Ultrastable frequency transfer through the REFIMEVE optical fiber network

E. Cantin, O. Lopez, C. Chardonnet, A. Amy-Klein, Laboratoire de Physique des Lasers, Université Sorbonne Paris Nord, CNRS, Villetaneuse, France

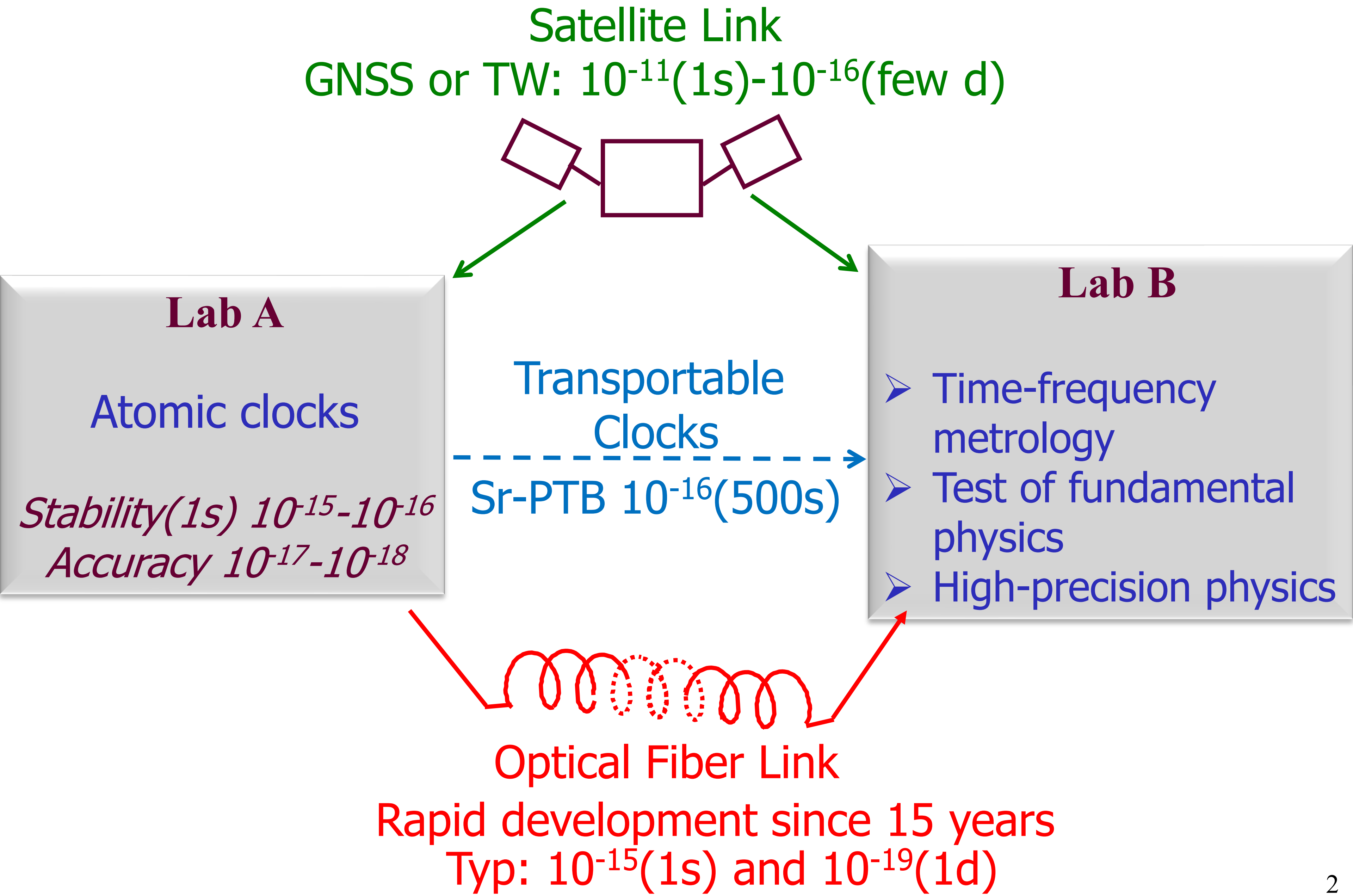
M. Tønnes, B. Pointard, M. Mazouth-Laurol, R. Le Targat. M. Abgrall, M. Lours, H. Le Goff, L. Lorini, P.-E. Pottie, LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Paris, France

M. Rabault, V. Ménoret, iXblue, Talence, France

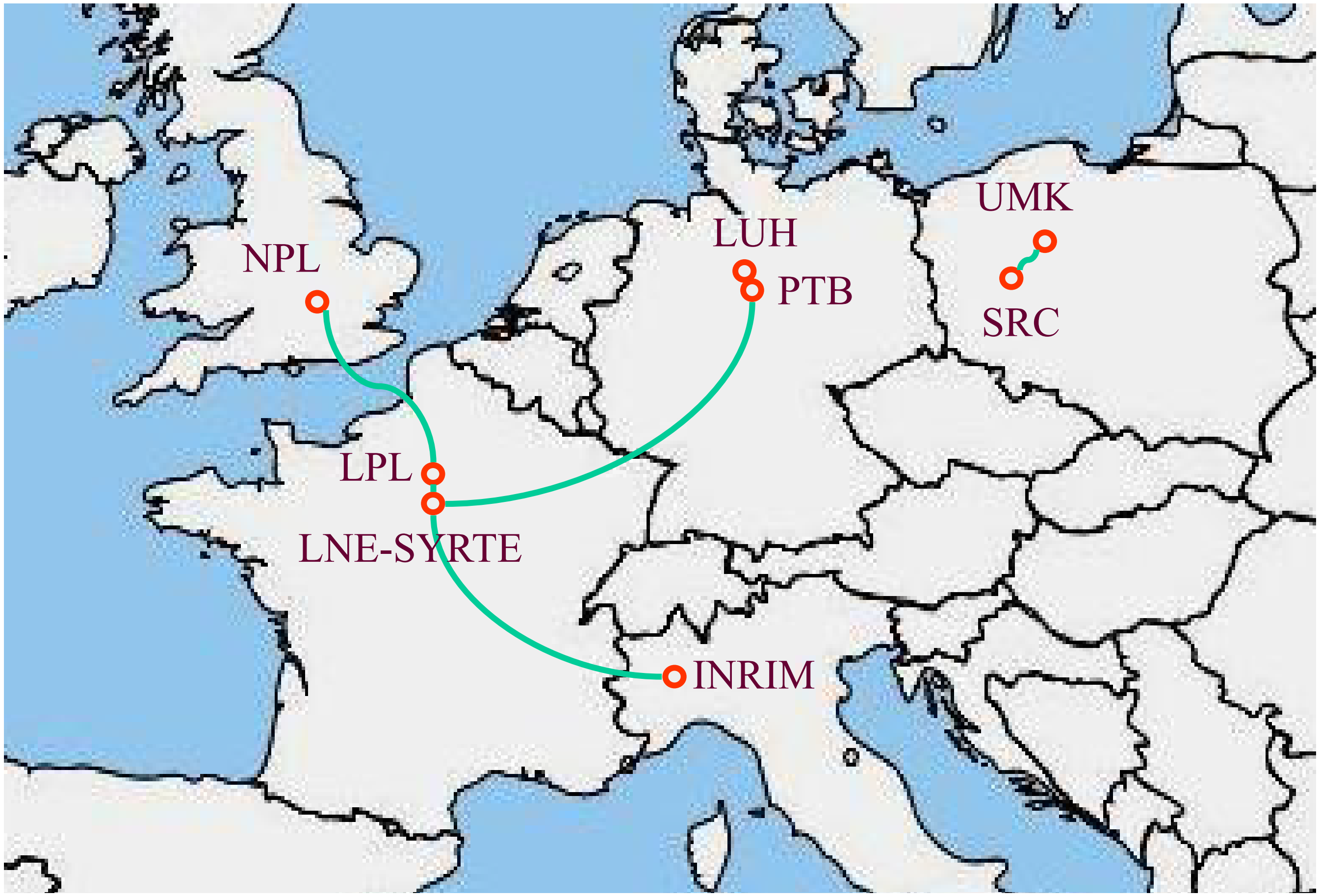
N. Quintin, RENATER, Paris, France

C. Clivati, M. Pizzocaro, E. K. Bertacco, S. Condio, G. A. Costanzo, S. Donadello, I. Goti, M. Gozzelino, F. Levi, A. Mura, M. Risaro and D. Calonico, INRIM, Torino, Italy

Context: ultrastable frequency dissemination



Optical fiber links for clocks comparison in Europe



Euramet project ROCIT

- T&F metrology
- Redefinition of second
- Test of special relativity, search for dark matter, …

Outline

I. Optical fiber link
   - Principle
   - Long-distance fiber link

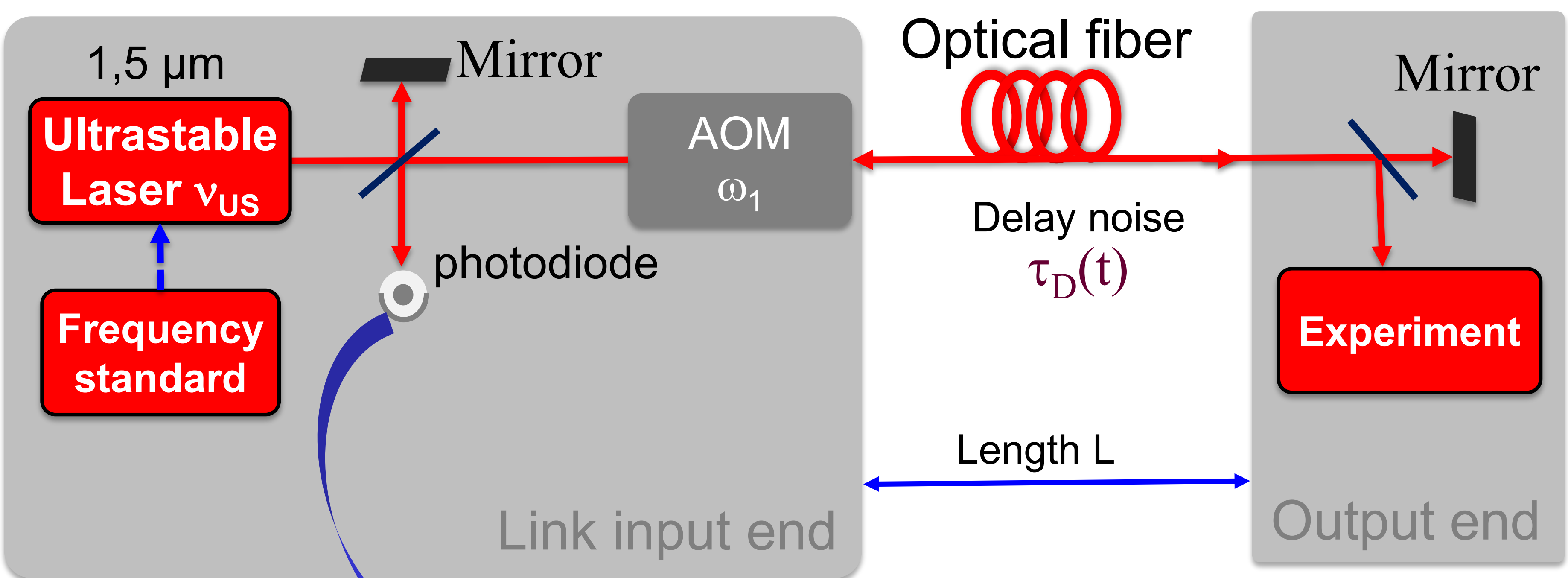
II. REFIMEVE research infrastructure

III. Paris-Torino fiber link for clocks comparison

Principle of an optical fiber link

Key points

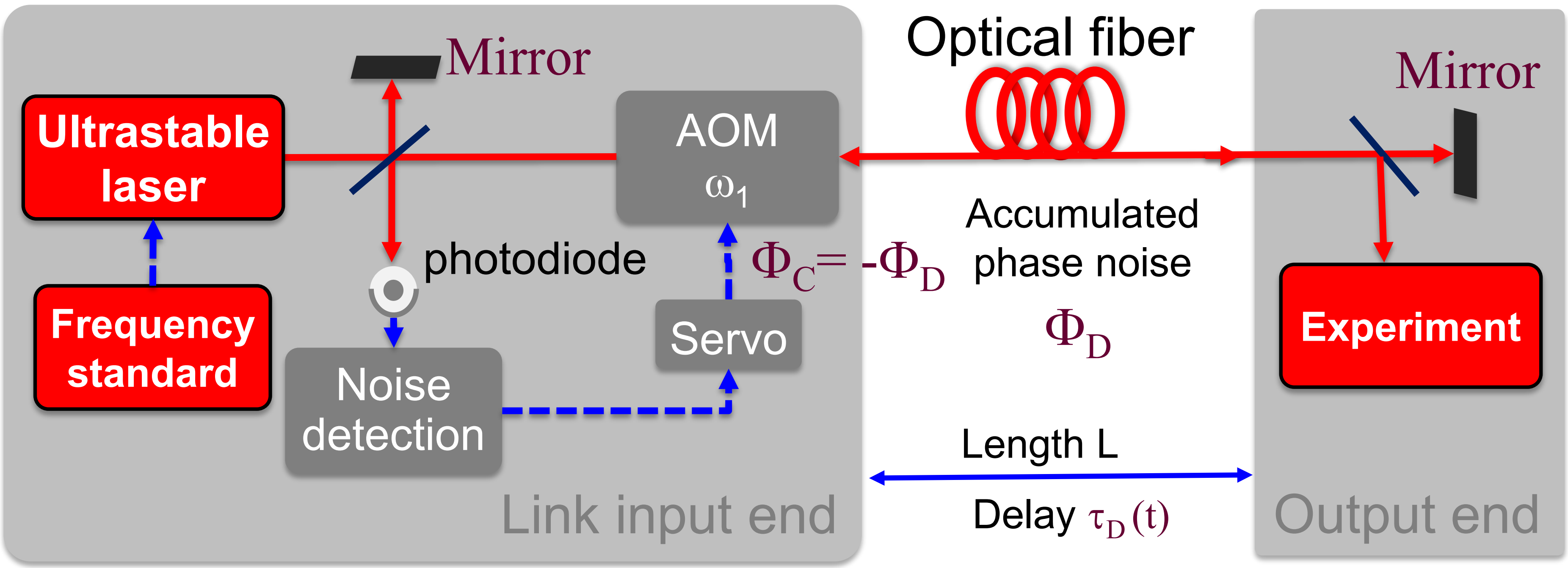
- Transmission of an optical signal: the frequency of an ultrastable laser
- Through a standard telecommunication fiber
- With correction of the delay noise (due to variations of n×L)



Round-trip phase noise: $2\Phi_D = 2\times 2\pi\nu_{US}\,\tau_D(t)$

Noise compensation in an optical fiber link

- Doppler noise compensation or active noise compensation



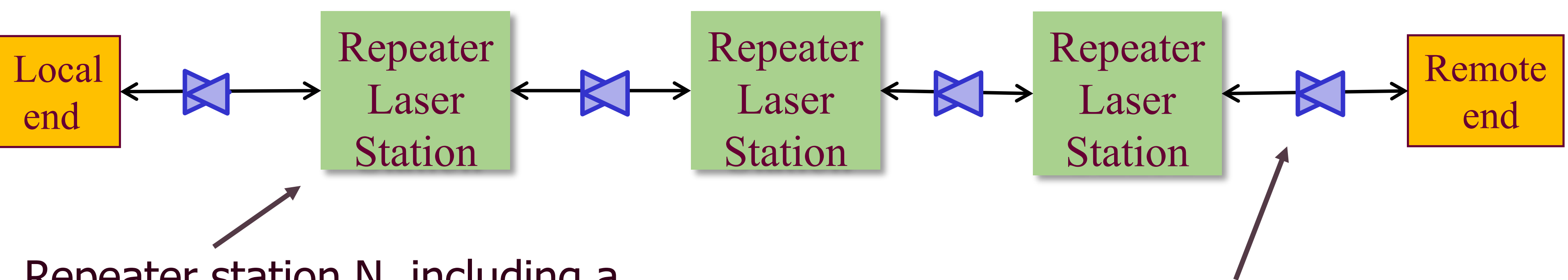
- Noise correction Φ_c applied at the link input : $2(\Phi_C + \Phi_D) = 0$
- Assumption : Forward noise = ½ Round-trip noise
  $\rightarrow$ corrects only reciprocal noise

Long-distance optical links

- Fiber noise increases: $\propto L$ with large variations depending on fiber location (factor>100)
- Attenuation due to fiber loss and connectors
  - ➢ bidirectional optical amplifiers
  - ➢ and/or signal regeneration

    $\rightarrow$ Link is divided into a few segments $\rightarrow$ cascaded link

    $\rightarrow$ shorter delay and better noise rejection



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

Bidirectional amplifiers (between stations) for fiber loss (partial) compensation

See Lopez, Opt Exp 2010; Chiodo, Opt Exp 2015

Performance of the frequency transfer

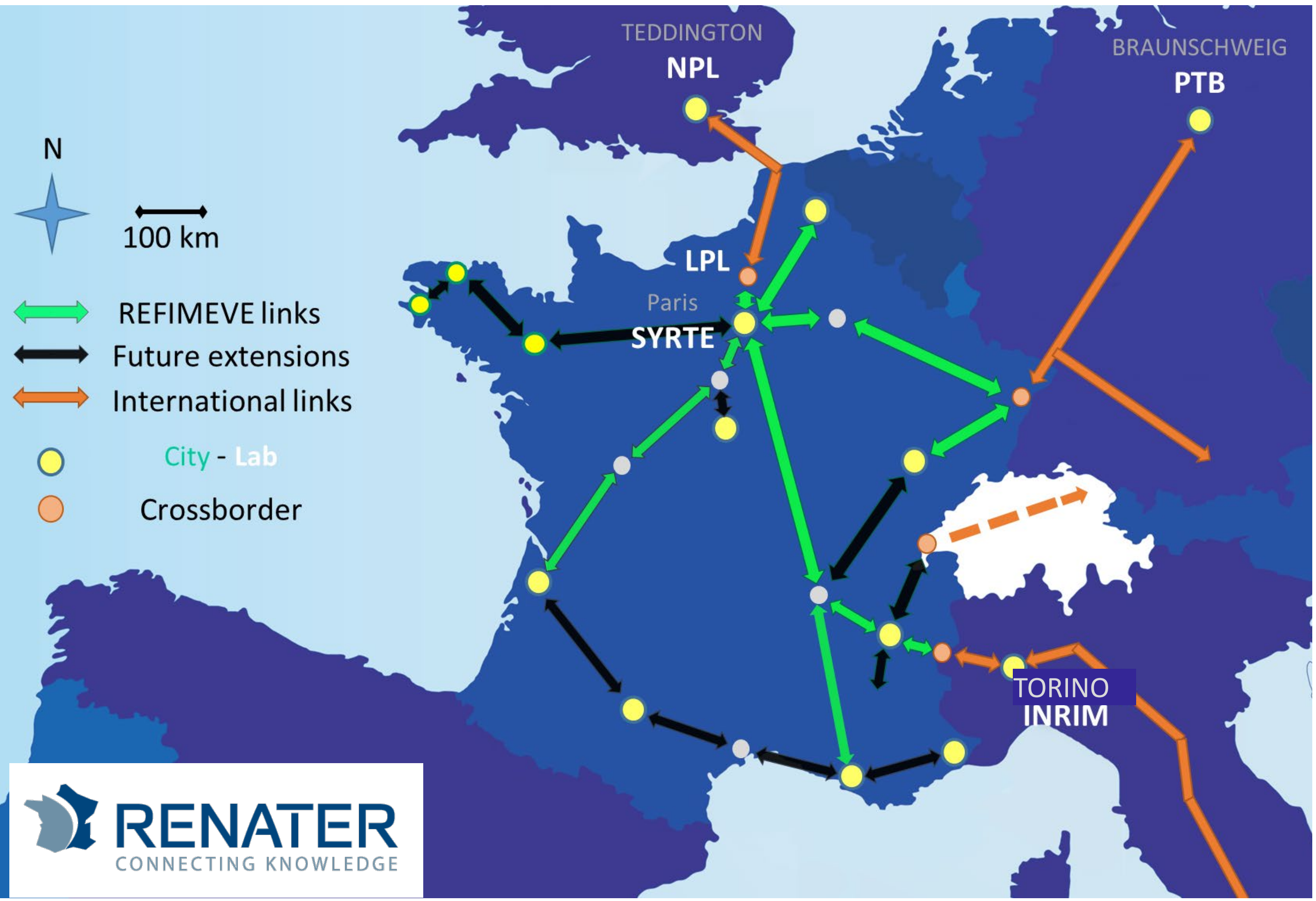
- Stability ~ 10^{-15} -10^{-16} @1s and ~ 10^{-18} -10^{-20} at long-term mainly depends on
  - Free-running noise and length of the fiber
  - Uncompensated fiber paths

- Accuracy of the frequency transfer
  - No limits at the level of 10^{-21} (but the stability)
  - But it required that the repeater laser stations don't introduce any uncertainty due to local RF oscillator (achieved with dedicated engineering of the RLS in the Refimeve network)

The REFIMEVE optical fiber network

National research infrastructure, led by LPL and LNE-SYRTE

Dissemination of an ultrastable and accurate frequency reference **from LNE-SYRTE** all around France, using mainly the academic network of RENATER



- Optical signal:

  Stab.@1s 10^{-15}

  Uncertainty 10^{-16}

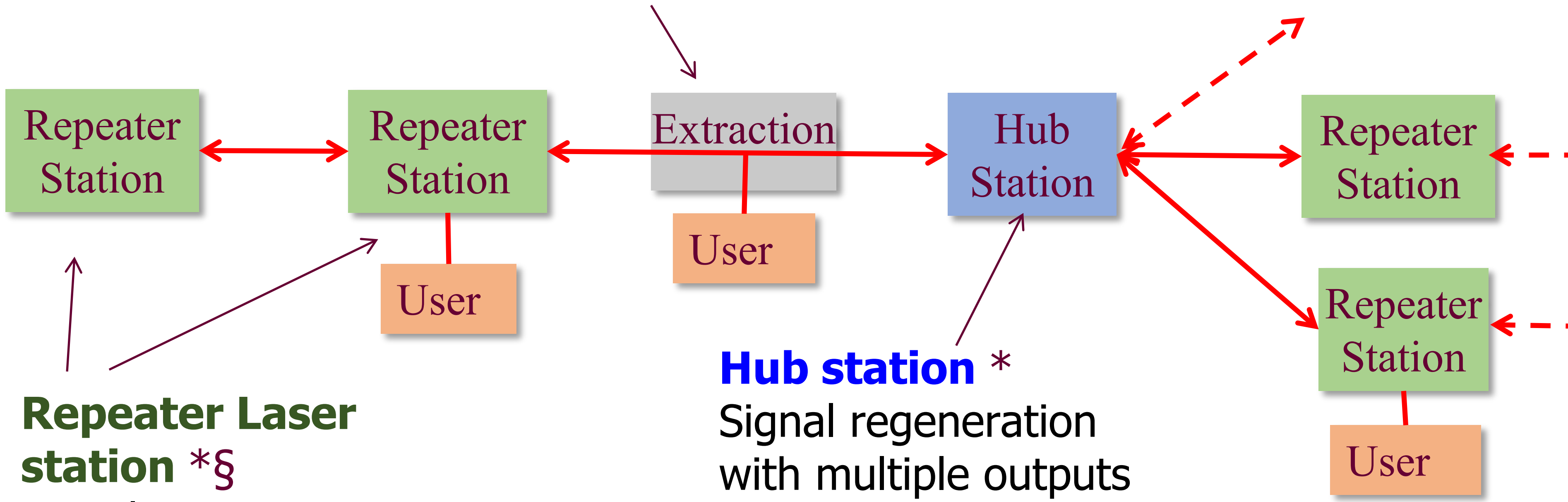
- **2022:** 2x3400 km with 3 european connections

- **Future:** > 2x4500 km network with >4 european connections + extension to RF/timing signal

REFIMEVE network equipment

iXblue

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



Repeater Laser station *§
Signal regeneration
Link noise correction
User output

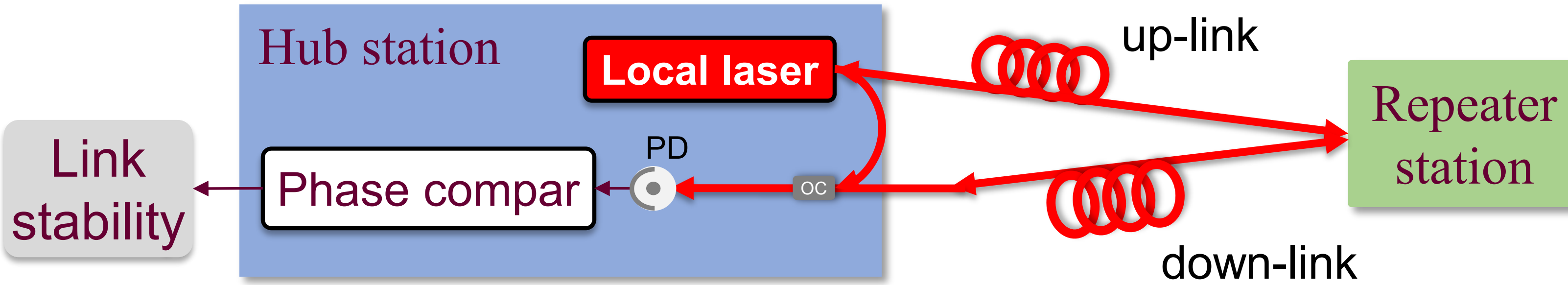
Hub station *
Signal regeneration
with multiple outputs
Link noise correction
Residual noise assessment

Cantin et al 2021
New J. Phys.

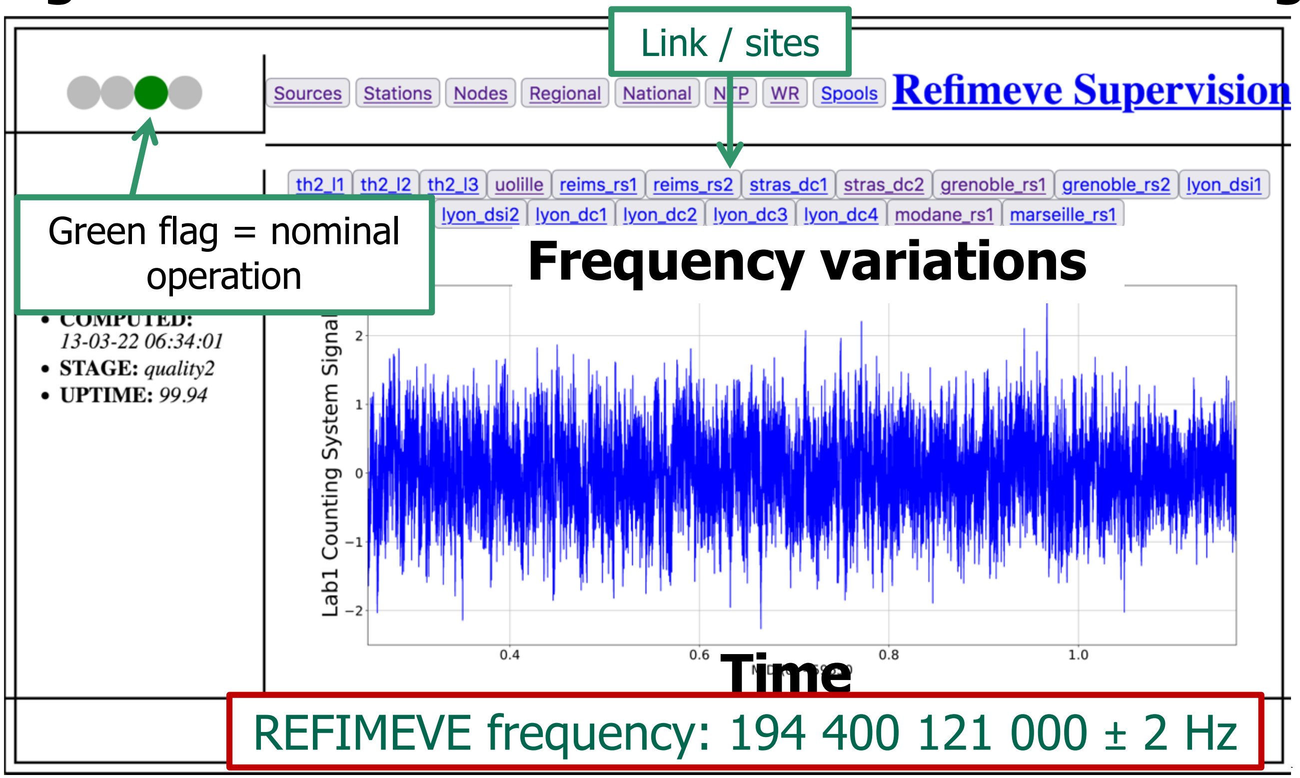
* Autonomous - Remotely controlled and supervised
§ Commercially available – Can be installed in telecom hub

Network real-time supervision

Out-of-loop detection of the transferred signal→ link stability & uncertainty



Signal available at user lab: real-time monitoring



- **Data processing**

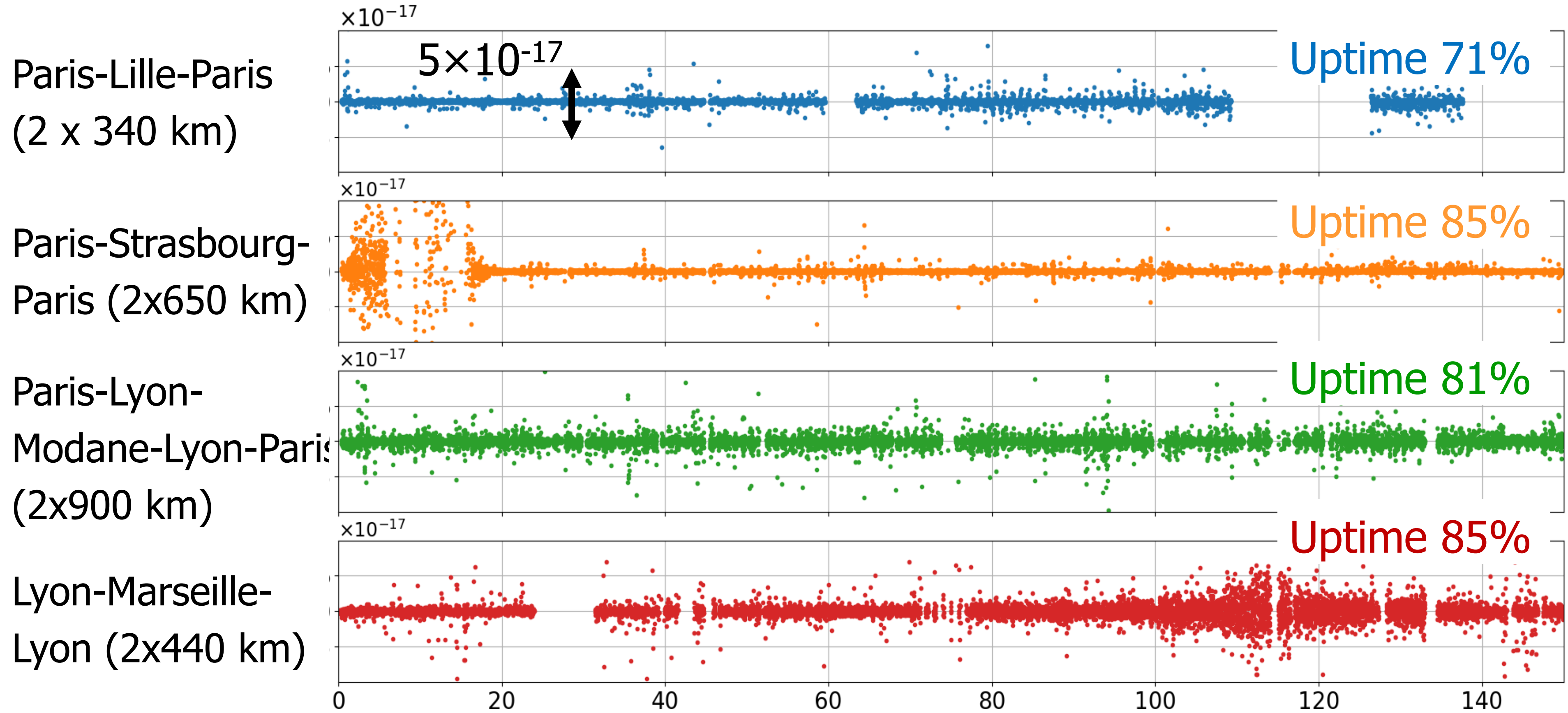
Automatic plots, rise alarms, process data for users…

- **Operation & Maintenance**

Archive data, monitor the equipment, rise alarms…

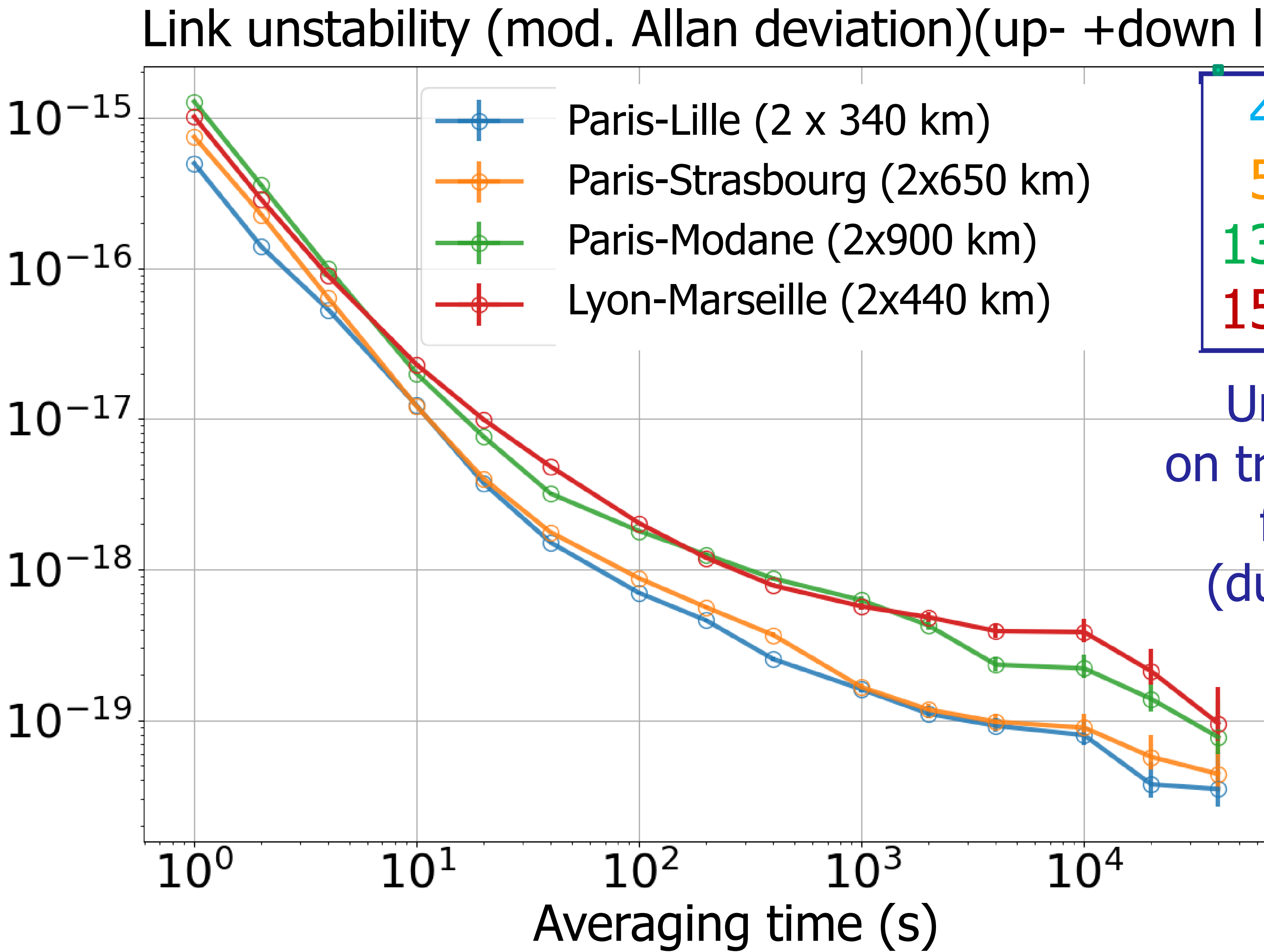
Residual frequency fluctuations

Relative frequency fluctuations (1000s/point) with time



5 months (january to may 2022)

Residual link unstability and uncertainty



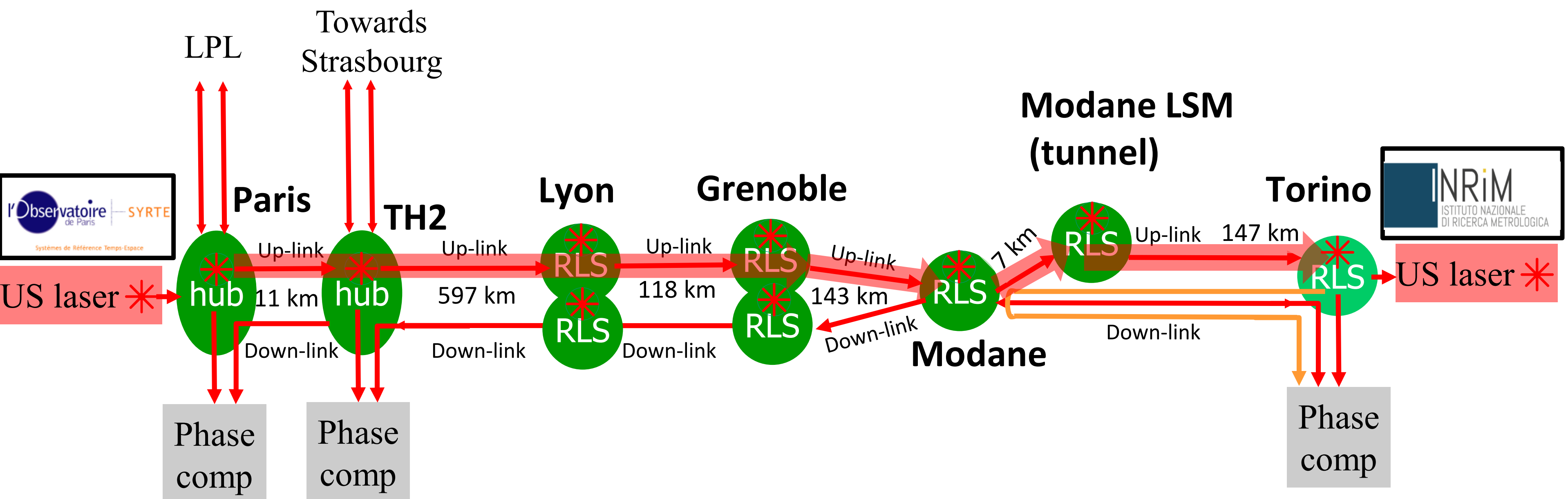
4.2×10^{-20}
5.9×10^{-20}
13.4×10^{-20}
15.6×10^{-20}

Uncertainty on transferred frequency (due to link)

1024-km fibre link between France and Italy

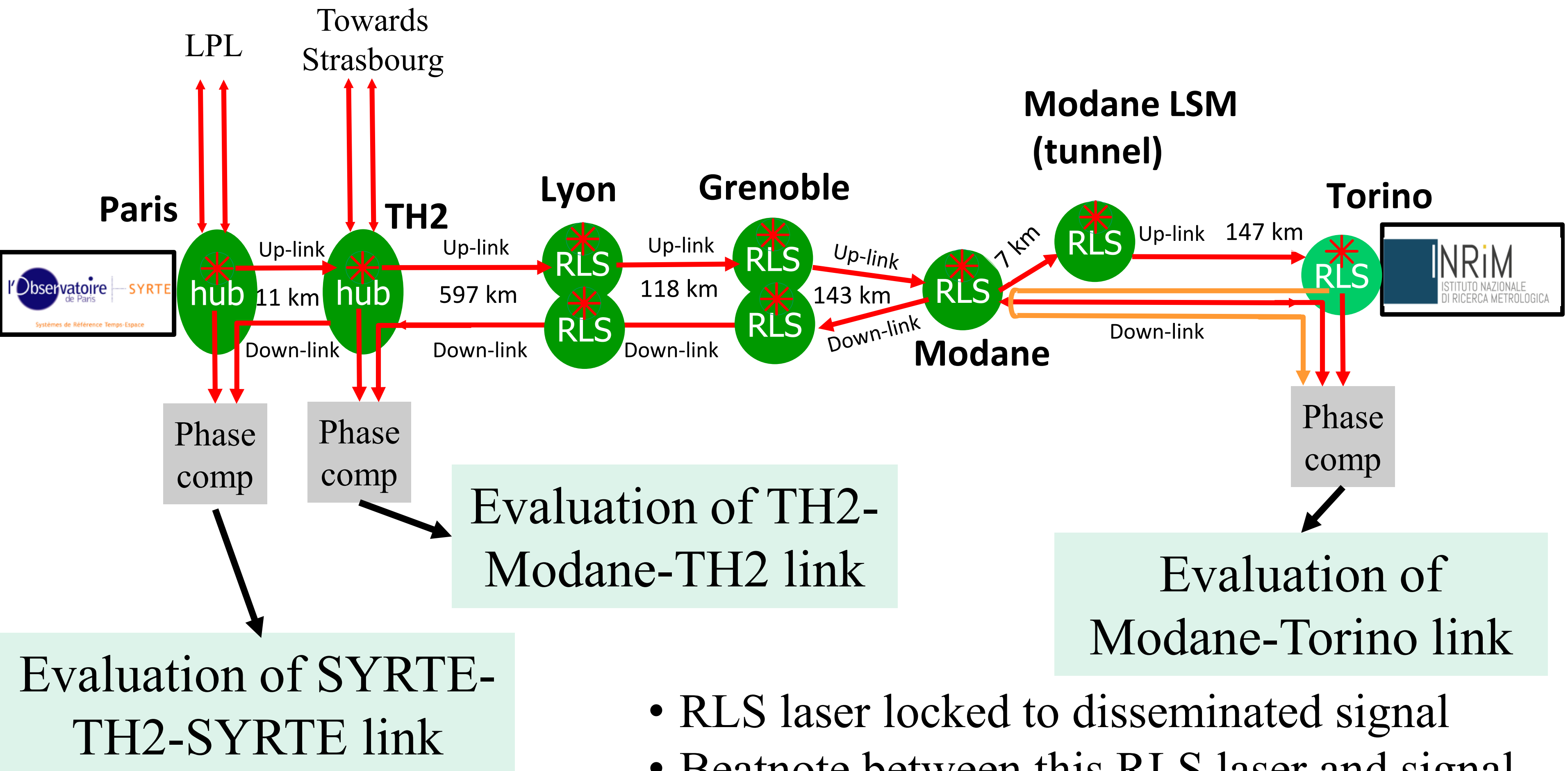
- Connects the research infrastructures Italian Quantum Backbone (IQB) and REFIMEVE
- IQB: 2x1850 km for quantum technologies, geodesy and radioastronomy
- With real-time assessment of the transfer stability and uncertainty

Architecture of the link



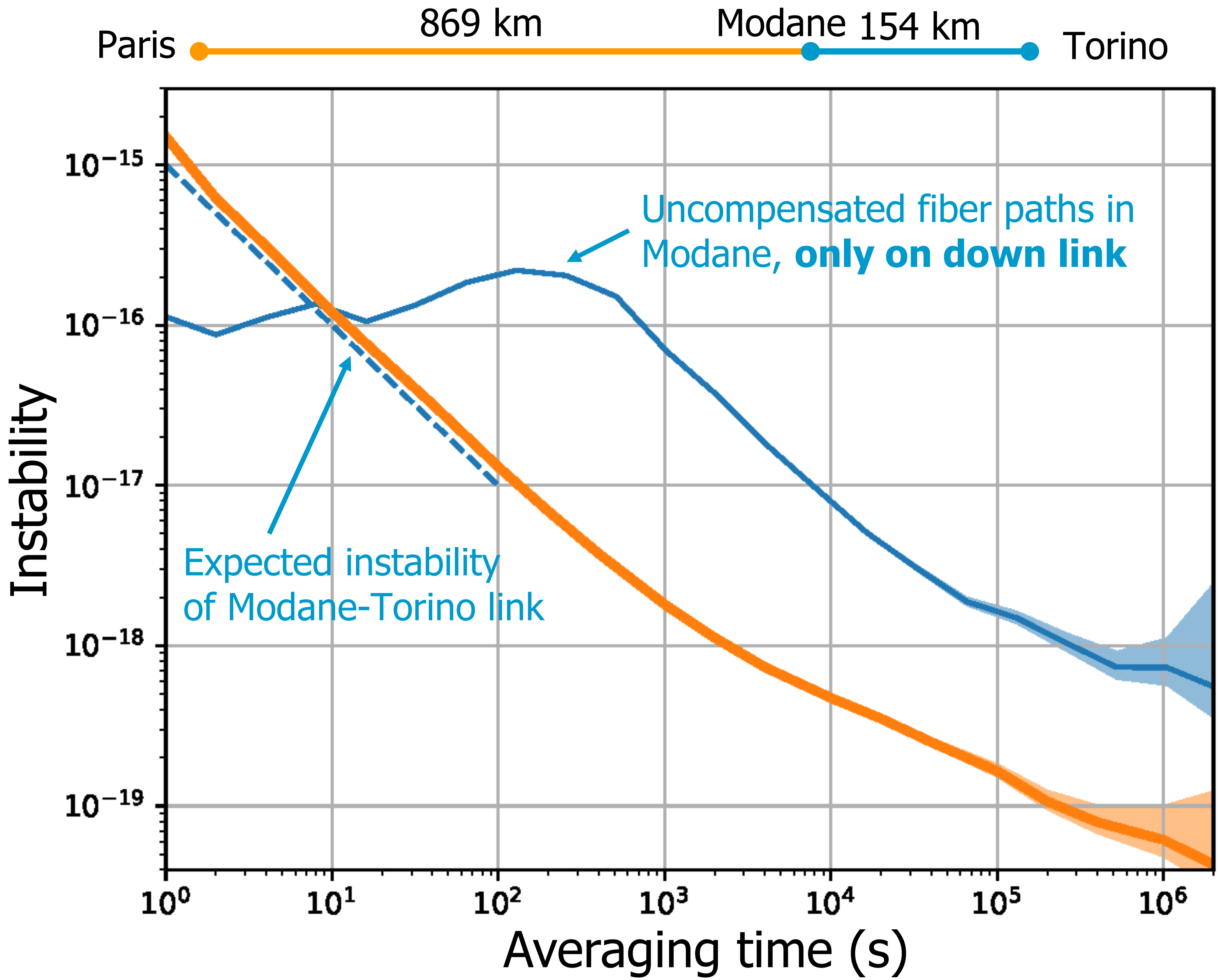
- At SYRTE, an ultrastable laser is sent to INRIM via Modane through the « up-links »
- At INRIM, a local laser is locked to the disseminated signal and compared with the INRIM ultrastable laser
- All the links are noise-compensated
- The down-links enable us to assess the up-links instabilities and errors

Architecture of the link

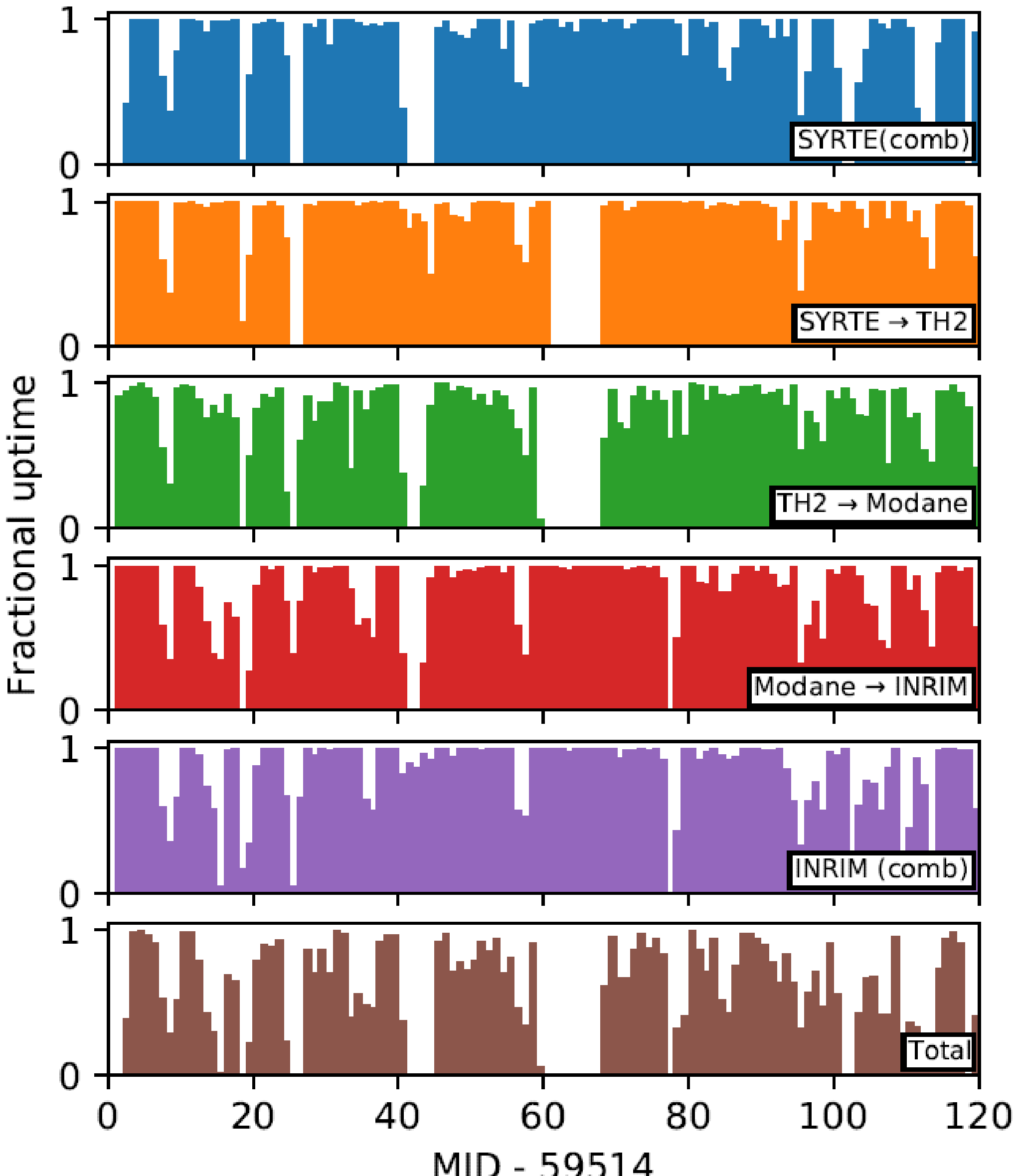


- RLS laser locked to disseminated signal
- Beatnote between this RLS laser and signal from down link
- Round-trip noise of down link detected and subtracted from beatnote

Paris-Modane-Torino link instability (upper value)



Robustness of the optical links comparison

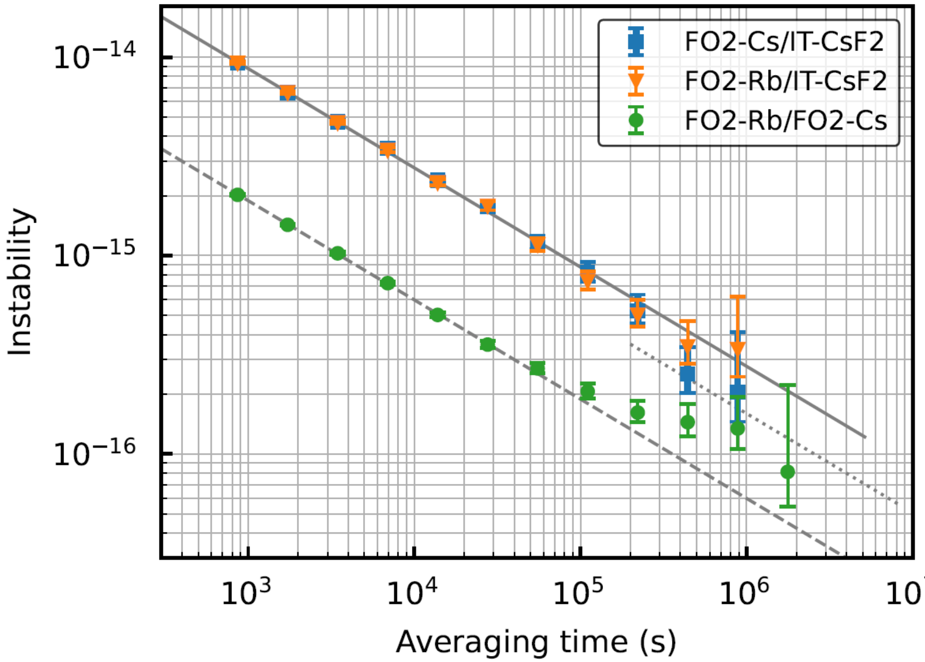


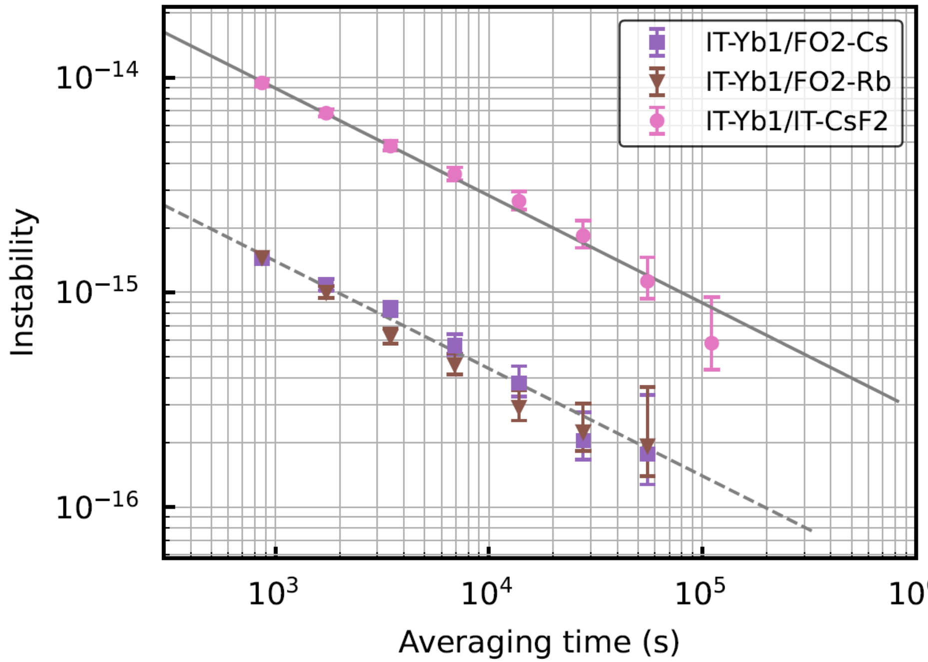
- 4 months campaign (27 Oct 2021 – 24 Feb 2022)
- Uptime 56 % on the full campaign
- Up to 72 % over January 22

- Interruptions due to
  - failure of recording
  - failure of autonomous relock (during unattended periods)

French-Italian clocks comparison

- comparison of Cs/Rb clocks (Fr) to Cs clock & Yb optical clock (It)
- Limited by clocks systematic uncertainty, links contribution is negligible
- Compatible with satellite clocks comparisons





$y(\text{FO2-Rb/IT-CsF2}) = -1.5(3.8)\times10^{-16}$

with - 60d of measurements

- stat unc 1.3×10^{-16}

unc limited by Cs Fountains

- 95h of measurements
- stat unc 1.9×10^{-16}

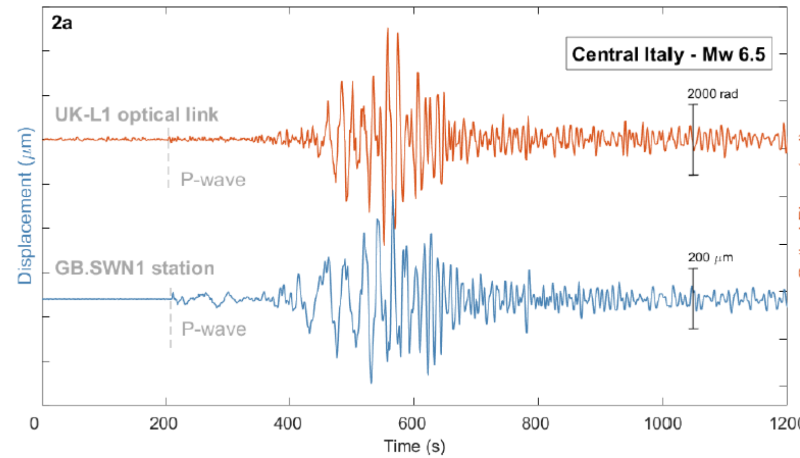
Conclusion

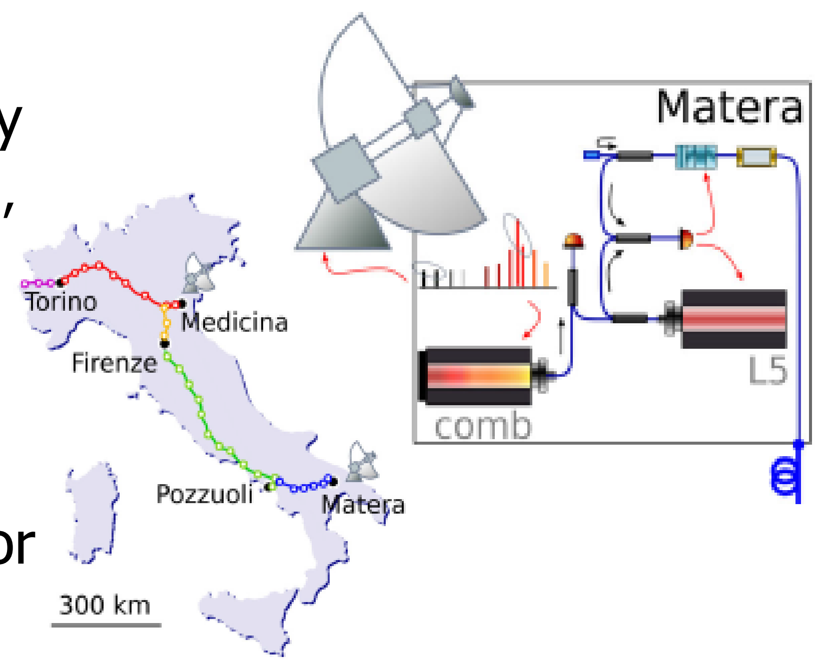
- Optical fiber links are mature and reach uncertainties $< 10^{-18}$ for >1000 km link
  - Optical clocks comparison between France, Germany, UK and Italy, in the frame of the Euramet ROCIT project
  - March 2022: 5 optical clocks compared

- Research infrastructures are being developed, as REFIMEVE in France or IQB in Italy
  - For clocks comparison and test of fundamental physics
  - For a wide range of applications, with dissemination to physics labs, space observatories…
  - Signal currently used for laser stabilisation, photonics, atomic and molecular spectroscopy…
  - Beneficial for any high-precision measurement

Outlook

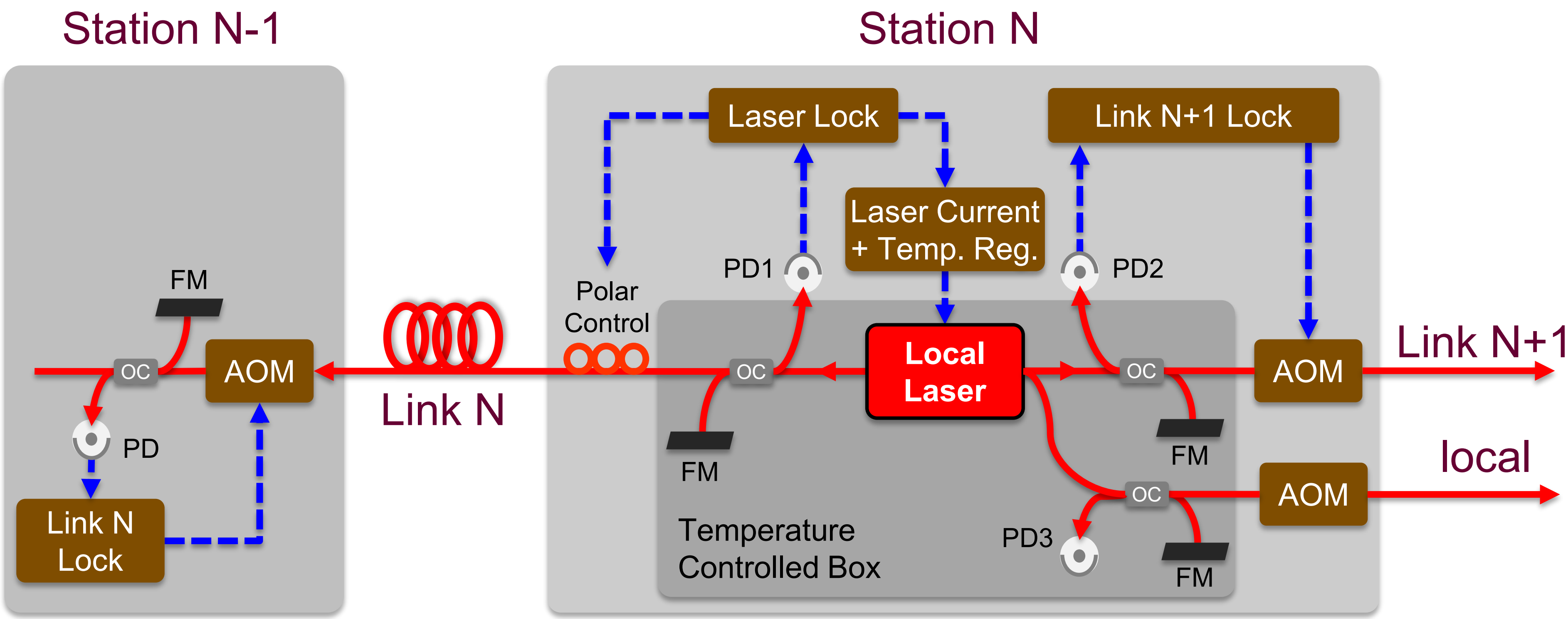
- Current development
  - Extension to RF and time transfer
- A lot of open applications
  - geophysical sensing and earthquake monitoring, Marra et al, Science 2018
  - frequency distribution to telescope facilities (VLBI), Clivati et al, Optica2020, Pizzocaro et al, Nat. Phys. 2020
  - high-precision molecular spectroscopy for atmospheric studies, Santagata et al, Optica 2018
  - long-distance quantum communications (TF-QKD) Clivati et al, Nature Comm 2022
  - chronometric levelling, for instance for sea level monitoring, Takano *et al.*, *Nat. Phot* 2016, Grotti et al, Nat. Phys. 2018





Thank you for your attention

Repeater laser station



- Optical regeneration + Links noise correction
- Amplification + fixed output polarisation
- Automatic relock/adjustment
- Remote control
- No stable RF clock required

iXblue

Lopez, Opt Exp 2010, Chiodo, Opt Exp 2015, Guillou-Camargo, App. Opt 2018