Italian Quantum Backbone: metrology, quantum communications and sensing on optical fibers

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SIG-TFN workshop, Amsterdam Oct. 16-17, 2024

10 years of optical fibers in Italy

2013:
1st span:
Turin-Firenze

2015:
Medicina VLBI telescope

2016:
Absolute
Spectroscopy
at LENS

2018:
Matera Space
Geodesy Center

Earthquake
Sensing

2020:
Common-Clock
VLBI

2021:
Clock comparison
Italy/France

Sensing on
Telecom networks

2022:
1st European
clock comp.

Quantum Key
Distribution

2023:
2nd European
clock comp.

2025:
3rd European
clock comp.

Funding:
Italian Government 2013-2015
EMRP NEAT-FT,
EMPIR ITOC, OFTEN, WRITE, TIFOON…
Horizon 2020 CLONETS, CLONETS-DS

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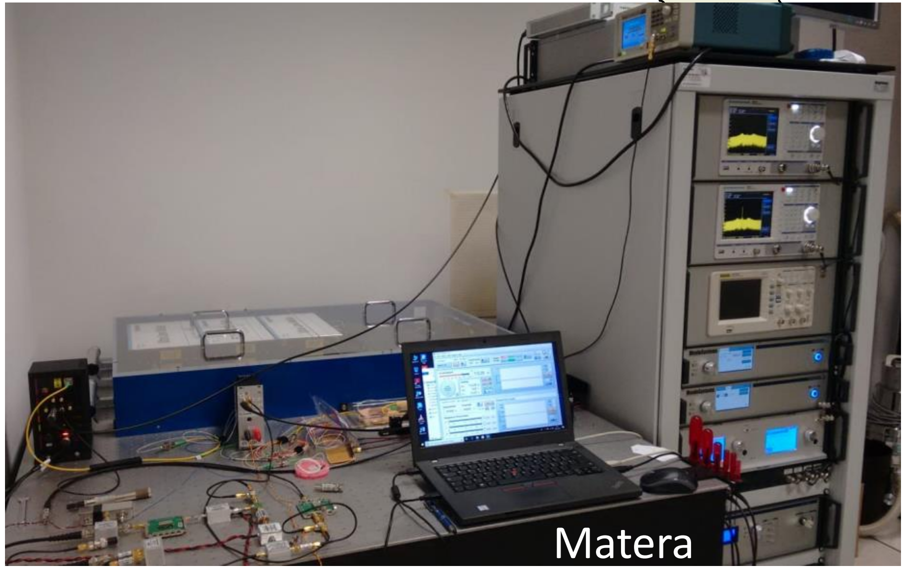
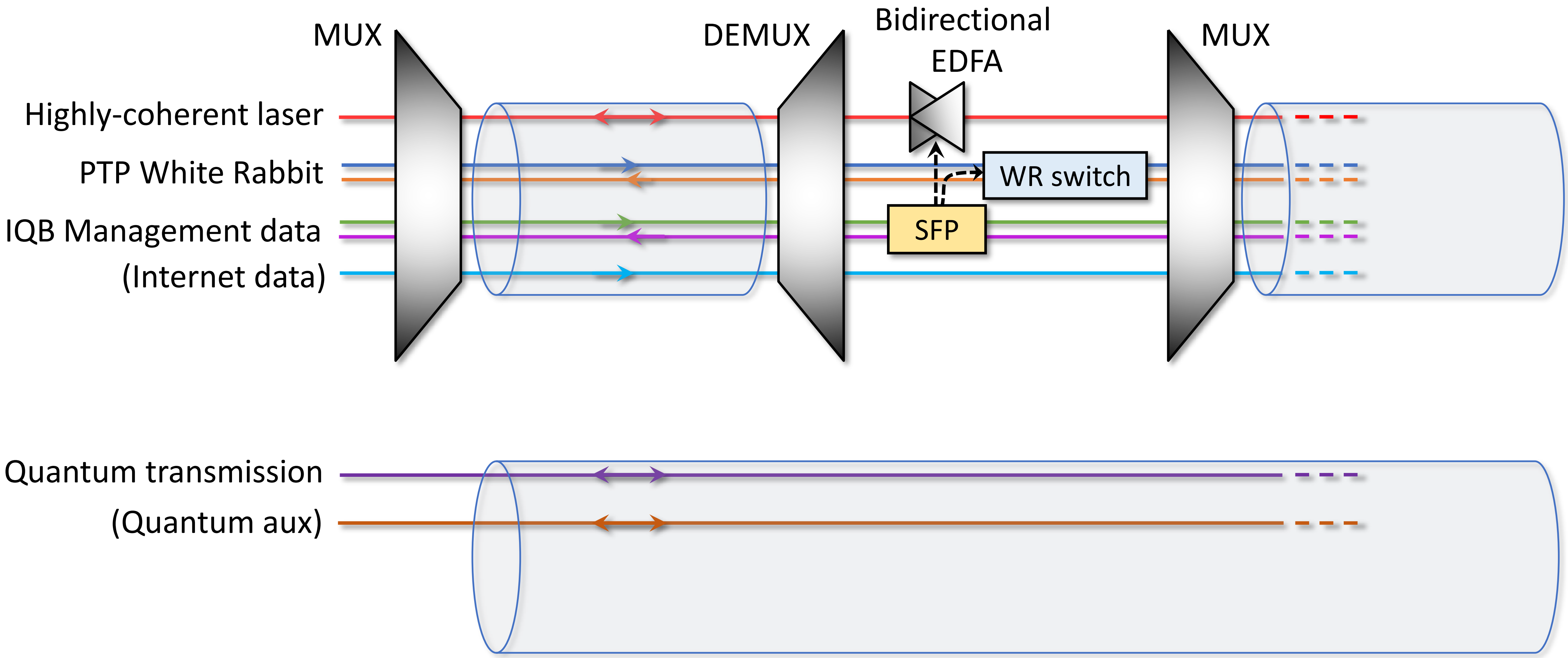
DI RICERCA METROLOGICA

The Italian Quantum Backbone

- Total length 1840 km
- 30 PoPs for amplification (EDFA) + time & RF extraction
- Coherent optical distribution in 5 segments
- 4 «home-made» RLS and local use
- Fully remote controlled & autonomous operation (EDFAs, polarization control, relock, alarms)



The Italian Quantum Backbone



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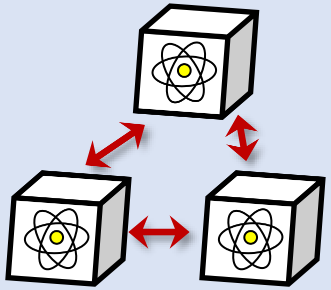
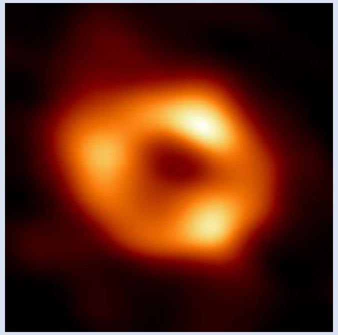
Science cases



Clock comparisons and GNSS validation

Time for critical infrastructures

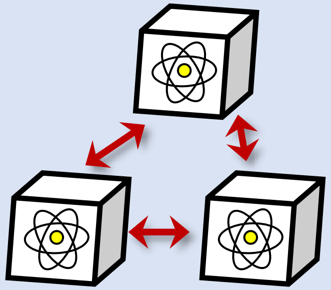


Referencing VLBI telescopes

Quantum communication

Remote sensing of earthquakes

Science case #1



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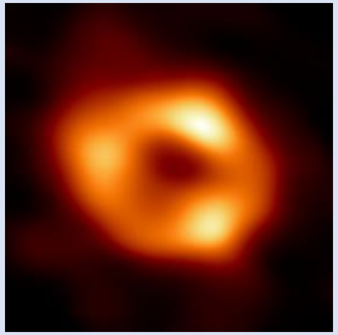

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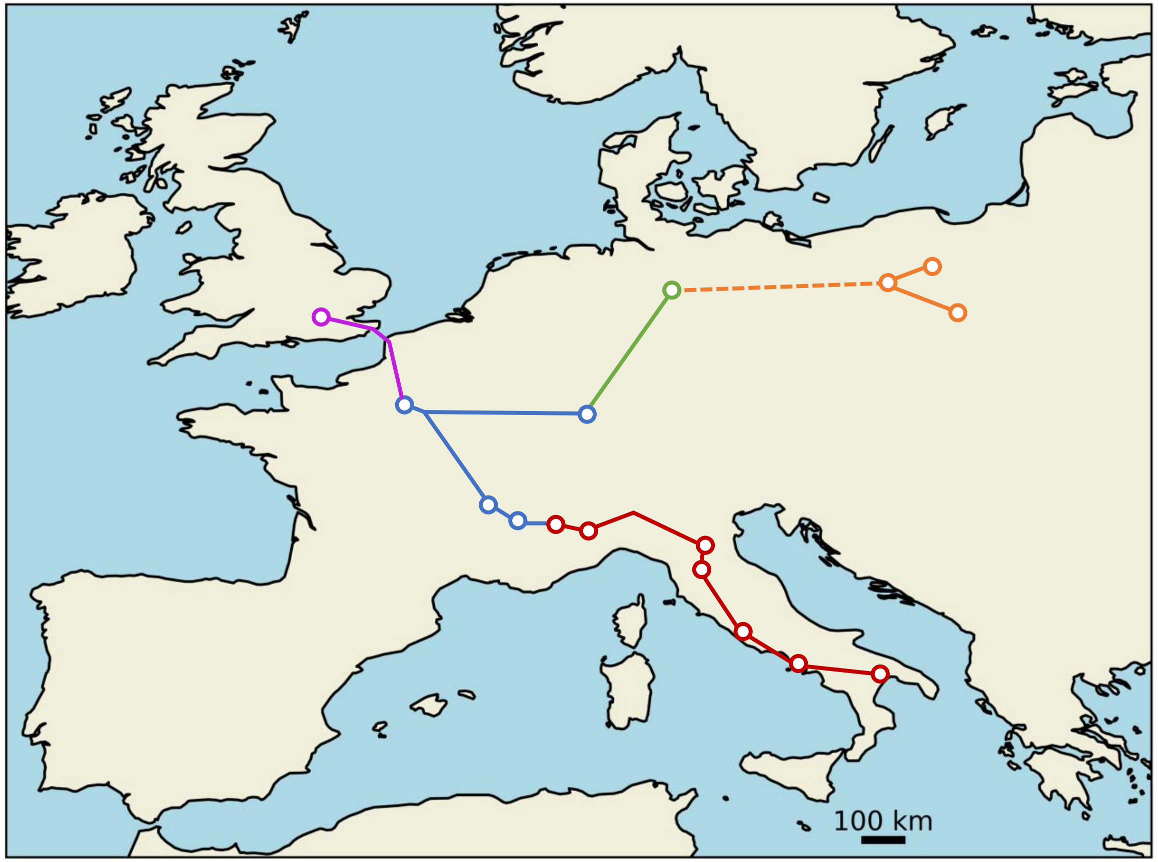
International Comparison of Optical Clocks

- Campaigns in March 2022, March 2023, March 2025
- **>11 optical clocks** from 7 laboratories, measured at the same time all over Europe, for at least 20 days, with high uptime

…the largest clock comparison ever!



l'Observatoire de Paris
UNIVERSITÉ PARIS 13
VTT
Central Office of Measures
CZECH METROLOGY INSTITUTE
NPL National Physical Laboratory
cnrs
LNE Le progrès, une passion à partager
CBK PAN
NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ
Leibniz Universität Hannover
PTB
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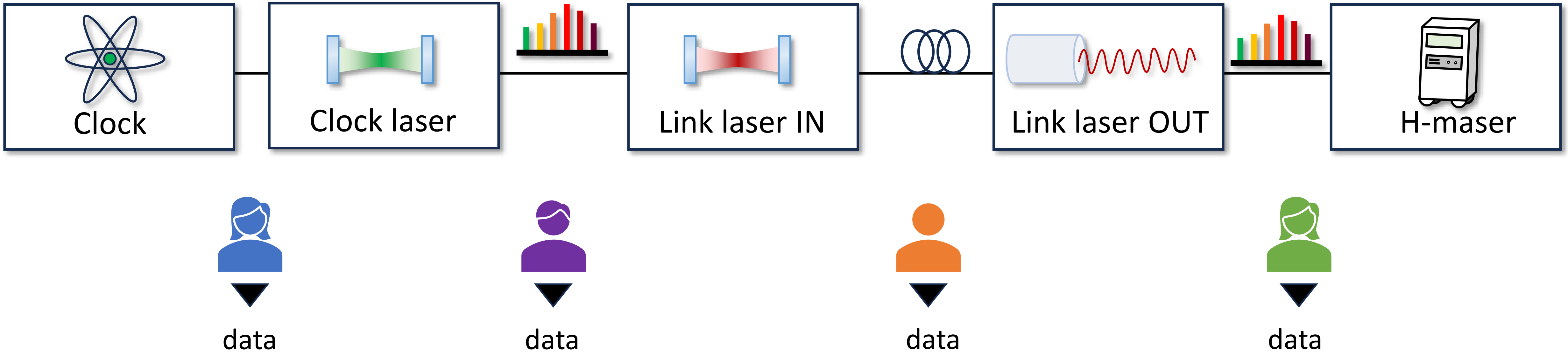
Building a protocol



- International coordination not trivial, and many different teams involved
- Universal formalism agreed (Lodewyck et al., Phys. Rev. Research, 2020) and FAIR approach to data
- Combined uptime still challenging

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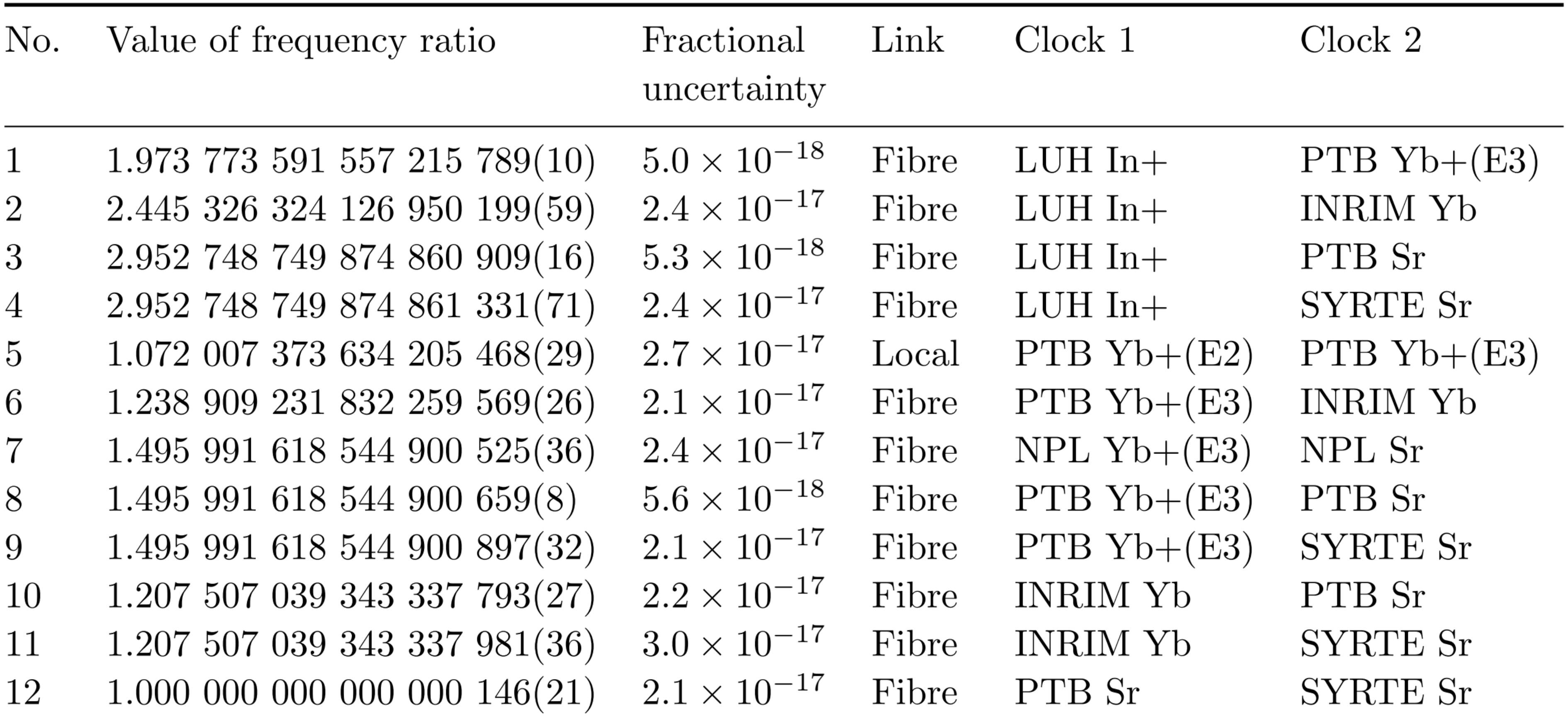
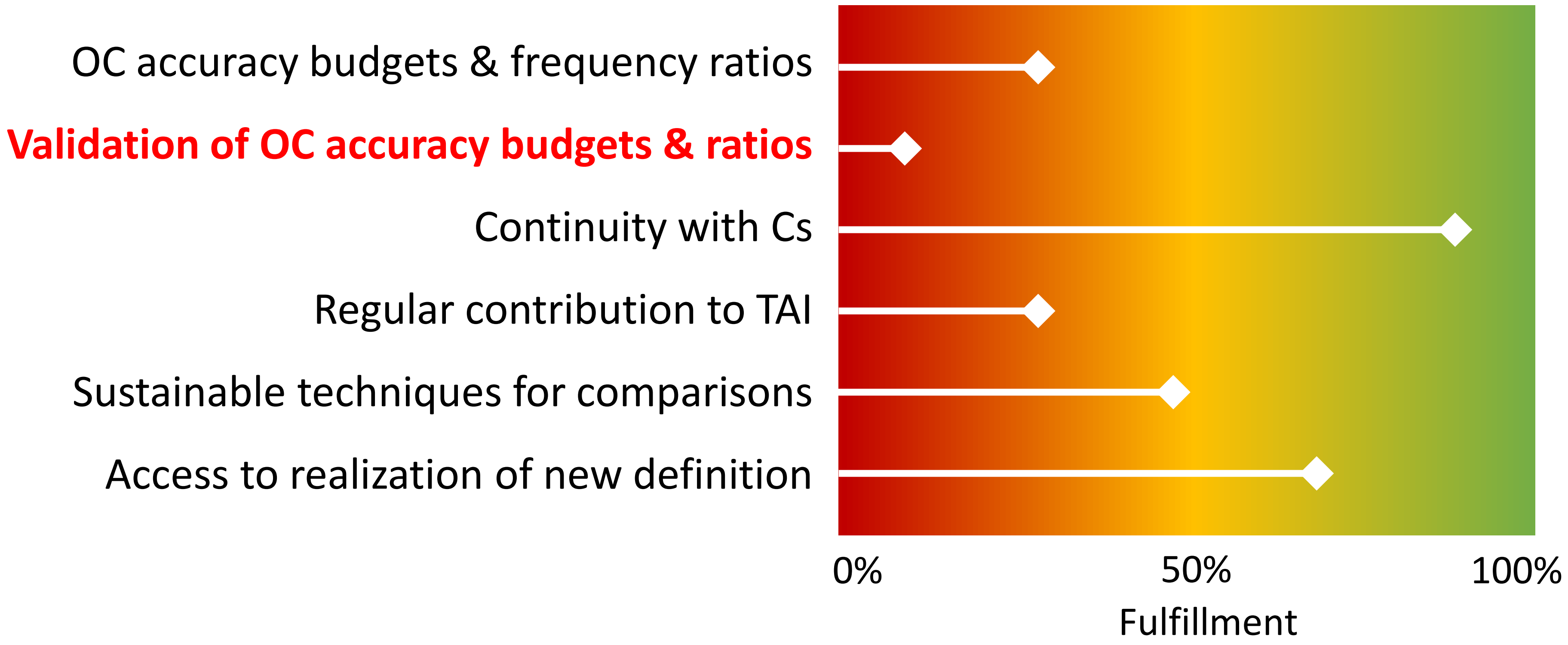
Summary of 2022 campaign



No.	Value of frequency ratio	Fractional uncertainty	Link	Clock 1	Clock 2
1	1.973 773 591 557 215 789(10)	5.0×10^{-18}	Fibre	LUH In+	PTB Yb+(E3)
2	2.445 326 324 126 950 199(59)	2.4×10^{-17}	Fibre	LUH In+	INRIM Yb
3	2.952 748 749 874 860 909(16)	5.3×10^{-18}	Fibre	LUH In+	PTB Sr
4	2.952 748 749 874 861 331(71)	2.4×10^{-17}	Fibre	LUH In+	SYRTE Sr
5	1.072 007 373 634 205 468(29)	2.7×10^{-17}	Local	PTB Yb+(E2)	PTB Yb+(E3)
6	1.238 909 231 832 259 569(26)	2.1×10^{-17}	Fibre	PTB Yb+(E3)	INRIM Yb
7	1.495 991 618 544 900 525(36)	2.4×10^{-17}	Fibre	NPL Yb+(E3)	NPL Sr
8	1.495 991 618 544 900 659(8)	5.6×10^{-18}	Fibre	PTB Yb+(E3)	PTB Sr
9	1.495 991 618 544 900 897(32)	2.1×10^{-17}	Fibre	PTB Yb+(E3)	SYRTE Sr
10	1.207 507 039 343 337 793(27)	2.2×10^{-17}	Fibre	INRIM Yb	PTB Sr
11	1.207 507 039 343 337 981(36)	3.0×10^{-17}	Fibre	INRIM Yb	SYRTE Sr
12	1.000 000 000 000 000 146(21)	2.1×10^{-17}	Fibre	PTB Sr	SYRTE Sr

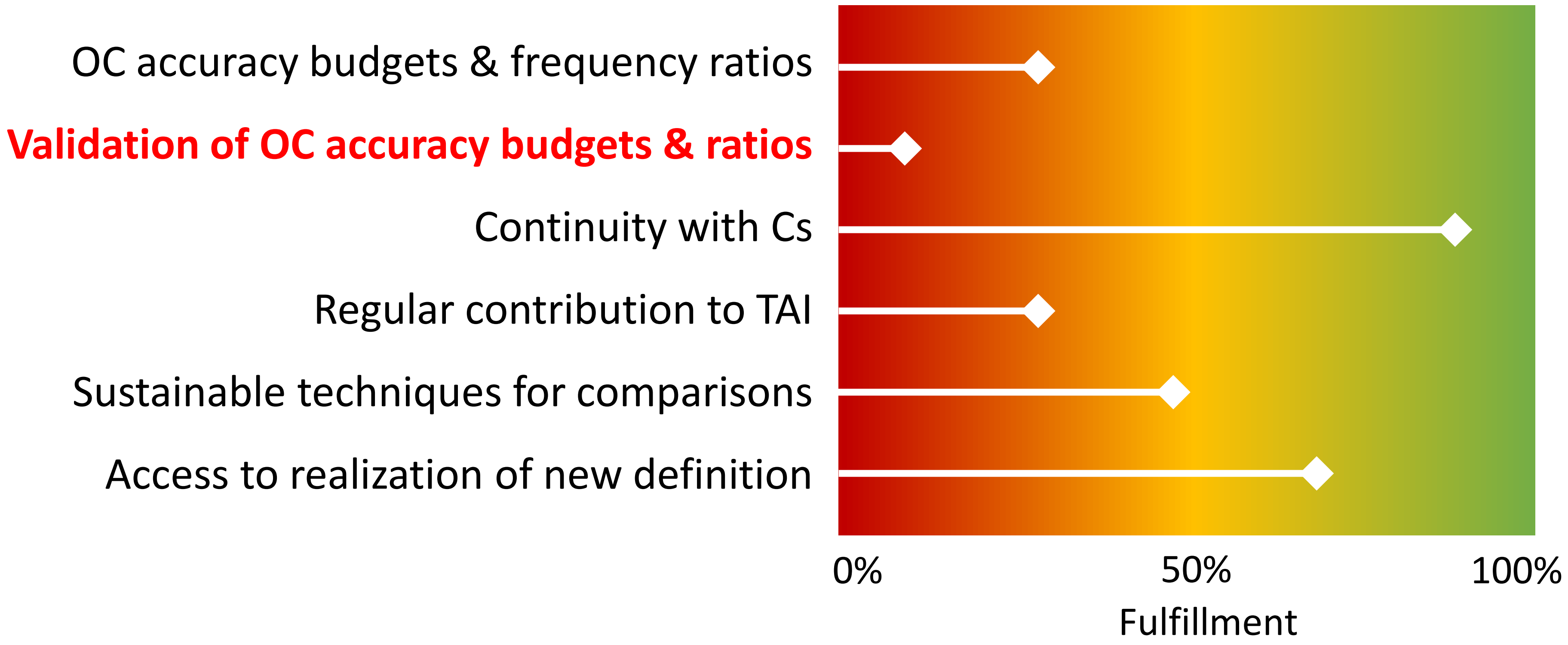
- Many ratio, uncertainties 10^{-18} to 10^{-17}
- Several new ratios involving In+ not available before
- New ratios involving Yb not available before

Toward the SI second redefinition

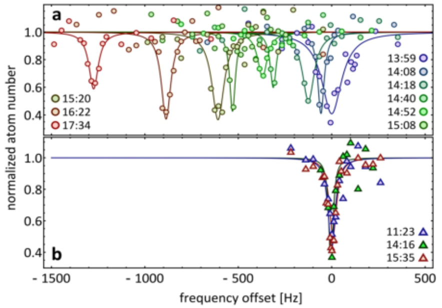


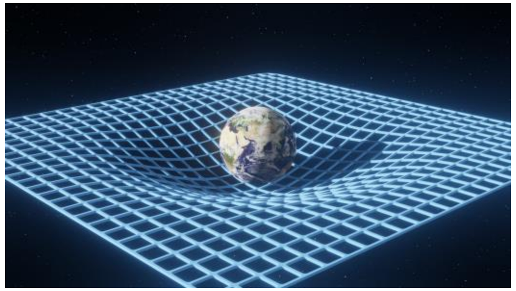
N. Dimarcq et al., Metrologia 61, 012001 (2024)

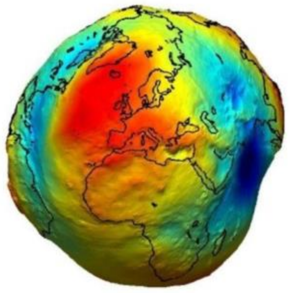
Toward the SI second redefinition



…and more science







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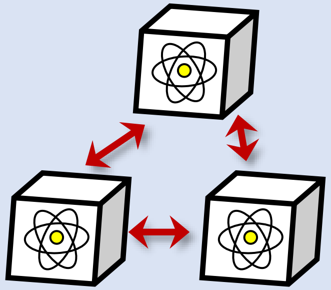
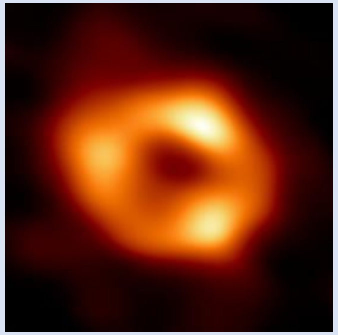
Science case #2



Clock comparisons and GNSS validation

Time for critical infrastructures



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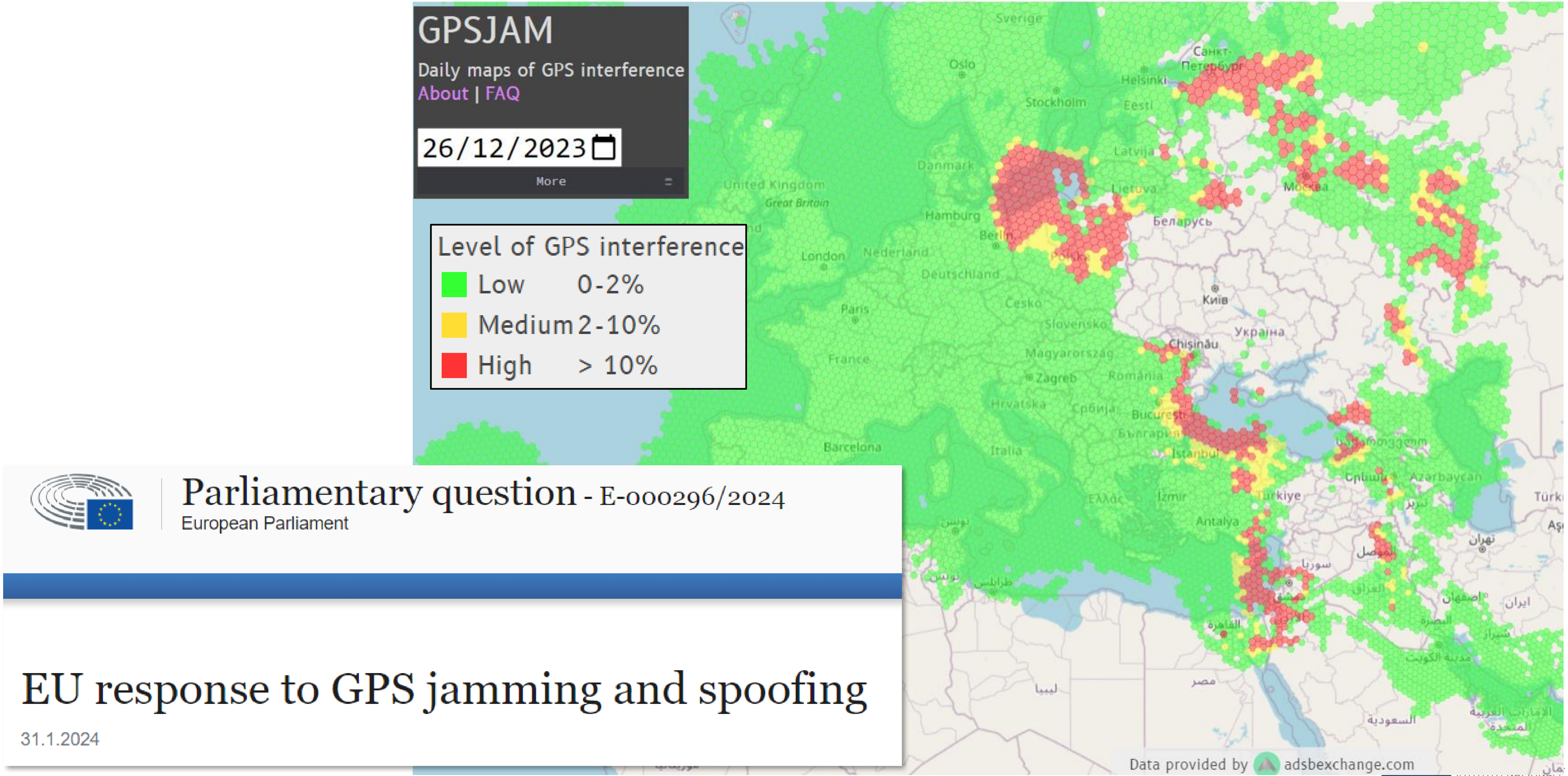
GPS attacks: a concrete concern



GPSJAM

Daily maps of GPS interference

About | FAQ

26/12/2023

More

Level of GPS interference

🟩 Low 0-2%

🟨 Medium 2-10%

🟥 High > 10%

Parliamentary question - E-000296/2024

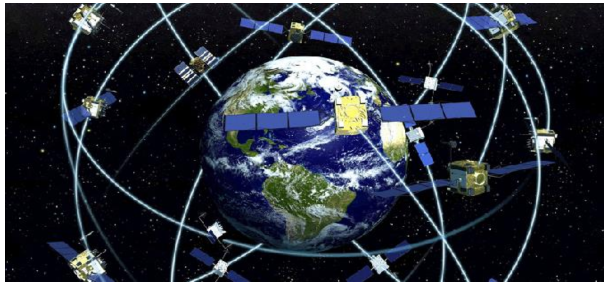
European Parliament

EU response to GPS jamming and spoofing

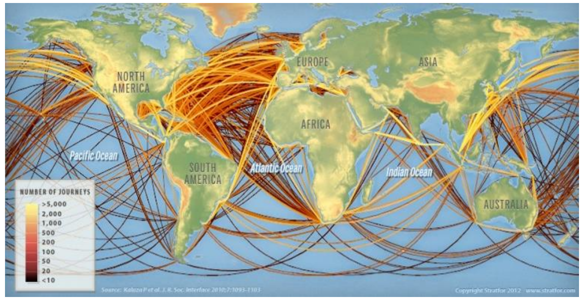
31.1.2024

Stake-holders

Telecommunication



Space & Navigation



Finance / e-commerce

Power grids

Need for:

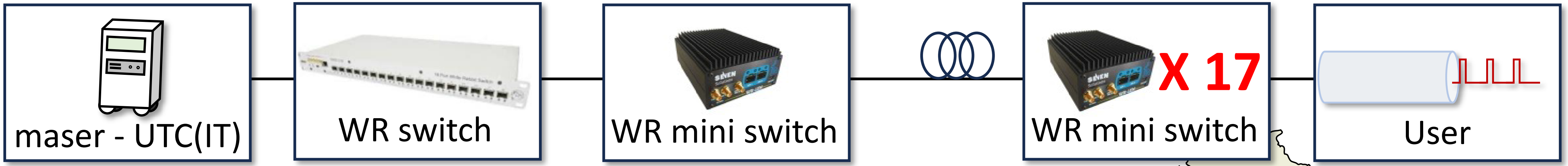
- Resilience & integrity
- Standardization & certification
- Mostly, 1 µs timing accuracy

Why White Rabbit

White Rabbit
COLLABORATION

- It's a Standard IEEE (IEEE-1588-v3)
- Performances are fine for 95% of our applications
- Fully compatible with telcom networks
- Solid supply chain

Time distribution on the IQB



maser - UTC(IT)

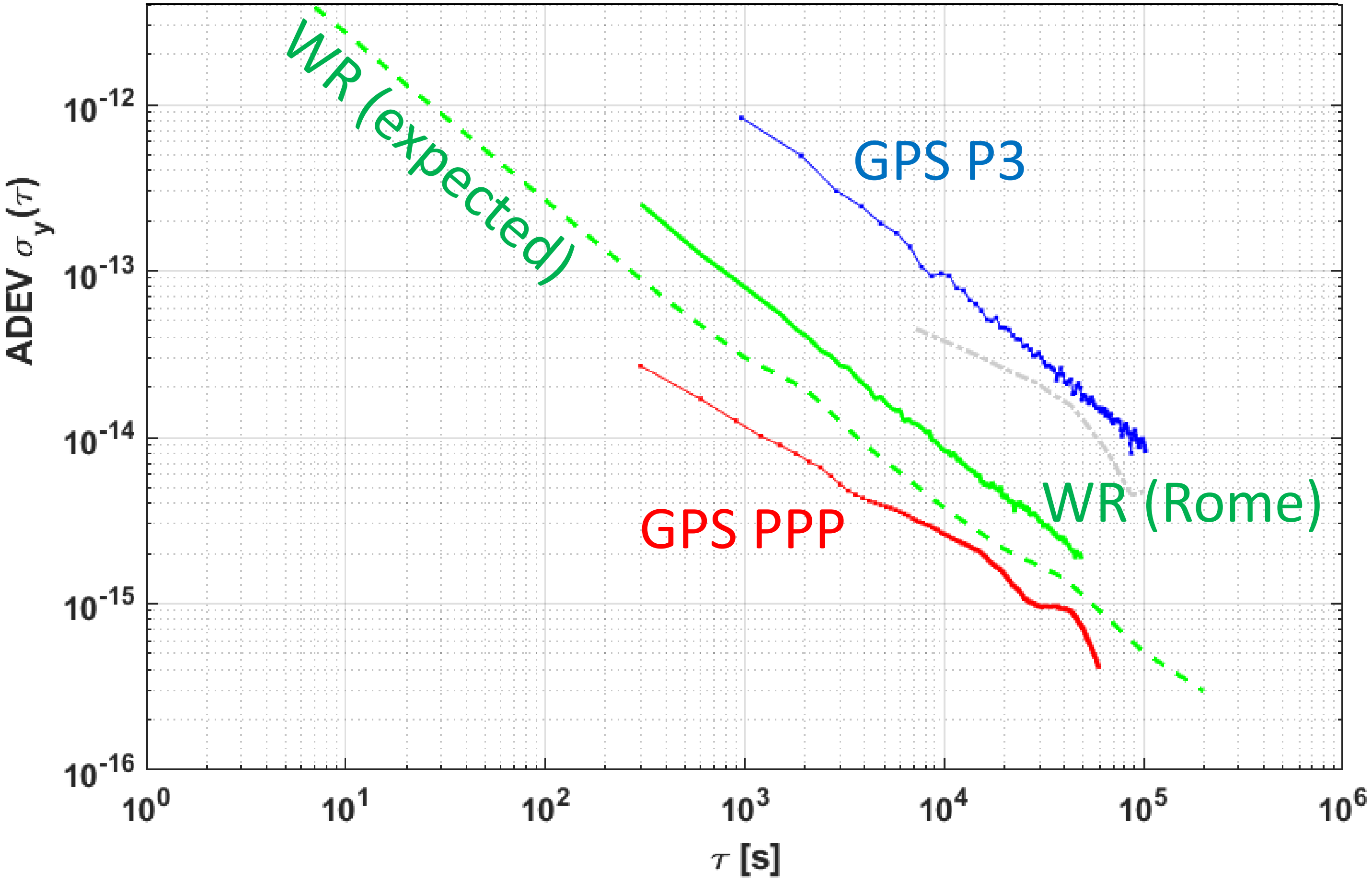
WR switch

WR mini switch

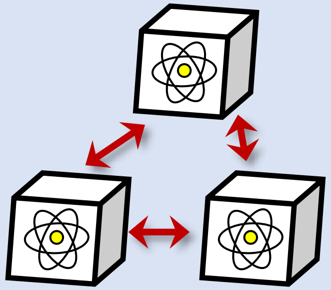
X 17

WR mini switch

User

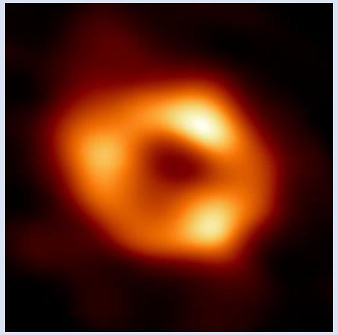


Science case #3



Clock comparisons and GNSS validation

Time for critical infrastructures



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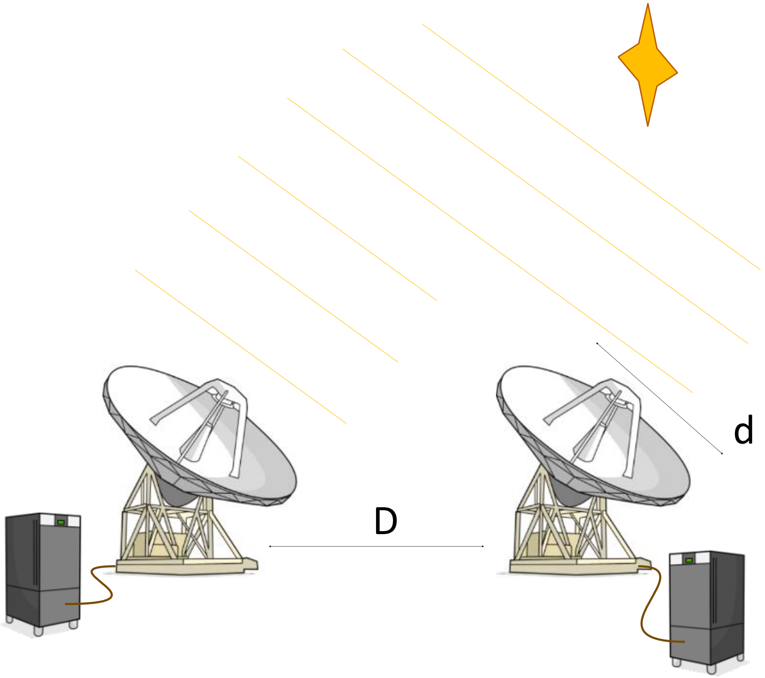
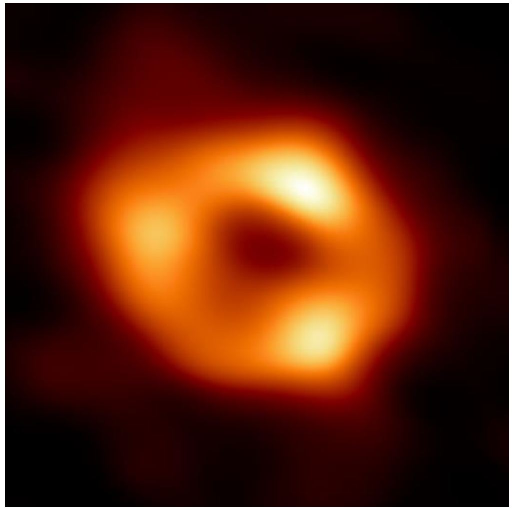
Very Long Baseline Interferometry

- Resolution of single telescope: θ ~ λ / d
- Resolution of VLBI: θ ~ λ / D
- Telescopes referenced H-masers

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).



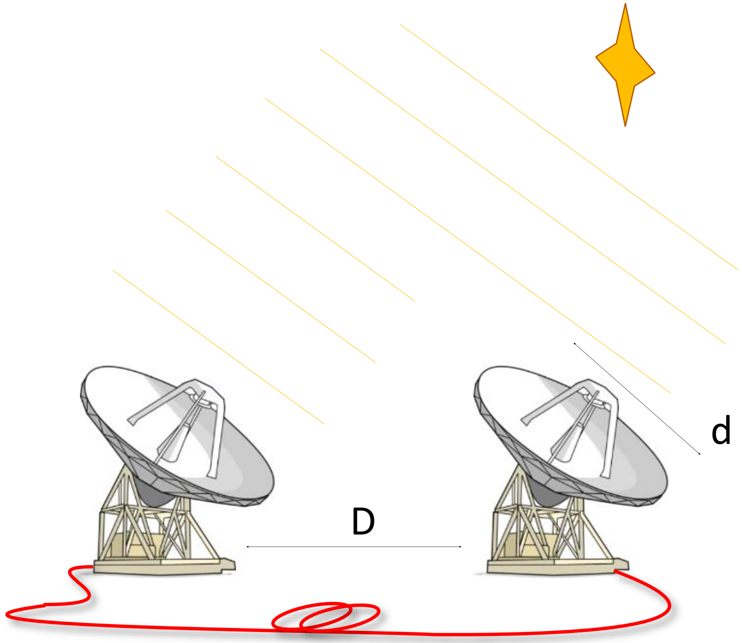


Sgr A*, the supermassive black hole at the centre of our galaxy, pictured by the Event Horizon Telescope using VLBI

EHT Collaboration, ApJL **930** L12 (2022)

Very Long Baseline Interferometry

Can high-precision *synthonization* of telescopes improve VLBI?

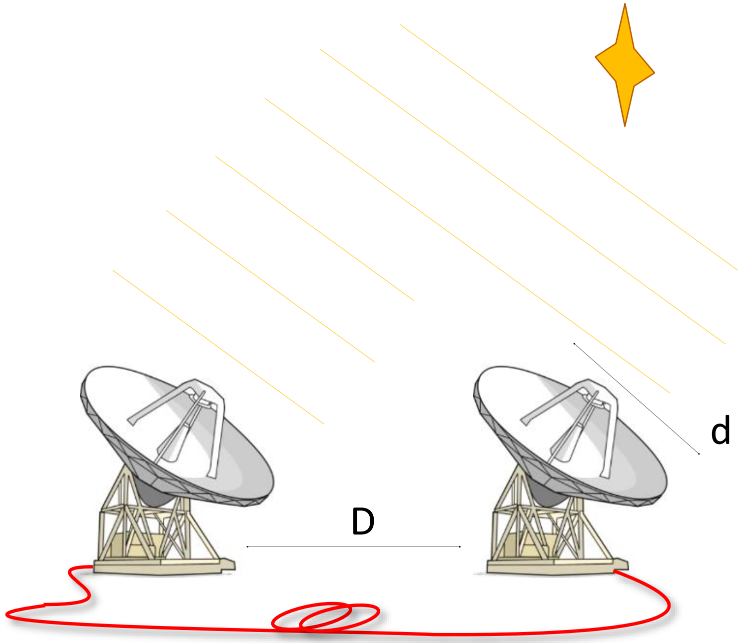


C. Clivati et al., Optica 7, 1031 (2020)

Very Long Baseline Interferometry

Can high-precision *synthonization* of telescopes improve VLBI?

- Dead times break phase coherence (discontinuities kill VLBI)
- Tight VLBI schedule / reliability
- Rigid analysis software (not easy to constrain clock conditions)



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

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Very Long Baseline Interferometry

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- Dead times break phase coherence (discontinuities kill VLBI)
- Tight VLBI schedule / reliability
- Rigid analysis software (not easy to constrain clock conditions)

- Proof-of-principle: done
- Above 100s GHz, H-maser instability is an issue
- A widespread, reliable optical network can be attracting

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

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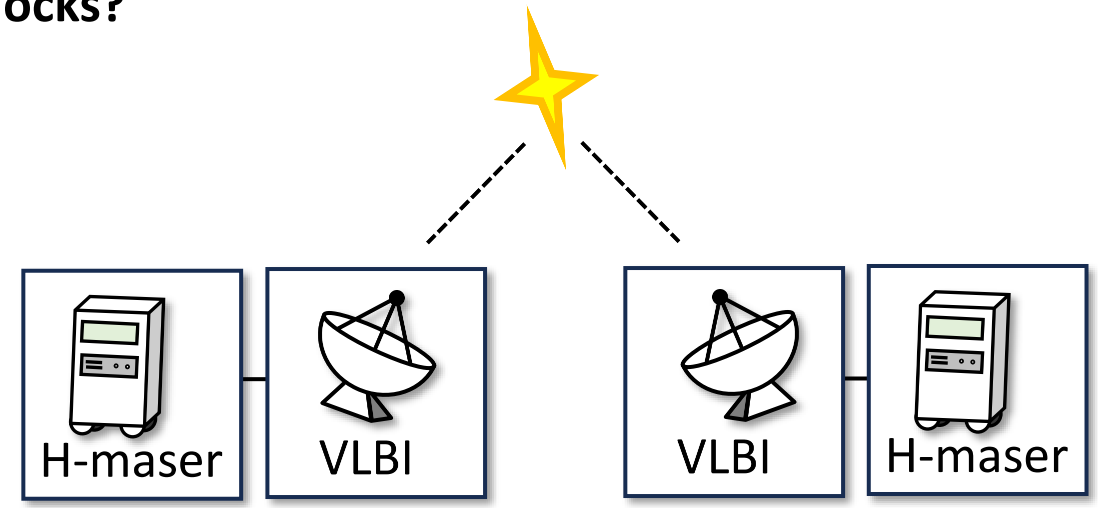
VLBI clock comparison

Can VLBI be used to compare distant atomic clocks?



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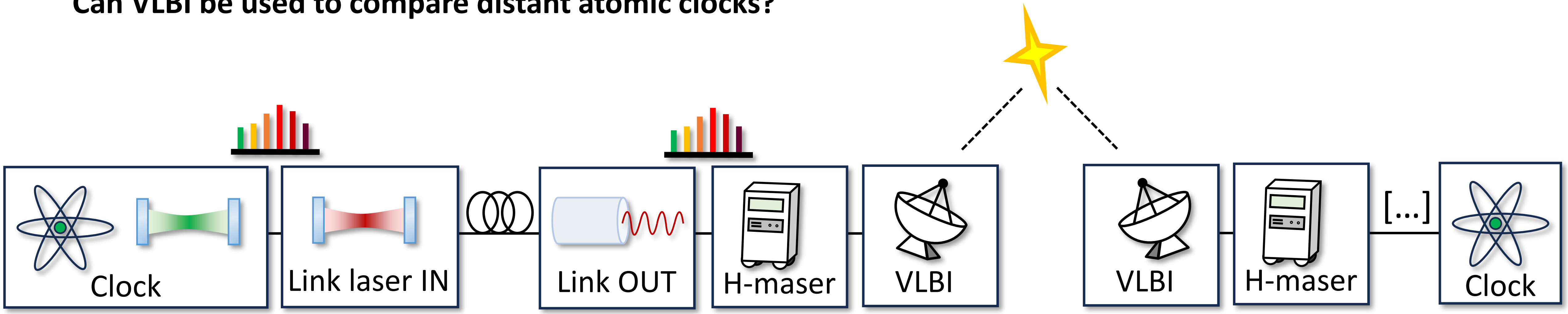

National Institute of Information and Communications Technology

M. Pizzocaro et al., Nat. Phys. 17, 223 (2021)

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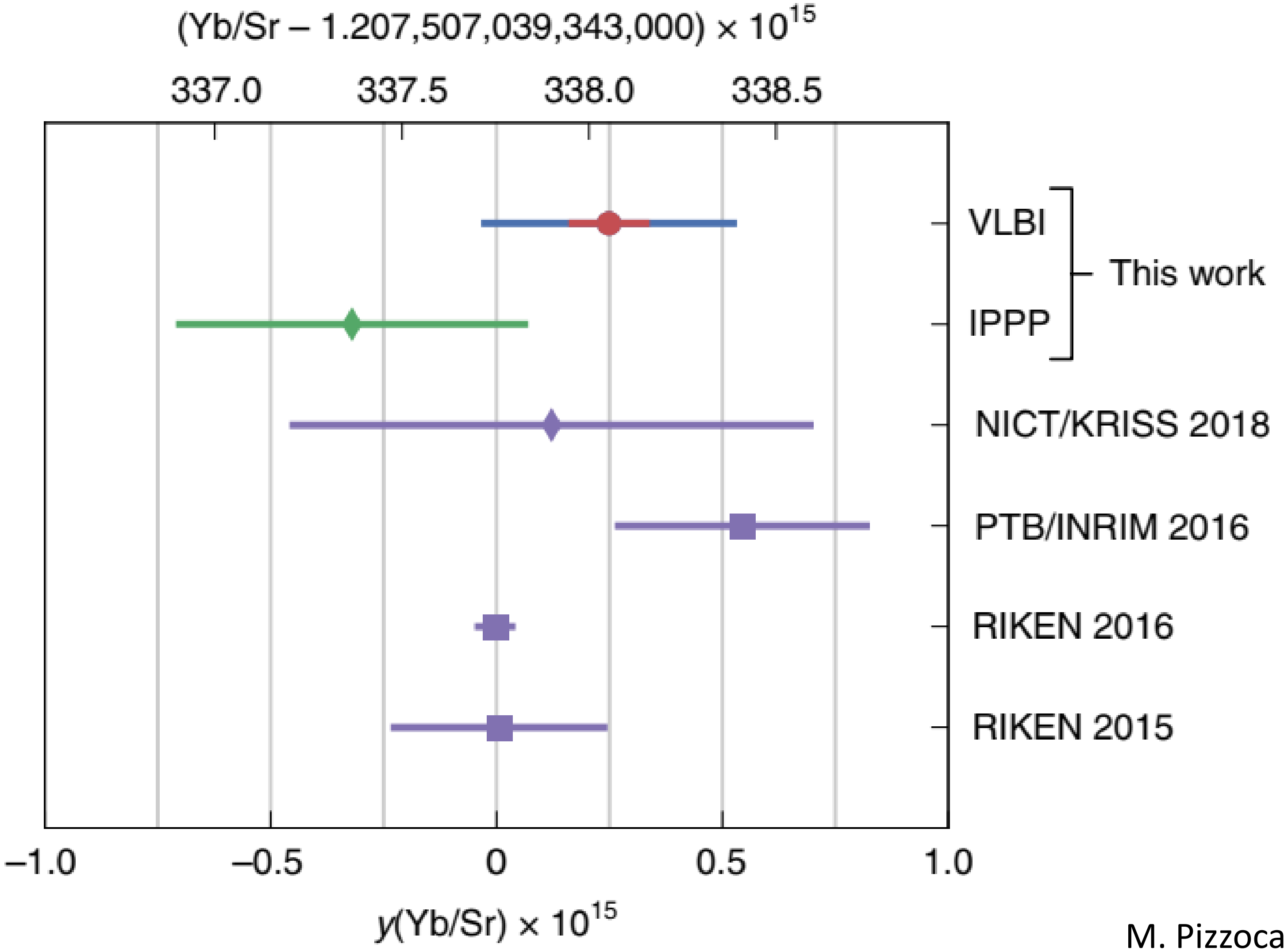
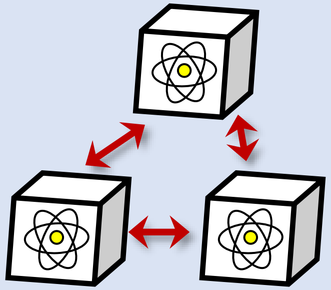


+ Follow-up collaboration with KRISS (Korea)

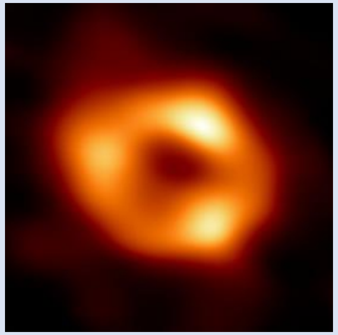
M. Pizzocaro et al., Nat. Phys. 17, 223 (2021)

Science case #4



Clock comparisons and GNSS validation

Time for critical infrastructures

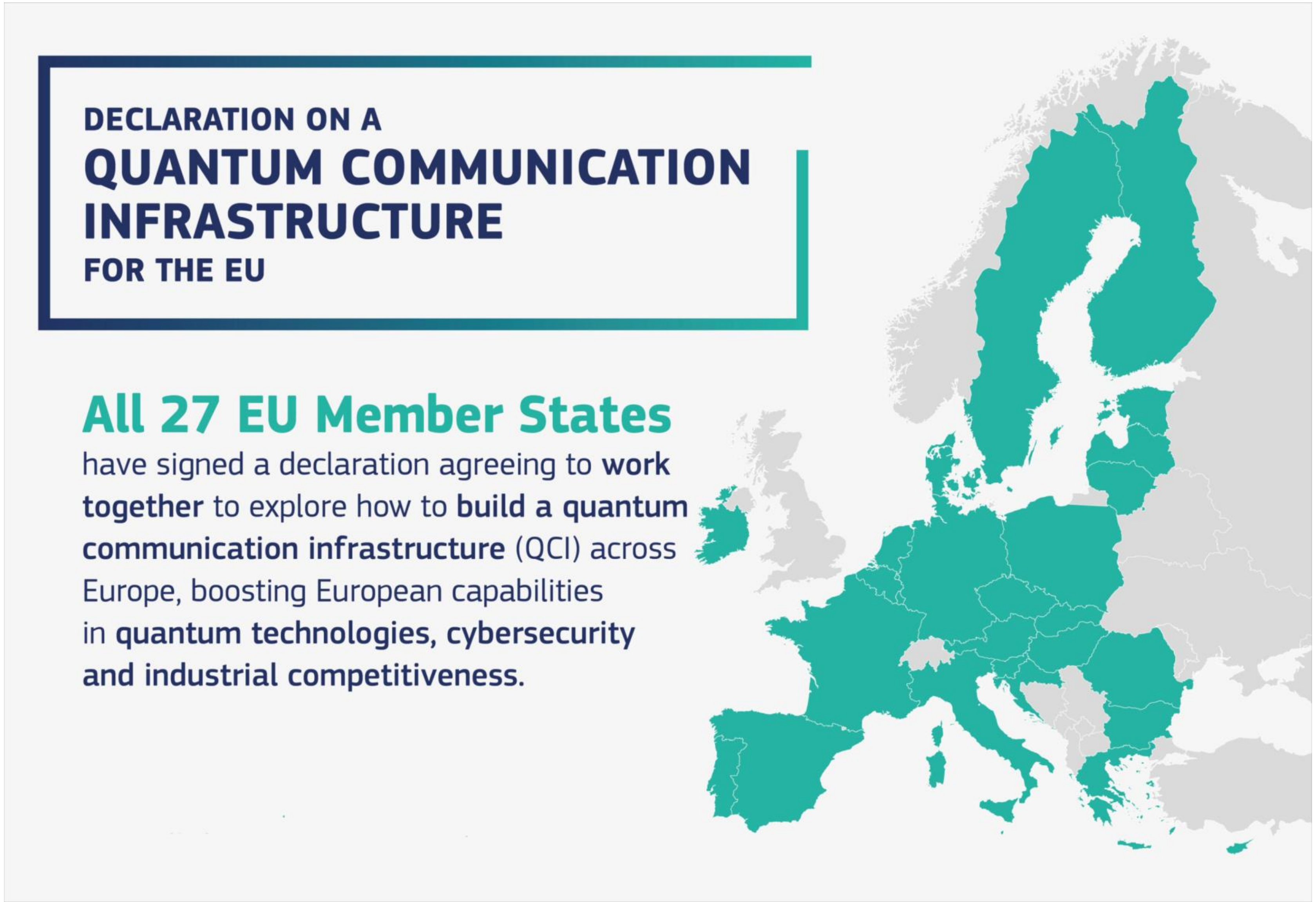


Referencing VLBI telescopes

Quantum communication

Remote sensing of earthquakes

EuroQCI



DECLARATION ON A
QUANTUM COMMUNICATION INFRASTRUCTURE
FOR THE EU

All 27 EU Member States have signed a declaration agreeing to **work together** to explore how to **build a quantum communication infrastructure** (QCI) across Europe, boosting European capabilities in **quantum technologies, cybersecurity and industrial competitiveness.**

- Quantum Key Distribution (QKD) for the protection of:
  - government data,
  - Telecom networks,
  - data centres,
  - critical infrastructures

- Target services by 2029

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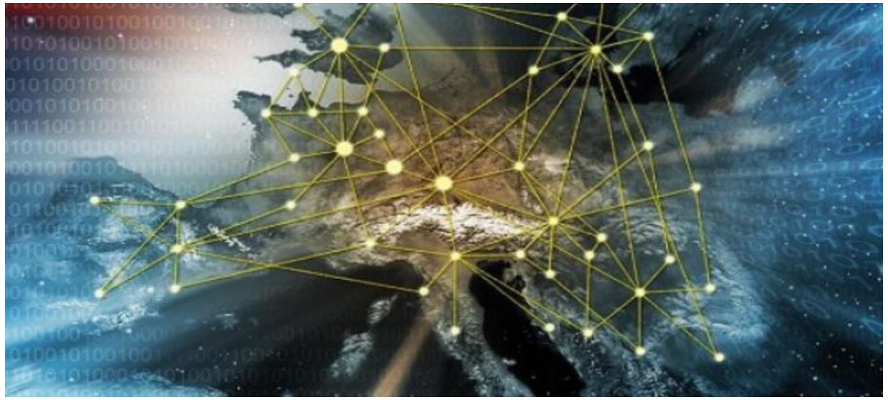
EuroQCI: challenges

Space and ground/space
for continental scale

Telecom fibers for local/regional scale
& cross-border links

TRL suited for real-world applications



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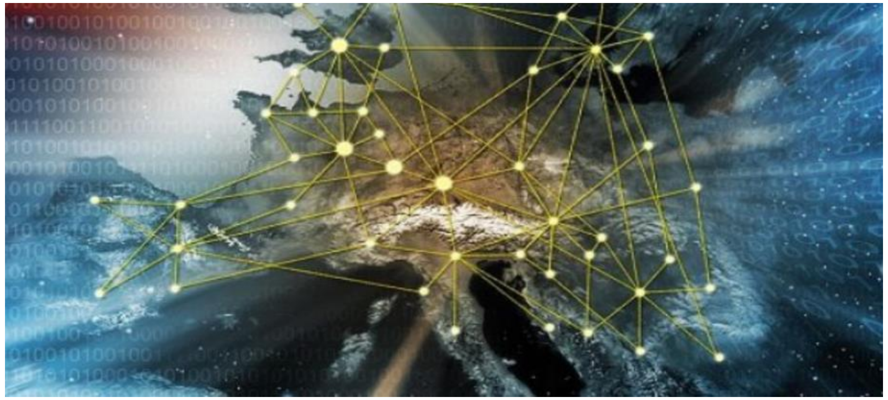

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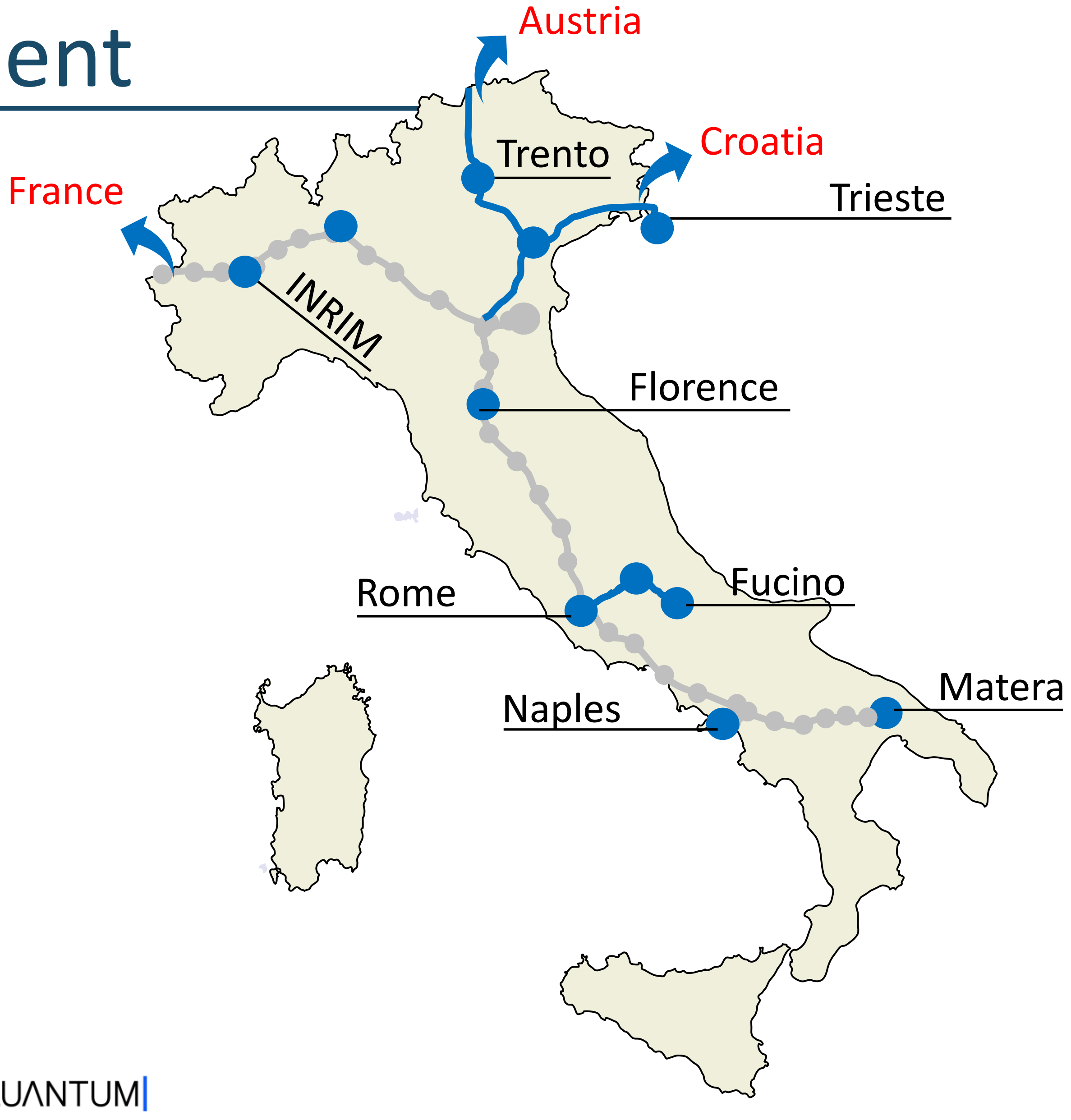
The Quantum Italy Deployment

QUID

QUANTUM ITALY DEPLOYMENT

- QKD testing & integration in telecom networks
- Quantum **Metropolitan Area Networks** in 9 cities
- **Use cases** in support of national QCI initiatives:
    - National/Regional governments,
    - Port authorities
    - Industrial sites
    - Main Italian ground/space interconnection



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ASI Agenzia Spaziale Italiana

Consiglio Nazionale delle Ricerche

cohaerentia FIBER OPTIC SENSORS FOR SMART DIAGNOSTICS

QTI Quantum Telecommunications Italy

ThinkQUANTUM

LEONARDO

TELESPAZIO a LEONARDO and THALES company

ThalesAlenia Space a Thales / Leonardo company

TIM

Telsy

top-ix WE DO CONNECTIONS

Metrology & QKD

- Ultrastable lasers
- Coherent broadcast of optical signals
- Sub-mrad optical path stabilization
- Sub-ns time synchronization of remote nodes

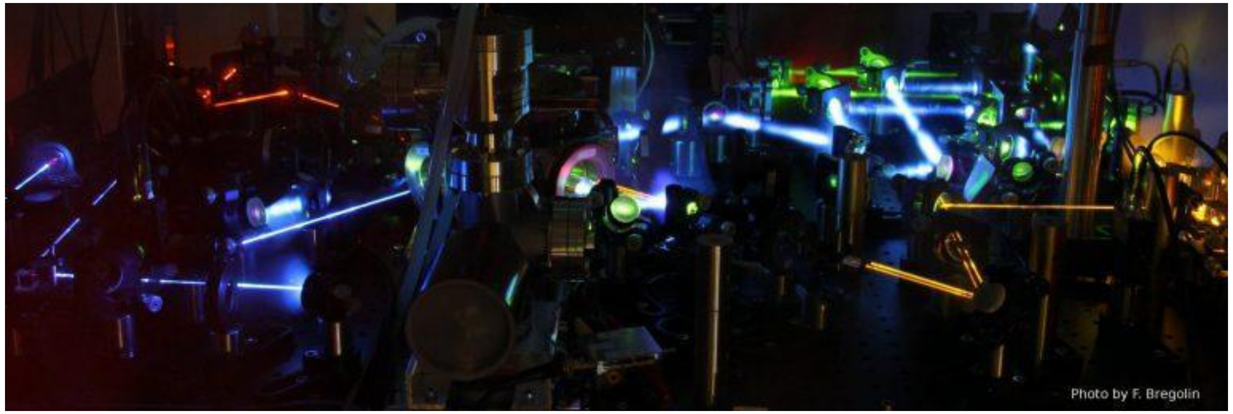
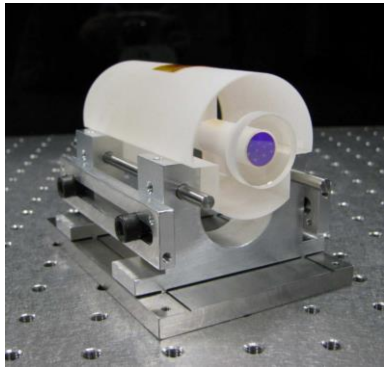
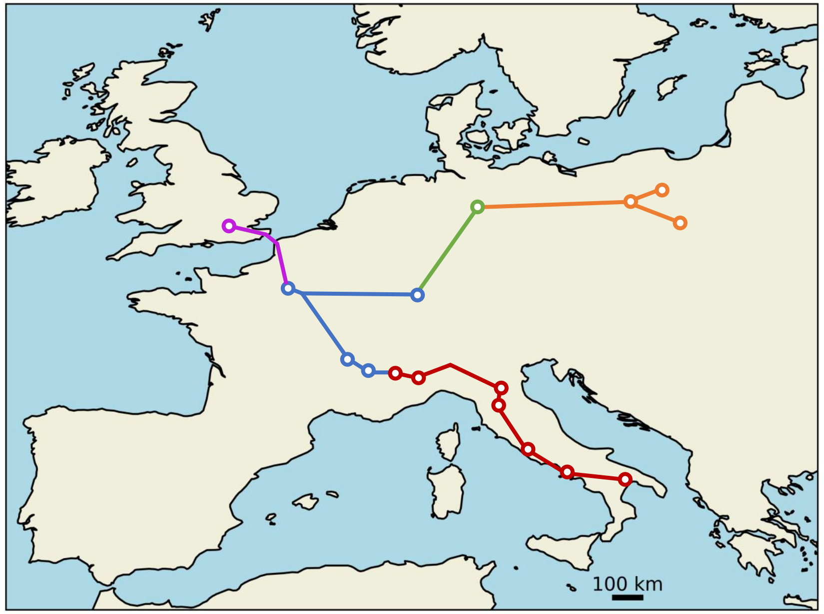


Photo by F. Bregolin





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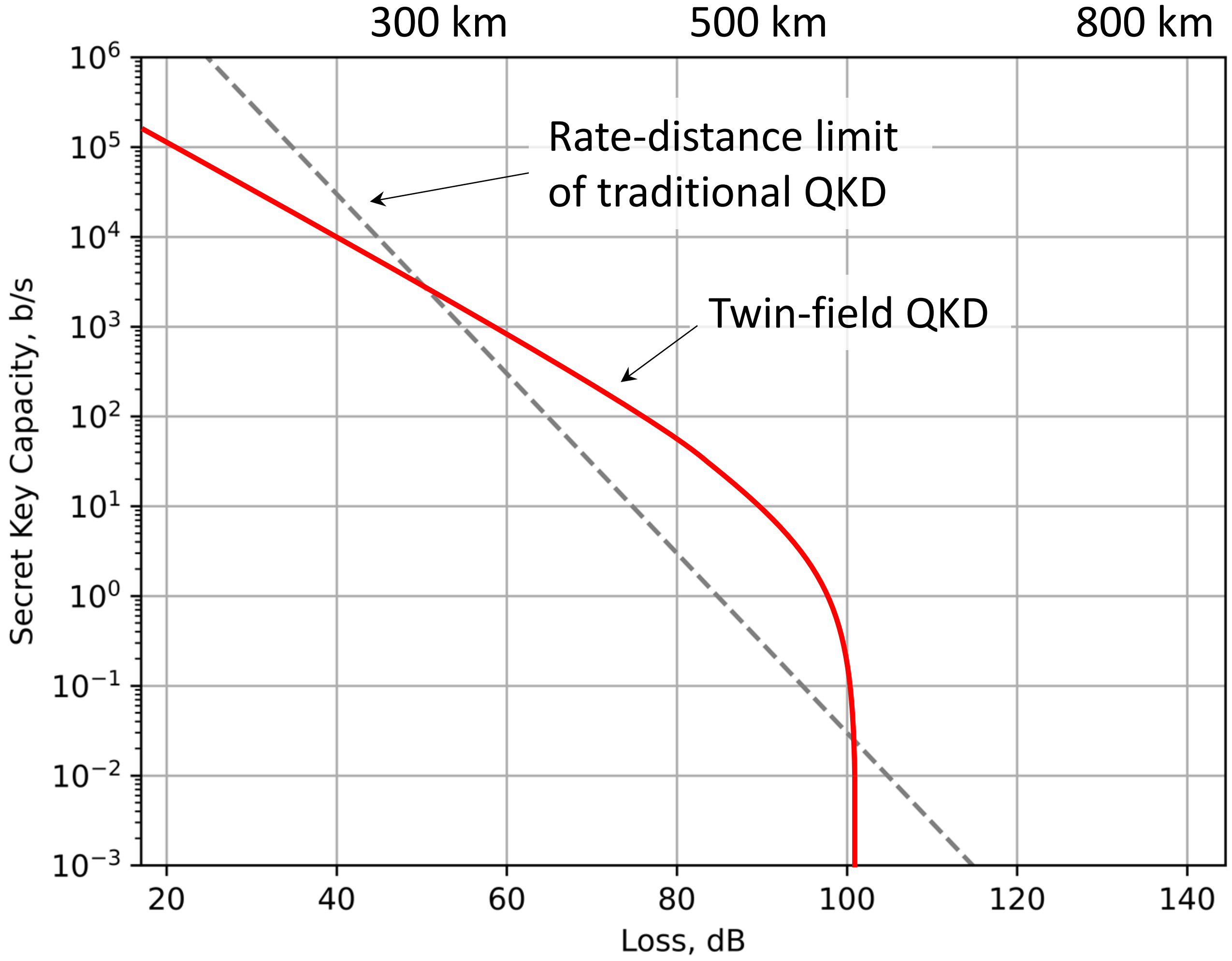
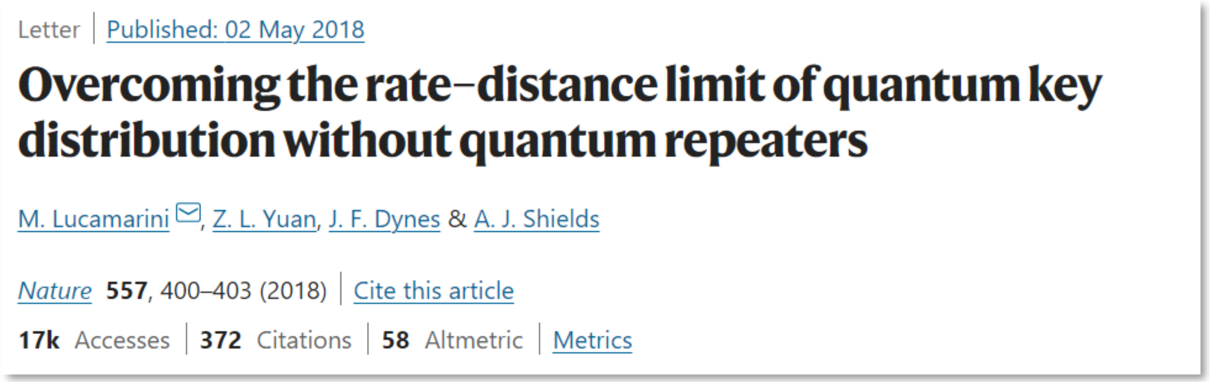
Twin-Field Quantum Key Distribution





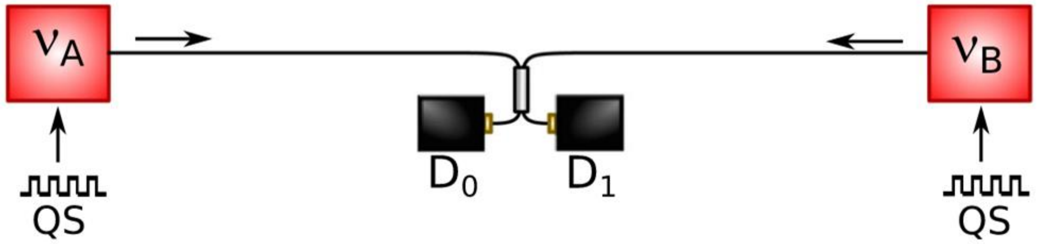
Letter | Published: 02 May 2018

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



Requests:
- ν_A and ν_B are phase-coherent!
- Noiseless propagation fibers

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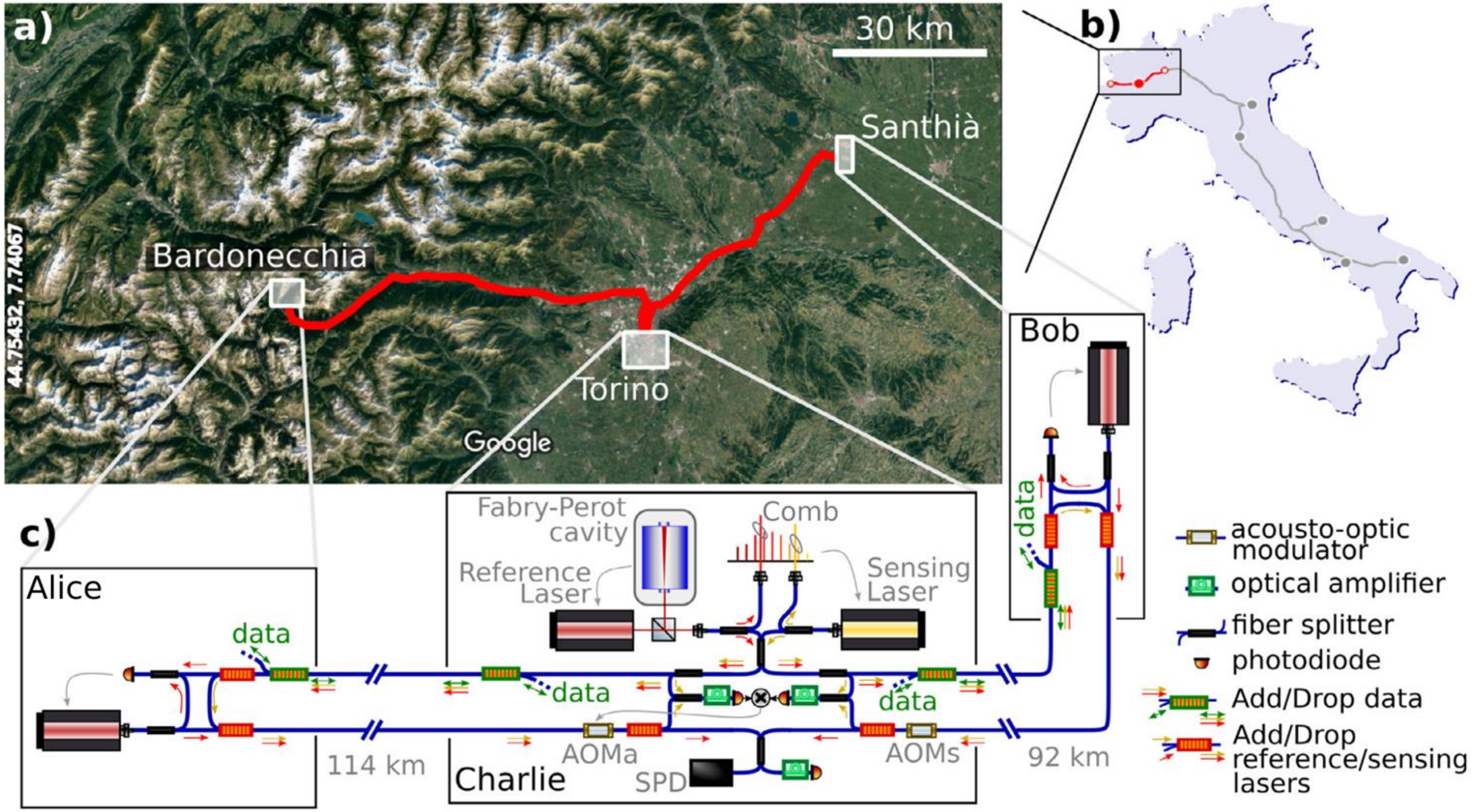
Coherent T-F QKD in real field

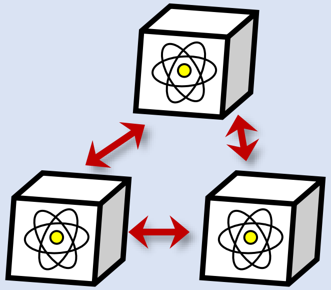
- Tested on 114 km real-world, 65 dB optical loss
- With ultrastable lasers: no QKD degradation even on unbalanced arms
- Coherence time grew from 50 µs to > 100 ms



10 x higher keyrate expected

C. Clivati et al., Nat. Comm. 13, 157 (2022)
G. Bertaina et al., Adv. Quantum Technol. 2400032 (2024)

Science case #5



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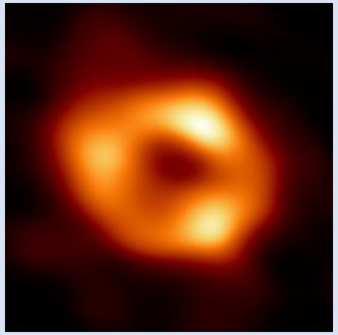

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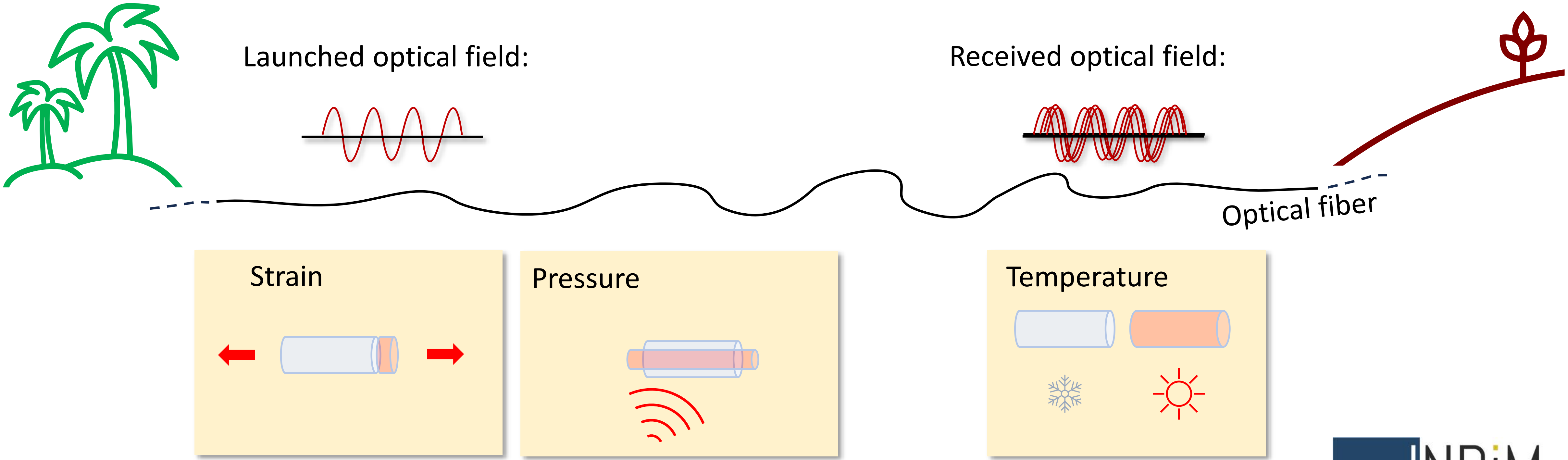
Distributed Fiber Sensing



Launched optical field:

Received optical field:

Optical fiber

Strain

Pressure

Temperature

Change in fiber length

Change in glass density

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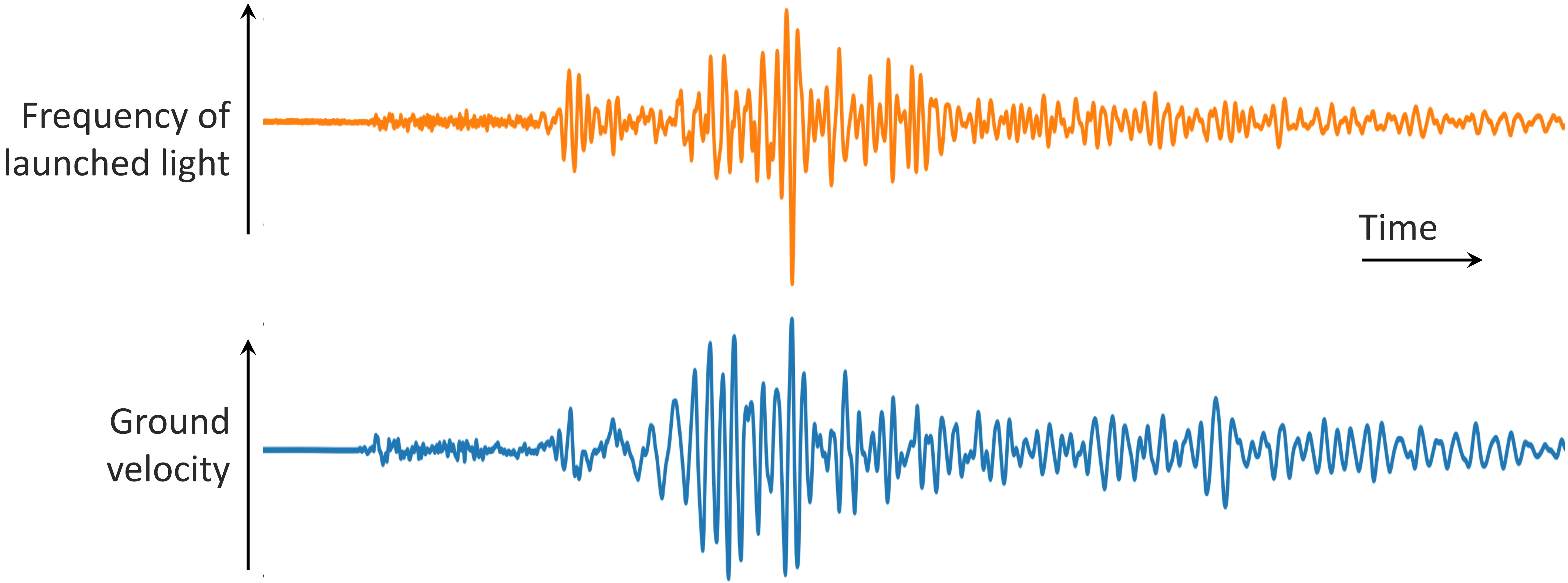
Metrological research applied to seismology



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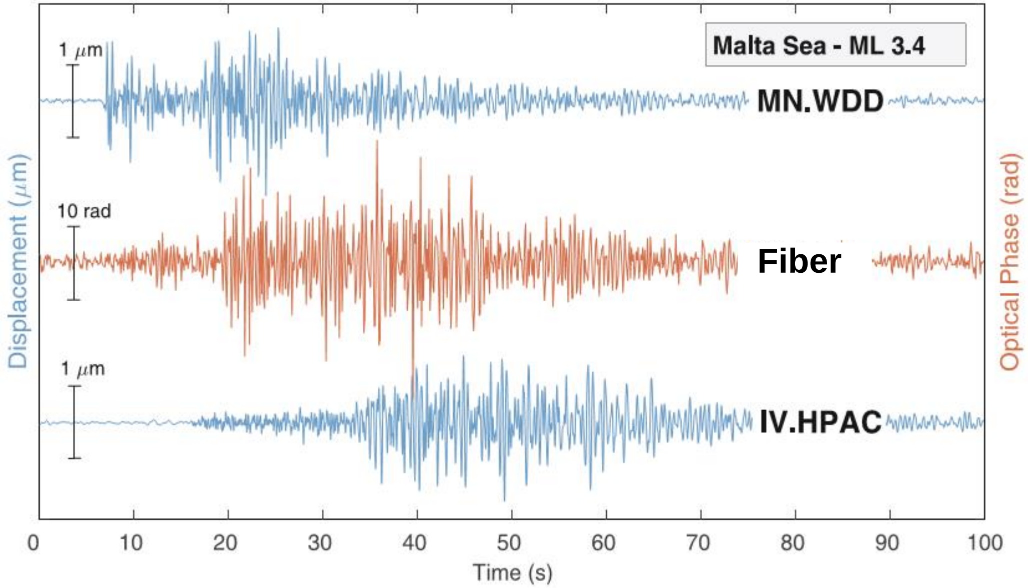
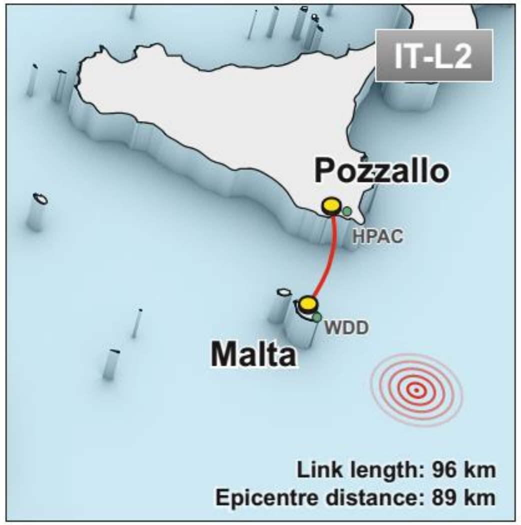
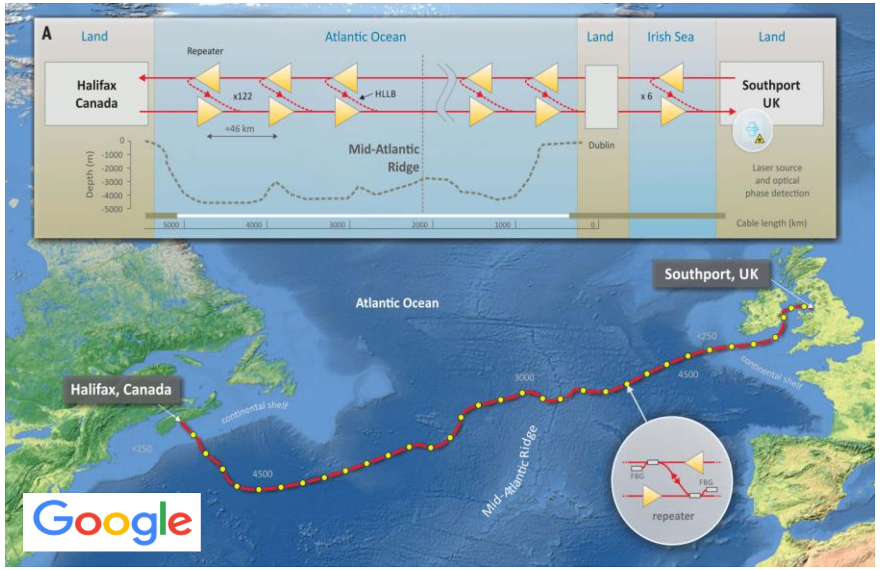
Exploring remote regions







G. Marra et al., Science 361, 6401 (2018)
G. Marra et al., Science 376, 874 (2022)

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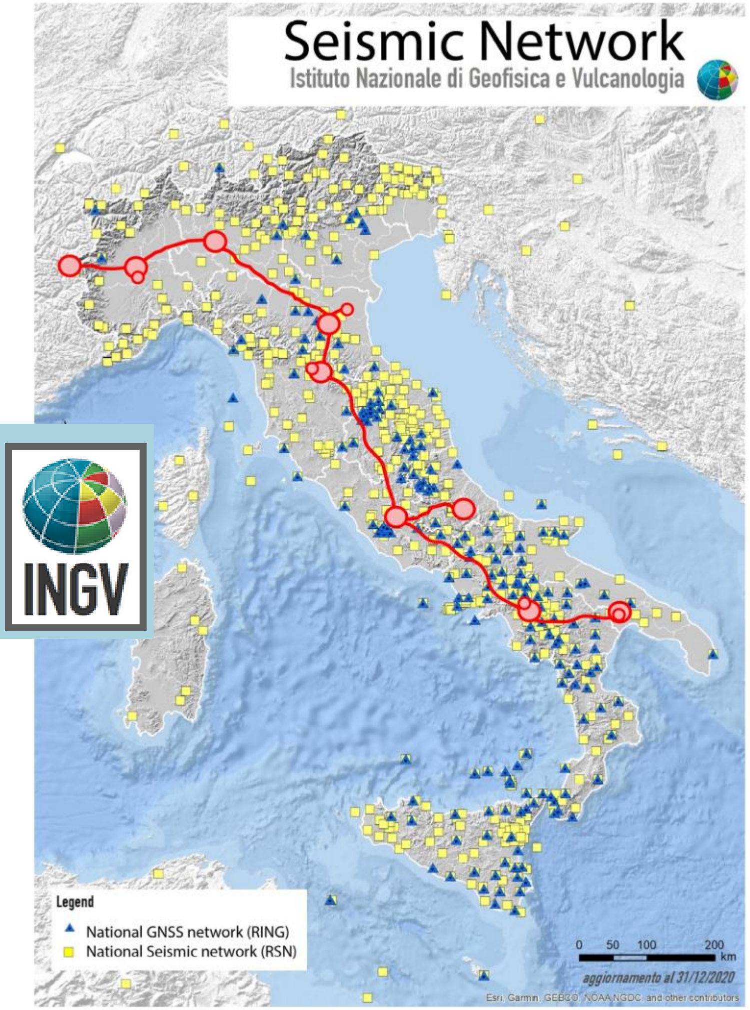
Earthquake detection in noisy areas

Fibers complement & enhance the existing sensor networks



Laser interrogator in network shelter

The link:
32-km long,
100 Gb/s QPSK

S. Donadello et al., Comm. Earth&Env. 5, 178 (2023)

Earthquake detection in noisy areas

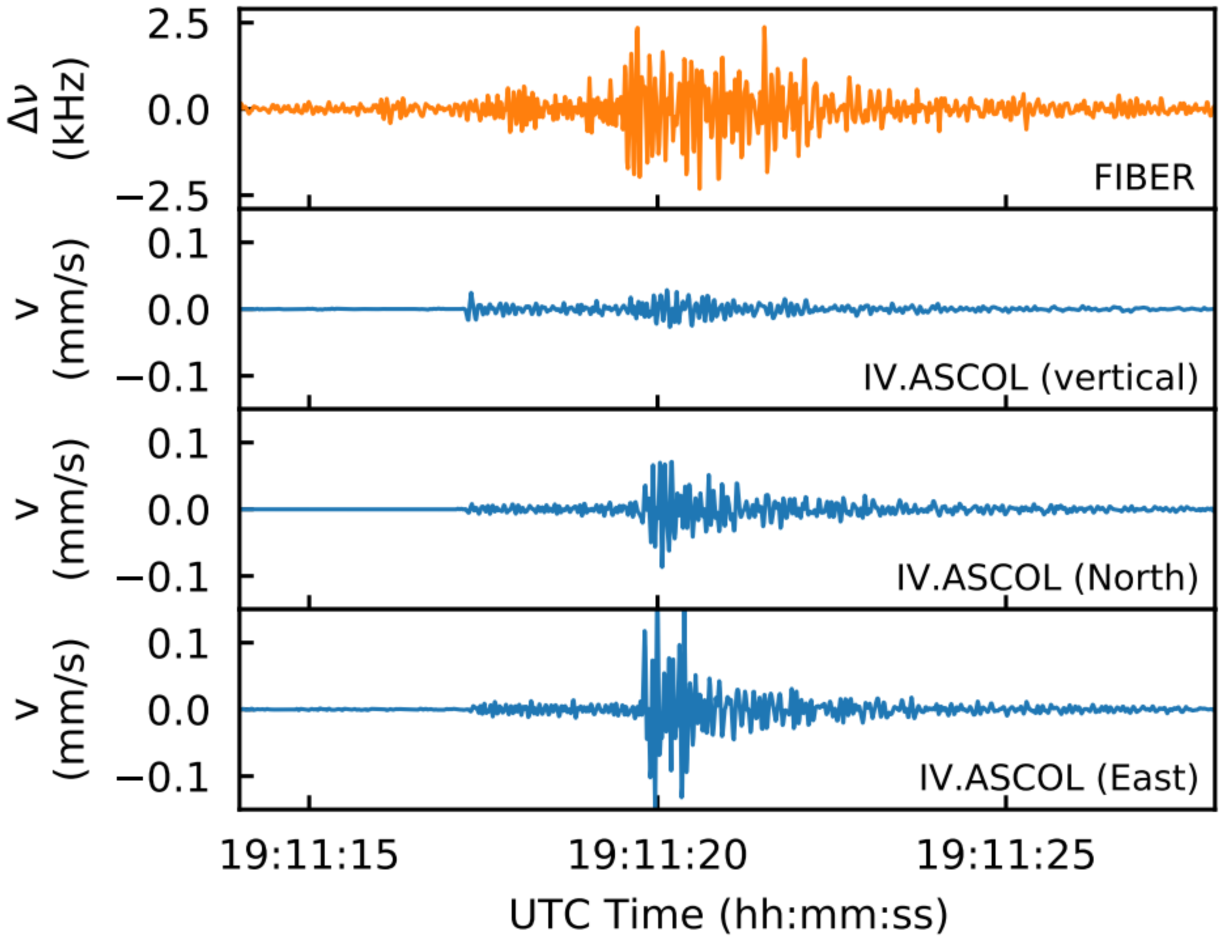
- 2-year-long acquisition & 100s events detected
- No disturbance to data traffic
- Quantitative studies

S. Donadello et al., Comm. Earth&Env. 5, 178 (2023)

Earthquake detection in noisy areas

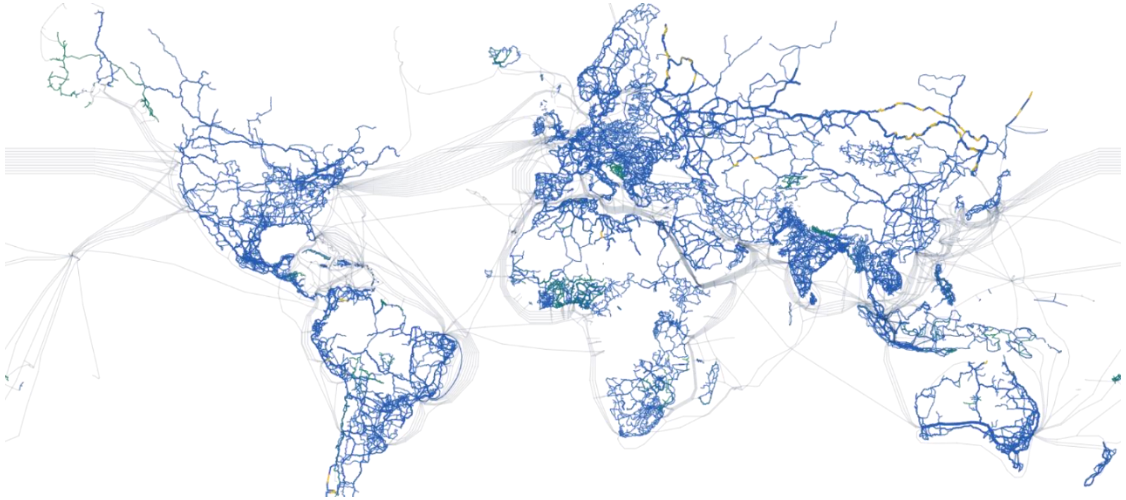
- 2-year-long acquisition & 100s events detected
- No disturbance to data traffic
- Quantitative studies
- Very weak events are detectable!

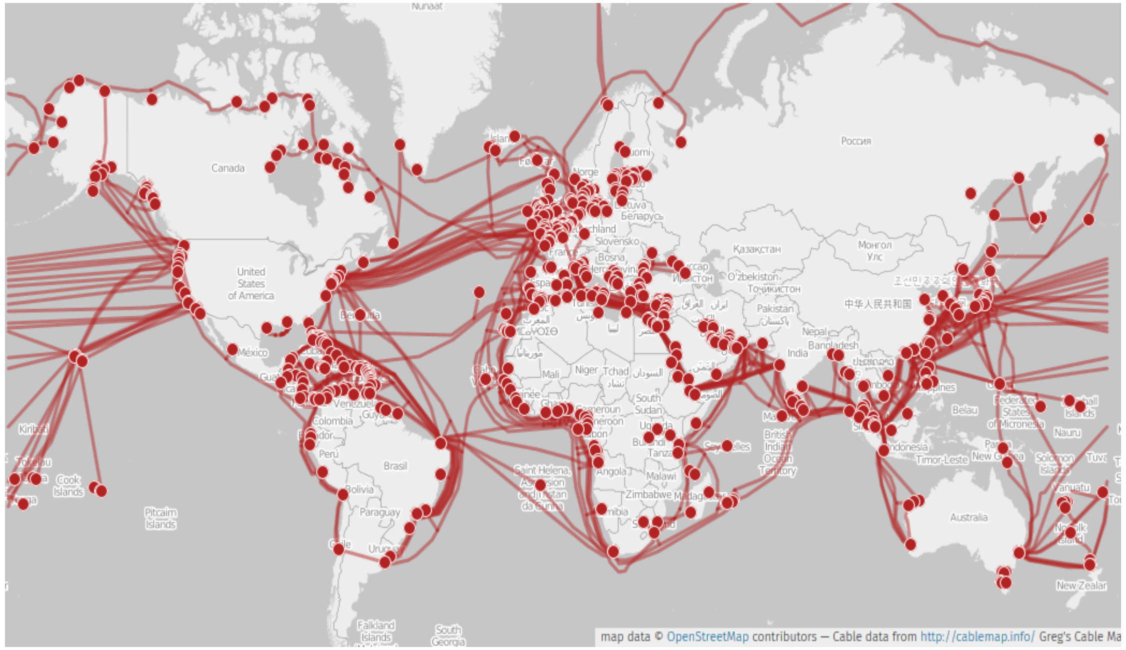
Civitella (TE), 2022/02/19, M=2.0, distance 18 km



S. Donadello et al., Comm. Earth&Env. 5, 178 (2023)

Sensitivity vs Coverage





map data © OpenStreetMap contributors – Cable data from http://cablemap.info/ Greg's Cable Ma

http://cablemap.info , https://bbmaps.itu.int/bbmaps/

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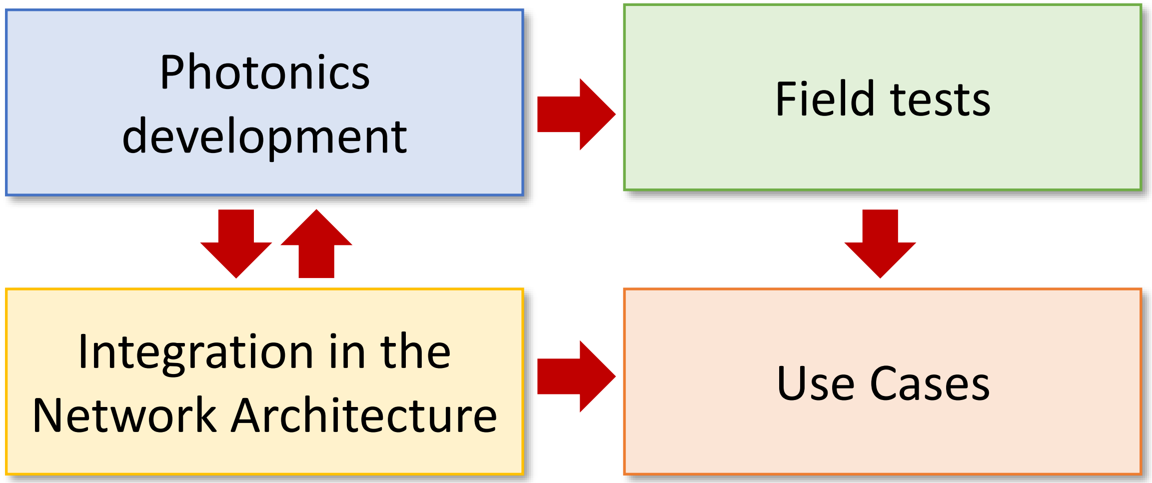
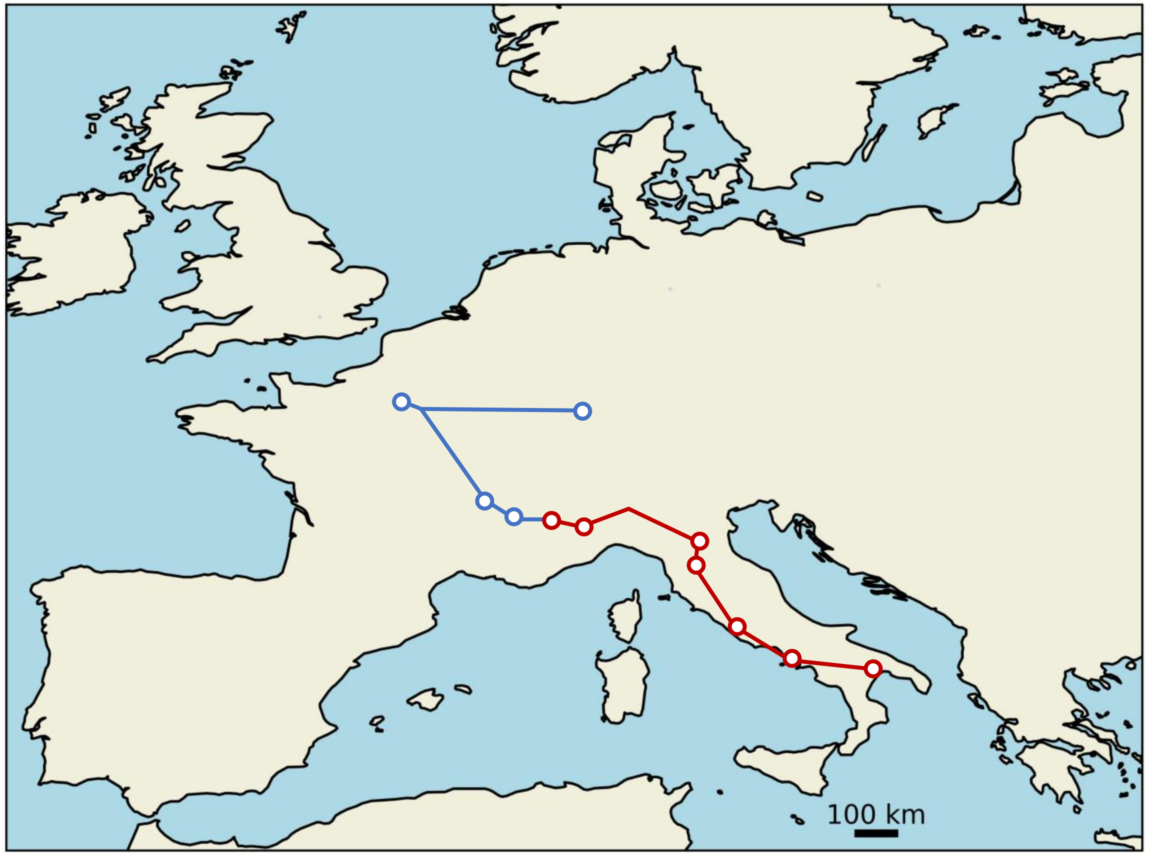
The SENSEI project

Smart **E**uropean **N**etworks for **S**ensing the **E**nvironment and **I**nternet quality

- Use the network as large-scale distributed sensor

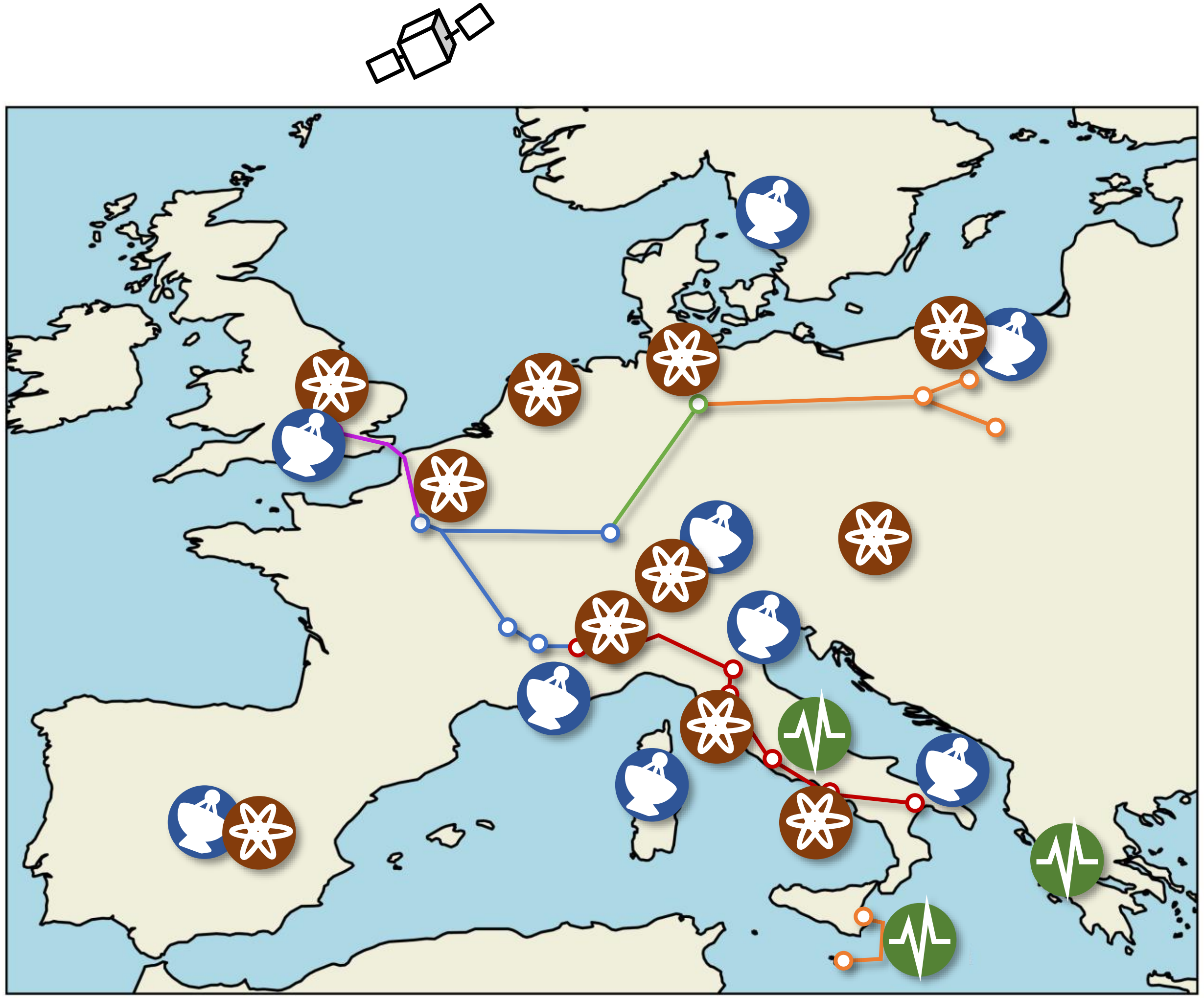
  …while transmitting data!
- 15 Partners from:
  - Metrology (INRIM, CNRS-SYRTE)
  - Seismology (INGV, GFZ, ISOR)
  - Photonics companies (NBL, Infinera, Exail, SMO)
  - Telecom providers (Open Fiber, GARR)
  - Universities (Politecnico Torino, U-Patras, U-Malta)





Wrap-up

- After 10 years, T/F over fibre links is more and more exciting
- Comparisons for the redefinition of the second: mature and sustainable
- Support to GNSS validation
- Interesting results demonstrated in different applications - 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



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Acknowledgments

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Thank you for your attention!

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