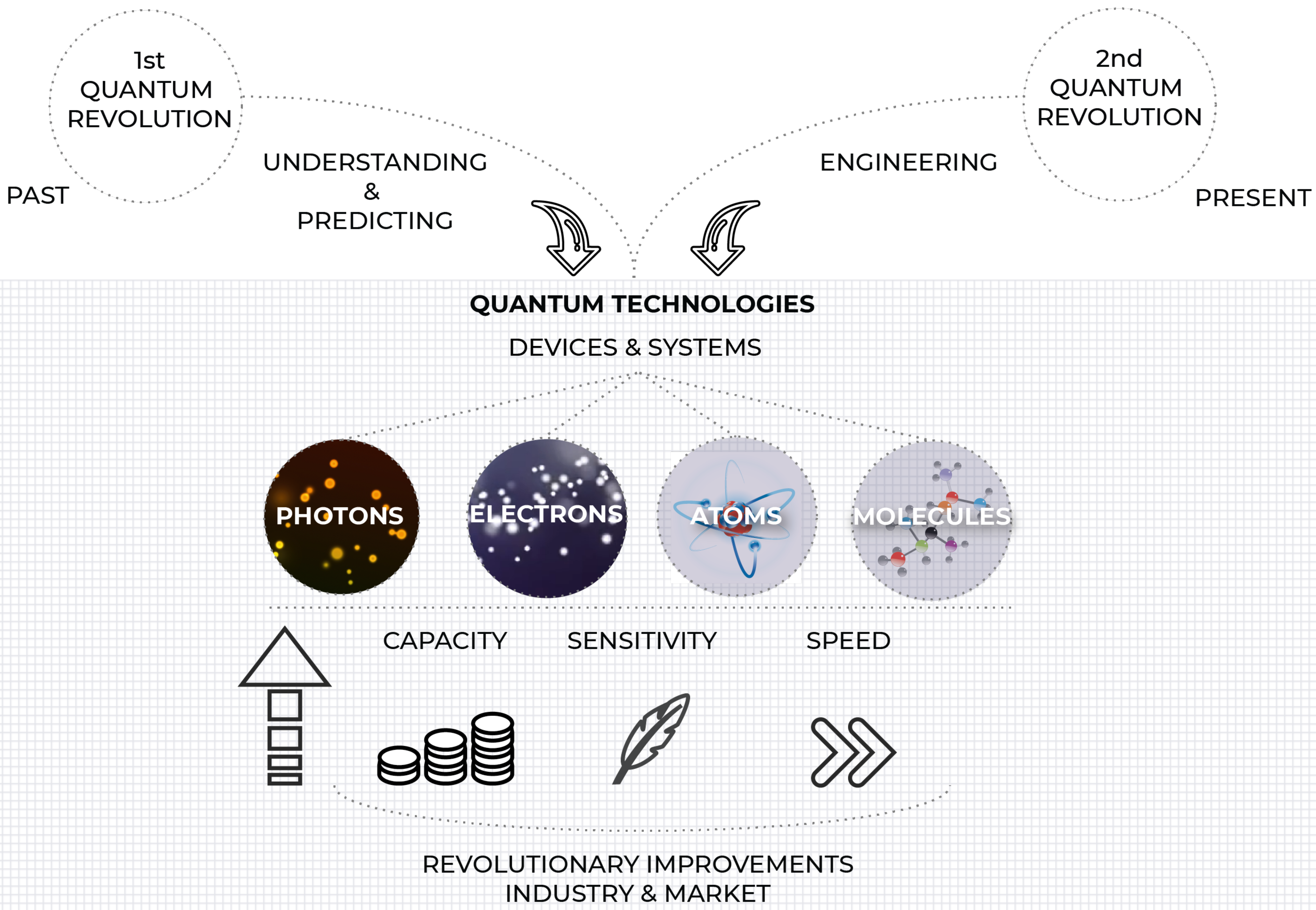
QUANTUM
FLAGSHIP

The Quantum Technologies Flagship

8 NOVEMBER 2019

Tommaso Calarco
Quantum Flagship Community Network

WHAT ARE QUANTUM TECHNOLOGIES?



1st QUANTUM REVOLUTION

PAST

UNDERSTANDING
&
PREDICTING

2nd QUANTUM REVOLUTION

PRESENT

ENGINEERING

QUANTUM TECHNOLOGIES

DEVICES & SYSTEMS

PHOTONS

ELECTRONS

ATOMS

MOLECULES

CAPACITY

SENSITIVITY

SPEED

REVOLUTIONARY IMPROVEMENTS
INDUSTRY & MARKET

QUANTUM TECHNOLOGY APPLICATIONS

Ultra-precise clocks

Navigation systems
Smart energy grids
Timestamp financial transactions

Medical Imaging Techniques

Nuclear magnetic imaging
Detailed visualization
Advancing Imaging Techniques

Quantum Key Distribution

Most Secure Communications
Eavesdropping detection

Quantum Computing

Machine Learning
Artificial Intelligence
Big data

Sensors

Oil and gas exploration
High-precision geodesy and navigation

Simulators

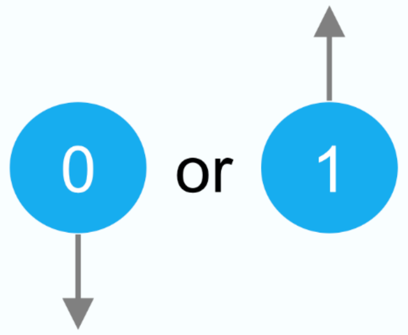
Quicker drug development
New materials

1 Because of two quantum phenomena, quantum computers can run many computations in fewer steps, making them potentially very fast and powerful

Qubits can form a running quantum computer through entanglement and superposition

Classical vs. quantum information

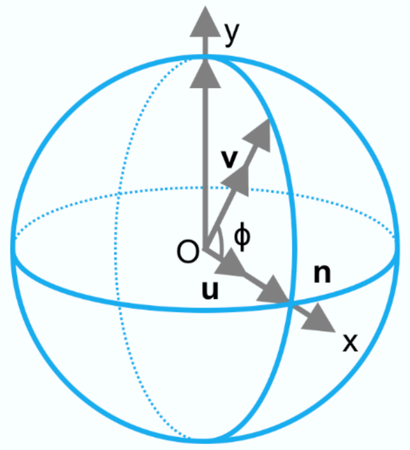
Classical



Discrete number of possible states: 0 or 1

Deterministic: repeated computations on the same input will lead to the same output

Quantum

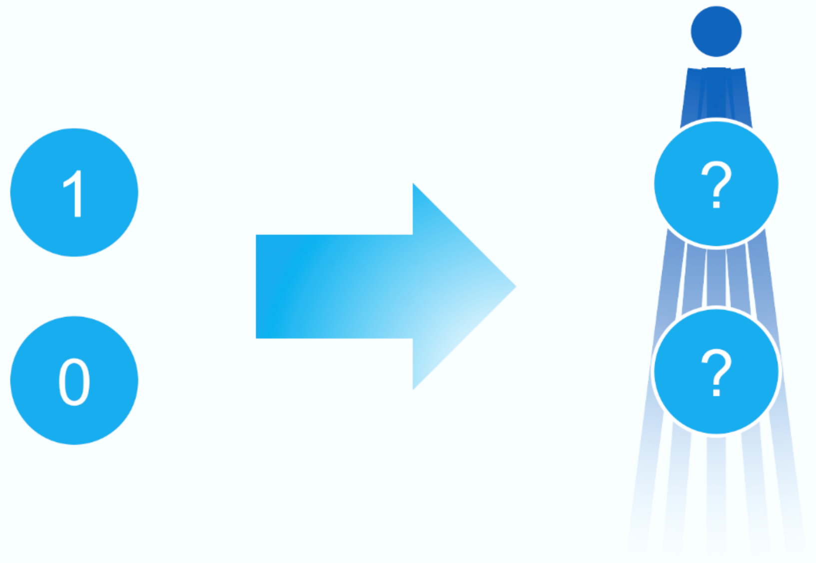


Infinite (continuous) number of possible states

Probabilistic: Measurements on superposed states yields probabilistic answers

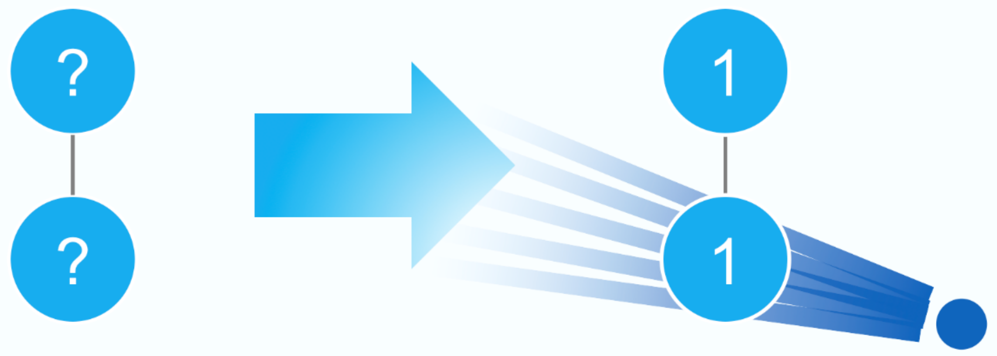
Entanglement – quantum systems communicate through space

Two unentangled Qubits



Entangled by e.g., laser manipulation; individual qubit values become indeterminate

Qubits can run calculations – operations on either qubit instantly affect the state of the other, regardless of distance



Measuring the values of either qubit (e.g., with laser light) breaks the entanglement and reveals both values

- Quantum computers use qubits to run calculations, relying on the **superposition** of states to exponentially **increase the amount of processable information – the more, the better**
- Calculations are run **during a short amount of time** in which two or more qubits are **entangled** – **the longer, the better**

SOURCE: Press search

1 The development of quantum computers started in 1982, but accelerated drastically in the past two years

NOT EXHAUSTIVE

1982
Richard Feynman formulates the vision of a quantum computer
"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

1999
EU invests €50-75 M in quantum technologies via FET program over next 7 years

2001
SK Telecom starts R&D on quantum communication

2005
Microsoft starts Station Q at UC Santa Barbara

2011
Lockheed Martin buys D-Wave 1[1] $10M

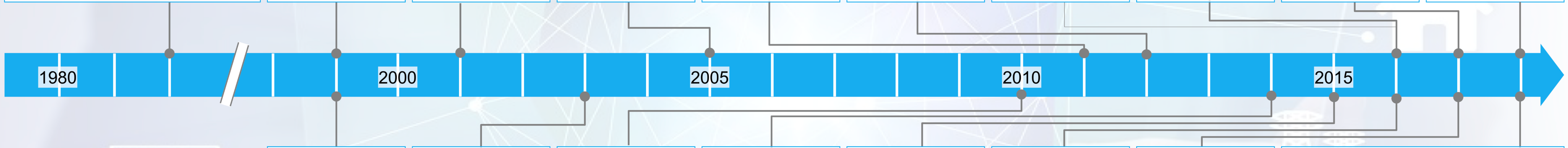
2012
1Qubit is founded

2016
Australian gov-ernment investing AUD$ 25 million investment over five years to the development of quantum com-puting hardware

2016
Canadian gov-ernment commits $ 76 millions to the University of Waterloo for quantum hard-ware and software

2017
- Volkswagen announcing co-develop-ment with Google
- Several dozens of startup are founded

2018
EU commission announces a US$ 1.13 billion project for support of a range of quantum technologies



1999
D-wave is founded

2003
DARPA launches the first quantum network

2010
Canadian government invests €78 M in quantum technologies over next 7 years

July 2014
IBM invests $3 B in research initiative that includes quantum computing

Sep 2015
Intel invests $50 M in QuTech Delft to develop a quantum computer

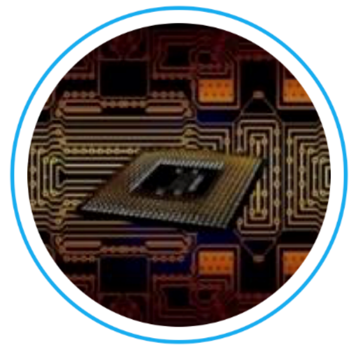
2016
IBM starts making their quantum computers available to the public for the first time with the IBM Q program

2017
1Qubit raises USD 45 mn from Accenture, Allianz and Fujitsu

2018
- DowDuPont announcing co-development with 1 qubit
- IBM and Google start to incubate and consolidate the start-up ecosystems

SOURCE: McKinsey analysis, expert interviews, press search

2 Four distinct quantum tools may enable use cases across industries – the capabilities rely on dedicated quantum algorithms

Quantum tool	Example
Quantum simulation for chemicals and materials 	▪ **Simulation of quantum systems for R&D on chemicals**, i.e. molecules, solids or polymers ▪ Scope ranging from **small molecules** up to huge **macro-molecules**, e.g., proteins ▪ Use of **variational quantum eigensolver** (VQE) and quantum subspace expansion (QSE) as algorithms
Optimization 	▪ Solving of **numeric** optimization **problems** with a **large number** of **variables**, e.g., in **manufacturing** and **finance** ▪ **Optimization** in business **operations** like **supply chain, logistics**
AI and machine learning 	▪ Better algorithms for **AI/machine learning** ▪ Potential applications in **manufacturing** or **pharma** (optimizing formulations, identifying APIs)
Prime factorization to crack/create encryption 	▪ **Handling of larger prime numbers** (factorization) ▪ **Encryption breaking** to get access to (military) intelligence ▪ Creation of safer communication systems and securing of critical data for finance ▪ Use of **Shor's** algorithm

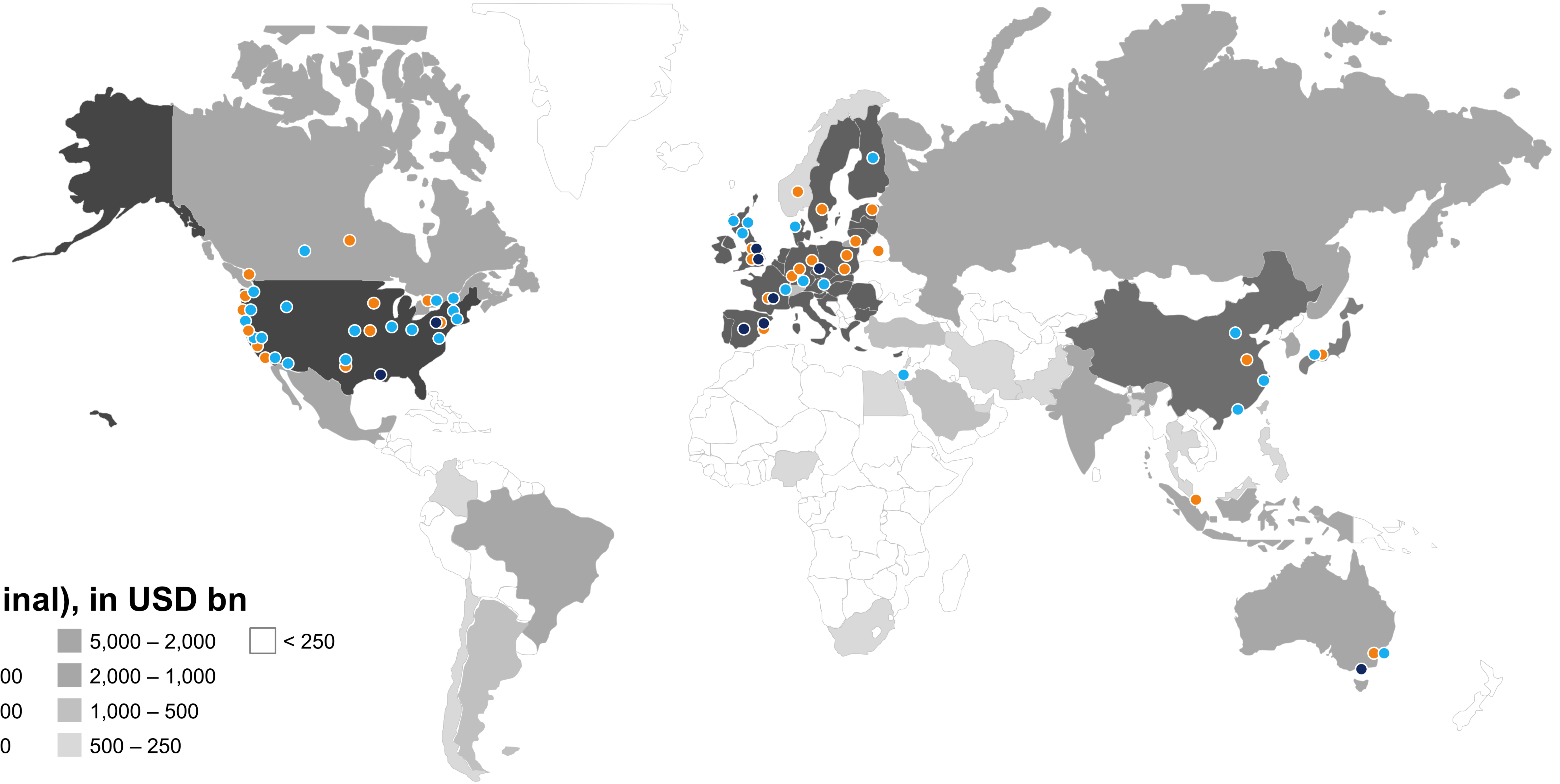
SOURCE: McKinsey analysis, expert interviews, press search

③ Plenty of players currently partake in quantum computing – the field is dominated by start-ups in Europe and North America

NOT EXHAUSTIVE

Where the quantum computing players are located in 2019 vs GDP (nominal)

● Software developer ● Hardware suppliers ● Enabling players



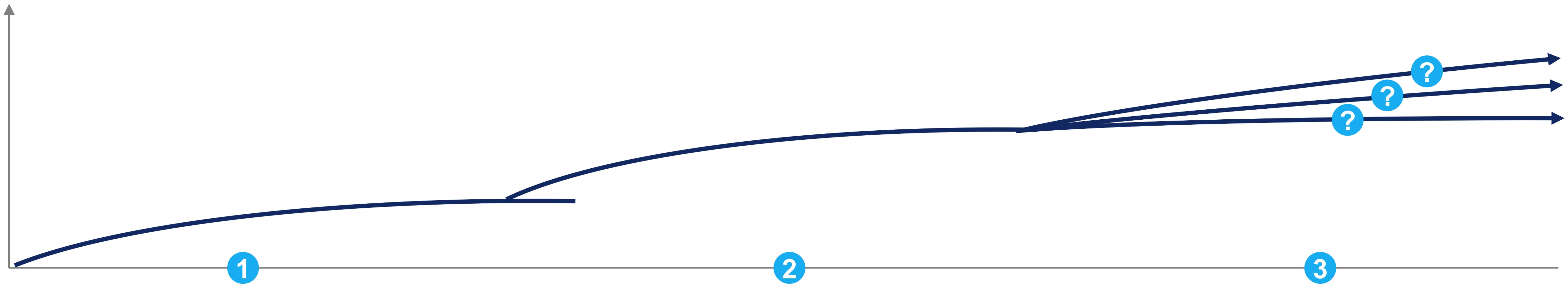
GDP (nominal), in USD bn

■ > 20,000	■ 5,000 – 2,000	☐ < 250
■ 20,000 – 15,000	■ 2,000 – 1,000	
■ 15,000 – 10,000	■ 1,000 – 500	
■ 10,000 – 5,000	■ 500 – 250	

More than 100 startups and established players across four continents offer services to potential QC software users, their scope covering a broad range of industries – currently, the players are mainly emerging in Western high-tech regions

SOURCE: McKinsey analysis, International Monetary Fund (2018), expert interviews, press search

④ The quantum computing market is likely to develop in distinct phases – by the early-to-mid 2020ies, a critical window will be reached

Window	**Early stage: Incubation** (1981 - 2020)	**NISQ[1] era: Midterm market development** (2020-2030)	**Universal quantum computing: Full value creation** (2030 onwards)
Maturity			
Key activities	**Target :** Basic research and echnology development ▪ Academic and 1st commercial R&D activities ▪ Disruptive changes occur	**Target :** Commercialization wherever QC can bring early value ▪ Commercial R&D and business development ▪ Disruptive and incremental changes occur	**Target :** Bring QC to the masses, maximize value and reduce cost ▪ Upscale and rollout to serve late adopters ▪ Incremental changes dominate
Source of funding	**Only governments or pioneers invest**	**QC is financed by corporate R&D budgets, VCs and governments**	**Value-based pricing**

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1 noisy intermediate-scale quantum computers, a concept coined by John Preskill

SOURCE: McKinsey analysis

THE QUANTUM FLAGSHIP

culmination point uniting ***all*** stakeholders

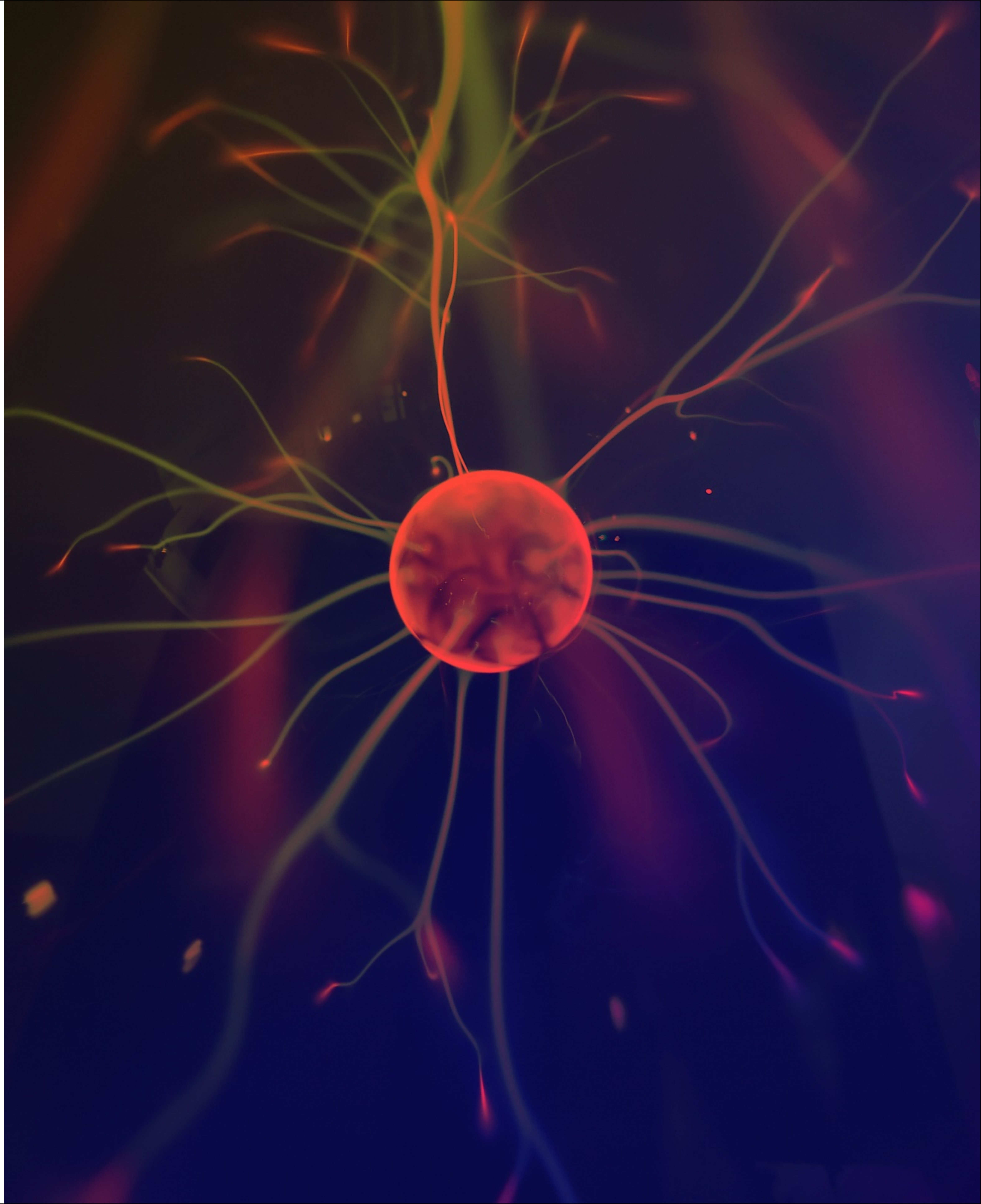
A long-term, large-scale research initiative

Foster world-leading knowledge and skills

Bring quantum technologies from the **lab** to the **market**

Develop technologies and open research facilities for quantum in Europe

Bring together research institutions, academia, industry, enterprises, and policy makers, in a joint and **collaborative initiative** on an unprecedented scale



GOALS

FLAGSHIP'S VISION FOR QUANTUM TECHNOLOGIES IN EUROPE

Consolidate and **expand** European **scientific leadership** and **excellence** in quantum research

Kick-start a **competitive** European industry in quantum technologies and position Europe as a **leader** in the future global industrial landscape

Make **Europe** a **dynamic** and **attractive** region for innovative **research**, **business** and **investments** in quantum technologies

THE QUANTUM FLAGSHIP AT A GLANCE

European Commission

October 2018

2000+
experts

10 years

1 billion €

2018-2021
Ramp-up phase

152 million €

141 proposals

20 projects

APPLICATION PILLARS

4 projects

QUANTUM Communication

For a Secure Digital Society and a Quantum-enabled Internet

Quantum Internet - secure communication and applications

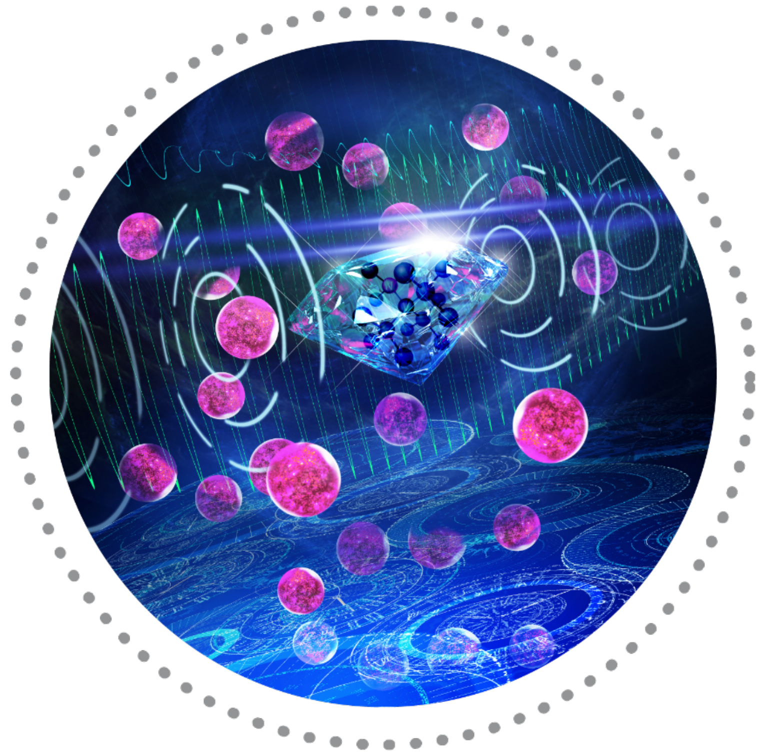
2 projects

QUANTUM Simulation

Simulating Complex Systems for Advanced Design and Development

By 2021 quantum simulators 20x more precise

4 projects



QUANTUM Sensing metrology

Bringing Accuracy And Performance To Unprecedented Levels

By 2021, sensors with resolution 1000x better

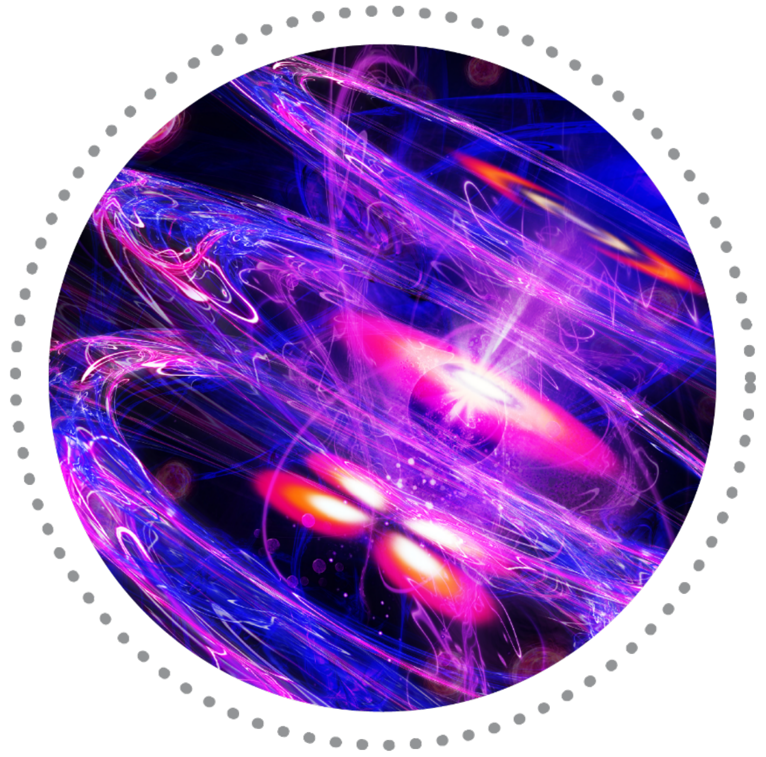
2 projects

QUANTUM Computing

Computing Power To Overcome Currently Unsolvable Problems

By 2021, quantum computers of 50-100 qubits demonstrating first quantum applications

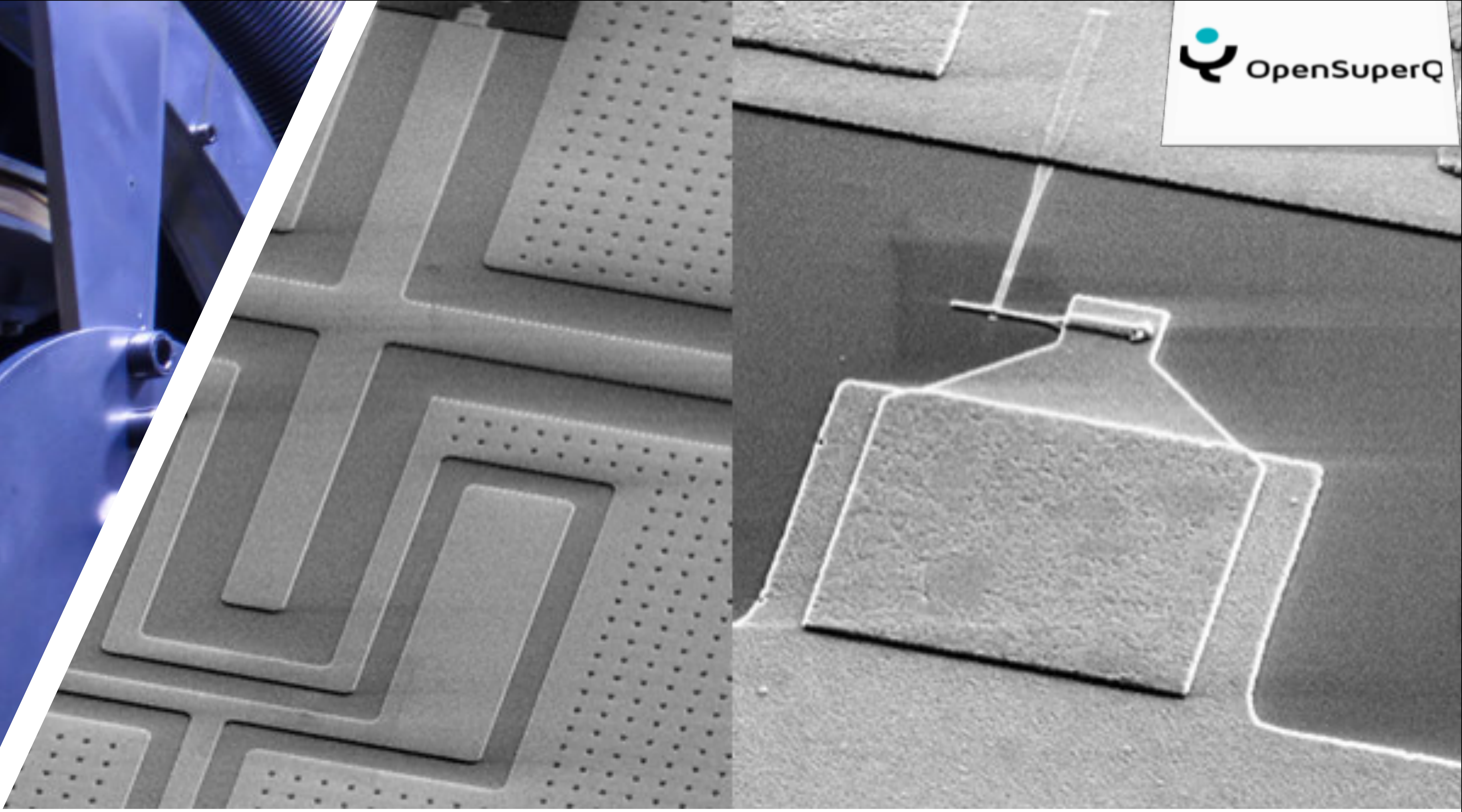
7 projects



QUANTUM Basic science

Addressing Foundational Challenges For Development Of Quantum Technologies

Discover & understand new fundamental quantum principles



QUANTUM Computing

2 projects

PROJECT: AQTION
(Advanced quantum computing with trapped ions)
Coordinating Institution:
UNIVERSITAET INNSBRUCK
Coordinator: Thomas Monz

PROJECT: OpenSuperQ
(An Open Superconducting Quantum Computer)
Coordinating Institution:
UNIVERSITAT DES SAARLANDES
Coordinator: Frank Wilhelm-Mauch

QUANTUM Communication

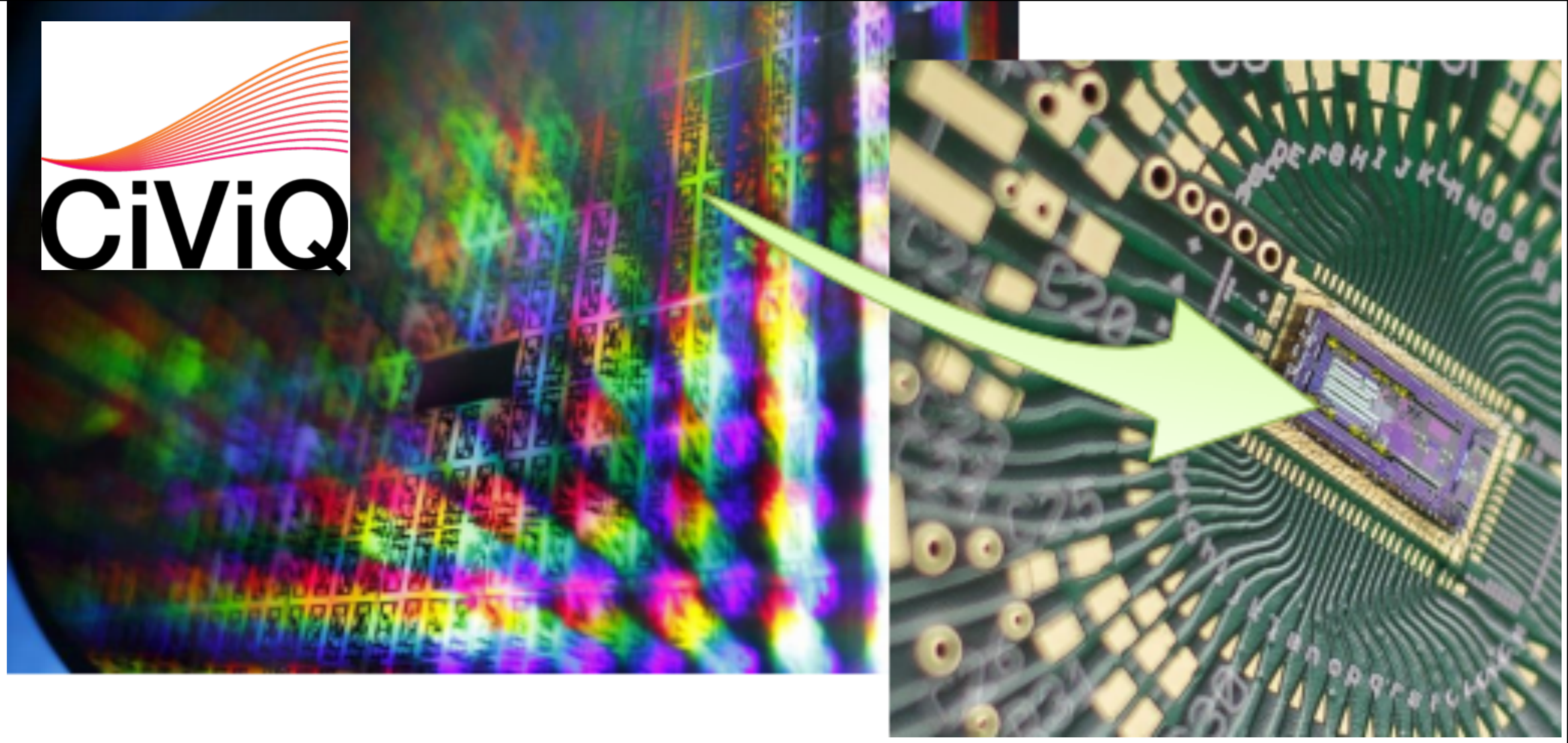
4 projects

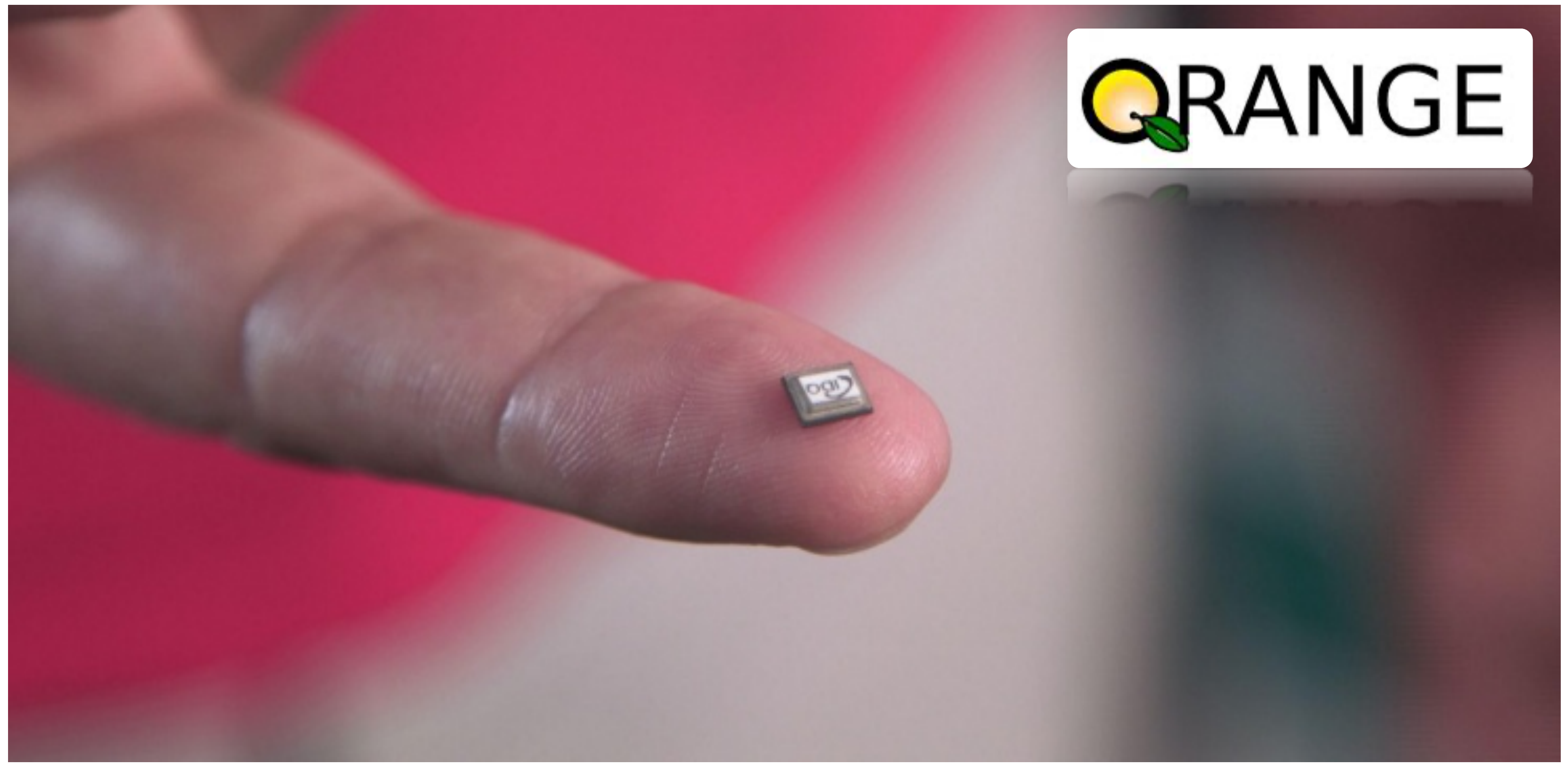
PROJECT: CiViQ
(Continuous Variable Quantum Communications)
Coordinating Institution:
ICFO - THE INSTITUTE OF PHOTONIC SCIENCES
Coordinator: Valerio Pruneri

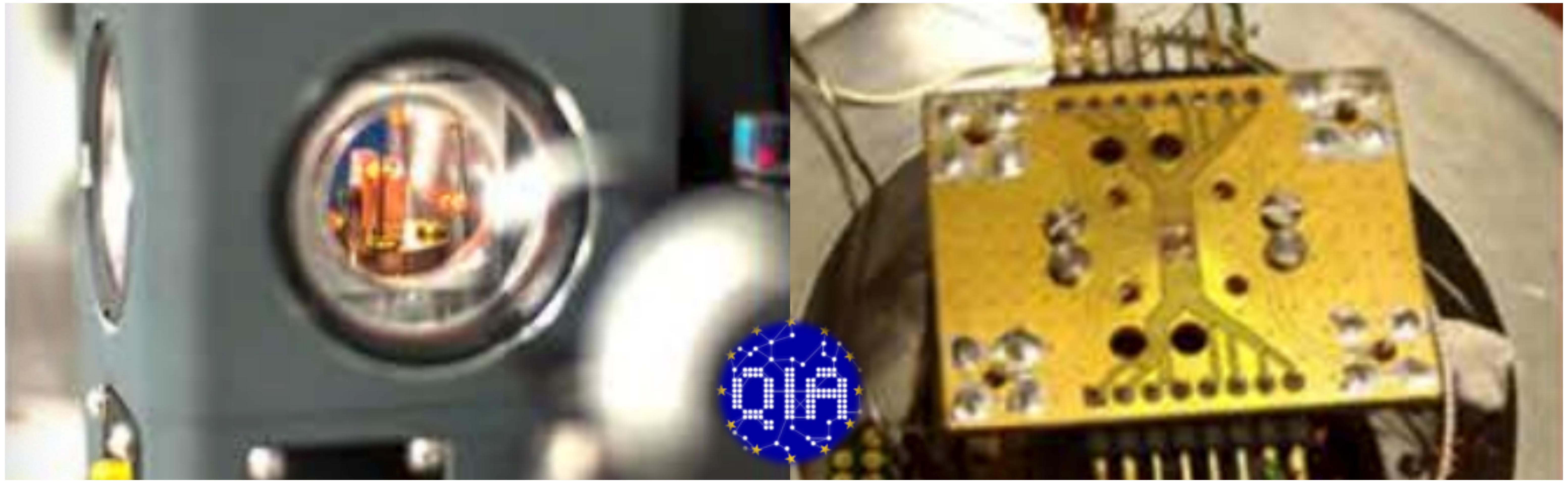
PROJECT: QIA
(Quantum Internet Alliance)
Coordinating Institution:
TECHNISCHE UNIVERSITEIT DELFT
Coordinator: Stephanie Wehner

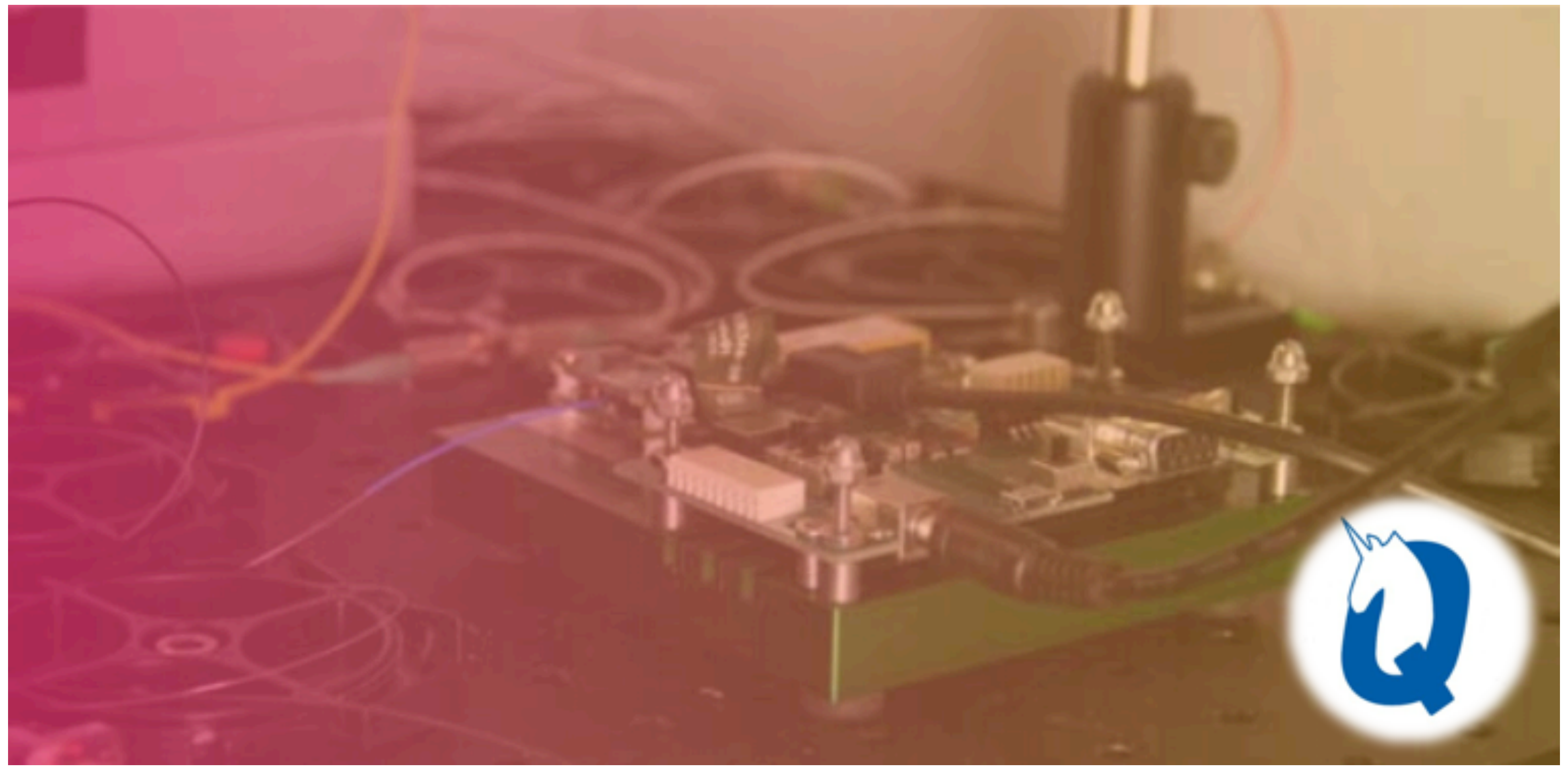
PROJECT: QRANGE
(Quantum Random Number Generators: cheaper, faster and more secure)
Coordinating Institution:
UNIVERSITE DE GENEVE
Coordinator: Hugo Zbinden

PROJECT: UNIQORN
(Affordable Quantum Communication for Everyone: Revolutionizing the Quantum Ecosystem from Fabrication to Application)
Coordinating Institution:
AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH
Coordinator: Hannes Hübel









QUANTUM Simulations

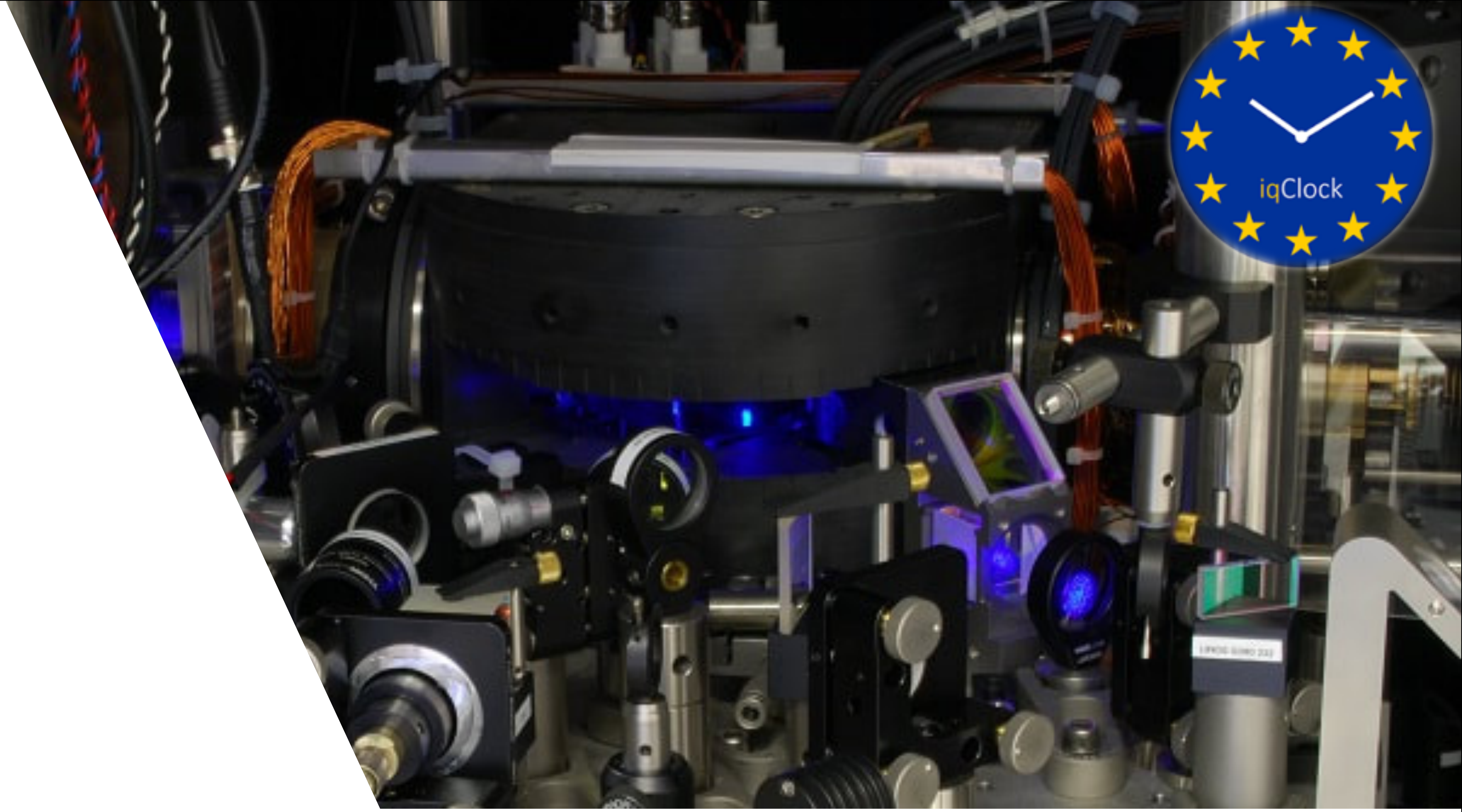
2 projects

PROJECT: PASQuanS
(Programmable Atomic Large-Scale Quantum Simulation)
Coordinating Institution:
MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTEN EV
Coordinator: Immanuel Bloch

PROJECT: Qombs
(Quantum simulation and entanglement engineering in quantum cascade laser frequency combs)
Coordinating Institution:
CONSIGLIO NAZIONALE DELLE RICERCHE
Coordinator: Augusto Smerzi

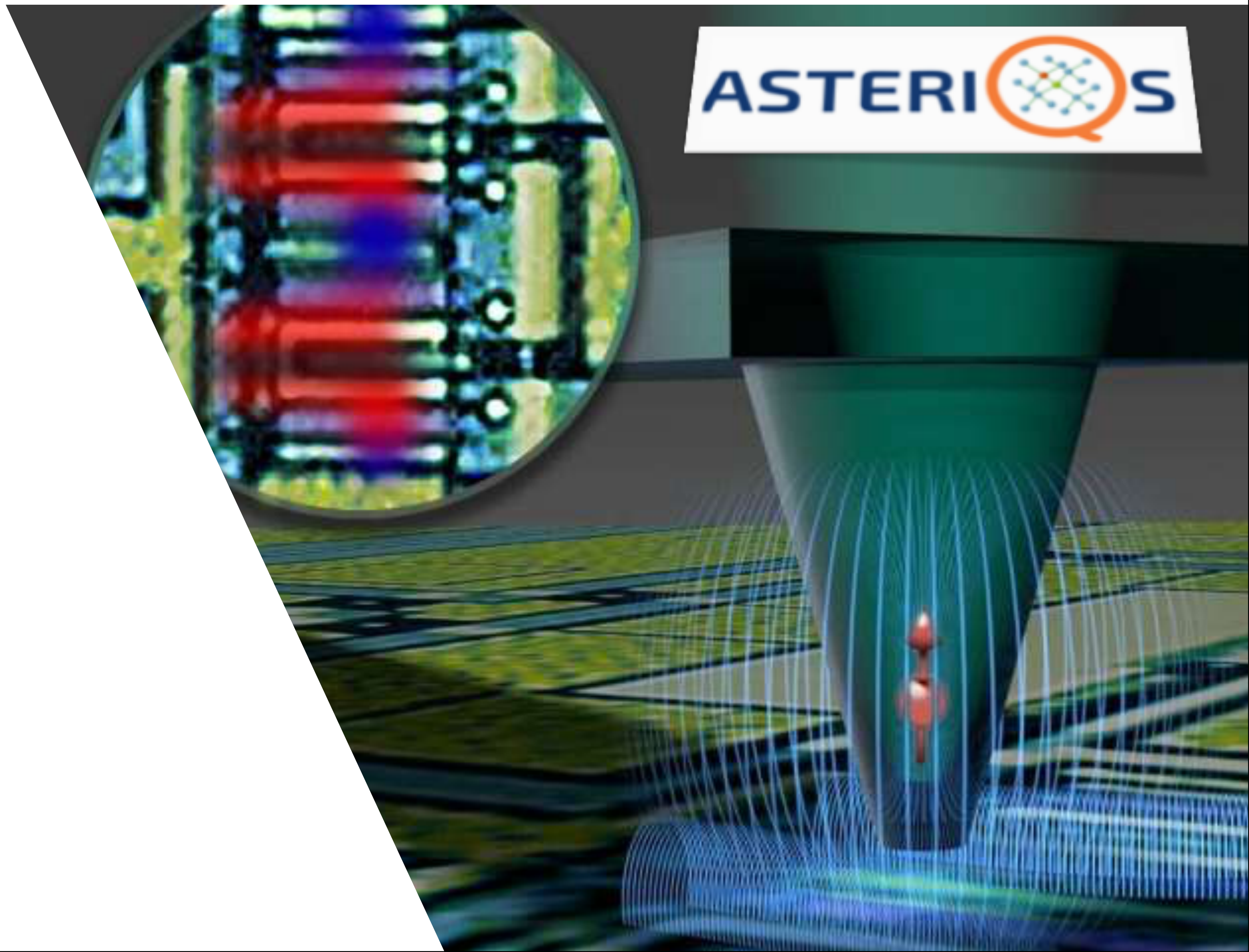
4 projects

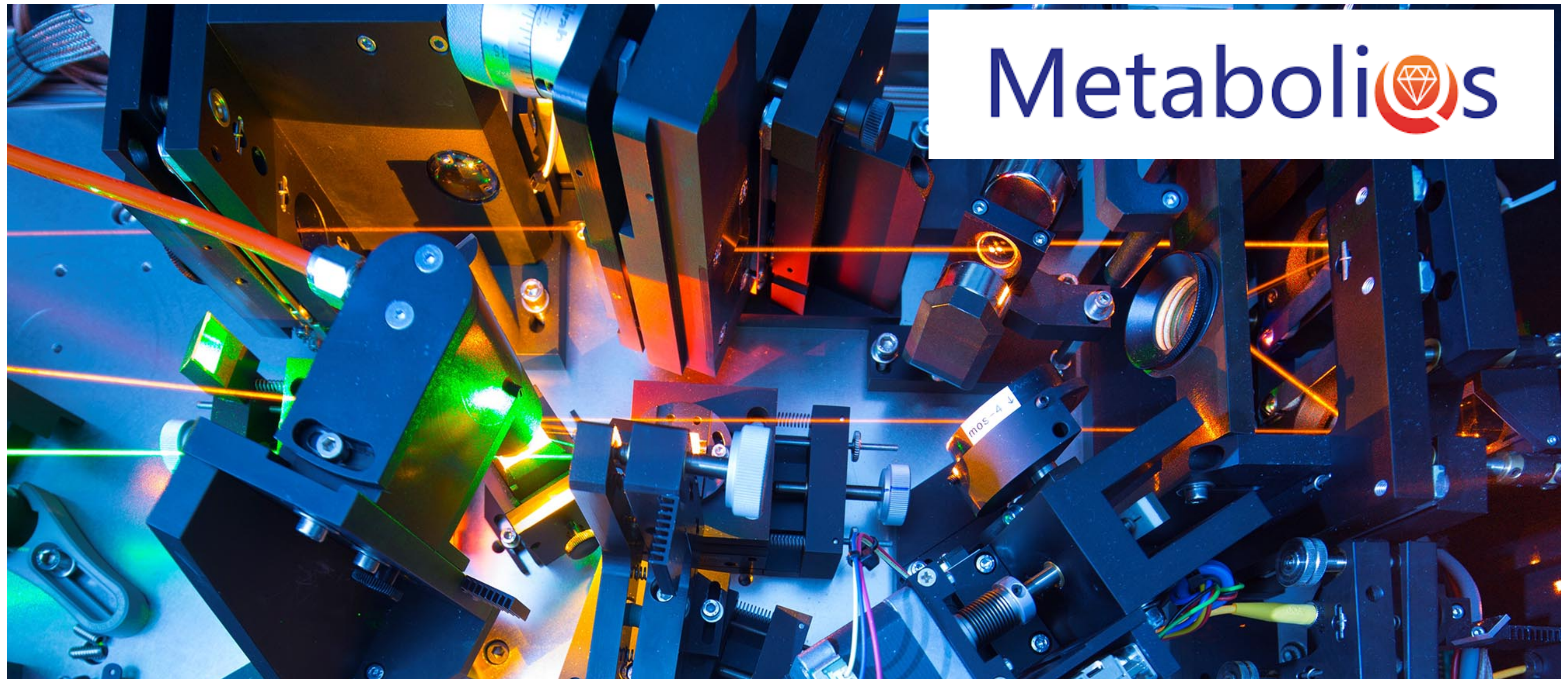
QUANTUM Sensing and Metrology



PROJECT: ASTERIQS
(Advancing Science and TEchnology thRough dIamond Quantum Sensing)
Coordinating Institution:
THALES SA
Coordinator: Thierry Debuisschert

PROJECT: iqClock
(Integrated Quantum Clock)
Coordinating Institution:
UNIVERSITEIT VAN AMSTERDAM
Coordinator: Florian Schreck





4 projects

QUANTUM Sensing and Metrology

PROJECT: MetaboliQs

(Leveraging room temperature diamond quantum dynamics to enable safe, first-of-its-kind, multimodal cardiac imaging)

Coordinating Institution:

FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.

Coordinator: Christoph Nebel

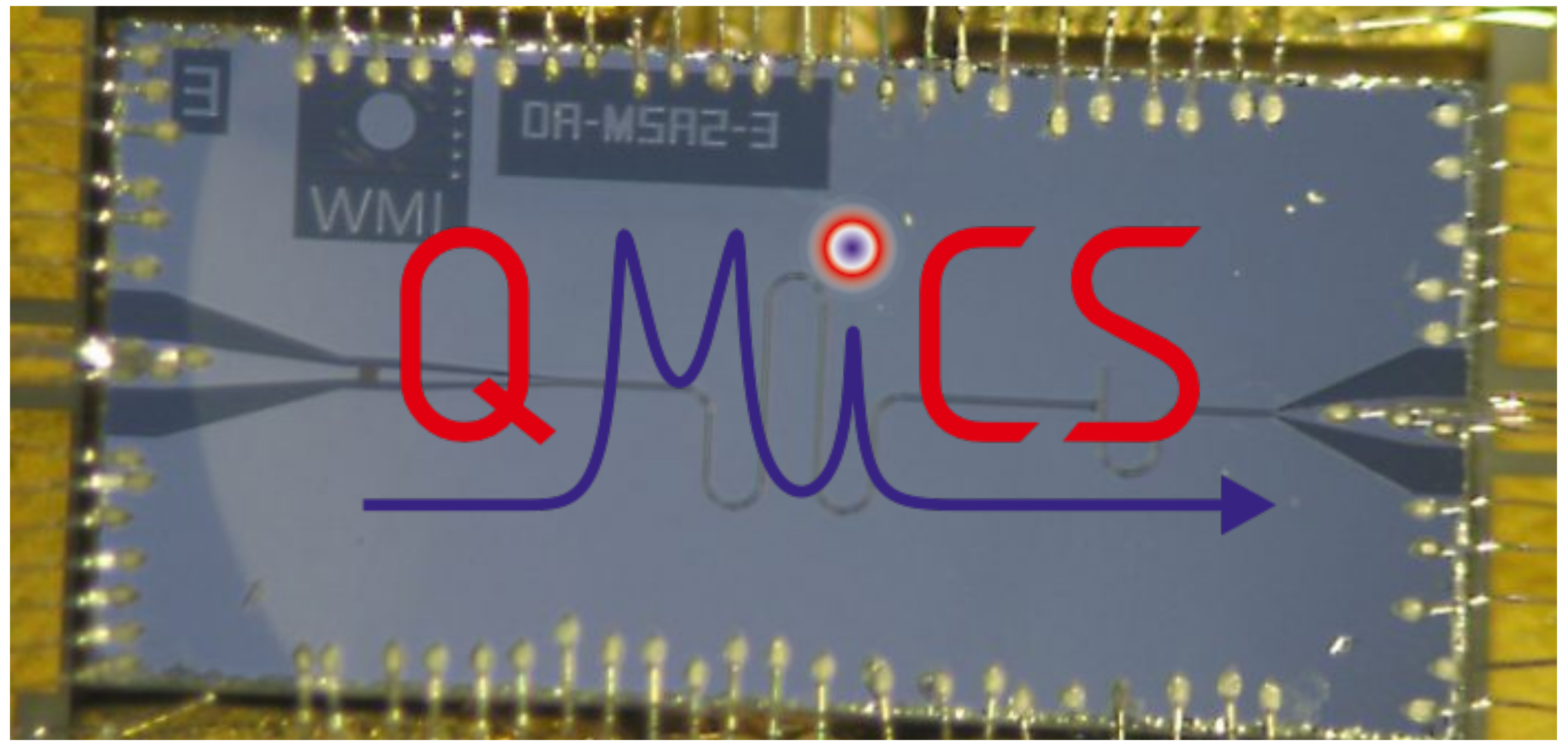
PROJECT: macQsimal

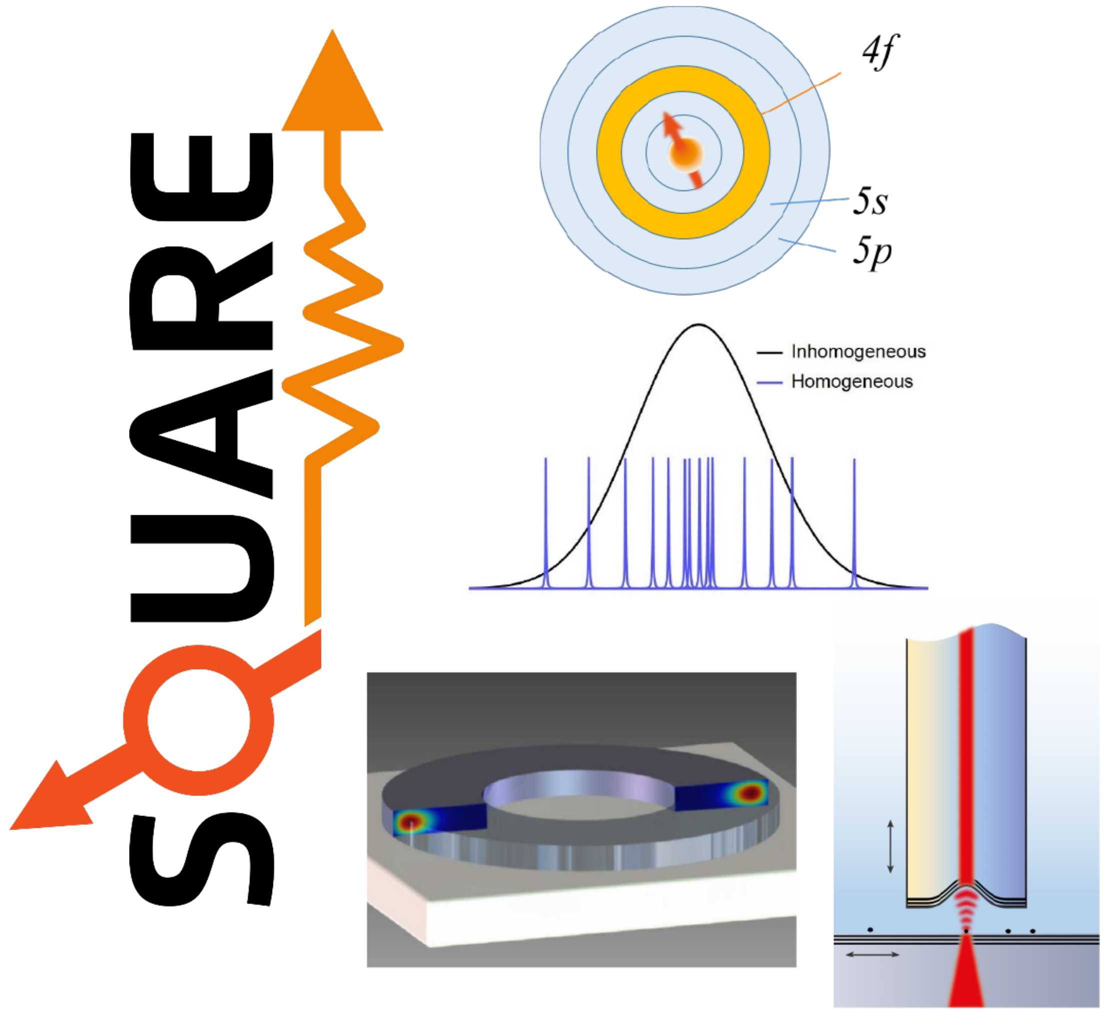
(Miniature Atomic vapor-Cells Quantum devices for SensIng and Metrology AppLications)

Coordinating Institution:

CSEM CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT

Coordinator: Jacques Haesler





QUANTUM Basic Science

7 projects

PROJECT: S2QUIP

(Scalable Two-Dimensional Quantum Integrated Photonics)

Coordinating Institution:

KUNGLIGA TEKNISKA HOEGSKOLAN

Coordinator: Klaus Jöns

PROJECT: 2D-SIPC

(Two-dimensional quantum materials and devices for scalable integrated photonic circuits)

Coordinating Institution:

ICFO - THE INSTITUTE OF PHOTONIC SCIENCES

Coordinator: Dmitri Efetov

PROJECT: QMiCS

(Quantum Microwave Communcation and Sensing)

Coordinating Institution:

BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Coordinator: Frank Deppe

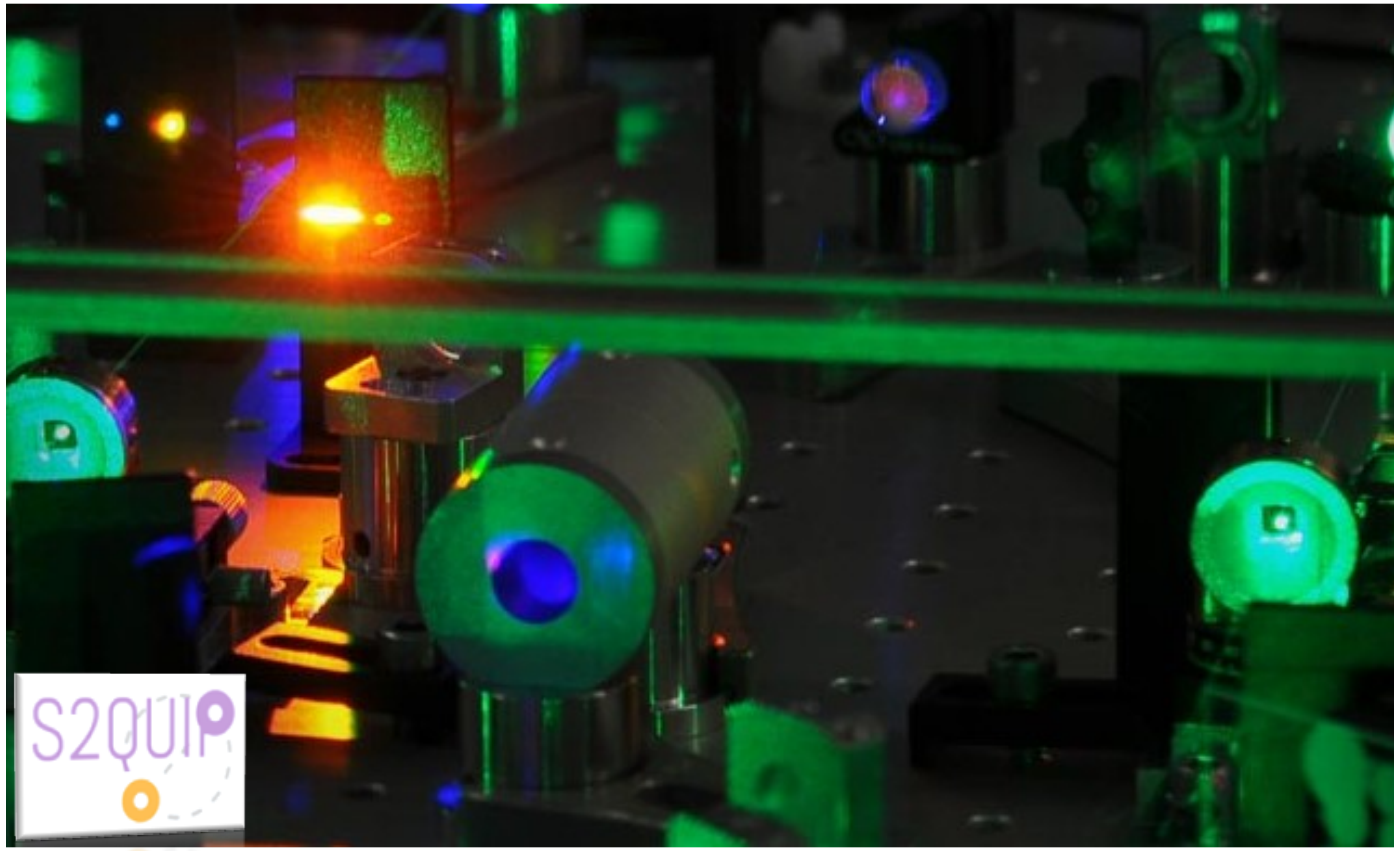
PROJECT: SQUARE

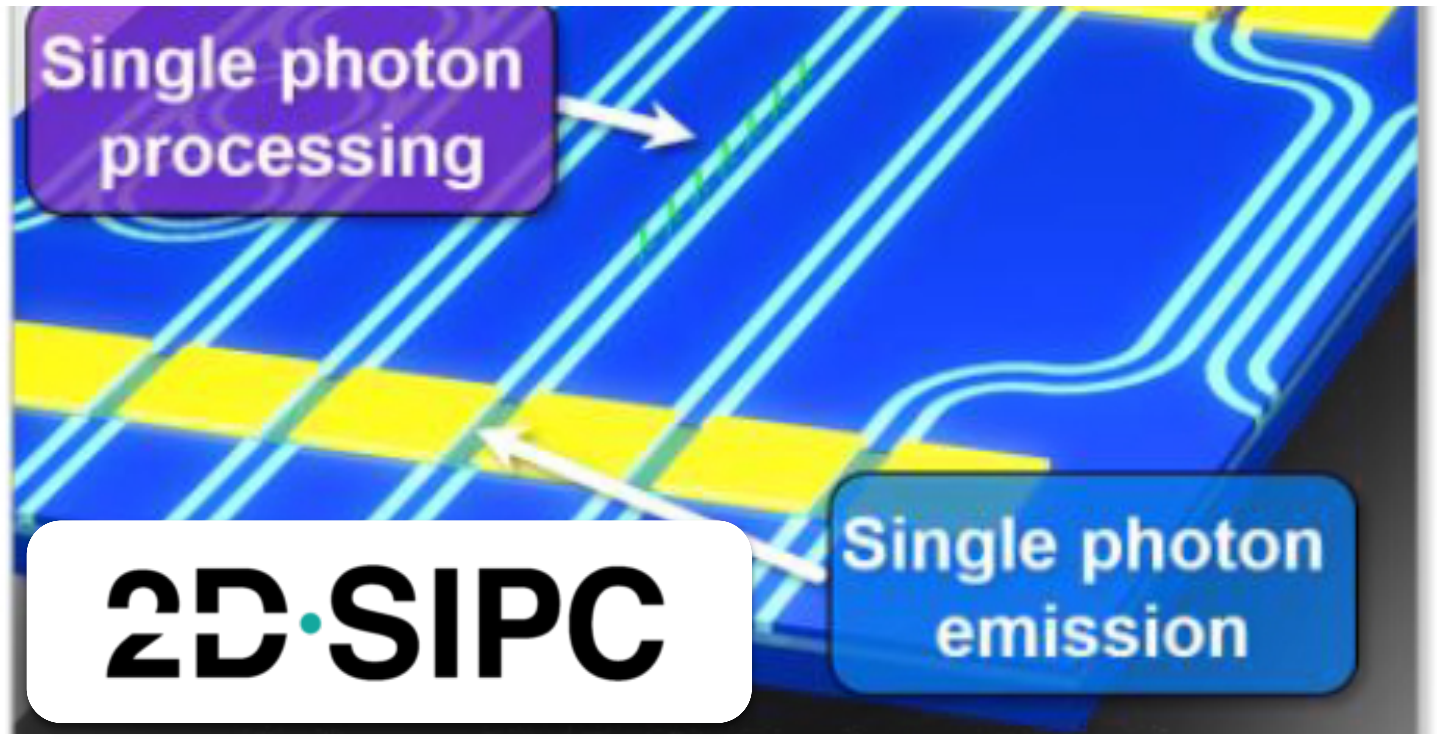
(Scalable Rare Earth Ion Quantum Computing Nodes)

Coordinating Institution:

KARLSRUHER INSTITUT FUER TECHNOLOGIE

Coordinator: David Hunger





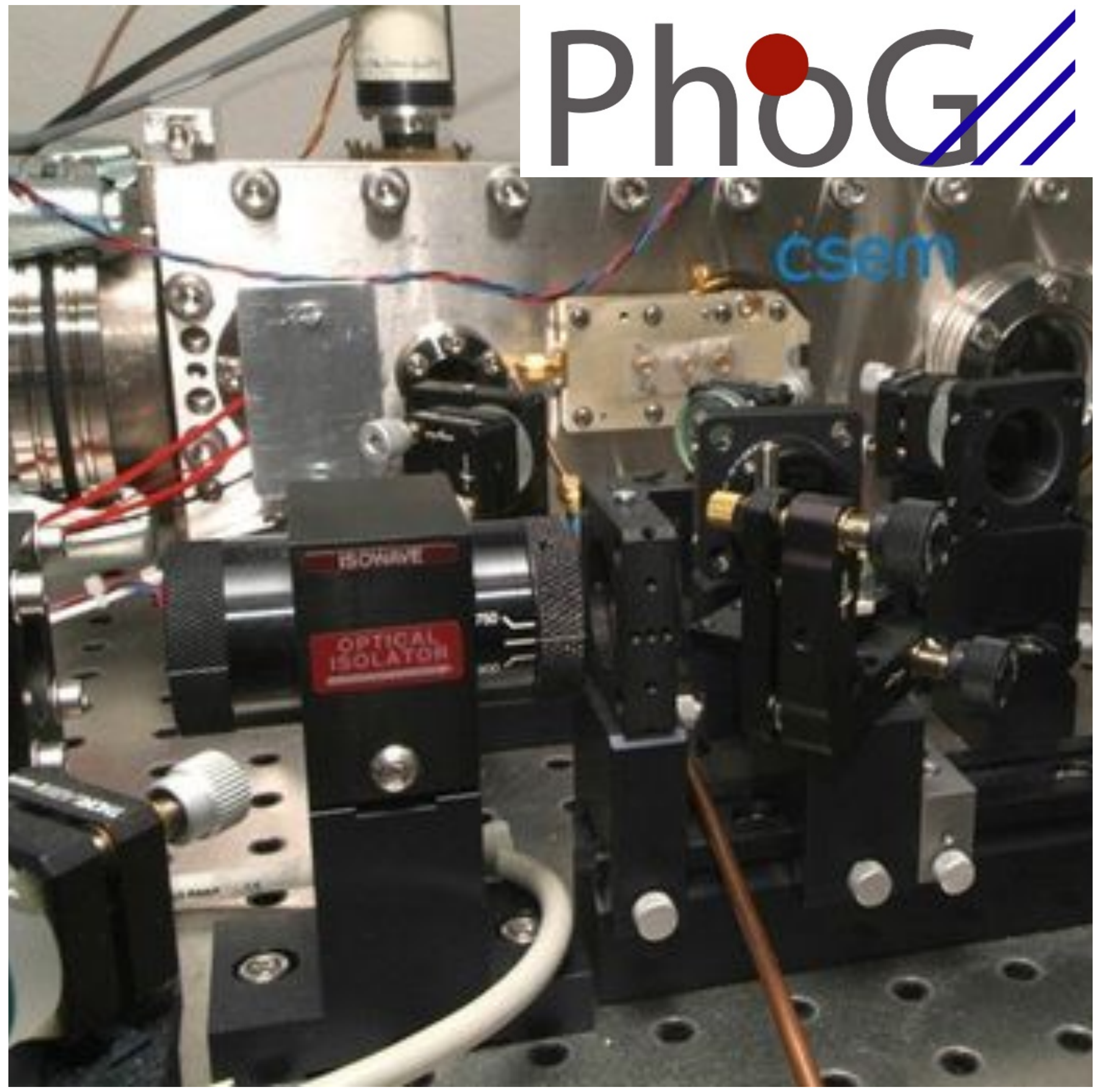
QUANTUM Basic Science

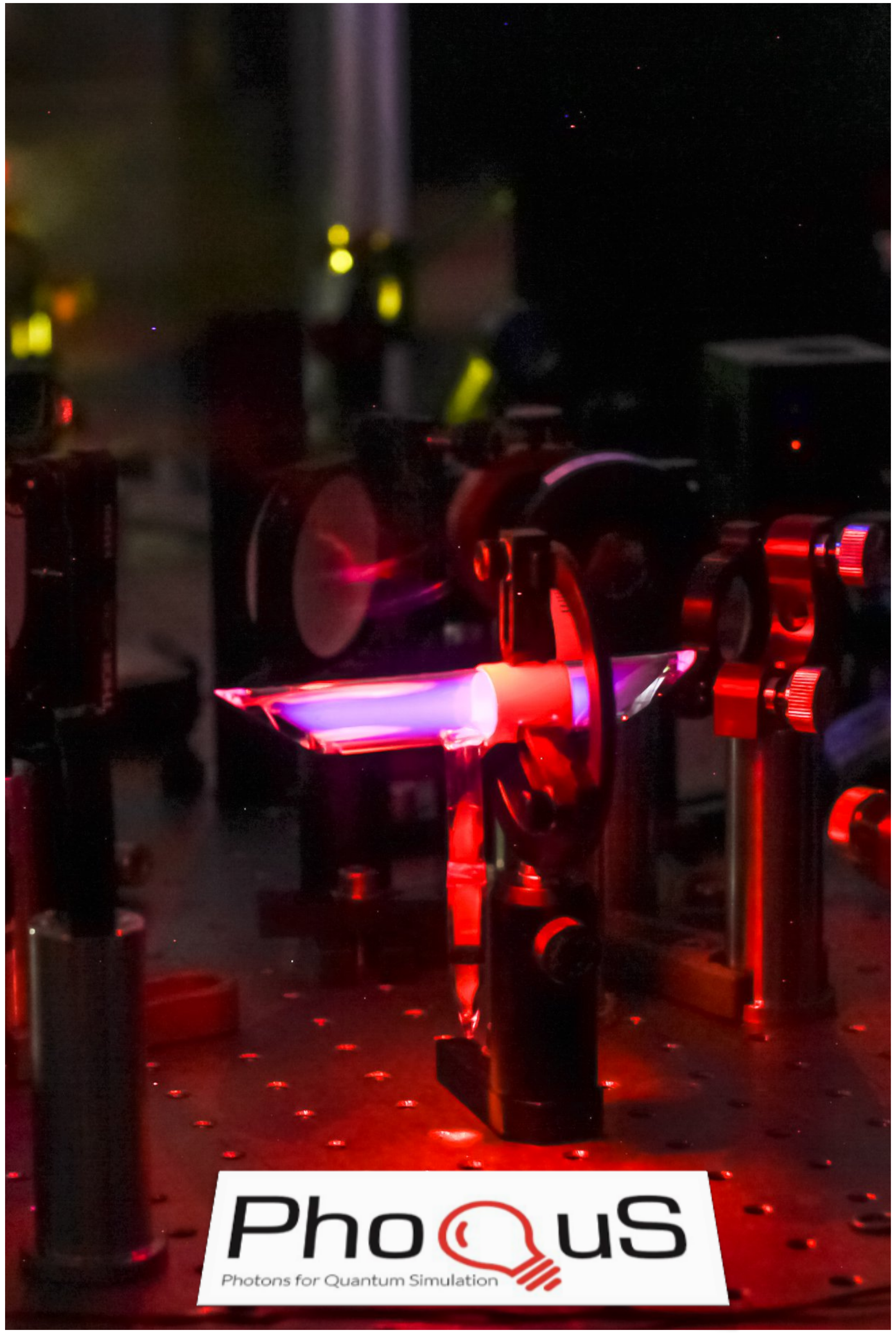
7 projects

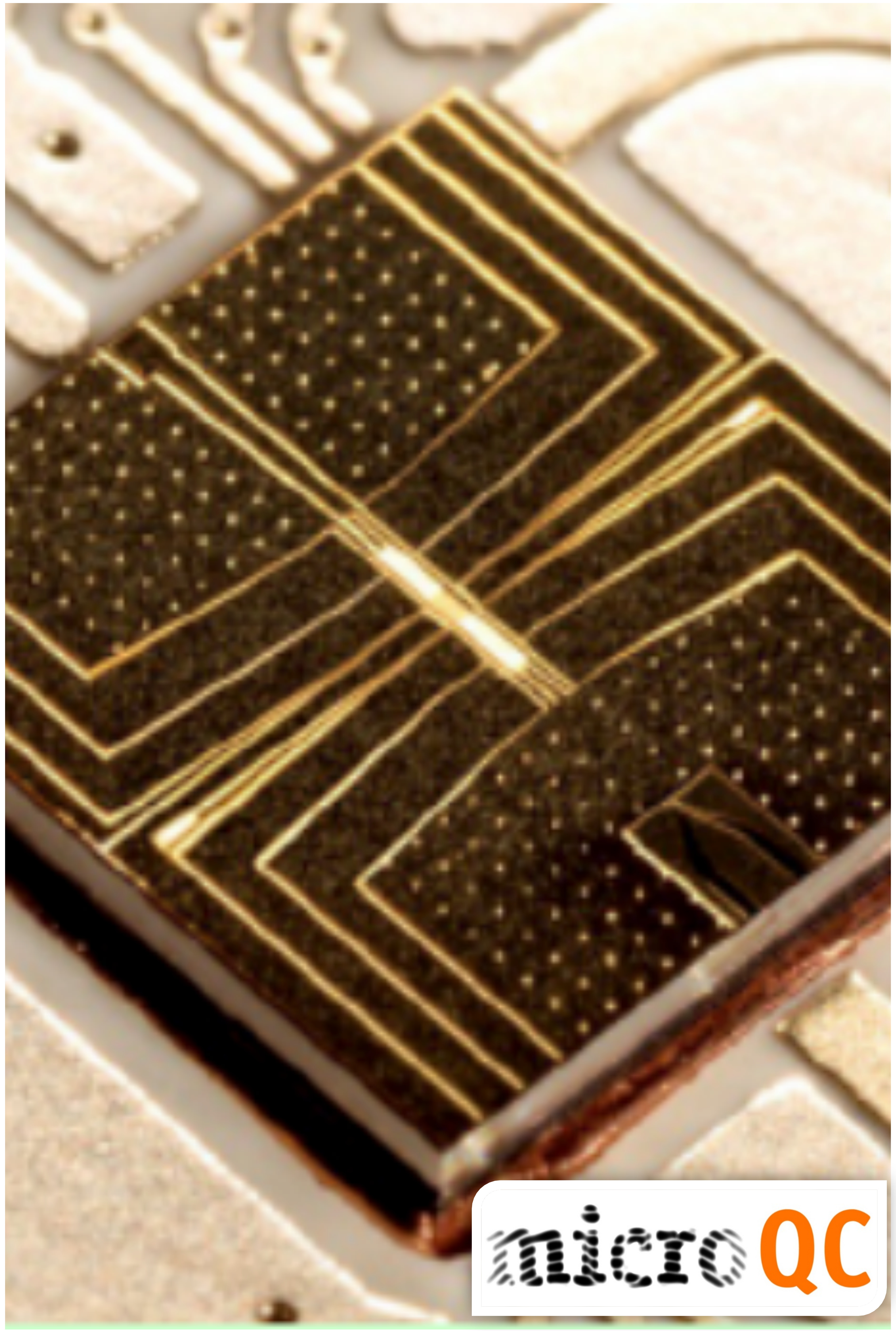
PROJECT: PhoG
(Sub-Poissonian Photon Gun by Coherent Diffusive Photonics)
Coordinating Institution:
THE UNIVERSITY COURT OF THE UNIVERSITY OF ST ANDREWS
Coordinator: Natalia Korolkova

PROJECT: PhoQuS
(Photons for Quantum Simulation)
Coordinating Institution:
SORBONNE UNIVERSITE
Coordinator: Alberto Bramati

PROJECT: MicroQC
(Microwave driven ion trap quantum computing)
Coordinating Institution:
FOUNDATION FOR THEORETICAL AND COMPUTATIONAL PHYSICS AND ASTROPHYSICS
Coordinator: Nikolay Vitanov

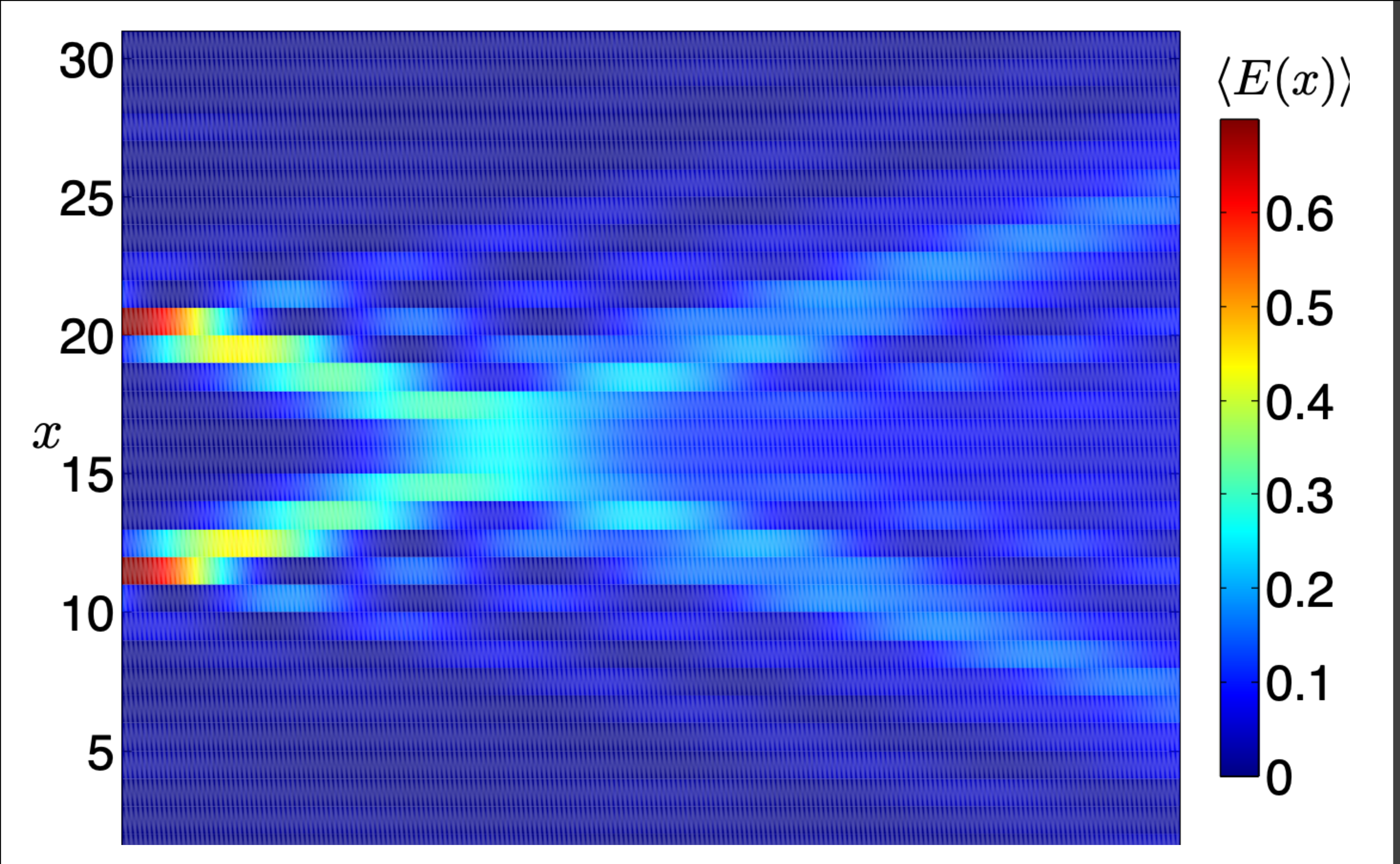


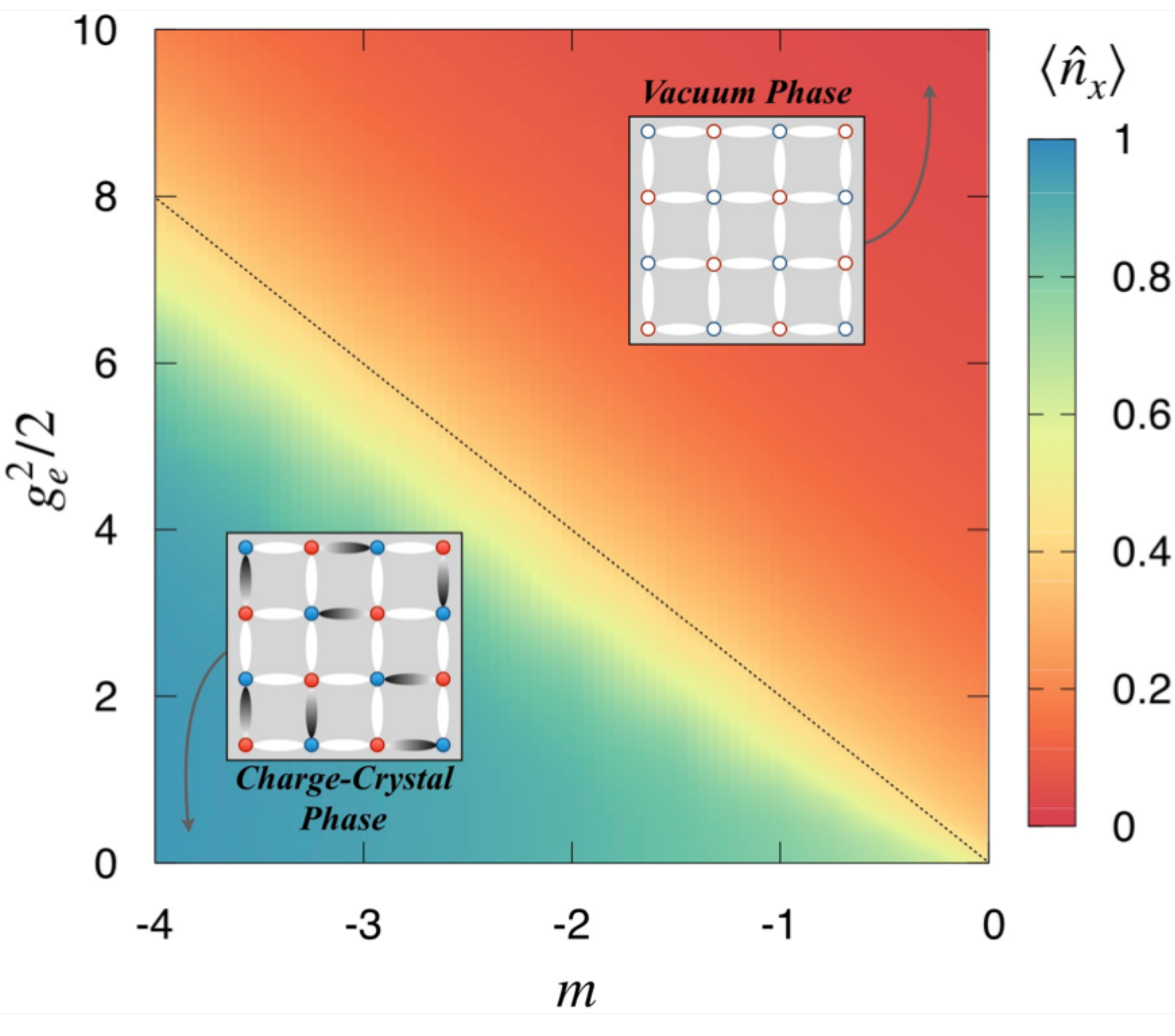


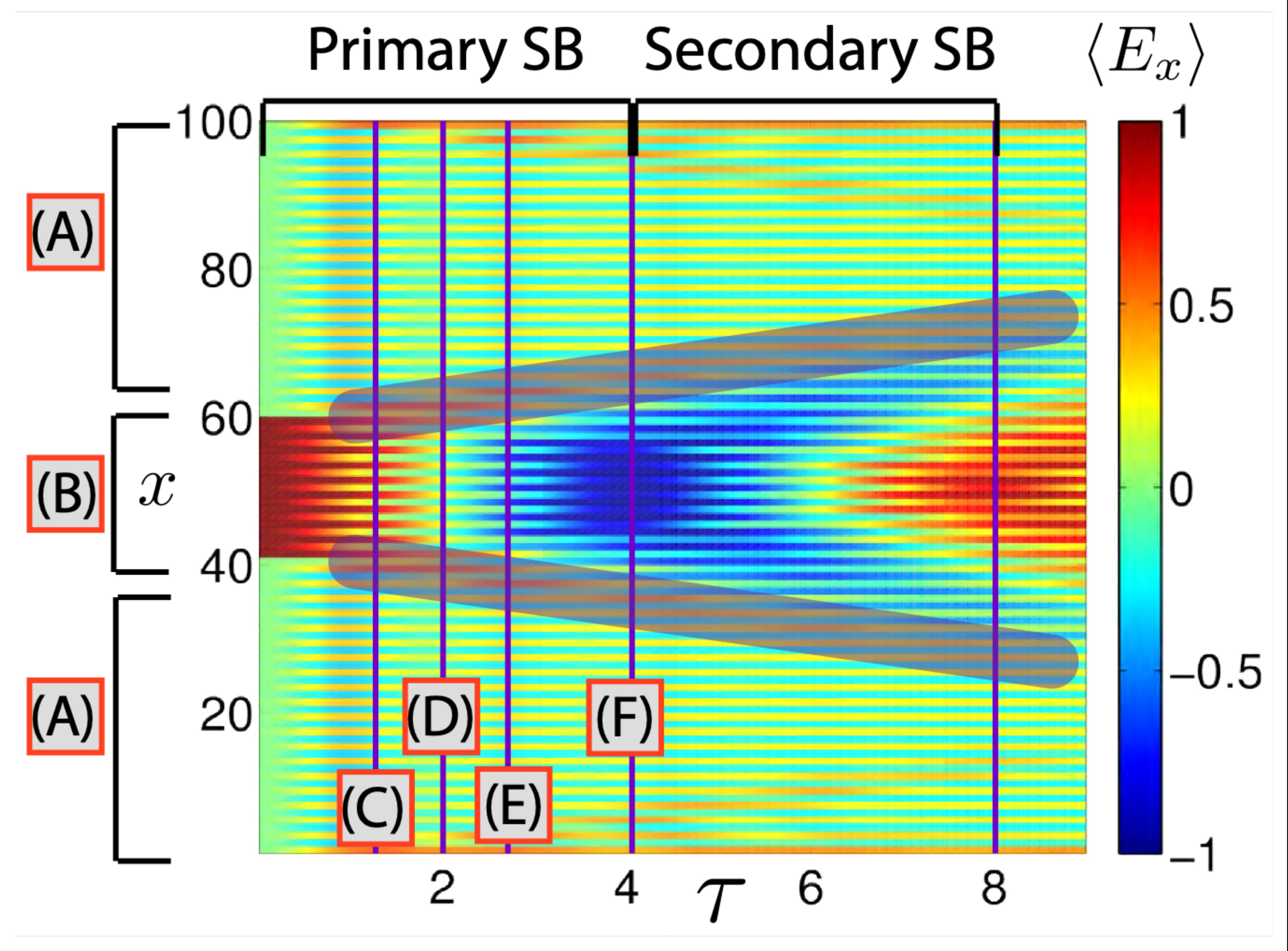


QUANTERA

- November 2016
- QuantERA ERA-NET cofund initiative
  → ERA-NET aims to increase Member States funding to challenge driven research and innovation agendas
- €67 million budget from European Commission and national funding agencies
- 26 European countries
- National and regional research funding programmes
- Complementary to the Quantum Flagship's activities







QTFLAG: Quantum Technologies for Lattice Gauge Theories

Member States: Austria, Belgium, Germany, Italy, Poland

INFN Node(s): PD

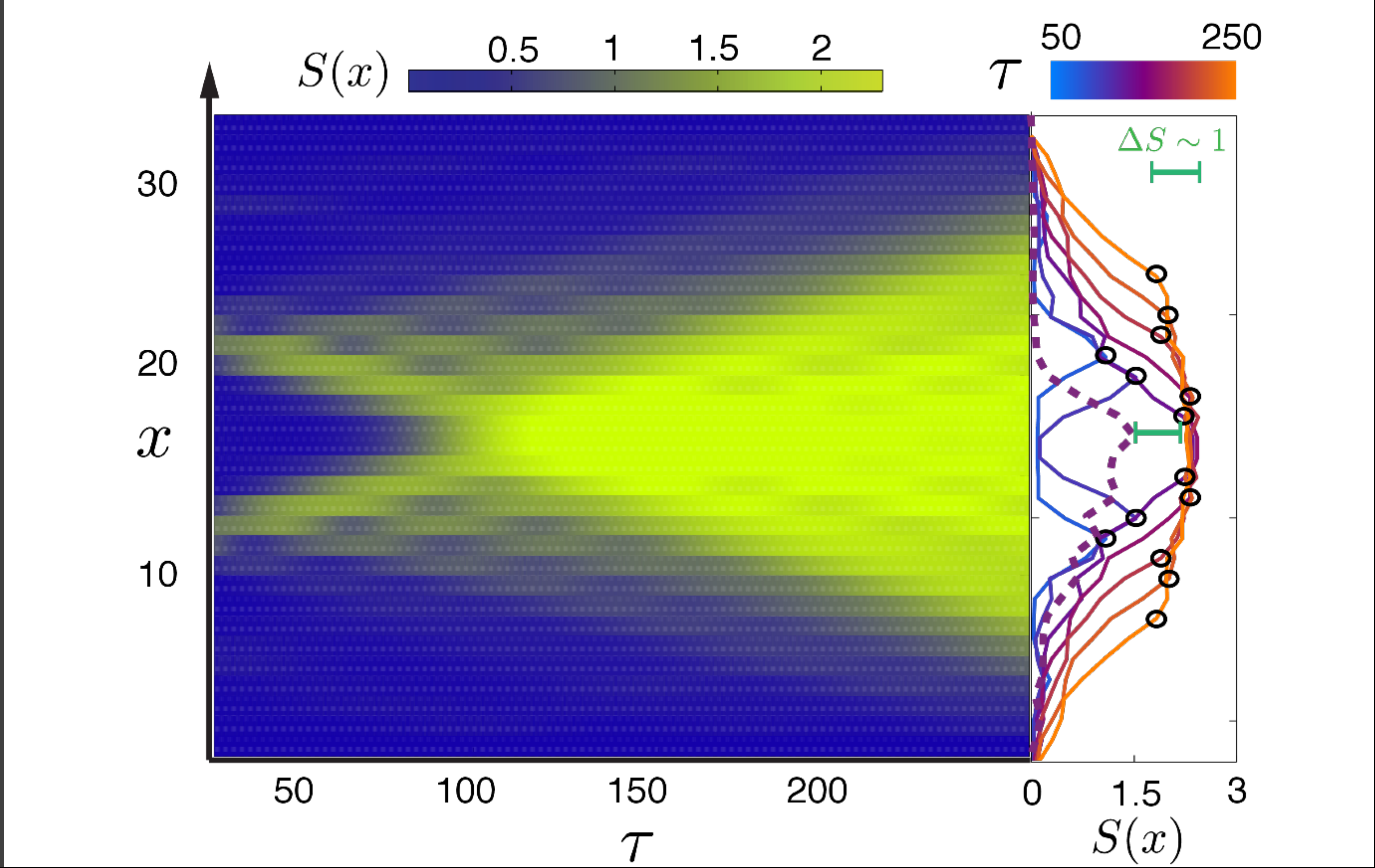
T. Pichler, E. Rico, M. Dalmonte, P. Zoller, and S. Montangero

Real-time dynamics in U(1) lattice gauge theories with tensor networks

Phys. Rev. X 6, 011023 (2016)

S. Montangero et al.

arXiv:19.11.xxxx



QUANTERA CALL 2019: INFN PROJECTS

2 projects

QUANTUM
Communication

QuICHE: Quantum information and communication with high-dimensional encoding
(INFN)

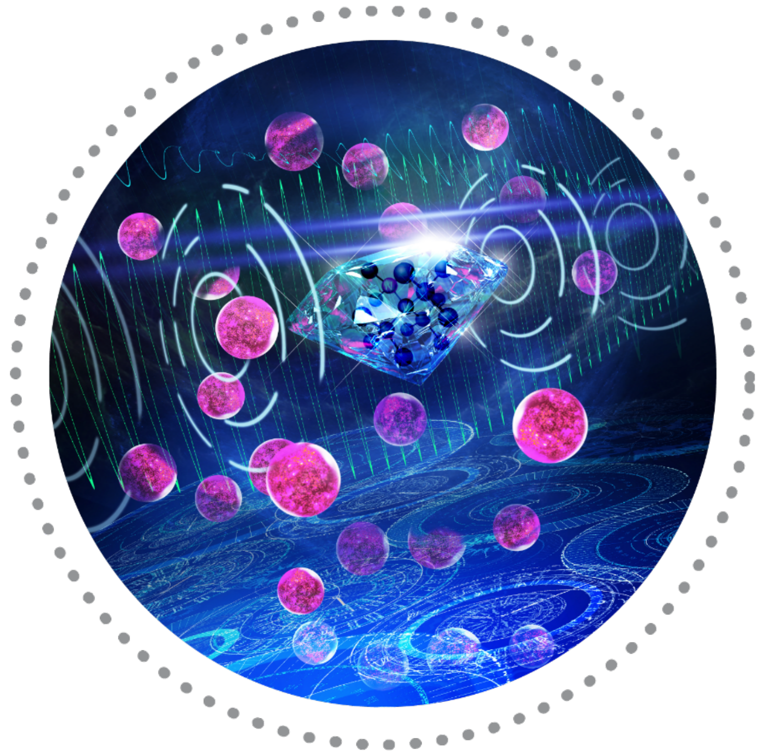
SECRET: SECuRe quantum communication based on Energy-Time/time-bin entanglement
(INFN)

1 project

QUANTUM
Simulation

QuantHEP: Quantum Computing Solutions for High-Energy Physics
(INFN + Regione Puglia)

1 project



QUANTUM
Sensing
metrology

Qu3D: Quantum 3D imaging at high speed and high resolution
(INFN)

1 project

QUANTUM
Computing

PACE-IN: Photon-Atom Cooperative Effects at Interfaces
(INFN + Regione Puglia)

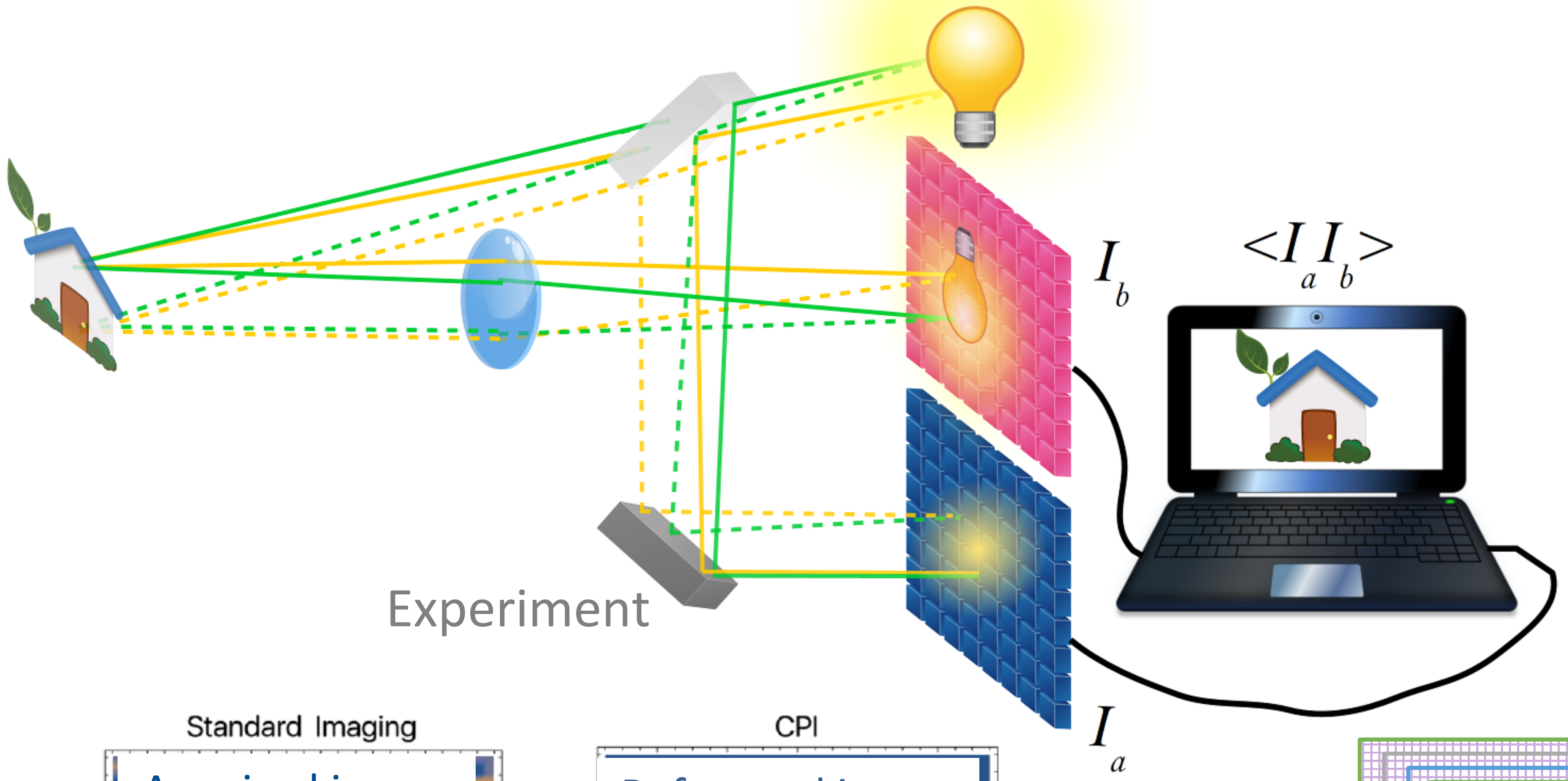
Qu3D: Quantum 3D imaging at high speed and high resolution

Member States: Check Republic, Greece, Italy, Switzerland

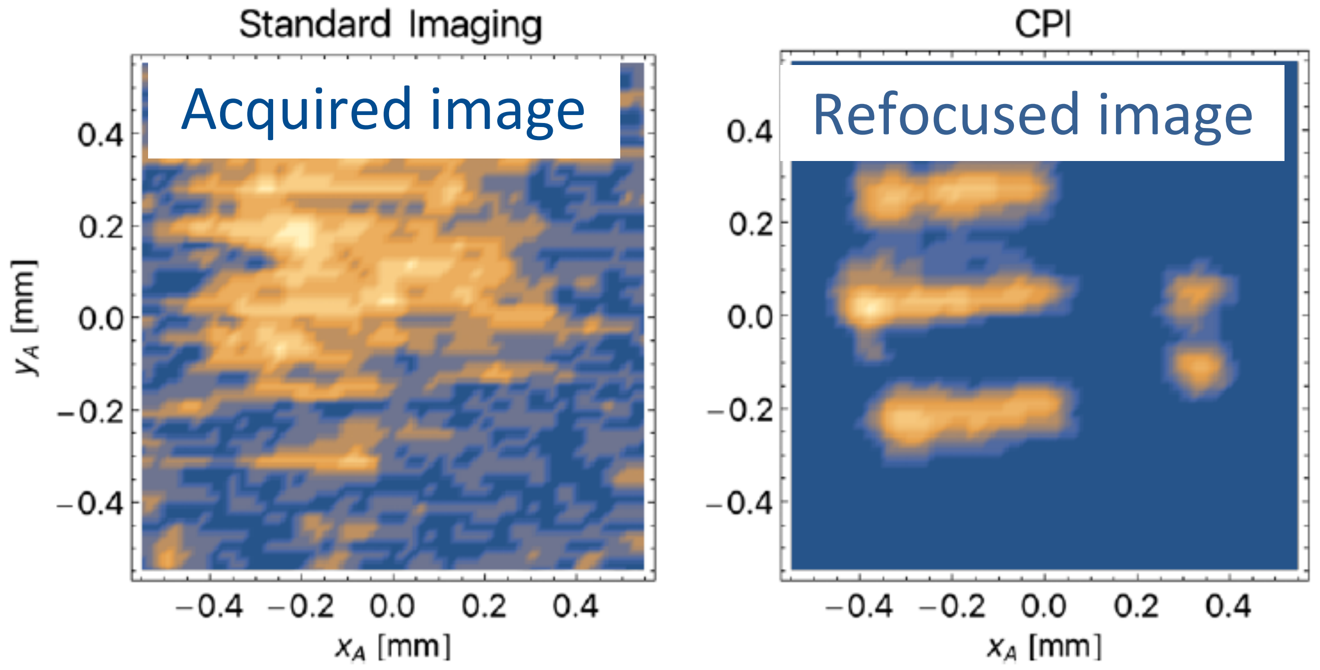
INFN Node(s): BA

Fundings: INFN

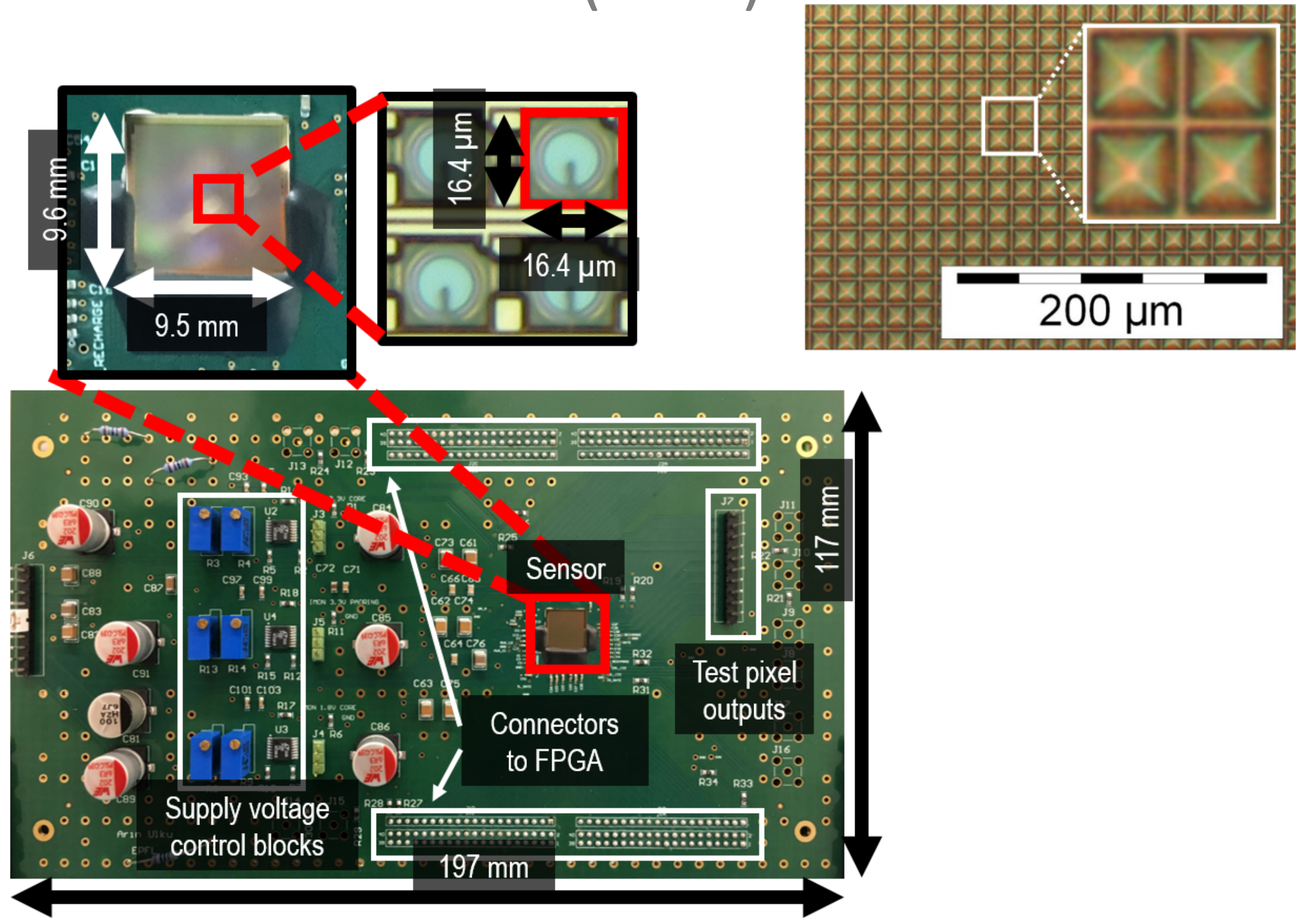
- ✓ Correlation plenoptic imaging (INFN)
  Working principle (INFN patent!)



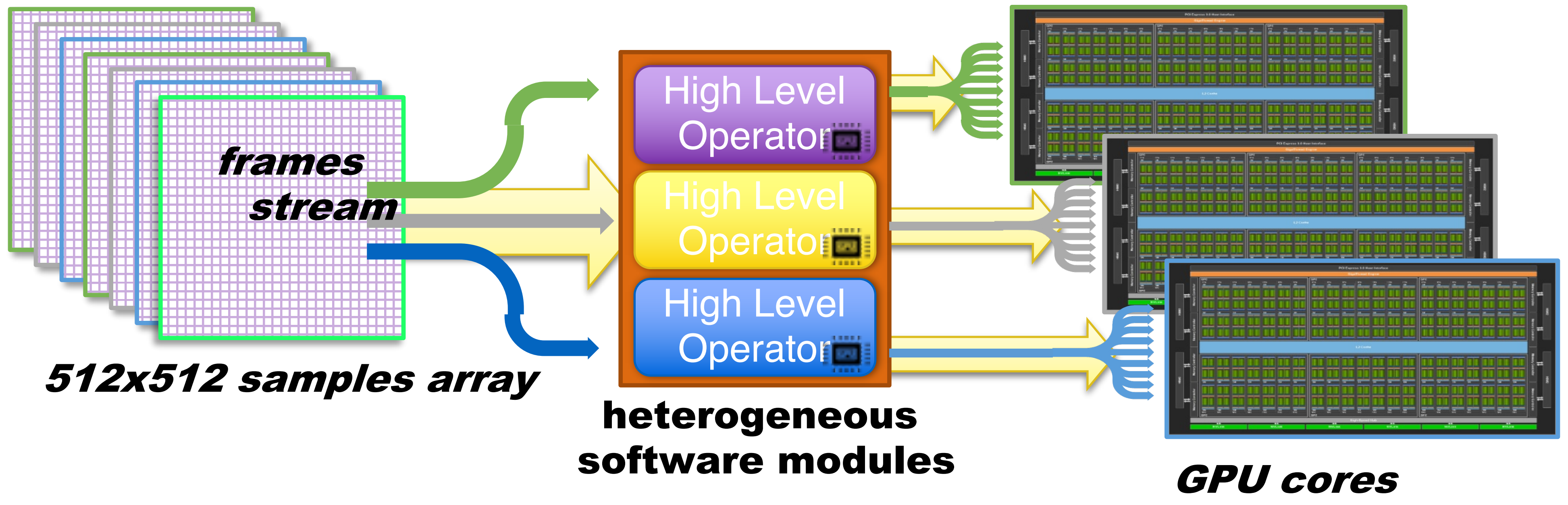
Experiment



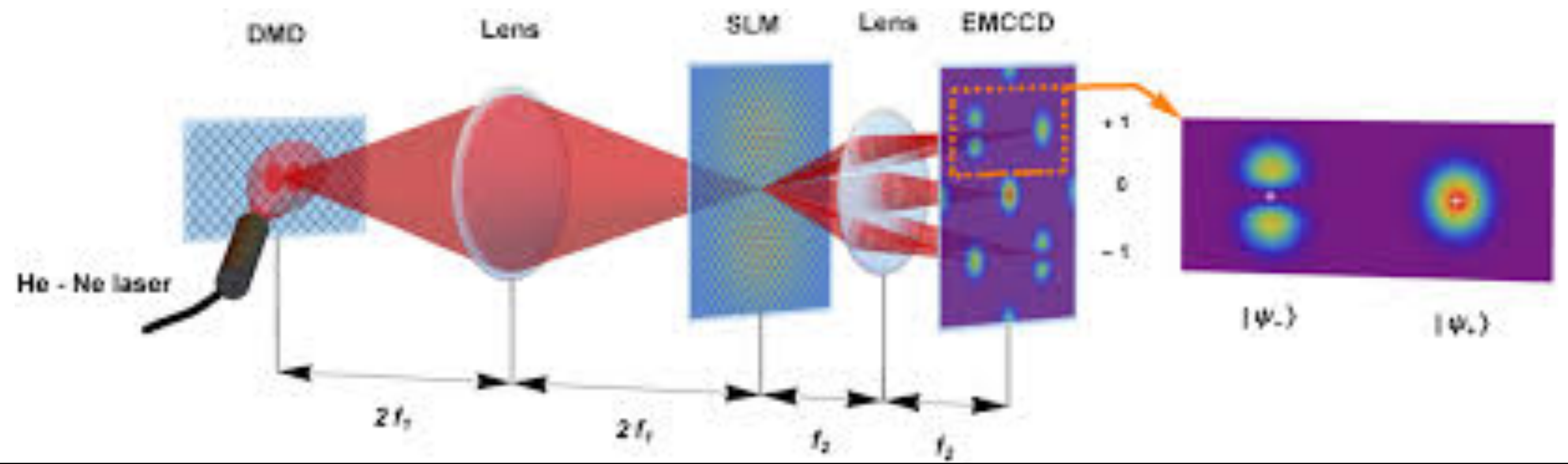
- ✓ Ultra-fast detectors (EPFL)

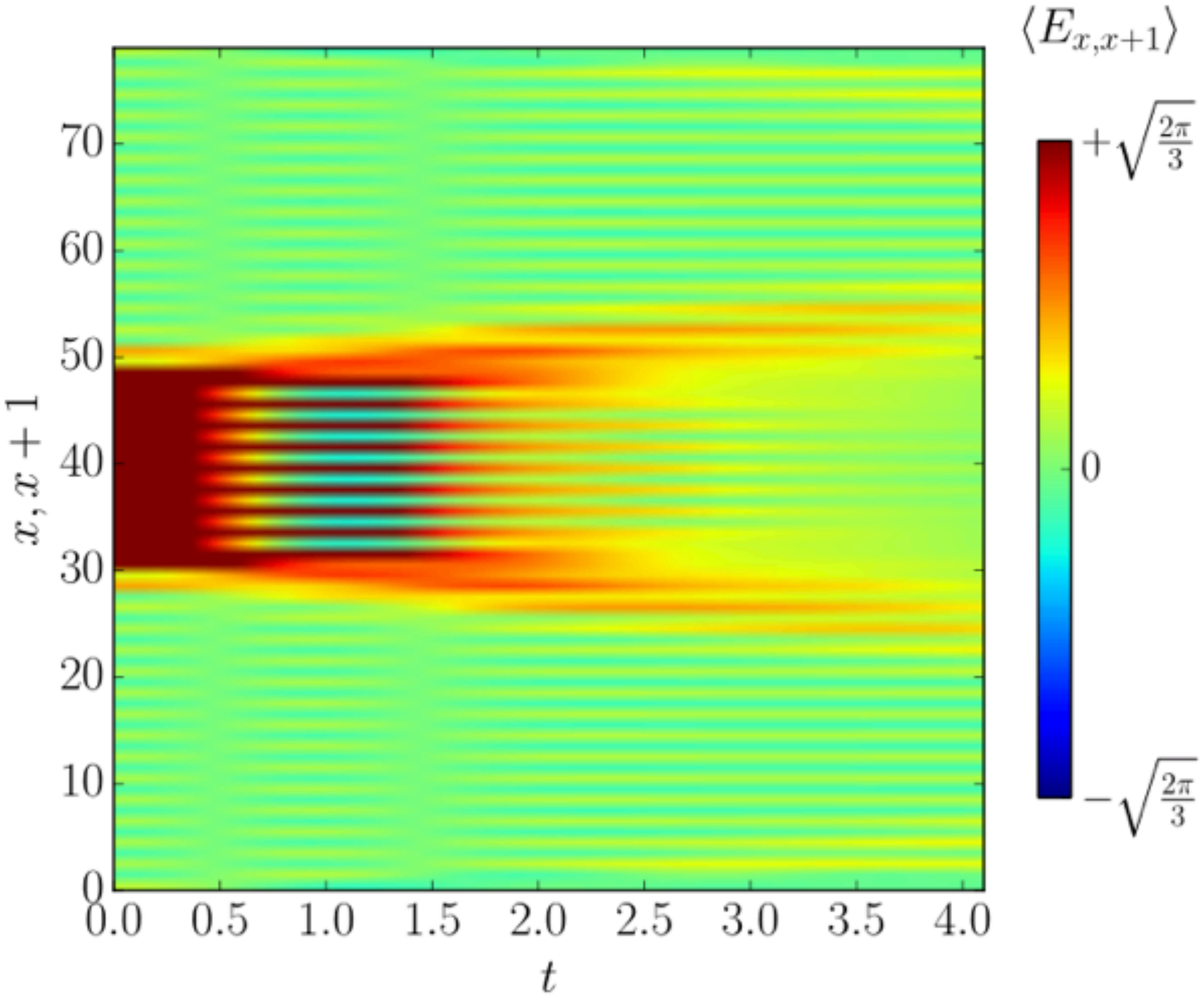


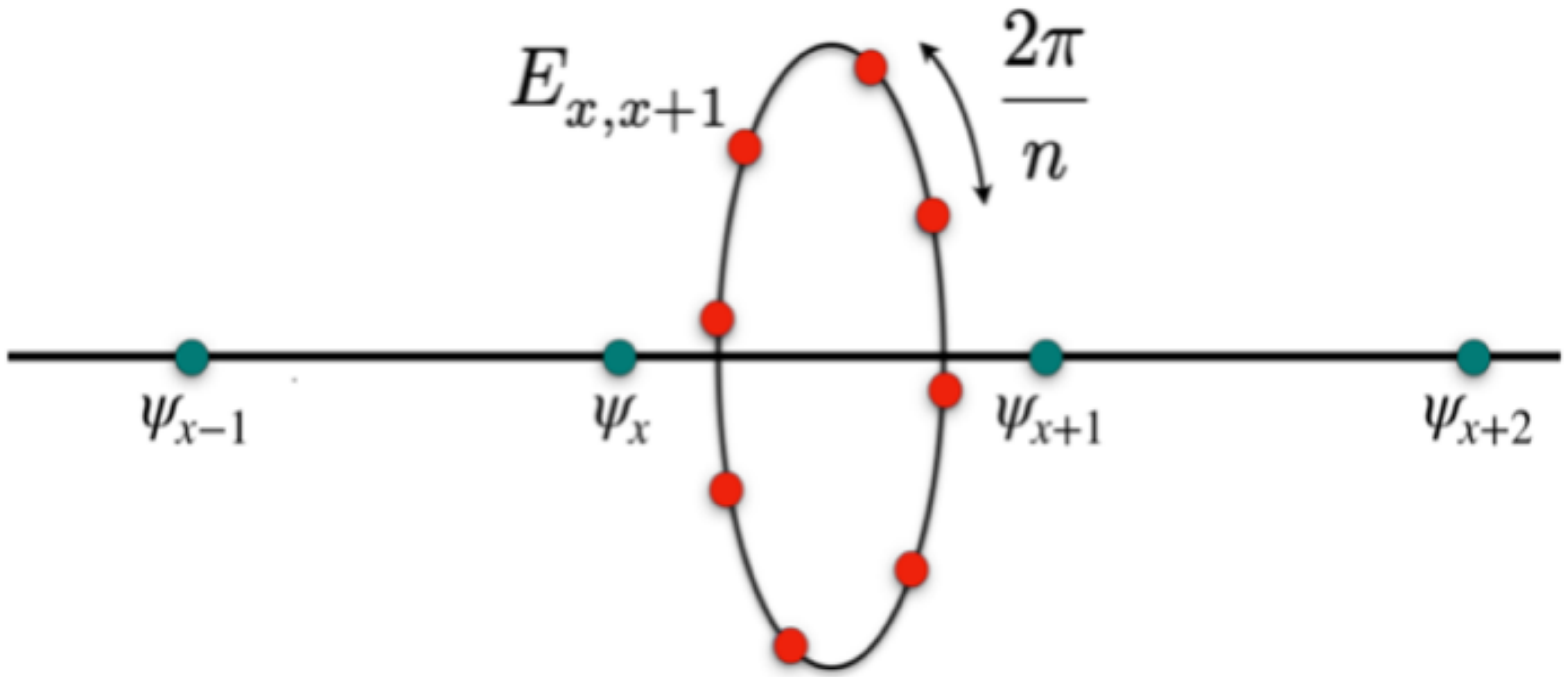
- ✓ Parallel computing (Planetek Hellas)



- ✓ Super-resolution by quantum Fisher information + quantum tomogrophy (University of Olomouc)







QuantHEP: Quantum Computing Solutions for High-Energy Physics

Member States: Italy**,** Latvia, Portugal

INFN Node(s): PD, BO, **BA**

Fundings: 1/3 INFN; 2/3 Regione Puglia

S. Notarnicola, E. Ercolessi, P. Facchi, G. Marmo, S. Pascazio and F. V. Pepe
Discrete Abelian Gauge Theories for Quantum Simulations of QED
J. Phys. A: Math. Theor. 48, 30FT01 (2015)

E. Ercolessi, P. Facchi, G. Magnifico, S. Pascazio and F. V. Pepe
Phase transitions in Zn gauge models: Towards quantum simulations of the Schwinger-Weyl QED
Phys. Rev. D 98, 074503 (2018)

S. Notarnicola, M. Collura, S. Montangero
Real time dynamics quantum simulation of (1+1)-D lattice QED with Rydberg atoms
arXiv:1907.12579 [cond-mat.quant-gas]

FROM VISION TO REALITY – THE EU'S COMMITMENT

Built with the support of the Commission's proposed Horizon Europe and Digital Europe programmes

HORIZON EUROPE

DIGITAL EUROPE

QUANTERA

Give **funding support** to **international research projects** in the field of Quantum Technologies

QUANTUM FLAGSHIP

Bring quantum technologies from the **lab** to the **market** and **consolidate** European **scientific leadership** in quantum research

QUANTUM COMMUNICATION INFRASTRUCTURE (QCI)

Build and **deploy** in the next decade a certified secure pan-European end-to-end QCI for **cybersecurity** services

QUANTUM COMPUTING INFRASTRUCTURE

Build and **deploy** an infrastructure for big data, artificial intelligence, high performance computing, among others

… Italian National Quantum Institute in next PNR

QUANTUM COMMUNICATION INFRASTRUCTURE

Integrate quantum cryptography into critical communication systems

Combine terrestrial and satellite components for wide coverage

Protection of data networks, clock synchronization, e-voting,…

Backbone infrastructure for the quantum internet

QUANTUM COMPUTATION & SIMULATION INFRASTRUCTURE

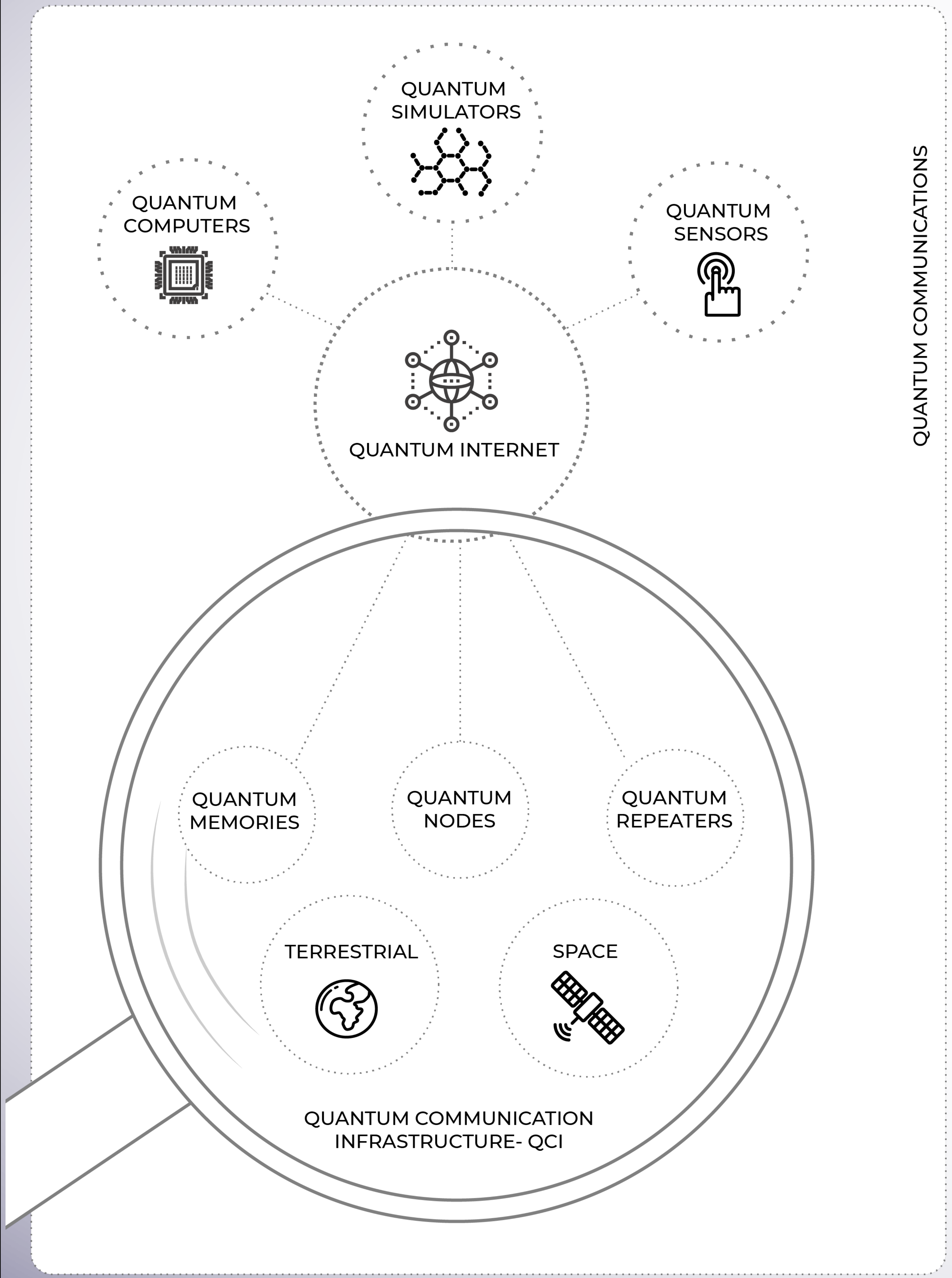
Classical quantum simulation hardware in HPC

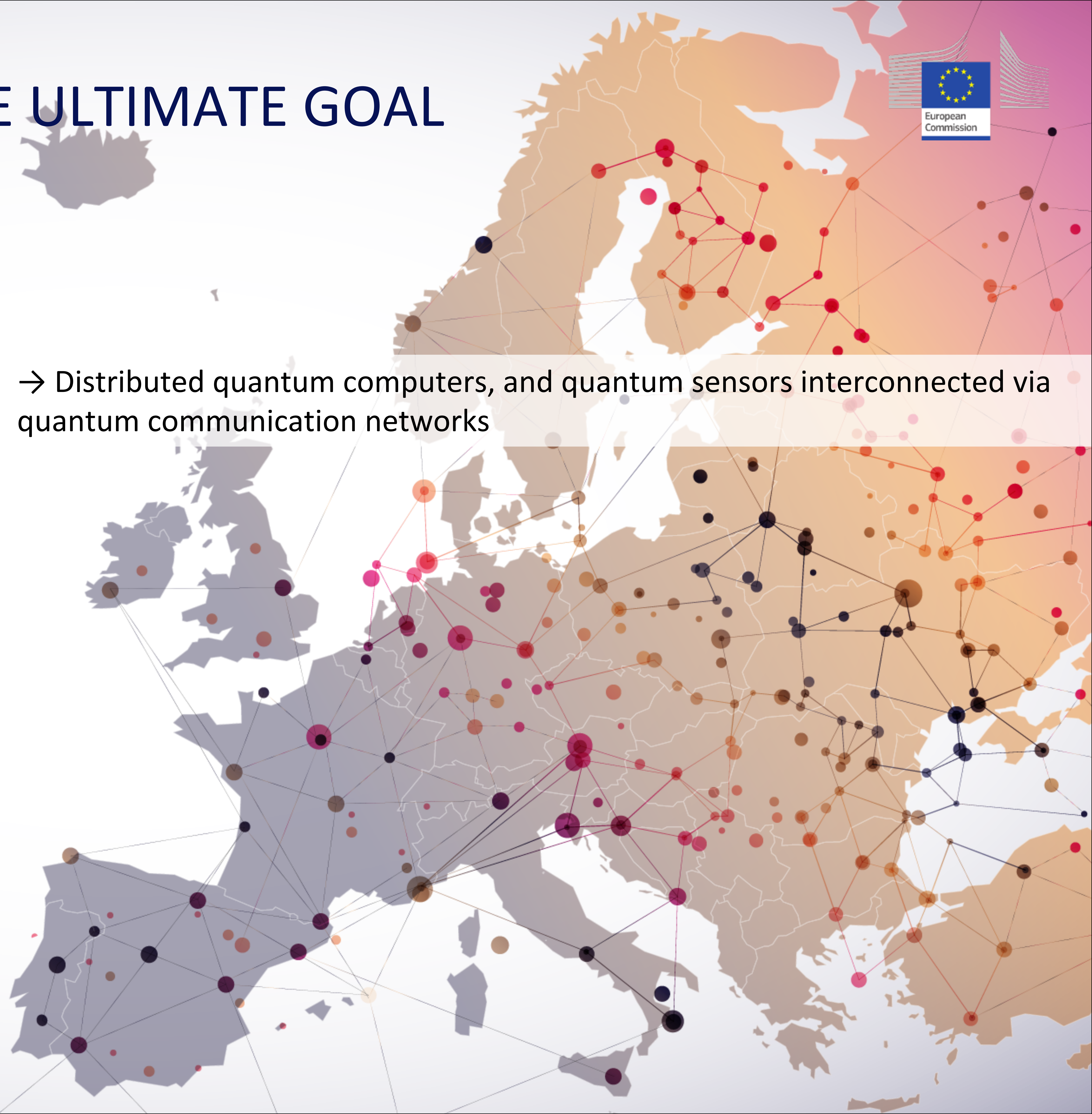
Quantum testbed facilities for hardware developers

Quantum computation and simulation hardware (ion traps, super-/semi-conducting qubits, spin qubits, phtonic circuits, neutral atoms)

Quantum application database (verification/validation, algorithms, apps)

QUANTUM INTERNET: THE ULTIMATE GOAL





→ Distributed quantum computers, and quantum sensors interconnected via quantum communication networks