Progress towards a metrological fiber wide-area network

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Outline

I. Ultrastable fiber link
   - Principle
   - Internet fiber link
   - Cascaded link

II. Current developments
   - 1100-km cascaded link
   - Multi-user dissemination
   - Time transfer

The challenge of ultrastable frequency dissemination

Lab A

Atomic clocks

Stability(1s) 10^{-15}-10^{-16}
Accuracy 10^{-17}-10^{-18}

Reference frequency →

Lab B

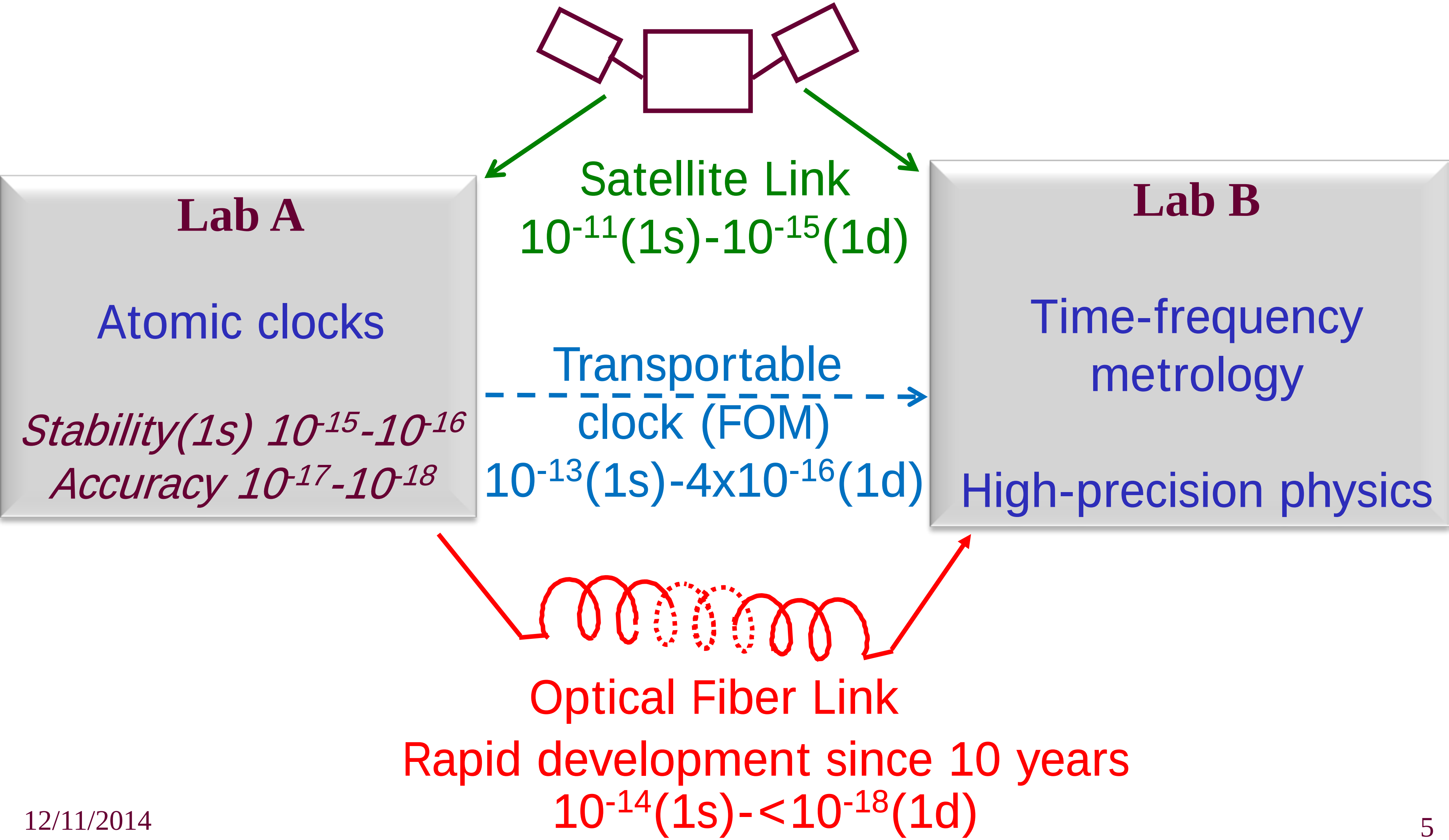
Time-frequency metrology

- Clocks comparison, evaluation, optimisation

High-precision physics

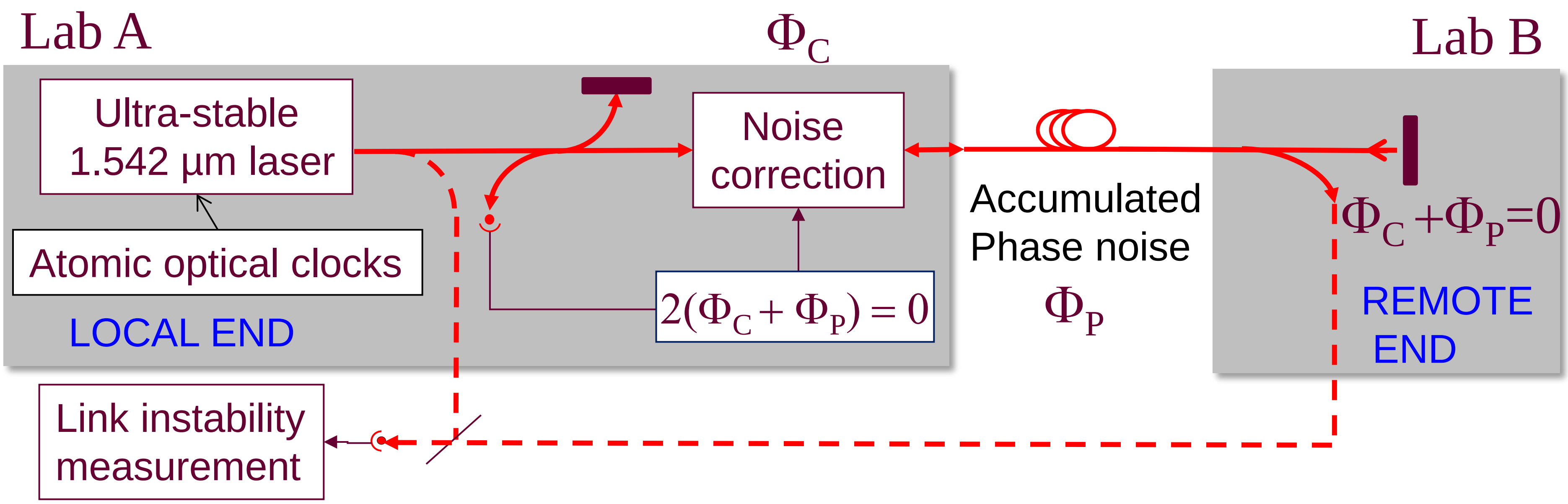
- Fundamental constants measurement (h/m, k_B...) and variation test (α ou m_e/m_p)
- Test of relativity, geodesy
- Synchronisation in astrophysics and particle physics
- Laser stabilisation, high-resolution spectroscopy

Means of ultrastable frequency dissemination



Simplified scheme of an optical fiber link

- Fluctuation of the propagation delay
- « Round-trip » method for noise compensation
- Propagation delay limits noise rejection bandwidth and amplitude



- Demonstration with 2 parallel fibers or one loop fiber : two ends at the same place

Strategy for a continental network

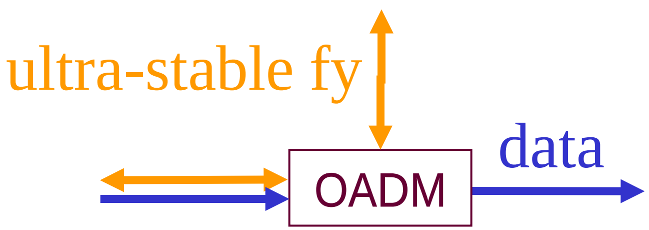
- Use public telecommunication fiber networks
  - Dense Wavelength-Division Multiplexing (DWDM)

    Digital data
    Ultra-stable frequency signal } → Simultaneous transmission on ≠ lambdas (or channels)

  -> Dark channel instead of dark fiber !

- Collaboration with RENATER : the French National Research and Education Network

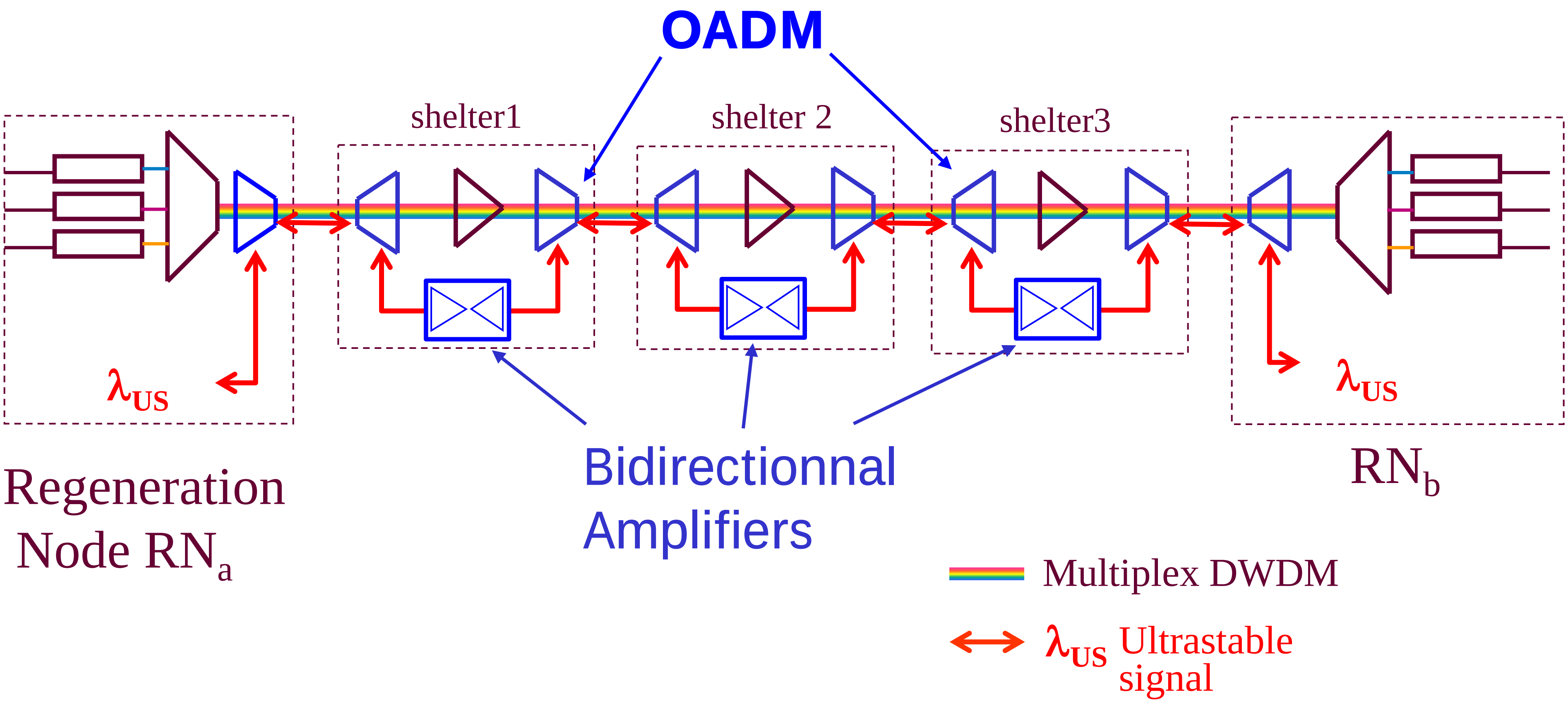
- OADM (optical add drop multiplexer) to add and extract signal



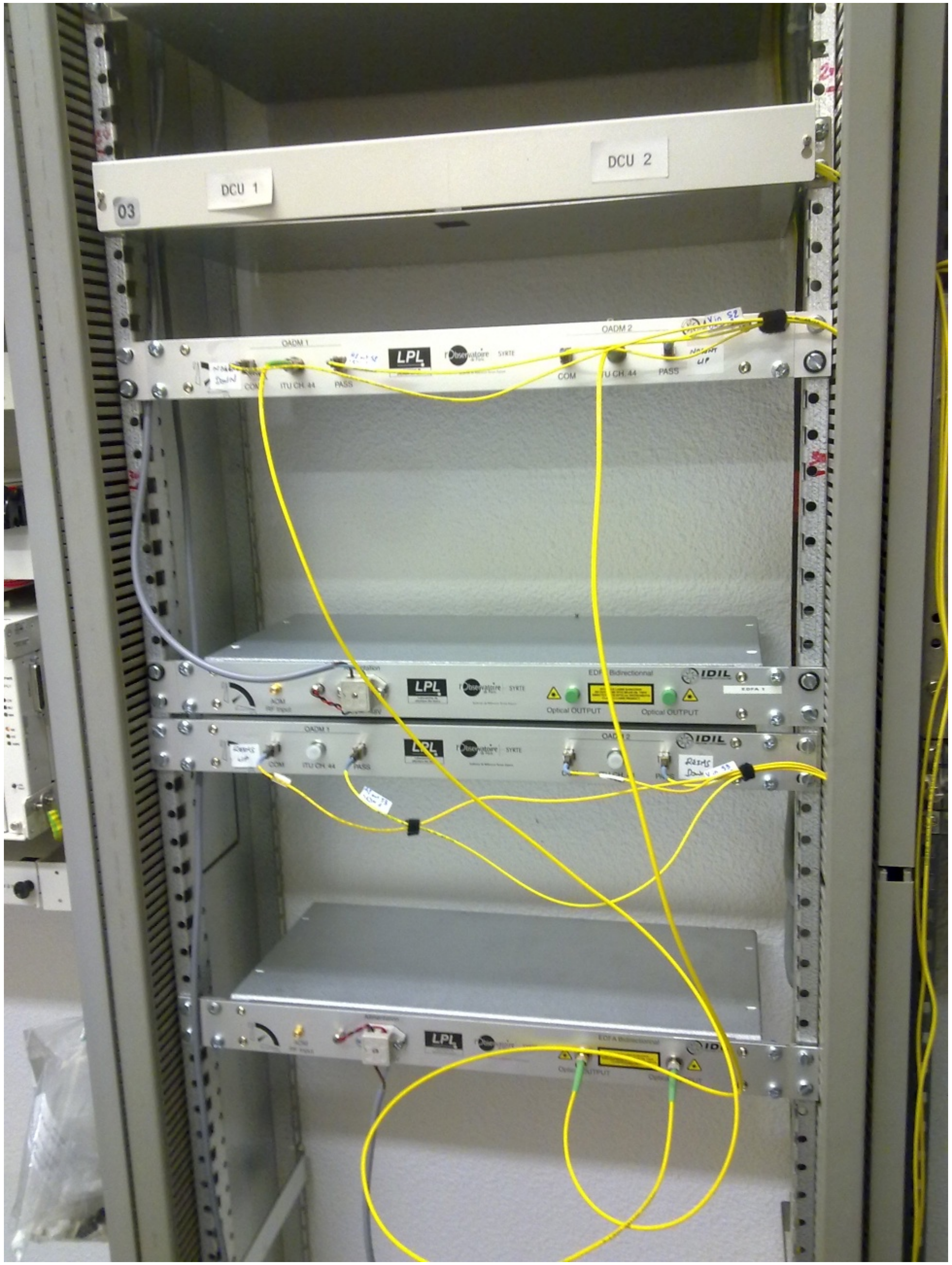
  - Commercial components (100 GHz filters)
  - Losses < 1dB, Isolation > 25 dB
  - Bidirectional

Typical scheme of a multiplex optical link

Key issue: bidirectional continuous propagation (for noise correction)



OADM and EDFA modules in Condé



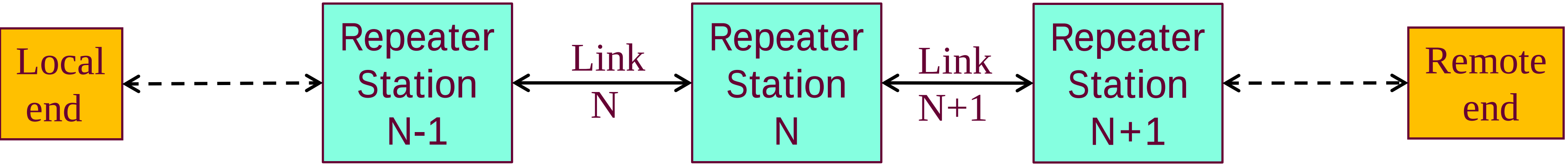
Long distance optical link

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

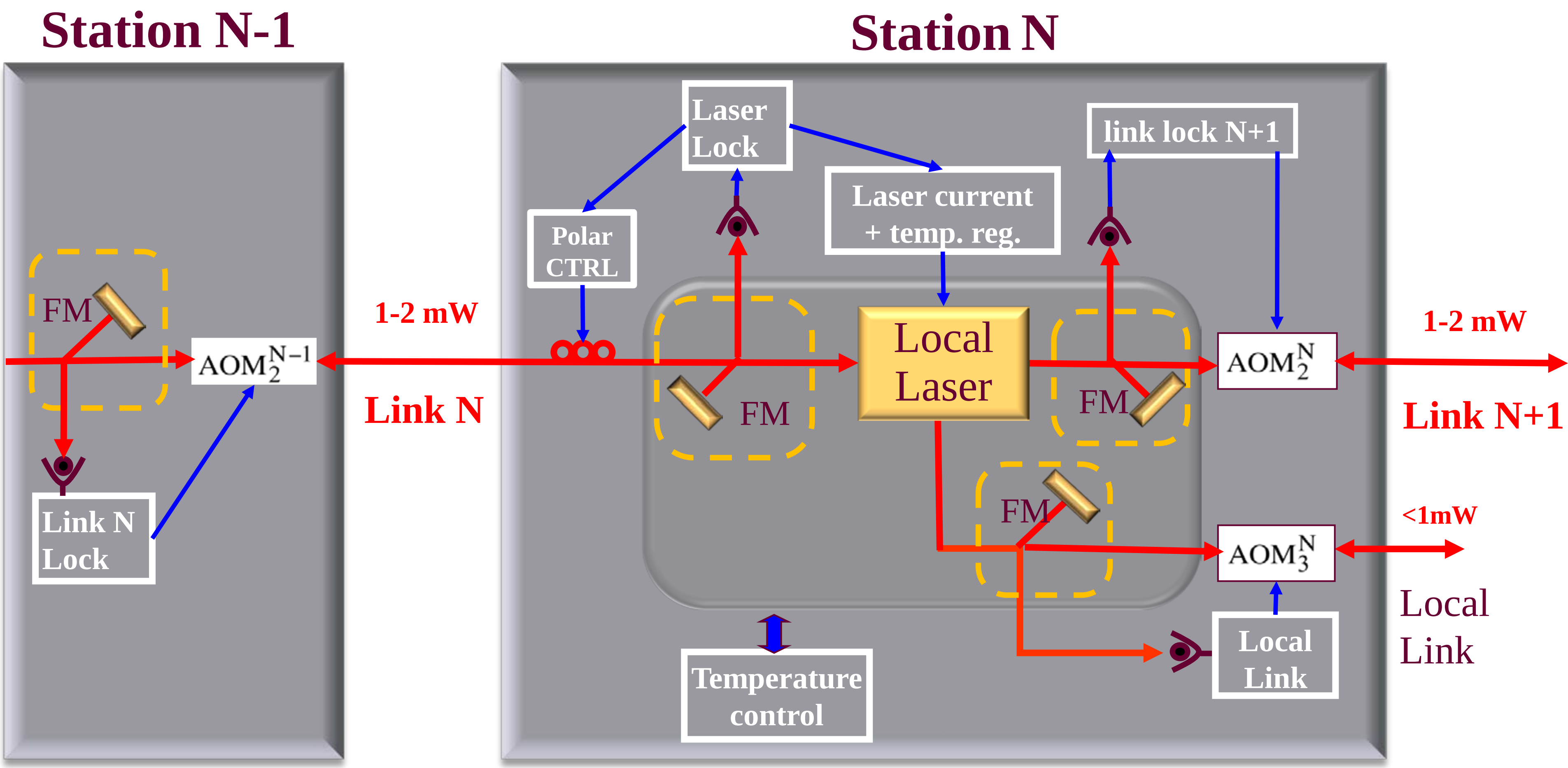
  → shorter propagation delay

  → 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



Optical regeneration station

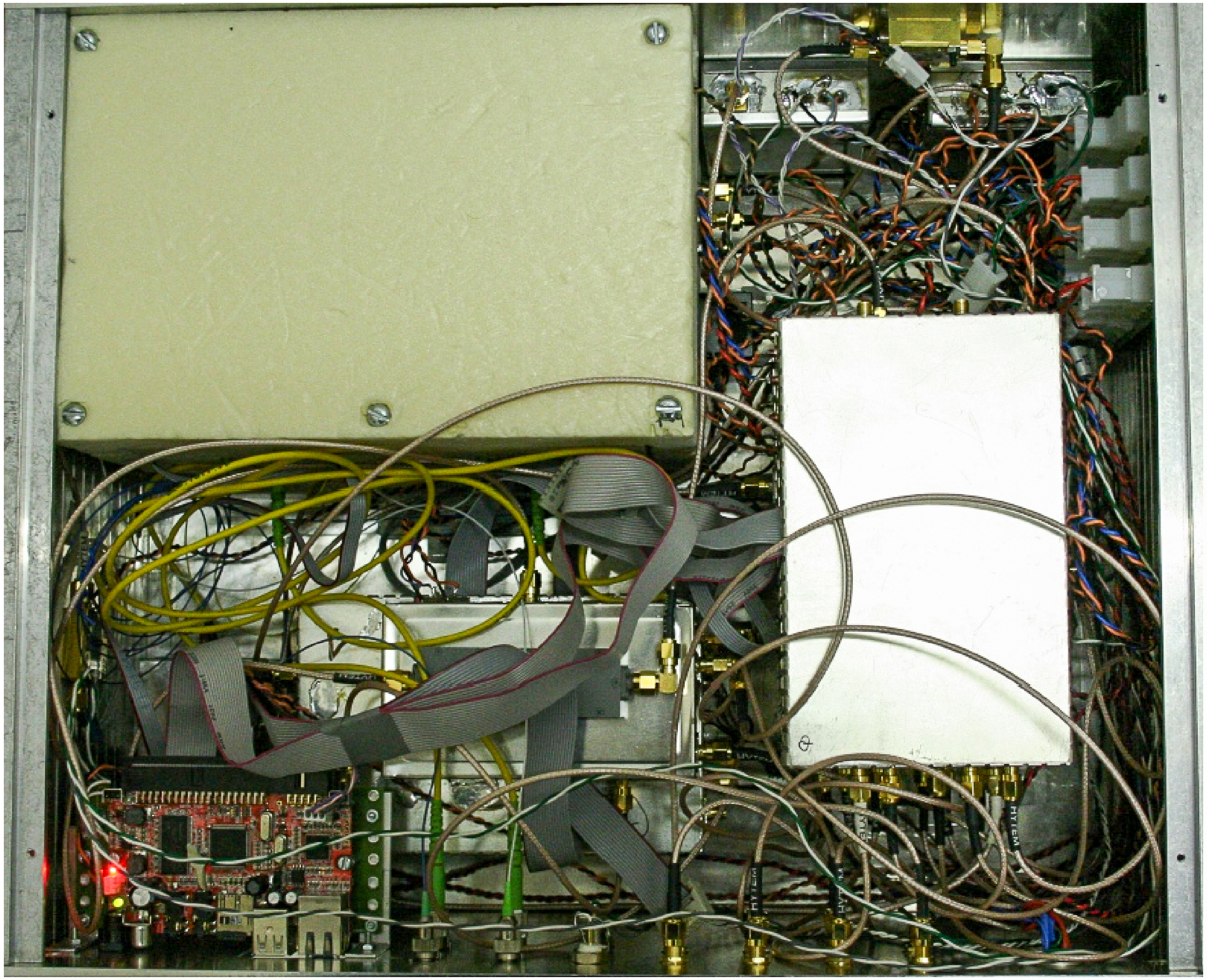


- Automated with remote control (IP)
- Polarization control
- No stable RF clock required

- Noise clean-up (optical regeneration)
- Retrace back signal to station N-1
- Correct Link N+1 noise

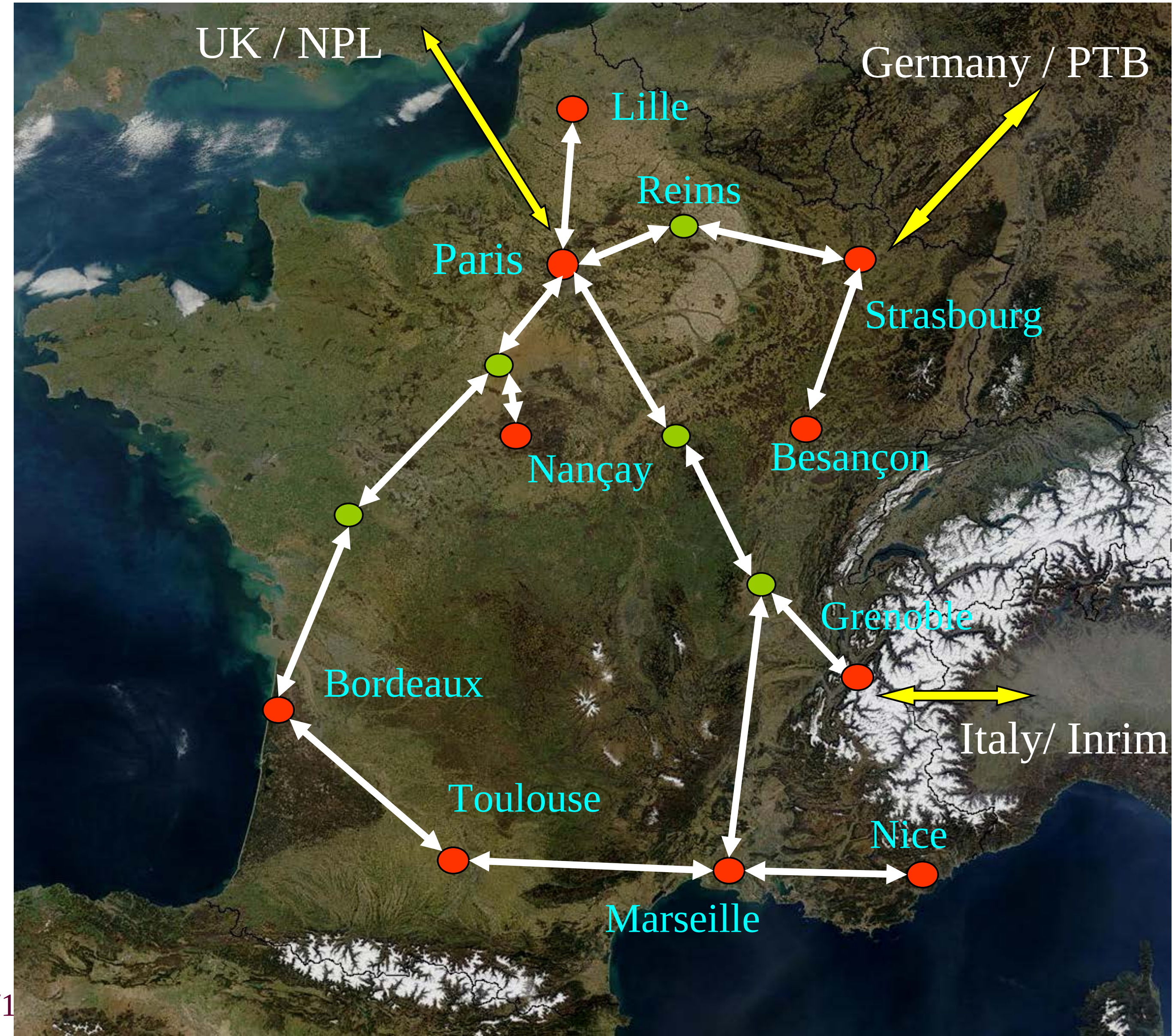
O. Lopez et al. Optics Express (2012)

Rgeneration station



- Dimensions : 4U 19” x 350mm
- Power < 100 W

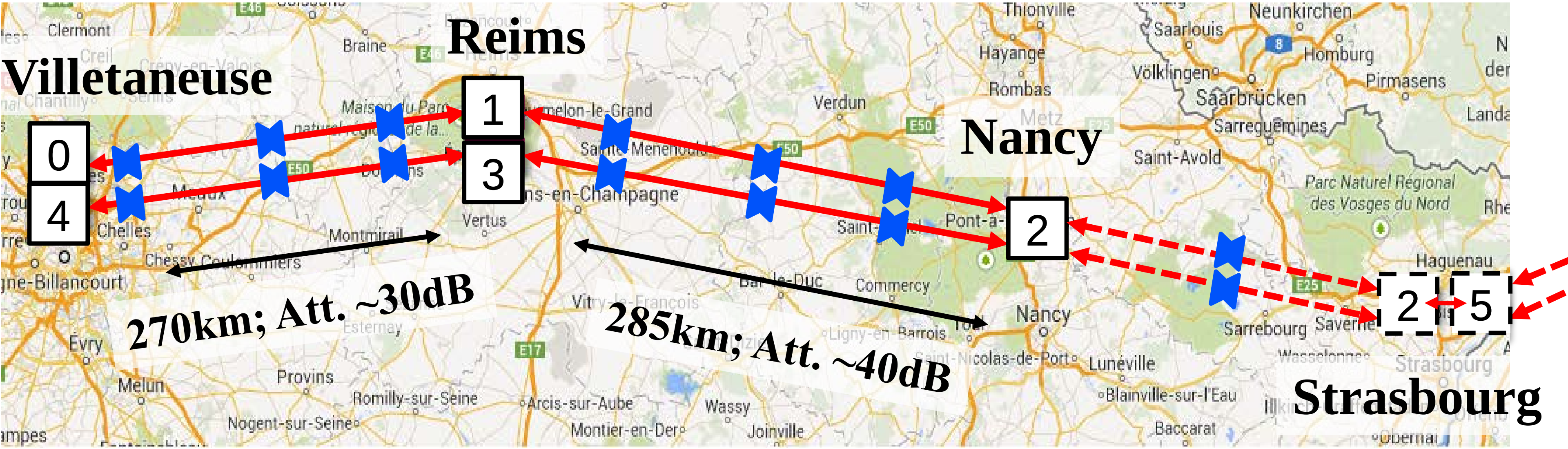
Ongoing development: metrological fiber network in France and Europe



In France
Refimeve+
Remif (IdF)
PI: C. Chardonnet

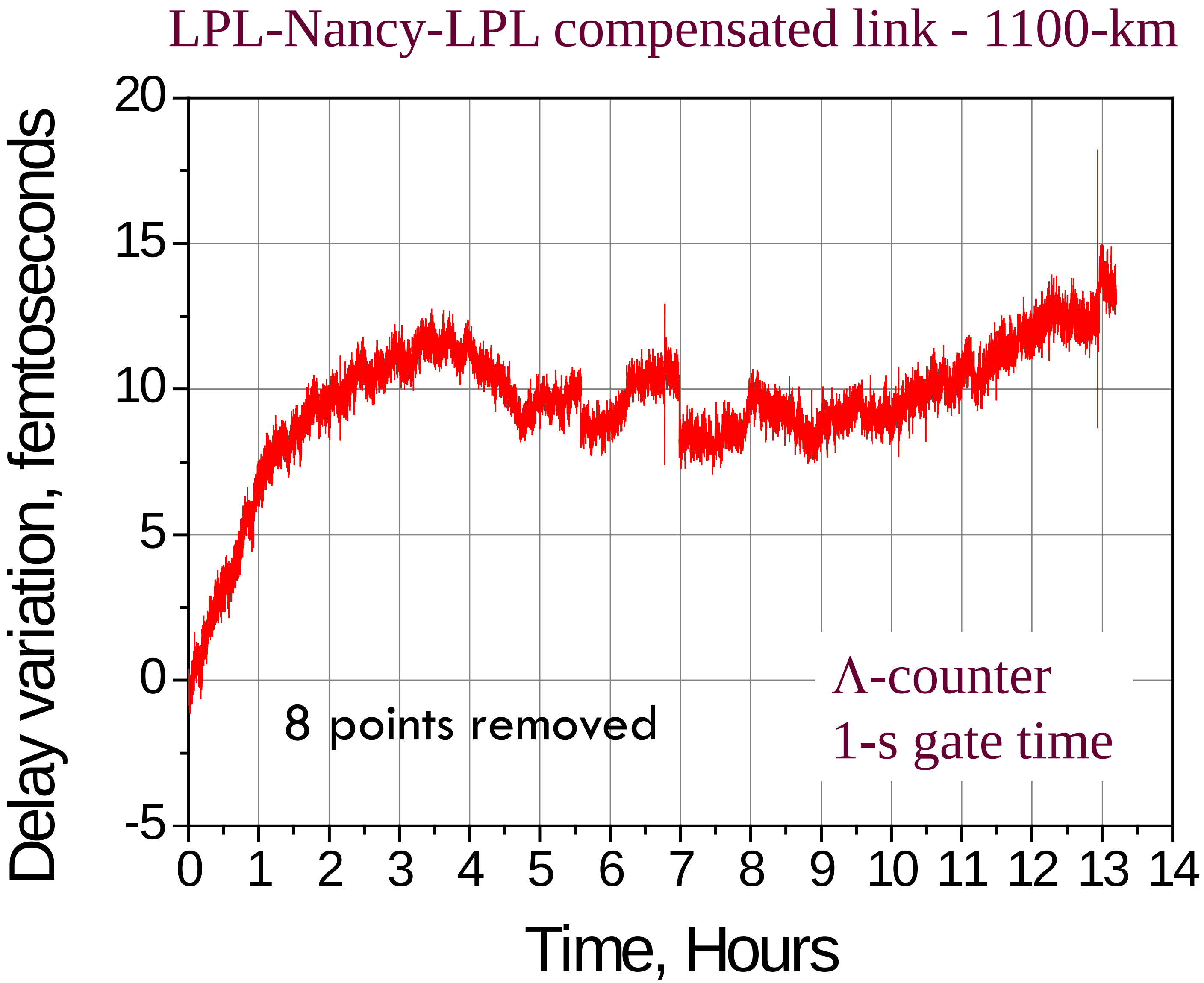
In Europe :
NEAT-FT
Funded 2012
PI: H. Schnatz (PTB)
See previous talk

Cascaded 1100-km LPL-Nancy-LPL link



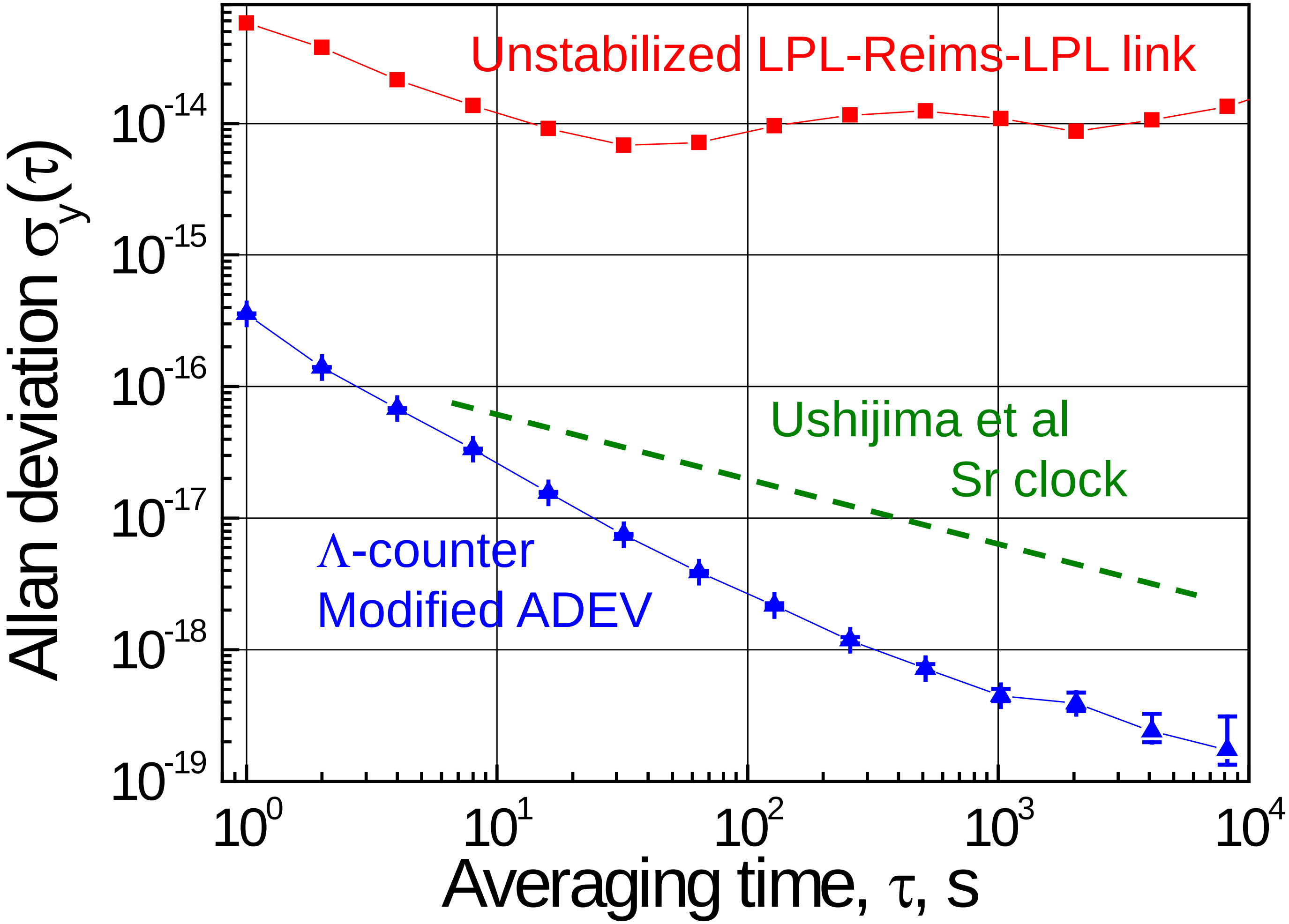
- 4 cascaded links with 2 end stations and 3 regeneration stations
- US signal: 1542,14 nm (ITU 44) /Data: 1542.94 + 1543.73 nm (ITU 43 & 42)
- 32 OADMs + 12 bidirectional EDFAs

End-to-end phase variation



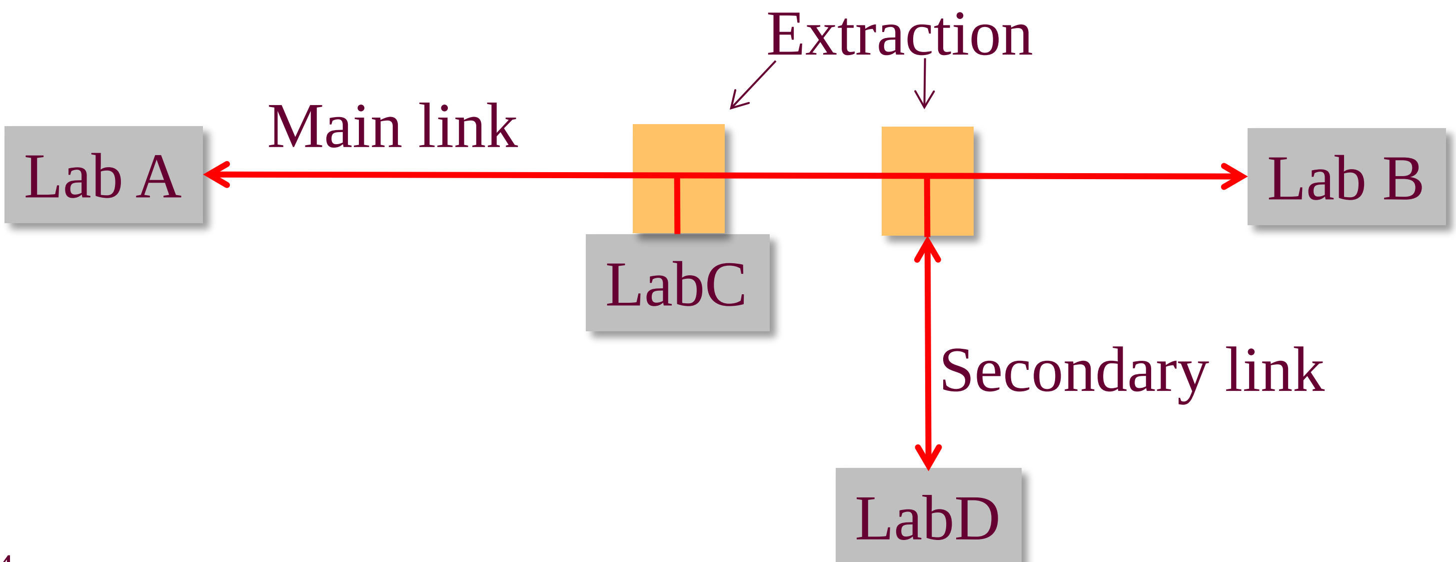
End-to-end stability

LPL-Nancy-LPL compensated link - 1100-km

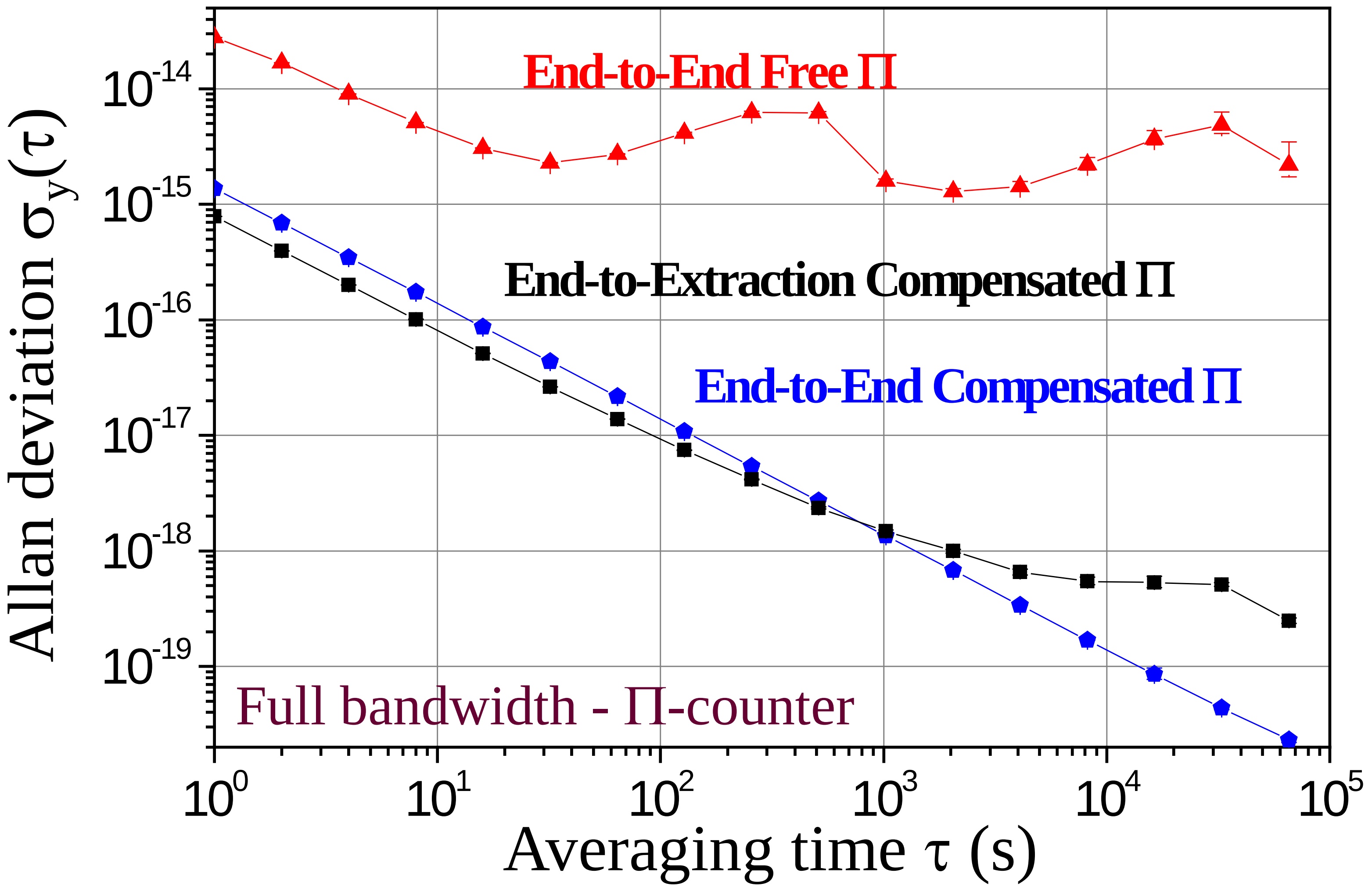


Multi-user dissemination

- Several labs spread in the same metropolitan area
  - For instance Paris
- Multi user Network architecture
  - Point-to-point distribution is fibers consuming
  - In-line extraction enables flexible distribution
  - First proposed by G. Grosche (PTB, Germany), in 2010

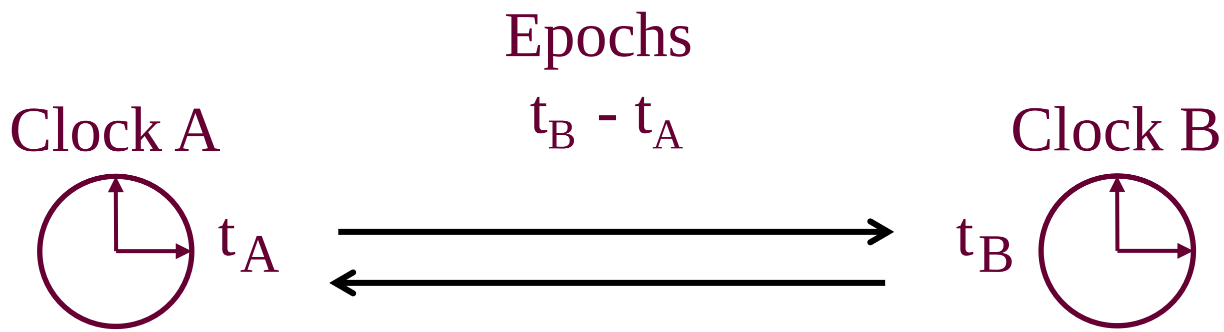


Extraction stability on a 86+6 km urban link



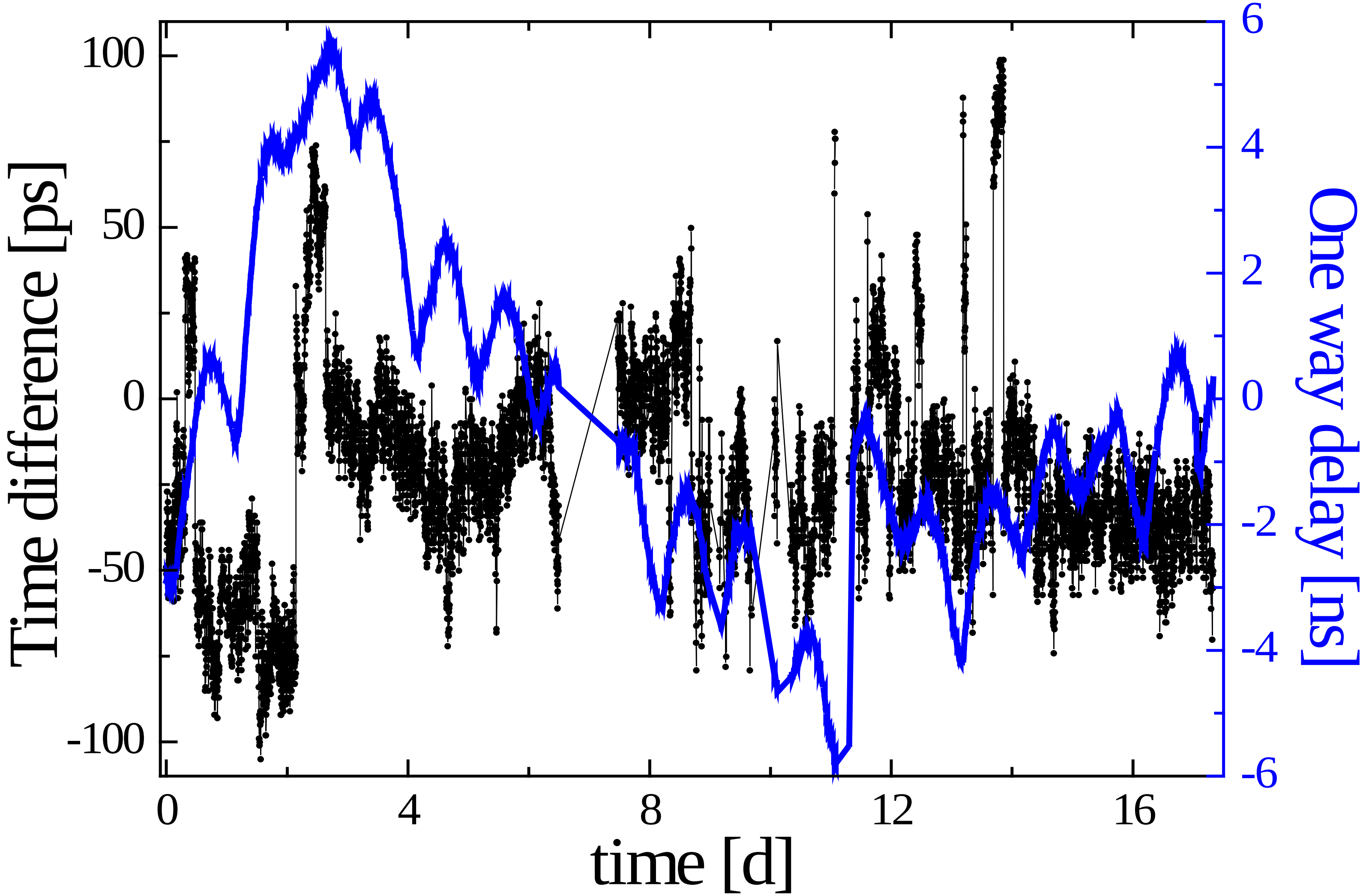
A. Bercy et al. JOSA B (2013)

Two-way time transfer through optical fiber



- Two-way time transfer demonstrated simultaneously with frequency transfer on the 540-km public fiber link
- The time signal is encoded using pseudo random noise modulation with Satre modems used for satellite time transfer

Time delay measurement on 540-km fiber link



Time transfer accuracy and stability

- Delay calibration < 50 ps
  - Sensitivity to link length, power, polarisation, dispersion....

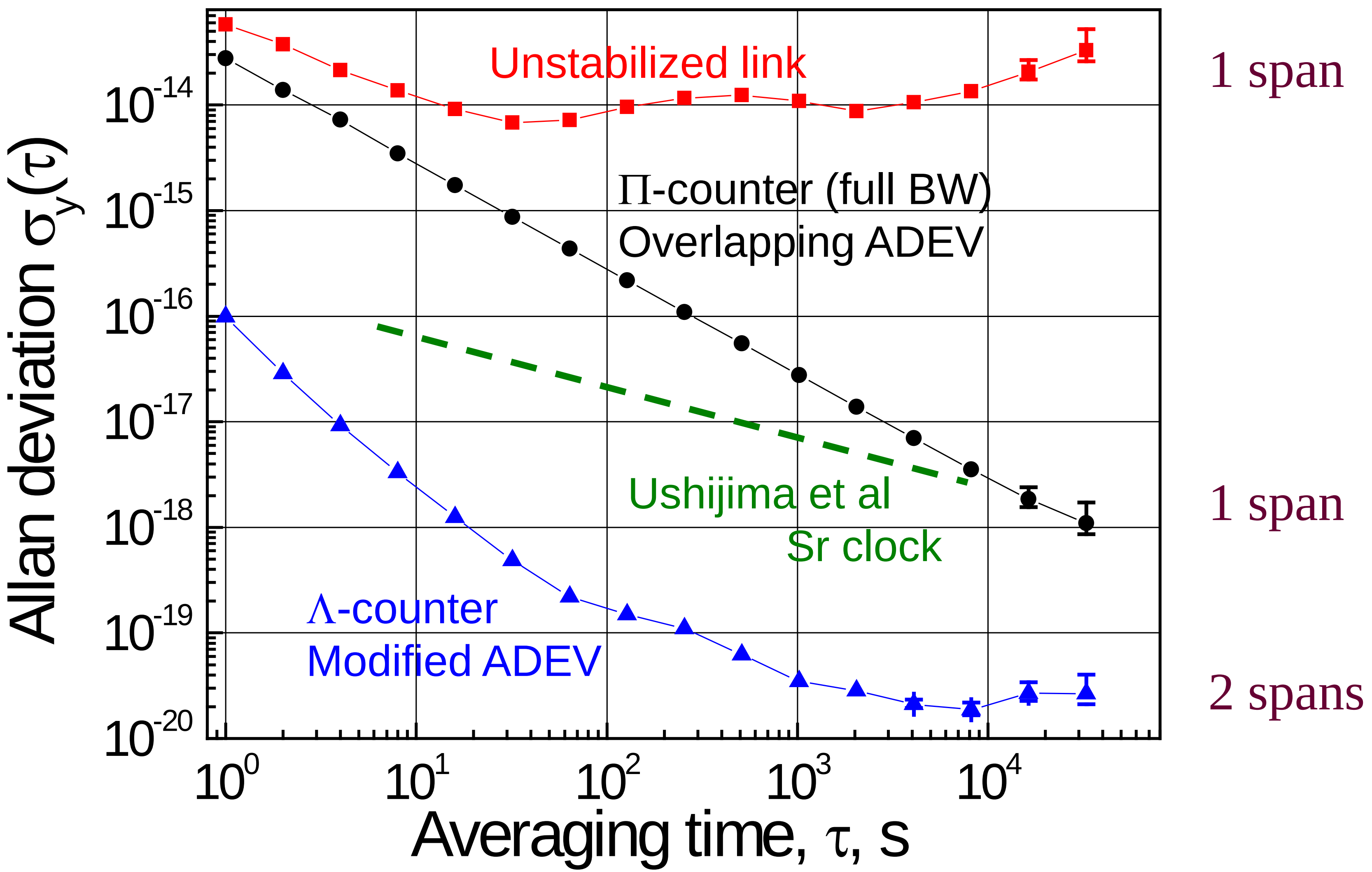
	Fiber time transfer	GPS carrier-phase	Two-way satellite time & fy transfer
Accuracy	~200 ps	~300ps	~500ps
Stability (1 day)	~20 ps	~100ps	~50 ps

O. Lopez et al. Applied Physics B (2013)

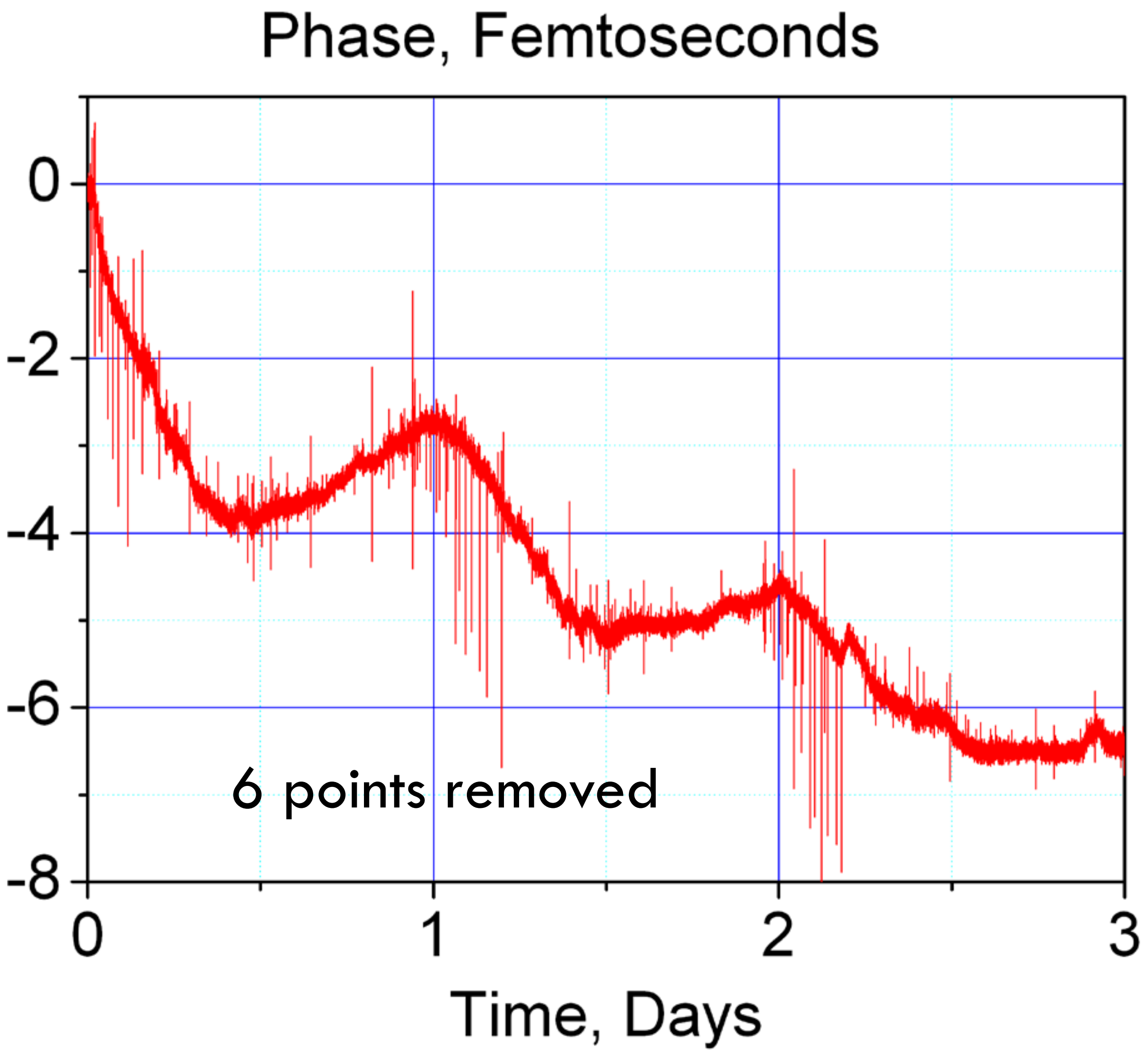
Summary and outlook

- Optical links are now mature
  - Paris-Nancy-Paris 1100 km non-dedicated fibers
  - Braunschweig-Munchen-Braunschweig 1840 km dedicated fibers
  - In progress : in-line extraction, fiber network development
- Perspective
  - Remote clock comparison, search for fundamental constants variation, relativistic geodesy…
  - Fundamental limits / Sagnac effect
  - Test of satellite links (ACES MW, Two-Way or advanced GPS)
  - Applications to high-resolution spectroscopy...

LPL-Reims-LPL 540-km stability

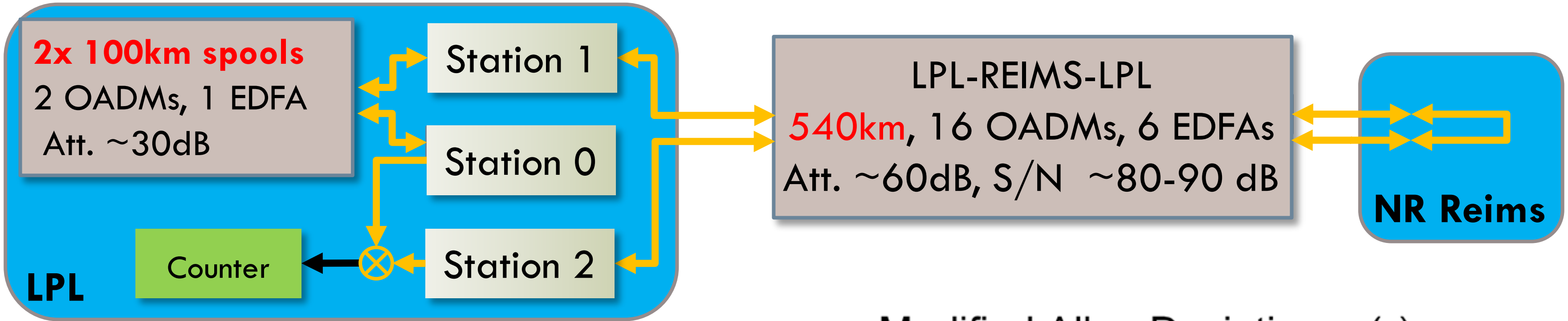


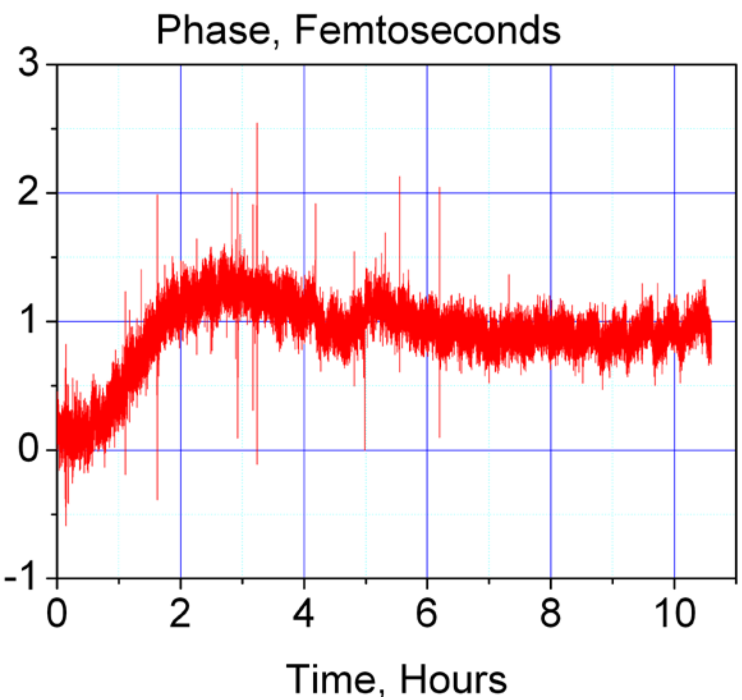
540-km end-to-end propagation delay

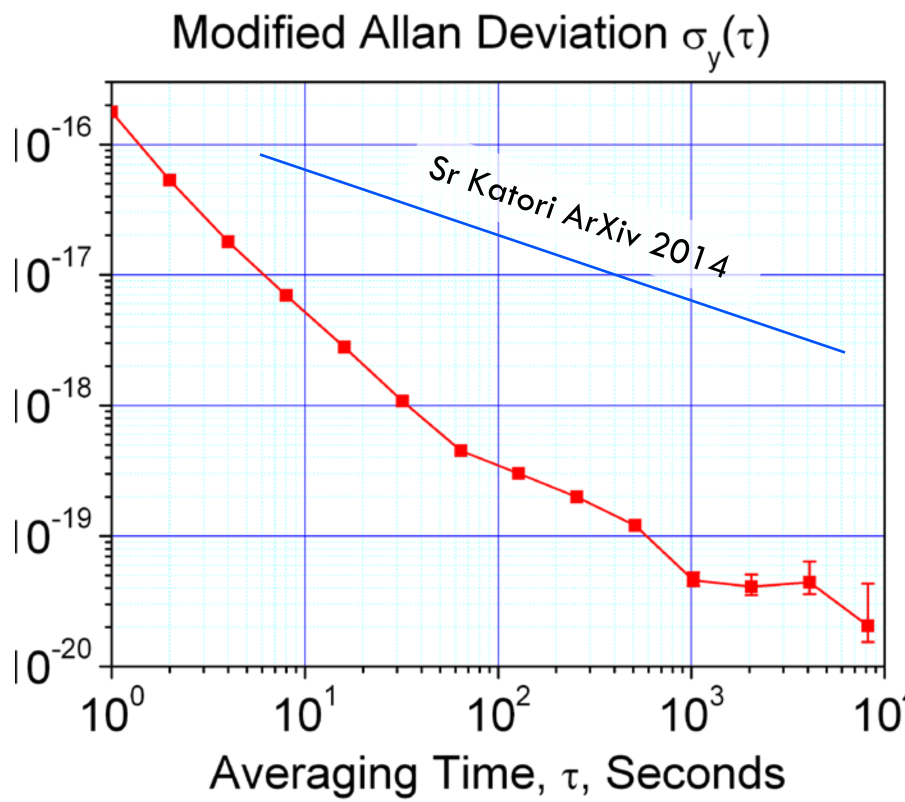


1 span LPL-Reims-LPL

Simulation of Paris-Strasbourg-Paris 740km







Time transfer reproducibility

- Systematics effects can be controlled to less than 50 ps
  - Delay calibration < 50 ps, power sensitivity< 15 ps/dB, fiber chromatic dispersion < 25 ps, polarisation mode dispersion < 50 ps
- But scarce phase jumps of ~100 ps
- Room for a lot of improvment !

	Fiber time transfer	GPS carrier-phase	Two-way satellite time & fy transfer	T2L2 Time Tr. by Laser Link
Accuracy	~250 ps	<3 ns	1 ns	~300 ps
Stability (1 day)	~20 ps	0.1 ns	40 ps	<10 ps (10-100 s et 1-10 d)

State of the art

- JILA-NIST (USA) optical carrier phase and frequency comb transfer
- SYRTE - LPL (Fr) 1100 km optical carrier phase
- PTB-MPQ-Hannover (Germany) 1840 km optical carrier phase
- NICT, NMIJ, UT (Japan) 120-km optical carrier phase
- JPL (USA) microwave optical link
- NPL (UK) frequency comb, optical carrier phase
- NIM, SIOM Shangai (China) microwave optical link
- INRIM, LENS (Italy) 670-km optical carrier phase
- UWA,NMI (Australia) optical carrier phase & microwave
- AGH (Poland) microwave time transfer
- ....

Paris Metropolitan Area Network

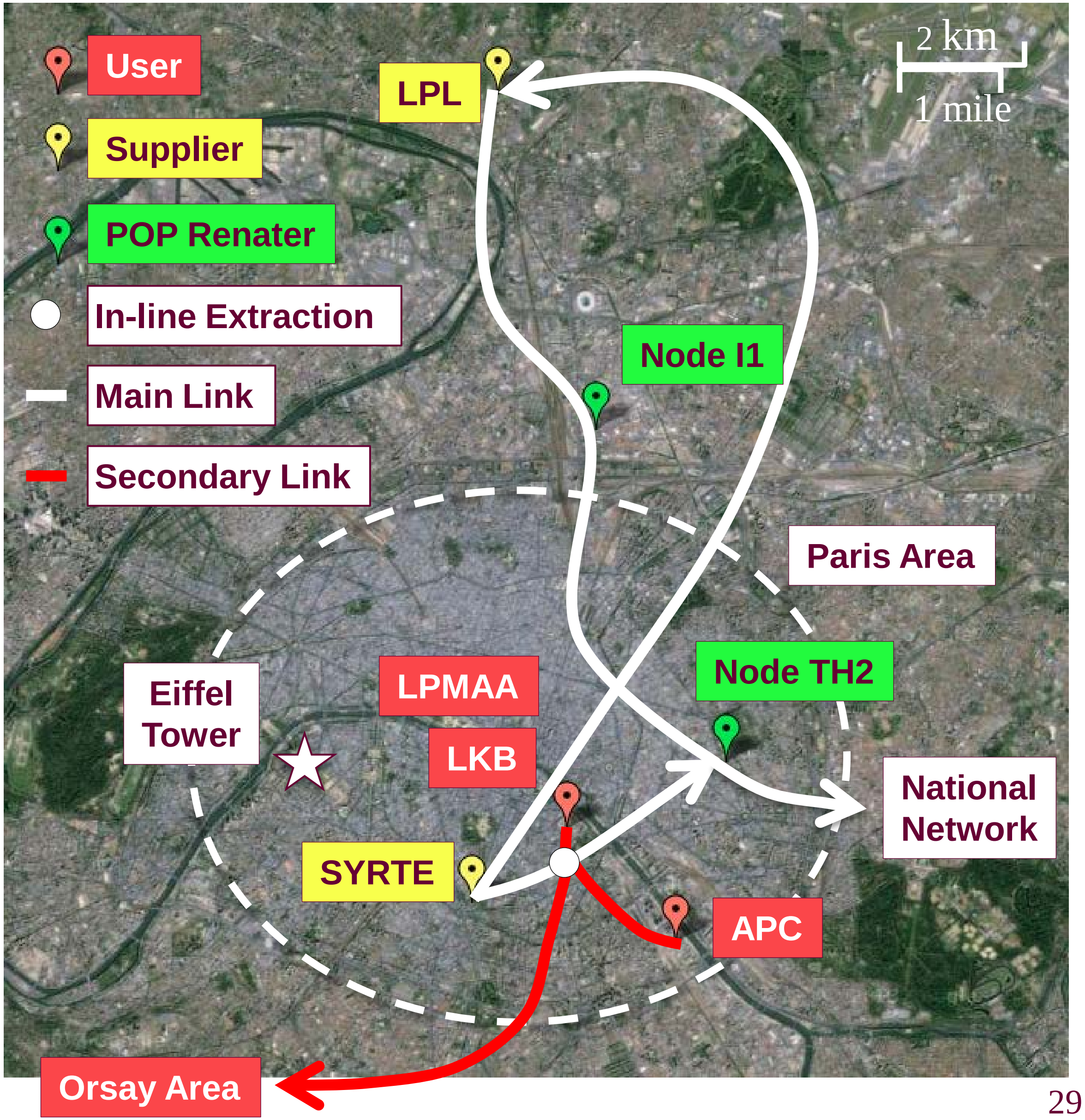
8 research labs

Laboratoire Kastler Brossel — Physique quantique et applications

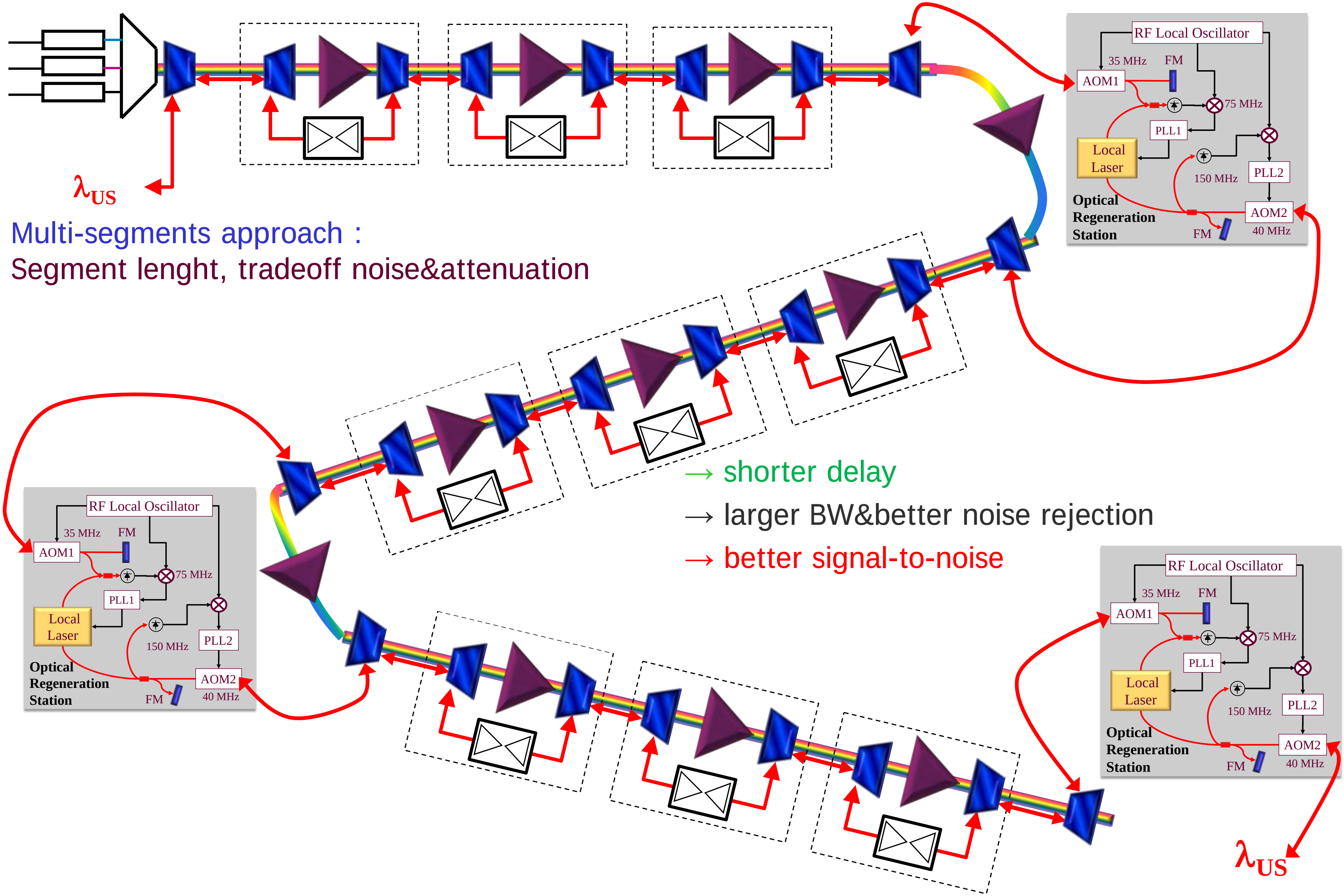
ISMO

INSTITUT d'OPTIQUE GRADUATE SCHOOL

LPMAA — Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique



Cascaded segments for long range links



Multi-segments approach :

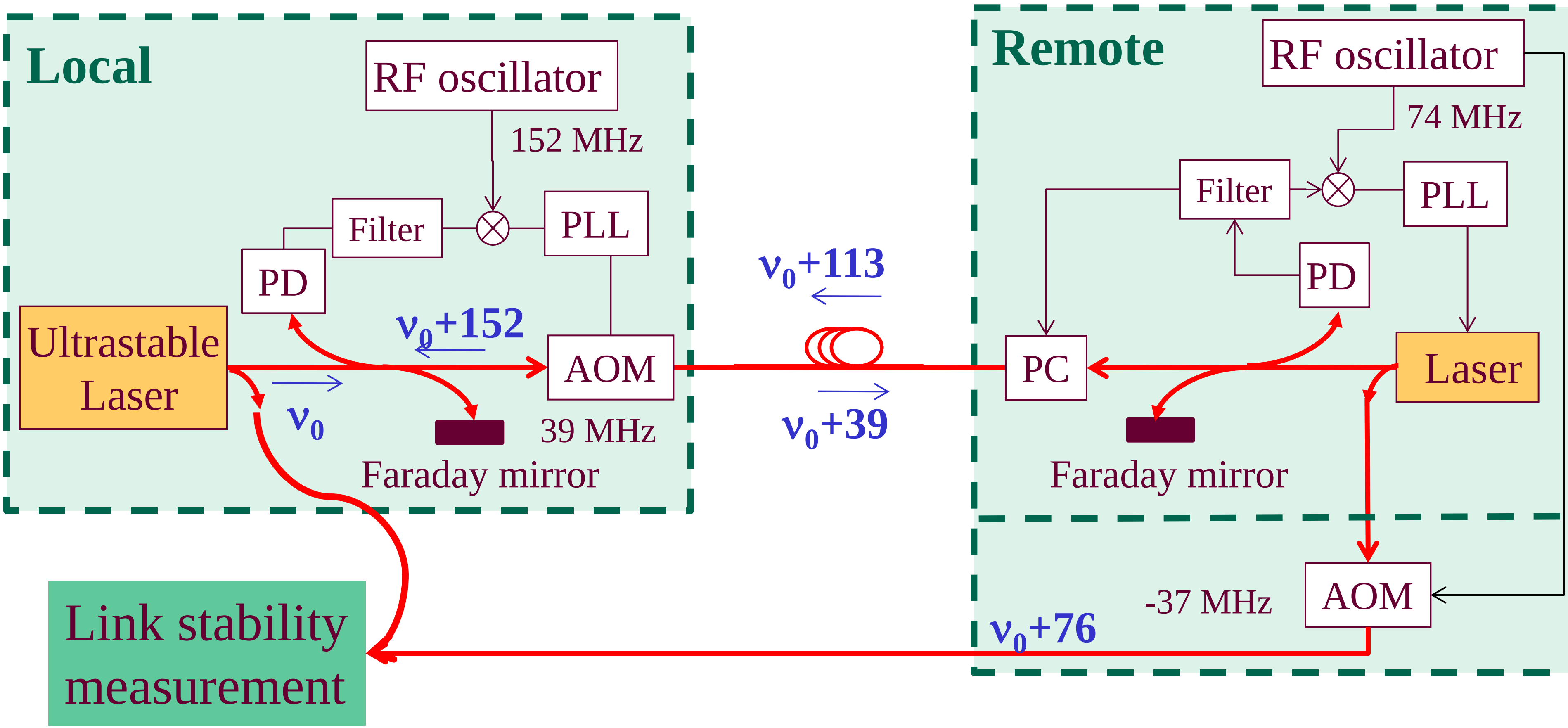
Segment lenght, tradeoff noise&attenuation

→ shorter delay

→ larger BW&better noise rejection

→ better signal-to-noise

Optical link set-up



Autonomous lock (microcontroller), no stable RF clock at remote end, optical regeneration (PLL), automatic polarisation controller,