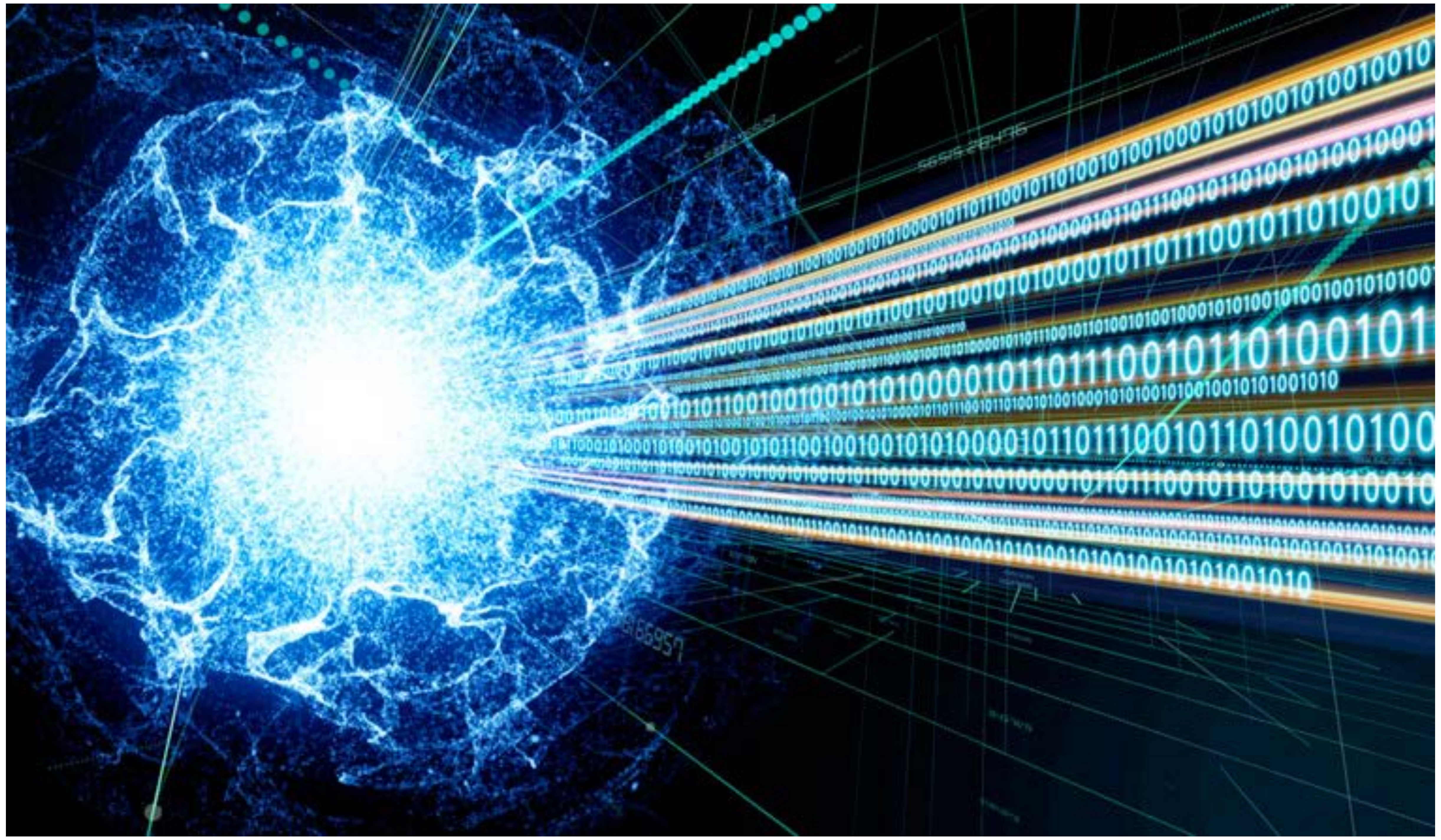
le réseau de liens stabilisés REFIMEVE: performances et opportunités

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

Outline

- REFIMEVE
  - Motivations
  - Network's map
  - Performances
- Synergies with quantum technologies
  - Telecommunications
  - Quantum sensors network

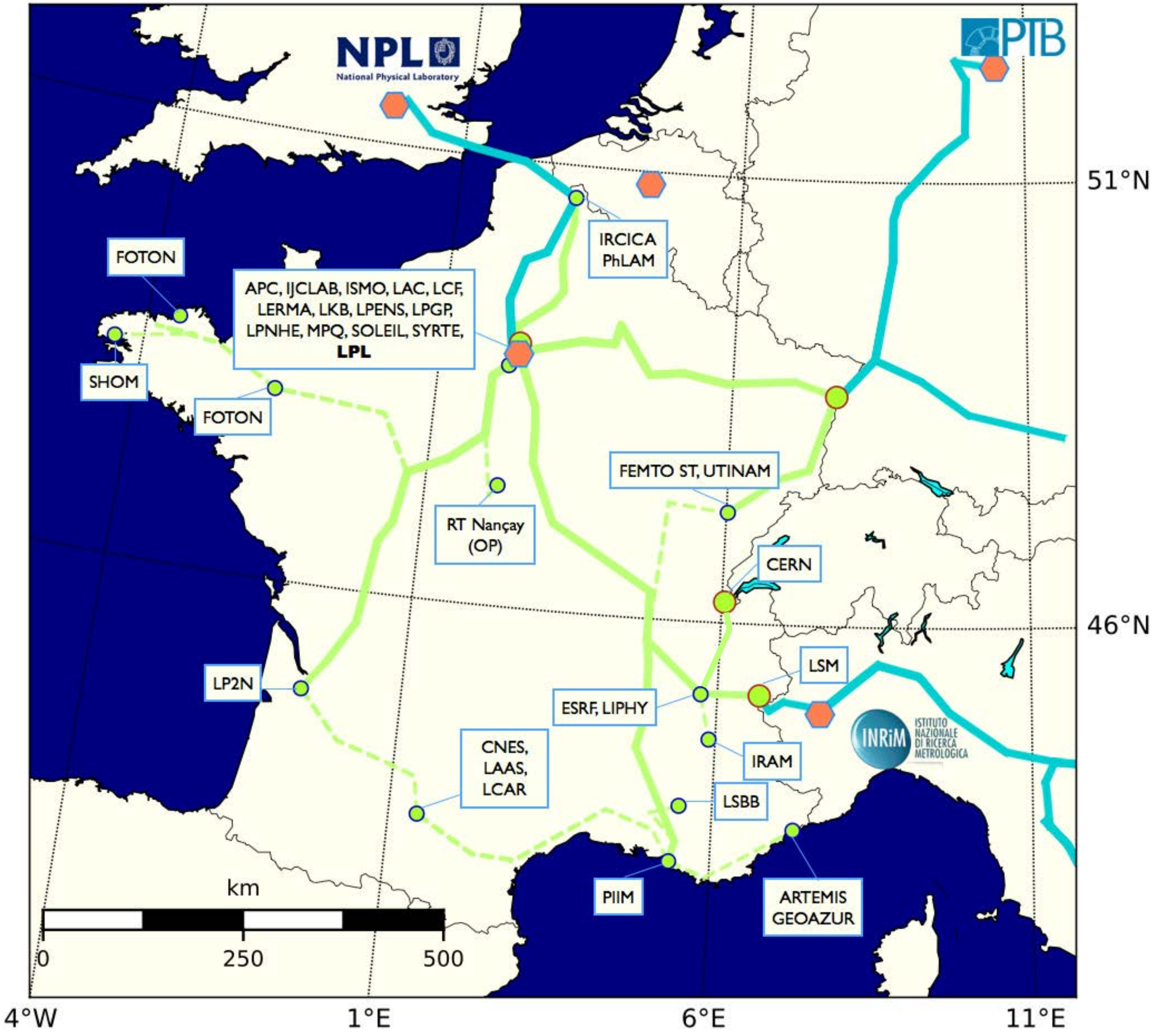


source: https://www.theweek.in/news/sci-tech/2023/04/10/quantum-noise-model-analysed--its-capacity-to-transfer-message-w.html

https://www.cnrs.fr/en/cnrsinfo/quantum-technology-new-france-canada-network

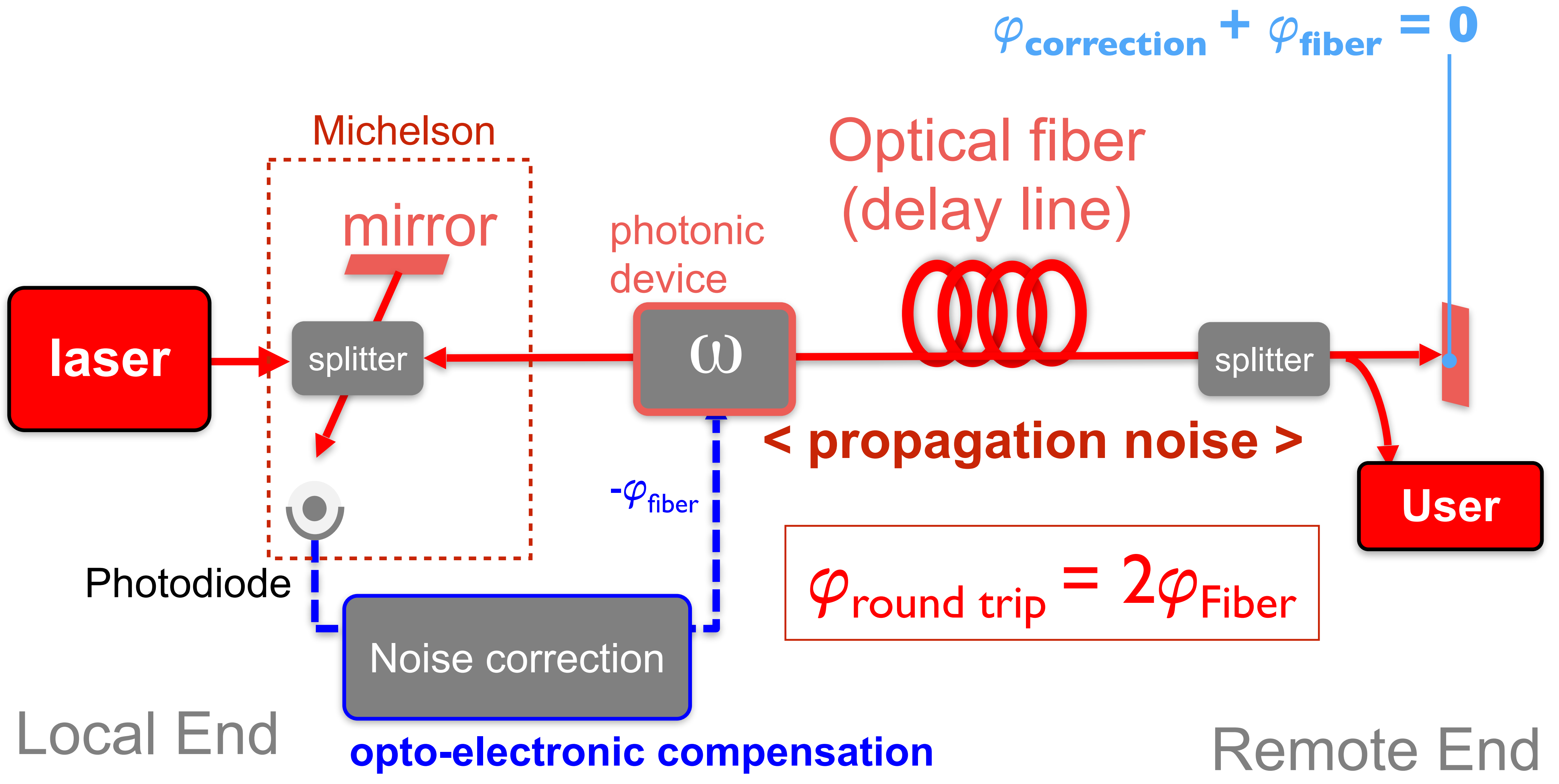
REFIMEVE : a fiber network for T/F metrology

- **Aim**
  - T/F dissemination to academic labs,
  - Covers wide scientific applications
  - Link between National Metrological Institutes (in Europe)
- **Key concepts**
  - Mutualisation
  - Accurate T/F as a service
- **Key facts**
  - Knowledge transferred to MuQuans> Exail
  - Network supervision: operational + scientific
  - Open science: data availability & usability (FAIR)



Optical frequency transfer : key elements

Refimeve+ Réseau fibré métrologique à vocation européenne



- Fully bi-directional. A 2nd link transfers back the signal
- Unbalanced Michelson interferometer
- Guided propagation: ensure paths reciprocity
- Assumption : Forward noise = ½ Round-trip noise
- → corrects only reciprocal noise
- Heterodyne detection: eliminates mutli-path
- 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

Hub station (multi-branches RLS)

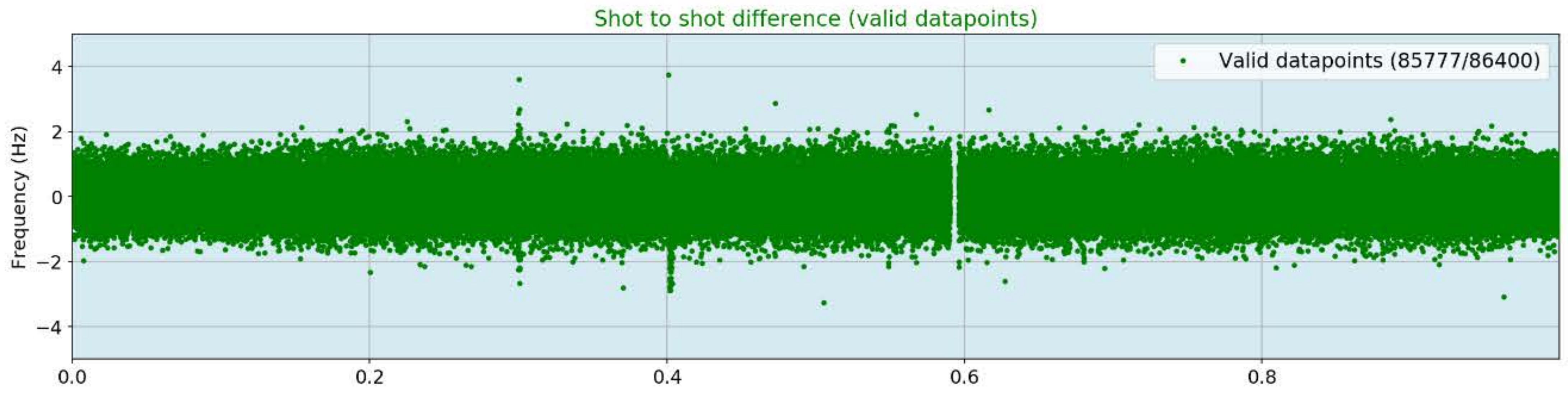
can correct the noise of several (~5) links

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

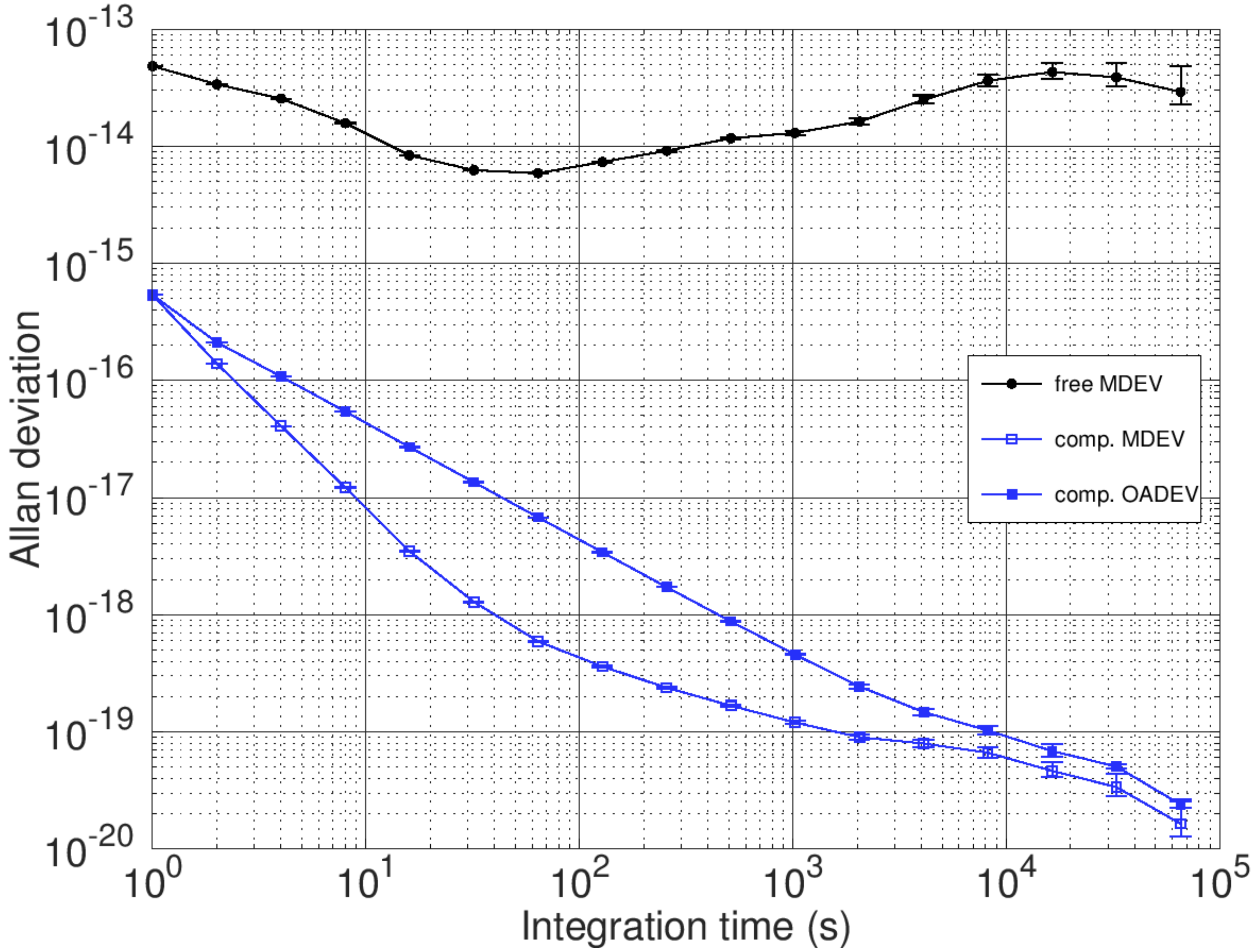
Optical frequency transfer : typical performances

Refimeve+ Réseau fibré métrologique à vocation européenne

- Signal generation monitoring example:



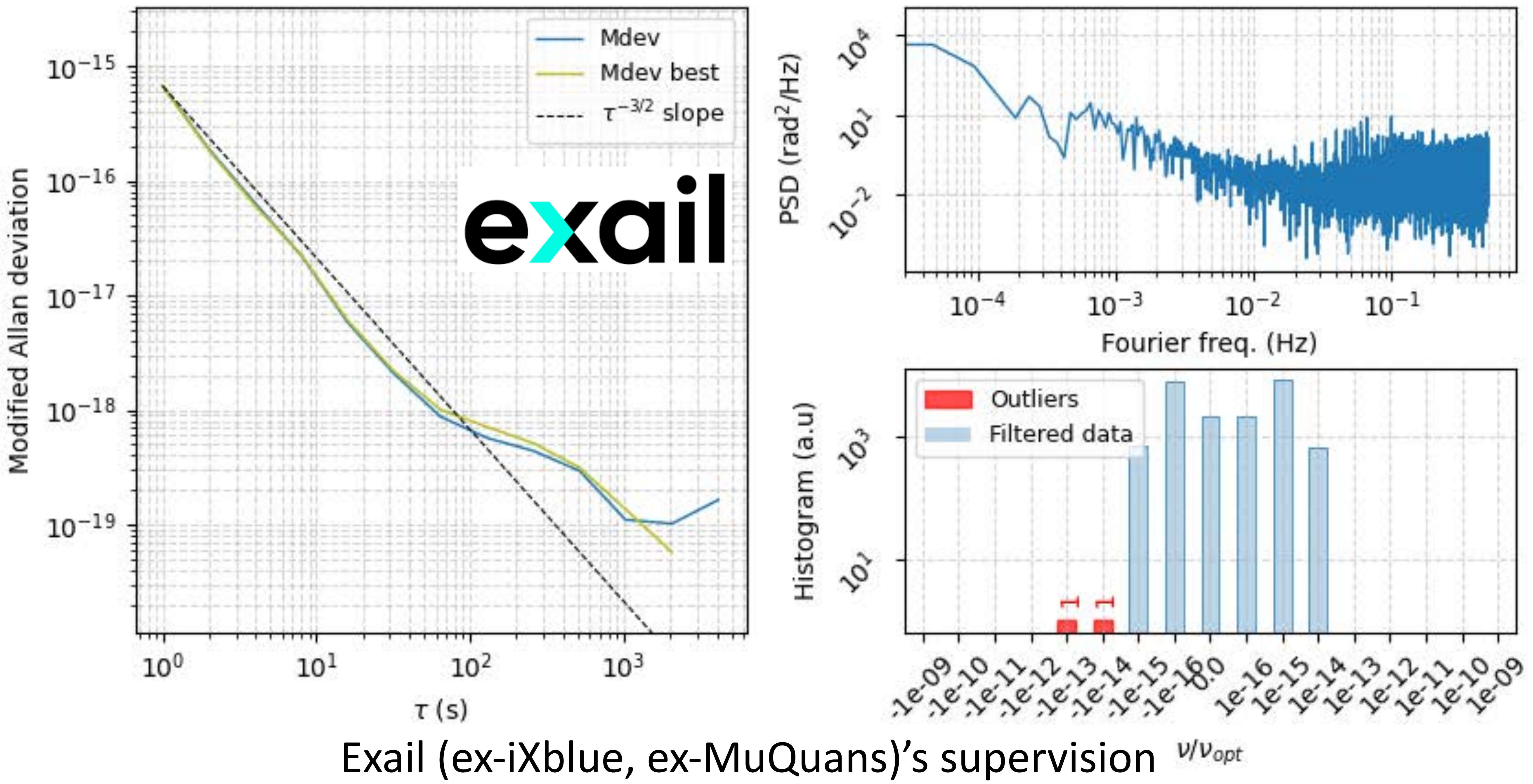
- Link performance and monitoring example



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

- REFIMEVE signal: copies stability laser x maser x cryo
- Enable comparisons with satellites links
- Source uptime since Dec. 2019 : 95 %
- REFIMEVE signal frequency: 194 400 121 000 000 +/- 2 Hz

  but since 2022: 194 400 121 000 000 +/- 25 Hz

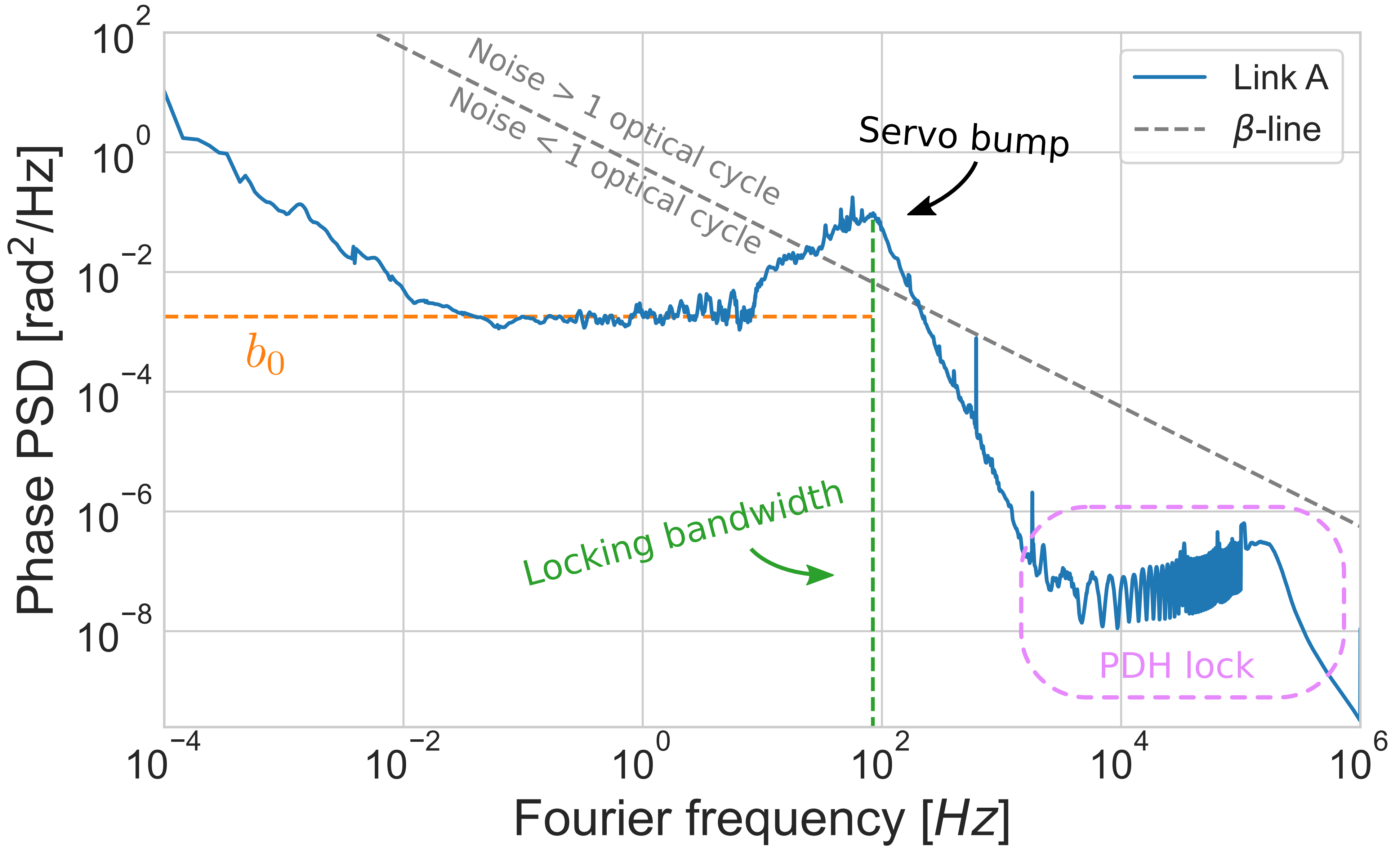


Exail (ex-iXblue, ex-MuQuans)'s supervision

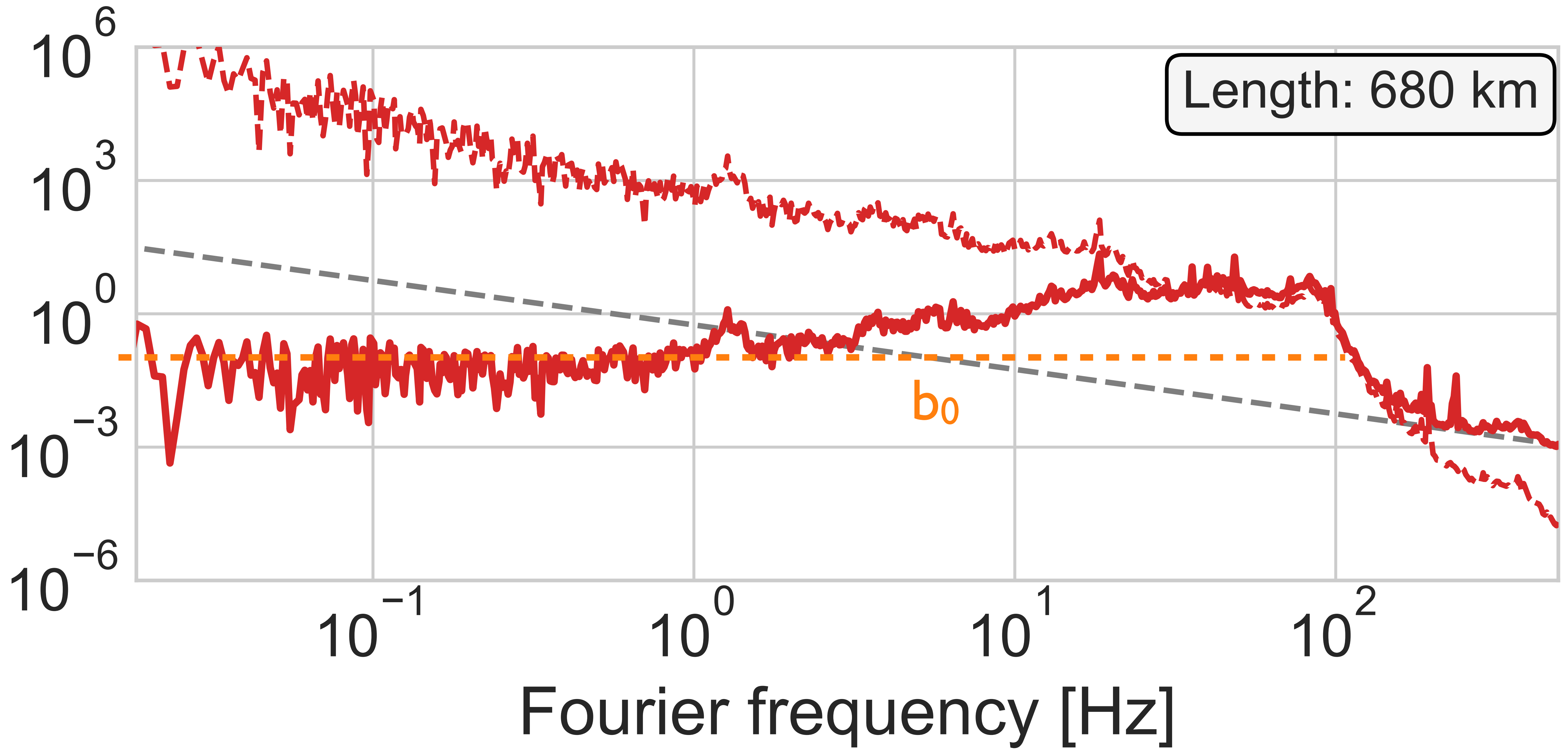
Optical frequency transfer : typical performances

- Output signal phase noise: the signal deteriorates with the length of the link

2x43 km



2x680 km



For short to mid-haul links (< 100 km) : negligible degradation / ultra-stable laser
For long-haul links (>100 km), coherence is retrieved after 1 s measurement time

- REFIMEVE will operate three ultra-stable laser remotely (Bordeaux, Grenoble, Calern)
- REFIMEVE will build a transportable lab. equipped with ultra-stable laser and comb

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

Towards a highly available signal

Relative frequency fluctuations with time (days)

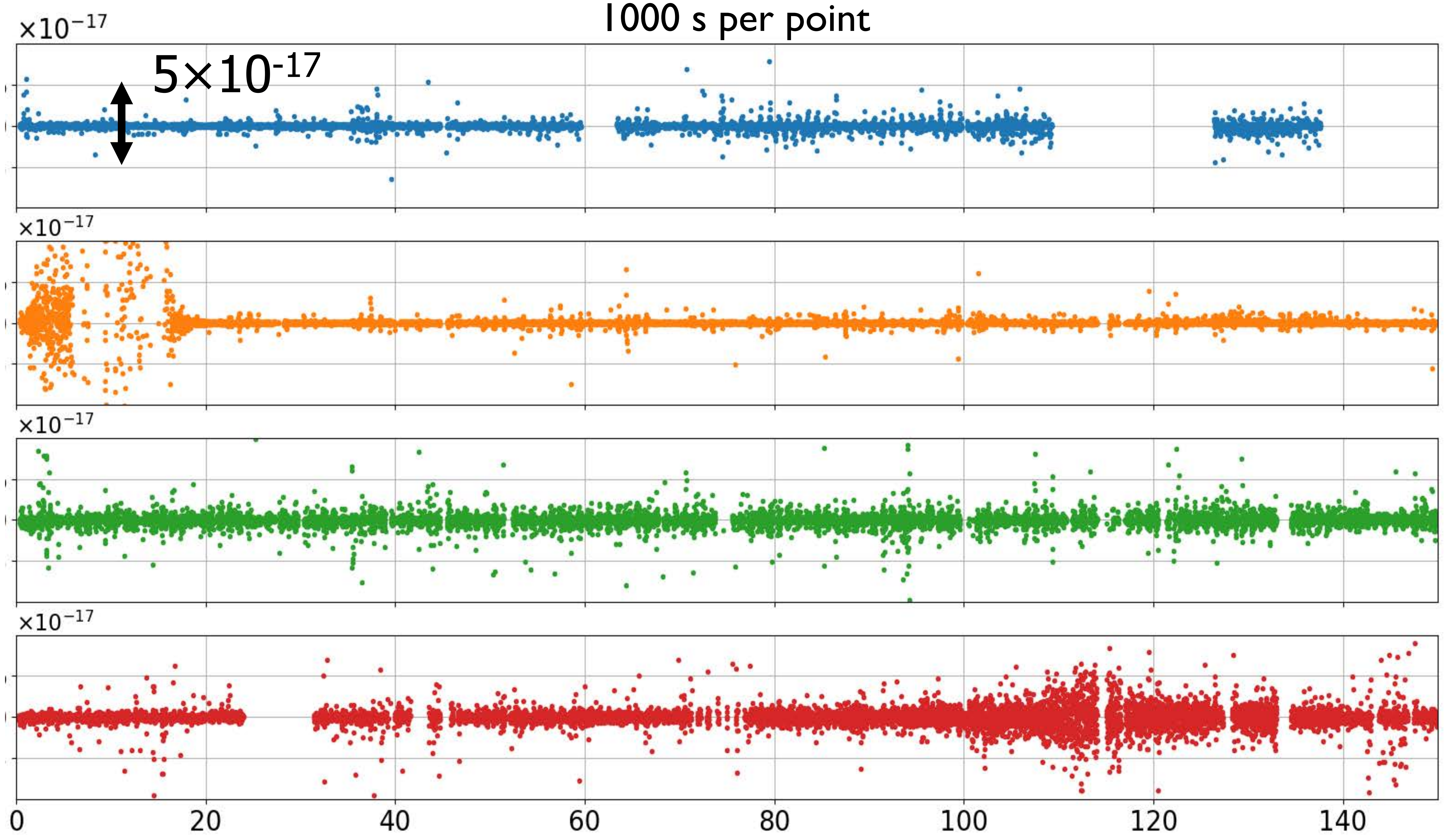
1000 s per point

Paris-Lille-Paris (2 x 340 km)

Paris-Strasbourg-Paris (2x650 km)

Paris-Lyon-Modane-Lyon-Paris (2x900 km)

Lyon-Marseille-Lyon (2x440 km)



Uptime 71%

Uptime 85%

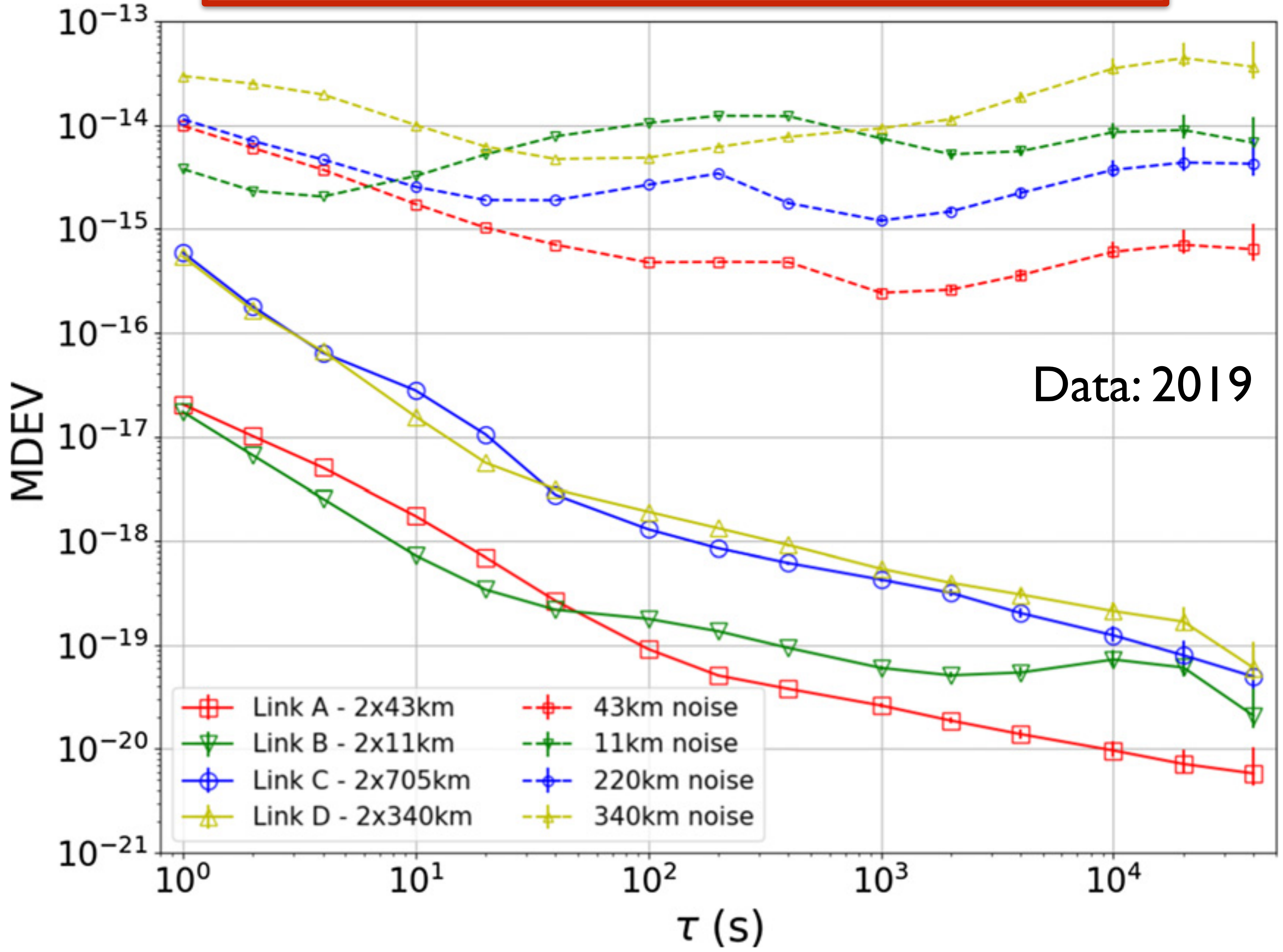
Uptime 81%

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

2023 update:

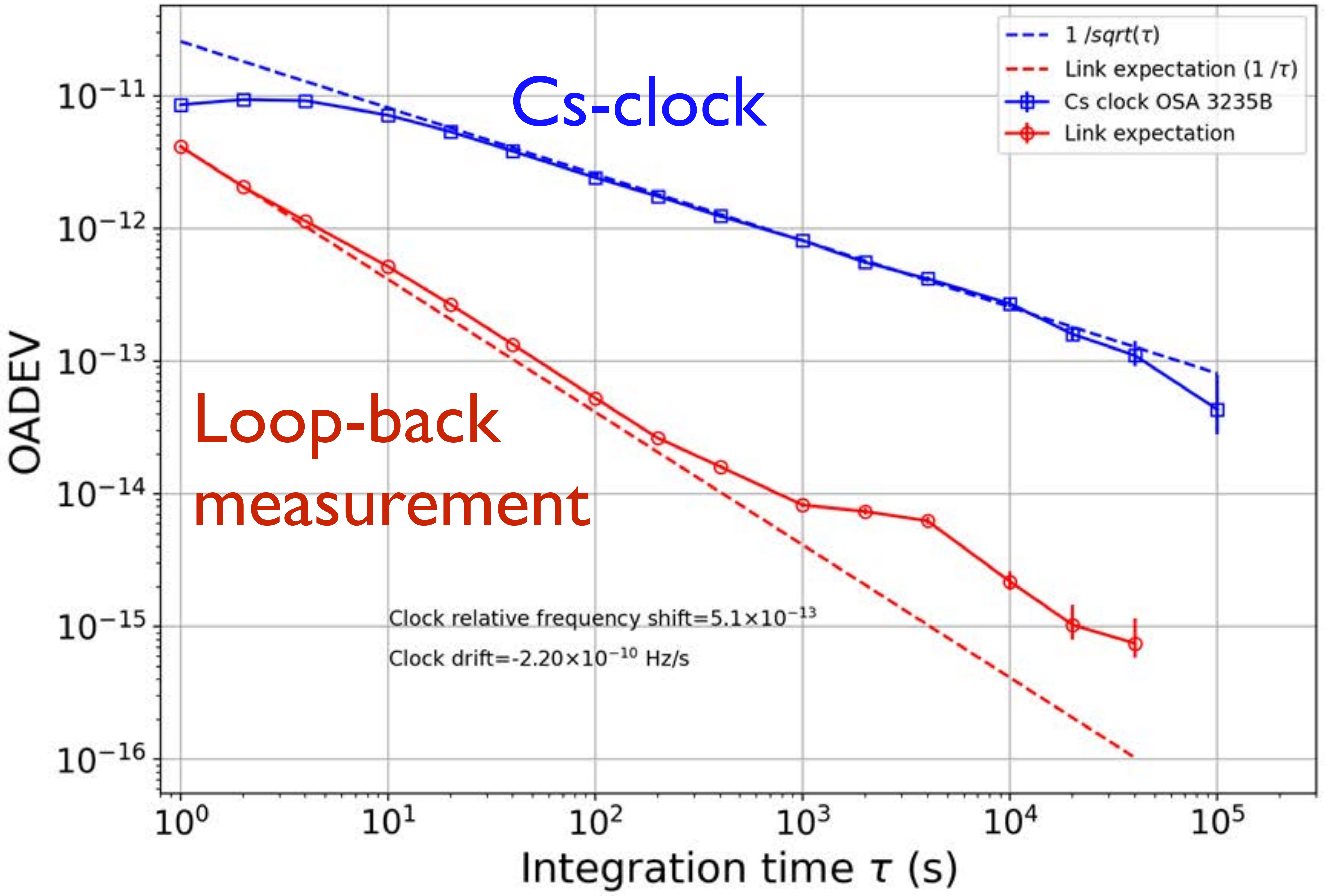
- 7 links operated in parallel
- 3800-km stabilized fiber links
- Data analysis over years measurement time

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

Extension to a White Rabbit signal

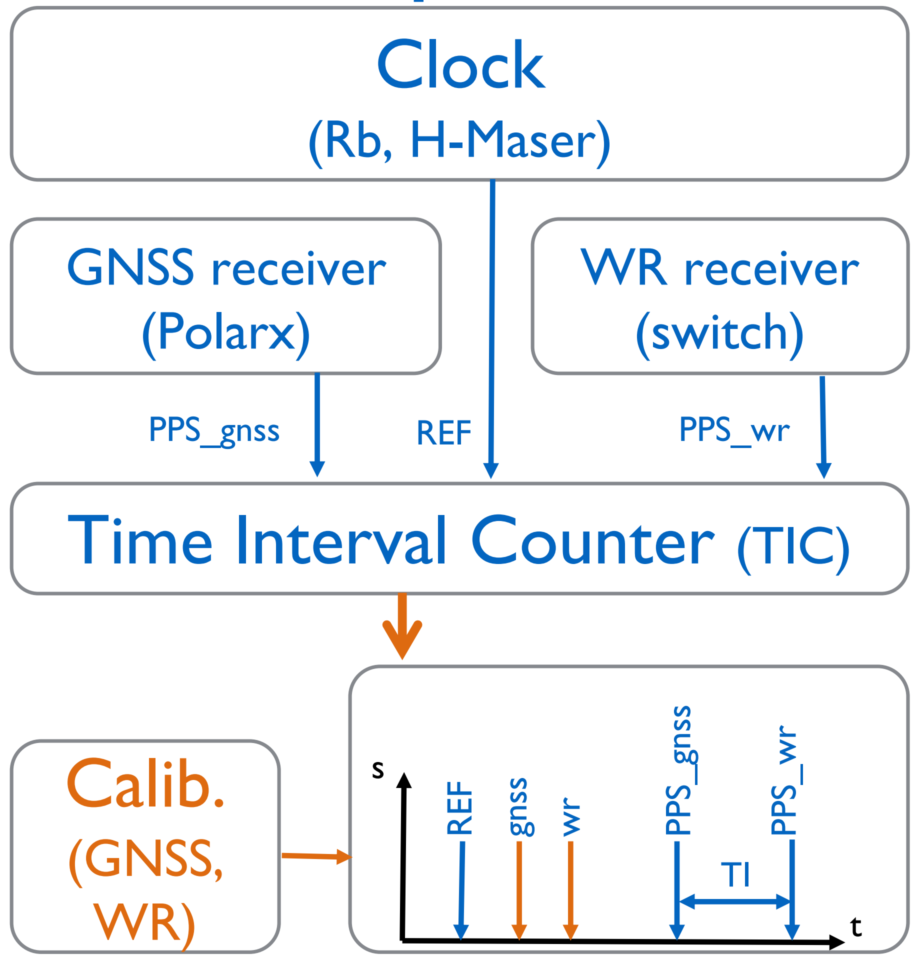
<u>What you need to know:</u>

- White Rabbit disseminates time and frequency over ethernet frames
  - Standardized at IEEE (1588, High accuracy profile)
- White Rabbit provides 10 MHz and 1 PPS signal output

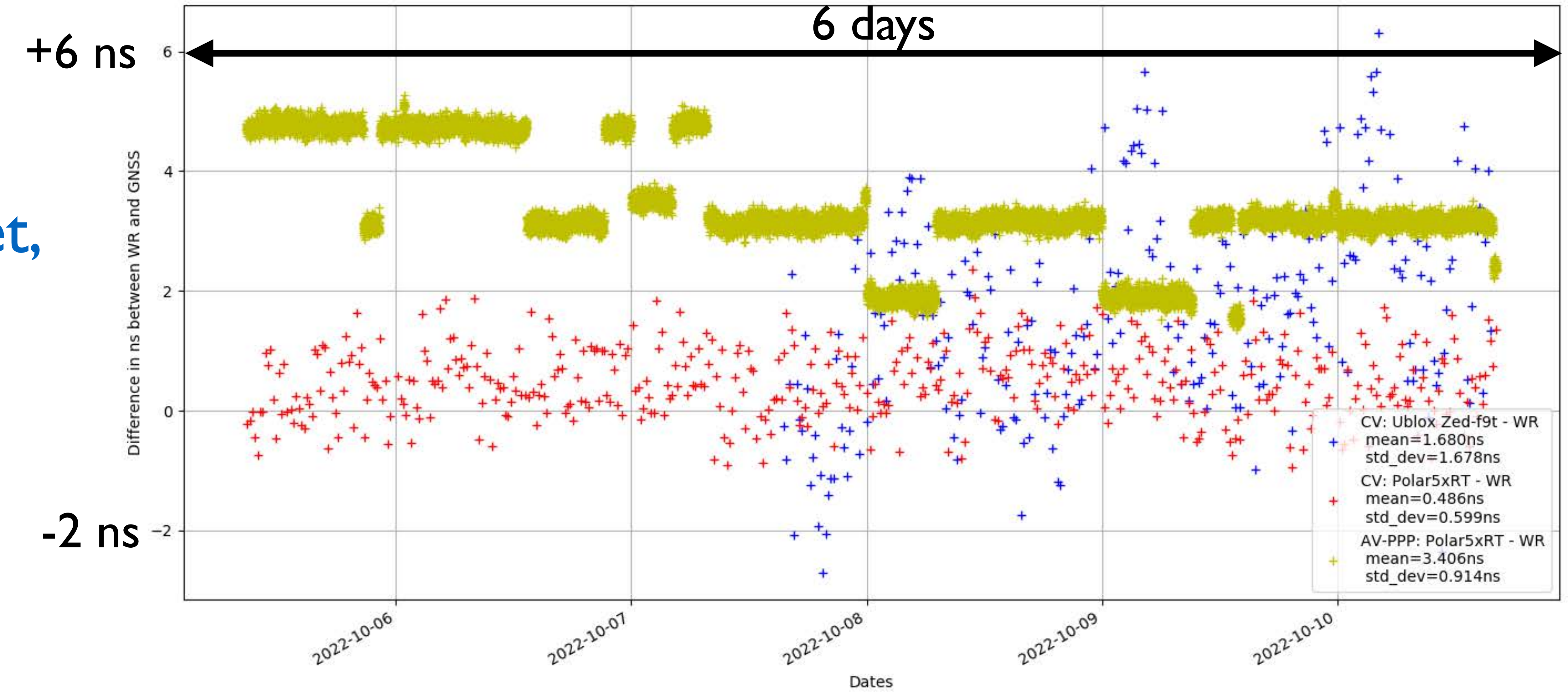


- Exemple #1 : Dissemination to Thales TAS (Velizy)
  - versus prior qualification of a Cs clock in the lab
  - Credit: O. Lelievre

- Exemple #2 : dissemination to LPNHE (Paris)



- Set up at LPNHE
- Credit: V. Voisin, L. Mellet, S. Russo, M. Guigue, B. Popov



Partnership

Kernel

LPL (USPN, CNRS)

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

RENATER

Industrials

30 Users

Cooperative networking

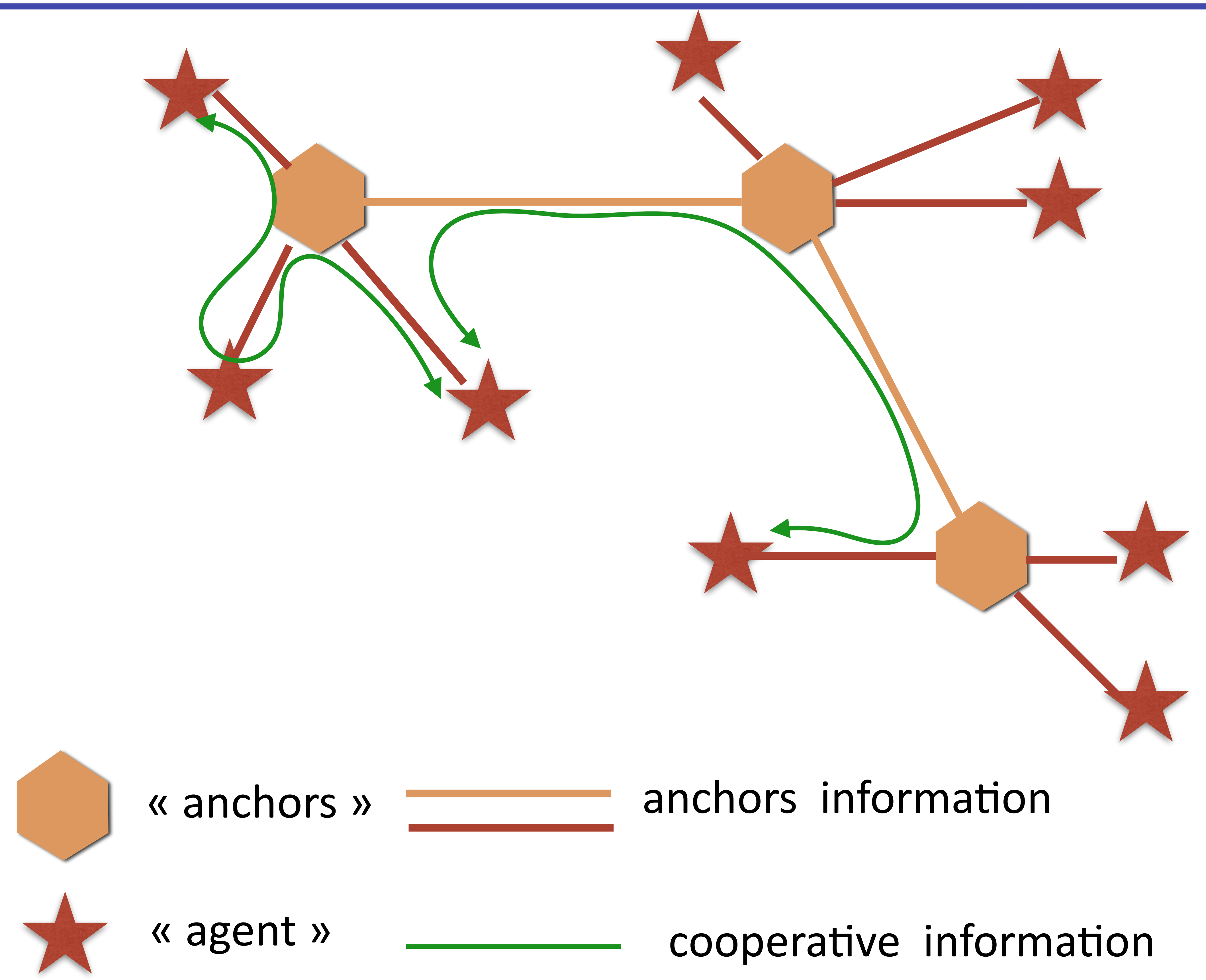
non-cooperative approach:

no communication between *agents*, only between *agents* and *anchors*

Cooperative approach:

Users in cooperative communication systems work cooperatively by relaying information(s) to each other

NB: Concepts used for wireless network, normally with broadcast communications



<u>REFIMEVE</u> :

Multicast network

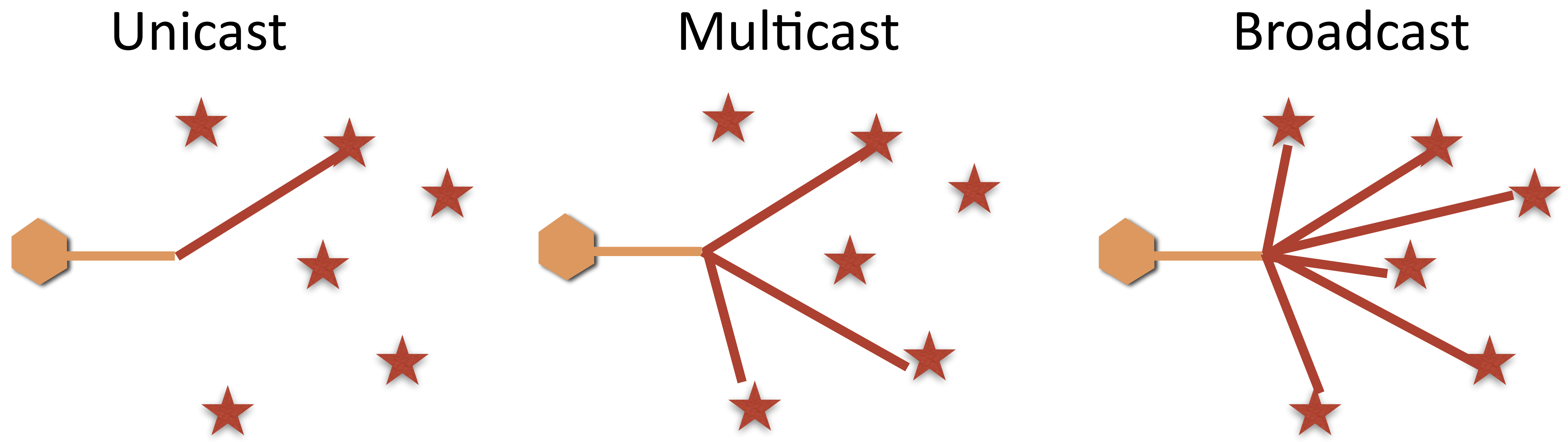
Cooperative approach in the clock network (between anchors so far)

>Play role of Open Data and real time access to the data

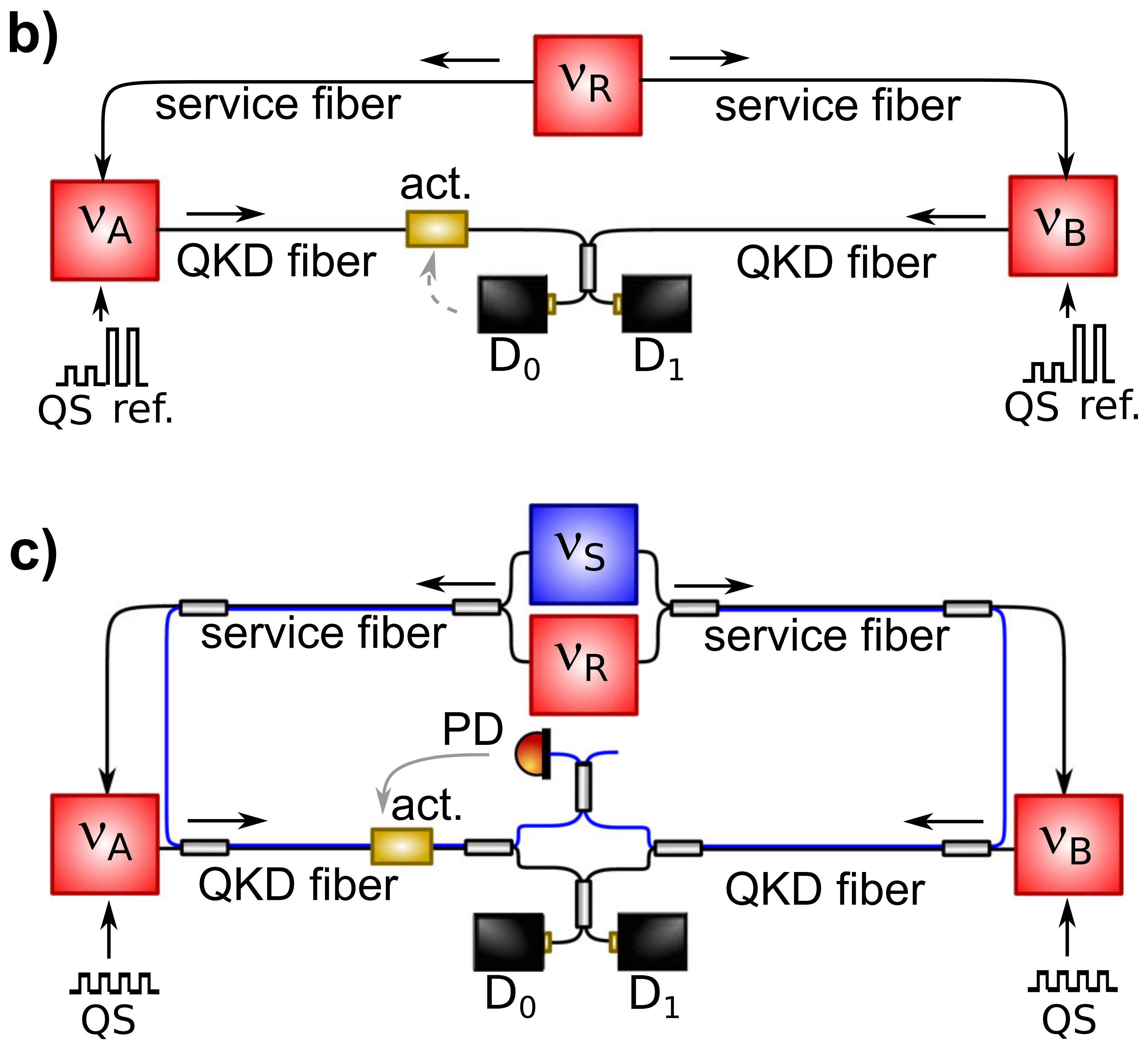
At the user end :

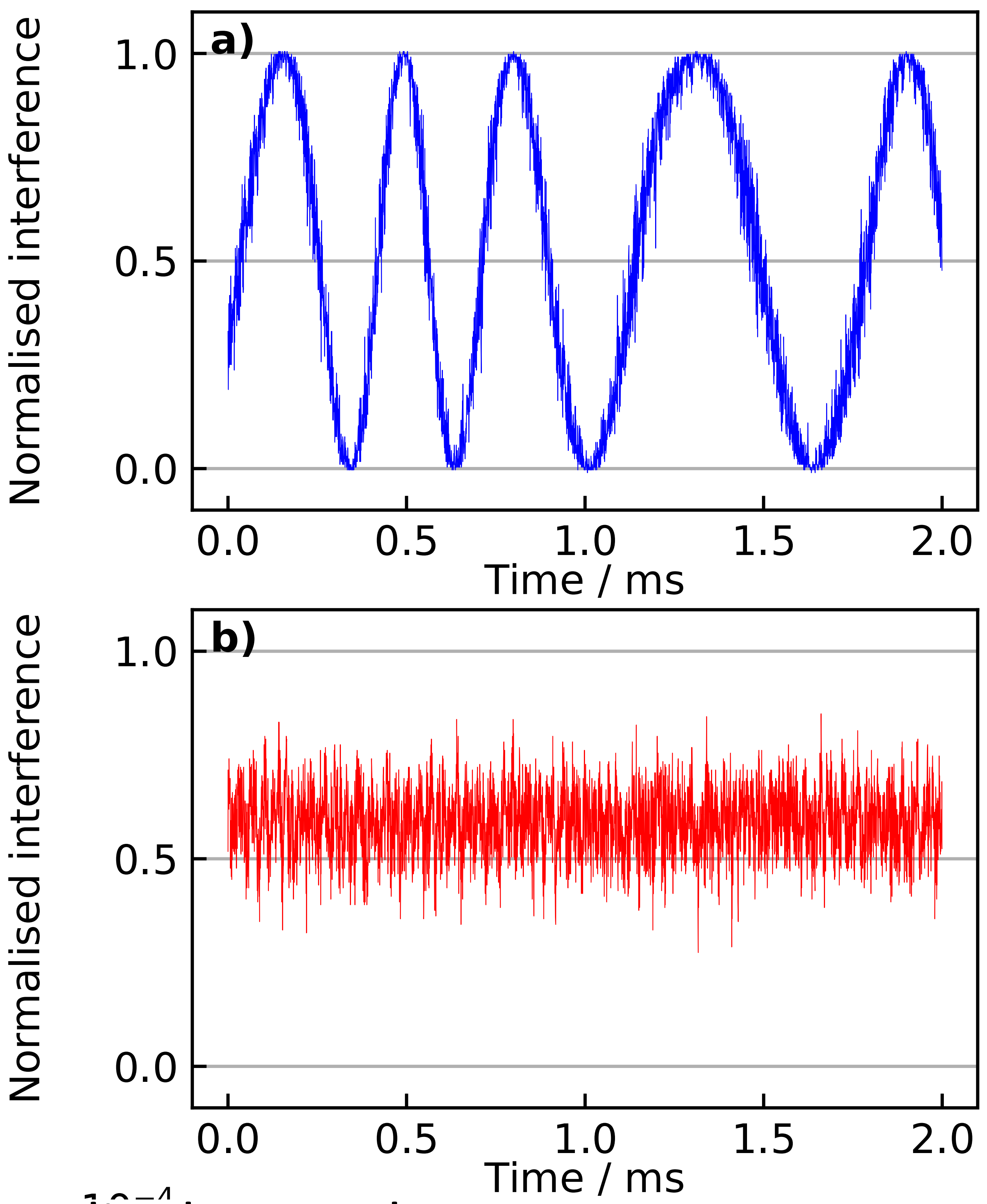
Can we develop an integrated cooperative architecture ?

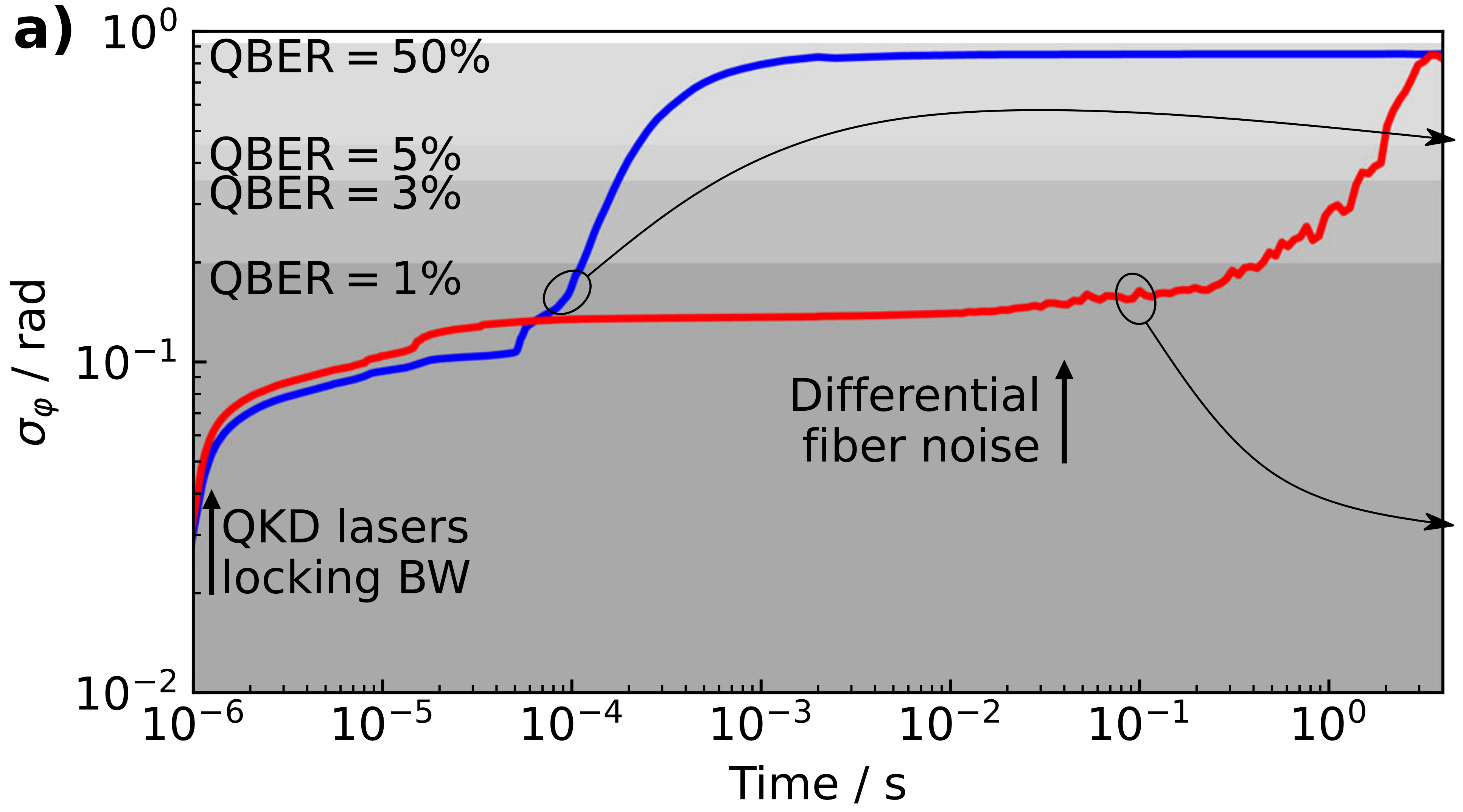
Can we build a quantum network ?



Quantum telecommunication: TF-QKD







- QKD lasers are phase-locked
- Fiber phase noise is cancelled
- Demonstrated over 206 km, 65 db Loss

Information is encoded as discrete phase states on dim laser pulses.

« Owing to the low phase jitter enabled by active phase stabilization, a secret key rate of up to 4.942 kb/s can be achieved »

10.8 dB gain / maximum secure key rate bound (aka POLB)

TF-QKD/206 km: C. Clivati et al., Nat. Comm. (2022) doi: 10.1038/s41467-021-27808-1.

see also:

TF-QKD / 650 km: J.-P. Chen et al., Phys. Rev. Lett., (2022), doi: 10.1103/PhysRevLett.128.180502.

CV-QKD: Y. Shao et al. Phys. Rev. A (2021), doi: 10.1103/PhysRevA.104.032608.

Bosonic dephasing channel: L. Lami et M. M. Wilde Nat. Photon. (2023), doi: 10.1038/s41566-023-01190-4.

NB: project submitted at EURAMET (industry call) this year
LIP6, GEOAZUR, SYRTE

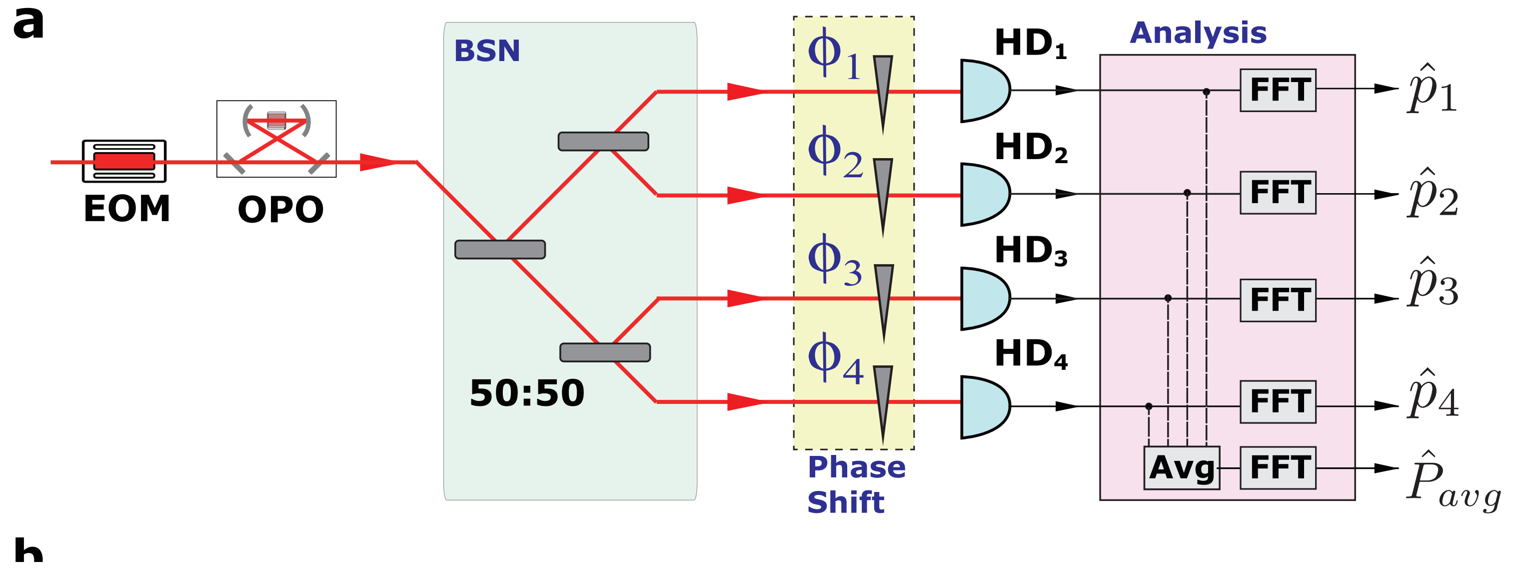
Continuous-variable QKD and distributed quantum sensing

Sensing from multiple, spatially distributed, entangled systems:

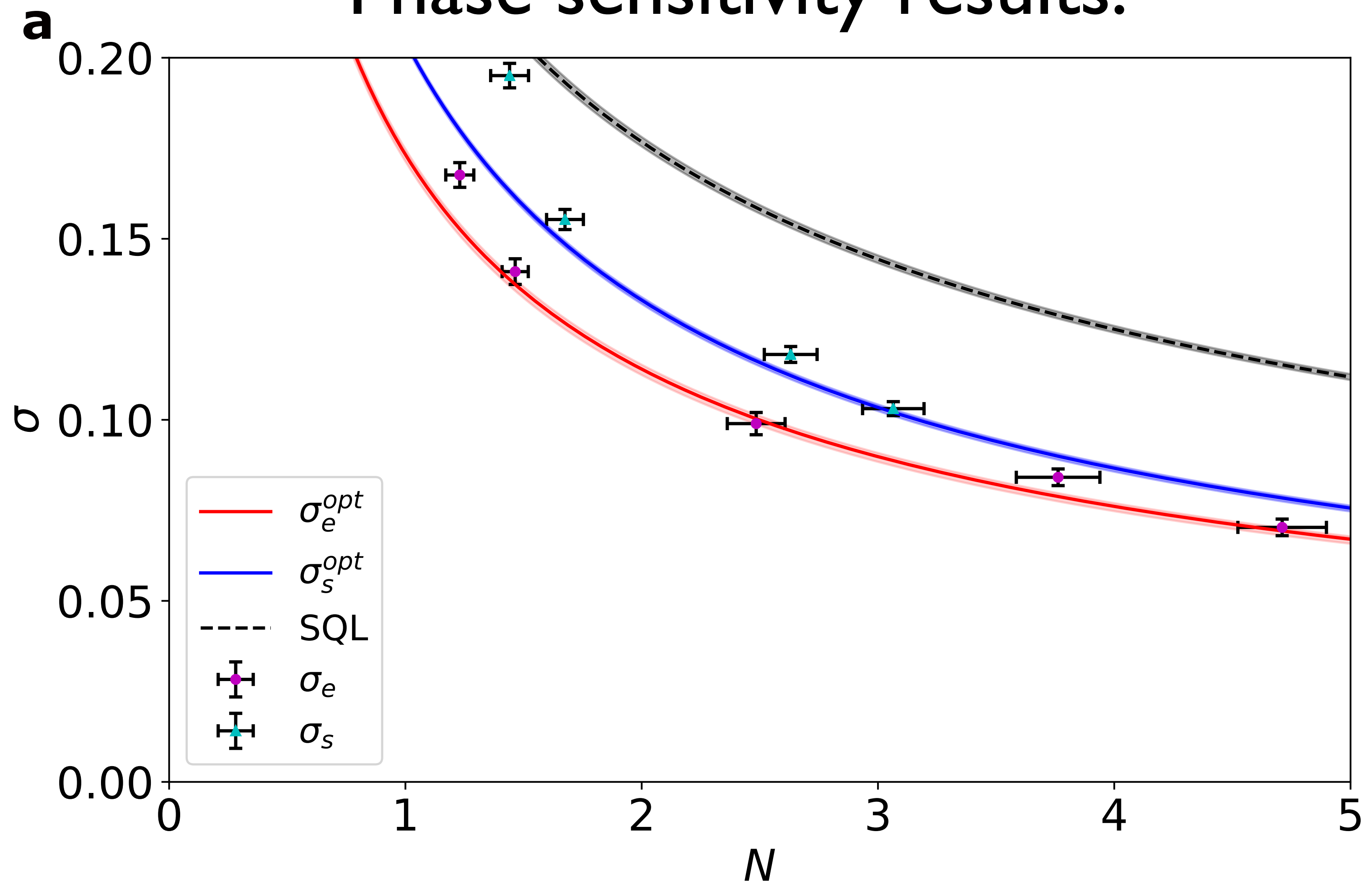
- Application for detection of gravitational waves, magnetic fields, and even biological measurements
- Either using twin-photons, Greenburger-Horne-Zeilinger states, CV-entanglement

Experimental demonstration of sensing of an averaged phase shift among N=4 distributed nodes

- *4-mode entangled continuous variable (CV) state,*
- *Deterministic quantum phase sensing with a better sensitivity for entangled (e) than separable (s) measurements*



Phase sensitivity results:



CV-QKD and distributed quantum sensing :
X. Guo et al., Nat. Phys. (2020), doi: 10.1038/s41567-019-0743-x.
Theoretical proposal: Q. Zhuang et al.,Phys. Rev. A (2018), doi: 10.1103/PhysRevA.97.032329.

<u>Related topics</u> :

Quantum repeaters and quantum memories see T. Miyashita *et al.*, (2021) arXiv:2108.13130 [quant-ph]

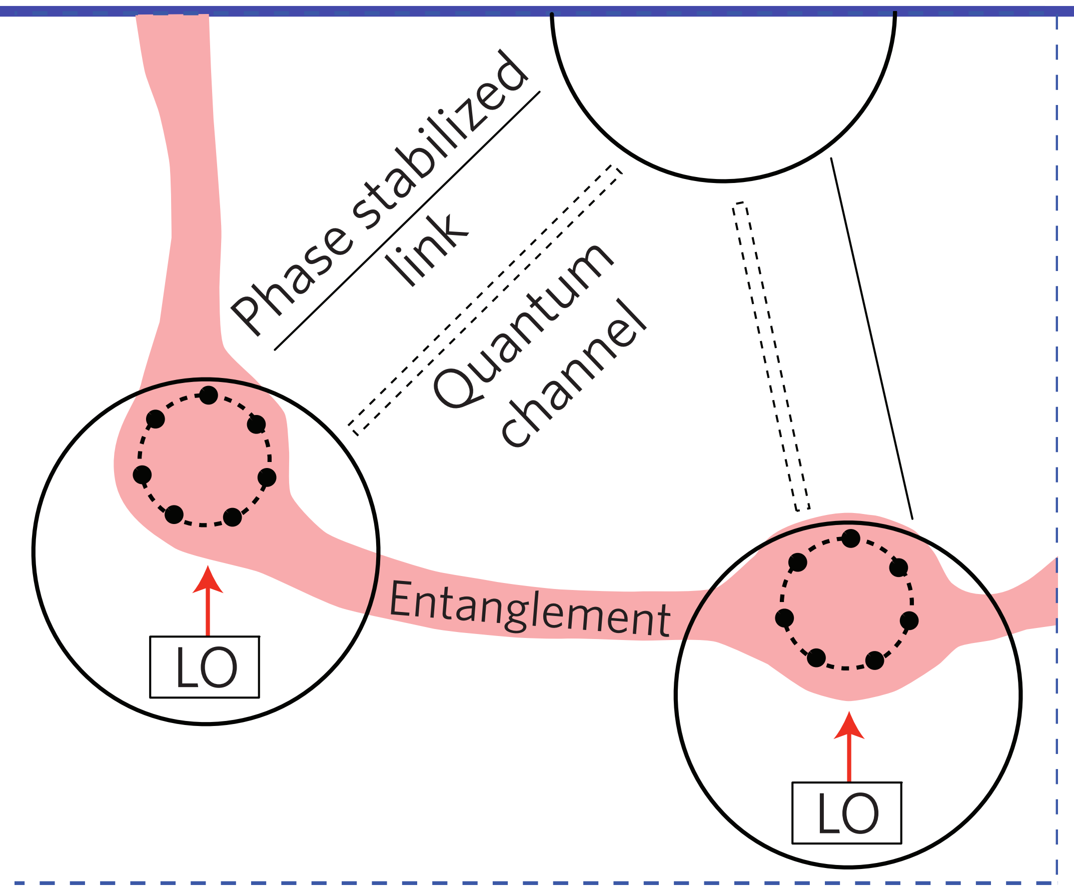
Frequency-stabilized lasers can realize the remote coupling of a quantum memory and an entangled photon source in quantum repeaters.

Quantum synchronisation: R. Quan et al., Sci. Rep. (2016) doi: 10.1038/srep30453.

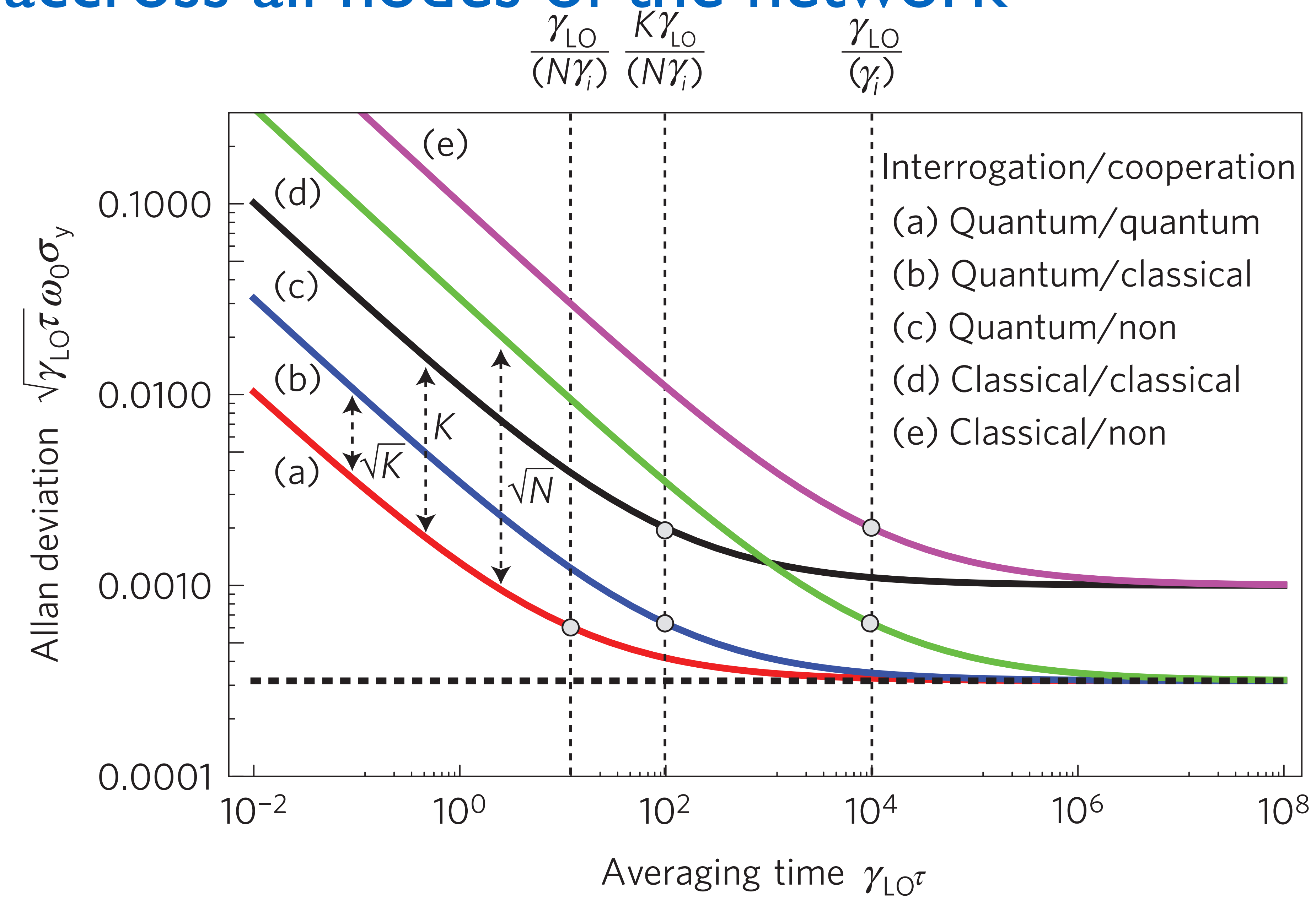
Biological measurement : M. A. Taylor et al., Nat. Photon, (2013), doi: 10.1038/nphoton.2012.346.

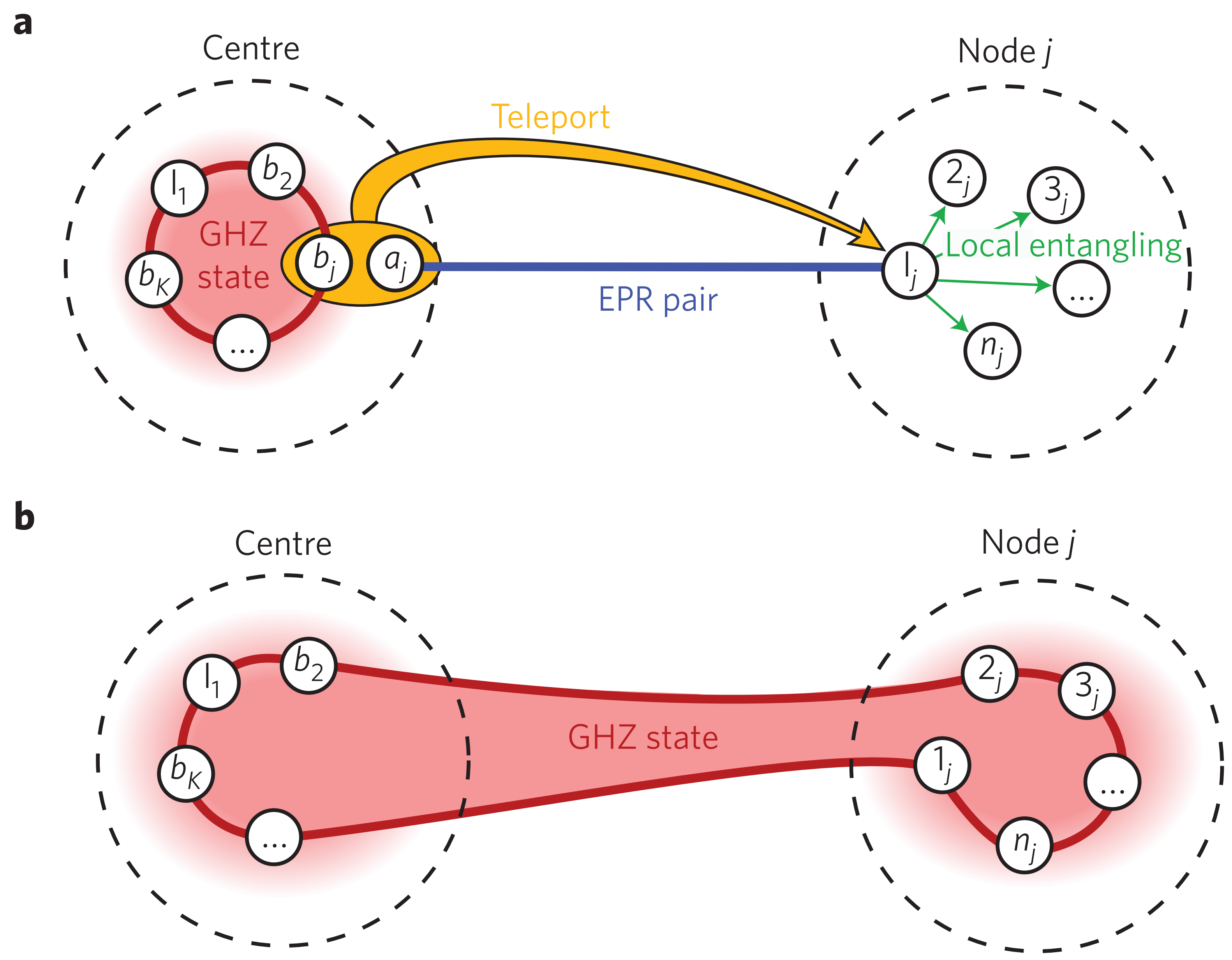
Quantum network of clocks

- Ye and Lukin's proposal of a cooperative network (2014)
  - Aim : maximise stability beyond quantum limit
  - Optical clocks + phase stabilized link + quantum channel
    - Qubits partition: ½ classical feedback to LO and ½ to form entangled states
    - GHZ quantum correlated states of « different size »
    - EPR pairs nodes-center
    - Quantum teleportation results in collective GHZ state accross all nodes of the network



Network-wide Greenburger–Horne–Zeilinger (GHZ) state preparation





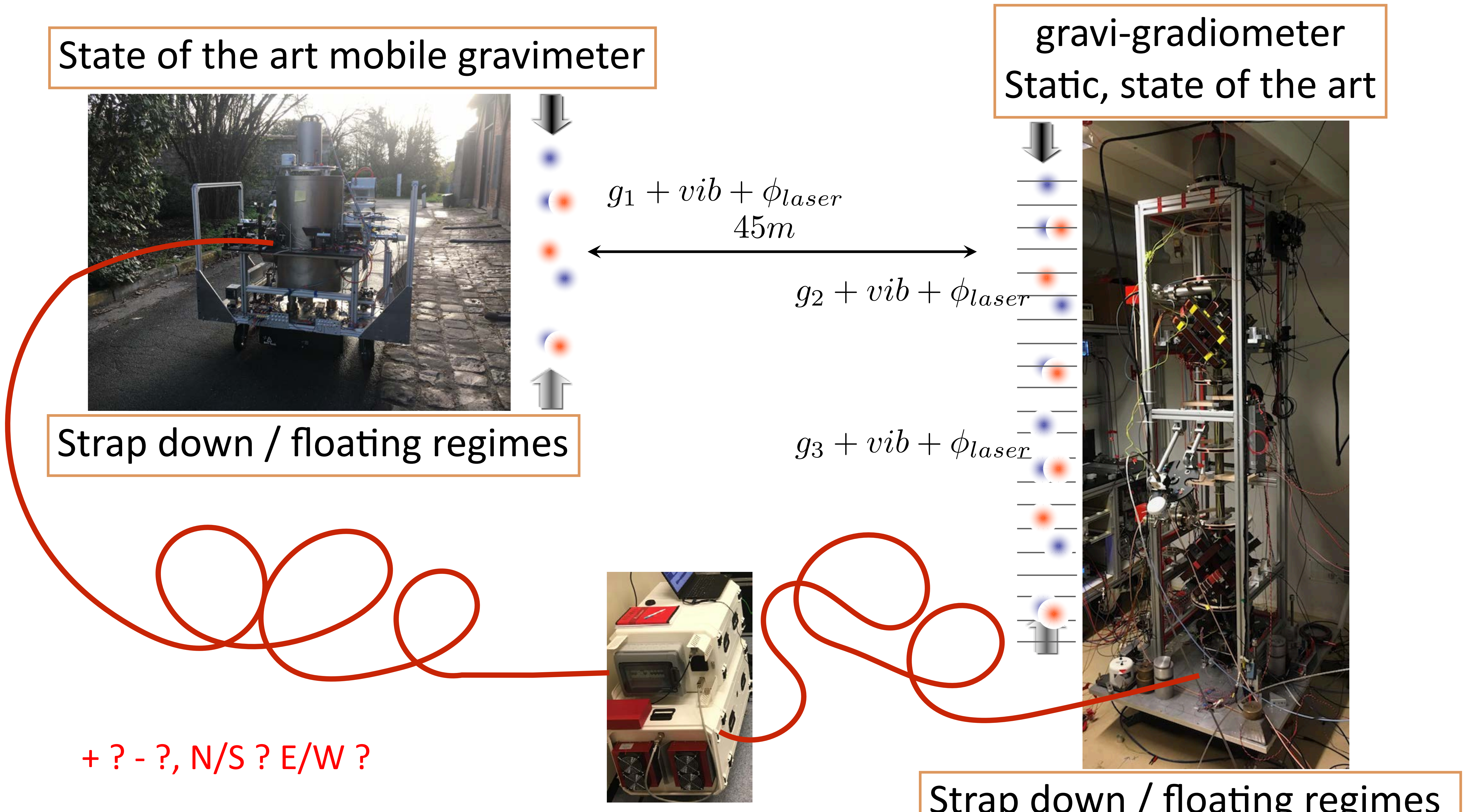
P. Kómár et al., Nat. Phys (2014) doi: 10.1038/nphys3000.

Quantum sensors network: a simple and classical approach

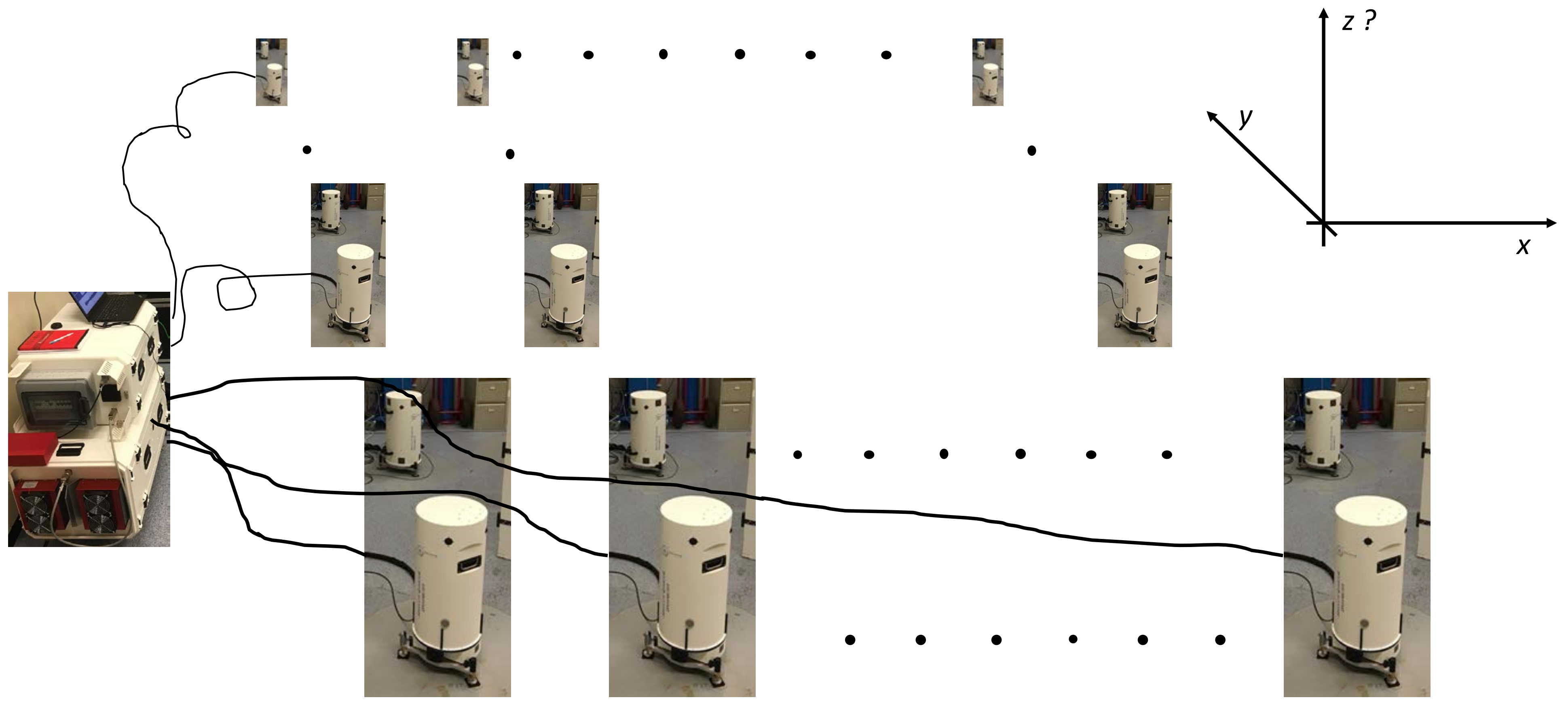
Proposal: S. Merlet (SYRTE) @ Journées capteurs quantiques du Bureau des Longitudes (2021) (Geo-Pos)

Aim : Investigation of correlated short-range probing of gravitational tensor components
Strap-down or “floating” (i.e. with vibrational isolation) regimes,
Hybridized with classical seismometer to track vibrations during acquisition

Local network tests



Expandable to a wide area network



Perspectives and conclusions

- REFIMEVE is operational, even if all links are not yet completed
  - Signal coherence at user's end distincts mid-haul and long-haul links
  - Unique capacity of REFIMEVE : parallel operation
  - Enable cooperative networking
- Optical, RF and time service
  - uptime > 60 % / year
  - optical: ~1e-15@1s, RF ~1e-12@1s, time ~a few ns
  - Coming soon: access to the data, codes, and collaborative tools

- Perspectives of application in quantum science
  - Telecommunication:
    - TF-QKD with time delay stabilization demonstrated
    - CV-QKD : not yet ?
    - Quantum synchronisation ?
  - Quantum sensing ?
  - Quantum network of sensors/clocks?
- Towards a cooperative network ?

Fundings

LIOM, REMIF, REFIMEVE+, T-REFIMEVE

LOFIC

INSU
GRAM

ROME, LICORNE, TORTUE, (…)

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

EU Research infrastructure

CLONETS
CLONETS-DS

FIBRE, TRANSF

TOCUP, ONSEPA, (…)

SCP Time

Thank you for your attention