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E L'INNOVAZIONE INDUSTRIALE

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LE TECNOLOGIE QUANTISTICHE PER LO SPAZIO

Giancarlo Varacalli

Responsabile Unità Telecomunicazioni e Navigazione

Agenzia Spaziale Italiana

Outline

- Quantum Technologies (QT) overview and role of space
- QKD activities
- ASI Quantum projects
- Role of Matera ASI site
- Next activities and national opportunities

Quantum Technology overview

Quantum Enabled Technologies

1. Quantum Computation and Simulation
2. Quantum Communication and Cryptography
3. Quantum Sensing and Metrology

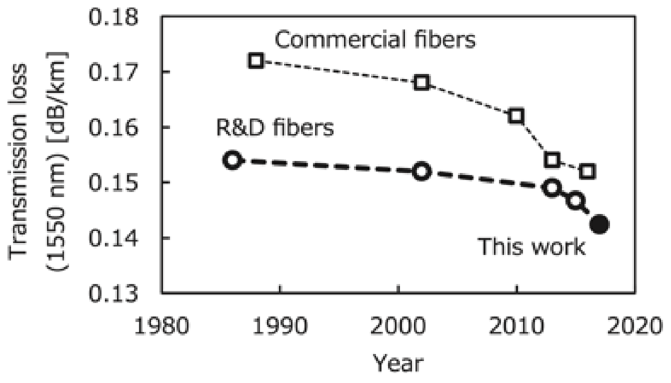
Examples of applications from space:

- Quantum Key Distribution (QKD)
- Quantum computing network
- Earth Observation (e.g. gravimetry)
- Time and Frequency Transfer
- Fundamental Physics (relativity, quantum mechanics, cosmology)

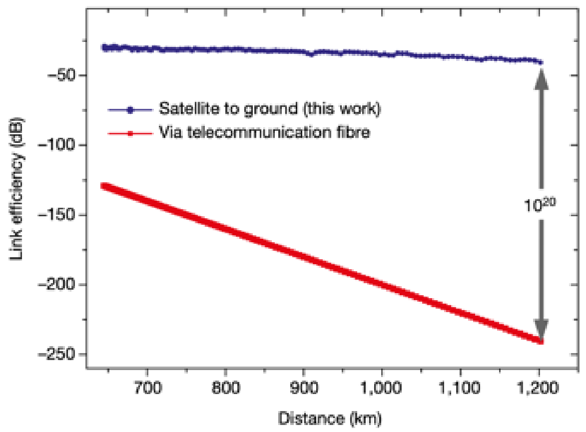
Multidisciplinary approach

- ❑ Engineering
- ❑ Software
- ❑ Research
- ❑ Theory/algorithms
- ❑ Protocols
- ❑ Procedure
- ❑ Verification & validation
- ❑ Education

Why QKD from space?



Tamura et al, JOURNAL OF LIGHTWAVE TECHNOLOGY 36, 1 (2018)

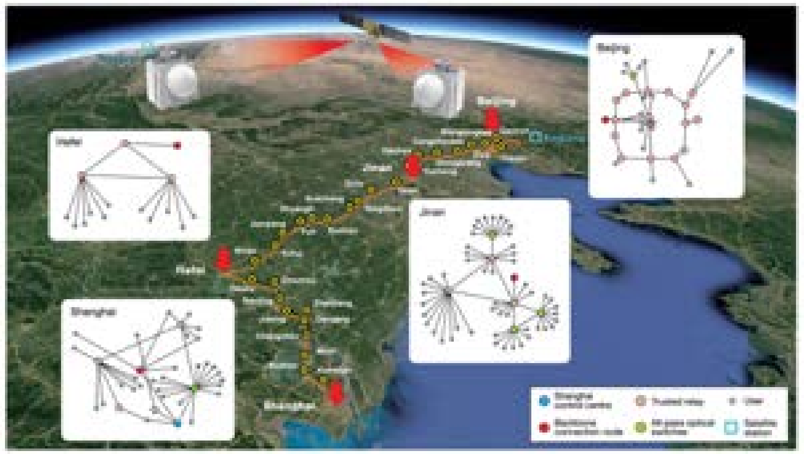


Liao et al, Nature 549, 43 (2017)

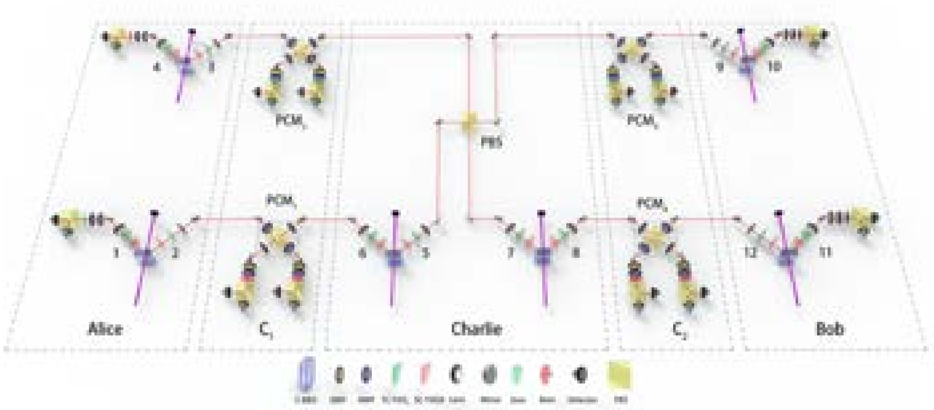
- Exponential attenuation in optical fibers makes it impossible to extend point-to-point QKD beyond several hundreds of kilometers.

"…over a distance of 1,200 km, even with a perfect 10-GHz single-photon source and ideal single-photon detectors with no dark count, transmission through optical fibres would result in only a 1-bit sifted key over six million years."

The limitations of intermediate nodes



Chen et al, Nature 589, 214-219 (2021)



Li et al, Nature Photonics 13, 644-648 (2019)

- **Trusted node** can be implemented to increase the reach of QKD. However, this solution increase the complexity and the risk of cyberattack.
- To cover a distance of 2000 km, 32 trusted relays have been used to connect Beijing to Shanghai.

Untrusted nodes are still in early development stages.

- ➢ Memory assisted schemes require quantum memory with long coherence time, fiber compatibility, efficient interfaces, multiqubit register…
- ➢ All-optics repeaters requires large repeater graphs state (RGS)

Connecting remote locations

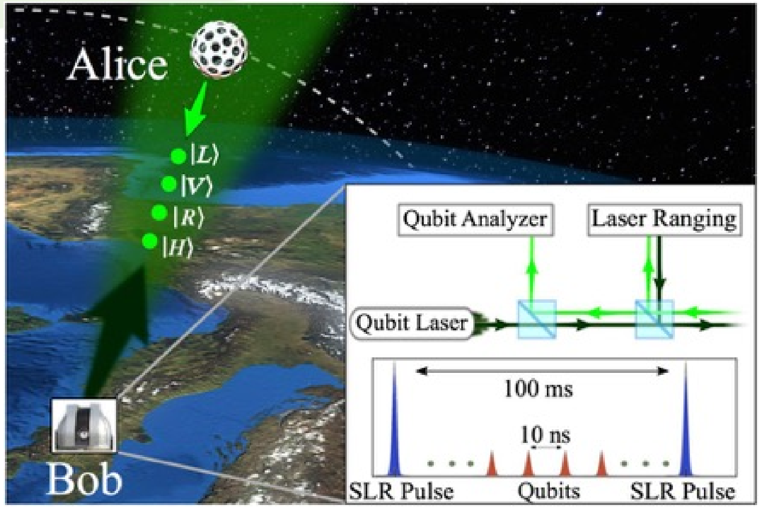
- QKD will most likely be used to protect critical infrastructures, to provide governmental/institutional secure communication. However, several impediments prevents the use of optical fibers: physical, political, economical.

Locations inaccessible to fibers

Isolated / hostile territory

Remote locations

Quantum communication @MLRO



- 2008 – Single photon transmission from LEO
- 2015 – Quantum state transmission from LEO
- 2016 – Single photon transmission from MEO
- 2016 – Interference from LEO
- 2017 – Delayed-choice experiment in space
- 2019 – Single photon transmission from GNSS

- The Matera Laser Ranging Observatory (MLRO) is a class 1.5 m telescope, designed for satellite laser ranging.
- Since 2006 MLRO has been used for test toward satellite quantum communication (passive mode: retroreflectors and active mode: first Micius test).

> The underlying idea is exploiting reflector on board of satellites to simulate a single photon sources.

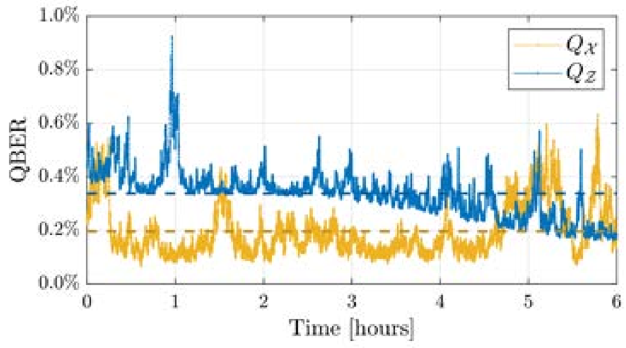
Recent activities

- 2020: Upgrade of the MLRO telescope and develop of a fully operative QKD receiver for BB84 QKD in NIR.

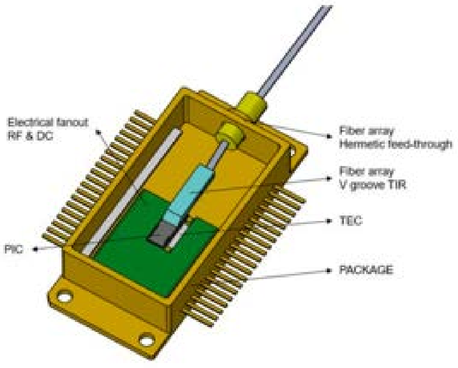
Quantum communication payload development

2017, technological developments and ground testing of the **receiver and transmitter of a Quantum Key Distribution** (QKD) were started, in particular:

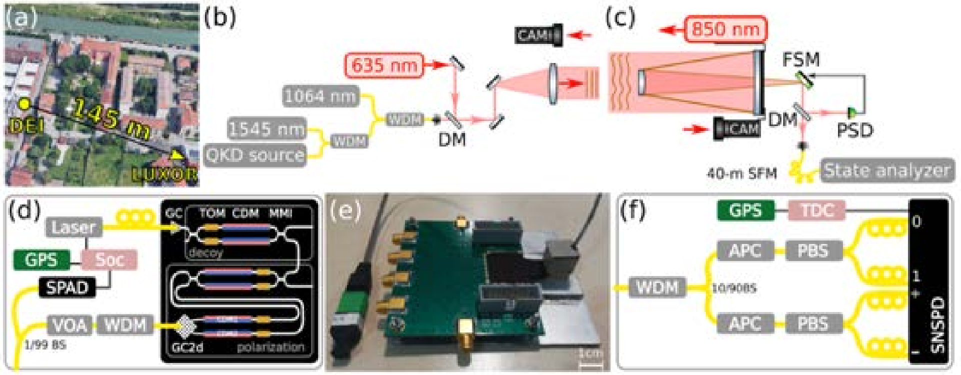
- On board Design optimization of QK transmitter
- High performance rugged quantum state transmitter
- Integrated silicon photonic chip for QK transmitter e Quantum Random Number Generator (QRNG)



Very low QBER transmitter



Integrated silicon photonics



Experimental demonstration day and night

Developments for satellite QKD system

- 2020: a **space qualified** packaged transmitter & QRNG (in a Integrated silicon photonic technology) developments are ongoing and the validation of the technology is planned within 2 years
- 2020: a **space qualified** bulk transmitter development in a classical technology is ongoing

- 2020, a mobile optimized ground station for quantum key exchange is under development (telescope, receiver, protocols etc…)
- 2021 Upgrade of the MLRO telescope to receive quantum communication is ongoing, in particular QK exchange

National view on satellite quantum communication

I-QKD
Quantum satellite

Collaboration with national backbone

UNIPD compact ground station

MLRO as reference ground station

Mobile ground station

National infrastructure will support also EC/ESA programs: EAGLE-1, EURO-QCI

ASI-labs

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New upgrade expected

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INRIM- ASI: The Italian Quantum Backbone in Matera

High resolution spectroscopy for fundamental physics test

Photonics development for ultimate metrology and quantum technology

Ultra-low noise optical frequency comb in Matera

In operation from November 2018

Common-clock very long baseline interferometry using a coherent optical fiber link

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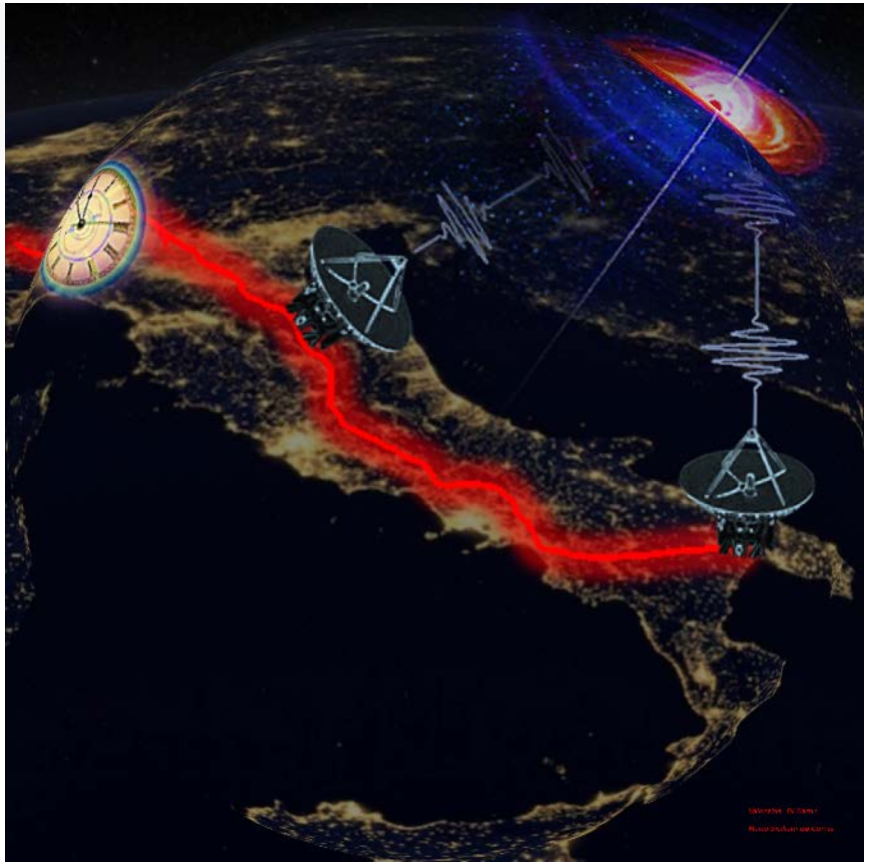
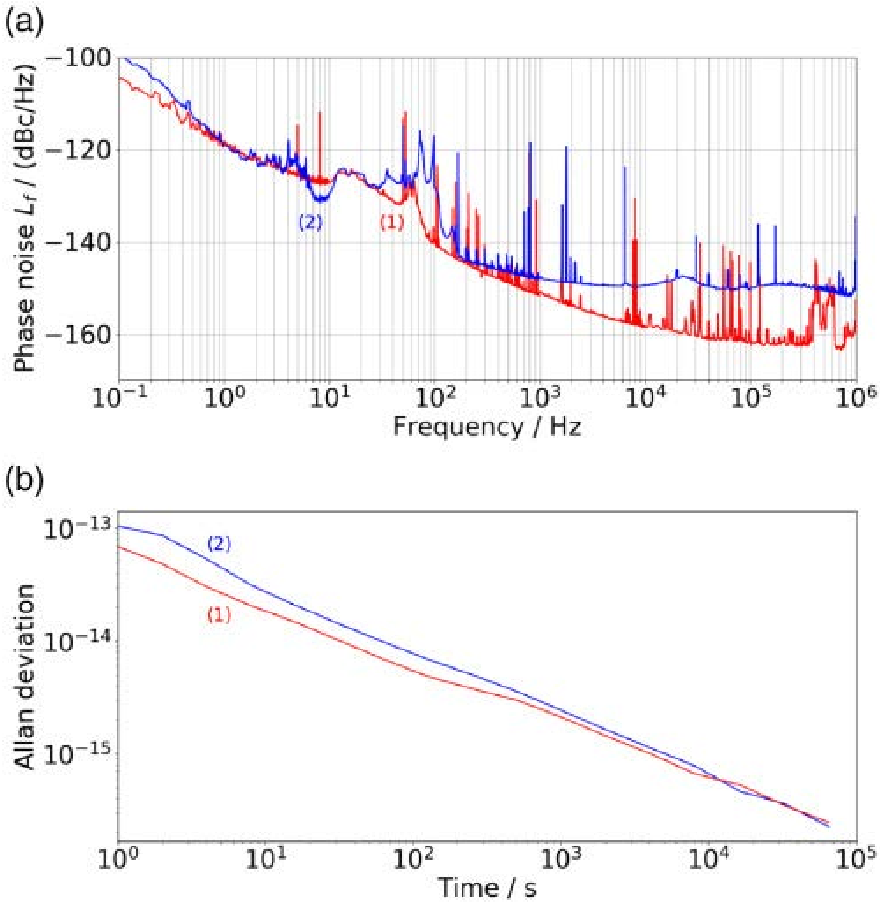
Synchronized view into the Universe

Italian researchers have successfully synchronized two remote radio telescopes by transferring time signals derived from Italy's atomic clocks to their individual local clocks – with the aid of frequency combs sourced from Menlo Systems. The technique promises to significantly enhance the precision of observations of radio emission sources in the Universe.

Observations of remote cosmological phenomena also involve long-distance communication on the terrestrial scale. To maximize resolution, astronomers simultaneously observe distant sources of radiation with radio-telescopes located as far apart as possible. This in turn requires the signals received by the different telescopes to be synchronized with reference to a master clock. Researchers from several Italian institutions now report in the journal *Optica*[1] a major breakthrough in correlation techniques. They used ultrastable laser light to transmit reference signals derived from an atomic clock at INRIM to radio telescopes in Medicina and Matera, thus providing a common timing standard for both. This enabled their observations to be precisely synchronized, effectively transforming the two instruments – which are more than 600 km apart – into one. The vital task of synthesizing the different frequencies used by the laser and the two telescopes was carried out by two FC1500 frequency combs and a PMWG-1500 system[2], designed and manufactured by Menlo Systems.

Figure: The telescopes at Medicina and Matera, and the overview map with the fiber link (Image credits: photos: J. Roda, INAF/IRA (Medicina), M. Siciliani De Cumis, ASI (Matera); map: figure adapted from [1])





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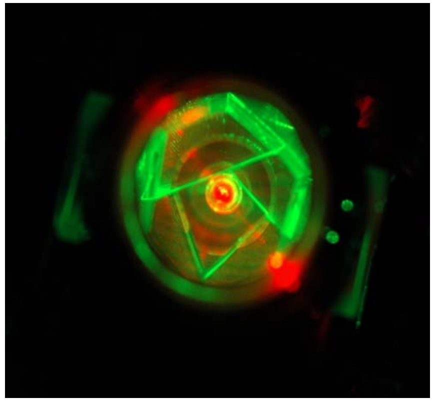
Whispering Gallery Mode Resonators for Metrology, Spectroscopy and Quantum Technologies (WhiTech – ASI project)

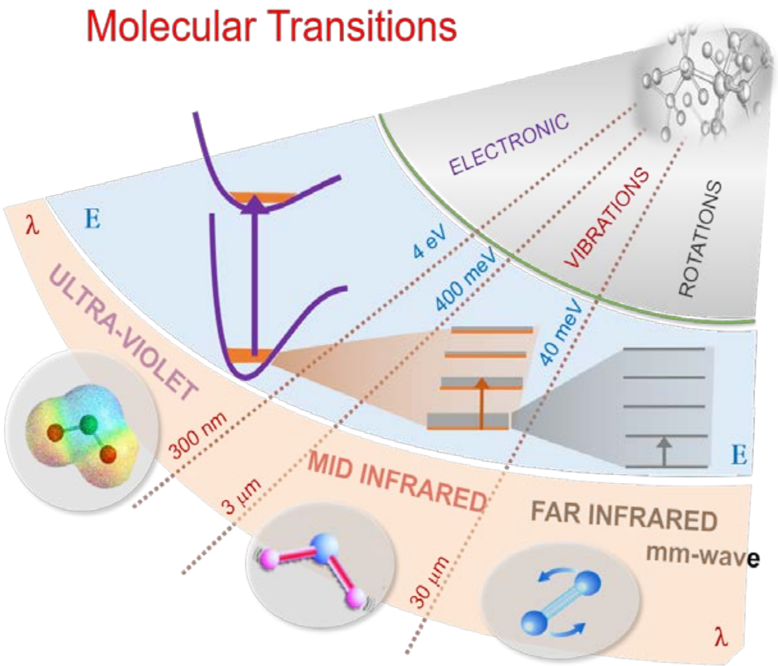
Crystalline WGMRs enable:

- active media (nonlinear processes, Kerr comb generation)
- passive devices (laser filtering or stabilization)
- wide transparency range and high Q-factor on a large variety of materials (silica, quartz, silicon nitride, Hydex glass, aluminium nitride, fluoride crystals, diamond,….)

Applications:

- Compact metrological reference and standard distribution of time and frequency (VLBI, Astrocomb, ecc.)
- Light sources suitable for integration in compact and robust laser modules for space missions (QCL Comb, WGM Comb, RF photonics) and high-sensitivity spectroscopy for earth and space observation
- Mid IR Quantum Communication
- Fundamental Physics testing: Time variation of fundamental constants (α, mp/me, …), Electric dipole moment of the electron, Parity violation in molecules, Relativistic effects …
- Mid IR and THz sources and detector for space applications
- Compact quantum sensors (temperature, trace gas, biosensing)
- QNRG devices





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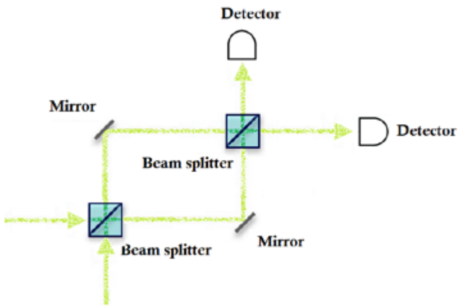
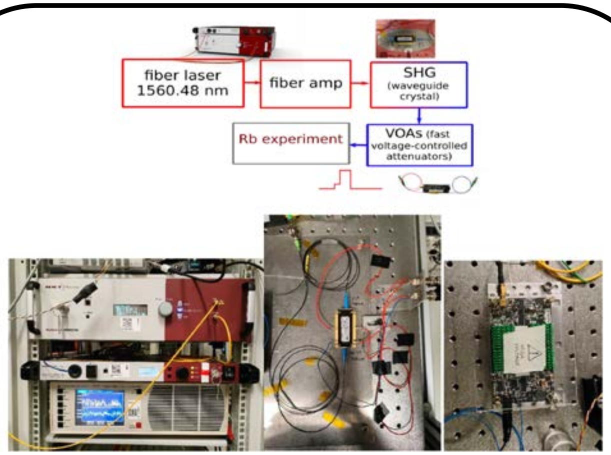
Non linear Interferometry at Heisenberg Limit (NIHL)

Classical Mach Zehnder Interferometer

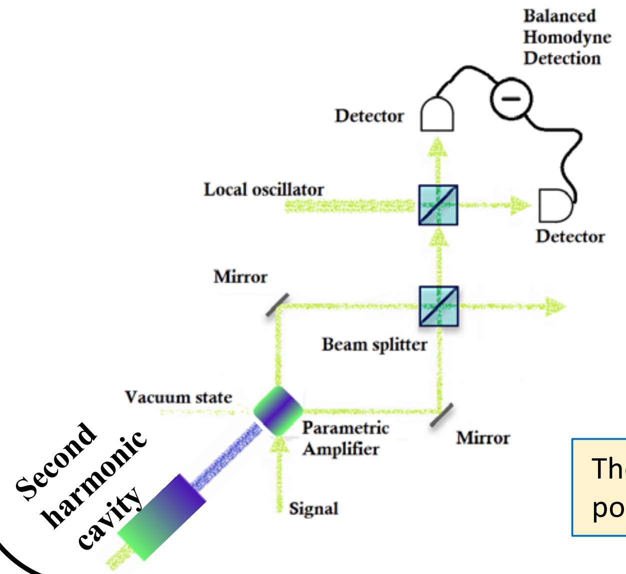




squeezing-enhanced atomic clock

Non linear Interferometer

replacing the conventional beam splitters by parametric amplifiers



In this configuration the interferometer sensitivity significantly overcomes the Standard Quantum Limit by a factor given by the gain of the parametric amplifier.

The practical demonstration of such an interferometer would permit searching for the ultimate limits of the quantum theory of measurement, **with disruptive impact in the field of quantum sensing and imaging.**

The setup has already been used to generate high rate polarization entangled states

Future perspectives

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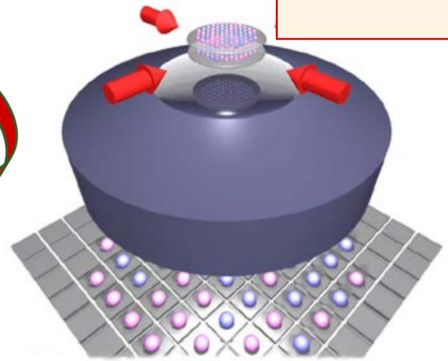
QOMBS project

- The Qombs Project is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement number 820419 →
- The target is the "quantum optimization" of quantum cascade lasers and in particular of Quantum Cascade Laser (QCL) frequency combs

Objectives and Addressed challenges

To realize a quantum simulator platform able to simulate a quantum cascade laser frequency comb (QCL-comb).

The quantum simulator will be based on ultracold fermions and bosons trapped in optical lattices.



QCLs are heterostructured semiconductor lasers operating in the mid and far infrared able to generate frequency combs.

GOAL

- ❖ Deliver **a new generation of QCLs and QCL-combs** able to emit squeezed light with entanglement among the modes.
- ❖ Demonstrate the possibility of quantum simulate the main dynamics proper of **a real device**.

- ❖ The carrier transport will be simulated by means of a gas of ultracold fermions trapped in an optical lattice.

Expected deliverable

- **A new generation of QCLs and QCL-combs, produced in collaboration with the European companies leader in their fabrication, which will be able to operate in a quantum regime, emitting squeezed light with entanglement among the modes.**

Applications

- **Quantum metrology, advanced (secure) free-space communication, high-sensitivity detection of pollutants and health monitoring.**

QUANCOM project

Security technologies in both the network transmission layers and in the application layers are becoming more and more complex and sophisticated but, nevertheless these efforts, they are not completely immune to attacks. In fact, even the computing power (parallel and distributed thanks to the network resource) is increasing and available to organizations that, for various purposes, have interests in appropriating of sensitive data.

The QUANCOM Project aims to overcome completely the impasse between attack and defence by proposing a coordinate action for the development and the field trail of an unconditional secure network build around a quantum cryptographic core. Quantum cryptography was invented more than 30 year ago and since then was been experimented in many lab experiments and prototype brass-boards. It is intrinsically secure and resists to whatever attack because based on the quantum bits (qu-bit) transmission which allows to transport secure key between the transmitter and the receiver (quantum distribution key, QKD).

Progetto PON “Sviluppo di sistemi e tecnologie quantistiche per la sicurezza informatica in reti di comunicazione” (QUANCOM) (Responsabile Scientifico Nazionale Prof. G. P. Pepe

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-Istituto nazionale di ricerca metrologica
- Università degli Studi di PADOVA
- Demetrix S.r.l
- Exprivia S.p.A.
- Memory Consult Srl

QUID – Quantum Italy Deployment

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QUID is the second project funded in the context of the Digital Europe Program. The project (QUID) proposes to start the deployment of the **Quantum Communication Infrastructure (QCI) in Italy**. QUID deploy systems and networks on the national territory to test quantum communication technologies, and in particular for the quantum distribution of cryptographic keys.

The project will be led by INRIM. The Consortium will provide its expertise in fiber procurement and deployment readiness for QKD, with and without data traffic.

Opportunities: QKD In-orbit Validation mission

- ASI issued the call for interest «Attività di Ricerca e Sviluppo di un dimostratore di bordo di Quantum Cyber Security, comprensivo della fase di In-Orbit Validation (IOV)»
- Main activities:
  - Study, definition and implementation of a flight payload for QKD;
  - Model qualification and interfaces definition;
  - Identification of satellite platform in LEO orbit with target lifetime of 2 years
  - Derisking activities related to satellite platform, optical payload, key performances;
  - QKD payload engineering
  - Satellite platform procurement
  - Graund segment
  - In-orbit operations for 2 years (In-orbit Validation phase)

Opportunities: Thematic calls

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1. Space systems new concepts studies

2. Quantum systems and technologies studies

3. Concurrent Engineering Facility exploitation


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