REFIMEVE fibre links and optical clock comparisons

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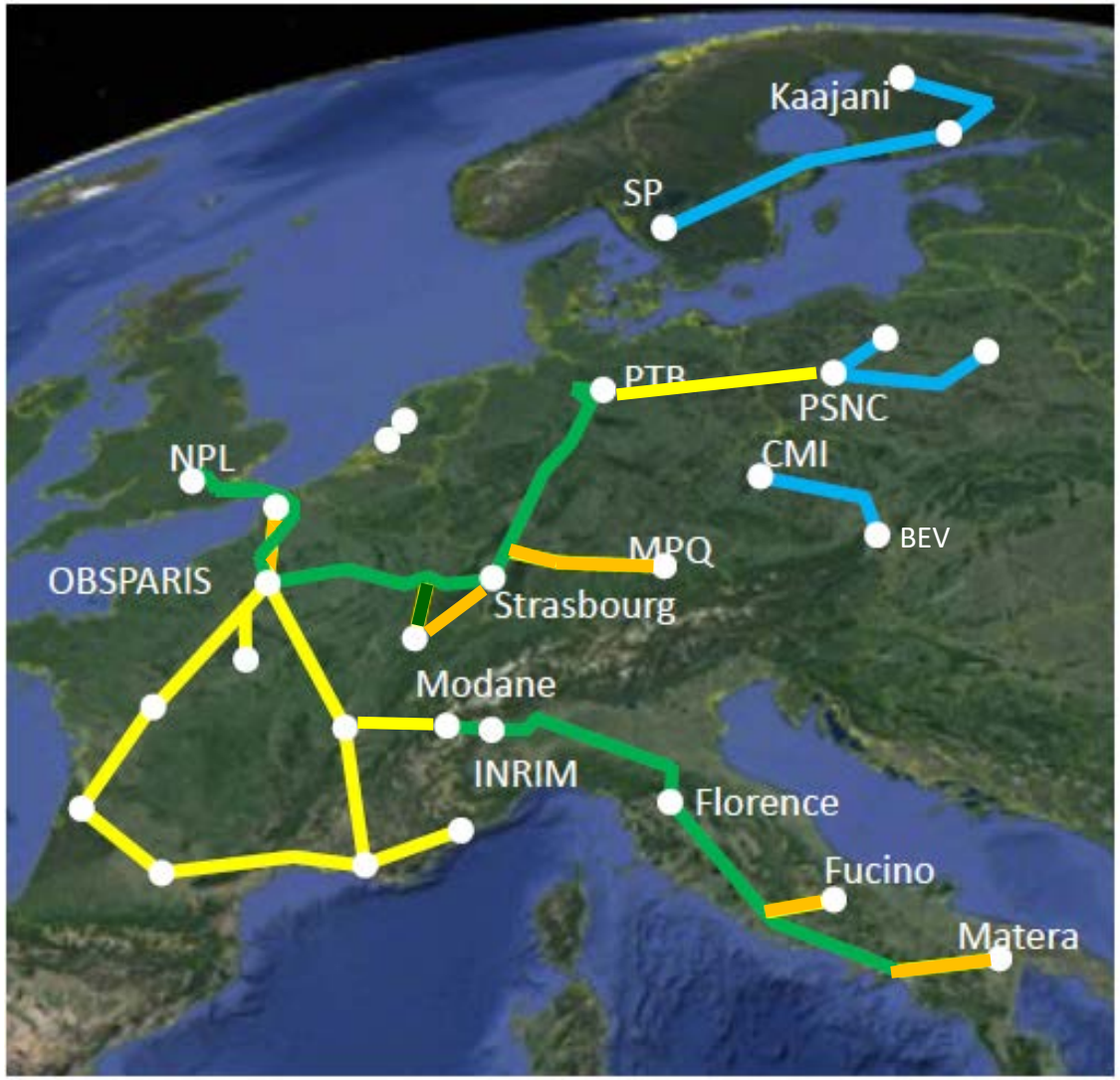
Towards a metrological fiber network in Europe



- In Europe (Euramet)
  OFTEN 2016-2019 (coord PTB)
  TIFOON 2019-2022 (coord NPL)

- In France: Refimeve+ (LPL/SYRTE)
  Dissemination to 20 academic labs

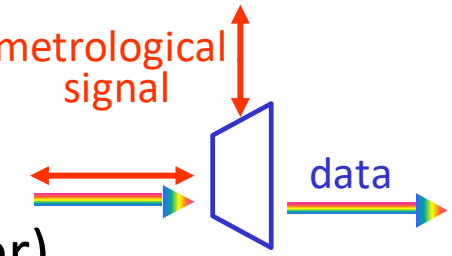
- In Italy: LIFT (INRIM/Lens)
  Dissemination to a few academic labs

Courtesy H. Schnatz (PTB)

Summary

- Long-distance optical link
  - Dark fiber or dark channel
  - Amplification and regeneration
- Towards a metrological network
- Application to clocks comparison

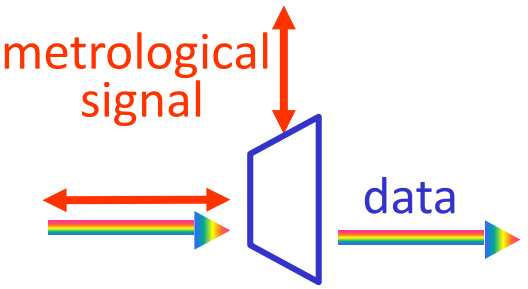
Long-distance optical link : fiber availability

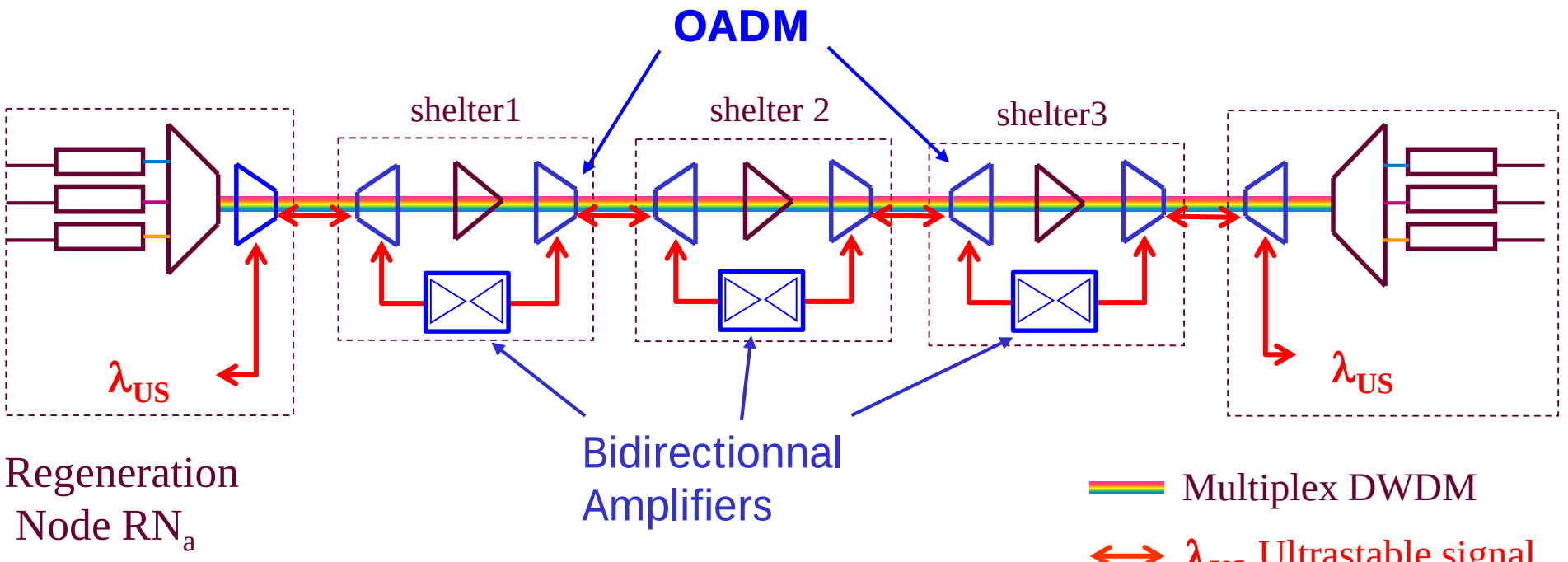
Dedicated fiber or dark fiber	Dedicated frequency channel or dark channel
You rent the fiber and use it for your own application	Partnership with a fiber network provider → transfer with simultaneous data traffic → Dense Wavelength Division Multiplexing (DWDM) with OADM (Optical-Add-Drop Multiplexer) 
Contract and maintenance Expensive Better free-running fibers: possibility of minimizing parasitic reflections and reducing losses by choosing better connectors or splicing fibers	Fibers easily available through National Research and Education Network – NREN Much cheaper Increased losses, restricted control of connectors

Typical scheme of a dark channel link

Key issue: bidirectional continuous propagation (for noise correction)

→ Every (unidirectional) network equipment is bypassed using bidirectional optical add drop multiplexer to add and extract signal





Issues of long-distance optical link

- Main difficulties
  - Attenuation
  - Fiber noise is higher – Simple rule : $\propto$ sqrt(length) but strongly depending on the fiber location (outside, buried)
  - Straight reflections, parasitic noise…

- Solutions
  - Amplification: bidirectional Erbium-doped fiber amplifier (EDFA) or Fiber Brillouin amplifier (FBA)
  - Multi-segments approach + regeneration

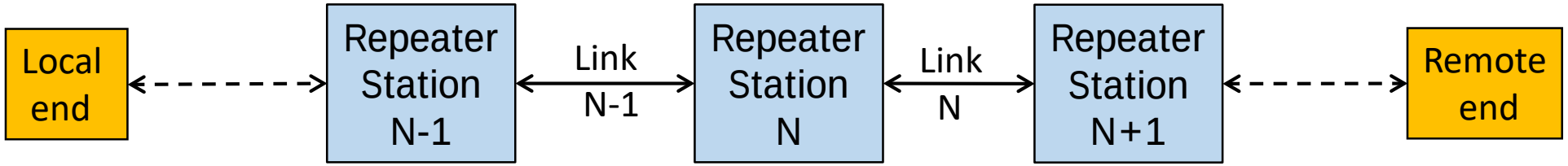
Cascaded link and regeneration

- Multi-segments approach
  - Link is divided into a few segments, depending on noise and losses

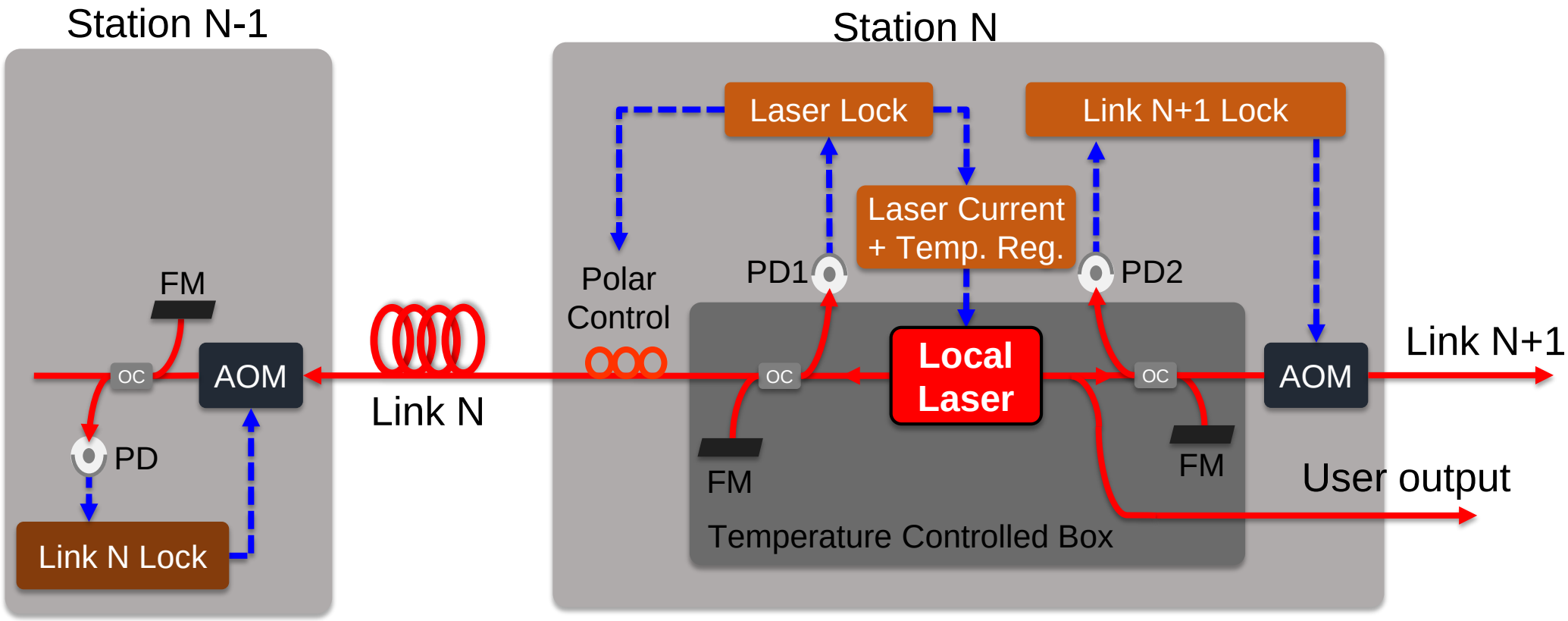
  → shorter propagation delay

  → larger bandwidth and better noise rejection

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



Repeater laser station - RLS



Chiodo et al, Opt. Express 2015

- Amplification + fixed output polarisation
- Retrace back signal to station N-1
- Correct Link N+1 noise

- Automated with remote control
- No stable RF clock required
- Compatible with dark channel technique

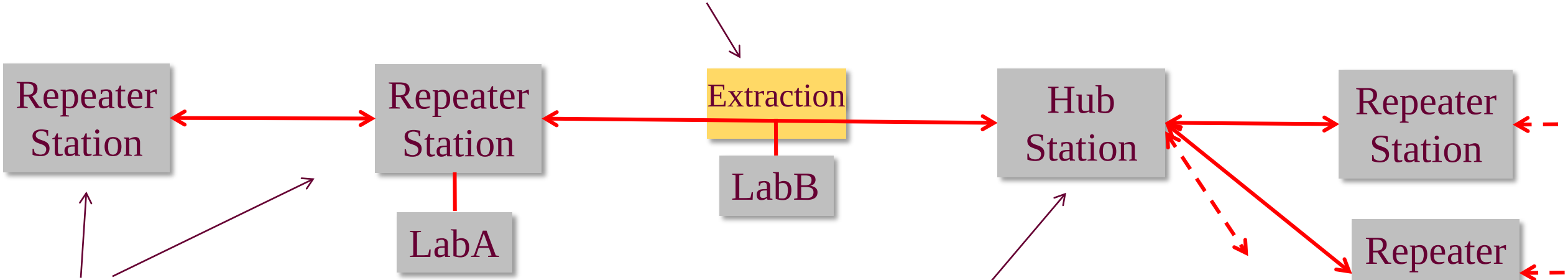
Towards a metrological network

- Aim
  - Connection of National Metrological Institutes in Europe
  - Also wide dissemination to academic labs
- Issues
  - Total 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 dissemination
- Main techniques
  - In-line extraction
  - Branching network
  - Hybrid links…

An example of multi-user network

In-line extraction station *§

noise detection/correction at extraction point



Repeater station *§

Signal regeneration

Link noise correction

User output

Hub station *

Signal regeneration

Link noise correction

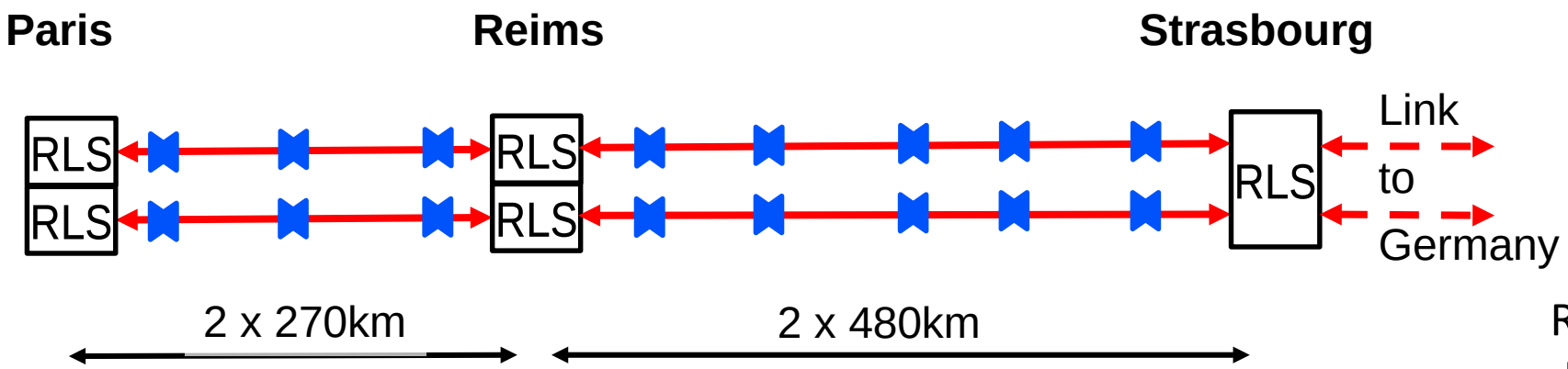
Residual noise assessment

with 3-5 outputs

* Autonomous - Remotely controlled

§ Commercially available – Can be installed in telecom hub

Example : 1410 km Paris-Strasbourg-Paris link



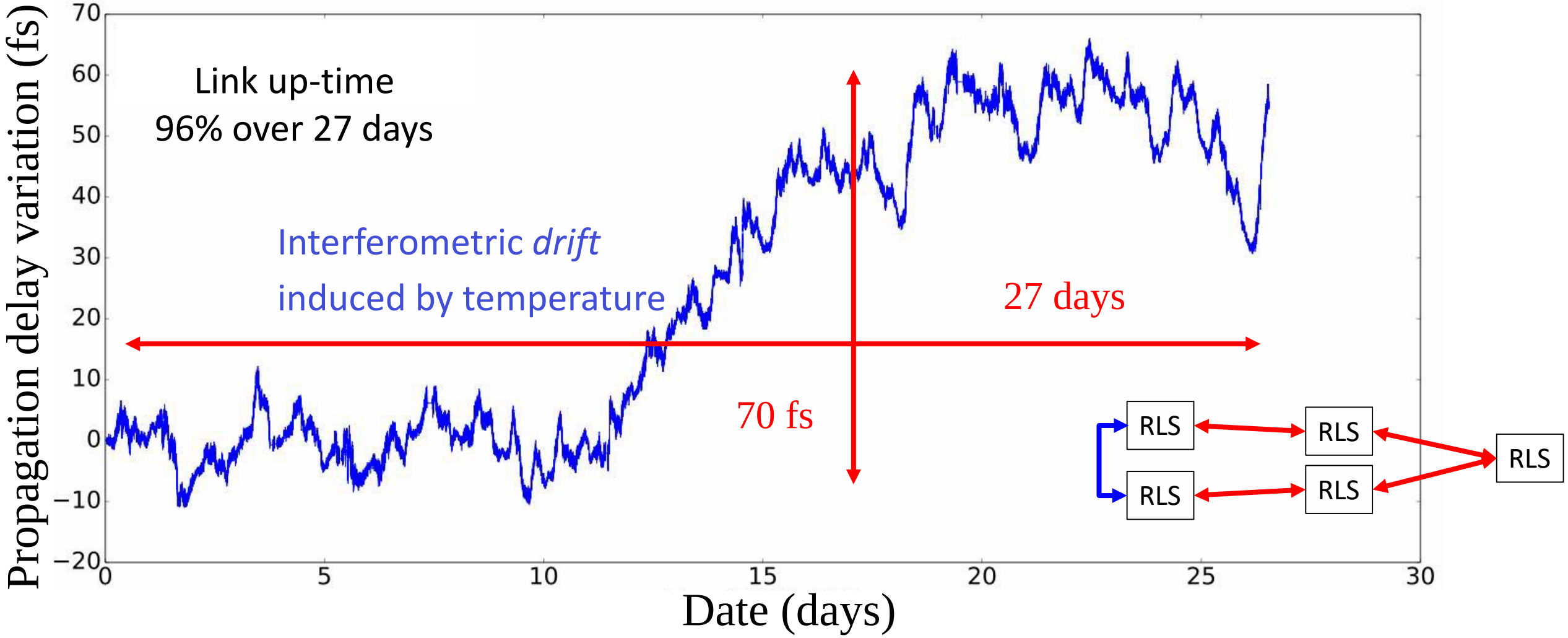
RLS = Repeater laser station

Bidir EDFA

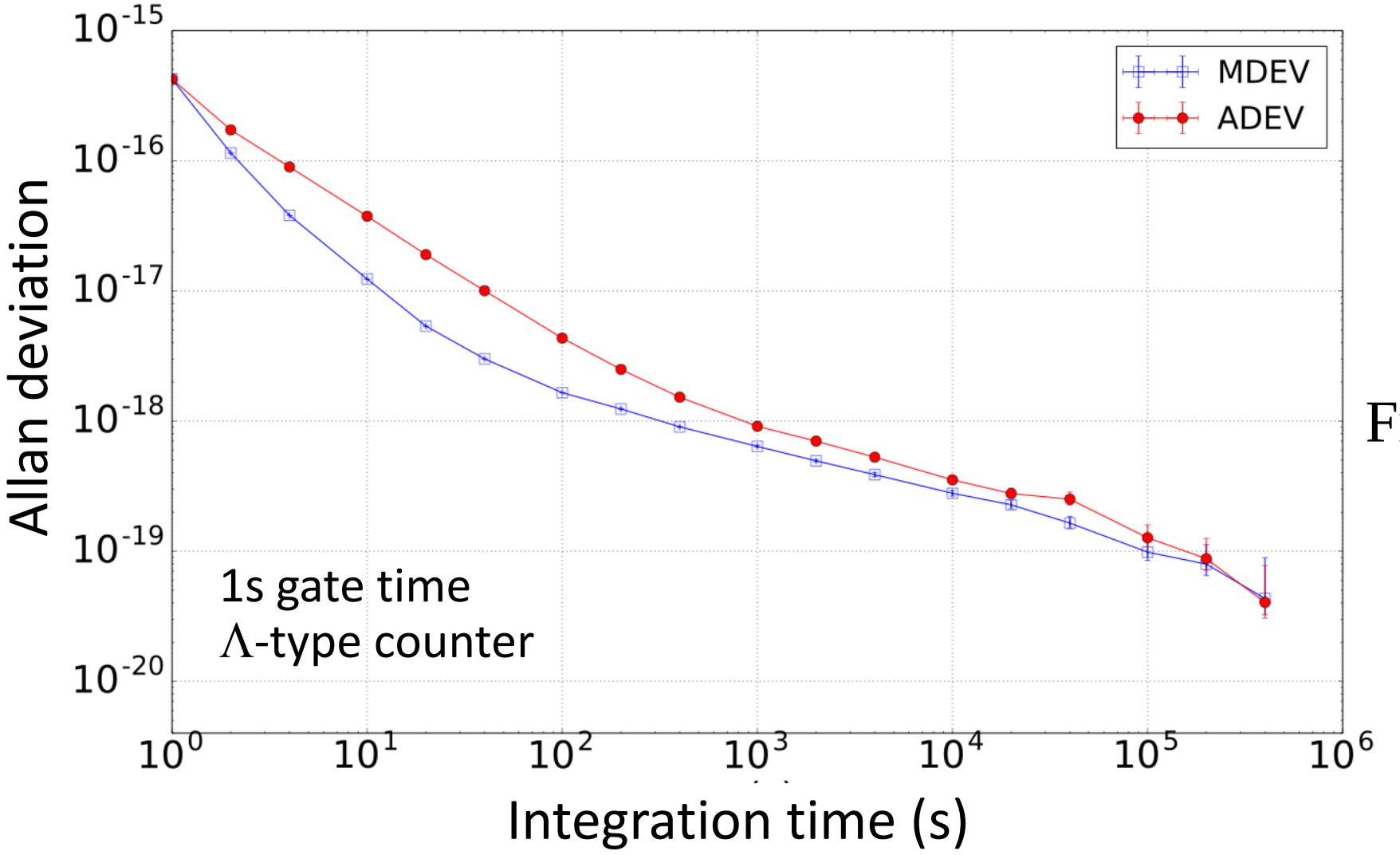
- **4 cascaded links** with 5 repeater laser stations (RLS)
- Transmission on an active telecom network: partnership with RENATER, the French National Research and Education Network
  - Metrological signal at 1542,14 nm, on ITU 44
  - Data at 1542.94 & 1543.73 nm, on ITU 43 & 42
- 40 OADMs (not shown) + 16 bidirectional EDFAs

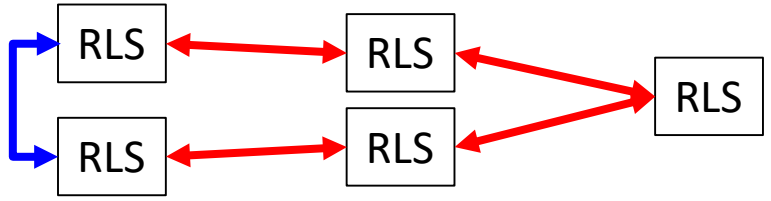
Chiodo et al, Opt. Express 2015

End-to-end propagation delay fluctuations



End-to-end stability and accuracy



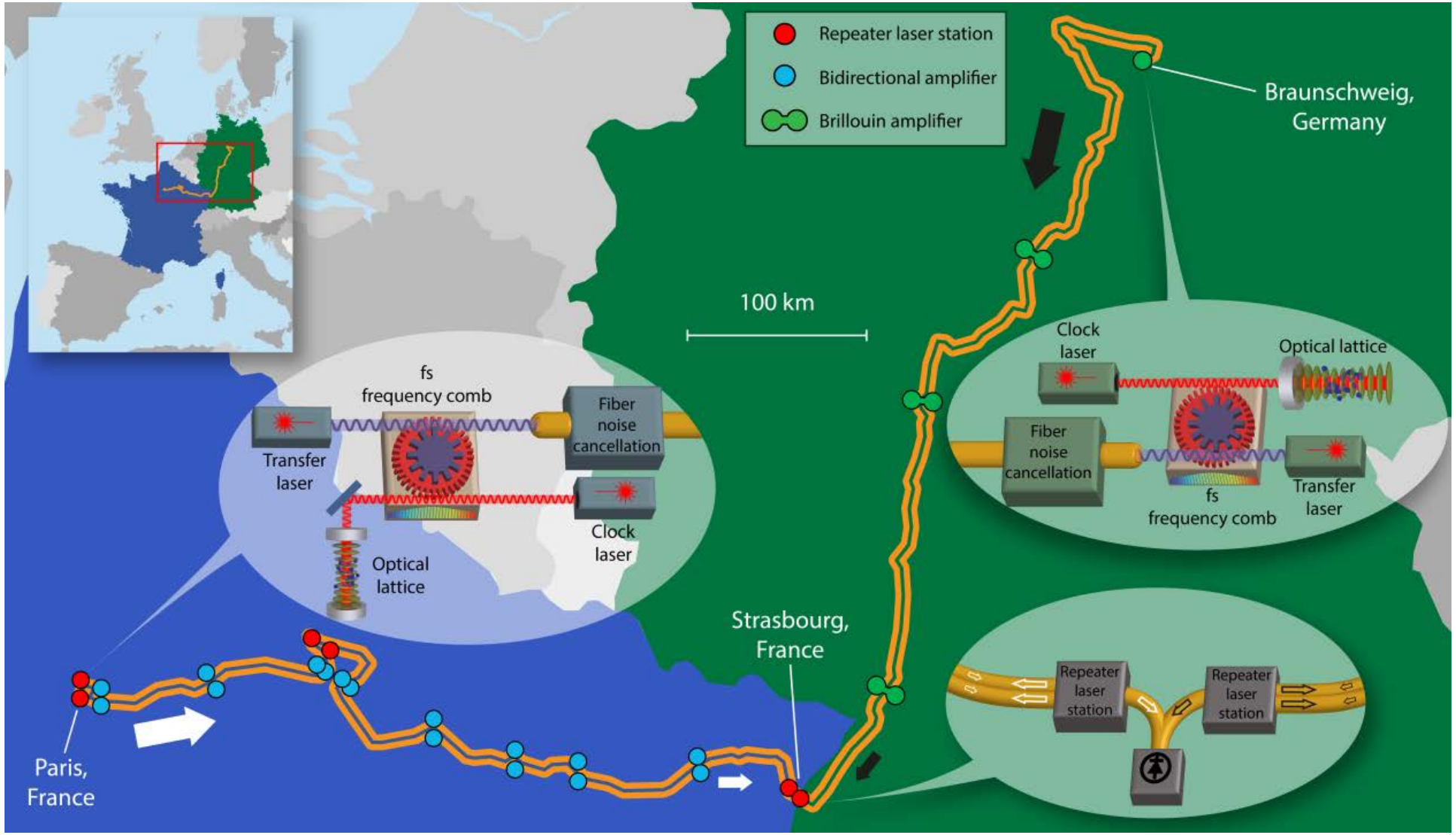


Frequency bias / Accuracy

10^{-19}

(mean = 5×10^{-20})

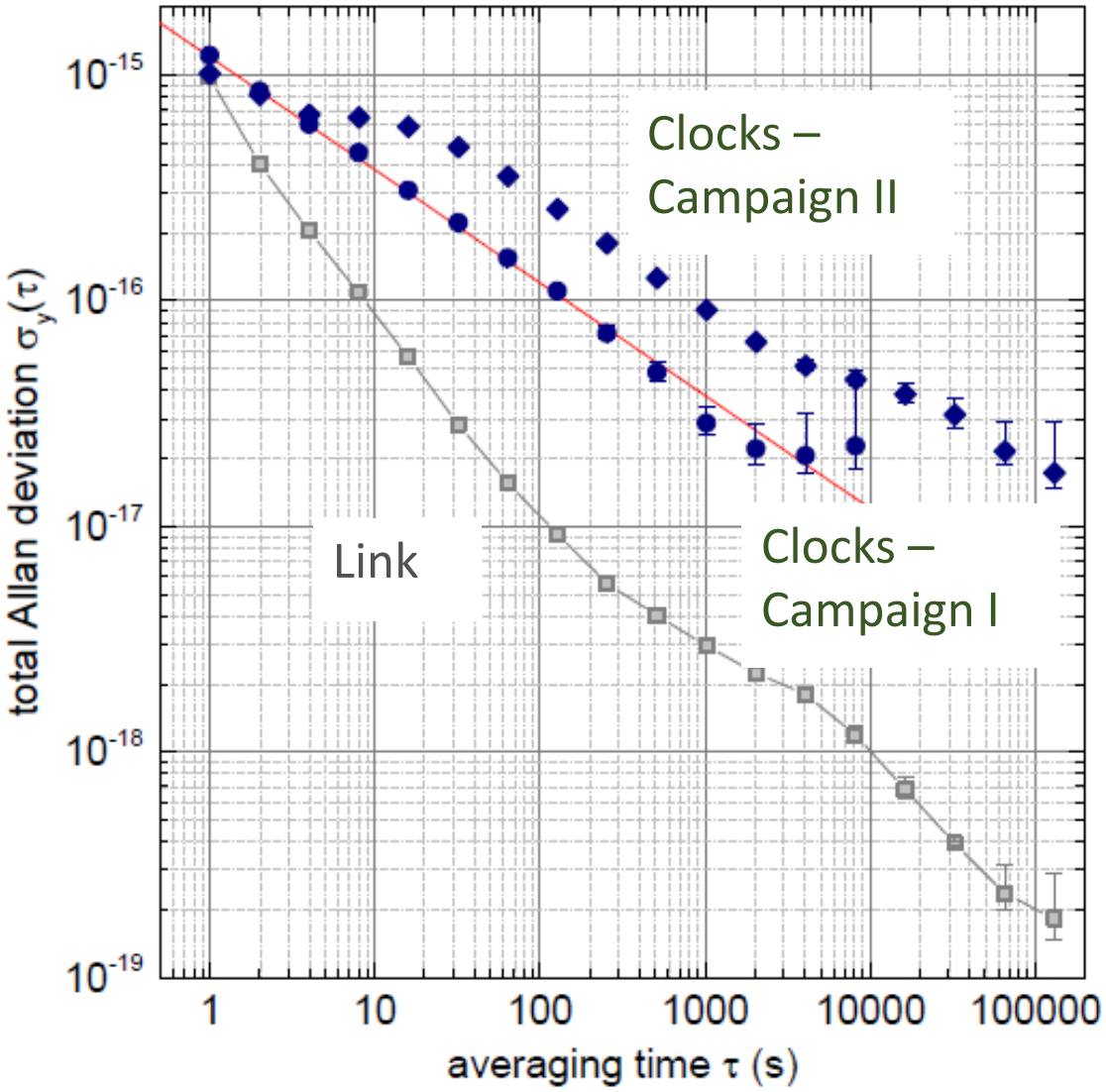
SYRTE-PTB Sr-clocks comparison



1415 km
optical link
(2x705+2x710 km)

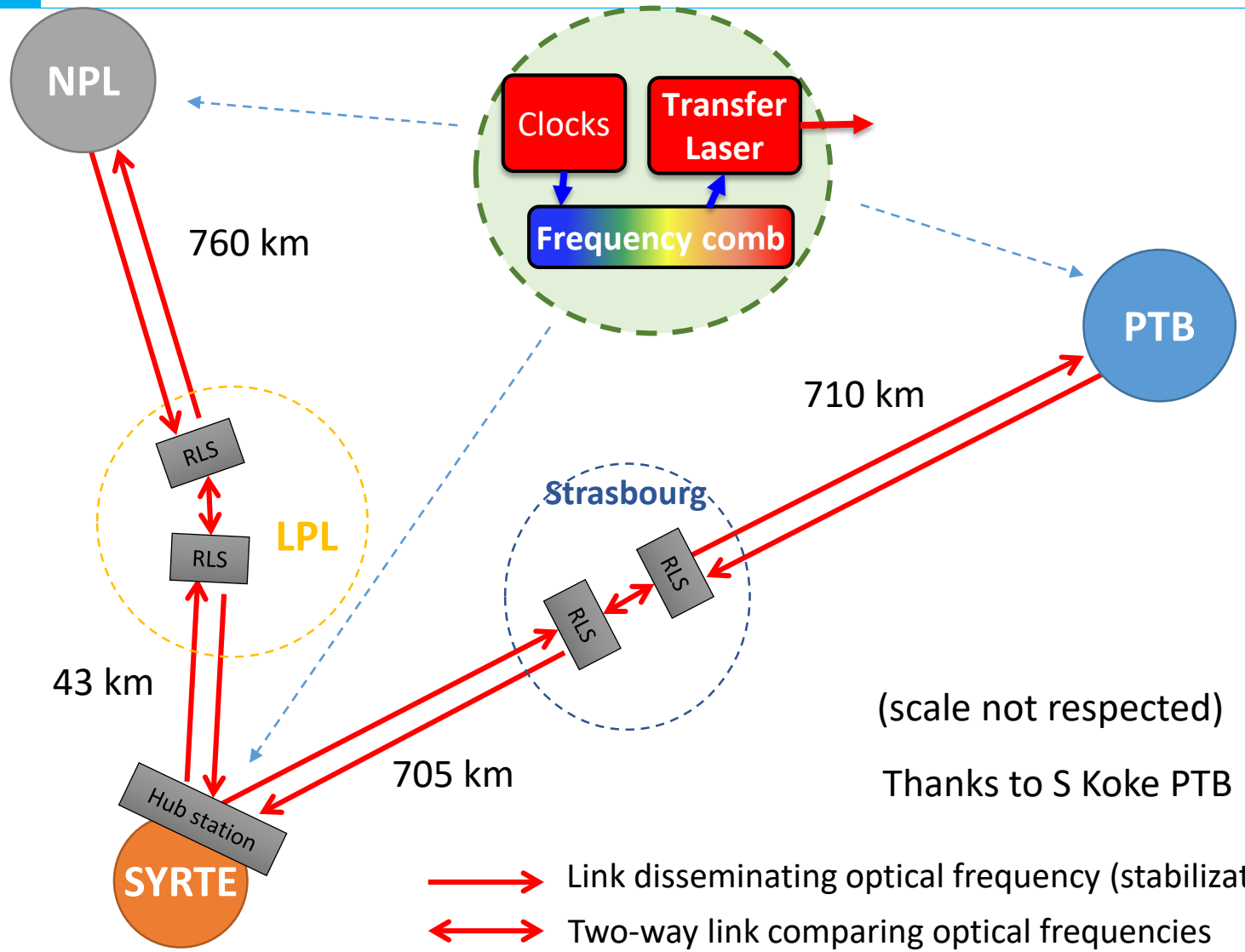
C. Lisdat et al, Nature Comm 2016

SYRTE-PTB Sr-clocks comparison



- Comparison not limited by optical link
- Link uncertainty $<3\times10^{-19}$
- Fractional offset between two clocks
  $(4.7\pm5)\times10^{-17}$
  - ✓ agreement
  - ✓ very good control of the systematics, among them the gravity potential correction
  - ✓ applications to relativistic geodesy
  - ✓ Also Cs-fountains comparison

NPL-SYRTE-PTB Sr-clocks comparison



- Multiclocks comparison
  - 7 optical clocks : Sr, Hg, Yb+
  - 3 Cs and Rb Clocks
- First application: test of time dilation

  Factor 2 improvment compared to state-of-the art

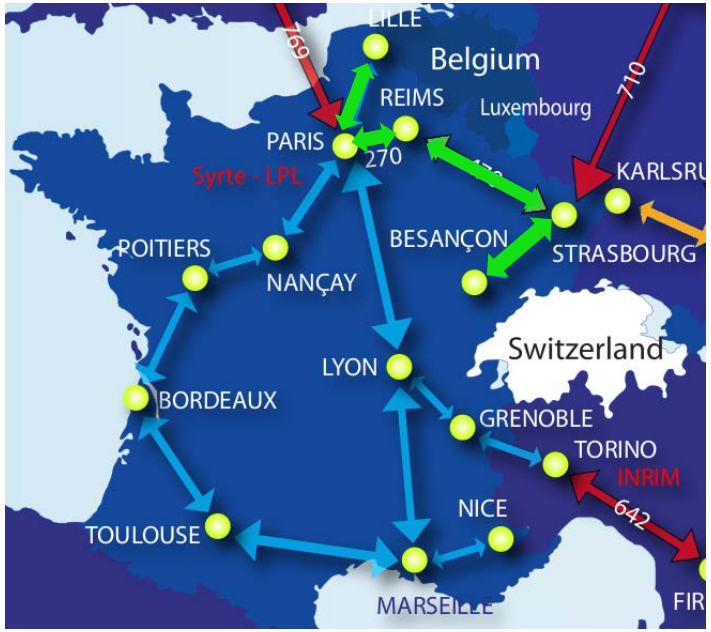
  Delva et al, PRL 2017

Other applications

- Remote laser stabilization for high-precision spectroscopy
  - Hydrogen spectroscopy: very accurate test of Quantum Electrodynamics
  - Rovibrational molecular spectroscopy: fundamental molecular physics, atmospherics studies, test of fundamental physics beyond standard model
- Geodesy and earth observation
  - Common-clock architecture for VLBI or geodetical network
  - Geophysical sensing, submarine earthquake monitoring
  - Giant fiber gyroscopes

Conclusion

- 2700 km of Refimeve links
  - Dark channel technique, using academic active network
  - Commercial equipments, network supervision in progress



- In progress
  - Dissemination to physics lab in France
  - Dissemination to Italy

- Many thanks to LPL, SYRTE and RENATER colleagues
  - D. Xu, E. Cantin, F. Frank, N. Quintin, F. Meynadier, P. Tuckey, O. Lopez, P.-E. Pottie

Thank you for your attention

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CLONETS – CLock NETwork Services

Strategy and innovation for clock services over optical-fibre networks

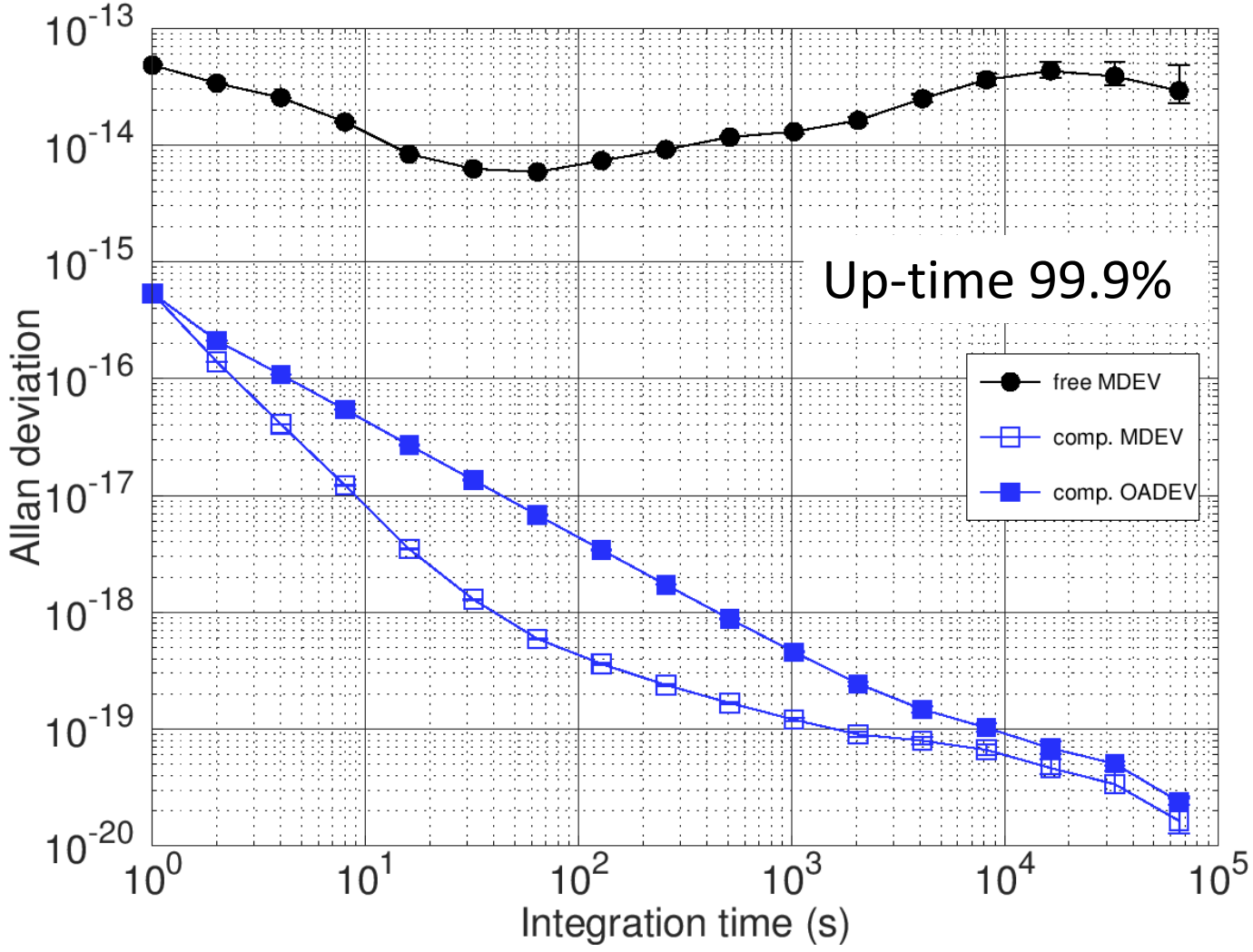
Proposal ID: **731107**
Topic: **INFRAINNOV-2016**
Duration: **30 months**
Start date: **1st January 2017**
Web page: **http://www.clonets.eu**

Coordinator

Participants

Third Parties

Paris-Lille Refimeve 680-km link



- First industrial-grade optical link
  - 2 cascaded links of 340 km using commercial repeater stations
  - Deployment and link optimisation = 1 month
- Frequency bias / Accuracy
  - 3×10-20

(mean = -3×10-21)

Guillou-Camargo et al, App. Opt. 2018

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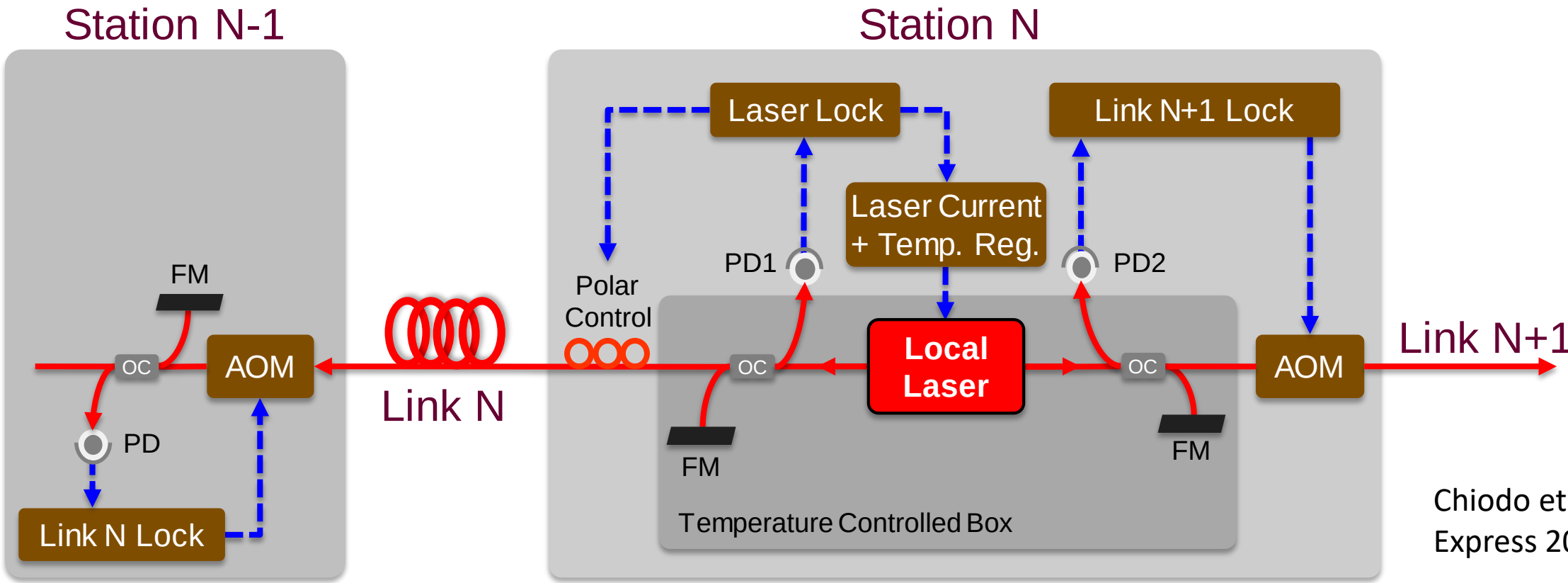

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