Quantum Computing e Quantum Technologies nel PNRR

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Outline

- Introduction: QC/QT and INFN, general considerations
- QC/QT within the PNRR – 1: Quantum Computing in ICSC
  - Structure of Spoke 10 (Quantum Computing)
  - INFN activities in Spoke 10
- QC/QT within the PNRR – 2: NQSTI (National Quantum Science and Technology Institute)
  - Structure, organizations and budget
  - INFN activities
- Conclusions

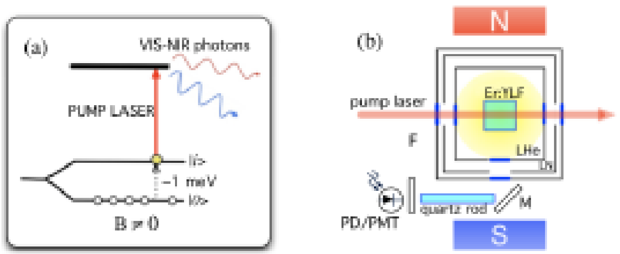
Quantum and INFN: WHAT and HOW?

- QC/QT have not been core business of INFN **until relatively recently**: things have changed in the last few years.
- The long-term goal (WHAT?):
  - Adopt all technologies that can allow better research in fundamental physics (e.g., detect very low energy quantum states).
  - Use Quantum computers/simulators, when available (reliable), to support our research (from Lattice QCD, to event classification in LHC, to Life Science applications).
  - Contribute to QC/QT with HEP-derived knowledge, know-how, technology (theory, SC resonant cavities , mK cryogenics,…).
- HOW?
  - Team with other players (in Italy and elsewhere), sharing scientific interests and/or technology options.
  - Develop a sound know-how and an expert workforce.

WHAT? Example 1: QT for Dark Matter search

- Learn to detect single quantum modes at the meV energy scale:
  - Pump it up in energy to the visible (or, at least, the IR) energy scale
  - The QC view: translate microwave q-bits into optical q-bits
  - The Particle Physics view: search for axions

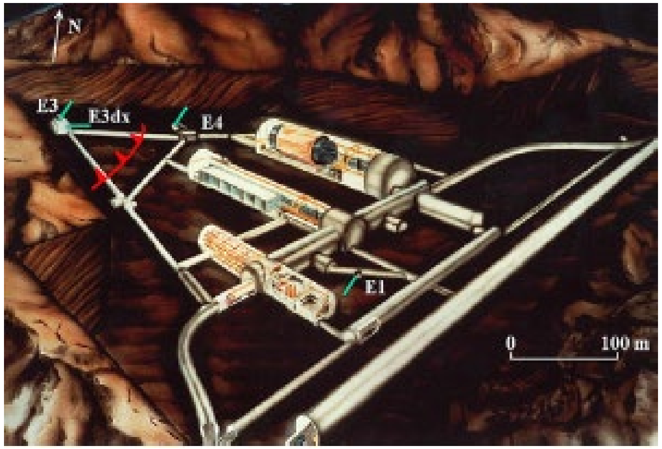
AXION DETECTION WITH ATOMIC TRANSITIONS

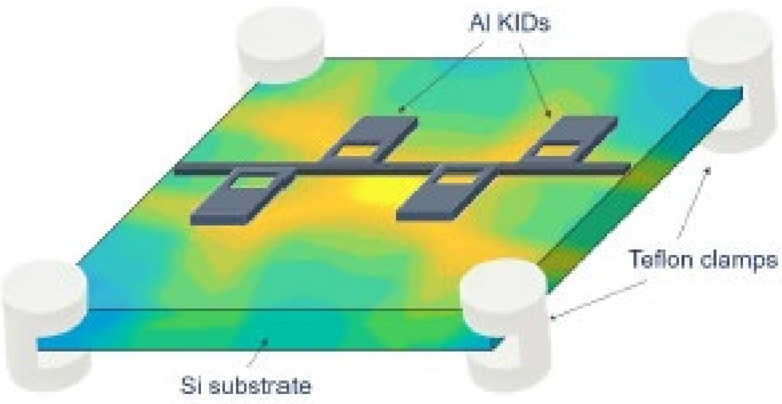


- axion-induced transitions take place between Zeeman-split ground state levels in rare-earth doped materials
- transitions involve electrons in the 4*f* shell (as if they were free atoms…)
- a tunable laser pumps the excited atoms to a fluorescent level
- crystal immersed in LHe and superfluid He

WHAT? Example 2: HEP technology helping QC/QT

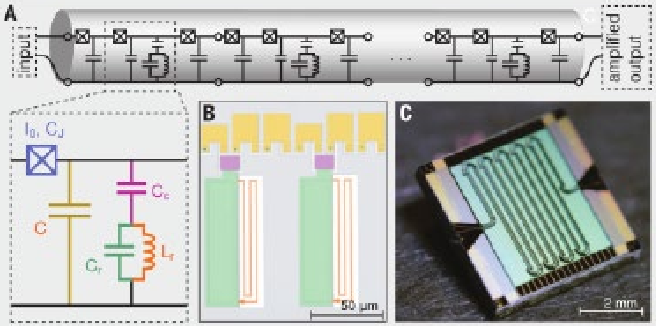
- Learn to measure and mitigate disturbances to QC devices from "environmental factors":
    - Result from (superconducting) detector developments for astroparticle physics
    - Used to measure fundamental properties of superconducting devices and of qbits
    - Aiming at making LNGS an established center for the characterization of Quantum devices/systems





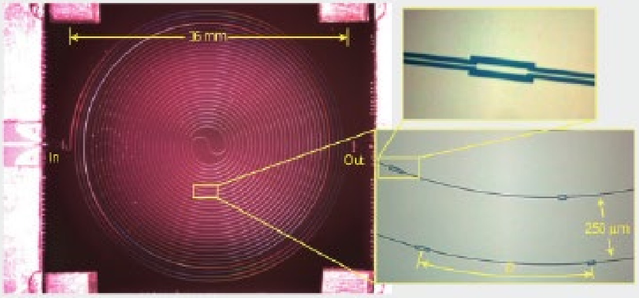
WHAT? Example 3: Mastering key-enabling technologies

Traveling Wave Josephson Parametric Amplifiers



- TWJPA implemented as a nonlinear lumped-element transmission line;
- One unit cell consists of a Josephson junction and a capacitive shunt to ground;
- Already demonstrated quantum-limited noise read out;
- High bandwidth: over a 4 GHz centred at 5 GHz;
- Limited gain: < 20 dB
- Small dynamic range: < -90 dBm

Dispersion-engineered Traveling Wave Kinetic Inductance

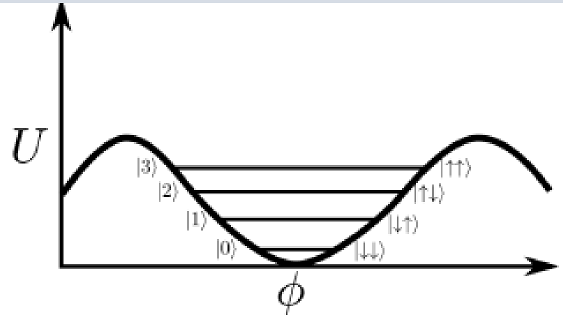


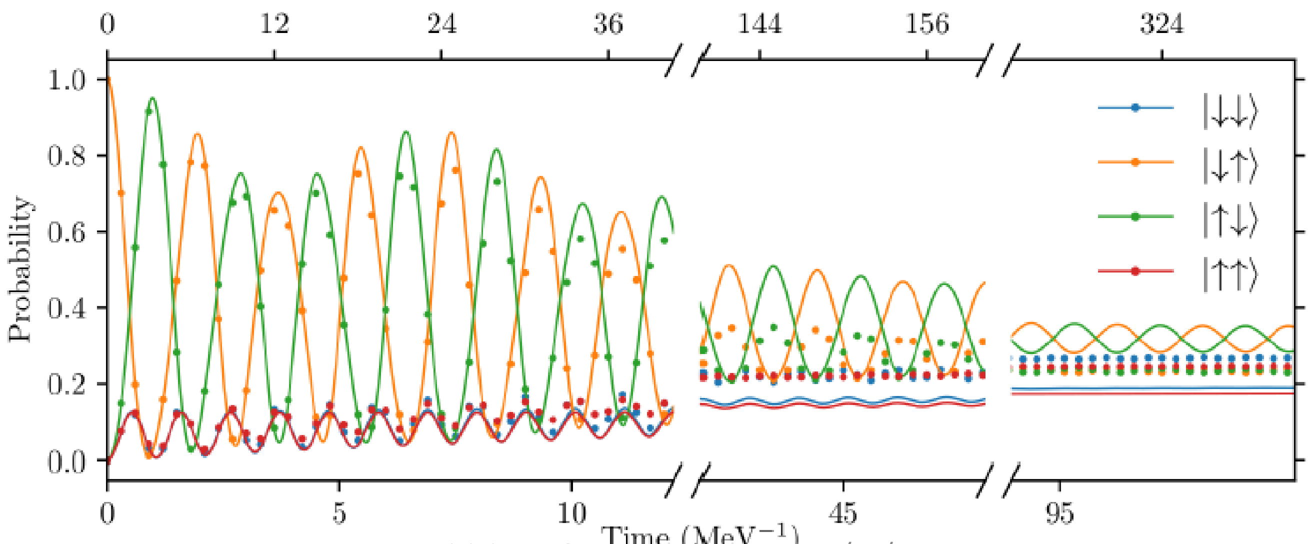
- DTWKI exploits the Nonlinear kinetic inductance of TiN and NbTiN superconducting film;
- Phase matching by Coplanar Waveguide (CPW) or lumped-element artificial transmission line;
- Noise near to quantum-limited
- High bandwidth: over a 4 GHz centred at 5 GHz;
- Limited gain: < 20 dB, and gain profile with large ripple
- High dynamic range: from -50 to -45 dBm

WHAT? Example 4: Quantum simulation

Transmons for Nuclear Physics

Use a (4-level) transmon to simulate the spin dependent nucleon-nucleon potential (E.T. Holland, F. Pederiva et al., Phys. Rev. A 101, 062307, June 2020)





Example 5: the DOE-SQMS Center (Superconducting Materials and Science)

- Financed by the U.S. DOE with 115 M$ (U.S. National Quantum Initiative), Director A. Grassellino, 5-year project
- INFN only European member of the Center (about 1.5 M$)

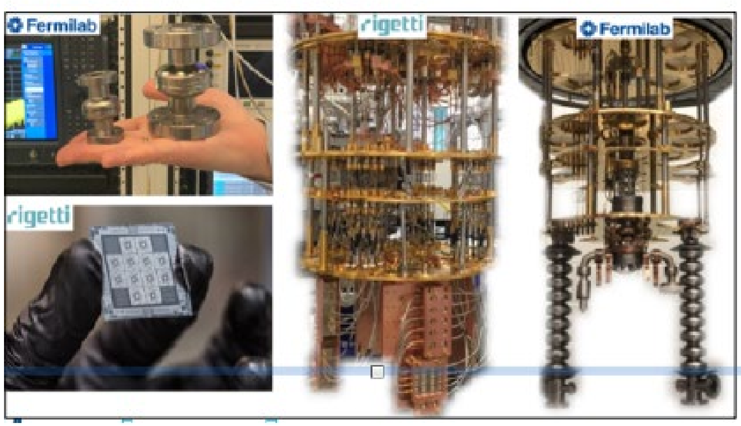
With the **Superconducting Quantum Materials and Systems** Center (SQMS), we bring the power of DOE laboratories, together with industry, academia and other federal entities, to "achieve transformational advances in the **major cross-cutting challenge** of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the final goal of enabling construction and deployment of superior quantum systems for **computing and sensing**."

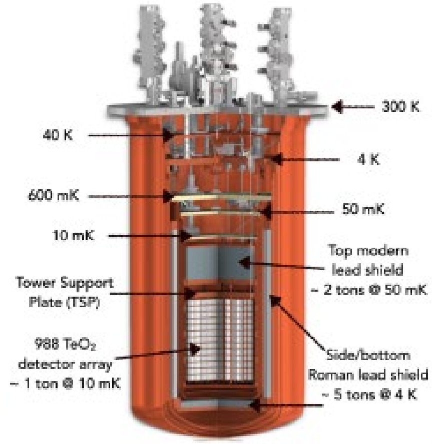
INFN within SQMS

- A Theory + Technology challenge, driven by HEP accelerator technology
- INFN units involved: LNF, LNGS, LNL, GGI, Padua, Florence, Ferrara, Rome, Trieste, Milan-Bicocca

ONE nine cell SRF cavity + **ONE** transmon =

SQMS 100+ qubits processor





QC/QT and PNRR

- Spoke dedicated to Quantum Computing within the National Centre for High Performance Computing (PNRR funding)
  - INFN leader of WP1 (Software): Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications
  - INFN actively involved in WP3 (Firmware and hardware platforms): Development and support of the quantum computer hardware chain.
- INFN involved in the National Quantum Science and Technology Institute (NQSTI) (Extended Partnerships, PNRR funding), recently admitted to Phase 2
  - *Focus on low-TRL R&D in the field of QST, for innovative applications in sensing, safe communication, processing of quantum information; development of concepts, new materials and devices (photonic, solid state and cold).*

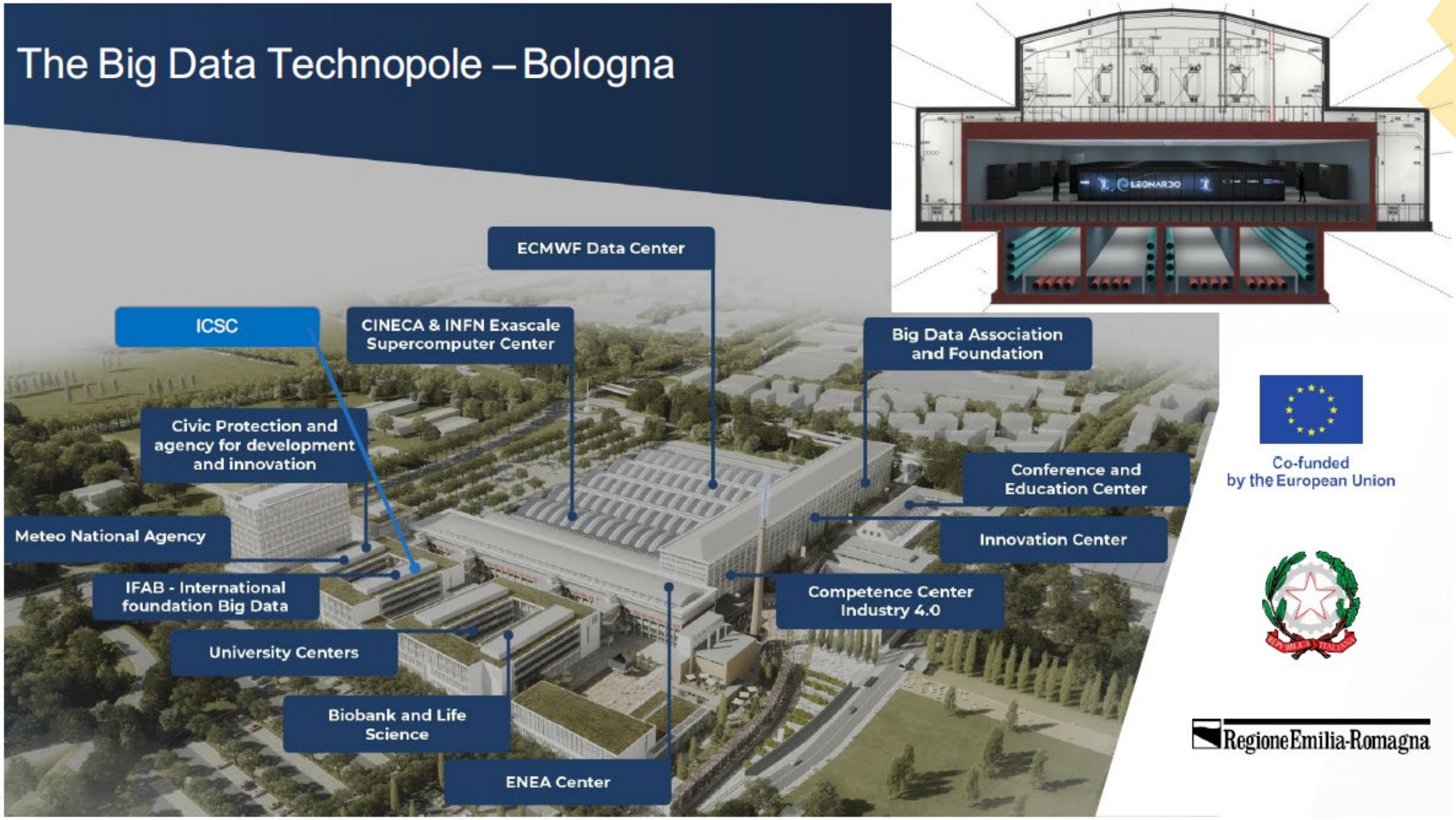
Quantum Computing within ICSC

Quantum Computing within ICSC

- ICSC aims and objectives
  - Create the **national digital infrastructure** for research and innovation, starting from the existing HPC, HTC and Big Data infrastructures ...
  - ... evolving towards a cloud datalake model accessible by the scientific and industrial communities through flexible and uniform cloud web interfaces, relying on a high-level support team …
  - …form a globally attractive ecosystem based on strategic public-private partnerships to fully exploit top level digital infrastructure for scientific and technical computing and promote the development of new computing technologies
  - ICSC Founding members: a public private partnership

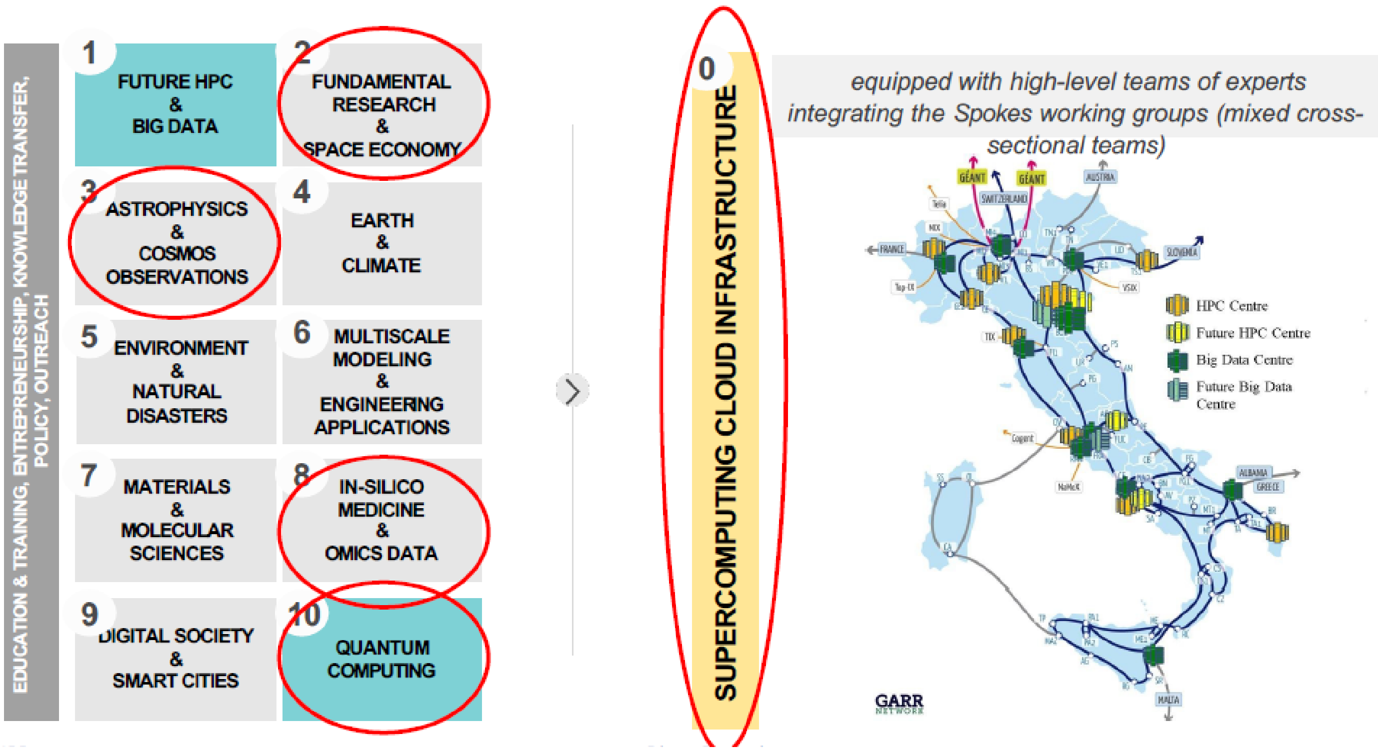
25	12	14
Universities	Research Institutions	Strategic private partners

Quantum Computing within ICSC

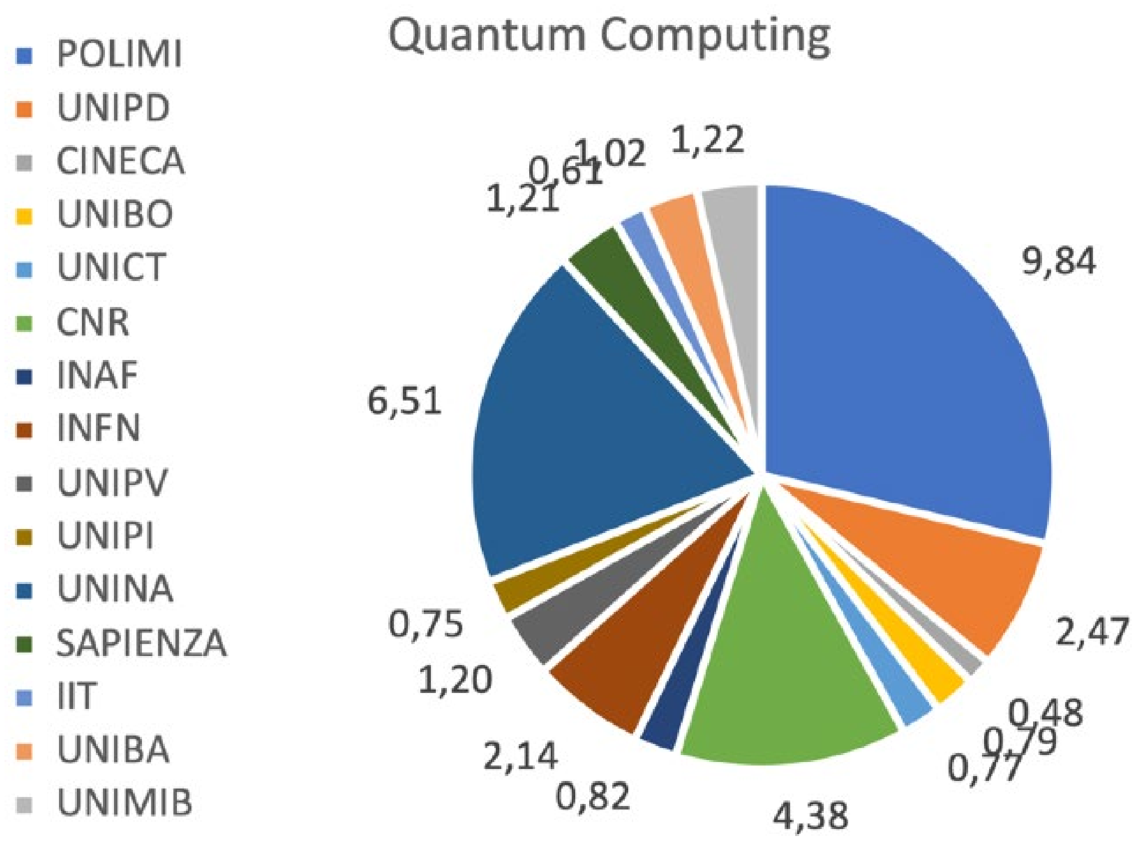


Quantum Computing within ICSC

- The ICSC will include *ten thematic spokes* and *one Infrastructure spoke*



Quantum Computing within ICSC



Spoke 10 overall budget: ~ 34 M€
INFN budget: ~ 2.14 M€

Quantum Computing (Spoke 10) within the National Centre for High Performance Computing

Quantum Computing

WP1. Software (Leader: INFN)	WP2. Mapping, compilation,and QC emulation (Leader: CINECA)	WP3. Firmware and Hardware platforms (Leaders: CNR, UniCT)
Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications.	Development of software for compilation, benchmarking, verification emulation of quantum computers and algorithms.	Development of low-level software for the physical operation of quantum computers. Development of the quantum computer hardware chain in its four most promising forms: ions, atoms, photons and superconductors.
T1.1 New Algorithms T1.2 Applications and use cases	T2.1 Mapping and compilation T2.2 Emulation	T3.1 Photonics T3.2 SC circuits T3.3 Atoms T3.4 Ions

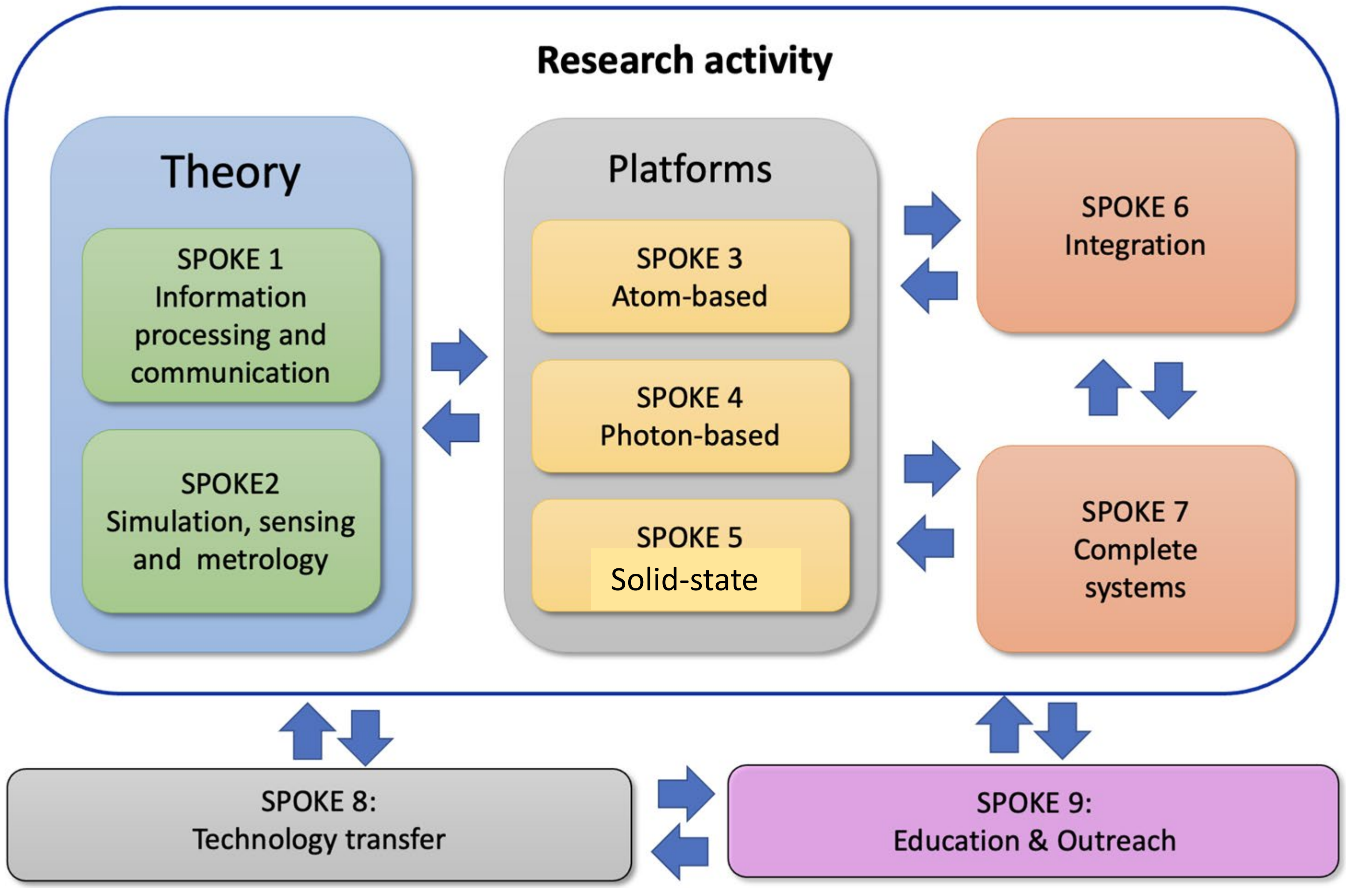
Partenariato Esteso sulle Scienze e Tecnologie Quantistiche (PE4)

- Focus "*sulla ricerca a basso TRL nel campo delle scienze, delle tecnologie quantistiche per applicazioni radicalmente innovative nel sensing, nella comunicazione sicura e nell'elaborazione della informazione quantistica e nella simulazione. A questi saranno affiancati i necessari sviluppi di concetti, materiali innovativi (anche allo scopo di ridurre l'impatto ambientale) e dispositivi di frontiera, da quelli fotonici a quelli a stato solido*"
- Due proposte presentate al MUR per il PE4: selezionata quella denominata National Quantum Science and Technology Institute (NQSTI), comprendente (come Universita'/Enti vigilati MUR):
  - Universita' di Camerino (Presentatore del Progetto)
  - Consiglio Nazionale delle Ricerche (CNR)
  - Istituto Nazionale di Fisica Nucleare (INFN)
  - Universita' di Bari
  - Universita' di Catania
  - Universita' di Firenze
  - Universita' di Milano Bicocca
  - Universita' di Napoli
  - Universita' di Parma
  - Universita' di Pavia
  - Universita' di Roma Sapienza
  - Universita' di Trieste
- Inoltre: 6 partners non vigilati MUR (FBK, ICTP, SISSA, IIT, S.S. Sant'Anna, SNS) e 2 partner industriali in cofinanziamento (THALES ALENIA SPACE, LEONARDO)

National Quantum Science and Technology Institute

- The mid-term objective (beyond the conclusion of the PNRR) is to create a consortium-like national Centre dedicate to QST.
- Struttura Hub-and-Spoke structure. 9 line di ricerca (in blu quelle nelle quali l'INFN e' direttamente coinvolto):
    1. Foundations and architectures for innovation in quantum information processing and communication.
    2. Foundations and architectures for quantum sensing, metrology, novel materials, and sustainability
    3. Atomic and molecular platforms for quantum technologies
    4. Photonic platform for quantum technologies
    5. Solid state platform for quantum technologies
    6. Integration of platforms
    7. Complete systems
    8. Technology Transfer
    9. Education & Outreach
- Budget complessivo ~ 115 M€
- Budget INFN ~ 11 M€

National Quantum Science and Technology Institute



National Quantum Science and Technology Institute

INFN activities

- Spoke 3 (Atomic and molecular platform)
  - Development of novel atomic/molecular systems to extend coherence time
  - Novel atom interferometry beyond the classical regime
  - Enhancing State Detection
- Spoke 4 (Photonic platform)
  - Development of semiconductor platforms for single photon sources
  - Development of single photon sources based on color centers in 2D and topological materials targeting integrated photonics
  - Design and development of integrated optical components to allow for single photon manipulation
  - Implementation of silicon photonics integrated circuits for quantum communication and quantum simulators
  - Full integration of silicon nitride photonics with silicon electronics
- Spoke 6 (Integration)
  - Integrated quantum photonic devices
  - Superconducting quantum gates
  - Coherent control and interfacing
  - Inter-platform functional elements

Conclusions

- The PNRR is a great opportunity to foster and consolidate the quantum-related research in areas of interest for INFN
- The INFN participation to ICSC (Spoke10) and NQSTI was inspired to criteria of complementarity
- It is necessary to have a long term-strategy well beyond the end of the PNRR
  - Focus and invest on the QC/QT activities: a) that are relevant for the INFN core mission, and b) in which we can contribute significantly
  - Create and expand the necessary national and international collaborations

Some of the current collaborations:

- Agreement with Amazon $\Rightarrow$ experimental access to real machines
- Agreement with CERN $\Rightarrow$ access to IBM-Q
- Agreement with CINECA for access to D-WAVE (quantum annealers), PasQal (quantum simulators) and AQT (general purpose QC, trapped ions)
- Agreement with TII (Abu-Dhabi) $\Rightarrow$ Support of Ph.D. training
- Supporting the WCRI Quantum Project at University of Padua (trapped-ions quantum machine)
- Agreement with the Q@TN Consortium to share facilities and know-how, and foster collaborations
- Strengthening existing collaborations with CNR, INRIM