Avancées scientifiques de l'instrument REFIMEVE

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- Current status

- New extensions to Nançay and LSCE

II. Current developments

- Transfer technique and performances

- Network upgrade with MLS and cavities

II. Perspectives and conclusion

REFIMEVE national network

A national research infrastructure

→ **Transfer of frequency and time references through optical fibers**

- Collaboration of more than 30 lab users: 22 users currently connected

- European connection to Germany, England, Italy and Switzerland

   → Future connection with Belgium, Netherlands, Spain, Poland...

The network

~8000km of fiber   RENATER   → Availability of the signal **>90%**
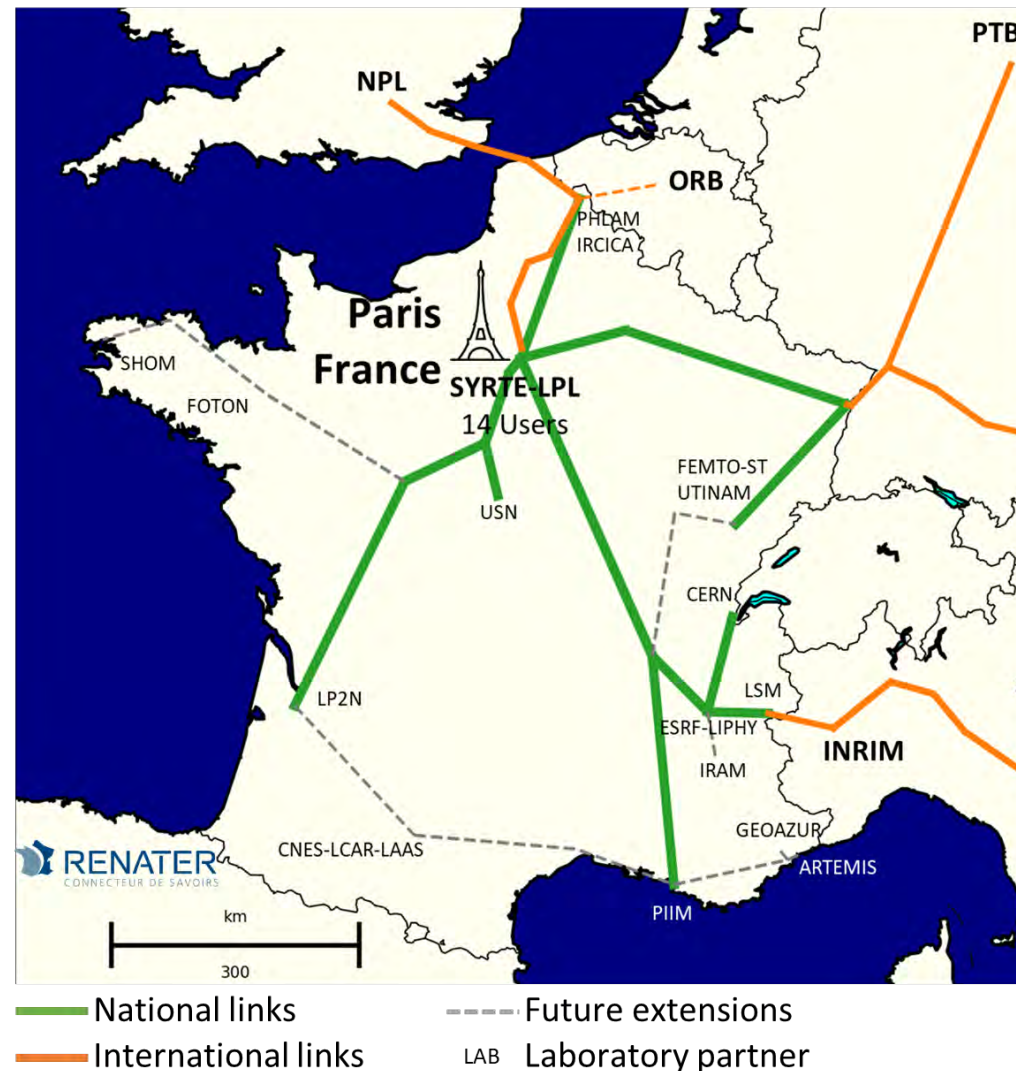
→ ~250 equipment in the field

Strong industrial partnership

→ highly mature techniques TRL=9

→ high availability of the signals >90%

National links   ---- Future extensions
International links   LAB Laboratory partner

A national research infrastructure

National links
International links
Future extensions
LAB Laboratory partner

→ **Transfer of frequency and time references through optical fibers**

- Collaboration of more than 30 lab users: 22 users currently connected

- European connection

→ Guy Roberts (GEANT)   → Raphaël Marion (ORB)

The network

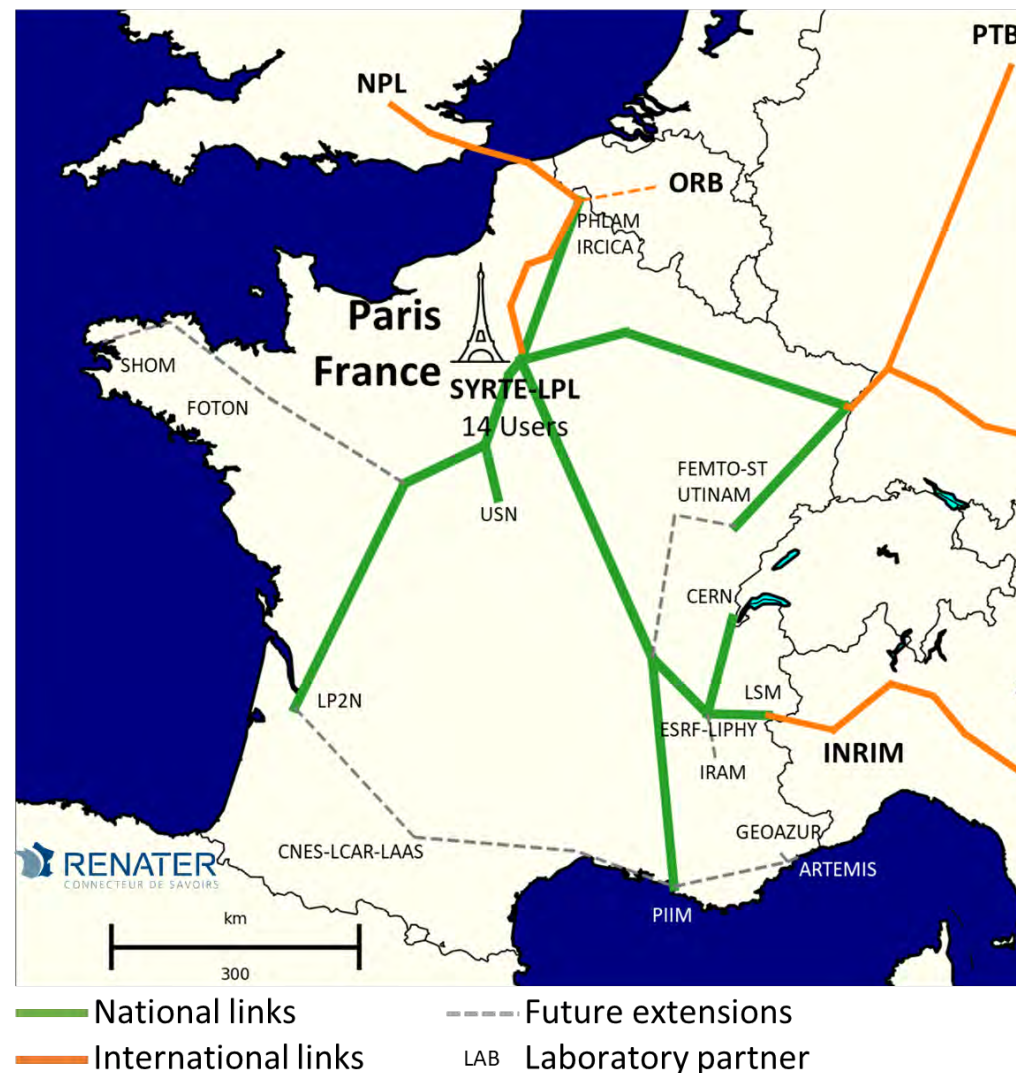~8000km of fiber   → Availability of the signal **>90%**

→ ~250 equipment in the field

Strong industrial partnership

→ highly mature techniques TRL=9

→ robustness and reliability

4

REFIMEVE regional network

Dissemination of 3 type of signals:

Optical (ultrastable cavity)

Time & frequency signals by White Rabbit transfer

RF modulation on optical career

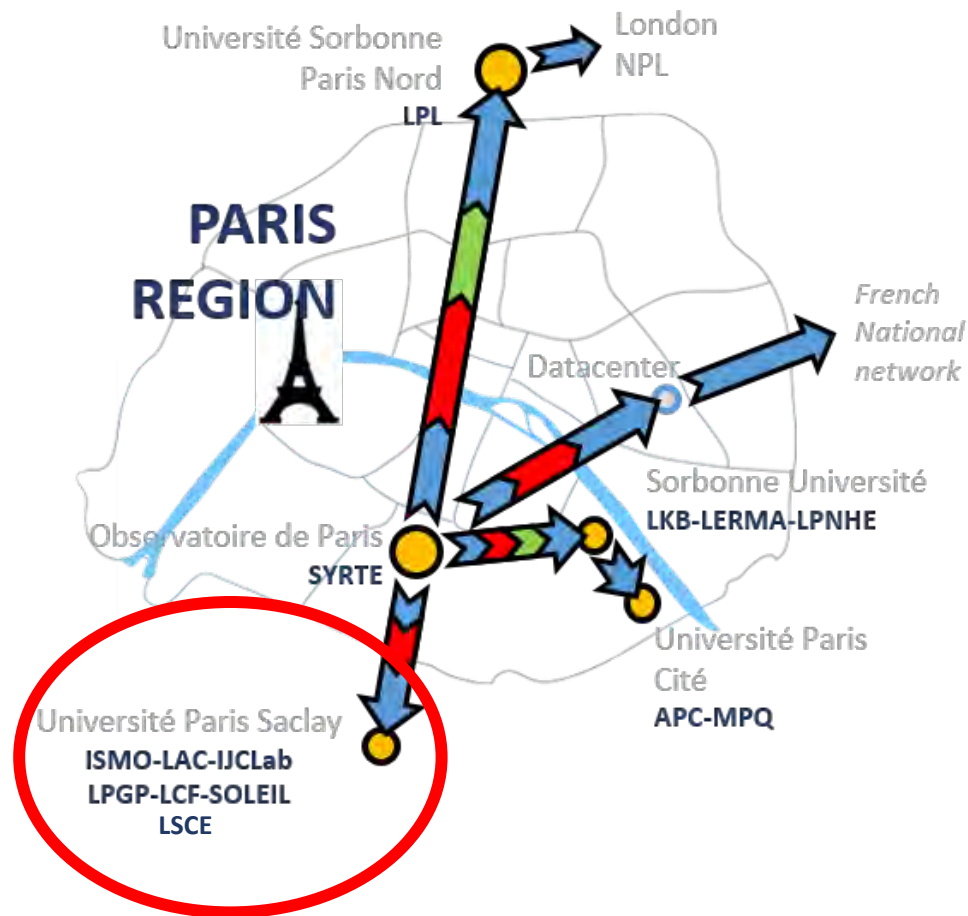# REFIMEVE regional network

Dissemination of 3 type of signals:

Optical → Rodolphe Le Targat (SYRTE)

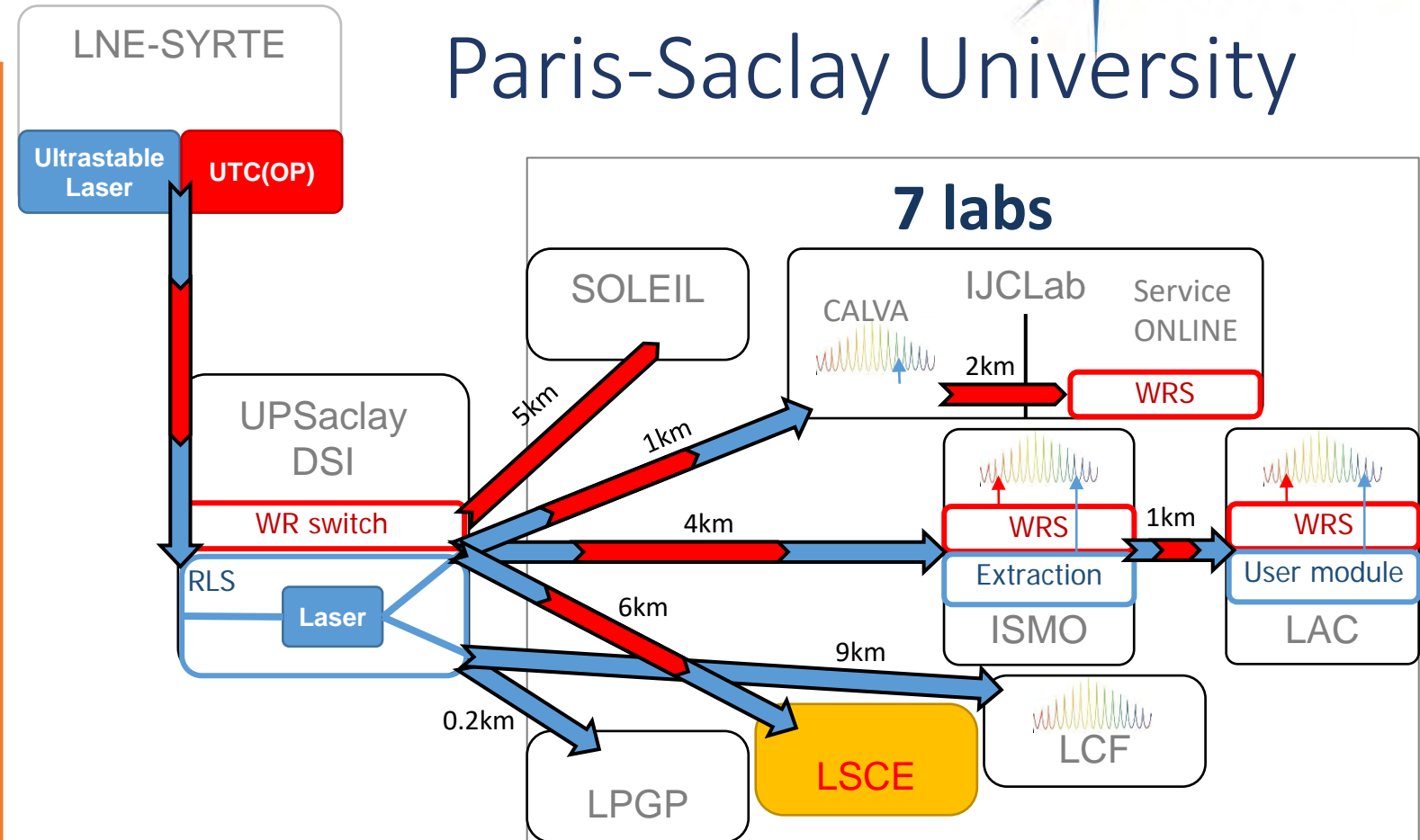Time & frequency signals by White Rabbit transfer

RF modulation on optical career

REFIMEVE regional network

Dissemination of 3 type of signals:

- Optical (ultrastable cavity)
- Time & frequency signals by White Rabbit transfer
- RF modulation on optical career

Paris-Saclay University

7 labs

- New connection to LSCE (Sciences du Climat et Environnement)
- 3 new Toptica combs for the exploitation in LAC, ISMO, IJCLab/LPGP
- Future: upgrade local architecture for higher performances
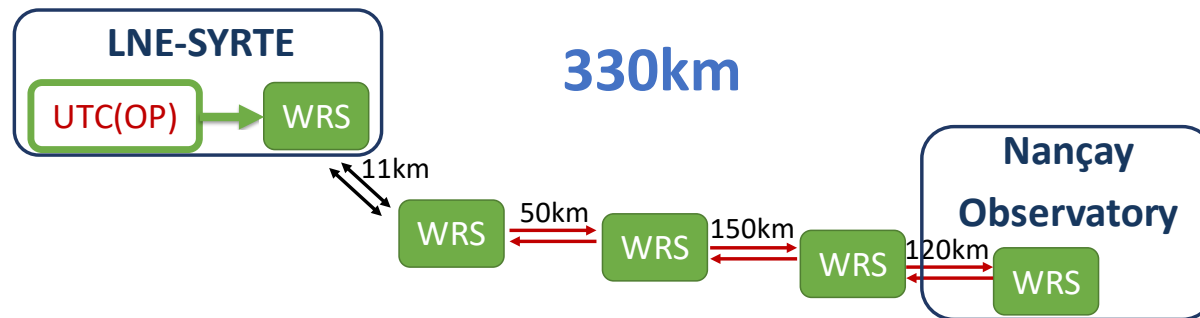
Observatoire Radioastronomique de Nançay
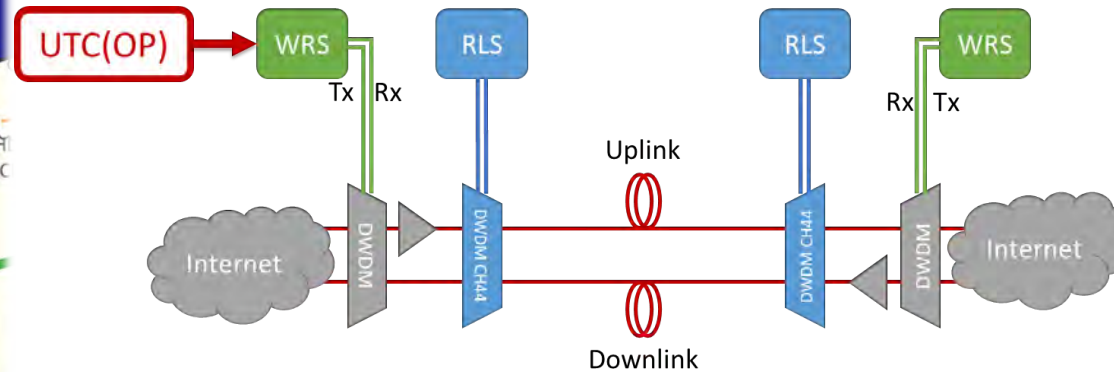
Implementation of WR on RENATER fiber network backbone

→on dark channels

→included in optical layer of the RENATER backbone

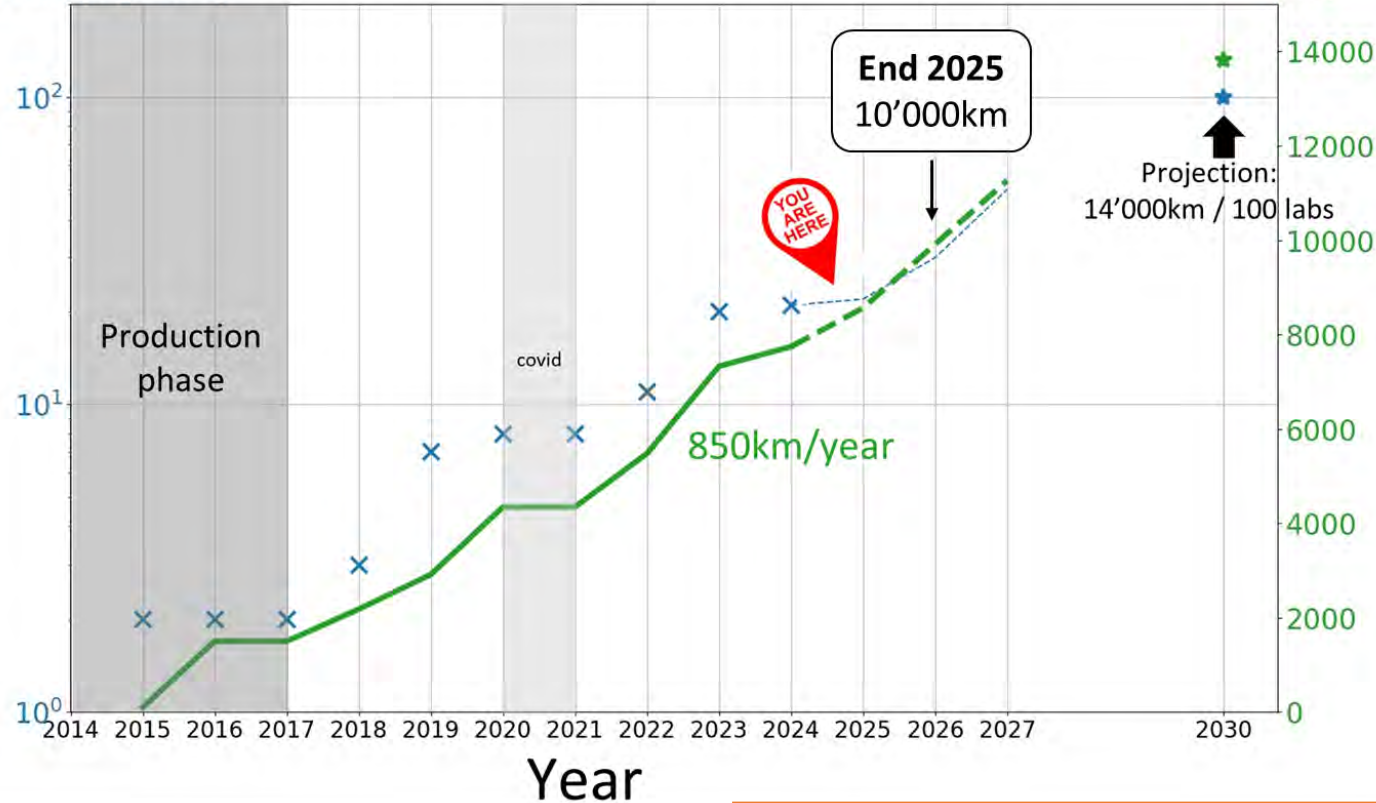**Time dissemination to Nançay Radio Astronomical Observatory**

330km

→Construction of a national White Rabbit network in France for 2026

A vast and growing network

→**22 labs currently** connected in 20 different universities

+ more than **15 new requests** (academics & companies)

Continuous operation and exploitation of the network

- Real-time supervision and monitoring of all the links
- User interface
→ REFIMEVE computing center

A vast and growing network

→ **22 labs currently** connected in 20 different universities

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Continuous operation and exploitation of the network

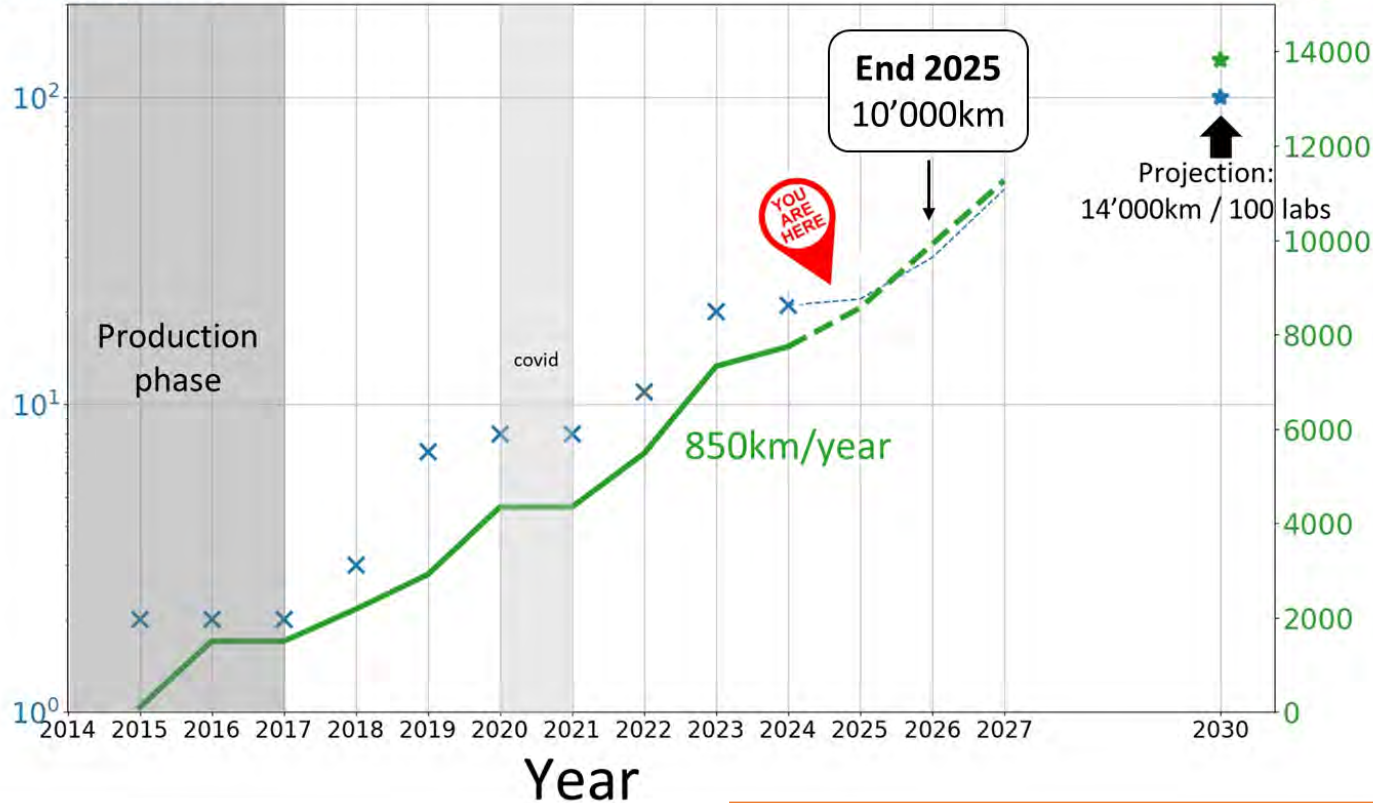- Real-time supervision and monitoring of all the links
- User interface

→ REFIMEVE computing center

Maintenance of the network

- Maintenance with the NOC RENATER
- Mainly remote actions, but physical interventions are inevitable
- **2021-2023**: 19 interventions/year

    → average of 63.5 person*days per year (~20% of my work)

Contents

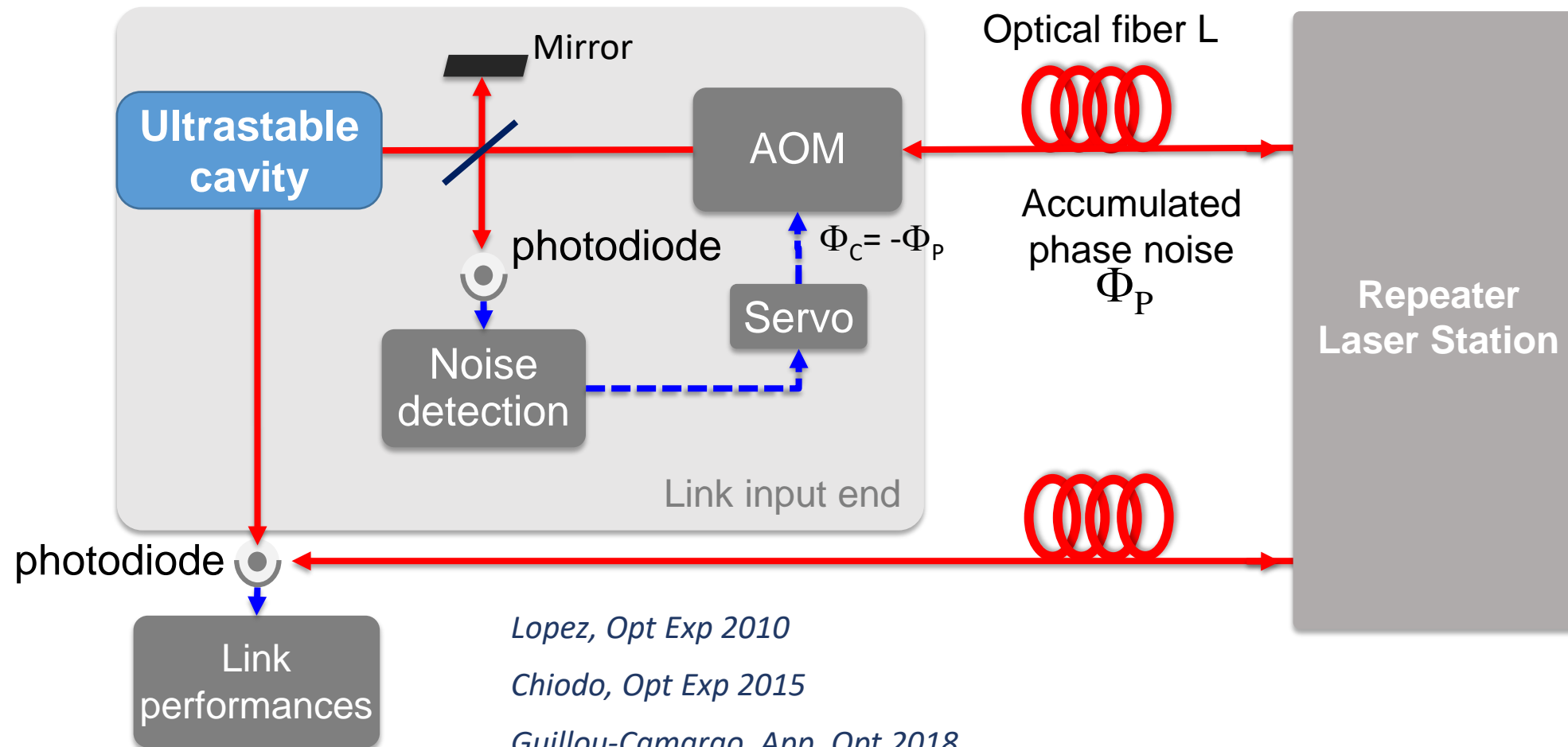# Frequency transfer technique

- Doppler noise compensation or **active noise compensation**
   - →Noise detection with a strongly unbalanced Michelson interferometer
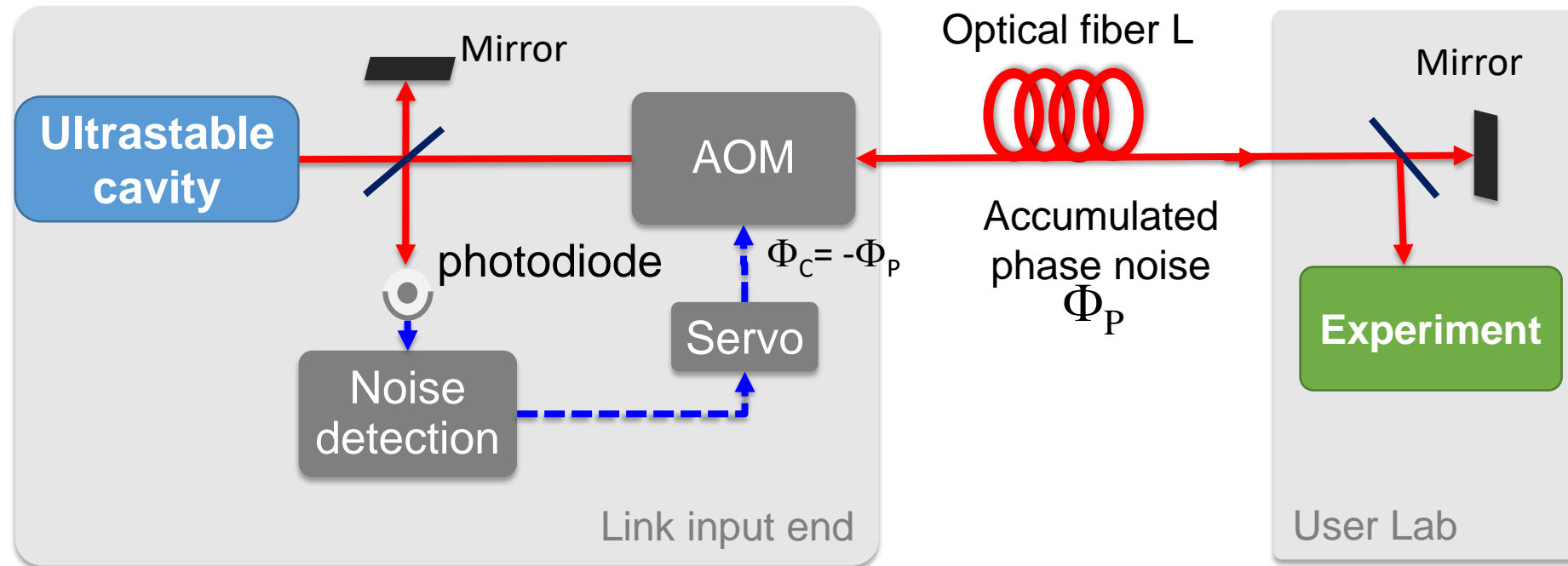
- Noise correction Φ_C applied at the link input: $\Phi_C + \Phi_P = 0$
   - →Limit of the time delay propagation in the fiber

N. R. Newbury et al., Optics Letters, vol. 32, n° 21, p. 3056, 2007

Frequency transfer technique

- **Characterization** of the link: out-of-loop detection of the transferred signal
  → a parallel downlink is implemented to assess link performance

Mirror

Ultrastable cavity

Optical fiber L

AOM

photodiode

$\Phi_C = -\Phi_P$

Accumulated phase noise Φ_P

Servo

Noise detection

Link input end

Repeater Laser Station

photodiode

Link performances

Lopez, Opt Exp 2010

Chiodo, Opt Exp 2015

Guillou-Camargo, App. Opt 2018

Performances of the links

Stability (MDEV)

Legend:
- Lyon-Marseille — 830km
- Paris-Modane — 1730km
- Paris-Lille — 680km
- Paris-Strasbourg — 1300km
- SYRTE-LPL — 52km

τ (s)

Phase fluct. (rad) — **Uptime** (2π rad = 5fs)

- > 96% — 12 ± 23
- > 99.4% — 1 ± 13
- > 98.6% — 0.9 ± 5.3
- > 99.5% — 0.2 ± 4.3
- > 97% — 0.2 ± 0.7

Time (day)
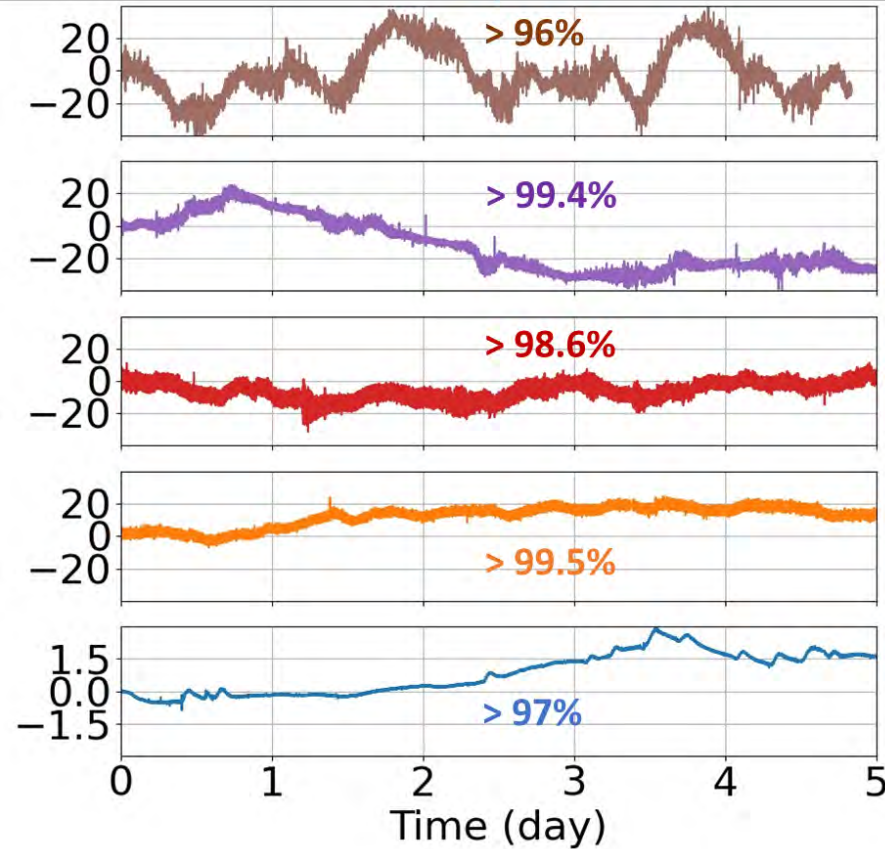
Uncertainty contribution ×10^{20}

Fundamental limit

Limit of interferometer → improved to 10^{-21} with MLS

Stability & Accuracy ≤ 10^{-19}
Uptime > 96%

Instrumental developments: MLS and cavities

Multibranch Laser Station

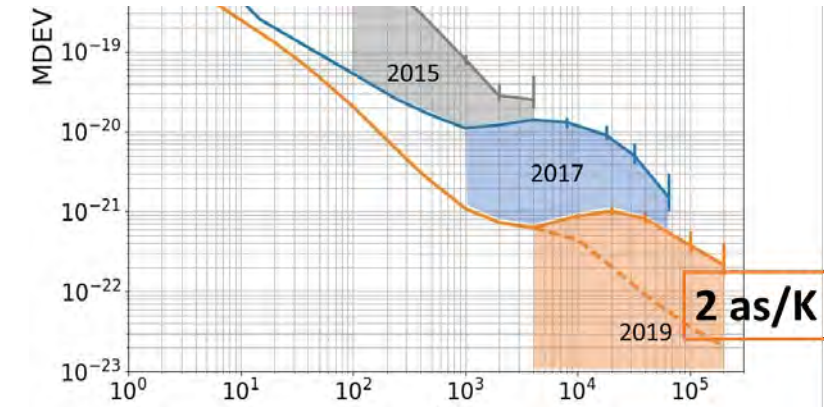- **Upgrade** the network and improves **long-term performances**

→Up to 5 network branches

→Interferometric noise floor down to 10^{-21}

→Better assessment of network performances

- Industrial version **validated** (TRL=9)

    →**8 units under production** exail

Future: regeneration cavities in the network

Residual noise through the different locks

→**linewidth broadening = ~**1-10kHz after 1000km (~no broadening below 100km)

→Installation of commercial ultra-stable cavities in the network

→Development of the system MLS+cavity in progress

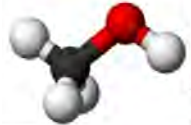# Scientific impact of REFIMEVE: examples

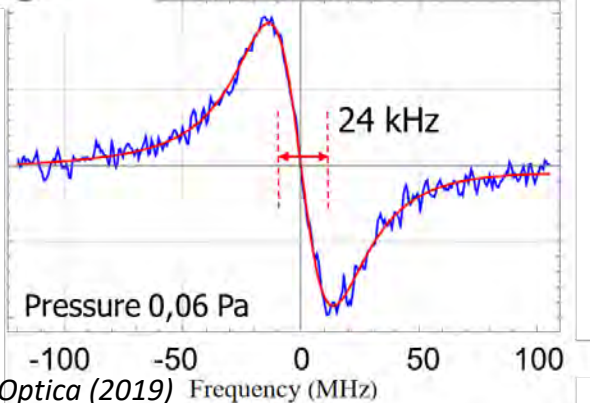## Fundamental Science

- Search for dark matter

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

- Precision molecular spectroscopy

Methanol (CH_3OH)

Santagata et al., Optica (2019)
Votava et al., Phys. Chem. Chem. Phys., (2022)
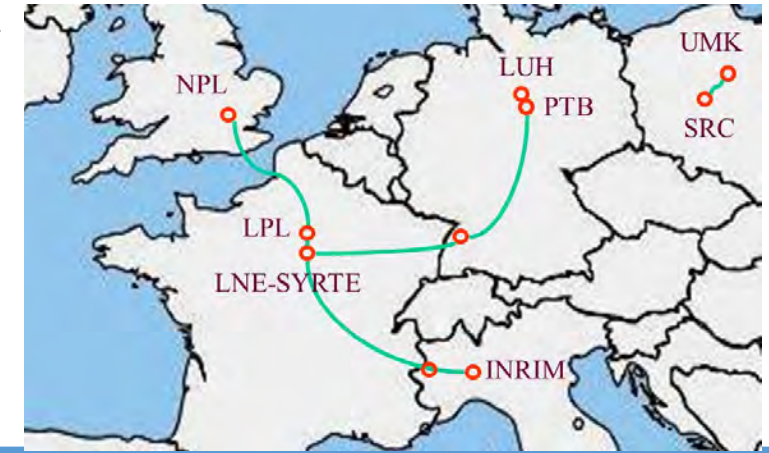
Astrophysics
→Synchronisation of array of telescopes

Time-frequency metrology

Redefinition of the second
→Clocks comparison

Lisdat et al., Nat. Commun. (2016)
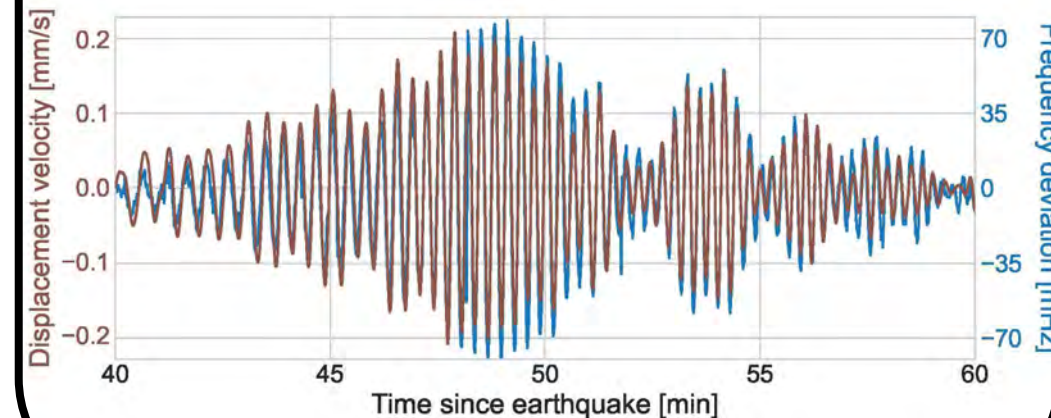*Schioppo et al.,Nat. Commun. (2022)*

Photonics

- Characterization of oscillator noise
- Laser stabilization

Steshchenko et al., Opt. Lett. (2022)
Manamanni et al., JOSA B (2022)

Earth observation – Geodesy
Climate change – Sismology

PhD Thesis, Mads Tønnes

Scientific impact of REFIMEVE: examples

Refimeve +

Fundamental Science

- Search for dark matter
- Precision molecular spectroscopy
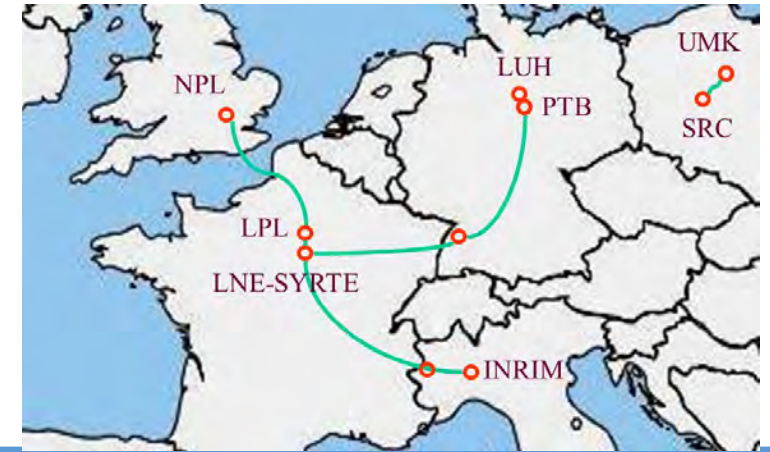
→ Olivier Dulieu (LAC)

→ Hélène Fleurbaey (LIPHY)

→ Pierre Cladé (LKB)

Time-frequency metrology

→ Jérôme Lodewyck (SYRTE)

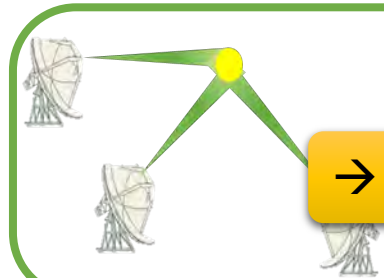→ Jacques Millo (FEMTO-ST)

Photonics

→ Mehdi Alouini (FOTON)

Earth observation – Geodesy
Climate change – Sismology

→ Paul Eric Pottie (SYRTE)

Astrophysics

→ Cédric Viou (USN)

Perspectives and conclusions

➤ **Extensions of the network**

- → Toulouse for CNES, LCAR, LAAS (14th October 2023)
- → Calern for OCA (mid-November)
- → Rennes for FOTON (Q1 2025)
- → Lannion-Brest
- ➤ Perspectives of extensions to ORB (Belgium), ROA (Spain)… and towards a european access point at CERN

➤ **Construction of a national White Rabbit network**

➤ **Developments:**

- ➤ MLS and cavity
- ➤ RF and time transfer on the current optical carrier
- ➤ mobile platform for ultra-precise measurement

Thank you for your attention!

$$f = 194400084.5\ Hz$$