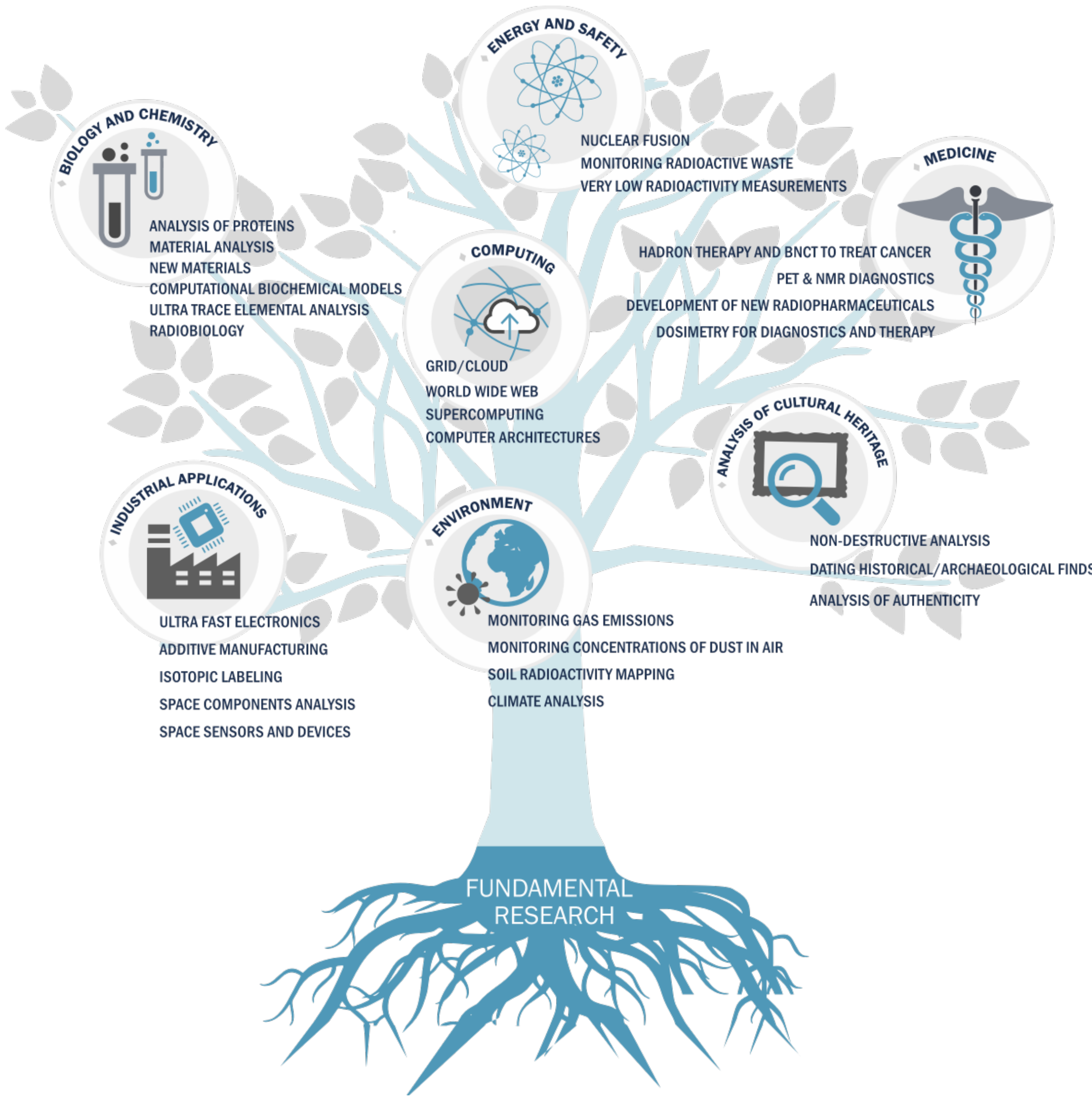


INFN Present and Future Perspectives on QT / QIS

Quantum Technologies for Fundamental Physics

Erice, Sep. 2nd, 2023
Prof. Marco Pallavicini - INFN Exec Board

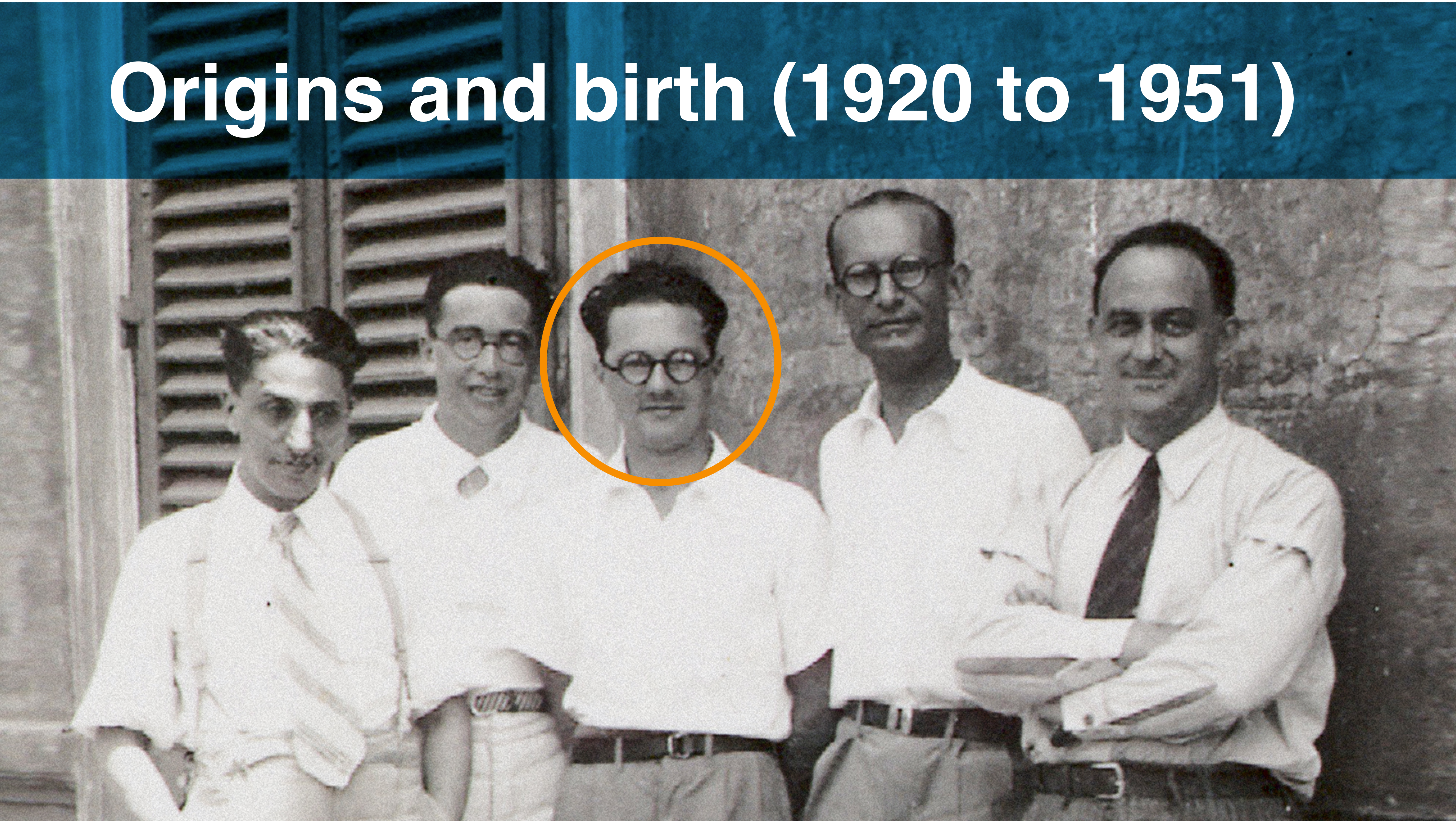
Credit: I am deeply in debt with **V. Bonvicini** for many slides

Contents

- INFN in a nutshell
  - A Touch of History
  - The Institute today and its Mission
  - Current main scientific endeavours

- INFN interest for Quantum
  - Quantum sensing
  - Quantum technologies
  - QM fundamentals
  - Quantum computing

Origins and birth (1920 to 1951)



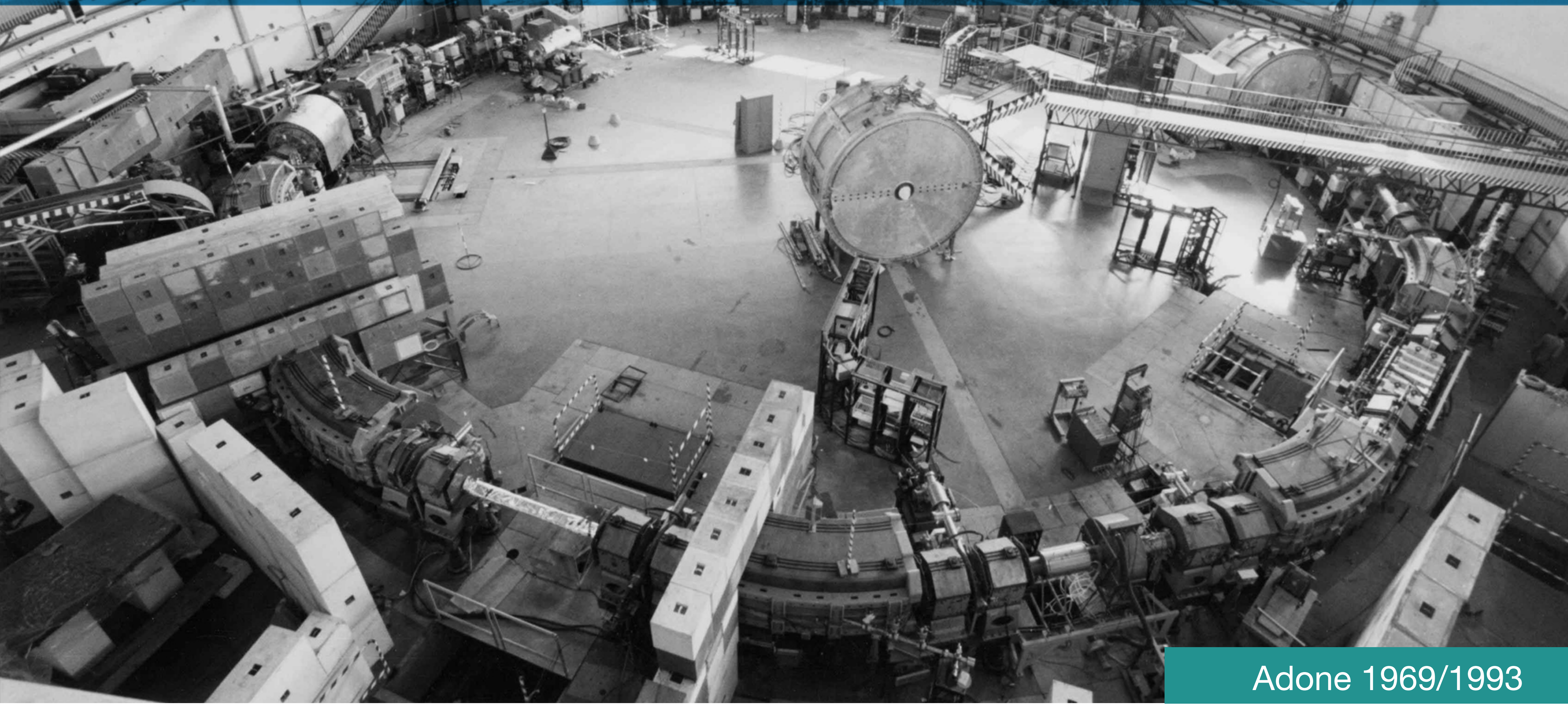
Roma 1930. From left: Oscar D'Agostino, Emilio Segrè, **Edoardo Amaldi,** Franco Rasetti and Enrico Fermi.

The early years

Launch of balloons with nuclear emulsions (Asti, 1955)

1951 /1961

AdA and Adone, the Italian primacy in high-energy research



Adone 1969/1993

1961 /1971

The reorganisation of the INFN and international collaborations

Super Proton Synchrotron (SPS) 1981/1984

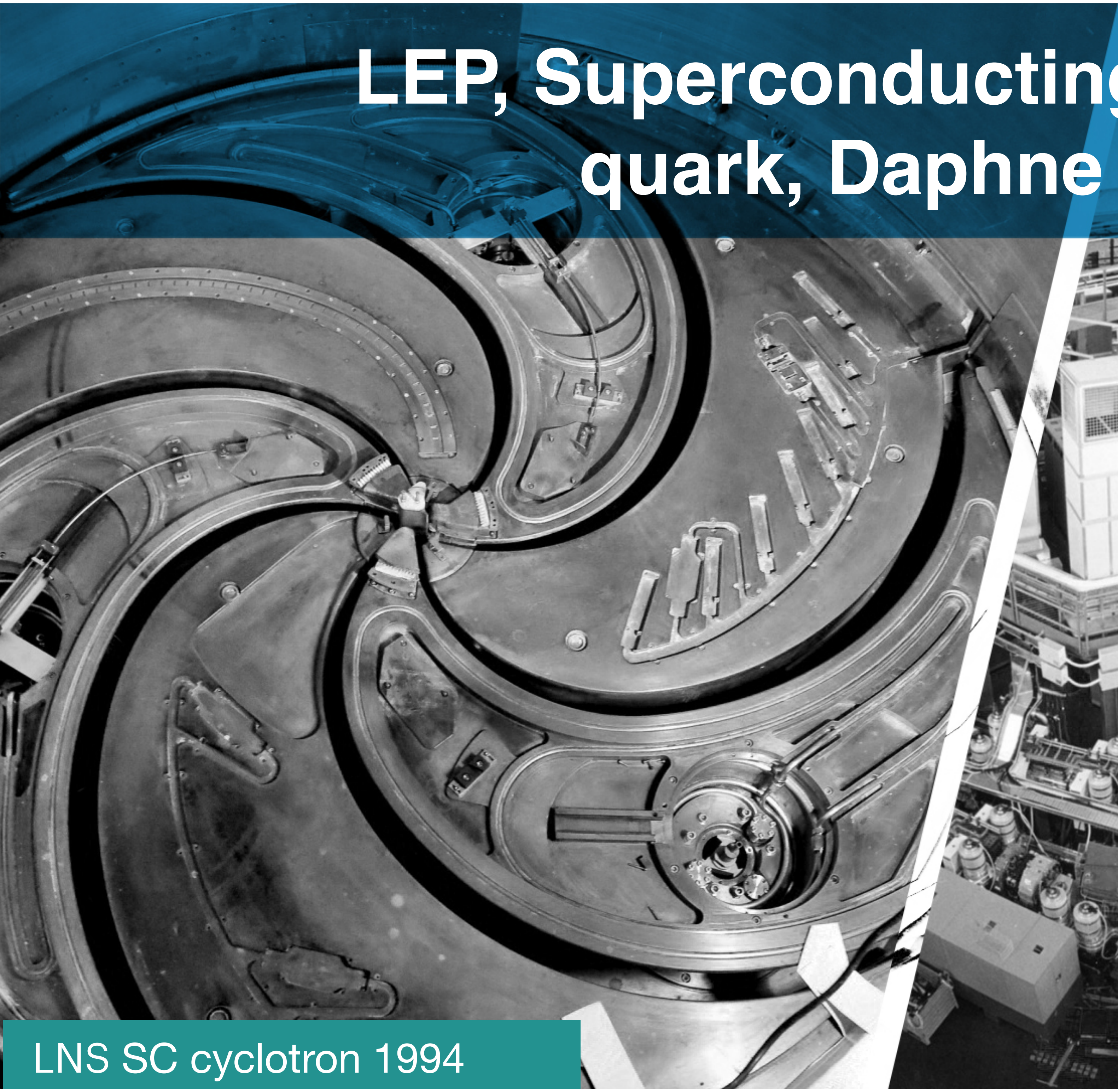
1971 /1981

The W and Z bosons, the Italian Supercomputing and the birth of the LNGS

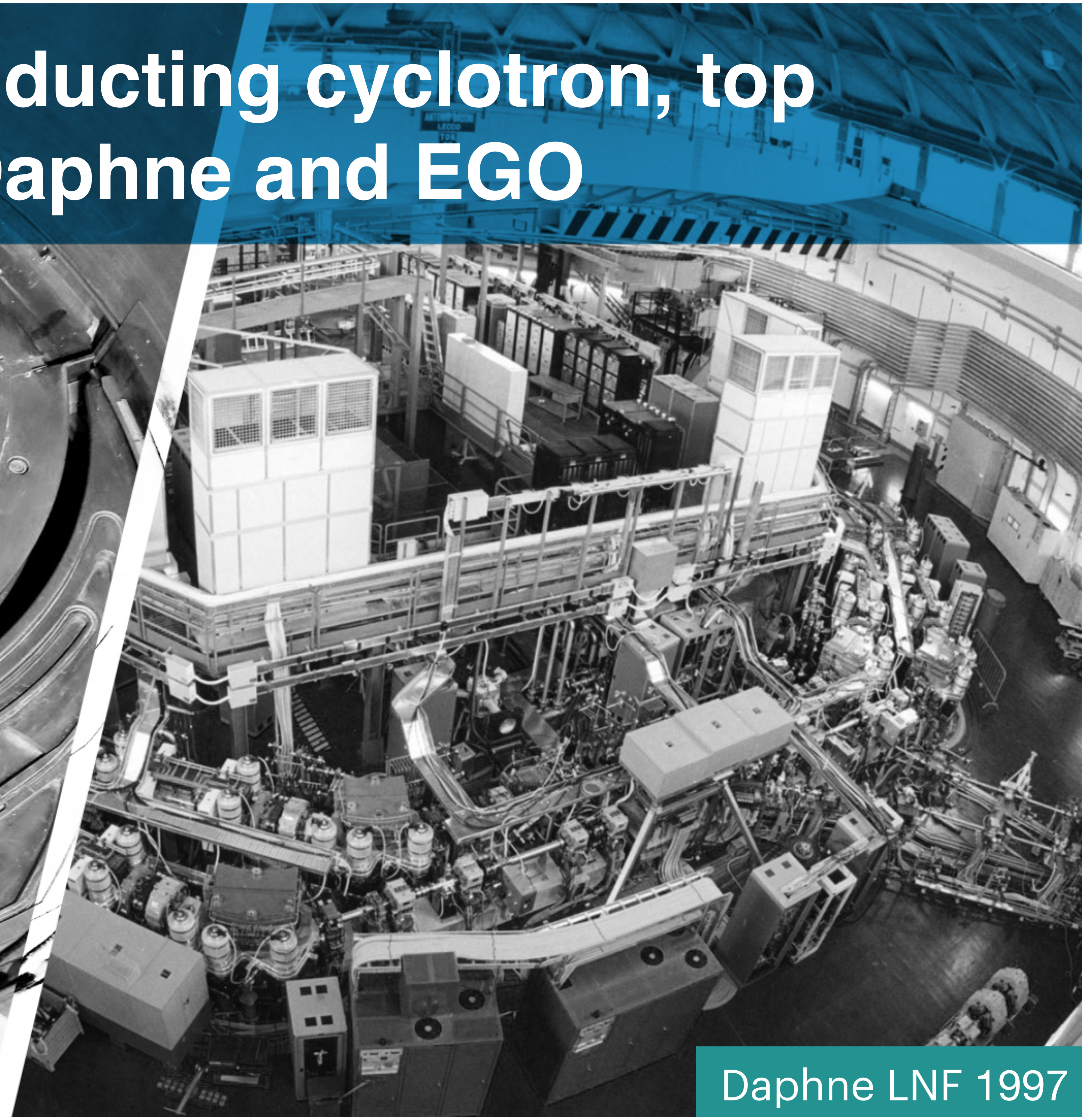
Laboratori Nazionali del Gran Sasso 1987

1981 /1991

LEP, Superconducting cyclotron, top quark, Daphne and EGO



LNS SC cyclotron 1994



Daphne LNF 1997

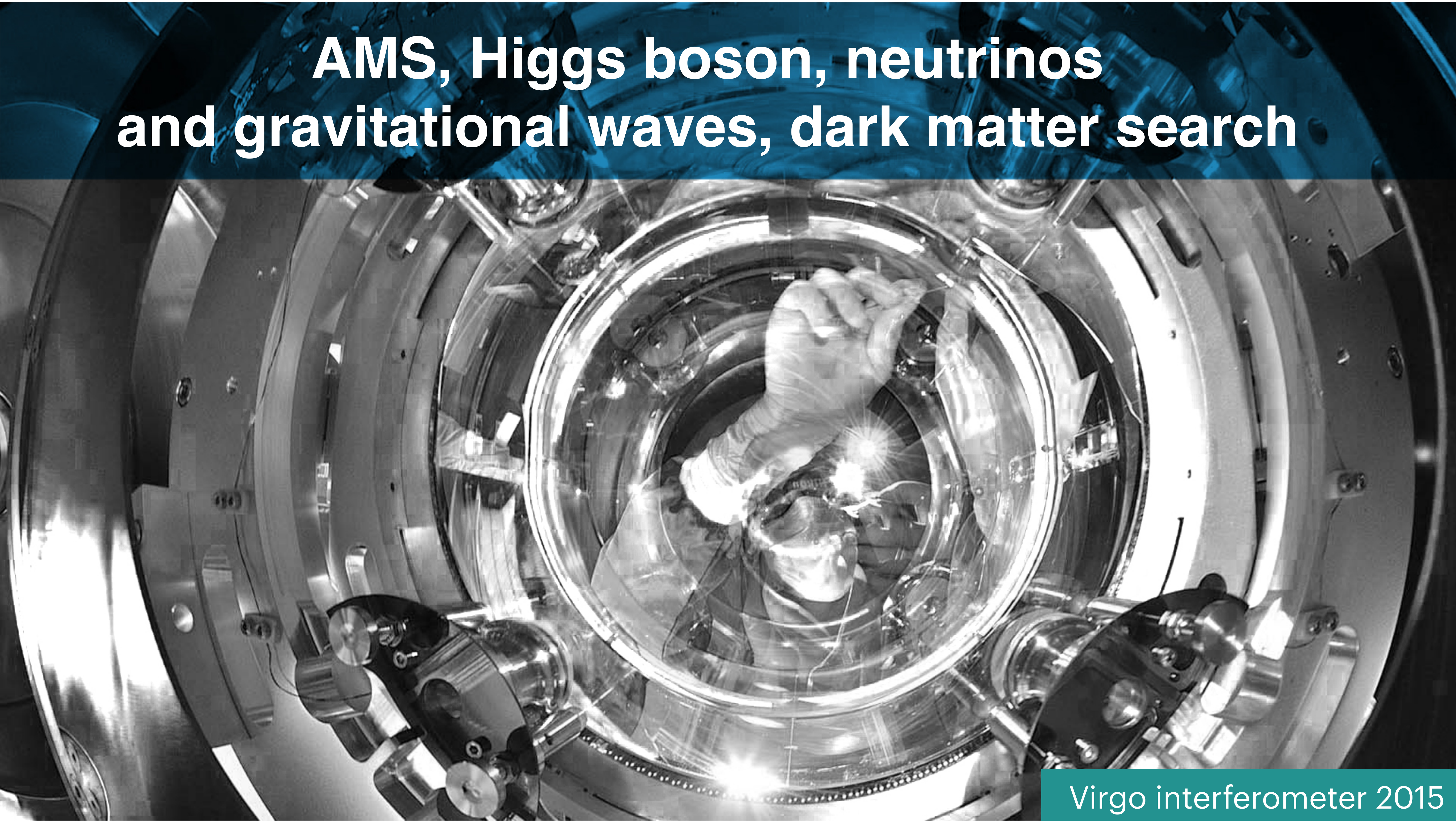
1991 /2001

Labec, Babar, LHC, Borexino

LHC 2008

2001 /2011

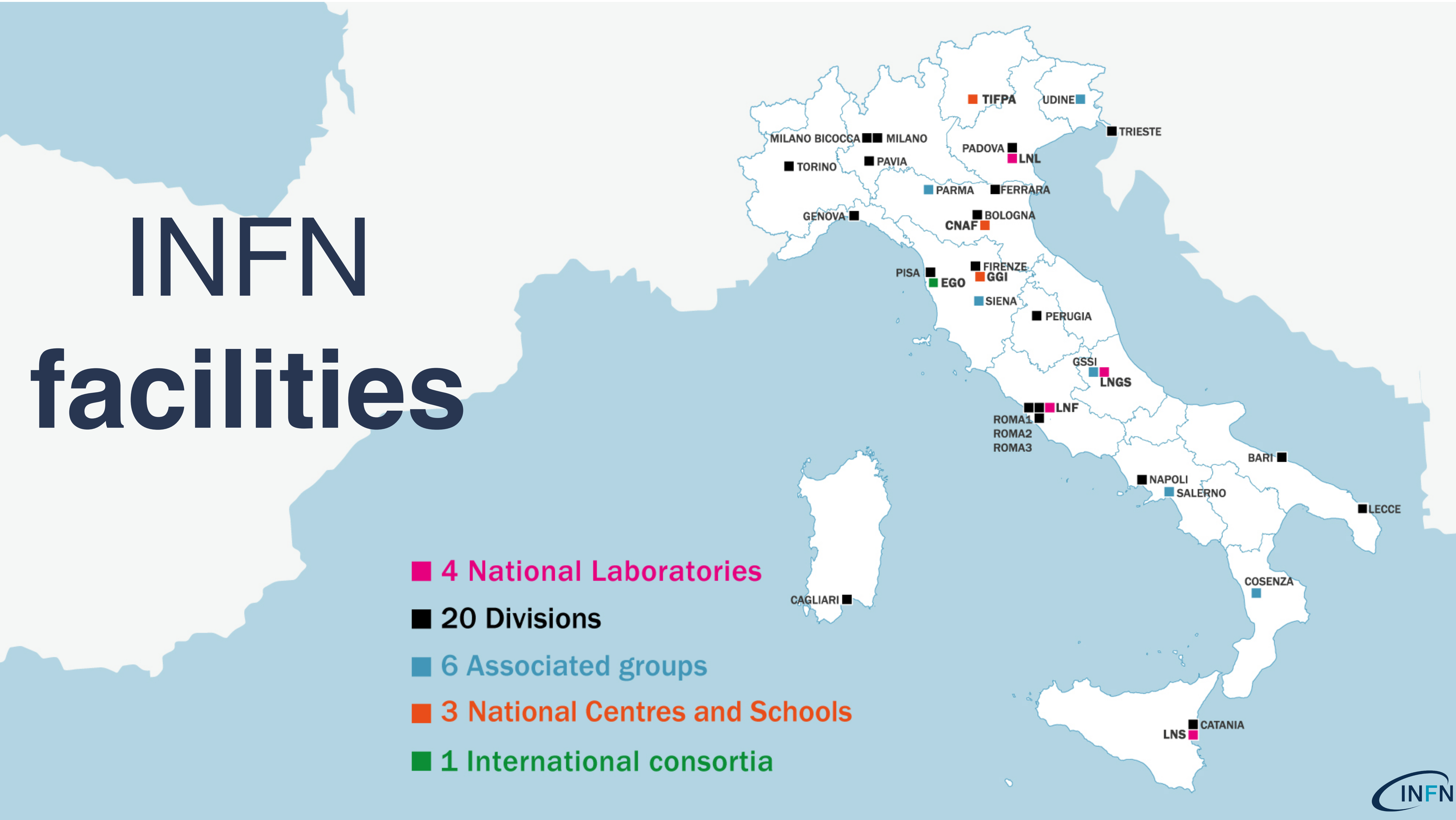
AMS, Higgs boson, neutrinos and gravitational waves, dark matter search



Virgo interferometer 2015

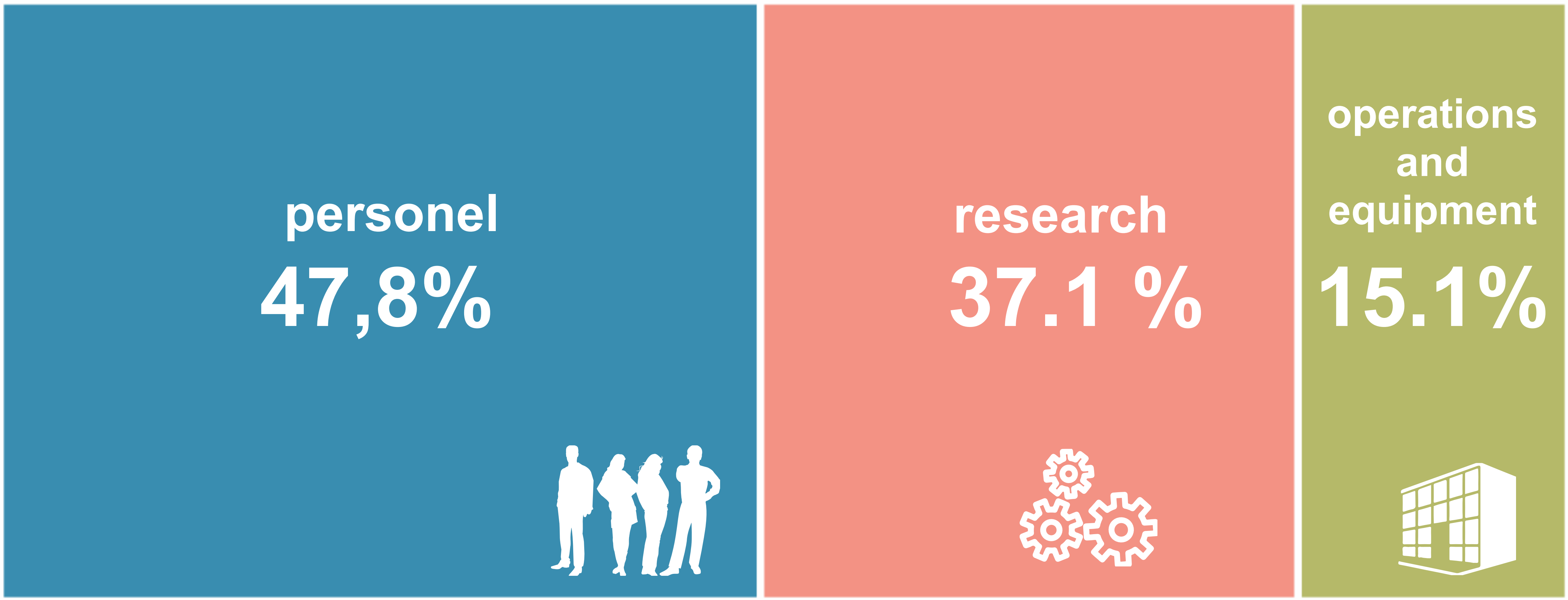
2011 /2021

INFN **facilities**



- 4 National Laboratories
- 20 Divisions
- 6 Associated groups
- 3 National Centres and Schools
- 1 International consortia

Profile of expenditure for research, personnel, operations and equipment



6700 people [INFN employees or associated University staff]
25% graduate students, post docs and contracts

Budget 2022

579 M€

Base budget from MUR

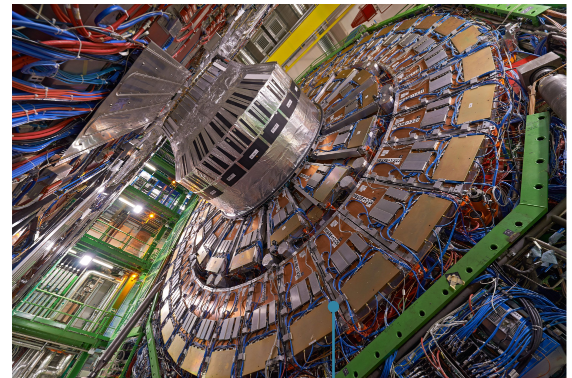
292 M€

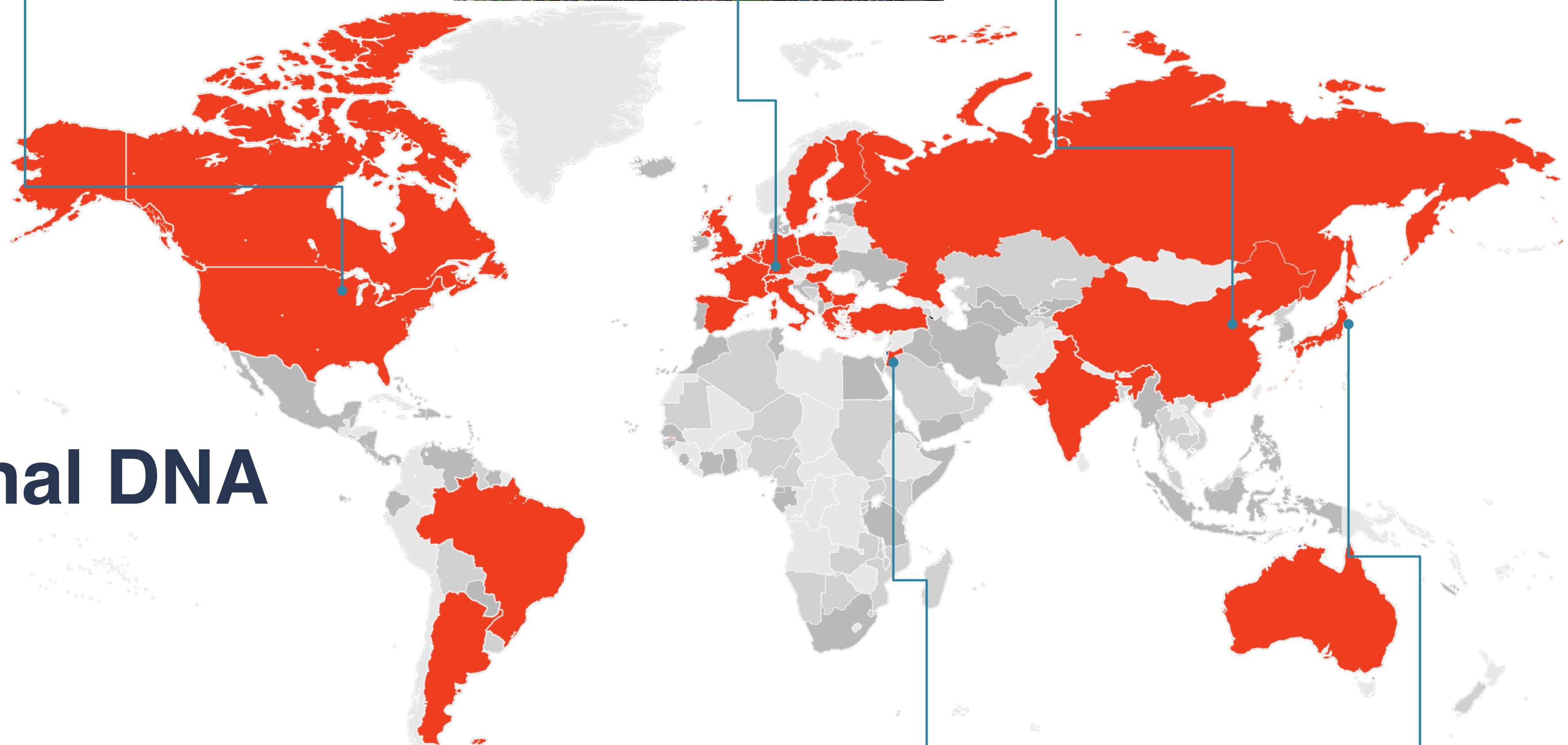
Special projects

121 M€

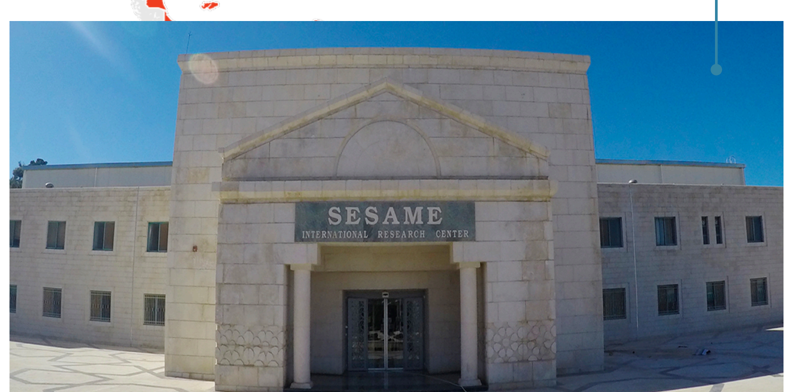
PNRR projects

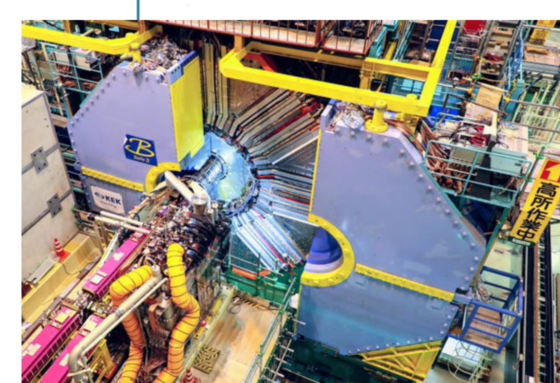
166 M€



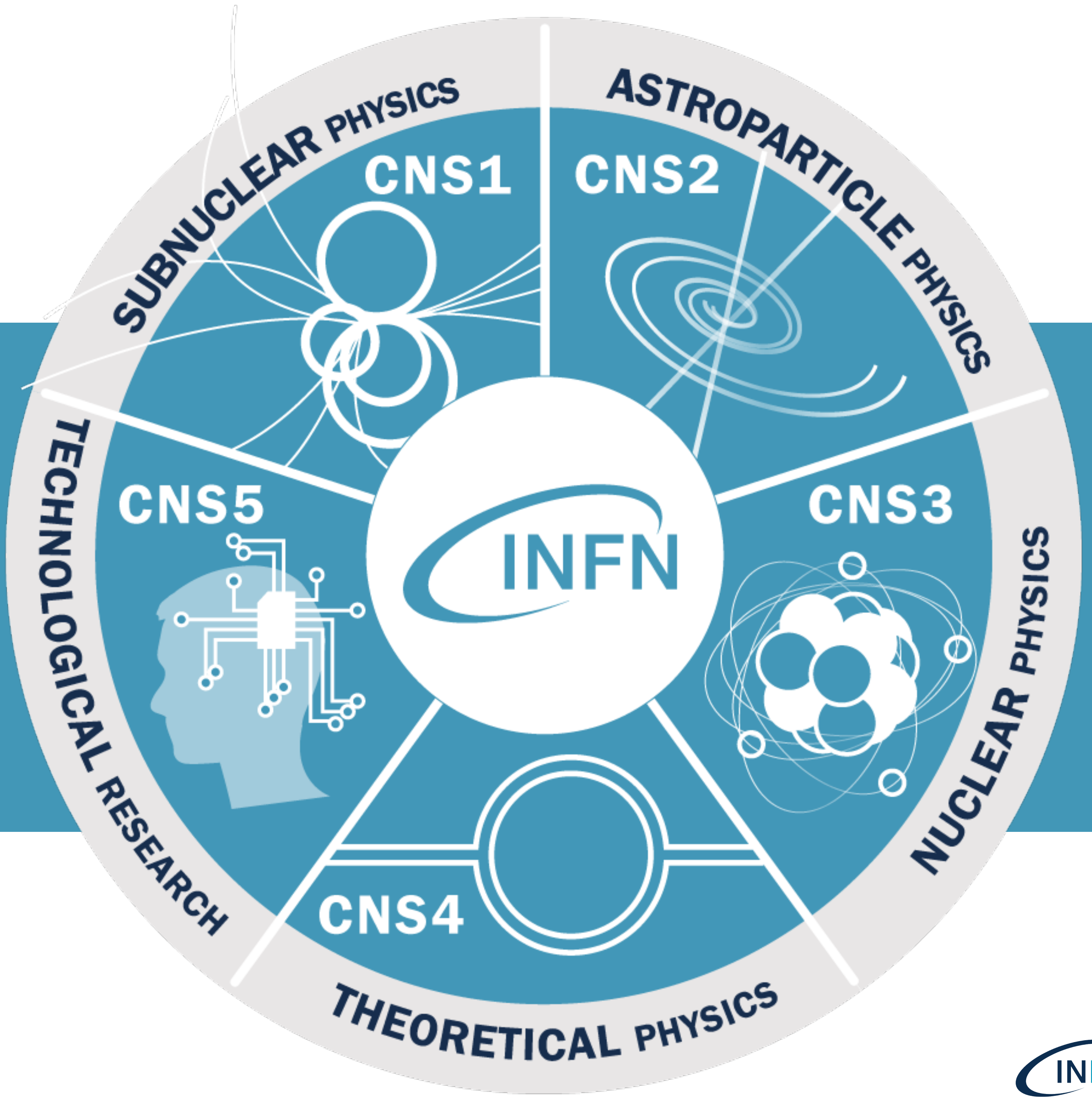


An
international DNA

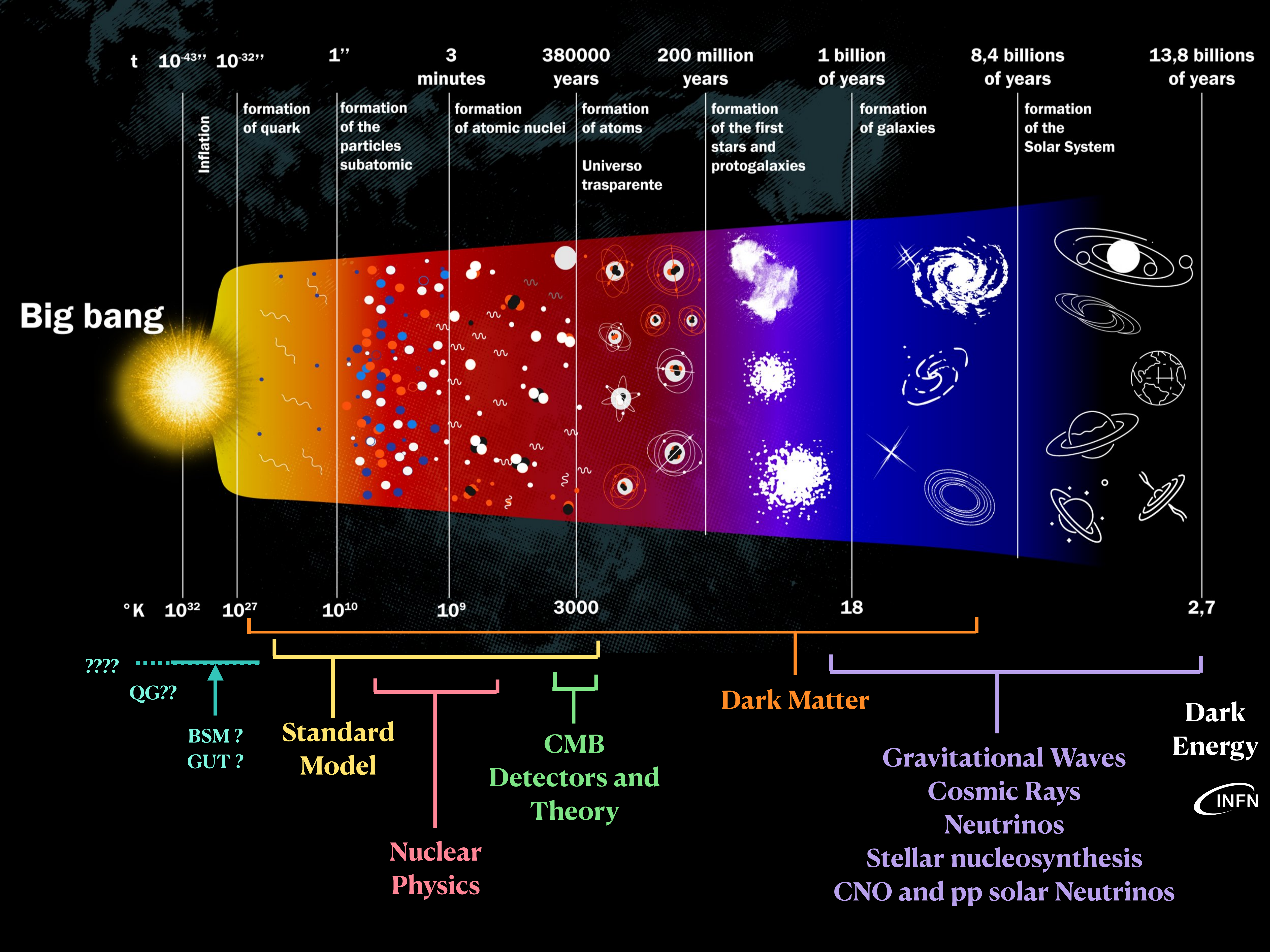




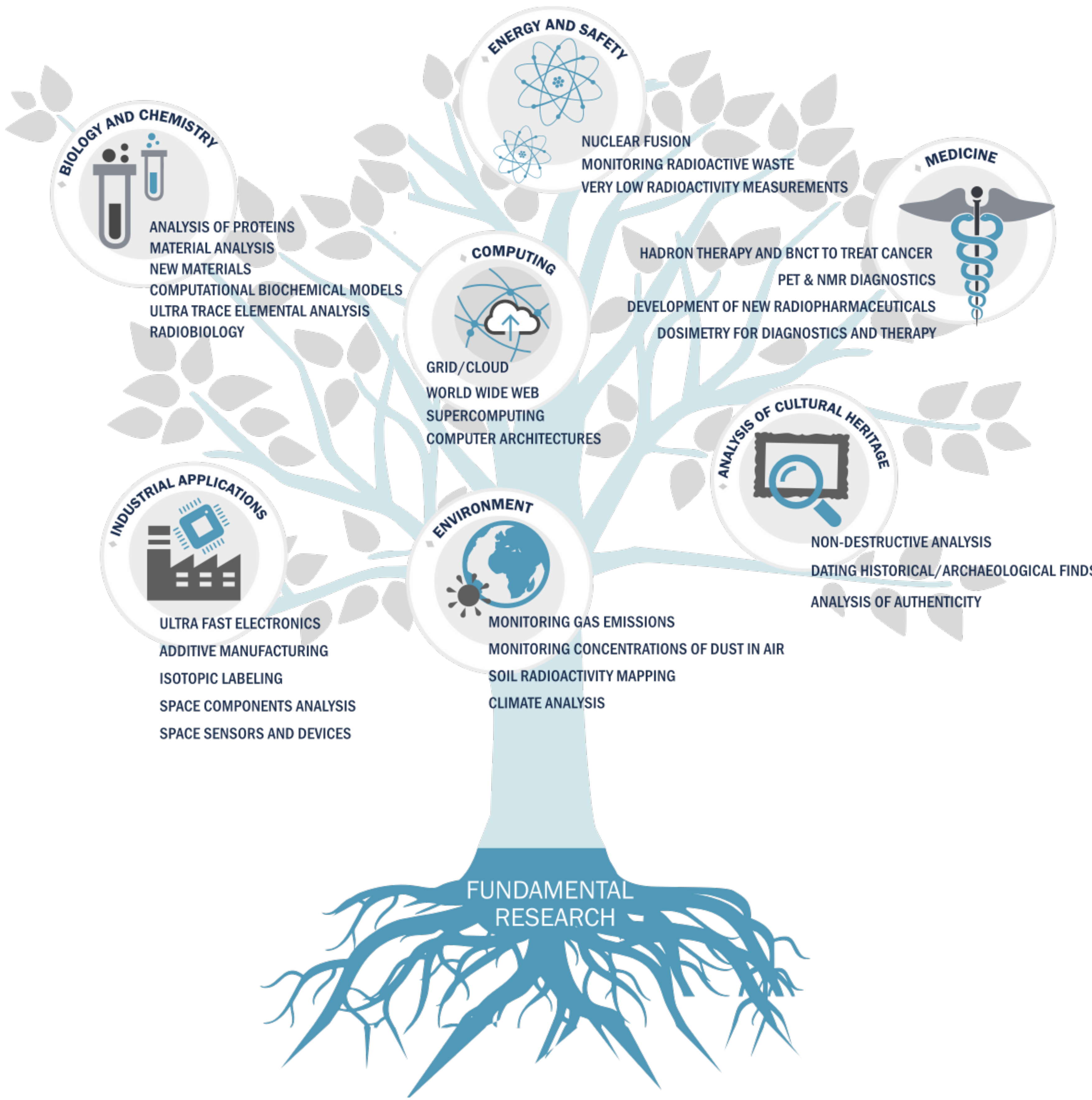
The **5 research lines** and the National Scientific Committees



INFN

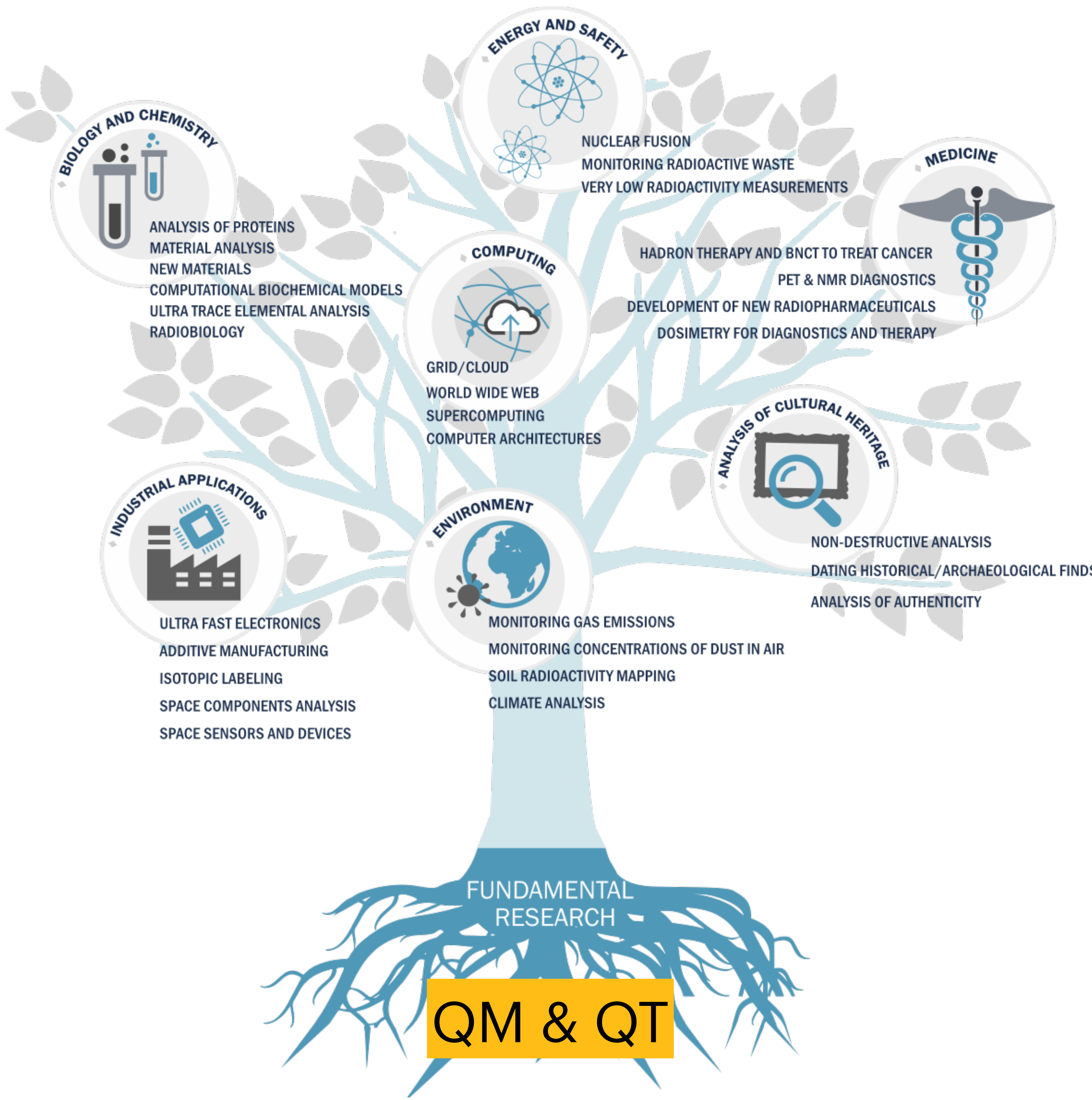

t
10-43'' 10-32''
1''
3 minutes
380000 years
200 million years
1 billion of years
8,4 billions of years
13,8 billions of years
Inflation
formation of quark
formation of the particles subatomic
formation of atomic nuclei
formation of atoms
Universo trasparente
formation of the first stars and protogalaxies
formation of galaxies
formation of the Solar System
Big bang
°K 10^32 10^27 10^10 10^9 3000 18 2,7
????
QG??
BSM ?
GUT ?
Standard Model
Nuclear Physics
CMB Detectors and Theory
Dark Matter
Gravitational Waves
Cosmic Rays
Neutrinos
Stellar nucleosynthesis
CNO and pp solar Neutrinos
Dark Energy
INFN

Transfer of Knowledge to Society



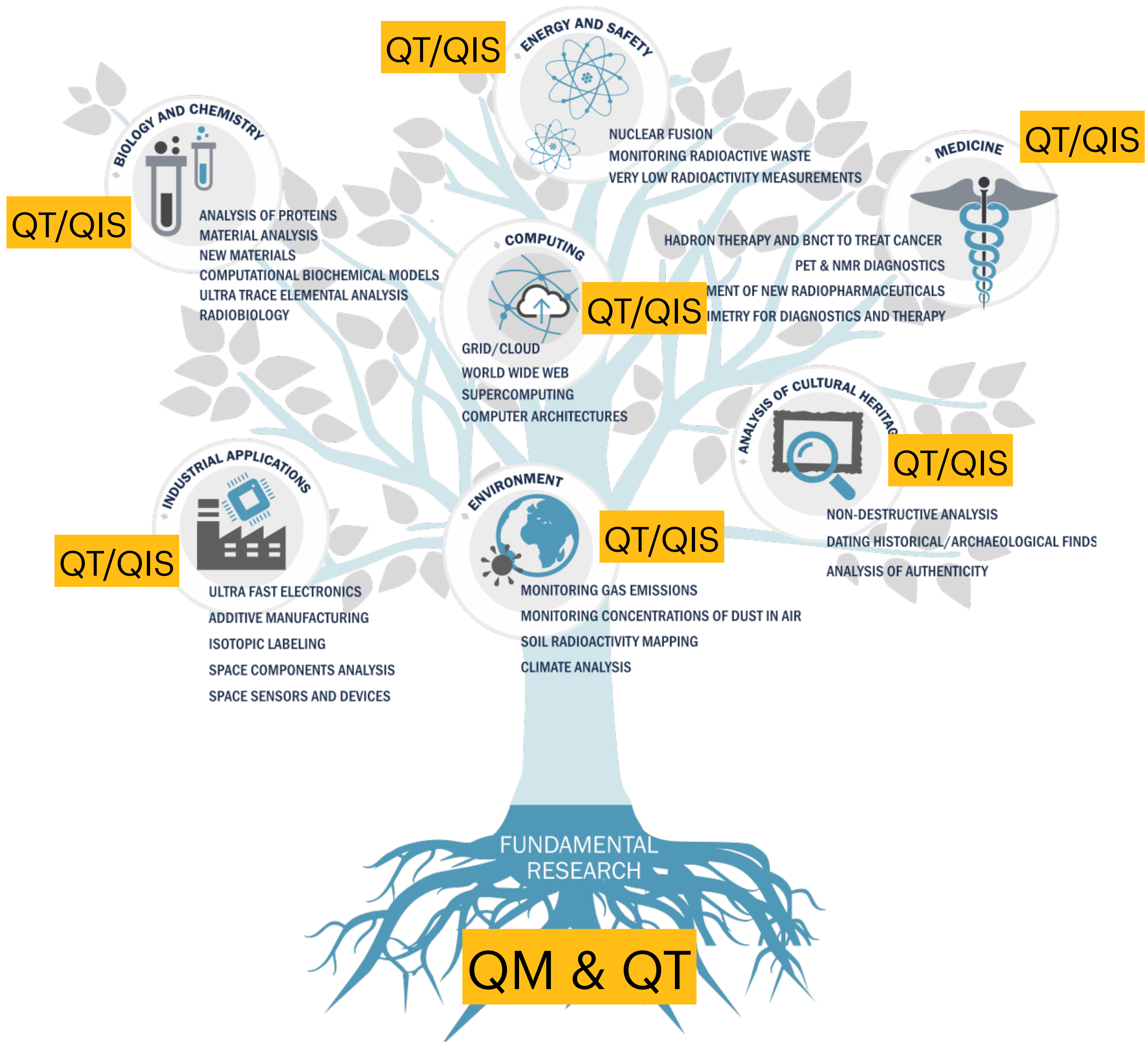
INFN

Transfer of Knowledge to Society



INFN

Transfer of Knowledge to Society



INFN

INFN interest in QT

- Four main lines, the first two are the main focus:

  - **Quantum sensing:** using **wave functions as probes or detectors**
    - New particle detectors
    - Single photon detection in low frequency domains
    - Innovative dark matter detectors

  - **Quantum technologies**
    - Using INFN technologies to develop new Quantum Devices

  - **Quantum computing**
    - Which fundamental physics problems can be addresses ?
    - Which algorithms ?

  - **Quantum devices** to explore **fundamental quantum mechanics**

QT/QIS @ INFN: the long term goal

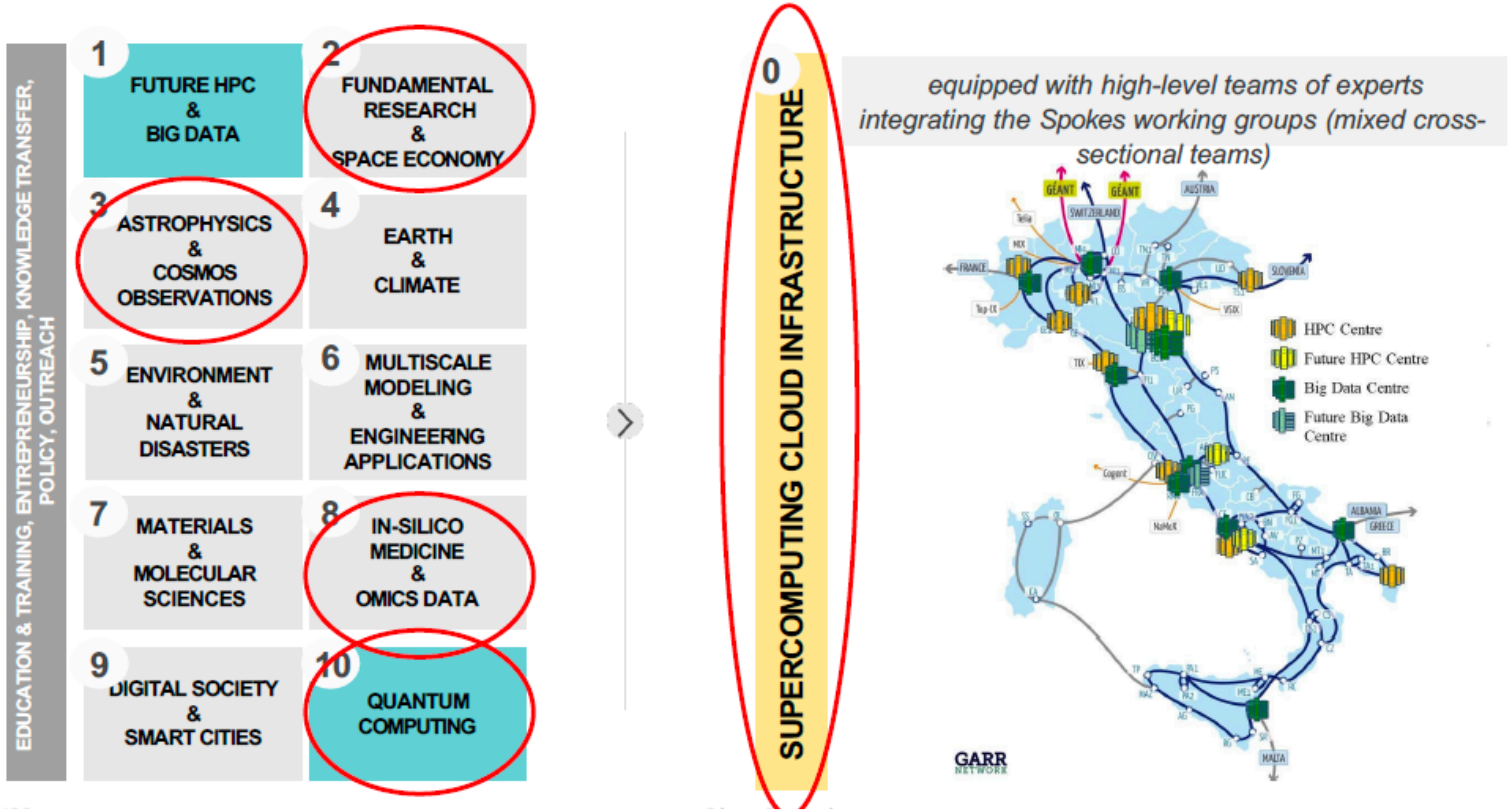
- **INFN and QIS/QT**
  - Adopt all technologies that can allow **better research in fundamental physics** (e.g., detect very low energy quantum states).
  - **Use Quantum computers/simulators to support our research** (from Lattice QCD, to event classification in LHC, to Life Science applications, …).
  - 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
  - Develop a sound know-how and an expert workforce
  - Develop a synergistic effort to increase the INFN role in the relevant areas

- **Main QIS/QT** current activities (carried on in INFN-financed experiments, within PNRR-financed projects, and in International projects):
  - Theory/algorithms
  - Technology:SC platform, Photonic platform, Cryogenic detectors (TES, KIDs, JJ,…), QL-parametric amplifiers, qubits for QC and sensing
  - Experiments: measurement of ν mass, Axion (and light DM) search, EDM, QML and quantum algorithms for HEP

PNRR funded activities (I)

- Quantum Computing in National Center for HPC

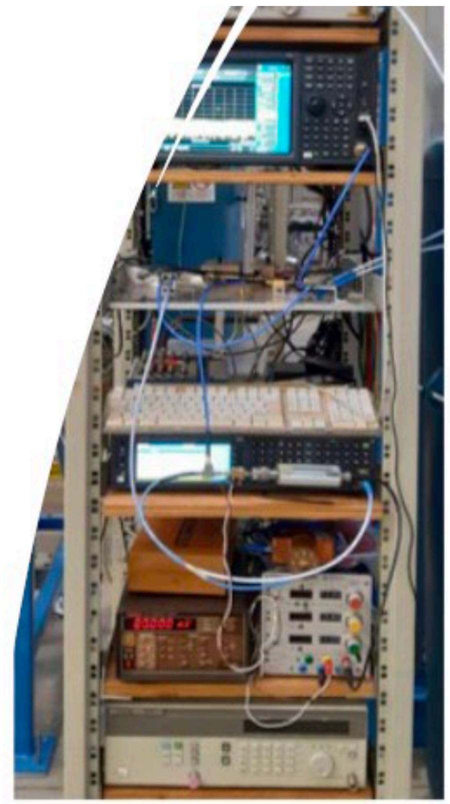


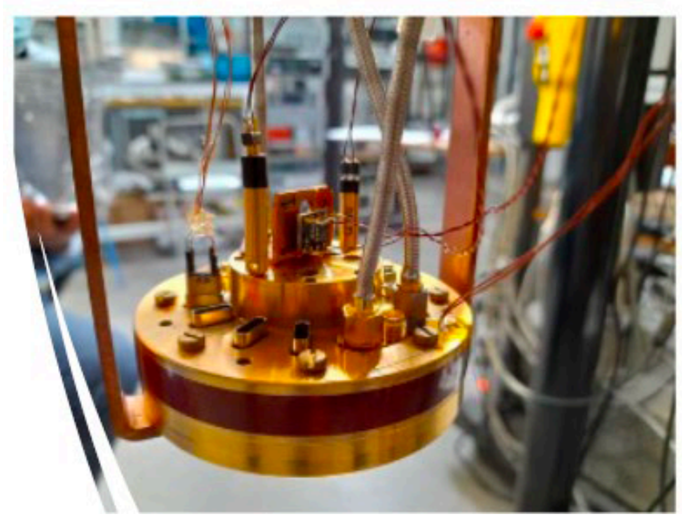
PNRR funded activities (II) - software

- Applied quantum algorithms
  - Exploit the potential of Quantum Computing to **change the paradigm of classification and reconstruction algorithms** used in fundamental physics research
    - Tackle classification problems within the framework of Q. Machine Learning
    - Study correlations amongst the features of a dataset, by measuring the entanglement correlations between qubits, and therefore extracting information on the underlying physics
    - Quantum algorithms can be employed to efficiently reconstruct physics objects, such as charged particle tracks, specifically to reduce combinatorial background during the initial seeding stage

PNRR funded activities (III) - hardware

- **Superconducting qubits**
  - Qubit **circuit design**
  - Qubit **control**
  - Test and Development of **Quantum Amplifiers** for fast qubit readout
  - Tests and Measurements
- **5 Labs** instrumented with dilution refrigerators and RF electronics
  - Synergies with many INFN experiments

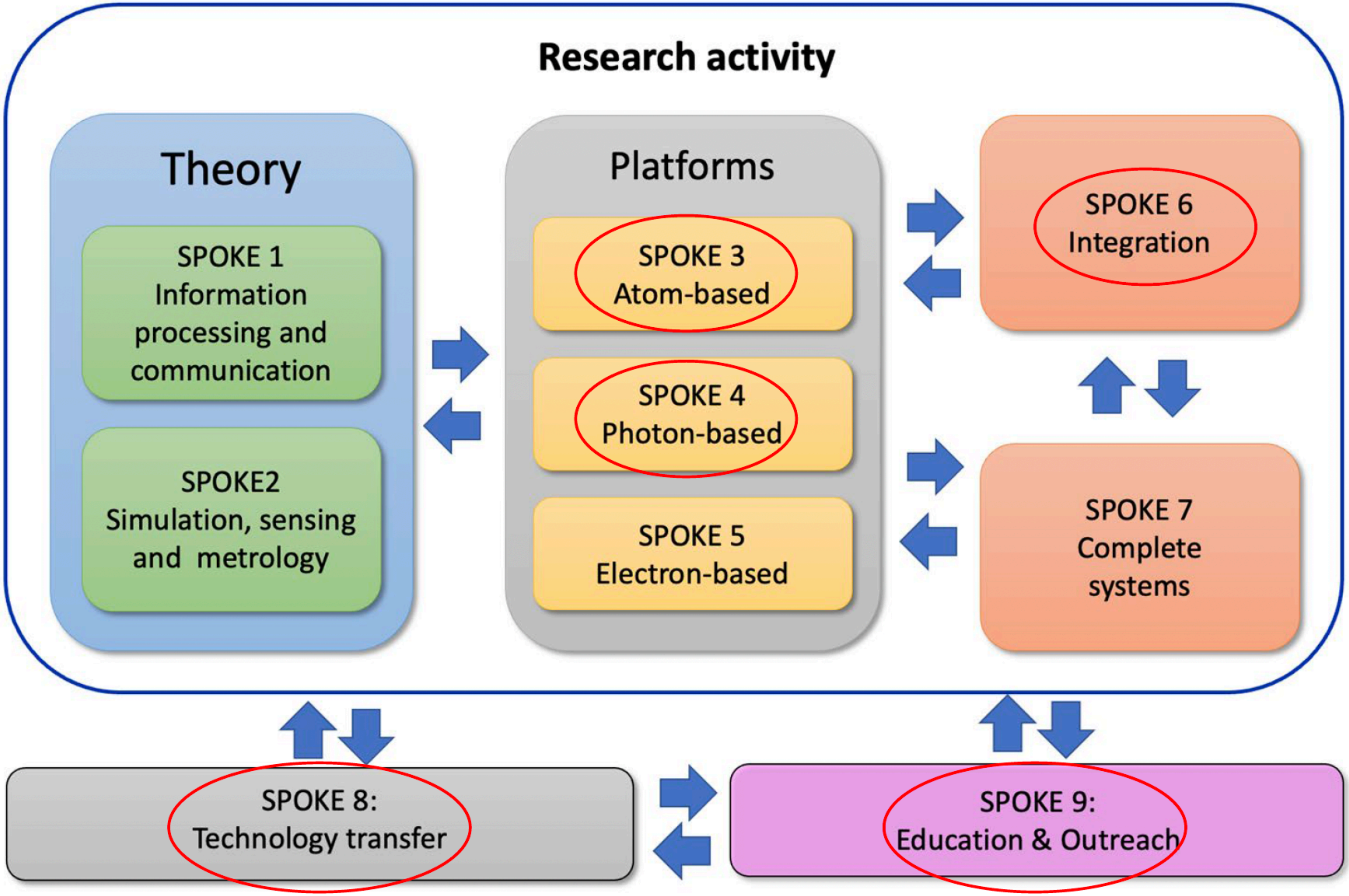




PNRR funded activities (IV): NQSTI

- **N**ational **Q**uantum **S**cience and **T**echnology **I**nstitute
  - A national consortium that will:
    - Team up Italian entities carrying out competitive and innovative research in QST.
    - Stimulate future industrial innovation in this field.
    - Provide a forum in which novel ideas and opportunities are transferred to companies.
    - Favour successful Italian participation to European and international programs

PNRR funded activities (V): NQSTI



Some examples [incomplete list]

- Precise Electric Dipole Moments (EDM) for e and p (n) exploring Long Coherence Spin in Molecules

- Macro-Coherent sensors for Dark Matter (neutrino?) detection
  - Axions, WIMPS, relic neutrinos (?), exotic physics

- Atomic Ion Source with High Charge State for Atomic Clocks
  - See e.g., S. A. King et al., Nature 611, 43-47 (2022)

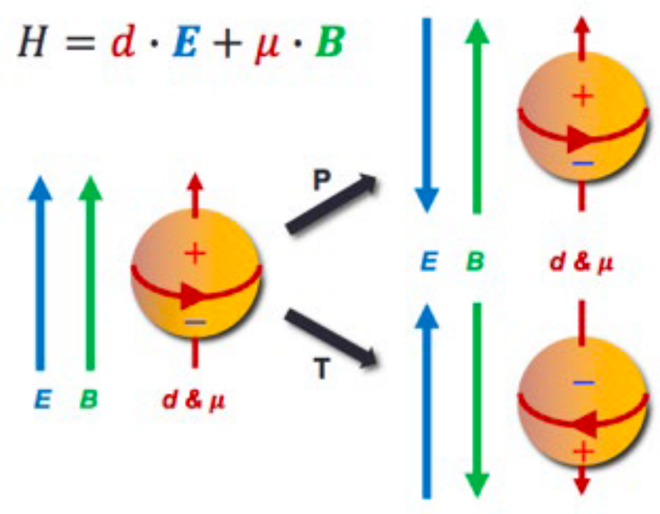
- Photonics

- Integration of different QT platforms

- Many more….

Electric Dipole Moments

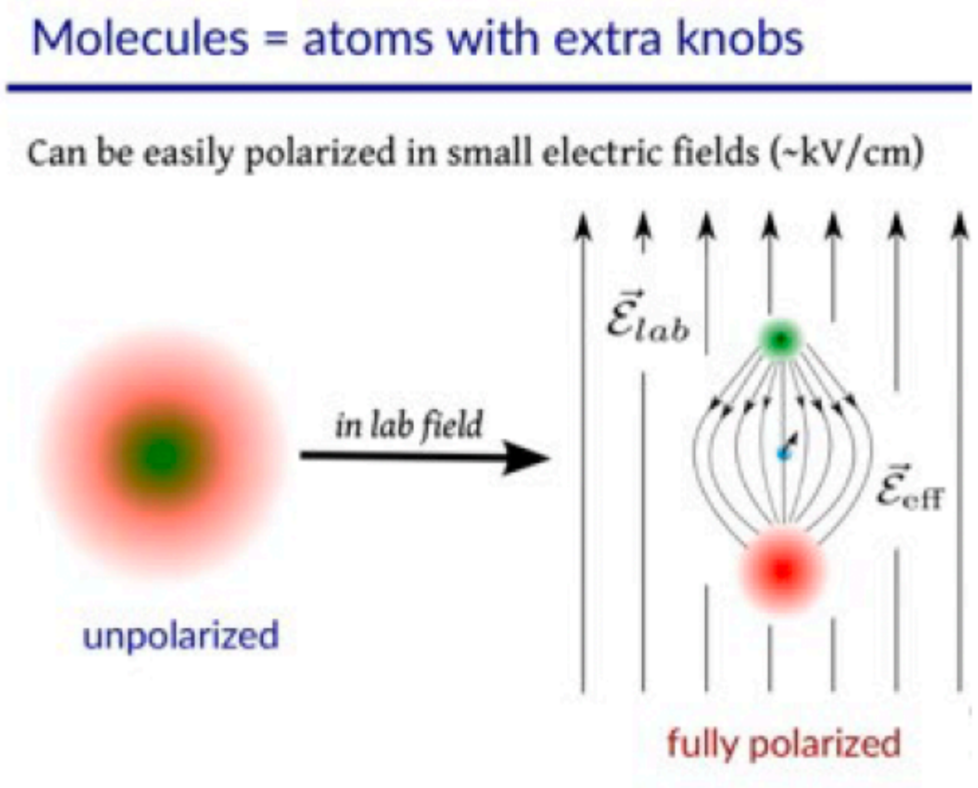
- A low energy portal to BSM physics
  - EDM violates T and P
    - In QFTs respecting CPT implies CP violation through mechanisms different from CKM and PNMS phases
    - EDM's in SM are tiny ($d_e < 10^{-38}$ e·cm, $d_n < 10^{-34}$ e·cm) but most BSM extensions include new CPV phases

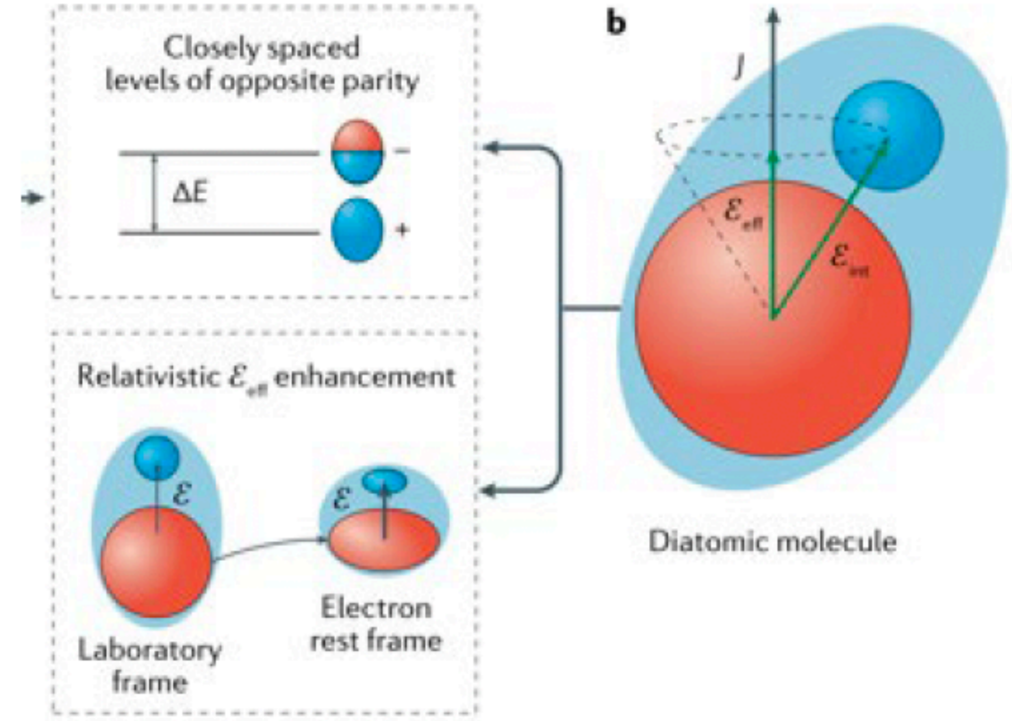


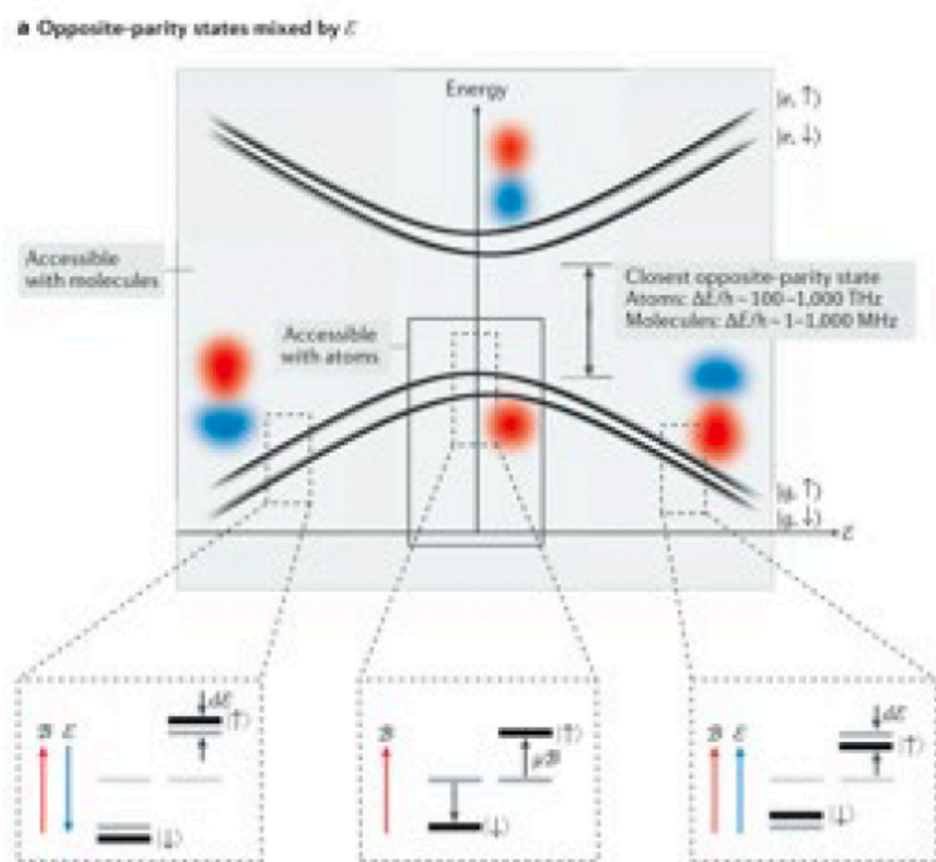
  - It probes scales unreachable to LHC and well beyond FCC too.

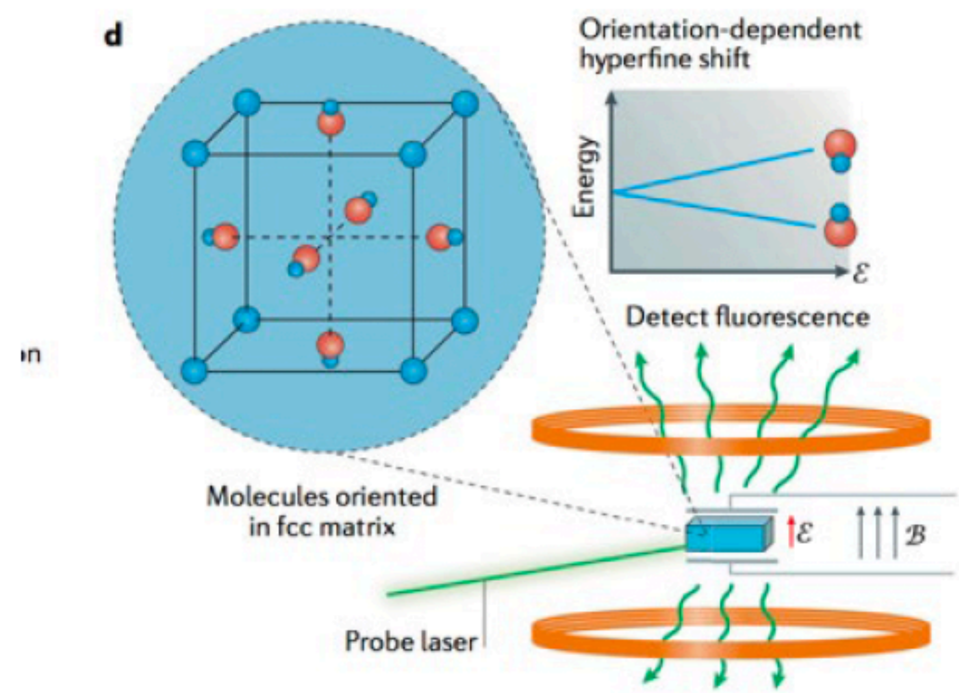
- Paramagnetic molecules confined in **long coherence time** conditions

One example: PHYDES experiment (CSN V)









Axions

- QCD should show CPV
  - Large non-perturbative CP violating interactions from QCD $\Rightarrow$ large n EDM
  - **Not seen!** Θ extremely small: naturalness problem for the SM!
  - Peccei - Quinn solution: Θ is a field accounted by a new symmetry that becomes spontaneously broken (at very high energies!)
    - Axion field is goldstone boson of such a broken symmetry
    - Axion mass inversely proportional to this energy scale

- Axions and ALPs
  - Abundantly created during BB
    - Valid candidates for DM
    - Essentially a classical boson field today because of cosmic cooling

- Experimental axion search exploits axion coupling to matter and radiation
  - Coupling to magnetic fields (conversion to photons)
  - Interaction with spins
  - Induction of EDM on particles

Example: QUAX (CSN II)

Dark matter could be composed by sub eV mass particles - possible candidate: **the axion**

In a typical apparatus exploiting

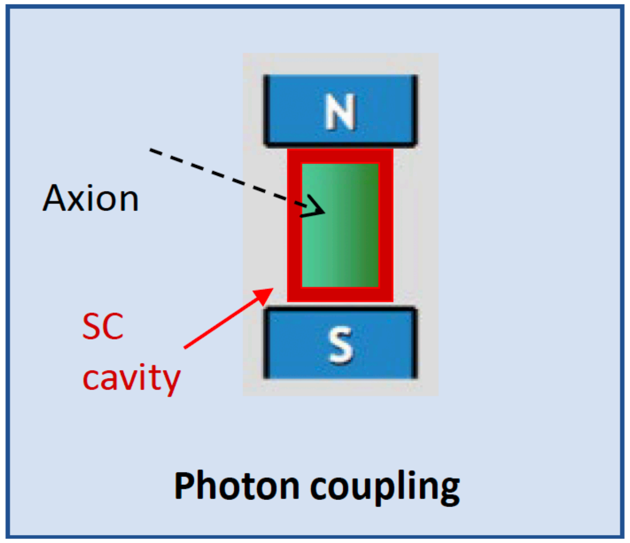
- strong magnetic fields (10 T)
- X band cavities (10 GHz)

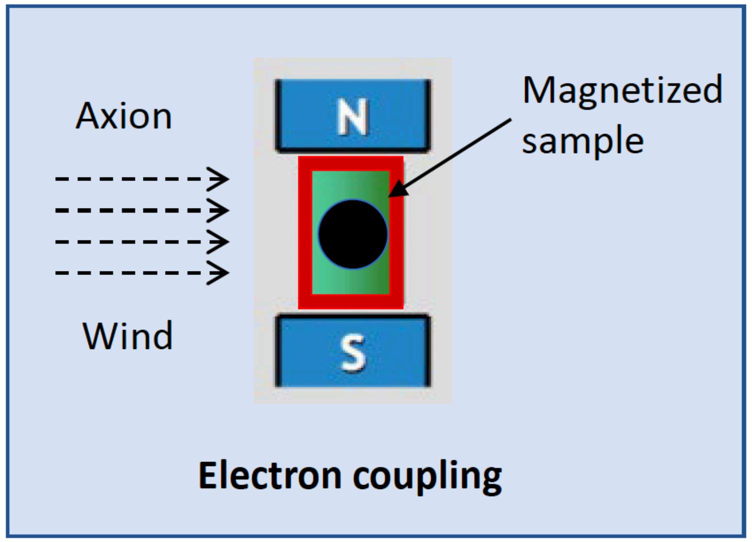
Look for excess powers in the cavity

$$P_{signal} \sim 10^{-23}\ \mathrm{W}$$

Such extremely low powers requires detection chain working at the quantum limit

Conversion of axions in resonant cavities immersed in a magnetic field





Sensitivity

$$\delta P_{\rm noise} = k_B T_N \sqrt{\frac{\Delta \nu_a}{\Delta t}},$$

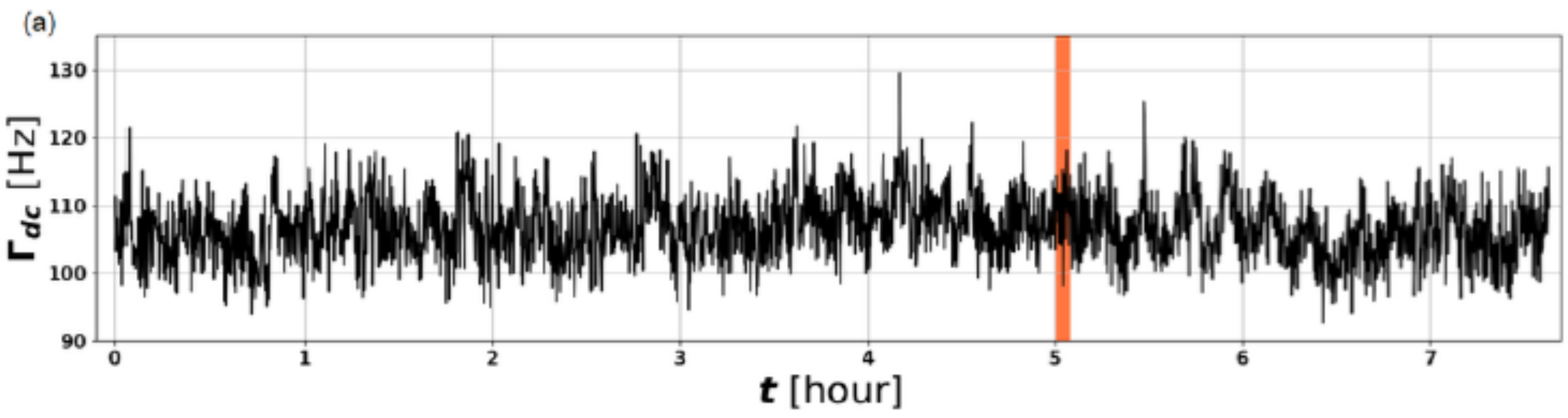
Noise temperature for a linear amplifier

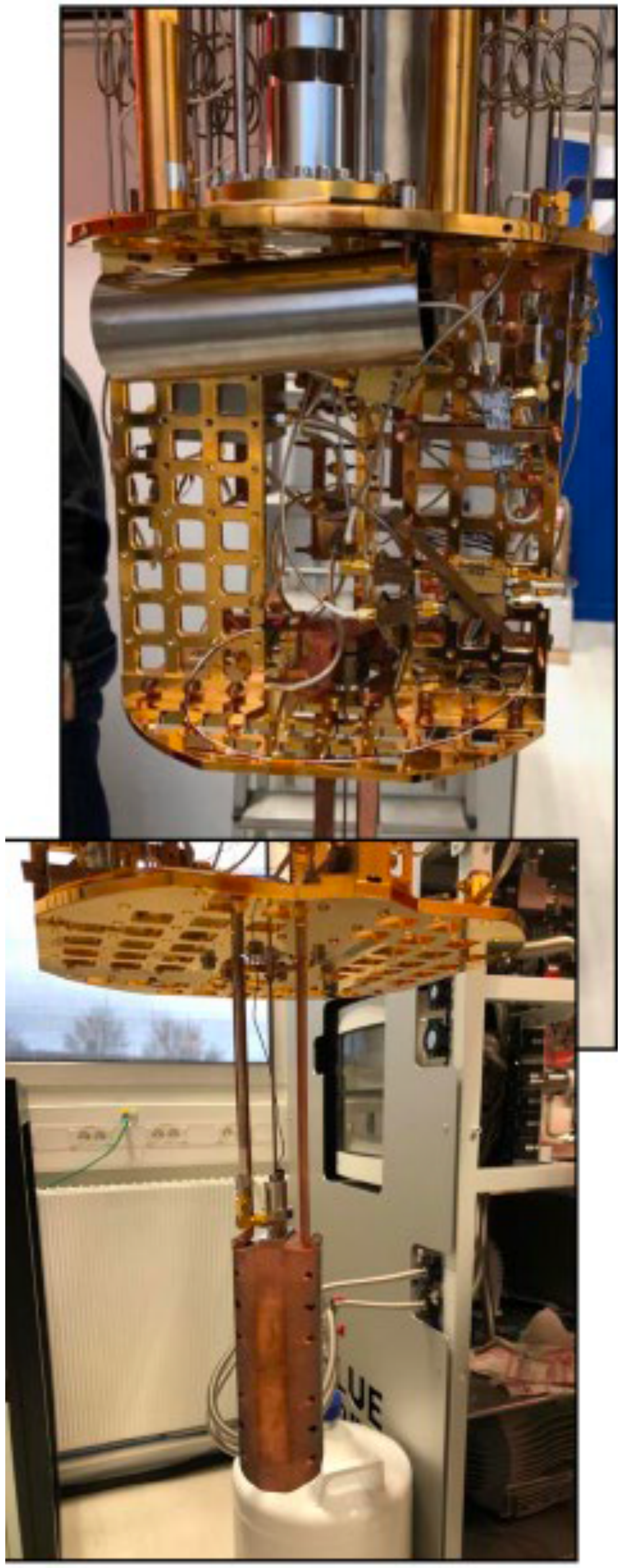
$$k_B T_N = h\nu\left(\frac{1}{e^{h\nu/k_B T}-1}+\frac{1}{2}\right)+k_B T_A.$$

- QUAX exploits both axion-electron couplings and axion-photon couplings, both close to quantum-limit
  - Electron: Josephson parametric amplifiers are the key tools
  - Photon: Wide Bandwidth Traveling Wave Parametric Amplifier
    - Calls for single photon counting at 10 GHz

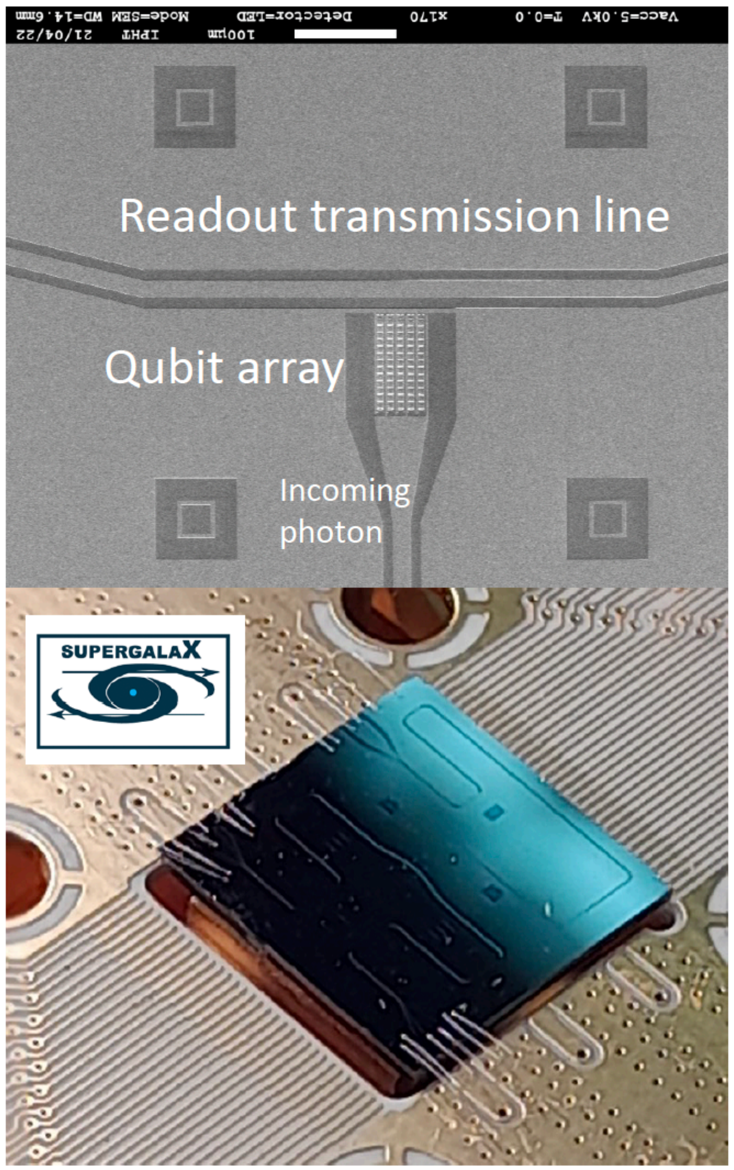
Microwave single photon counting

- Single Microwave Photon Detectors (SMPDs) developed in the context of Quantum Information Science have the potential to greatly improve the sensitivity and the search speed at haloscopes
  - A pilot experiment is ongoing with researchers from INFN (Padova, LNL) and the Quantronics group (CEA Saclay)
  - Tunable, high-Q cavity
  - Its TM_{010} mode $\nu_c \sim 7.3$ GHz is read-out by a SMPD

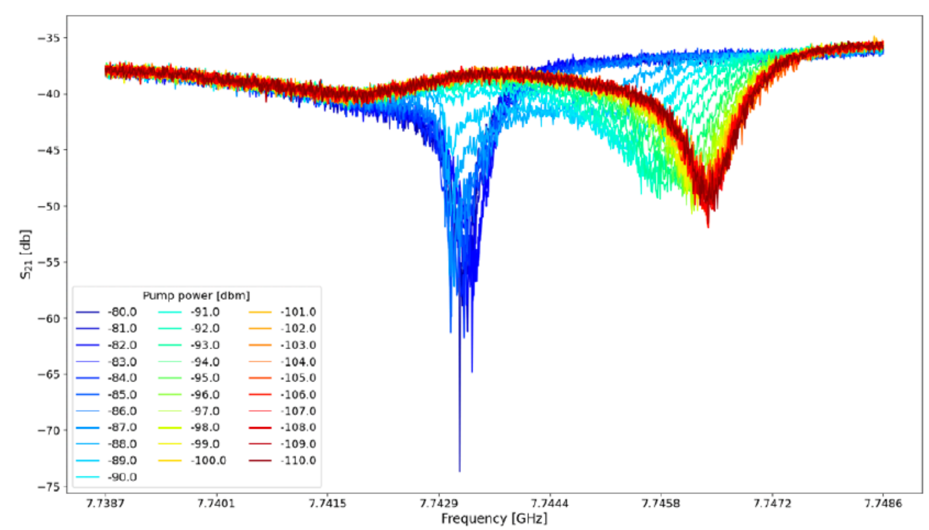




SMPD in axion DM search



Coherent Quantum Network of SC Qubits as a Highly Sensitive Detector of Microwave Photons

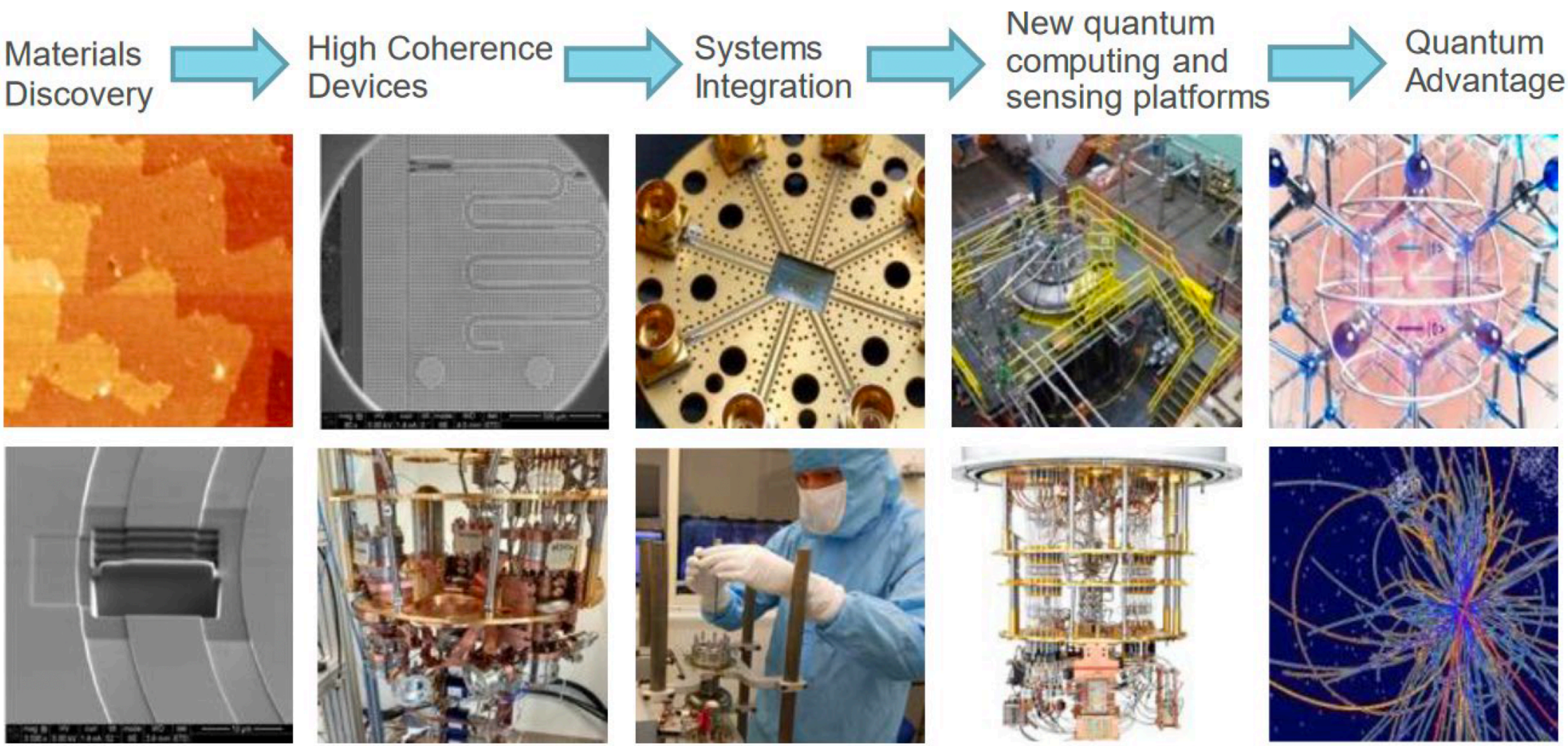


A substantial variation of the transmission properties was measured in a transistor-type detector based on 10 flux qubits when power was applied to the "base" terminal.

IEEE Transactions on Applied Superconductivity DOI 10.1109/TASC.2023.3263807

A key international agreement with DOE

SQMS Roadmap: from material discovery to quantum advantage



INFN is a contributing partner

INFN role in SQMS

- Theory + Technology challenge, driven by HEP technology
  - LNF, LNGS, LNL, GGI, Padua, Florence, Ferrara, Rome, Trieste, Milan-Bicocca (~30 people)

- Three Focus Areas + development of the QIS ecosystem (Workforce Development):
  - Focus Area 1
    - **Materials for 2D and 3D quantum systems**
      - Characterisation of SC components (e.g., cavities and qubits), including the assessment of the impact of environmental perturbation in the very **low radioactivity environment of the LNGS**
      - Development of appropriate mitigation techniques against environmental perturbation
  - Focus Area 2
    - **Quantum Device Integration, Prototypes and QPUs**
      - mK State-of-the-art cryogenics, low-noise facility for the characterisation and test of quantum devices.
  - Focus Area 3
    - **Quantum Physics & Sensing, INFN contributes in:**
      - Improvements to the design and sensitivity of haloscope detectors at high frequency (~10 GHz), including the continued development of high-Q cavities in high B fields.
      - Demonstration of the use of these detectors for Dark Matter searches.

  - **Theoretical support** for all areas and activities

Conclusions

- The explicit involvement in QT is **new** but its **roots are as old as the institute**

    - QT is seen as:
        - **a portal to new sensors** and devices for fundamental research
        - **a new computing tool** for fundamental research problems (lattice QCD e.g. but also data analysis)
        - **a probe to QM fundamentals** (theory and experiment)
        - **a new technology** to develop and transfer to industry and society

    - **Substantial investments** recently, also benefiting from PNRR

    - No conclusion, just the beginning of a beautiful long journey

Thank you. Have a nice, productive and beautiful week in Erice