MISSIONE 4
ISTRUZIONE
RICERCA

NATIONAL QUANTUM SCIENCE AND TECHNOLOGY INSTITUTE (NQSTI)

SCIENZE E TECNOLOGIE QUANTISTICHE

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Tematica 4 - SCIENZE E TECNOLOGIE QUANTISTICHE

Obiettivi *(Sez A dell'Annex 1)*

INTRODUCTION

This proposal targets the creation of the ***National Quantum Science and Technology Institute*** (NQSTI), a consortium that (i) will team up Italian entities carrying out competitive and innovative research in the field of quantum science and technology (QST), and (ii) will stimulate future industrial innovation in this field, providing a forum in which novel ideas and opportunities are transferred to companies. In order to ensure a long-term positive effect on the Italian economic growth and development, the whole innovation chain was considered: from the strengthening and coordination of the low-TRL research, to its translation into prototypes, favoring interfacing with industrial needs thanks to strong outreach and continued-education programs. Importantly, the creation and incubation of spin-offs and start-ups that can move research outcomes up in the TRL-ranking are included in the proposal scope with significant resources and a special focus onto the southern regions.

The starting point for the elaboration of this proposal was the creation of a group of 23 experts from Academia and Research institutions in the fall of 2021, following the publication of the government guidelines. These experts shared an analysis of the QST know-how available in the country, of the obstacles to its full valorization and translation into economic growth and sustainable development, and a vision of the main directions capable of bringing the ***radical innovation*** requested by the guidelines. This study was then shared with leading enterprises operating in Italy: new goals and needs completed this analysis. Our vision is that the ***extraordinary*** PNRR funding can of course be used to update technical facilities and strengthen the QST community in the next few years, but even ***more importantly*** it must be used to drive this community into an ***ordinary and sustainable*** condition of increased impact, visibility, and capacity to modernize and support the competitiveness of the Italian economy.

This Annex 1A is devoted to the **description of the scientific vision and of the technical means deployed**, but a few additional strategic elements of this proposal need to be spelled out in this introduction.

Highly-qualified scientists in the QST sector do exist in Italy, but the panorama is too fragmented. This is the reason why the creation of NQSTI is vital; the example of particle physics in the country is paradigmatic, and we intend to learn from that lesson to maximize impact and visibility in QST. The same pattern applies to industry: the backbone of Italian enterprises is small and medium in size. Within NQSTI we shall create a dedicated single-point provider for SMEs where they will be able to find educational programs for their existing staff, new QST-trained personnel, and opportunities to innovate products and processes by participating, through dedicated open calls, to collaborative projects with our project participants. The quantum revolution is pervasive and will soon impact all economic sectors: the country can not afford to lag behind because of this intrinsic structural weakness. This is the reason why we made *Technology Transfer* and *Outreach and Education* relevant and structural parts of the proposal. Large high-tech companies do exist in Italy, of course: we selected the ones that are already in tune with the QST revolution to be an integral part of this proposal as active partners in NQSTI. Others will join NQSTI during project life as a result of our program activities. An additional weakness we want to address with this proposal is the difficult ty to translate research ideas into new industrial enterprises in Italy. To this end, we designed within our *Technology Transfer* program a ***QST incubator*** that will provide resources and overall support for the creation of new companies by and with scientists active in QST, particularly in the south: this is a novel instrument that we strongly believe is much needed in the Italian system.

The format of the present call did not make it possible to include in the project activities all the teams that can contribute to our vision for NQSTI. We selected the project participants as the most qualified in the country by considering the balance in their specializations and their readiness to contribute to project goals.
Importantly, we earmarked significant funding to support a number of highly-focused open calls that we believe will allow us to gather all the available expertise and ensure the maximum efficacy of the project stimulating and synergizing Italian research in QST. Specific actions will be dedicated to attract young QST-qualified scientists and address gender-balance issues in our community: considering the salary rigidity of the positions that can be offered within the project frame, we plan to introduce specific incentives for relocation that will boost the **international dimension** of our community and favor the **participation of women**. Coherently with the PNRR objective, we shall reserve the bulk of allocated *Technology Transfe*r and *Outreach and Education* funds for entities operating in the south in order to boost their strength and competitiveness and foster the creation of new industrial enterprises.

PROJECT OVERVIEW

In order to illustrate our vision and show how we addressed the entire QST innovation chain, we shall begin by presenting the foundational investigations planned that we believe will provide new understanding and indicate new directions for QST research; we shall then move onto the presentation of the technologies that
we plan to exploit to translate these novel concepts in physical QST devices; we shall than present how these will become building blocks of functional quantum modules and complete innovative QST systems and architectures. Finally, we shall present the means we intend to deploy to favor the exploitation of our investigations for industrial innovation and for the creation of new enterprises, particularly in southern Italy.

1. QST Theoretical Foundations and Novel Paradigms

The development of QST requires sound and comprehensive theoretical research, which is pivotal to advancing the knowledge of quantum information science and physical systems as well as to designing new devices and implementing new quantum protocols for applications at the industrial level. The topics investigated in this project will cover novel foundations and architectures in quantum physics and information, with particular focus on **information processing**, **communication**, **sensing and metrology**, and **simulation**. These concepts and protocols will be specified and, where appropriate, tailored for the different available technological platforms. This research activity will adopt a general holistic approach that will develop along four directions, characterized by different levels of generality.
The ***first direction*** will focus on **fundamental concepts of quantum information theory** that transcend specific implementation platforms. This research activity will span from new approaches to encode and process information in a quantum system to the theories able to quantify the quantum resources, such as entanglement, that are necessary to reach quantum advantages in information processing. An important aspect will be the study of **open quantum systems** that play a major role in realistic implementations of **quantum protocols.** On the one hand, we shall focus on developing general theoretical frameworks able to understand and model **noise and decoherence** that can degrade the performance of quantum protocols. On the other hand, we shall devise new advanced quantum algorithms and protocols, including those based on quantum machine learning and artificial intelligence, to optimize the necessary resources for specific tasks.
The ***second direction*** will deal with the theory of quantum information processing and communication in **specific quantum systems**, such as those based on atoms, photons, and other excitations in solid-state platforms. On the one hand, we shall focus on **designing new quantum devices**, identifying for each specific platform the most effective phenomena and protocols for encoding and processing information.

Attention will be given to the modeling of systems dynamics in the presence of strong nonlinearities, which are at the basis of the generation and manipulation of entanglement. On the other hand, we shall develop theories and protocols for **distributing and storing quantum information**, including the study of the role played by complexity and topology in quantum networks. Within the context of quantum communication, we shall also advance in the modeling of phenomena and protocols at the basis of **interfacing different quantum systems**, with particular focus on efficient atom-photon and superconductor-photon interfaces.

Within our ***third direction***, **quantum complexity** in quantum matter and devices will be investigated, classified and quantified, paying attention to the **emergence of collective phenomena** and their exploitation for quantum information purposes. Strong focus will be on **innovative materials and metamaterials** (e.g., van der Waals and other multilayer heterostructures, topological, atomically-thin 2D materials, innovative hybrid configurations, time crystals) and their use for **quantum information processing and simulations**.

Emphasis will be given to the design and assessment of schemes for enhanced sensing and metrology in these contexts, based on quantum phase transitions, chiral, topological and nonreciprocal systems. Also the concept of complex synthetic quantum networks will be explored and exploited for the transport of information and sensing, designing general methods for performance assessment in terms of rate, fidelity, robustness and security. The local probing and control of complex quantum networks, and their use for distributed **entanglement-enhanced quantum sensing** will be exploited for the development of the future quantum internet.

The ***fourth research direction*** concerns the investigation of the energetic aspects of quantum technologies, in order to establish their **energetic and environmental footprint**, and design a viable path towards sustainability. We shall study the **quantum thermodynamics of devices for the production, storage, and transfer of energy**. More specifically, we shall analyze work extraction at the quantum level, design interconnected networks of energy processors, define how to estimate and measure the energy consumption in quantum networks for information processing, and study the quantum thermodynamics of quantum computation.

These foundational theoretical activities will impact all project research lines and will set the ground for the development of a supply chain that starts from these concepts and proof-of-principle demonstrations and arrives at industrial products. At the same time the results achieved will strengthen our key competences, significantly facilitating the ability to integrate QSTs in systems and services.

2. Technology Platforms for QST

Conceptual paradigms proposed in part one above will be translated into physical implementations by taking advantage of the most suitable quantum platforms available. The strategic and long-term vision of our project lead us to include groups that bring state-of-the-art expertise for the design and realization of quantum architectures based on atoms, photons, and electrons. The most suitable physical entity for the implementation of a given quantum configuration identified as valuable by our theoretical research will be chosen in light of the most effective technologies, but, whenever possible, different implementations will be realized and compared in terms of efficiency, suitability for technological transfer, and cost-effectiveness.

The technological bases for these three platforms (atom-, photon- and electron-based) are different, and distinct groups will make available the needed expertise. In some cases these will be selected via dedicated open calls; we underline that within each specific research line we shall include activities towards the implementation of interfacing modules in order to pave the way to the realization of complete, functional integrated systems that combine optimized modules based on different platforms. In the following we describe the quantum toolbox we plan to deploy.

● ***Atom and molecule-based implementations***

Neutral atoms, molecules and ions in electromagnetic potentials are powerful platforms for the realization of quantum devices thanks to the **absolute purity and isolation of the samples** and to the **excellent level of coherent control** achievable in both internal and external degrees of freedom. The result is the **ability to 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.

Future challenges to be addressed are: **engineering of coherently-operated modules** and their preparation in a quantum state relevant to the task at hand; **optimization of the global design/architecture** of the hardware and the operation protocols so as to maximize the fidelity and yield/rate of quantum information handled by the devices; **implementation of efficient and robust quantum state read-out schemes** to fully harvest the operational results of the devices; **development of the most efficient methods for the transfer of quantum information** realizing novel interconnects of quantum platforms by dynamically controlling their coupling.

To address these challenges, we shall **import novel paradigms from the upstream theoretical activities** in order to **develop and experimentally demonstrate**: novel techniques and resources for preparing atomic, molecular and ionic homogenous and hybrid systems with reduced entropy, enhanced control of external fields and optimized encoding of quantum states; novel techniques for atomic interferometry beyond the classical limit; new schemes for quantum-state detection with high spatial, temporal and spectroscopic resolution whenever possible non-destructively; quantum optimal-control protocols that maximize the fidelity and speed of specific quantum tasks, also in the presence of strong entanglement/correlations;

reliable, robust and controllable quantum interfaces between different atomic, molecular and optical systems to connect them with one another and with those based on solid state platforms. By providing technological solutions to these problems, we shall upgrade the technological readiness of individual quantum-operated modules, establish new paradigms for multi-task quantum devices and enable their functional integration by optimizing their ability to “adapt to each other” thus feeding innovative devices to the downstream activities in our proposal.

● ***Photon-based implementations***

Photon-based quantum technologies are identified as the set of basic research and applied technologies exploiting **photons as carriers of quantum information**. This involves all aspects of the interaction between non-classical light and matter in order to deliver tasks **from the generation of non-classical light to its manipulation and detection**, embracing fundamental and applied research themes.

Applications include **the whole spectrum of QST applications** from quantum communication to the simulation of quantum chemical and physical systems. We anticipate their broad usage in large-scale secure networks, enhanced measurement and lithography, and quantum information processors; the pivotal role of photonics is justified by the high-speed transmission and the outstanding low-noise properties of photons. Indeed, the advantages offered by quantum states of light will be fully exploited thanks to the versatility of the platform:

these technologies may use single photons, quantum states of bright laser beams, or both, and will undoubtedly apply and drive innovation in all fields of photonics.

The present proposal builds on these premises to develop all technologies needed to **generate, manipulate, and detect quantum states of light** across a broad range of frequencies, using bulk and integrated components, and employing different material platforms. This research line will push the boundaries of knowledge beyond the state of the art in all aspects of the chain: from the **production of quantum states of light using innovative materials**, **novel integrated photonics**, to the realization of **complex quantum devices capable of manipulating photons and providing nonlinearities at a quantum level**. The strong ability to innovate of the research groups studying fundamental aspects of quantum phenomena and nanoscale-engineered materials and devices will be highly valued within this partnership. Indeed, this will foster a synergetic effort aimed at consolidating and setting the basis for the development of a complete set of quantum technologies highly competitive at the international level.

● ***Electron-based implementations***

Electrons, individually or collectively, represent a very flexible tool to implement many quantum paradigms of interest for QST. In fact they can be molded into a vast range of **charge-, phase-,** and **spin-based configurations** of interest for the whole array of QST applications. In turn, such electronic configurations can be experimentally realized by suitably tailoring shape, chemical composition, and structure of **solid-state systems**. This platform will build on advanced nanofabrication, materials-science, and quantum-device-engineering expertise to produce such artificial quantum solid-state systems while, at the same time, pursuing their integrability within microelectronic architectures in an effort to favor practical implementations that can be introduced within existing fab plants.

All leading national facilities and competence groups for **advanced device and material design, nanofabrication,** and **materials production** join this effort together with groups capable of providing the thorough demonstration of the quantum functionality of the systems realized, when necessary by setting up *ad hoc* tools and protocols. Groups active in this research line will target innovation and advancement beyond the state of the art in all aspects of the activity: from methodologies for the **design** of the physical system of interest to their **production** with a broad variety of bottom-up and top-down approaches. A special emphasis will be devoted to novel hybrid systems and tailored many-body and spin-orbit effects. Participants already master techniques for the realization of superconductor- (S-), semiconductor (Sm)-based and hybrid S-N or S-Sm systems: the research effort here will be directed to novel hybrid configurations with innovative Sm portions (e.g. nanoflags, twisted 2D stacks, tailored 2D materials…), ferromagnets and systems in which emerging electronic excitations are the fundamental building block (e.g. anyons and fractional excitations in hybridized systems). **Novel techniques and protocols to probe electronic quantum configurations** will also be investigated in order to demonstrate the quality and performance of the methods and systems developed.

3. Integration, System Architectures

The development of quantum technologies is expected to follow the path of miniaturization and integration already experienced by micro/nanoelectronics and telecommunication technology. The successful implementation of QST systems will rely on excellent science, novel technological solutions, wide availability of technologies, cost reduction through industry standardized processing, and verified **demonstrators**.

This will have to be accompanied with demonstrations of well-understood and engineered **quantum systems** – outperforming classical systems or performing new functions - to accelerate the uptake of solutions by companies and to bring these systems earlier to the market. The research and development activities described here will bring together excellence in academic science, technological capabilities of excellent research addition, the integration techniques adopted here will be chosen carefully, to ensure interoperability of the various components and keep losses and decoherence processes at the various interfaces under control. We shall concentrate on the integration of individual quantum objects into devices and modules with the general scope of i) engineering scalable quantum components and devices, ii) developing new high-fidelity device read-out and control, iii) increasing the number of interacting quantum devices and components in a single module, and, finally, iv) developing components that allow for close-to- room-temperature applications to keep energy consumption of QST devices under control. Therefore, we shall develop and test complete systems in the laboratory for specific research activities of relevance in the areas of (i) quantum imaging, ii)

quantum point sensing, (iii) quantum communication and IoT, and (iv) quantum-simulator systems.
The integration and realization of quantum models and devices will pick up results and developments of all the different platforms used in QST (atom-, photon-, and electron-based). We shall combine more than one platform to develop highly relevant building blocks for QST such as optimized atomic circuits to implement quantum simulators, miniaturized atomic cells in MEMS technology for atom-based QST-systems, scalable sources for NIR entangled photons, integrated sender and receiver modules for QKD, high-fidelity superconducting qubit gates, custom imaging modules with time stamping NIR SPAD imagers for super-resolution microscopy, hybrid quantum memories.
Demonstration of systems will include two- and multi-photon fluorescence microscopy with entangled photons for in-vivo imaging, point-sensing systems, miniaturized magnetic field sensors, quantum-communication systems based on integrated photonic circuits with continuous variables in non-linear materials, quantum-based nano thermometers. All quantum systems will be tested in laboratory experiments aimed at demonstrating their potential for future industrial scaling.

4. Technology Transfer, Education, and Outreach

The present proposal is not only focused on the pursuit of its ambitious QST research program, but it also strives to represent a catalyst of innovation, to translate Italian scientific excellence into new processes, new products, and new services that will reach the market. To this end, as indicated by the PNRR call, we shall dedicate a significant fraction of the project resources to support a comprehensive education program, to favor technology transfer to companies, and to implement a robust outreach program to make QST pervasive in the society.
One of the major challenges to fully develop the QST potential at the industrial level is the lack of the quantum-aware workforce necessary to turn discoveries into industrial products and services. In order to address this problem we shall support dedicated Master courses to train new professional figures and to contribute to the European QTEdu experience. To be successful, such a program demands for a strong involvement of the private sector, through which new ideas will turn into the economic growth of the country. Consequently, from the very beginning of the project, selected large companies and multinational corporations operating in Italy will be actively involved in both research and education, capitalizing on their existing know-how and favoring the merging of our low-TRL research with their industrial R&D. On the other hand, we shall organize specific open calls that will provide co-funding of R&D collaborative projects, and, particularly for SMEs, training of their personnel, and even the supply of staff. We believe this will allow the PNRR action to make available QST engineers and scientists capable of answering to the growing Italian and European demand of QST experts in industry.
While QST research can certainly penetrate the existing industrial substrate, we believe that the high level of innovation of our program has the unique potential to stimulate the birth of a new industrial infrastructure. For this reason, NQSTI will strongly support entrepreneurship through a **QST incubator** program that will provide new spin-offs and start-ups seed funding and services, including consulting and financial matching.
Patenting and licensing will be promoted and supported together with know-how transfer through cooperative research, joint laboratories, personnel exchanges, networking, participation in roadshows, and the organization of an international technology fair. In all the above actions and in line with the PNRR vision, we shall give particular attention to the southern regions by allocating the dominant fraction (70%) of the funding in these themes, in order to make the quantum revolution a powerful tool to help their industrial development.
Finally, in all these activities we shall actively promote diversity by monitoring the situation at all levels from high-school education to the scientific and industrial communities, raising

awareness on gender-balance issues and inclusion. This will also be done through our recruitment program, that includes specific financial resources destined to relocation packages tailored to make our country an attractive destination for young and bright scientists and entrepreneurs from all over the world.

CONCLUDING REMARKS

The European Quantum Flagship vision, which is fully recognized in the Italian National Research Plan, foresees the development of Quantum Technologies along three parallel lines: (i) the creation, within the Horizon Europe program, of a network of National Quantum Institutes to activate synergies and optimize the use of resources bringing research results in industrial products; (ii) the inclusion of novel Quantum Computing capabilities within the High Performance Computing Infrastructure (HPC/QC); (iii) the realization of a novel European Quantum Communication Infrastructure (EuroQCI), the latter two to be developed within the Digital Europe Program. True to this vision, our proposal completes the existing national efforts for the HPC/QC Center and the proposed Italian deployment of the EuroQCI by providing an interdisciplinary, holistic and problem-solving approach for the creation of the NQSTI: a new innovation ecosystem in which the ability to study and manipulate quantum objects (atoms-molecules, photons, electrons) is ultimately translated into industrial applications. To this aim we shall develop new technical infrastructures, define new standards, train new technical-professional figures, and create a new coordination center between public and private sectors with a particular focus on the development of the southern Italian regions.

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Partner

N TOTALE SOGGETTI: 20

Proponente: Università degli Studi di Camerino

Partecipanti:

SOGGETTI PUBBLICI

Università

- Università degli Studi di Camerino

- Sapienza Università di Roma
- Università degli Studi di Bari Aldo Moro
- Università degli Studi di Firenze
- Università degli studi di Milano-Bicocca
- Università degli Studi di Napoli Federico II
- Università degli Studi di Parma
- Università di Pavia
- Università degli Studi di Catania
- Università degli Studi di Trieste

Organismi di Ricerca

- Consiglio Nazionale delle Ricerche
- Istituto Nazionale di Fisica Nucleare
- International Center for Theoretical Physics
- Scuola Internazionale Superiore di Studi Avanzati
- Scuola Normale Superiore di Pisa
- Scuola Superiore Sant'Anna di Pisa

SOGGETTI PRIVATI:

Organismi di Ricerca

- Fondazione Bruno Kessler
- Istituto Italiano di Tecnologia

Imprese

- Leonardo SpA
- Thales Alenia Space

Gli Spoke

Spoke n. 1 Information processing and communication

Leader spoke: Università di Pavia

Affiliati allo spoke:

- Fondazione Bruno Kessler
- International Center for Theoretical Physics
- Università degli Studi di Camerino
- Università degli Studi di Bari Aldo Moro
- Università degli Studi di Firenze
- Università degli Studi di Napoli Federico II

- Università degli Studi di Parma
- Università degli Studi di Catania
- Università degli Studi di Trieste

Spoke n. 2 Simulation, sensing and metrology

Leader spoke: Università degli Studi di Camerino

Affiliati allo spoke:

- Consiglio Nazionale delle Ricerche
- Università di Pavia
- Scuola Internazionale Superiore di Studi Avanzati
- Scuola Normale Superiore di Pisa
- International Center for Theoretical Physics
- Università degli Studi di Bari Aldo Moro
- Università degli Studi di Napoli Federico II
- Università degli Studi di Parma

Spoke n. 3 Atom based

Leader spoke: Consiglio Nazionale delle Ricerche
Affiliati allo spoke:

- Istituto Nazionale di Fisica Nucleare
- Leonardo SpA
- Università degli Studi di Firenze
- Università degli Studi di Trieste
- Scuola Internazionale Superiore di Studi Avanzati

Spoke n. 4 Photon based

Leader spoke: Sapienza Università di Roma

Affiliati allo spoke:

- Università degli studi di Milano-Bicocca
- Istituto Italiano di Tecnologia
- Fondazione Bruno Kessler
- Università degli Studi di Camerino
- Consiglio Nazionale delle Ricerche
- Istituto Nazionale di Fisica Nucleare
- Leonardo SpA
- Università degli Studi di Firenze
- Università di Pavia
- Università degli Studi di Napoli Federico II

Spoke n. 5 Electron based

Leader spoke: Scuola Normale Superiore di Pisa
Affiliati allo spoke:

- Università degli Studi di Catania
- Università degli Studi di Parma
- Università degli Studi di Trieste
- Sapienza Università di Roma
- Università degli studi di Milano-Bicocca
- Istituto Italiano di Tecnologia
- Università degli Studi di Camerino
- Consiglio Nazionale delle Ricerche
- Università degli Studi di Firenze
- Università degli Studi di Napoli Federico II

Spoke n. 6 Integration

Leader spoke: Università degli studi di Milano-Bicocca
Affiliati allo spoke:

- Scuola Superiore Sant'Anna di Pisa
- Sapienza Università di Roma
- Fondazione Bruno Kessler
- Consiglio Nazionale delle Ricerche
- Istituto Nazionale di Fisica Nucleare
- Leonardo SpA

Spoke n. 7 Complete systems

Leader spoke: Fondazione Bruno Kessler
Affiliati allo spoke:

- Thales Alenia Space
- Università degli Studi di Catania
- Università degli Studi di Bari Aldo Moro
- Università di Pavia
- Università degli studi di Milano-Bicocca
- Scuola Superiore Sant'Anna di Pisa
- Sapienza Università di Roma
- Consiglio Nazionale delle Ricerche
- Leonardo SpA

Spoke n. 8 Technology transfer

Leader spoke: Consiglio Nazionale delle Ricerche
Affiliati allo spoke:

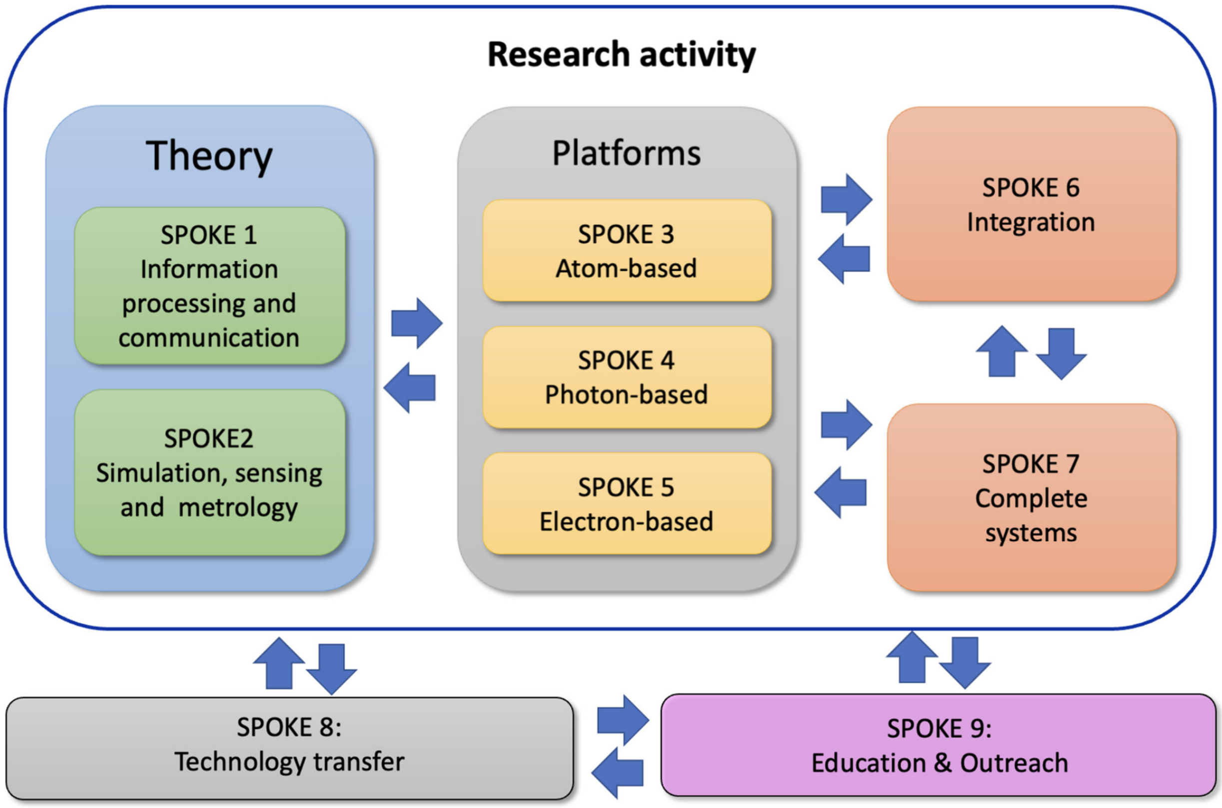
- Scuola Normale Superiore di Pisa
- Istituto Italiano di Tecnologia
- Fondazione Bruno Kessler
- Scuola Superiore Sant'Anna di Pisa
- Sapienza Università di Roma
- Università degli studi di Milano-Bicocca
- Università degli Studi di Camerino
- Università degli Studi di Firenze
- Università degli Studi di Bari Aldo Moro
- Università di Pavia
- Università degli Studi di Parma
- Università degli Studi di Trieste
- Università degli Studi di Napoli Federico II

Spoke n. 9 Education & Outreach

Leader spoke: Università di Catania

Affiliati allo spoke:

- Istituto Nazionale di Fisica Nucleare
- Consiglio Nazionale delle Ricerche
- Scuola Superiore Sant'Anna di Pisa
- Sapienza Università di Roma
- Scuola Internazionale Superiore di Studi Avanzati
- Scuola Normale Superiore di Pisa
- Università degli studi di Milano-Bicocca
- Università degli Studi di Camerino
- Università degli Studi di Firenze
- Università degli Studi di Bari Aldo Moro
- Università di Pavia
- Università degli Studi di Parma
- Università degli Studi di Napoli Federico II



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