Detection of Microwave Photons with SC Qubits for Axion Searches

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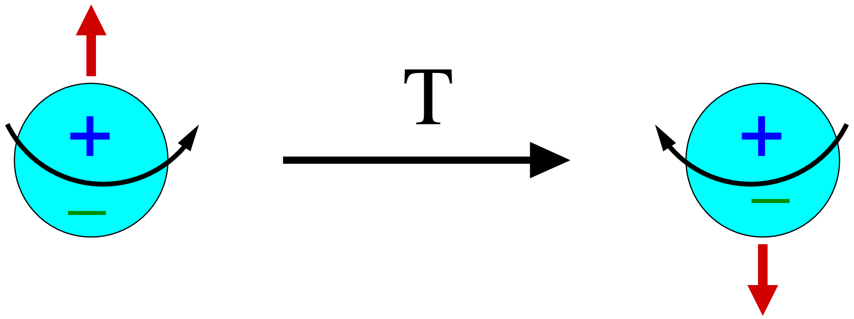
Axion: CP violation in QCD

$$\mathcal{L}_{QCD} = \ldots + \theta \frac{\alpha_s}{8\pi} G_{a\mu\nu} \tilde{G}_a^{\mu\nu}$$

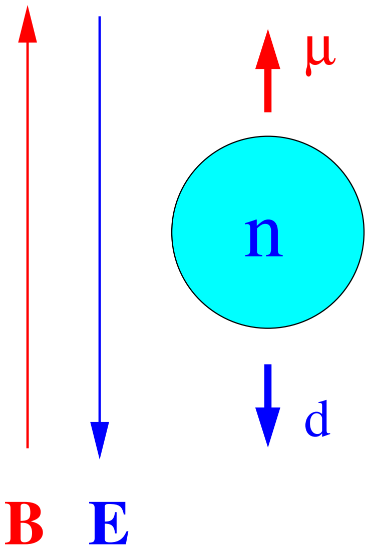
This term violates T (CP) symmetries and induces a neutron electric dipole moment (EDM)



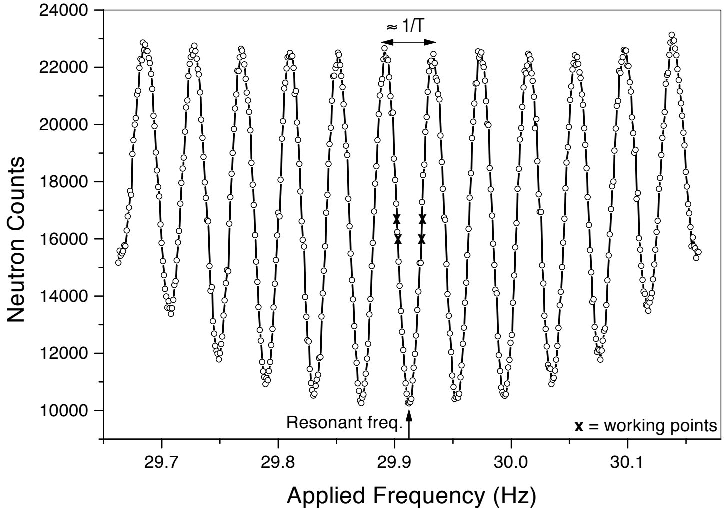
$$d_n \simeq \theta \frac{m_q}{M_n} \frac{e}{M_n} \sim \theta \times 10^{-3} e \ \mathrm{GeV}^{-1} \sim \theta \times 10^{-15} e \ \mathrm{cm}$$

Axion: Neutron EDM

$$h\nu = |2\mu_n B \pm 2d_n E|$$



PRL 82(5) (1999) p.904ß



$$d_n < 2.9 \times 10^{-26} e \text{ cm}$$

$$\theta < 10^{-10}$$

Axion: θ=0?

Diagonalization of quark mass matrix (M_q) has the effect of shifting the value of θ:

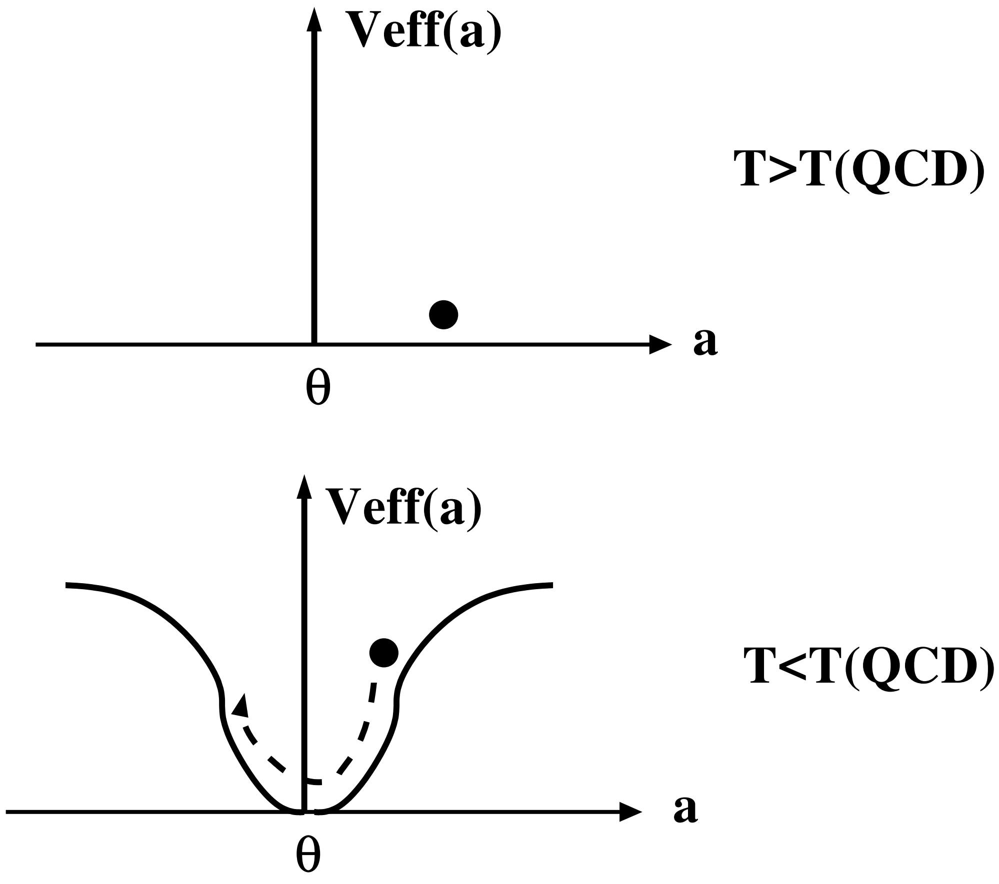
$$\theta = \underbrace{\theta_0}_{\text{QCD origin}} + \underbrace{\arg \det M_q}_{\text{EW origin}}$$

Strong CP problem: why the combination of QCD and EW parameters is so small?

Axion: The solution

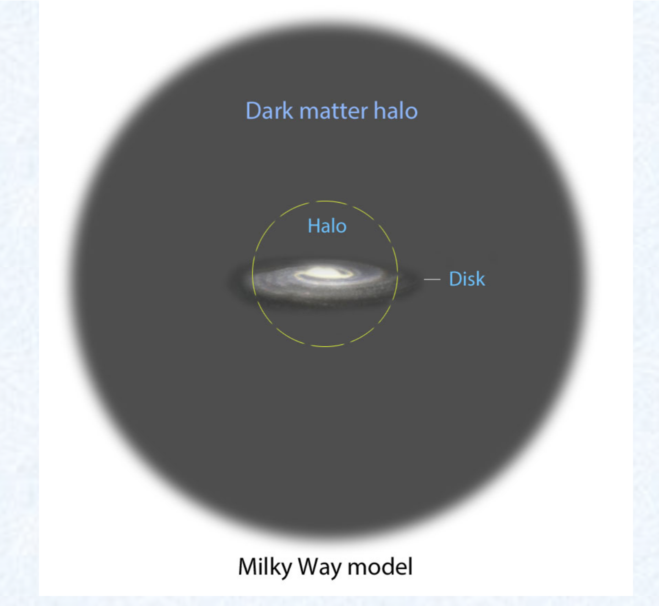
$$\mathcal{L}_{QCD} = \ldots + \frac{\alpha_s}{8\pi}(\theta - \frac{a}{f_a})G_{a\mu\nu}\tilde{G}^{\mu\nu}_a$$

"a" is a new scalar field.
When the temperature approaches the QCD scale the potential V_{eff} turns on and the axion acquires a mass.
(Asztalos Ann.Rev.Part. Sci. 2006 56: 293-326)



Peccei Quinn Weinberg Wilczek

Axions: CDM



$$\rho \simeq 0.3GeV/cm^3$$

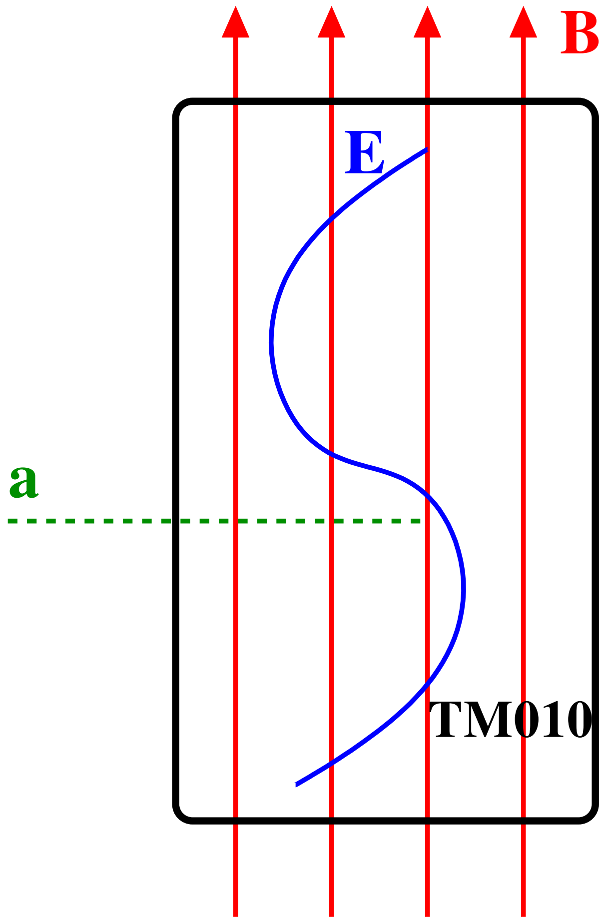
$$n_a \simeq 3 \times 10^{12} \left(\frac{100\mu eV}{m_a}\right) 1/\mathrm{cm}^3$$

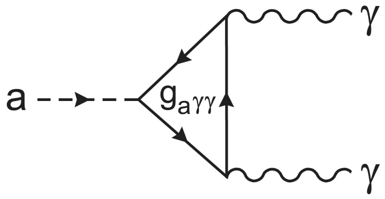
$$\beta_a \sim 10^{-3}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6} \qquad \frac{\omega}{2\pi} = 24(\frac{m_a}{100\mu eV})\mathrm{GHz}$$

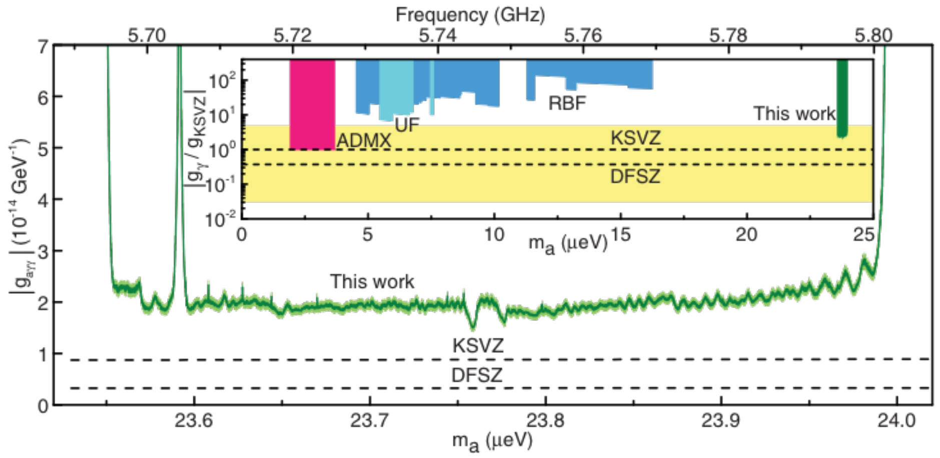
$$a = a_0 \cos\omega t$$

Galactic Axion Searches: ADMX-HF





$$P_S = \left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\rho_a}{\Lambda^4}\right) \left(\omega_c B_0^2 V C_{mnl} Q_L \frac{\beta}{1+\beta}\right)$$

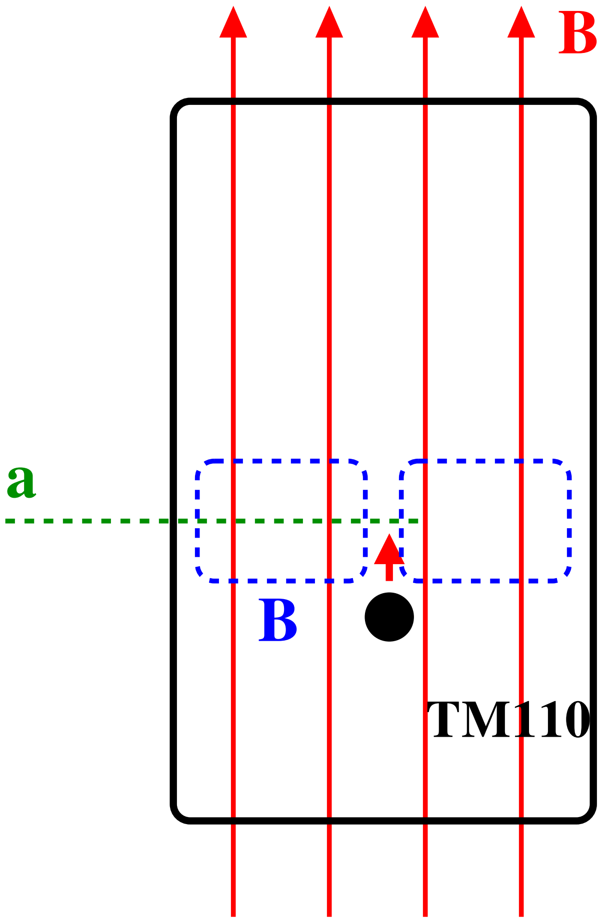


Phys. Rev. Lett. **118**, 061302

$$P_S \simeq 5 \times 10^{-24} \mathrm{W}$$

$$R_S \simeq 1 \mathrm{Hz}$$

Galactic Axion Searches: Quax



Electron coupling

$$\frac{g_p \hbar}{2m} \sigma \cdot \nabla a$$

$$P_S \sim 5 \times 10^{-26} \mathrm{W}$$

$$R_S \sim 1 \times 10^{-3} \mathrm{Hz}$$

$$m_a = 200 \mu \mathrm{eV}$$

Physics of the Dark Universe 15 (2017), 135-141

Amplifier vs photon counter

$$P_{min} = k_B T_S \sqrt{\frac{\Delta\nu}{\tau}}\ \mathrm{W} \quad \Longrightarrow \quad P_{min} = \hbar\omega \sqrt{\frac{\Delta\nu}{\tau}}\ \mathrm{W}$$

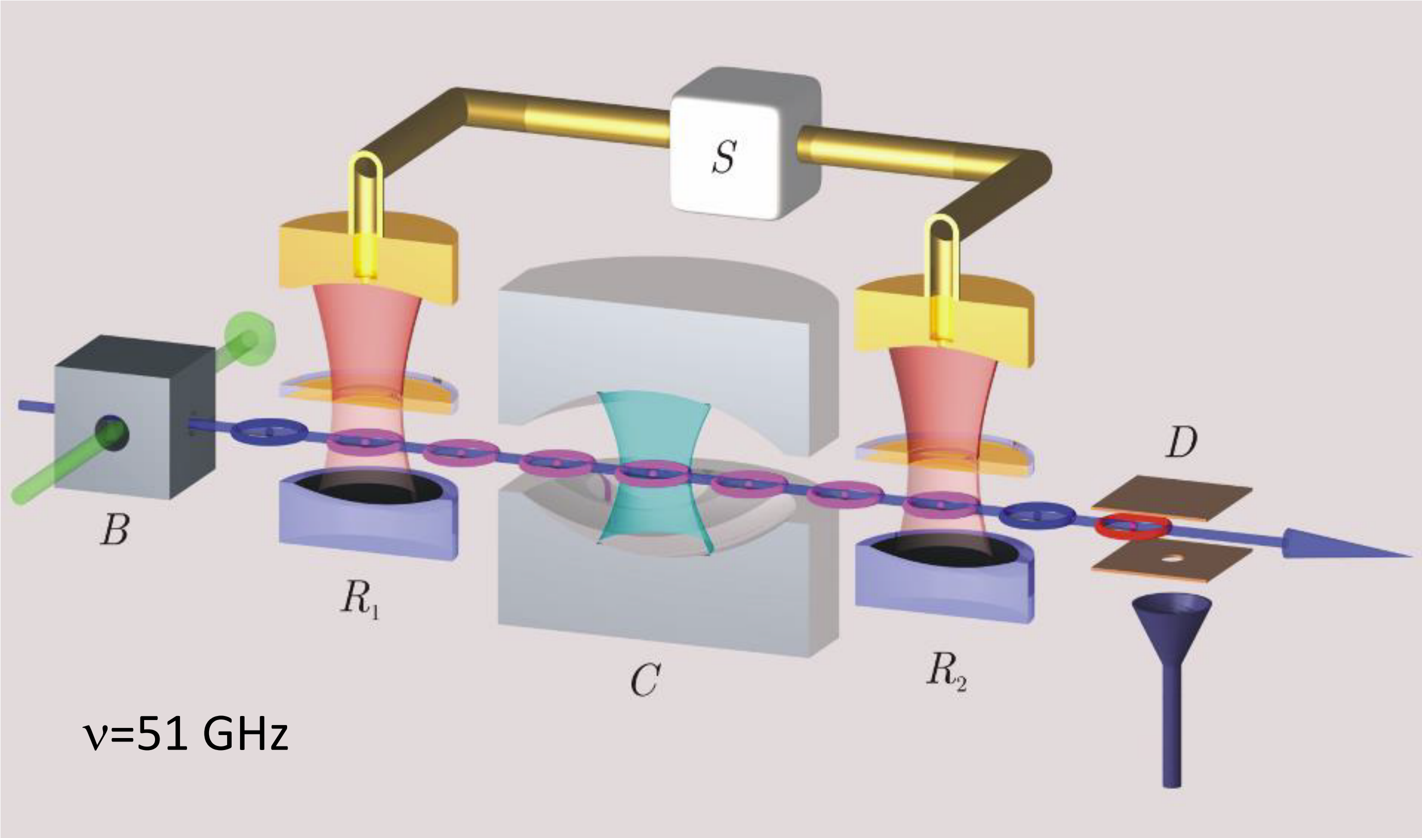
Linear amplifiers add noise to the signal, at least $\hbar\omega$. Caveas PR D26 (1982)

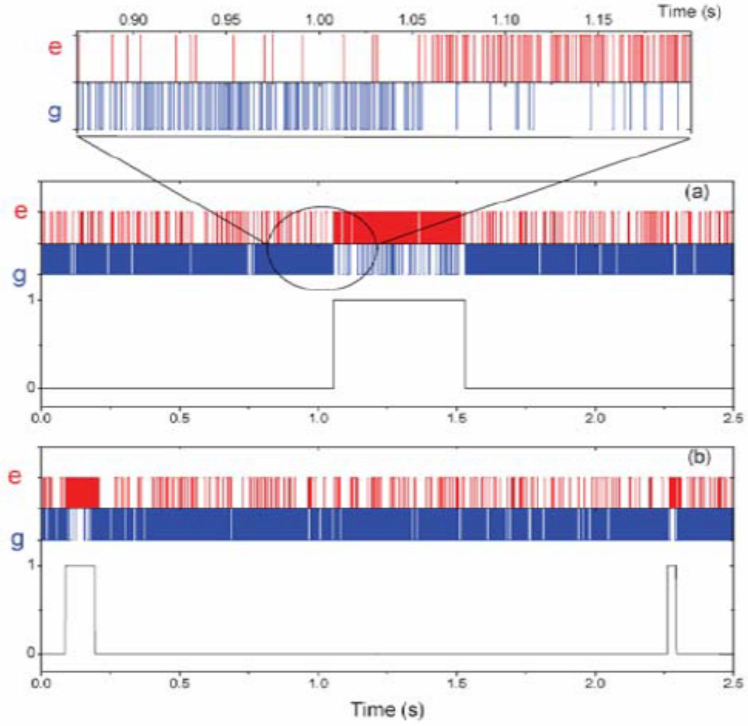
$$\tau \sim 10^4\ \mathrm{s}$$

$$P_{min}^{Quax} = 4 \times 10^{-23}\ \mathrm{W}$$

Need a single photon counter to evade standard quantum limit (SQL)

Birth and Death of a Photon





Nature 446, 297-300 (2007)

Cavity QED

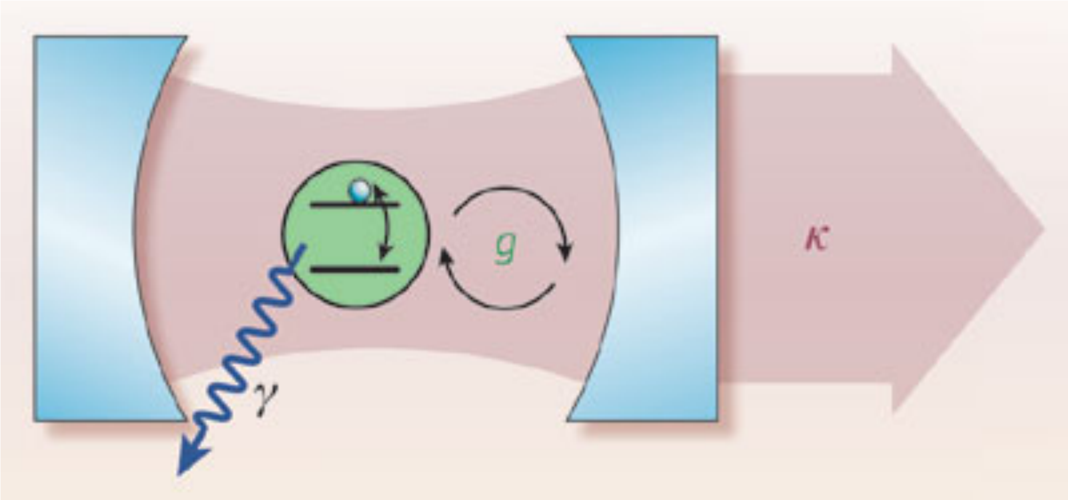
Two level atom interacting via dipole coupling with a cavity is described by the Jaynes-Cummings hamiltonian:

$$H_{JC} = \hbar\omega_c(a^\dagger a + 1/2) + \hbar\frac{\omega_a}{2}\sigma_z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

Photons in cavity

Two level atom

Dipole interaction



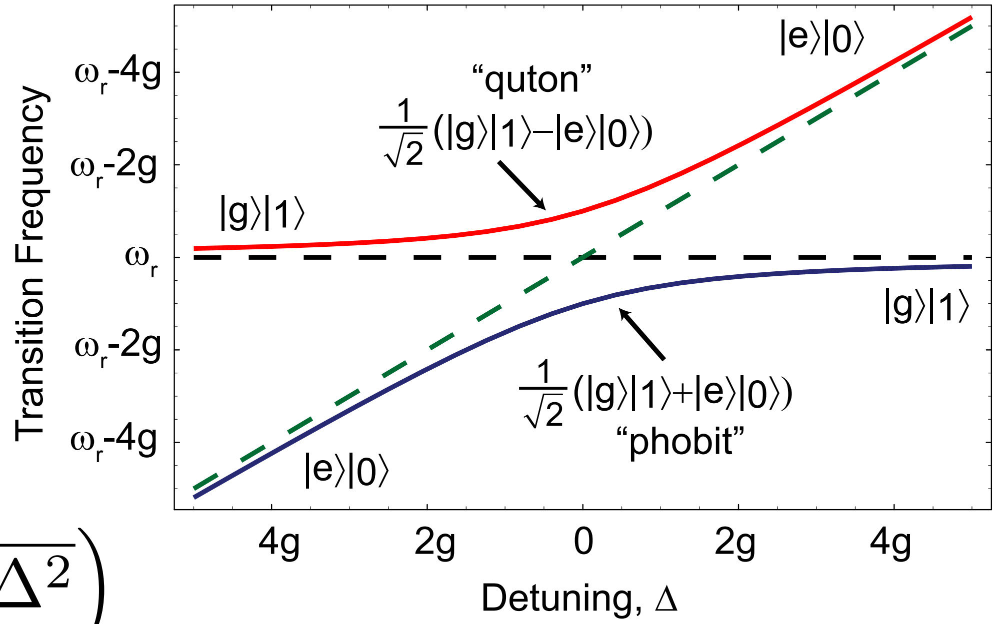
D.I.Schuster "Circuit QED" PhD Thesis

Cavity QED

$$
\begin{aligned}
|-,n\rangle &= \cos\theta_n|g,n\rangle - \sin\theta_n|e,n-1\rangle \\
|+,n\rangle &= \sin\theta_n|g,n\rangle + \cos\theta_n|e,n-1\rangle
\end{aligned}
$$

$$\theta_n = \frac{1}{2}\arctan\left(\frac{2g\sqrt{n}}{\Delta}\right)$$

$$\Delta = \omega_a - \omega_c$$



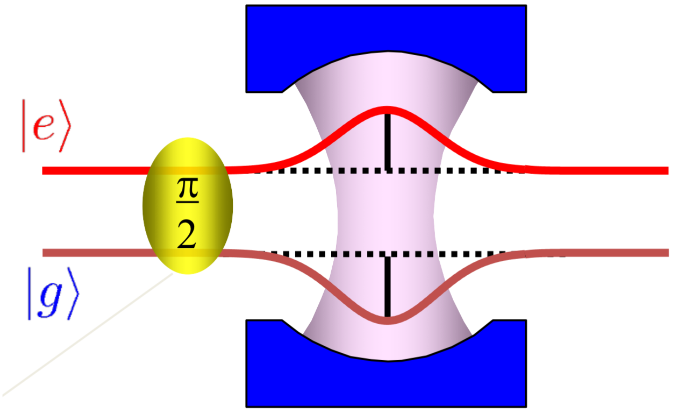
$$E_{\pm,n} = \frac{\hbar}{2}\left((n-1)\omega_c + \omega_a \pm \sqrt{4ng^2 + \Delta^2}\right)$$

In the strong coupling limit ($\Delta \ll g$) photon is continously absorbed and re-emitted inside the cavity with the atom oscillating between ground and excited state.

Cavity QED: Dispersive Limit ($\boldsymbol{\Delta} \gg \mathbf{g}$)

$$H_{JC} \simeq \hbar\omega_c(a^\dagger a + 1/2) + \frac{\hbar}{2}\left(\omega_a + \frac{2g^2}{\Delta}a^\dagger a + \frac{g^2}{\Delta}\right)\sigma_z$$

The electric field in the cavity produces a Stark-shift in the atom energy levels.



Dispersive limit allow quantum non destructive (QND) measurement of photons in the cavity

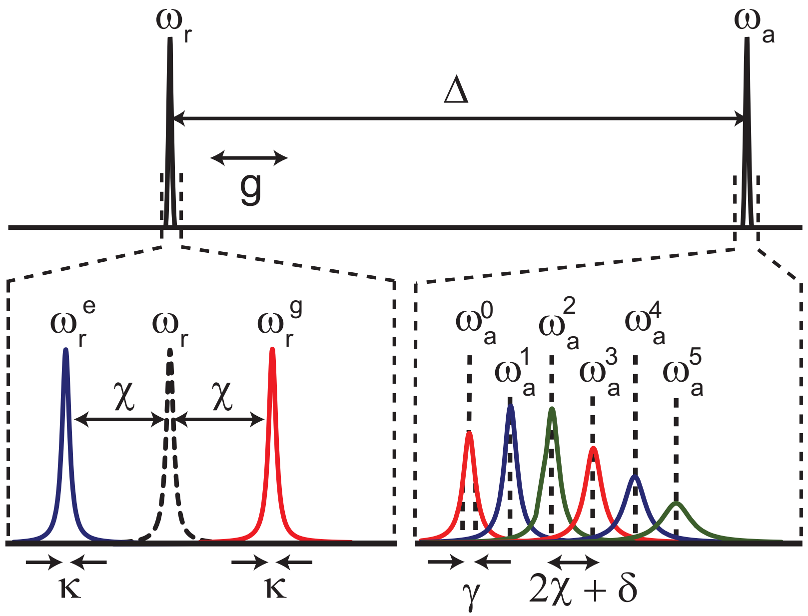
S.Deleglise https://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=12992

Cavity QED: Strong Dispersive Limit

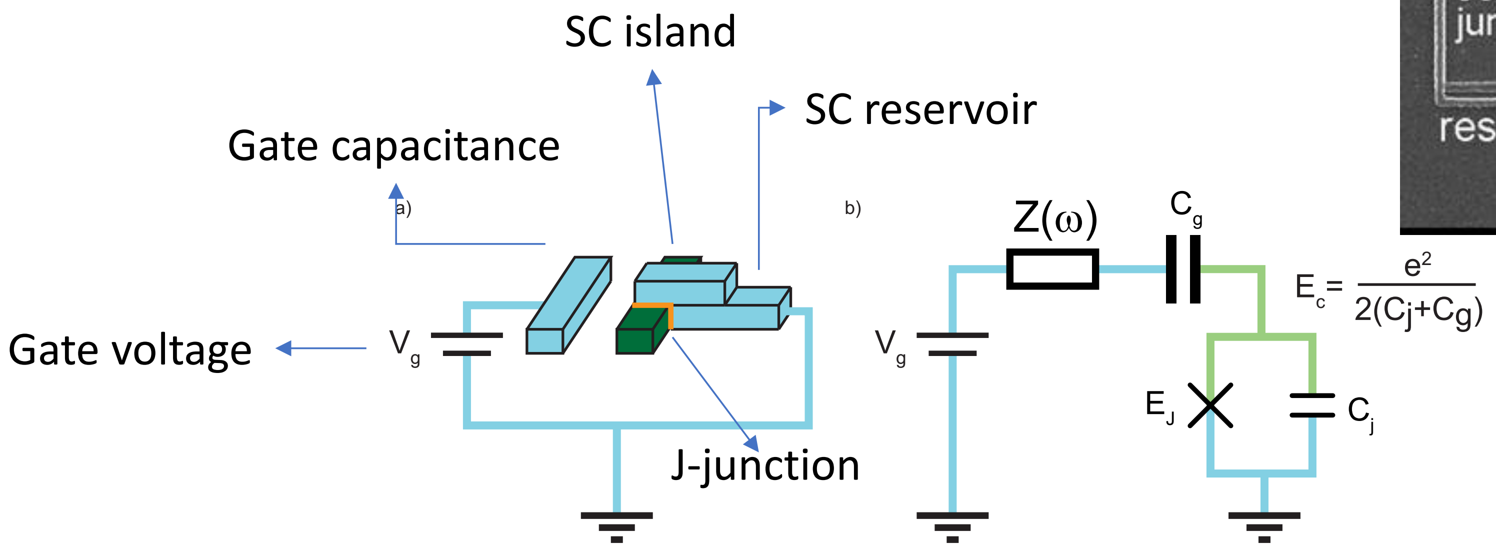
In the strong dispersive limit the energy shift is larger than natural width of atom (κ) and cavity mode (γ):

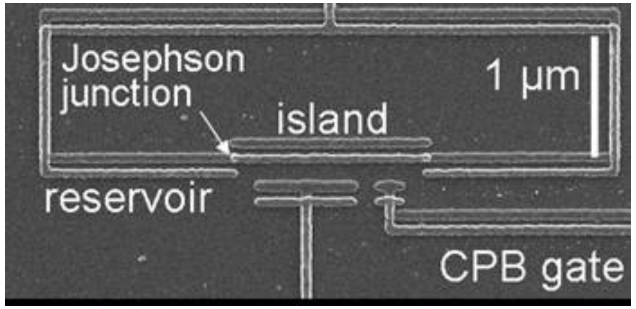
$$g^2/\Delta \ll \gamma, k$$

Photon number in the cavity are measured by performing spectroscopy on the atom to measure the energy shift.



Artificial atoms: The Cooper Pair Box



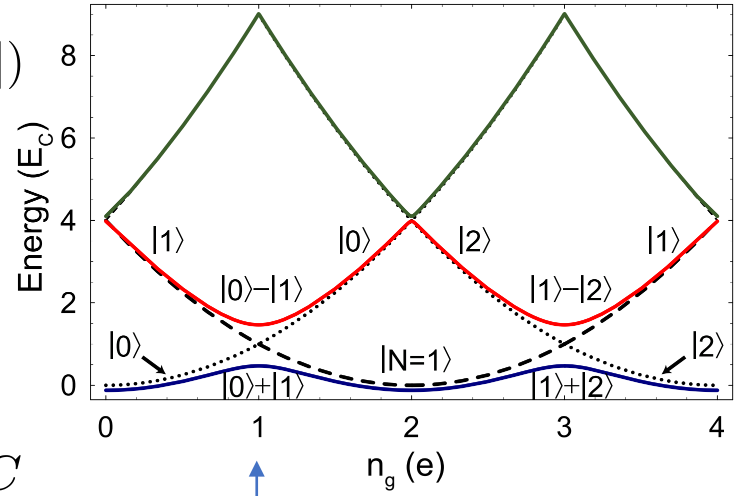


CPB consists of a SC island connected to a reservoir via a Josephson junction. The gate voltage induces tunneling of Cooper pairs.

V. Bouchiat Phys. Scrip. T76 (1998) 165-170

The Cooper Pair Box

$$H_{CPB} = 4E_C \sum_n (n - n_g/2)^2 |n\rangle\langle n| - \frac{E_J}{2} \sum_n \left(|n\rangle\langle n+1| + |n+1\rangle\langle n|\right)$$



n excess of Cooper pairs in the island
E_C electrostatic energy to charge a single electron
E_J Josephson energy

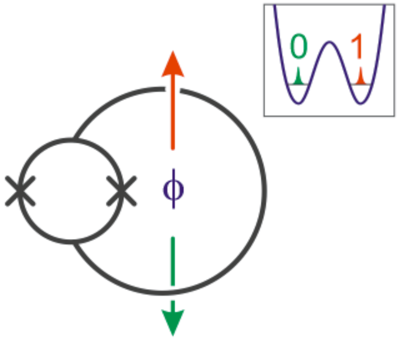
For n_g=1 the circuit behaves as a two state atom: $E_J \ll E_C$

$$|+\rangle = (|0\rangle - |1\rangle)/\sqrt(2)$$
$$|-\rangle = (|0\rangle + |1\rangle)/\sqrt(2)$$

$$E_\pm = E_C \mp E_J/2$$

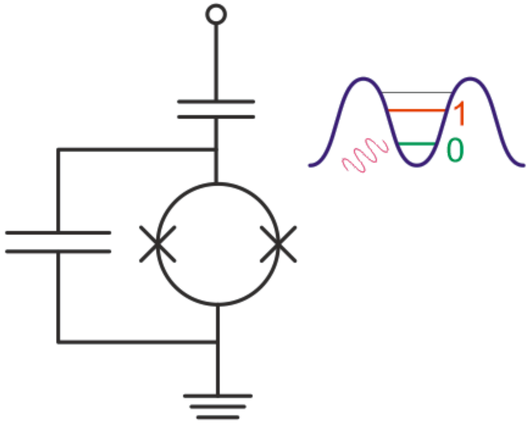
Superconducting Qubits

Flux Qubit



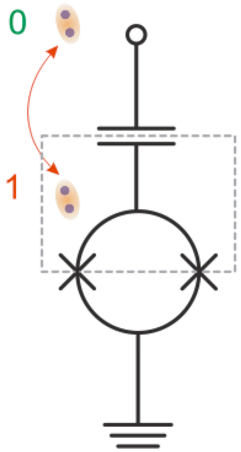
$$E_j > E_L \gg E_c$$

Transmon Qubit



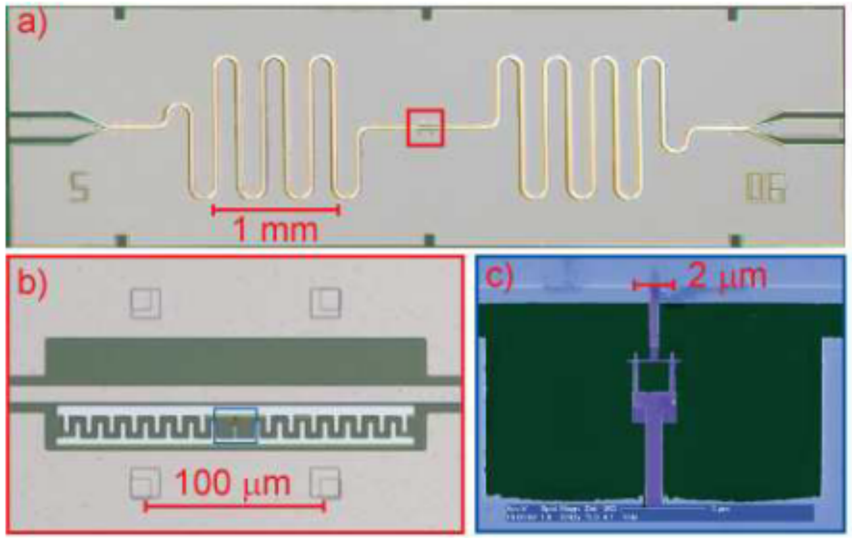
$$E_j > E_c$$

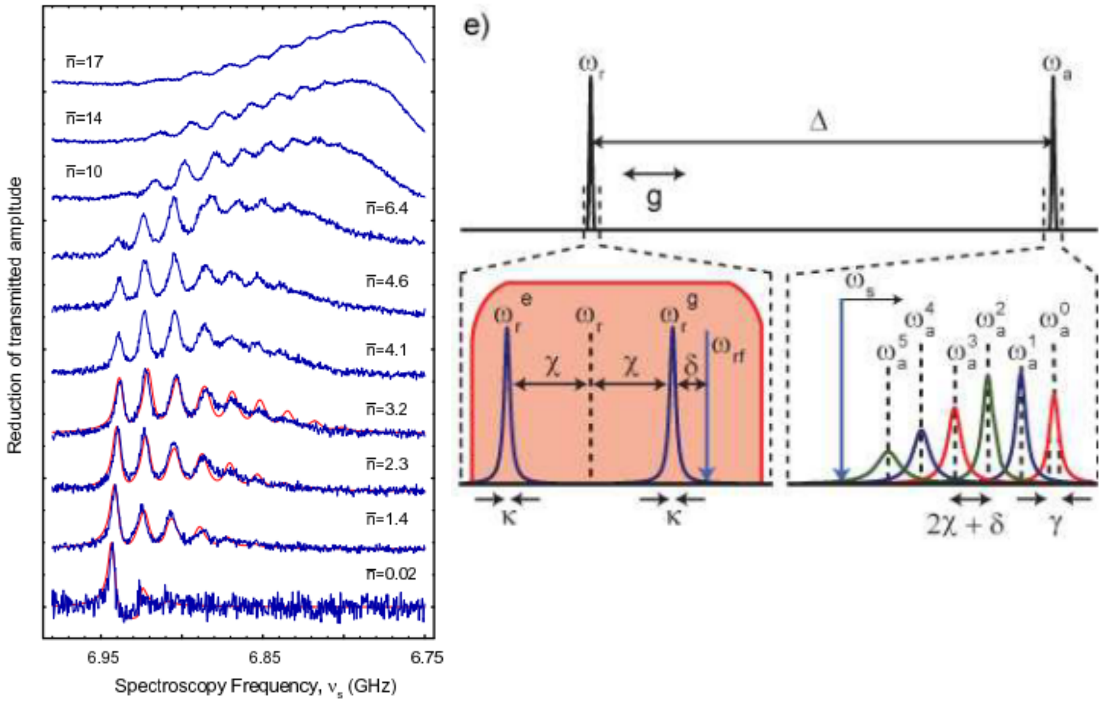
Cooper Pair Box Qubit



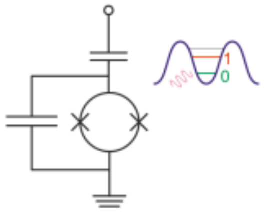
$$E_j < E_c$$

Resolving Photon Number States in SC Circuit



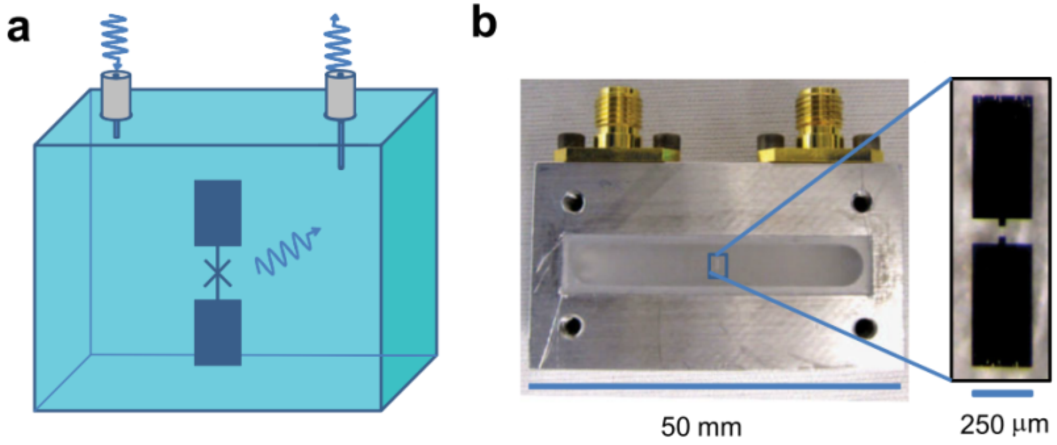


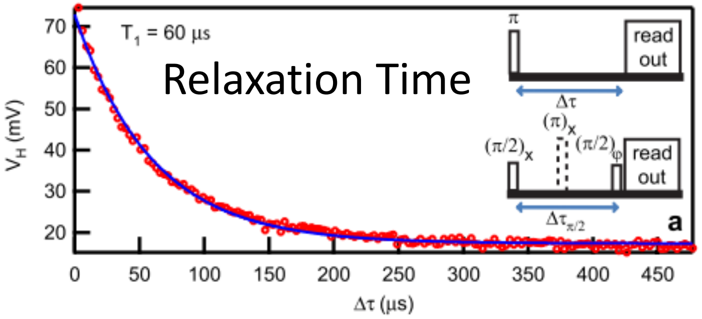
$$\nu_c = 5.7\mathrm{GHz}$$
$$Q \simeq 22,000$$
$$\tau_c \simeq 4\mu\mathrm{s}$$
$$\tau_a \simeq 0.5\mu\mathrm{s}$$



D. I. Schuster et al., Nature **445**, 515–518 (2007).

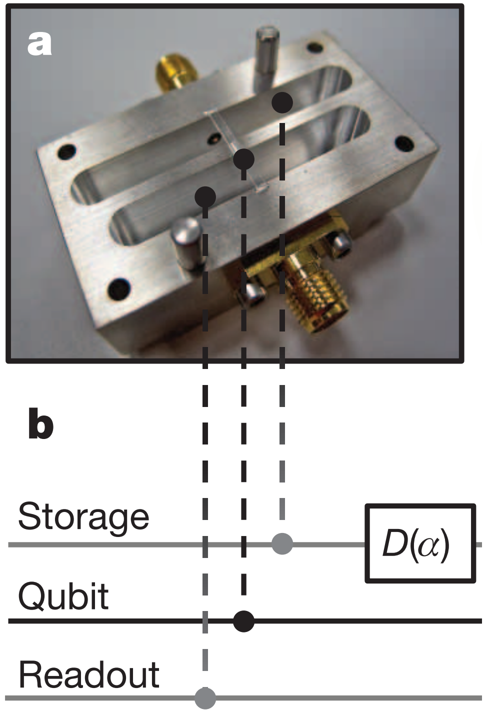
3D Cavities





$$\nu_c = 8\text{GHz}$$
$$Q \simeq 10^6$$

H. Paik, Phys. Rev. Lett. **107** (2011).



L.Sun, Nature 511 (2014), 444

Conclusions

There is a rising interest in axions searches … (no Susy at LHC?)

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SC Qubits may be the solution …

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Single photon counter in microwave regime required to reach ultimate sensitivity

SC Qubits may be the solution … R&D already started for ADMX-HF!


Detecting Axion Dark Matter with Superconducting Qubits

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