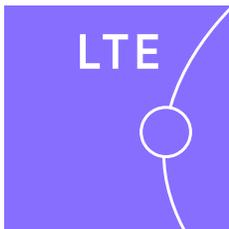


# CAVITIES FILTERING FOR REFIMEVE CAVITÉS DE FILTRAGE POUR REFIMEVE

**BIPLAB DUTTA**<sup>1</sup>, OLIVIER LOPEZ<sup>1</sup>, ADÈLE HILICO<sup>1</sup>, HANIFFE MOUHAMAD<sup>1</sup>, MAËL ABDELHAK<sup>1</sup>, ANNE AMY-KLEIN<sup>1</sup>, CHRISTIAN CHARDONNET<sup>1</sup>, PAUL-ERIC POTTIE<sup>2</sup>, ETIENNE CANTIN<sup>1</sup>

<sup>1</sup>LABORATOIRE DE PHYSIQUE DE LASERS, UNIVERSITÉ SORBONNE PARIS NORD, CNRS, VILLETANEUSE, FRANCE  
<sup>2</sup>LABORATOIRE TEMPS ESPACE (LNE-OP), OBSERVATOIRE DE PARIS, UNIVERSITÉ PSL, SORBONNE UNIVERSITÉ, UNIVERSITÉ DE LILLE, LNE, CNRS, PARIS, FRANCE



# CONTENTS

The Network

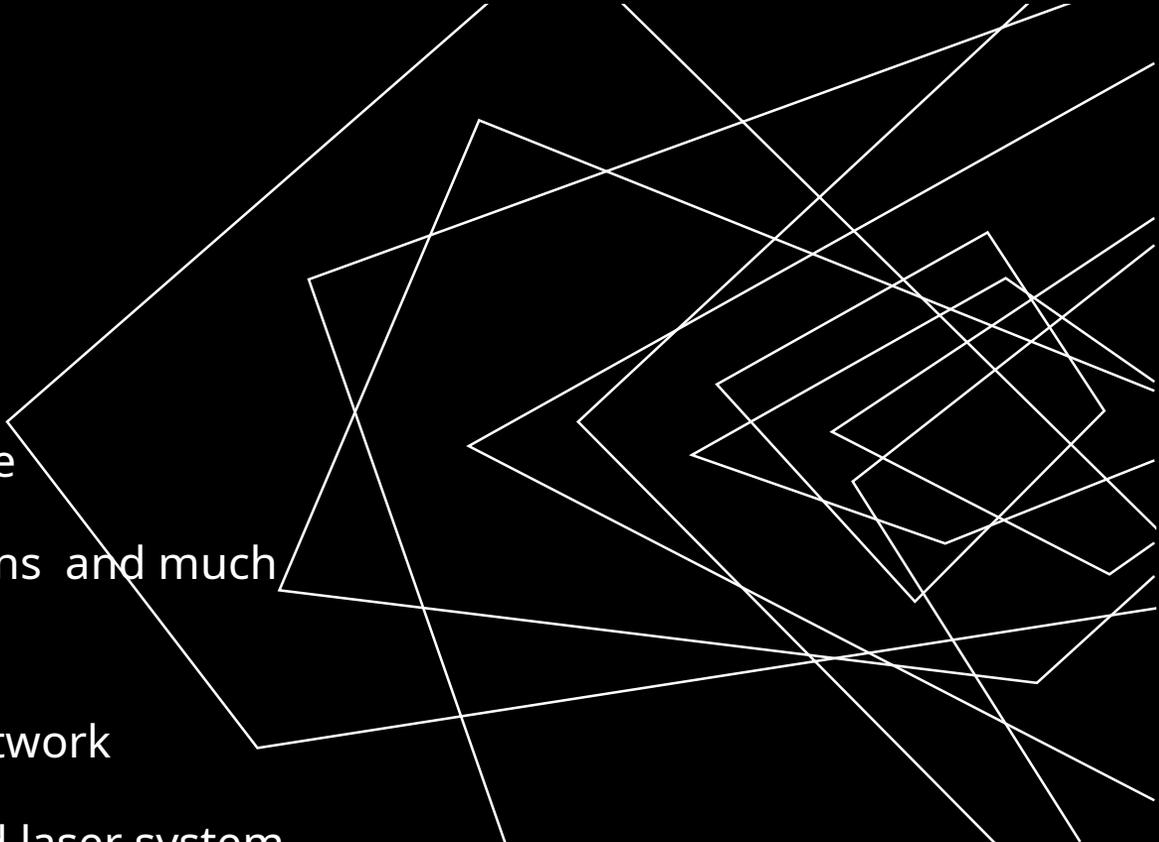
Optical frequency transfer technique

Fundamental limits, solutions and much  
more

Clean up oscillators in REFIMEVE network

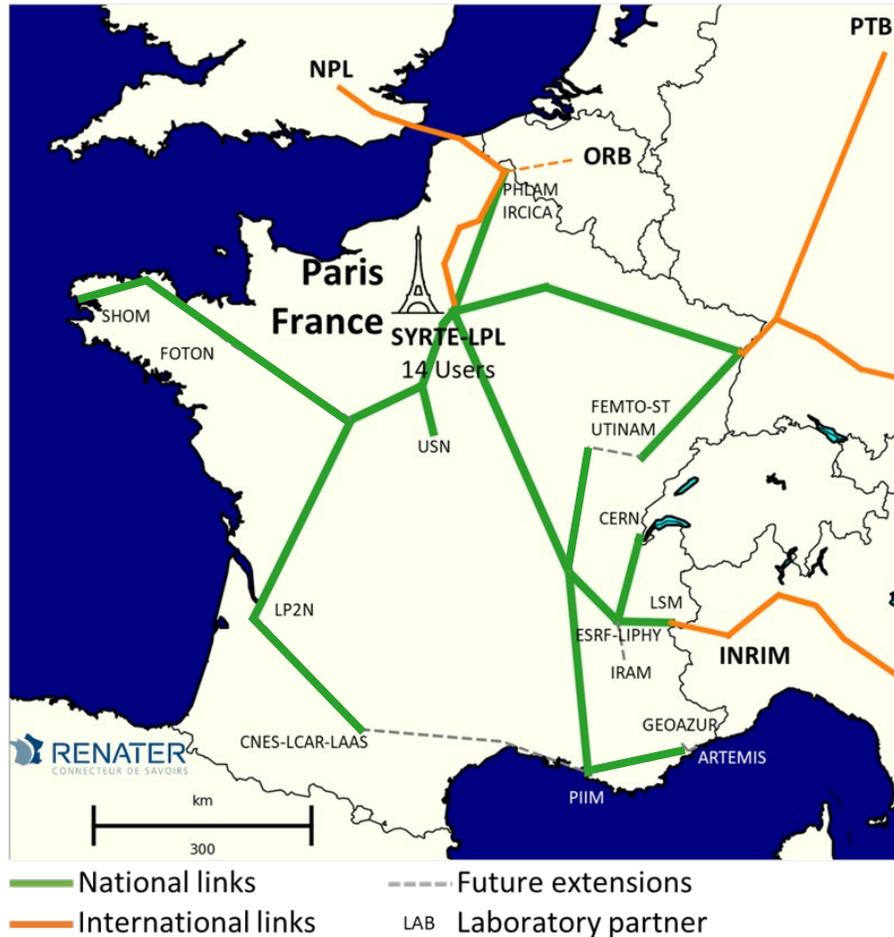
Ultra-stable cavity stabilized laser system

Perspectives



# THE NETWORK

## REFIMEVE NATIONAL NETWORK



**REFIMEVE** is a national research infrastructure composed of **optical fiber links** to **disseminate time and frequency reference** signals from the **French National Metrological Institute, LNE-SYRTE**, to more than **30 research labs** and **research infrastructures** simultaneously all over France, through the optical fiber backbone of **RENATER**, the French National Research and Education Academic Research and developments

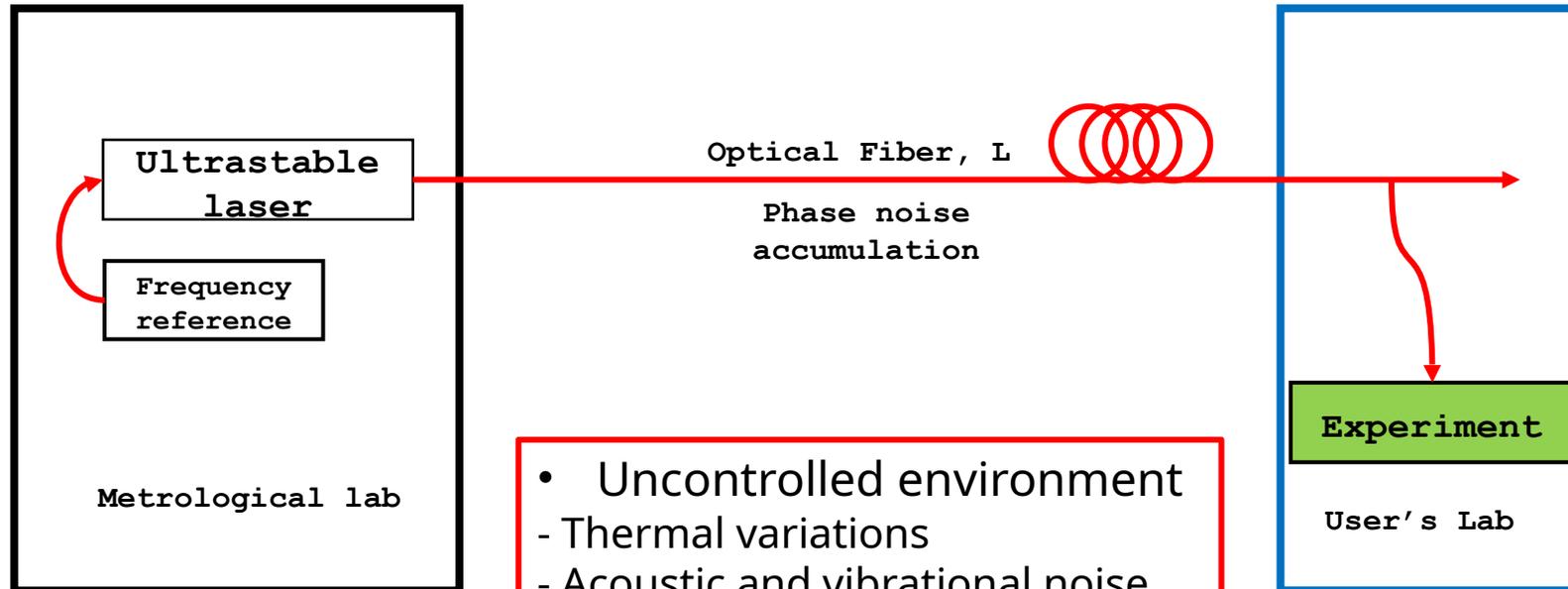
are led by Laboratoire de Physique des Lasers (**LPL**) & Laboratoire national de métrologie et d'essais (**LNE**)

**For more general overviews and utilization of REFIMEVE (following talk's of Christian CHARDONNET, Etienne CANTIN**



# OPTICAL FREQUENCY TRANSFER TECHNIQUE

# OPTICAL FREQUENCY TRANSFER TECHNIQUE



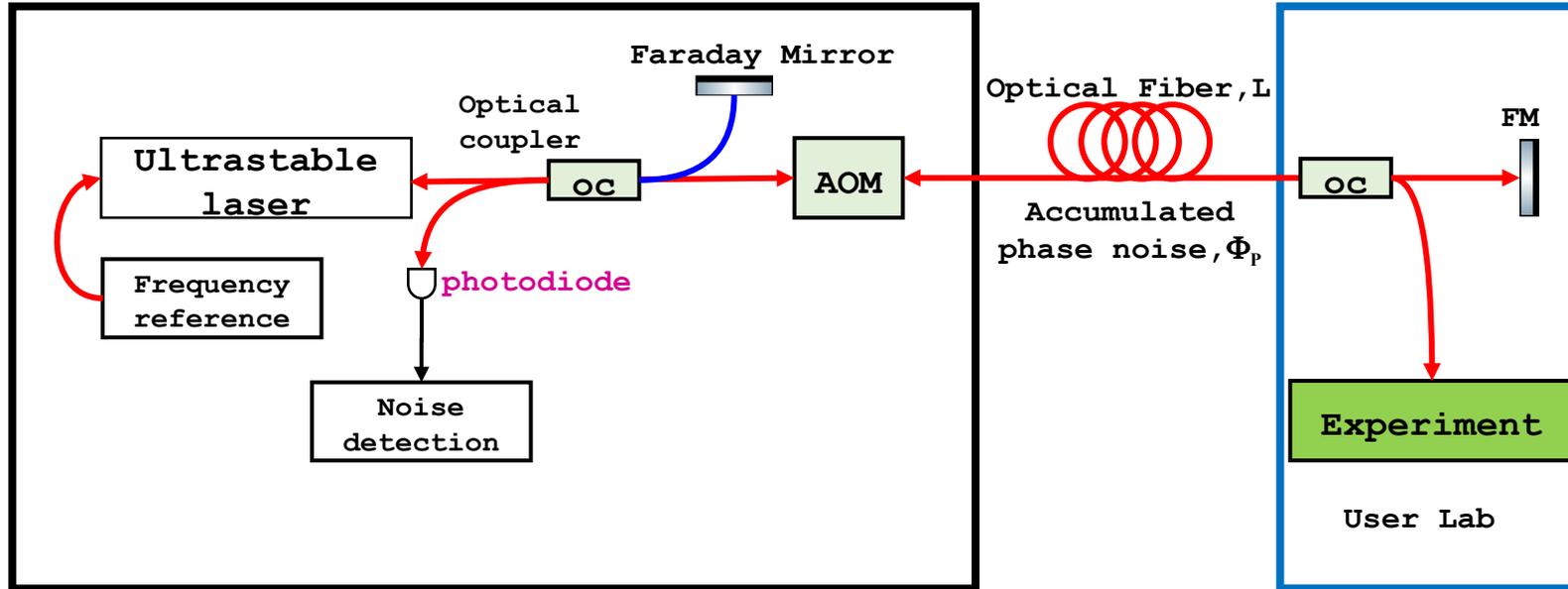
- Uncontrolled environment
  - Thermal variations
  - Acoustic and vibrational noise

- Controlled environment
  - Exact value at  $10^{-16}$
  - Relative frequency fluctuations  $dv/v < 10^{-15}$

- Degradation of Signal
- Need fiber noise correction.

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

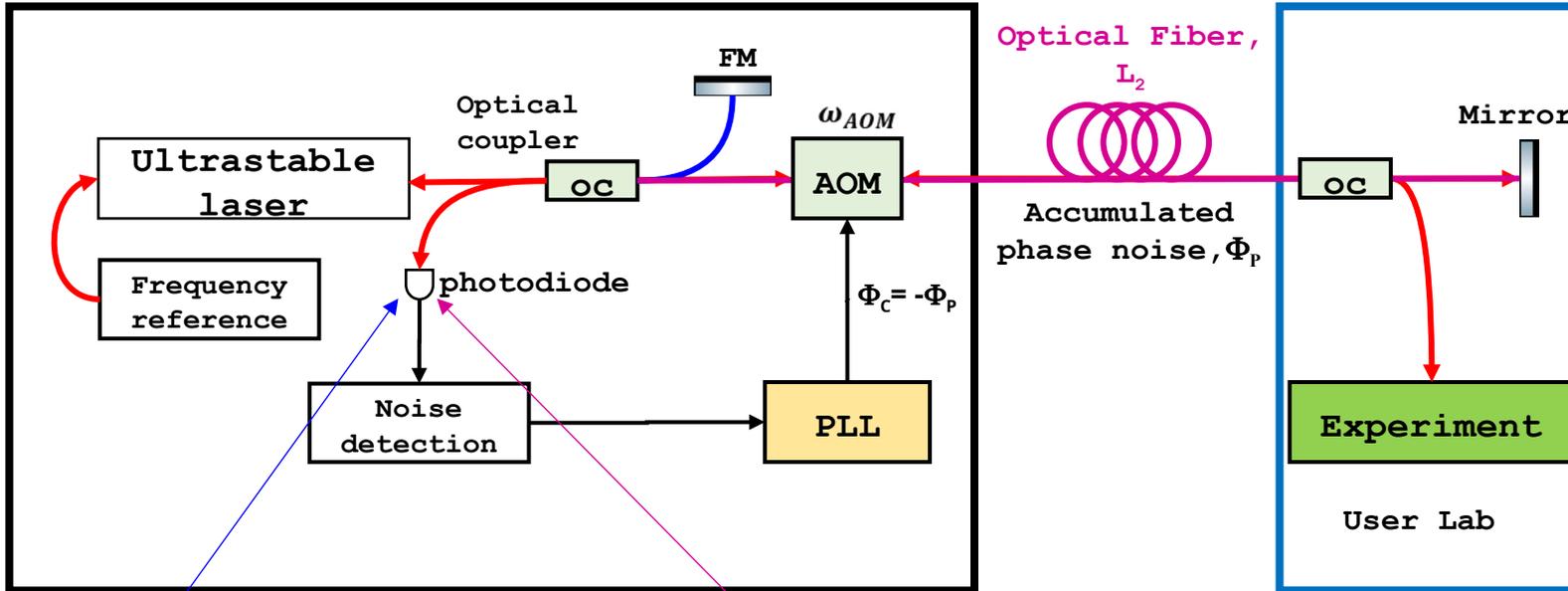
## ACTIVE FIBER NOISE COMPENSATION ALONG THE FIBER



- **Noise detection** with a **strongly unbalanced Michelson interferometer**
  - Long arm = fiber to the user
  - Short arm = reference arm
- **Heterodyne detection** between the reference signal and the reflected signal

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## ACTIVE FIBER NOISE COMPENSATION ALONG THE FIBER



$$E_1 = E_{01} \cos \left( \omega t - \frac{\omega}{c} n_1 2L_1 \right)$$

$$E_2 = E_{02} \cos \left( \omega t - \frac{\omega}{c} n_2 2L_2 + 2\omega_{AOM} + 2\Phi_P \right)$$

Light intensity detected by the photodiode

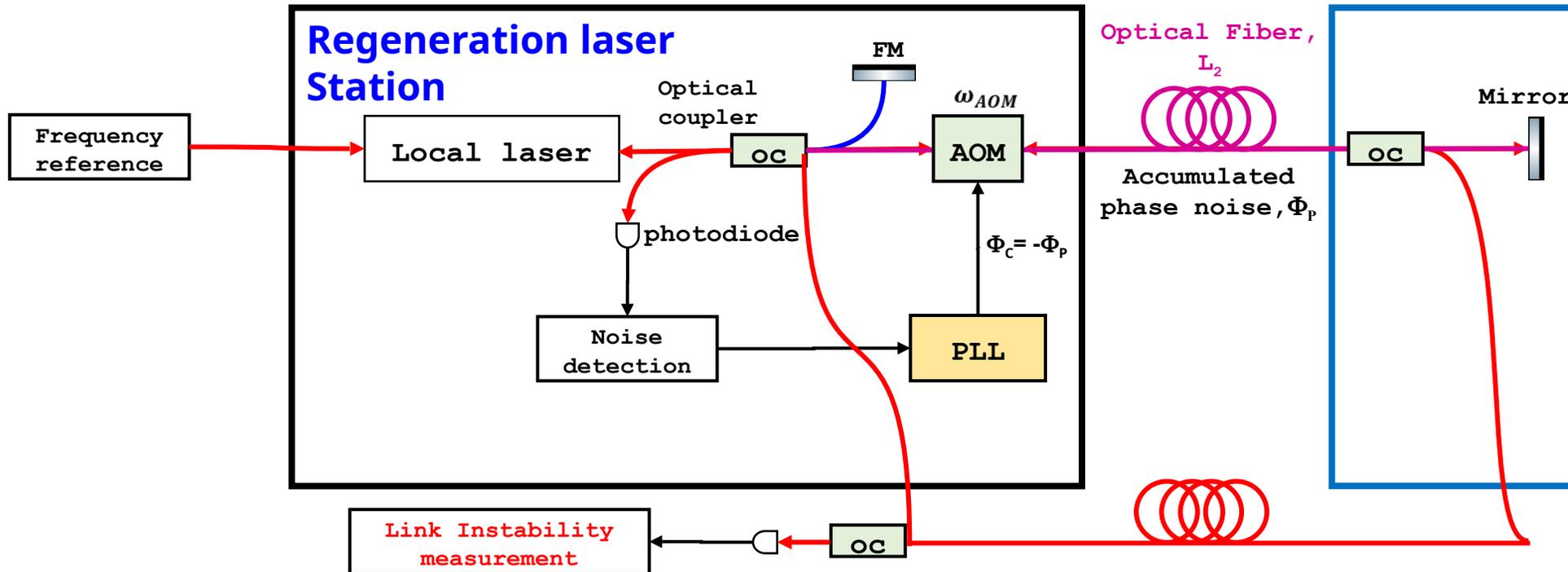
$$I = K \langle (E_1 + E_2)^2 \rangle = A + B \cos \left( \omega/c (2n_1 L_1 - 2n_2 L_2) + 2\omega_{AOM} + 2\Phi_P \right)$$

Noise induced due to propagation :  $\Phi_p = \text{variation of } (\omega/c) n_2 L_2$

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## ACTIVE FIBER NOISE COMPENSATIONS ALONG THE FIBER

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

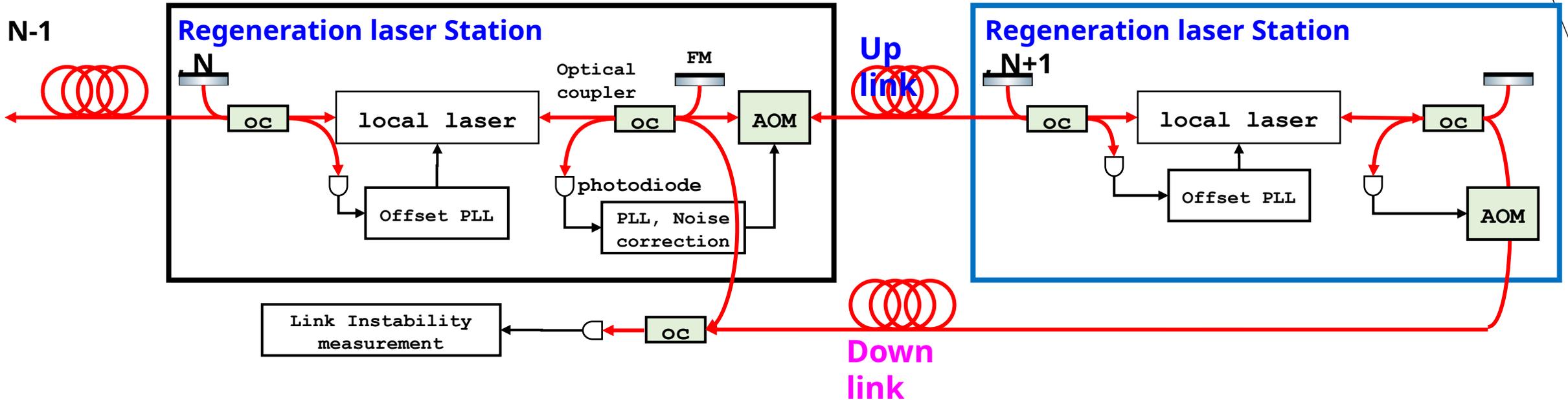


**E2E measurement** : characterization of the transfer with out-of-loop detection of the transferred signal

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Cascade Spans+ Regeneration laser stations + E2E measurements

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



### Link visualisation :

- **Up link** : for the dissemination of the signal
- **Down link** : out-of-loop detection of the transferred signal

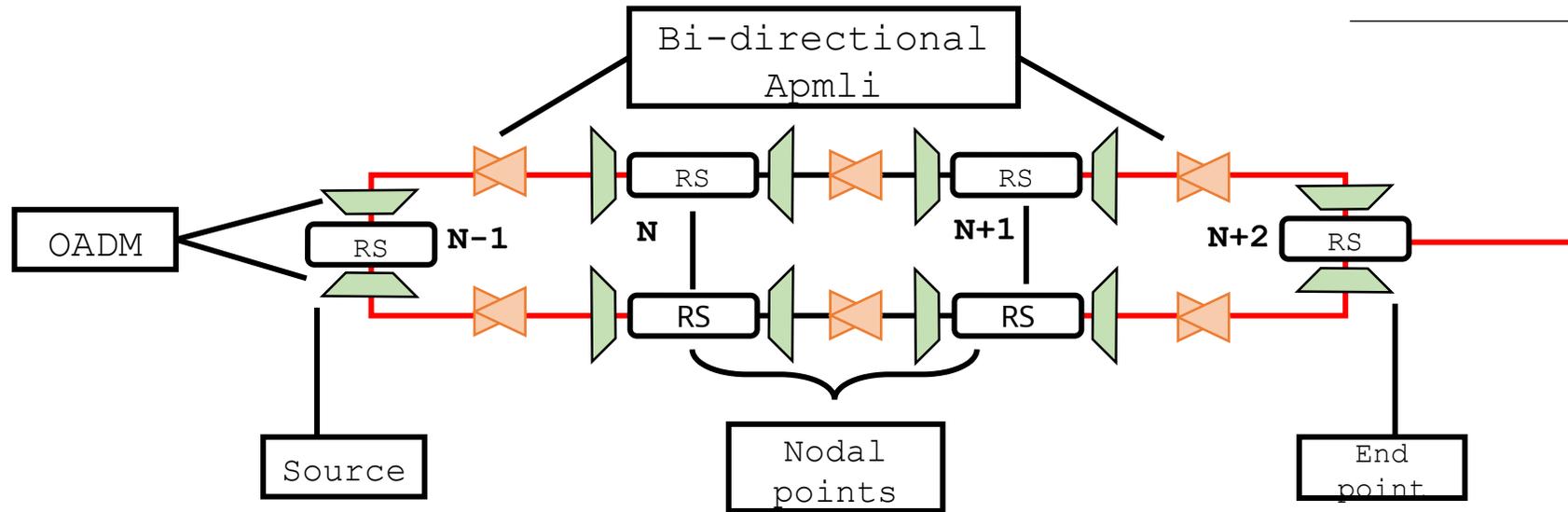
Paris - Lille - 1 cascade - 680 km  
Paris - Modane - 3 cascades - 1730 km

### Multi-segments approach :

- Link is **divided into segments**, depending on noise and losses
- better S/N
- Improves the transfer performance

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Basic Network architecture : Long distance Optical Link



- **Repeater station N** send back signal to **station N-1**, forward to **station N+1**, correct the noise fiber, also **amplify** and **filter**,

**Use public telecommunication networks (Mostly RENATER):**

- Already existing and potentially less expensive
- Dense Wavelength-Division Multiplexing (DWDM)
  - Digital data + Ultra-stable frequency signal

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

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Stations for

● RLS  
★ MLS



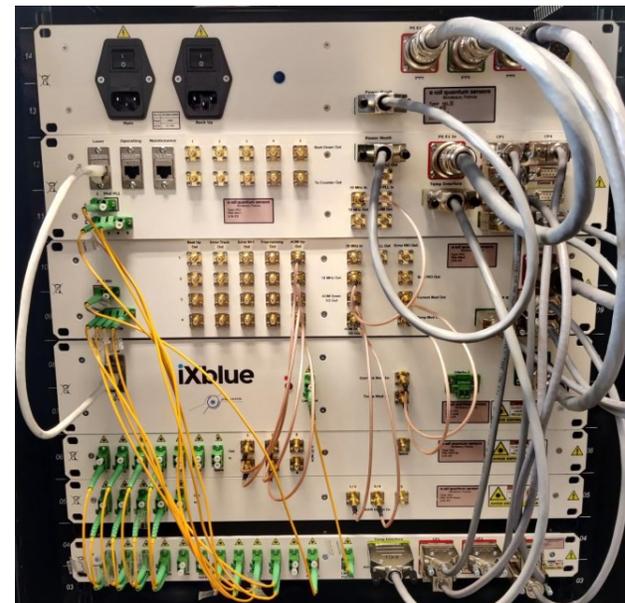
- For optical reference transfer :

**RLS** (Regeneration laser Station) + **MLS** (Multibranch laser Station)

- phase-coherent dissemination up to 6 link
- Improved long-term performances
- simplification to current network architecture
- 3 New generation MLS are already in the network (TH2, Strasbourg, Tours)
- Soon 1 at Grenoble



RLS



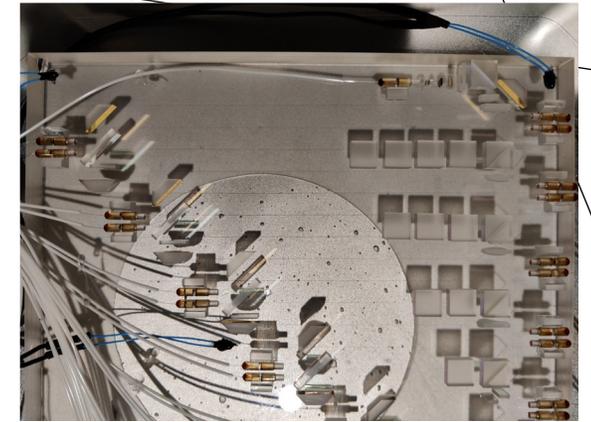
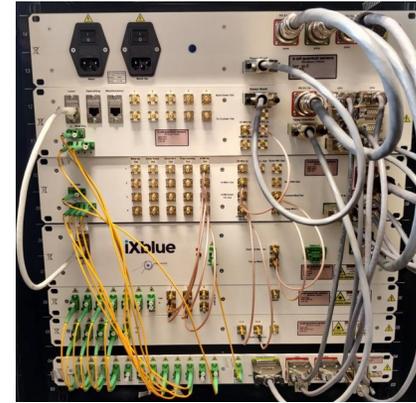
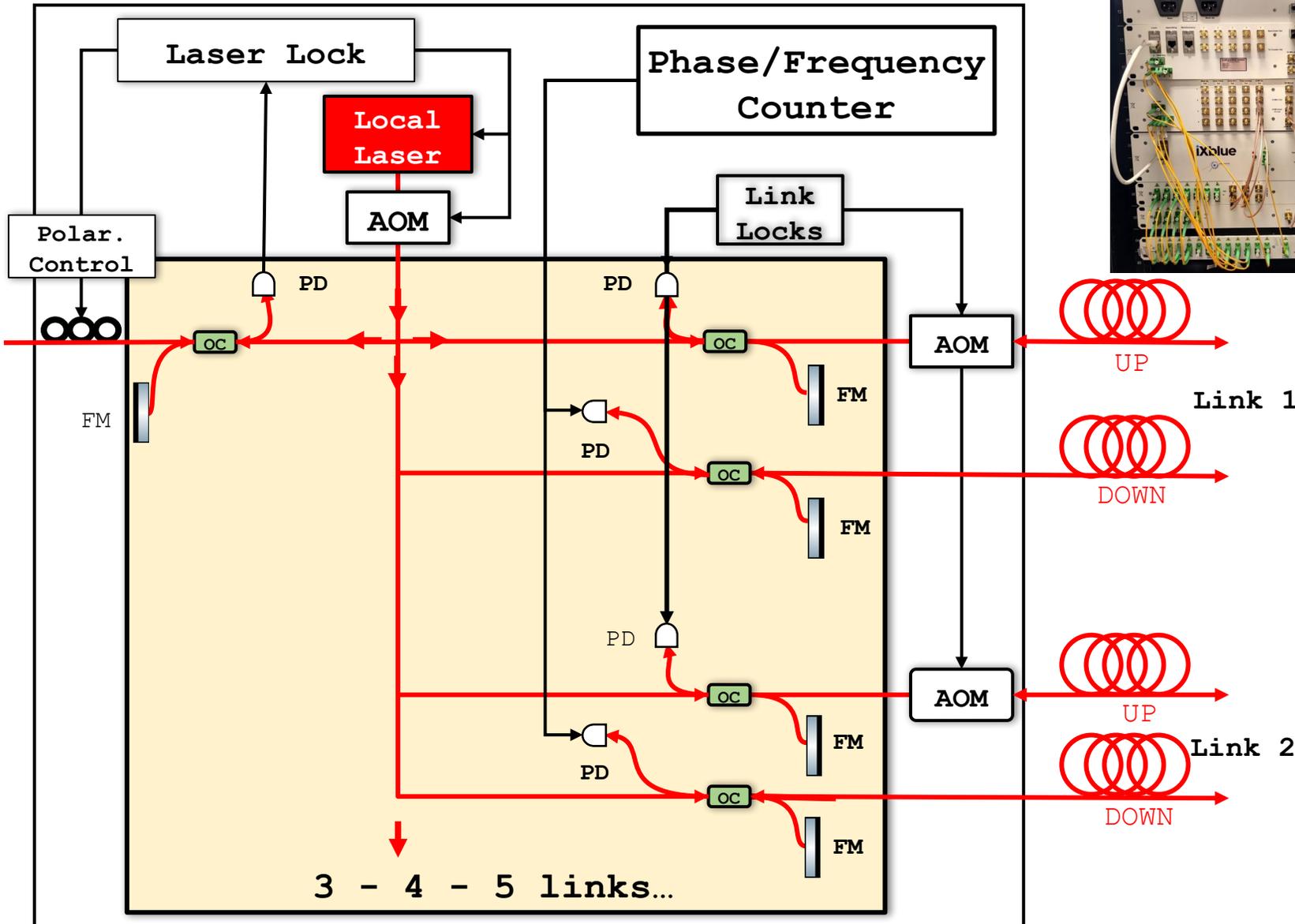
MLS

See Exail for Details

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

See Exail for Image and Details

## Multibranch laser stations MLS and upgrades



### Balanced multi-arm interferometer :

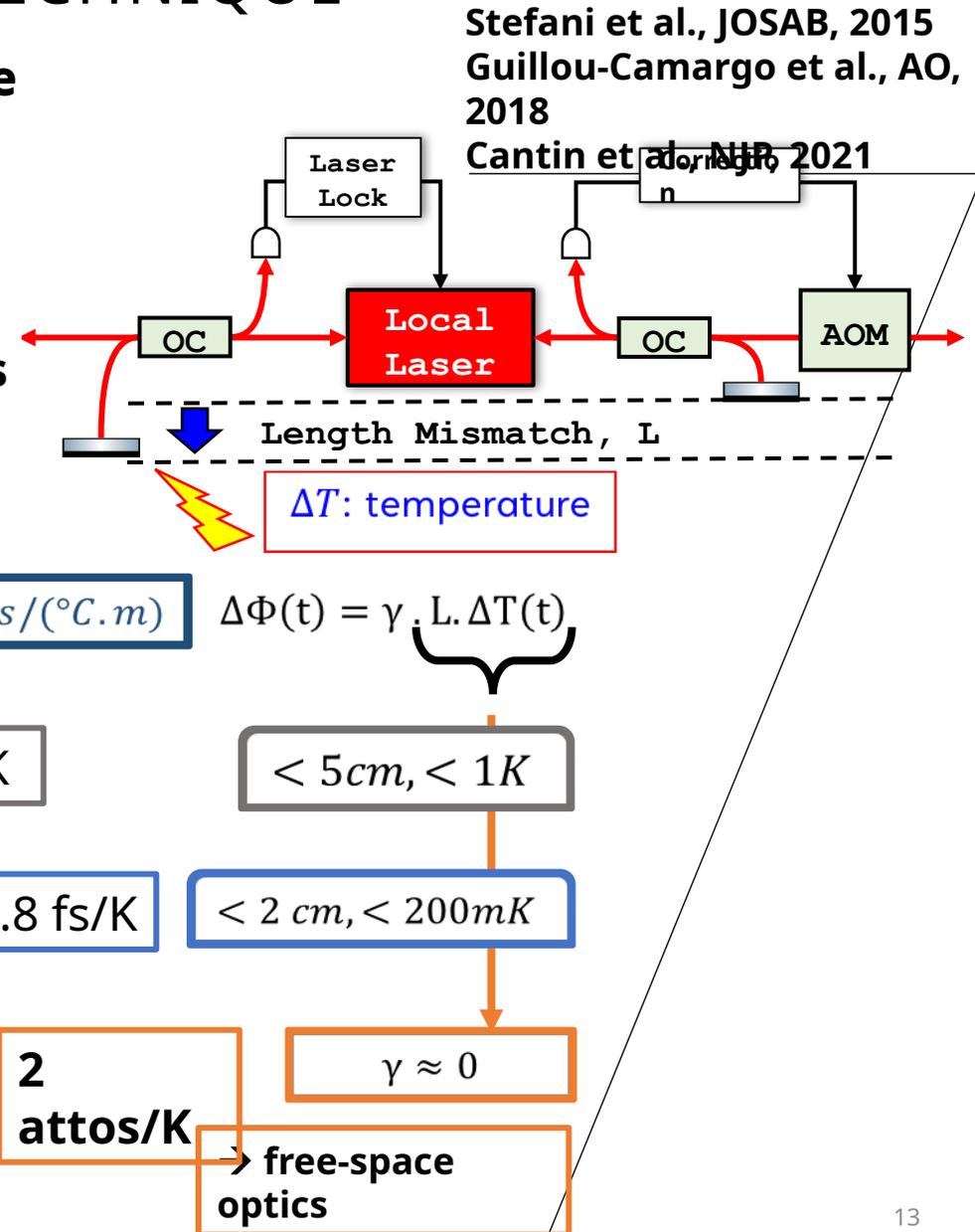
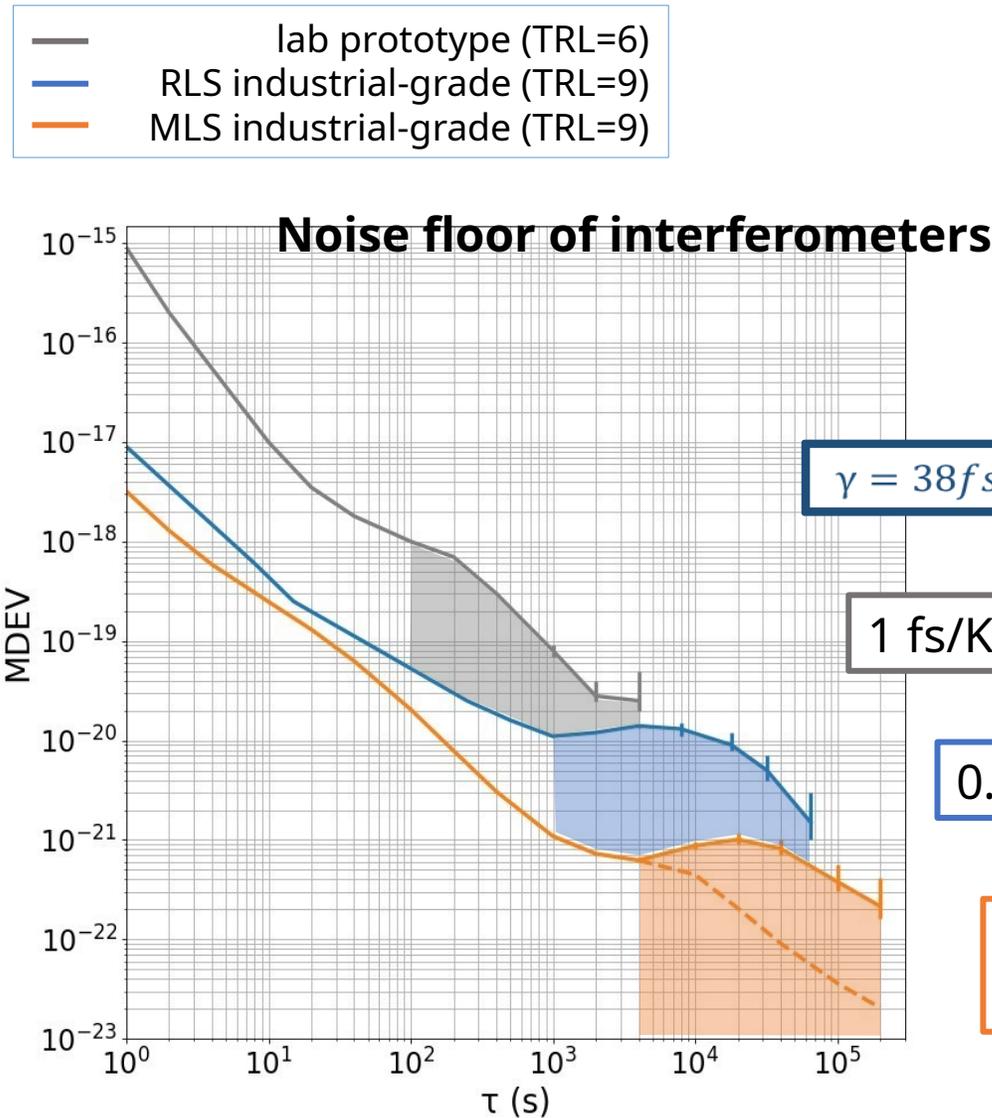
- Same optical path for all outputs
- All the output ports are equi-phase

### PHASE COHERENT INTERFEROMETRY

- allowing us to **coherently disseminate the REFIMEVE optical signal to several labs**, allowing **large-scale, correlated measurements of fundamental effects possible.**

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Long-term performances - Interferometric noise



OPTICAL  
FREQUENCY  
TRANSFER  
TECHNIQUE  
FUNDAMENTAL  
LIMITS

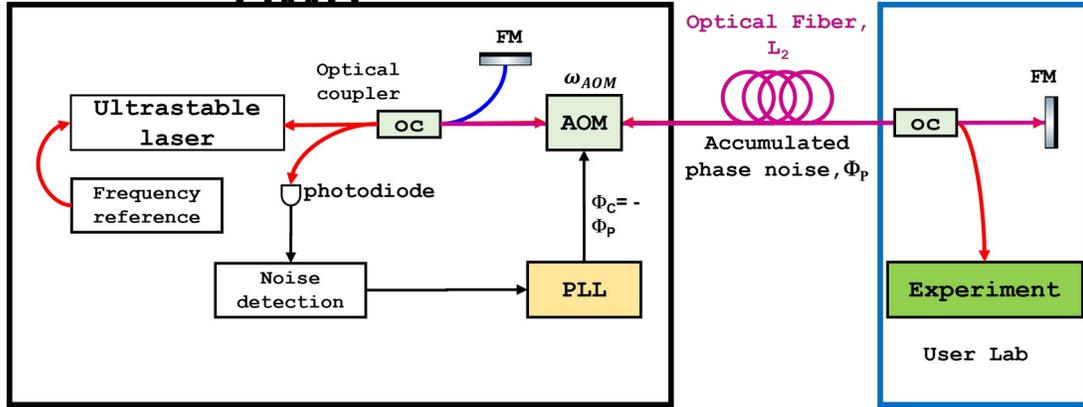


# OPTICAL FREQUENCY TRANSFER TECHNIQUE

N. R. Newbury et al., Optics Letters, 2007

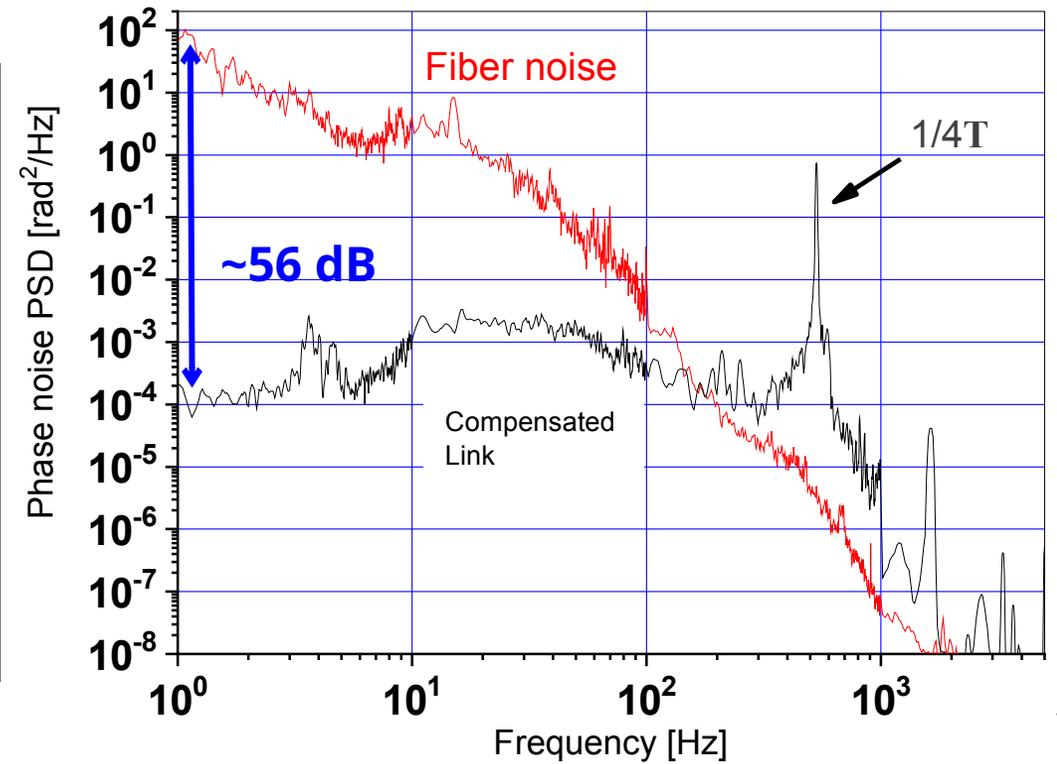
Jiang et al, JosaB 2008

## PROPAGATION DELAY & FUNDAMENTAL BANDWIDTH



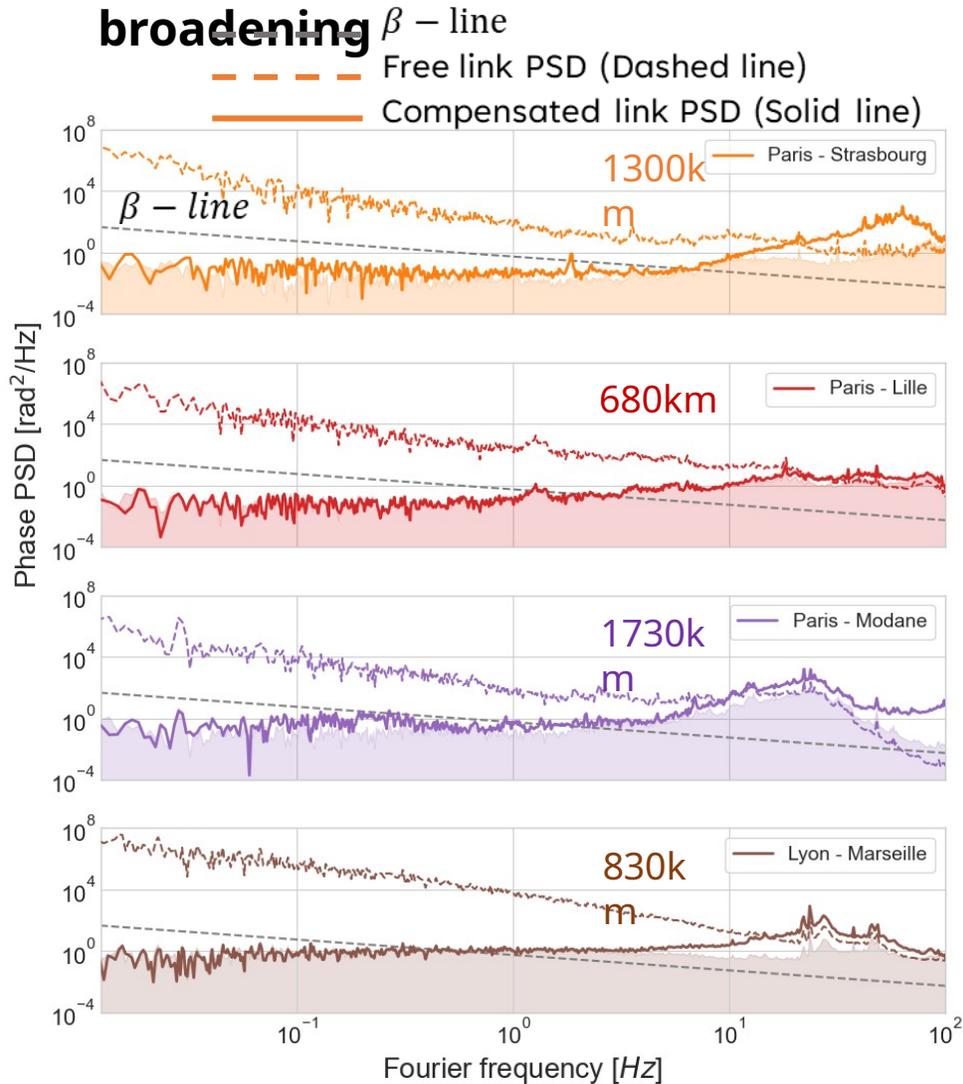
Link Length	$\tau$ (delay)	BW limit
10 km	0.049 ms	~ 5 kHz
100 km	0.49 ms	~ 500 Hz
300 km	1.47 ms	~ 170 Hz
900 km	4.4 ms	~ 55 Hz

PHASE NOISE OF THE 86 KM OPTICAL LINK



- One-way delay:  $\tau = nL/c$
- Round-trip delay:  $T = 2\tau$  (for 86 km : 0.4 ms)
- Servo bandwidth limited by delay:
 
$$f_{BW} \approx 1/(4\tau) = c/(4nL)$$
 (for 86 km : 580 Hz)
- Limited noise suppression:
 
$$G \approx 1/3 (2\pi \times f \times T)^2$$
 (for 86 km :  $G = -56$  dB @ 1 Hz)
- Residual noise PSD  $\approx$  fiber noise PSD  $\times (2\pi \times f \times T)^2$

## FUNDAMENTAL BANDWIDTH LIMIT & Linewidth broadening



- Finite delay → imperfect noise cancellation

$$\text{Linewidth: } \Delta\nu = \sqrt{8 \ln(2) A}$$

A, the area of the spectrum that exceeds the  $\beta$ -line

linewidth at the user's side can be approximated by

$$\Delta\nu_{user} = 1/\sqrt{2} \Delta\nu_{E2E}$$

Linewidth broadening contributions, calculated with a bandwidth of 500 Hz.

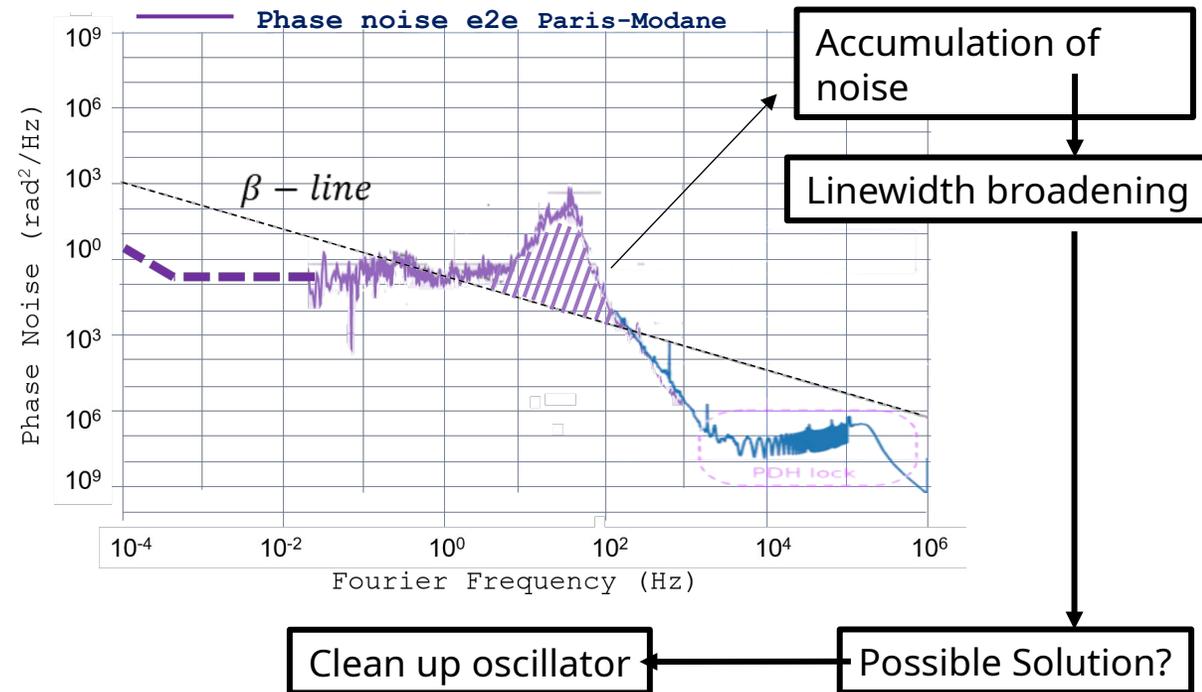
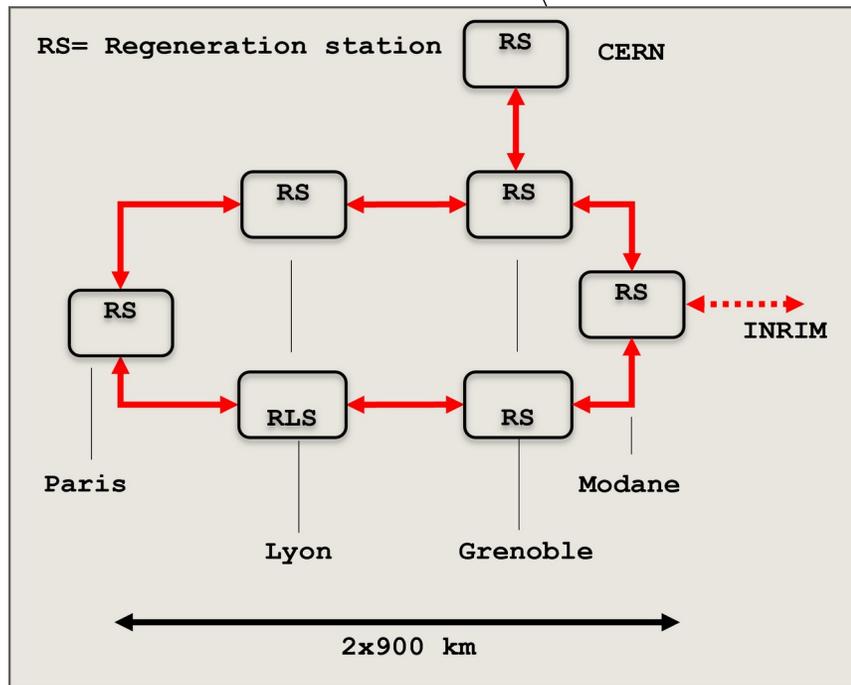
	LTE-LPL <90 Km				LTE-TH2 <90 Km				Paris-Grenobl e				Paris-Marseille			
	LTE-LPL <90 Km	LTE-TH2 <90 Km	Paris-Grenoble	Paris-Marseille	LTE-LPL <90 Km	LTE-TH2 <90 Km	Paris-Grenoble	Paris-Marseille	LTE-LPL <90 Km	LTE-TH2 <90 Km	Paris-Grenoble	Paris-Marseille	LTE-LPL <90 Km	LTE-TH2 <90 Km	Paris-Grenoble	Paris-Marseille
$\Delta\nu_{E2E}$ [kHz]	0.47	0.43	14.1	11.3	0.47	0.43	14.1	11.3	0.47	0.43	14.1	11.3	0.47	0.43	14.1	11.3
$\Delta\nu_{user}$ [kHz]	0.33	0.3	10	8	0.33	0.3	10	8	0.33	0.3	10	8	0.33	0.3	10	8

All the long-haul links are at the fundamental limit

# CLEAN UP OSCILLATORS IN REFIMEVE NETWORK

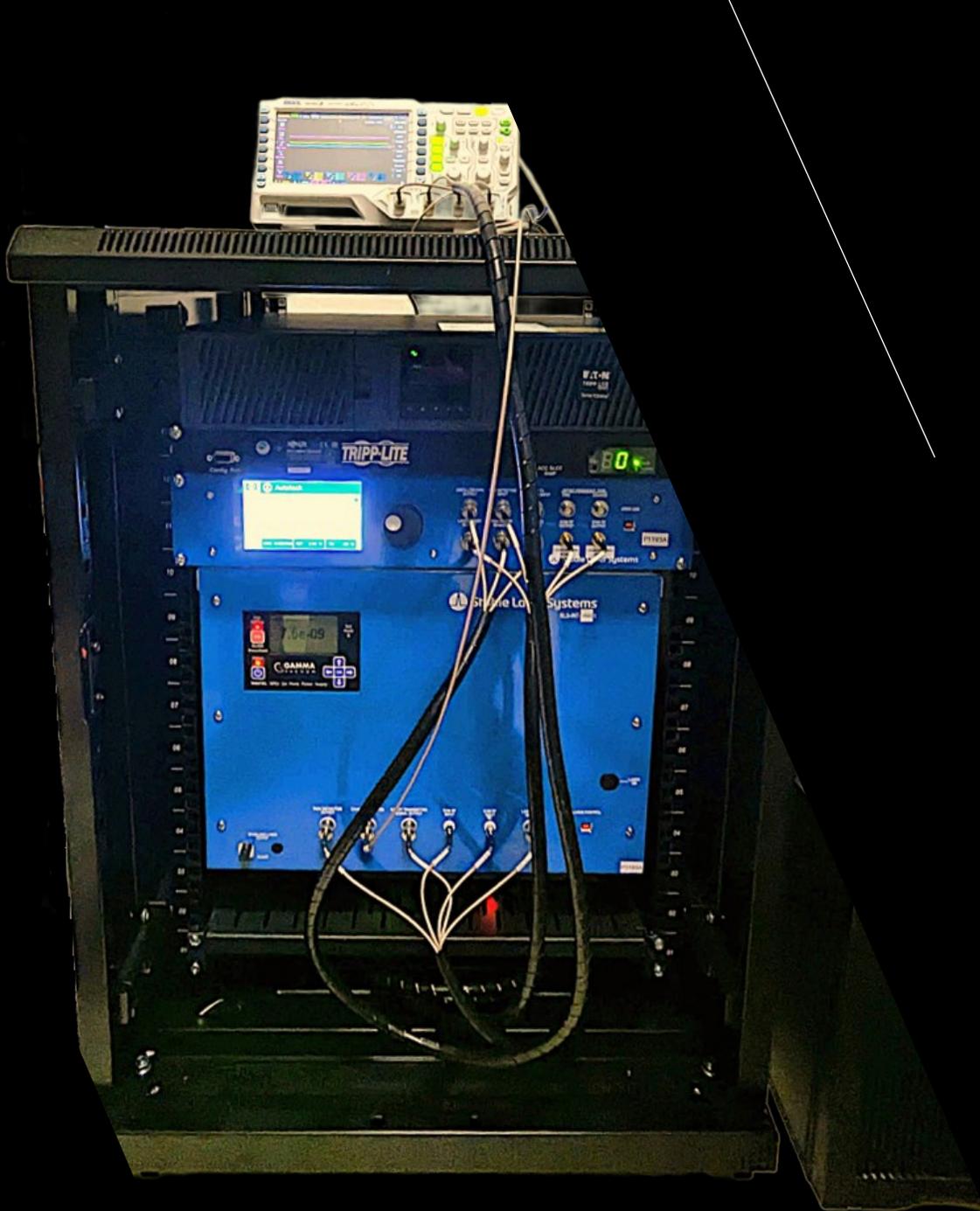
## FUNDAMENTAL BANDWIDTH LIMIT & Linewidth broadening

- For example : REFIMEVE Paris - Grenoble link



Two possible solutions from REFIMEVE:

- **ULTRA STABLE CAVITY**
- **SILENTSYS - SLIM LINER (see Adèle's Poster)**



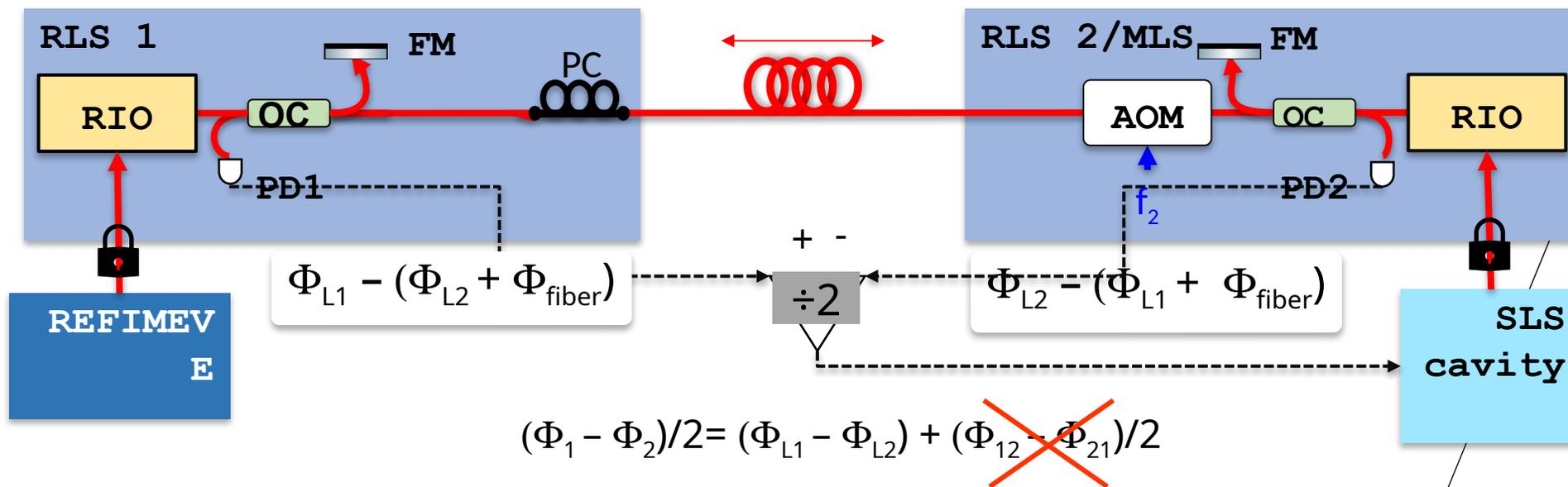
CLEAN UP  
OSCILLATORS IN  
REFIMEVE  
NETWORK



# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Two way comparison for measuring the frequency drift of the cavity

- Two way comparison for comparing two oscillator



- Two Michelson-type interferometers at each end to detect the phase difference signal
- Same (or better) performance as with an active noise compensated link
- Not limited to the fiber induced phase noise

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Ultra-stable cavity stabilized system (LUS) integrated to the exiting network

See stable laser system for Details

Stable Laser Systems



15	Eaton Tripp Lite SmartOnline (PDU)	15
14		14
13	Shelf	13
12	STS	12
11	Locking system SLS	11
10	Shelf	10
9		9
8		8
7	SLS cavity	7
6		6
5		5
4		4
3	Anti Vibration platform (TS 150 LP)	3
2		2
1	Etagère	1

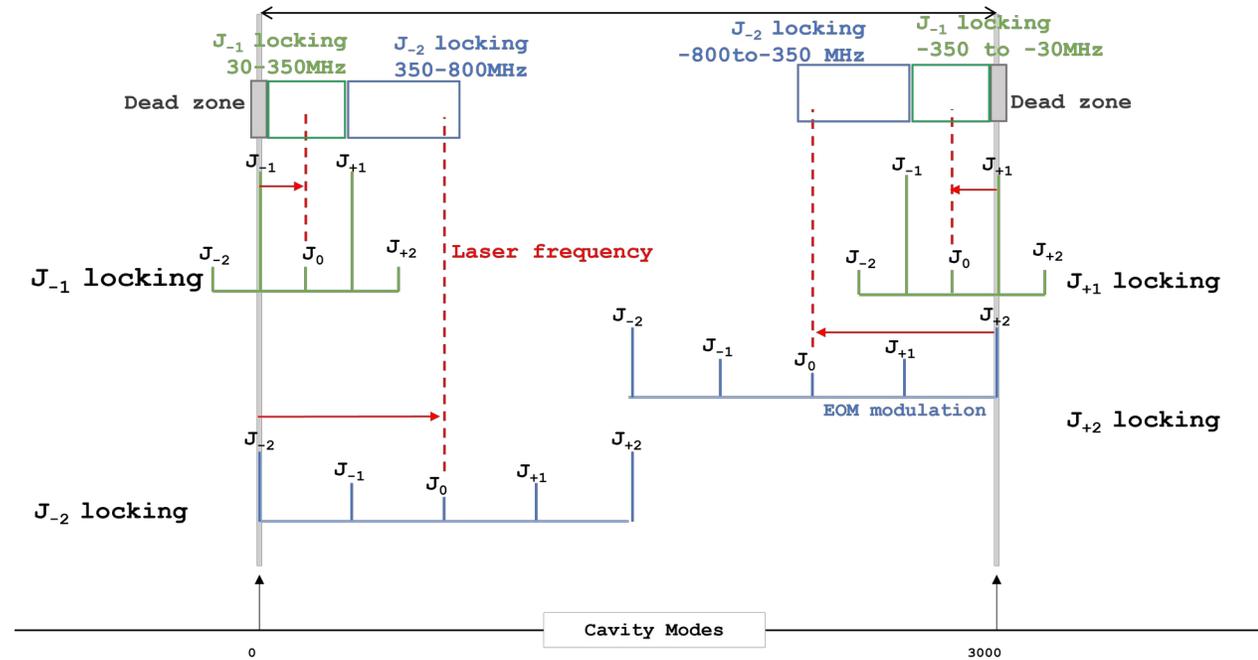
### Cavity

### configuration

- Cubic 5 cm ULE

### Offset phase locking

FSR = 3 GHz



- SLS System (received first unit 2 weeks age):

- UPS +STS
- Locking Electronics
- Cavity + laser System



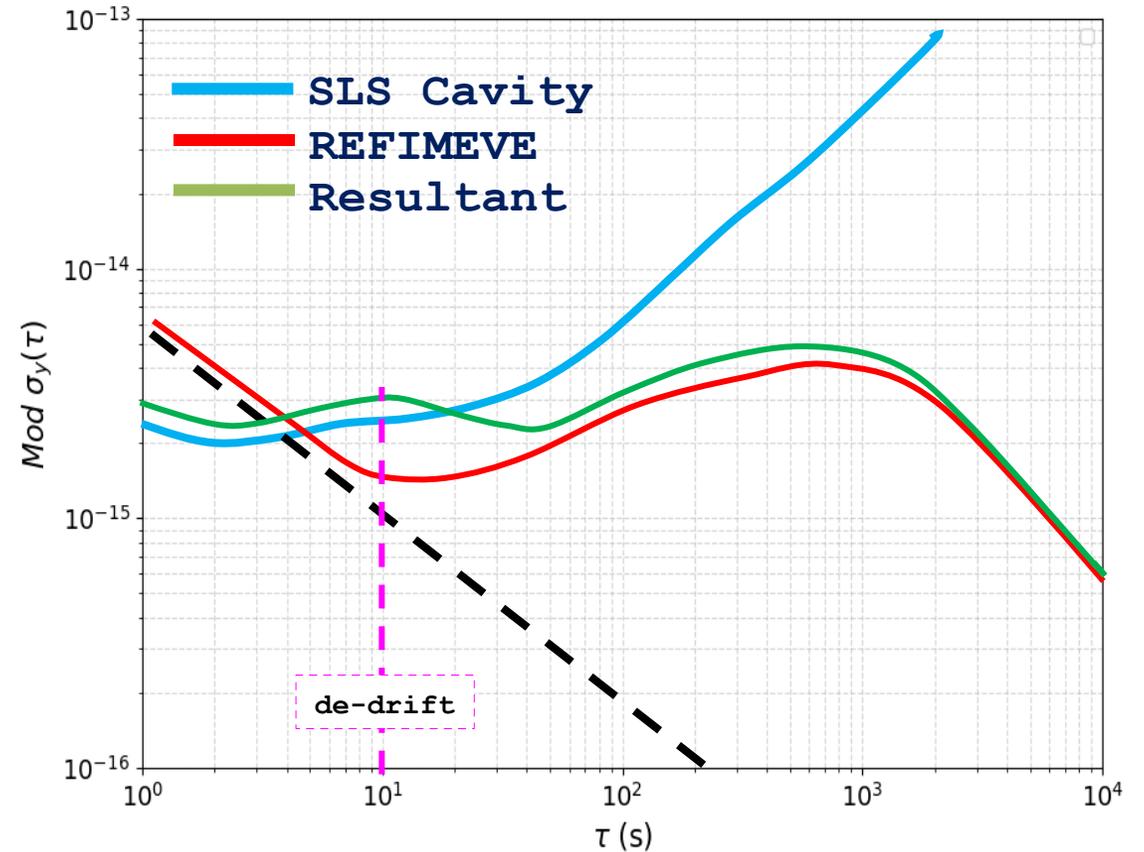
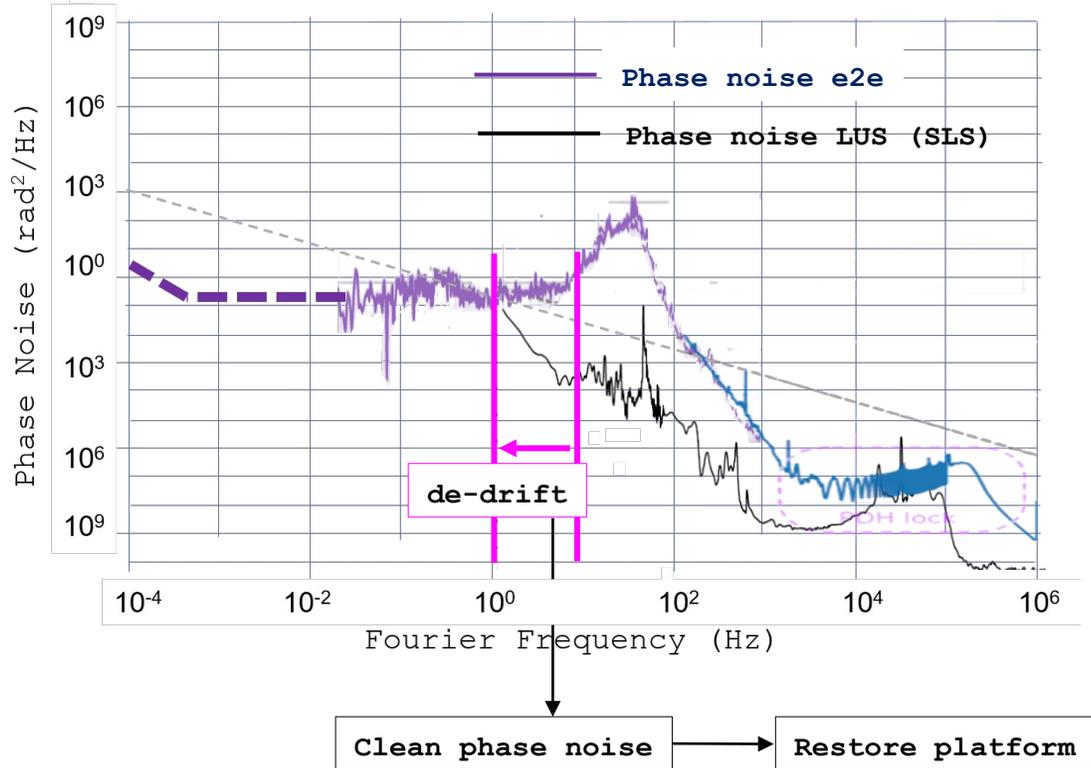
### Drift compensation

- Correction to the internal offset phase locking point

# OPTICAL FREQUENCY TRANSFER TECHNIQUE

## Expected performance of REFIMEVE signal with cavity

- Phase noise e2e  Stable Laser Systems



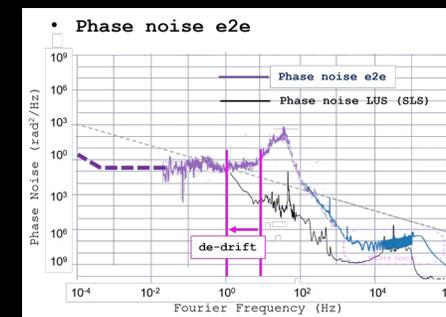
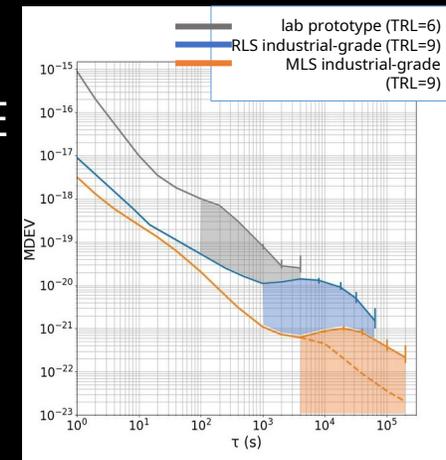
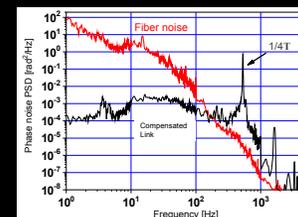
- Restore the linewidth to  $< 1 \text{ Hz}$
- Stability expected around  $2 - 3 \times 10^{-15}$  @  $1 - 10 \text{ (s)}$

# CONCLUSION

Newly Improved MLS for REFIMEVE

Fundamental limits

Ultrastable cavities for REFIMEVE



# PERSPECTIVES

## Possible Roadmap for future

- First infield MLS + Cavity System by Q2 2026
  - Testing and deployment at Grenoble
- By Q4 2026 other two cavities
  - integrate ultra-stable lasers aside of the RLS, at Bordeaux and Plateau de Calern, in order to provide ultra-low phase noise signal in these areas

- Cavity + MLS/RLS system usage !
  - Local User
  - Also improves the overall performance of the network





# THANK YOU

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Debanjan Shaw , Maël Abdelhak, Neelam Yadav

Laboratoire de Physique des Lasers

LNE-SYRTE

