AG Labex 2015

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Recent development on metrological urban network & frequency comparison

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Actuellement en 3ème année de thèse à l'Université Paris 13

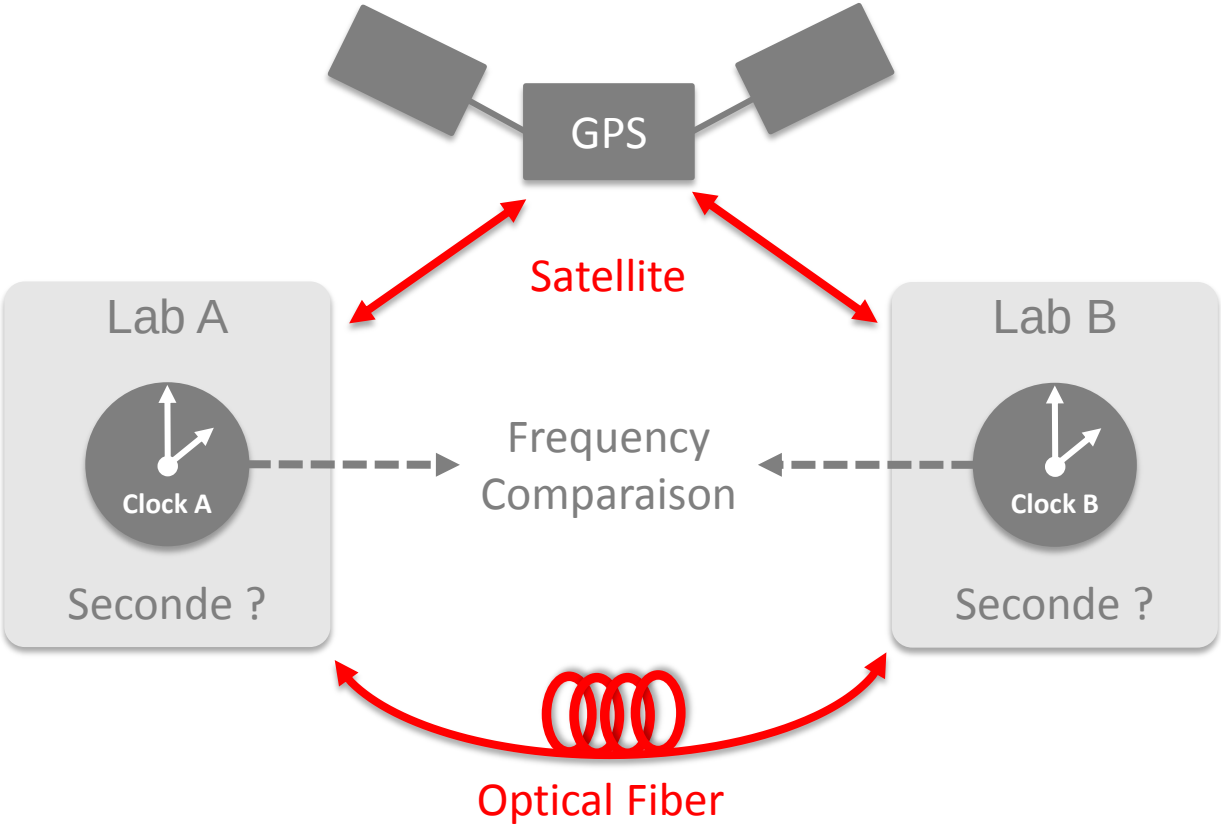
1 Laboratoire de Physique des Lasers

2 Systèmes de Référence Temps-Espace

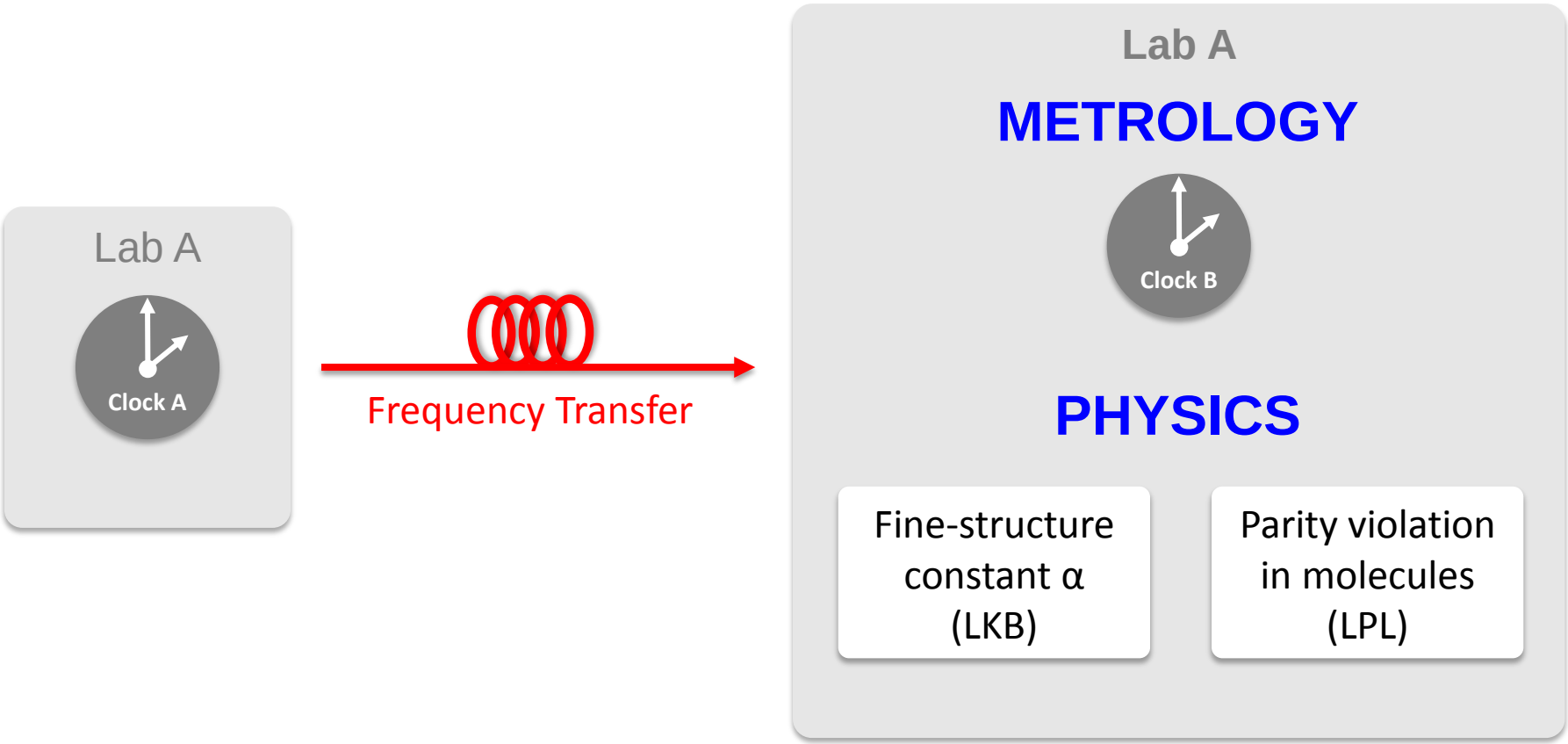
3 Laboratoire Kastler Brossel

4 Laboratoire Photonique, Numérique et Nanoscience

MOTIVATIONS



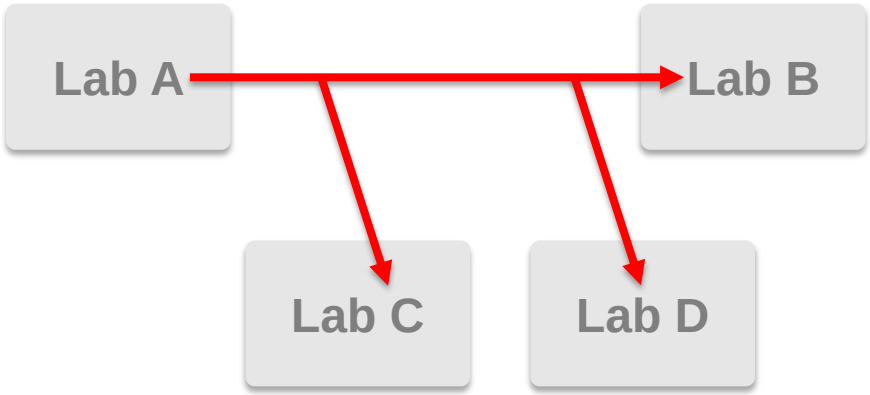
MOTIVATIONS



TRANSFERT / COMPARISON

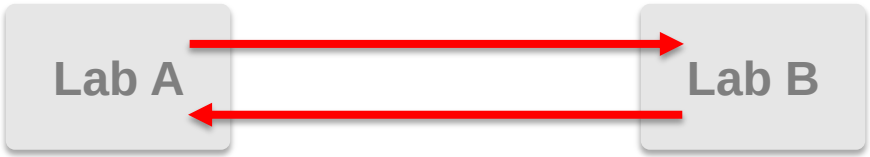
TRANSFERT

Optical frequency reference to several remote users



COMPARISON

Two reference optical signals by "two-way" method



PLAN

MOTIVATIONS

TRANSFERT

IN-LINE EXTRACTION : FIRST SETUP

IMPROVED SETUP & PRELIMINARY RESULTS

COMPARISON

FIRST TECHNIQUE : TWO-WAY BI-DIRECTIONAL

SECOND TECHNIQUE : TWO-WAY UNI-DIRECTIONAL

CONCLUSION

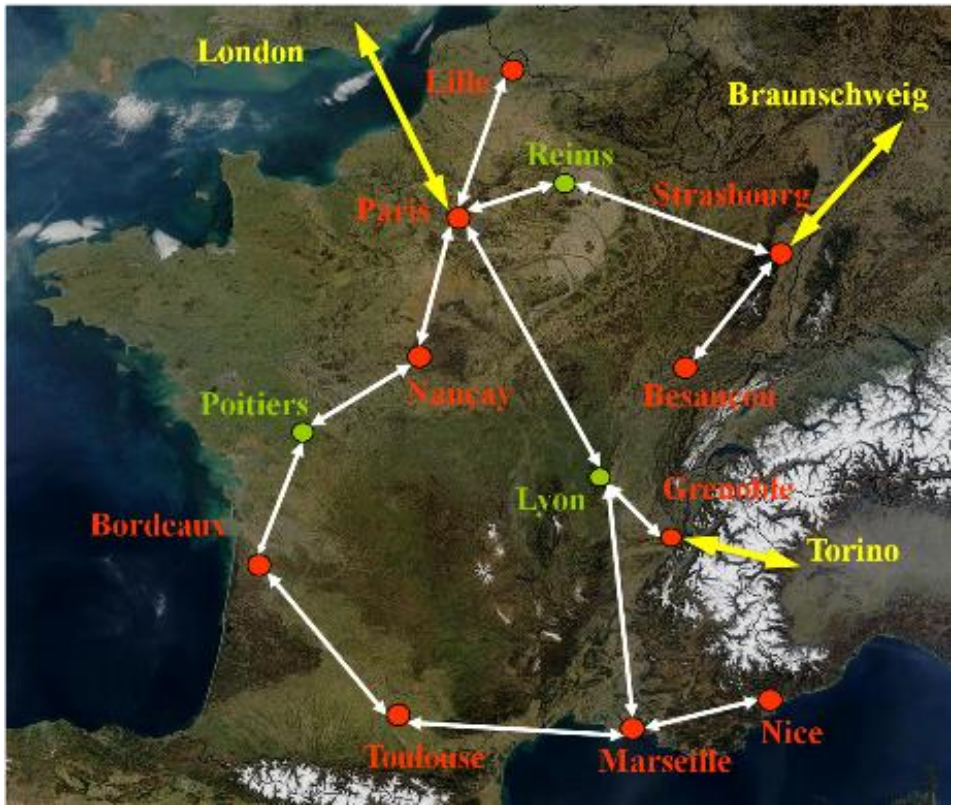
TRANSFERT

OPTICAL LINK IS MATURE with development on dedicated fibers or on **Telecom Network (in France : RENATER)**

LONG DISTANCE LINKS demonstrated **with repeater** (Lopez *et al*, Optics Express 2012)

EXTENSION OF FIBER LINKS around the world :

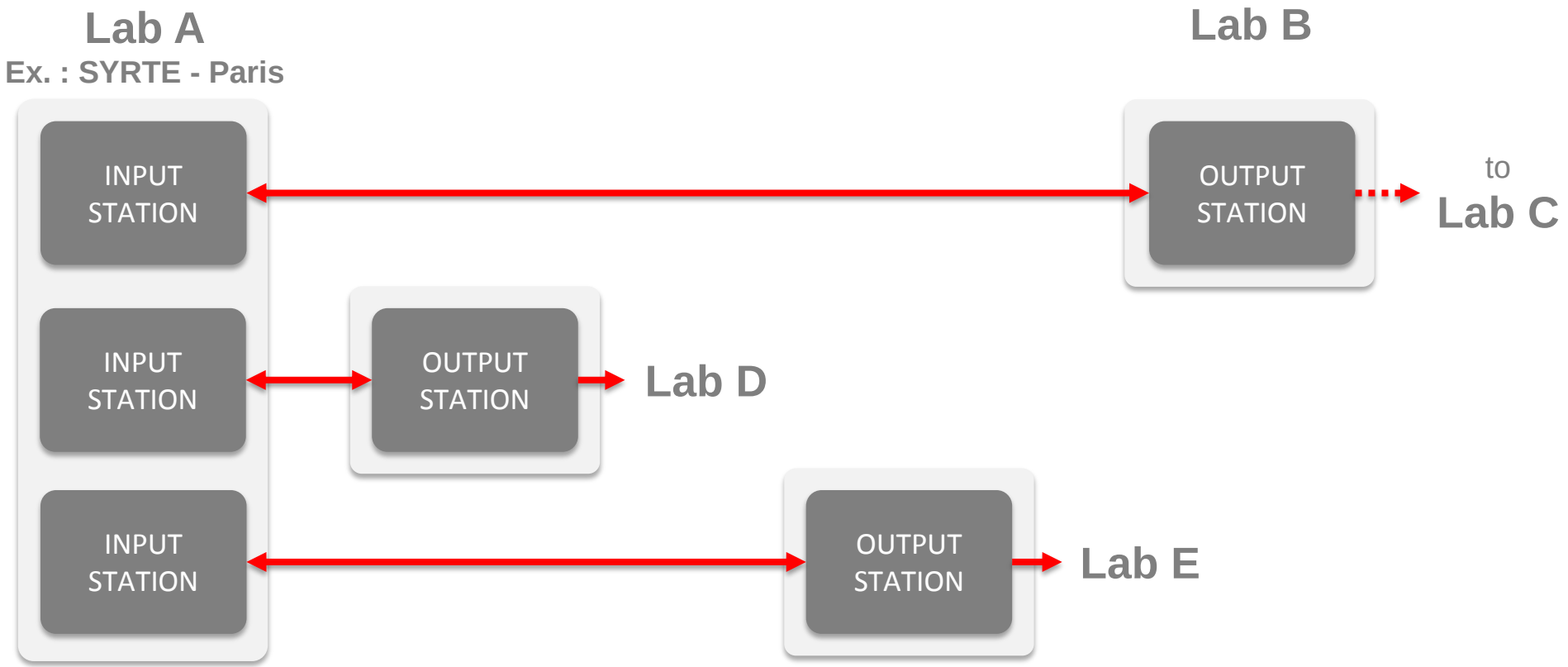
- **Refimeve+ Project** in France with 20 labs
- **Neat-FT Project** in Europe
- **New links** in Italy, UK, Poland...



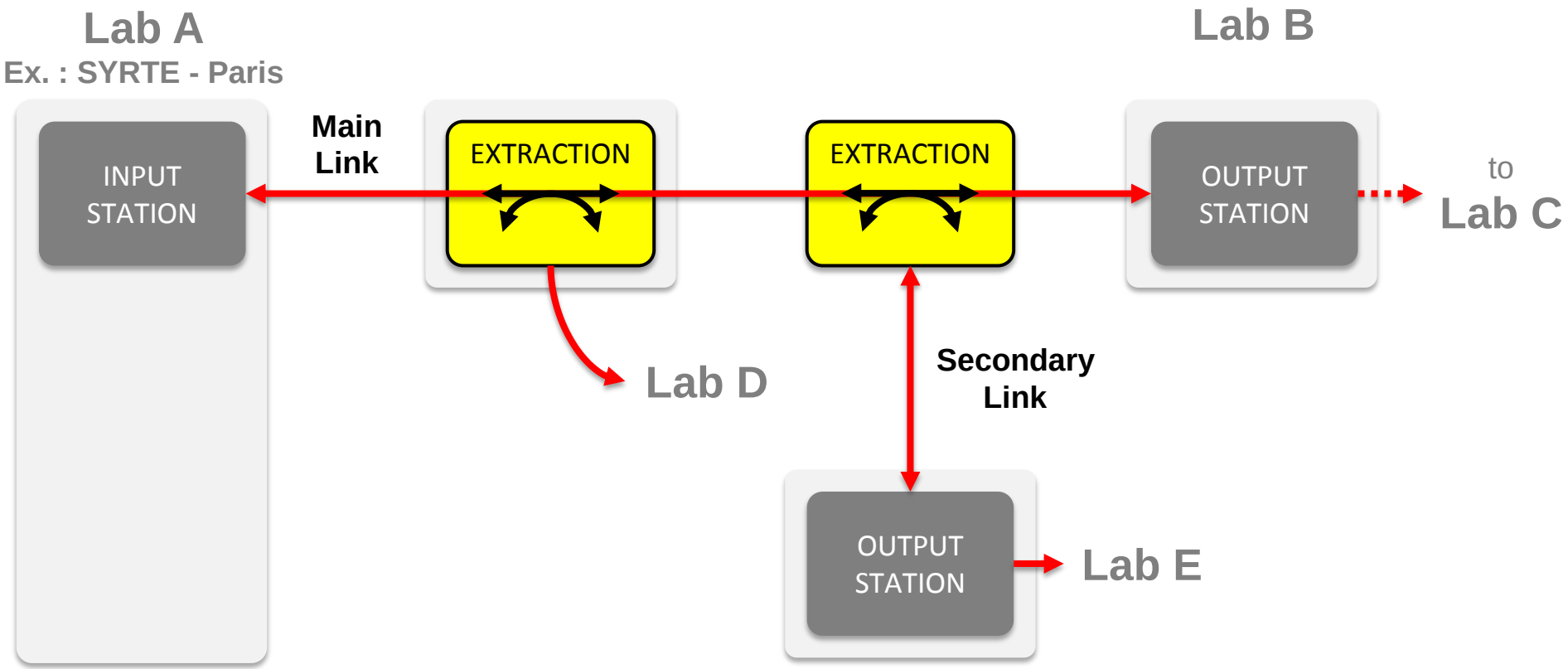
Refimeve+
Réseau fibré métrologique à vocation européenne

RENATER
CONNECTEUR DE SAVOIRS

NETWORK ARCHITECTURE

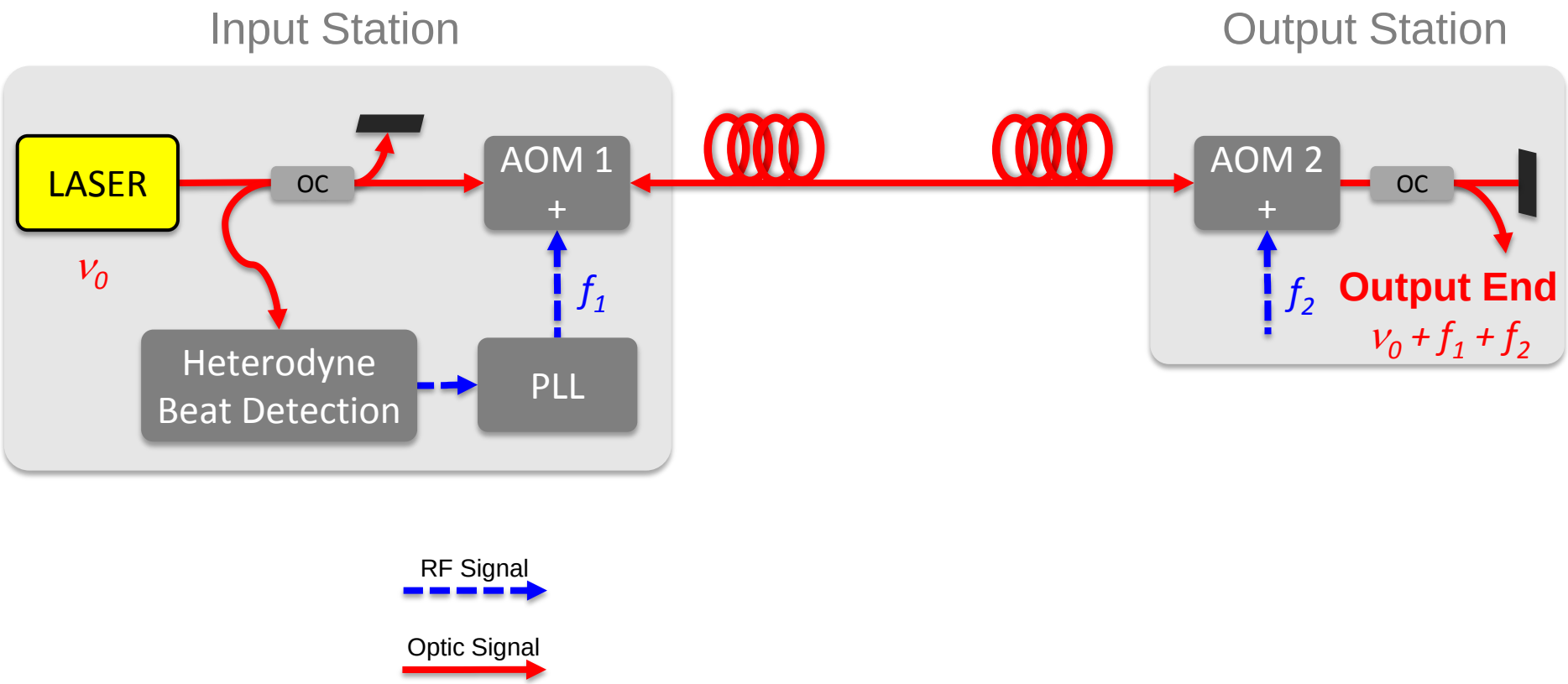


NETWORK ARCHITECTURE

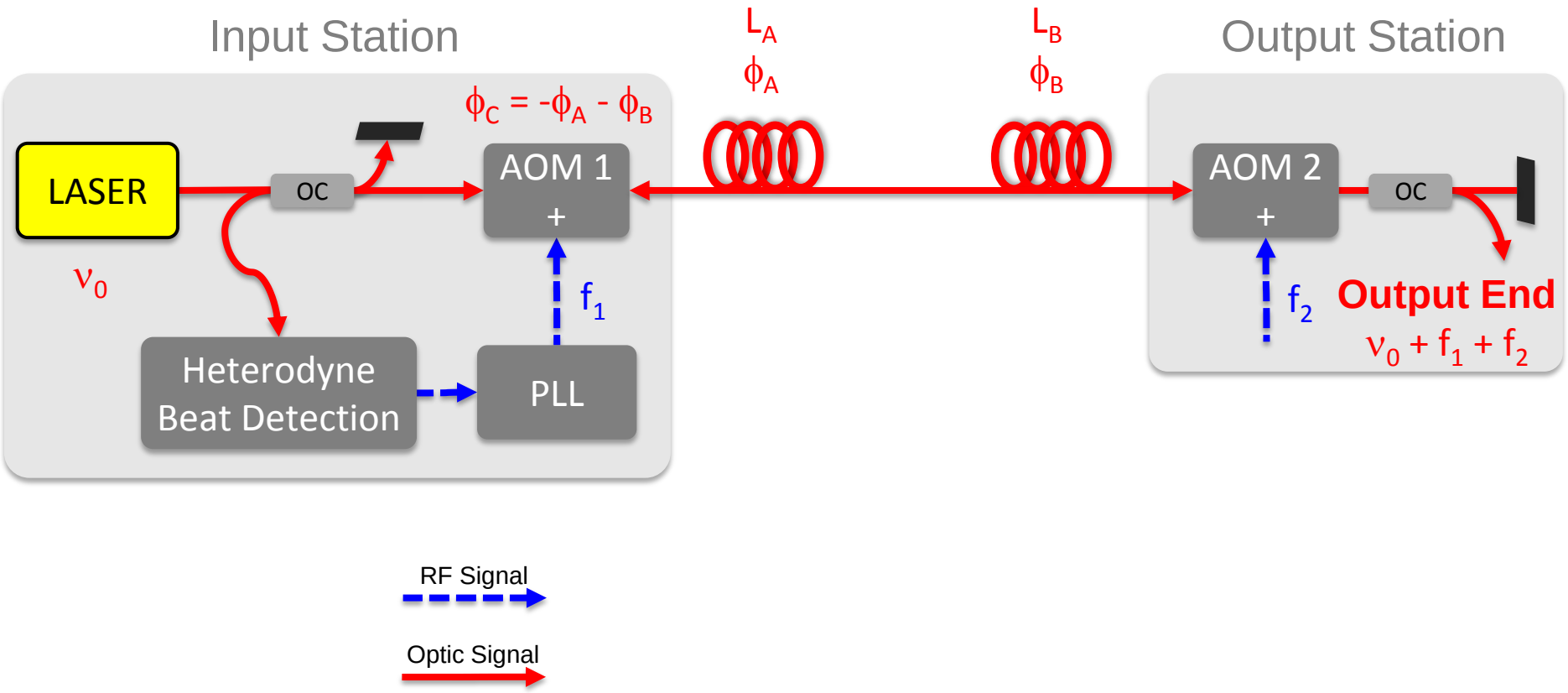


First proposed by G Grosche, patent application DE 10.2008.062.139 (2010)

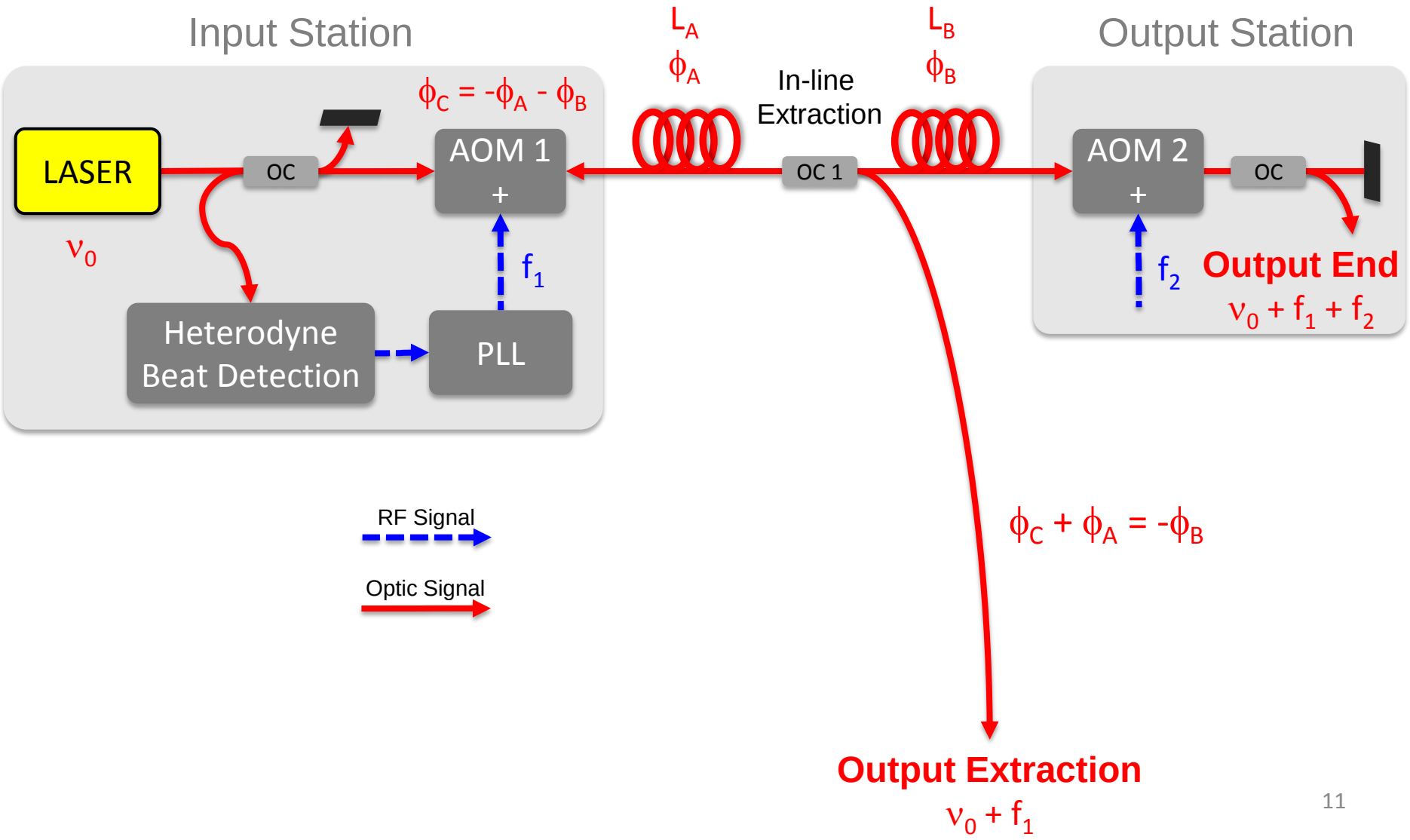
EXTRACTION


Input Station
Output Station
LASER
OC
AOM 1
+
AOM 2
+
OC
ν_0
f_1
f_2
Heterodyne
Beat Detection
PLL
Output End
$\nu_0 + f_1 + f_2$
RF Signal
Optic Signal

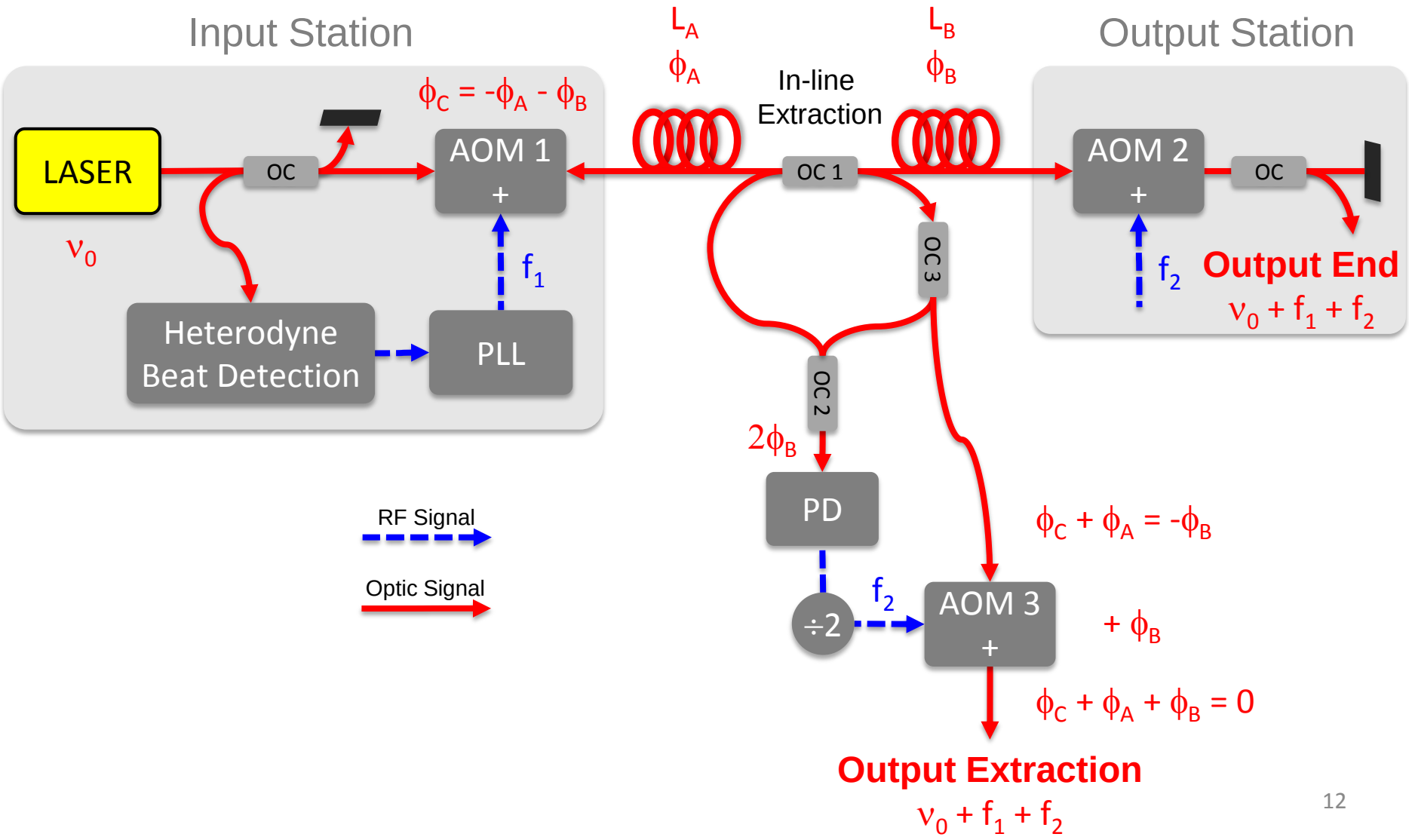
EXTRACTION


Input Station
L_A
ϕ_A
L_B
ϕ_B
Output Station
$\phi_C = -\phi_A - \phi_B$
LASER
OC
AOM 1
+
AOM 2
+
OC
ν_0
f_1
f_2
Output End
$\nu_0 + f_1 + f_2$
Heterodyne
Beat Detection
PLL
RF Signal
Optic Signal

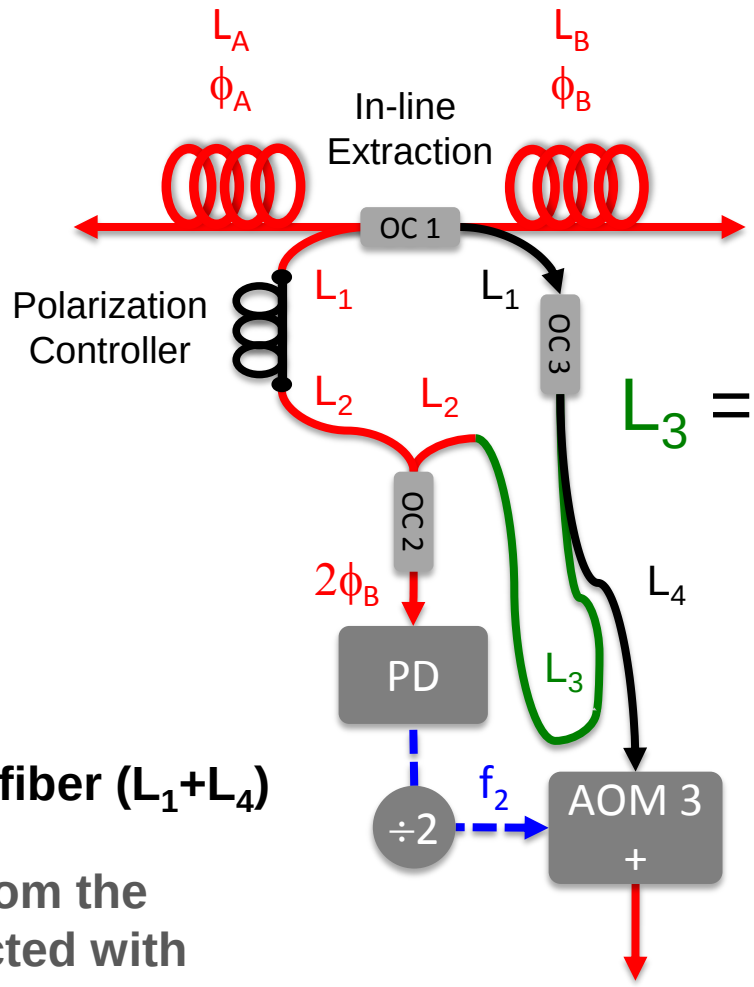
EXTRACTION


Input Station
Output Station
L_A
ϕ_A
L_B
ϕ_B
In-line
Extraction
$\phi_C = -\phi_A - \phi_B$
LASER
OC
AOM 1
+
OC 1
AOM 2
+
OC
ν_0
f_1
f_2
Heterodyne
Beat Detection
PLL
Output End
$\nu_0 + f_1 + f_2$
RF Signal
Optic Signal
$\phi_C + \phi_A = -\phi_B$
Output Extraction
$\nu_0 + f_1$

EXTRACTION


Input Station
Output Station
L_A
ϕ_A
L_B
ϕ_B
In-line Extraction
$\phi_C = -\phi_A - \phi_B$
LASER
OC
AOM 1
+
OC 1
AOM 2
+
OC
ν_0
f_1
f_2
Output End
$\nu_0 + f_1 + f_2$
Heterodyne Beat Detection
PLL
OC 3
OC 2
$2\phi_B$
PD
RF Signal
Optic Signal
$\phi_C + \phi_A = -\phi_B$
f_2
÷2
AOM 3
+
$+ \phi_B$
$\phi_C + \phi_A + \phi_B = 0$
Output Extraction
$\nu_0 + f_1 + f_2$

FIBER LENGTH



$$L_3 = 2 \times (L_1 + L_4)$$

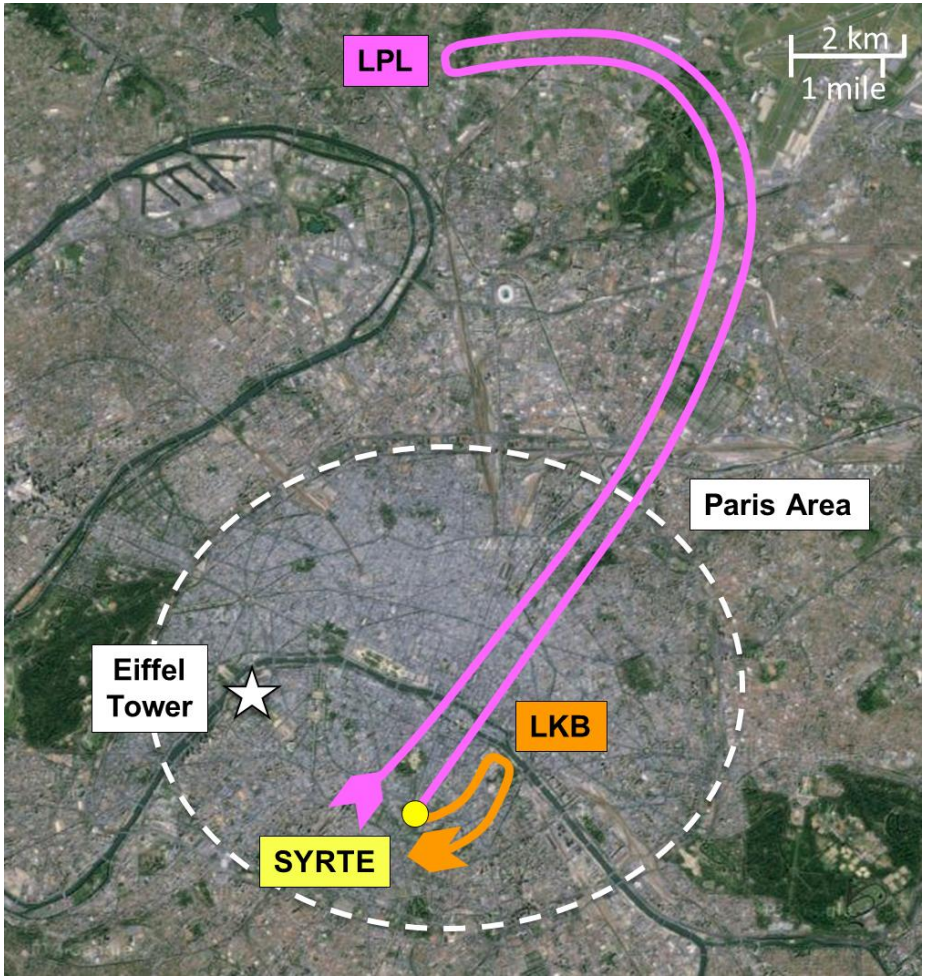
To compensate the noise accumulated on the black fiber (L_1+L_4)

Half of the noise arising from the green fiber (L_3) is substracted with AOM 3

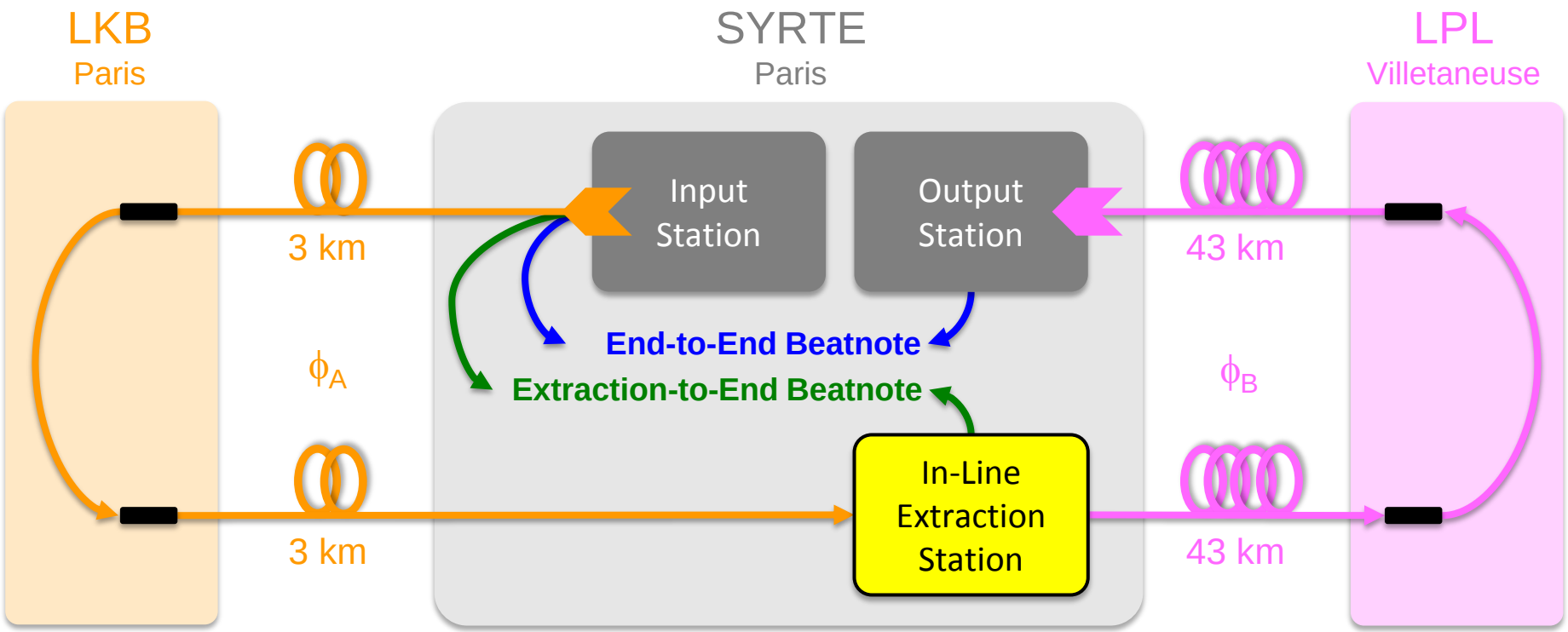
EXPERIMENTAL SETUP

92 KM URBAN LINK WITH

- **LPL loop : 2 fibers of 43 km**
- **LKB loop : 2 fibers of 3 km**
- **In-Line Extraction @ SYRTE**

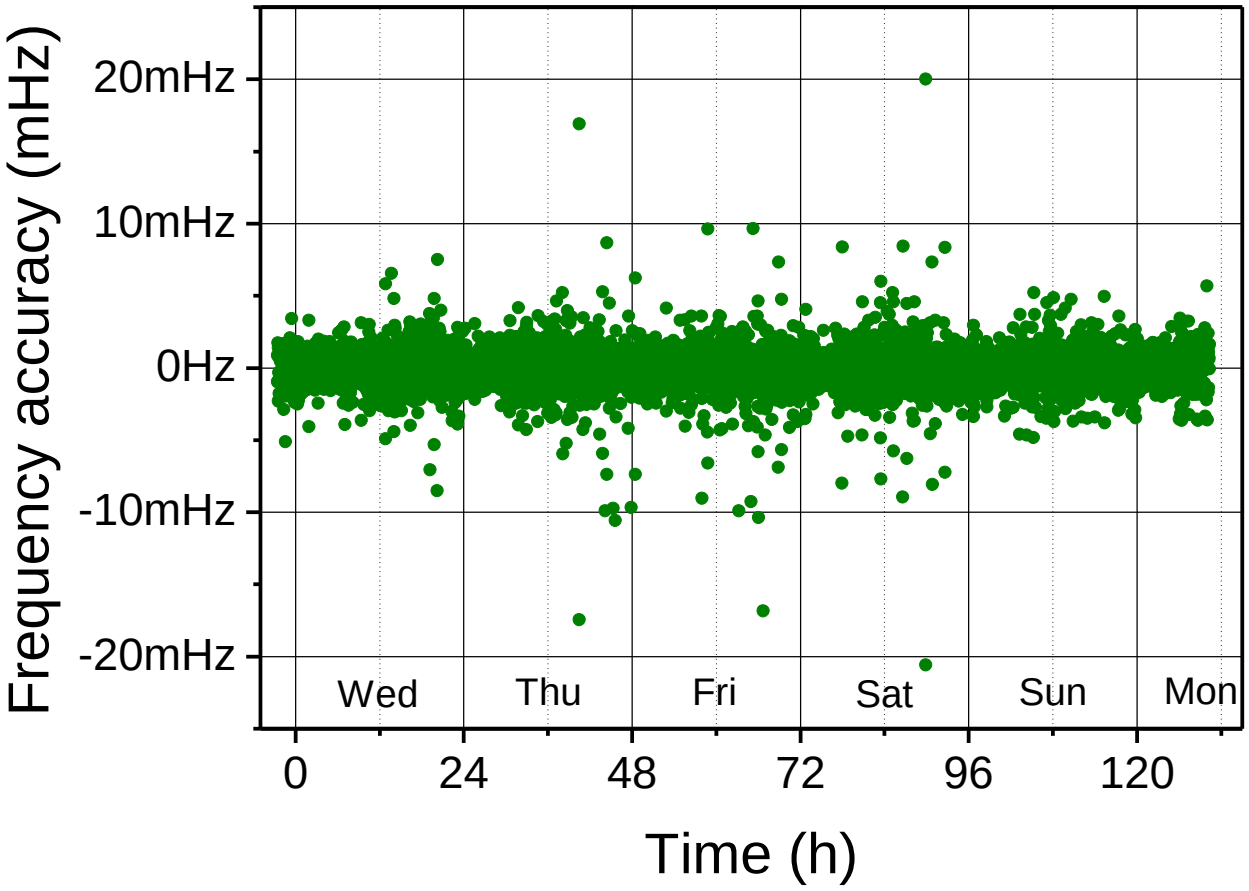


EXPERIMENTAL SETUP



ACCURACY

In-line Extraction @ 6 km



Mean frequency shifted by

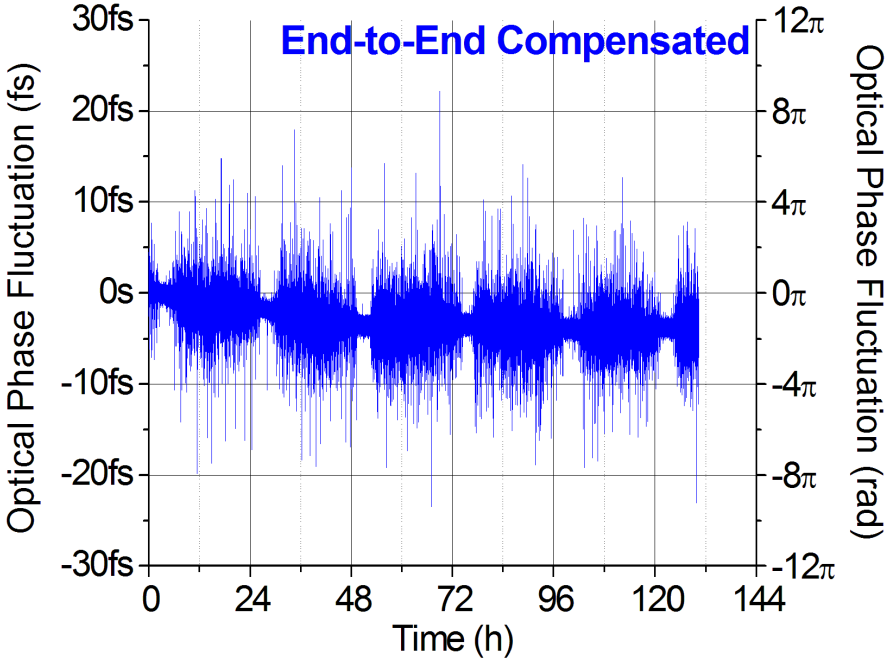
-1.1×10^{-19}

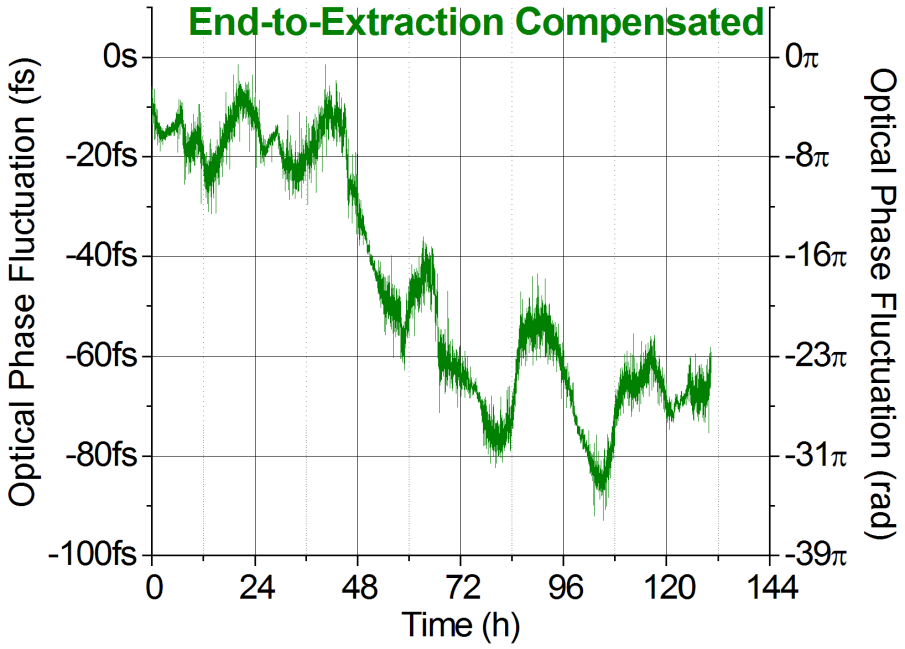
Statistical uncertainty on the mean frequency

9×10^{-20}

PHASE FLUCTUATION

In-line Extraction @ 6 km

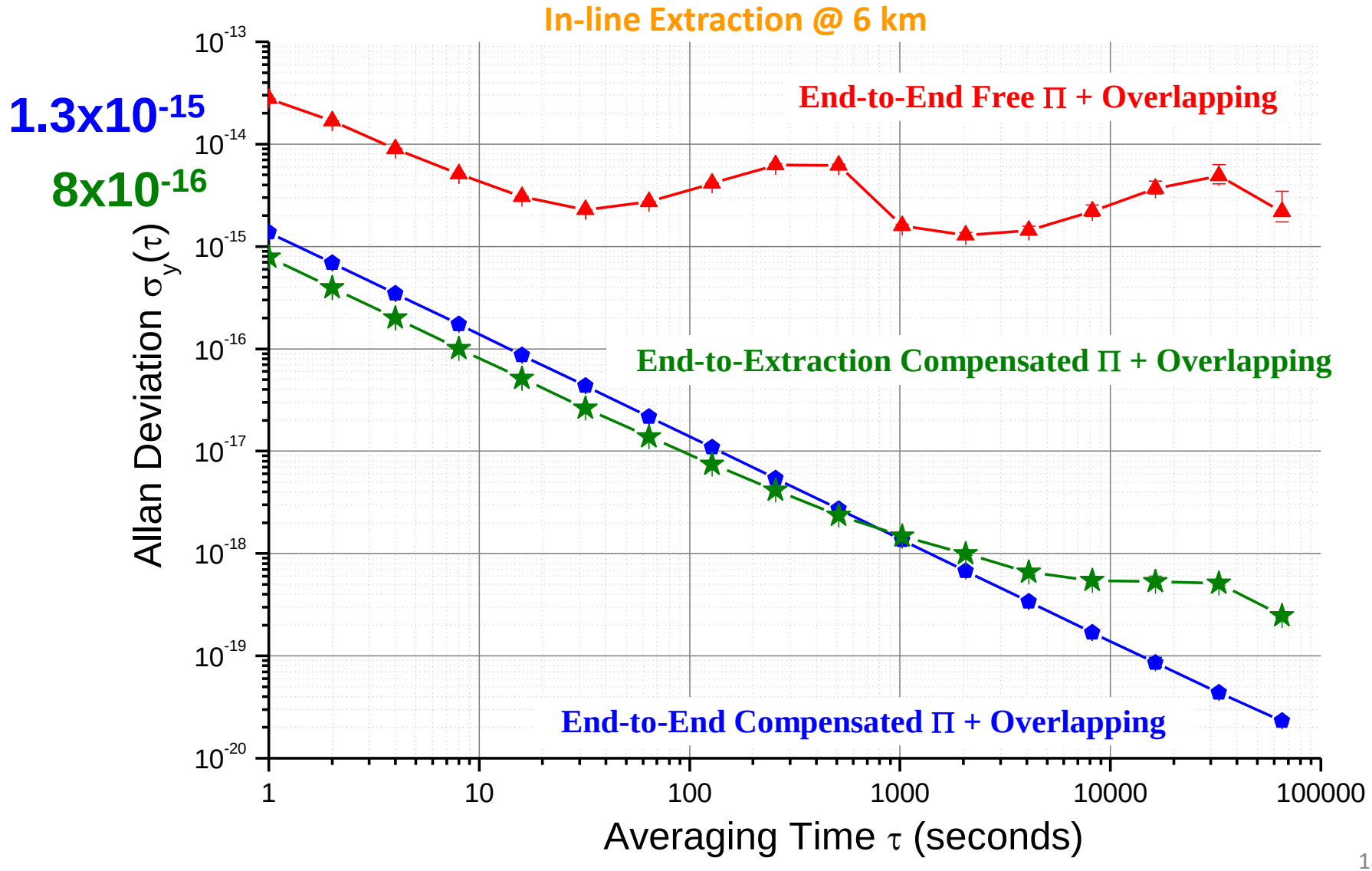




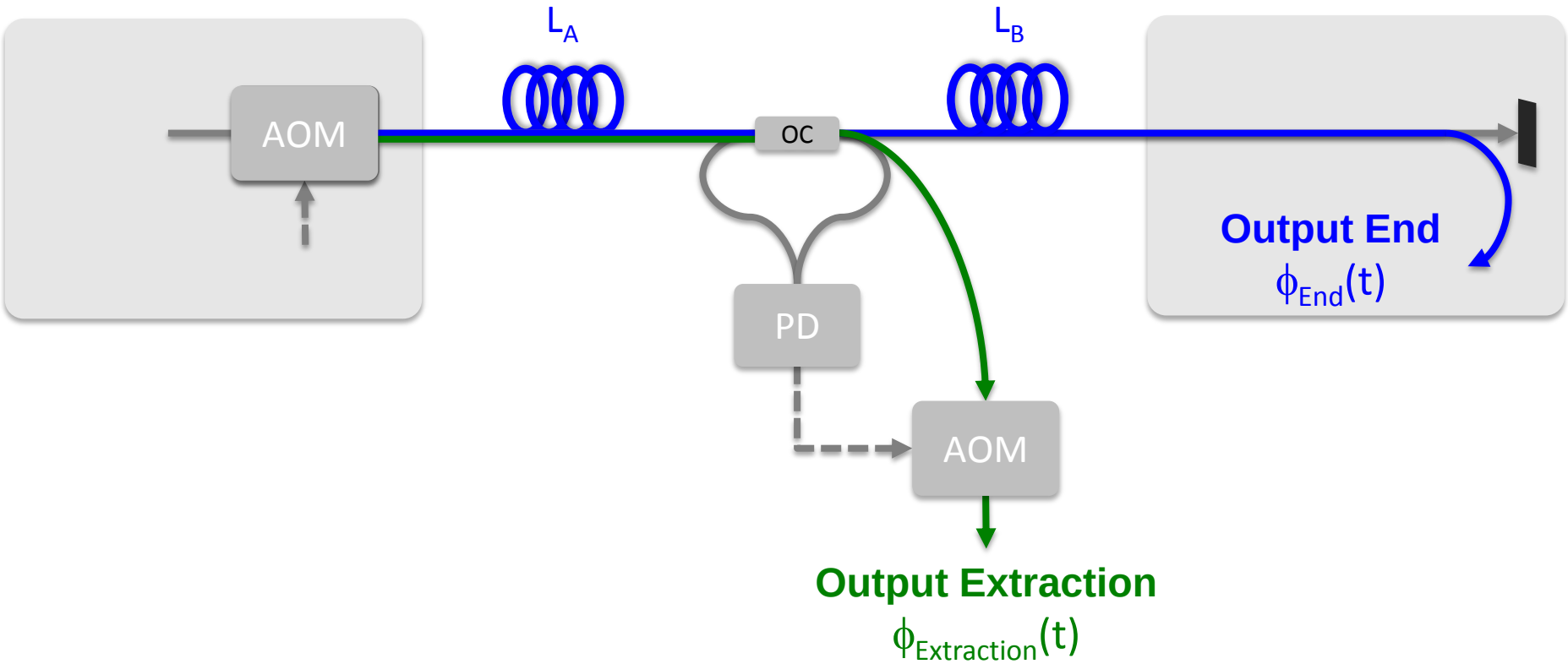
- Residual Phase Noise = 10 fs
- Parisian Subway Off between 1am and 5 am

- Residual Phase Noise = 10 fs + long term fluctuation
- Long term fluctuation due to the unperfect compensation of fiber paths

FREQUENCY STABILITY



NOISE COMPENSATION MODEL



$\phi_{Ext}(t)$ —Autocorrelation→ $\overline{\phi_{Ext}(t)\,\phi_{Ext}(t+\tau)}$ —Fourier Transform→ Phase noise PSD $S_{Ext}(f)$

FREQUENCY STABILITY

In-line Extraction @ 6 km **@ 86 km**

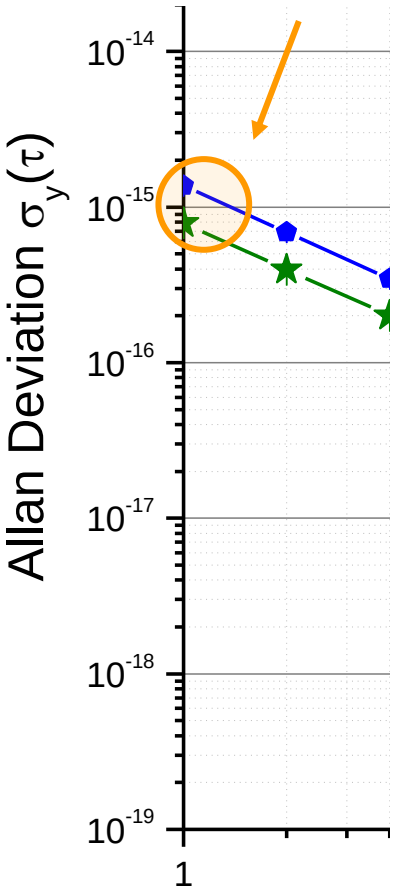
Output Extraction Phase Noise PSD

$$S_{Extraction} = F \times S_{End}(f)$$

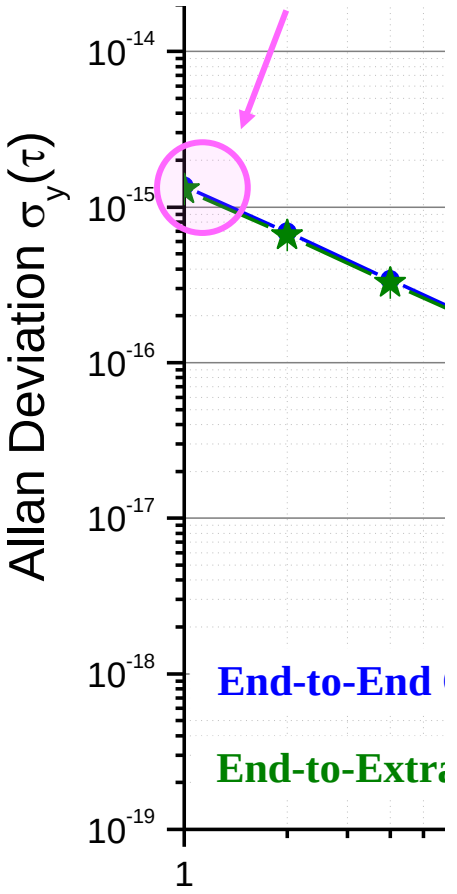
Output End Phase Noise PSD

$$F = \left(\frac{L_A}{L}\right)^2 \left(3 - 2\frac{L_A}{L}\right)$$

Near the Input End
F << 1

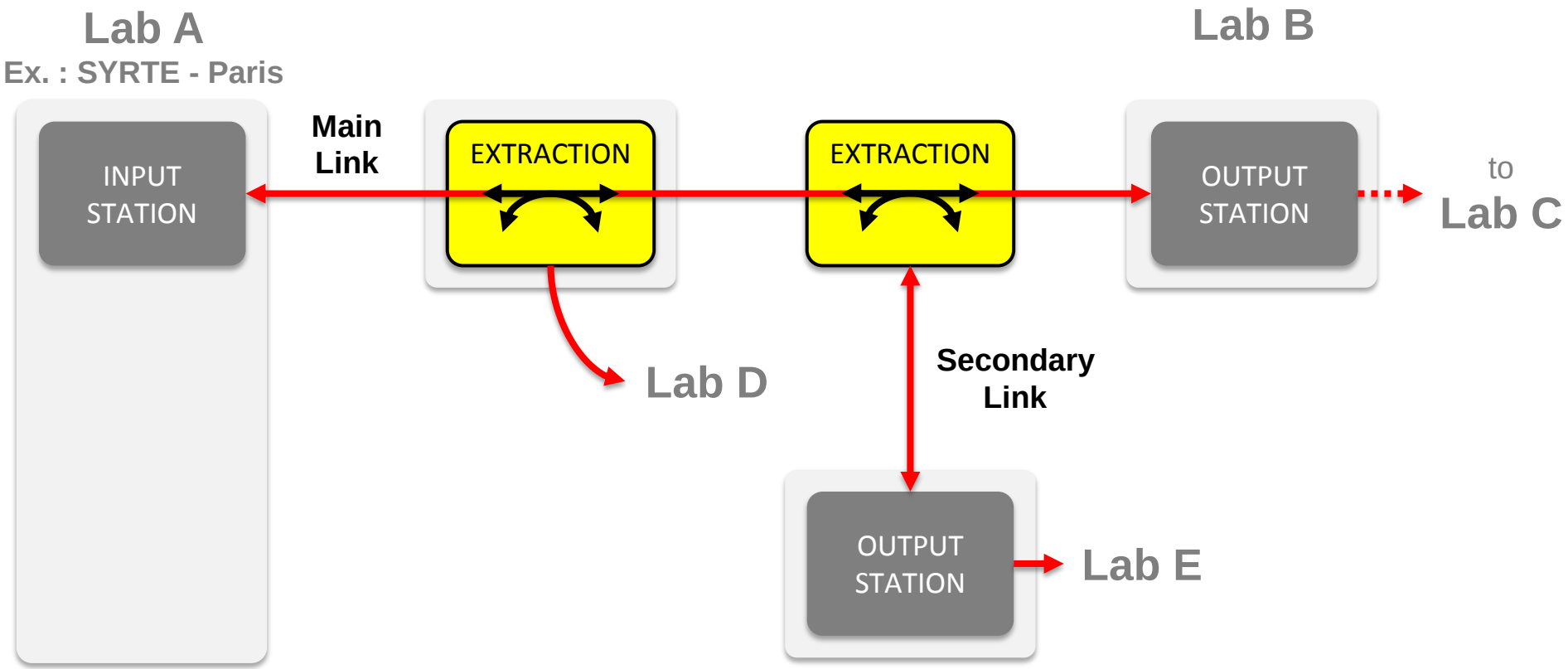


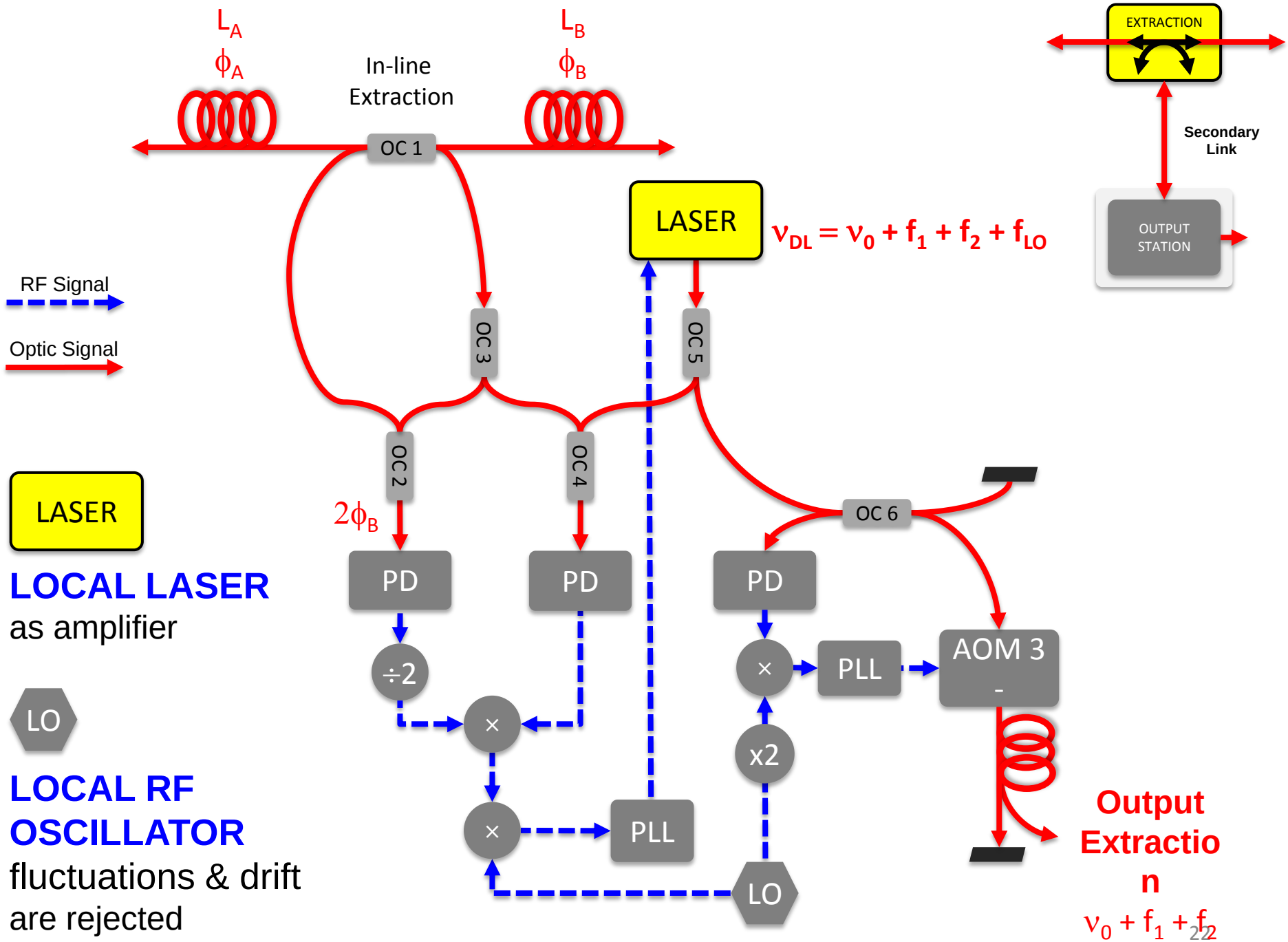
Near the Output End
F ≈ 1



(Bercy *et al*, JOSA B 2014)

NETWORK ARCHITECTURE




L_A
ϕ_A
In-line Extraction
L_B
ϕ_B
OC 1
EXTRACTION
Secondary Link
OUTPUT STATION
LASER
$\nu_{DL} = \nu_0 + f_1 + f_2 + f_{LO}$
RF Signal
Optic Signal
OC 3
OC 5
OC 2
OC 4
OC 6
$2\phi_B$
LASER
PD
PD
PD
÷2
×
×
PLL
×
PLL
AOM 3
-
x2
LO
LO
LOCAL LASER
as amplifier
LOCAL RF OSCILLATOR
fluctuations & drift are rejected
Output Extraction
$\nu_0 + f_1 + f_2$

PLAN

MOTIVATIONS

TRANSFERT 

IN-LINE EXTRACTION : FIRST SETUP

IMPROVED SETUP & PRELIMINARY RESULTS

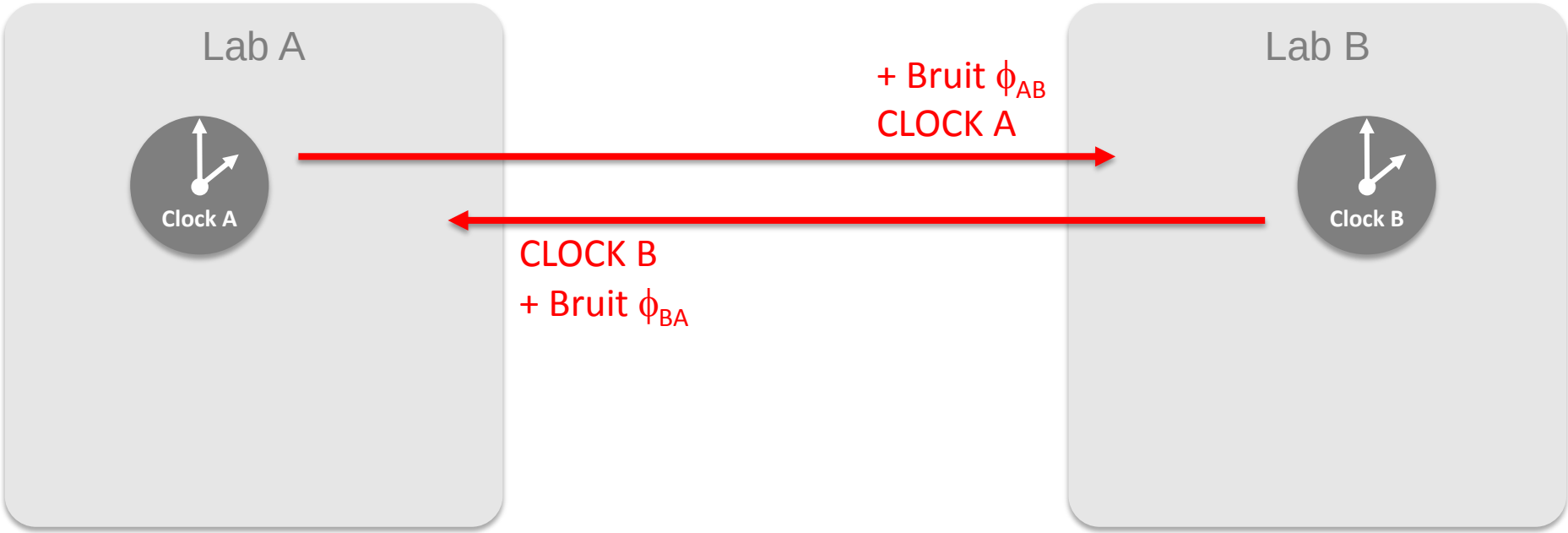
COMPARISON 

FIRST TECHNIQUE : TWO-WAY BI-DIRECTIONAL

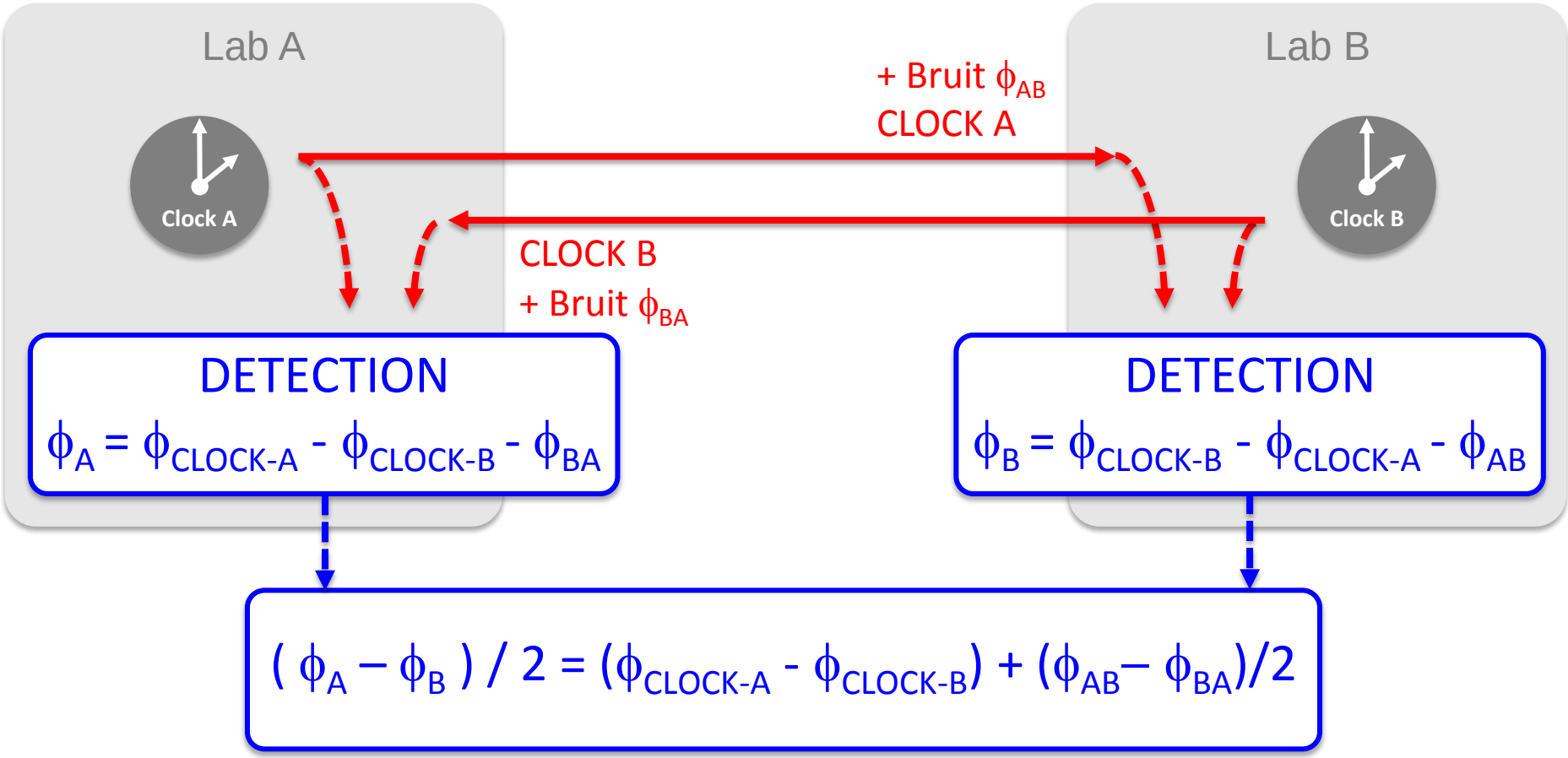
SECOND TECHNIQUE : TWO-WAY UNI-DIRECTIONAL

CONCLUSION

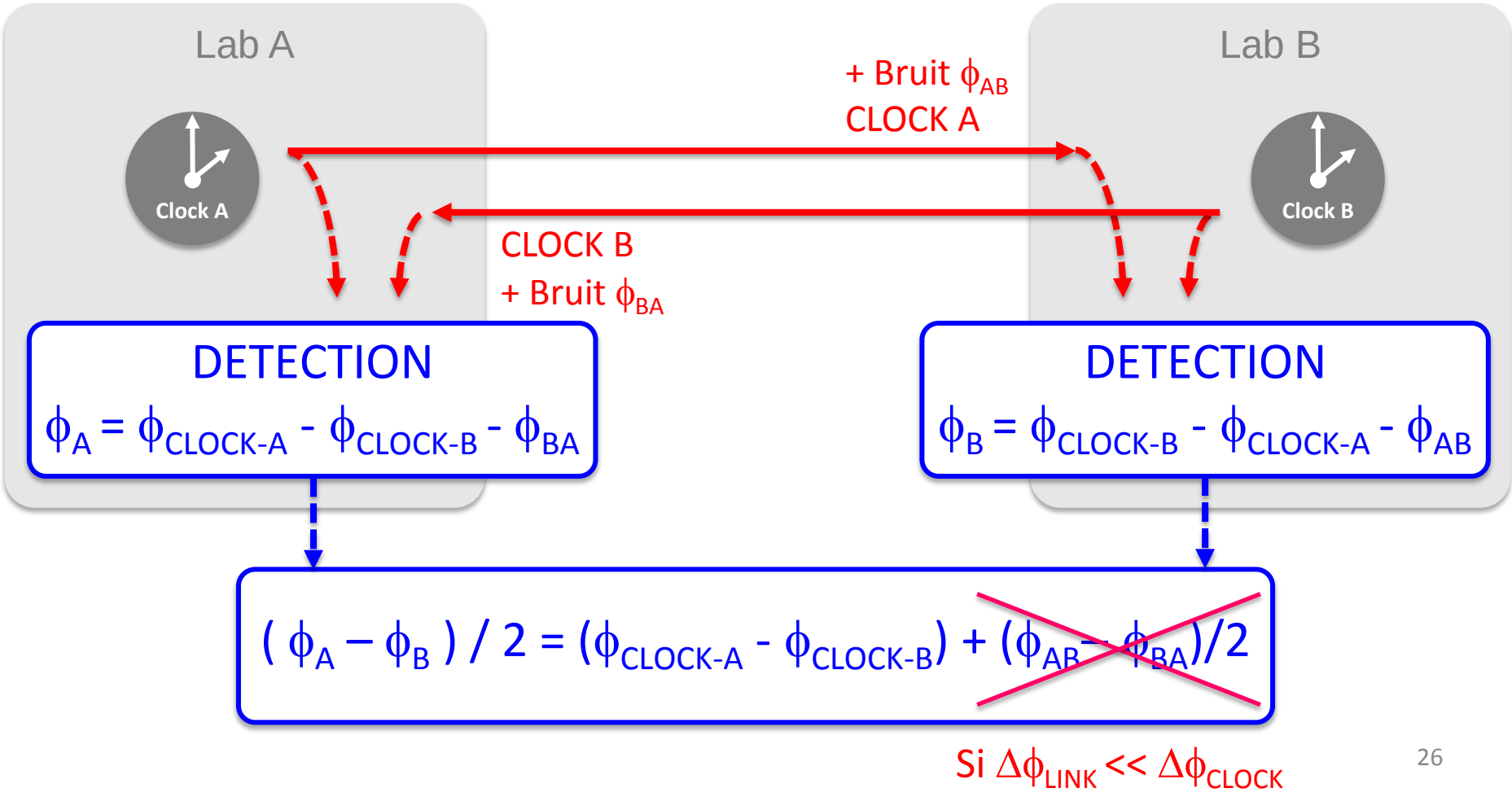
TWO-WAY


Lab A
Lab B
+ Bruit ϕ_{AB}
CLOCK A
Clock A
Clock B
CLOCK B
+ Bruit ϕ_{BA}

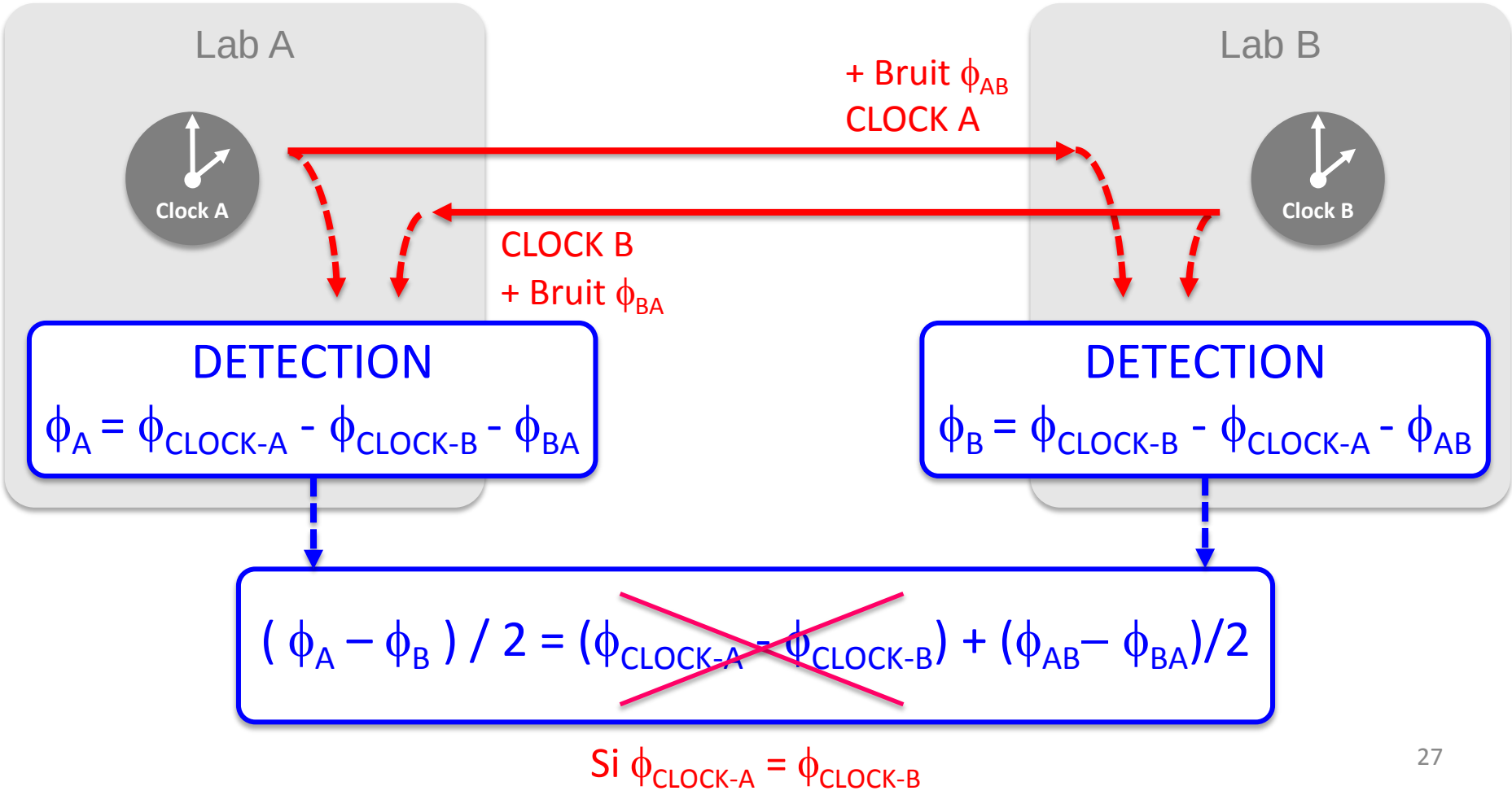
TWO-WAY


Lab A
Lab B
Clock A
Clock B
+ Bruit ϕ_{AB}
CLOCK A
CLOCK B
+ Bruit ϕ_{BA}
DETECTION
$\phi_A = \phi_{CLOCK-A} - \phi_{CLOCK-B} - \phi_{BA}$
DETECTION
$\phi_B = \phi_{CLOCK-B} - \phi_{CLOCK-A} - \phi_{AB}$
$(\phi_A - \phi_B) / 2 = (\phi_{CLOCK-A} - \phi_{CLOCK-B}) + (\phi_{AB} - \phi_{BA})/2$

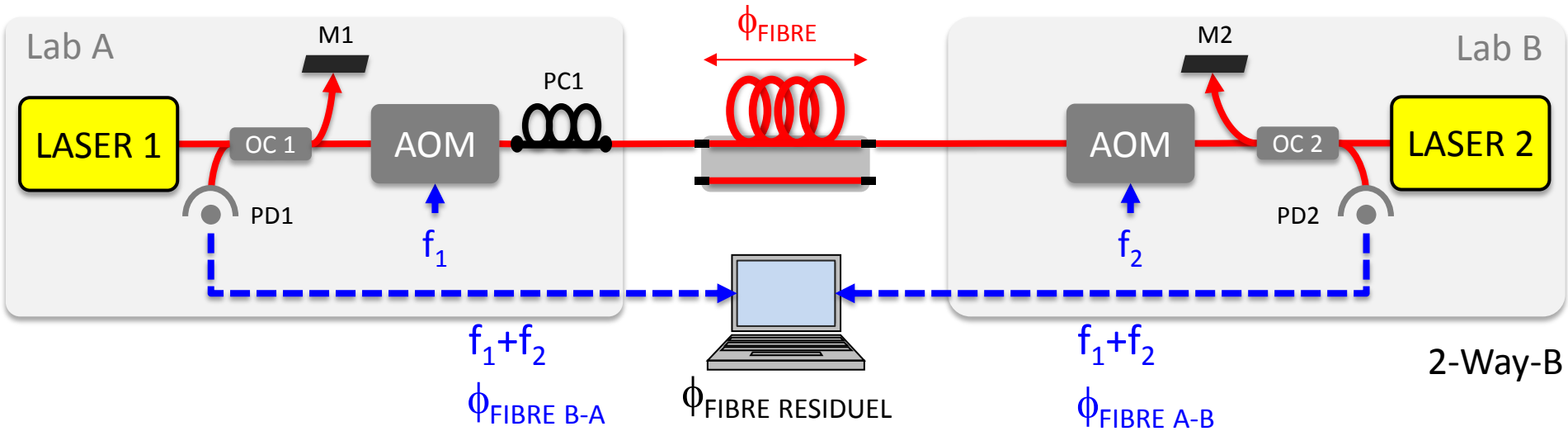
TWO-WAY


Lab A
Lab B
Clock A
Clock B
+ Bruit ϕ_{AB}
CLOCK A
CLOCK B
+ Bruit ϕ_{BA}
DETECTION
$\phi_A = \phi_{CLOCK-A} - \phi_{CLOCK-B} - \phi_{BA}$
DETECTION
$\phi_B = \phi_{CLOCK-B} - \phi_{CLOCK-A} - \phi_{AB}$
$(\phi_A - \phi_B) / 2 = (\phi_{CLOCK-A} - \phi_{CLOCK-B}) + (\phi_{AB} - \phi_{BA})/2$
Si $\Delta\phi_{LINK} << \Delta\phi_{CLOCK}$

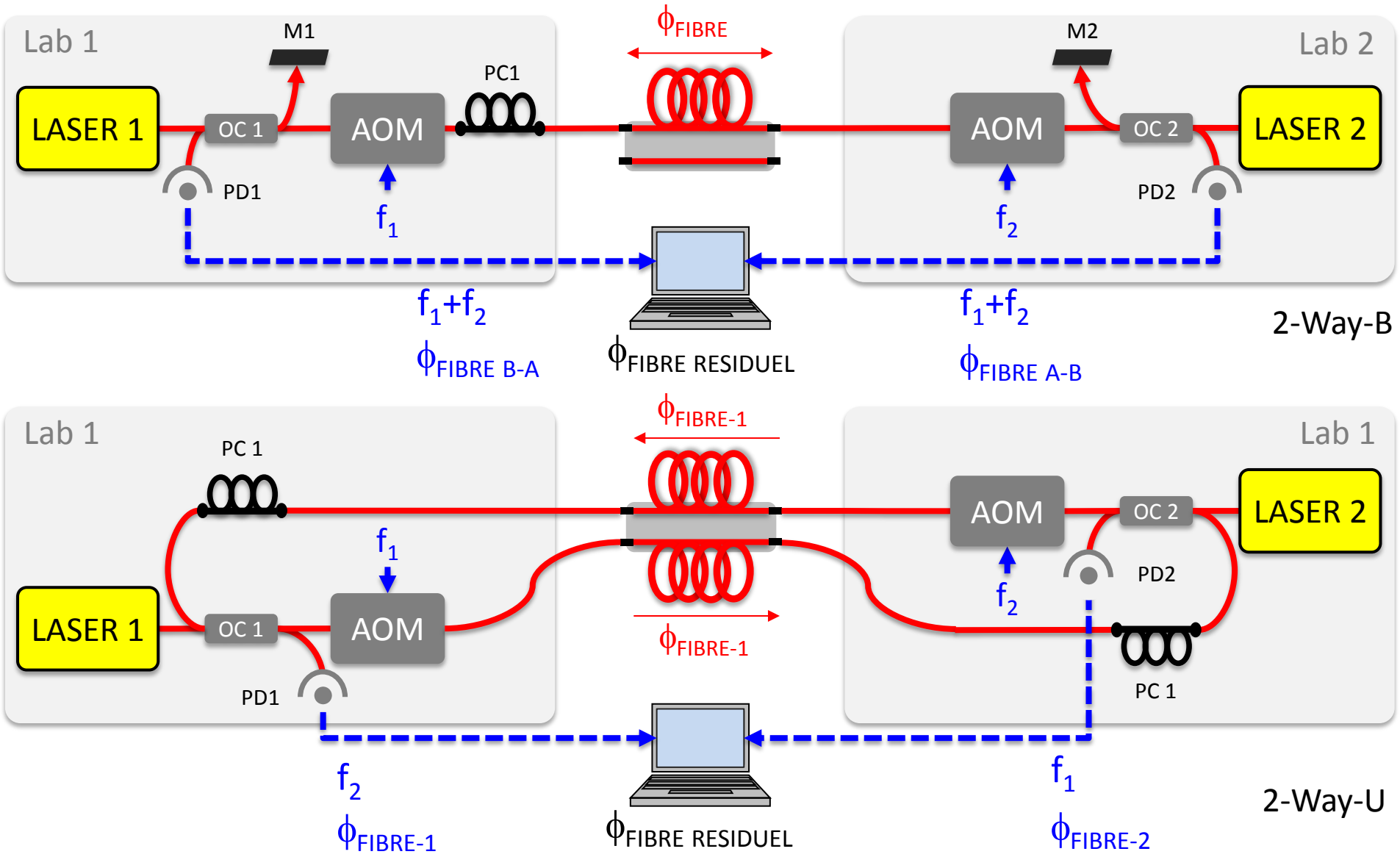
TWO-WAY


Lab A
Lab B
Clock A
Clock B
+ Bruit ϕ_{AB}
CLOCK A
CLOCK B
+ Bruit ϕ_{BA}
DETECTION
$\phi_A = \phi_{CLOCK-A} - \phi_{CLOCK-B} - \phi_{BA}$
DETECTION
$\phi_B = \phi_{CLOCK-B} - \phi_{CLOCK-A} - \phi_{AB}$
$(\phi_A - \phi_B) / 2 = (\phi_{CLOCK-A} - \phi_{CLOCK-B}) + (\phi_{AB} - \phi_{BA})/2$
Si $\phi_{CLOCK-A} = \phi_{CLOCK-B}$

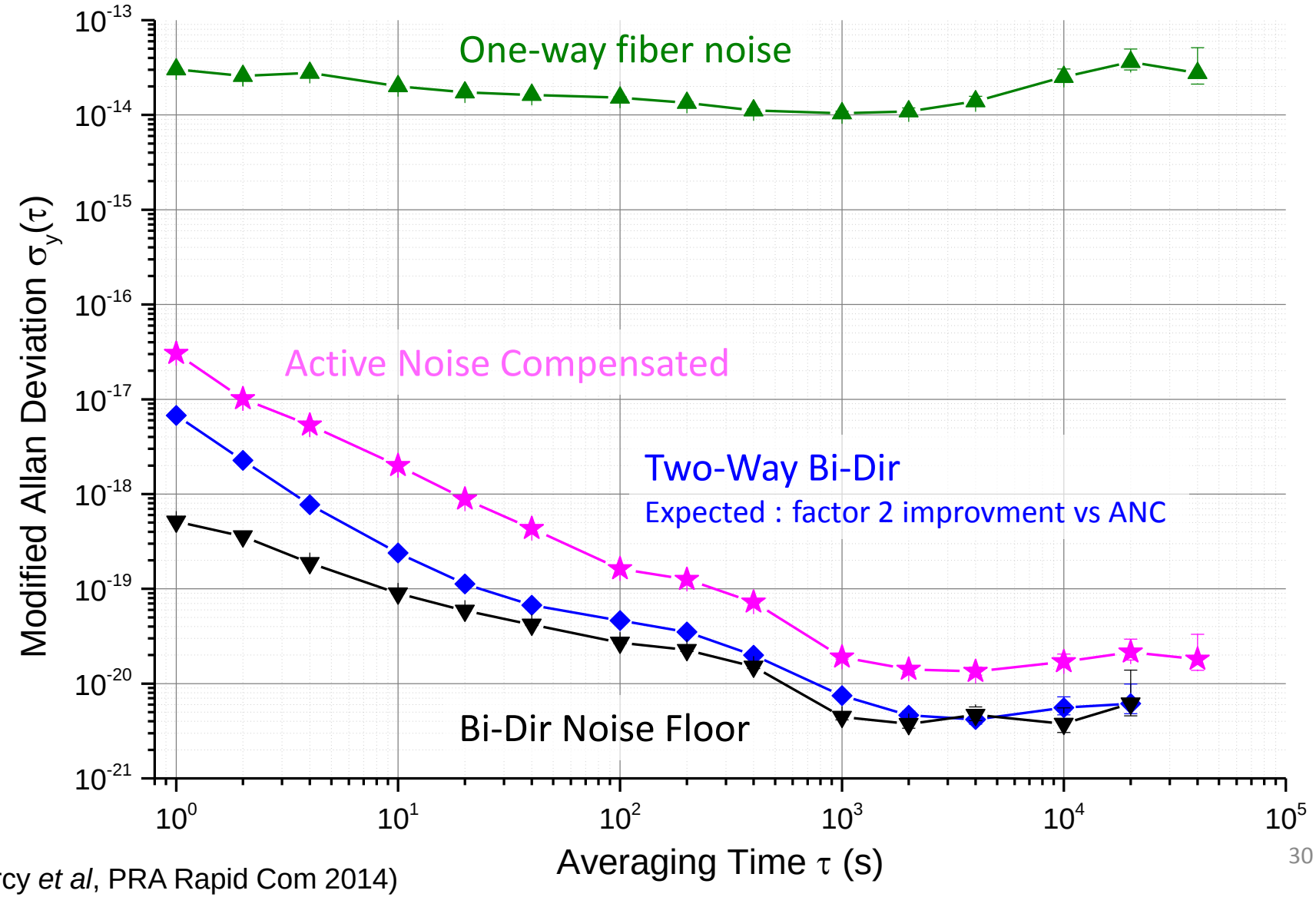
TWO-WAY BI-DIRECTIONAL



TWO-WAY UNI-DIRECTIONAL

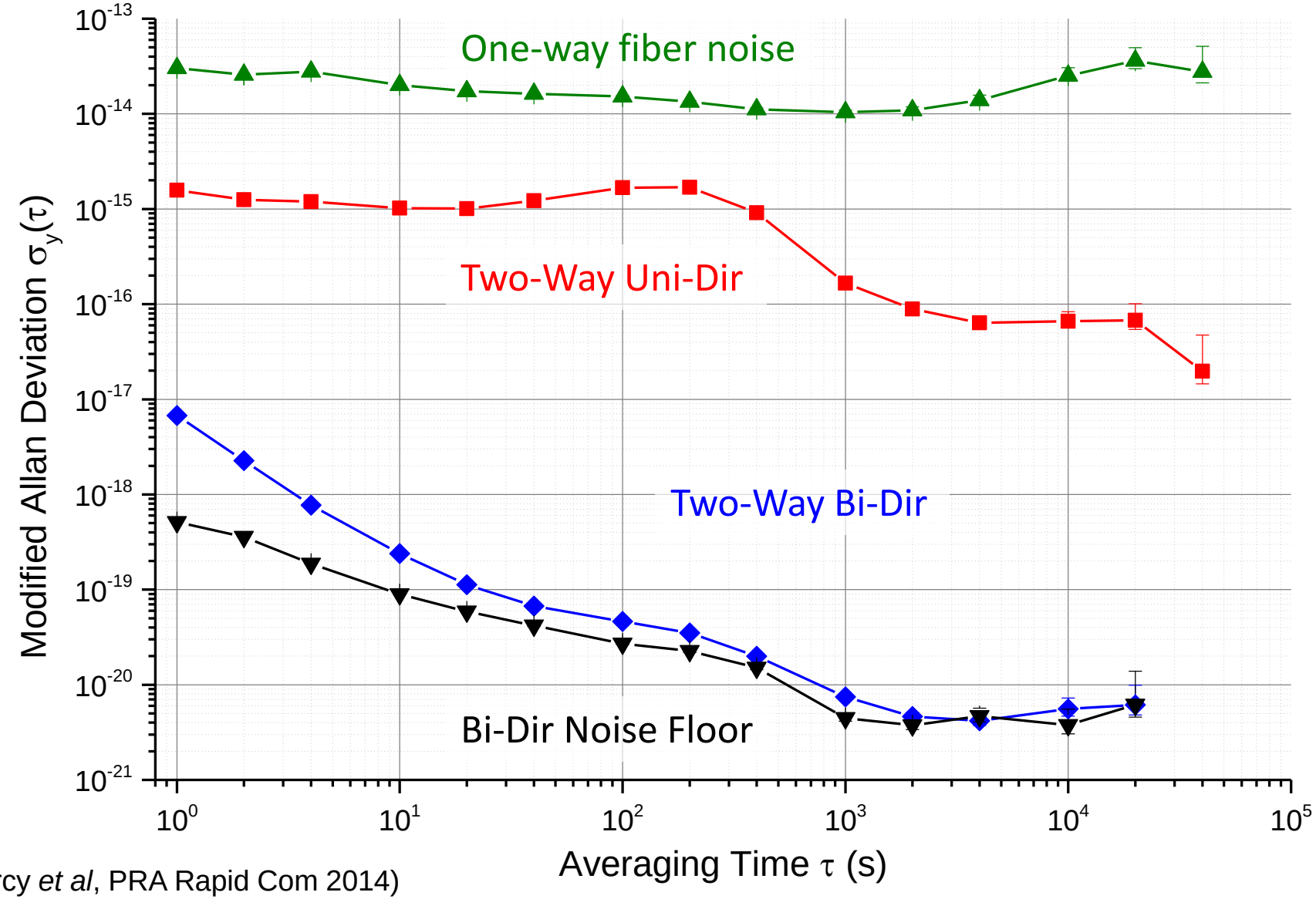


TWO-WAY BI-DIRECTIONAL



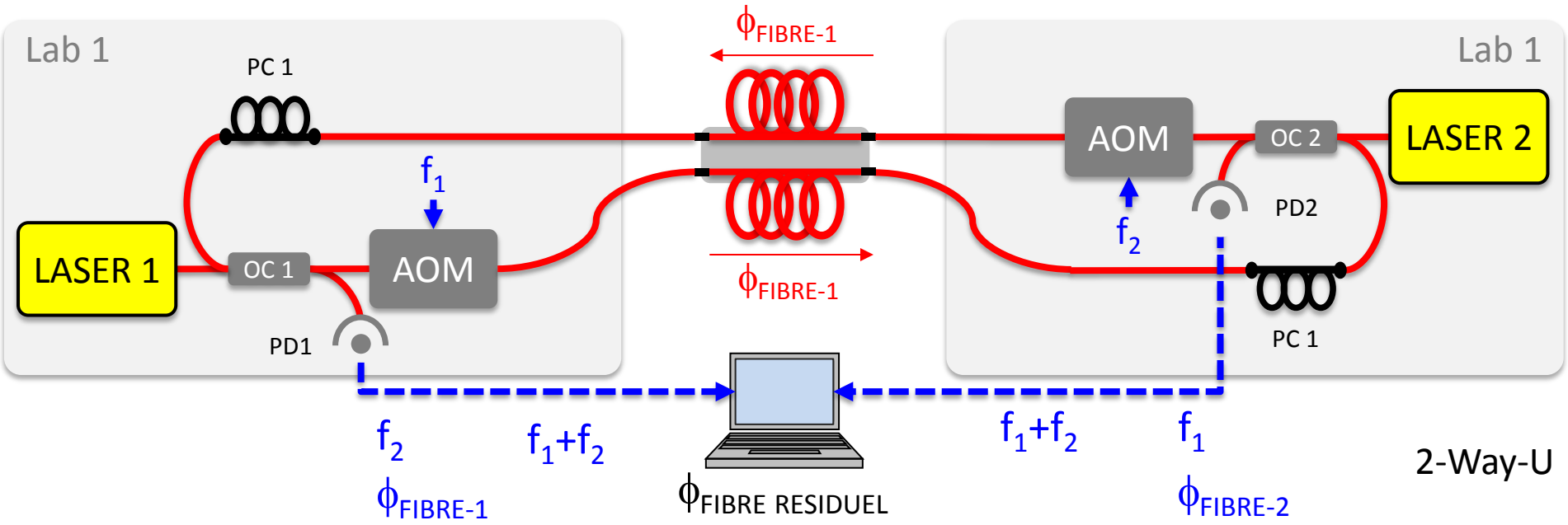
(Bercy *et al*, PRA Rapid Com 2014)

TWO-WAY UNI-DIRECTIONAL



(Bercy *et al*, PRA Rapid Com 2014)

TWO-WAY UNI-DIRECTIONAL



CONCLUSION

TRANSFERT

DEMONSTRATION OF SIMPLE AND EFFICIENT IN-LINE EXTRACTION SETUP on a 100 km urban link
(Bercy *et al.*, JosaB 2014)

PRELIMINARY RESULTS OF THE SECOND SETUP with Laser Diode & Secondary Link

FUTURE : implementation in different labs in Paris area
(as for instance LKB in Jussieu)

COMPARISON

DEMONSTRATION OF A TWO-WAY METHOD ON A FIBER LOOP with Bi-Directional and Uni-Directional techniques, the latter being compatible with Internet long-haul link
(Bercy *et al.*, PRA Rapid Com 2014)