Tecnologie Fotoniche per la Metrologia Primaria di Tempo e Frequenza

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INRiM
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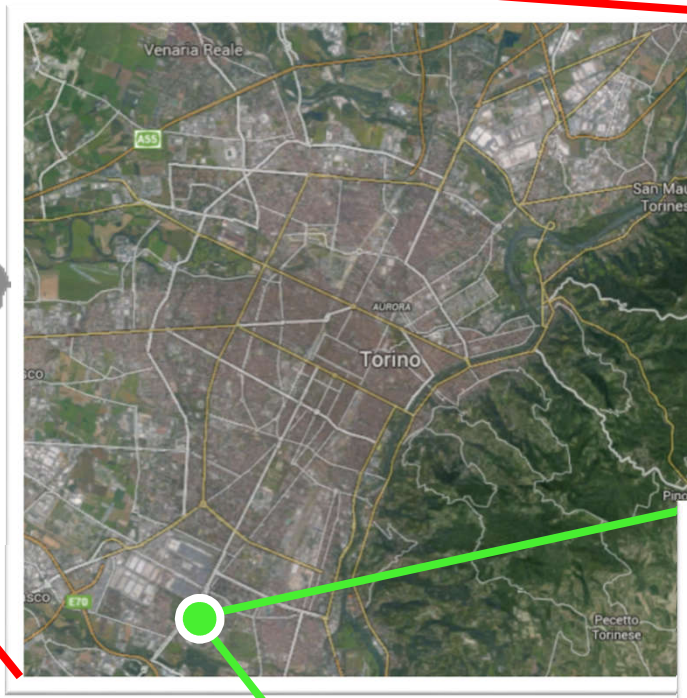
DI RICERCA METROLOGICA

POLITECNICO DI TORINO 1859 1906

PHOTONEXT

Buon compleanno!

INRIM IN BREVE



INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

- Istituto Metrologico Nazionale
- Realizza e Diffonde le unità campione
- 4° Istituto Metrologico in Europa
- 5° Ente Pubblico di Ricerca in Italia
- Forte Legame con Università e industria

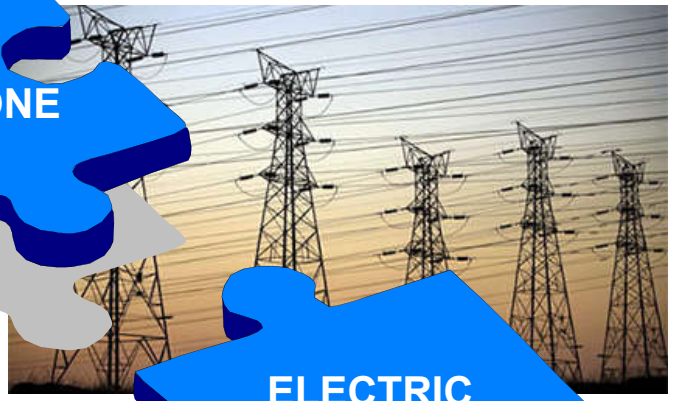
Time and Frequency Metrology:
Cui prodest? ….and what about Photonics?

Utenti T&F

POSITIONING

TELECOMUNICAZIONI

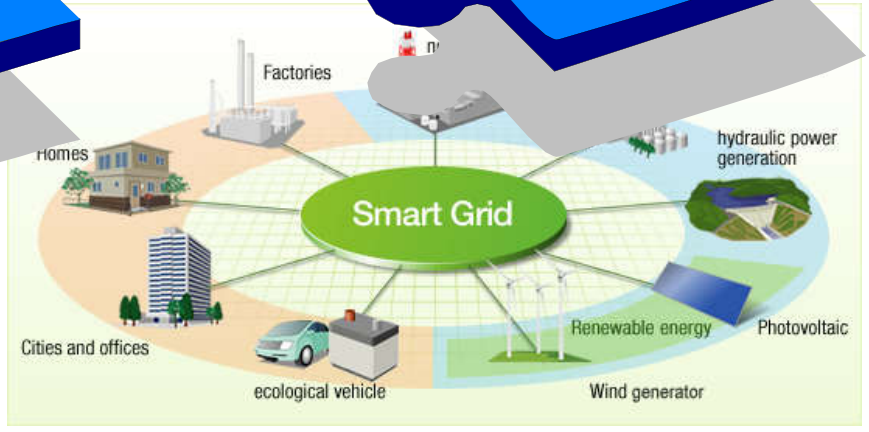
DATAZIONE



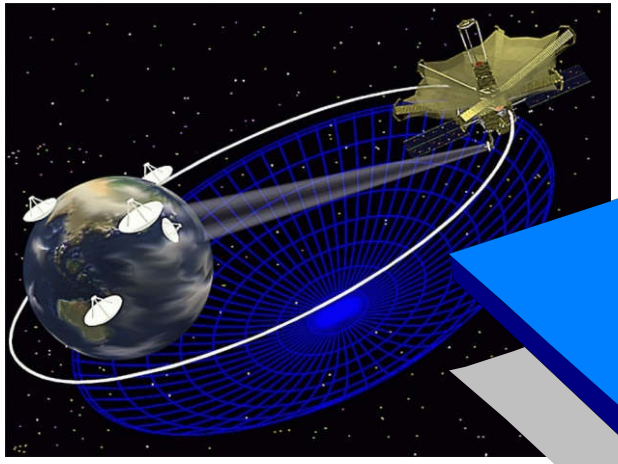
TRASPORTI

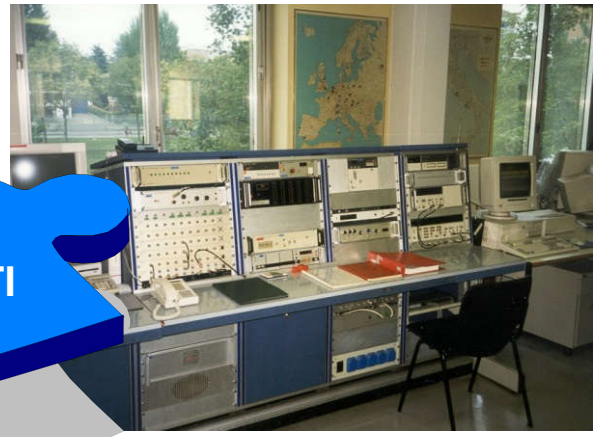
ELECTRIC POWER

E-COMMERCE



Utenti T&F

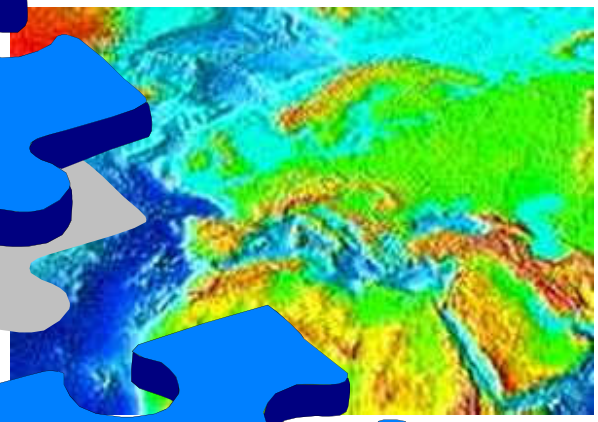




STRUMENTI

SPAZIO

GEODESIA

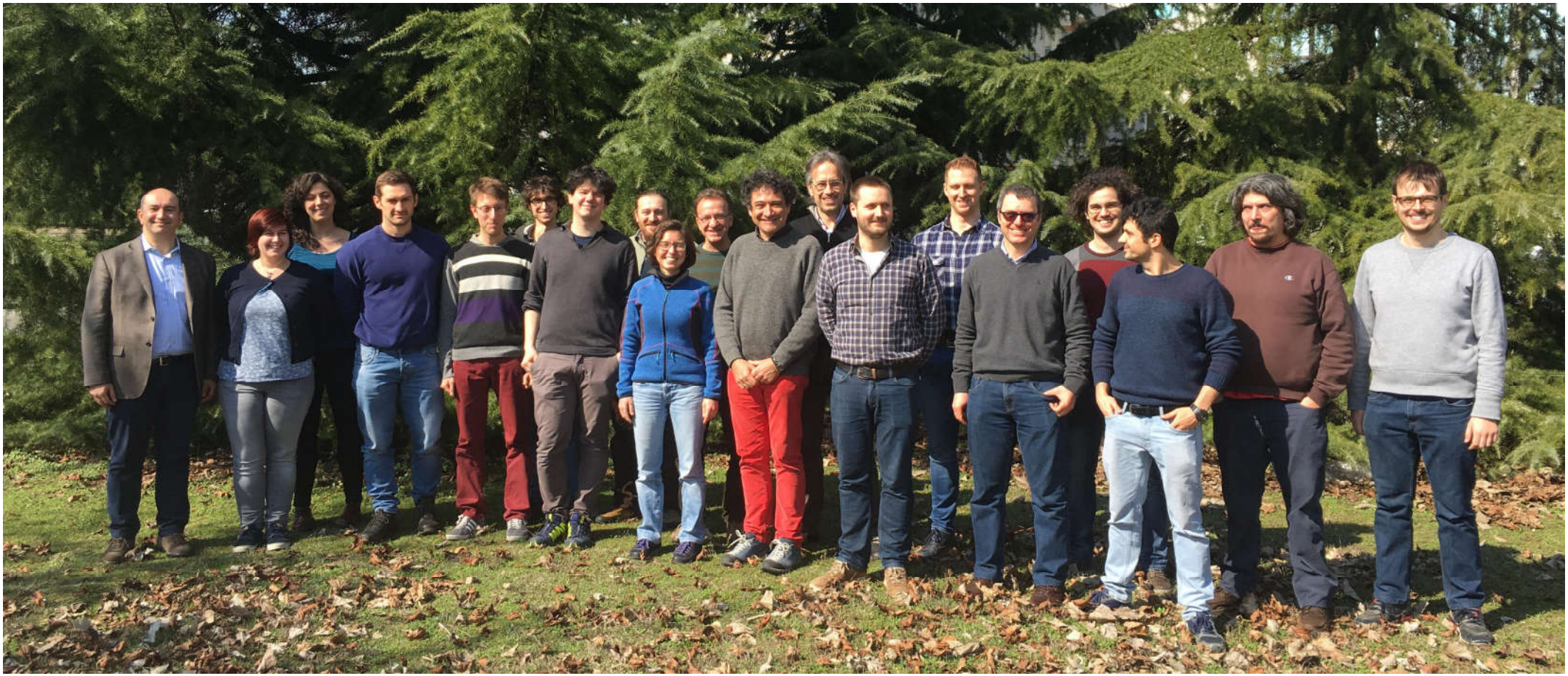


RICERCA FONDAMENTALE

AGRICOLTURA

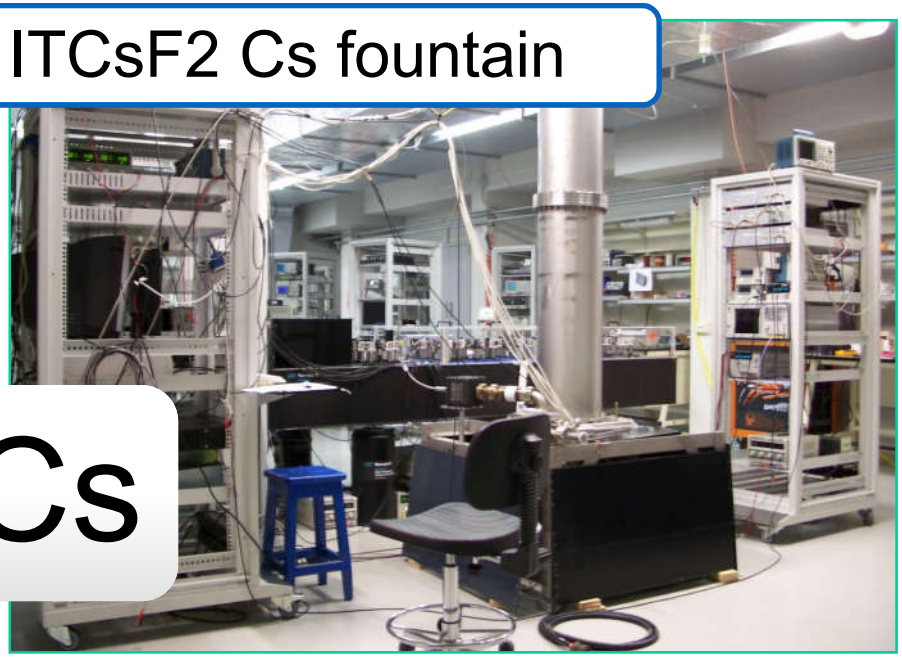
DIFESA

INRIM 2018 : Atomic Frequency Standards



INRIM 2018 : Atomic Frequency Standards

ITCsF2 Cs fountain

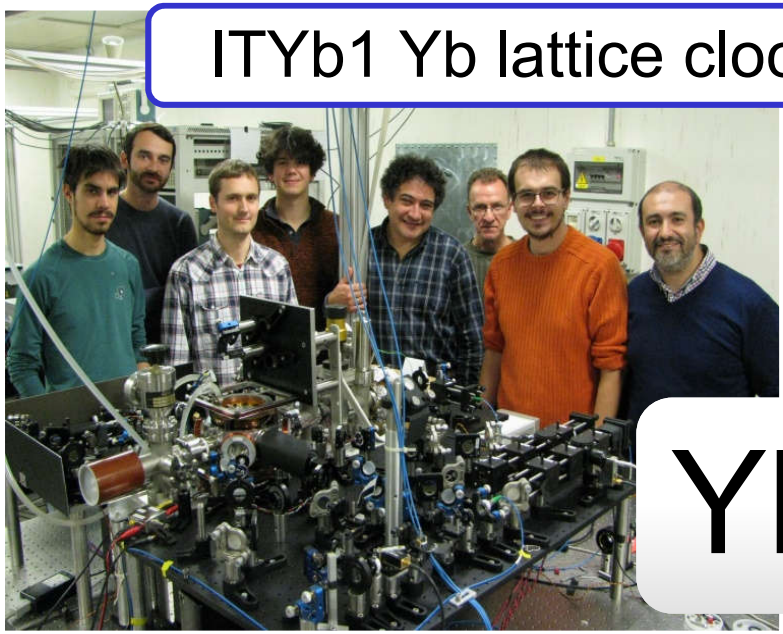


Cs

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

Accuracy: 2e-16

ITYb1 Yb lattice clock

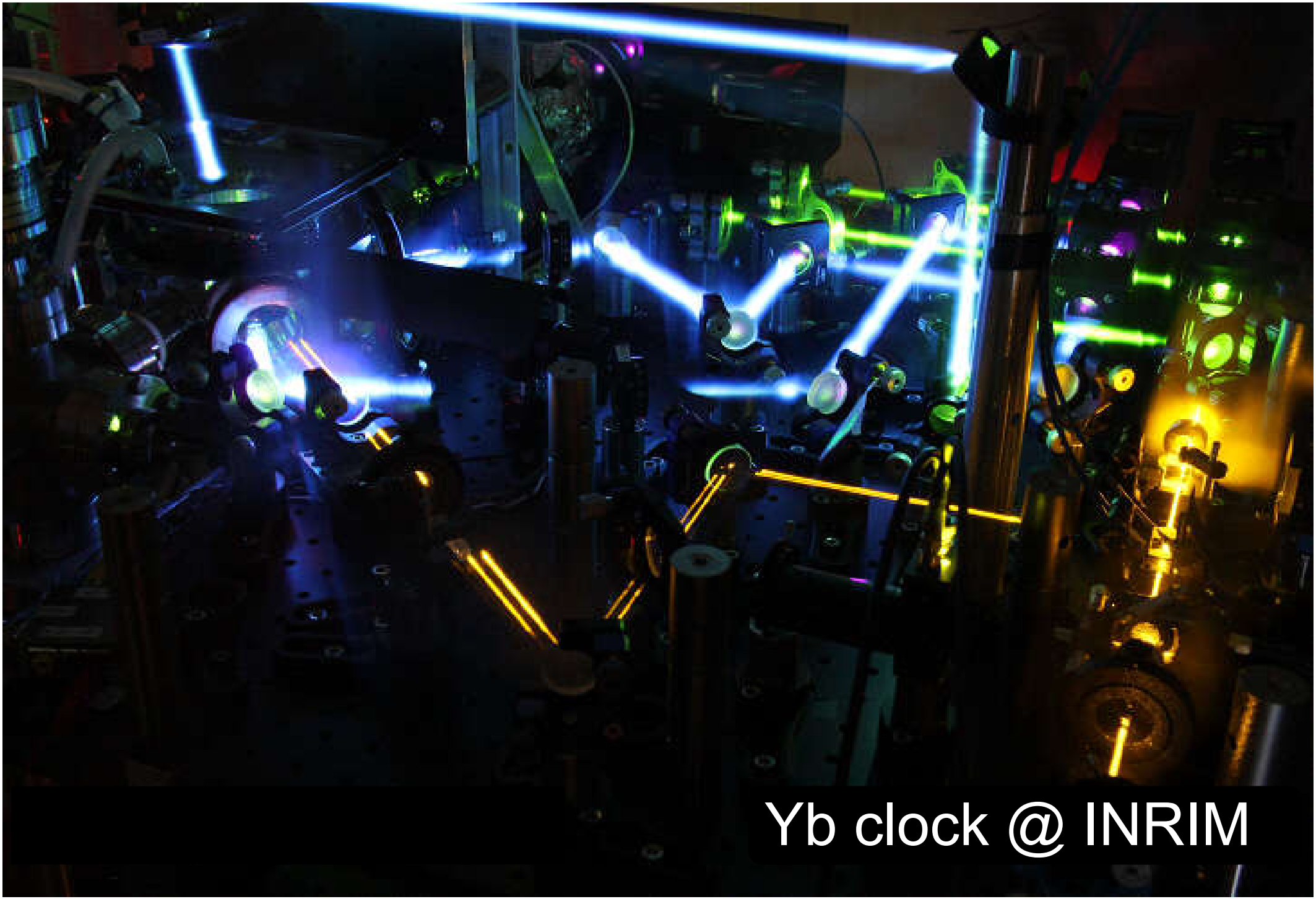


Yb

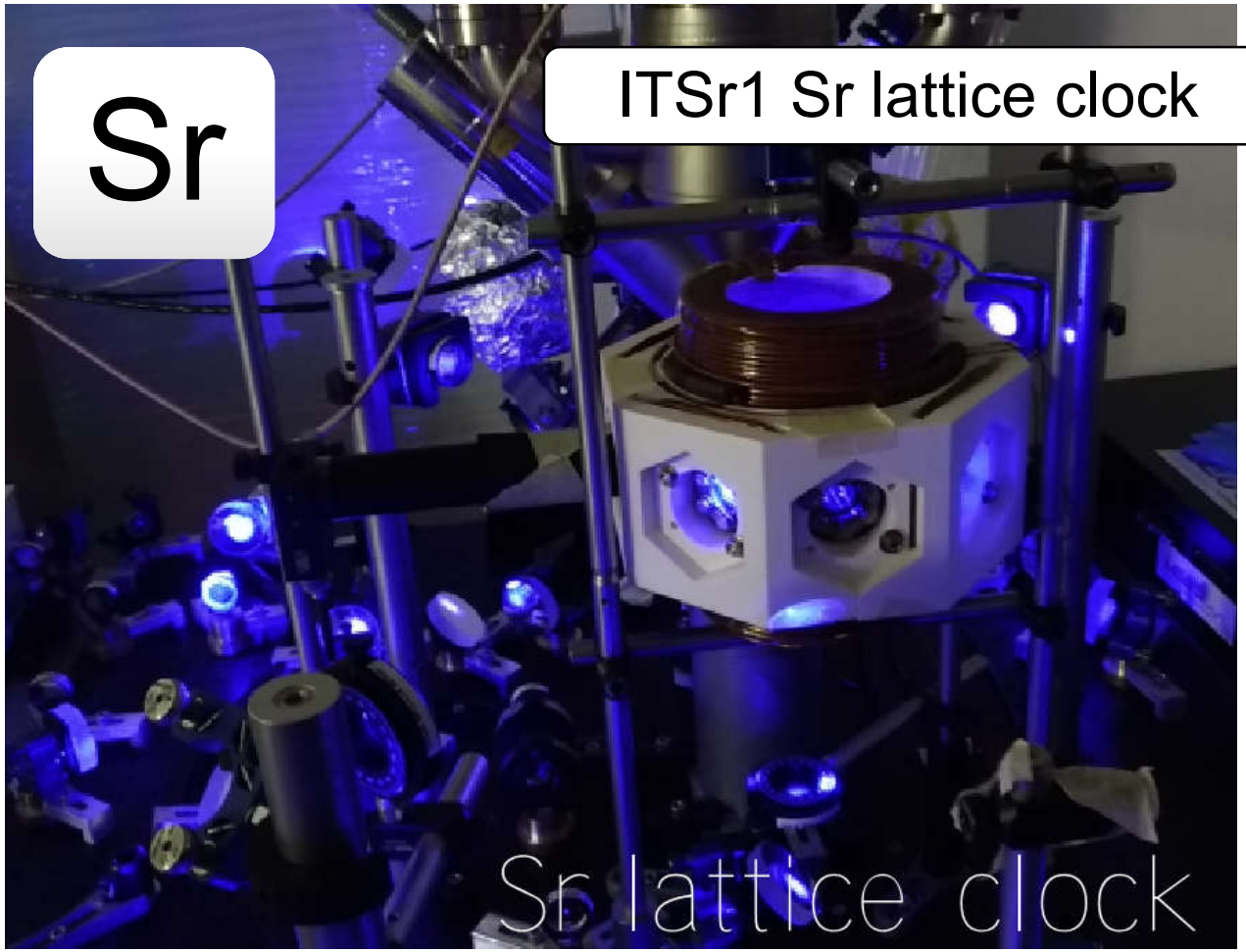
M. Pizzocaro, et al., Metrologia, 54, 102 (2017);

Accuracy: 4e-17

Realization of the SI second in Italy.
UTC(IT) timescale.
Towards redefinition of the second by optical clocks


Yb clock @ INRIM

INRIM 2018 : Atomic Frequency Standards

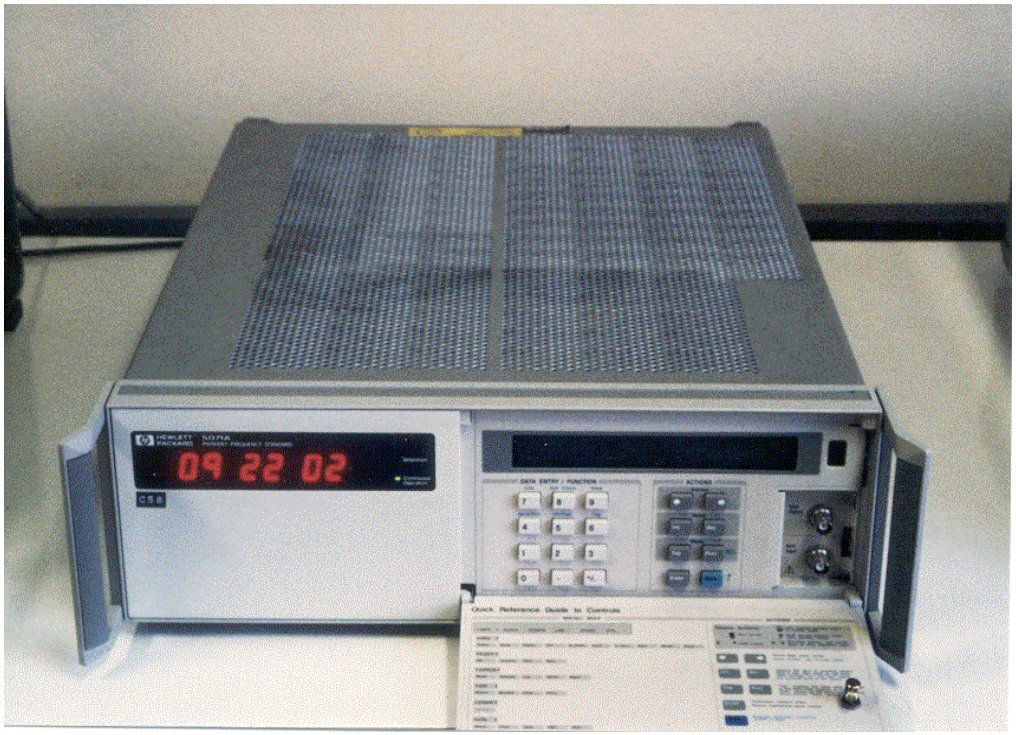


In progress:

- possible ridefinition of the second
- Quantum Technologies (Optical Clock enhanced by Quantum Squeezing)

INRIM 2018 : Atomic Frequency Standards

6 orologi commerciali al Cesio



≈40 cm

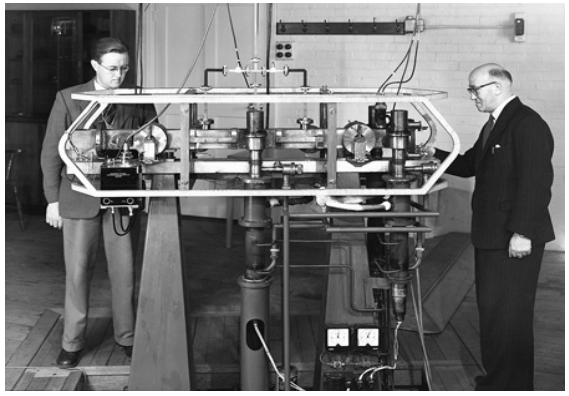
Orologio al Cesio commerciale

4 orologi commerciali all'Idrogeno

≈1 m

Maser all'Idrogeno commerciale

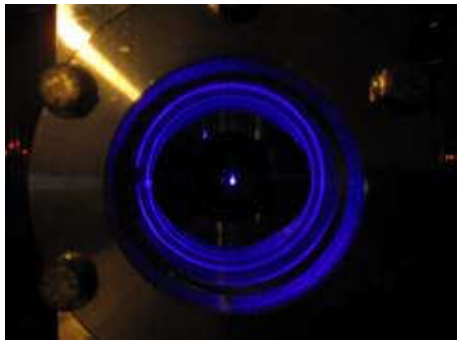
Atomic clocks relative accuracy



First Cs beam clock
(1955)

First Cs fountain
(1996)

Cs fountain clocks
(today)



Best optical clocks
(today)

10^{-8}

10^{-10}

10^{-12}

10^{-14}

Satellite
techniques
(1 day averaging)

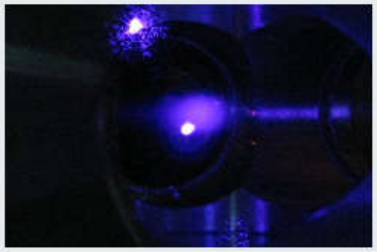
10^{-16}

10^{-18}

10^{-20}

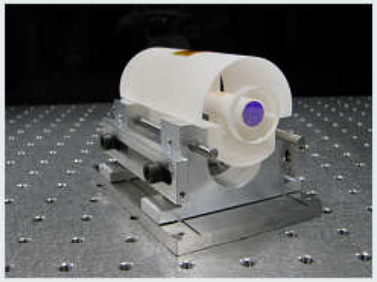
Optical links
(1 day averaging)

Critical technologies for Optical Clocks

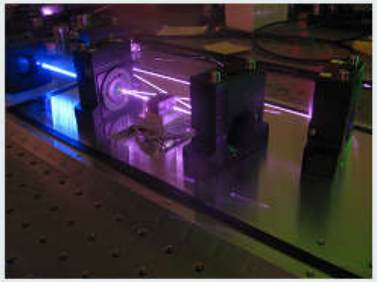


Laser cooling & trapping of neutral atoms and single ions

- Long interaction time
- Suppression of Doppler shifts



Stabilization of laser frequency on high-finesse Fabry-Pérot cavities and **hertz-wide lasers**, needed for high-resolution spectroscopy.



Non-linear optics exploited to generate the laser wavelengths for cooling and probing.

The introduction of the **optical frequency comb** made possible to directly and reliably scale a frequency measurement from the optical to the microwave domain.

Pettine Ottico di Frequenza: Uno strumento da Nobel

Ted Haensch
Premio Nobel in Fisica 2005

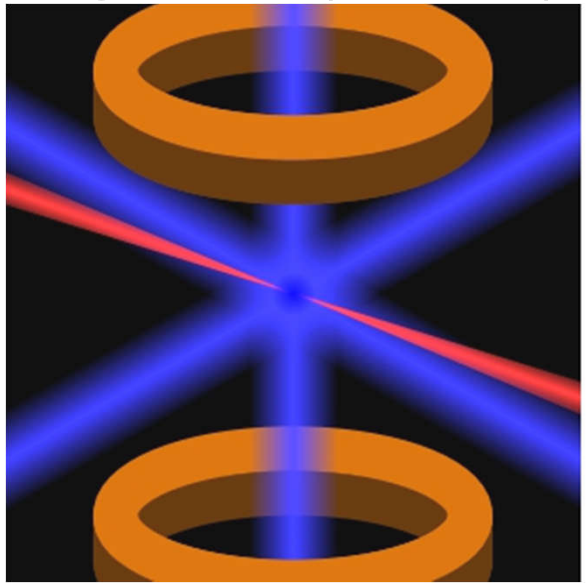
The headquarters of Menlo Systems in Martinsried outside Munich.

Nel 2001, fonda l'azienda
che produce i Pettini Ottici
Oggi impiega 80 ricercatori
Con un fatturato >4 Meuro

Yb optical clock: operation cycle

Blu Trap 399 nm → **Green Trap 556 nm** → **Lattice Trap 759 nm** → **Clock 578 nm**

Yb @ 1 mK (20 cm/s)



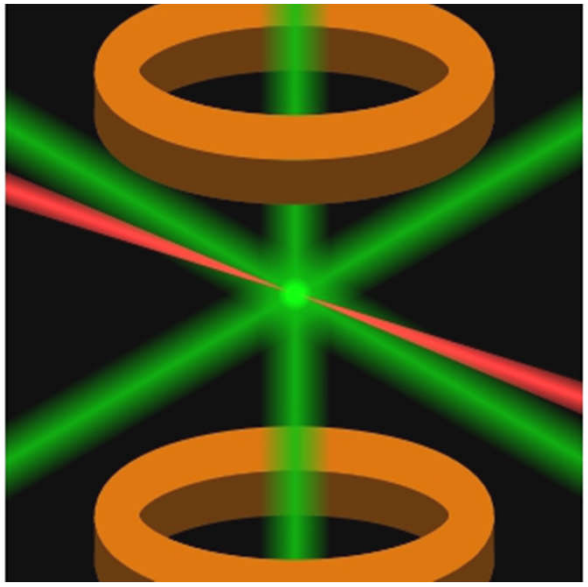
- **Blue MOT**

Up to 1x10^{7} Yb171 Atoms

150 ms loading time

Oven temperature 400 °C

Yb @ 10 μK (1 cm/s)



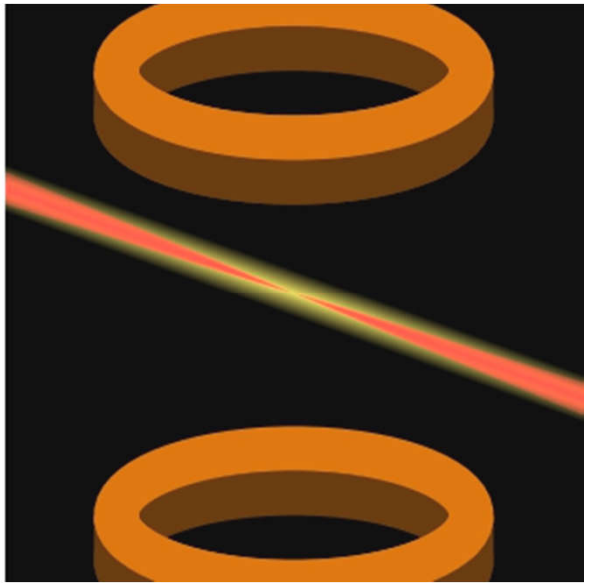
- **Green MOT**

70% transfer efficiency

3 frequency stages

Atoms temperature 10 μK

Yb localized @ 5 μK



- **Lattice and Clock**

Up to 4)x10^{4} atoms

Usually 1x10^{4} atoms

3 s lifetime in the trap

Yb optical clock: operation cycle

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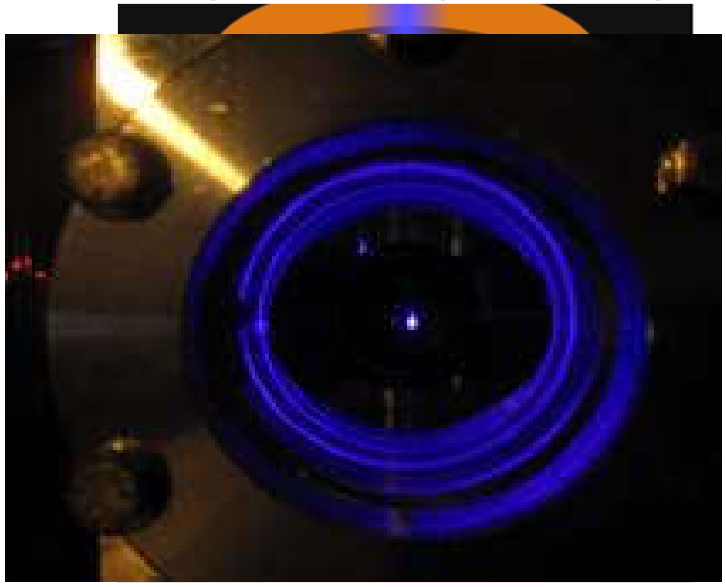
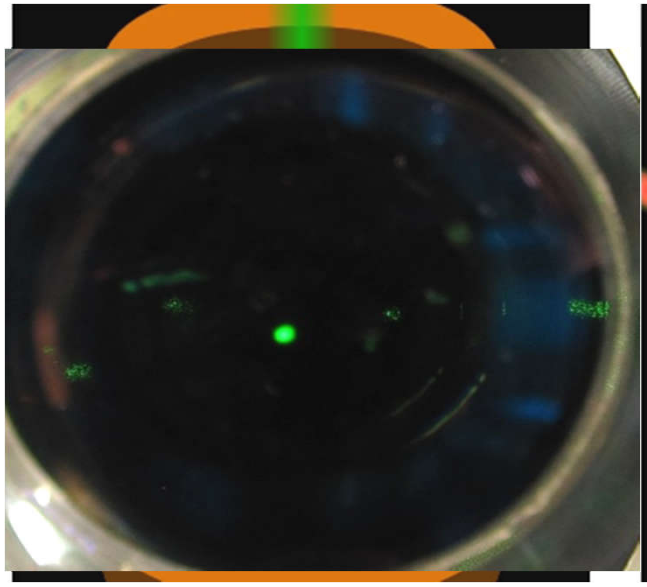
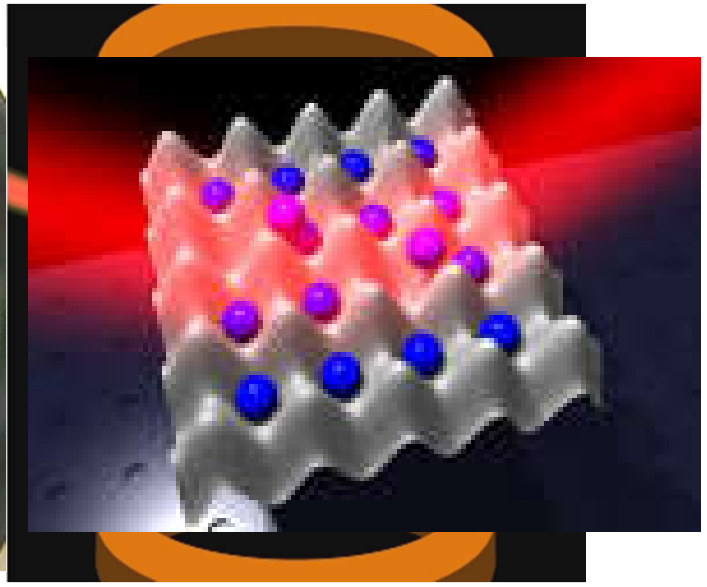
Yb @ 1 mK (20 cm/s)



Yb @ 10 μK (1 cm/s)



Yb localized @ 5 μK



- **Blue MOT**

Up to 1x10^7 Yb171 Atoms
150 ms loading time
Oven temperature 400 °C

- **Green MOT**

70% transfer efficiency
3 frequency stages
Atoms temperature 10 μK

- **Lattice and Clock**

Up to 4)x10^4 atoms
Usually 1x10^4 atoms
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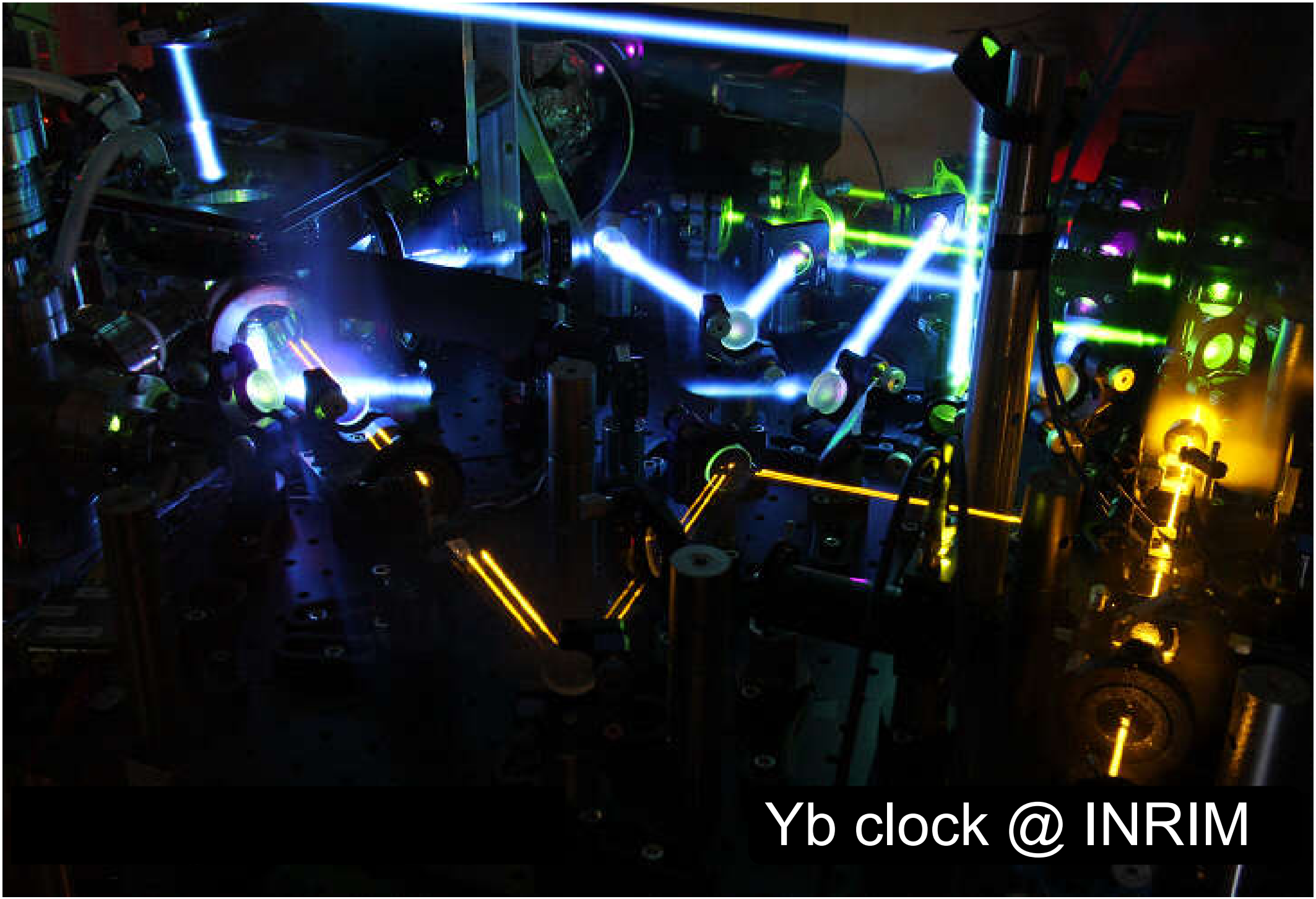
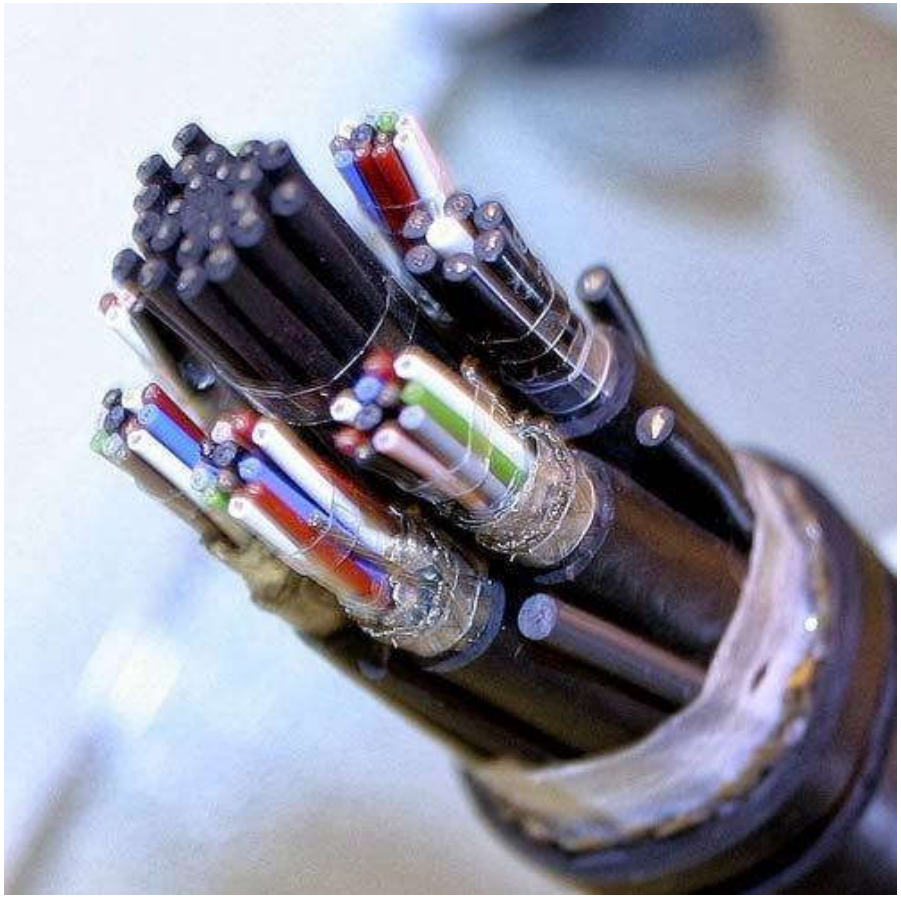

Yb clock @ INRIM

Standard telecommunication optical fibre



- Coherent Technique
- “Protocol based” Techniques

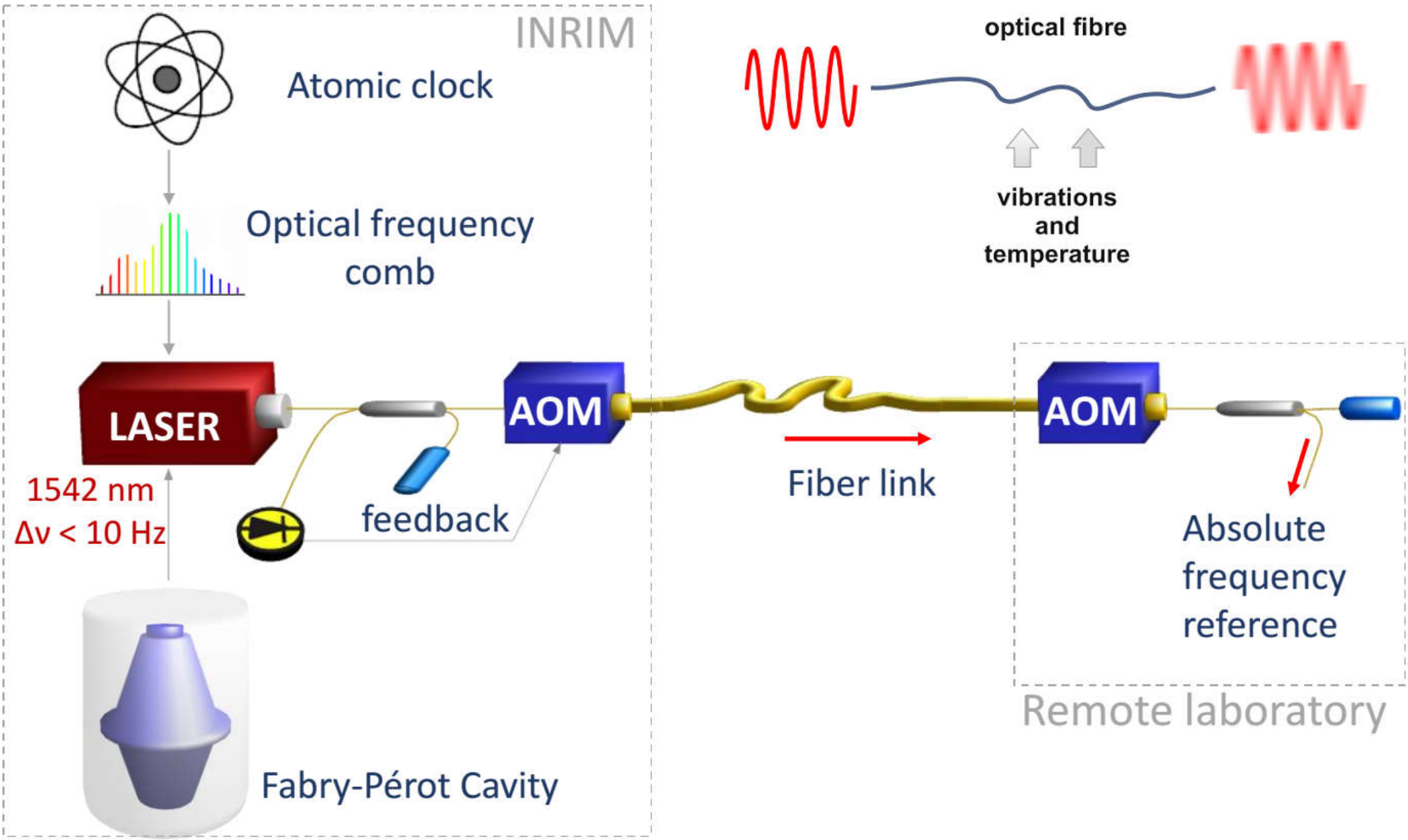
- Single fibre
- Fibre pair

Architectures:

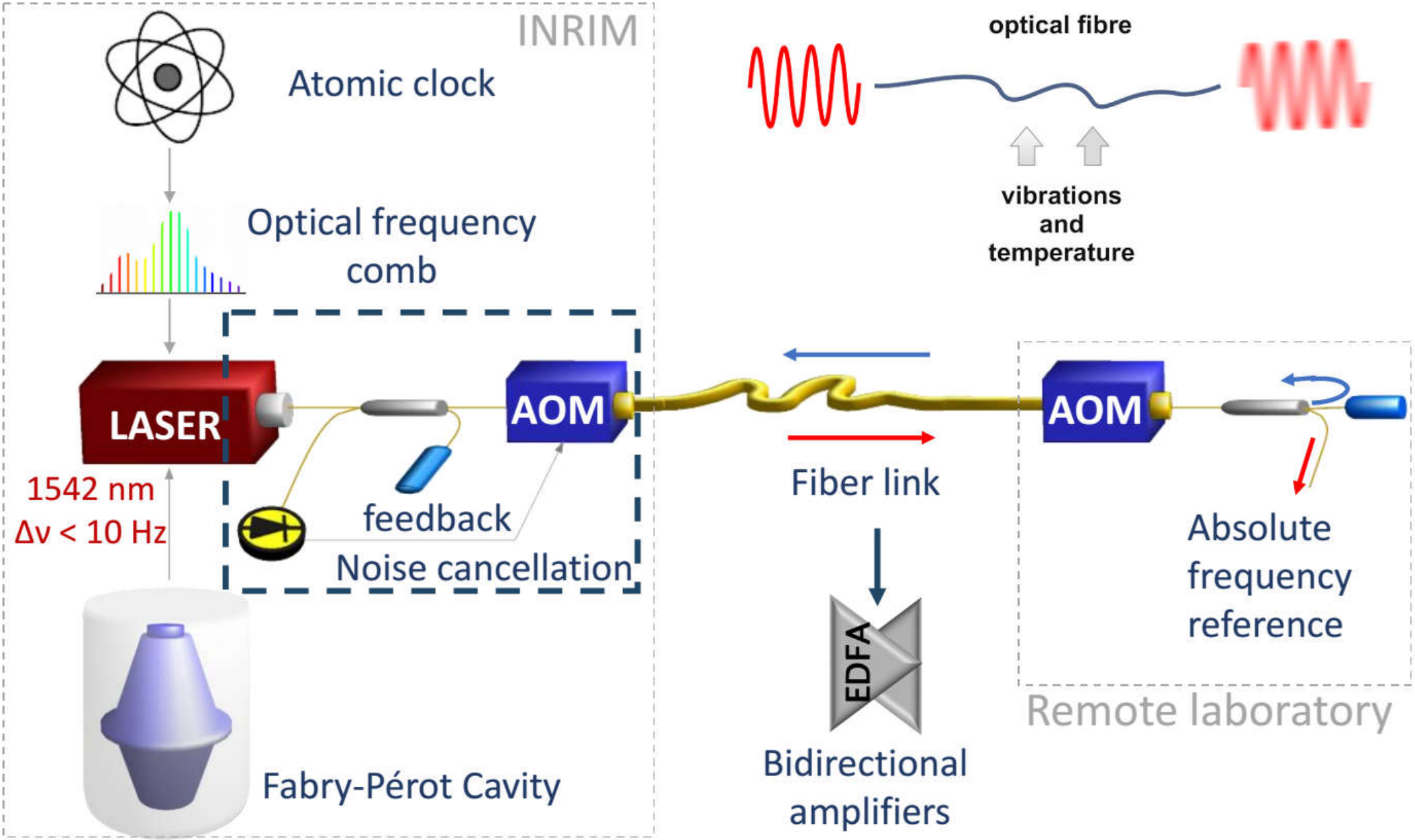
- Dark Fibre (dedicated)
- Coarse Division Wavelength Multiplexing (CWDM): spectrum divided into channels (16 nm each)
- Dense Division Wavelength Multiplexing (DWDM): spectrum divided into channels (100 GHz each, but also 12.5 - 50 GHz) ITU grid: “channel ITUxx”

In Europe, hystorically, we use ITU44 with a central wavelength at 1542.14 nm

Optical fiber links (Coherent)



Optical fiber links



ITALIAN QUANTUM BACKBONE, 1800 km

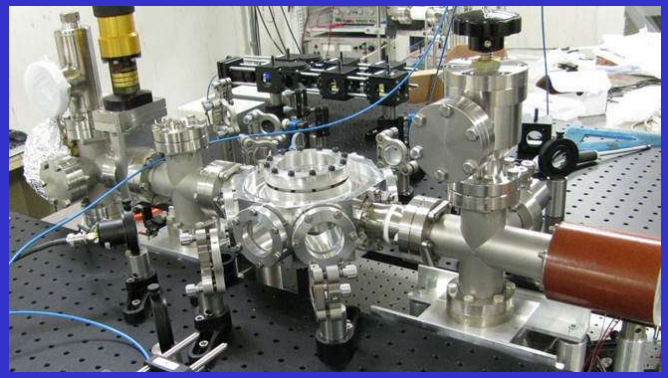
- Quantum Technologies
- Radioastronomy
- Ultracold atoms Physics
- Space - Galileo
- Finance

7 Research Institutes linked:
CNR – National Research Council
ASI – Italian Space Agency
INAF – Italian Astrophysics Institute

3 Industrial Users
Thales Alenia Space Italy
Telespazio;
Consortium Top-IX

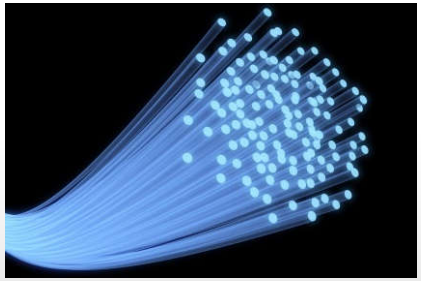
Coherent Technique (now)
To be added: WR-PTP

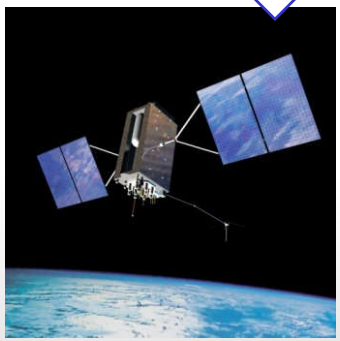
Accurate Time for all: How to?



National Metrological Institues
(Atomic Clocks)

Optical Fiber
Techniques

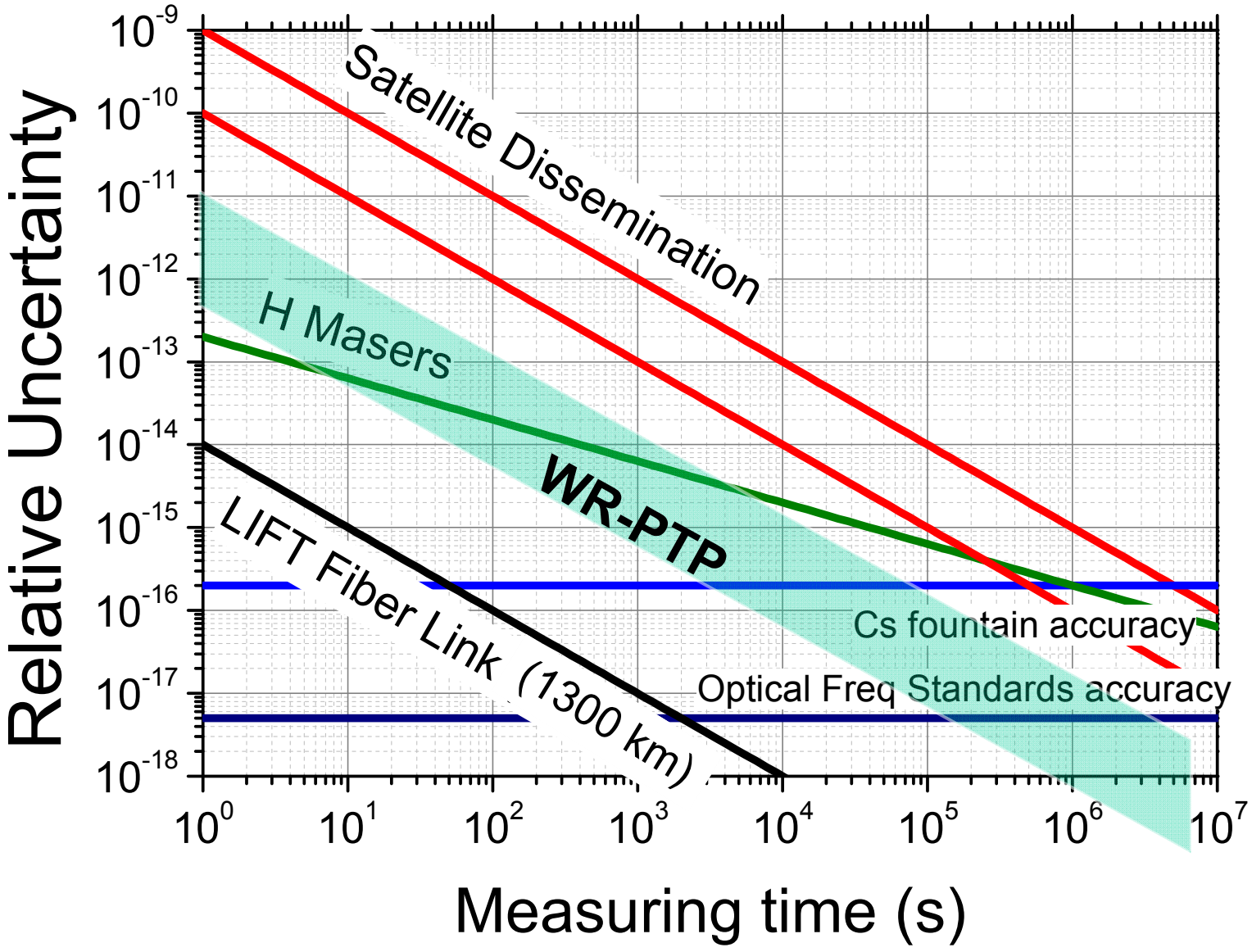




Satellite
Techniques

USERS

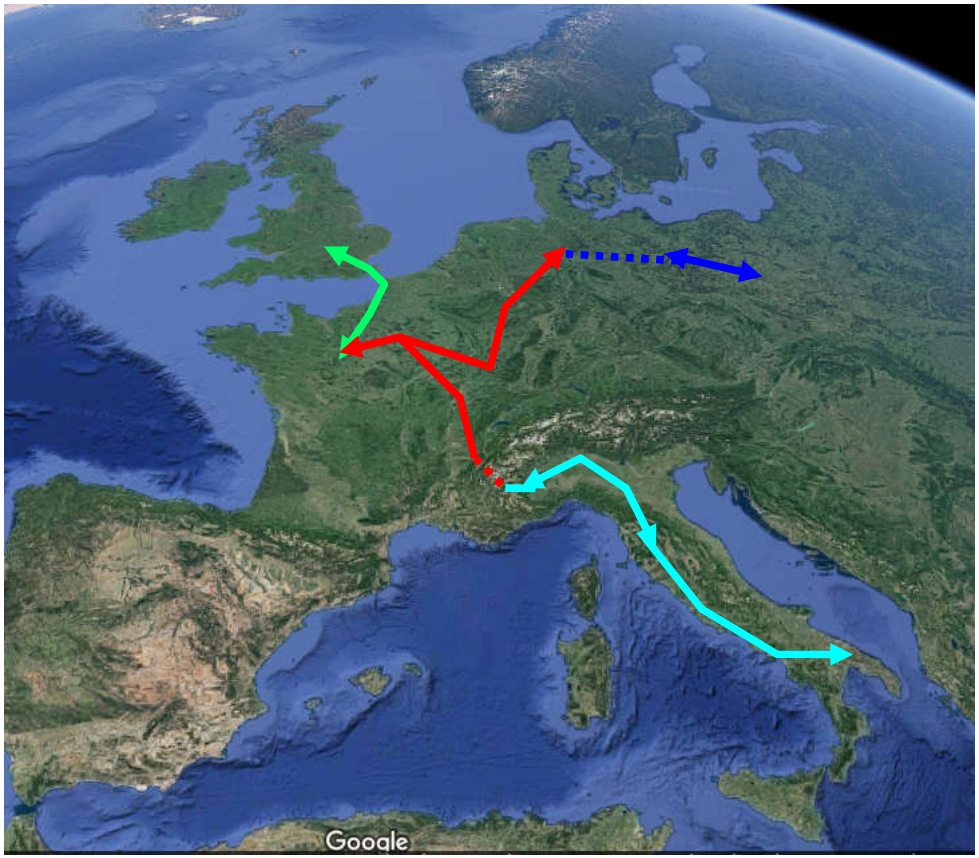
Atomic clocks: comparison and dissemination



When the redefinition of the second?

Towards a European T/F fiber network

- First developed to compare remote atomic clocks
- Since 2008: operational fiber-based frequency dissemination in the world



Metrology

- Fiber-based atomic clocks comparisons

[Ch. Lisdat et al., Nat.Comm. 7, 12443 (2016)]
[J. Guéna et al., Metrologia 54, 348 (2017)]
[P. Delva et al., Phys. Rev. Lett. 118, 221102 (2017)]

Fundamental Science

- Special relativity tests

[P. Delva et al., Phys. Rev. Lett. 118, 221102 (2017)]

- Relativistic geodesy (chronometric levelling)

[T. Takano et al., Nat. Photon. 10, 662 (2016)]
[J. Grotti et al., Nature Physics (2018)]

Experimental physics

- Very Long Baseline Interferometry

[C. Clivati et al., Sci. Rep. 7, 40992 (2017)]
[P. Krehlik et al., Astron. Astrophys. 603, A48 (2017)]

- High-resolution spectroscopy

[B. Argence et al., Nature Photon. 9, 456 (2015)]
[C. Clivati et al., Opt. Express 24, 11865 (2016)]

- Seismology

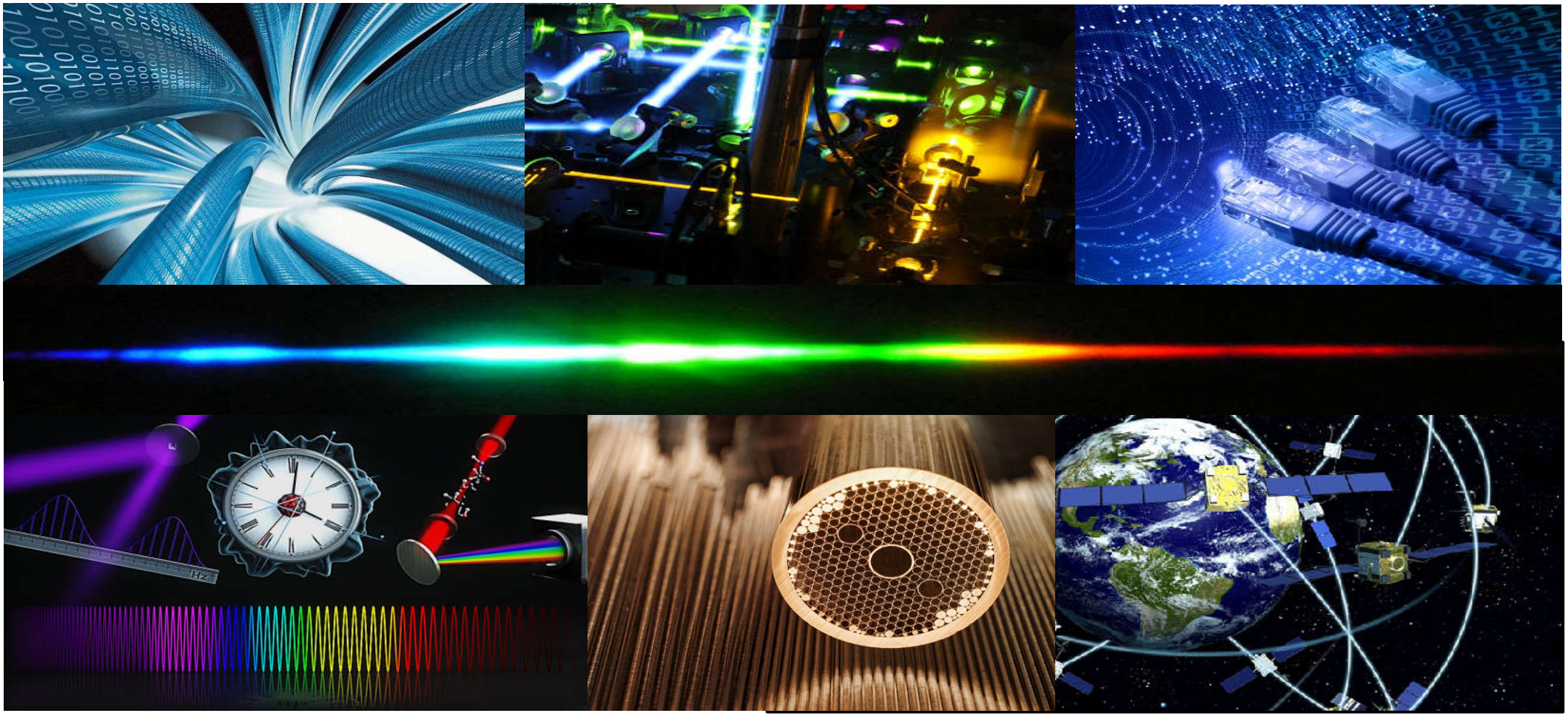
[G. Marra et al., Science 361 (2018)]

Towards a European Network of fibre links

H2020-INFRAINNOV

Strategy and innovation for clock services over optical-fibre networks
16 partners, Coordination: OP

2nd level Specializing Master's Programme in PHOTONICS FOR DATA NETWORKS AND METROLOGY



POLITECNICO DI TORINO

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

CLONETS CLOCK NETWORK SERVICES

top ix torino piemonte internet exchange

COURSES

1 **Digital Communication**
2 **Optical Transmission**
3 **Photonic Devices**
4 **Time and frequency metrology**
5 **Ultrabroadband access network**
6 **Long-haul optical transport**
7 **Photonic Networks**
8 **Quantum Communications**
9 **Photonics applications in metrology**
10 **Time and frequency laboratory**
11 **Security for ICT**
12 **Communications laboratory**
13 **INTERNSHIP**

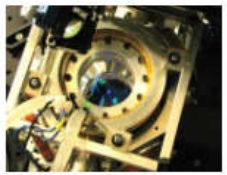
Deadline: Oct 29th 2018 (11:59 a.m.)
Participation fee: € 4.000
Campus: Politecnico – Lingotto, Turin
Format: full time
Language: English,
ECTS: 69
Internship: at companies and/or research institutes in the photonic technologies field
Number of participants: 10 – 25

https://didattica.polito.it/master/photonics/2019/apply

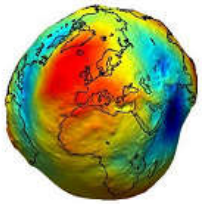
The 2nd level Specializing Master's Programme is also supported by:

AGH University of Science and Technology
CLONETS Clock Network Services
CISCO
ISMB Istituto Superiore Mario Boella
JUNIPER NETWORKS
LPL Laboratoire de physique des lasers
MenloSystems
OCLARO
PSNC
SEVEN Solutions
smoptics
SYNOPSYS
l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace
Tektronix
TIM
TELECOM INFRA PROJECT
top IX
ÚSTAV PŘÍSTROJOVÉ TECHNIKY Akademie věd České republiky

Optical Fibre Links: a broad range of applications

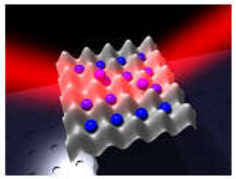


Remote clocks comparisons

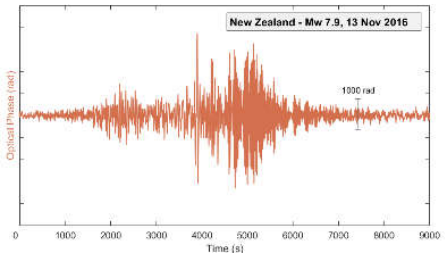


Relativistic Geodesy

VLBI radioastronomy and geodesy



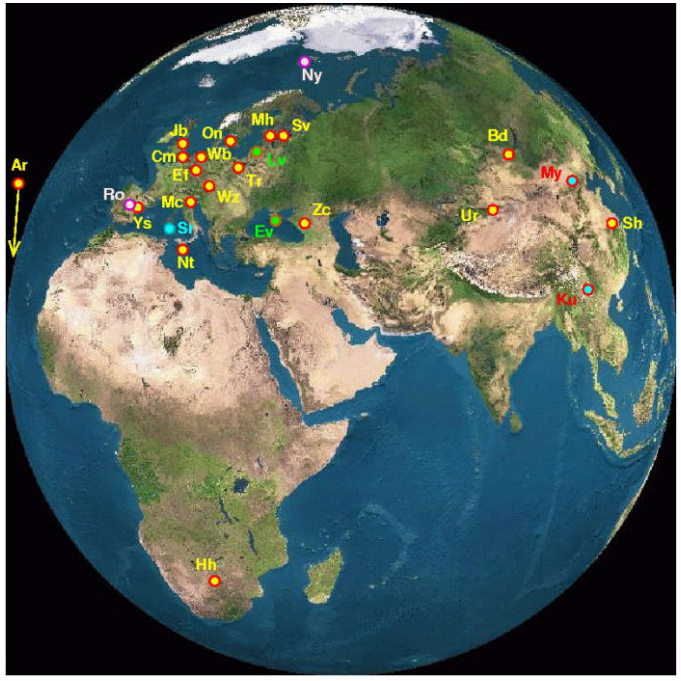
High-precision spectroscopy

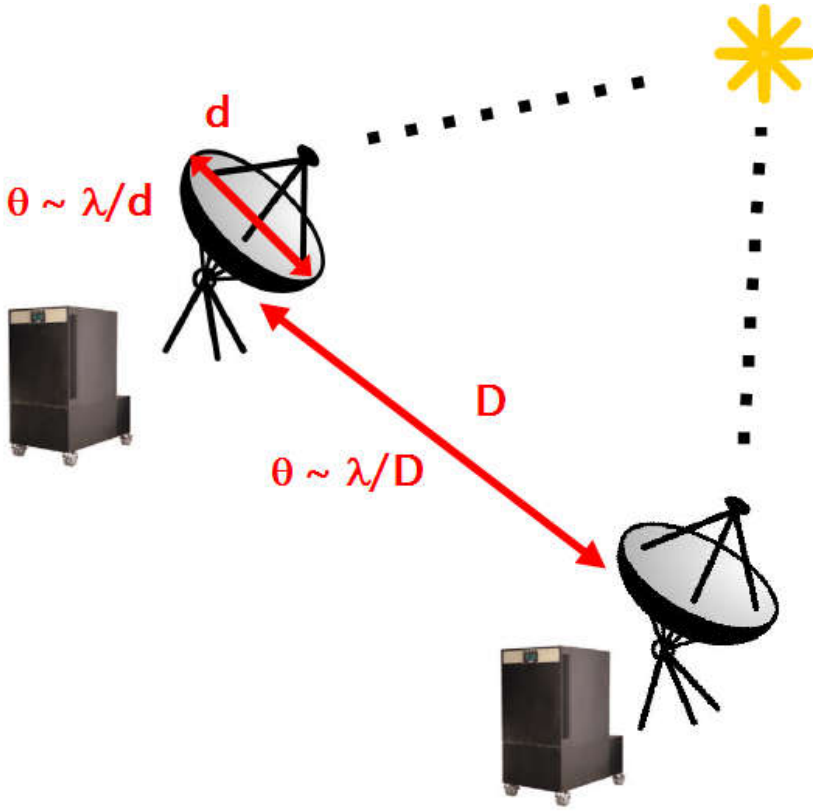


Seismology

Quantum
Key Distribution

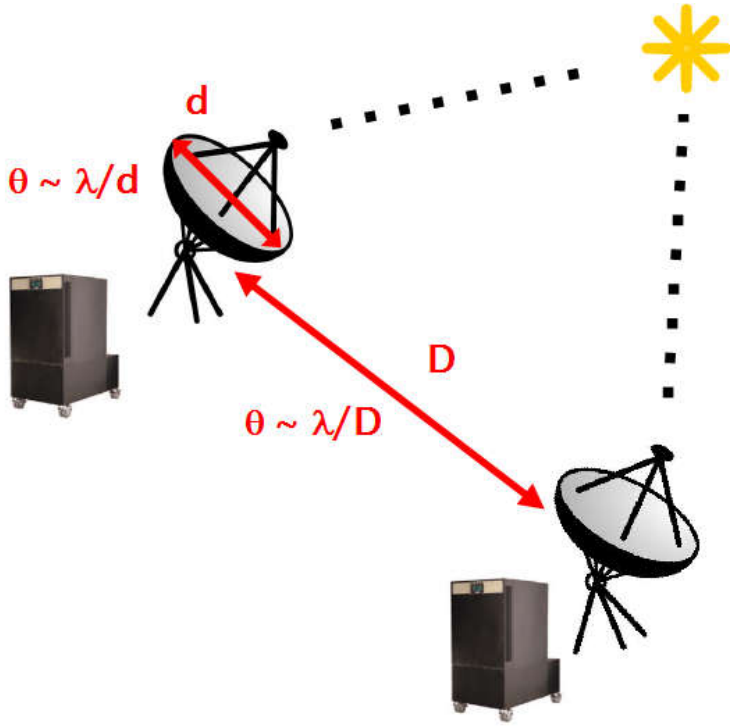
VLBI e orologi atomici





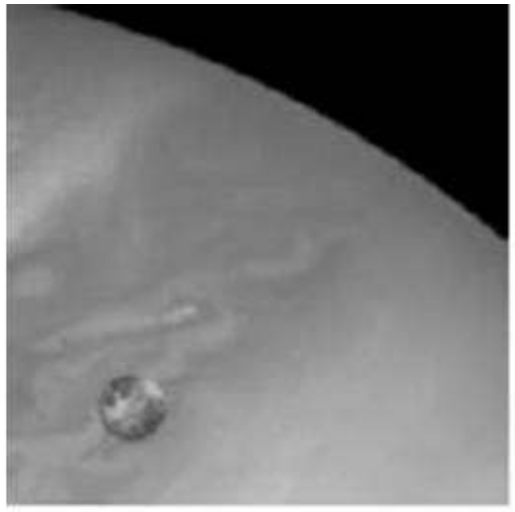
La sincronizzazione necessaria
solo se si usano
orologi atomici ultrastabili
come i **Maser all'Idrogeno**

VLBI e orologi atomici



1’ (minuto d’arco)
Radiotelescopio 140 m

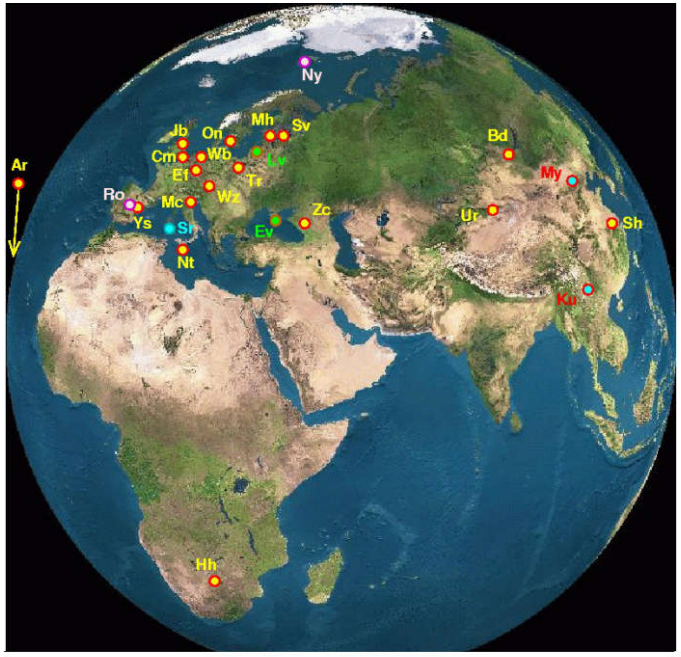
1’’ (secondo d’arco)
Array 8 km

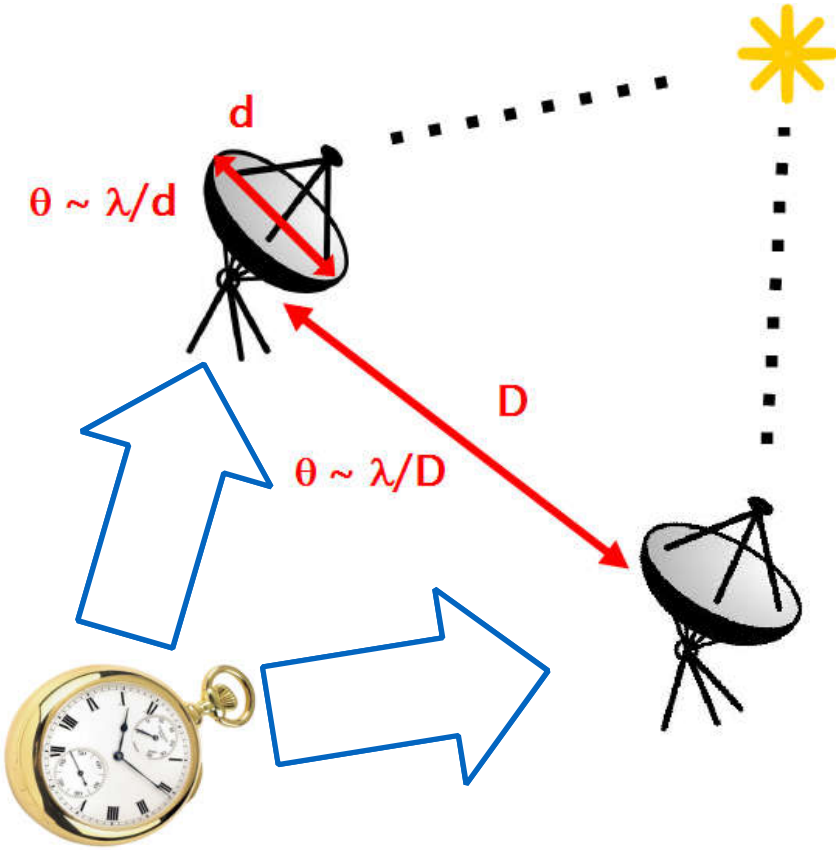


0,05’’
Large Array 160 km

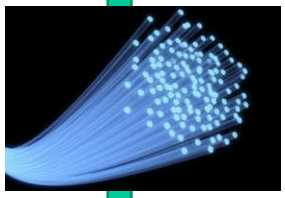
0,001’’
VLBI 8000 km

VLBI e orologi atomici





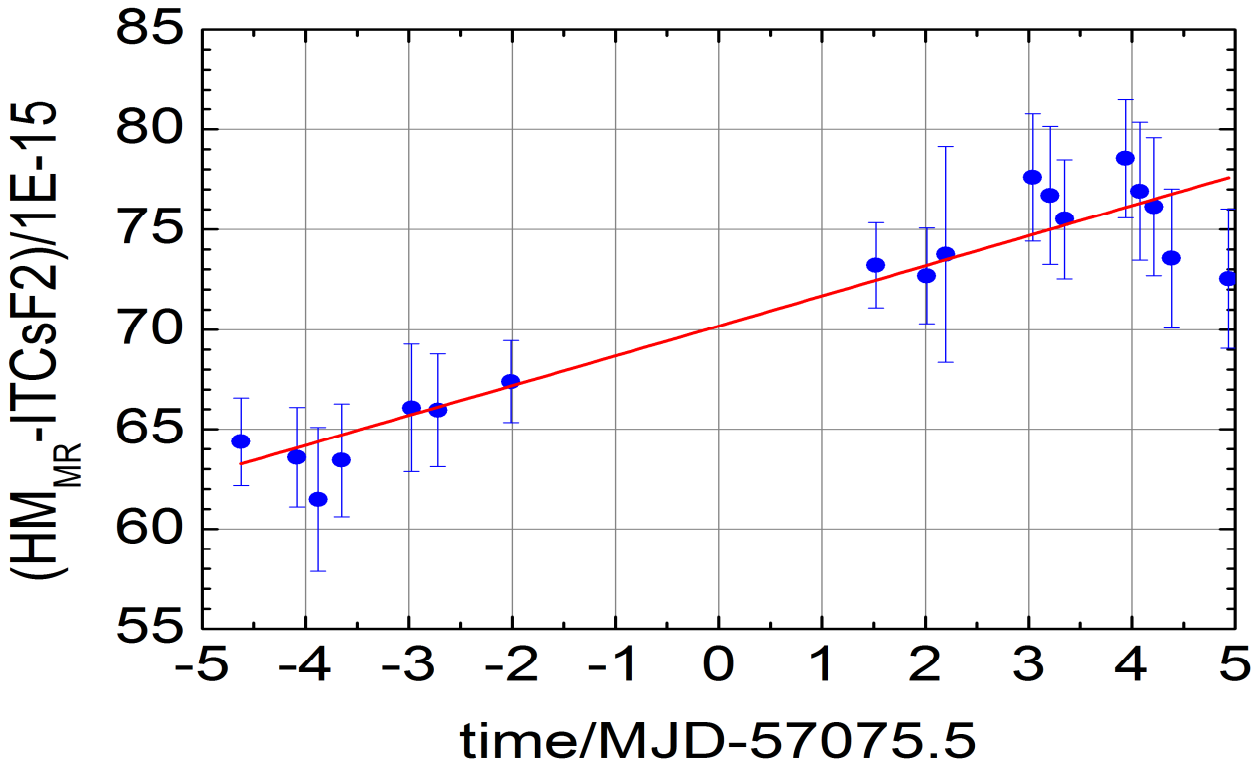
Perché non usare
un common clock?



INRIM-Medicina (550 km) fibre link for radioastronomy

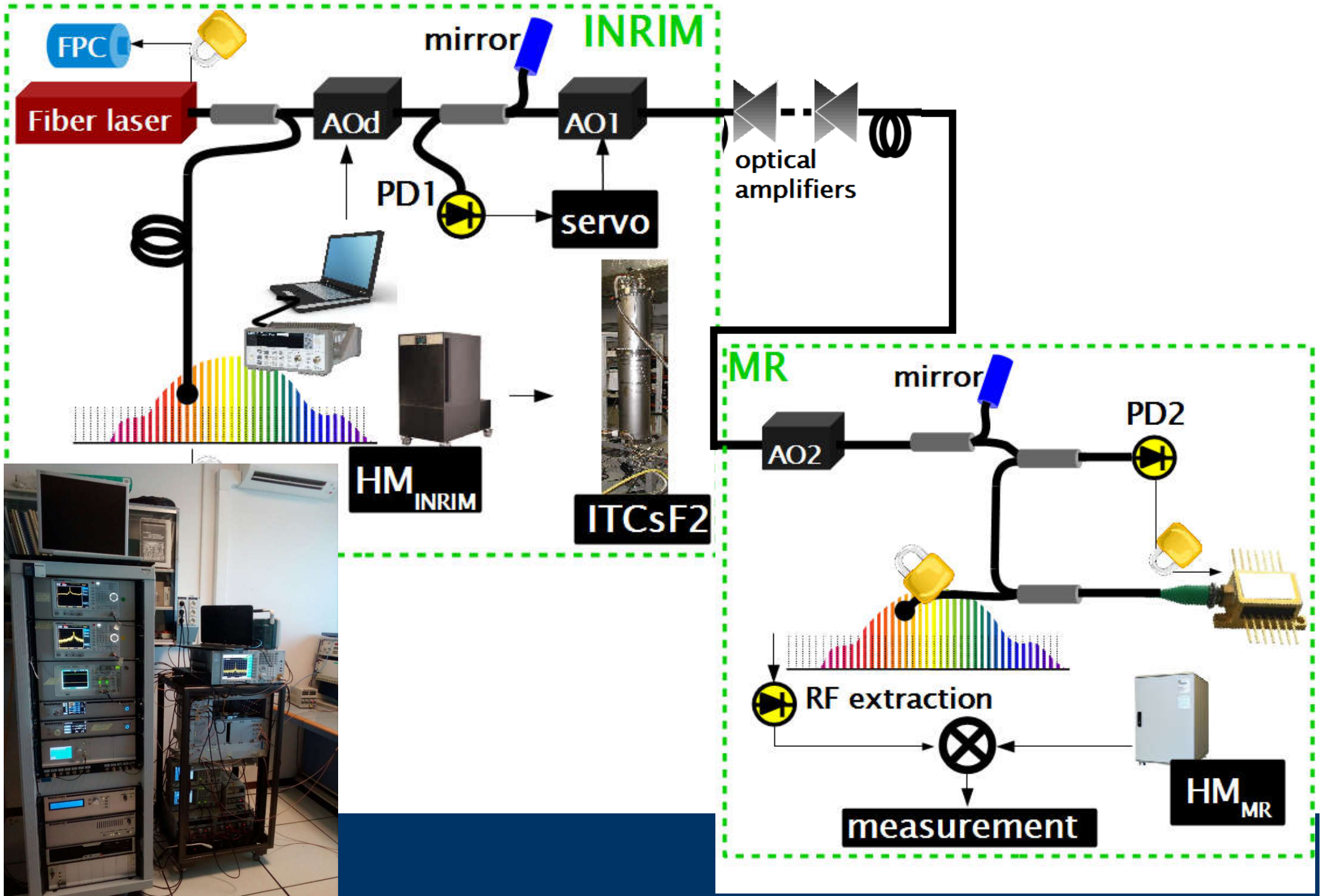
- HM frequency = (70.2 ± 0.4)10^{-15}
- HM drift = (1.5 ± 0.1)10^{-15}/day

- 4 x10^{-16} Uncertainty, dominated by HMs
- Accuracy and resolution otherwise impossible



C. Clivati er al., IEEE TRANS. UFFC, 62, 1907 (2015)

Fiber Link from INRIM to Medicina: set-up



ITALIAN QUANTUM BACKBONE, 1800 km

Next Steps:

- Optical clock to the Radioantenna

(better clock)

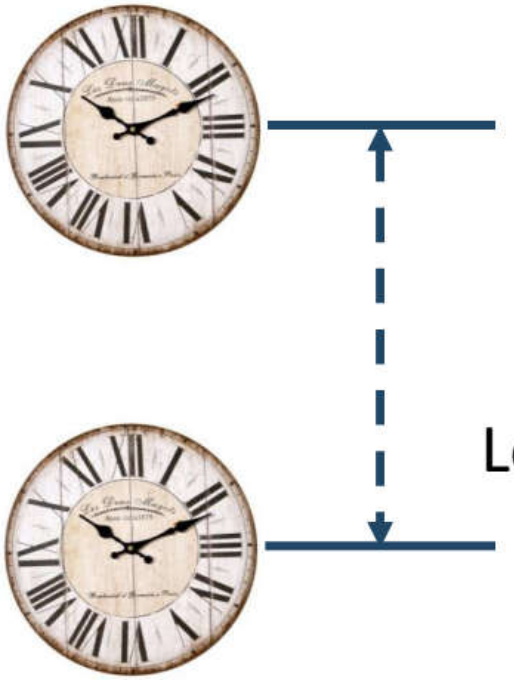
- Same clock to 2 radioantennas (Medicina and Matera)

(common clock)

Infrastructure completed (dedicated fibre, bidirectional coherent link)

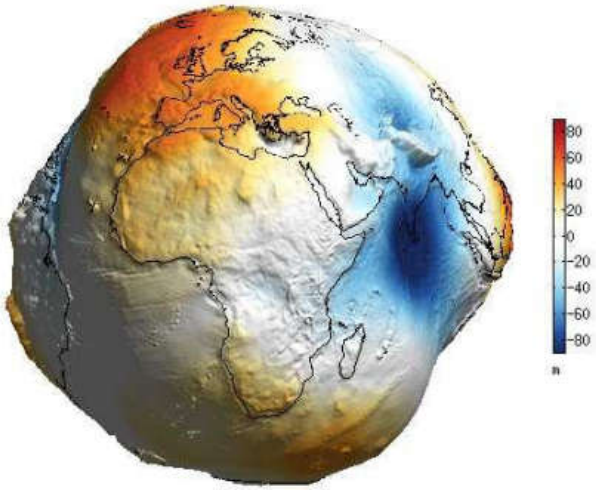
Chronometric levelling (Relativistic Geodesy)

Because of General Relativity…



$$\frac{\Delta U}{c^2} = \frac{\Delta \nu}{\nu} \approx 10^{-16}/m$$

Lower clocks run slower

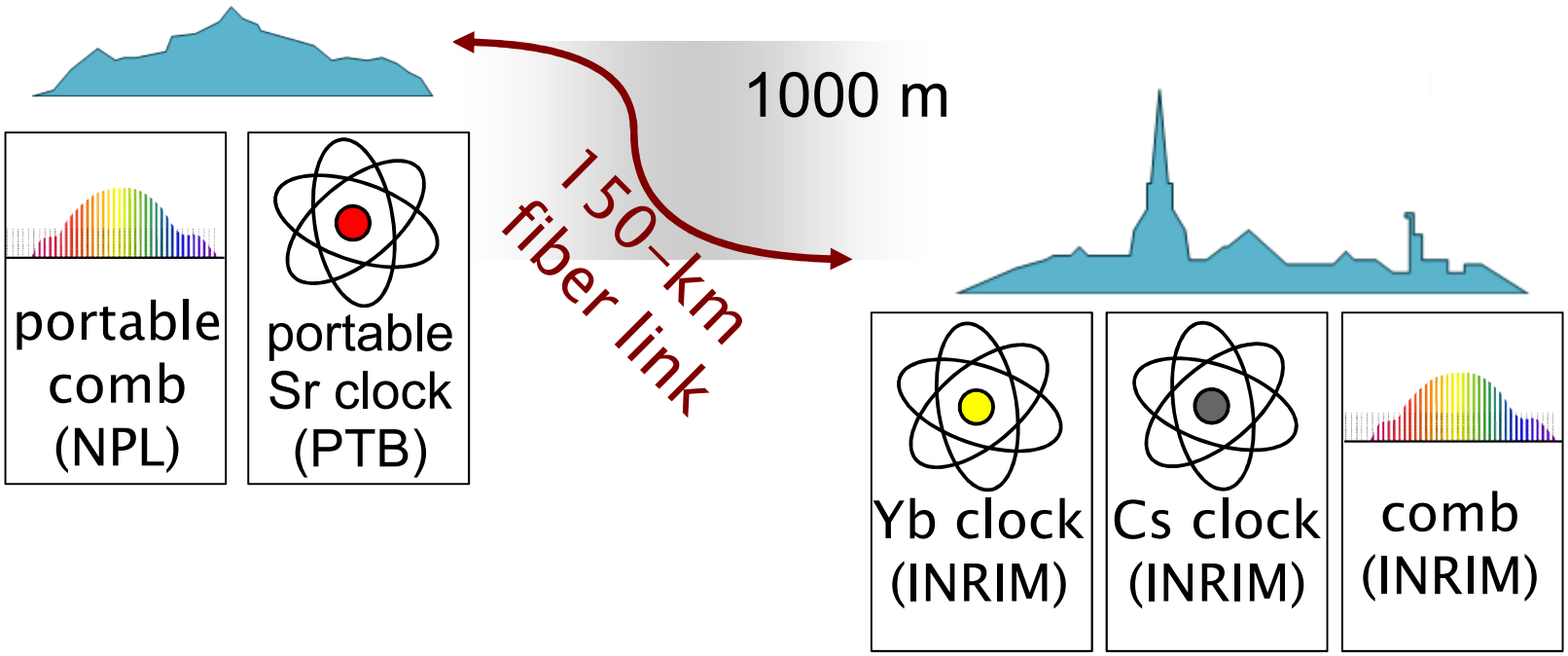


Atomic clocks can be used as sensors of the gravitational potential for chronometric levelling.

Chronometric levelling

- How to translate this into a “real instrument”?

→ A proof-of-principle geodesy experiment between INRIM and the French Alps (Frejus Tunnel)



J. Grotti et al., Nature Phys. **14**, 2018

Earthquake detection with coherent optical fibers

A coherent optical fiber link is a giant Michelson interferometer
→ Able to detect fiber length changes as small as ~ 1 μm
→ Detection of seismic signals is feasible (...Earthquakes!)

Science

REPORTS

Cite as: G. Marra *et al.*, *Science* 10.1126/science.aat4458 (2018).

Ultrastable laser interferometry for earthquake detection with terrestrial and submarine cables

Giuseppe Marra[1*], Cecilia Clivati[2], Richard Luckett[3], Anna Tampellini[2,4], Jochen Kronjäger[1], Louise Wright[1], Alberto Mura[2], Filippo Levi[2], Stephen Robinson[1], André Xuereb[5], Brian Baptie[3], Davide Calonico[2]

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Submarine Earthquakes detection

Two testbeds available in the Mediterranean Sea, Sicily to Malta:

- A 96.4 km telecom cable
(fiber only, buried 1 m below sand)
- A 117 km cable along electrical interconnection
(fiber + HV power, 1 m below sand)

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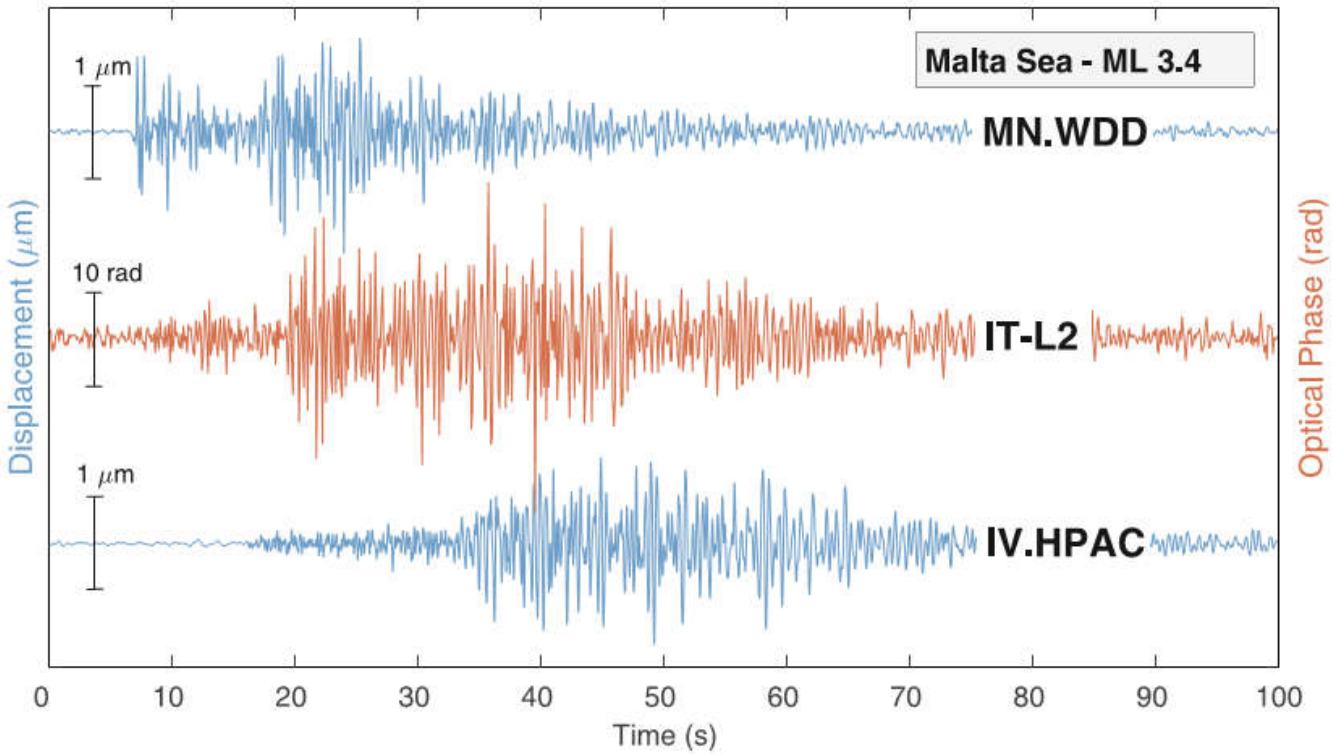
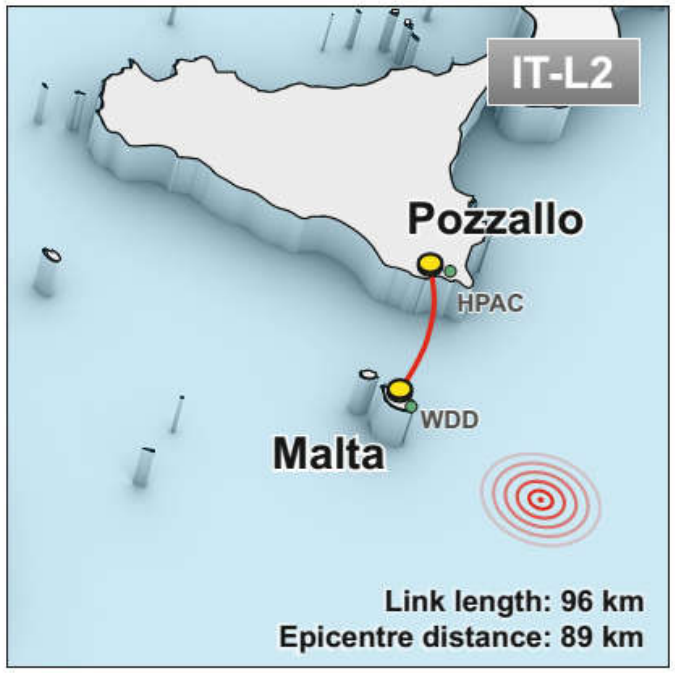
L-Università ta' Malta

C. Clivati et al., Optica **14** (2018)
G. Marra et al., Science **361** (2018)

Submarine Earthquakes detection

- Two seismic events (ML = 3.4 and Mw = 5.1) detected on submarine fiber





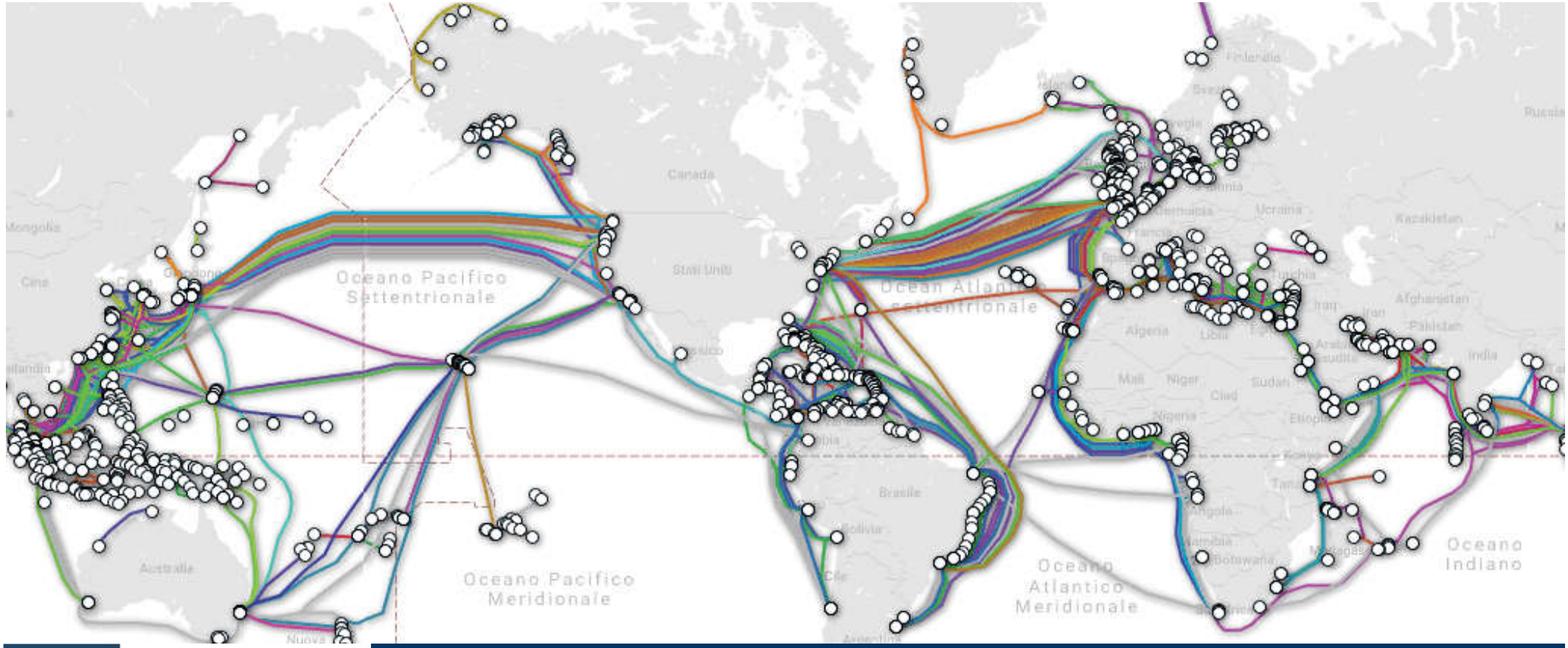
G. Marra et al., Science **361** (2018)

Submarine Earthquakes detection

- Almost 70% of Earth covered by waters
- Ocean Bottom Seismometers: few, costly, difficult to operate

→ most of submarine Earthquakes undetected

- ...Optical fibers can be used as a deployed seismic sensors



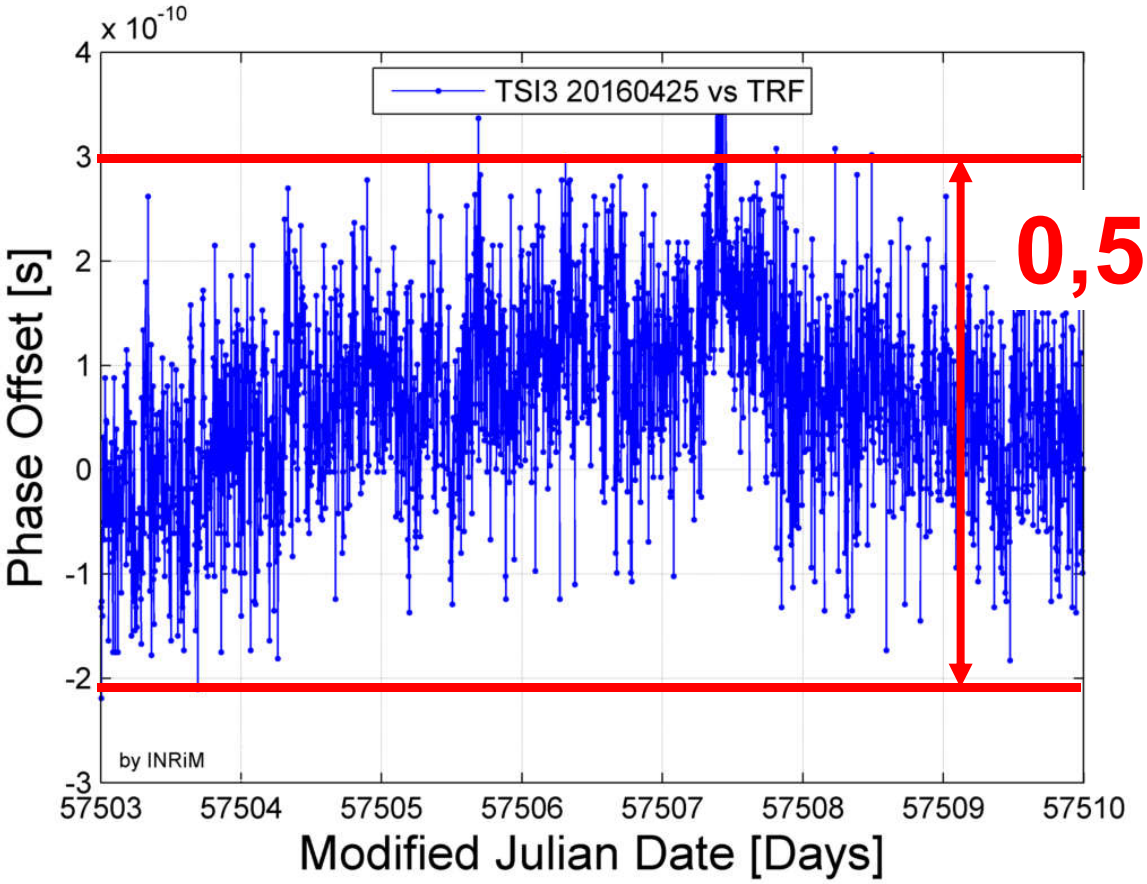
Time over Fibre for the Financial Market

- 160 km Fibre link dedicated to financial users
- Now available as a service (Certified, Resilient Traceability to UTC)
- White Rabbit / IEEE1588 Time dissemination
- Collaboration with Consortium TOP-IX (telco company), on an infrastructure used for data traffic (DWDM architecture)

UTC(IT) @INRIM

Colocation Italian Stock Exchange in Milano

Time over Fibre for Finance: performances



Up to 400 km real link with WR-PTP

The technique is the closest to optical communications world (protocol based, Sync-E)

Validation:

- First in closed loop (equivalent haul, start/end at INRIM, no offset at <1 ns level .
- Then, comparison vs independent GPS-PPP, accuracy<5ns (GPS limited)

Time over Fibre for Space Industry

Time dissemination to Telespazio premises in Fucino (1000 km fibre haul)

Project ASI-INRIM «Time and Frequency over fiber DTM-Galileo»:

- Space applications
- Support for Timing of the Galilleo System

White Rabbit Industrial Timing Enhancement (2018- 2021)

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Improving WR-PTP for primary metrology and industry
(Scalable Calibration Techniques; Resilience and Redundancy;
Improving Performances; In-field industrial installation and validation)

11 partners, Coordination: D. Calonico, INRIM

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

VTT MIKES METROLOGIA

LEONARDO

THALES ELECTRON DEVICES

NPL National Physical Laboratory

RISE Research Institutes of Sweden

VSL

Nikhef

l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

SEVEN Solutions

opnt. TIME PROVISIONING

Conclusions

Just one single take-home-message:

Photonics is a pillar of modern time and frequency metrology

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- Research, Innovation and Development Trust of the University of Malta
- Department for Business, Energy and Industrial Strategy (BEIS) as part of the UK National Measurement System programme.
- European Metrology Program for Innovation and Research (EMPIR) projects OFTEN , which have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.
- H2020 Project CLONETS
- Special thanks to Melita Limited and Enemalta plc for providing us with access to the submarine fiber links
- The facilities of IRIS Data Services, and specifically the IRIS Data Management Center, were used for access to waveforms, related metadata, and/or derived products used in this study. IRIS Data Services are funded through the Seismological Facilities for the Advancement of Geoscience and EarthScope (SAGE) Proposal of the National Science Foundation under Cooperative Agreement EAR-1261681.

EMPIR EURAMET

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energise your ideas