Istituto Nazionale di Fisica Nucleare

Piano Triennale

2025 | 2027

LECCE

Alberto Quaranta

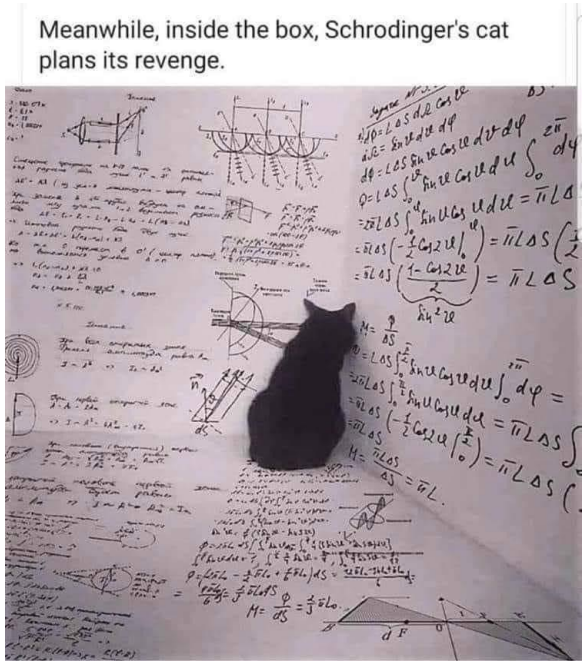
CSN5

Tecnologie Quantistiche @INFN

INFN

La sfida delle Tecnologie Quantistiche

- Collocazione dell'INFN nel panorama delle TQ.
- Panoramica delle attività in corso.
- Prospettive per il futuro.

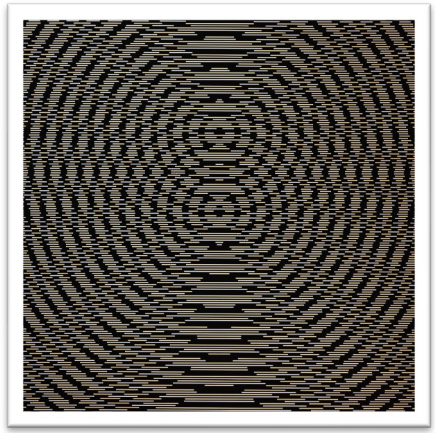


Cosa si intende per Tecnologie Quantistiche?

Le tecnologie quantistiche sfruttano proprietà quantistiche per realizzare prestazioni che superano i limiti teorici delle attuali tecnologie.

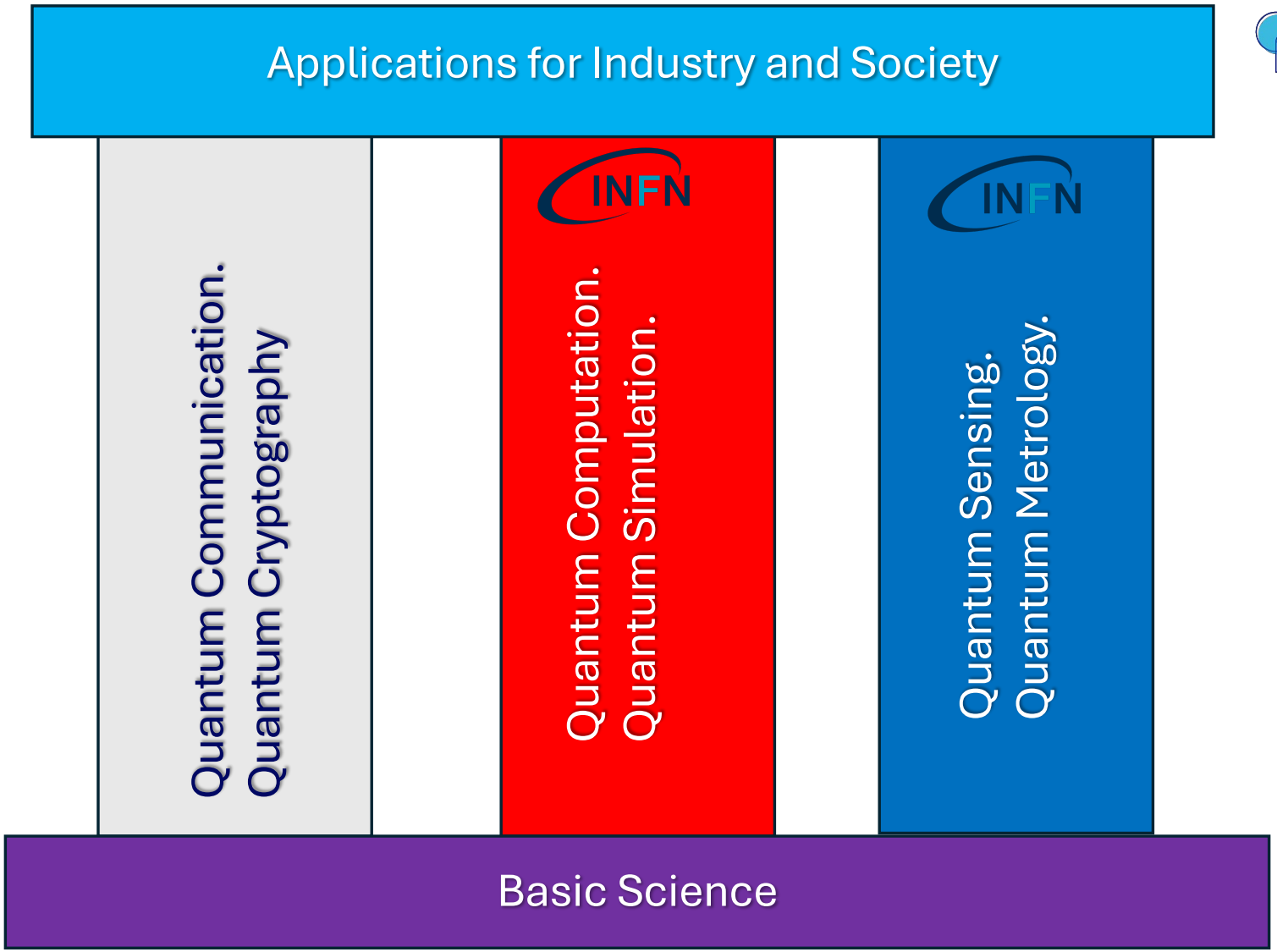
Quantum Superposition

Quantum Entanglement



Quantum Coherence

Pillars


Applications for Industry and Society
Quantum Communication.
Quantum Cryptography
INFN
Quantum Computation.
Quantum Simulation.
INFN
Quantum Sensing.
Quantum Metrology.
Basic Science

Dove tutto iniziò...

CSN5 Ricerca Tecnologica

Come sta continuando...

QUANTUM COMPUTING AND SIMULATION CENTER

NQSTI
National Quantum Science and Technology Institute

AI@INFN - Artificial Intelligence at INFN

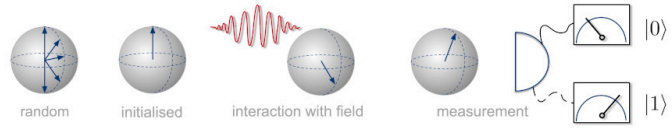
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Q@TN

Quantum Technologies (Computing, Sensing & Simulation)
Torino, 7-9 Giugno 2023

1–7 Sept 2023
EMFCSC (Erice, Italy)
Europe/Rome timezone

QUANTUM TECHNOLOGIES FOR FUNDAMENTAL PHYSICS



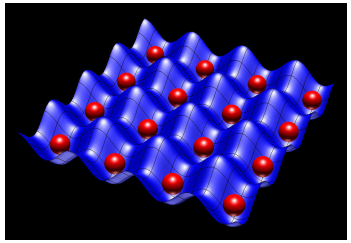
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER
Dipartimento di Fisica e Astronomia Galileo Galilei
UNIVERSITÀ DEGLI STUDI DI PADOVA
INFN
Istituto Nazionale di Fisica Nucleare

Quantum Computing @ INFN

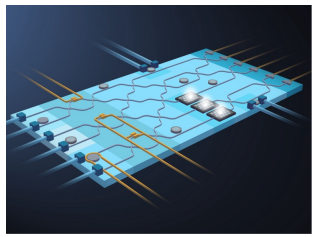
14–15 Nov 2022
Bologna
Europe/Rome timezone

All'inizio fu il QUBIT

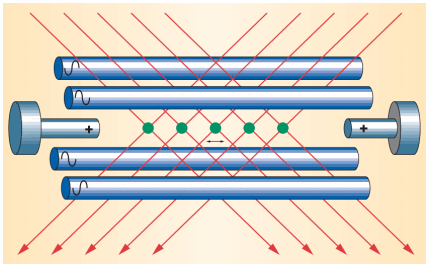
$$N \rightarrow 2^N$$



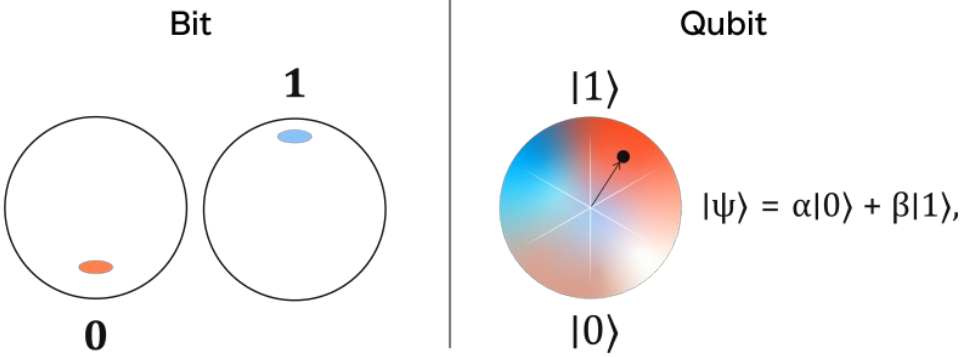
Ultracold atom lattices



Integrated optical circuits

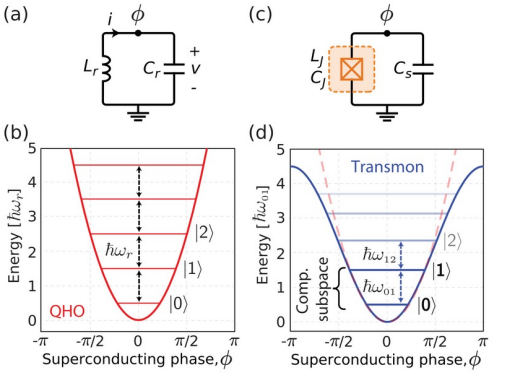


Cold ions

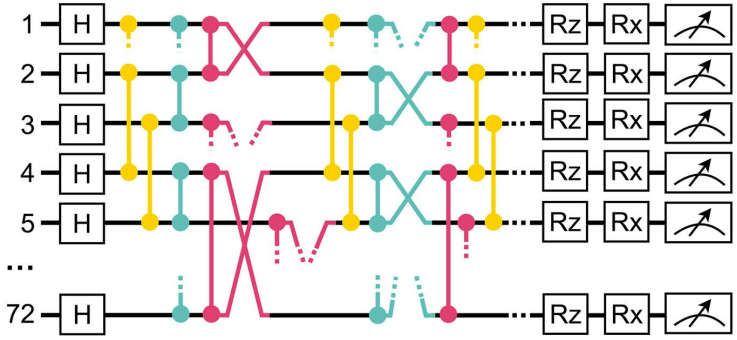


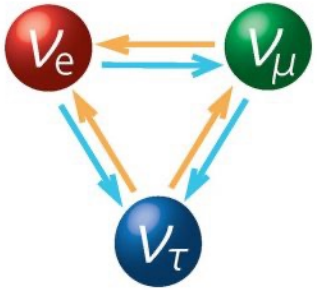
- Sistema quantistico (o similare) a due livelli.
- Inizializzabile con la sovrapposizione dei due stati e leggibile.
- Crescita esponenziale della potenza di calcolo.
- Tempo di coerenza.
- Connessione stabile fra più qubit.

Superconducting transmons

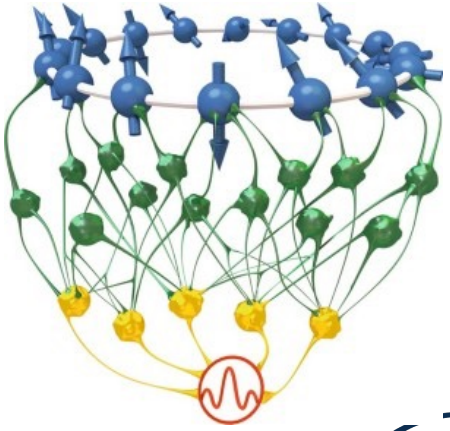


Quantum Computing @INFN

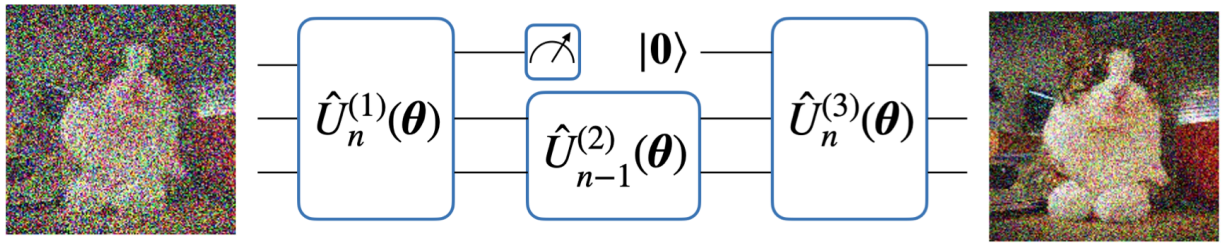




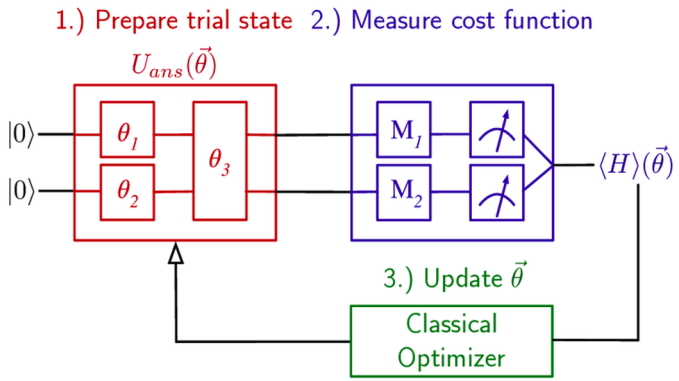
- Data parametrization.
- Rare signal extraction.
- Pattern recognition of particle tracks.
- Neutrino collective oscillations.
- Many body real simulation.
- Full wavelength storage.



Un paio di esempi...

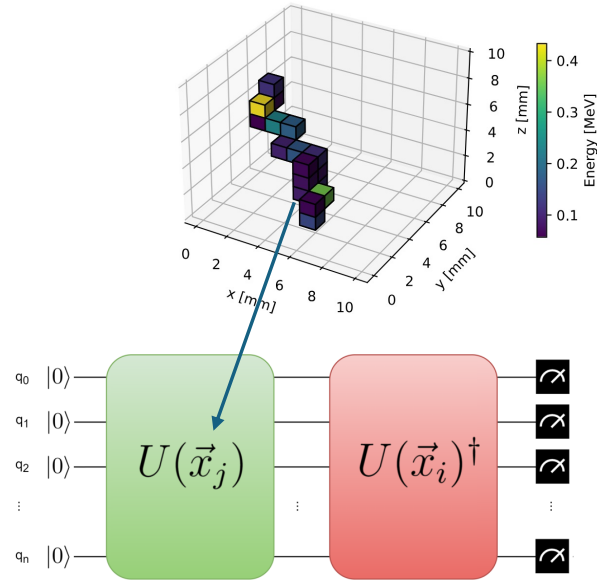


Quantum denoiser



Variational Quantum Eigensolver (VQE)
Hybrid Quantum Computing

Credit: Rodolfo Carobene
Advisors: Andrea Giachero



Background suppression for $\boldsymbol{0\nu\beta\beta}$ decay of the ^{136}Xe isotope

Credit: Roberto Moretti
Advisors: Andrea Giachero, Francesco Terranova.

- 39 public RFOs from 31 countries.
- 2019.
  - **Qu3D** - Quantum 3D Imaging at high speed and high resolution, *Milena D'Angelo* (BA).
  - **QuICHE** - Quantum Information and Communication with High-dimensional Encoding, *Chiara Machiavello* (PV).
  - **QuantHEP** - Quantum Computing Solutions for High-Energy Physics, *Simone Montangero* (PD).
  - **SECRET** - SECuRe quantum communication based on Energy-Time/time-bin entanglement, *Giuseppe Vallone* (PD).
  - **PACE-IN** - Photon-Atom Cooperative Effects at Interfaces, *Paolo Facchi* (BA).
- 2021.
  - **SQUEIS**: Squeezing-Enhanced Inertial Sensing, *Guglielmo Tino* (FI).
  - **T-NiSQ**: Tensor Networks in Simulation of Quantum matter, *Simone Montangero* (PD).

Centro Nazionale HPC (…and Quantum Computing)

- QC for optimization, simulation & ML.
- Quantum algorithms.
- Quantum algorithms on classical computers.
- Hybrid systems.
- HL quantum software for general purpose (scientific & industrial).
- Libraries and frameworks.
- LL quantum software for physical simulations.
- Benchmarking and verification.

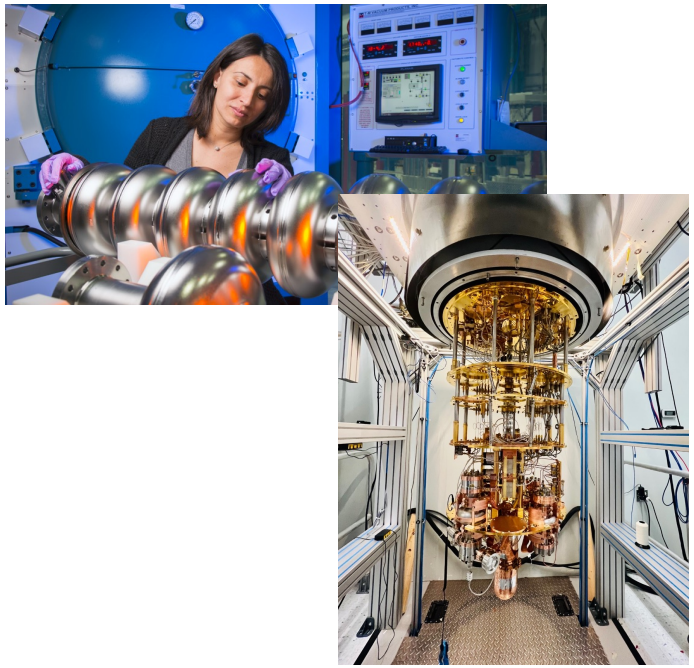
Centro Nazionale HPC: Spoke 10

Quantum Computing

WP1. Software **Leader: INFN**	WP2. Mapping, compilation and quantum computing emulation. **Leader: CINECA**	WP3. Firmware and hardware platforms **Leaders: CNR, CT**
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 PV, BO, IIT, CT, CINECA, CNR, PI, Sapienza, BA, P.Mi, PD **T1.2 Applications and use cases** IIT, BO, CINECA, CNR, INAF, INFN, PV, PI, BA, MIB, Polimi, PD	**T2.1 Mapping and compilation** BO, CNR, PI, Polimi **T2.2 Emulation** CINECA, INAF, BA, PD	**T3.1 Photonic** (RM1, CNR, MIB, PV, NA) **T3.2 SC circuits** (NA, INFN, MIB, CNR, CT) **T3.3 Atoms** (CNR, PD); **T3.4 Ions** (PD, CNR); **T3.5 Models and firmware** (CT, Polimi, BA, PD, MIB, CNR, PI)

SQMS

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



Credit: Anna Grassellino

- Abbattimento della decoerenza in qubit SC con l'uso di cavità SC.
- Studio del background radioattivo (LNGS).
- Cavità Superconduttive.

Radiazioni cosmiche & DM vs. Qubit

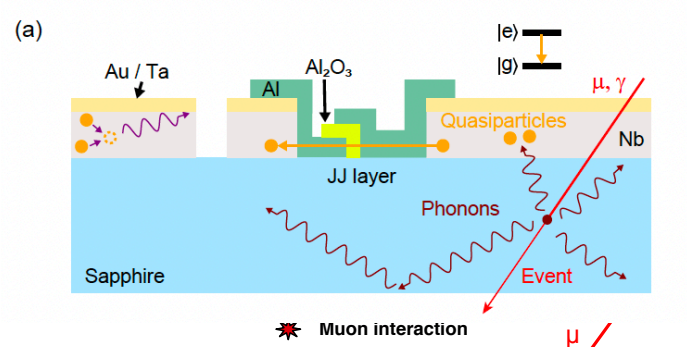
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

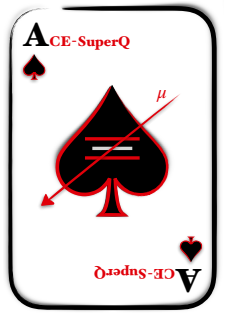
Fermilab

SAPIENZA UNIVERSITÀ DI ROMA

Ministero degli Affari Esteri e della Cooperazione Internazionale

Credit: Laura Cardani

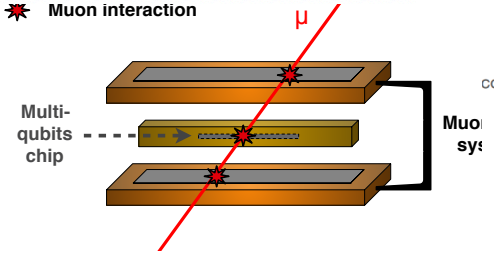


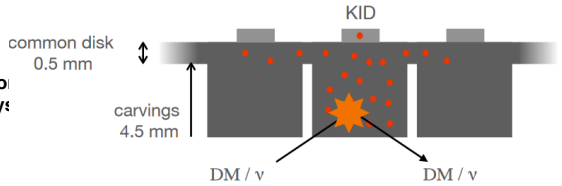


CSN5 Ricerca Tecnologica

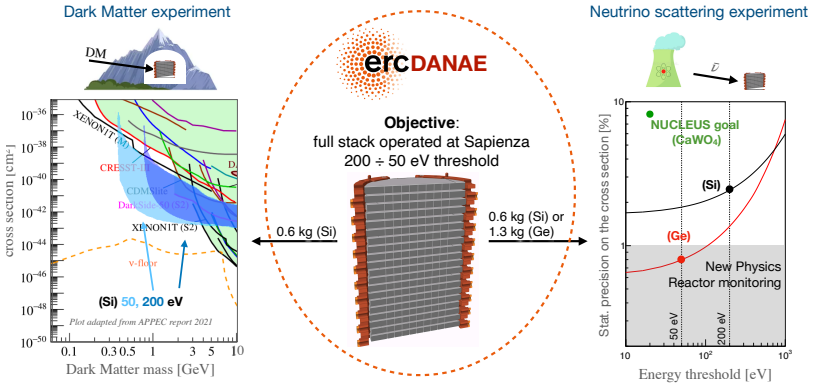
Ambra Mariani
ovani Ricercatori 2024-26

- Impatto della radiazione ambientale sul tempo di coerenza del qubit.
- Fononi dal substrato che distruggono le coppie di Cooper nella giunzione SC.
- Primi esperimenti underground (LNGS).
- Qubit anche come rivelatori di particelle.





Relationship of DANAE to other projects



Credit: Angelo Cruciani
Andrea Mazzolari

INFN

Meanwhile in CSN4&5…

- Iniziative specifiche in CSN4.
  - Foundational studies, theory of measure, entanglement (**BELL**).
  - Quantum Systems: entanglement, simulations, information (**QUANTUM**).
- Sviluppi tecnologici e calcolo in CSN5 (anche per il sensing).
  - **DARTWARS**.
  - **QUB-IT.**
  - **UNIDET.**
  - **AI_INFN.**
  - **QUANTEP**.
  - …
- Iniziative congiunte CSN4/5…

QUANTEP (QUANtum Technologies Experimental Platform)

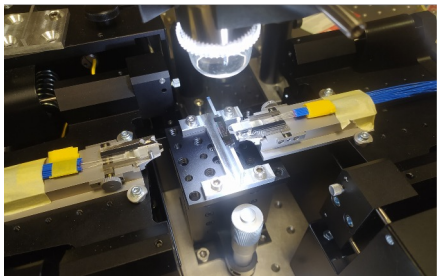
NQSTI National Quantum Science and Technology Institute

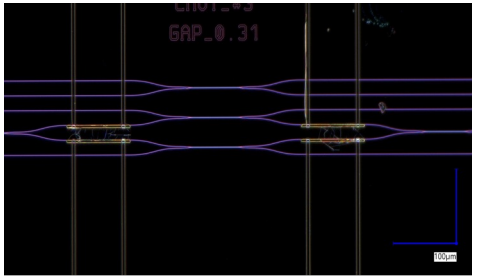
Spoke 4 (generation, manipulation and detection of quantum states of light)

Spoke 6 (integration of individual quantum objects into the building blocks of emerging quantum technologies architectures)

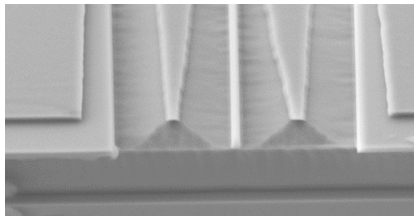
- Sviluppo di competenze @INFN di circuiti di ottica integrata per logica quantistica.

CSN5 Ricerca Tecnologica

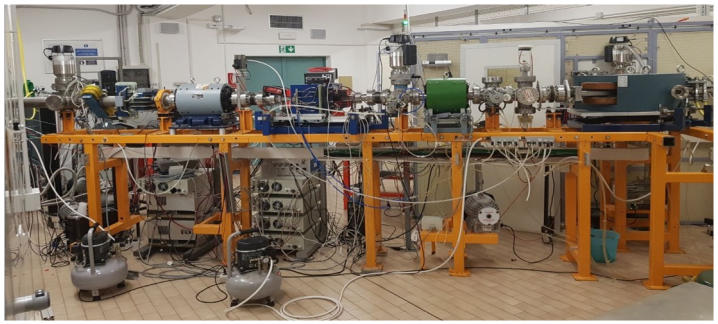




Optical logical circuits



Nanofabrication & manipulation

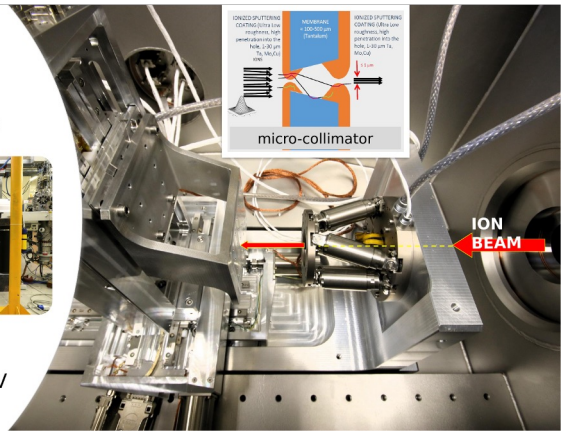


Credit: Andrea Salamon

Deterministic implantation

Single Ion Irradiation ASIDI apparatus for QUANTEP at the the LNL Legnaro microprobe line (AN2000 Accelerator)

High precision targeting with MeV ions



AI_INFN (Artificial Intelligence Technologies for INFN Research)

BA
BO
CNAF
FE
FI
GE.DTZ
MIB
NA.DTZ
PD
PG
PI
RM1
RM3
TO.DTZ

AI_INFN: ARTIFICIAL INTELLIGENCE TECHNOLOGIES FOR INFN RESEARCH

CSN5 Ricerca Tecnologica

WP4. *Machine Learning* su FPGAs e Processori Quantistici

Coordinamento: Stefano Giagu, Roma 1

Mandato

Studiare e connettere tra loro le molte attività di ricerca in corso sul tema delle tecniche di accelerazione hardware innovative, per esempio basate su FPGA e Calcolo Quantistico, agevolandone la fruzione via INFN Cloud e potenziandone l'usabilità per applicazioni di *Machine Learning*.

Strutture coinvolte: Bologna CNAF Ferrara Milano Bicocca Napoli Padova Perugia Roma1

Deliverables

- **D4.1** Dimostratore operativo di acceleratori FPGA fruiti tramite Cloud;
- **D4.2** Sviluppo e documentazione nella *Knowledge Base*, di tecniche di compressione e ottimizzazione (occupazione risorse FPGA, latenza e throughput nella fase di inferenza) di modelli classici di *Machine Learning* e *Deep Learning* per utilizzo su acceleratori FPGA commerciali;
- **D4.3** Esempio di *Quantum Machine Learning* documentato nella *Knowledge Base*;
- **D4.4** Sviluppo di metodologie basate su *Machine Learning* classico per la preparazione, ottimizzazione (*e.g. transpiling*, simulazione realistica di sorgenti di errore), e *quantum error correction*, di circuiti quantistici di tipo NISQ, documentate nella *Knowledge Base*;
- **D4.5** Dimostratore operativo di interfaccia tra INFN Cloud e le risorse di quantum computing da fornitori esterni (per esempio IBM, o risorse ICSC).

- Network di calcolo per applicazioni ML su processori quantistici.

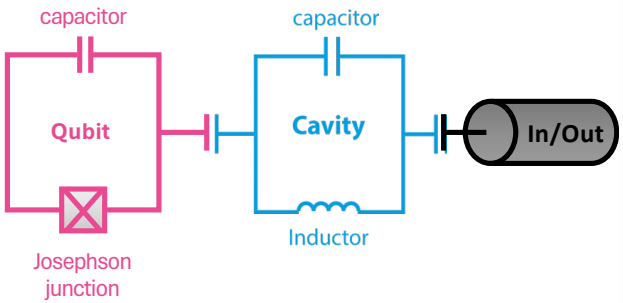
At the beginning…

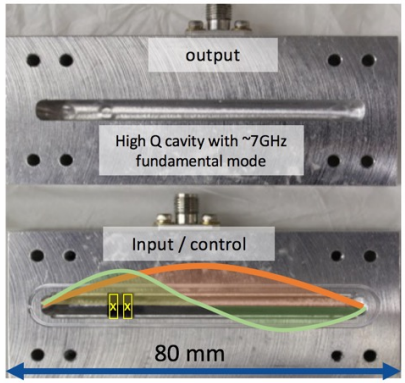
EQC – Experimenting with Quantum Computing (2019-2022)

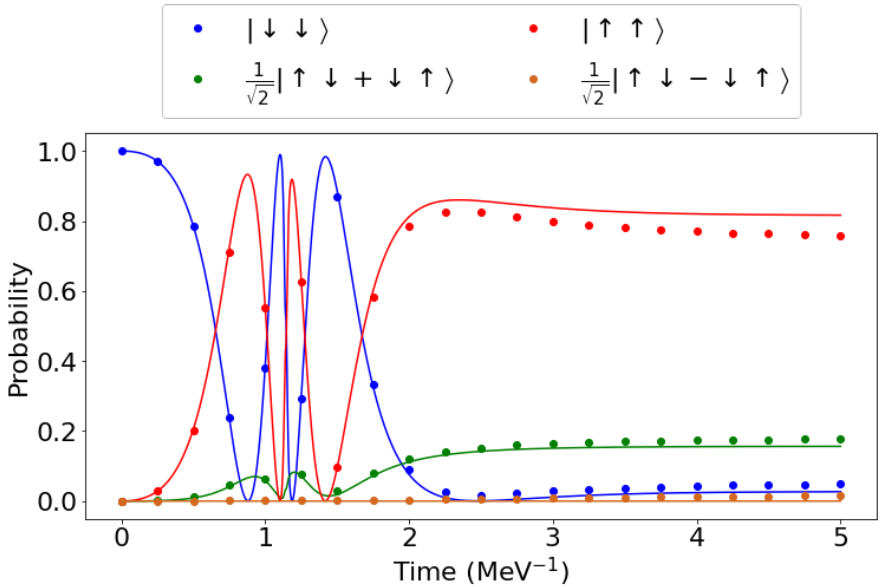
Fabio Schifano

Credit: Lucio Anderlini

Quantum Simulation/Computing with Qubits and Cavities (4+5=...)





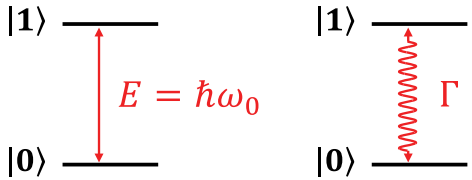


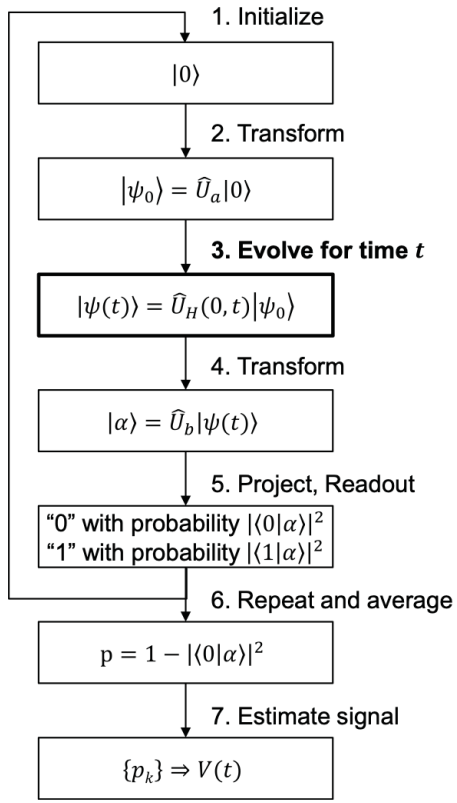
- Studio dell'interazione di spin fra due neutroni con qubit a più livelli (qudit) accoppiati a cavità.
- Il sistema può essere simulato con una Hamiltoniana equivalente e leggendo il qubit ad intervalli di tempo successivi si può seguire l'evoluzione del sistema in tempo reale.

Credit: Francesco Pederiva

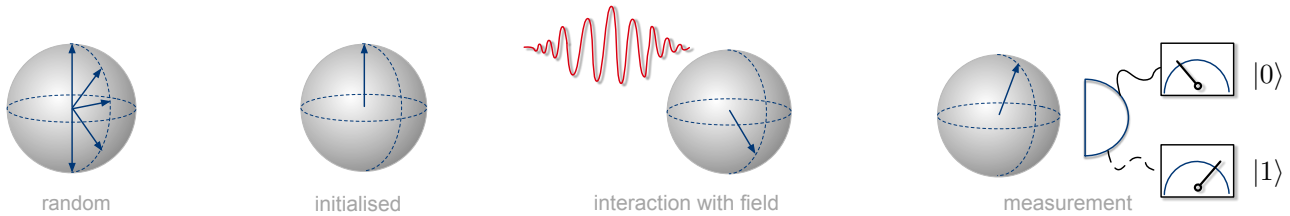
QUANTUM SENSING

- «Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels.»
- «Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity. »
- «Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.»





Degen, Reinhard and Cappellaro, *Rev. Modern Phys.* 89 (2017) 035002.



Quantum sensing for...

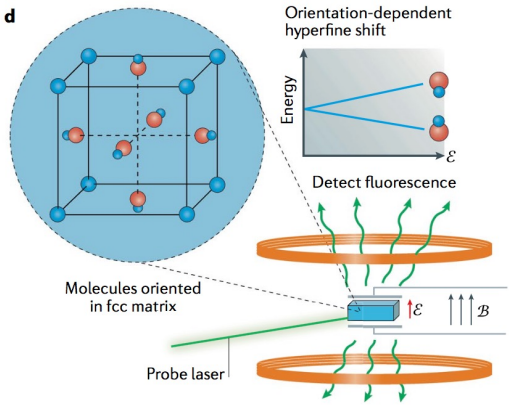
- Fenomeni legati ad accoppiamenti deboli materia-campo.
- Dark matter.
- Rivelazione di assioni.
- Misura delle costanti fondamentali.
- Test del modello standard (eEDM, CP violation).
- Orologi ad alta precisione.
- Rivelazione di particelle con rilascio di energia sub-eV, di piccola massa e debolmente interagenti.
- Interferometri gravitazionali.
- **Esperimenti table-top di fisica delle particelle**.

PHYDES (Para-HYdrogen and Diatomic molecules for eEDM Study)

CSN5 Ricerca Tecnologica

NQSTI National Quantum Science and Technology Institute

Spoke 6 (integration of individual quantum objects into the building blocks of emerging quantum technologies architectures)



- Rivelazione EDM elettronico per violazione CP.
- Molecole in criocristalli (p-H_2, next Ne).
- Esperimento table-top equivalente ad un esperimento su collider con scale di energia 30-50 TeV.

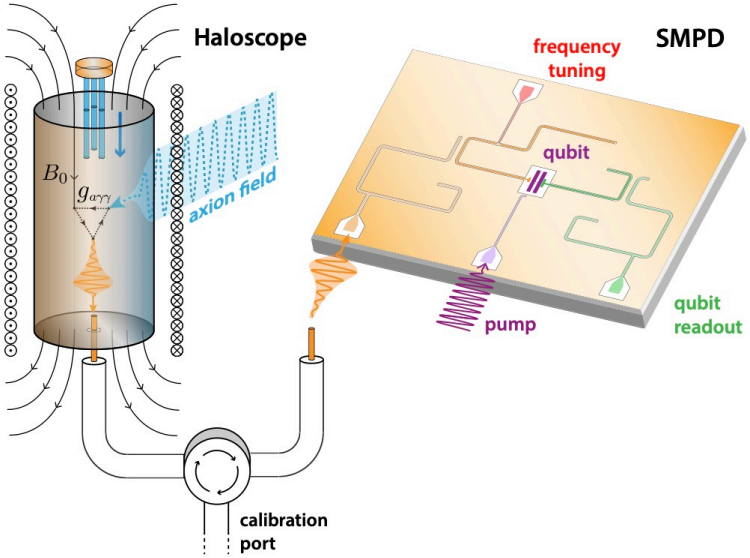
Credit: Giovanni Carugno

INFN

Haloscopes for axion detection


SMPD (top) and cavity

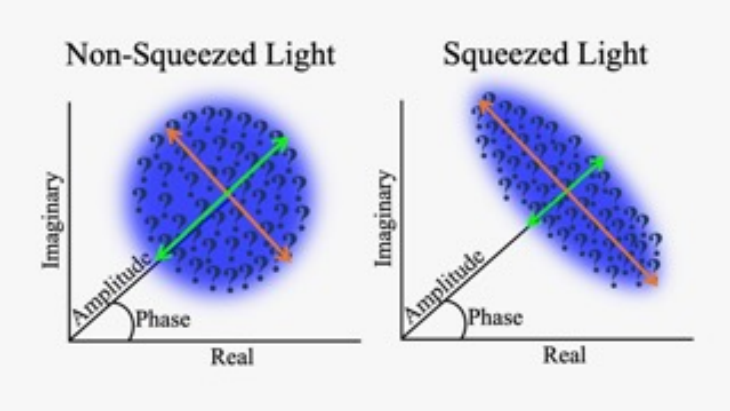
SC magnet

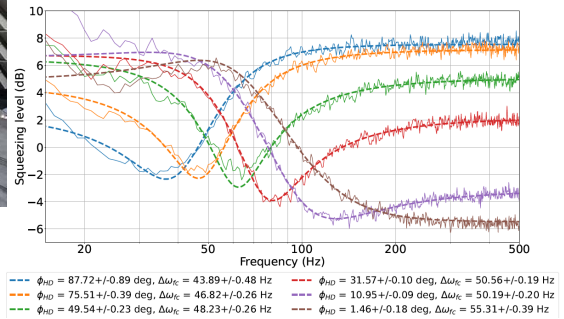


- Rivelazione di assioni tramite fotoni MW secondari.
- Superamento del limite quantistico con *single photon detection*.
- Modulazione in frequenza per ampliare il range utile.
- Fattore 100 sulla scan rate e 80 di vantaggio quantistico.

Credit: Caterina Braggio

Squeezed Light

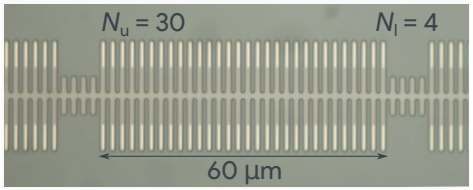


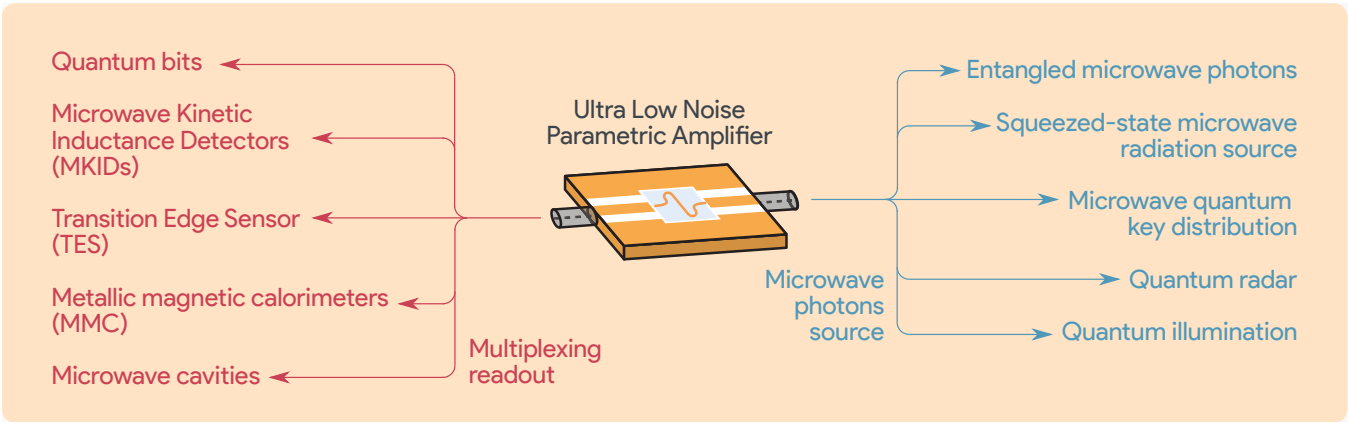


- Squeezed light per ridurre il contributo del *quantum noise* al rumore.
- Riduzione del rumore e rivelazione pressione della radiazione quantistica.
- Ongoing: ulteriori miglioramenti con sistemi entangled.

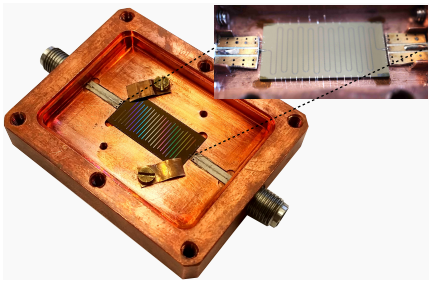
Credit: Jean-Pierre Zendri

DARTWARS (Detector Array Readout with Traveling Wave AmplifieRS)





- Amplificatore parametrico per molteplici usi nelle tecnologie quantistiche.
- Sviluppo di competenze interne in questo tipo di tecnologie.

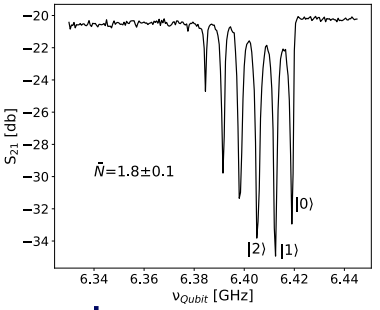


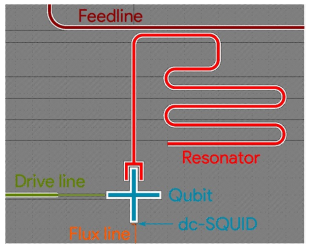
Credit: Andrea Giachero

QUB-IT

(Quantum sensing with superconducting qubits for fundamental physics)

Spoke 6 (integration of individual quantum objects into the building blocks of emerging quantum technologies architectures)

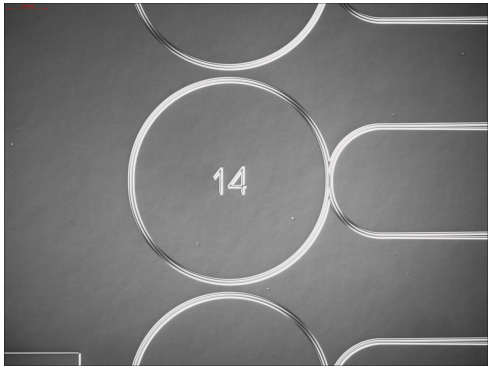


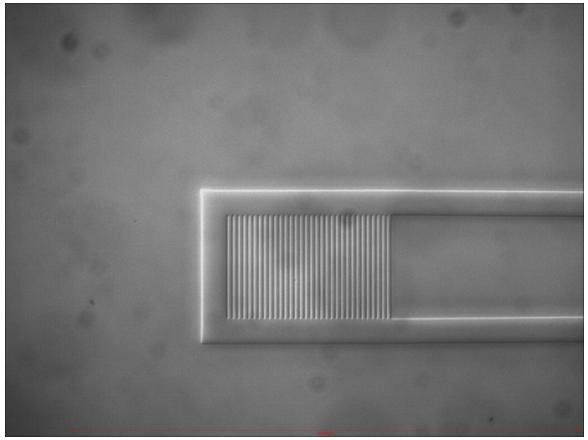


- Sviluppo di competenze per il design e la produzione di Qubit superconduttivi.
- Qubit per Quantum Non Demolition (QND) Detection di fotoni singoli MW.
- Cavità con Qubit 2D e 3D per entanglement fra qubit e fotone.
- Next: 2-Qubit accoppiati per migliorare l'efficienza.

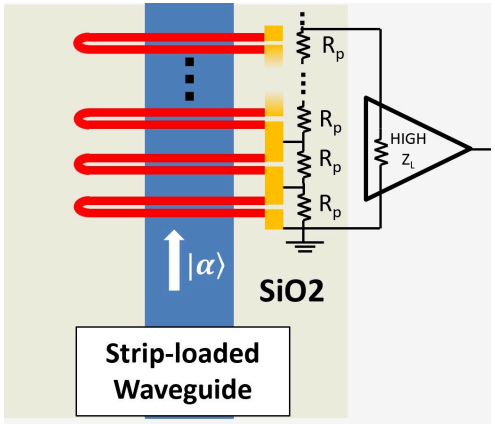
Credit: Claudio Gatti

UNIDET (UNIversal DETector for quantum light)



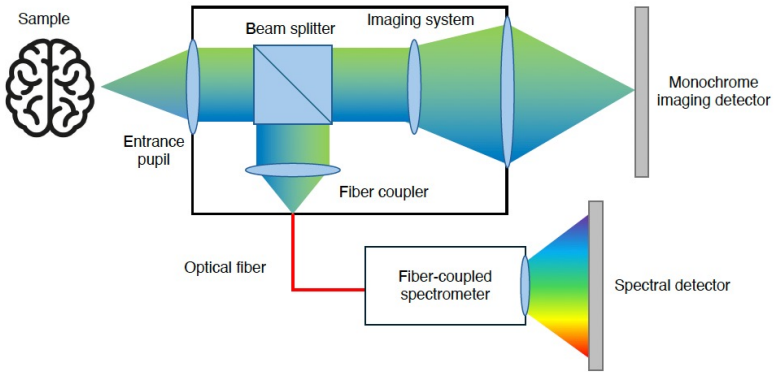


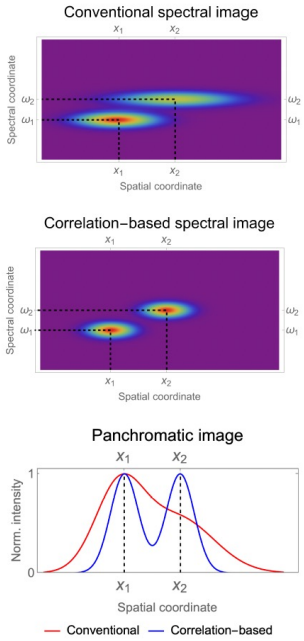
- Rivelatore integrato *photon number resolving*.
- Ingegnerizzazione stati quantistici per computazione e sensing (stati entangled).
- Misure di stati squeezed.

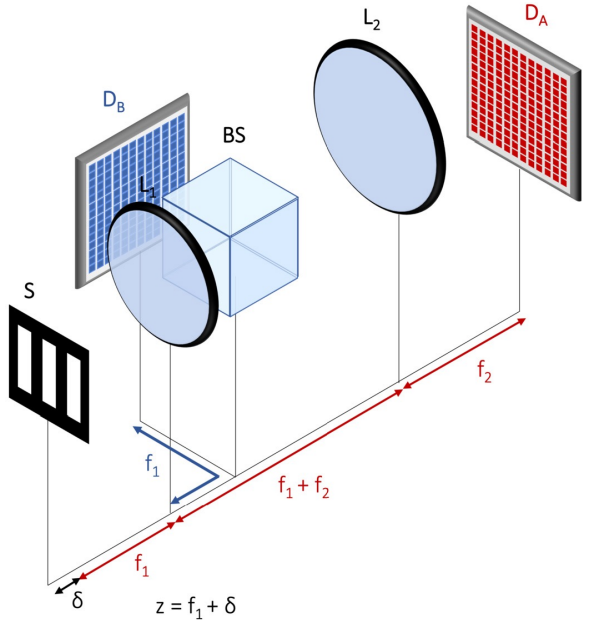


Credit: Mirko Lobino

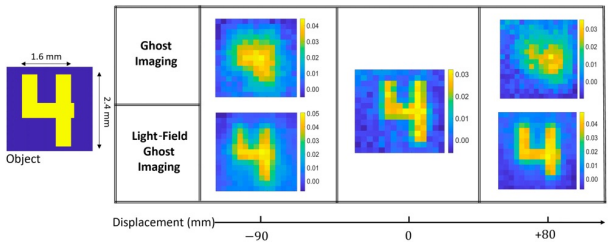
QUISS (QUantum Imaging with new Sources and Sensors)







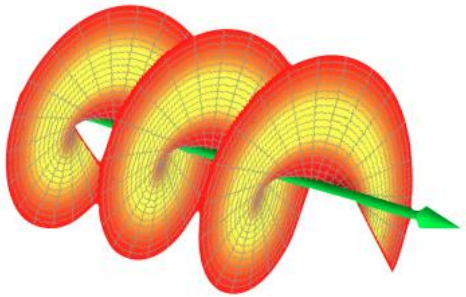
- Imaging con fotoni entangled per abbattere i limiti classici di SNR.

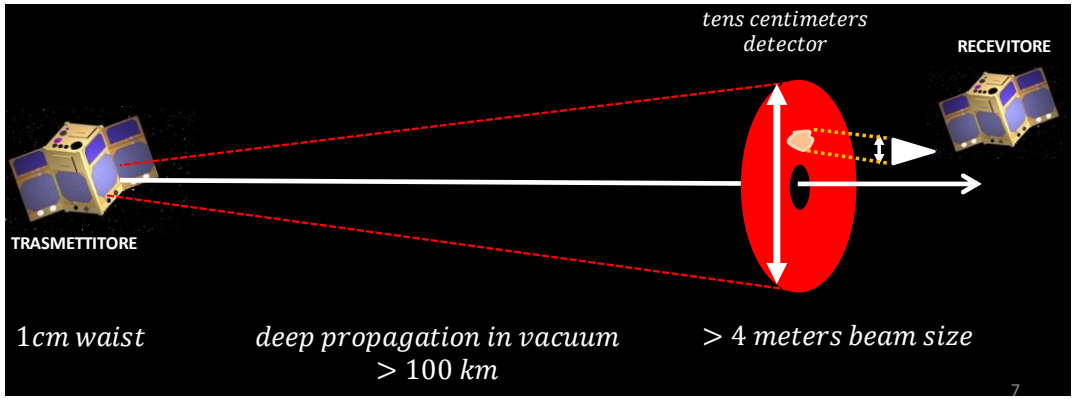


- **QuantERA + Regione Puglia**: «Qu3D» (2020-23). Coordinatore (200 k€), in collaborazione con Planetek Hellas, EPFL, Olomouc Univ. (INFN + UniBA)

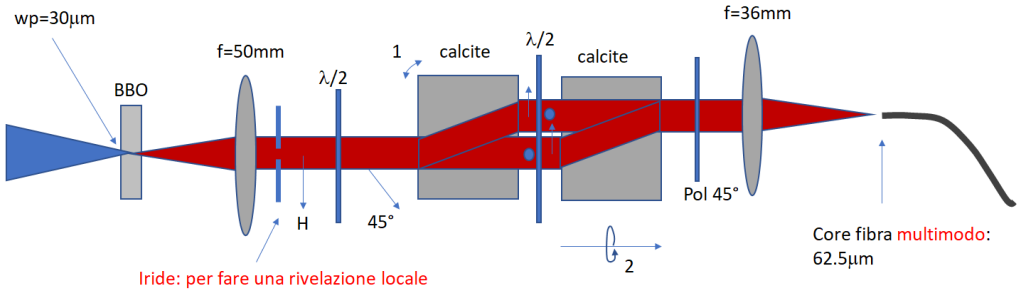
Credit: Milena D'Angelo

MOONLIGHT (Quantum protocol via local detection of OAM entangled states in pulsed light)





- Sviluppo di protocolli di comunicazione basati su stati entangled di momenti angolari orbitali di fotoni.



Credit: Bruno Paroli

La sfida continua...

- Si sono formati nuclei di interesse e competenze interne all'Ente.
- L'INFN può diventare un punto di riferimento per una comunità ancora sparsa.
- Concentrando gli sforzi in settori di nicchia e di interesse è possibile raggiungere primati internazionali.
- È possibile inaugurare o rafforzare linee di ricerca di base parallele alle «tradizionali».


L'unico modo per scoprire I limiti del possibile è avventurarsi un po' oltre, nell'impossibile.
- Arthur C. Clarke