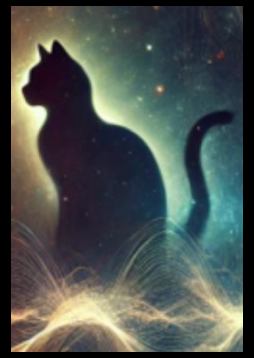
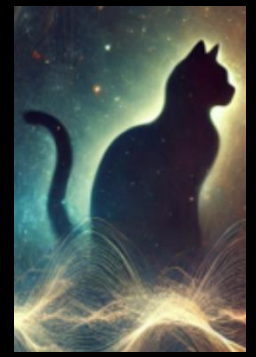


Testing Quantum Foundations in the 2025 Quantum Year

LNF — Frascati

20 - 22 October, 2025



Quantum circuits for fundamental physics

Alessio Rettaroli

INFN – Laboratori Nazionali di Frascati

Outline

- Josephson Junctions
- Superconducting Qubit

Quantum Sensing

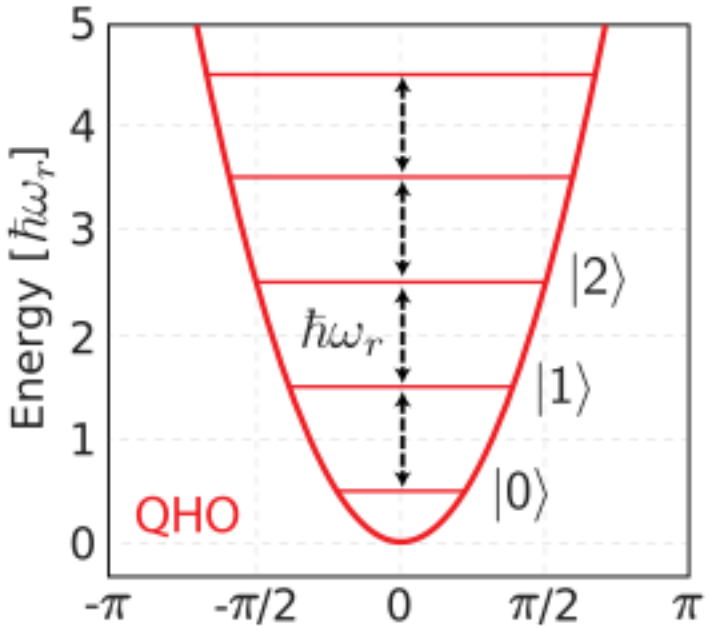
- CBJJ
- Single qubit
- Two qubits

QUART&T

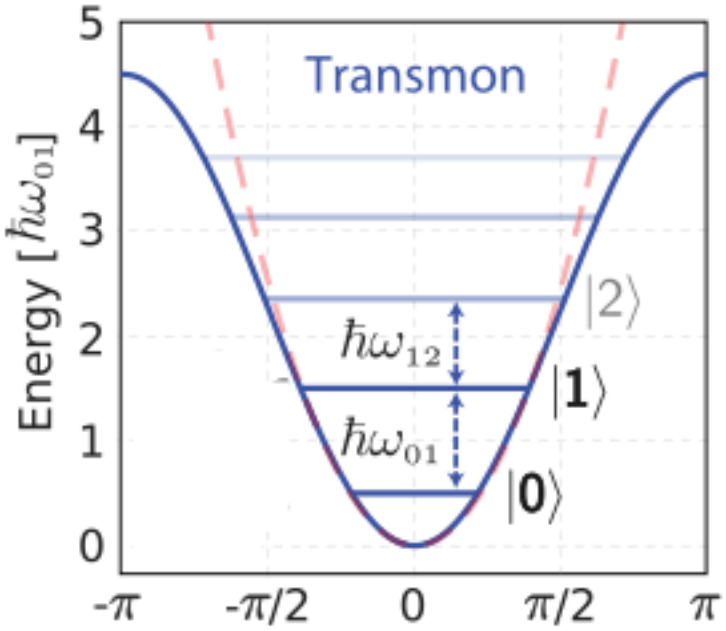
- Quantum architectures
- Quantum simulators

Quantum systems

Harmonic oscillator

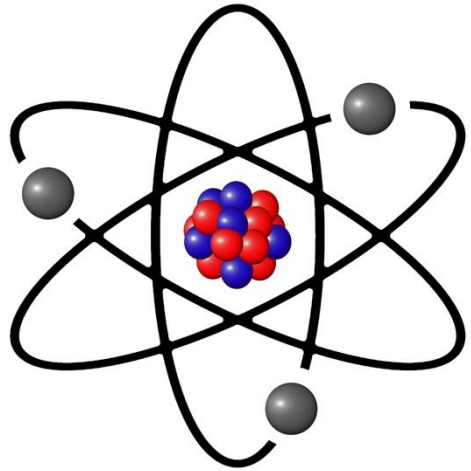


Anharmonic oscillator



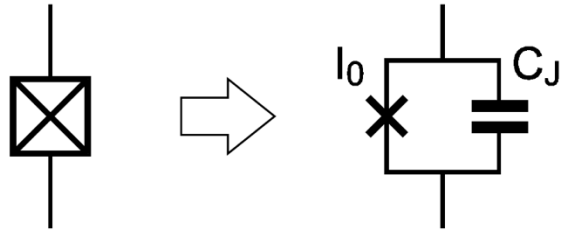
Artificial atom

=



Superconducting quantum circuits are artificial atoms

Josephson Junctions

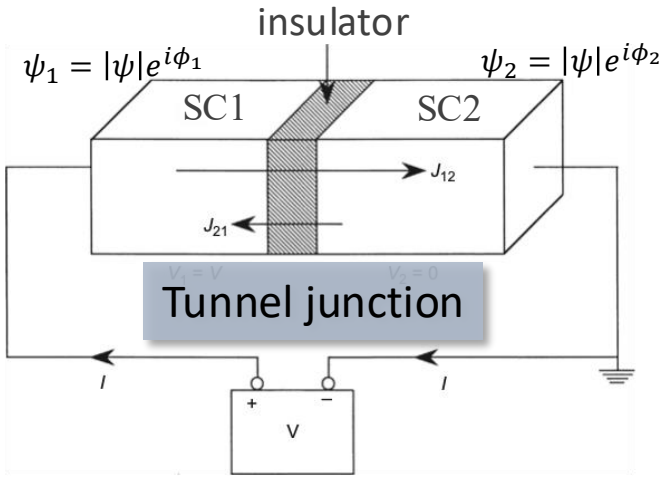


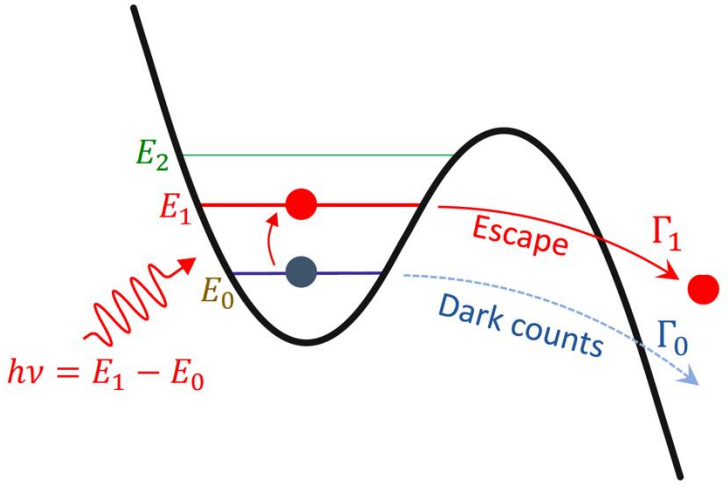
Tunneling current

$$I = I_c \sin\varphi$$

Voltage across the junction

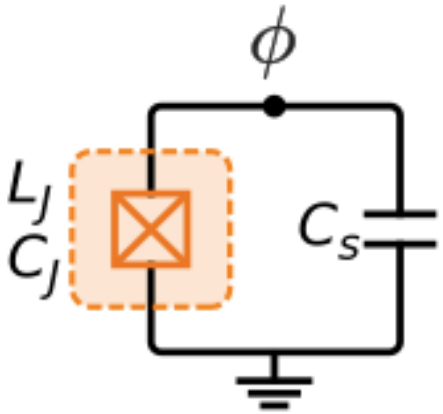
$$V = \frac{\hbar}{2e}\frac{d\varphi}{dt}$$





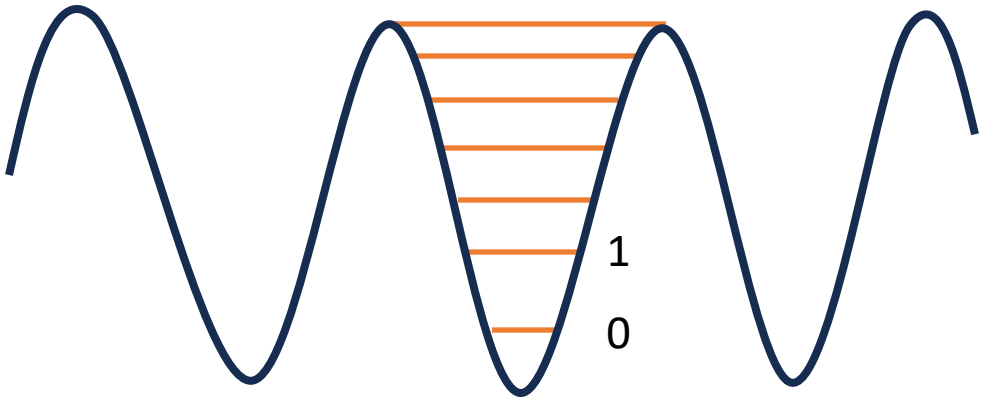
Superconducting quantum circuits are artificial atoms

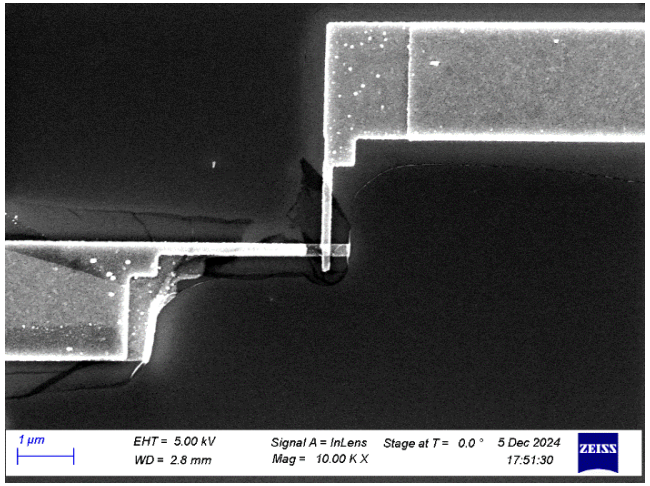
Qubits



$$E = \frac{Q^2}{2C} - E_J cos 2\pi\phi/\phi_0$$

$$E_J = \frac{\phi_0 I_C}{2\pi}$$ Josephson energy





$$E_{n+1} - E_n = E_n - E_{n-1} - E_C$$

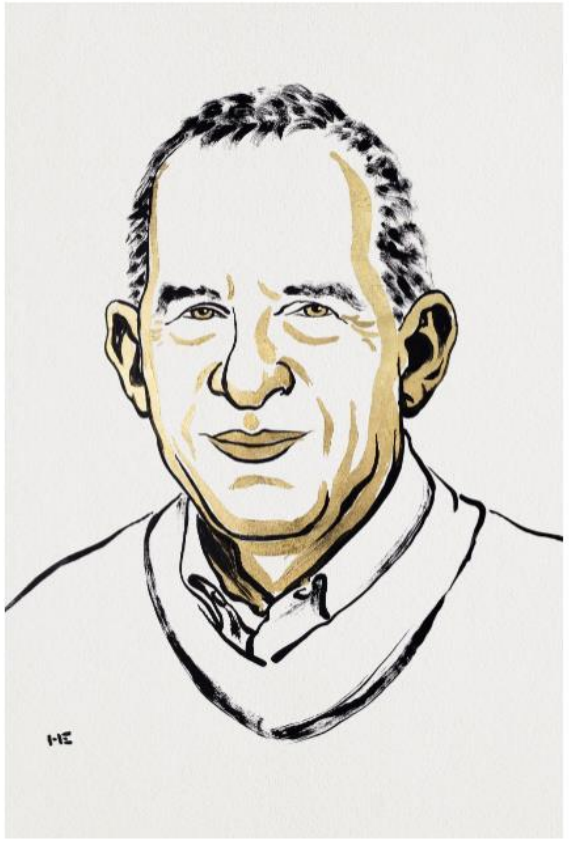
Anharmonicity

$$E_C = \frac{e^2}{2C}$$

“For the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit”

Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke



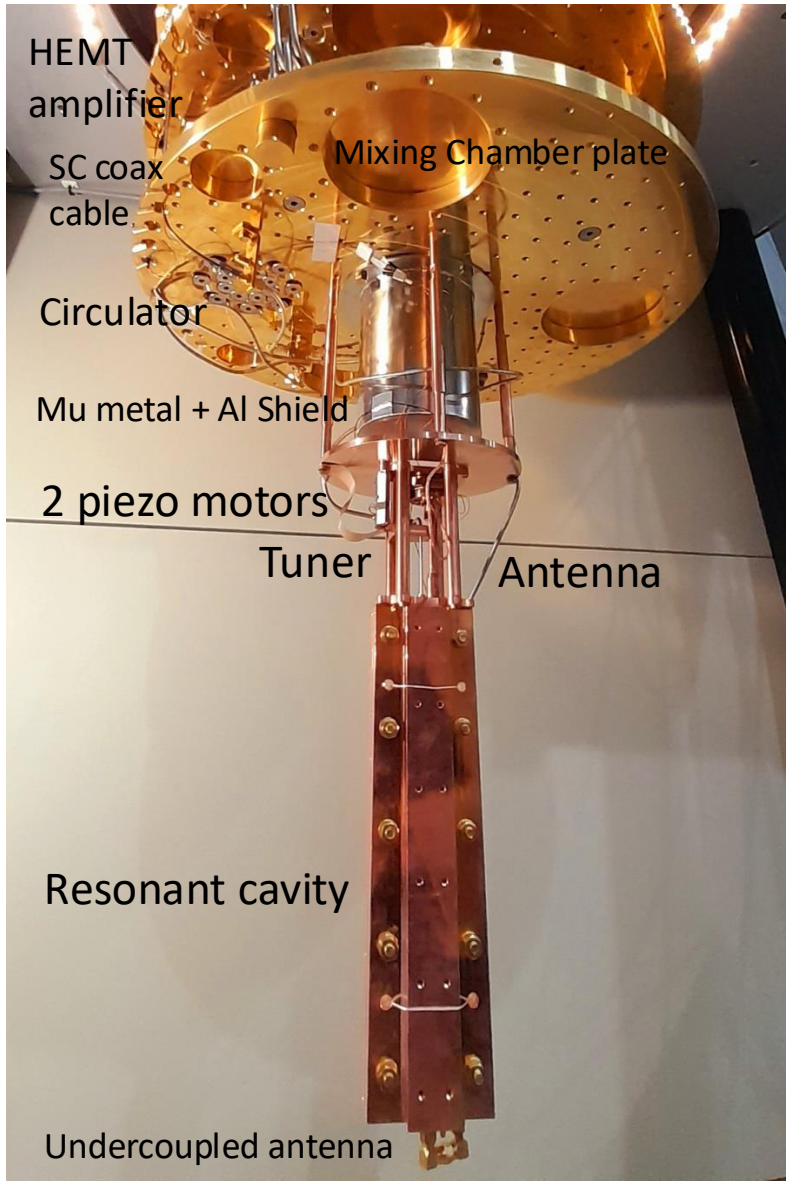
Ill. Niklas Elmehed © Nobel Prize Outreach

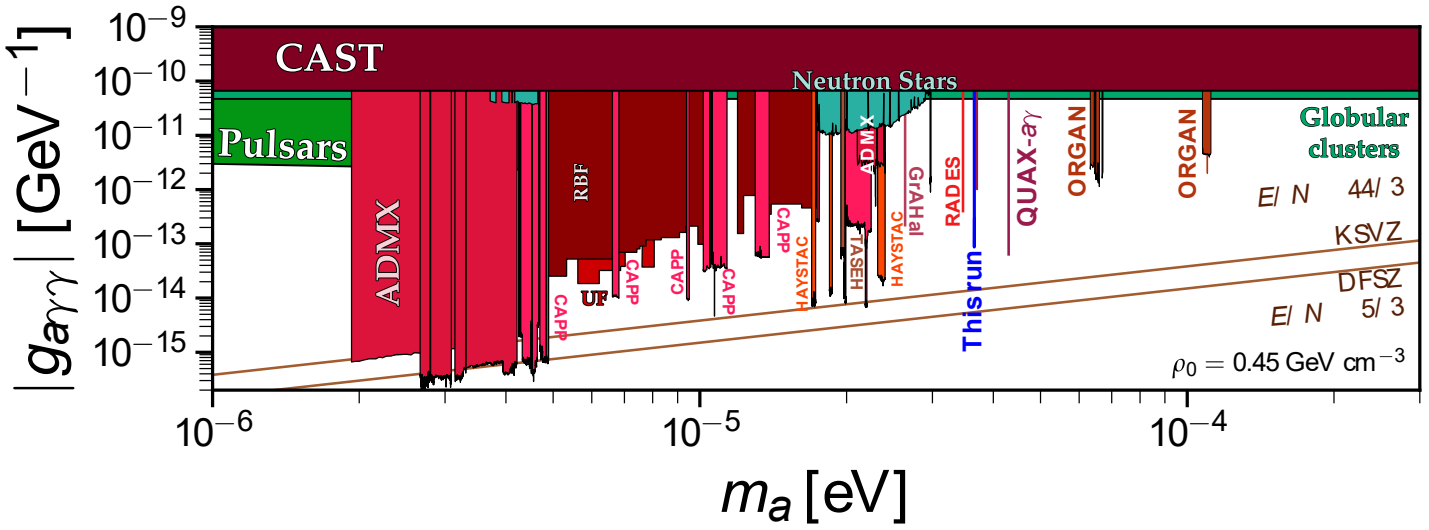
Michel H. Devoret

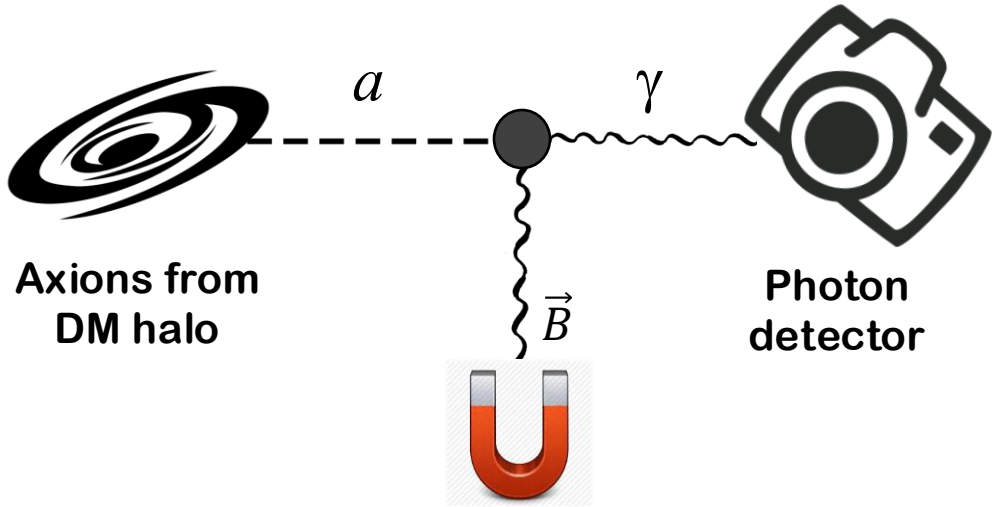
Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

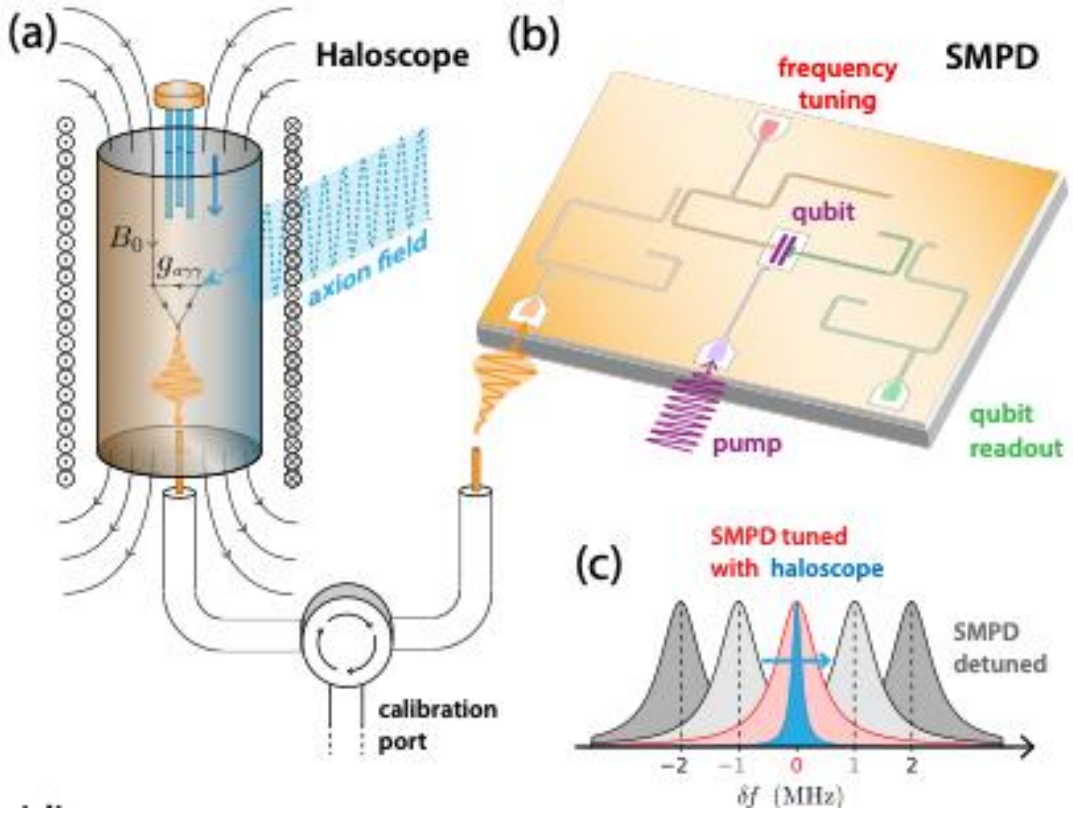
Quantum sensing for Dark Matter search

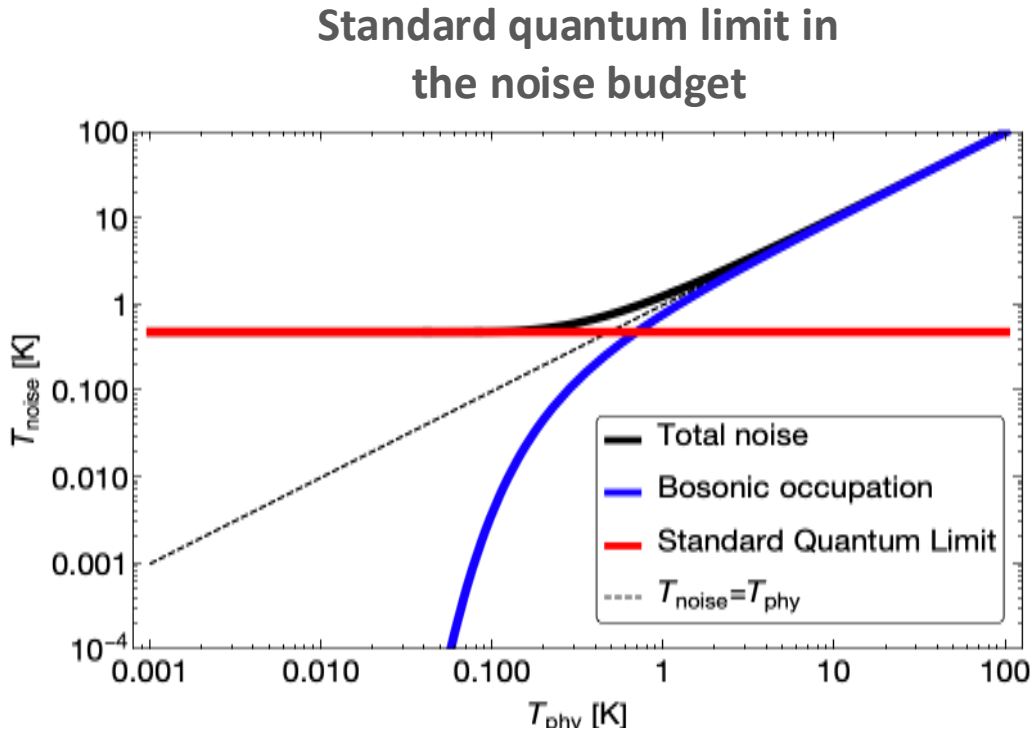






Quantum sensing for Dark Matter search

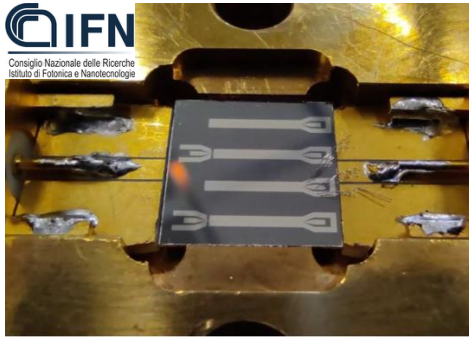




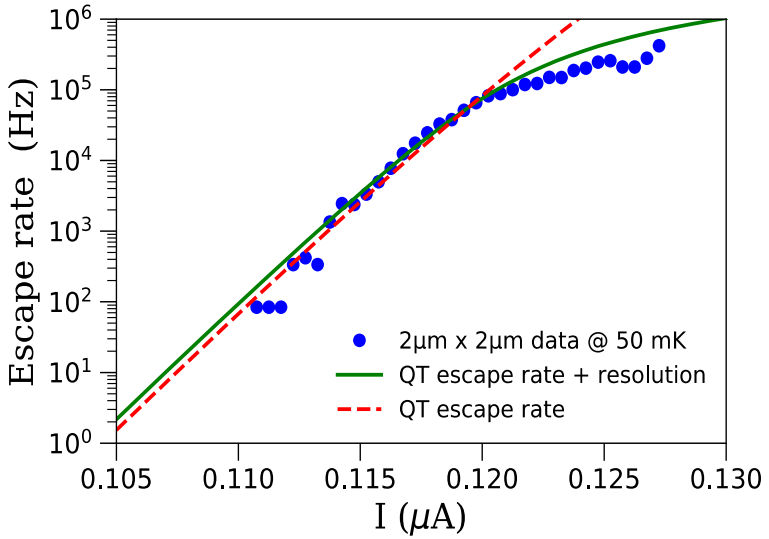
Phys. Rev. X **15**, 021031 (2025)

Current-Biased Josephson Junctions

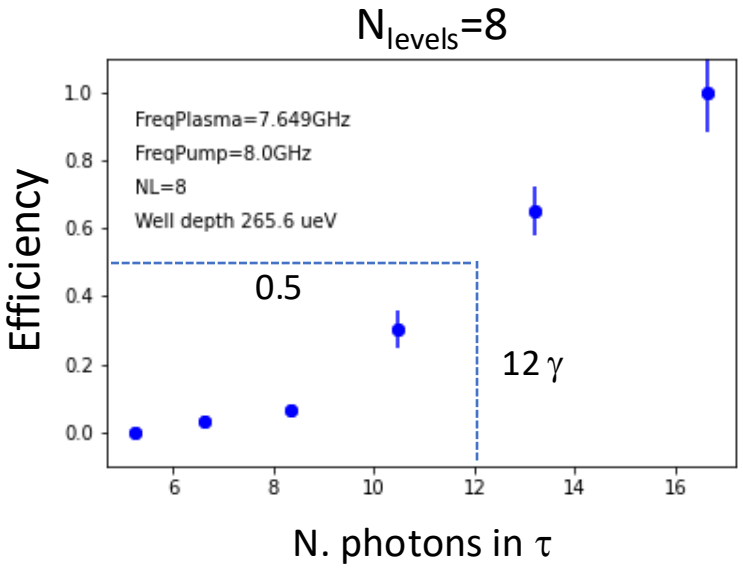
- JJ + Transmission Line fabricated at CNR-IFN
- Itinerant microwave photons reflected by the JJ
- Dark count is estimated as the escape rate when biased with a current I



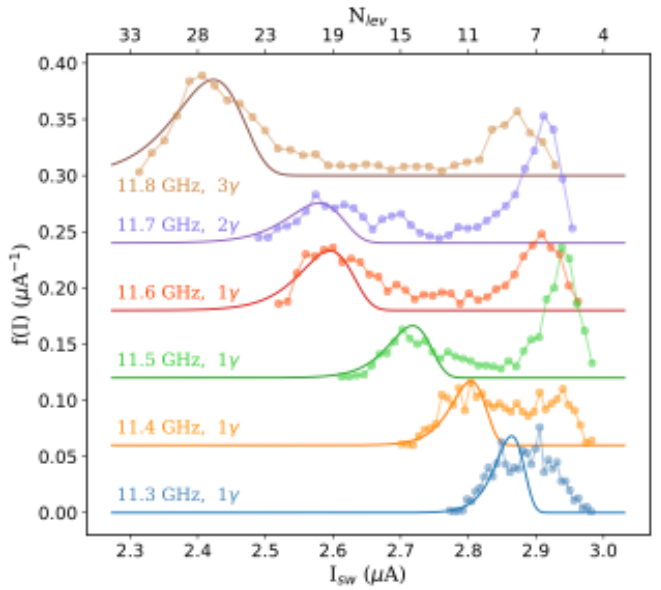
Extrapolated dark count



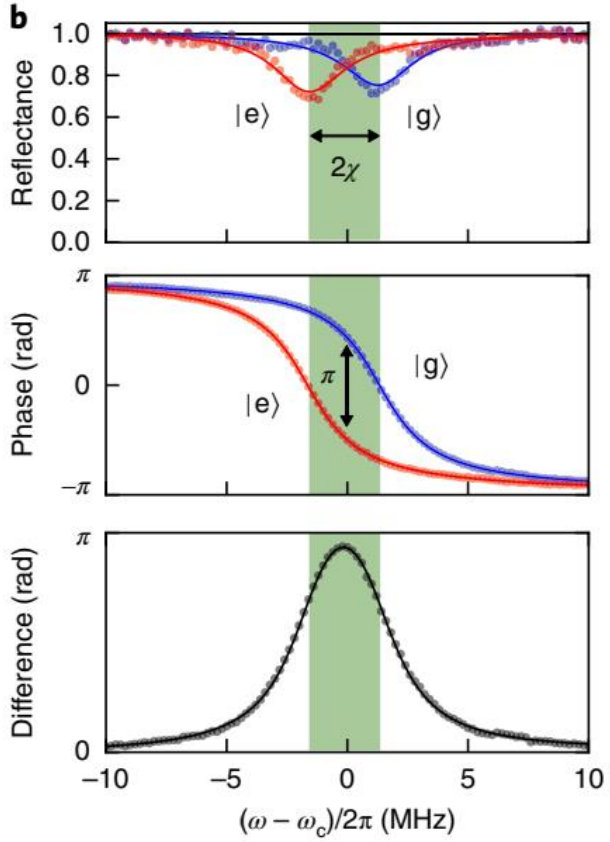
- Demonstrated that JJs switch when $N_\gamma \simeq N_{levels}$

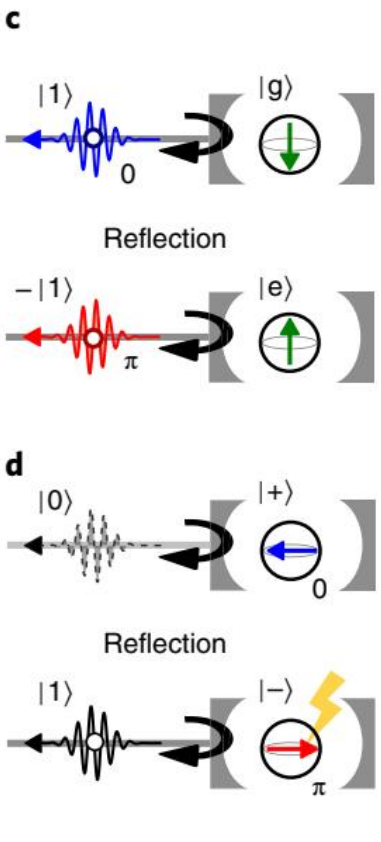


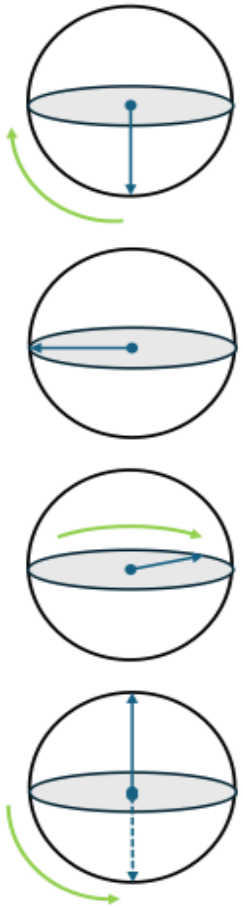
Resonant activation with RF



Single qubit – Quantum non-Demolition







Ramsey Measurement $H_{int} = \epsilon\sigma_z$

$|\psi\rangle = |0\rangle$

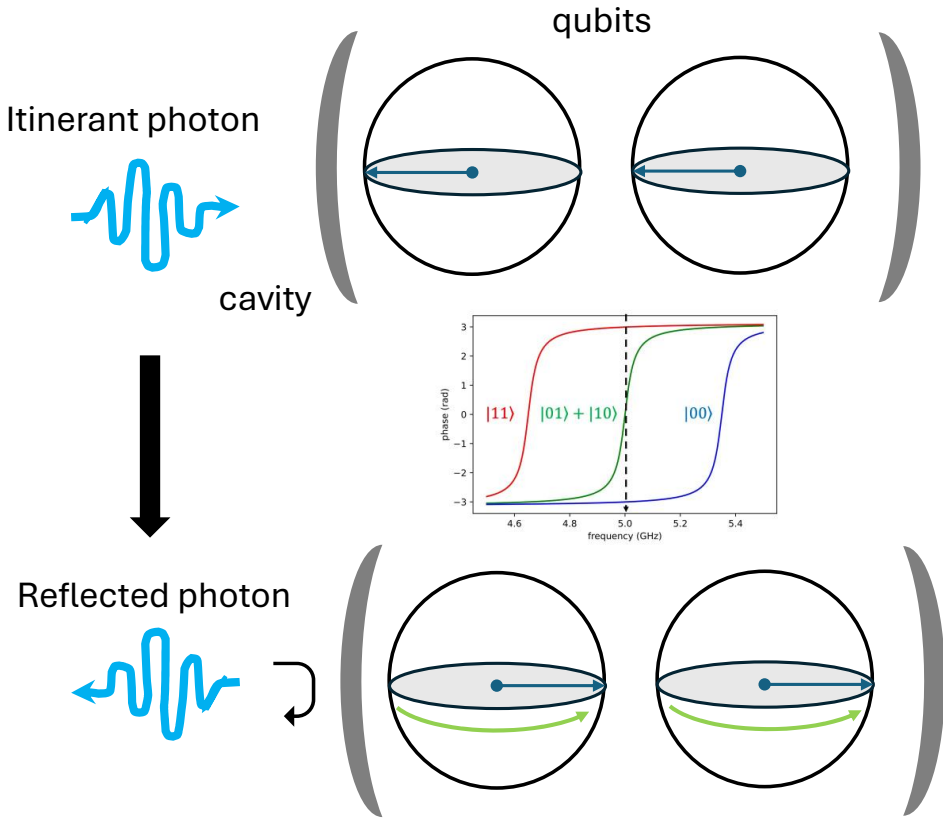
$|\psi\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$

$|\psi\rangle = \left(|0\rangle + e^{-i\omega_0 t}|1\rangle\right)/\sqrt{2}$

$P(1) = 1 - |\langle 0|\psi\rangle|^2 = \sin^2\left(\frac{\omega_0 t}{2}\right)$

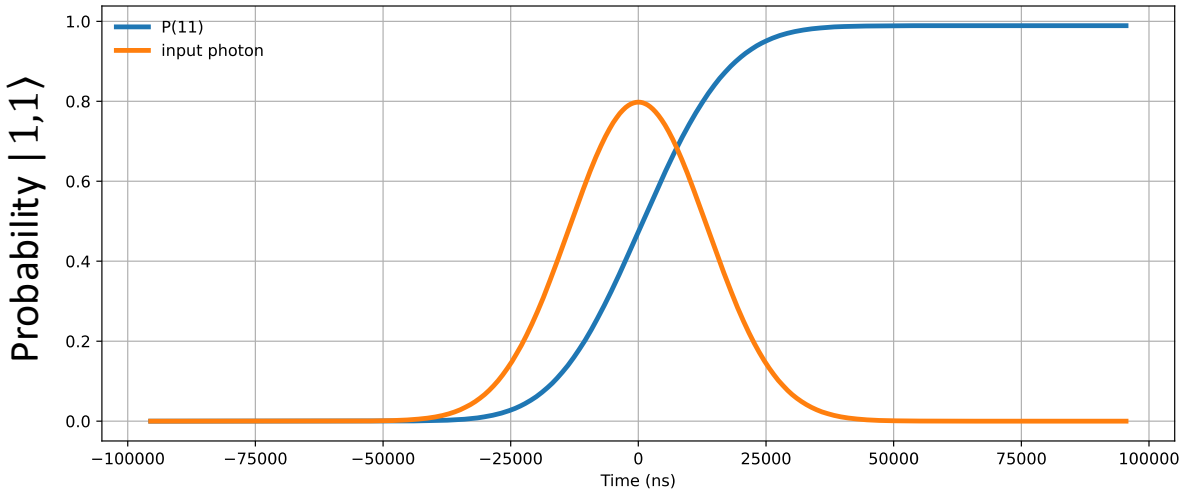
Nature Physics | VOL 14 | JUNE 2018 | 546–549

Double qubit – Error correction



Expected dark count rate

$$R = \frac{p(1|0)^2}{T_2/2} \approx \frac{2\times10^{-4}}{26\ \mu s} = 8\ Hz$$

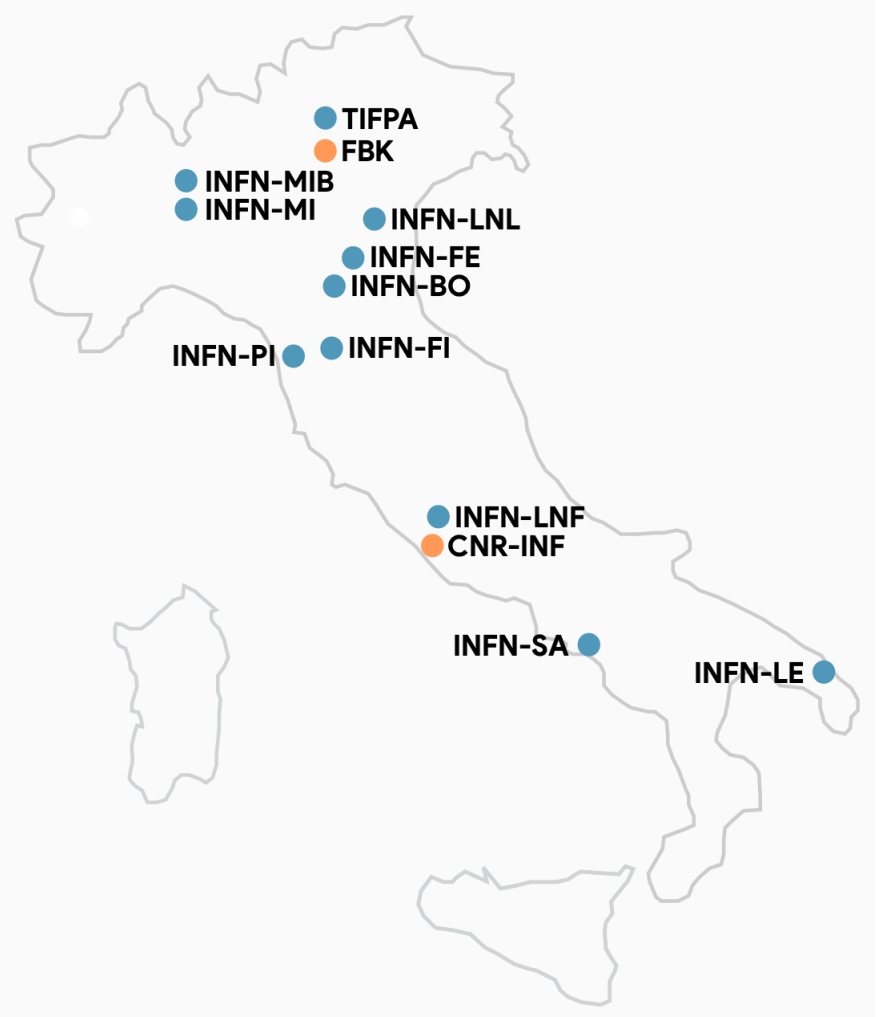


A D'Elia Appl. Sci. 2024, 14(4), 1478

3-year project in INFN CSN5

QUANTUM ARCHITECTURES FOR THEORY & TECHNOLOGY

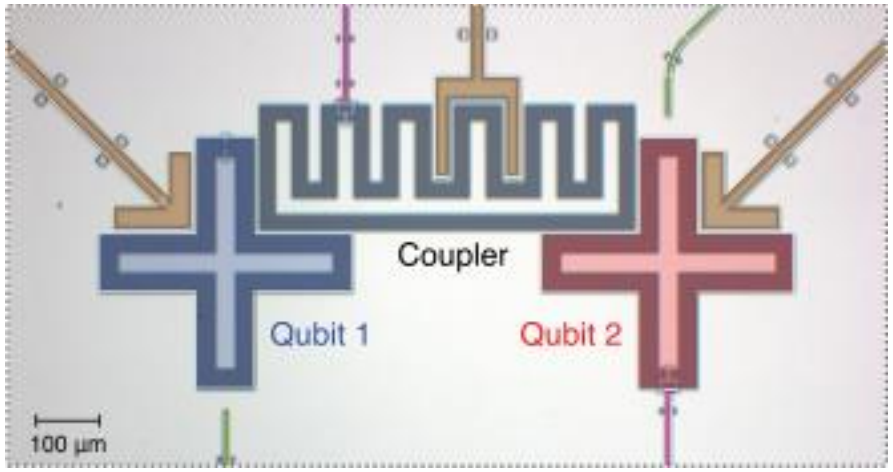
CSN5 Technological research

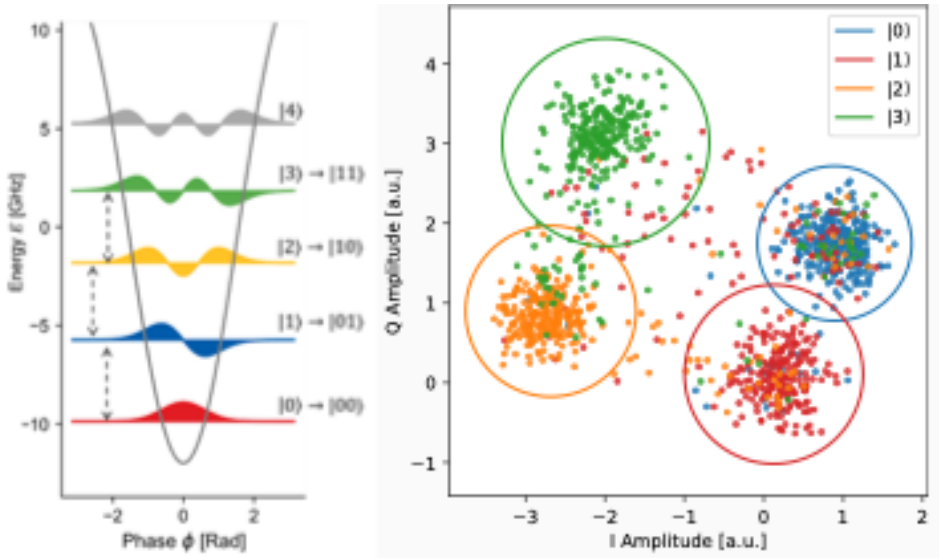


P.I. Andrea Giachero (MiB)

QUART&T goals

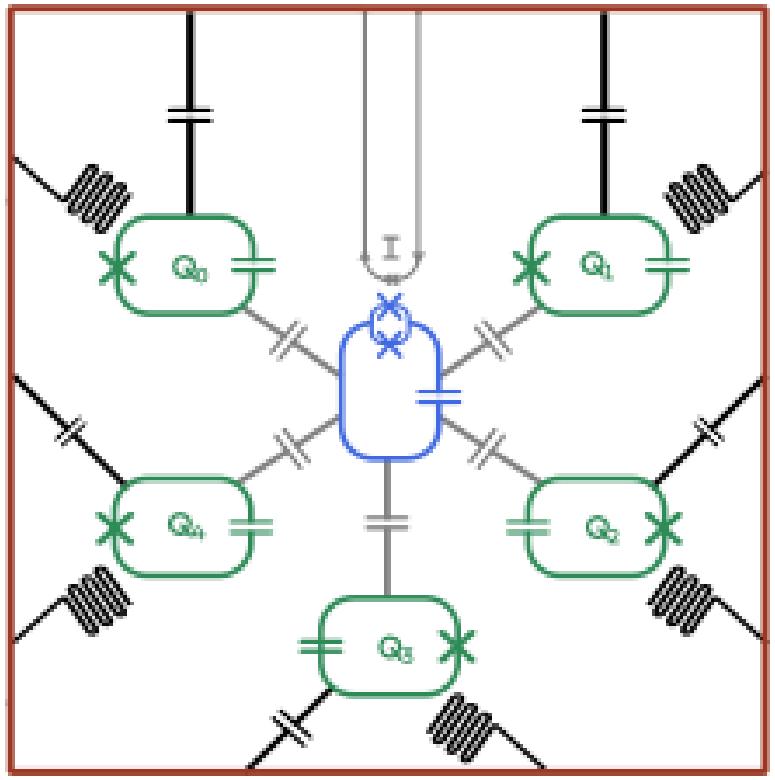
- **Tunable couplings:** possibility to implement and control the required couplings between qubits
- **All-to-all connectivity:** tunable qubits coupled to a common bus resonator have the advantage of enabling all-to-all couplings
- **Qudits:** The quantum device developed within the project will also be exploited as higher-dimensional quantum systems (qudits), offering increased computational power and flexibility





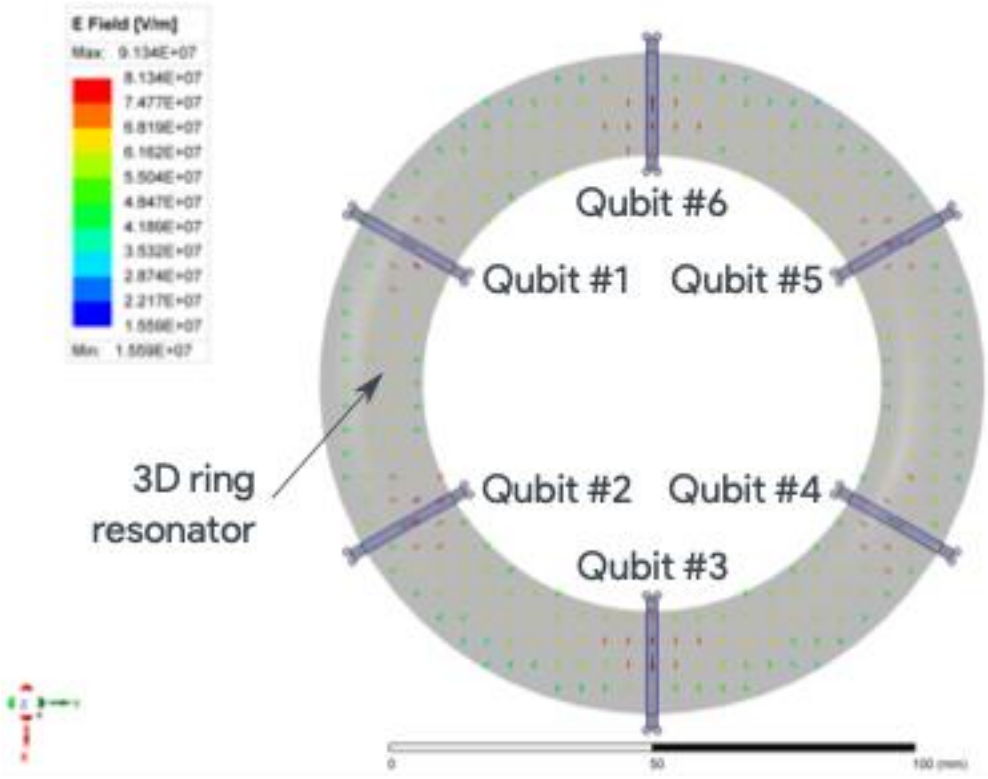
All-to-all connectivity realizations

5 qubits in planar resonators



- Planar qubits more easily scalable
- Tunable coupling provided by SQUID or another qubit
- Suitable for all-to-all connectivity

6 qubits in 3D cavity



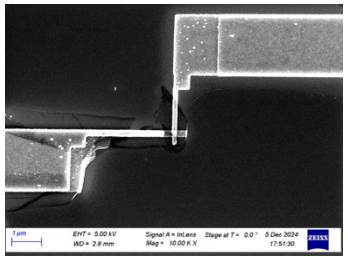
- 3D qubits provide higher coherent times
- More difficult to scale
- But ideal solution for implementing qudit

Nanofabrication facilities

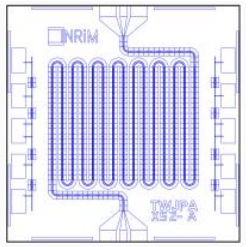
Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

FONDAZIONE BRUNO KESSLER

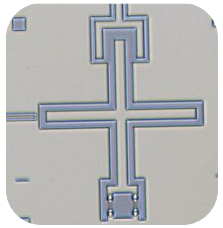
IFN
Consiglio Nazionale delle Ricerche
Istituto di Fotonica e Nanotecnologie



INRiM
ISTITUTO NAZIONALE DI RICERCA METROLOGICA



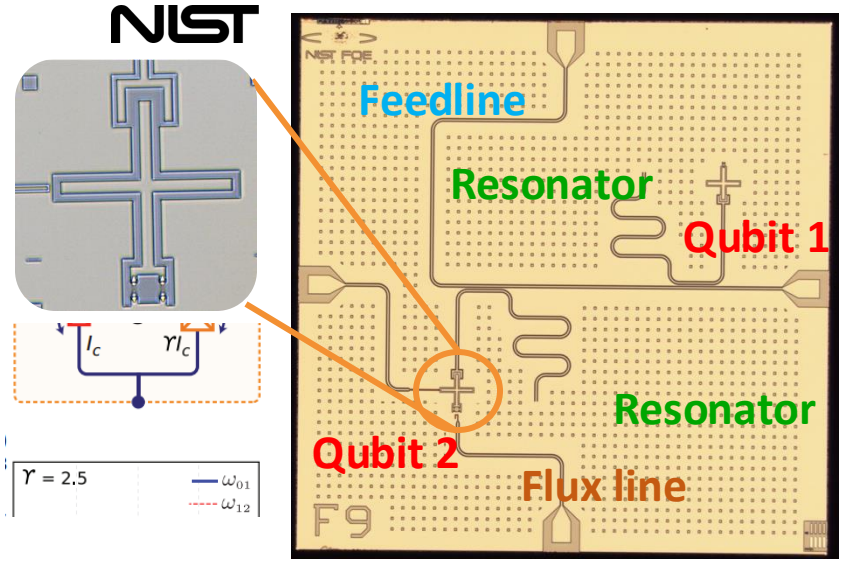
NIST



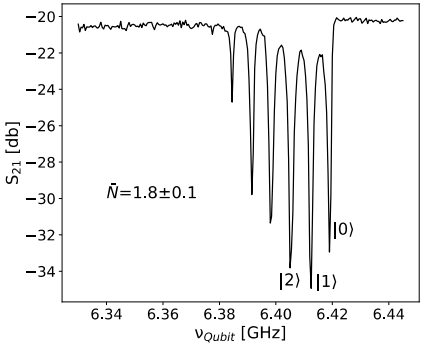
TII
Technology Innovation Institute

CHALMERS
UNIVERSITY OF TECHNOLOGY

Qubit measurements

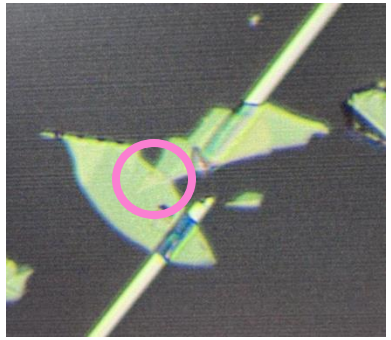


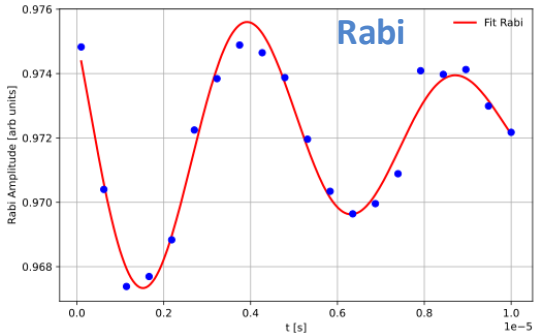
Ability in the single-qubit control (decoherence times, dispersive shift and couplings, qubit spectroscopy, qubit tunability, resolving photon number)

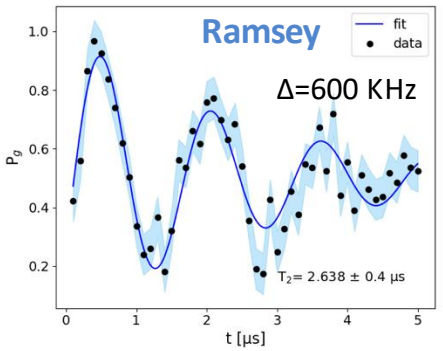


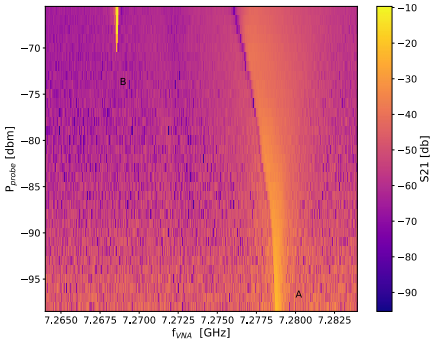
Appl. Sci. 2024, 14(4), 1478

Homemade NbSe2 (A. D'Elia)

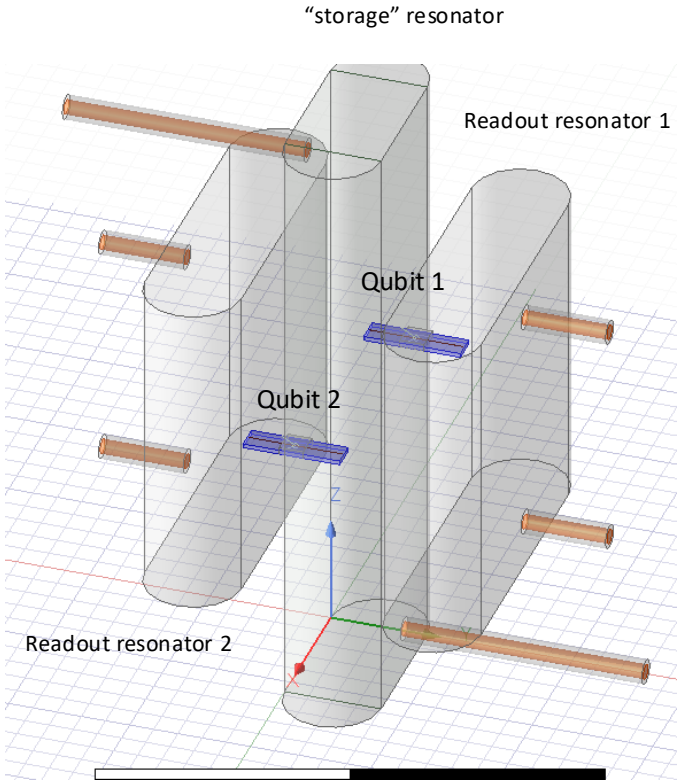


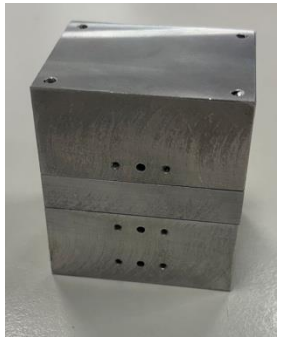


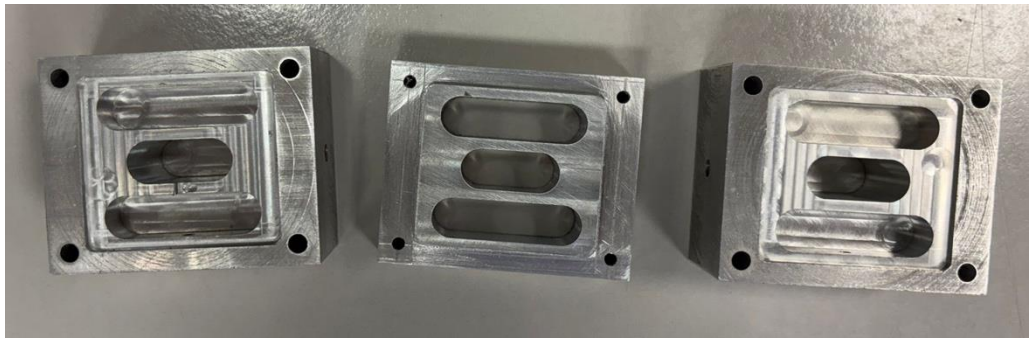


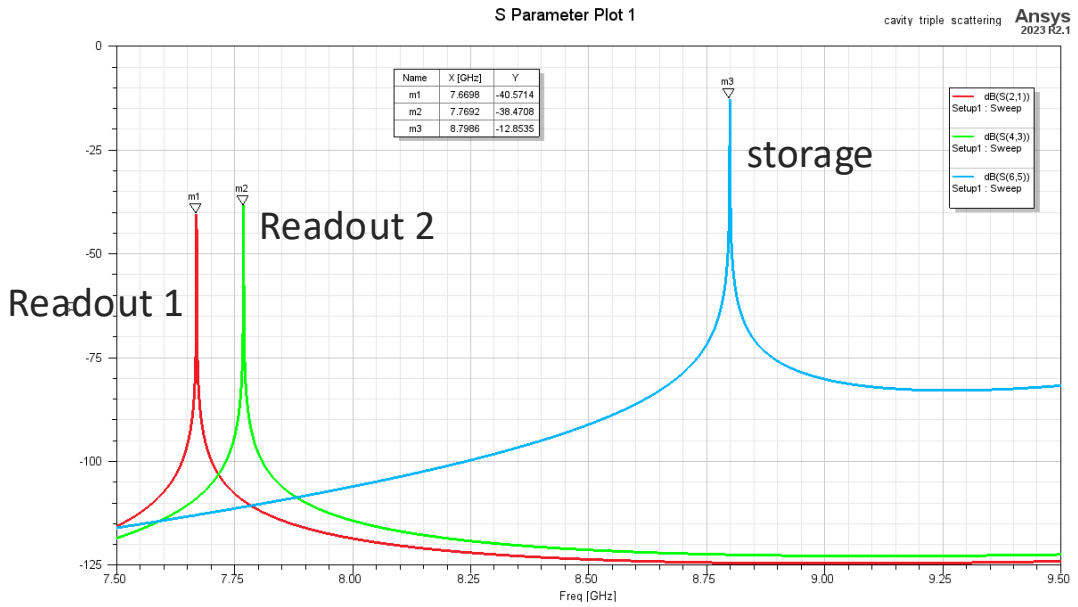


2-qubit realization for quantum sensing







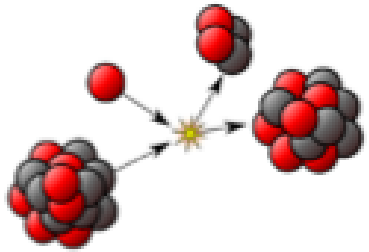


Analogue quantum simulations

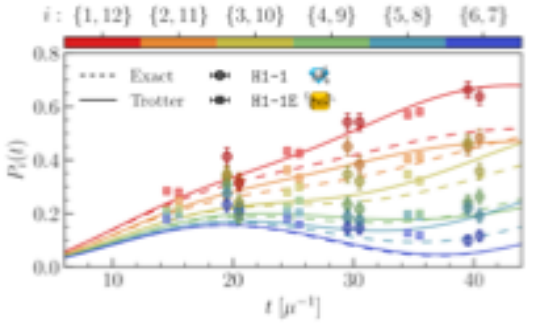
The dynamics of many-body systems is challanging.

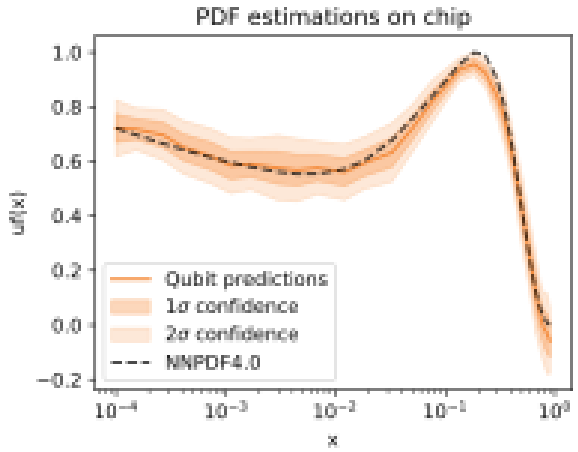
A quantum architecture can mimic and study the behavior of other quantum systems, such as

- **neutrinos**
- **QCD**
- **nuclear physics**
- **quantum gravity**
- **condensed matter**
- **…**



Implementing in the quantum platform a quantum dynamics following a Hamiltonian that is similar to the one of the simulated quantum system.





u-quark parton distribution funtion

Hawking radiation

Fermionic lattice-model-type realization of an **analogue black hole** by using a chain of **10 SC transmon qubits** with interactions mediated by 9 transmon-type tunable couplers

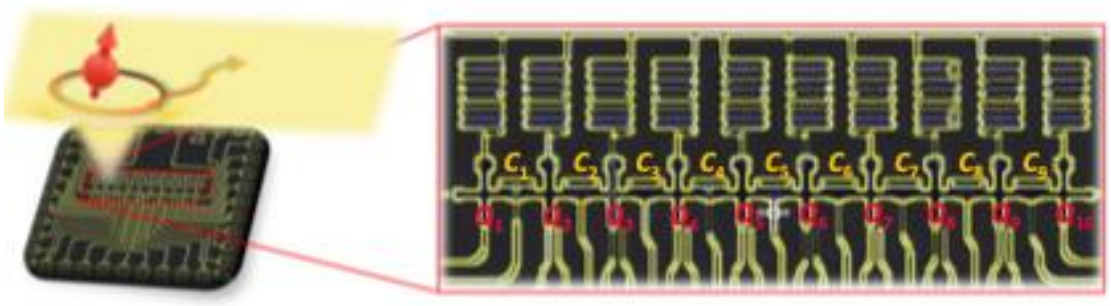
Dirac equation

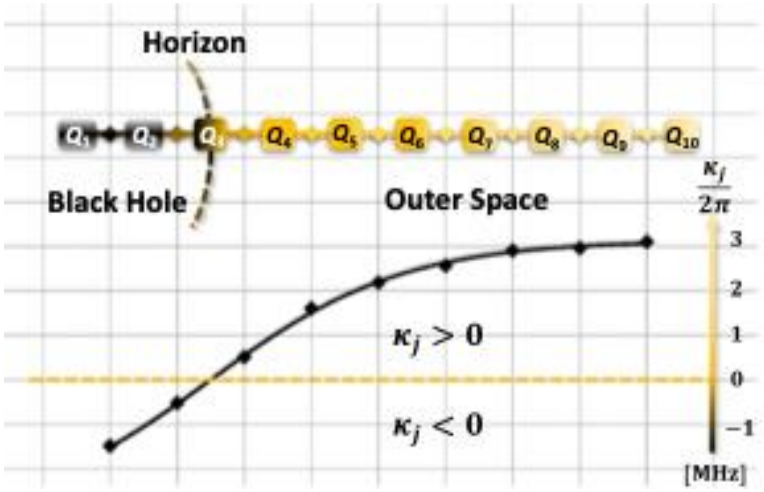
$$i\gamma^a e^{\mu}_{(a)}\partial_\mu\psi+\frac{i}{2}\gamma^a\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}e^{\mu}_{(a)}\right)\psi-m\psi=0,$$

mapped into

$$\hat{H}=-\sum_j \kappa_j\left(\hat{\sigma}_j^+\hat{\sigma}_{j+1}^-+\hat{\sigma}_j^-\hat{\sigma}_{j+1}^+\right)-\sum_j \mu_j\hat{\sigma}_j^+\hat{\sigma}_j^-$$

quantum system Hamiltonian





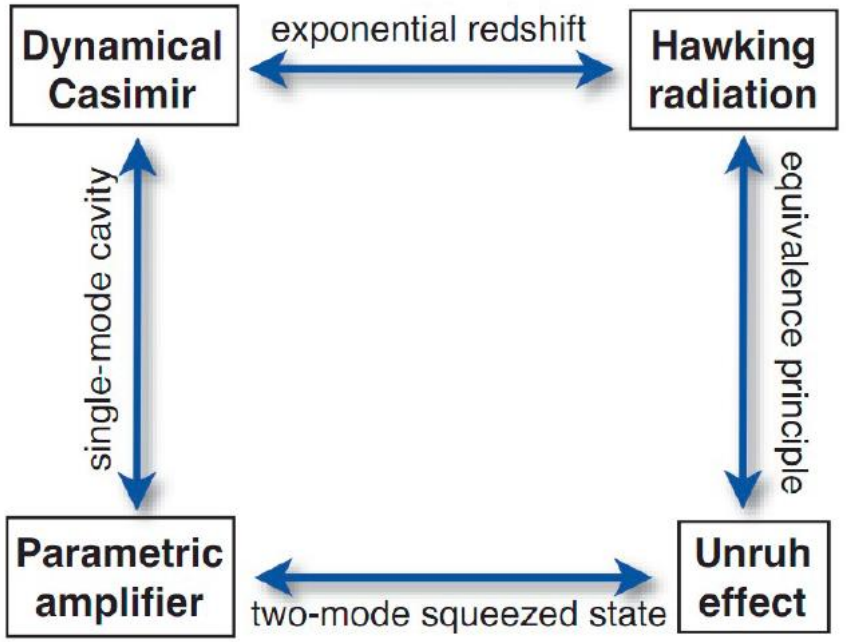
Yun-Hao Shi et al. Nature Communications | (2023) 14:3263

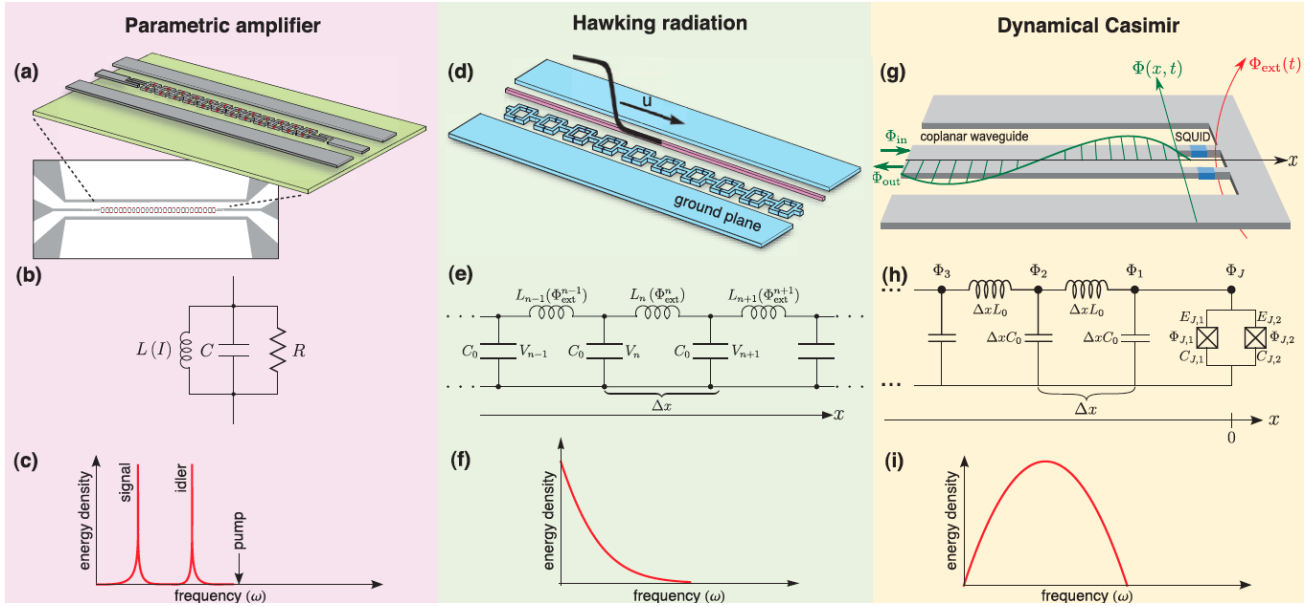
Conclusions

- Superconducting quantum circuits are extremely sensitive devices, allowing to
  - Break down the sensitivity in light dark matter searches, where sub-Standard Quantum Limit detection is required
  - Have access to enhanced computational power with respect to classical simulators
  - Set up table-top laboratories to test fundamental physics with Analogue Quantum Simulators
- Italian institutes are growing in expertise
- Tested Current-biased Josephson junctions as microwave switching detectors
- Single qubit measurements and control
- Double qubit design on the way

backup

Amplifying the Quantum Vacuum with Superconducting Circuits





https://doi.org/10.1038/nature10561