. Exp 2020

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The REFIMEVE optical fiber network

French metrological network with an European vocation

Dissemination of time/frequency reference from LNE-SYRTE all around France

- Mainly using a dark channel of **RENATER** fiber network
- **Labelled as** National research infrastructure
- **2023:** 2x3800 km with 4 european connections
- **Future:** > 2x4500 km network

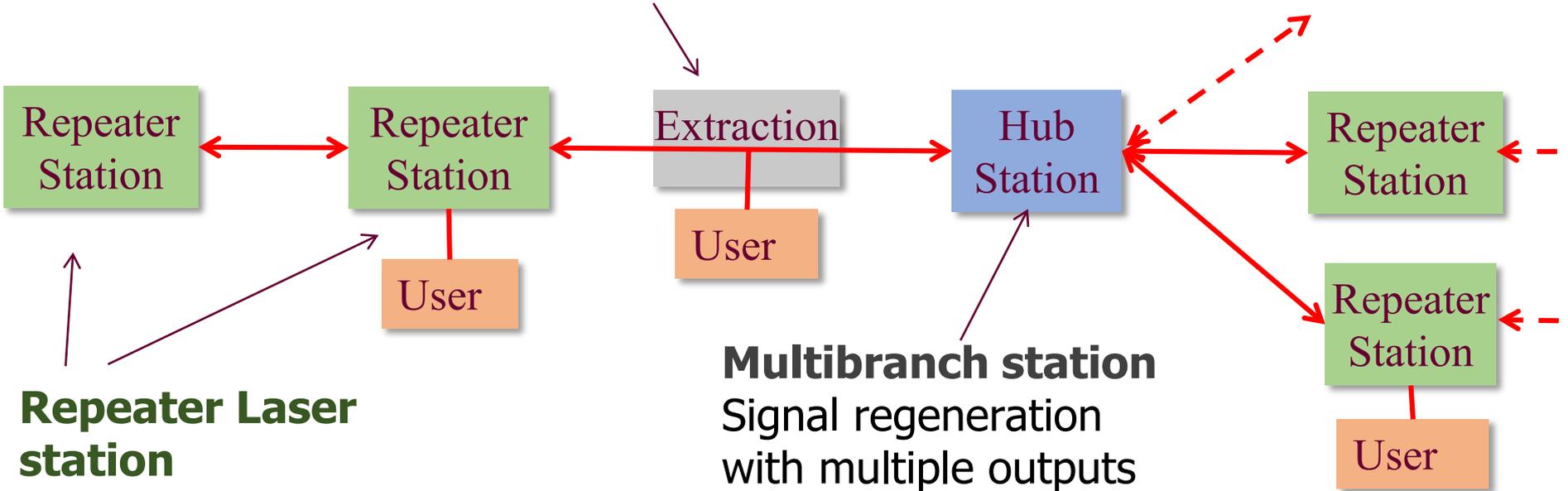# Time/frequency signals distributed with REFIMEVE

- **Time/frequency signals generated at LNE-SYRTE**

- **Optical frequency reference**
  - Ultrastable laser actively dedrifted versus H-maser/cryogenic oscillator
  - Fixed frequency at ±1 Hz (with cryogenic oscillator) or ±10 Hz (H-maser)
  - Stability@1s ~ 10^{-15} (0,5 Hz BW)
  - Uncertainty a few 10^{-15} (potentially a few 10^{-16})

- **White Rabbit**
  - Currently only in Paris region to all main universities (>10 labs)
  - See P.E Pottie poster

- **Future : ultra-stable timing signal**

REFIMEVE network equipment

exail (Muquans)

In-line extraction station
noise detection/correction at extraction point

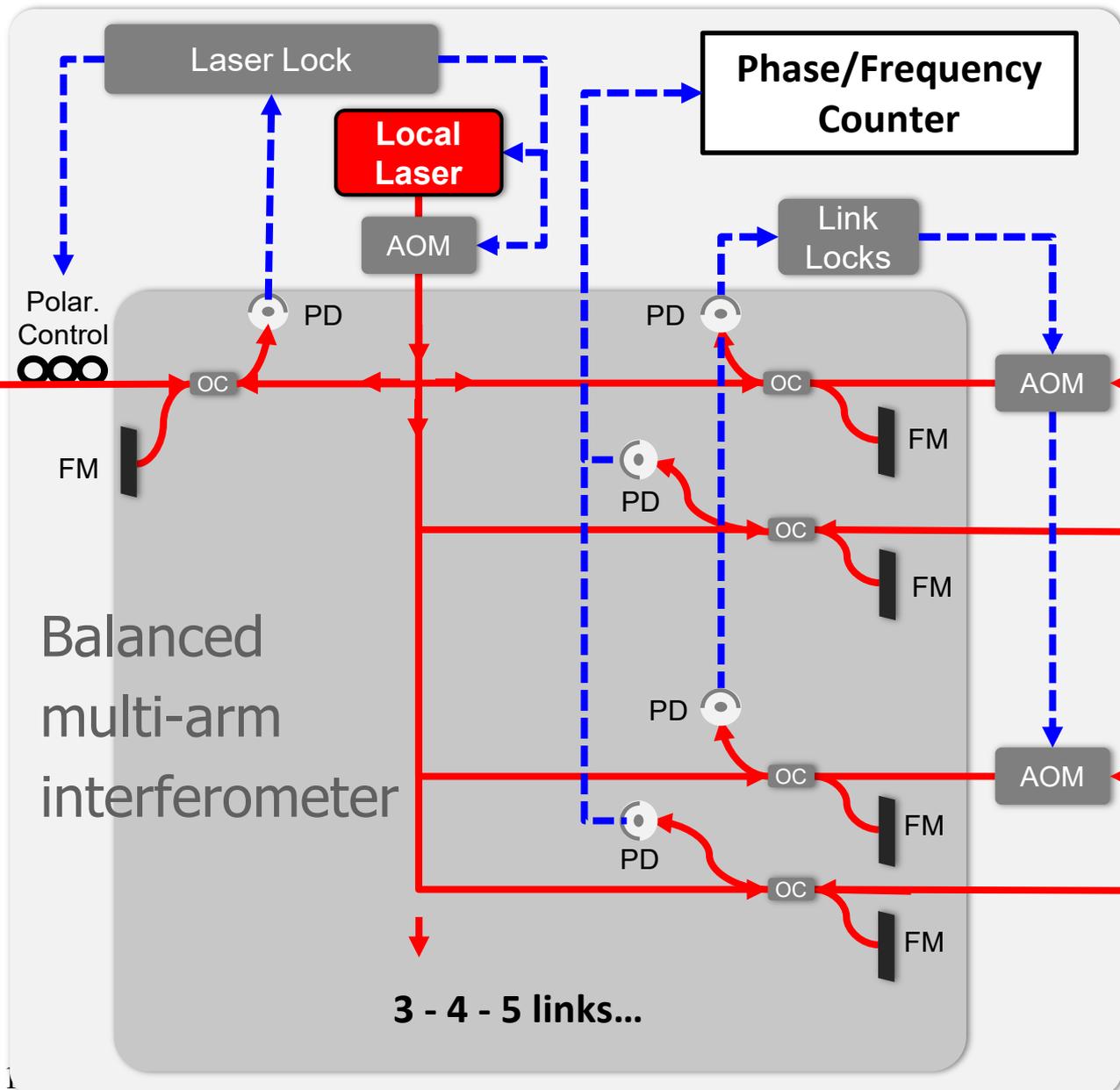| Repeater Station		Repeater Station		Extraction		Hub Station		Repeater Station

User

User

User

Repeater Station

User

Repeater Laser station
Signal regeneration
Link noise correction
User output

Multibranch station
Signal regeneration
with multiple outputs
Link noise correction
Residual noise assessment

Automated - Remotely controlled
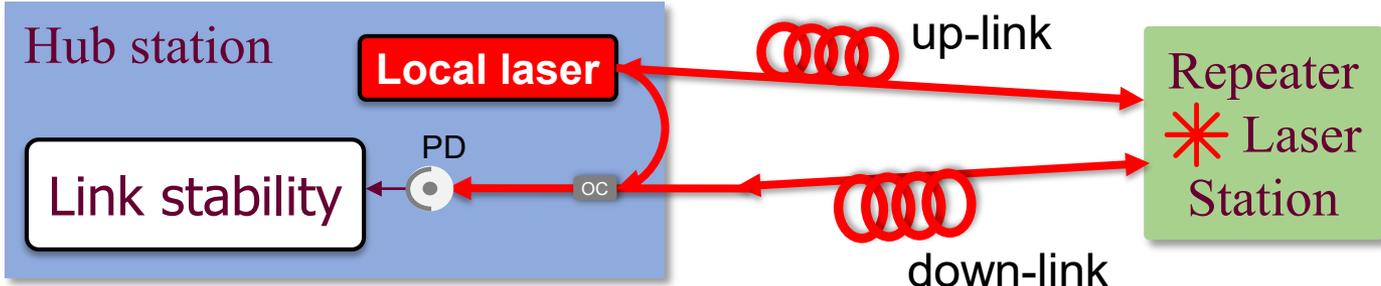Commercially available – Can be installed in telecom hub
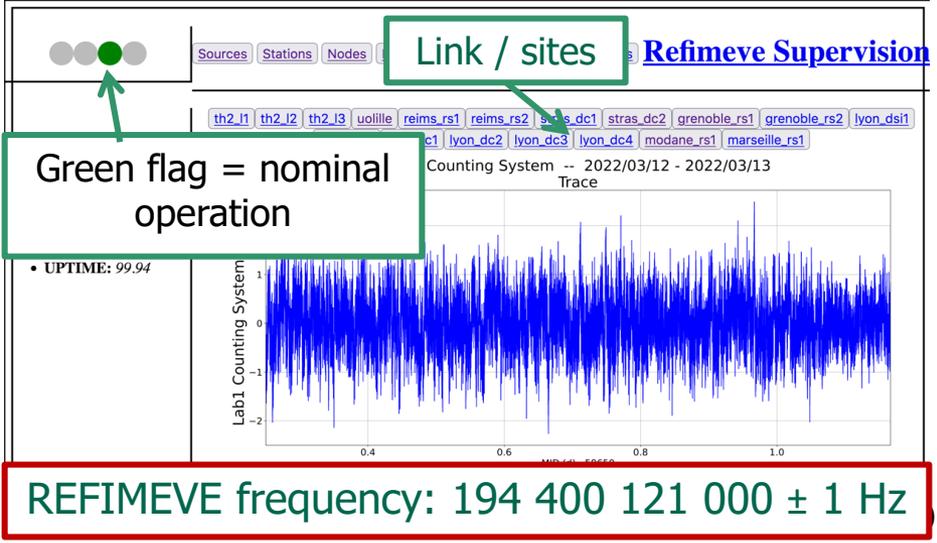
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Hub station = Multi-branch laser station (MLS)

- Same robust design than RLS

Cantin et al 2021
New J. Phys.
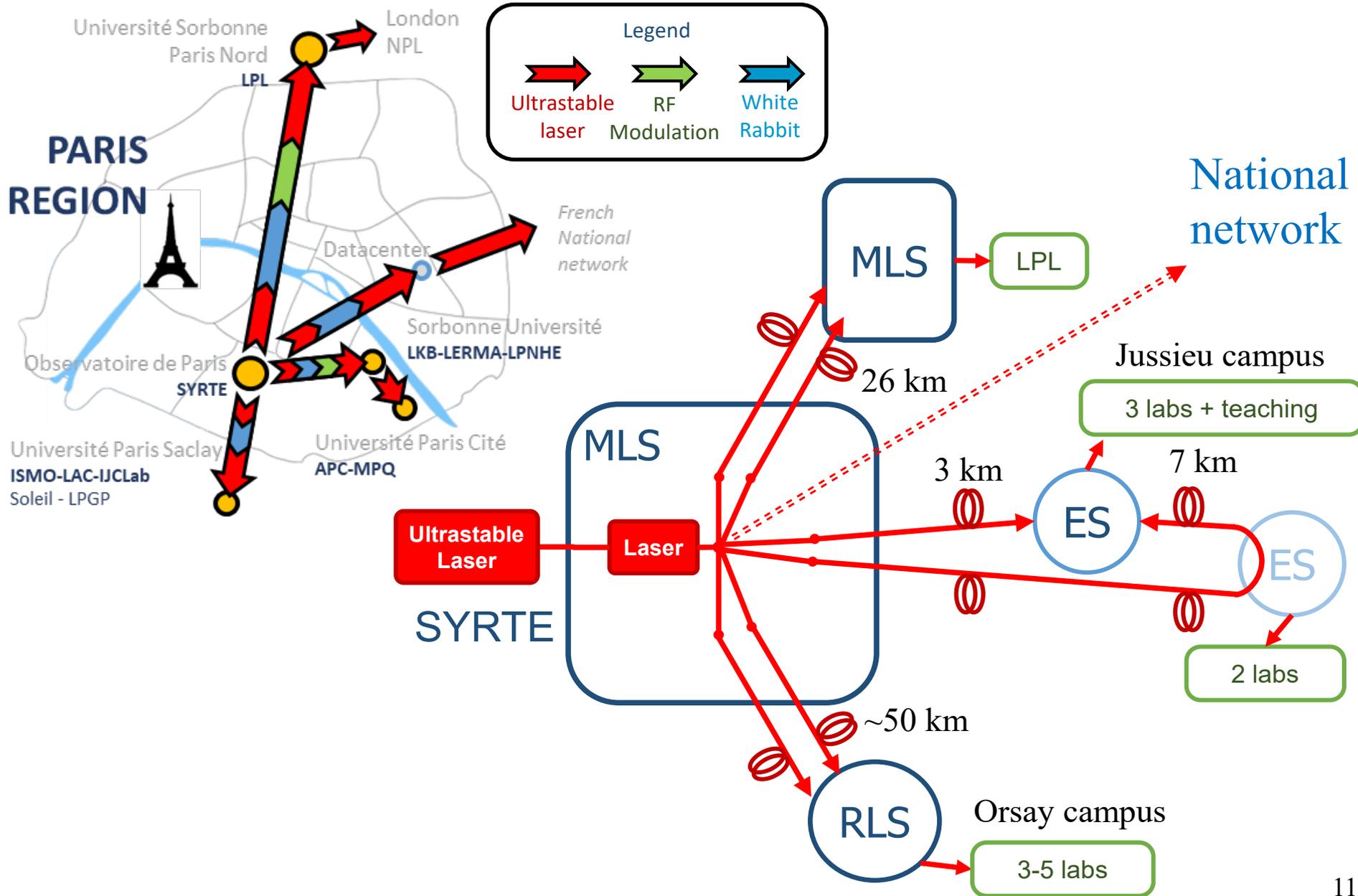
Network real-time supervision

- Throughout the network, a parallel downlink is implemented to assess link performance → out-of-loop detection of the transferred signal
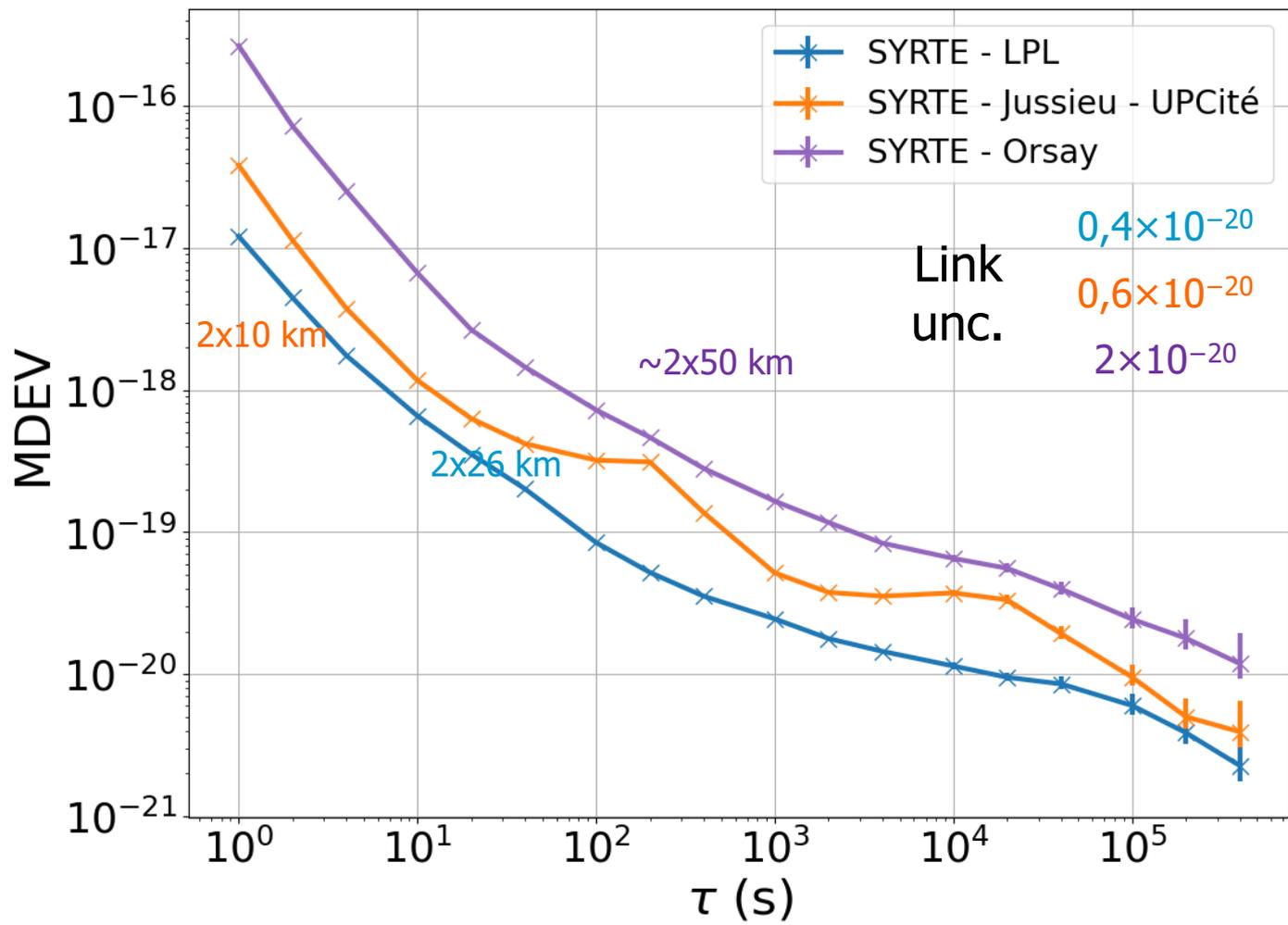 - → upper value of up-link stability & uncertainty

- Supervision of all equipment (RLS, amplifiers…)

  - through RENATER supervision network
  - centralized system
  - with data processing (automatic plots, flags..)
  - with data backup
  - future : more alarms, smarter processing …
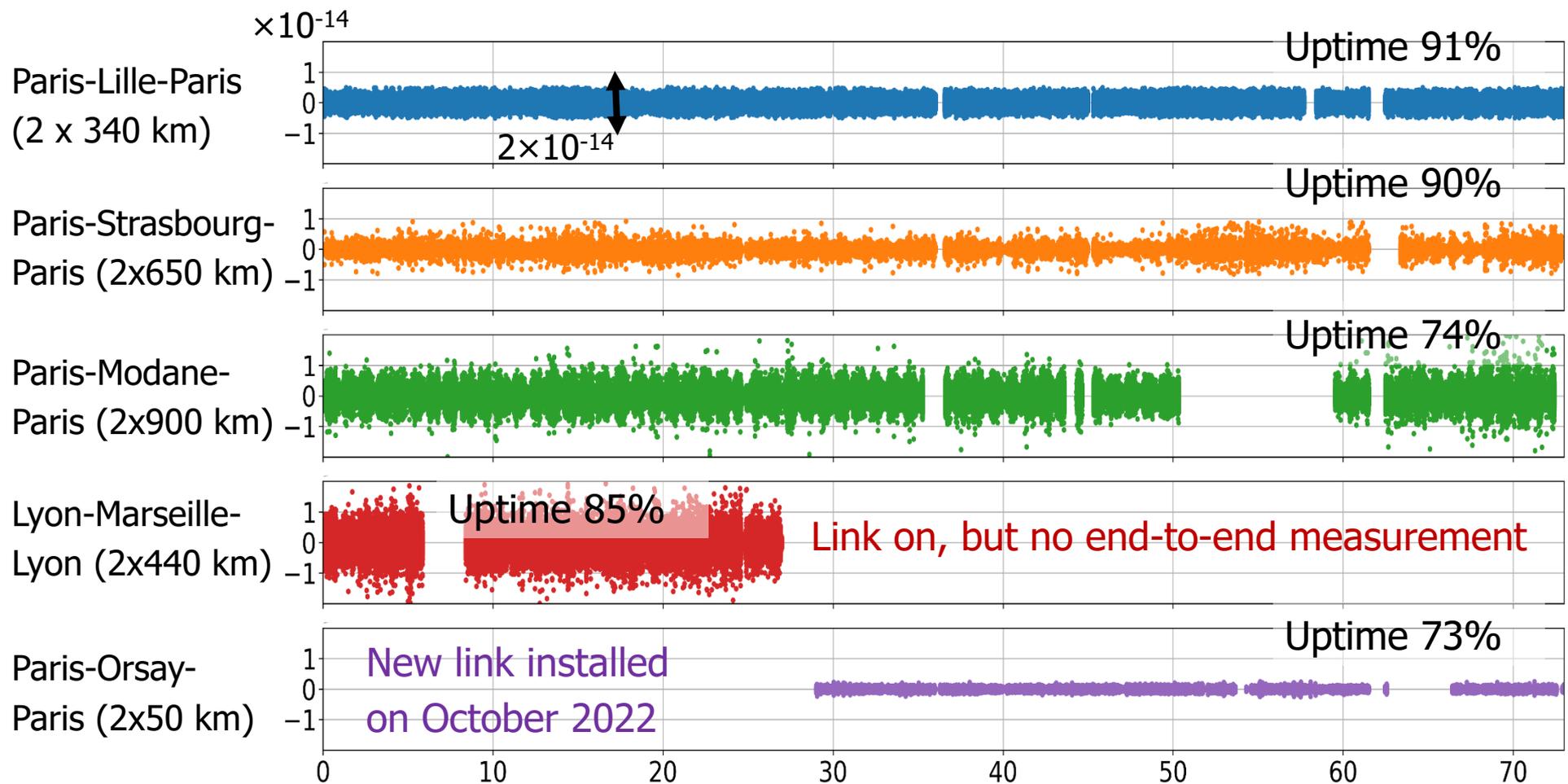

exail

Dissemination to >10 labs in Paris region

Frequency transfer over 2x3800 km of optical links
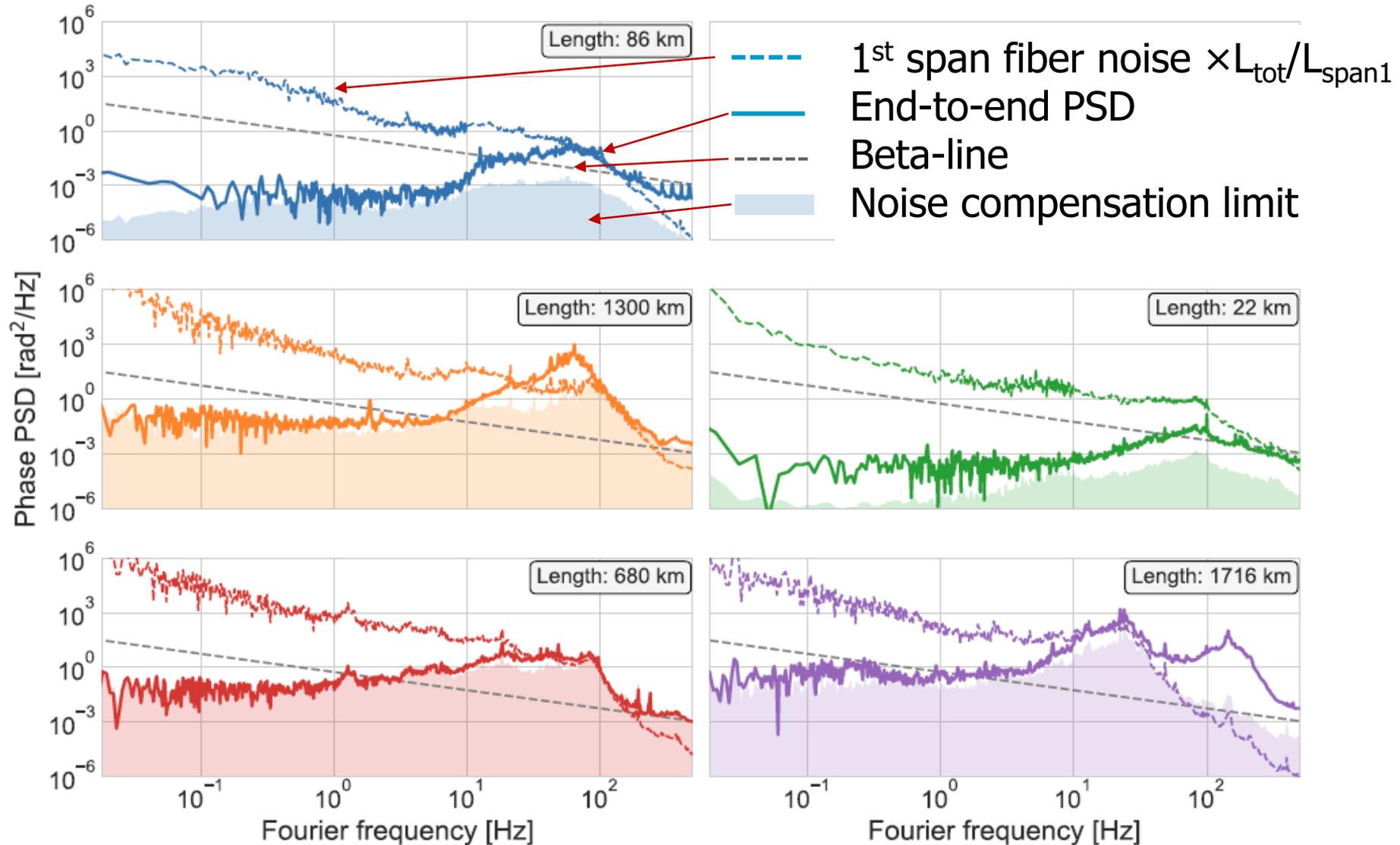
Relative frequency fluctuations (1s/point) with time

Paris-Lille-Paris (2 x 340 km) — Uptime 91%

$\times 10^{-14}$

2×10^{-14}

Paris-Strasbourg-Paris (2x650 km) — Uptime 90%

Paris-Modane-Paris (2x900 km) — Uptime 74%

Lyon-Marseille-Lyon (2x440 km) — Uptime 85% — Link on, but no end-to-end measurement

Paris-Orsay-Paris (2x50 km) — New link installed on October 2022 — Uptime 73%

73 days (september-november 2022)

Residual link unstability and uncertainty

Up- & down link residual unstability

2x340 km — Paris - Lille
2x650 km — Paris - Strasbourg
2x900 km — Paris - Modane
2x440 km — Lyon - Marseille
2x50 km   — Paris - Orsay

3×10^{-20}
1×10^{-20}
3×10^{-20}
8×10^{-20}
1×10^{-20}

Uncertainty on transferred frequency

Up- and down links phase noise PSD

18/10/2023

Link Grenoble-CERN-Grenoble (2 x 200 km)

Paris ⟷ 600 km ⟷ Lyon ⟷ 440 km ⟷ Marseille

Lyon ⟷ 120 km ⟷ Grenoble ⟷ 200 km ⟷ Cern

Grenoble ⟷ 145 km ⟷ Modane ⟷ 155 km ⟷ Torino

5 days
97,5% uptime

7 hours
99,9%
uptime

Uncertainty on
transferred frequency
$1{,}4 \pm 4.2 \times 10^{-19}$

Noise study/processing at yearly scale (M. Tønnes PhD)

- 5 years data on the 2x700 km Paris-Strasbourg link
- Stability estimated with various processing method
  - Concatenation of data
  - Replacement of missing data by simulated data

M. Tønnes *et al.*, Metrologia. **18**, 054009 (2022)

Outline

I. REFIMEVE network
    – A few reminders on active noise compensation
    – REFIMEVE equipment
    – Network development
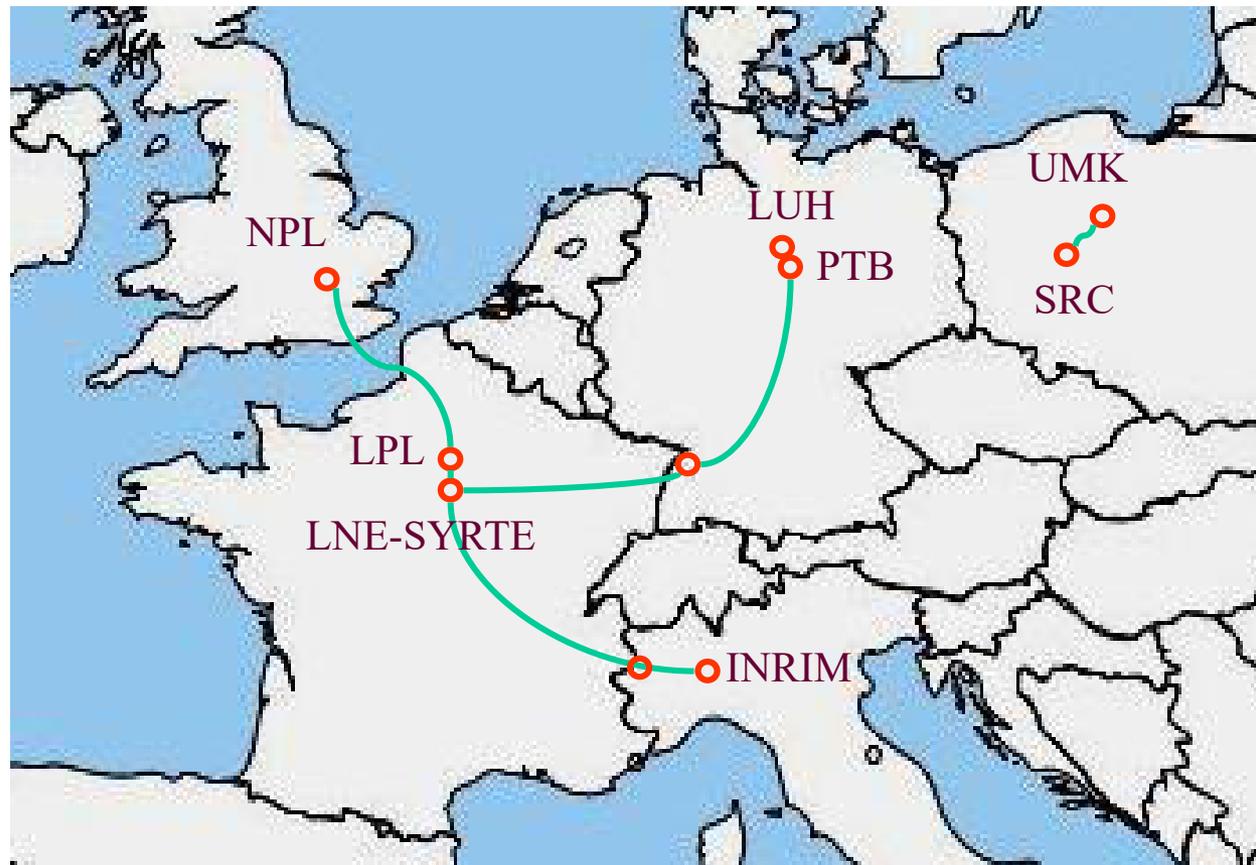   – Results and performance

II. **Recent applications**
    – **International clocks comparison**
    – **High resolution molecular spectroscopy**
    – **Earthquakes sensing**

Optical fiber links for clocks comparison in Europe

8th FSM : 1st european clocks comparison by optical fiber link, SYRTE and PTB Sr clocks, with gravity potential correction
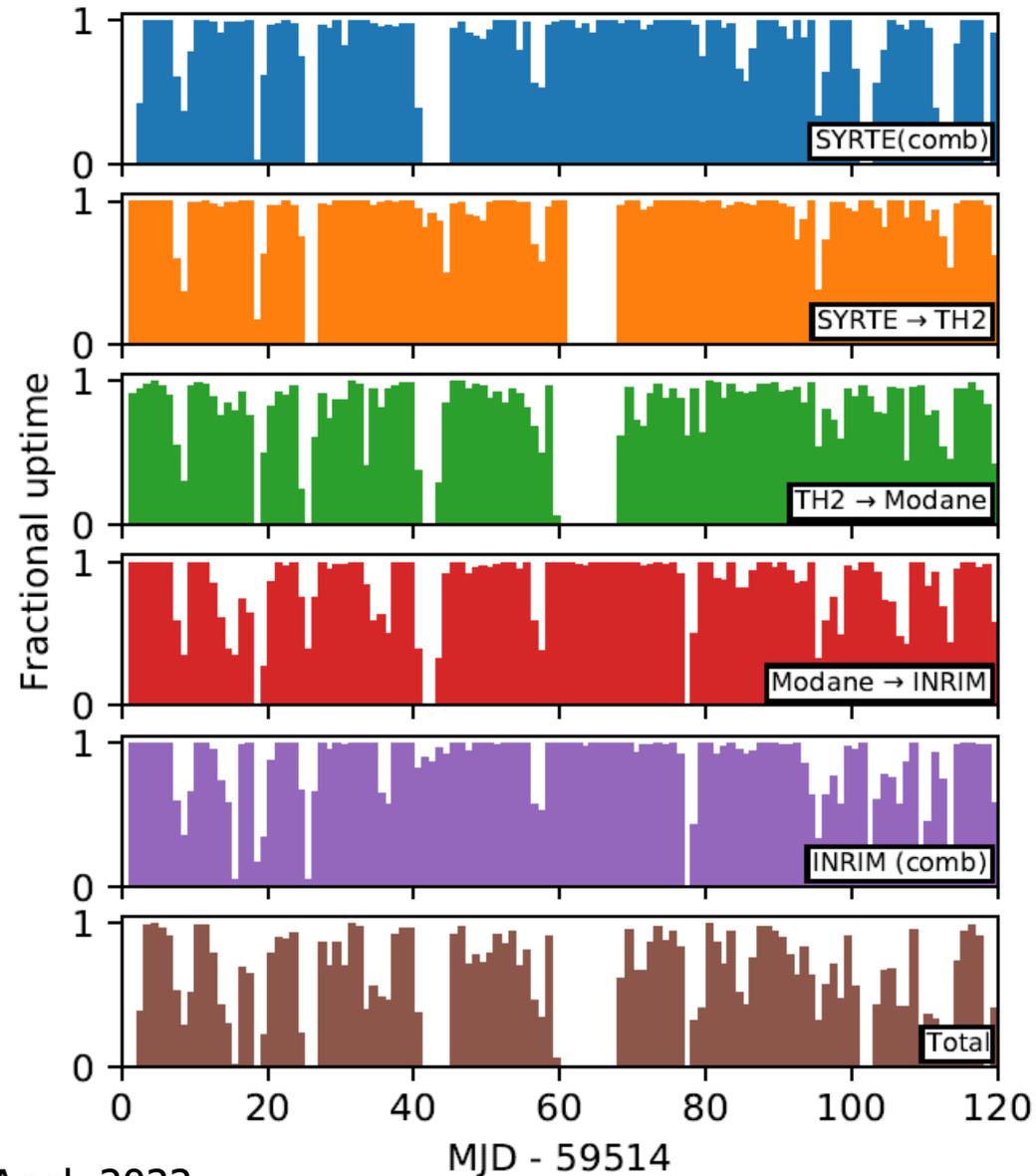
2015-2023 : many campaigns, including ROCIT campaigns

- ➢ T&F metrology, redefinition of second
- ➢ Chronometric geodesy (Lisdat et al, Nat. Comm 2016)
- ➢ Test of special relativity (Delva et al, PRL2017), **search for dark matter** (Roberts et al, NJP2020) …

Schioppo et al, Nat. Comm. 2022 ; Clivati et al, Phys. Rev. Appl. 2022

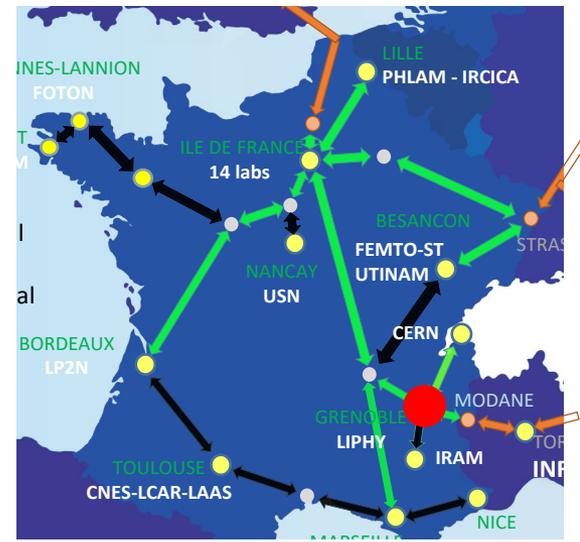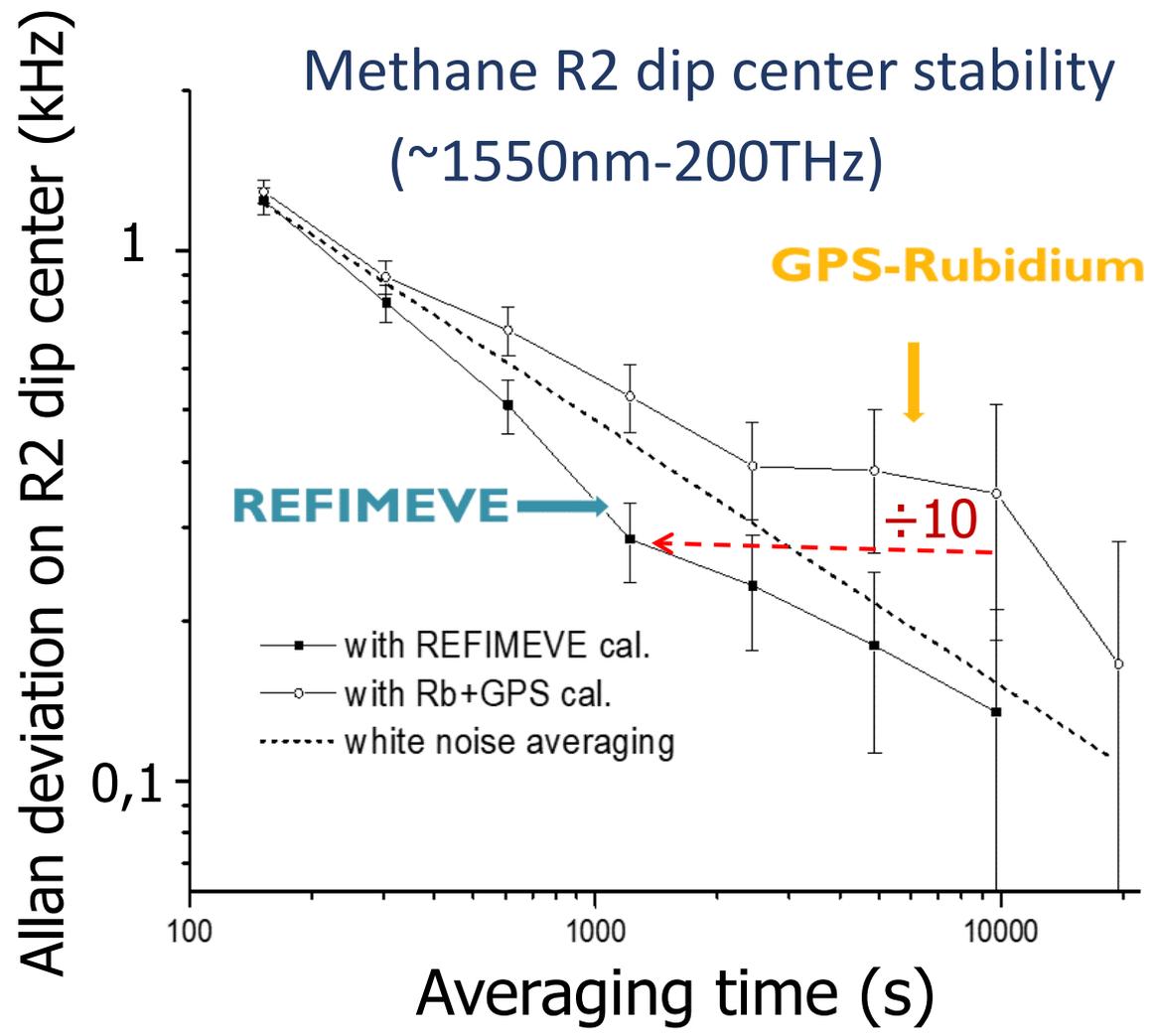# Towards more frequent comparison campaigns

- **Uncertainty** better than 10^{-18} even for longer links

- **Robustness** improved by automatisation as required for long campaign / multiple links (3 links >700 km in France)

- Example : SYRTE(Paris) – INRIM(Torino) link with 4 months campaign (2021-2022)

  - Uptime 56 % on the full campaign (with combs)
  - Up to 72 % over 1 month

Clivati et al, Phys. Rev. Appl. 2022

High resolution molecular spectroscopy using REFIMEVE signal at LIPHY

730 km from SYRTE, user output on the link to Italy

Methane R2 dip center stability (~1550nm-200THz)

GPS-Rubidium

REFIMEVE →

÷10

- with REFIMEVE cal.
- with Rb+GPS cal.
- white noise averaging

Allan deviation on R2 dip center (kHz)

Averaging time (s)

See O. Votava, S. Kassi, A. Campargue, D. Romanini, *PCCP 2022*
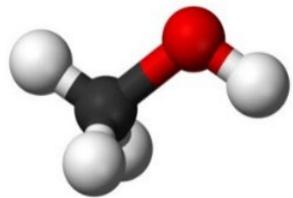
High precision measurement in the mid-Infrared

- REFIMEVE signal stability and accuracy is copied to the Quantum Cascade Laser (~10 μm or 30 THz) at LPL
  - ➢ QCL noise reduction → better resolution
  - ➢ QCL frequency traceable to SYRTE primary standards

$$\nu_{QCL} = \frac{n}{N} \nu_{REF} + \textit{other known terms}$$

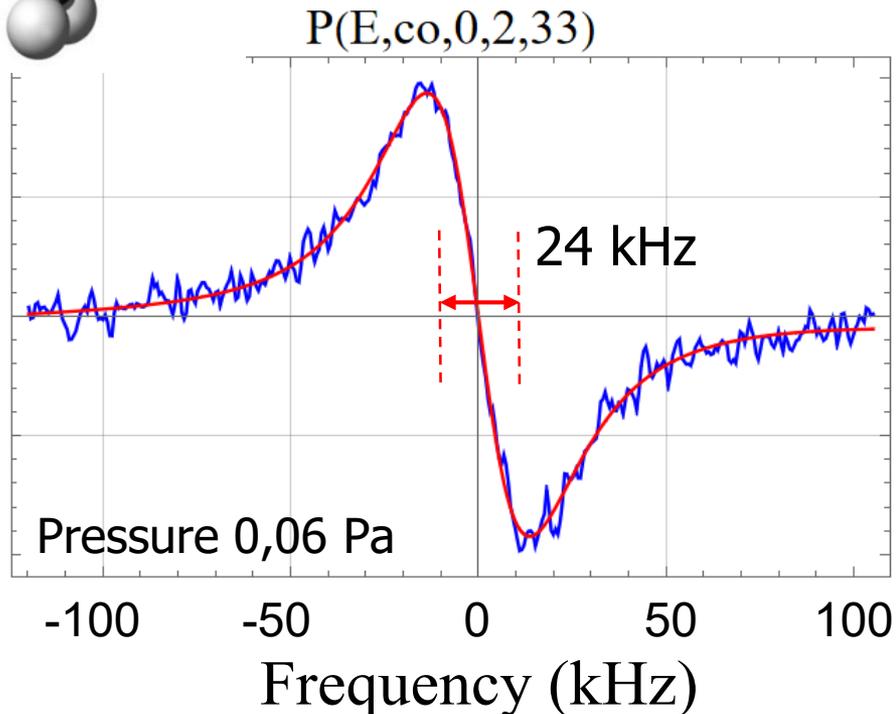Santagata et al, Optica 2018

Precision molecular spectroscopy

Frequency control → QCL → (Fabry-Perot cavity / molecular gas) → Photo-detector

Work performed by N. Cahuzac, Y. Liu, O. Lopez, M. Manceau, **B. Darquié**

Methanol (CH_3OH)

P(E,co,0,2,33)

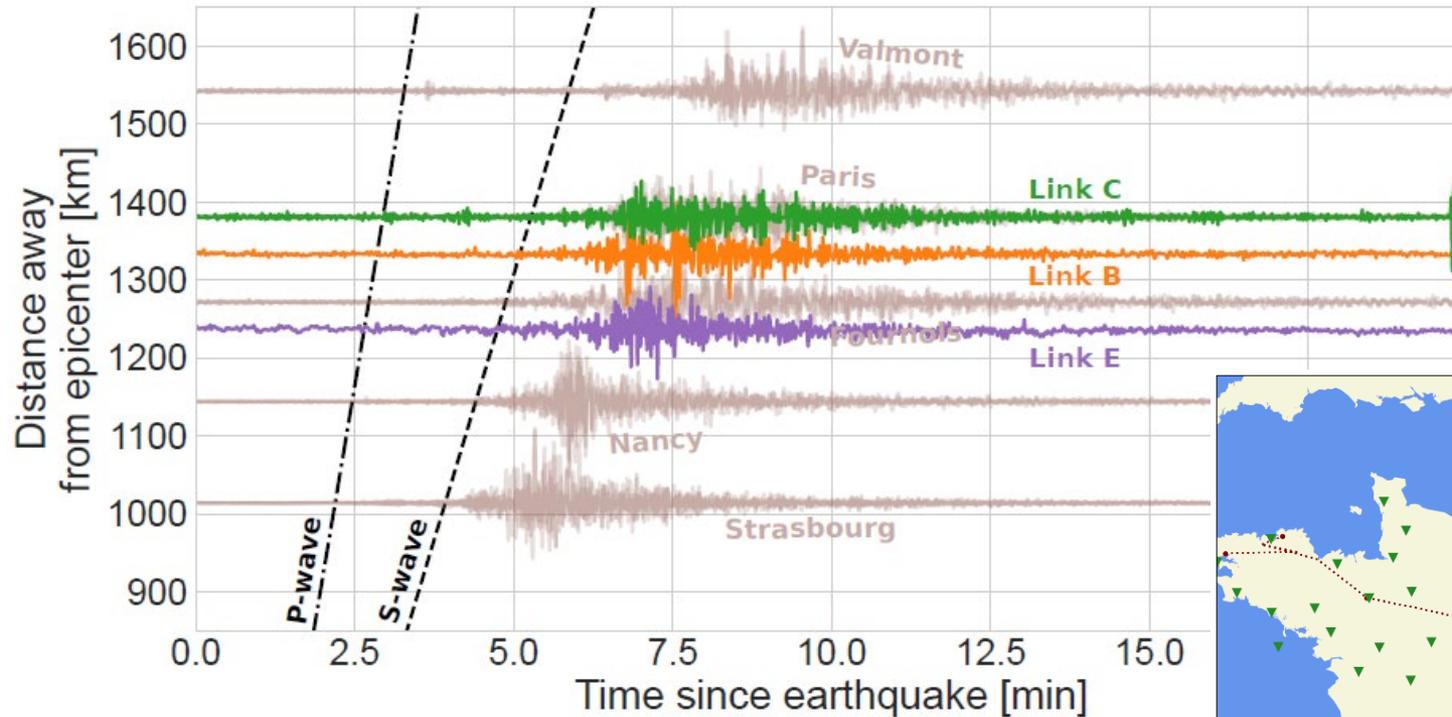24 kHz

Pressure 0,06 Pa

-100   -50   0   50   100

Frequency (kHz)

➤ Molecule of interest for atmospheric studies & fundamental molecular spectroscopy

➤ Also for improving test of m_p/m_e spatial variation in milky way, limited by lab data, $\Delta\mu/\mu < 2\times10^{-8}$

➤ Line center uncertainty **0,6 kHz,** limited by systematic shifts
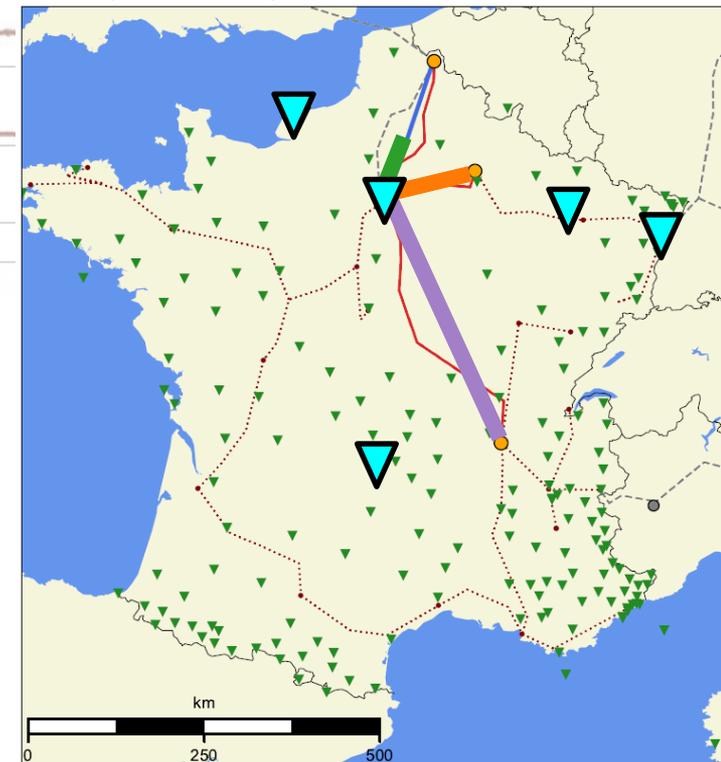
Earthquakes sensing with fiber links

➢ Fiber links are sensitive to seismic vibrations → they act as seismometers

Detection of an Mw 5.7 earthquake in
Bosnia (from M Tønnes, PhD thesis, 2022)

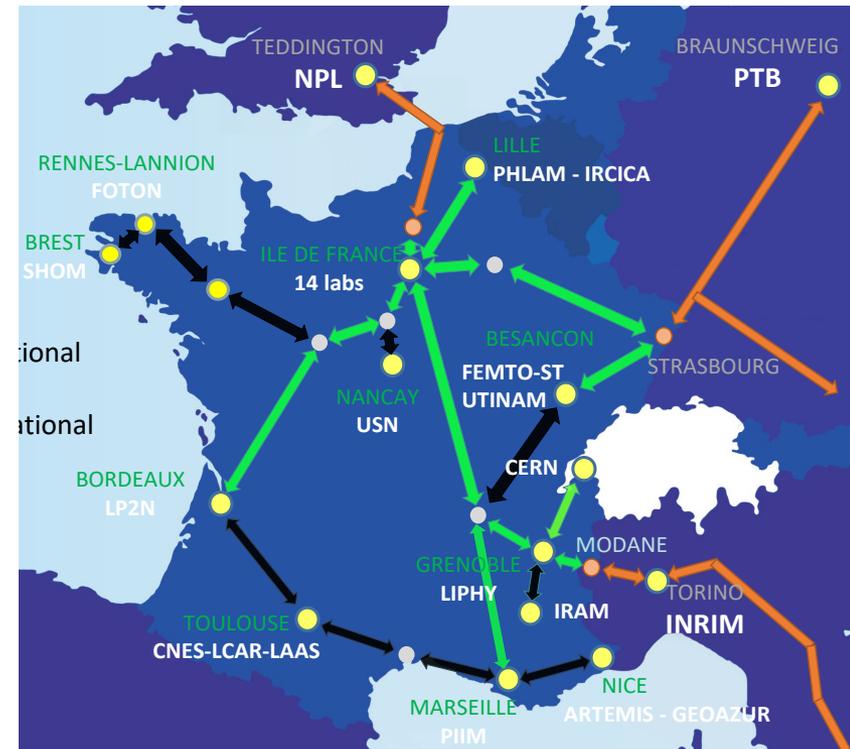See next talk of D Calonico

Outlook

- **REFIMEVE infrastructure**
  - +15 labs connected in France
  - Clocks comparison with UK, Germany, Italy

- **Current development**
  - Extension to > 30 labs in France
  - Extension to RF and time transfer

- **Applications beyond metrology**
  - Search for fundamental constants variation or for dark matter, sea level monitoring with chronometric levelling...
  - Earthquakes sensing, synchronization for astrophysics (VLBI) or high-energy physics ...
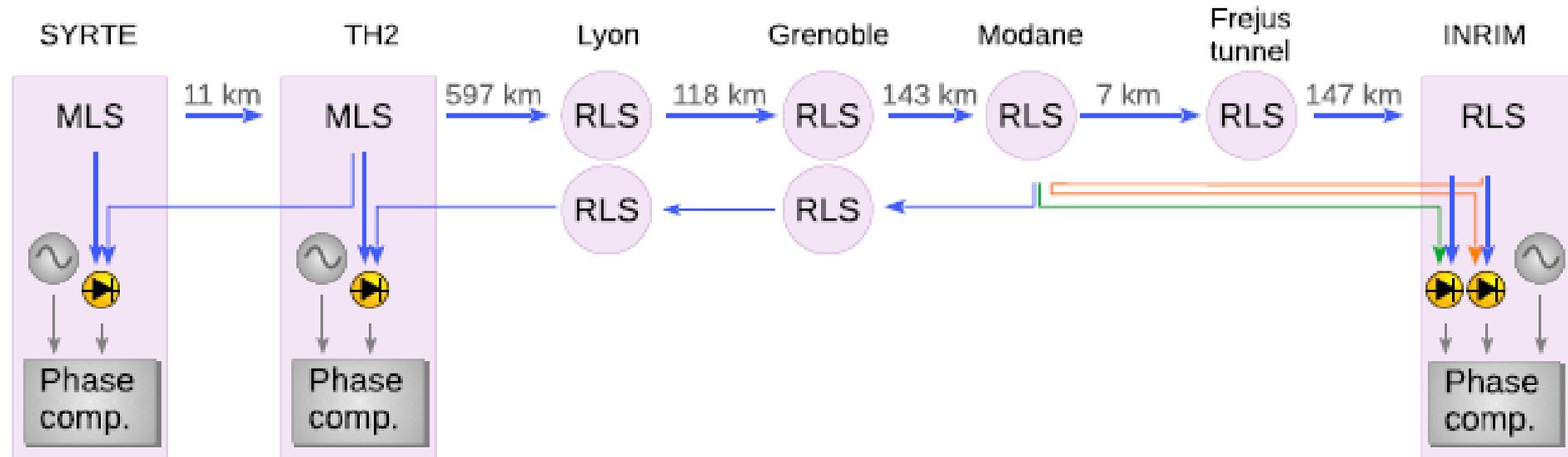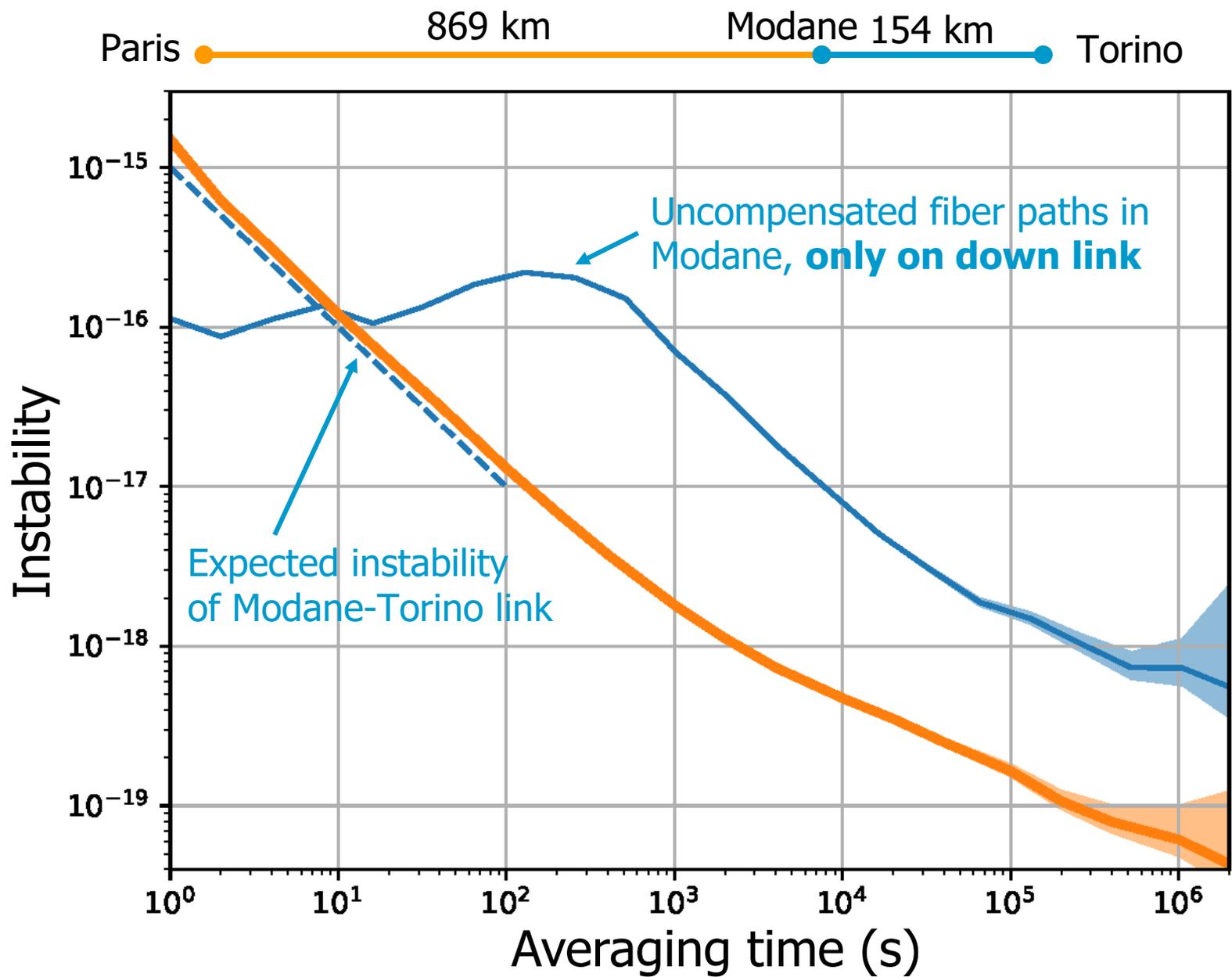
Thank you for your attention

Co-Fundings

Link budget

	Shift	Statistical	Systematic
Remote frequency reference	$1.7 \cdot 10^{-18}$	$1.0 \cdot 10^{-19}$	-
Desynchronization of counters	$2.9 \cdot 10^{-22}$	$2.6 \cdot 10^{-30}$	-
Desynchronization of computers	$2.4 \cdot 10^{-24}$	$3.6 \cdot 10^{-24}$	$3.7 \cdot 10^{-22}$
Uncompensated fiber noise, Link B	$1.7 \cdot 10^{-20}$	$4.5 \cdot 10^{-20}$	$< 1 \cdot 10^{-19}$
Uncompensated fiber noise, Link C	$1.1 \cdot 10^{-20}$	$1.4 \cdot 10^{-20}$	$< 1 \cdot 10^{-19}$
Total	$1.7 \cdot 10^{-18}$	$1.1 \cdot 10^{-19}$	$< 1.4 \cdot 10^{-19}$

TABLE 5.1: Uncertainty budget of the French network for the clock comparison between SYRTE and PTB in March 2022.
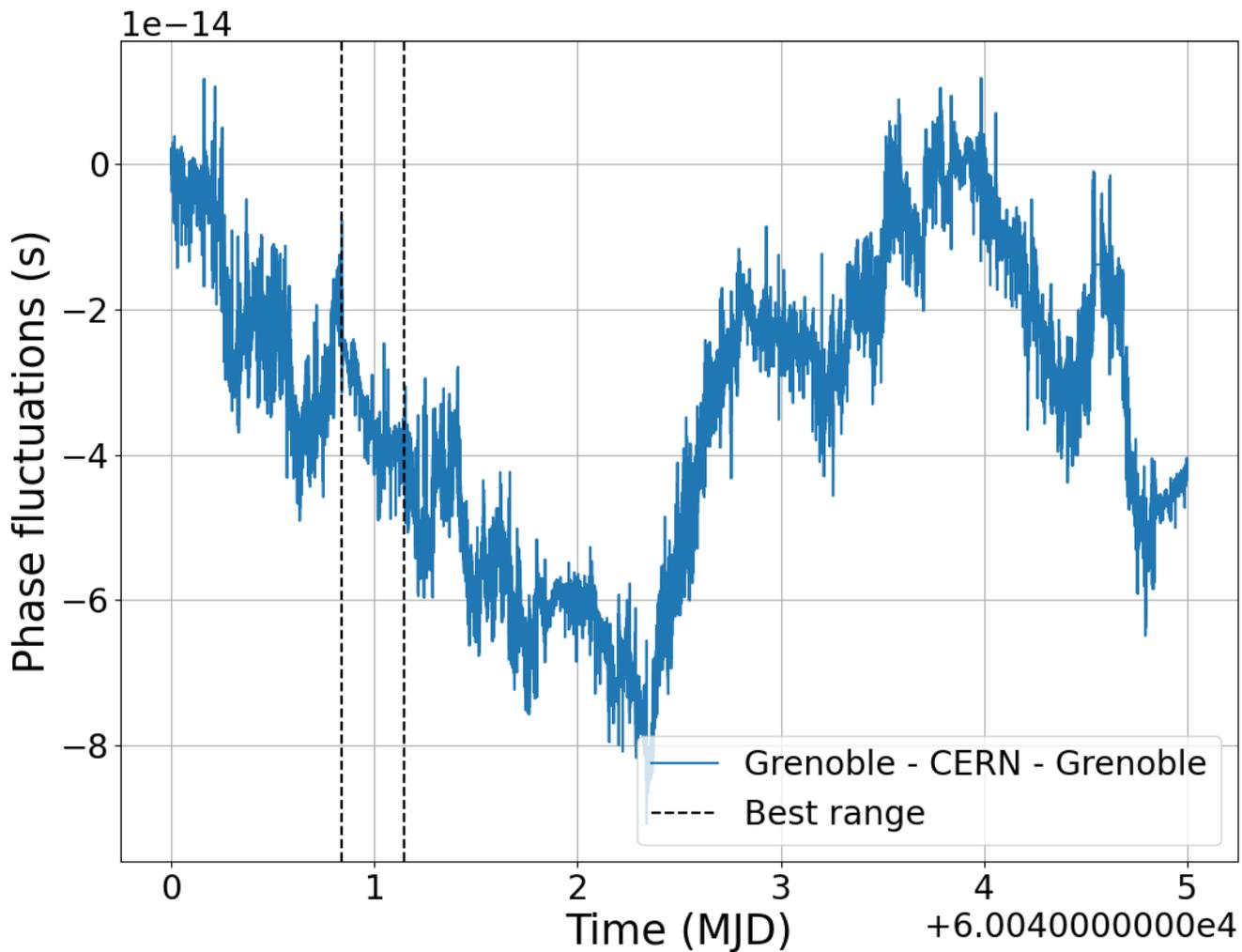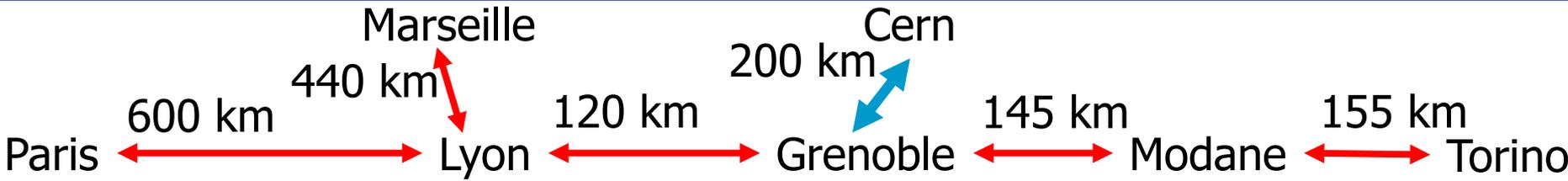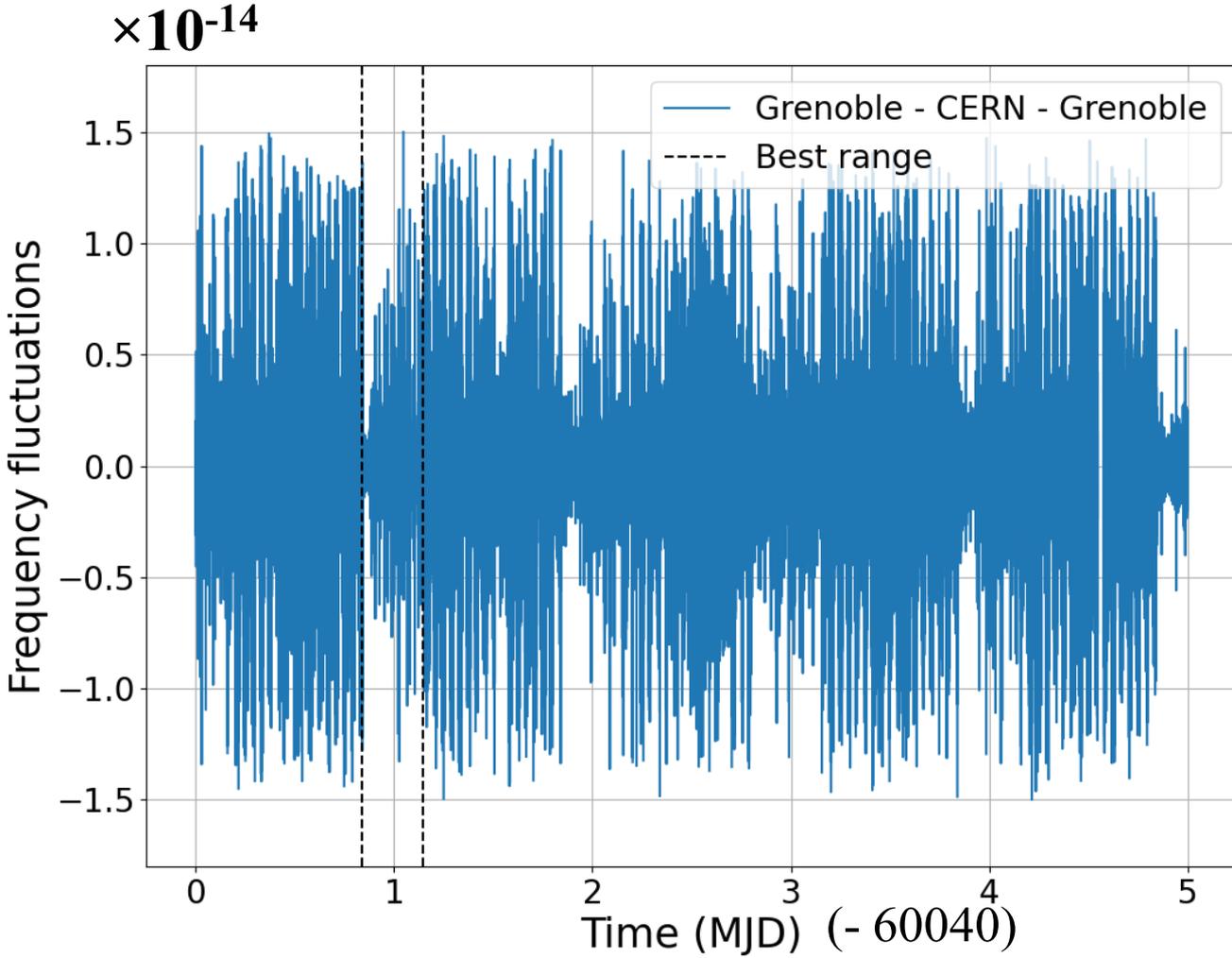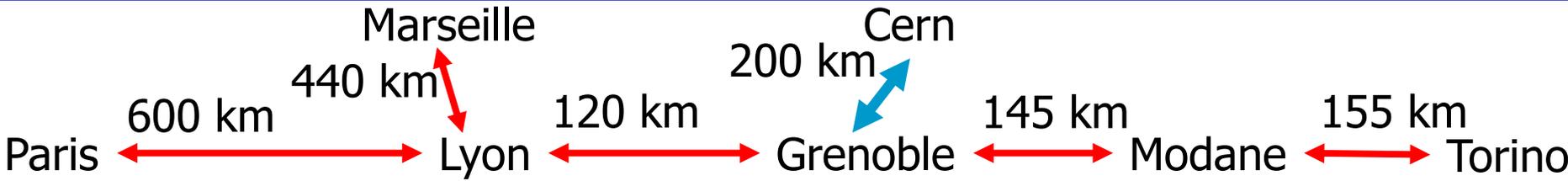
Paris-Torino link

Paris-Modane-Torino link instability (upper value)

Paris — 869 km — Modane 154 km — Torino

Uncompensated fiber paths in Modane, **only on down link**

Expected instability of Modane-Torino link

Instability

Averaging time (s)

Link Grenoble-CERN-Grenoble (2 x 200 km)

Link Grenoble-CERN-Grenoble (2 x 200 km)

National network

18/10/2023

Frequency fluctuations (Hz)

Link SYRTE-NPL (outside REFIMEVE)

NPL
National Physical Laboratory

NPL dark fibers

W Huang , J. O. Gaudron, N. Kaur, [J Kronjaeger]

LPL-NPL
Preliminary
with raw filtering

19-21 March
85% uptime

- ➤ ~ 20% outliers: very noisy link, not stationary
- ➤ An intermediate regeneration would help

- ➤ Day-dependent, long-term stability around or <10^{-18}
- ➤ Uncertainty around or below 10^{-18}

QCL (10 μm) frequency stabilization

SYRTE

$\nu_{\textbf{REFIMEVE}}$

fiber link

LPL

OFC

f_0

1.82 μm   **1.55 μm**

f_{rep}

$q\,f_{\textbf{rep}} + f_0$

SFG
AgGaSe$_2$

$p\,f_{\textbf{rep}} + f_0$

10.3 μm

QCL

$\nu_{\textbf{QCL}}$

$q\,f_{\textbf{rep}} + f_0 + \nu_{\textbf{QCL}}$

PLL

$\nu_{\textbf{QCL}} - (\textbf{p-q})\,f_{\textbf{rep}}$

Step 1
Comb repetition rate locked to SYRTE frequency reference (and f_{CEO} RF-locked or removed)

Step 2
QCL locked to comb using sum-frequency generation of comb and QCL in a nonlinear crystal

$$\nu_{\textbf{QCL}} = \frac{\textbf{n}}{\textbf{N}}\,\nu_{\textbf{REF}} + \Delta$$

9-11 μm tunability - 1,4 GHz continuous tunability