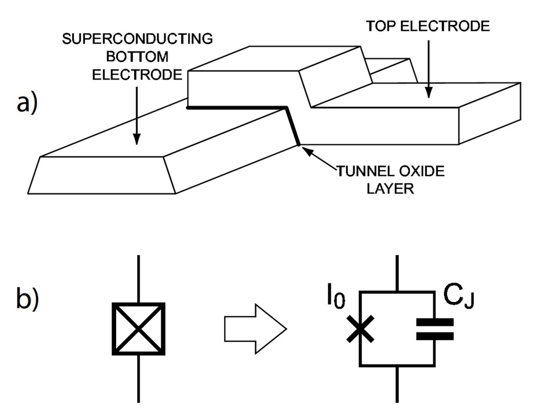
Qub-IT: Quantum sensing with superconducting qubits for fundamental physics

D. Labranca on behalf of the Qub-IT collaboration

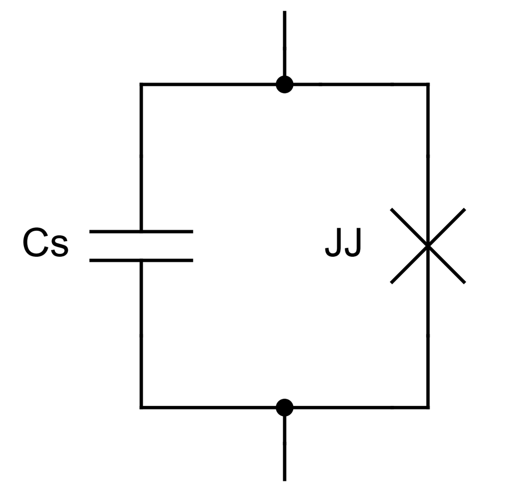
The goal of the Qub-IT project is to realize an itinerant single-photon counter exploiting QND measurements and entangled qubits, in order to surpass current devices in terms of efficiency and low dark-count rates. Such a detector has direct applications in Axion dark-matter experiments, which require the photon to travel along a transmission line before being measured. The simulation phase of superconducting qubits devices is fundamental in order to converge to the desired properties before moving to the manufactoring stage. The design and simulation of the first superconducting device consisting of transmon qubits coupled to resonators is being performed with Qiskit-Metal (IBM) and Ansys HFSS.

Superconducting qubits

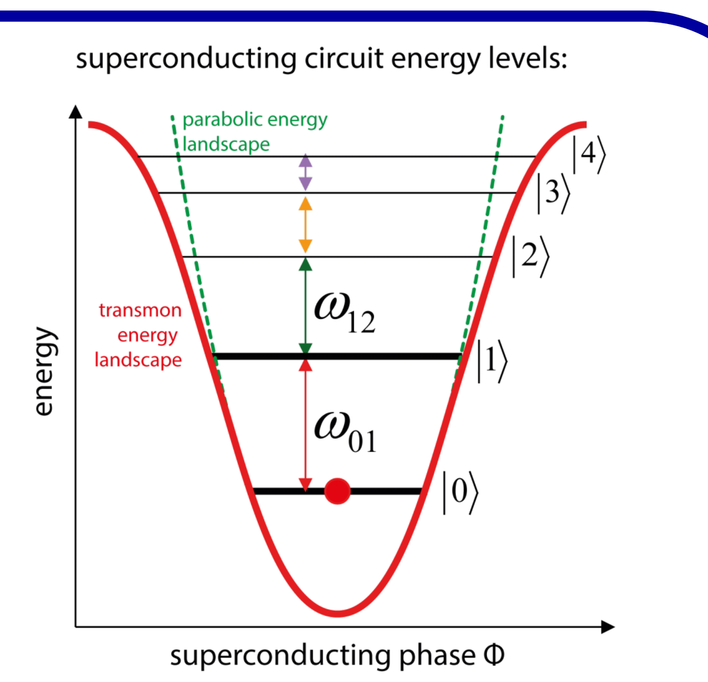
- Superconducting qubits: - Slightly anharmonic resonator
  - Josephson junction shunted by a capacitance
- Josephson junction: non linear inductance introducing anharmonicity
- Transmon qubits: - Large anharmonicites
  - Low sensitivity to charge noise



Sketch of a Josephson junction, fundamental cell of superconducting qubits

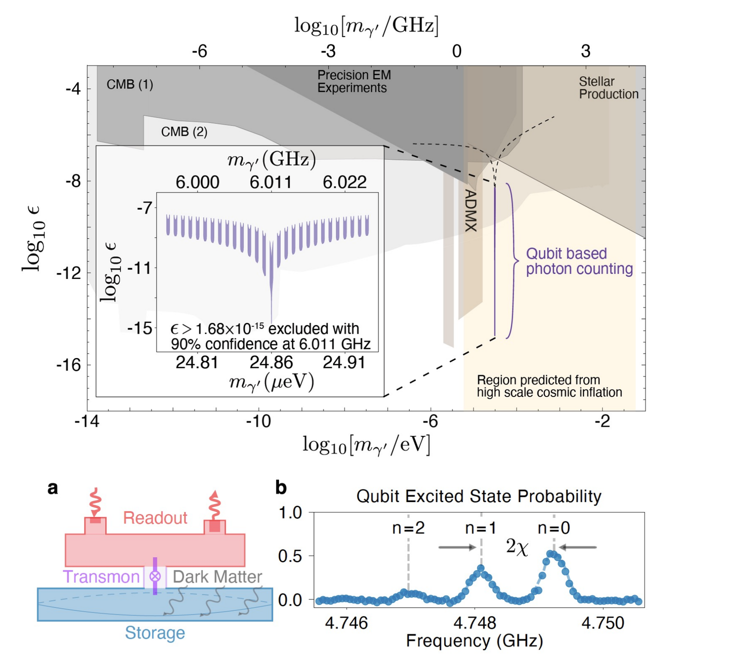


Equivalent circuit of a superconducting qubit



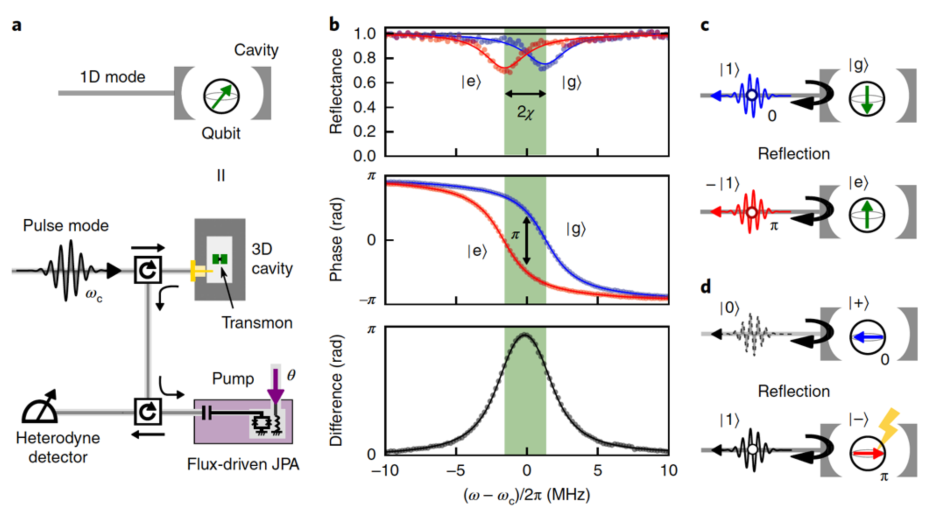
The Qub-IT project

- Main goal: Itinerant single-photon counter with low dark-count rates and high efficiency based on superconducting qubits
- Quantum systems can store the information of an interaction within the phase of the state Quantum Non Demolition (QND) detection
- Applications: Photon sensing for light dark matter candidates, such as Dark Photons and axions (direct application in the QUAX experiment)
- Enhanced sensitivity: - QND detection → multiple measurements of the same photon
  - entangled qubits → reduce dark count rates and phase shift is proportional to the number of entangled qubits
- Fast High-Fidelity readout achievable with Traveling Wave Parametric Amplifiers (TWPAs) developed within the DARTWARS experiment



Example of a QND measurements with localized photon device. The transmon coupled to a large Q cavity allowed up to 30 measurements of the same single photon.

A. V. Dixit et al., "Searching for dark matter with a superconducting qubit," Phys. Rev. Lett. 126, 141302 (2021).

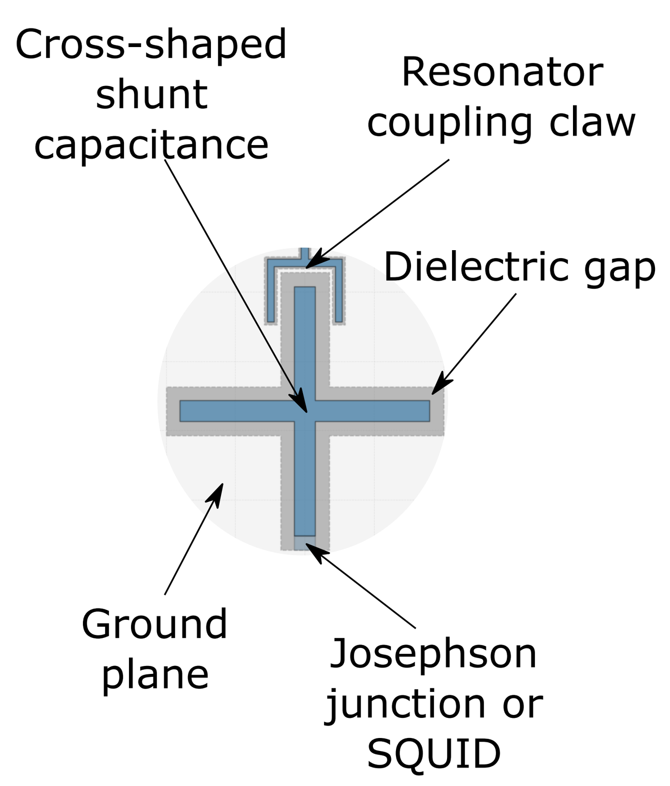


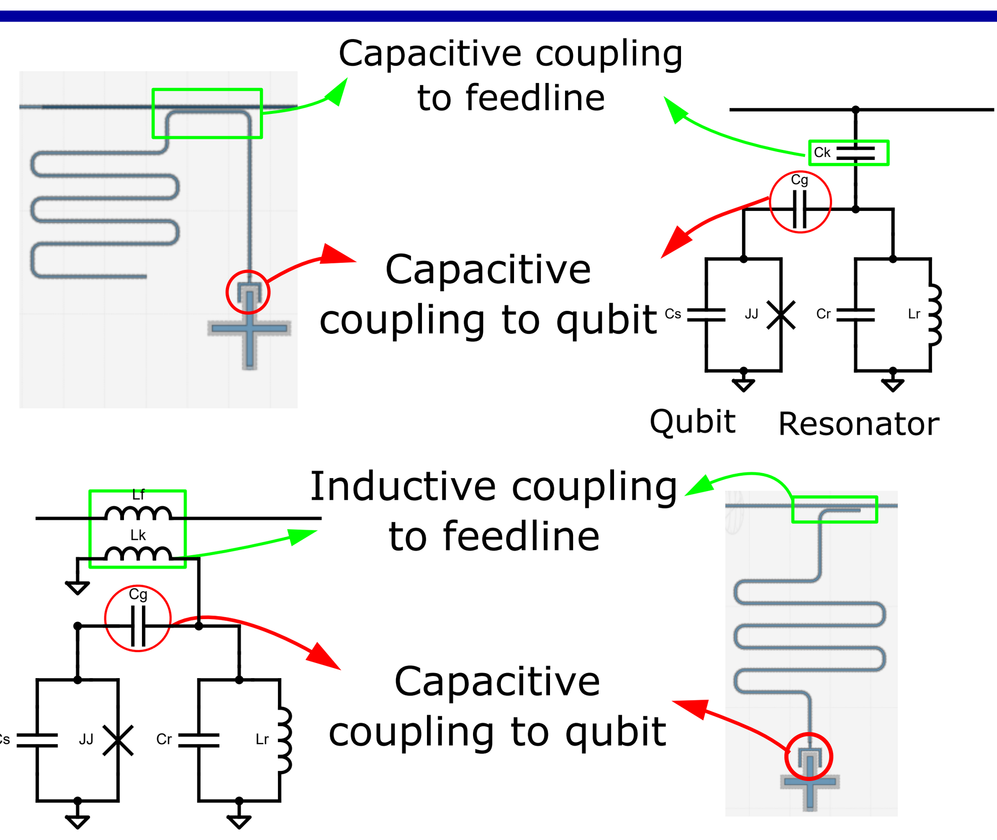
Scheme of an itinerant photon measurement with superconducting qubits.

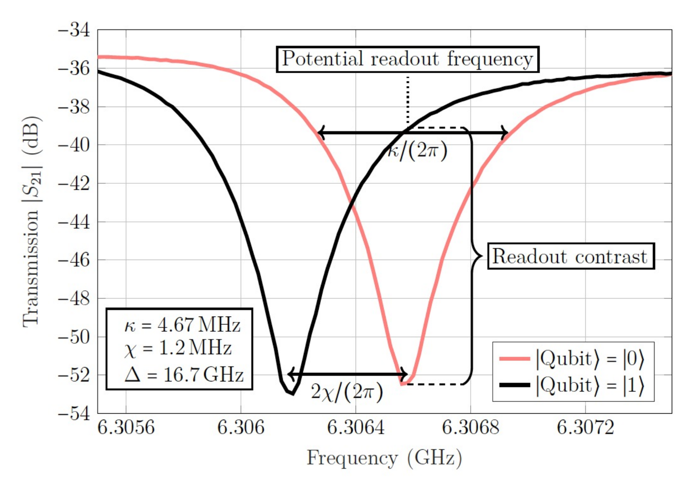
Kono, S. et al. Quantum non-demolition detection of an itinerant microwave photon. Nature Phys 14, 546–549 (2018).

Design of the first chip

- Design based on Xmon-type qubits: Josephson junction shunted by cross-shaped capacitance
- Qubits capacitively coupled to quarter-wave resonators for dispersive readout
- Resonators can be capacitively or inductively coupled to a coplanar waveguide feedline
- The design is defined with Qiskit-Metal: this tool features a valid and handy framework for superconducting circuit set-up







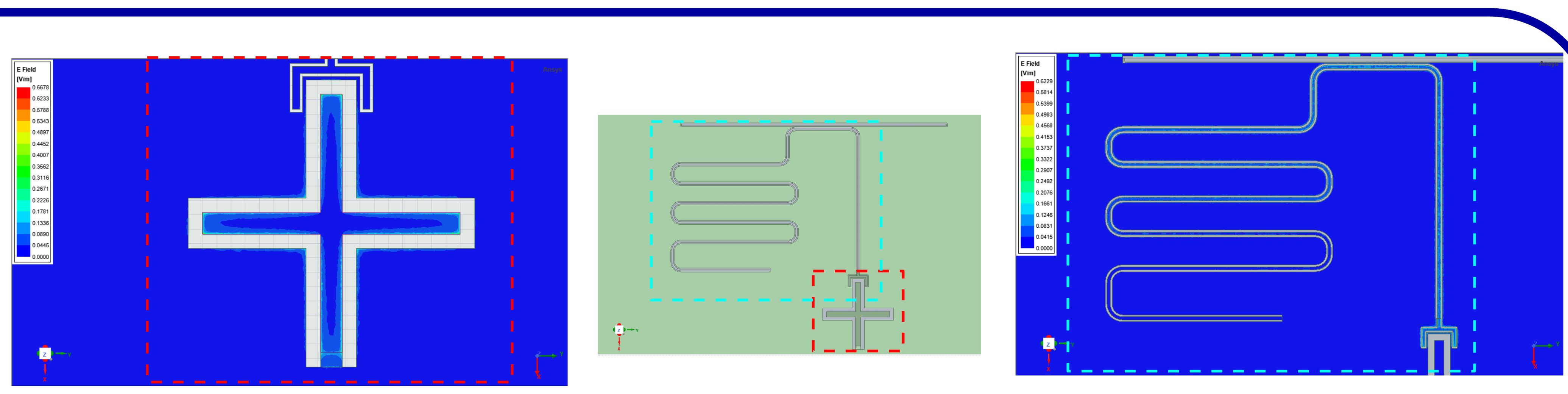
Qubit-resonator simulation

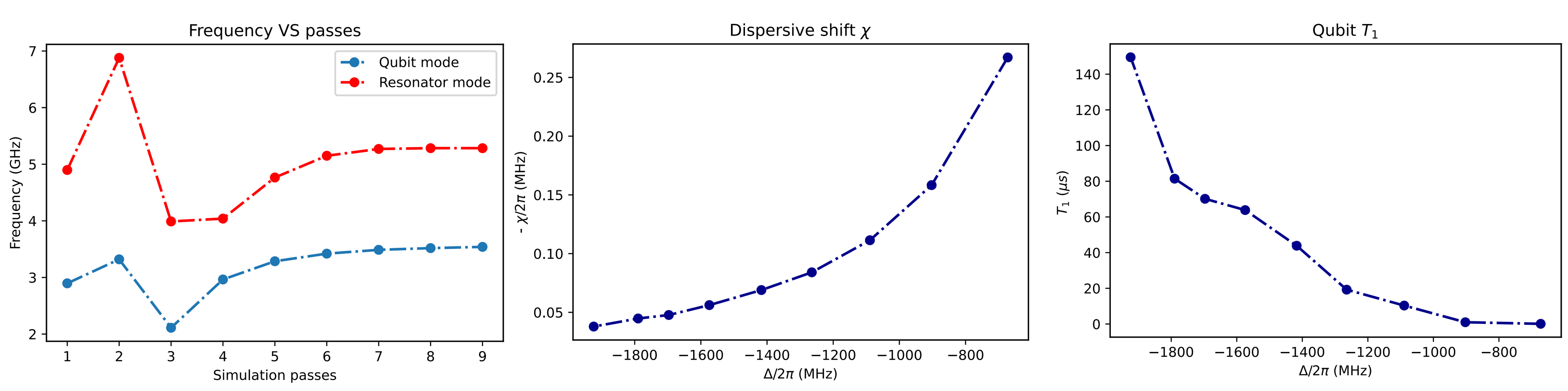
- The simulations are performed with the Energy Participation Ratio (EPR) method: *Minev, Z.K. et al. Energy-participation quantization of Josephson circuits. npj Quantum Inf 7, 131 (2021). https://doi.org/10.1038/s41534-021-00461-8*
- The electromagnetic fields and the eigenmodes of the circuit are calculated with Ansys HFSS
- The EPR (p_m): fraction of the total inductive energy stored in the non linear element (Josephson junction). It is calculated from the electromagnetic fields simulated in Ansys HFSS
- Knowing the EPR and the eigenmode frequencies, the total dispersive shift, Lamb shifts and the anharmonicity of the modes are calculated

Kerr matrix $$\chi_{mn} = \sum_{j=1}^{J} \frac{\hbar\omega_m\omega_n}{4E_j} p_{mj} p_{nj}$$ with J total number of junctions

Anharmonicity $$\alpha_m = \frac{\chi_{mm}}{2}$$

Detuning $$\Delta = \omega_{01} - \omega_r$$





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