Quantum Sensing with Superconducting Qubits for fundamental Physics (Qub-IT collaboration)

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Topics

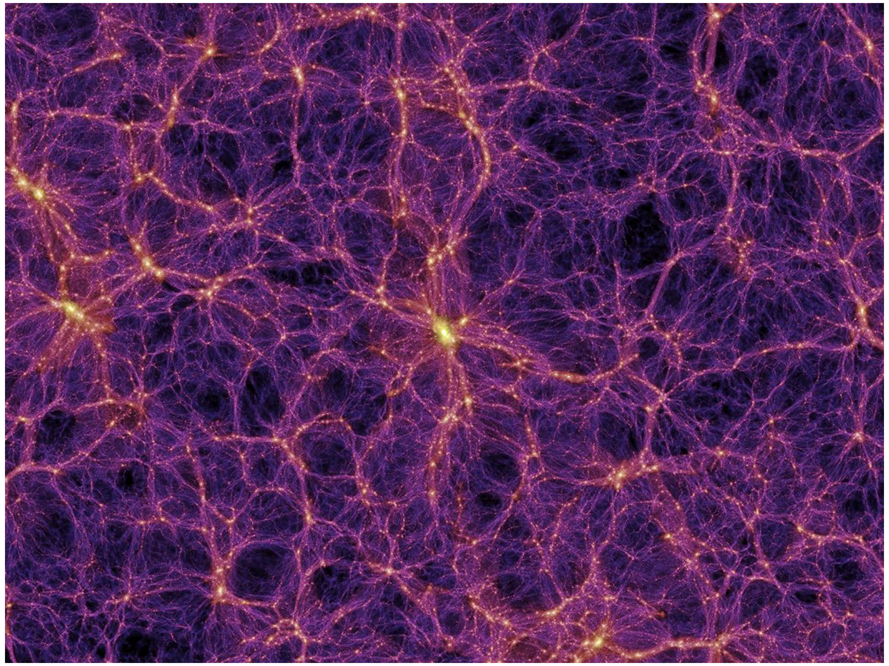
1. Axions
2. Quantum sensing
3. Quantum nondemolition measurements
4. Superconducting qubits
5. Trasmons
6. Quantum sensing with trasmons
7. Qub-IT experiment goals

What is an axion

Axion (ϴ):

- elementary particle introduced by Peccei-Quinn theory (1977)
- postulated to solve CP violation issue in QCD
- mass > 5µeV (10^{-11} times electron mass 0.510 Mev)
- simulations estimate mass between 0.02 and 0.1 meV

Buschmann, Foster, Safdi (2020) "Early-Universe Simulations of the Cosmological Axion". Physical Review Letters. 124 (16) doi:10.1103/PhysRevLett.124.161103.



Axion – QDM Lab

How an axion can interact

Lagrangian of an axion field:

$$\mathcal{L}_{\mathrm{EM}} = J^e_\mu A^\mu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu},$$

where $\tilde{F}_{\mu\nu} = \varepsilon_{\mu\nu\sigma\rho} F^{\sigma\rho},$

and $g_{a\gamma\gamma}$ is the small, unknown coupling between an axion ***a*** and a photon.

The axion current is then:

$$J^\mu_a = g_{a\gamma\gamma}(\mathbf{B} \cdot \boldsymbol{\nabla} a, -\mathbf{E} \times \boldsymbol{\nabla} a + \partial_t a \mathbf{B}),$$

that leads to the modified Maxwell's equations:

$$\boldsymbol{\nabla} \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \boldsymbol{\nabla} a,$$

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0,$$

$$\boldsymbol{\nabla} \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\boldsymbol{\nabla} \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma} \left(\mathbf{E} \times \boldsymbol{\nabla} a - \frac{\partial a}{\partial t} \mathbf{B} \right).$$

Starting from these equations, it can be shown that axions could convert into microwave photons in the presence of a strong magnetic field, so that ***they can be detected***.

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Quantum sensing

Quantum Sensing review (https://arxiv.org/abs/1611.02427)

I. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.

II. Use of quantum coherence (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity.

III. Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible in a classical framework.

Quantum sensors

I. Microwave-photons: ”Electromagnetic signals are always composed of photons, although in the circuit domain those signals are carried as voltages and currents on wires, and the discreteness of the photon's energy is usually not evident. However, by coupling a superconducting quantum bit (qubit) to signals on a microwave transmission line… the presence or absence of even a single photon can have a dramatic effect.” DOI: 10.1038/nature05461

II. Phonons: discrete quantized energy levels of vibration, recently become accessible at the “single-particle“ level through high-quality mechanical oscillators that are strongly coupled to light.

III. Magnons: excited magnetic states that can be excited in light scattering via direct magnetic dipole coupling or an indirect electric dipole coupling which proceeds through a spin-orbit interaction(Fleury and Loudon, 1968).

Quantum sensing elements

- Quantum nondemolition measurements
- Charge insensitive superconducting qubits (transmons)

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where Hs�� is the unperturbed Hamiltonian of the signal system to be measured, HM�� is that of the meter system, and HI�� describes the way in which the meter measures
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Quantum nondemolition measurements

Measurements can be described as follows:

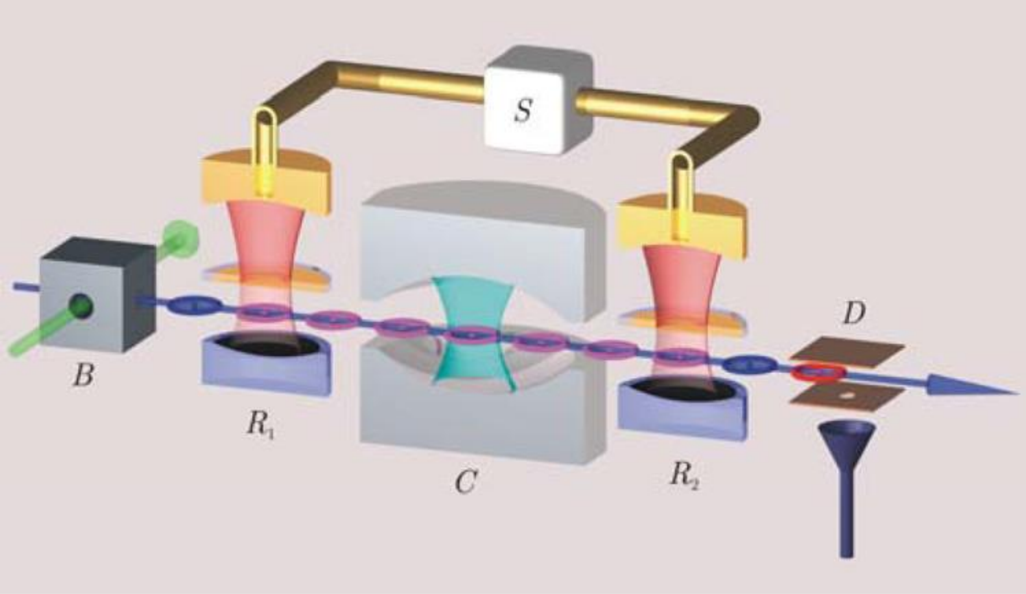
$$H = H_S + H_M + H_I$$

where H_S is the unperturbed Hamiltonian of the signal system, H_M is that of the meter system, and H_I describes the way in which the meter measures the signal

Given an observable A_S , Quantum Nondemolition Measurement (QND) consists in measuring A_S trough the change in the observable A_M in the meter system, with:

$$[H_S\,, A_S] = 0; [H_I\,, A_S] = 0; [H_I\,, A_M] \neq 0.$$

Detecting number of photons in a cavity



Quantum Non-Demolition Measurement of Photons
https://www.intechopen.com/chapters/58843#B10

- A Rydberg atom is prepared in **B** with two states: ground $|g\rangle$ and excited $|e\rangle$
- R1 prepare the atom in the state: $|+\rangle = |g\rangle + |e\rangle$
- **The atomic frequency is detuned from the cavity mode** so the atom cannot absorb the photon but accumulates a phase passing in the Fabry-Perot cavity:

  $$|\pm\rangle = |g\rangle \pm e^{i\Phi_n}|e\rangle$$

  where the phase Φ_n depends on the number n of photons in the cavity.
- A second classical pulse in R2 turns $|+\rangle \rightarrow |g\rangle$ when $\Phi_n = 0$
  or $|-\rangle \rightarrow |e\rangle$ when $\Phi_n = \pi$ before the atom state is measured in D.
- The combination R1, R2 and D acts as a spectrometer that maps the number of photons inside the cavity into the atom state.

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Josephson junction

Josephson effect: “supercurrent” generated at ΔV = 0 in a physical arrangement called Josephson Junction (S-I-S, S-nsM-S, S-C-S)

Theoretical context:

- Landau-Ginzburg theory
- Cooper Pairs
- Josephson Equations (https://www.feynmanlectures.caltech.edu/III_21.html)

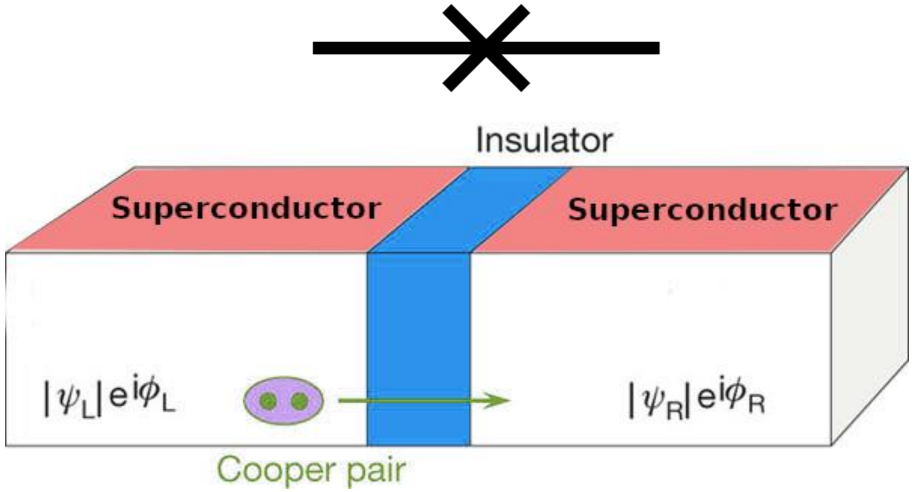
$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}=\begin{pmatrix}eV & K\\ K & -eV\end{pmatrix}\begin{pmatrix}\sqrt{n_A}e^{i\phi_A}\\ \sqrt{n_B}e^{i\phi_B}\end{pmatrix}, \quad \varphi=\phi_B-\phi_A.$$

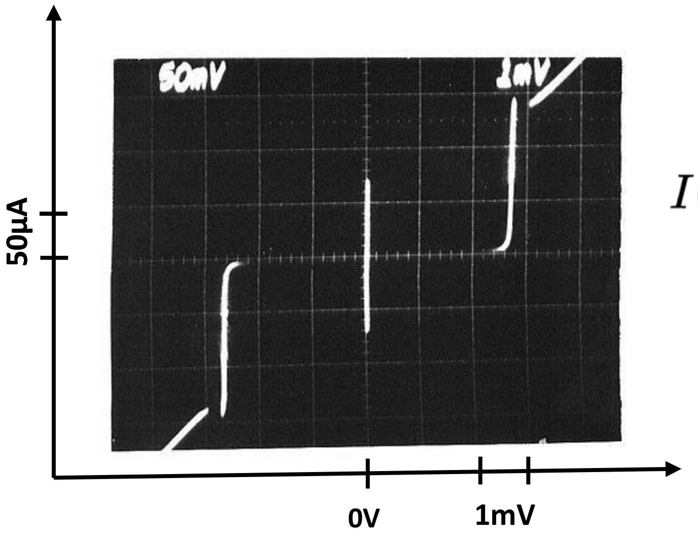
V is the electric potential difference across the junction

K is the characteristic constant of the junction

The equations lead to:

$$\dot{n}_A=\frac{2K\sqrt{n_An_B}}{\hbar}\sin\varphi \quad \text{and} \quad \dot{\phi}_A=-\frac{1}{\hbar}\left(eV+K\sqrt{\frac{n_B}{n_A}}\cos\varphi\right).$$





$$I(t)=I_c\sin(\varphi(t))$$

$$\frac{\partial\varphi}{\partial t}=\frac{2eV(t)}{\hbar}$$

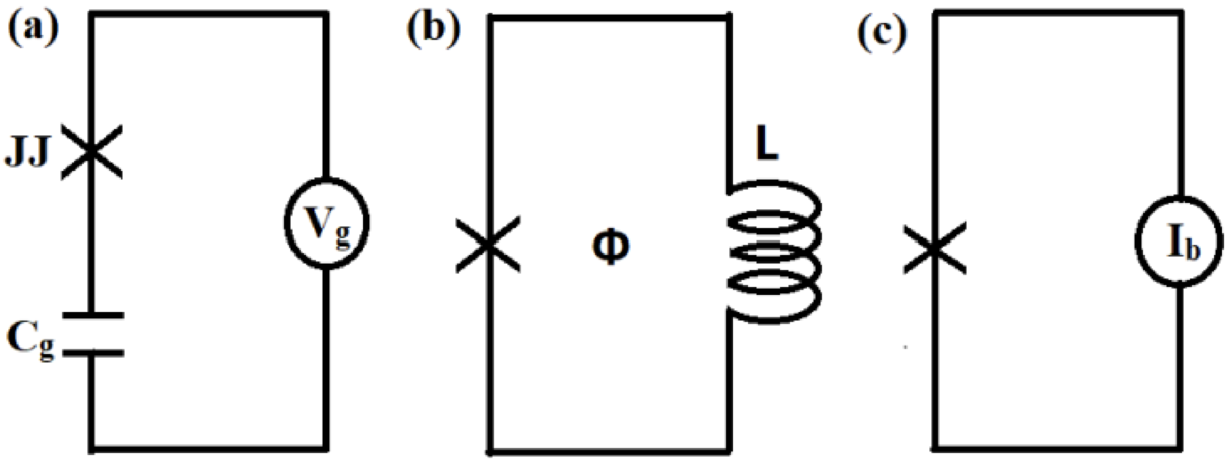
Superconducting qubits

Superconducting qubit circuit diagram (https://arxiv.org/abs/2006.10433)

a) Charge qubit composed of a Josephson junction and a capacitor. Adjusting the voltage V_g can control the number of Cooper pairs.

b) Flux qubit. L is the loop inductance. Changing the bias, flux Φ can adjust the energy level structure of the qubit.

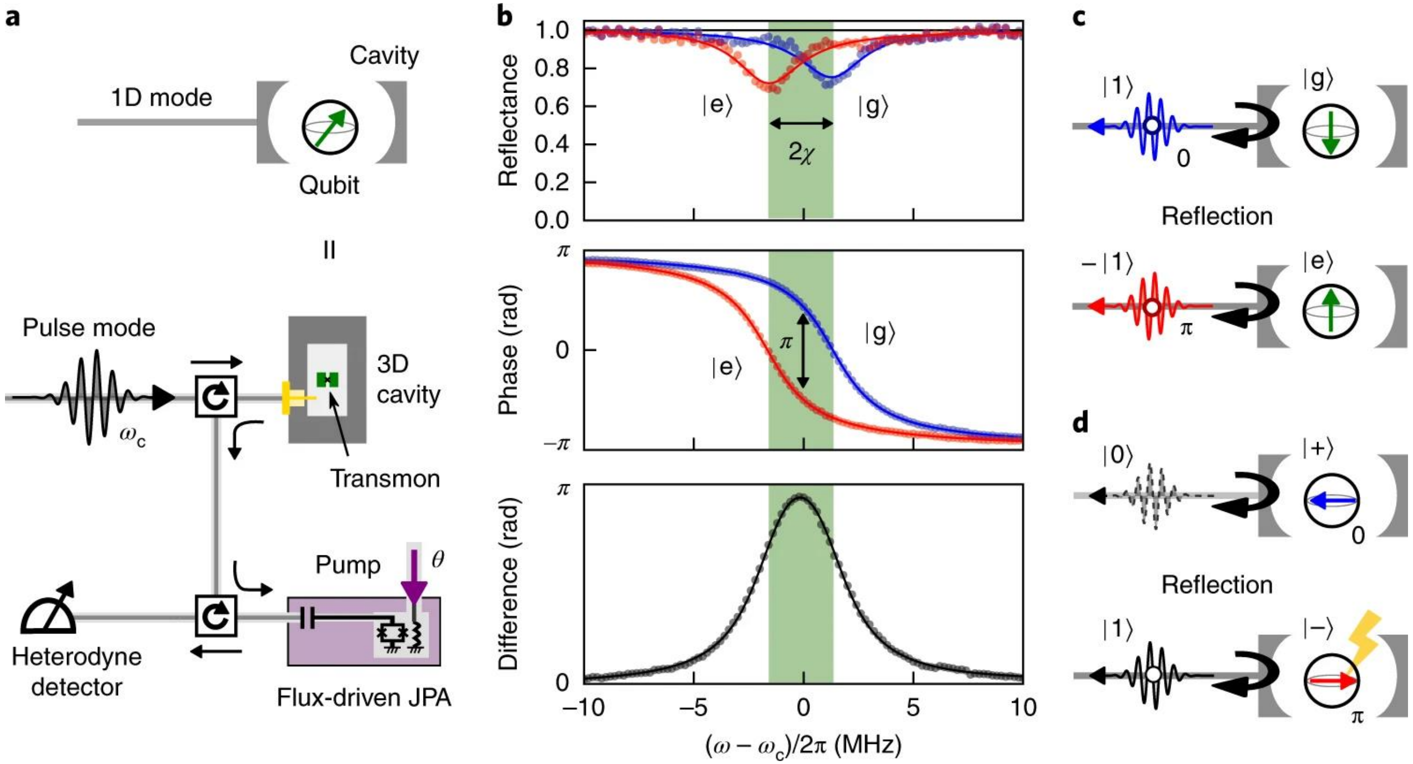
c) Phase qubit. A current-biased Josephson junction, operated in the zero voltage state with a non-zero current bias.

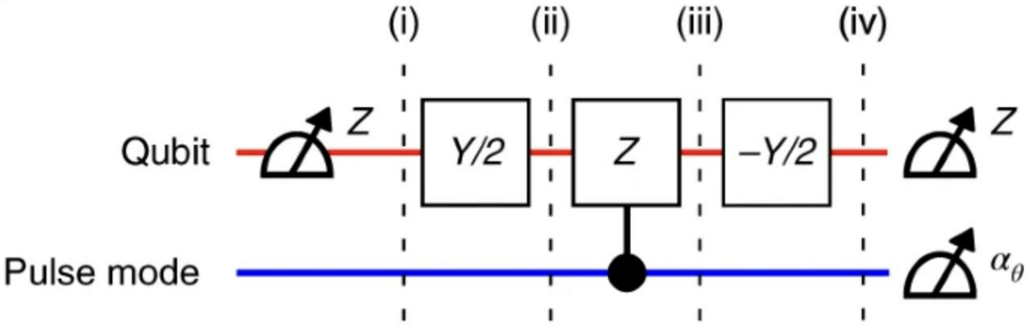


Detecting itinerant photons with entanglement

Quantum non-demolition detection of an itinerant microwave photon:

- demonstrated in optical domain by Reiserer et alii (https://arxiv.org/abs/1311.3625)
- and with microwave photons by Kono et alii: (https://doi.org/10.1038/s41567-018-0066-3)





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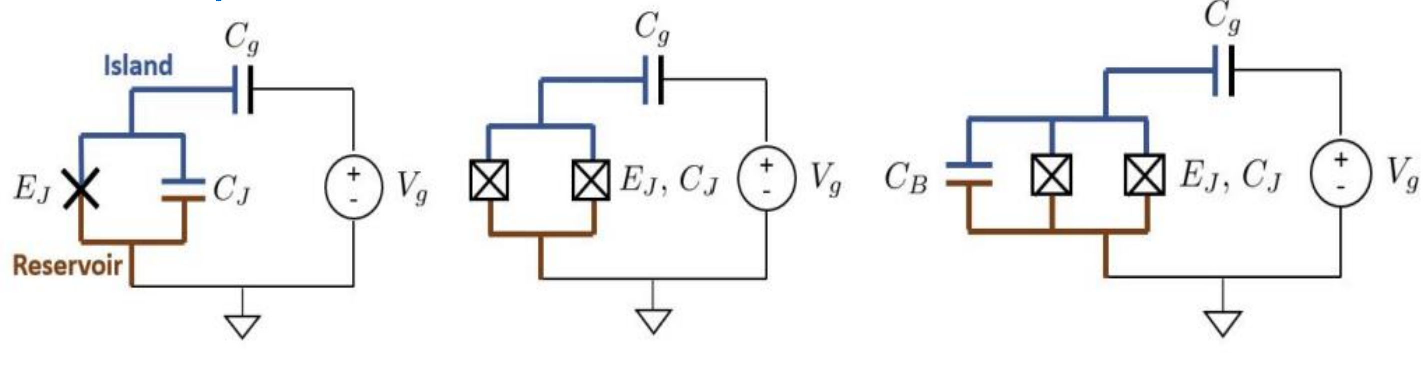
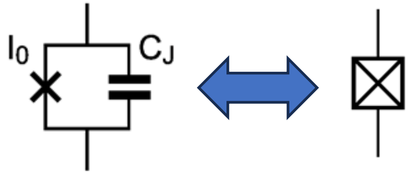
Trasmons

Trasmon: charge-unsensitive superconducting qubit
Developed by Schoelkopf, Devoret, and Girvin at Yale University in 2017



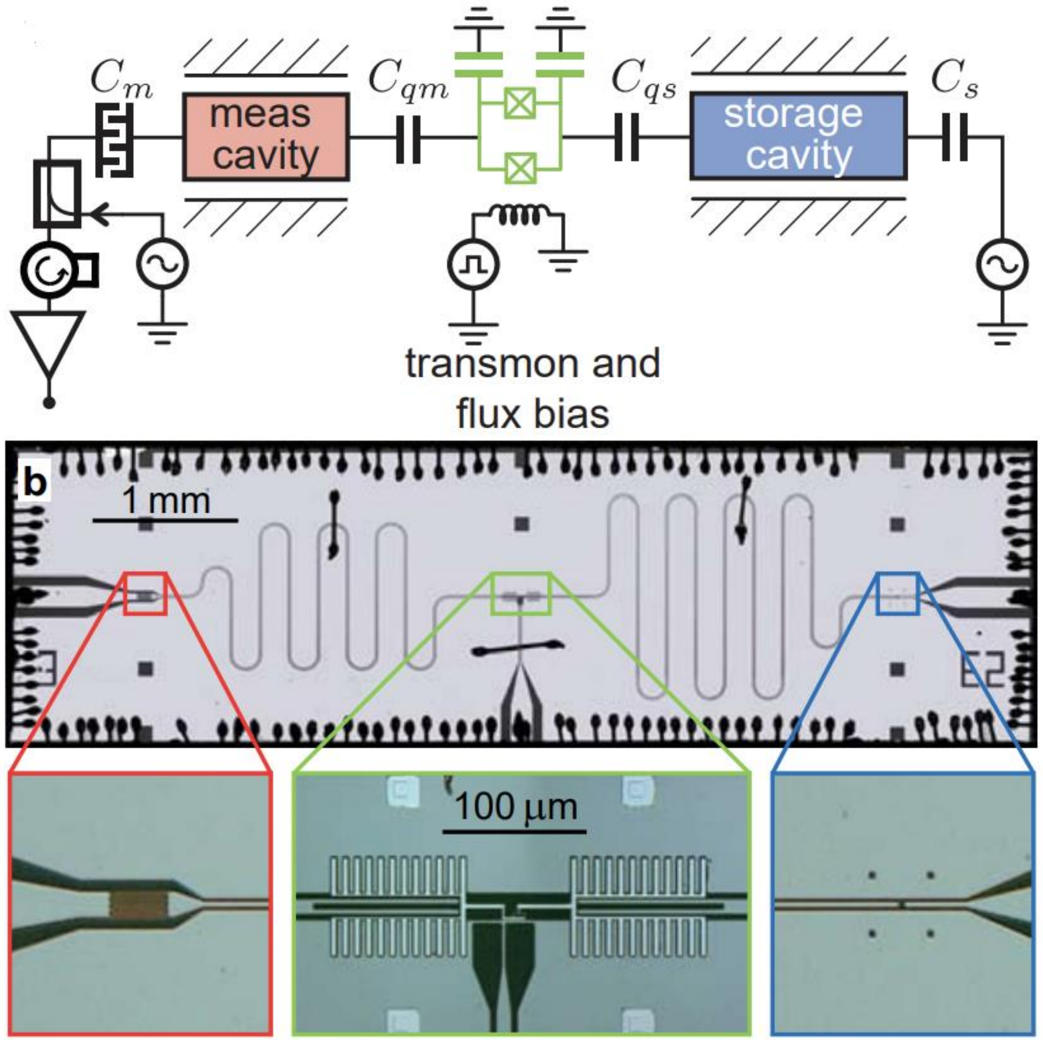
(a) (b) (c)



Circuit schematics for the evolution of a Cooper Pair Box (CPB) to a transmon.

(a) Cooper Pair Box
(b) split CPB
(c) transmon.

Detecting number of photons in a cavity with a trasmon



Circuit schematic showing two cavities coupled to a single transmon qubit.

It has a charging energy $E_C/2\pi = 290$ MHz and maximal Josephson energy $E_J/2\pi \approx 23$ GHz. At large detunings from both cavities, the qubit coherence times are $T1 \approx T2 \approx 0.7$ µs.

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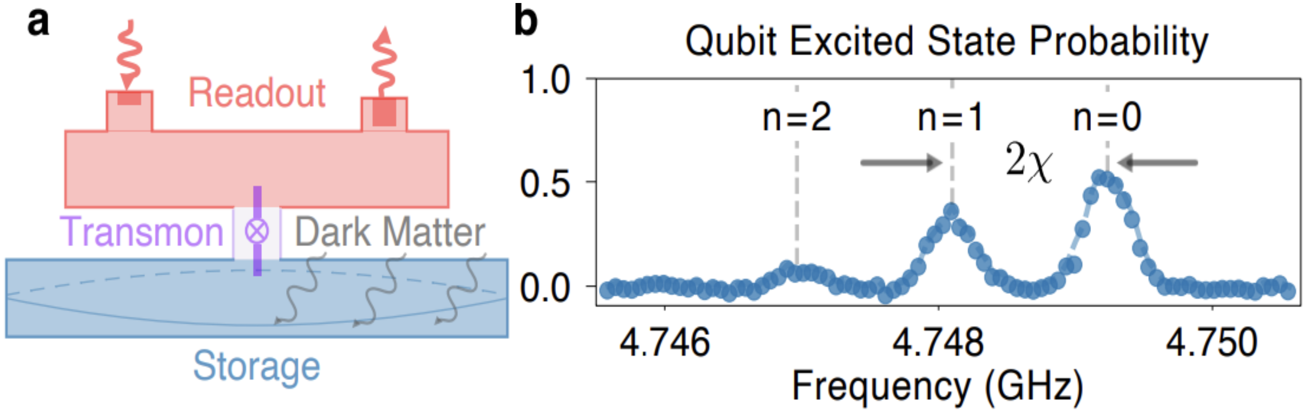
Photon Sensing – Dark Photons

Searching for Dark Matter with a Superconducting Qubit
Dixit et alii: https://doi.org/10.1103/PhysRevLett.126.141302

Jaynes-Cummings Hamiltonian:

$$\mathcal{H}/\hbar = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$



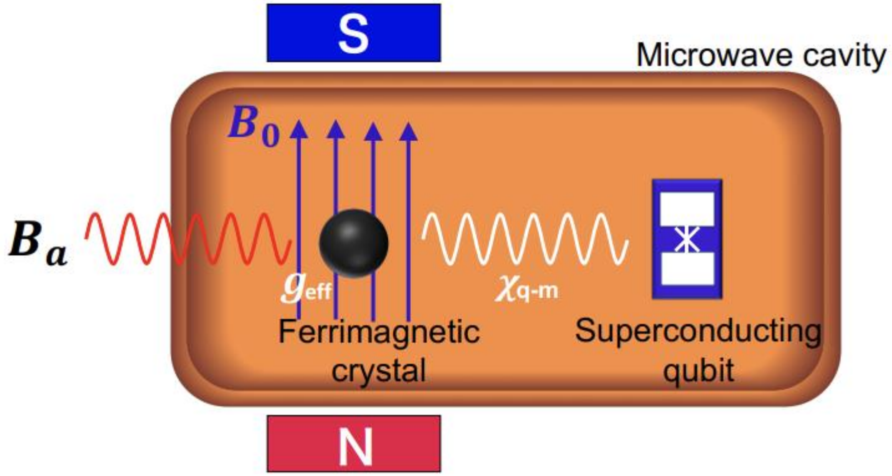
($\omega_q = 2\pi \times 4.749$ GHz), ($\omega_c = 2\pi \times 0.957 = 6.011$ GHz)

a) Schematic of photon counting device consisting of storage and readout cavities bridged by a transmon qubit. The interaction between the dark matter and electromagnetic field results in a photon being deposited in the storage cavity.

b) Qubit spectroscopy reveals that the storage cavity population is imprinted as a shift of the qubit transition frequency. The photon number dependent shift is 2χ per photon ($|2\chi| = 2\pi \times 1.13$ MHz).

Magnon Sensing – Axions

Quantum nondemolition detection of magnon:
quanta of collective spin excitations in solid, which is expected to be excited by the axion–electron interaction predicted by the Dine-Fischer-Srednicki-Zhitnitsky (DFSZ) model.



Schematic illustration of the detector:

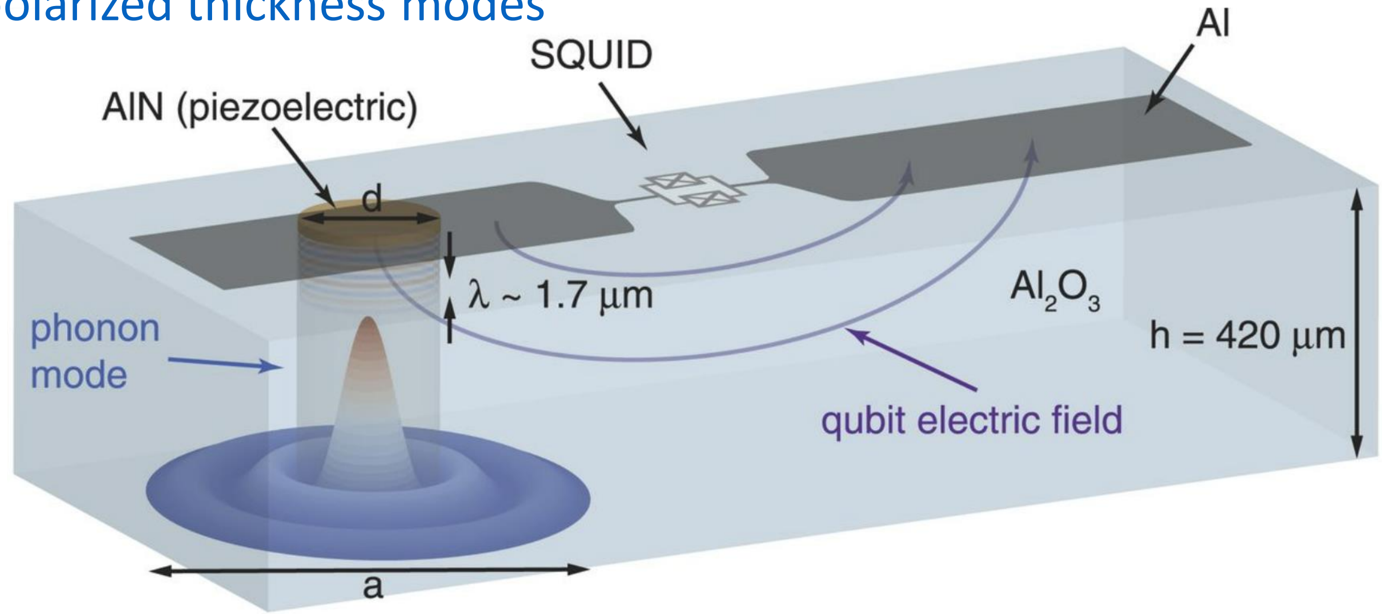
- A spherical ferrimagnetic crystal and a transmon–type superconducting qubit are coherently coupled through a microwave cavity.
- The effective magnetic field of the axion DM coherently drives the uniform spin–precession mode (Kittel mode) in the ferrimagnetic crystal with an effective coupling constant geff .
- Each magnon excited in the Kittel mode shifts the resonance frequency of the qubit by $2\chi q_{-m+\Delta}a$, where χq_{-m} is the dispersive shift and $\Delta a = \omega_m^g - \omega_a$ is the detuning between the frequency ω_a of the axion–induced effective magnetic field and the frequency ω_m^g of the Kittel mode with the qubit in the ground state |g>

Phonon Sensing – Dark Photons or G-Waves

Quantum acoustics with superconducting qubits (doi:10.1126/science.aao1511):
Piezoelectric materials are natural choices for achieving large coupling strengths between single electrical and mechanical excitations

The detector consists of a frequency-tunable aluminum transmon coupled to phonons. The top surface of the AlN film and the bottom surface of the sapphire form a phononic Fabry-Pérot resonator that supports longitudinally polarized thickness modes

Light Dark Matter or high frequency GW can induce oscillation (from MHz to GHz) of piezoelectric quartz bulk acoustic wave (BAW) resonators cooled at mK temperature: Doi:10.1088/2058-9565/abcfcd.



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Qub-IT experiment goals

- SO1. Design and simulation of a SC qubit coupled to resonators
- SO2. Fabrication of circuits with SC qubit
- SO3. Single-shot measurement of SC qubit with quantum amplifier
- SO4. Control of SC qubit with FPGA board
- SO5. Quantum sensing experiment with entangled qubits

The End