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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

NQSTI

The National Quantum Science and Technology Institute

https://nqsti.it/

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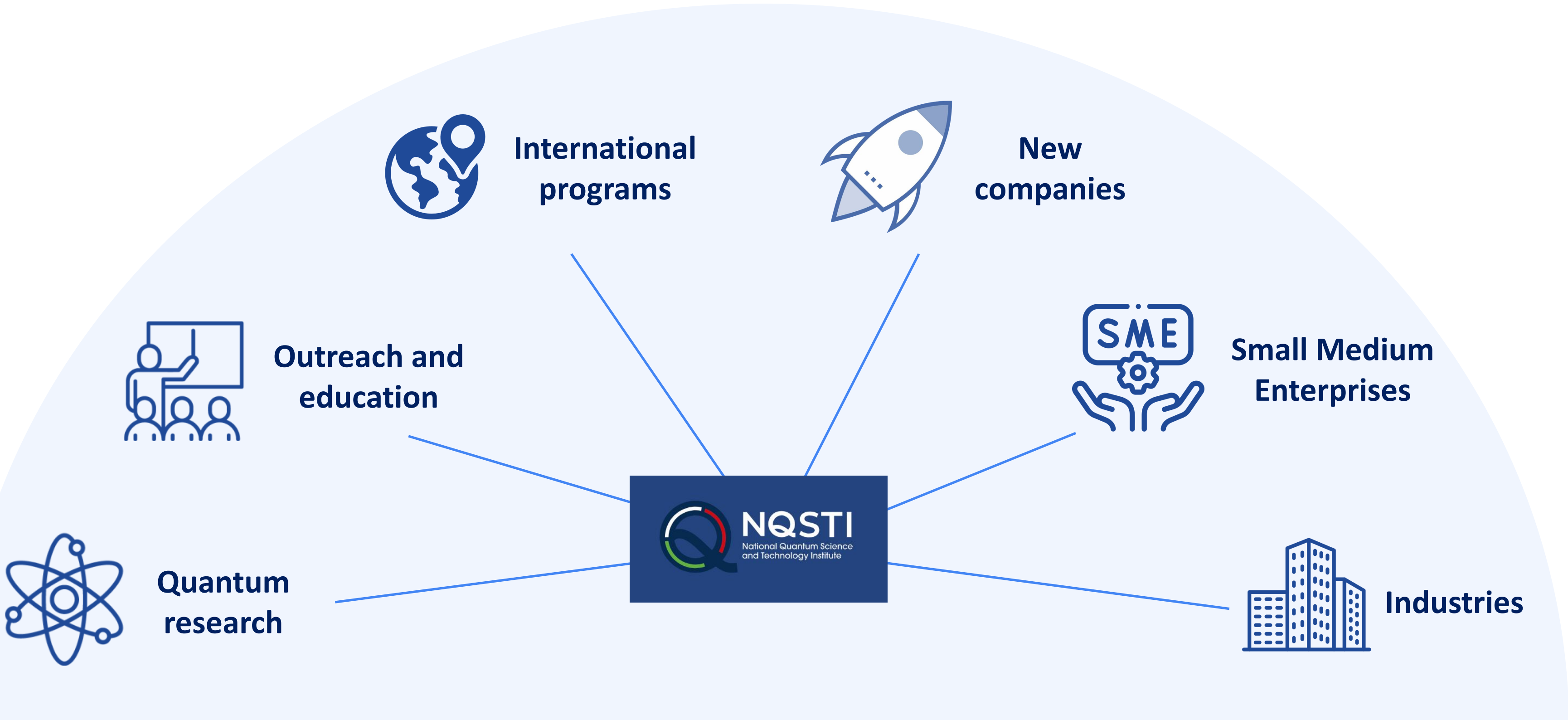

Research TRLs
1-4

20 Institutions

Researchers
322

New RTD-A
94+10

MUR funding
116 M€

Open calls
23 M€

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NQSTI
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Italian National Research Council

UNICAM
Università di Camerino
1336

ISTITUTO ITALIANO DI TECNOLOGIA

UNIVERSITÀ DEGLI STUDI DI TRIESTE

SISSA

Università di Catania

SCUOLA NORMALE SUPERIORE

SAPIENZA
UNIVERSITÀ DI ROMA

FONDAZIONE BRUNO KESSLER

Sant'Anna
Scuola Universitaria Superiore Pisa

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

UNIVERSITÀ DI PARMA

UNIVERSITÀ DI PAVIA

ICTP
The Abdus Salam International Centre for Theoretical Physics

LEONARDO

ThalesAlenia
a Thales / Leonardo company
Space

NQSTI@BiQuTe

NQSTI geographical distribution (today)

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hub

spoke

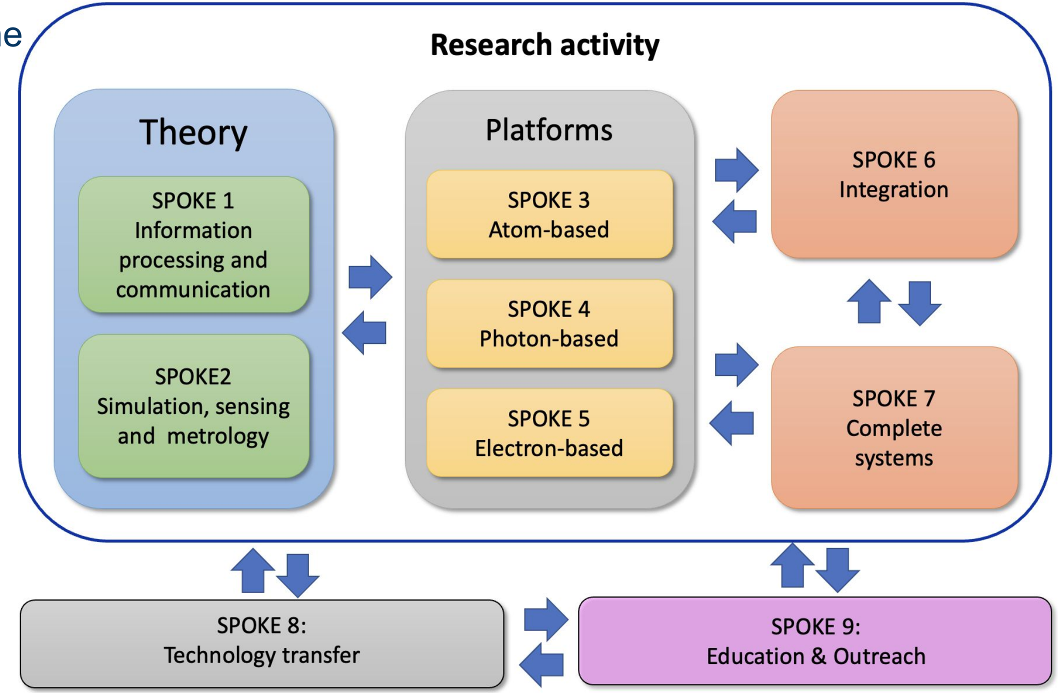
spoke affiliate

Hub

- Limited reliability consortium based in Rome at the CNR
- all participants in the project and winners of the cascade calls are invited to be members

Spoke

1. Università di Pavia
2. Università di Camerino
3. Consiglio Nazionale delle Ricerche
4. Università di Roma Sapienza
5. Scuola Normale Superiore
6. Università di Milano Bicocca
7. Fondazione Bruno Kessler
8. Consiglio Nazionale delle Ricerche
9. Università di Catania



NQSTI project structure

QST Theoretical Foundations and Novel Paradigms

Spoke 1 (M. Liscidini) and 2 (D. Vitali)

Technology Platforms for QST

Spoke 3 (F. Cataliotti), 4 (F. Sciarrino), and 5 (F. Beltram)

Integration, System Architectures

Spoke 6 (G. Gorini) and 7 (A. Simoni)

Technology Transfer; Education and Outreach

Spoke 8 (G.R. Greco) and 9 (E. Paladino)

CEO

Isabella D'Apolito

(New board of directors to be appointed soon)

Industrial Advisory Board

Representatives from participating companies

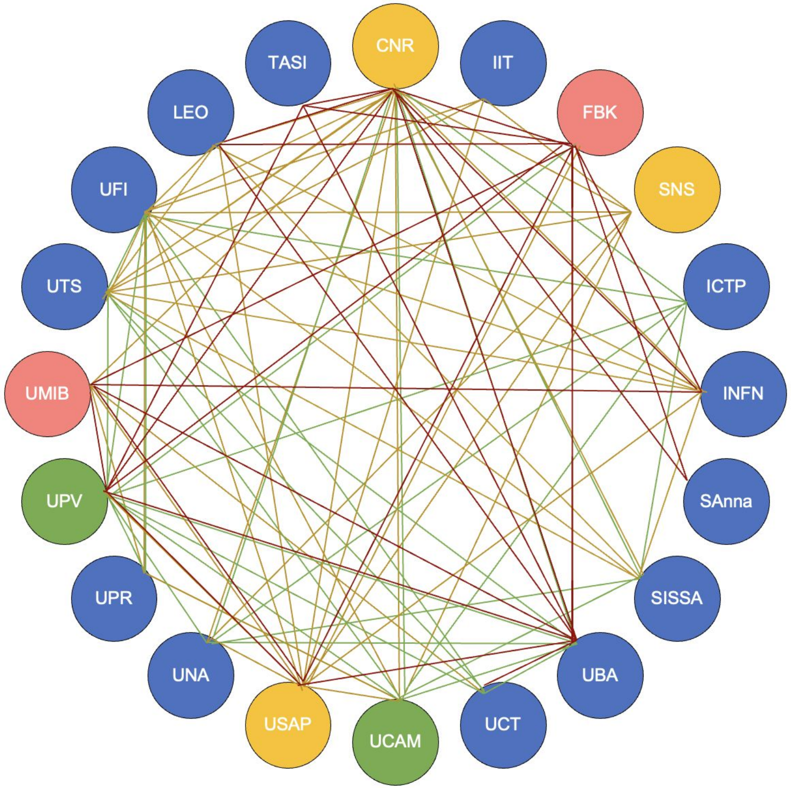
MIMIT

Confindustria

HPC ICSC

Scientific Advisory Board

Collaborations created by NQSTI activities



Spoke 1 - Objectives

Regarding **information processing and communication** with quantum systems, the spoke aims at:

1. Consolidating the foundations of processes and protocols at the basis of quantum information (QI) and quantum technologies (QT).
2. A detailed exploration of quantum phenomena, concepts, and systems.
3. Identifying new potentials of development for QI and QT.
4. Specifying concepts and protocols for the available technological platforms.

Up to now **more than 80 papers** (arXiv preprints or published)

Spoke 1 - Foundations and architectures for quantum information processing and communication

A1.1	**Quantum nonlinear dynamics**
A1.2	**Interfacing different quantum systems**
A1.3	**Complex quantum systems**
A1.4	**Open quantum systems**
A1.5	**Advanced quantum algorithms and protocols**
A1.6	**Artificial Intelligence against quantum noise**
A1.7	**New approaches for storage/processing quantum information**
A1.8	**Quantum resources**

Spoke 2 - Objectives

Spoke 2 investigates driven-dissipative and **complex many-body systems**, assessing their ability to provide benefit for **quantum information processing, quantum simulation, and quantum sensing.**

Special attention is paid to **novel materials, metamaterials, and novel phases of matter**. We investigate the energetic aspects of quantum technologies, in order to establish their **energetic footprint**, and make them sustainable.

We study **decoherence sources**, and design **quantum control techniques to harness their deleterious effects**. We investigate **quantum error correction**, also going beyond the qubit paradigm, open-loop and closed-loop schemes, applying them also to enhanced quantum sensing and thermodynamics.

Up to now **more than 80 papers** (arXiv preprints or published)

Spoke 2 - Foundations and architectures for quantum sensing, metrology, novel materials, and sustainability

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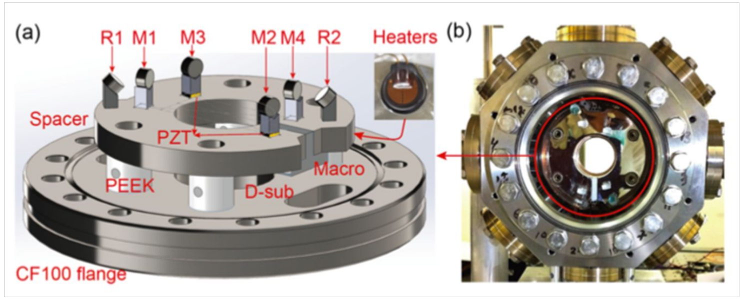
A2.1	Innovative quantum systems and metamaterials
A2.2	Emergence of collective properties in quantum matter and devices
A2.3	Complex synthetic quantum networks for transport of information and sensing
A2.4	Quantum thermodynamics and quantum devices for the production, storage, and transfer of energy
A2.5	Assessment and strategies for reducing the energy consumption in quantum information processing
A2.6	Enhanced sensing and metrology and other quantum technologies including those based on many-body effects, quantum phase transitions, chirality and nonreciprocity
A2.7	Quantum control for improving quantum technologies
A2.8	Platform-specific modeling of decoherence for the simulation of quantum architectures in realistic scenarios
A2.9	Encoding beyond the qubit for quantum information processing

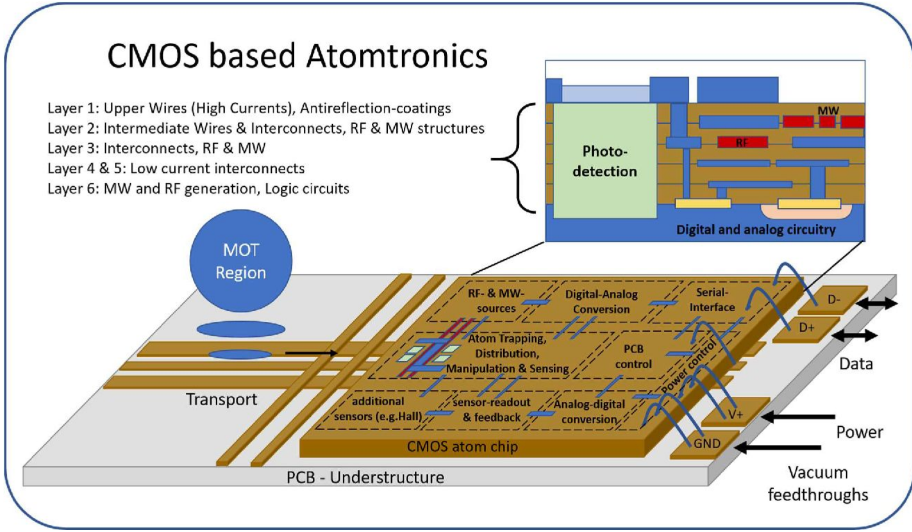
Spoke 3- Atomic, molecular platform for QTs

Spoke 3 will exploit **neutral atoms, molecules and ions** to **quantum engineer systems from first principles**, with thorough control of interactions, particle statistics, system dimensionality, and even topological or transport properties **all the way to the single particle level**.

Generation of entangled (squeezed) states in a cavity (Salvi, Tino)



- Development of **advanced homodyne detection** methods through the optical cavity.
- Exploration of **noise and decoherence** sources and their mitigation.
- Advanced **coherent control** of atomic internal and external dynamics.
- **Atom interferometry on a single-photon transition** and upgrade of the existing apparatus towards an **atomic fountain with significant metrological gain beyond the Standard Quantum Limit.**



Spoke 3 - Atomic, molecular platform for quantum technologies

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A3.1	Development of novel atomic/molecular systems to extend coherence time
A3.2	Development of novel hybrid atomic systems
A3.3	Novel atom interferometry beyond the classical regime
A3.4	Optimized approaches for interfacing quantum optical fields and macroscopic atomic ensembles
A3.5	Enhancing State Detection
A3.6	Techniques for coherent quantum state control and entanglement engineering

Spoke 4 - Photonic platform for quantum technologies

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SOURCES	A4.1	Semiconductor based sources of single/two photon quantum states
	A4.2	Development of scalable single photon sources based on molecular systems or 2D materials
	A4.3	Development of integrated non-classical light sources with non-linear material
	A4.4	Heterostructured quantum source
MANIPULATION	A4.5	Manipulation of photonics quantum states via integrated photonics
	A4.6	Innovative free-space methodologies for quantum photonics manipulation
	A4.7	Manipulation of photonics quantum states via nonlinear optical systems
DETECTORS	A4.8	Semiconductor based sources of single/two photon quantum states
INTERFACES	A4.9	Development of interfaces between photons and other quantum systems

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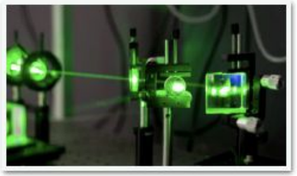
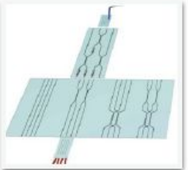
Spoke 4 aims to develop all **technologies** needed **to generate** in either single photon or multi-photon configurations, **manipulate**, and **detect quantum states of light** across a broad range of frequencies (from the visible to the far-infrared).

Targered Platforms



Bulk optics

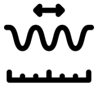


Integrated photonics

Aiming to…

Multiphoton

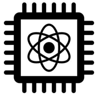
Single-photon



Broad wavelength

Nanofabrication

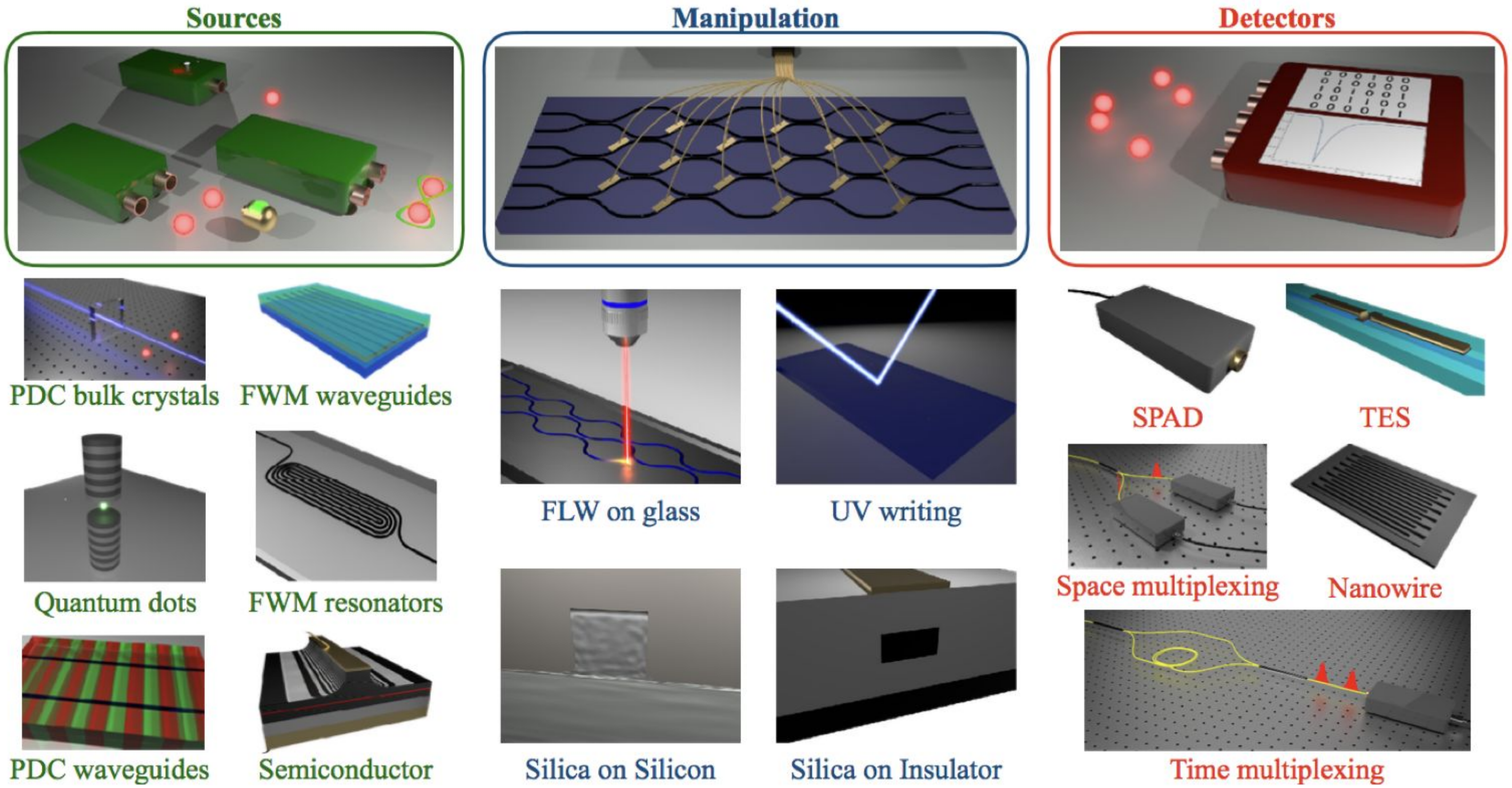
Single photon devices



Passive and active Integrated optical components

Passive and active integrated optical components for manipulating/modulating/switching the generated quantum states of light or for probing/imaging quantum properties at the micro- and nanoscale will be also devised to complement this groundbreaking program of technological development.

Photonics platform



Spoke 5 - Electron-based for quantum technologies

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A5.1	Tunable emerging electronic configurations in hybrid/topological systems
A5.2	Novel nanomaterials for hybrid architectures
A5.3	Phase-sensitive architectures
A5.4	Quantum energy management
A5.5	Tailored defects and molecules for QT
A5.6	Quantum interfacing, control and readout
A5.7	Innovative characterization techniques to probe quantum nature and performance

ELECTRON-BASED QS&T

- Emphasis on hybrid material systems
- Hybrid physical systems (QHE/S, quasiparticle hybridization)
- New architectures and functional modules
- Pursue compatibility with existing (opto)electronics technology

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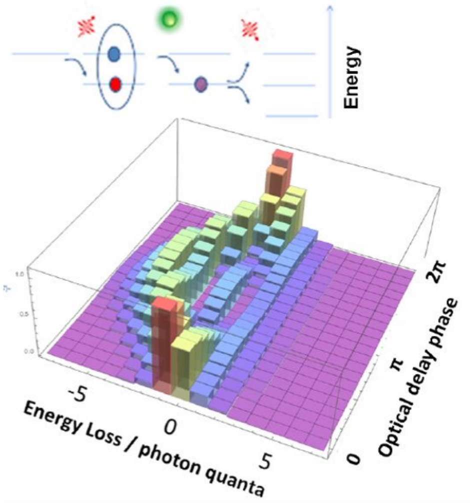
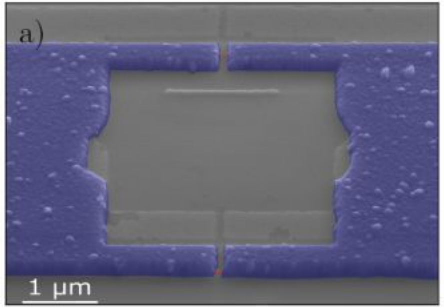
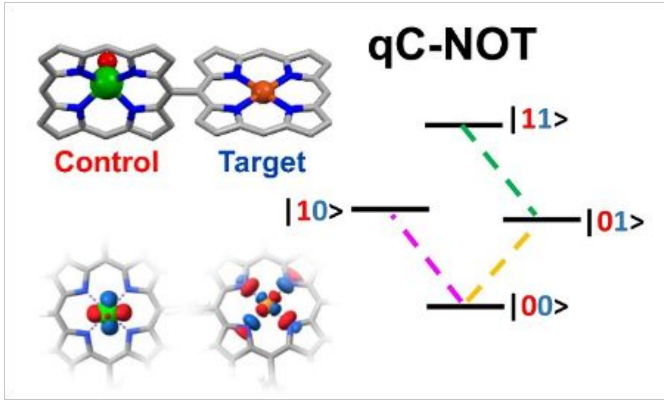


Calculations of an electron-photon entangled state in **Quantum-TEM** based on the density matrix representation. The electron amplitude probability is shown in the energy-phase parameter space after two electron-photon interaction points with a two-level quantum system in a metastable superposition state



Micrograph of an **Al SQUID embedding 3D Al nanobridges. These SQUIDs implement a supercurrent diode**, a nonreciprocal device possessing different critical currents in the two directions.



Sketch of the structure of Cu-VO bisporphyrinato complex with resulting energy differences between states **involving control (red) and target qubit (blue and green)** electronic spin transitions: In the bottom left panel the surfaces of magnetic orbitals on the two centers are reported.

Spoke 6 - Integration

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6.1 Integration of atomic circuits

- Implementation of atomic circuits to resemble electron-based networks of different classes of conductors, semiconductors, superconductors or magnets

6.2 Integration of photonic devices

- Implementation of chip-size packaged devices with integrated photon sources and detectors for quantum simulation and quantum key distribution

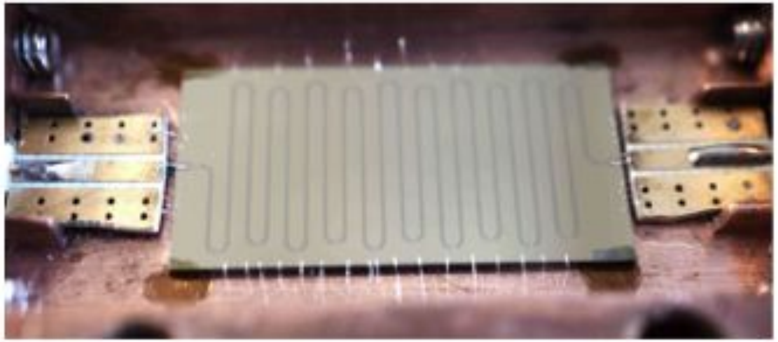
6.3 Integration of electronic quantum devices

- Implementation of superconducting quantum gates and quantum networks integrating devices with read-out and control systems for sensing and simulation

6.4 Integration of inter-platform quantum devices

- Demonstration of light-atom interfaces at telecom wavelengths with integrated entangled photon sources
- Multiplexed arrays of superconducting SPD with number resolution for metrology and simulators
- 2D/3D hybrid quantum memories (superconducting qubits coupled to spin ensembles or EM cavities)
- Generation of two-mode squeezed vacuum states for microwave quantum illumination

Travelling Wave Parametric Amplifiers



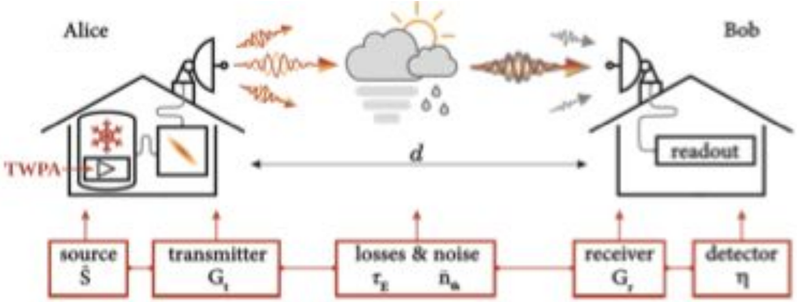
Prototype designed by Unimib in collaboration with INFN and produced at FBK within NQSTI – Spoke 6

- TWPAs allow for phase-insensitive amplification with high gain values (~20 dB) and broad bandwidths (~3 GHz) and noise at the quantum limits at cryogenic temperatures;
- Typically used for multiplexing readout of qubit, detectors, and cavities;
- Suitable for any application that needs high gain and low noise in the microwave regime;

Space Applications

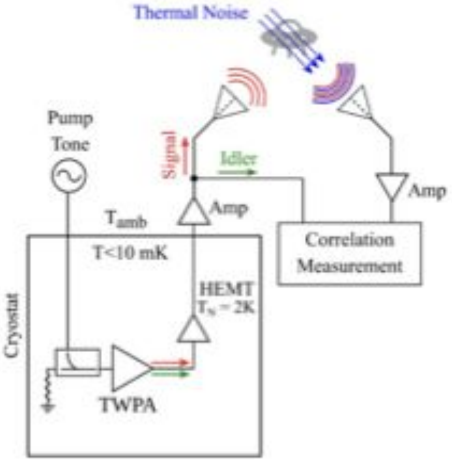
- TWPA showed impressive performance operating at 4 K;
- KI-TWPA can operate at various temperature stages (from 10 mK to 4 K) thus enabling applications even in space environments;
- KI-TWPA can replace noisy solid-state amplifiers in communication satellites, space observatories, and space probes

Quantum Communication & Quantum Radar



Quantum communication

- Quantum resources are known to be susceptible to noise and losses;
- In order to finalize the prepare-and-measure the key distribution protocol the used linear amplifiers requires a remarkable quantum efficiency;
- TWPAs are potentially able to approach the quantum-limited regime in a broad bandwidth providing a high quantum efficiency;



Quantum Radar

- Quantum entanglement can enhance the task of object detection in the presence of a strong background noise;
- This demands the realization of a reliable source of continuous-variable entangled state in the microwave range
- TWPAs are optimal candidate as entangled radiation sources for quantum-enhanced detection of objects in the microwave regime;

Spoke 7 - Complete Quantum Systems

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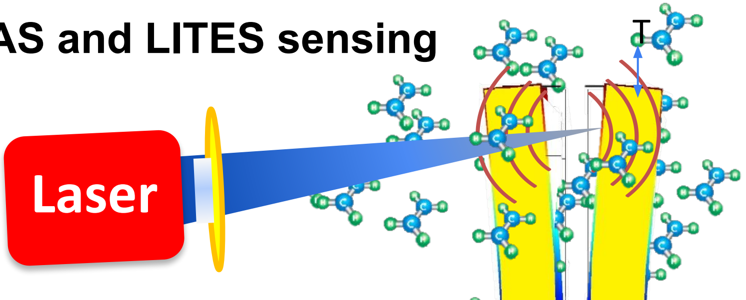
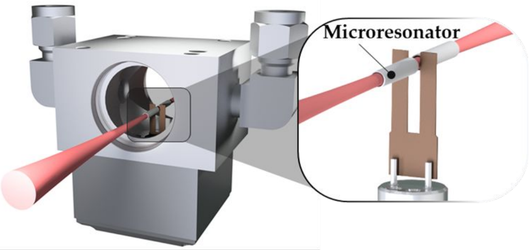
A7.1	Imaging Systems
A7.2	Point Sensing Systems
A7.3	Communication & IoT Systems
A7.4	Simulation Systems

A7.2 - Point Sensing Systems

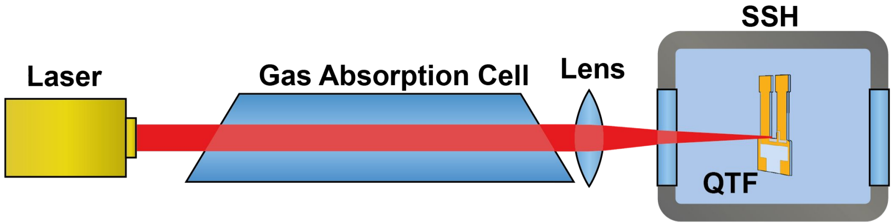
Development of spectroscopy-based sensing systems for biomedical and environmental inspection. (UniBA, FBK)

QEPAS and LITES sensing





- <u>Small sensing module</u> and sample volume (a few cm^3)
- <u>Wavelength independent</u>
- <u>Optical detector is not required</u>
- <u>Wide dynamic range</u>
- Immune to environmental acoustic noise
- Acoustic micro-resonator(s) to enhance the QEPAS signal



Enable the realization of highly sensitive trace gas sensors, portable for in situ & real time detection

Appl. Phy. Rev. 5, 011106 (2018)
Appl. Phy. Rev. 8, 041409 (2021)
Anal. Chim. Acta 1202, 338894 (2021)

(3 patents)

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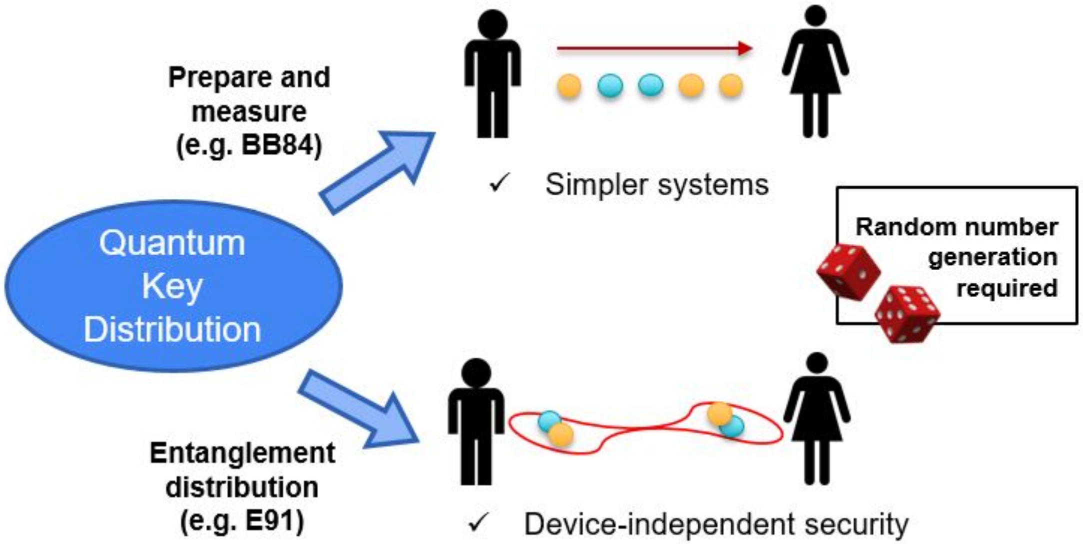
A7.3.1: Development of QKD links with integrated photonics

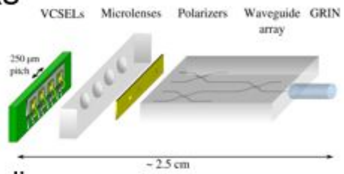


Fiber optics links

Time bin encoding

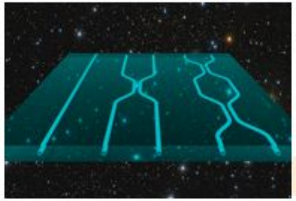
Polarization insensitive devices

Free-space links



Polarization encoding

IEEE JSTQE 21, 6600607 (2015)



Integrated components qualified for satellite use

Laser & Phot. Rev. 15, 2000167 (2021)

A7.4 - Simulation Systems

Development of an optical quantum simulator (FBK, U.PV, CNR, U.MIB, U.SAP)

Several options will be considered for the input/detection combination (non-gaussian inputs/single photon detection, squeezed input/#resolving detector)

Several degrees of freedom will be considered for the unitary transformation.

Solution to mathematical problems (search on graphs), simulation of molecular spectra…

Spoke 8 - Technology Transfer

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Spoke 8
Technology Transfer

QuIC — QUANTUM FLAGSHIP

A8.2	NQSTI-industry joint laboratories and prototyping ***Goal: to favor the exploitation of our laboratories for the strengthening of the innovation capability, process characterization, and product certification***
A8.3	Open calls for industrial collaborations ***Goal:*** **to favor the penetration of QST know-how into the existing R&D of large companies and SMEs through project-oriented open calls based on a co-funding scheme**
A8.4	QST Incubator ***Goal:*** **to support for the creation of new spin-offs and start-ups with and by project participants. NQSTI will provide mentoring, legal and administrative support**

WG1	Market trends and use Cases ***Goal:*** **to actively identificate market trends and use cases; to promote QT to companies**
WG2	Intellectual Property and Trade ***Goal:*** **to boost licensing activities and to create Italian Intellectual Property Portfolio**
WG3	Standards ***Goal:*** **to make NQSTI a key player in the identification of international standards**
WG4	Strategic Industry Roadmap & Technology Intelligence ***Goal:*** **to monitor the status and progress of QT in Europe and worldwide**

NQSTI - SPOKE 9

Education and Outreach

EDUCATION

TRAINING

DISSEMINATION

Development of **quantum-technology-oriented education and training** from high-school to higher education and training at professional level (**Education**).

Raise **awareness of Quantum Science and Technologies** with **companies** and **professional organizations** and, more generally, with **civil society**. (**Outreach**).

The planned actions are in line with and will contribute to the European *QTEdu* experience. Wide access to the QST field, taking into account gender equality and diversity, will be guaranteed.

Coaching of the QT-workforce

- Identification of **standards for implementing educational strategies in QT** enabling the italian community to efficiently develop, test and apply materials for teaching QT in **universities and high schools**, for **industry workforce**, and to the **general public**.

- **Minors in QT** for **non physicists** providing the core competence in quantum technology (for students holding at least a bachelor degree)

- **I and II level one year professional Masters** in order to form the reference figures of the Competence Framework for QT, in cooperation with industries. (**open calls**, *the bulk of funds will be devoted to initiatives in the southern Italian regions.*)

- Within existing Masters, establishment of **student's specialization internships** in dedicated academic/industrial laboratories.

- **Seminars of QT** for **undergraduates, PhD students** and **young researchers** with a scientific background.
- **National schools for PhD students and young researchers** on the QST-related activities (spokes 1 – 7) with the participation of international speakers also from industry.
- Organization of **summer schools** and **specific courses** on QT for **secondary school students.**

Training courses for interested industry employees and for high-school teachers.

- **Short (2/3 days) course** to get a basic "general QT awareness" certificate, repeated twice a year.
- **Brief (3 or 4 weeks)** course to get a "Quantum Technology Strategist" certificate, once a year.
- Establishment of **training courses for high school teachers** on QT topics in line with the MUR "piano nazionale di formazione per il personale della scuola".

DISSEMINATION

Development at **the Italian level** of **standard communication and outreach channels** as well as **specialized** and **broad audience publications.**

- Participation and support to **European outreach initiatives on QTs**.
  - **World quantum day → Italian Quantum Weeks**
  - **European Research Night**
- Organization of **outreach events for the civil society,** for instance "quantum art" and "quantum music" interactive exhibitions or plays and short movies on QT.

NQSTI website https://nqsti.it/

Prospects for a national quantum initiative

NQSTI has been designed for favouring successful **Italian participation to European** and international **programs**.

First example: Italian National contribution (1 M€) **to the 2023 QUANTERA Call**

(but see more in Francesco Cataliotti's talk)

QUANTERA

Countries participating in the Call:

Austria, Belgium, Bulgaria, Canada, Croatia, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Israel, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom.

Prospects for a national quantum initiative

Strong synergy with the **HPC Center ICSC** (see Simone Montangero's talk)

and with the just launched (September 2023)

SISTEQ (**Società Italiana di Scienze e Tecnologie Quantistiche**), which is is just to start its activities and it is a complementary action involving all "quantum" people, from enthusiasts to different levels of stakeholders.