LIFT

LInk ottico nazionale per la Frequenza e il Tempo

The Italian Time and Frequency Optical Link Project

Davide Calonico – Istituto Nazionale di Ricerca Metrologica

The LIFT team

- Torino: INRIM

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- Bologna: INAF

Roberto Ambrosini

- Torino: Politecnico

Giovanni Costanzo

- Milano: CNR/IFN

Gianluca Galzerano

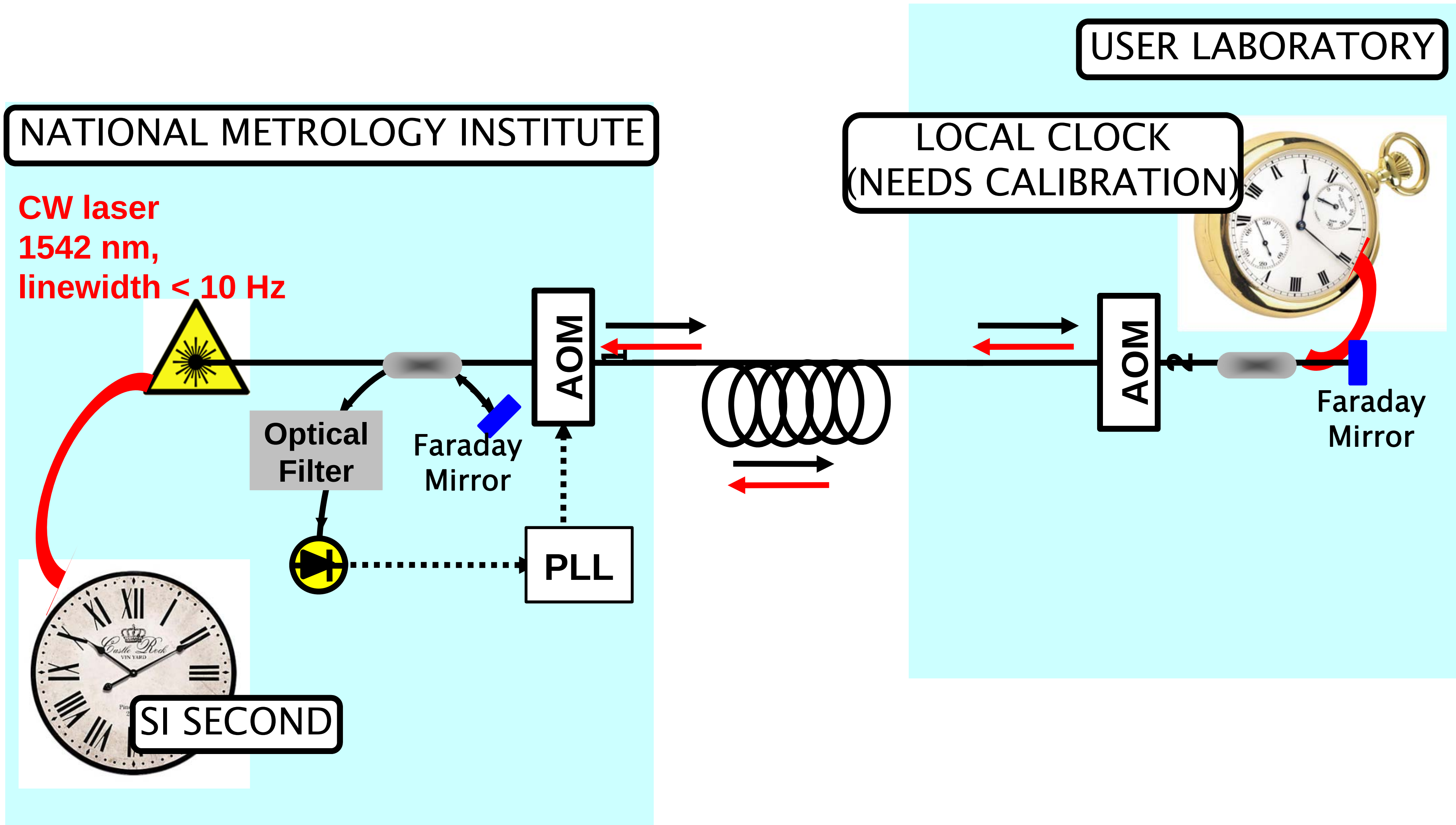
INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

INO-CNR ISTITUTO NAZIONALE DI OTTICA

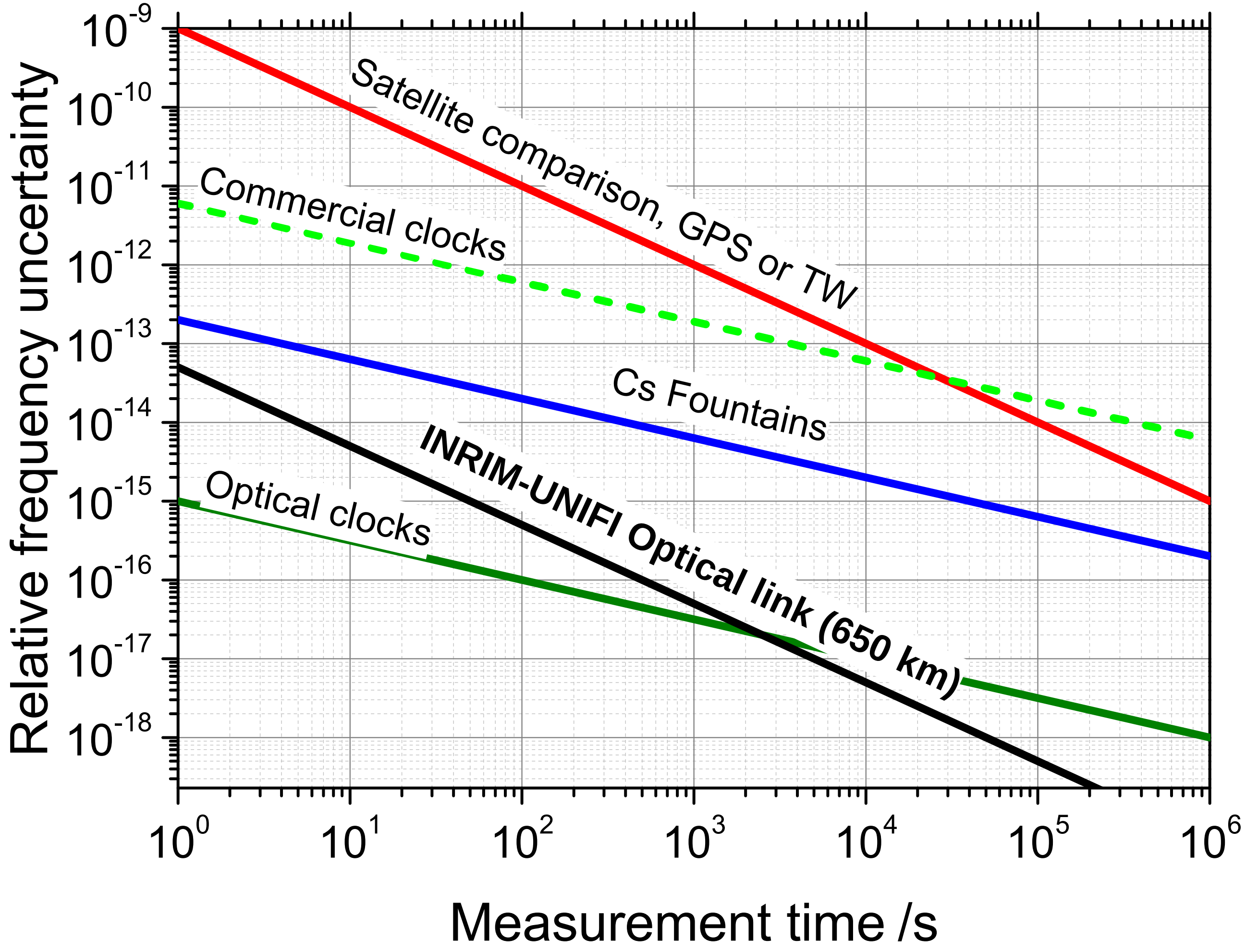
CNR IFN Istituto di Fotonica e Nanotecnologie

POLITECNICO DI TORINO

Coherent Optical link with commercial fiber and noise compensation



Need for optical links



Coherent Optical Links in Europe

K. Predehl et al., Science 336, 441 (2012)

O. Lopez et al., Appl. Phys. B, 110, 1 (2013)

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

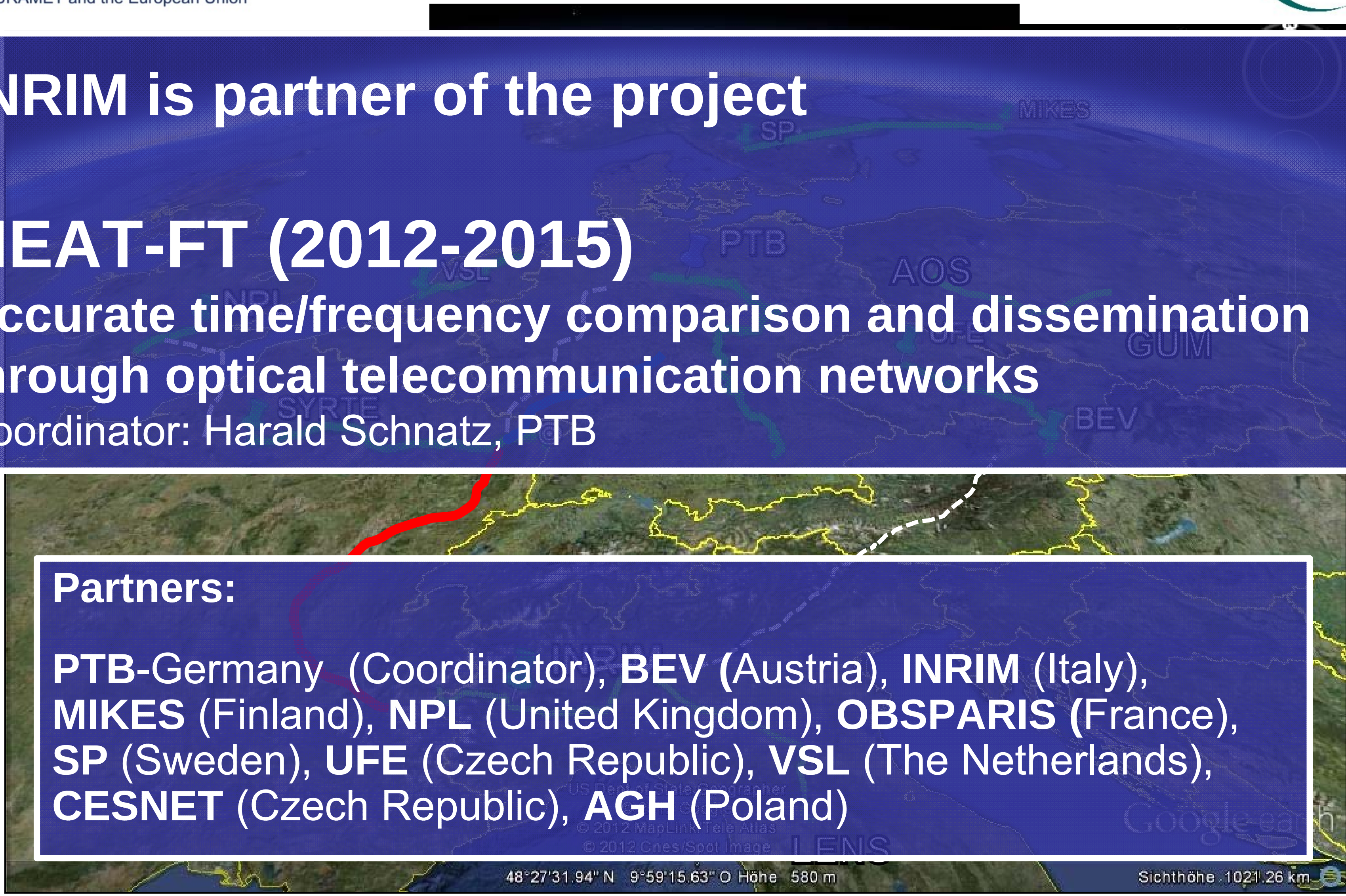
EURAMET
European Association of National Metrology Institutes

INRIM is partner of the project

NEAT-FT (2012-2015)

Accurate time/frequency comparison and dissemination through optical telecommunication networks

Coordinator: Harald Schnatz, PTB

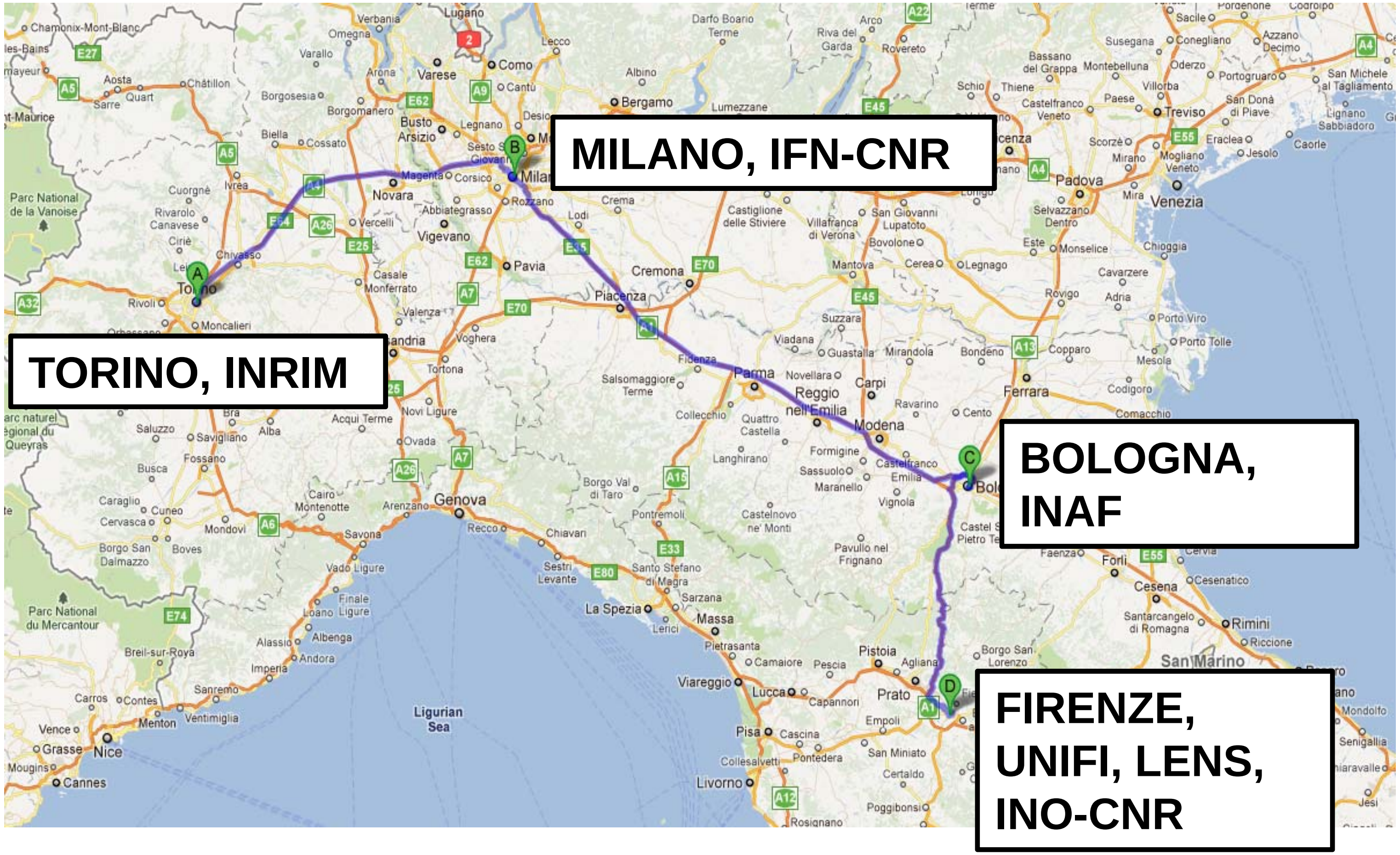


Partners:

PTB-Germany (Coordinator), **BEV** (Austria), **INRIM** (Italy), **MIKES** (Finland), **NPL** (United Kingdom), **OBSPARIS** (France), **SP** (Sweden), **UFE** (Czech Republic), **VSL** (The Netherlands), **CESNET** (Czech Republic), **AGH** (Poland)

H. Schnatz et al. (NEAT-FT Team), Proc. EFTF 2012, Goteborg (SW), April 2012

Italy: LIFT Project



D. Calonico, et al., Proc. of the EFTF, Gothenburg, 396-399 (2012)

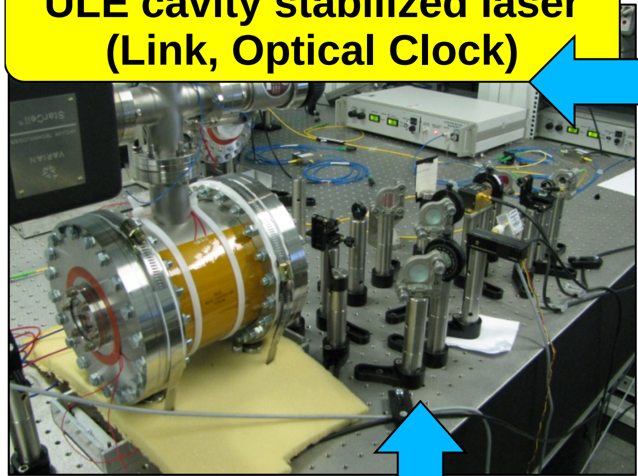
LIFT Objectives

- ✓ Create a national backbone for high accuracy dissemination of time and frequency signals.
- ✓ The remote user will have a primary frequency standard signal in house and in real time.
- ✓ Direct comparison of remote frequency standards, optical and microwave (Accuracy $<10^{-16}$).
- ✓ Disseminate high stability frequency signals (better than H-Maser) for astronomic users.
- ✓ Create a high technological T&F infrastructure for Italy.

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

INRIM clock ensemble

ULE cavity stabilized laser
(Link, Optical Clock)

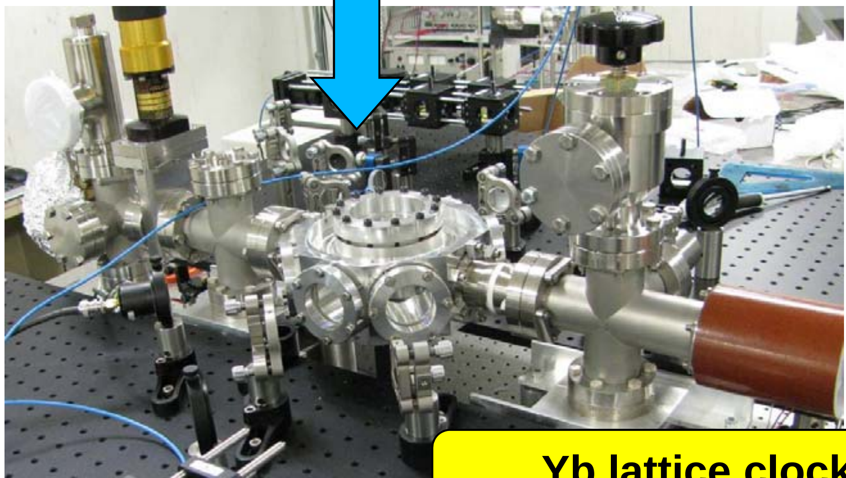


1+2 Fiber laser
2 Ti:Sa
femtosecond comb

Cryogenic
Cs Fountain
ITCsF2

Cs Fountain
ITCsF1

Cs Primary References



Yb lattice clock
(in progress)

3 H-Masers
HM1 HM2 HM3

Cs cryogenic fountain INRIM ITCsF2

Cryogenic structure @ 89 K
$\sigma_y(\tau)=1.5\cdot10^{-13}\ \tau^{-1/2}$
Accuracy: $2\cdot10^{-16}$

F. Levi, et al., IEEE Tran.s on UFFC, 57, 600 – 605, (2010)

INRIM, Cs Fountains ITCsF1 and ITCsF2: Accuracy Budget

ITCsF1
$\sigma_y(\tau)=1.5\cdot10^{-13}\ \tau^{-1/2}$
Accuracy: $5\cdot10^{-16}$

ITCsF2
$\sigma_y(\tau)=1.5\cdot10^{-13}\ \tau^{-1/2}$
Accuracy: $2\cdot10^{-16}$

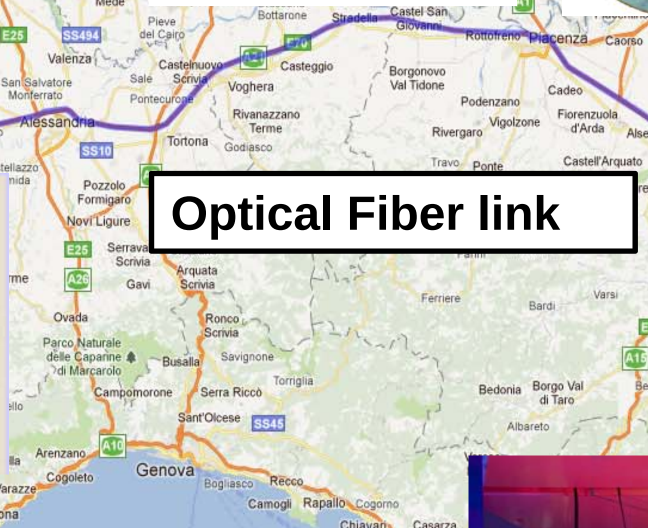
	u ITCsF1	**u ITCsF2**
Zeeman	2E-16	8E-17
Collisions	3E-16	1E-16
Blackbody	3E-16	1E-17
Microwave related	2E-16	1E-16
Redshift	1E-17	1E-17
Totale	**5E-16**	**2E-16**

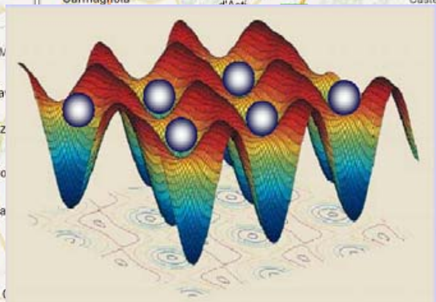
2012-2013: UNIFI-INRIM-POLITO

Absolute Measurement of Optical Frequency Standards by optical fiber link

TORINO, INRIM
2 Cs Fountains
Yb clock

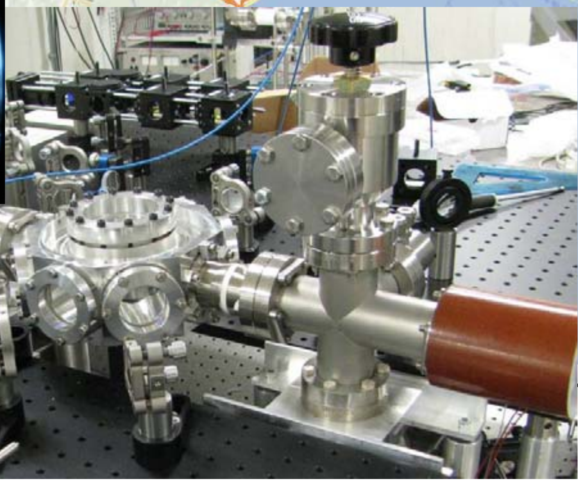
ISTITUTO NAZIONALE DI RICERCA METROLOGICA

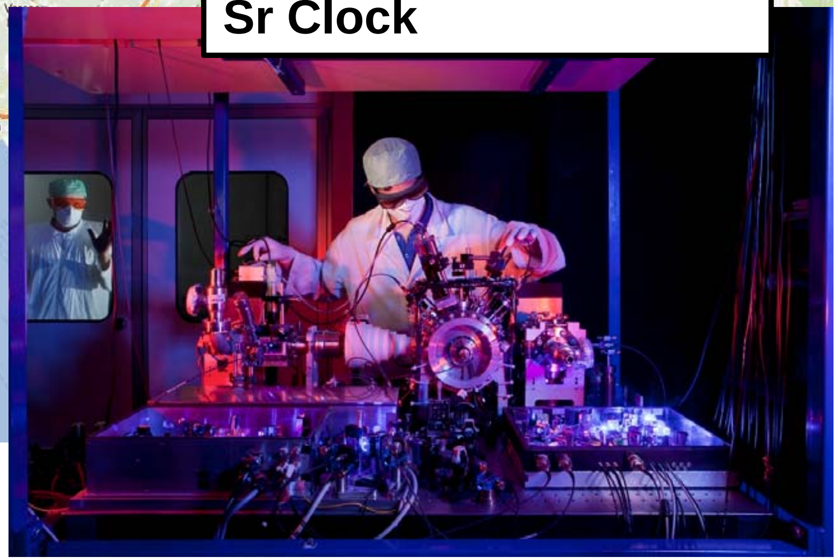




Optical Fiber link

FIRENZE, UNIFI-LENS
Sr Clock

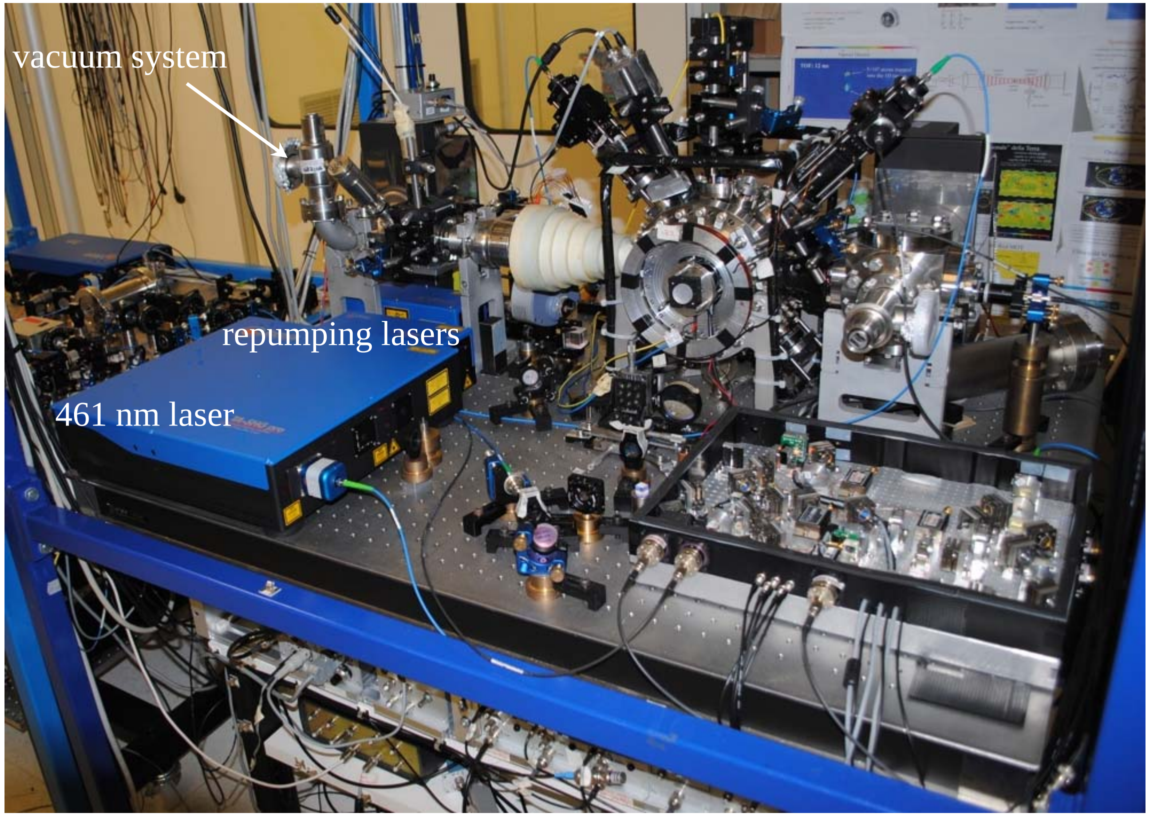


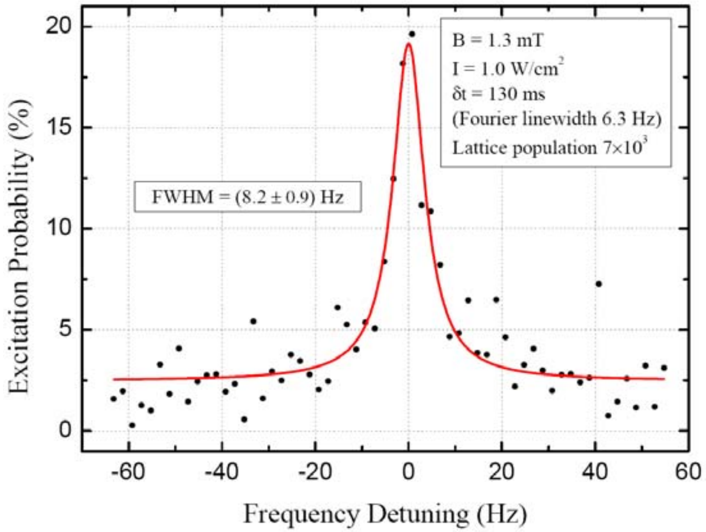


UNIFI: Laser-cooled strontium clock

main guidelines:

1. compact design and reduced power consumption
2. operation reliability and stability
3. modularity





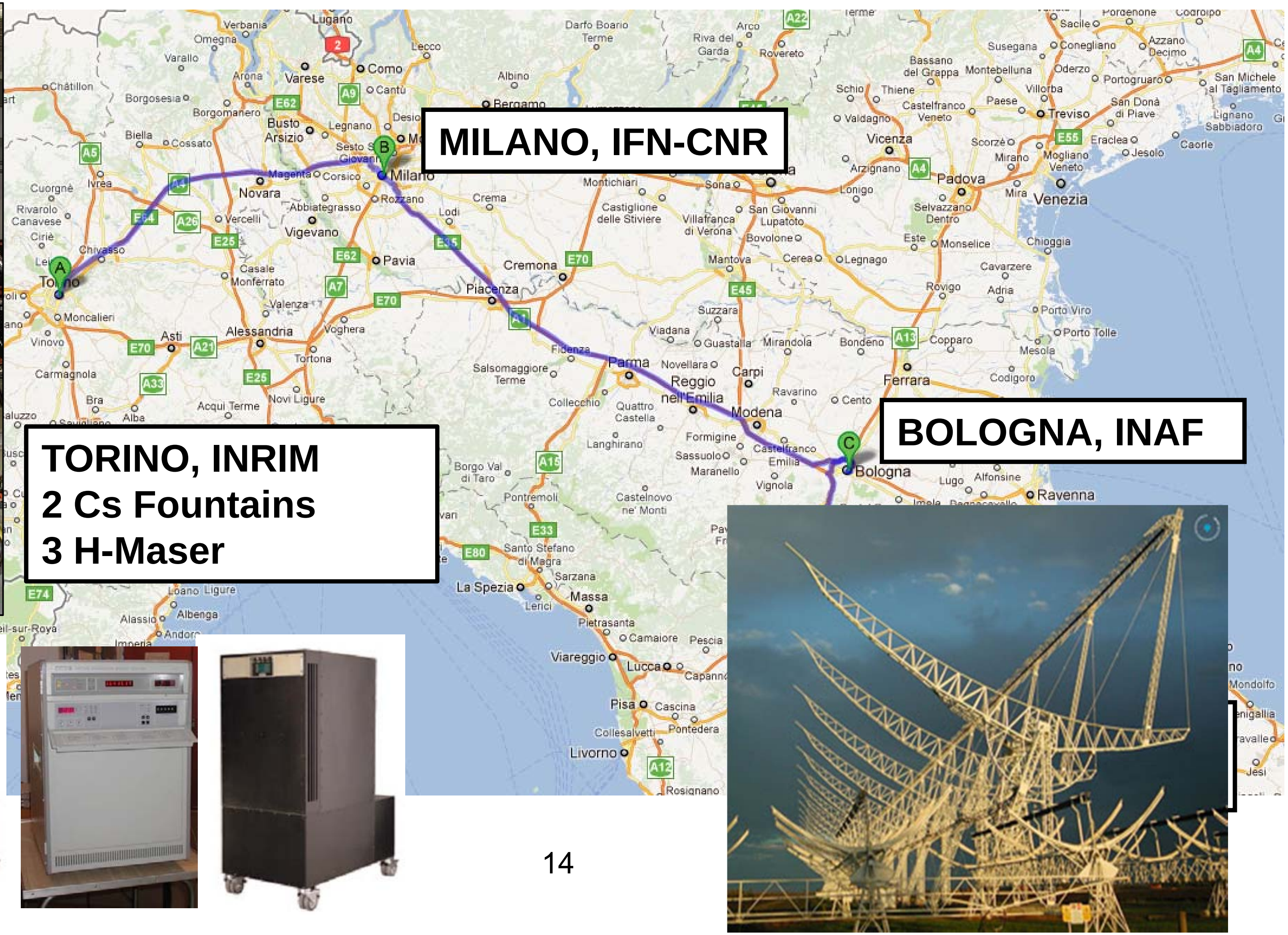
- "Space Optical clocks" (SOC) - ESA

- SOC2 –EU-FP7

Schiller et al. (SOC2 team), "*The Space Optical Clocks Project: Progress report*", IEEE (2012)

M.Schioppo et al., *Proceedings of EFTF 2010*

2014-2015: INRIM-INAF
T&F REFERENCES FOR RADIOASTRONOMY



MILANO, IFN-CNR

TORINO, INRIM
2 Cs Fountains
3 H-Maser

BOLOGNA, INAF

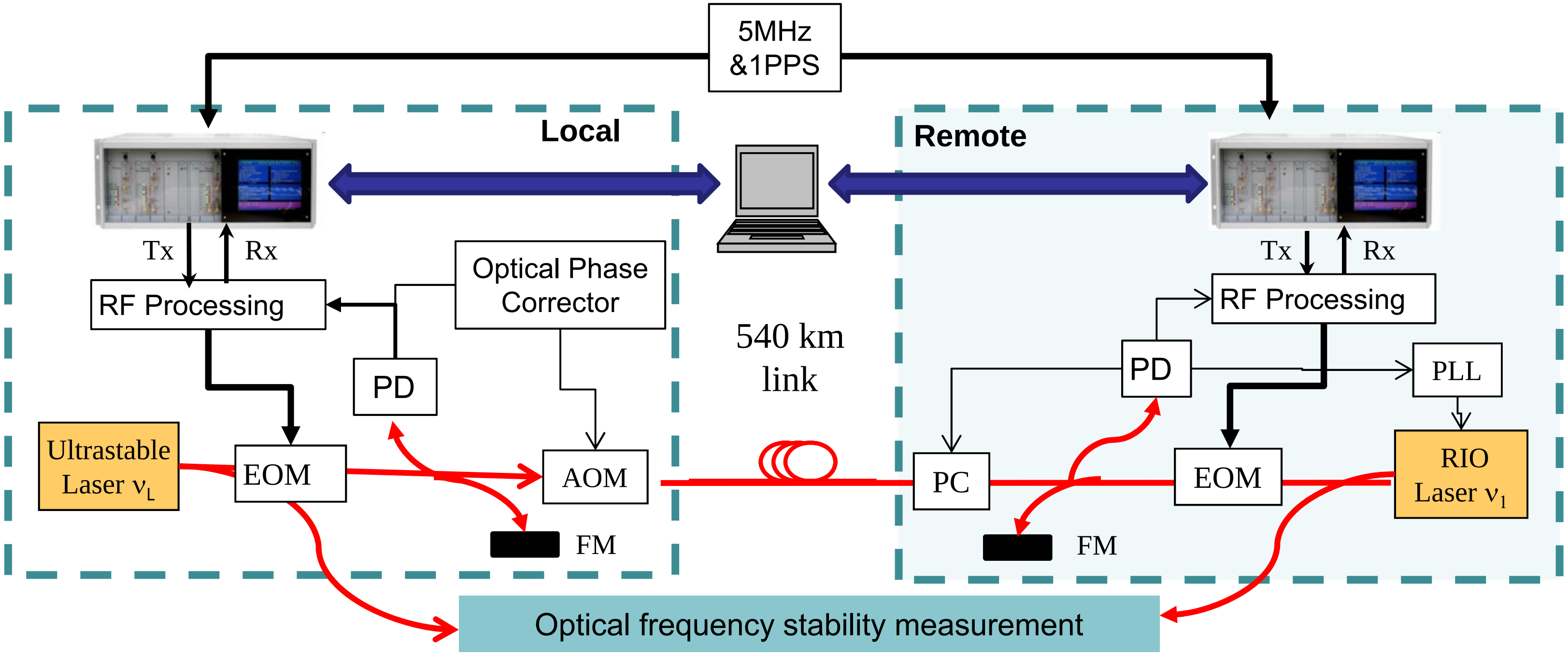
2014-2015: INRIM-INAF :
T&F METROLOGICAL REFERENCES FOR RADIOASTRONOMY

The **Medicina Observatory** hosts both a 32 meter dish for Very Long Baseline Interferometry (VLBI) and a 20'000 m^2 collecting area for Pulsar research:

- ✓ needs **accurate timing for VLBI**, now also in real time VLBI, by 1Gb/s fiber.
- ✓ needs **Frequency dissemination at 10^{-15} level** for Pulsar monitoring on long and very long time scales.
- ✓ offers **T**&**F** cross checks by direct comparisons with Pulsar and Quasar, now defining the best possible inertial frame of reference

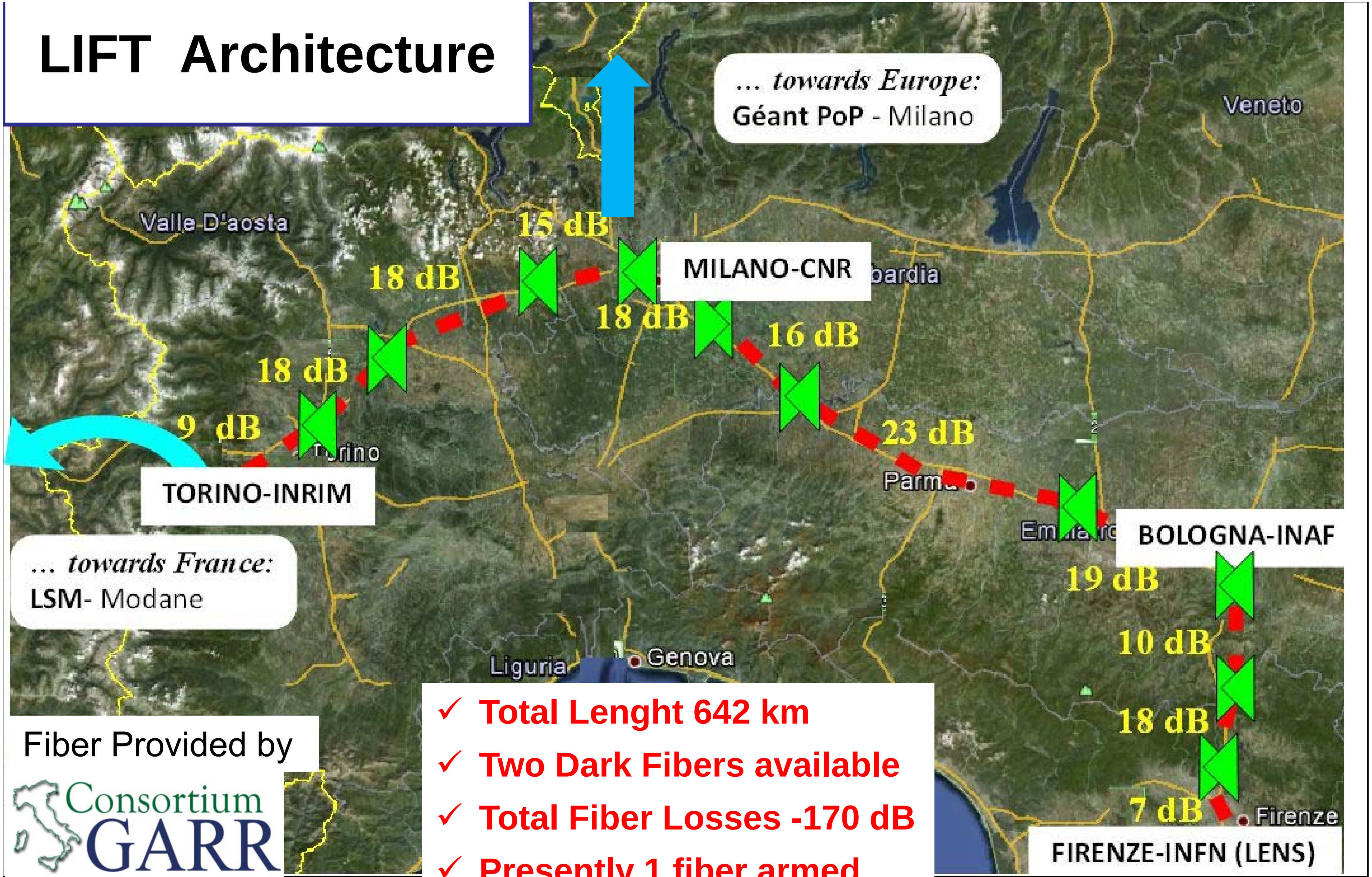
Time dissemination for LIFT

O.Lopez, A. Kanj, P.-E. Pottie, D. Rovera, J. Achkar, C. Chardonnet, A. Amy-Klein and G. Santarelli
Applied Physics B: Lasers and Optics, s00340-012-5241-02012 (2012)



- Frequency transfer with « round-trip » method for fiber noise compensation
- Two-way time transfer using Satre modems

LIFT Architecture

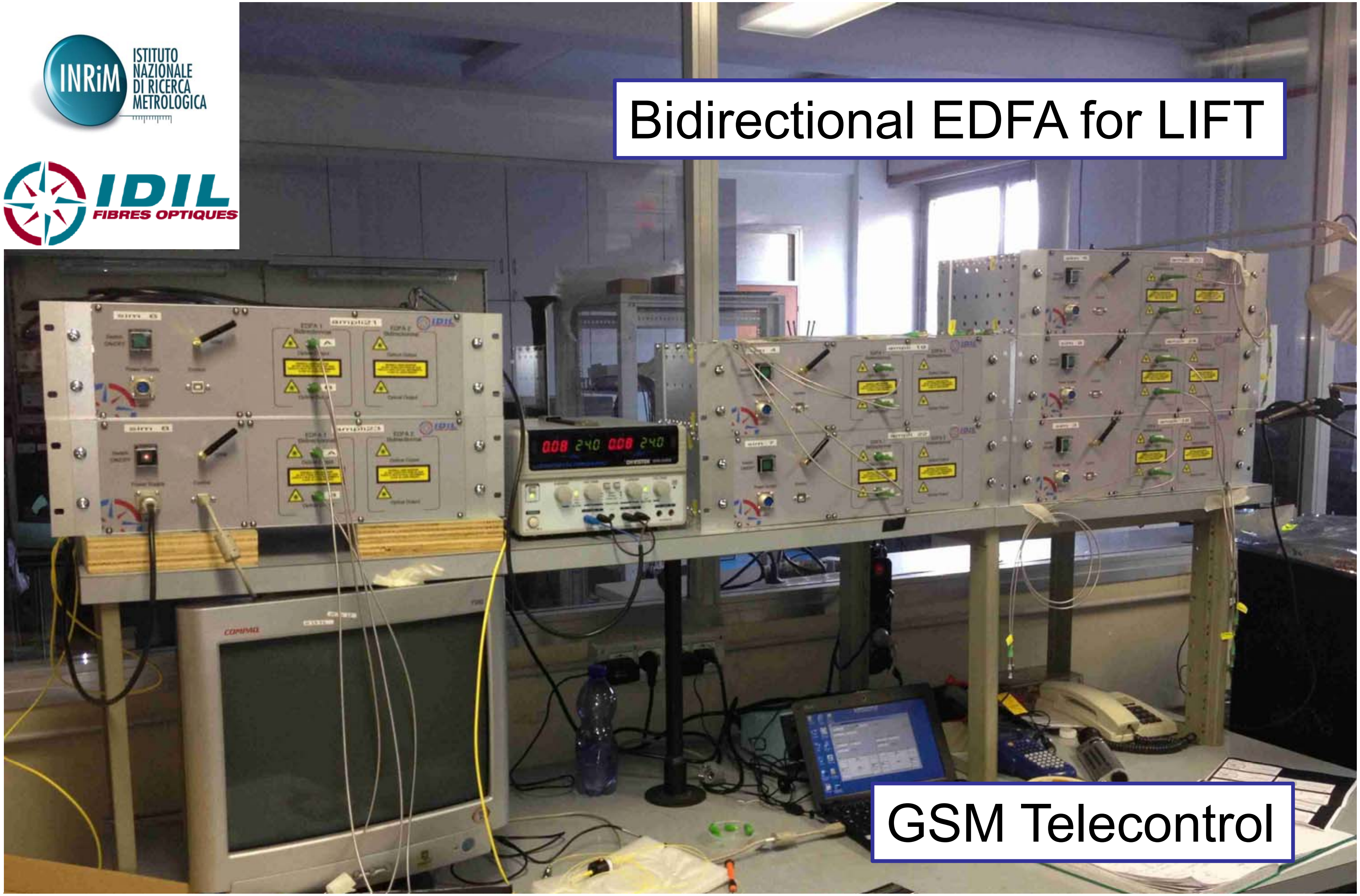


Fiber Provided by

Consortium GARR

- ✓ **Total Lenght 642 km**
- ✓ **Two Dark Fibers available**
- ✓ **Total Fiber Losses -170 dB**
- ✓ **Presently 1 fiber armed**
- ✓ **9 b-EDFA are used**

Bidirectional EDFA for LIFT

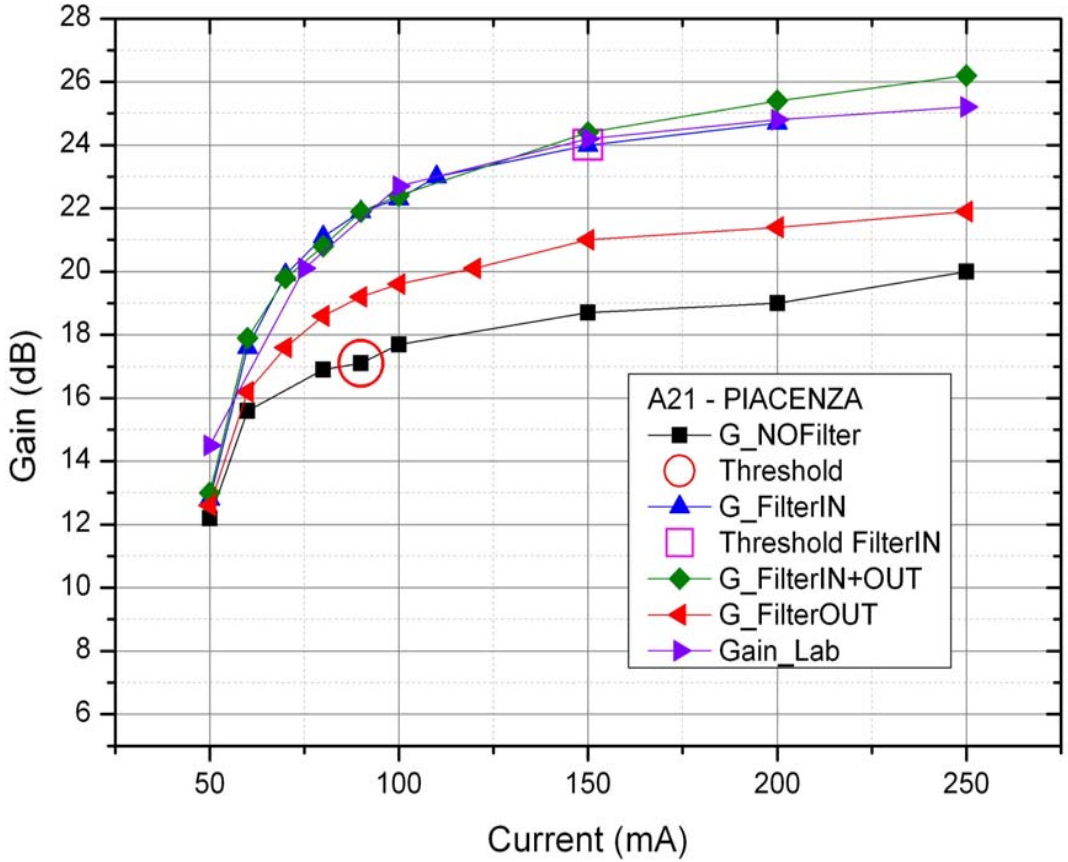


GSM Telecontrol

LIFT b-EDFA: test in laboratory and in-field

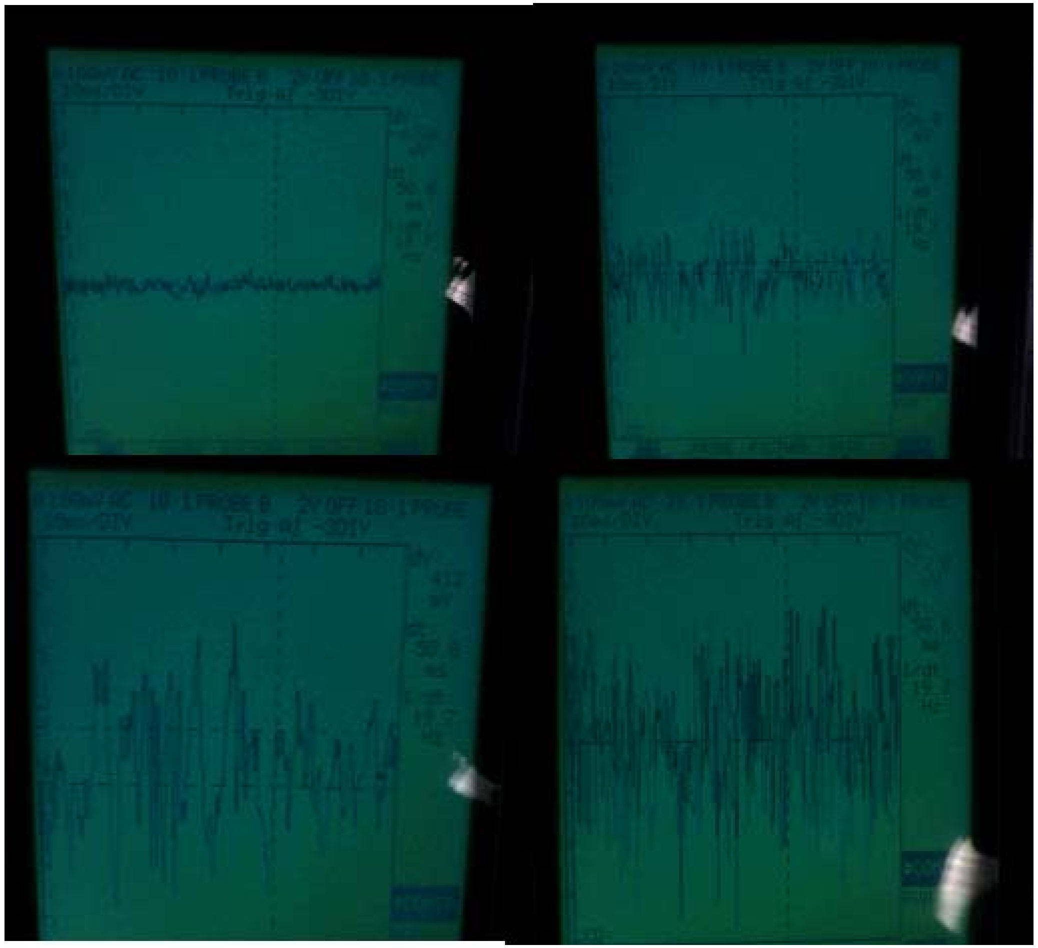
Each amplifier tested in laboratory and in-field. Each site presented its own characteristics, with some common general features.

e.g. **PIACENZA Site**, with respect to Lab:
w/o **100 GHz ITU44 Filters**: pump current threshold 90mA, Gain <7 dB
filter OUT: no threshold, lower gain
filter IN + OUT: gain~lab without threshold
filter IN: gain ~lab, threshold of 150mA



Reflections effects setting a pump current threshold

After the threshold, large anomalies in the reflected light to a test photodiode.
We keep the pump current below the threshold.



Distributed Amplification

...in Raman amplification

✓High gain (~30 dB)

✓ No phase noise added

✓Large gain bandwidth (~10 THz)
→ Autonomous operation

✗ High pump power required (~1 W)

✗ Pump -signal offset 13 THz
→ Suitable in DWDM networks?

...and in Brillouin amplification

✓High gain (~50 dB)*

✓No phase noise added

✗ Gain bandwidth ~20 MHz

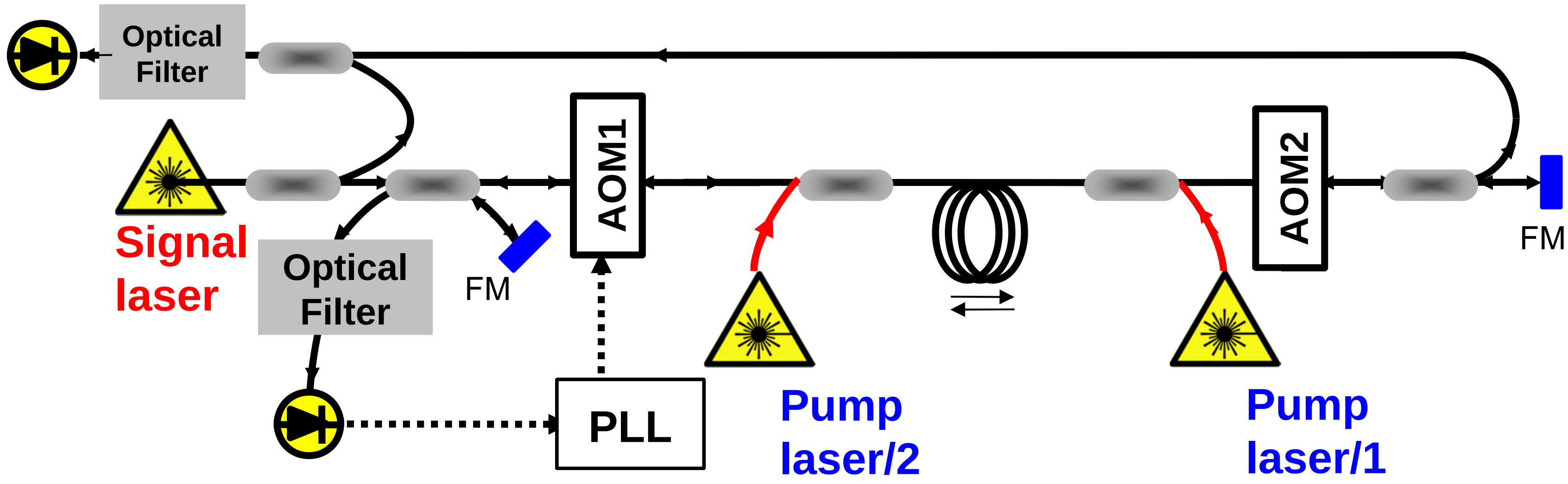
✓Small pump power (~10 mW)

✓Pump -signal offset 10 GHz
→ everything in one ITU channel

***Only counterpropagating signal is amplified**

O. Terra et al., Opt. Expr. 18 (2010)

Fiber Raman Amplification/Gain



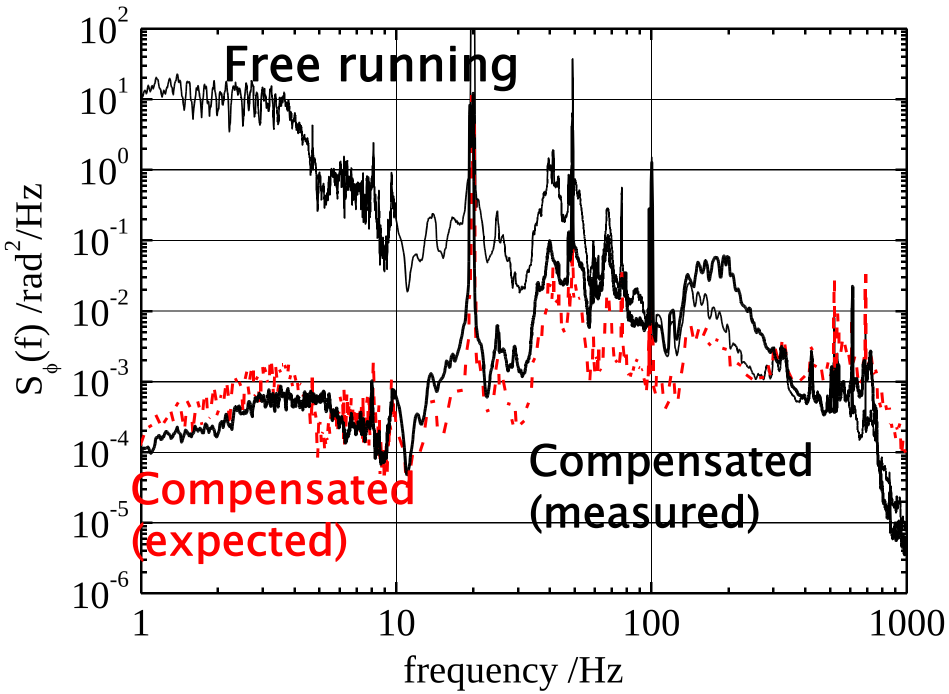
- up to 32 dB with a double pump

(limited by the power available with our pumps)

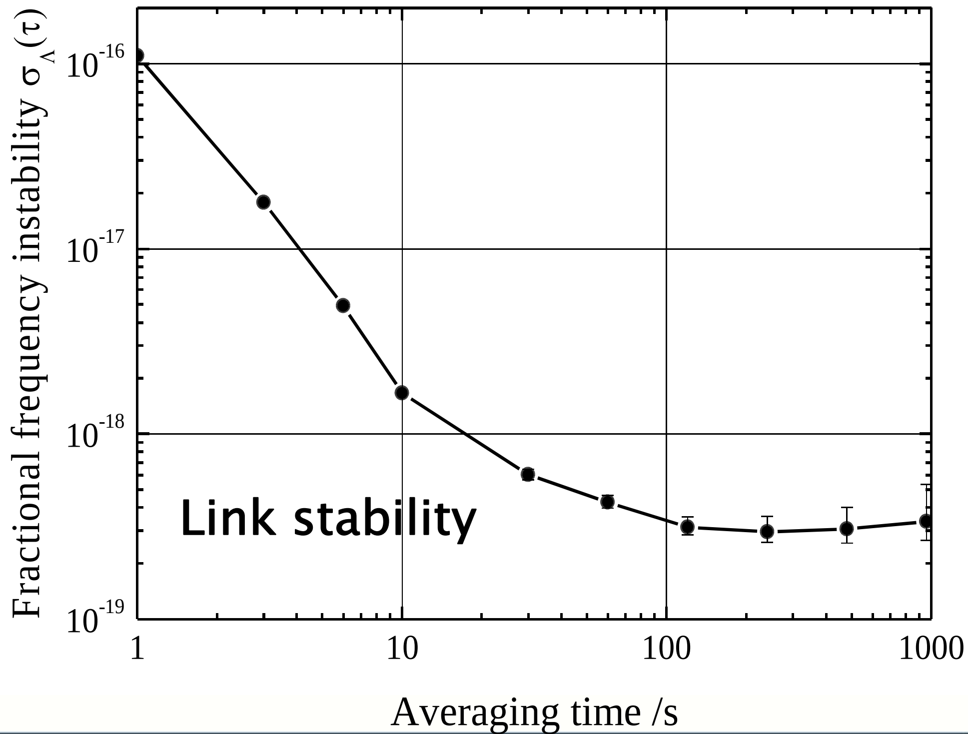
- In a real network, span length may double with respect to EDFA

double pump scheme requires careful design

Fiber Raman Amplification
200 km fiber spool



- Residual phase noise as expected (delay limited, from 100 km w/o amplification)
- Suitable for remote clock comparison and ultrastable frequency transfer



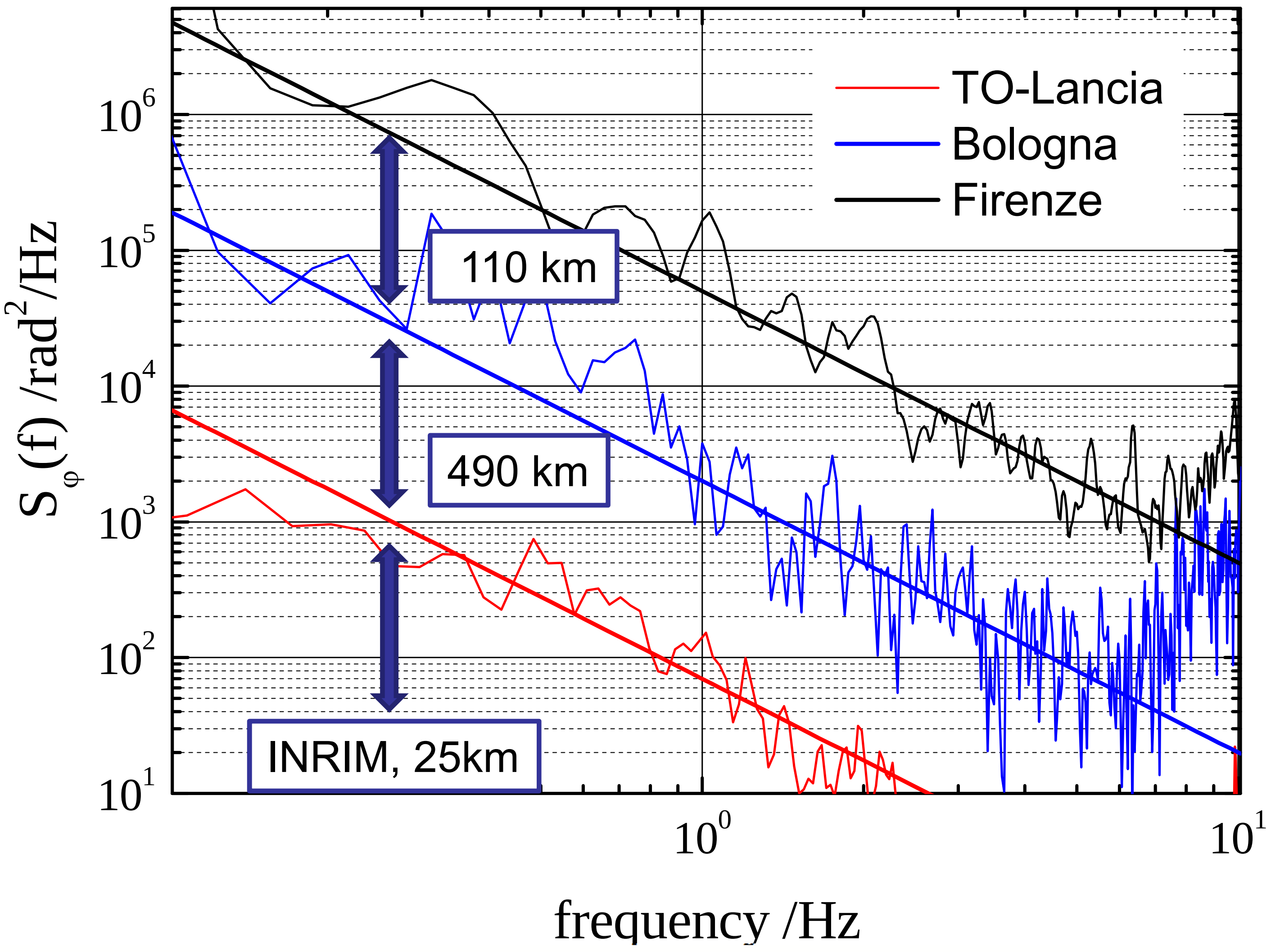
C. Clivati et al., accepted for publication in Photon. Technol. Lett., arXiv:1211:3910

LIFT Architecture: Spans, Losses, Amplification

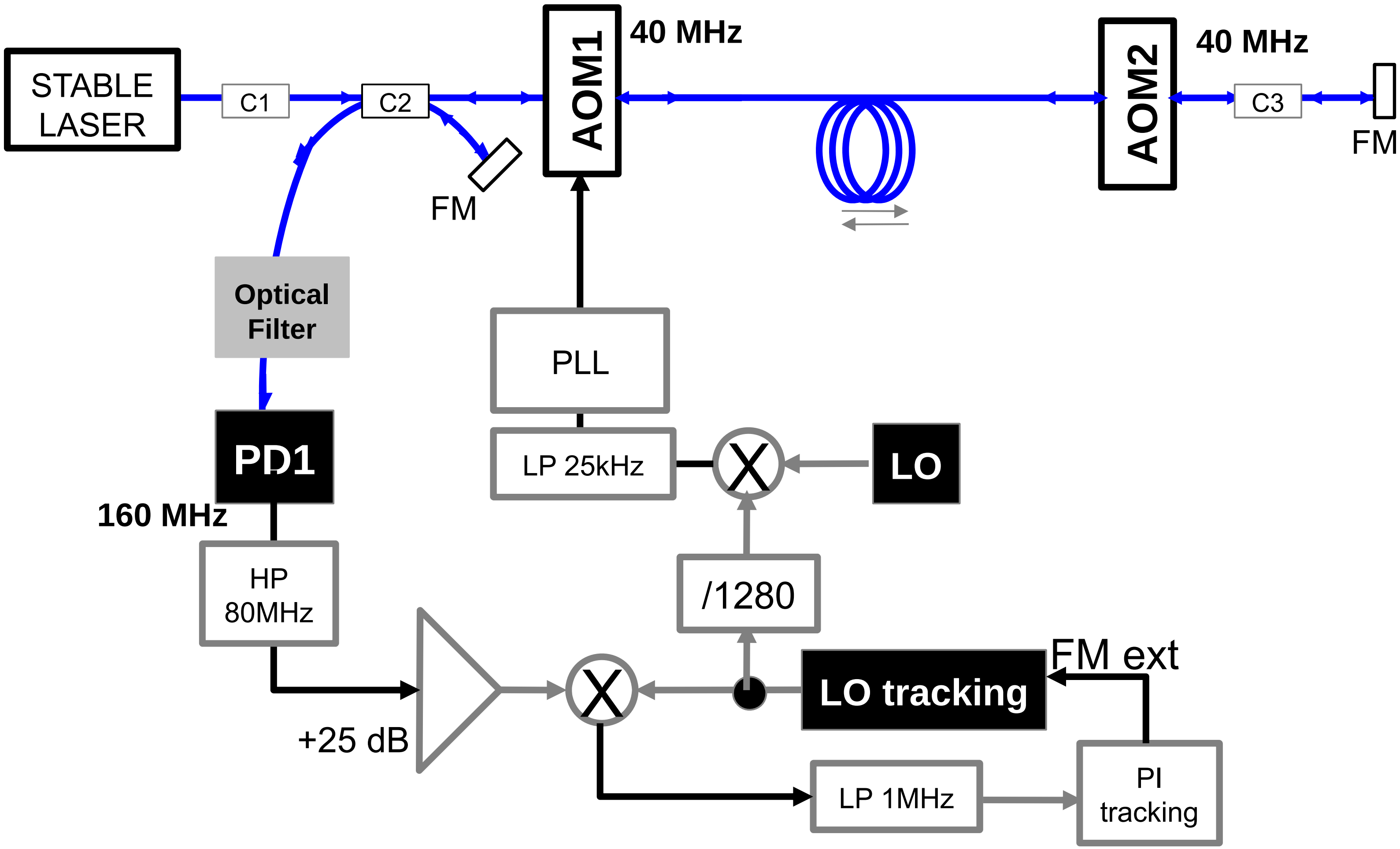
Span	Start	Stop	Lenght km	Losses dB	bEDFA Gain dB
1	INRIM	Torino Lancia	25	-8.7	
2	Torino	Santhià	67	-17.7	19
3	Santhià	Novara	77	-17.6	16
4	Novara	Lainate	50	-14.6	17.5
5	Lainate	Milano Rogoredo	60	-18.3	9
6	Milano	Piacenza	67	-15.8	17
7	Piacenza	R.Emilia	94	-22.7	22
8	R.Emilia	Bologna	74	-19.1	21
9	Bologna	Rioveggio	38	-9.9	19
10	Rioveggio	Firenze	72	-17.8	22
11	Firenze	LENS	18	-7.1	
	Total		**642 km**	**-170 dB**	**162 dB**

Fiber losses ~0.26 dB/km average ; +10 dB losses due to extra connectors

Fiber phase noise along the way

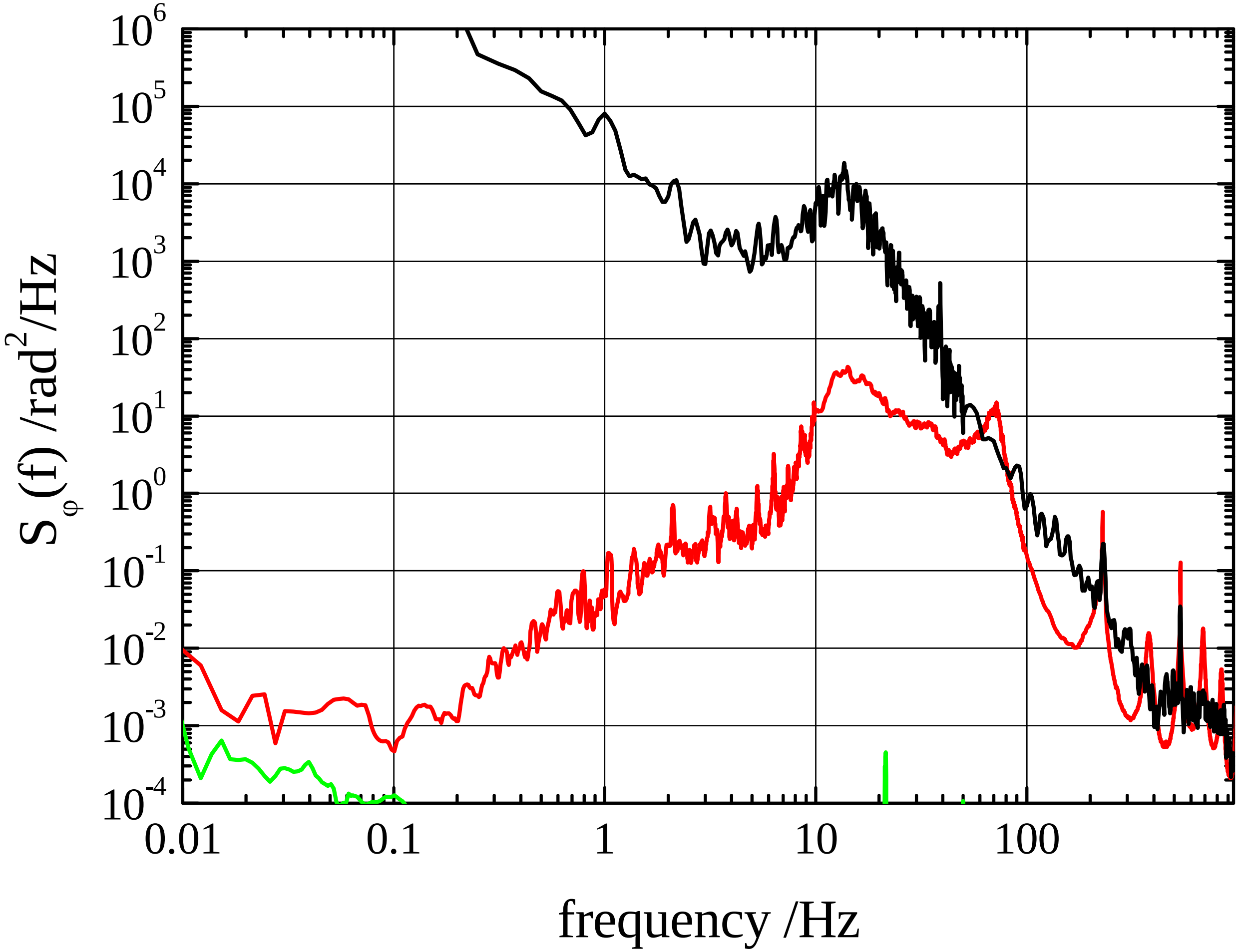


LIFT : Closing the Loop

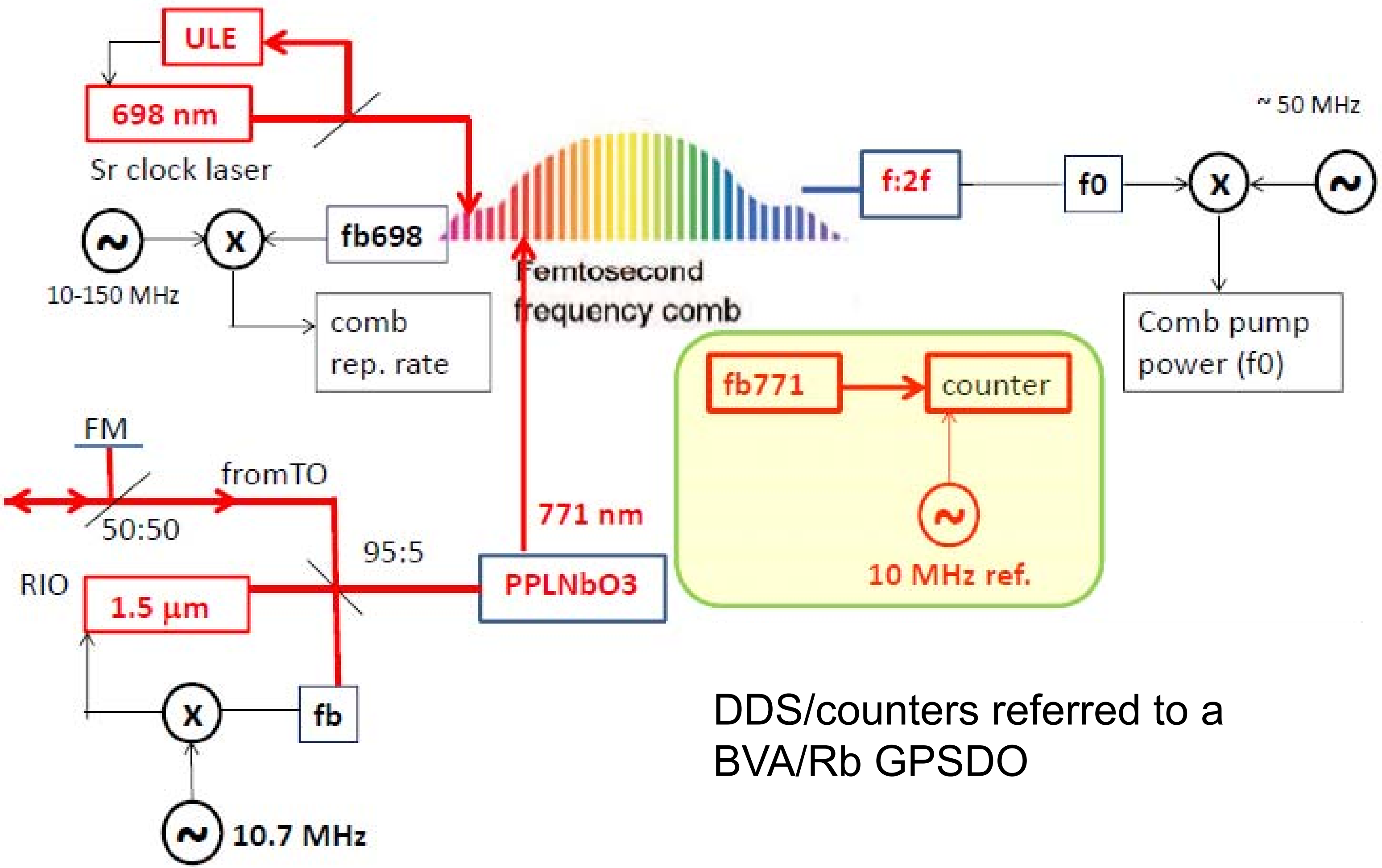


LIFT Phase noise:open/closed loop

First Result: April, 26th

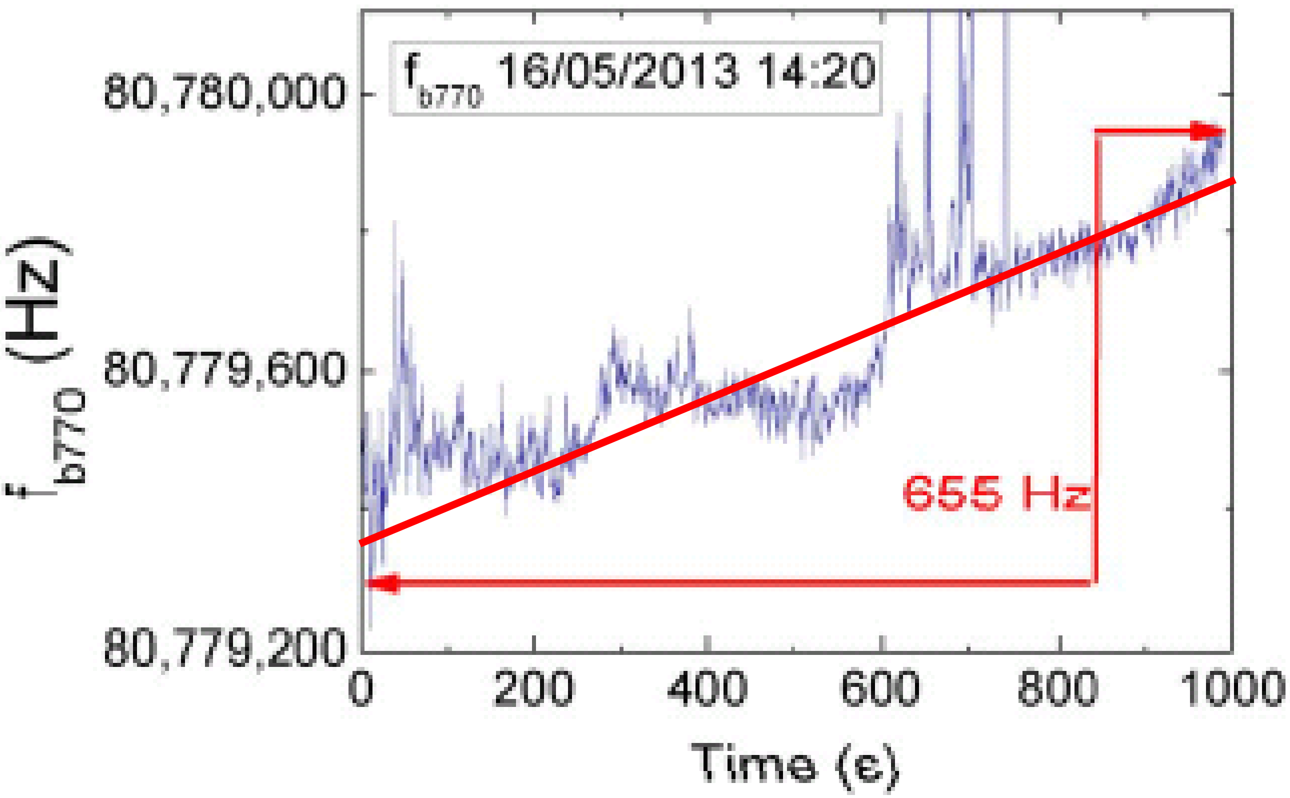


Test in Florence (from May, 2nd)

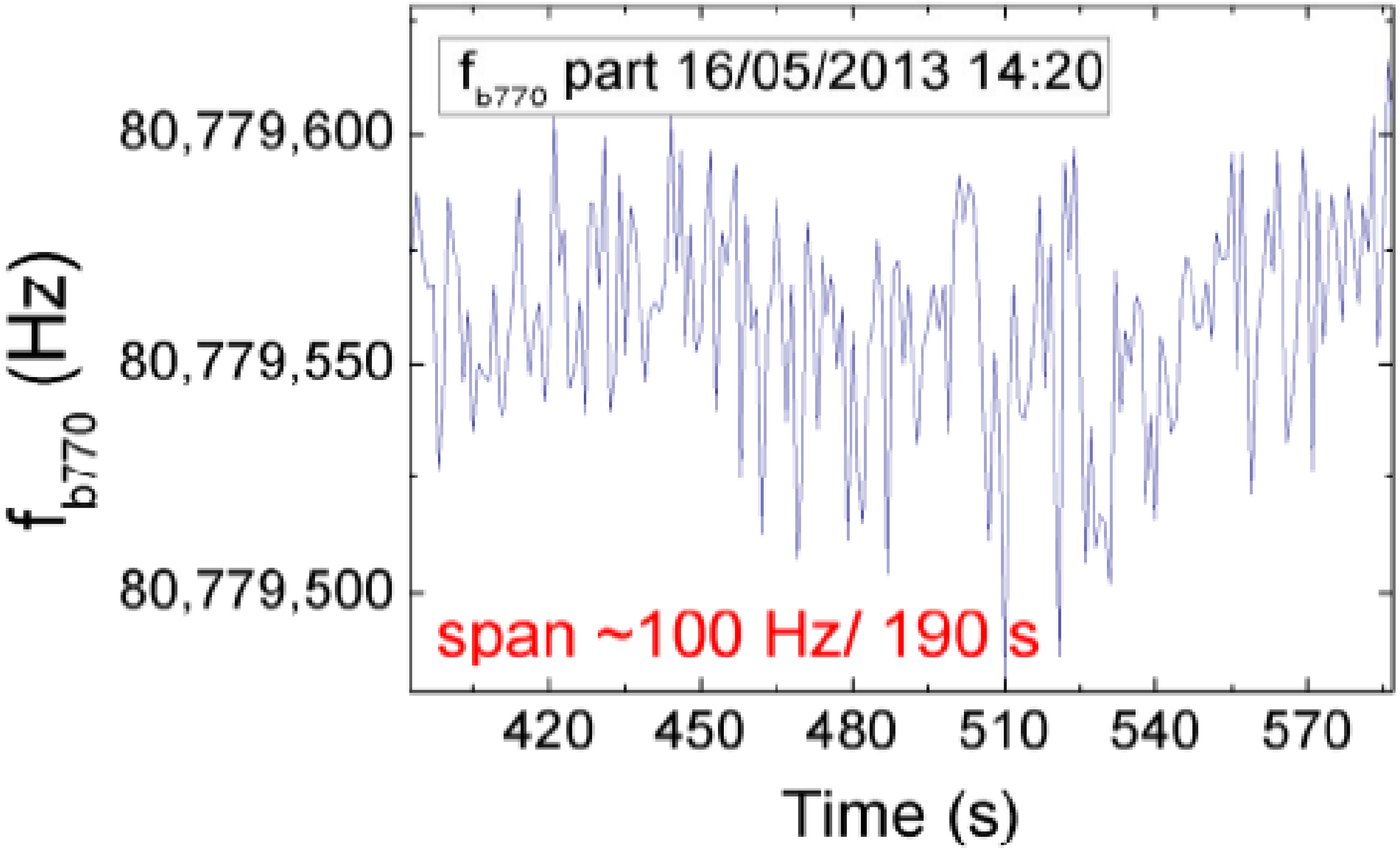


DDS/counters referred to a BVA/Rb GPSDO

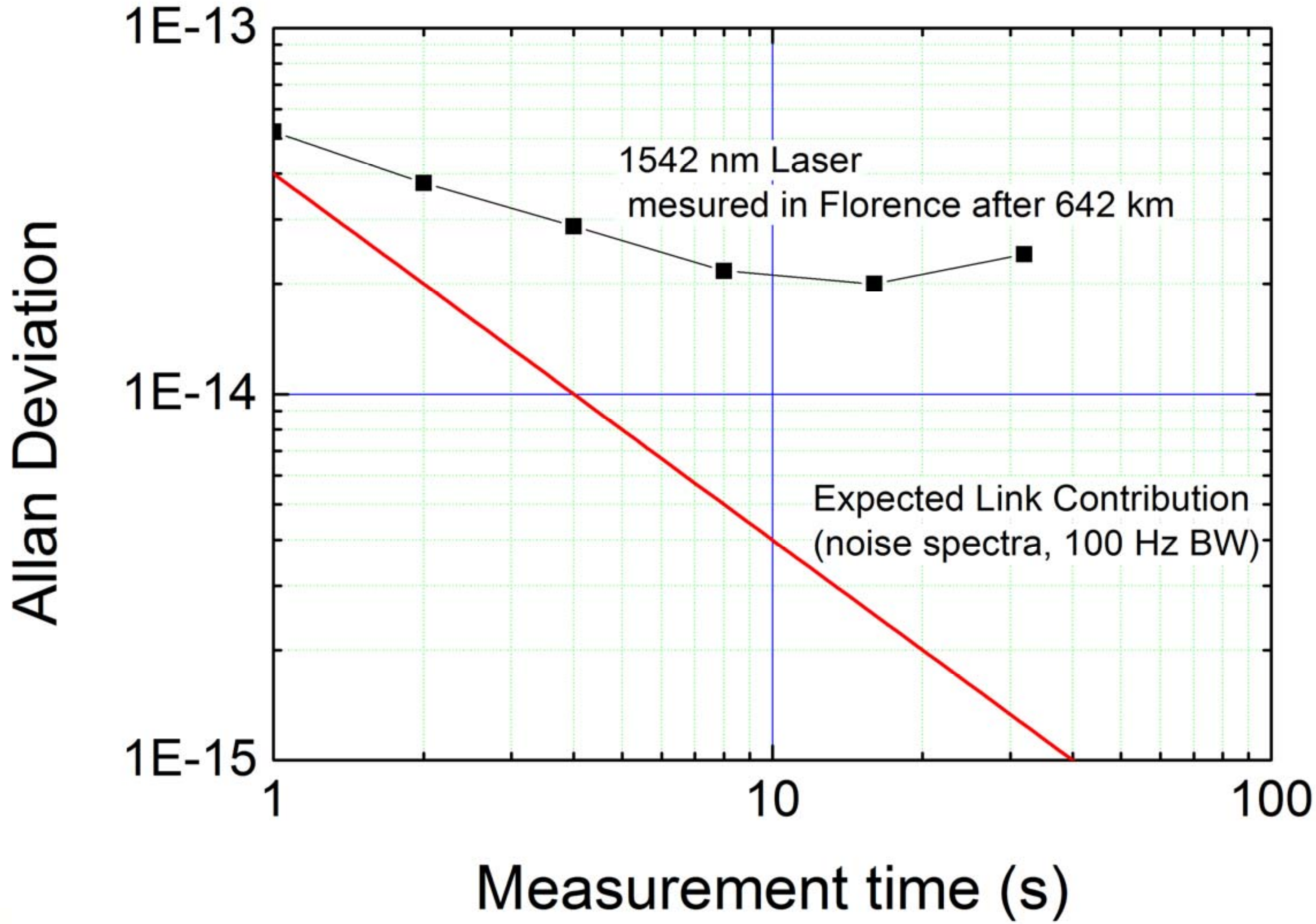
INRIM 1.5 μm Laser first measurements in UNIFI (Florence)



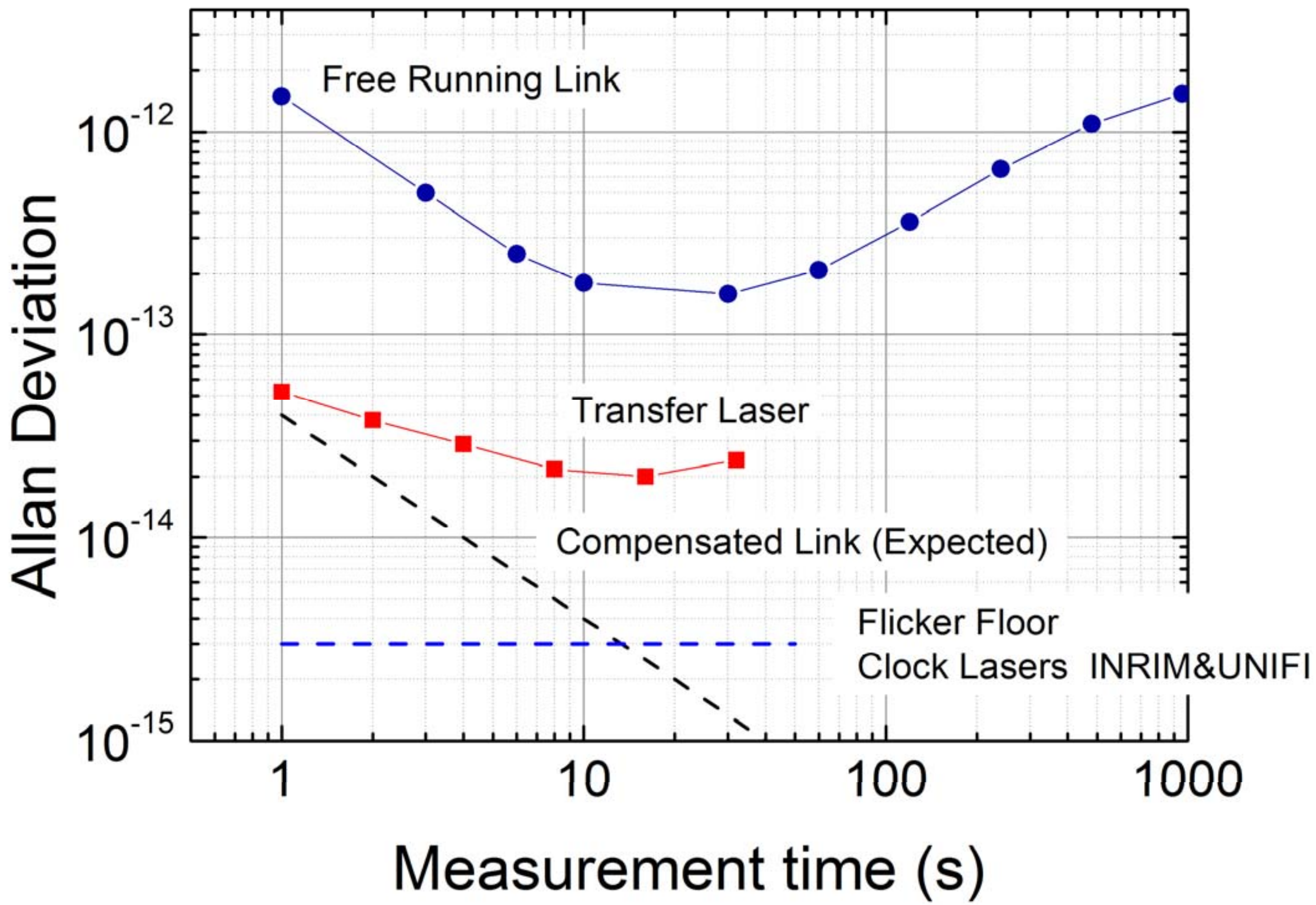
INRIM 1.5 μm Laser
first measurements in UNIFI (Florence): Data subset



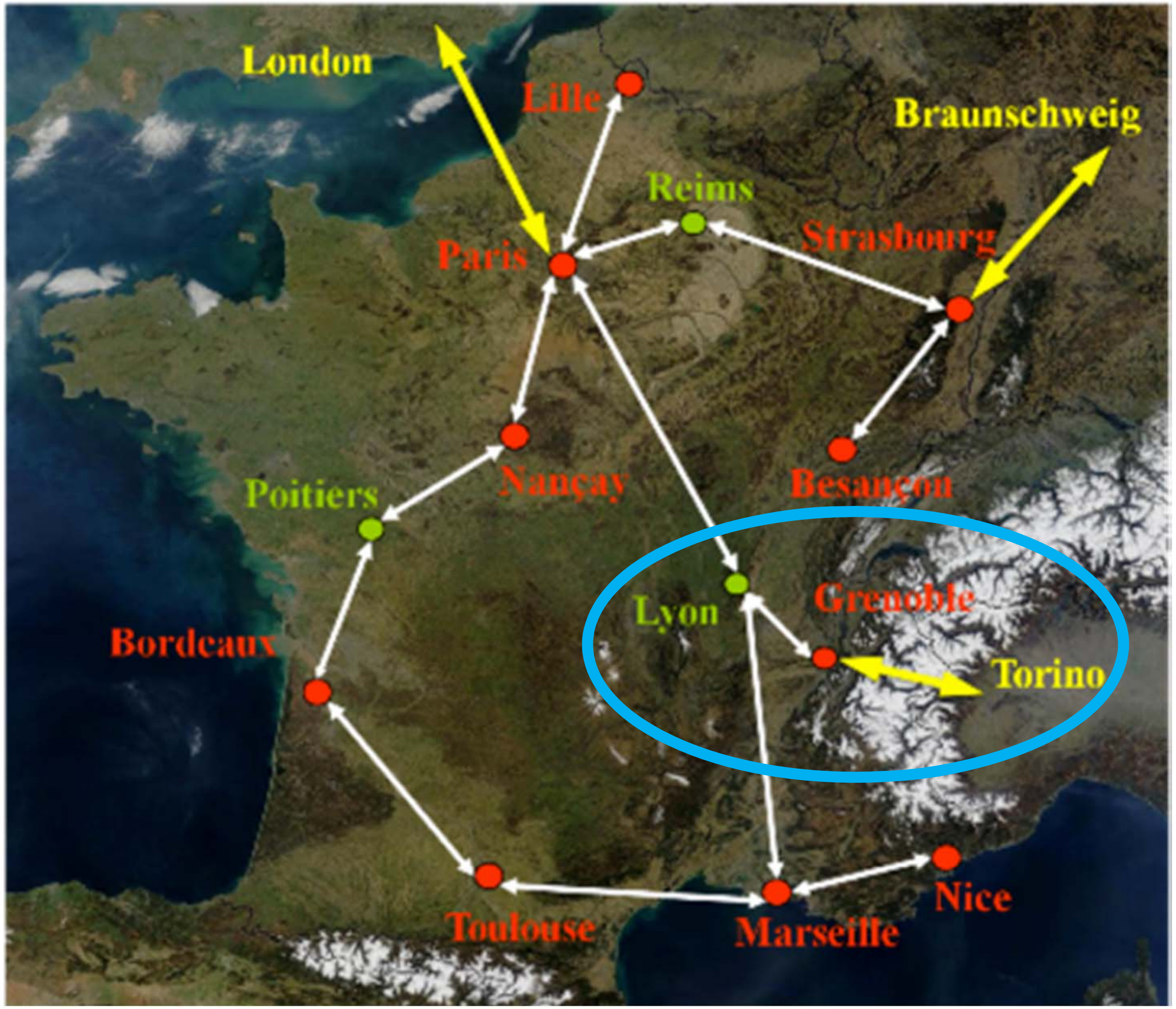
1542 nm laser from INRIM to UNIFI (642 km), May 16th



1542 nm laser from INRIM to UNIFI (642 km)



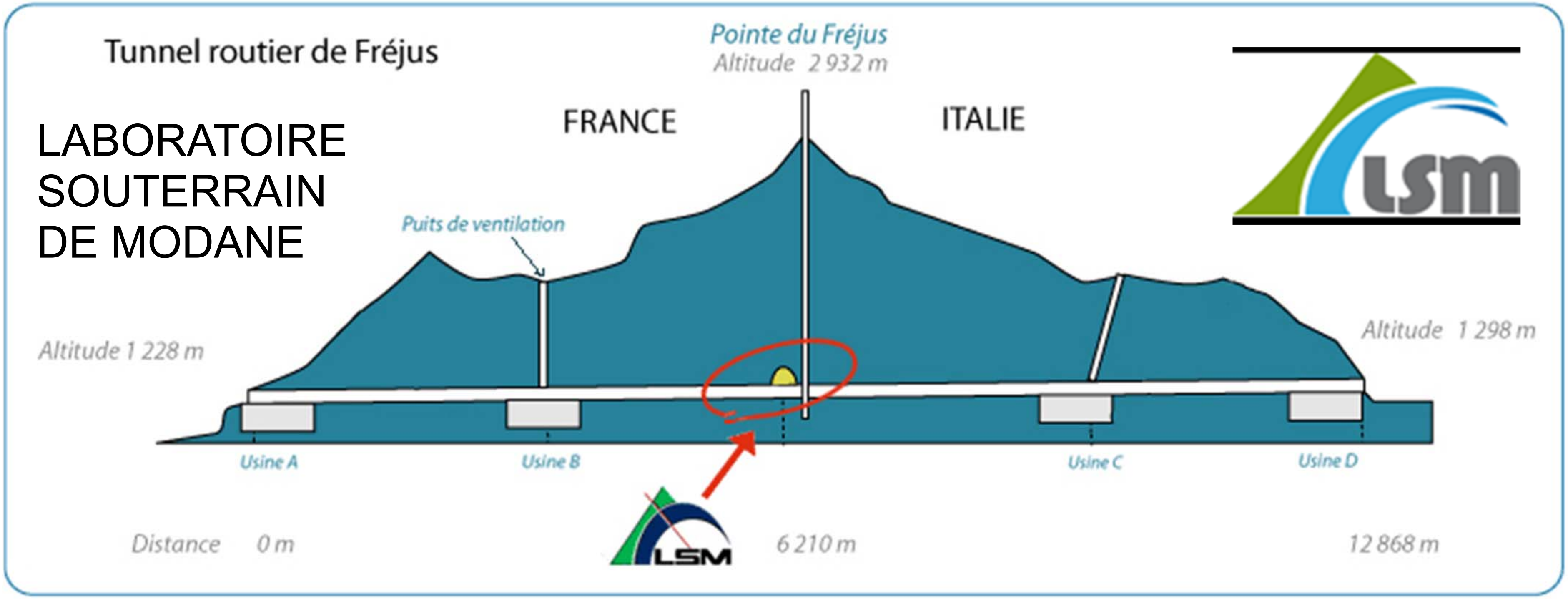
LIFT and REFIMEVE+



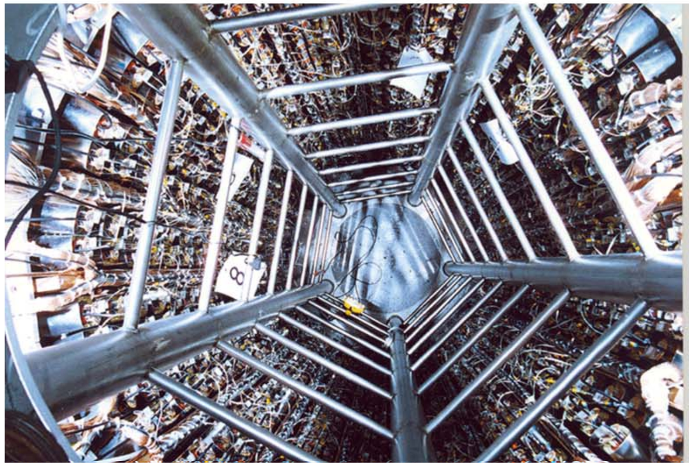
Italy-France cross border on Frejus Tunnel

Torino–Modane, about 100 km
First step to Lyon, then Paris via Strasbourg
Collaboration with RENATER?

LABORATOIRE SOUTERRAIN DE MODANE



LSM core business is astrophysical particles, mainly neutrinos



EMRP
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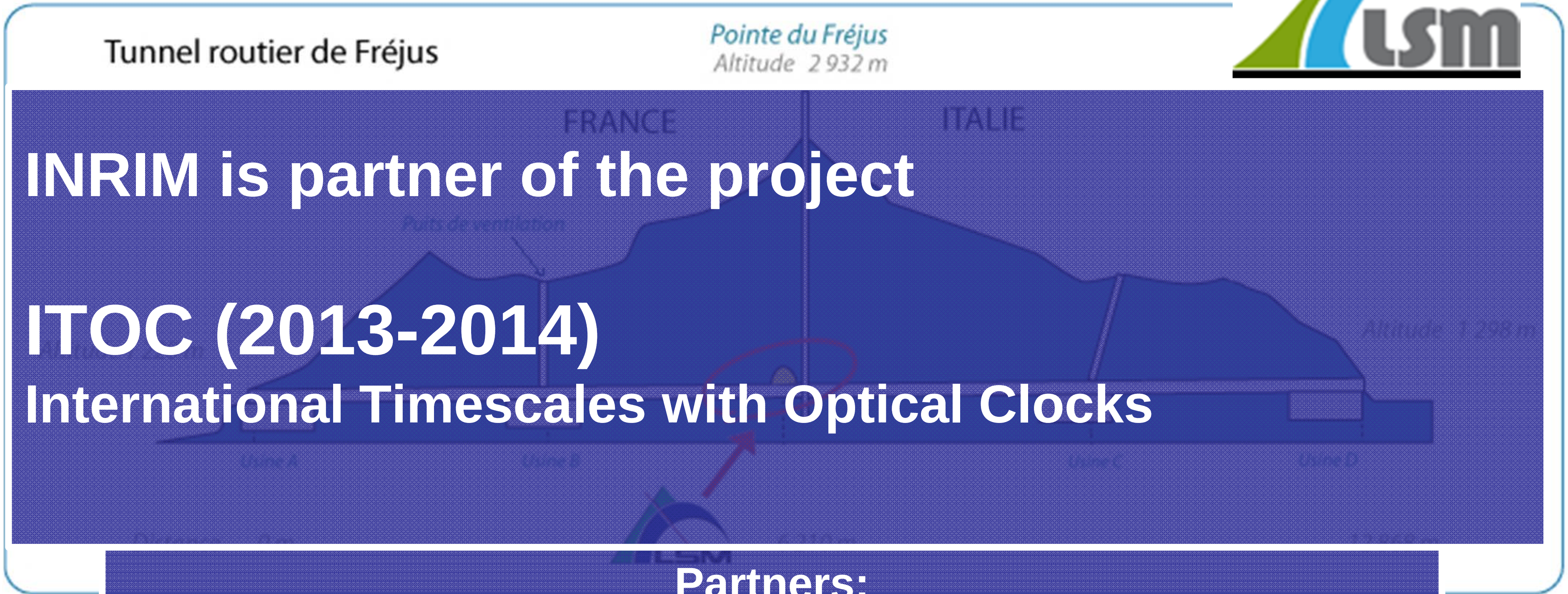


INRIM is partner of the project

ITOC (2013-2014)

International Timescales with Optical Clocks

Partners:

NPL (United Kingdom, Coordinator), **PTB** (Germany), **INRIM** (Italy), **MIKES** (Finland), **OBSPARIS (**France), **CMI** (Czech Republic), **LUH** (Germany), **LSM** (France)

Torino-Frejus:
dislivello
Test di ge
con gli orologi

ITOC project structure

Coordinated programme of optical clock comparisons

WP1

- Local frequency comparisons
- Absolute frequency measurements

WP2

- Frequency comparisons using transportable optical clocks

WP5

- Remote clock comparisons via satellite links
- Analysis for timescale steering

REG

Gravity potential for optical clock comparisons

WP3

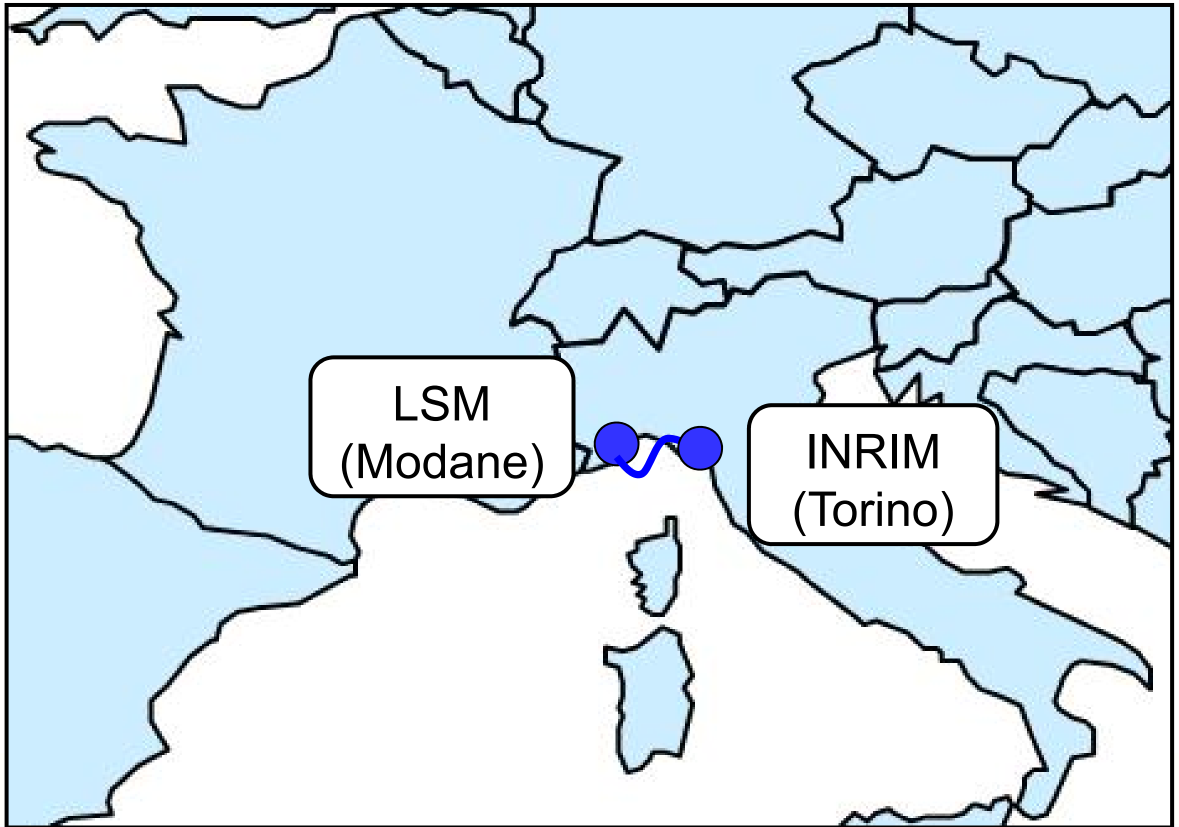
Relativistic timescales and geodesy

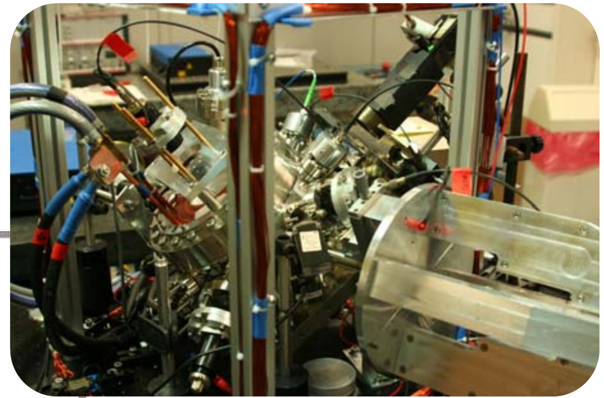
WP4

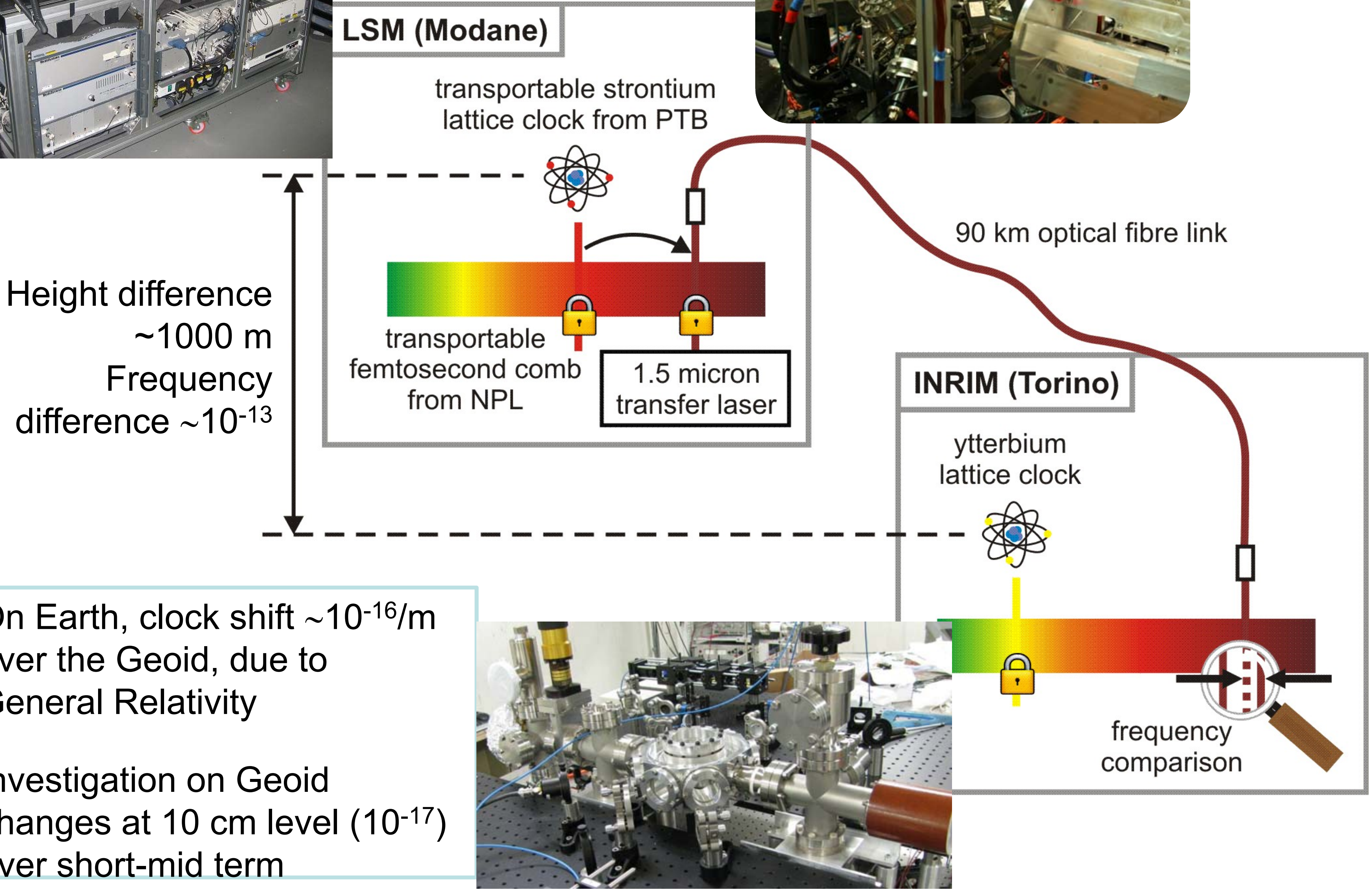
Proof-of-principle relativistic geodesy experiment

WP4: Proof-of-principle relativistic geodesy experiment (INRIM WP leader; Measurement Experiment: 2014)

Aim: To show that optical clocks can be used to measure gravity potential differences over medium – long baselines with high temporal resolution (10 cm geoid height level over few hours)







On Earth, clock shift ~10^{-16}/m over the Geoid, due to General Relativity

Investigation on Geoid changes at 10 cm level (10^{-17}) over short-mid term

A high sensitivity fiber optic gyroscope on a multiplexed telecommunication network

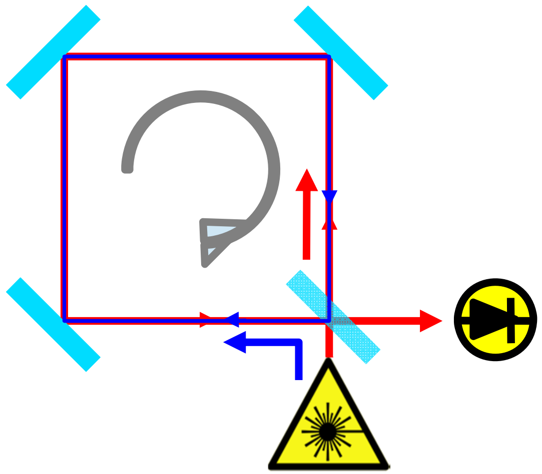
D. Calonico[1], C. Clivati[1,2] ,G. A. Costanzo[1,2], A. Mura[1], M. Pizzocaro[1,2], F. Levi[1]

[1] *Istituto Nazionale di Ricerca Metrologica-INRIM, Torino, Italy*

[2] *Politecnico di Torino, Torino, Italy*

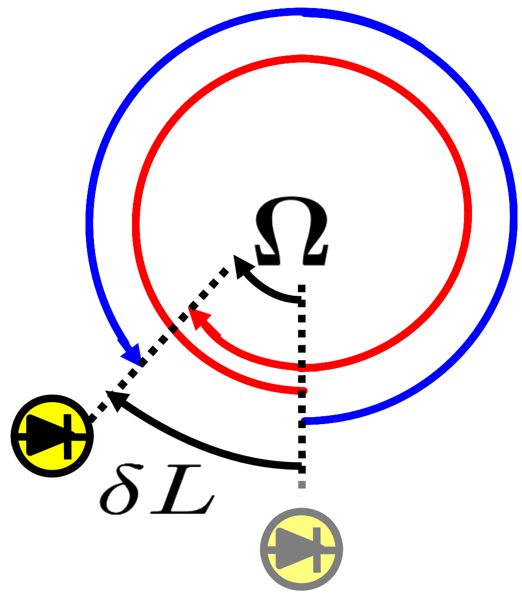
What is a laser gyroscope

- Two beams follow the same path but in opposite directions
- The optical path must enclose an area
- The platform rotates



- The two beams accumulate a phase shift

$$\varphi_S = \frac{8\pi\nu}{c^2}\mathbf{A}\cdot\mathbf{\Omega}$$

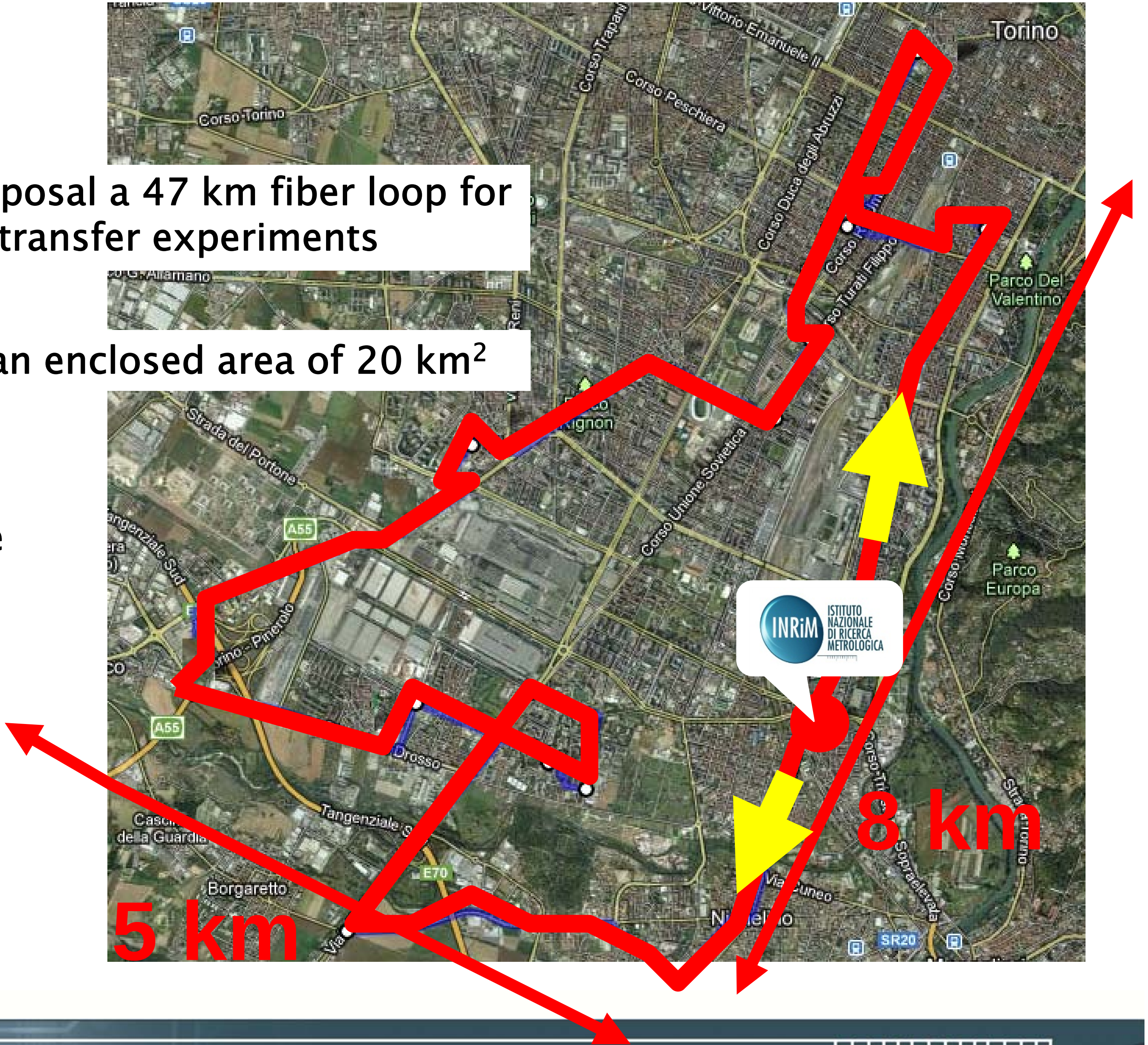


- The sensitivity depends on: – enclosed area
  – orientation

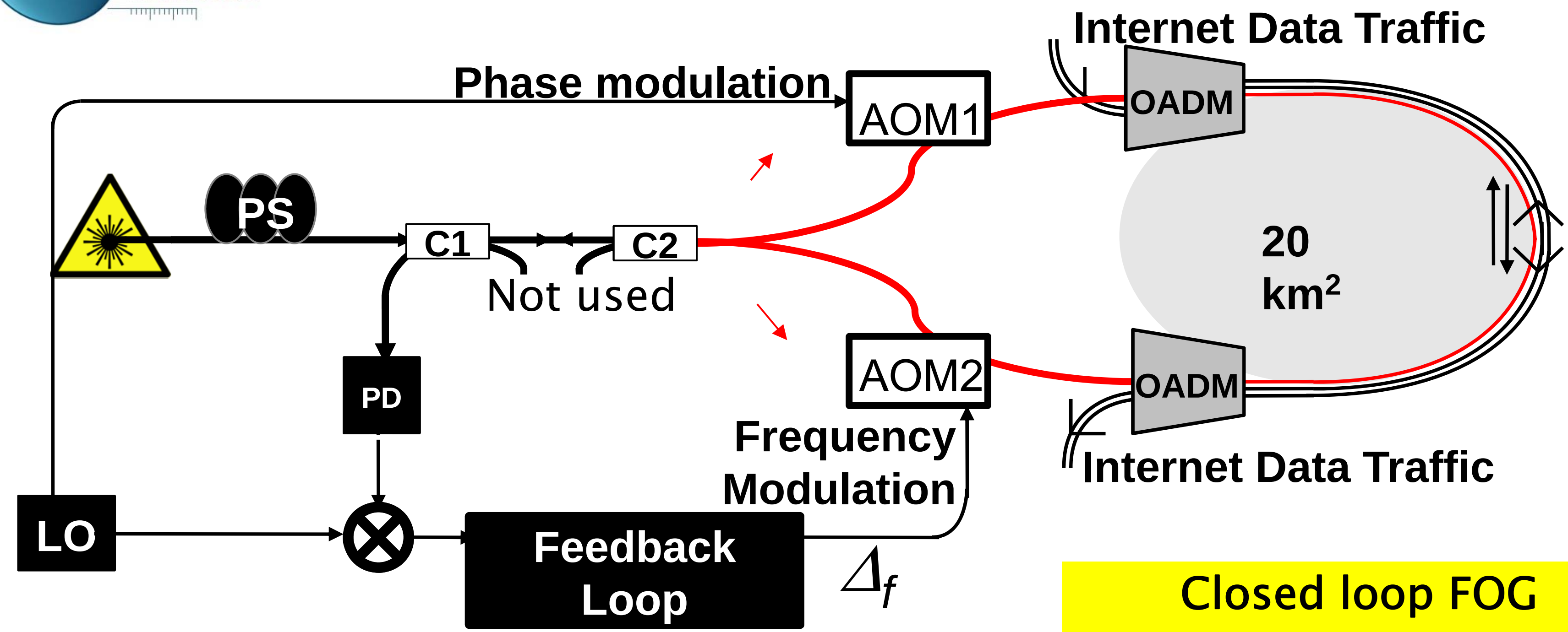
INRIM has at disposal a 47 km fiber loop for coherent phase transfer experiments

Fiber ring with an enclosed area of 20 km^2

Expected phase shift due to Earth rotation ~55 rad



Our experiment



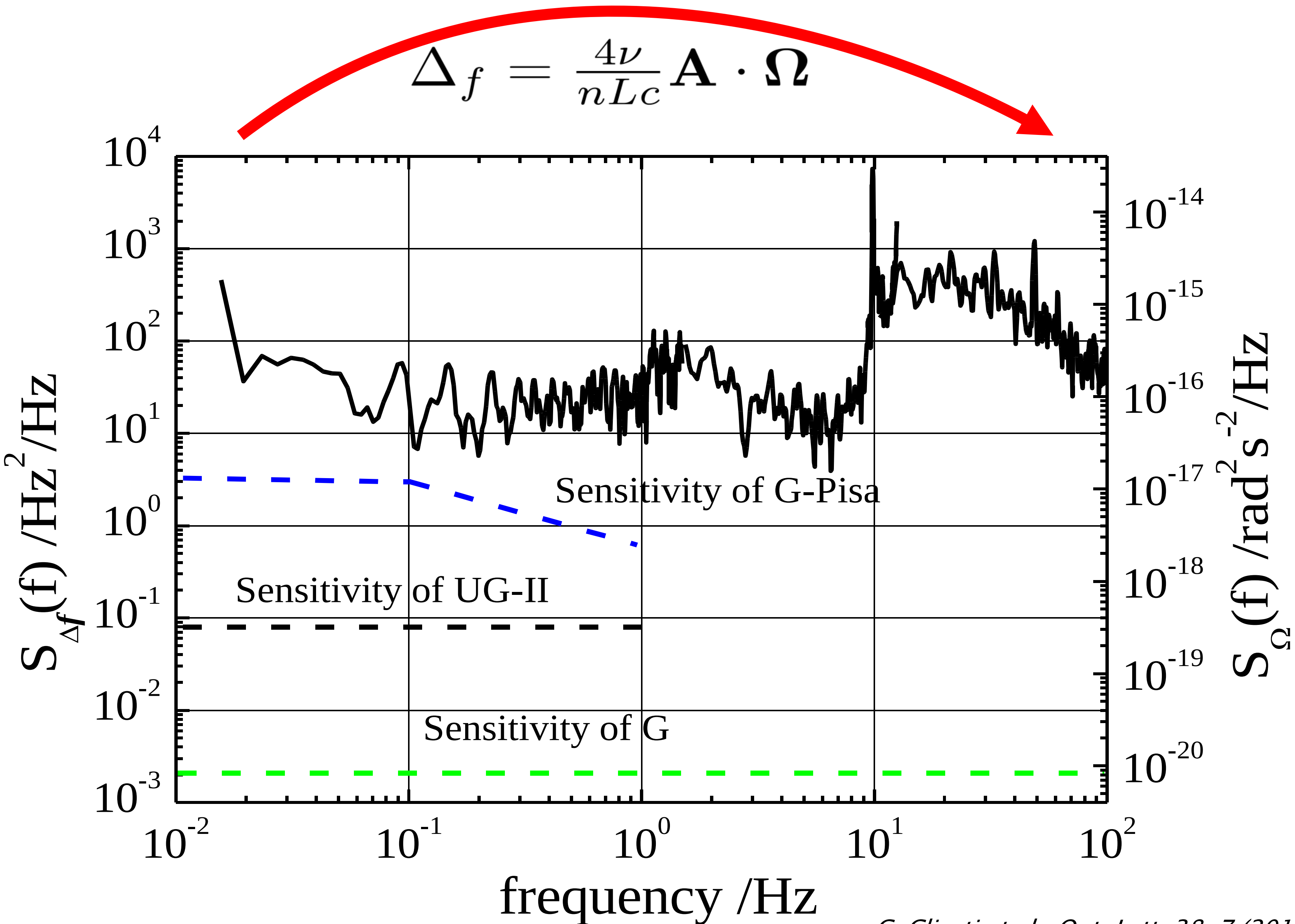
- ✓ Dedicated DWDM ITU 44 channel
- ✓ Non synchronous phase modulation
- ✓ Mixer output depends on senφ_S
- ✓ Feedback loop: frequency offset Δ_f to compensate the Sagnac phase

Closed loop FOG

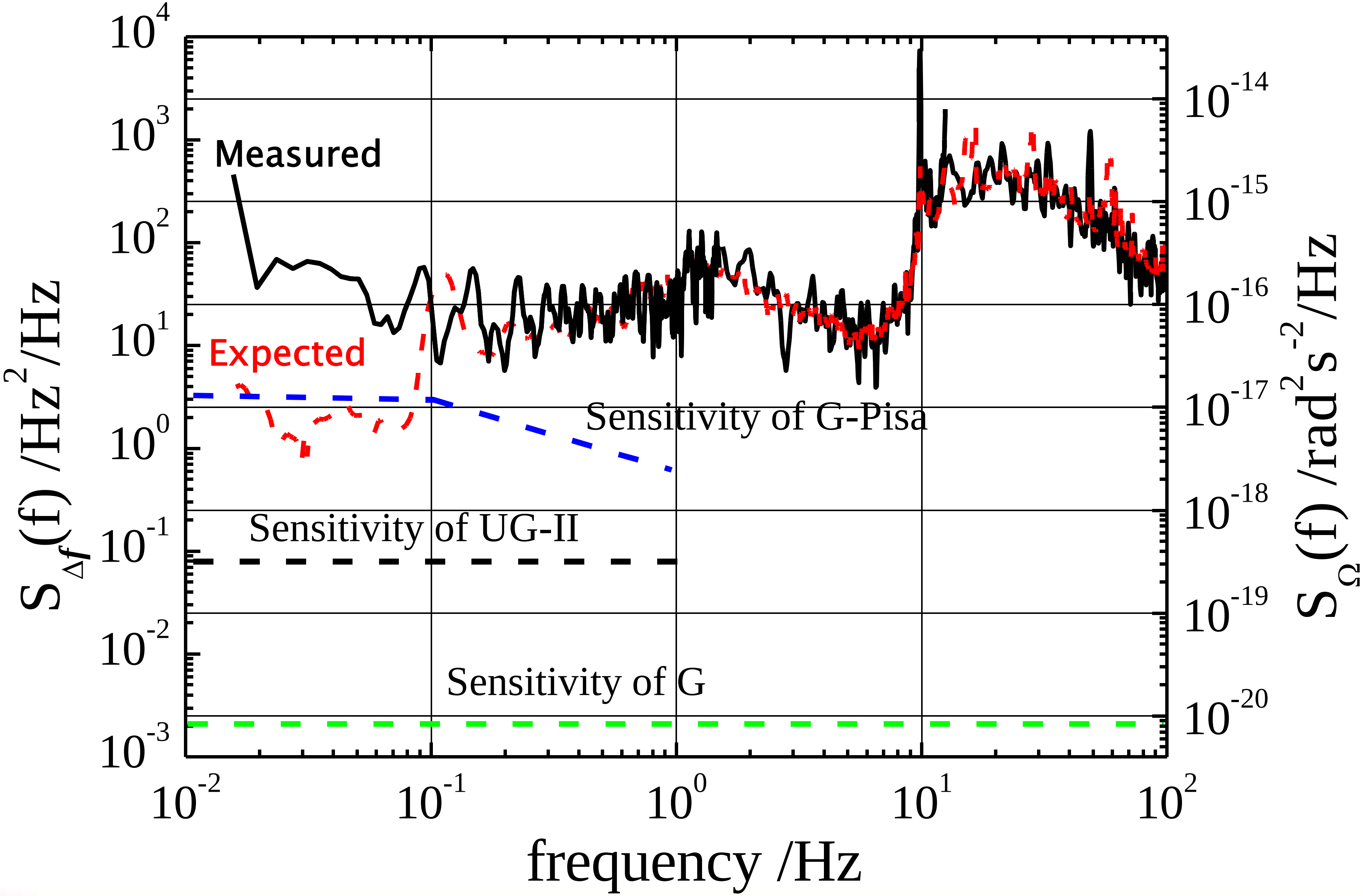
$$\varphi = 2\pi \frac{L}{c} \Delta_f \pm 2\pi k$$

$$\Delta_f = \frac{4\nu}{nLc} \mathbf{A} \cdot \mathbf{\Omega}$$

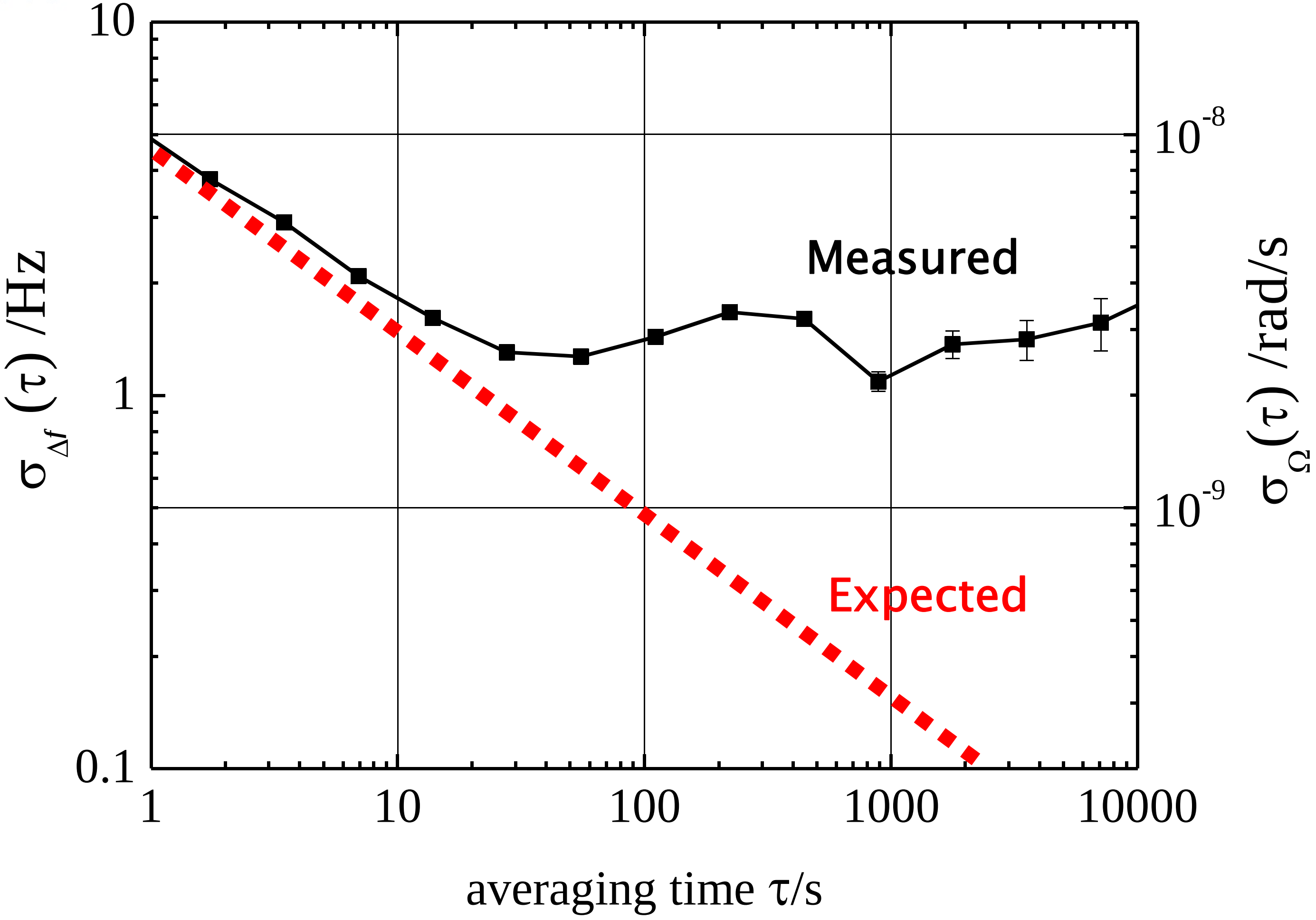
J. L. Davis et al., Opt. Lett. 6, 10, (1981)
C. Clivati et al., Opt. Lett 38, 7 (2013)



C. Clivati et al., Opt. Lett. 38, 7 (2013)

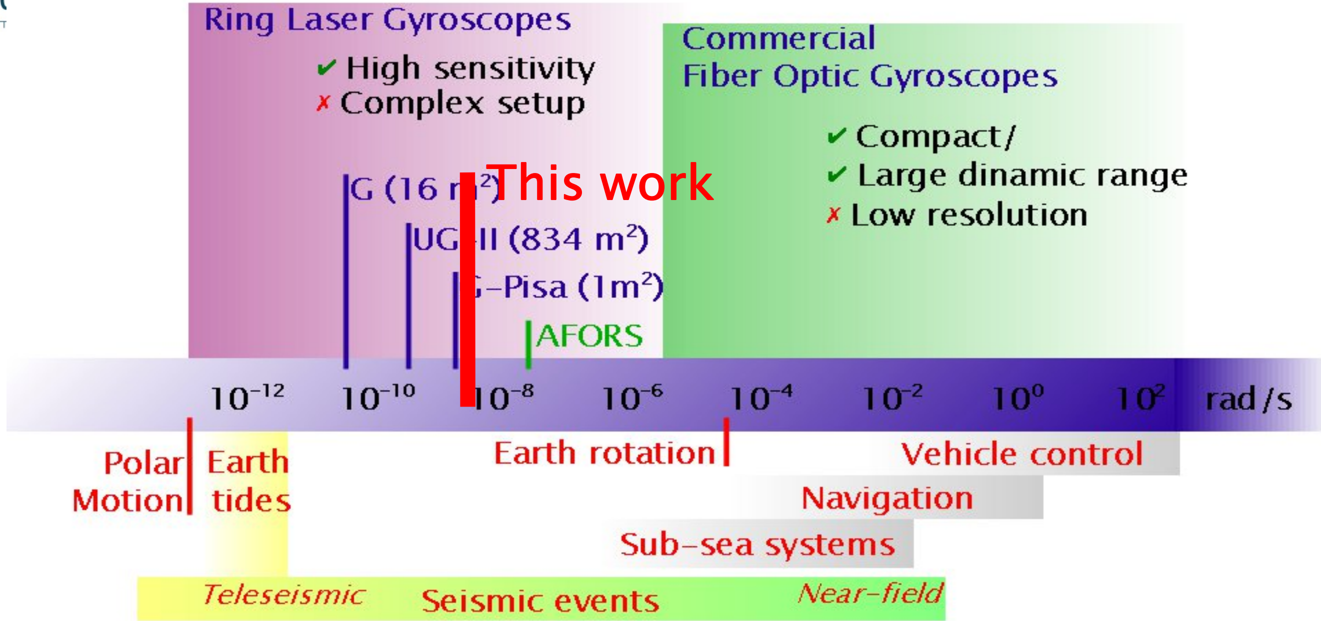

Measured
Expected
Sensitivity of G-Pisa
Sensitivity of UG-II
Sensitivity of G
$S_{\Delta f}(f)$ /Hz^2/Hz
$S_\Omega(f)$ /rad^{2}s^{-2}/Hz
frequency /Hz
10^{-2}
10^{-1}
10^0
10^1
10^2
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
10^{-15}
10^{-14}

Long term stability



On the long term, sensitivity limited by not complete polarization scrambling

Applications and perspectives



- Ultimate sensitivity 3 x 10^{-9} rad/s (10^{-8} (rad/s)/$\sqrt{}$Hz)
- Could open new opportunities for geophysical research
- Understanding how the ground motion is seen by a large sensor
- REFIMEVE+ : a giant Sagnac Fiber Gyro

Conclusions

- Fast acceleration toward a realization of an European Network, already in 2015;
- In Italy, LIFT backbone under operation since May 2013, 642 km total length;
- LIFT could be “linked” to REFIMEVE+ via the Frejus Tunnel
- European project ITOC and NEAT-FT;
- Sagnac fiber gyroscope experiment;

POSITIONS AVAILABLE AT INRIM:
2 Visiting scientist positions
2 Post Doc Position; 1 PhD

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Ministero dell'Istruzione dell'Università e Ricerca

Compagnia di San Paolo

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Yb Lattice Clock at INRIM

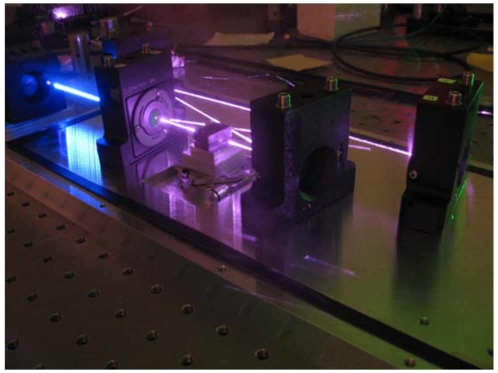
Lasers Ensamble is Completed

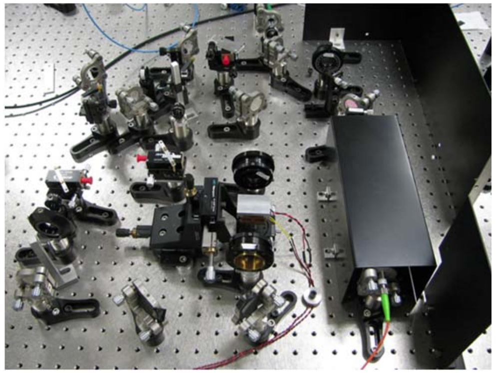
- **Blue** Second harmonic generation
  of a Ti:sapphire laser
  798 nm → 399 nm
  Ouput power = 0.6 W

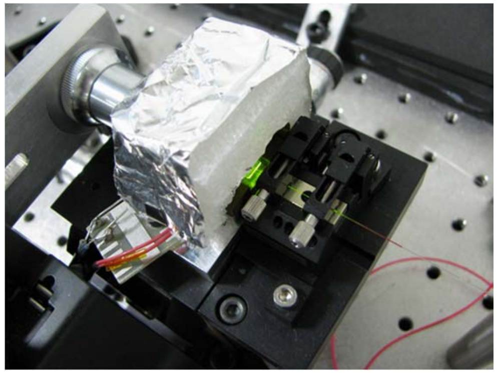
- **Green** Second harmonic generation
  of a amplified fiber laser
  1112 nm → 556 nm
  Ouput power = 20 mW

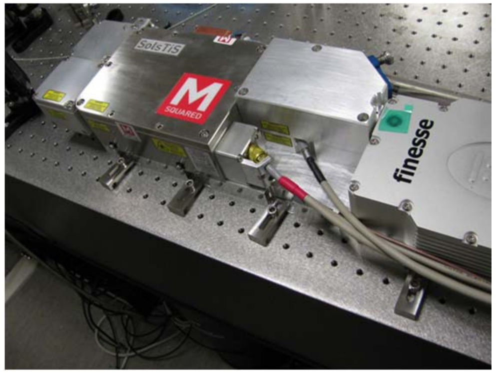
- **Yellow** Sum Frequency generation
  of a Nd:YAG laser and a fiber laser
  1319 nm + 1030 nm → 578 nm
  Ouput power = 10 mW

- **Lattice** Ti:Sapphire laser 759 nm
  Ouput Power = 3 W



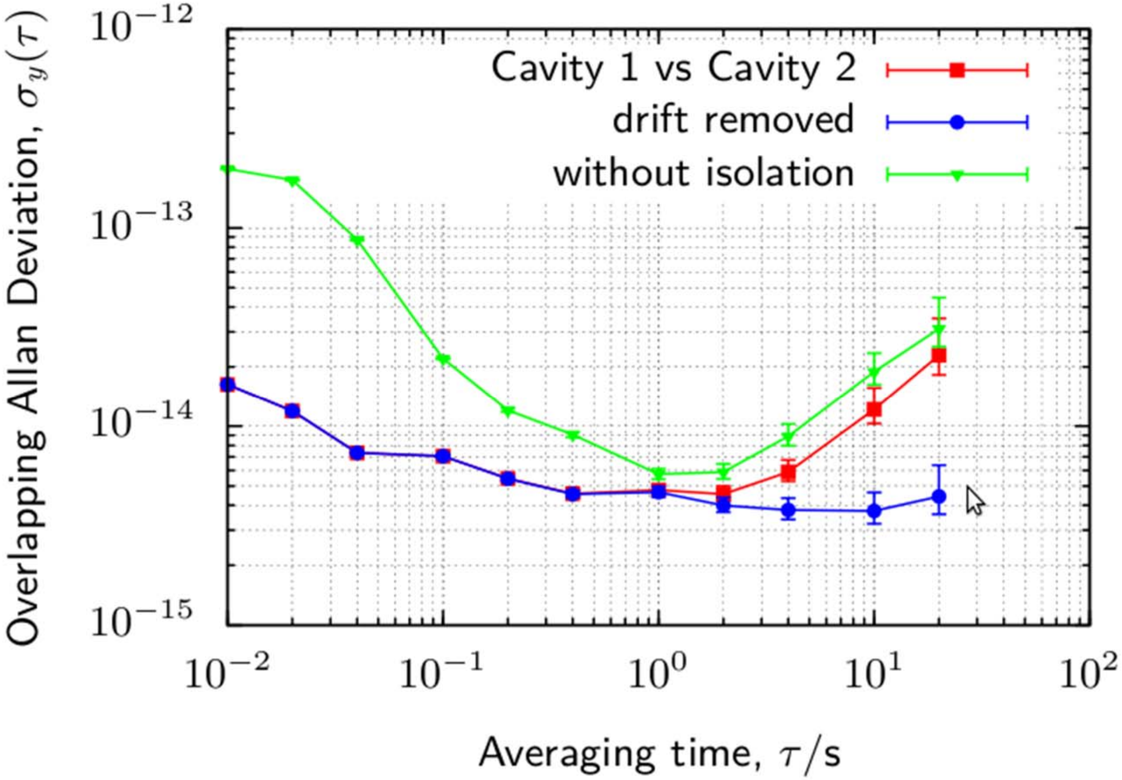






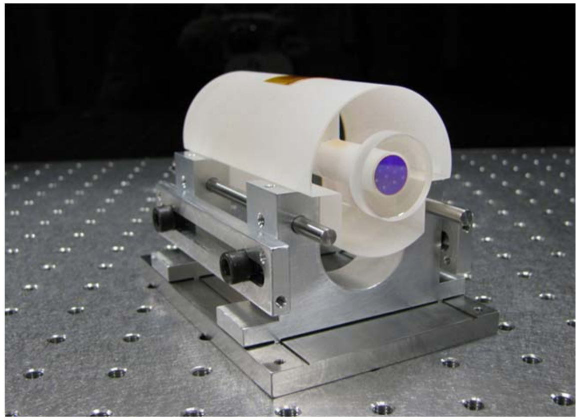
Yb Lattice Clock at INRIM

Stabilization of the Clock Laser



- The yellow laser is stabilized
- on a ULE cavity (10 cm length)
- Two indipendent cavities
- (the laser is split ; two AOMs
  with indipendent lock)

- Single laser stability
- 3x10-15 @ 1 s

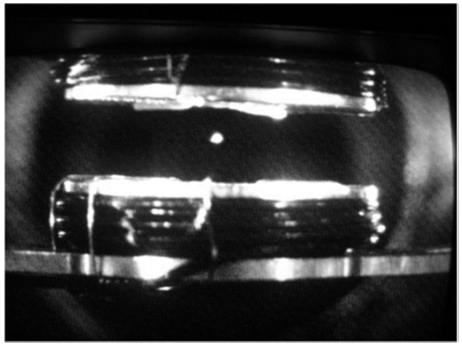


Pizzocaro, M. et al., IEEE Trans. On UFFC, 59, 426 - 431 (2012)

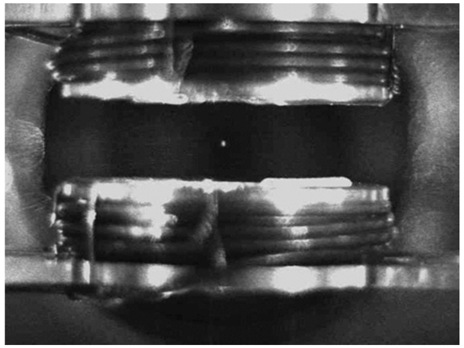
Yb Lattice Clock at INRIM

Old Chamber: Transfer of atoms in the green MOT

Blue MOT
($1x10^5$ atoms)



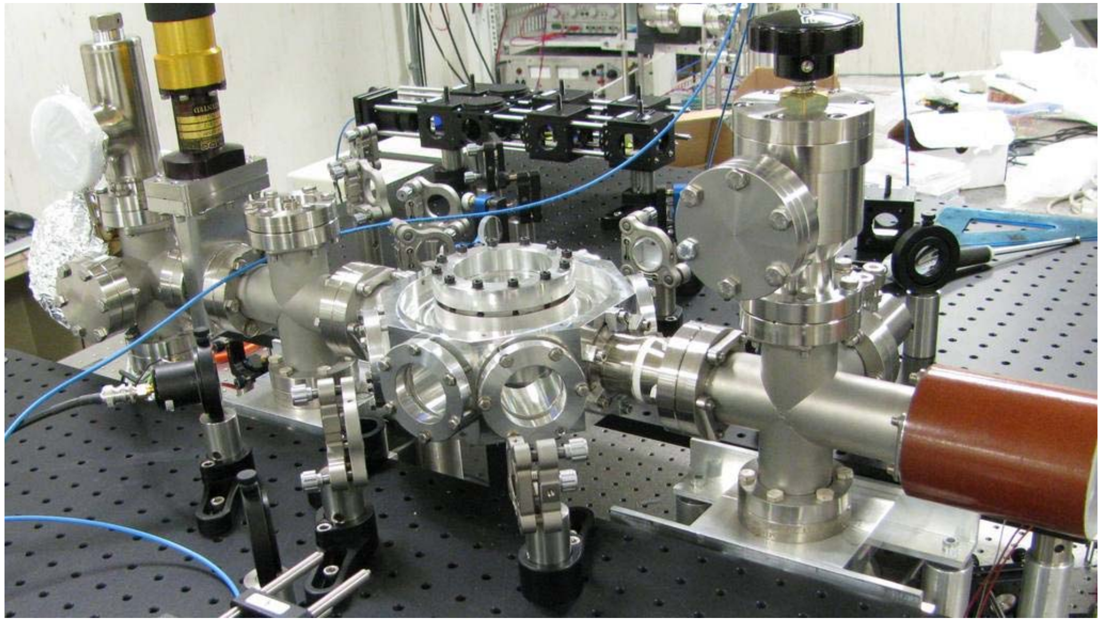
Green MOT
($4x10^4$ atoms)



Green MOT

- Fractional Transfer 40%
- Lifetime 1.25(6) s

Yb Lattice Clock at INRIM
New chamber is now being assembled



- Indium-sealed viewports
- Compact high efficiency oven
- Atomic beam shutter
- Increased number of trapped atoms expected
- Better vacuum
- Under operation early June

Coherent Optical link with commercial fiber