

# Orologi ottici e link in fibra: metrologia primaria di frequenza e fisica fondamentale.

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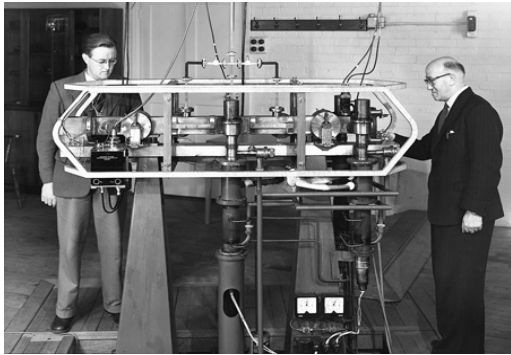


# Outline:

- Yb optical frequency standard
- The fiber link
- Applications and fundamental physics



# Atomic clocks accuracy in the last 50 years

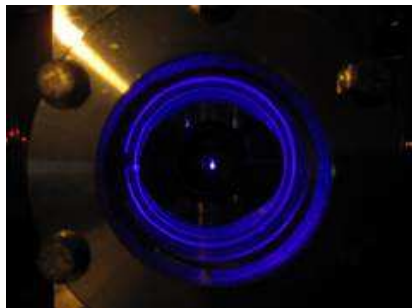


First Cs beam clock  
(1955)

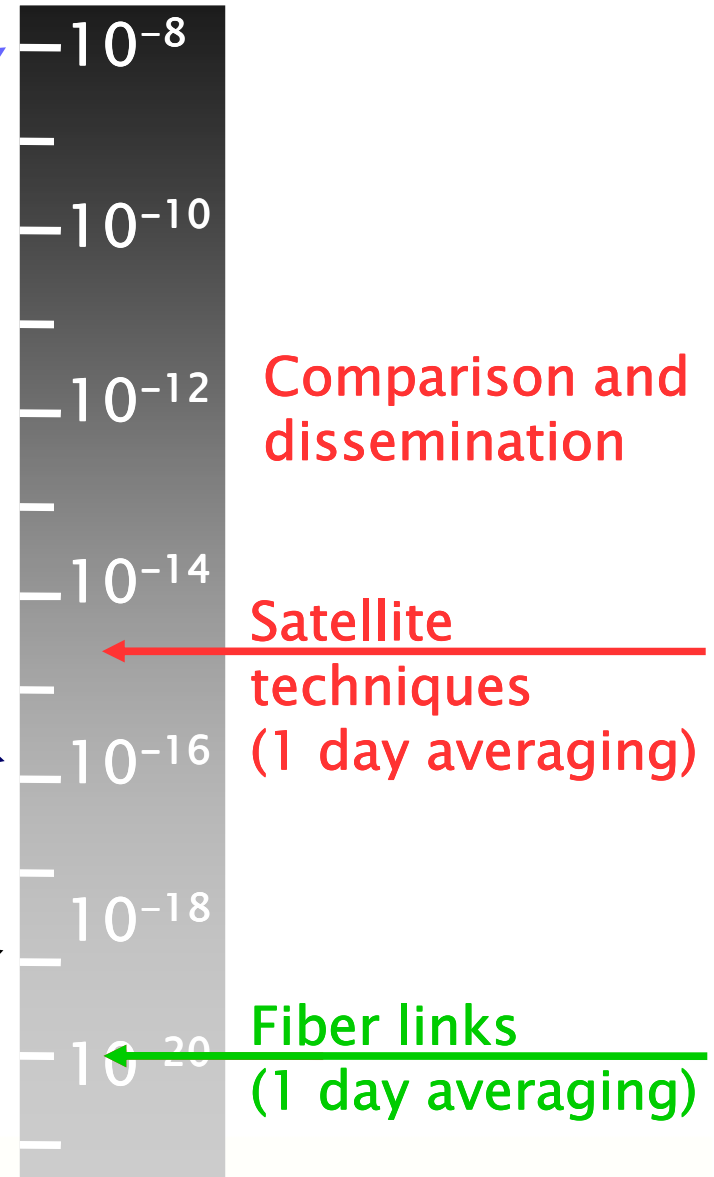


First Cs fountain  
(1996)

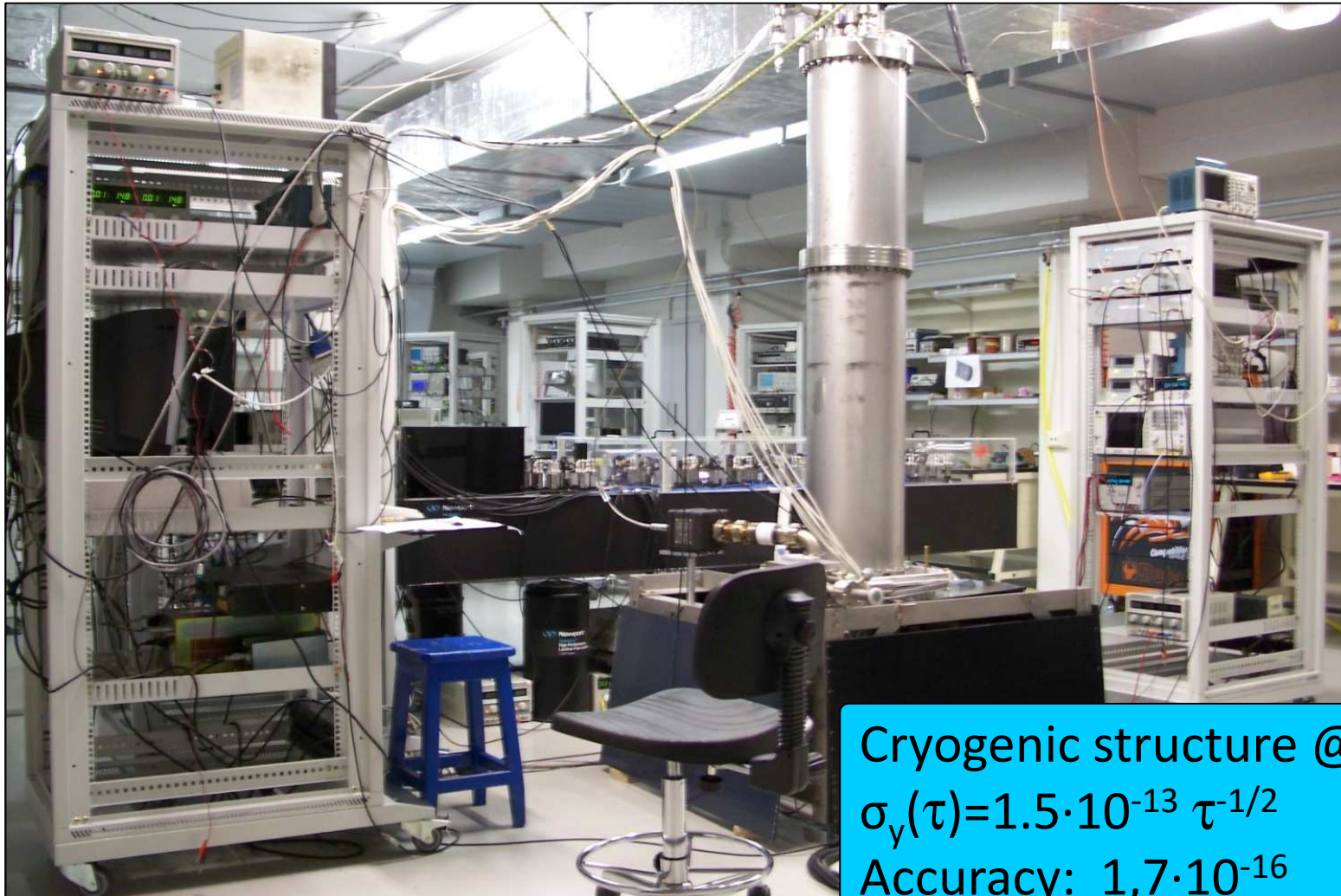
Cs fountain clocks  
(today)



Best optical clocks  
(today)



# Cs cryogenic fountain INRIM ITCsF2



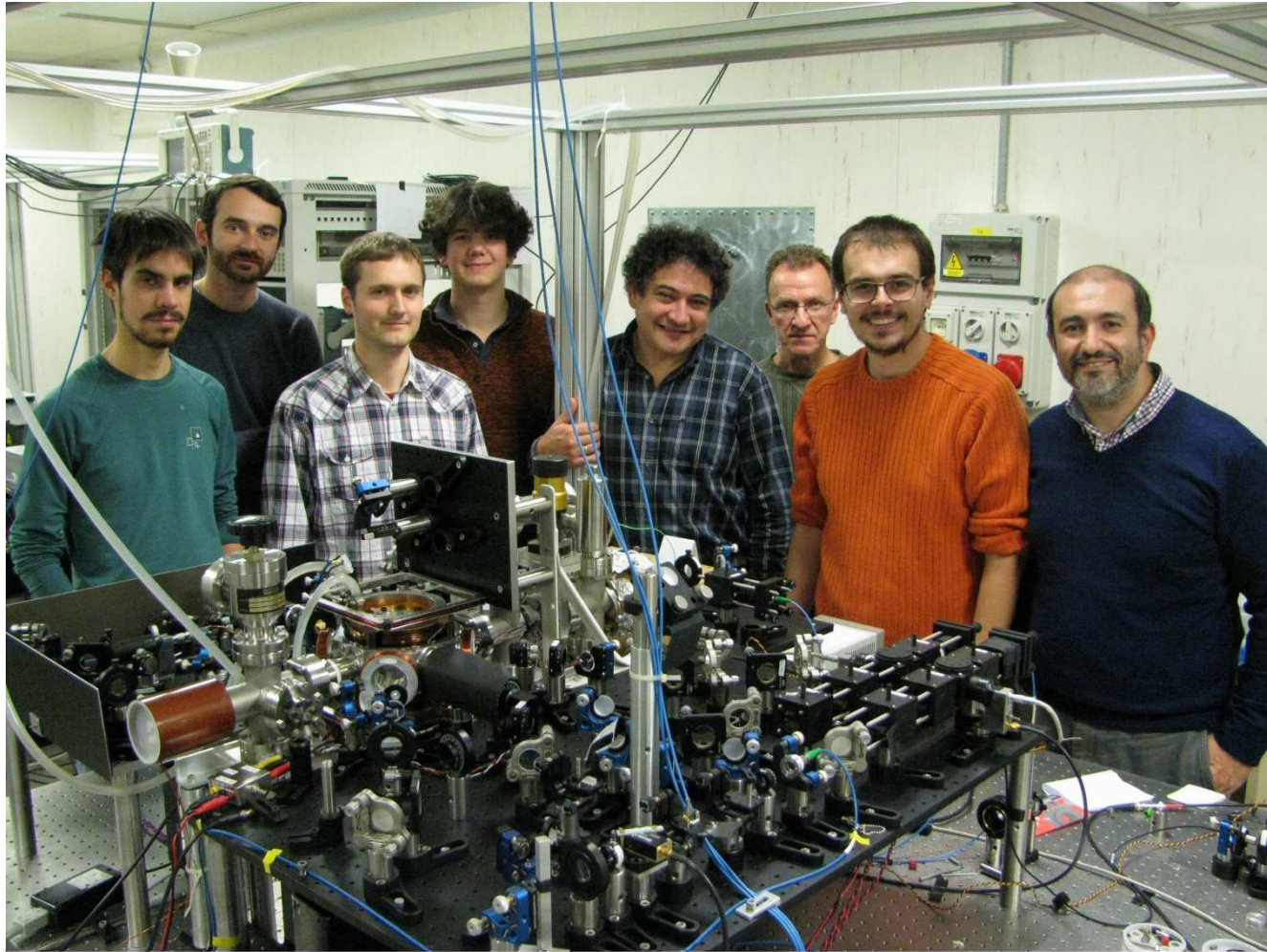
Cryogenic structure @ 89 K  
 $\sigma_y(\tau) = 1.5 \cdot 10^{-13} \tau^{-1/2}$   
Accuracy:  $1,7 \cdot 10^{-16}$

F. Levi, et al., Metrologia, 51, 270 (2014);

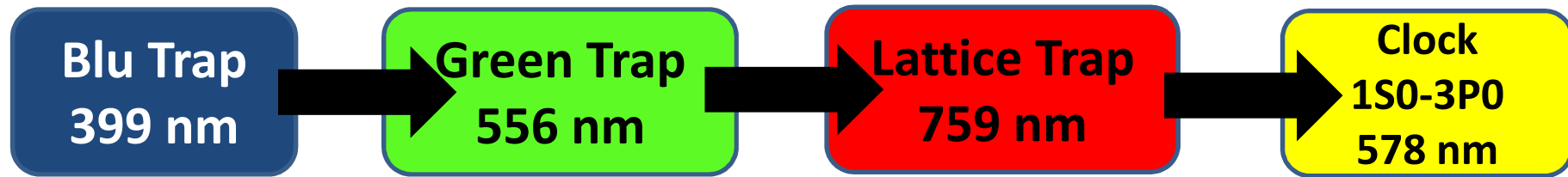
S. R. Jefferts et al. Phys Rev Lett, 112, 050801 (2014 )



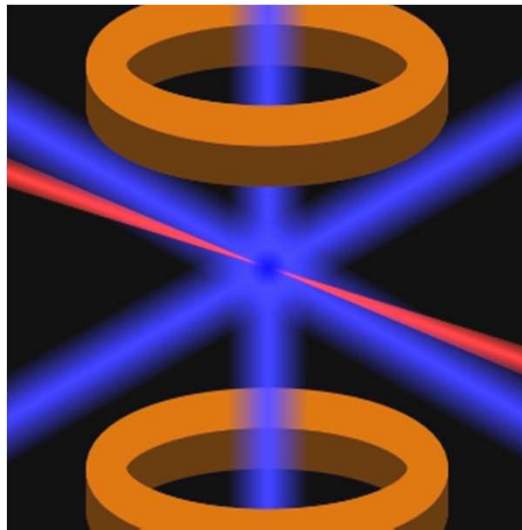
# Yb Lattice Clock at INRIM



# Yb optical clock: operation cycle

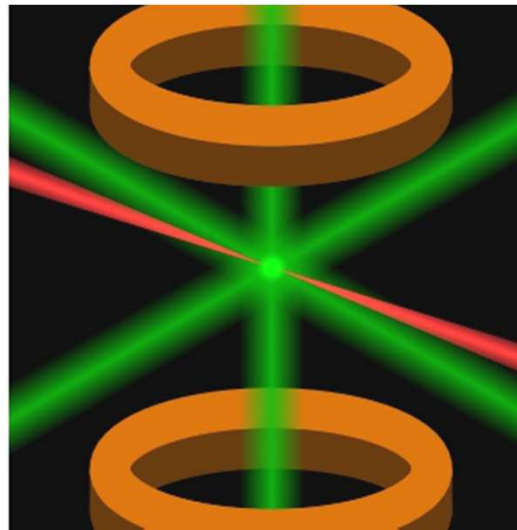


Yb @ 1 mK (20 cm/s)



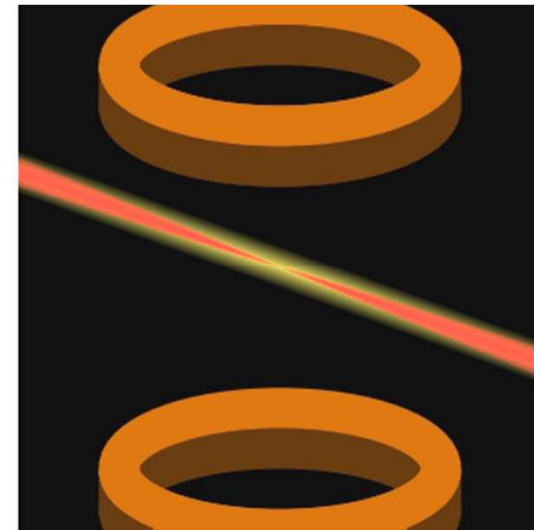
- **Blue MOT**  
Up to  $1 \times 10^7$  Yb171 Atoms  
150 ms loading time  
Oven temperature 400 °C

Yb @ 10  $\mu$ K (1 cm/s)



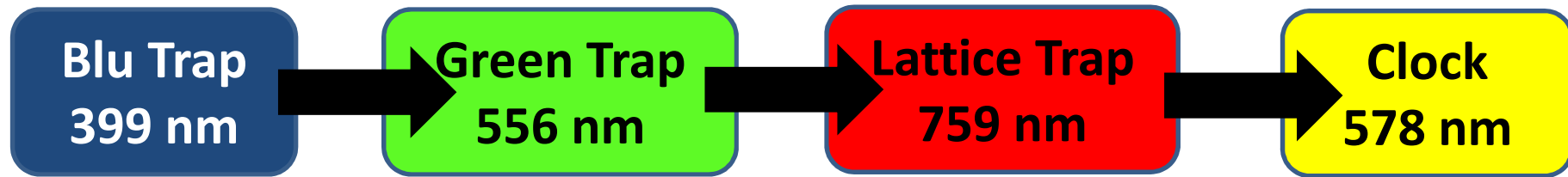
- **Green MOT**  
70% transfer efficiency  
3 frequency stages  
Atoms temperature 10  $\mu$ K

Yb localized @ 5  $\mu$ K

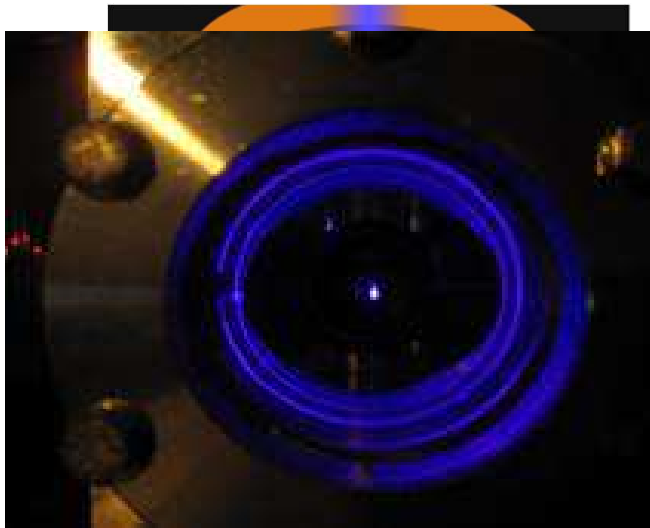


- **Lattice and Clock**  
Up to  $4 \times 10^4$  atoms  
Usually  $1 \times 10^4$  atoms  
3 s lifetime in the trap

# Yb optical clock: operation cycle



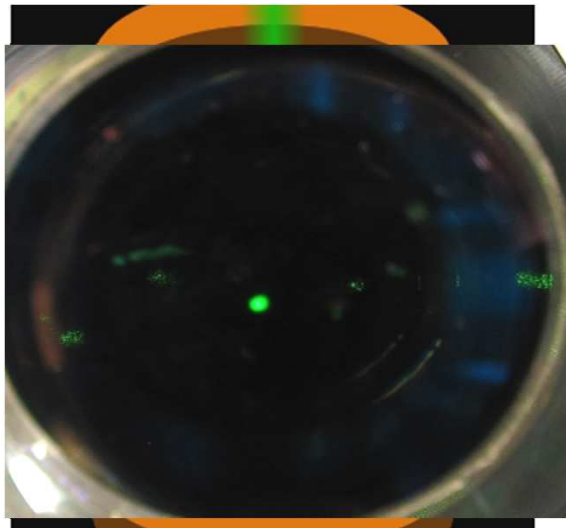
Yb @ 1 mK (20 cm/s)



- **Blue MOT**

Up to  $1 \times 10^7$  Yb171 Atoms  
150 ms loading time  
Oven temperature 400 °C

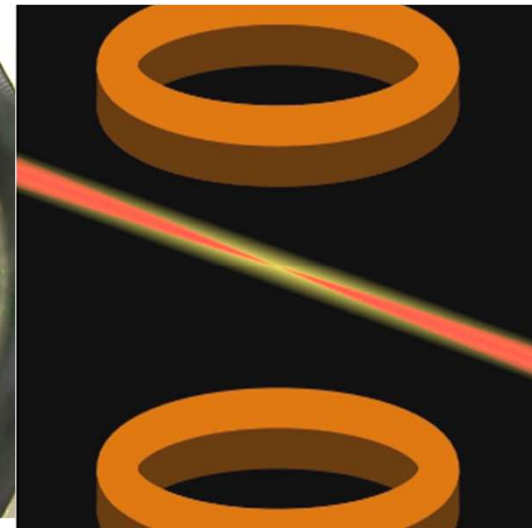
Yb @ 10  $\mu$ K (1 cm/s)



- **Green MOT**

70% transfer efficiency  
3 frequency stages  
Atoms temperature 10  $\mu$ K

Yb localized @ 5  $\mu$ K

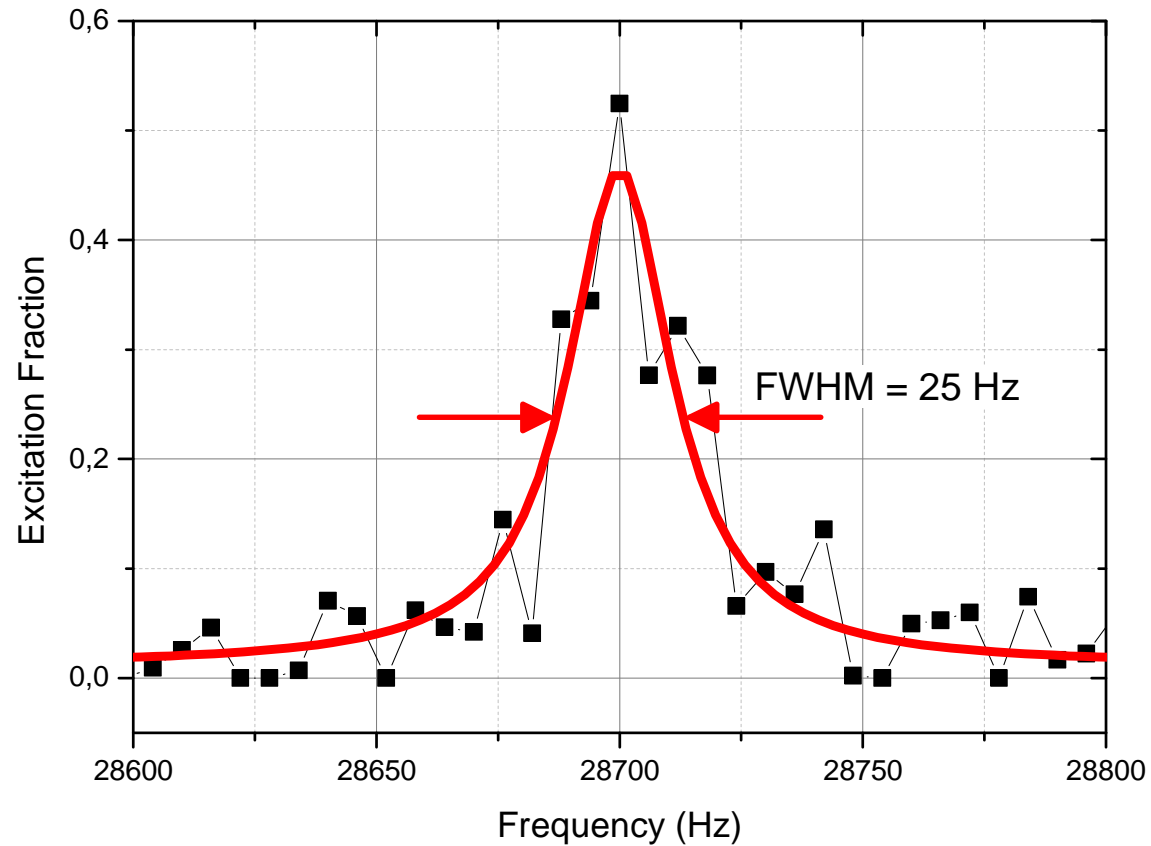


- **Lattice and Clock**

Up to  $4 \times 10^4$  atoms  
Usually  $1 \times 10^4$  atoms  
3 s lifetime in the trap



# Clock Spectroscopy



Present possibilities: resolution  $<10^{-16}$  in  $10^4$  s  
Target : 10x improvement



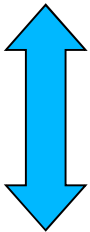
# Ongoing Yb absolute measurement

Optical Comb

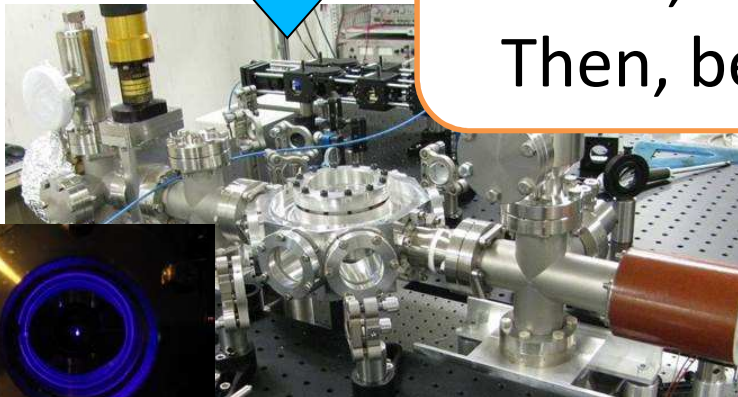


Cryogenic Cs fountain

Accuracy target:  
First,  $1 \times 10^{-17}$   
Then, beyond



H Masers



Yb lattice clock

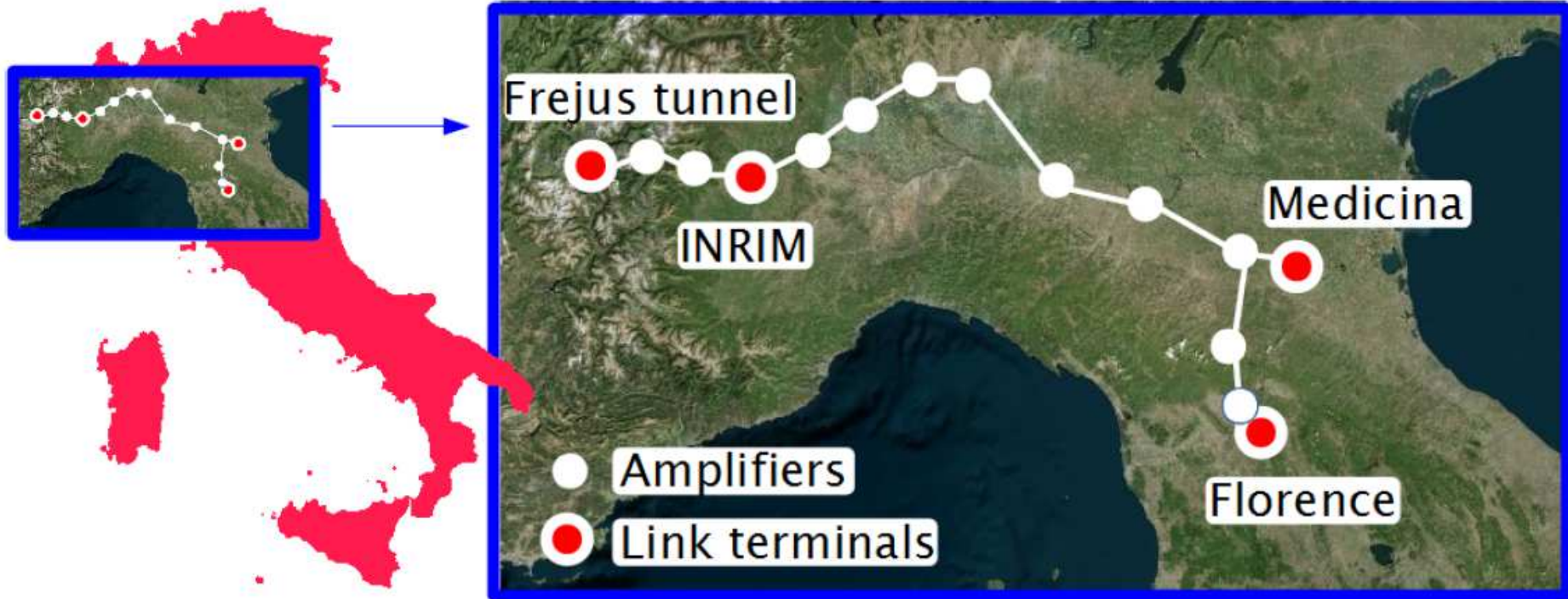


# Outline:

- Yb optical frequency standard
- **The fiber link**
- Applications and fundamental physics

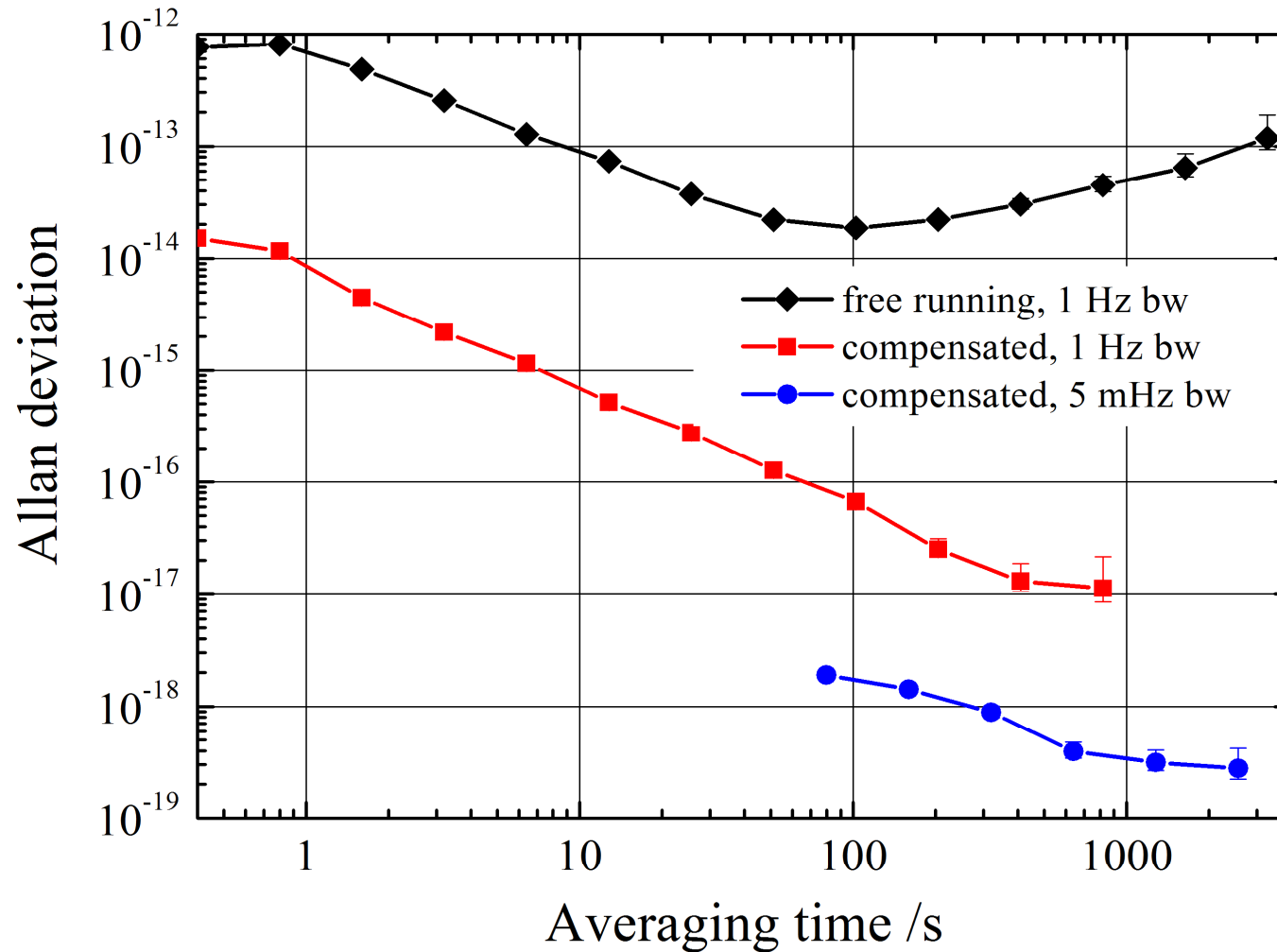
# LIFT

## Italian Link for Time and Frequency



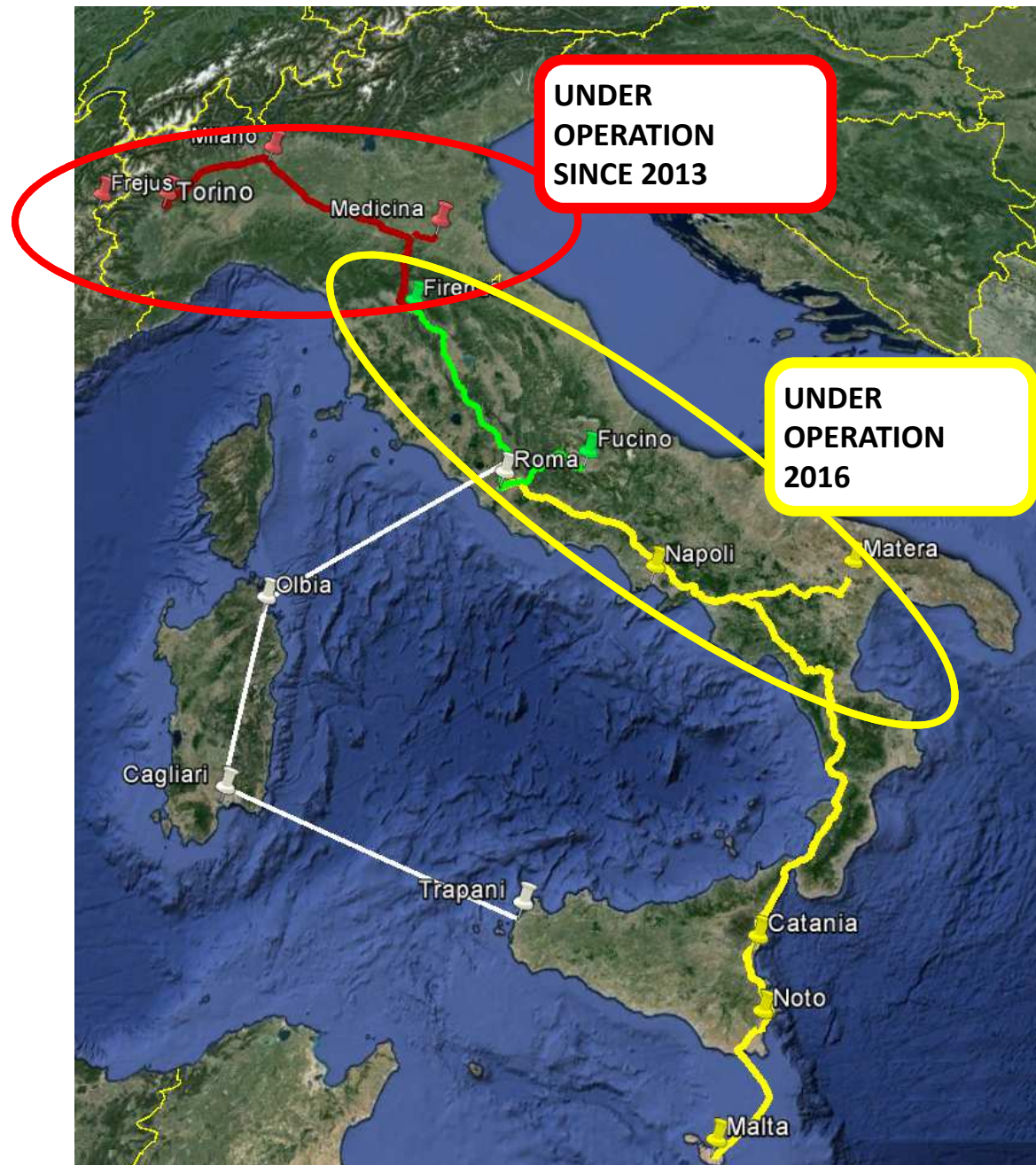
- ✓ Total Fiber Haul 800 km
- ✓ Two Commercial Dark Fibers available / DWDM and CWDM channels
- ✓ 11 bidirectional Erbium Doped Fiber Amplifier
- ✓ Fiber provided by Consortium GARR and Consortium TOP-IX

# Link uncertainty contribution, 642x2 km



There is not an offset between delivered and original signal at the  $5 \times 10^{-19}$  level

*D. Calonico et al., Applied Physics B, 117, 979 (2014).*



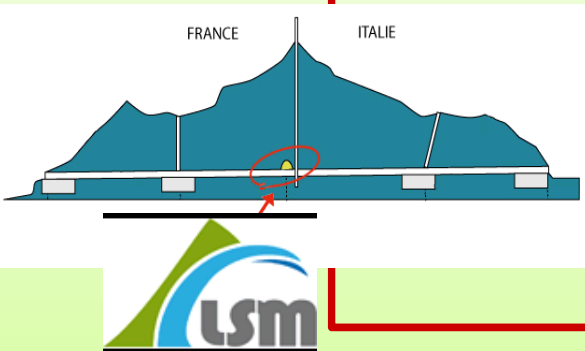
# LIFT FIBER LINK: extension

# Outline:

- Yb optical frequency standard
- The fiber link
- Applications and fundamental physics

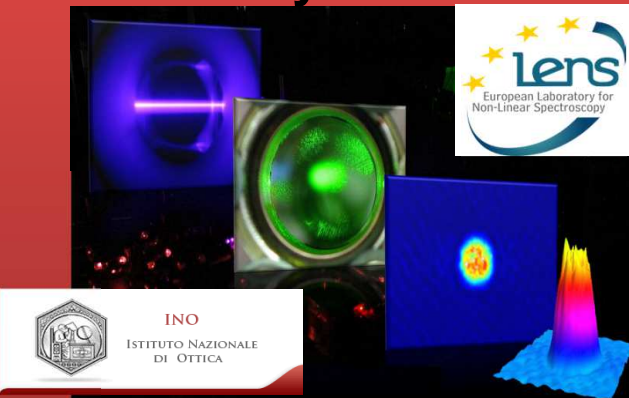
# LIFT present impact on research

### Frejus: Relativistic Geodesy




The diagram shows a cross-section of the Alps between France and Italy. A satellite is positioned in the sky, with a red circle around it. A red arrow points from the satellite towards the right, indicating the direction of the experiment. The LSM logo is at the bottom left.

### Firenze: Atomic and Molecular Physics



The collage includes images of a laser beam, a green laser beam, a blue laser beam, and a colorful spectrum. The Lens logo (European Laboratory for Non-Linear Spectroscopy) is in the top right. The INO logo (Istituto Nazionale di Ottica) is in the bottom left.


### Bologna Radio-astronomy VLBI



The image shows a large radio telescope dish in a field. The INAF logo (Istituto Nazionale di Astrofisica) is in the bottom right, with the text 'NATIONAL INSTITUTE FOR ASTROPHYSICS'. The location 'Cagliari' is written above the INAF logo, and 'Noto' is written below it.

### Matera

### Space Geodesy



The image shows a radio telescope dish. The ASI logo (Agenzia Spaziale Italiana) is in the top left.

# LIFT present impact on research

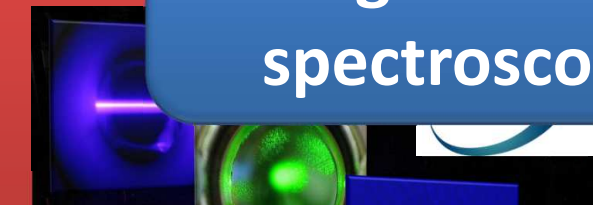
**Frejus: Relativistic Geodesy**

**Testing GR**



**Firenze: Molecular**

**INRIM/LENS**  
Yb degenerate gas spectroscopy



**INRIM/CNR**  
Cold molecules  
me/mp stability test

**Bologna**  
Radio-astronomy  
VLBI



**Matera**



**INRIM/INAF/ASI**  
Common clock VLBI





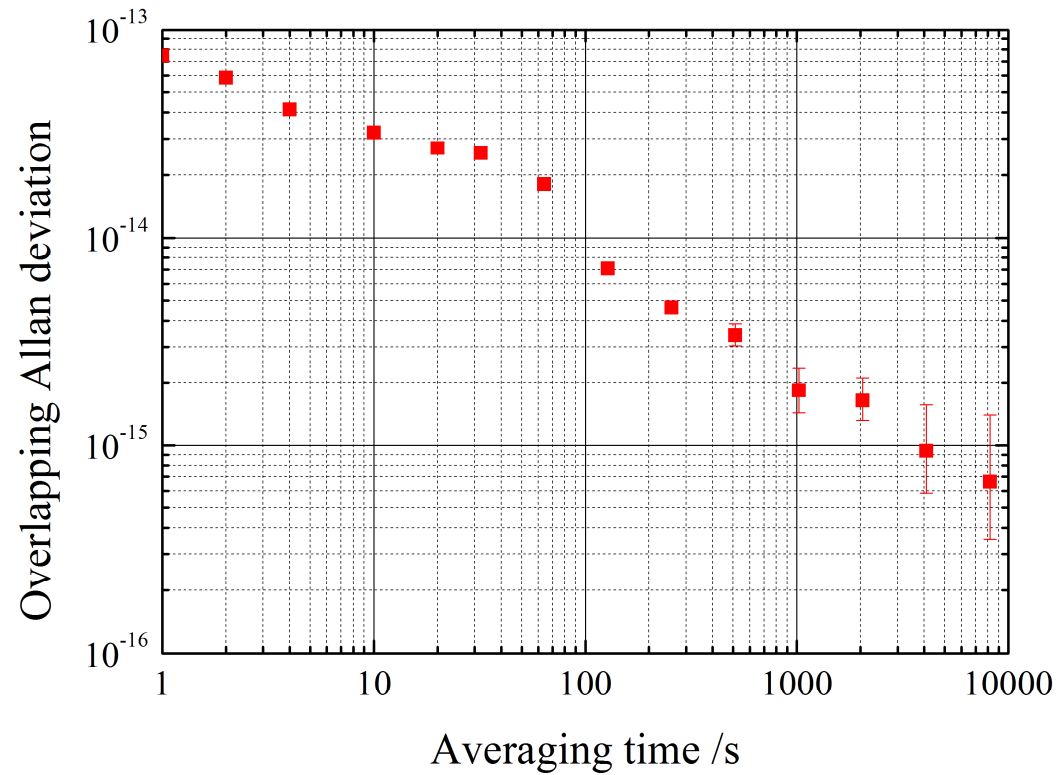
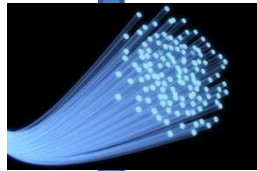
# Towards common clock VLBI: extension to Matera





# Towards radioastronomical application:

Medicina H- Maser vs INRIM fountain  
measured in real time using the fiber link



**(This result is not possible using Satellites techniques)**

*Accepted tbp on IEEE T-UFFC*

**Testing Einstein geodetic motion**  
**INRIM-ASI- ESA**  
**(July 2017- January 2019)**



Microwave Link  
Torino-ISS



Laser Ranging  
Matera-ISS

Optical Link  
Torino-Matera



**High accurate Atomic  
clocks**



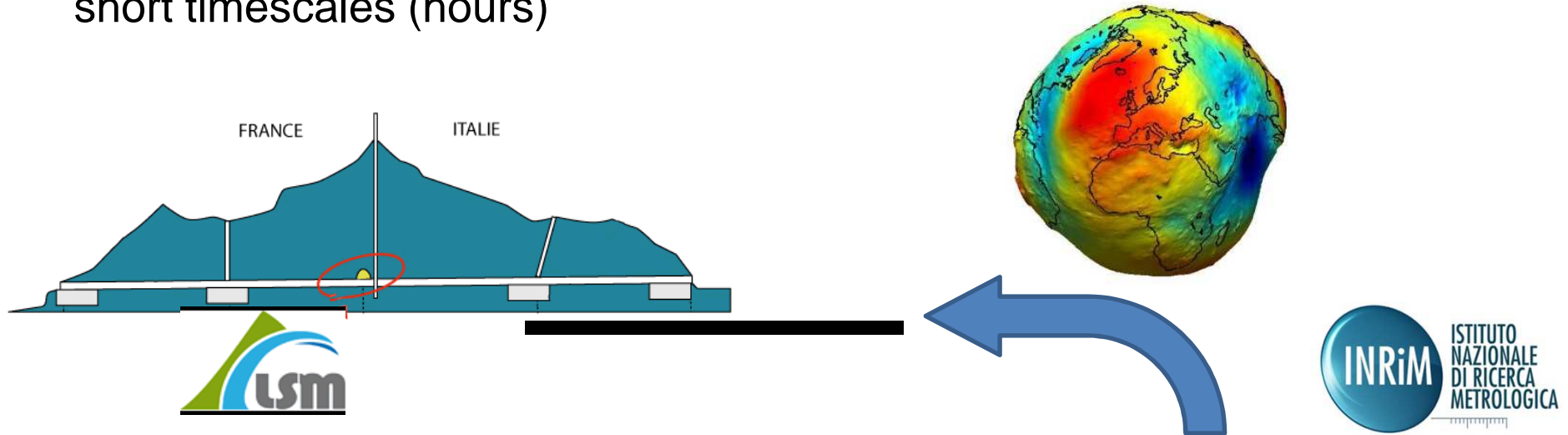
**1 500 km optical fiber**

**Space Geodesy  
Center Bepi  
Colombo**



# Relativistic Geodesy on the Alps

Given high accurate clocks and a fiber link connection, we can directly measure the potential difference at levels better than 10 cm ( $10^{-17}$ ) on short timescales (hours)

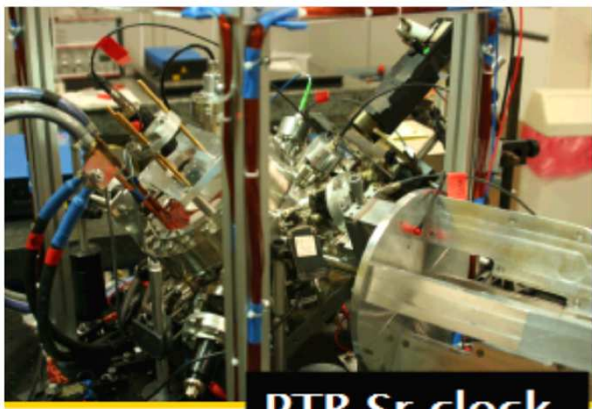


Frejus Tunnel, 1263 m

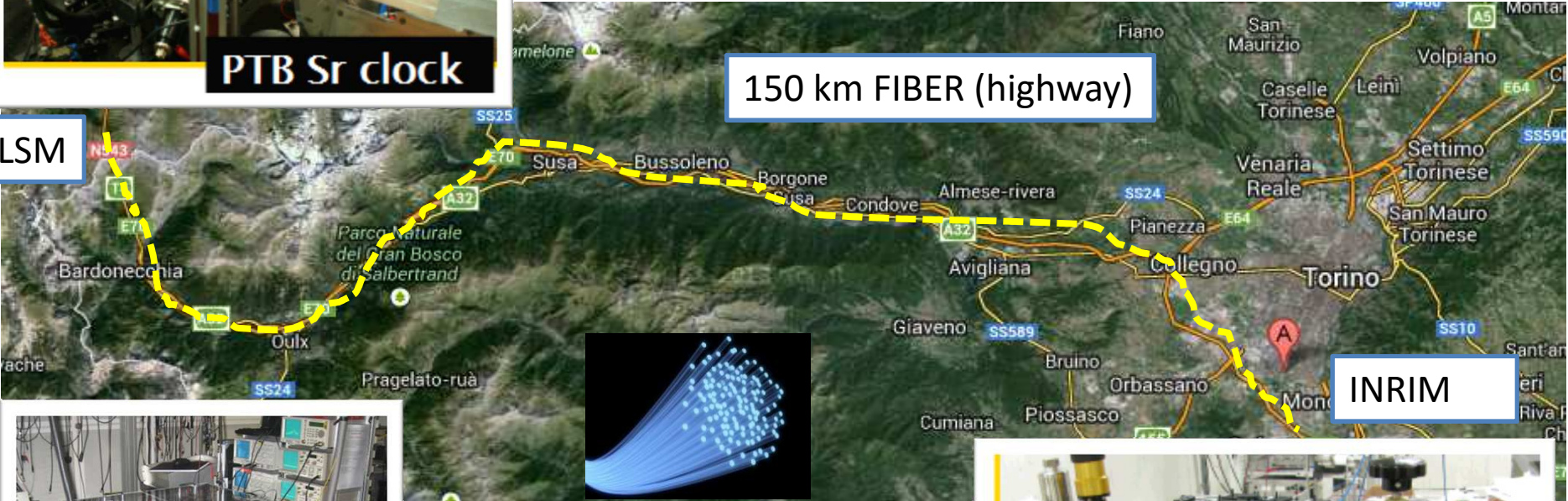
Torino, 240 m

1000 m height difference means frequency offset  $\sim 10^{-13}$  to be studied at a level better than  $10^{-17}$  (test level  $< 10^{-4}$ )

# Relativistic Geodesy on the Alps



LSM



# Optical Links in Europe



D. Calonico et al., *European Physics Letters* 110, 40001 (2015)

# Conclusions and perspectives

- INRIM ITCsF2 primary frequency standard with  $1.7 \times 10^{-16}$  accuracy.
- The Yb frequency standard is now under characterization.
- Up to 800 km of fiber connect different scientific sites by a coherent link

## **NEXT steps:**

- A second Yb clock
- The link extension in South Italy (Space Geodesy) and to Paris

## Perspectives:

Relativistic Geodesy

Radioastronomy

High accuracy spectroscopy

Redefinition of the second

# Thanks to...

## Thank you for your attention



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➤ the European Metrology Research Programme (EMRP) under SIB-02 NEAT-FT and SIB55-ITOC.

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



**EMRP**  
European Metrology Research Programme  
Programme of EURAMET



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# INRIM Atomic Frequency Standards Group

