Applications of time and frequency signals on optical fiber

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INRiM
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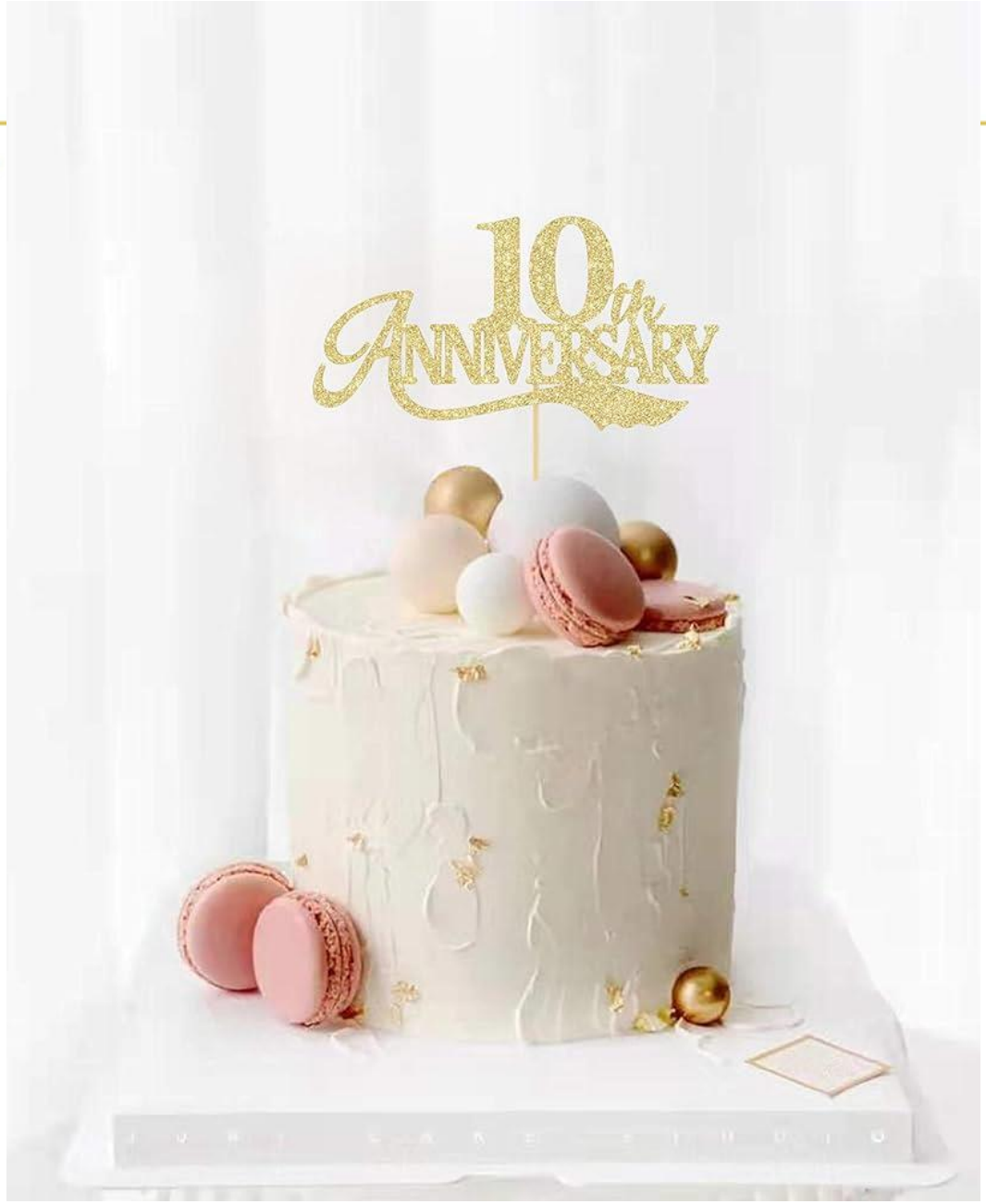
DI RICERCA METROLOGICA



Italian Quantum Backbone was born with the Project LIFT (Link in Italy for Frequency and Time).

First Signals Turin-Florence:

February 2013

Published the year after

Appl. Phys. B
DOI 10.1007/s00340-014-5917-8

Applied Physics B
Lasers and Optics

High-accuracy coherent optical frequency transfer over a doubled 642-km fiber link

D. Calonico · E. K. Bertacco · C. E. Calosso · C. Clivati · G. A. Costanzo · M. Frittelli · A. Godone · A. Mura · N. Poli · D. V. Sutyrin · G. Tino · M. E. Zucco · F. Levi

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Italian Quantum Backbone steps

2014 650 km Link

2015 **8th Symposium on Frequency Metrology**

2016 Remote SI traceability for spectroscopy

// Remotely enabling quantum simulation

2018 Chronometric Levelling (Relativistic Geodesy)

// Submarine Cables and Earthquake sensing

2017- 2020 1850 km optical link // Radioastronomy

2021 1000 km White Rabbit Timing

2022 Atlantic cable - seabottom sensing

//Clock comparisons

//Quantum Communication

2023 Seismic permanent Observatory

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Italian Quantum Backbone: exploring applications

- INRIM IQB: 1850 km fibre research infrastructure
- 7 public research laboratories/institutes, 3 industrial companies connected
- Primary frequency metrology (comparison and dissemination)
- Certified atomic time and frequency
- Platform for quantum metrology and communication
- Coherent Fibre Sensing

Absolute frequency reference dissemination and comparisons

C. Clivati et al., Opt. Express 24, 11865 (2016)
L. Livi, et al. Phys Rev Lett 117, 220401 (2016)
S. Borri et al, Sci. Rep. 7, 12780 (2017)
C. Clivati et al, Phys. Rev. Applied 18, 054009 (2022)

Relativistic geodesy

J. Grotti et al., Nature Physics (2018)

Radioastronomy (Very Long Baseline Interferometry)

C. Clivati et al., Sci. Rep. 7, 40992 (2017)
C. Clivati, et al. Optica 7, 1031-1037 (2020)
M. Pizzocaro, et al. Nature Physics, 17, 2, (2020)

Seismology/Geophysics

G. Marra et al., Science 361 (2018)
C. Clivati et al. Optica (2018)
G. Marra, et al. Science, 376, 6595 (2022)

Quantum Communication

S. Wengerowsky, et al., PNAS 116, .6684-6688 (2019)
D. Bacco, et al. EPJ Quantum Technology, 6, 1(2019)
S. Wengerowsky, et al. 6, 1 Nature PJ Quantum Information (2020)
D. Bacco, et al. Advanced Quantum Technologies 4, 7 (2021)
C. Clivati, et al. Nature Communnications, 13, 1 (2022)

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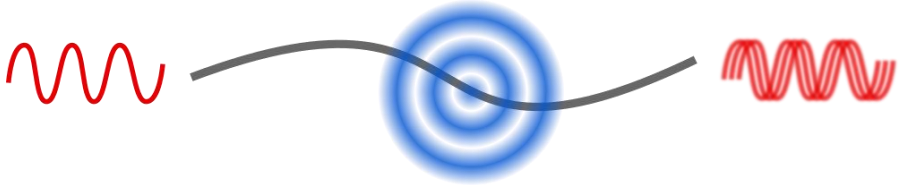
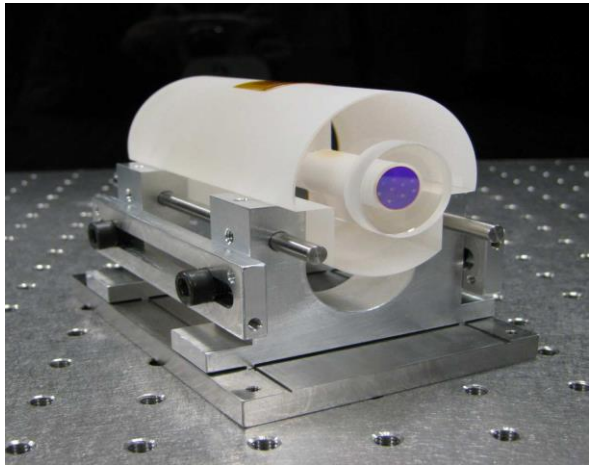
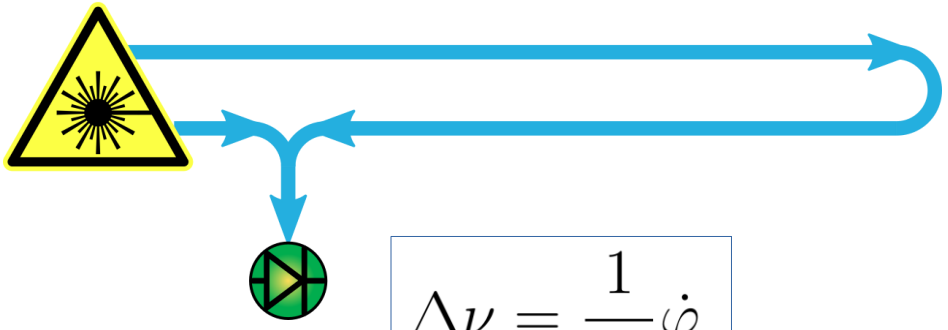
Coherent laser interferometry

Basic principles:

- interference between **coherent light**
- **optical phase** measurement
- **Ultrastable lasers – laser noise < fiber noise**
- **Doppler noise cancellation**







$$\Delta\nu = \frac{1}{2\pi}\dot{\varphi}$$

Interferometry over the fiber network:

- **compatible with telecom infrastructure**
- **coexistence with internet data traffic**
- **high sensitivity and linearity**
- **long range**, can be amplified + high coherence

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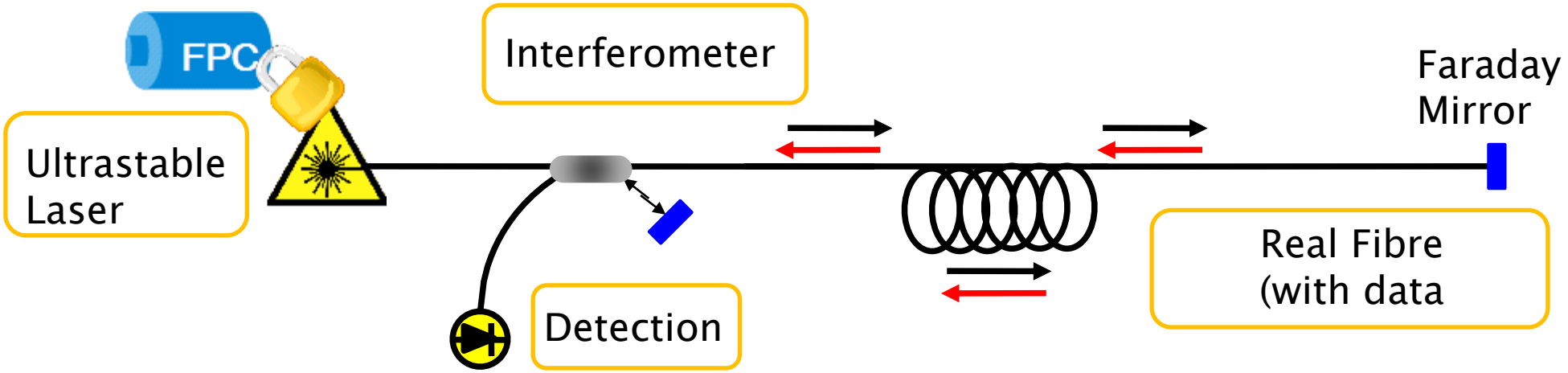
Coherent laser interferometry



$$V_{photodiode} \propto \sin[2\pi/\lambda\,(\Delta L_{short} - \Delta L_{long})] \sim \sin[(2\pi/\lambda)\,\Delta L_{long}]$$

November 1, 1994 / Vol. 19, No. 21 / OPTICS LETTERS 1777

Delivering the same optical frequency at two places: accurate cancellation of phase noise introduced by an optical fiber or other time-varying path

Long-Sheng Ma,* Peter Jungner,† Jun Ye, and John L. Hall‡

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440

1284 J. Opt. Soc. Am. B/Vol. 25, No. 8/August 2008 Williams *et al.*

High-stability transfer of an optical frequency over long fiber-optic links

P. A. Williams,* W. C. Swann, and N. R. Newbury

National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA
**Corresponding author: pwilliam@boulder.nist.gov*

Received February 25, 2008; revised May 2, 2008; accepted May 31, 2008;
posted June 9, 2008 (Doc. ID 93074); published July 17, 2008

Optical Fiber Links: a worldwide snapshot

1 Fiber Link in use

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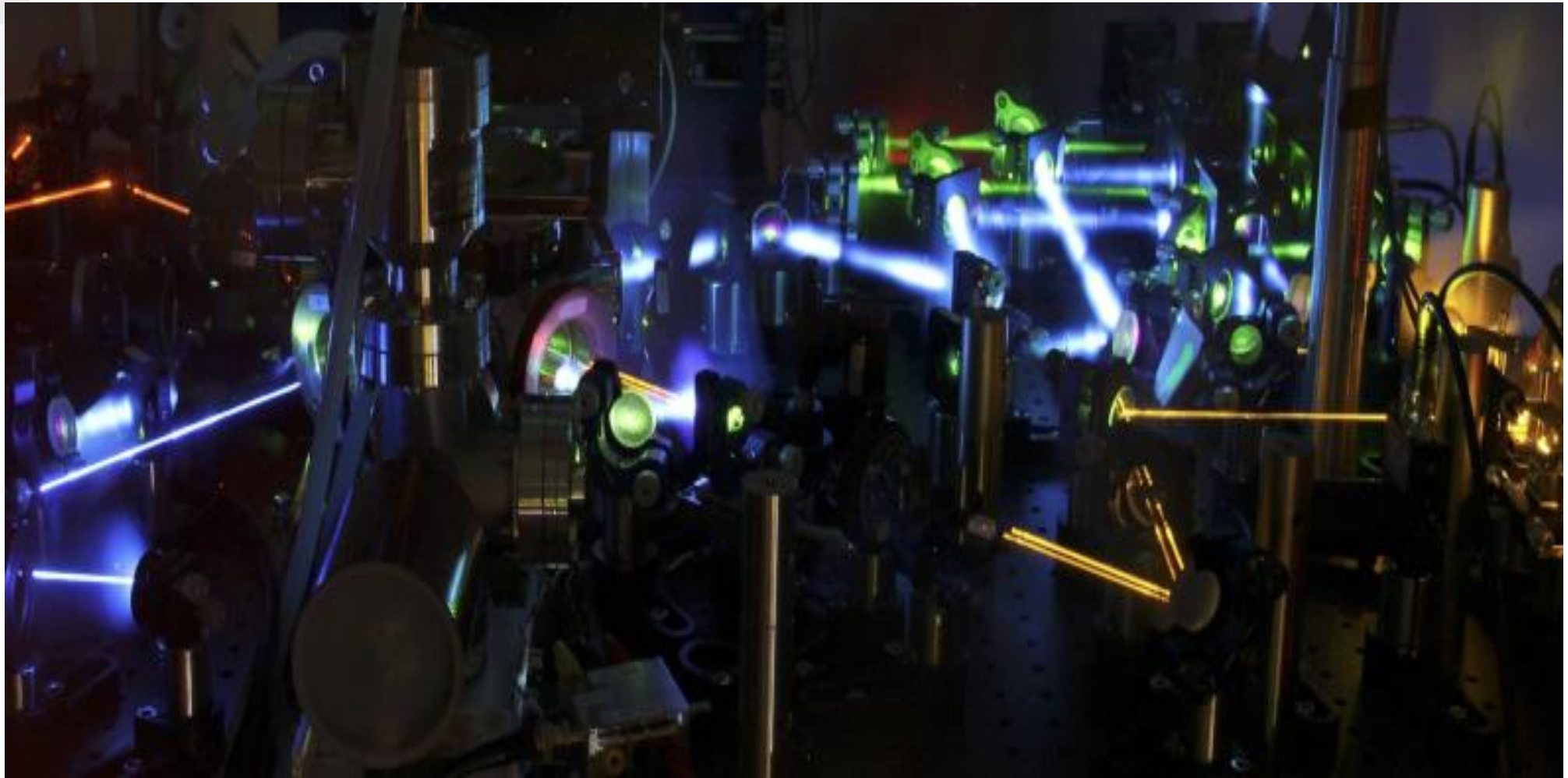
Remote frequency measurements



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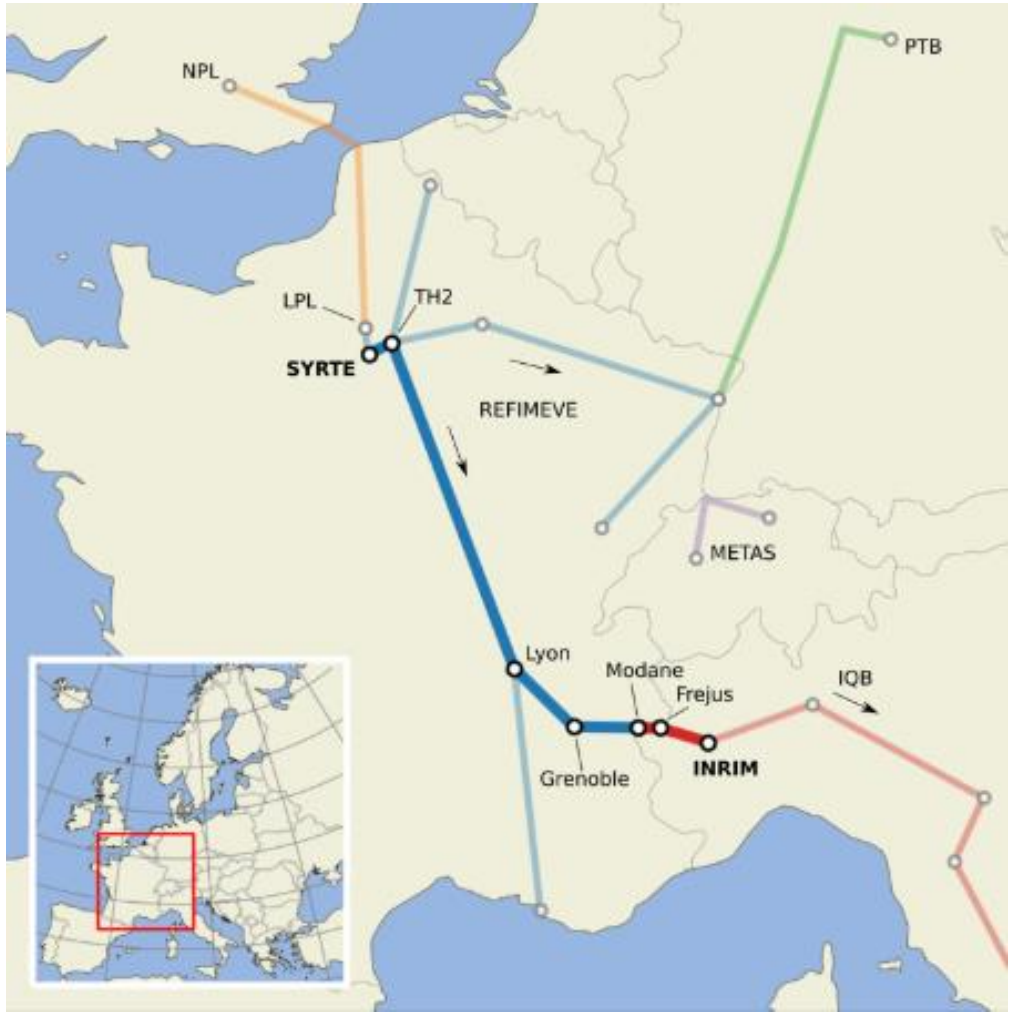
Remote frequency measurement

Yb vs fountains at SYRTE (Paris)



Via **optical link** INRiM-SYRTE:
1023 km long $u < 1 \times 10^{-18}$

Optical comparison between **INRIM** and **SYRTE** (Systèmes de Référence Temps-Espace) + **LPL** (Laboratorie de Physique des Lasers)

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SYRTE l'Observatoire de Paris | PSL

SYstèmes de Référence Temps-Espace

LPL Laboratoire de physique des lasers

C. Clivati et al., 2022 Phys. Rev. Applied 18, 054009

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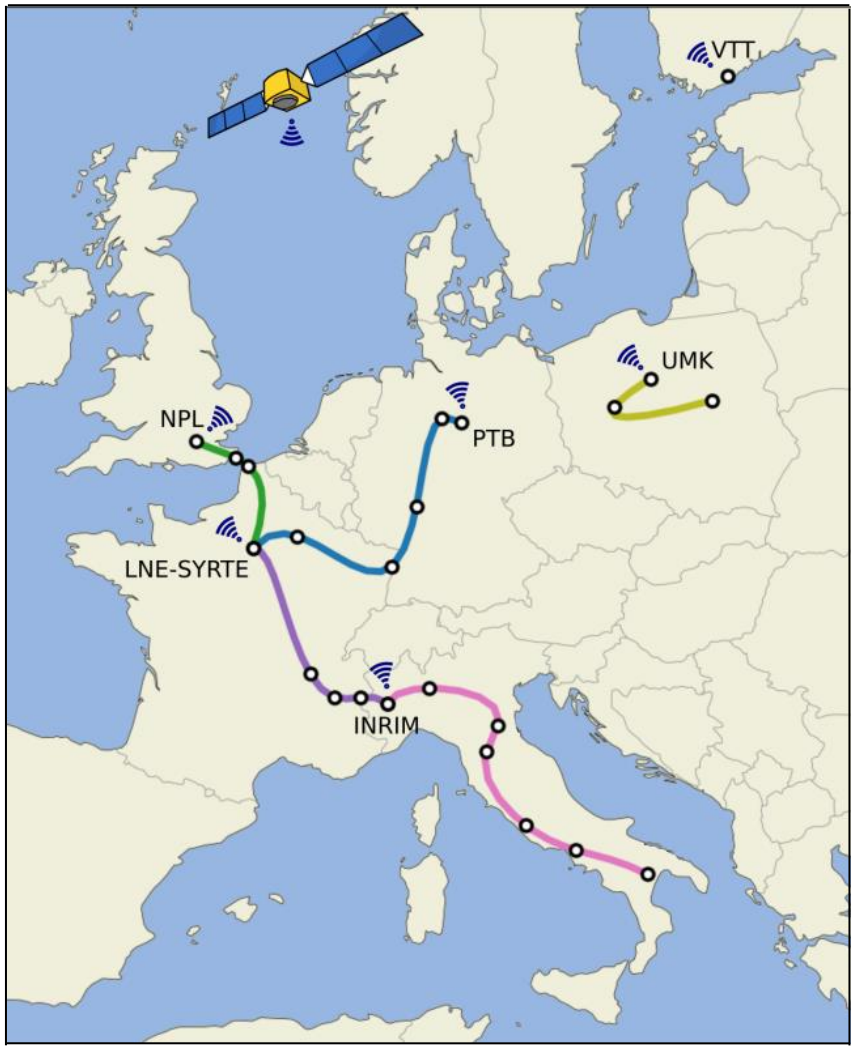
Ongoing optical clocks comparisons



Two European optical clock comparisons

- **ROCIT campaign (March 2022)**:
  - **11 optical clocks** involved
  - 7 different countries linked via GPS
  - **INRiM, SYRTE and PTB** connected via **fiber link**
  - NPL, VTT, UMK and NMIJ connected via GPS

- 2023 campaign (March and April 2023):
  - **INRiM, SYRTE, PTB and NPL** connected via **fiber link**
  - **6 optical clocks** involved
  - **2 transportable clocks developed at** PTB and RIKEN hosted at NPL

Data under analysis

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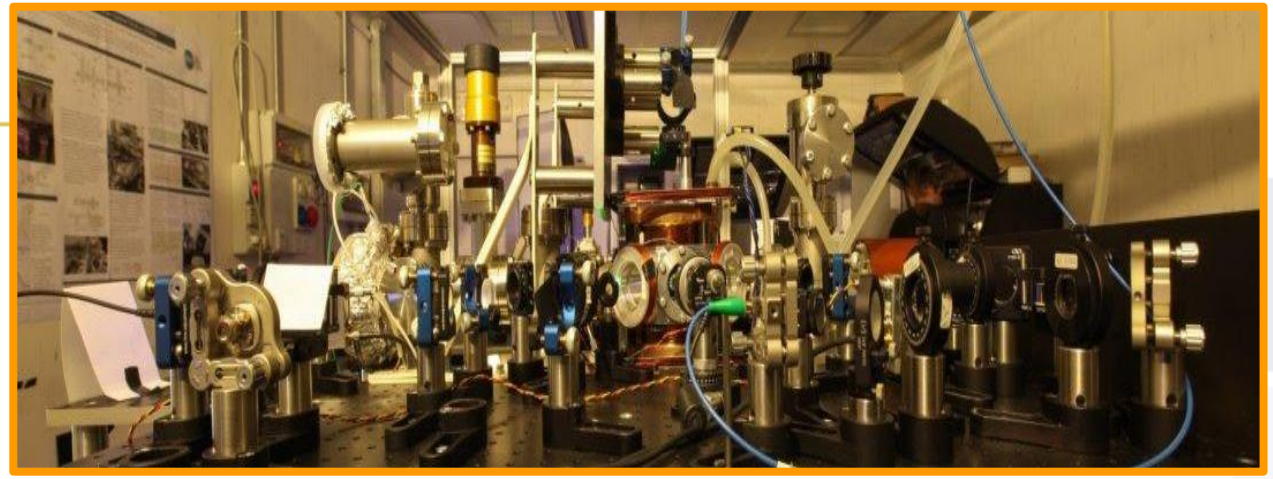
INRIM AFS



INRiM – Yb clock

Accuracy: $2 \cdot 10^{-17}$

Stability: $2 \cdot 10^{-15}$ @ 1 s

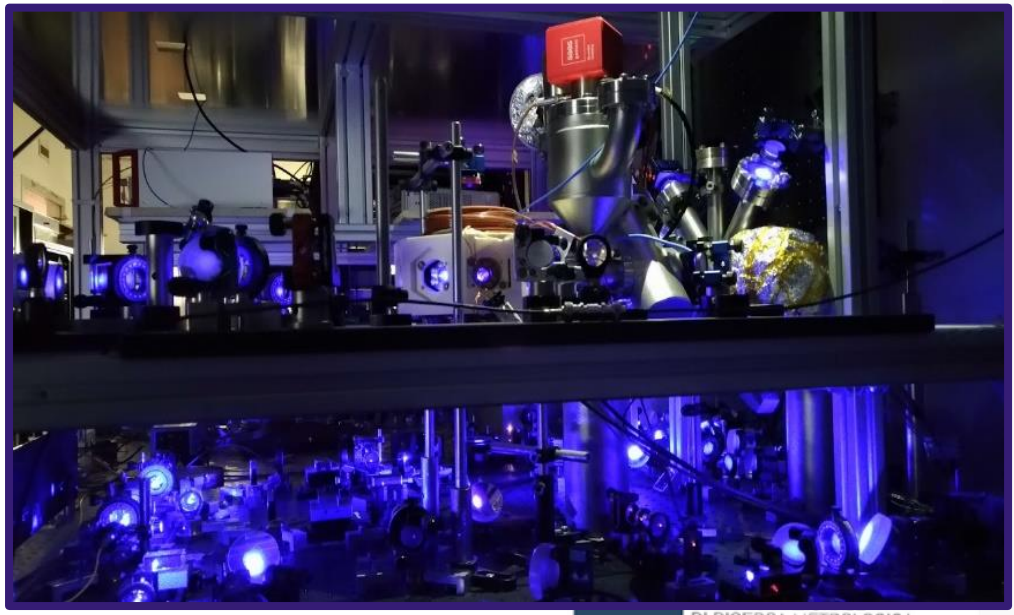
M. Pizzocaro, et al., Nature Phys 17, 2 (2021)

INRiM – Cs fountain

Accuracy: $1.7 \cdot 10^{-16}$

Stability: $1.5 \cdot 10^{-13}$ @ 1 s

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



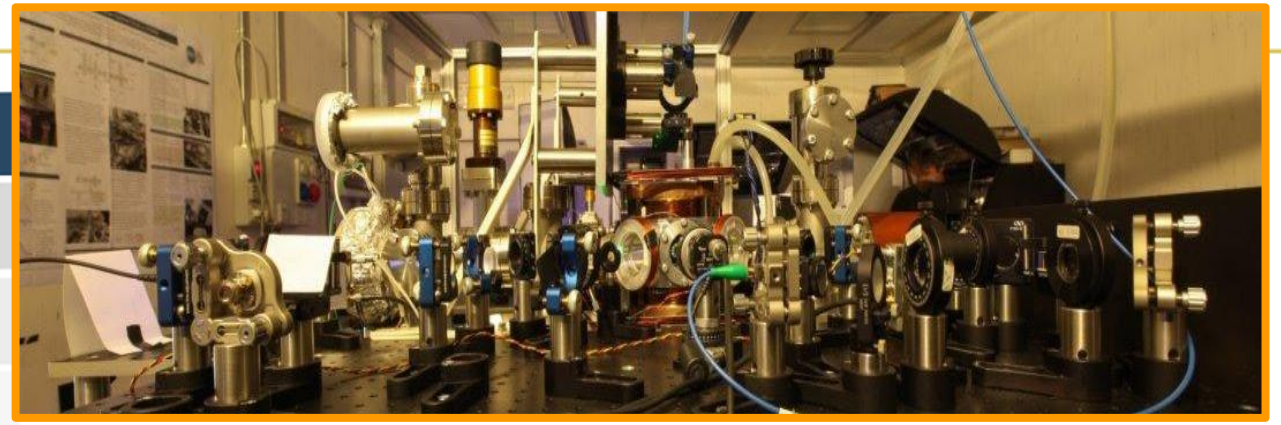
INRiM – Sr clock

Accuracy: $1 \cdot 10^{-14}$

Stability: $8 \cdot 10^{-14}$ @ 1 s

Barbiero, M et al. , IEEE Trans I&M, 71, 1501509 (2022)

INRIM AFS

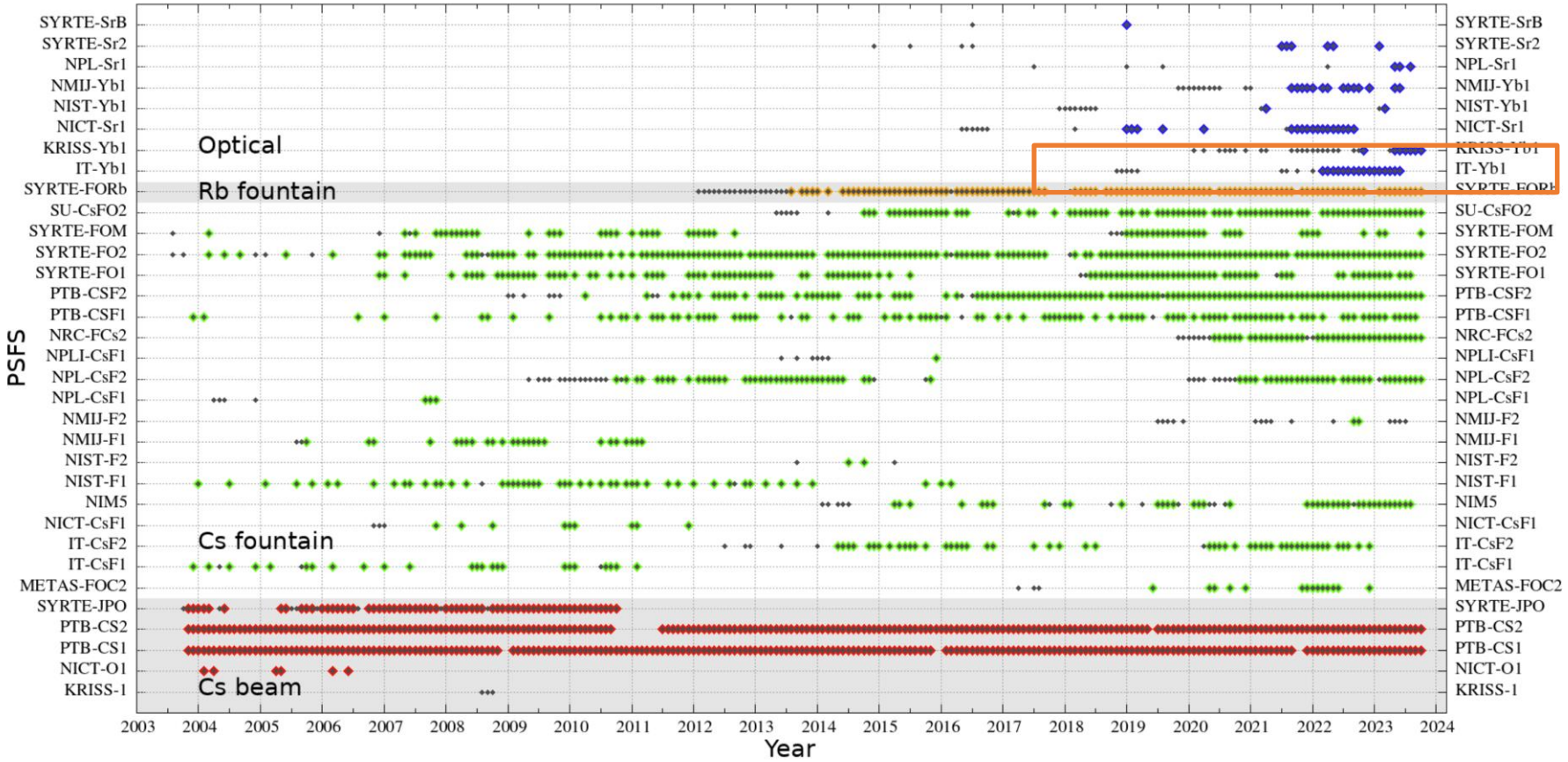


INRiM – Yb clock ITYb1

Accuracy: $2 \cdot 10^{-17}$

Stability: $2 \cdot 10^{-15}$ @ 1 s

IT-Yb1 contributed to TAI real-time for 16 months



I. Goti et al., Metrologia 60, 035002 (2023)

M. Pizzocaro, et al., Nature Phys 17, 2 (2021)

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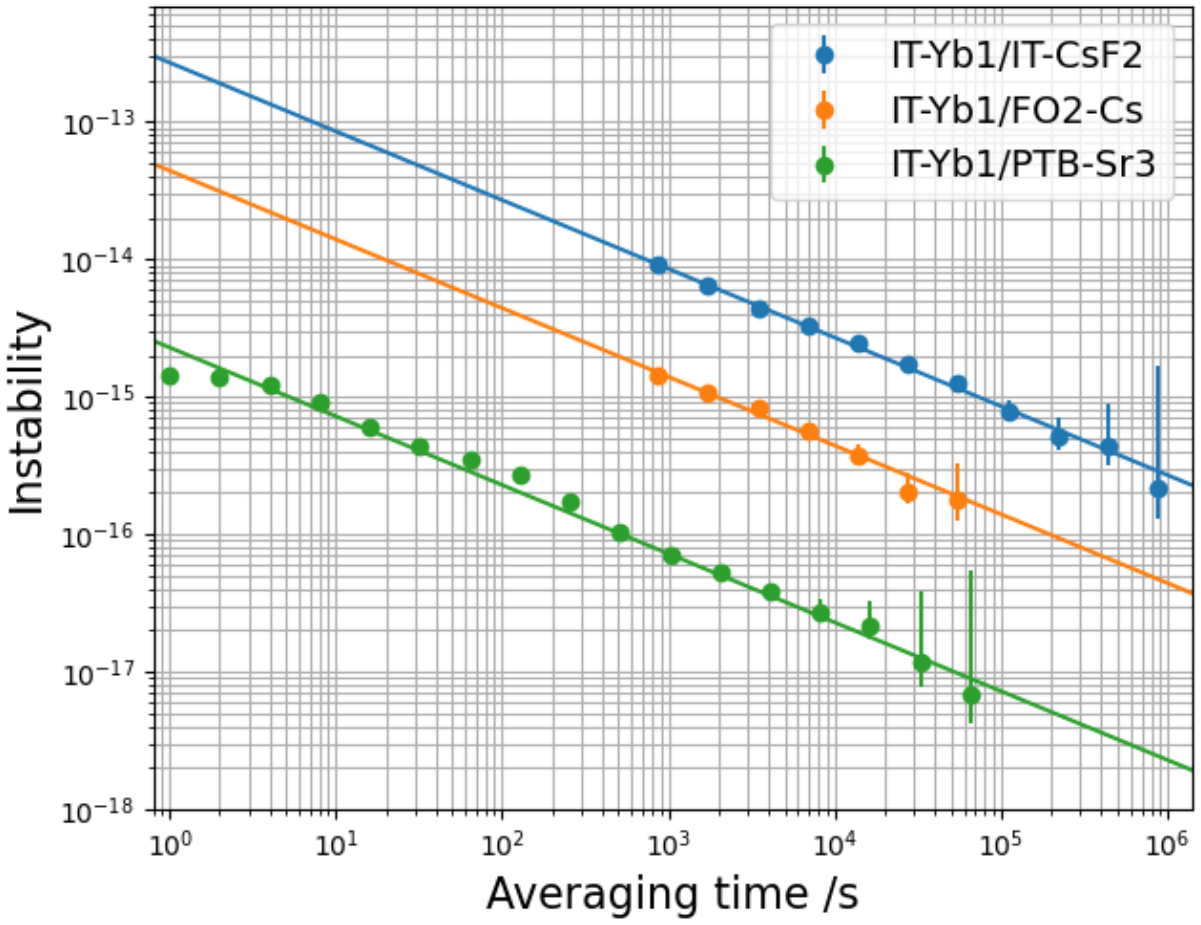
Instability of clocks comparisons



Stability:

IT-CsF2 $= 2.7 \times 10^{-13}/\sqrt{\tau/s}$

FO2-Cs $= 4.4 \times 10^{-14}/\sqrt{\tau/s}$

IT-Yb1 $= 2.3 \times 10^{-15}/\sqrt{\tau/s}$

IT-Yb1/FO2-Cs

f(Yb) = 518 295 836 590 863.61(17) Hz

IT-Yb1/FO2-Rb

f(Yb)/f(Rb) = 75 833 197.545 114 168(24)

Results in agreement with value recommended by CIPM

I. Goti et al., 2023 Metrologia 60 035002

C. Clivati et al., 2022 Phys. Rev. Applied 18, 054009

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Towards the redefinition of the second

Uncertainty
< 2×10^{-18}

Regular contribution
to TAI
@ 2×10^{-16}

Continuity with the definition
based on Cs < 3×10^{-16}

Validation of frequency ratios
< 5×10^{-18}

Access to the realization
of the new definition

In 2022 the CCTF proposed a **roadmap** toward a redefinition with clear criteria and **quantitative conditions**

GOAL: Redefinition by 2030

1. The 2022 and 2023 campaigns in Europe demonstrated the maturity of the comparison process
2. In 2023, first involvement of a transportable optical clock in intercontinenal comparisons
3. Given 6 years 2024-2030: 2 campaigns/yr means 12 campaigns
4. This should a very good pace for demonstrating solid numbers (i.e. consistency)

N. Dimarcq et al., arXiv preprint arXiv:2307.14141 (2023)

Radioastronomy Geodesy

VLBI Common clock via optical fibre

INRIM
National
Metrology Inst.

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

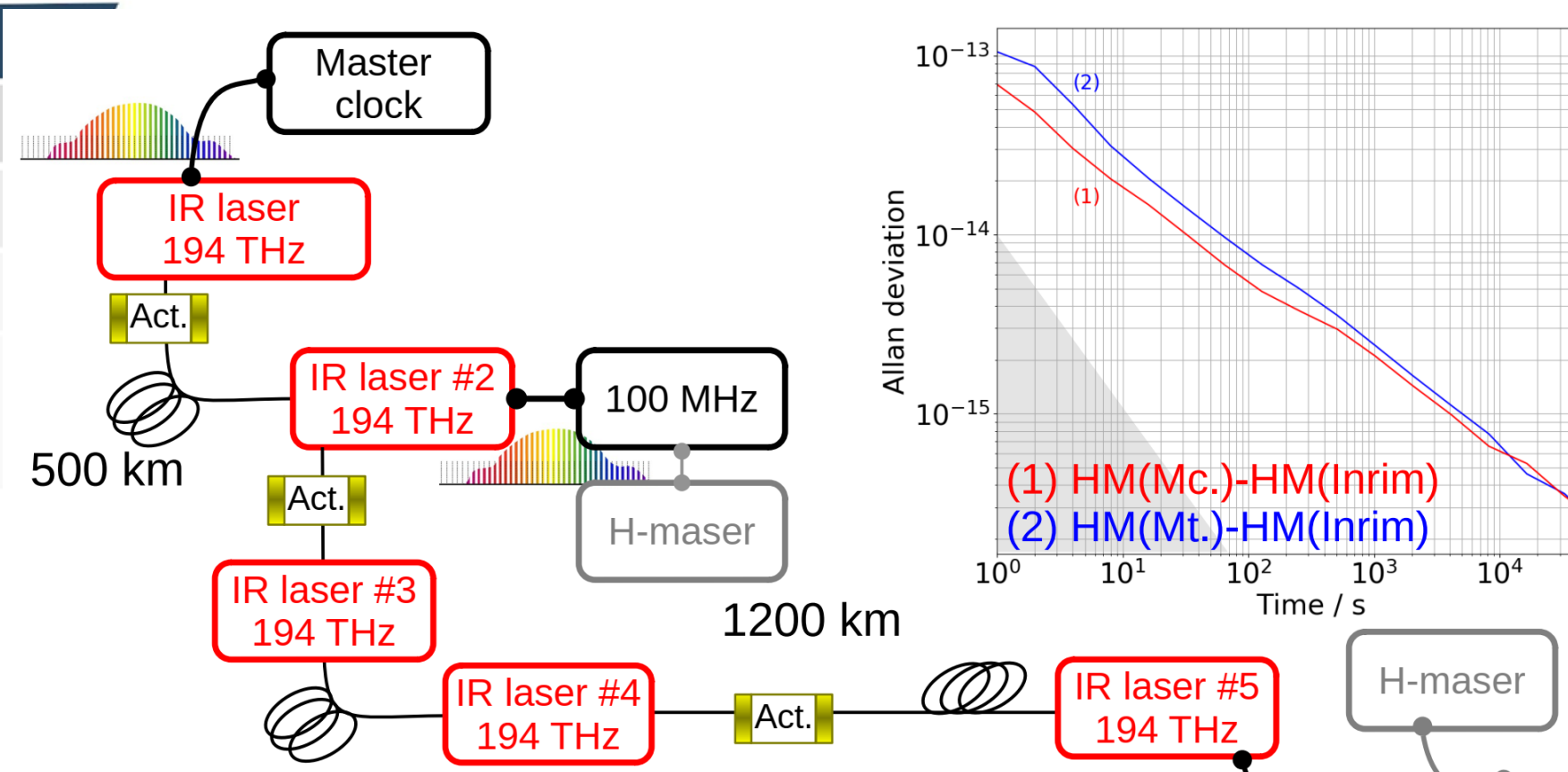
Medicina Radio Observatory
(National Inst. Astrophysics)

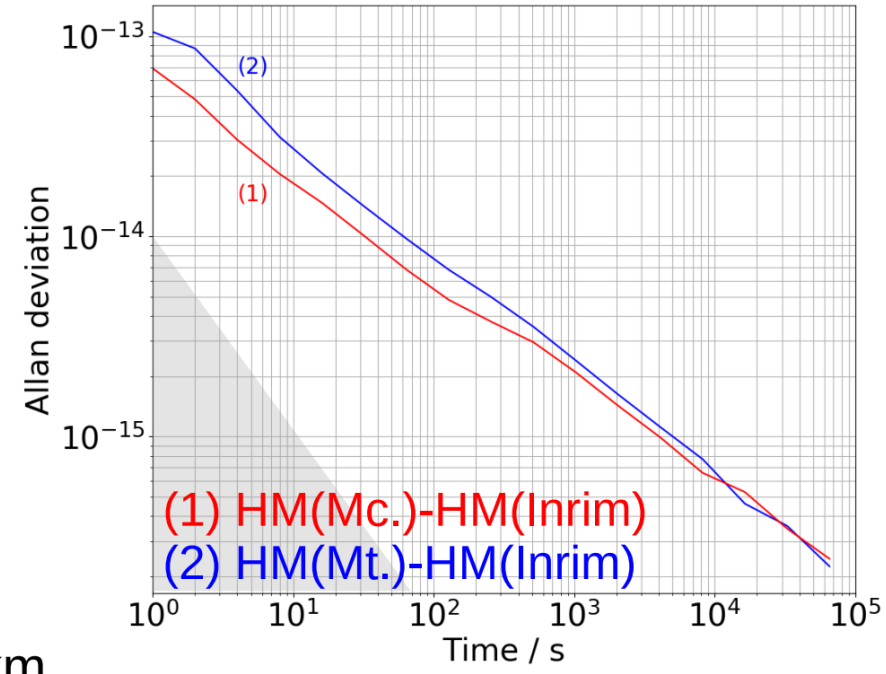
ASI
Agenzia Spaziale Italiana

Matera Space Geodesy Centre
(Italian Space Agency)

C. Clivati, et al. Optica 7, 1031-1037 (2020)

VLBI Common clock via optical fibre





- 1739 km of fiber, 30 optical amplifiers
- Ultrastable cavity
- 4 slave lasers
- 3 combs

C. Clivati, et al. Optica 7, 1031-1037 (2020)

Dissemination of better clocks for

- Better mm-VLBI: above 80 GHz, H-Masers are the main limit to resolution
  M. Rioja, et al. Astron. J., vol. 144, no. 4, art. no. 121, 2012.
  B. Nikolic, et al. Astron. Astrophys., vl. 552, art. no. A104, Apr. 2013.
  M. Rioja and R. Dodson, Astron. J., vol. 141, no. 4, art. no. 114, 2011
- In Geodesy VLBI, accuracy is relevant and 1-mm positioning accuracy requires clocks uncertainties at 1e-16.
  A. Neill, et al. Report of Working Group 3 to the IVS Sep. 2005.Directing Board
- Study of compact radio sources (better angular resolution) and interstellar molecular clouds
- Studying Pulsar through absolute accurate time (1E-15 stability @years)
- Improve atmospheric models

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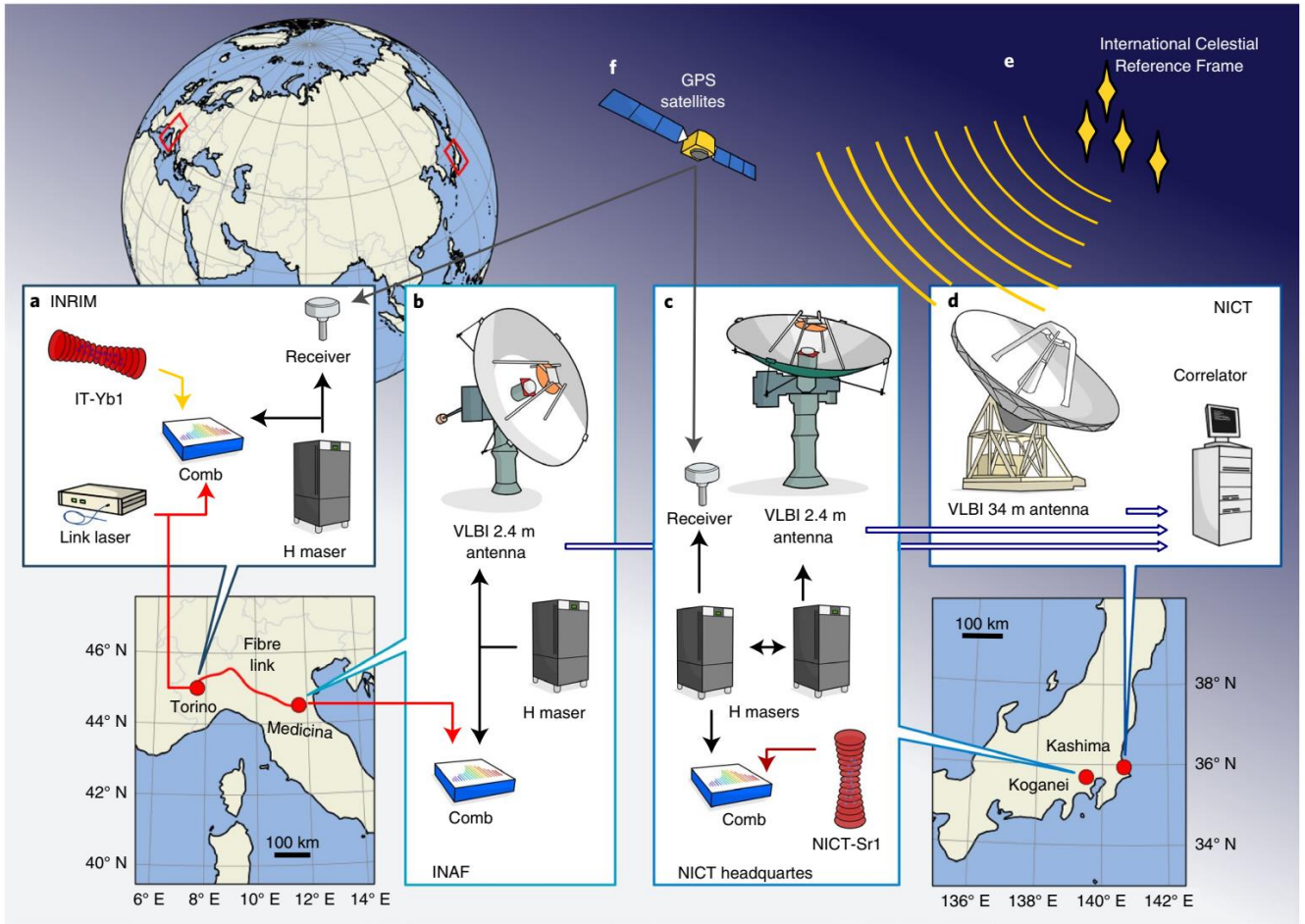
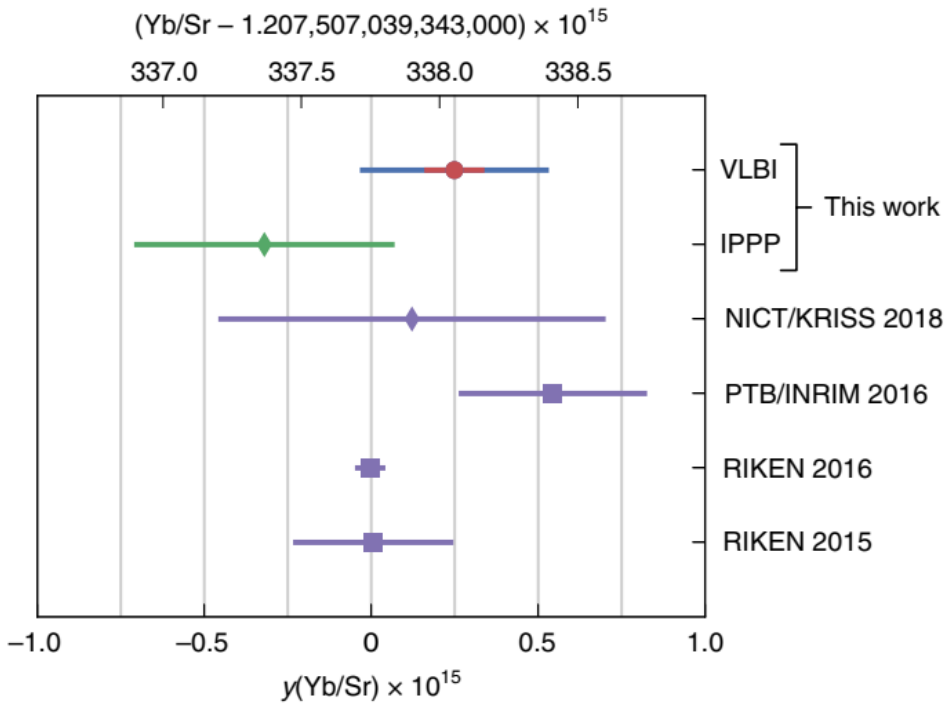
VLBI for intercontinental OFS comparisons





National Institute of Information and Communications Technology

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INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

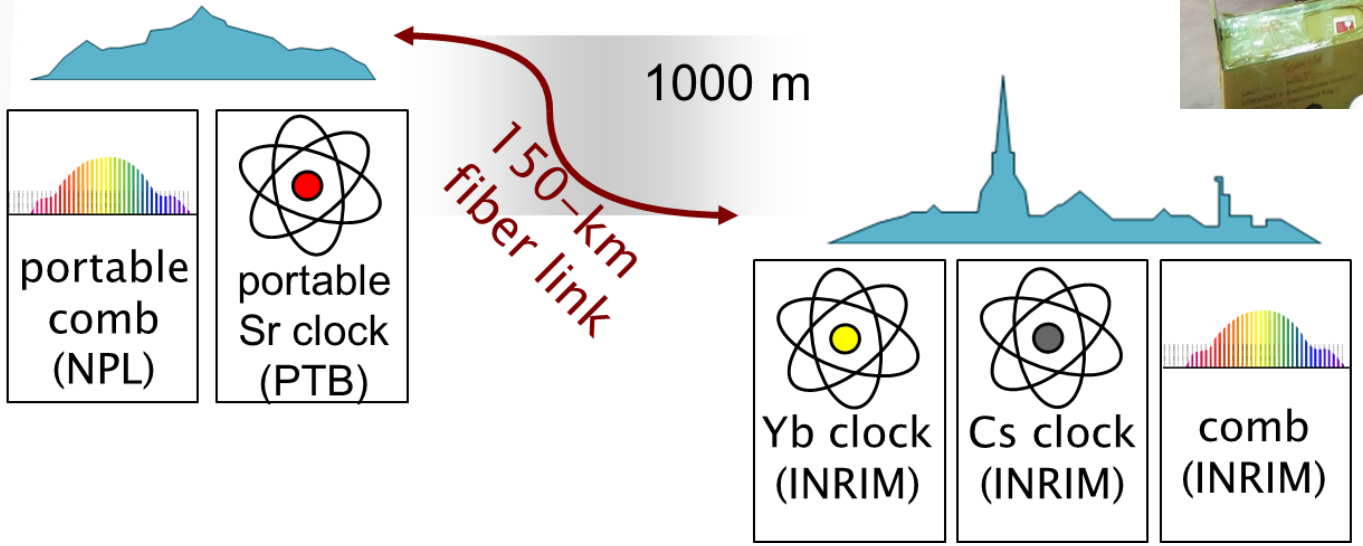
M. Pizzocaro, et al. Nature Physics, 17, 2, (2020)

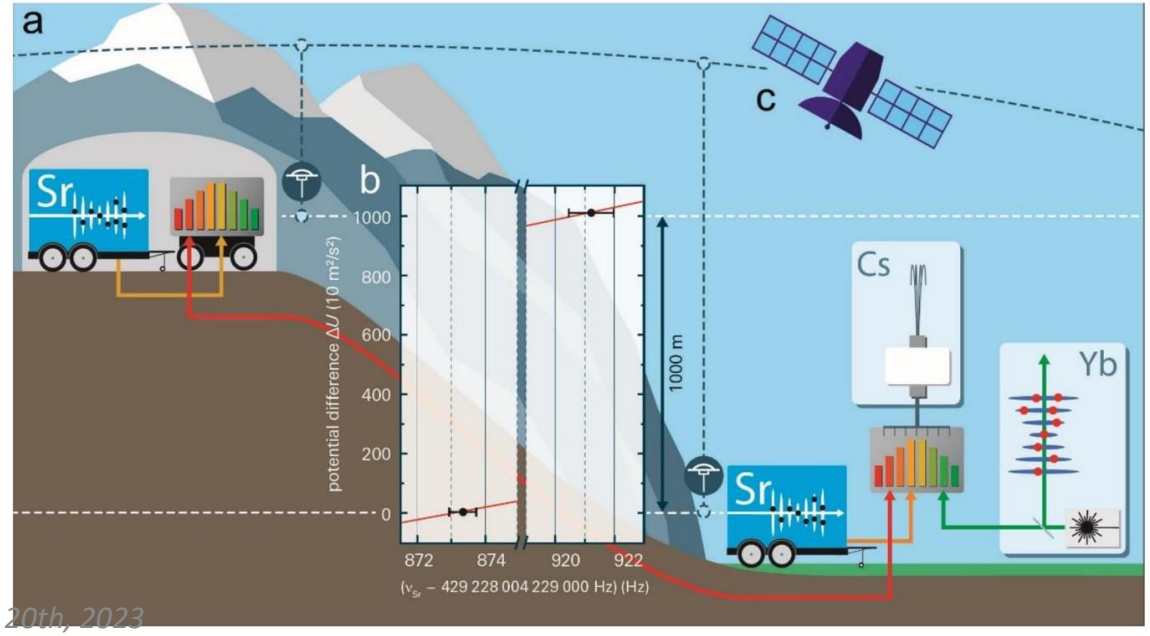
Chronometric levelling

- *How to translate this into a "real instrument"?*

→ Transportable optical clocks + fibre link

A proof-of-principle geodesy experiment on the Alps





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

Earthquakes

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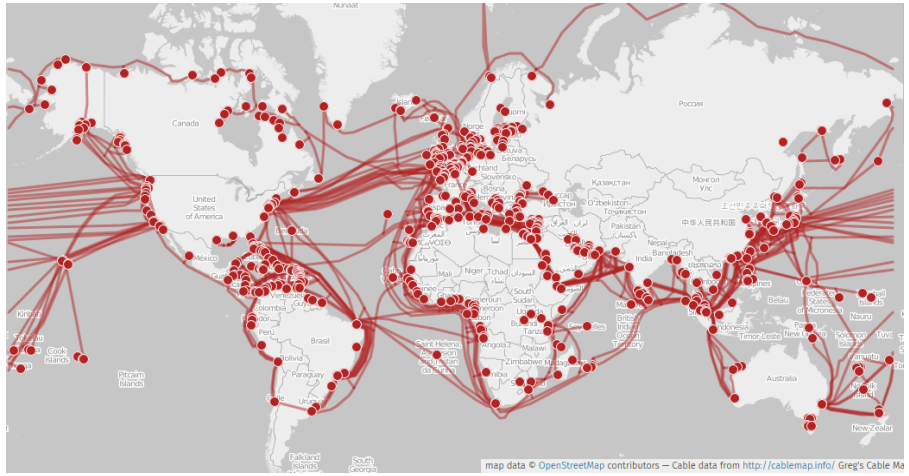
Earthquake monitoring with subsea fibers

- *Underwater cables:*
- **unmonitored seafloors**
- important for **early warning**
- deep seas are **quiet environments**
- **ideal for sensing** (earthquakes, waves, tides...)



Research Article Vol. 5, No. 8 / August 2018 / Optica 893
optica

Optical frequency transfer over submarine fiber links

Cecilia Clivati,[1] Anna Tampellini,[1,2] Alberto Mura,[1] Filippo Levi,[1] Giuseppe Marra,[3] Pauline Galea,[4] André Xuereb,[5] and Davide Calonico[1,*]

OPTICAL SEISMOLOGY

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]

GEOPHYSICS

Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable

G. Marra[1*], D. M. Fairweather[2], V. Kamalov[3], P. Gaynor[1], M. Cantono[3], S. Mulholland[1], B. Baptie[4], J. C. Castellanos[3], G. Vagenas[1], J.-O. Gaudron[1], J. Kronjäger[1], I. R. Hill[1], M. Schioppo[1], I. Barbeito Edreira[1], K. A. Burrows[1], C. Clivati[5], D. Calonico[5], A. Curtis[2]

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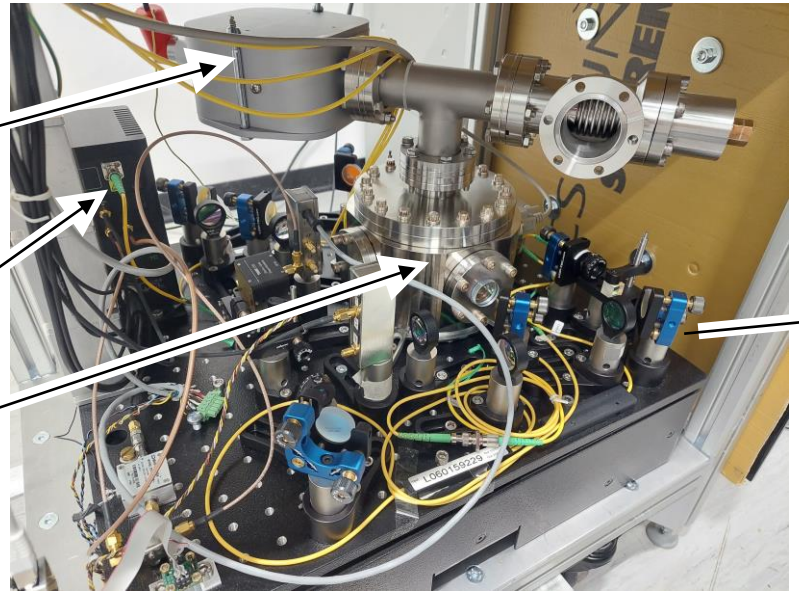
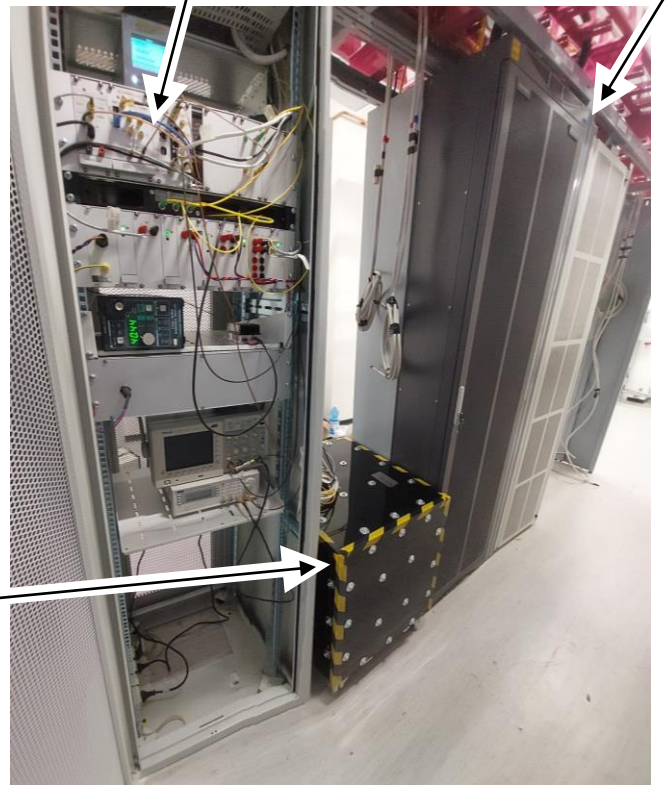
The experimental setup (today)

In-field installation:

- **transportable ultrastable lasers** at data centers
- **standard fiber with internet traffic**





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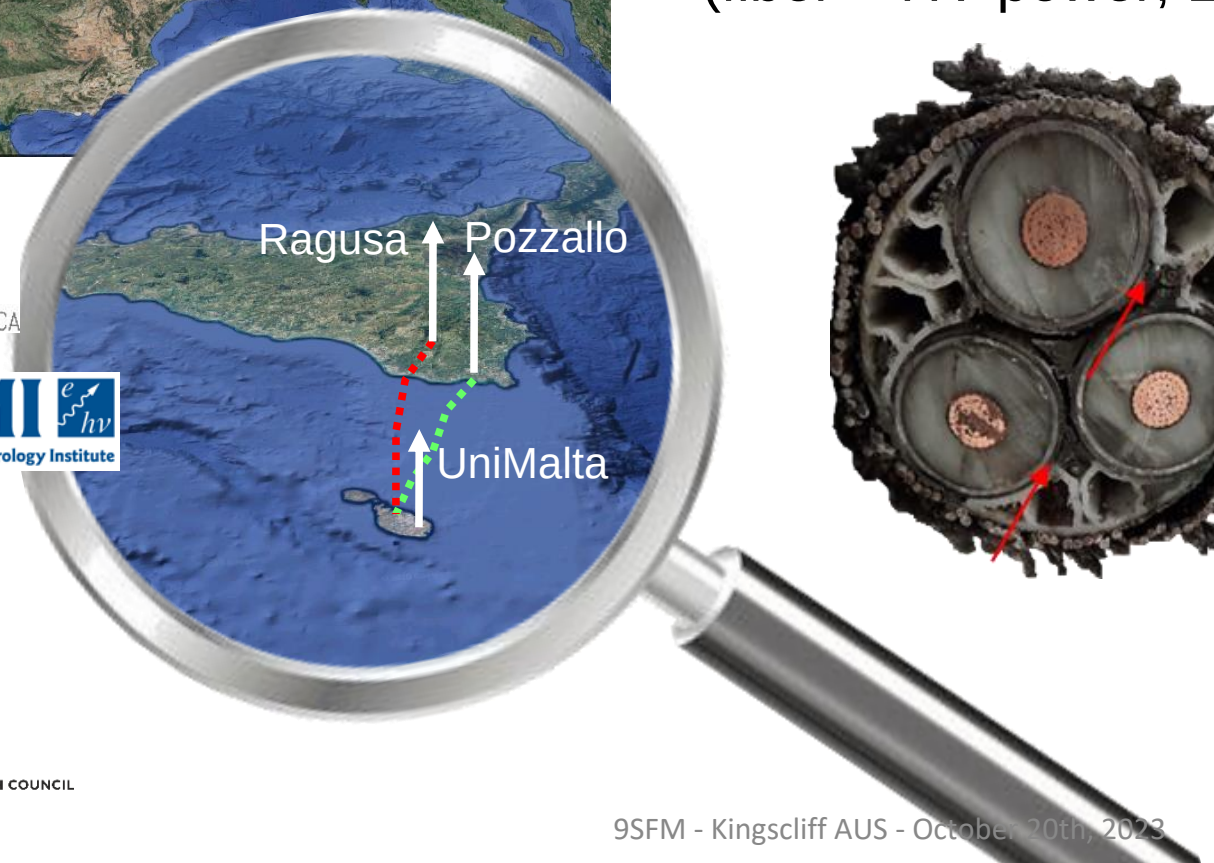
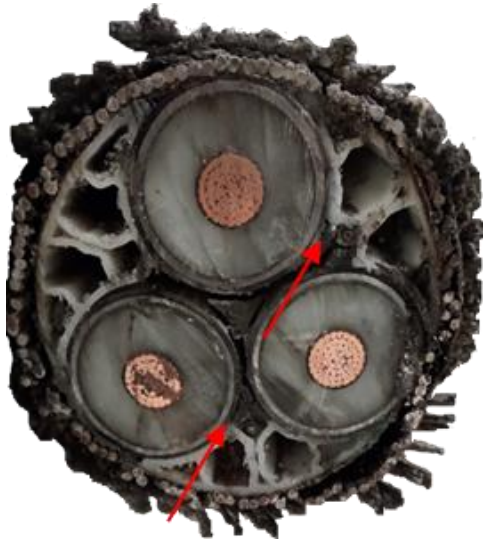
Submarine Earthquakes detection



Two testbeds 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)



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

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L-Università ta' Malta

British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

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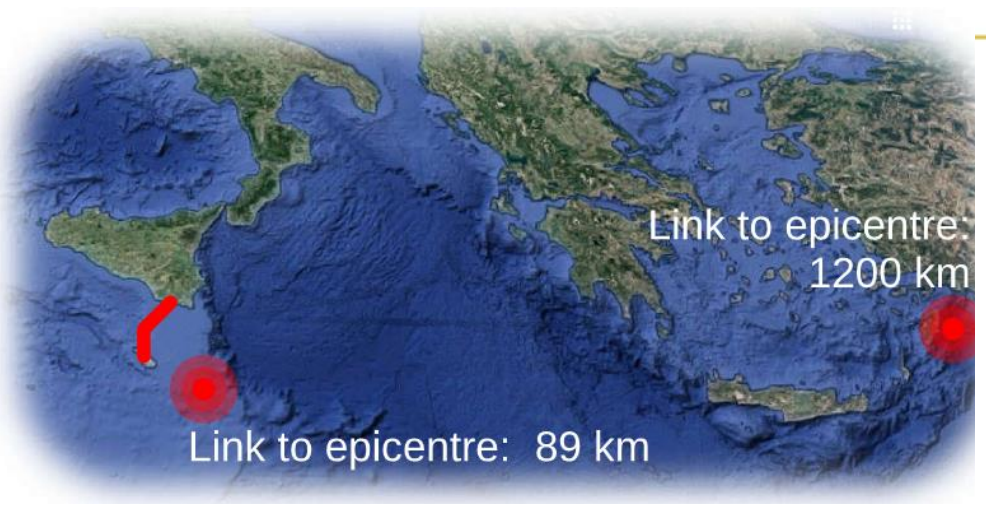
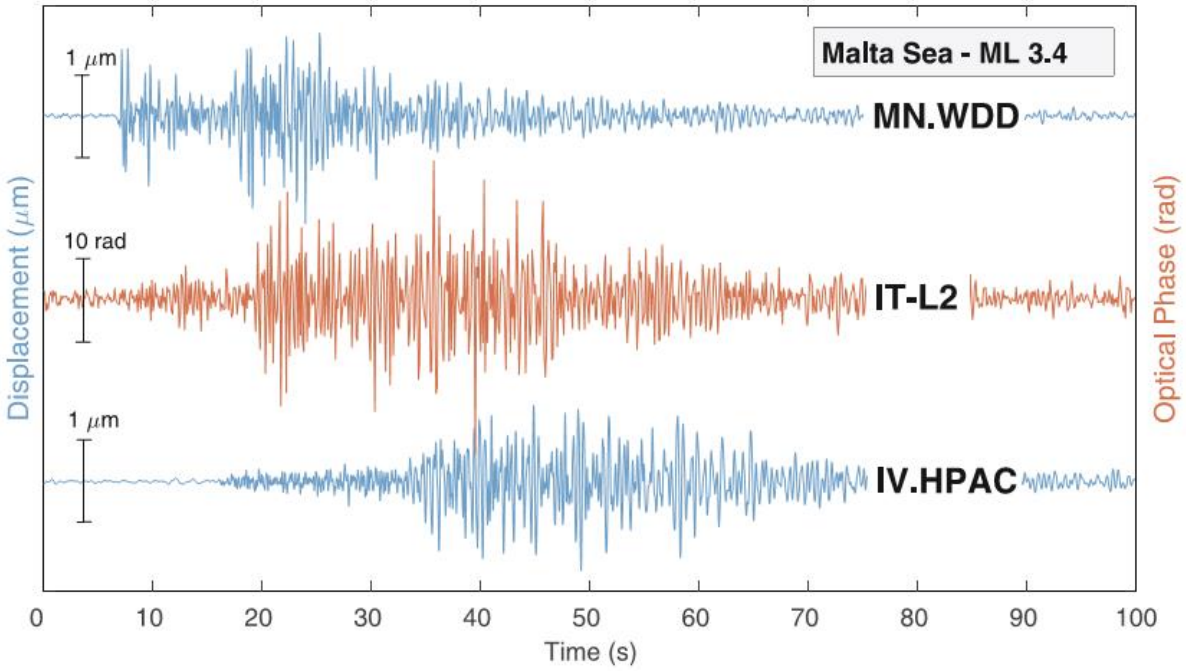
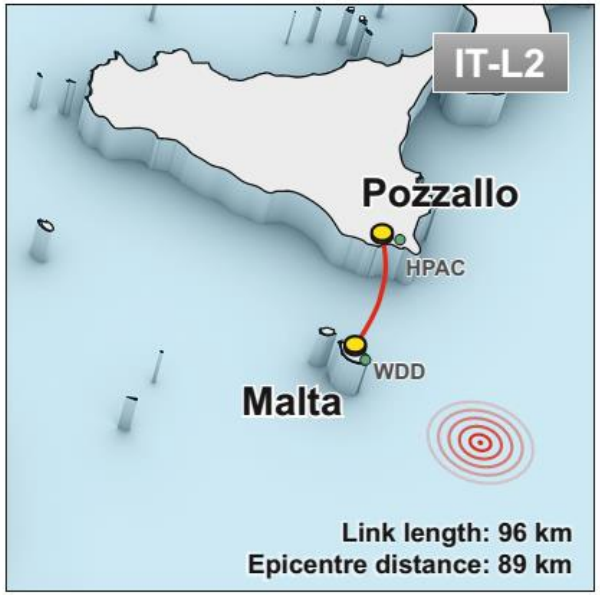
Submarine Earthquakes detection

- Greece, 2017/09/01, M=5.1
  Malta, 2017/09/02, M=3.4
  detected on **Malta-Sicily link (IT-MT, 92 km)**

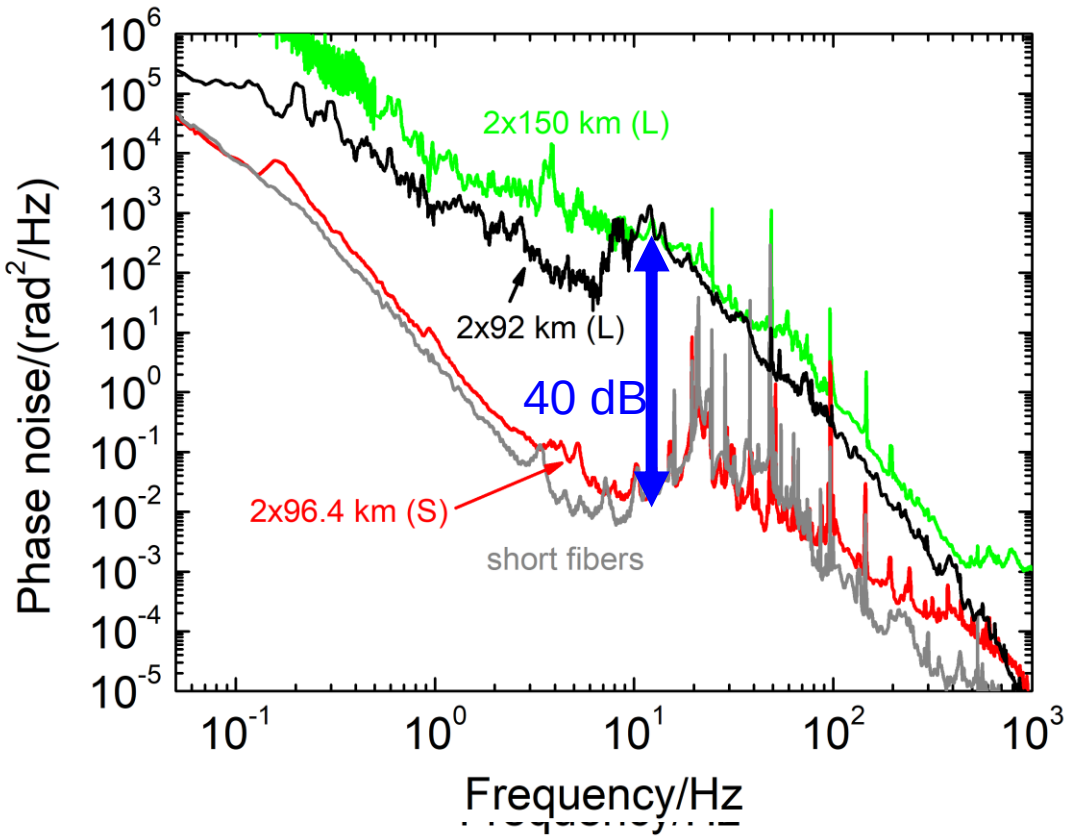


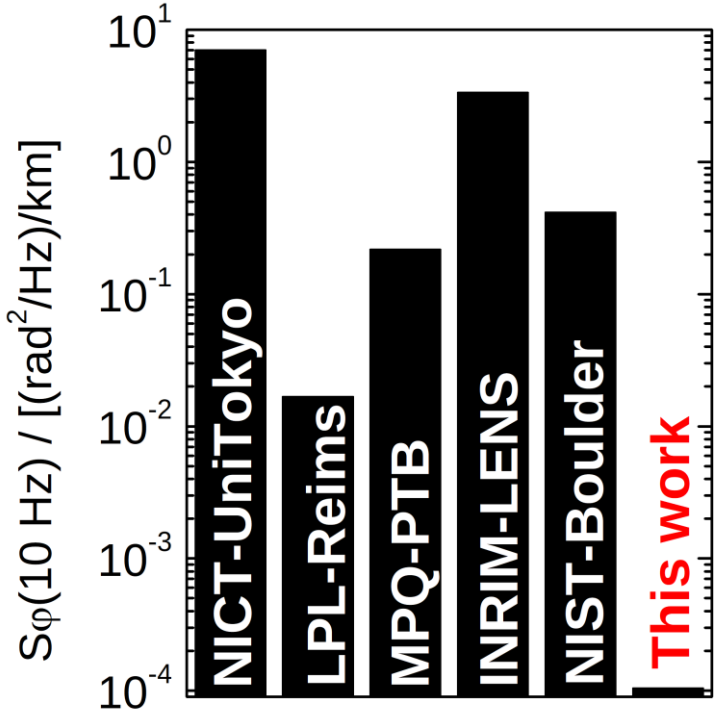




G. Marra et al., Science **361** (2018)

Submarine Earthquakes detection





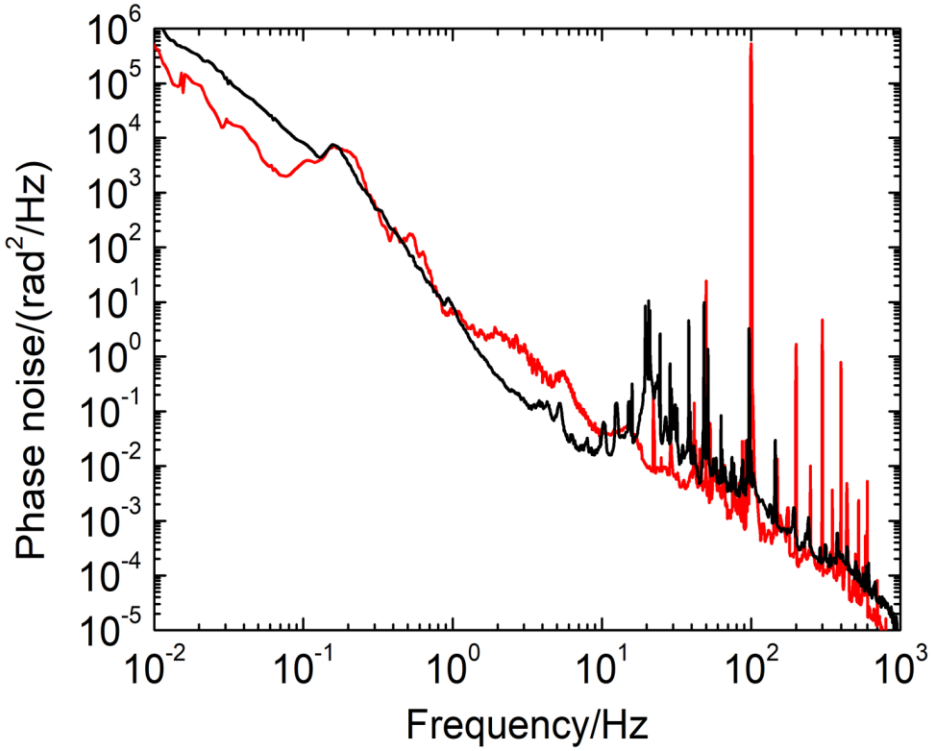
C. Clivati et al., Optica **14** (2018)

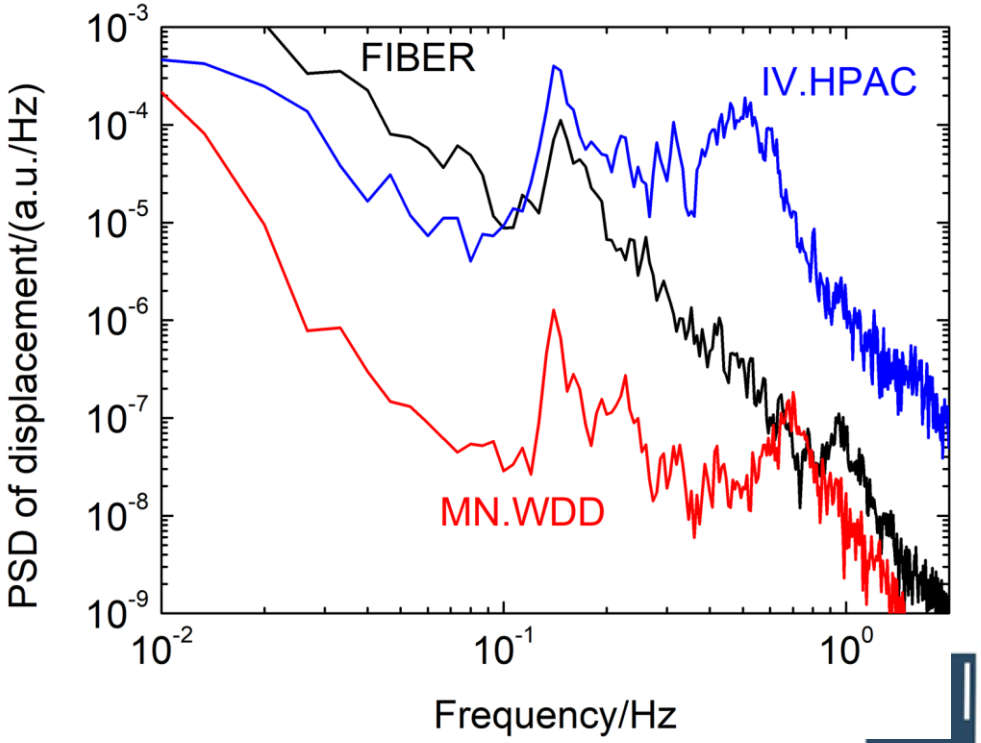
- Submarine fibers have up to 20 dB lower noise than terrestrial fibers
- High SNR achievable even on transoceanic links

C. Clivati et al., Optica **14** (2018)

Geo-sensing: sea-bottom seismic noise

- Generated by wind-sea interaction,
- propagates down to seabed
- Characteristic peaks at 0.1 Hz< f < 0.2 Hz
- (twice the wave's frequency)
- Affected by wind, coasts, water depth...





C. Clivati et al., Optica **14** (2018)

Submarine cables: from 200 km to 2x6000 km

NPL National Physical Laboratory | QMI Quantum Metrology Institute

Google

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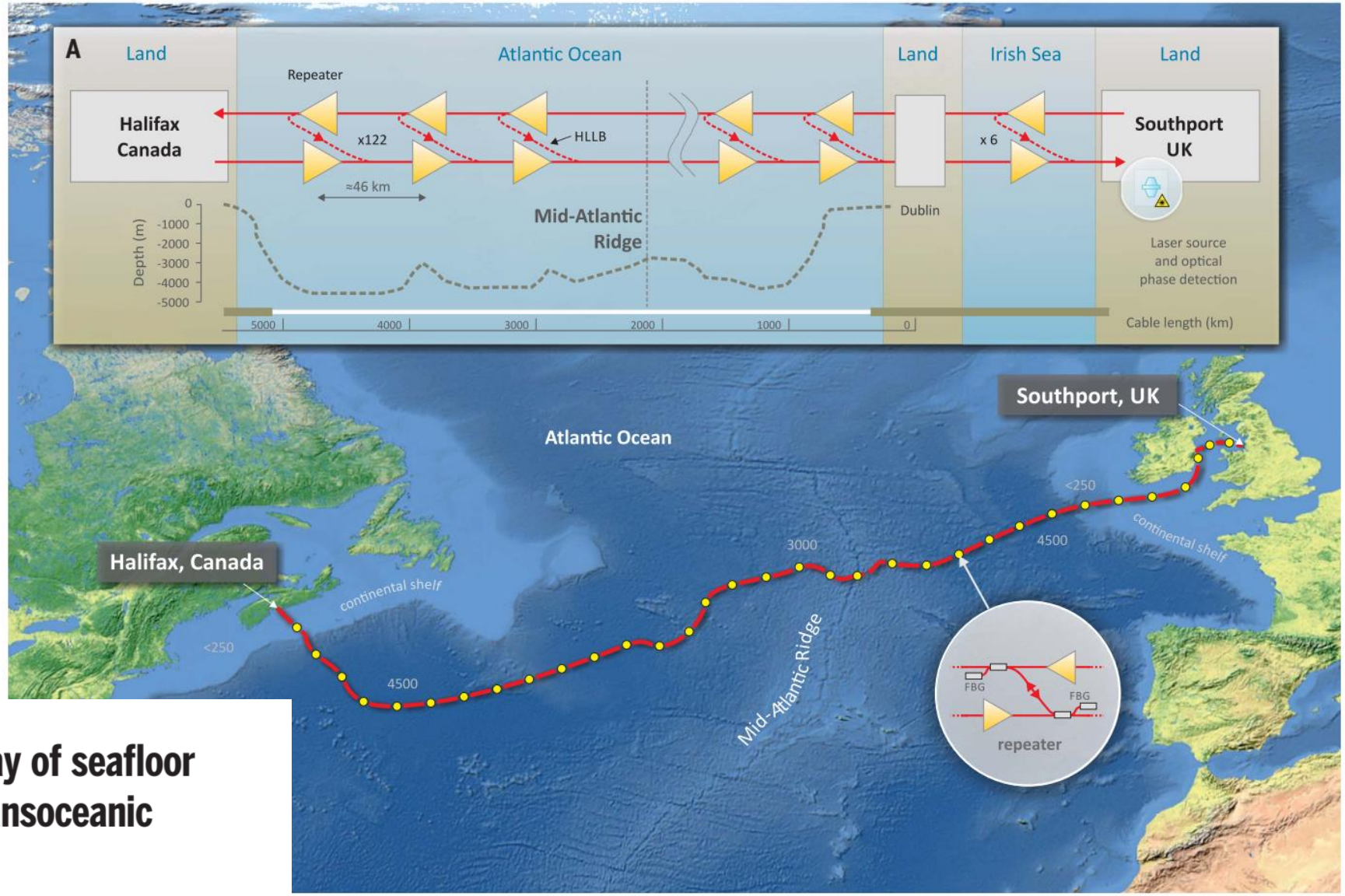
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL



GEOPHYSICS

Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable

G. Marra[1]*, D. M. Fairweather[2], V. Kamalov[3], P. Gaynor[1], M. Cantono[3], S. Mulholland[1], B. Baptie[4], J. C. Castellanos[3], G. Vagenas[1], J.-O. Gaudron[1], J. Kronjäger[1], I. R. Hill[1], M. Schioppo[1], I. Barbeito Edreira[1], K. A. Burrows[1], C. Clivati[5], D. Calonico[5], A. Curtis[2]

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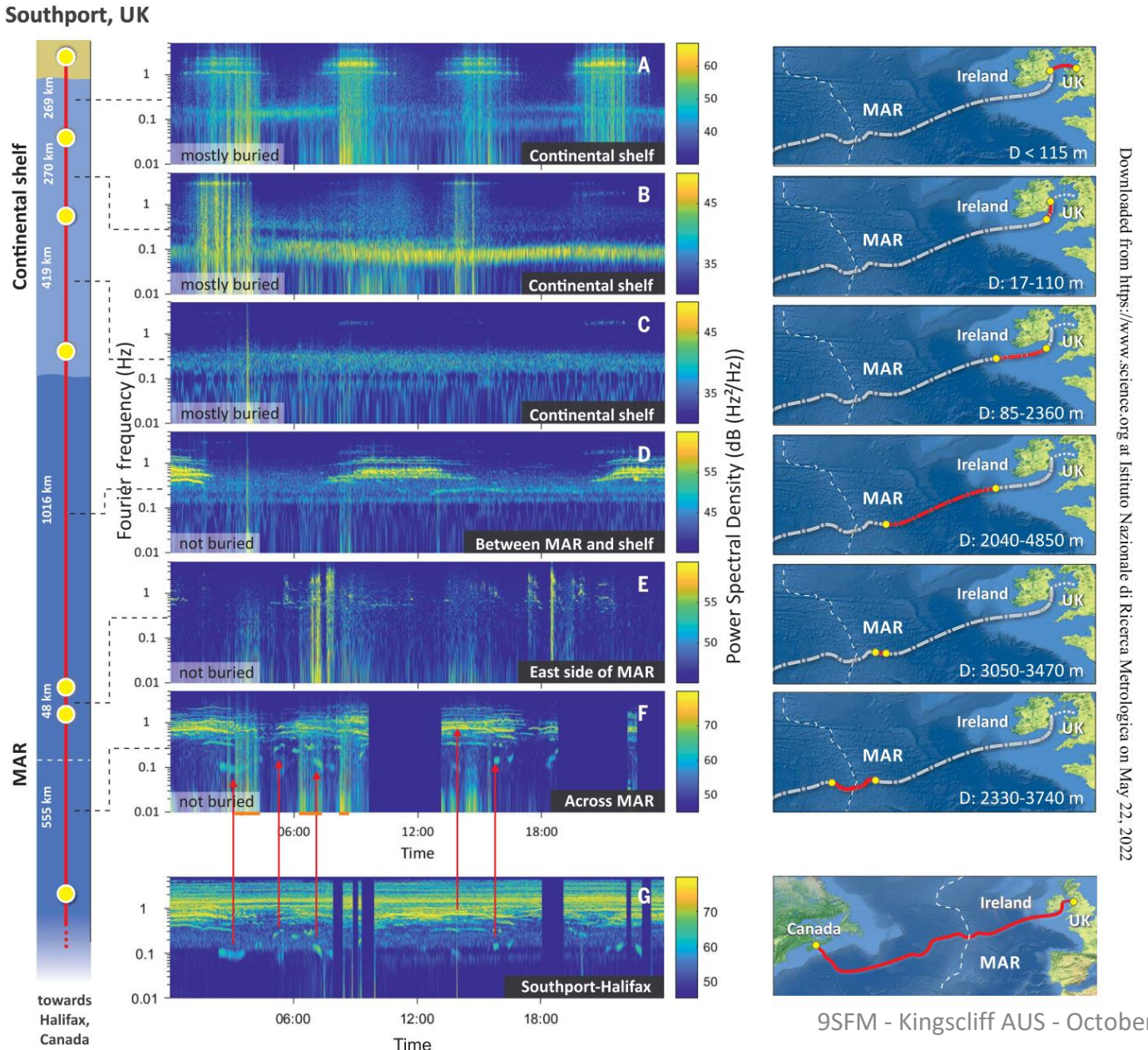
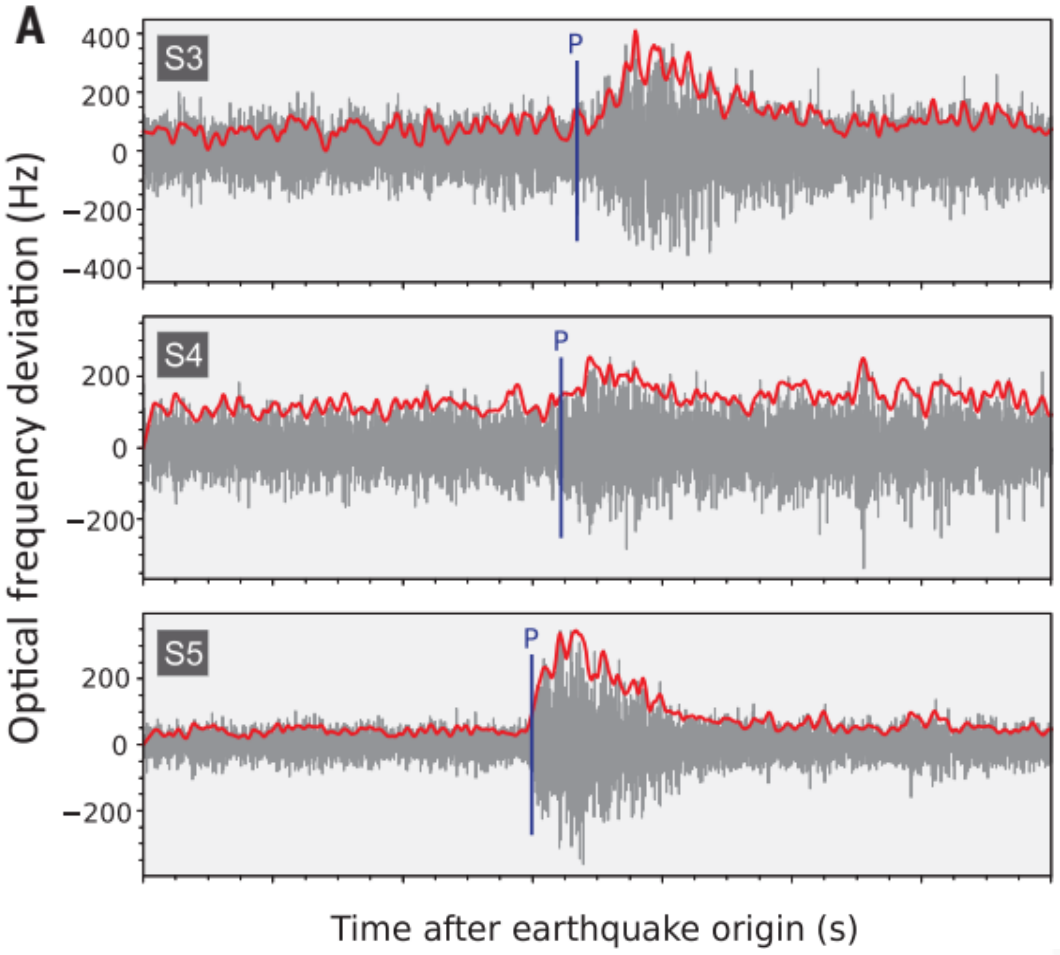
Submarine cables over the Atlantic: geophysics and earthquakes

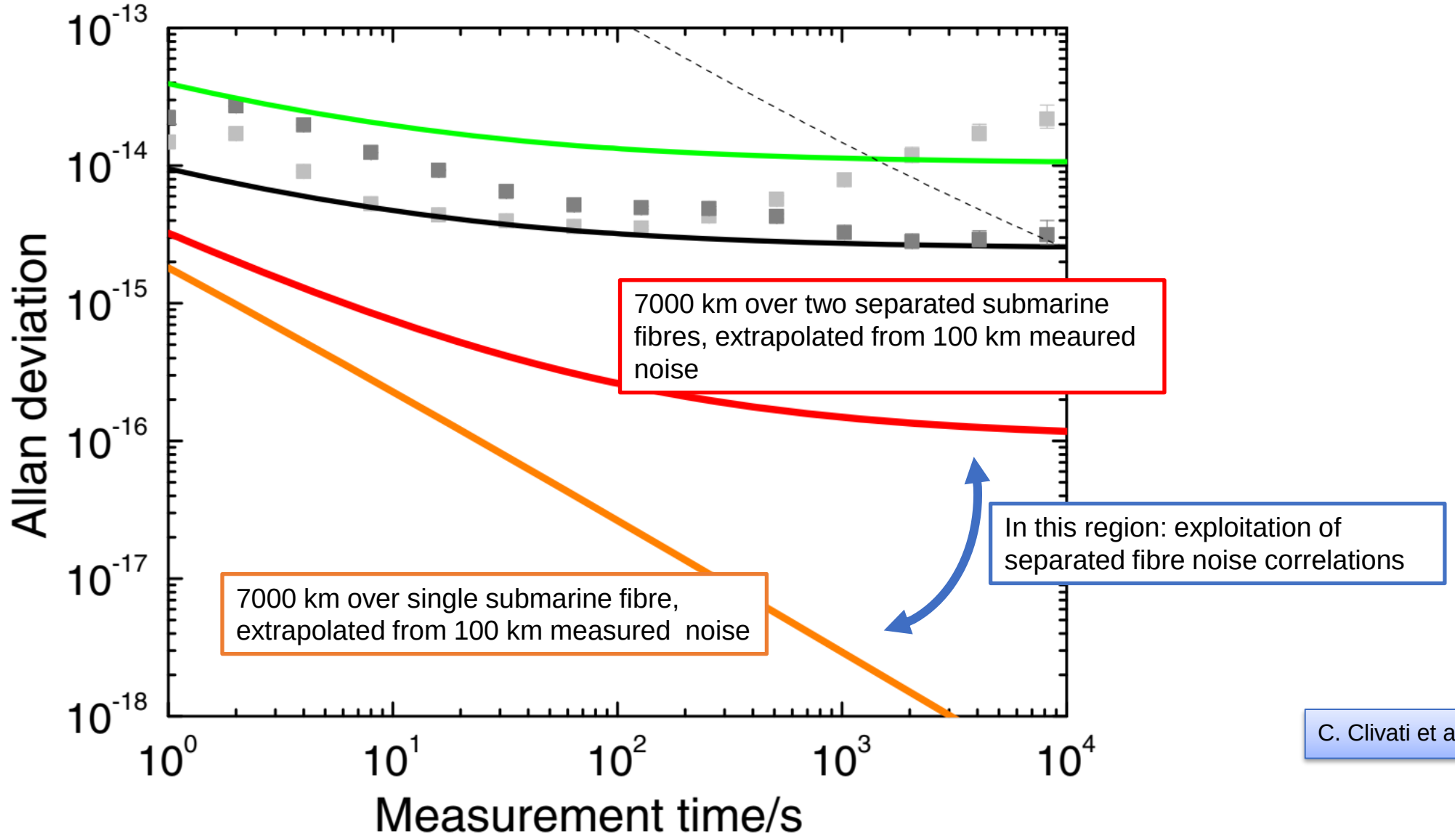


Downloaded from https://www.science.org at Istituto Nazionale di Ricerca Metrologica on May 22, 2022



G. Marra et al., Science (2022

Intercontinental clock comparisons expectations: 7000 km fibre



C. Clivati et al., Optica **14** (2018)

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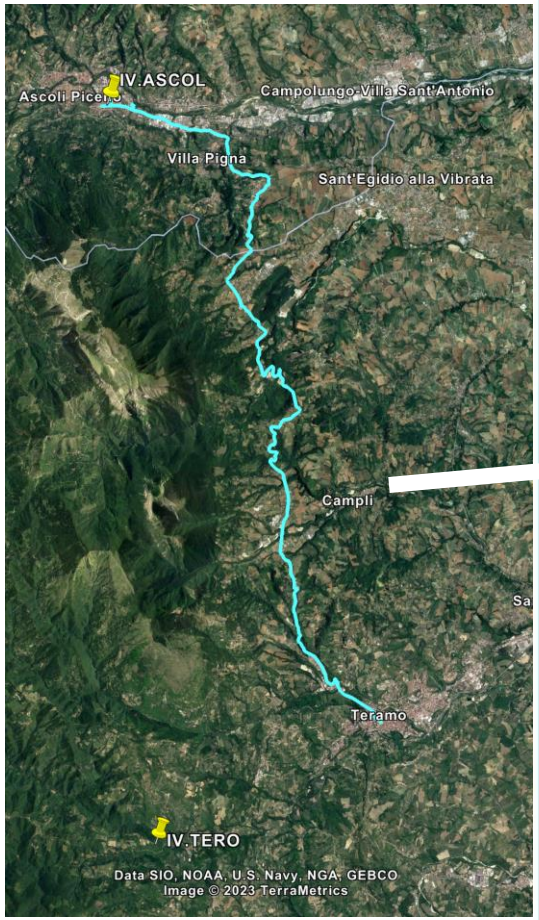
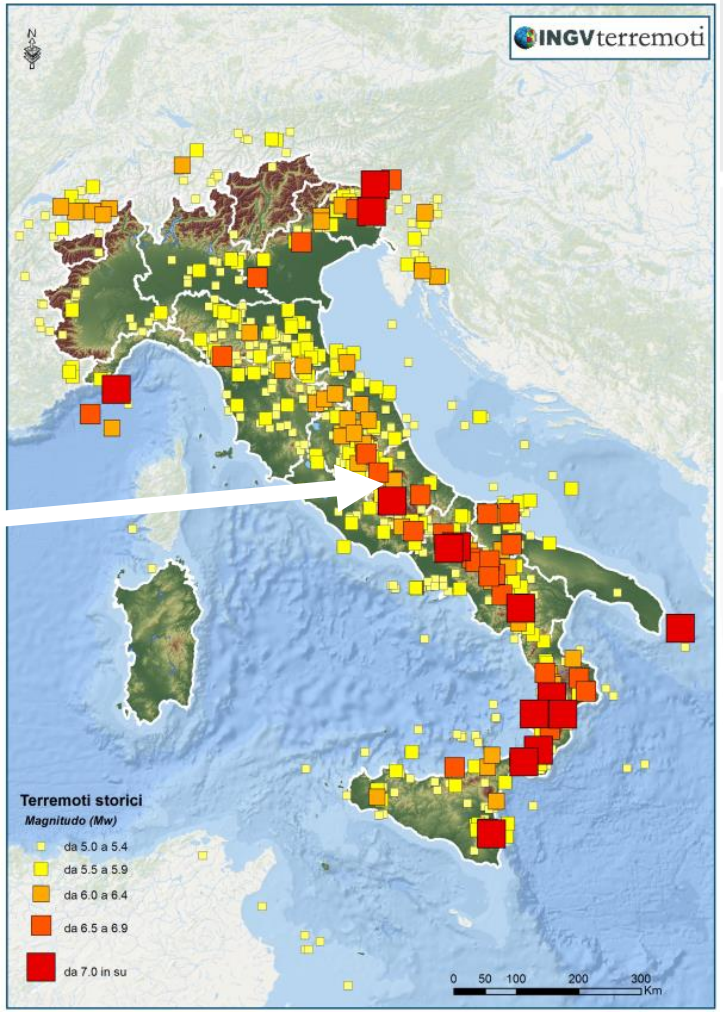
Sensing with terrestrial fibers: the permanent observatory MEGLIO in central Italy

- 36 km commercial link pair (Ascoli Piceno - Teramo)
- **highly seismic area**
- populated towns and road traffic
- 1 sensing DWDM channel
- **coexistence with data traffic**
- comparison with local seismometers





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open fiber

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Metallurgica Bresciana

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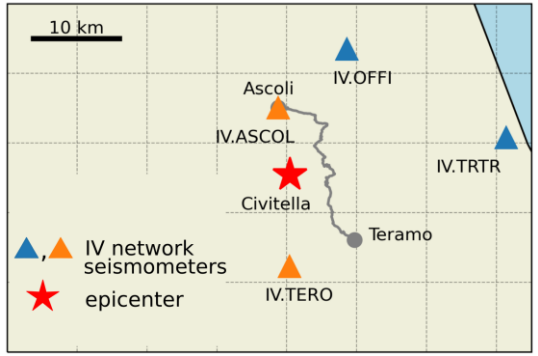
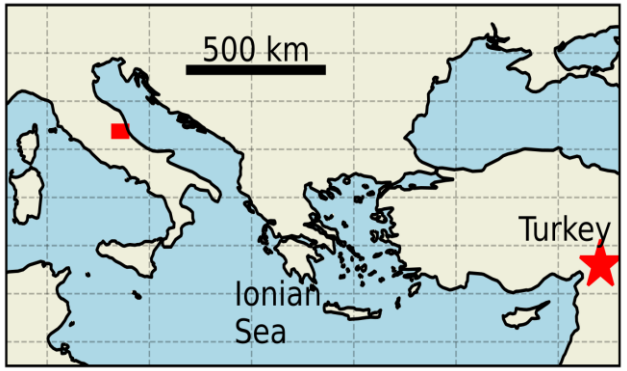
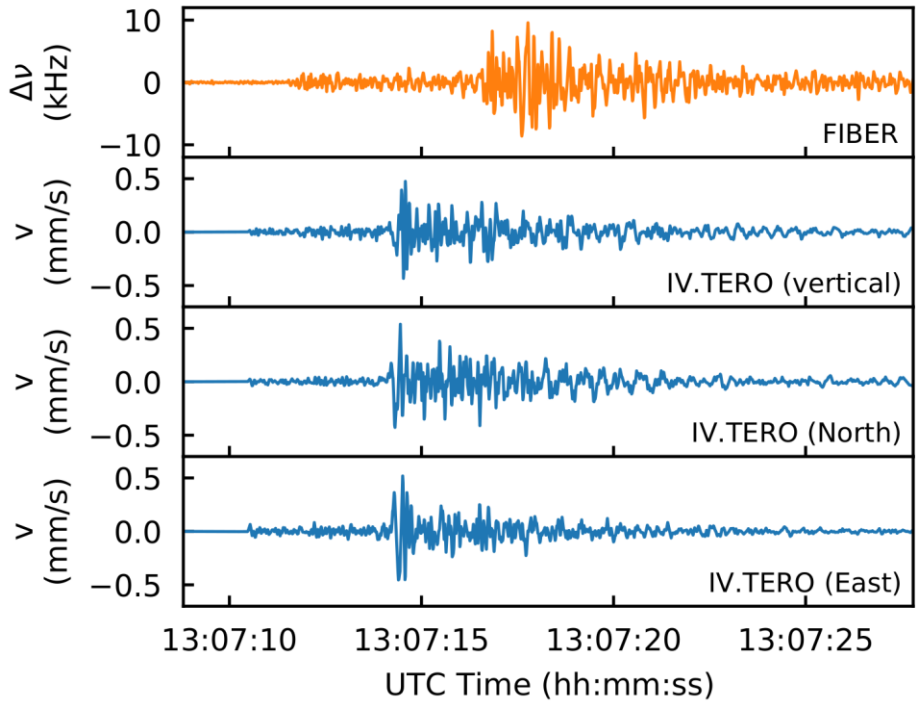
Detection of weak, local, earthquakes... ... and strong, distant, earthquakes

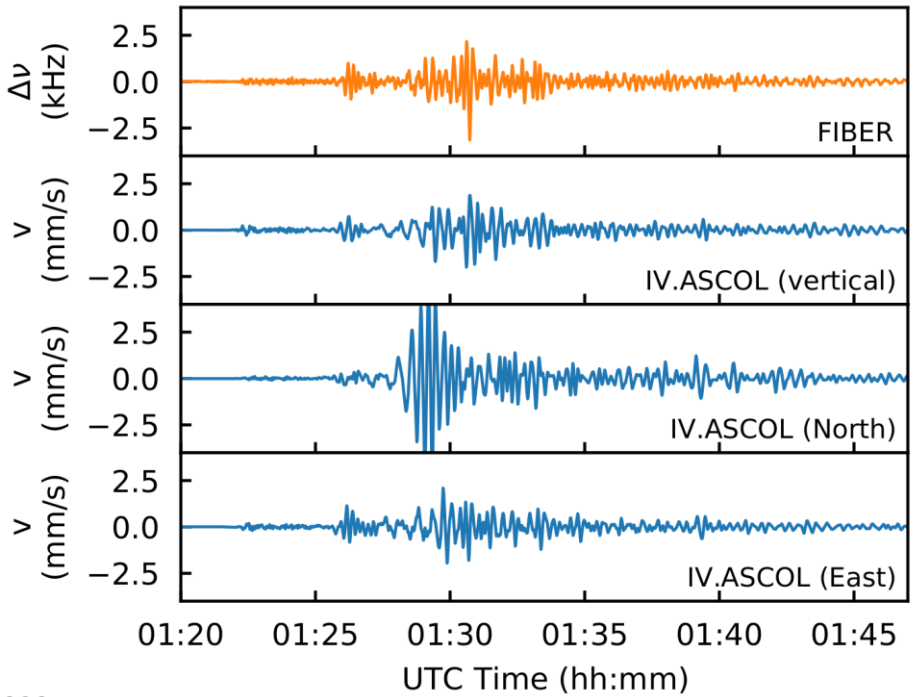
Civitella (Italy),
Feb. 19th, 2022
magnitude 2.0
distance 18 km



Turkey,
Feb. 6th, 2023
magnitude 7.9
distance 2100 km



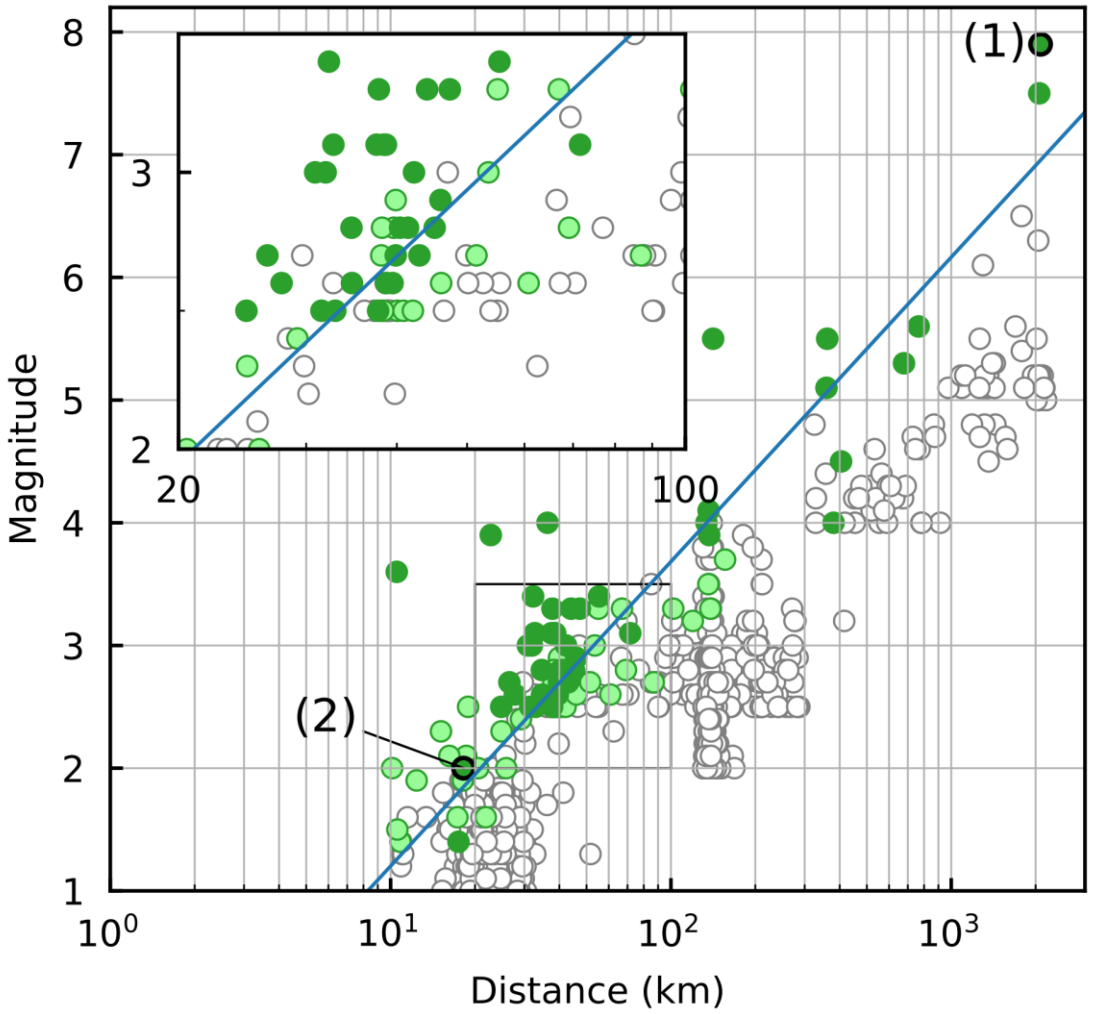




Two years of observations: the sensitivity curve

- *Analysis over ~ 570 events: (June 2021 to September 2022)*
- detection of ~ 70 events
- good sensitivity
- down to M ~ 1
- **detection probability: distance ⇔ magnitude**

$$P = A_2 \frac{10^{A_1 M}}{d}$$



Donadello et al., (2023), arXiv:2307.06203

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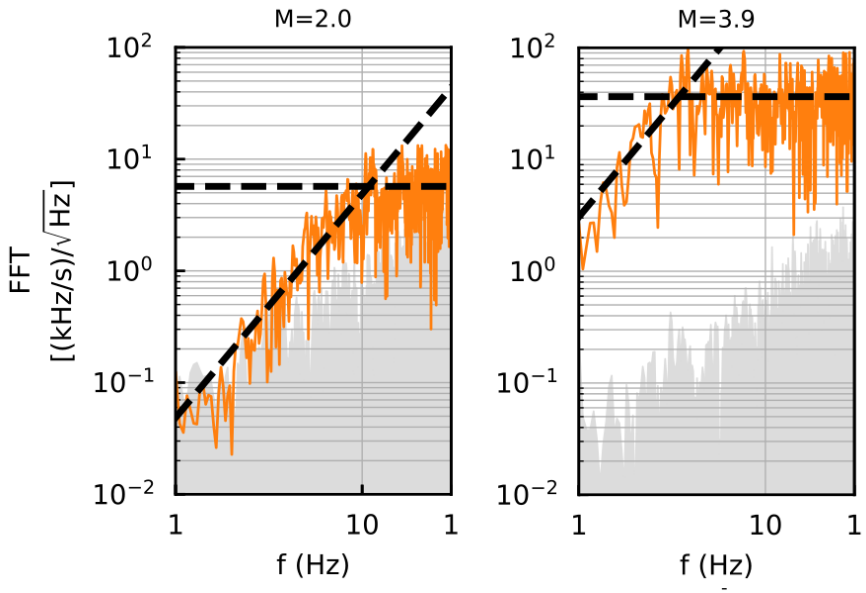
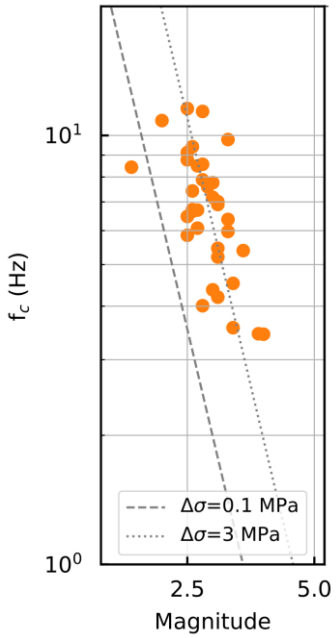
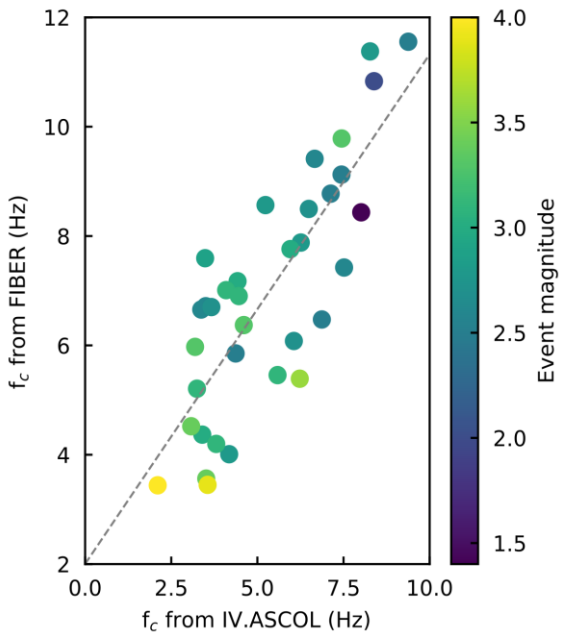
Fourier analysis and earthquake magnitude estimation

- *Brune's model:*
- ground acceleration spectrum
- **corner-frequency ⇔ magnitude**

$$f_c = kC_d\beta\left(\frac{16}{7}\frac{\Delta\sigma}{M_o}\right)^{1/3}$$







Donadello et al., (2023), arXiv:2307.06203

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Shaping Europe's digital future

DIGIBYTE | 13 June 2019

The future is quantum: EU countries plan ultra-secure communication network

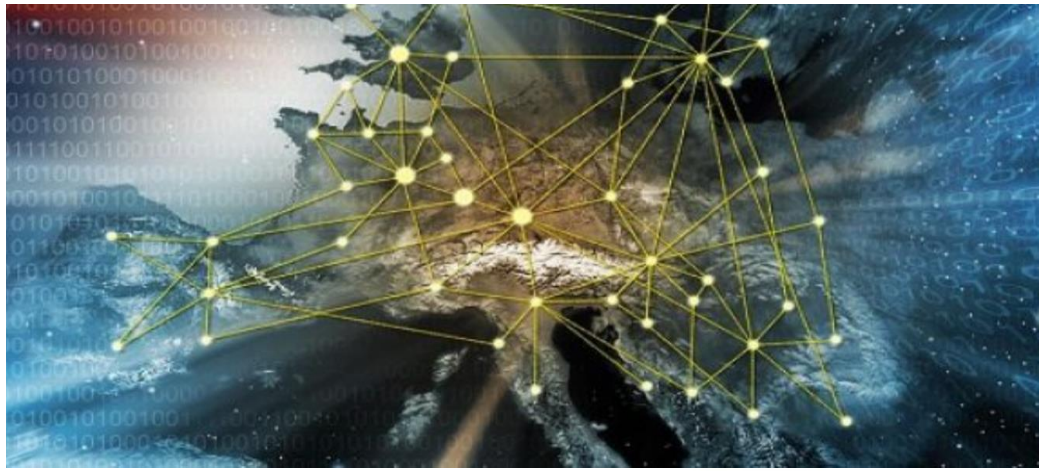
EuroQCI: European Quantum Communication Infrastructure

European Quantum Communication Infrastructure

- **An integrated satellite and terrestrial system spanning the whole EU for ultra-secure exchange of cryptographic keys (Quantum Key Distribution)**
- Quantum communication infrastructure (QCI) is part of the European Cybersecurity Strategy and is **to be integrated in the new Secure Space Connectivity initiative 'IRIS²'**

EuroQCI space segment
Distribution of quantum-secured encryption keys on a global scale

EuroQCI terrestrial segment
Federation of national terrestrial QCI networks with cross borders connections



Source: European Commission

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QUID: EuroQCI Italy

QUID

QUANTUM ITALY DEPLOYMENT

- **Coordination: INRIM**
- 18 Partners: 9 Public + 9 Private
- Large companies and SME
- Budget: 9.45 Meuro
- Duration 30 months

- **Deploy EuroQCI in Italy, advanced national quantum systems and networks for testing quantum communication** technologies and for integrating them with existing communication networks
- **Quantum Metropolitan Area Networks (QMAN), >14 points in 9 towns:** Turin, Milan, Bologna, Padua, Trieste, Florence, Rome, Naples, Matera.
- Use these quantum systems and networks for developing and **testing use cases in support of national QCI initiatives**
- Initial Connection of QMANS **by Italian Quantum Backbone (IQB)**, from North to South Italy.

•Acknowledgements – This presentation has been developed in the project The Project QUID (QUantum Italy Deployment) which is funded by the European Commission in the Digital Europe Programme under the grant agreement No 101091408

EuroQCI

Commissione Europea

MUR Ministero dell'Università e della Ricerca

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ITALY DEPLOY NATIONAL: Extensions

Today: INRIM Italian Quantum Backbone

Time Distribution, VLBI Geodesy, Aerospace-Galileo

Metropolitan Q-comm tests,

Several collaborations (Pubblic and Private)

QUID: extension and operation

Long range QKD / 7 Q-MAN / 9 Use Case / 18 partners

Time and Frequency distribution from IQB

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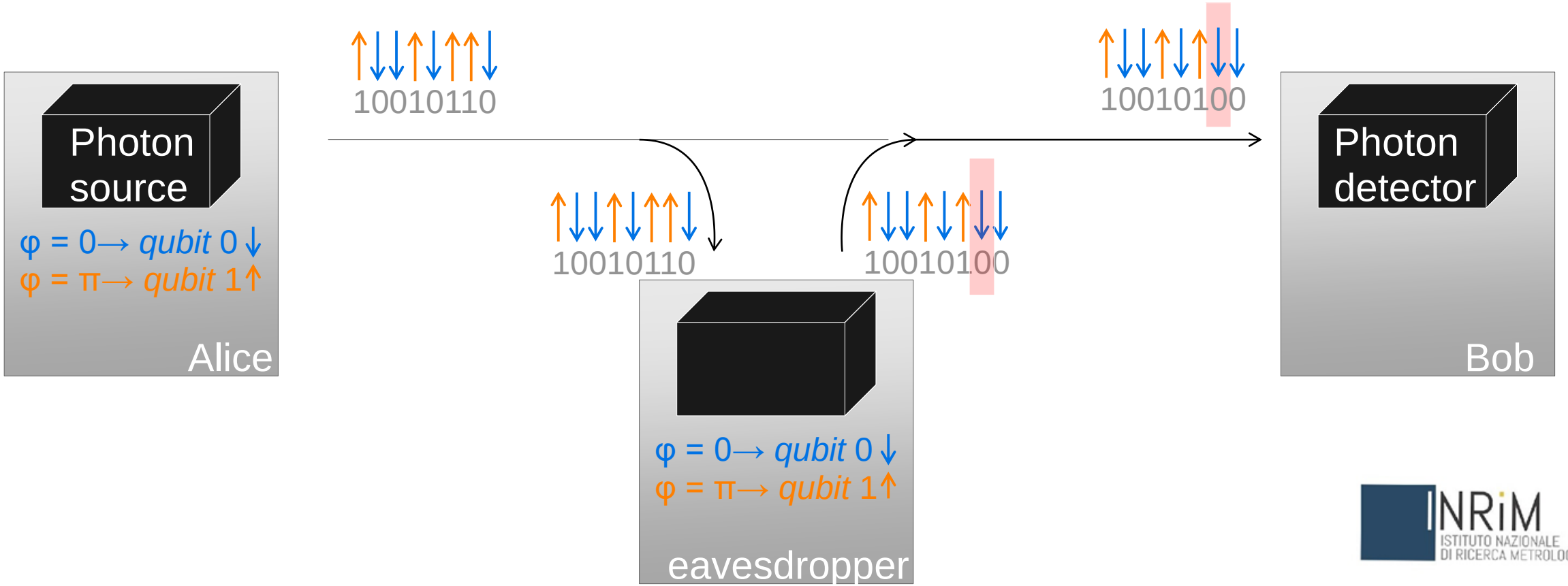
Quantum Key Distribution

- In classical information, bits (0, 1) are encoded in power, phase, or polarization of a laser beam
- In quantum information, ***qubits*** are encoded in phase or polarization **of single photons**
- Quantum Key Eavesdropping implies ***measuring***, ***hence destroying*** the quantum state



INRiM
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QKD in Real-World limits: losses

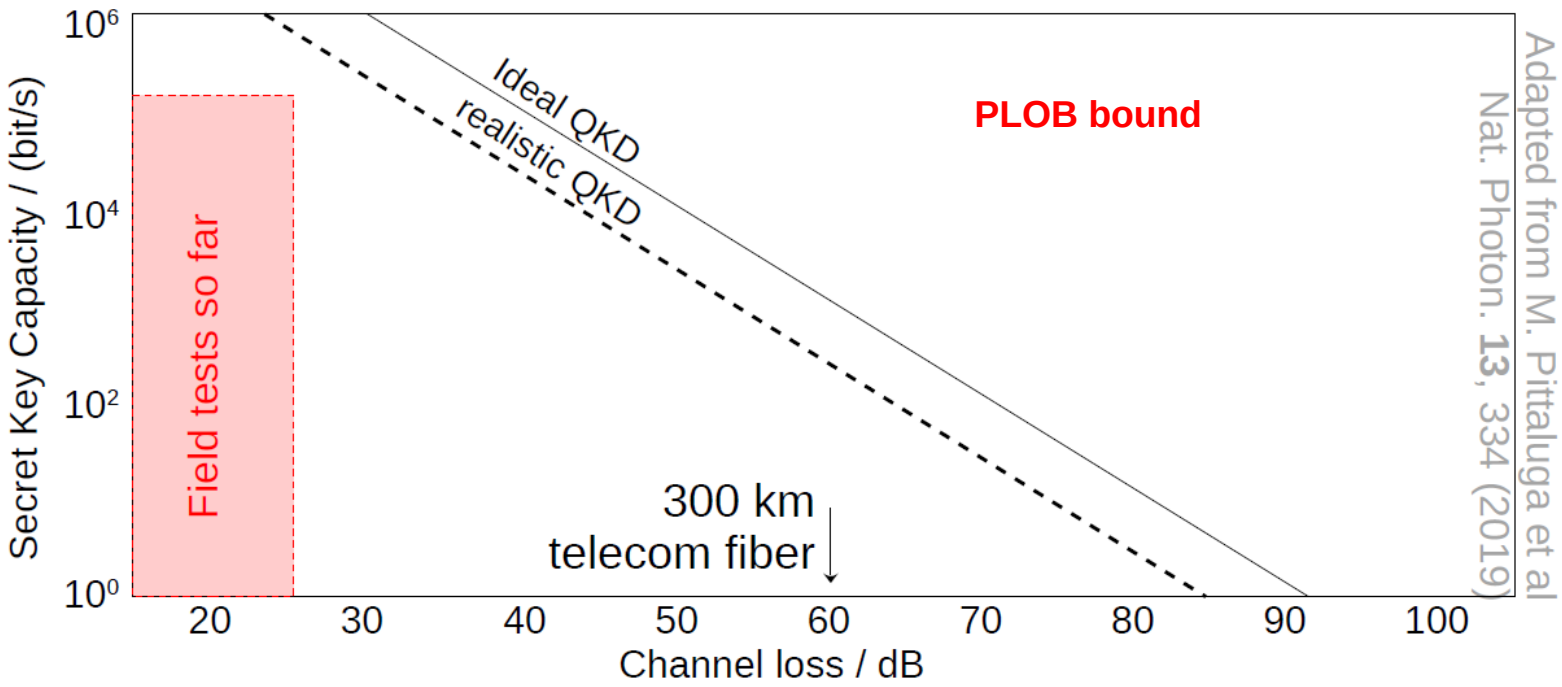
Open Access | Published: 26 April 2017

Fundamental limits of repeaterless quantum communications

Stefano Pirandola, Riccardo Laurenza, Carlo Ottaviani & Leonardo Banchi

Nature Communications **8**, Article number: 15043 (2017) | Cite this article

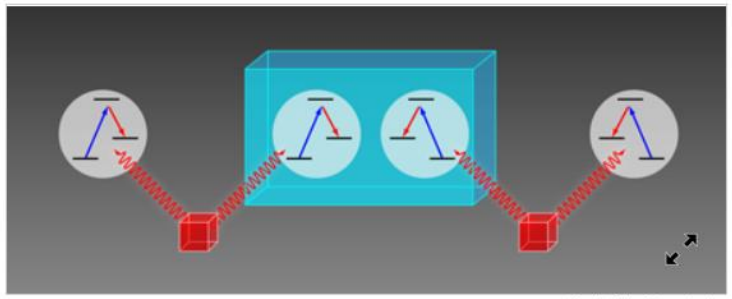
15k Accesses | **553** Citations | **13** Altmetric | Metrics



Adapted from M. Pittaluga et al Nat. Photon. **13**, 334 (2019)

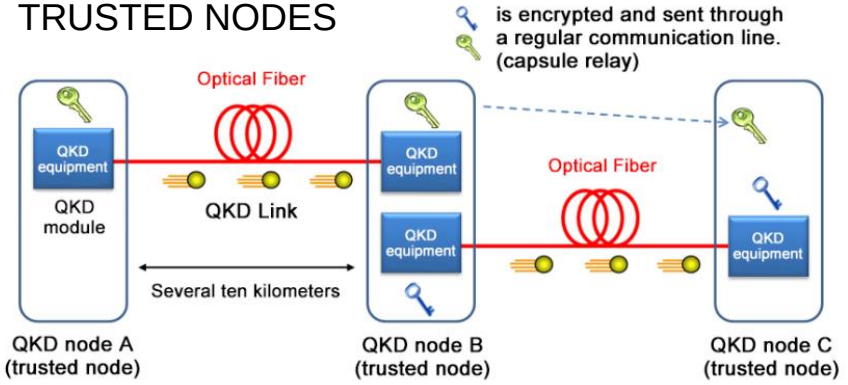
OPTICAL AMPLIFIERS

QUANTUM REPEATERS



Credit: Alan Stonebraker

TRUSTED NODES



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Twin-field QKD

Letter | Published: 02 May 2018

Overcoming the rate–distance limit of quantum key distribution without quantum repeaters

M. Lucamarini, Z. L. Yuan, J. F. Dynes & A. J. Shields

Nature **557**, 400–403 (2018) | Cite this article

17k Accesses | **372** Citations | **58** Altmetric | Metrics

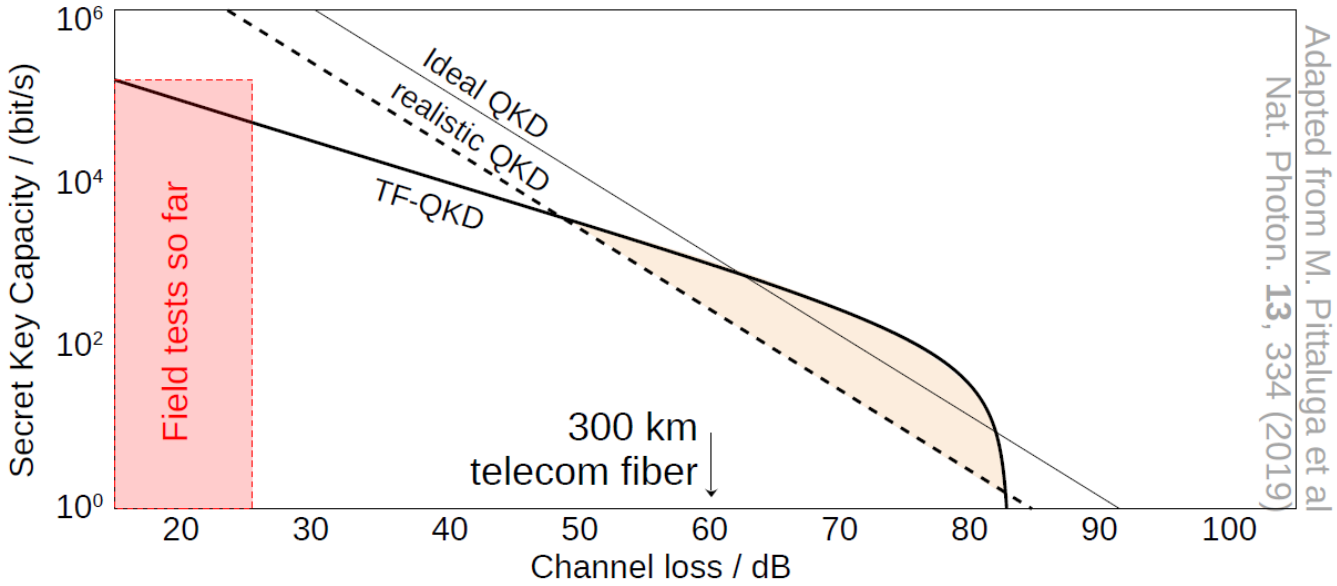
Article | Published: 04 March 2019

Experimental quantum key distribution beyond the repeaterless secret key capacity

M. Minder, M. Pittaluga, G. L. Roberts, M. Lucamarini, J. F. Dynes, Z. L. Yuan & A. J. Shields

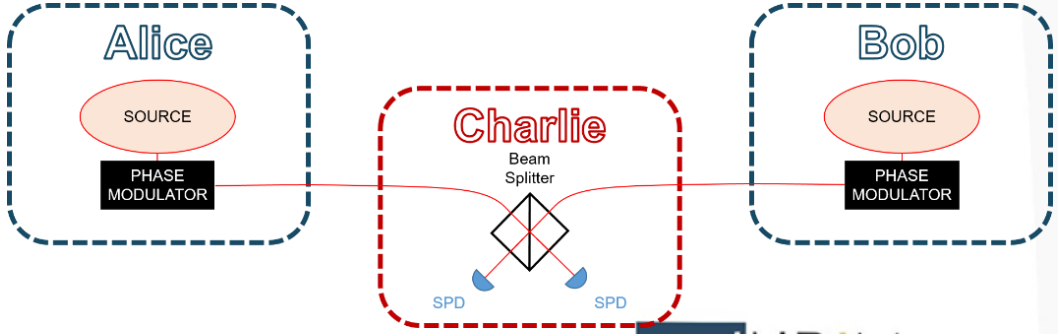
Nature Photonics **13**, 334–338 (2019) | Cite this article

7681 Accesses | **133** Citations | **15** Altmetric | Metrics



Adapted from M. Pittaluga et al Nat. Photon. **13**, 334 (2019)

DOUBLING THE DISTANCE BETWEEN TRUSTED NODES



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Frequency Metrology and TF- QKD: technological convergence

Article | Open Access | Published: 10 January 2022

Coherent phase transfer for real-world twin-field quantum key distribution

Cecilia Clivati, Alice Meda, Simone Donadello, Salvatore Virzì, Marco Genovese, Filippo Levi, Alberto Mura, Mirko Pittaluga, Zhiliang Yuan, Andrew J. Shields, Marco Lucamarini, Ivo Pietro Degiovanni & Davide Calonico

Nature Communications **13**, Article number: 157 (2022) | Cite this article

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TOSHIBA

UNIVERSITY of York

- Alternative solution derived from atomic clocks comparison technology
- The transmission of coherent laser radiation over thousand-kilometer-long fibers is exploited for the comparison of distant atomic clocks at the highest accuracy
- Ultrastable lasers + the active cancellation of the noise introduced by connecting fibers → clock comparison

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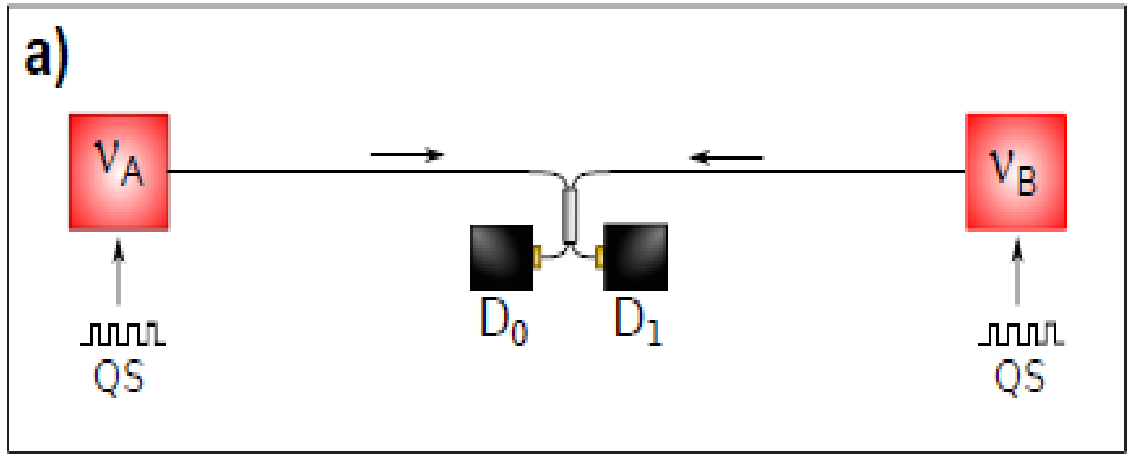
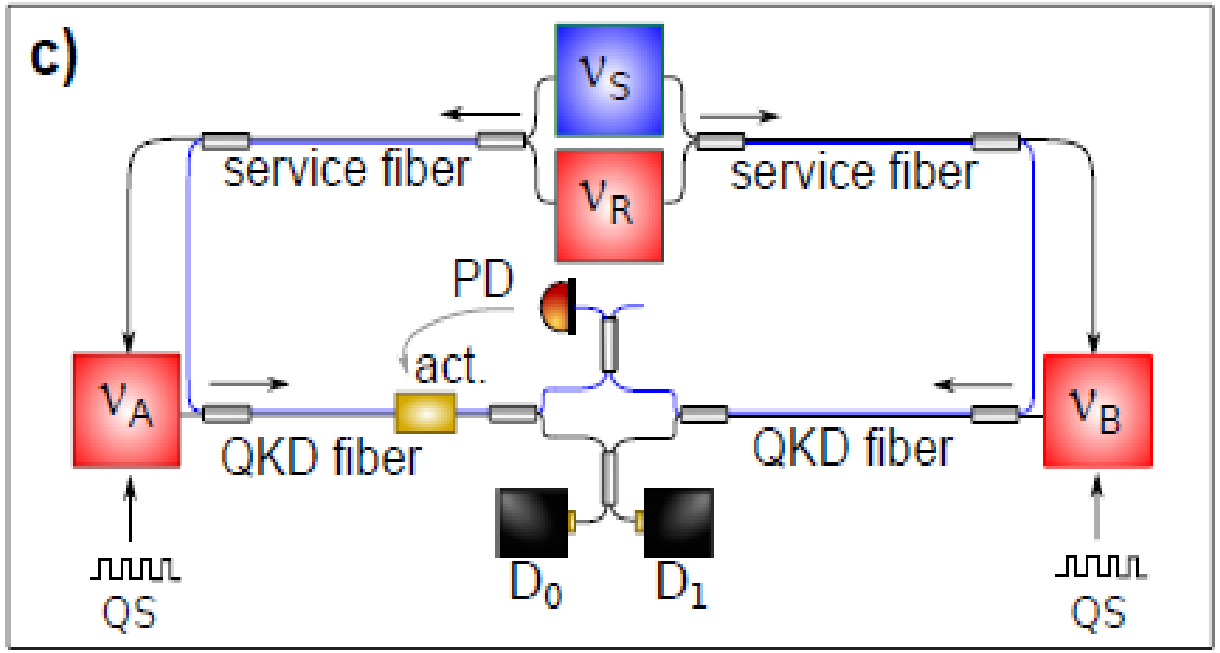
Twin-field QKD setup



- tight control of the fiber noise
- simultaneous key streaming

Our approach: a reference laser frequency ν_R to Alice and Bob + an additional sensing laser frequency ν_S over the service fiber with the reference laser, and the QKD fibers together with the QKD lasers

Ideal TF-QKD: Alice and Bob encode quantum states on local lasers with equal frequencies $\nu_A = \nu_B$



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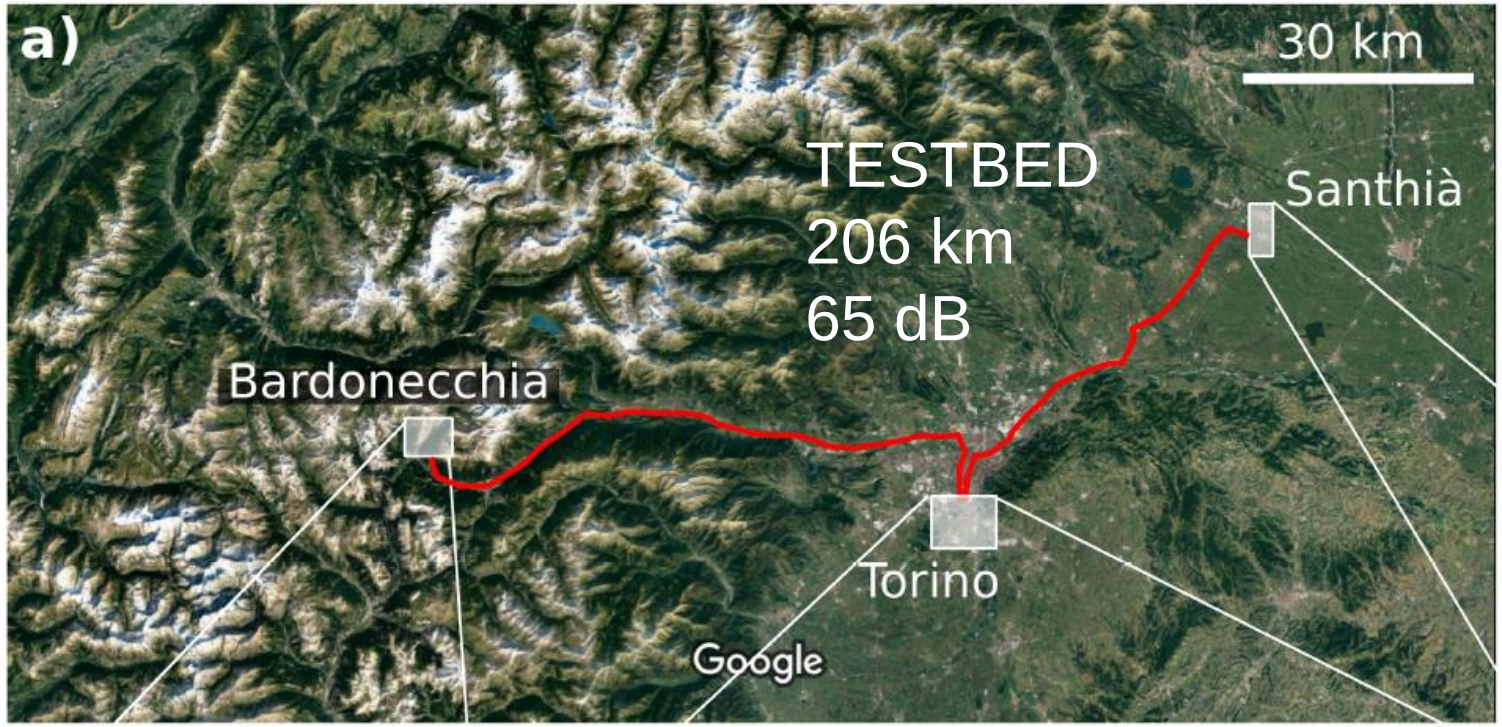
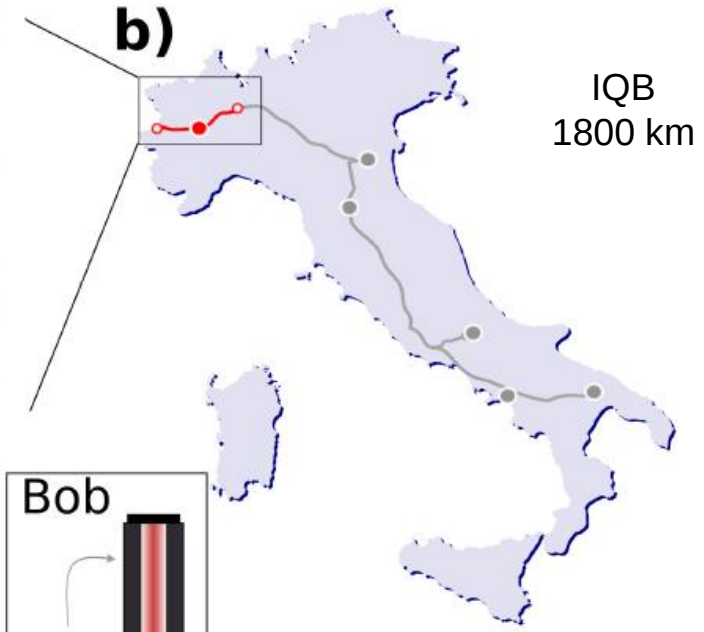
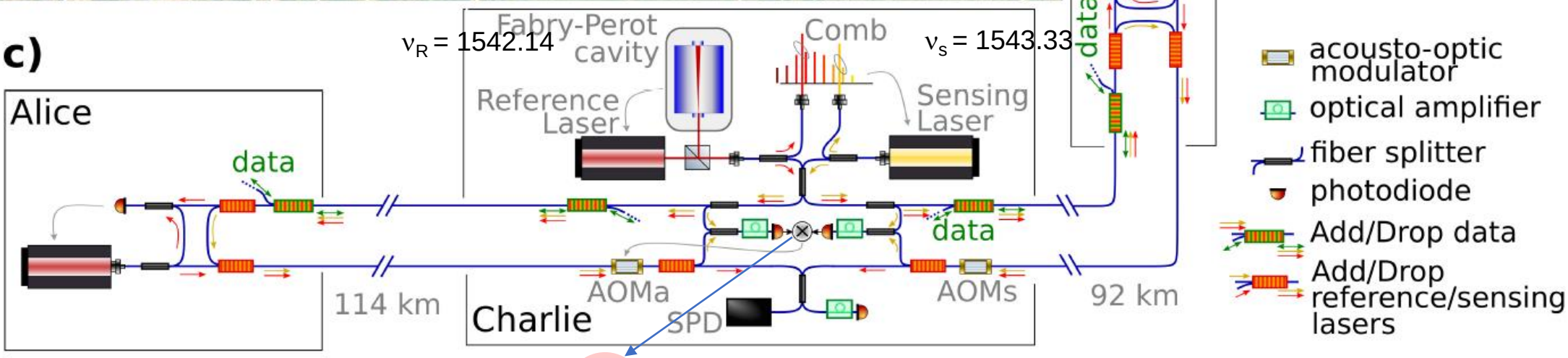
Twin-field QKD on IQB (real world)







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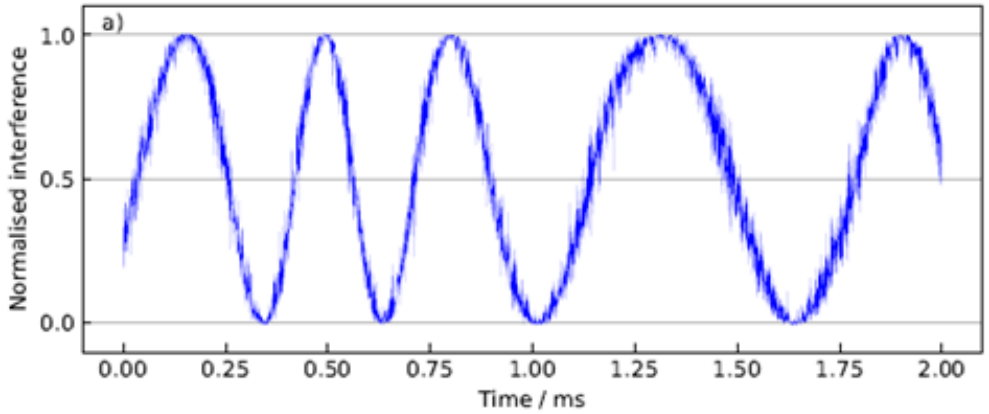
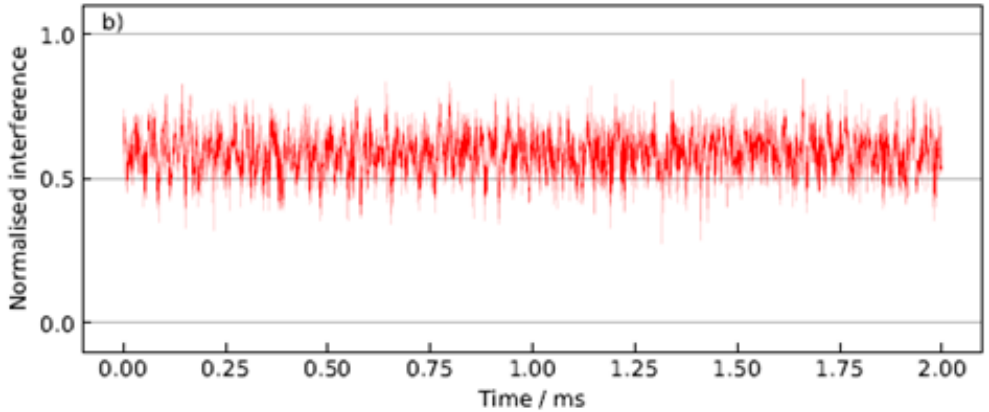
Results /1

Unstabilized condition: an instantaneous phase drift by 30 rad/ms is observed

Stabilized condition: the phase remains stable over the whole acquisition frame





G. Bertaina et al., arXiv:2310.08621v1 (2023)

C. Clivati, et al. Nature Communnications, 13, 1 (2022)

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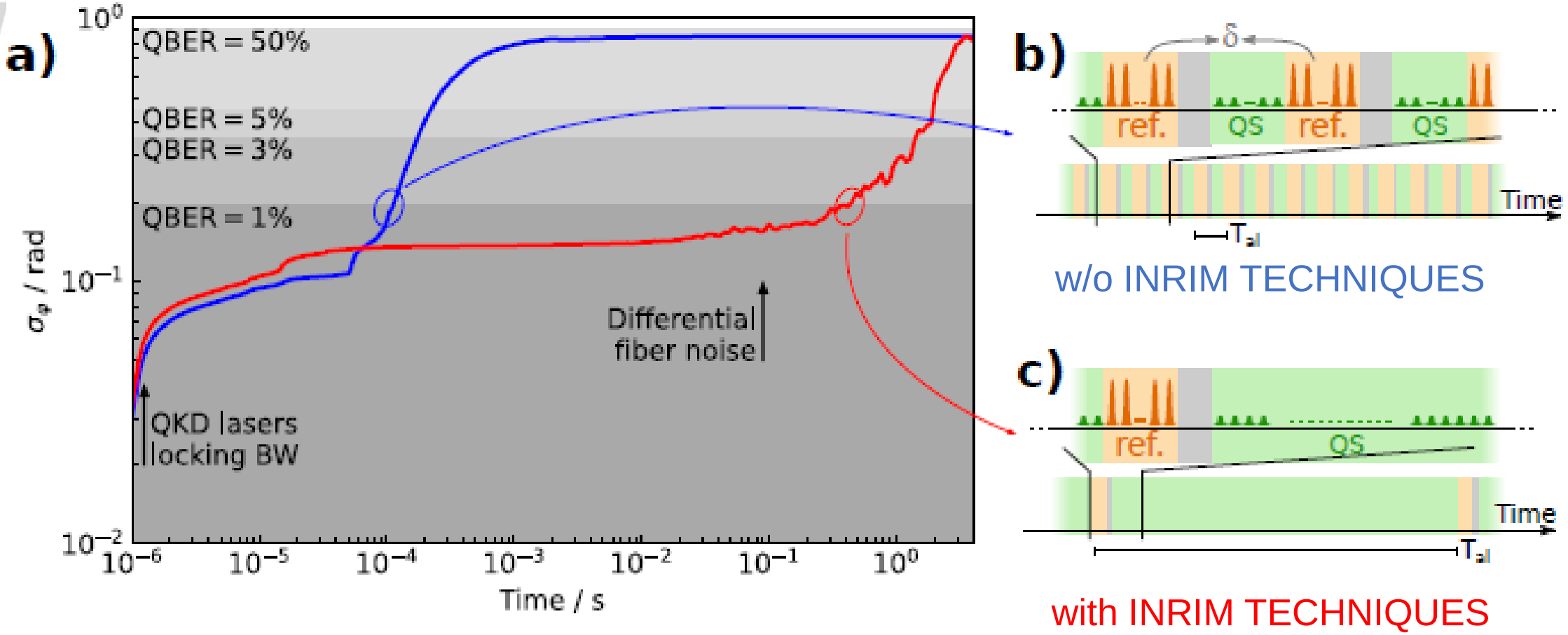
Results /2: QBER and duty cycle



Secret key rate SKR of 4.942 kb/s is achievable

C. Clivati, et al. Nature Communnications, 13, 1 (2022)

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Conclusions

- After 10 years, T/F over fibre links is more and more exciting
- Comparisons for the redefinition of the second: mature and sustainable
- Interesting results demonstrated in different applications
- Areas interested / yet to be fully explored: Radioastronomy, Geodesy, Sensing, Q-Comm
- Paradigm: T/F knowledge enables new measurements possibilities and insights, then a convergent technological platform is possible

Acknowledgements

EMPIR EURAMET

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

EuroQCI

Commissione Europea

This work was supported by:

European Metrology Program for Innovation and Research
(projects 18SIB05 ROCIT, 20FUN08 NextLasers; 19NET02 EMN Quantum)

Horizon2020 (project Clonets-DS)

This presentation has been developed in the project The Project QUID (QUantum Italy Deployment) , which is funded by the European Commission in the Digital Europe Programme under the grant agreement No 101091408

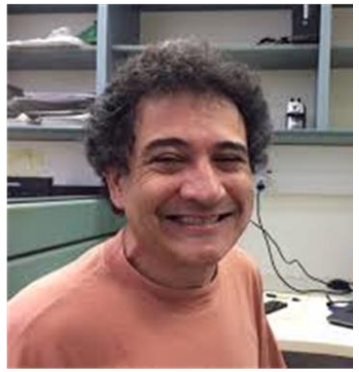
CloNetS DS
Clock Network Services Design Study

QUID
QUANTUM ITALY DEPLOYMENT

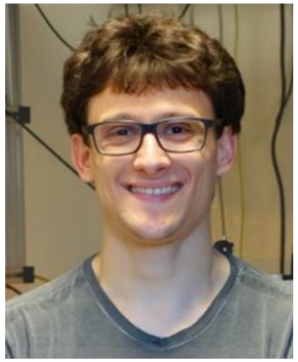
Fibre Team at INRIM

Cecilia Clivati

Alberto Mura



Filippo Levi



Simone Donadello

Davide Calonico

Ytterbium Clock

M. Pizzocaro
I. Goti
S. Condio
F. Levi
D. Calonico

Cesium Fountain

F. Levi
G. Costanzo
M. Gozzellino

Quantum Optics

I.P. Degiovanni
A. Meda
M. Gramegna
S. Virzi
G. Bertaina
M. Genovese

THANK YOU.

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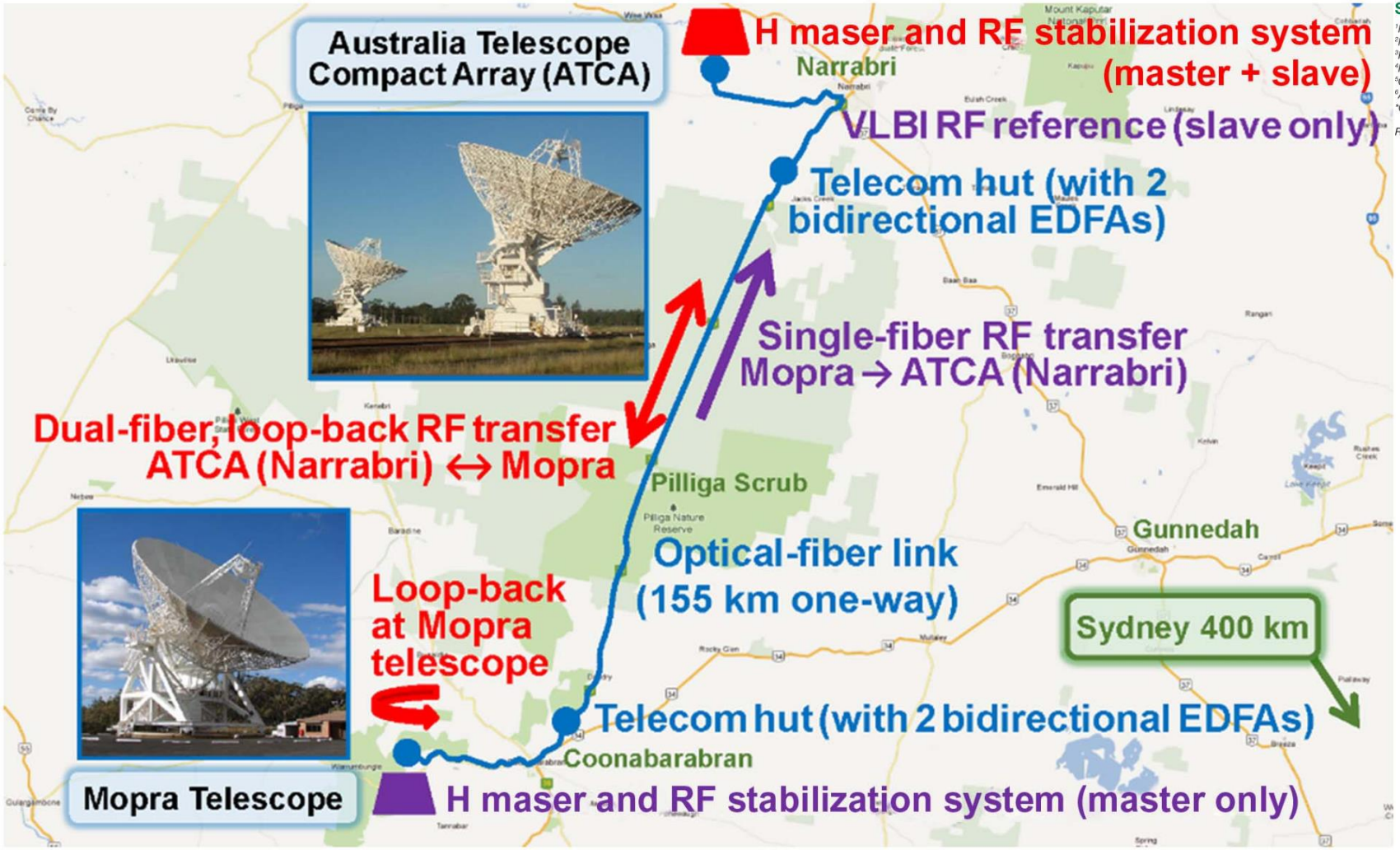
Optical fibre link in Australia



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Long-distance telecom-fiber transfer of a radio-frequency reference for radio astronomy

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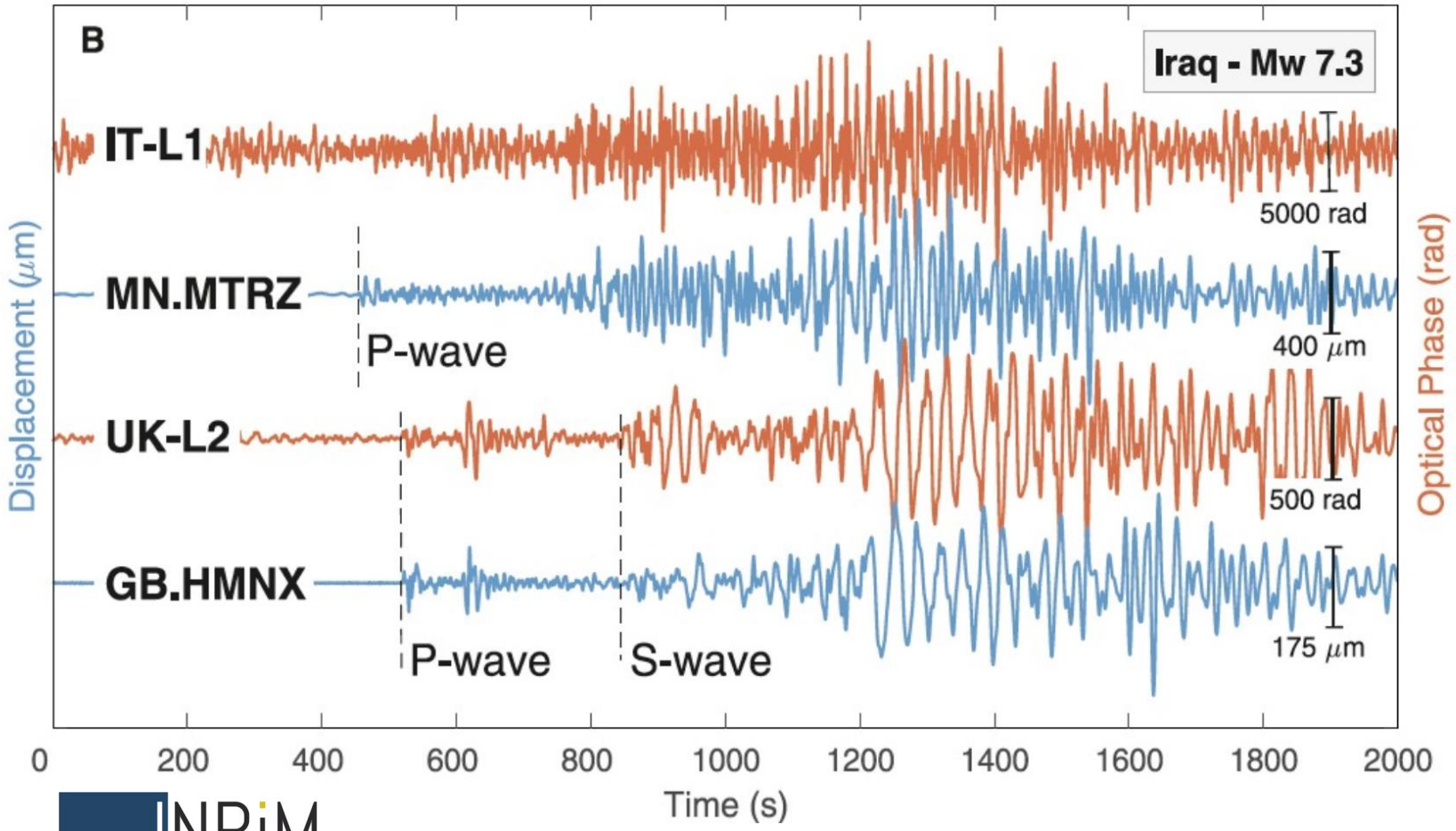
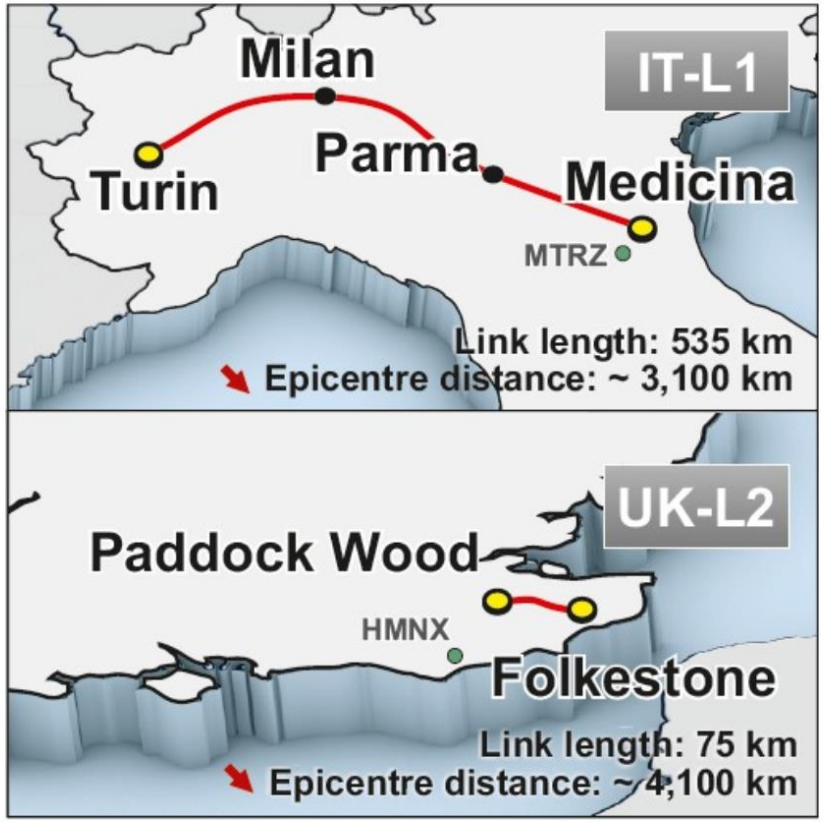
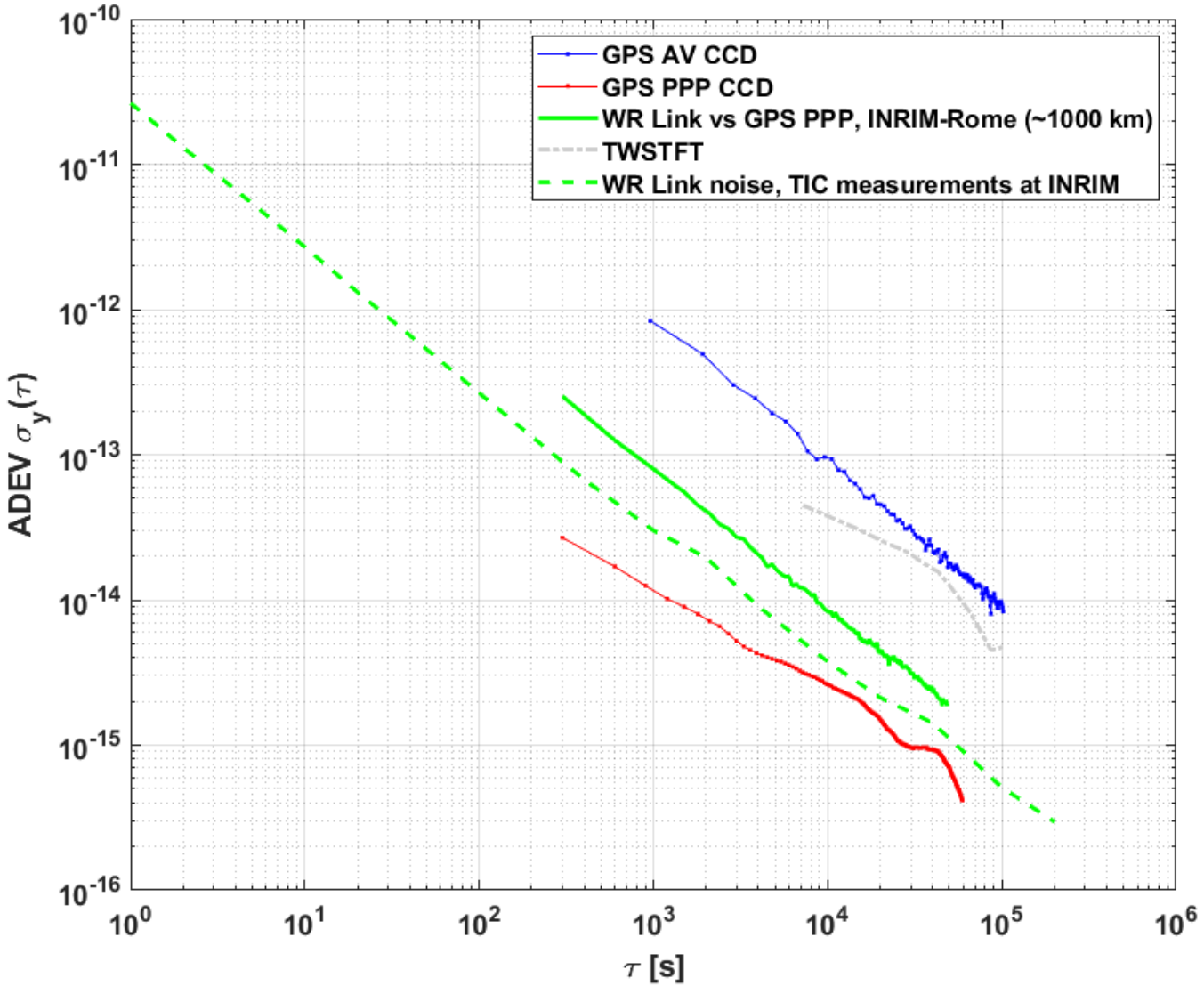
Sensing with terrestrial fibers

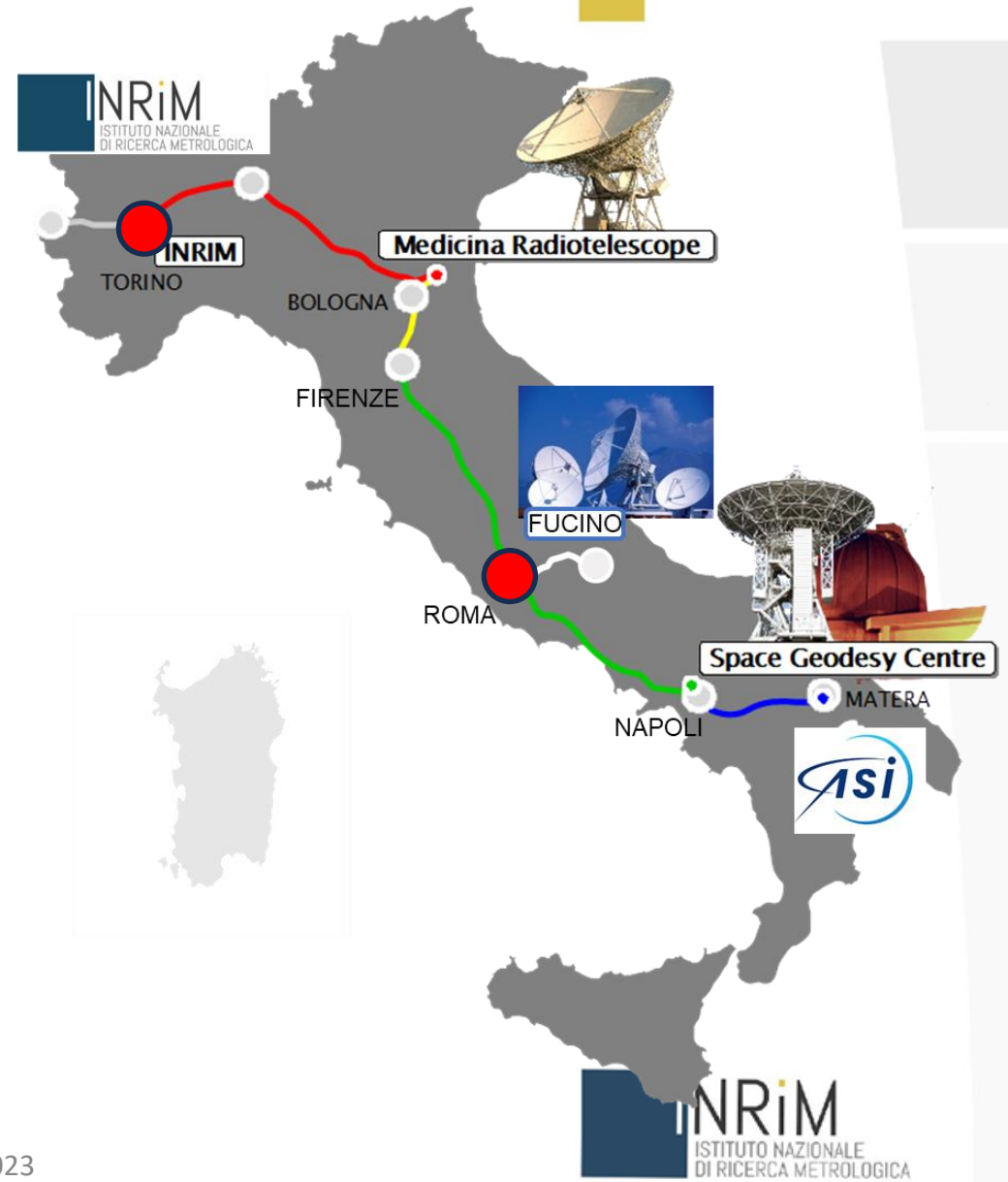




G. Marra et al., Science **361** (2018)

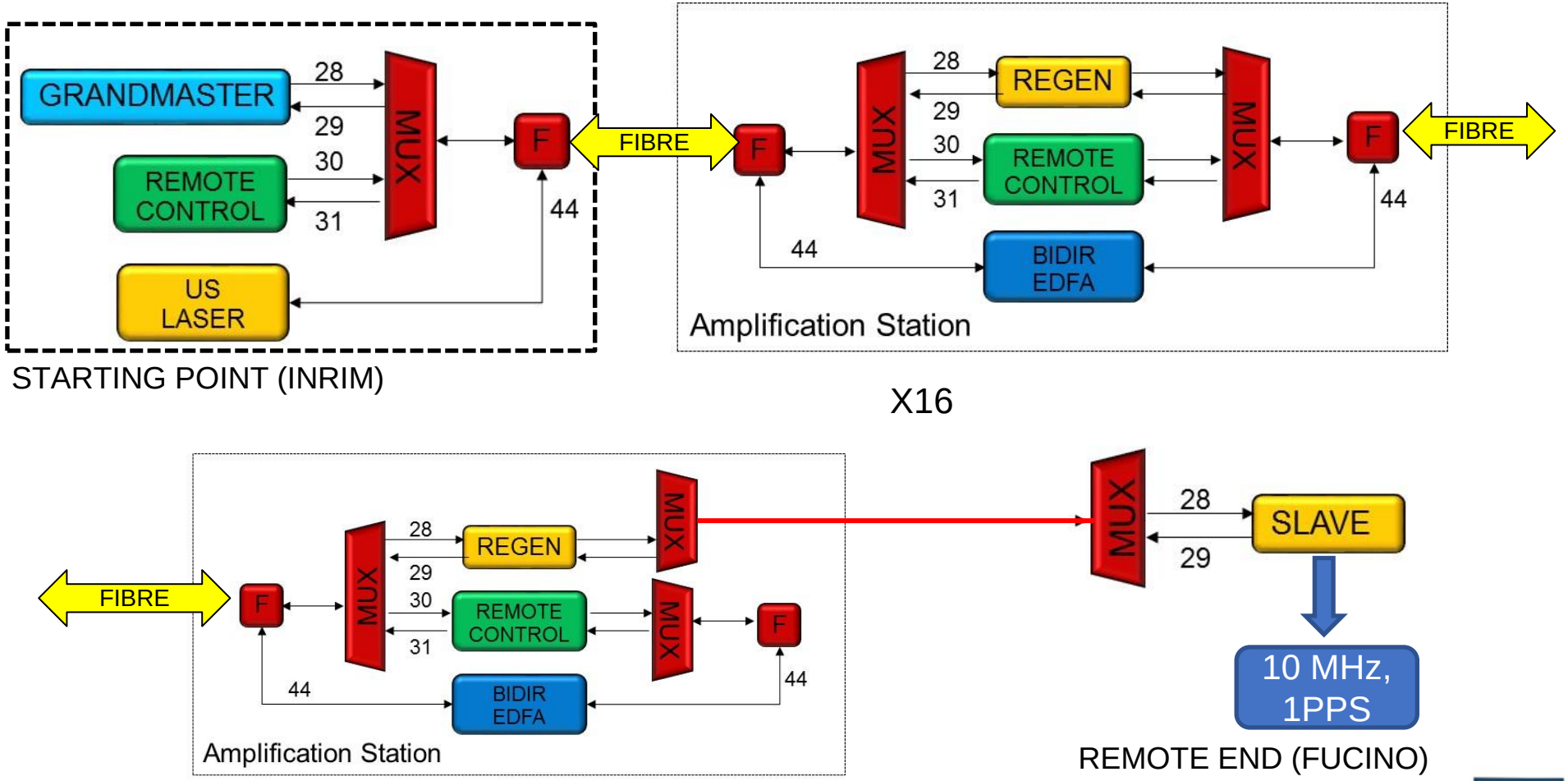
WR-PTP over 1200 km (Turin to Rome and Fucino)





Coherent + WR-PTP Architecture

1233 km, single fibre, 18 regeneration stations, 1 end receiver



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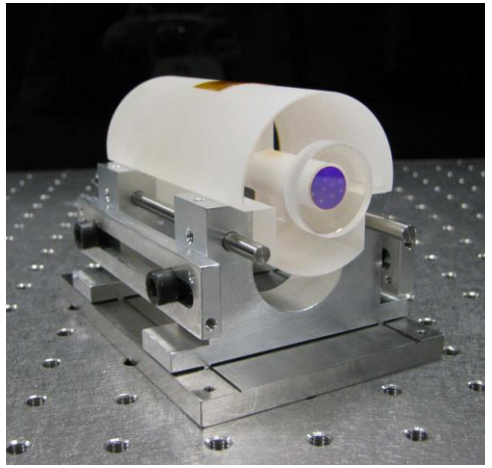
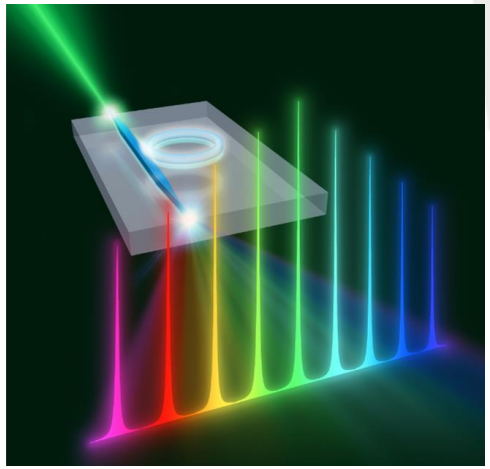
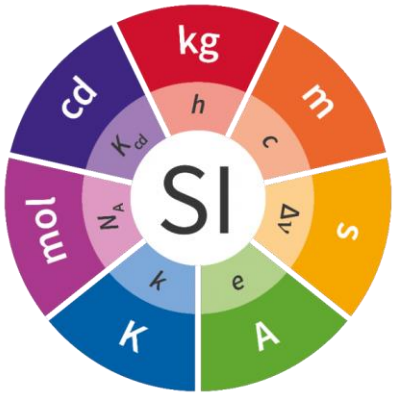
Coherent link needs ultrastable lasers

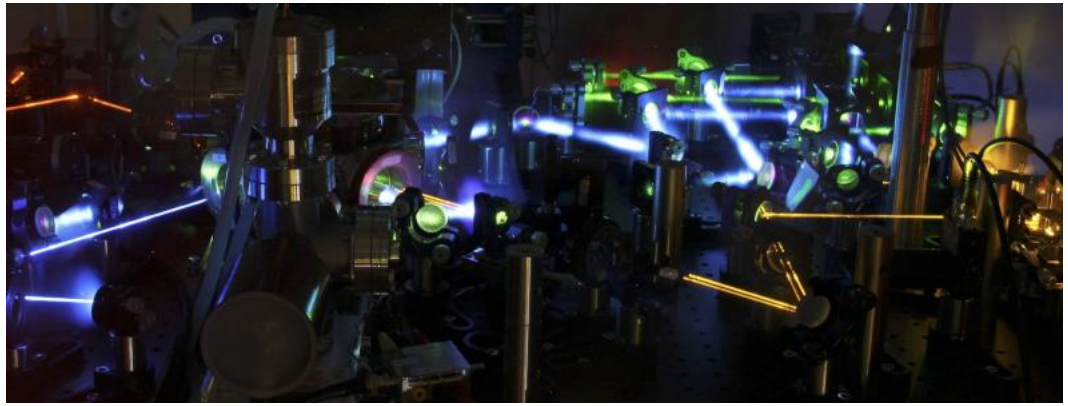
Optical clock techniques:

- laser locked to **ultrastable cavity**
- **ultra-low-noise** narrow-linewidth lasers
- **laser noise < fiber noise**
- high coherence ⇔ **very long range** (> 1000 km)









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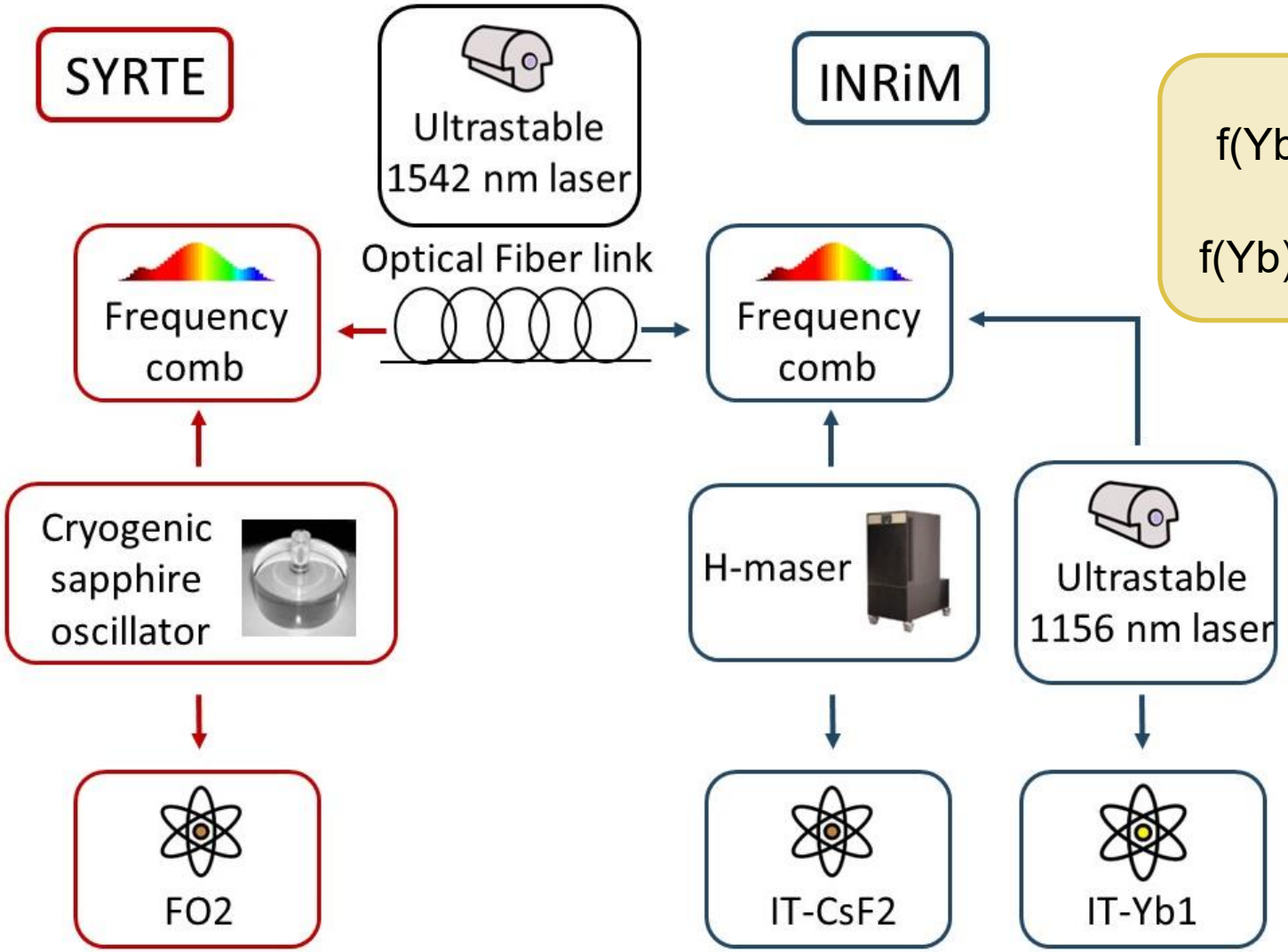
Remote frequency measurement vs FO2 (SYRTE)



IT-Yb1/FO2-Cs
f(Yb) = 518 295 836 590 863.61(17) Hz
IT-Yb1/FO2-Rb
f(Yb)/f(Rb) = 75 833 197.545 114 168(24)

Results in agreement with value recommended by CIPM

C. Clivati et al., 2022 Phys. Rev. Applied 18, 054009

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