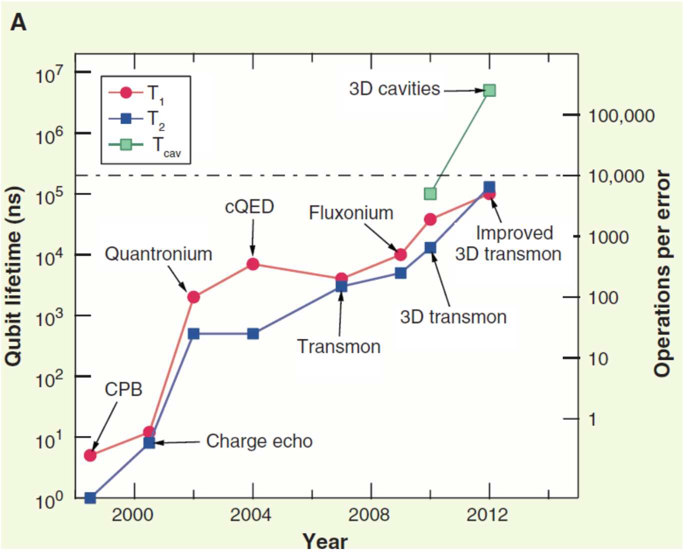
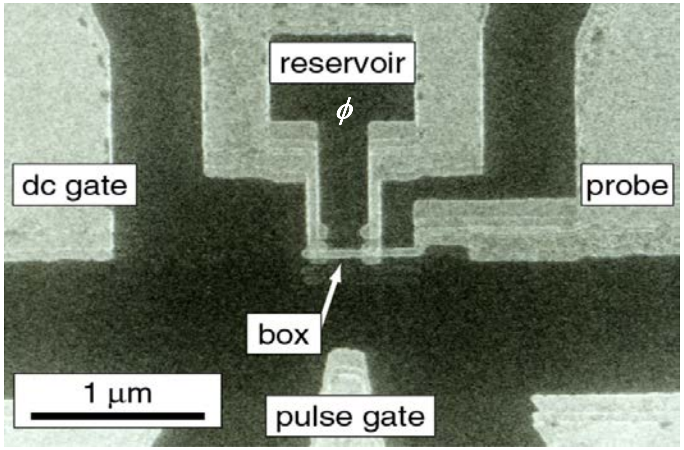
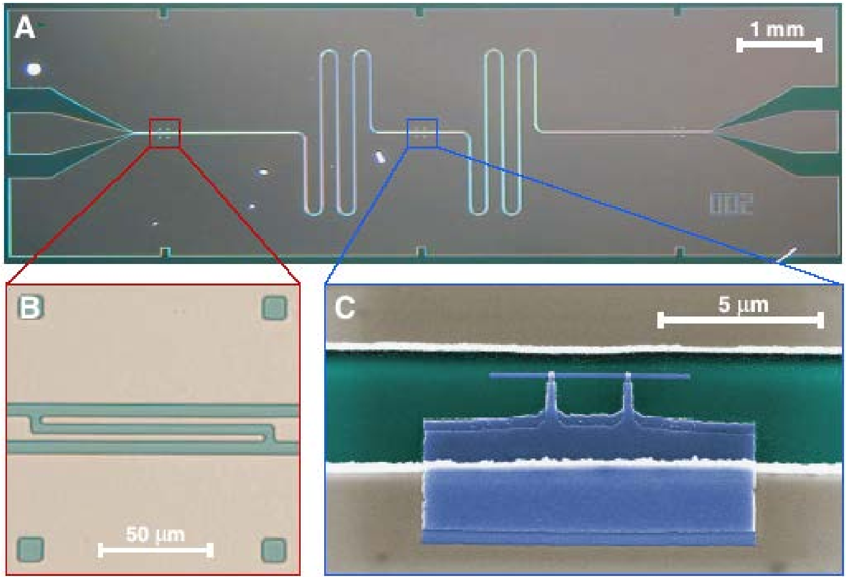
Quantum Computing Architectures

Budapest University of Technology and Economics 2018 Fall



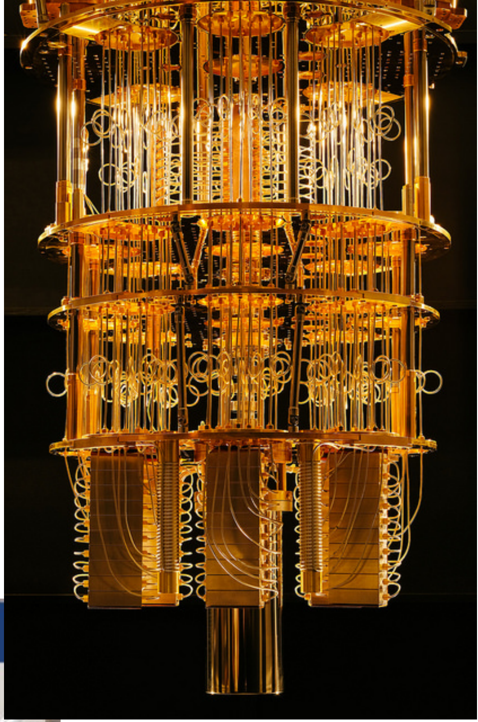


Lecture 8: Cavity QED
Qubit coupling



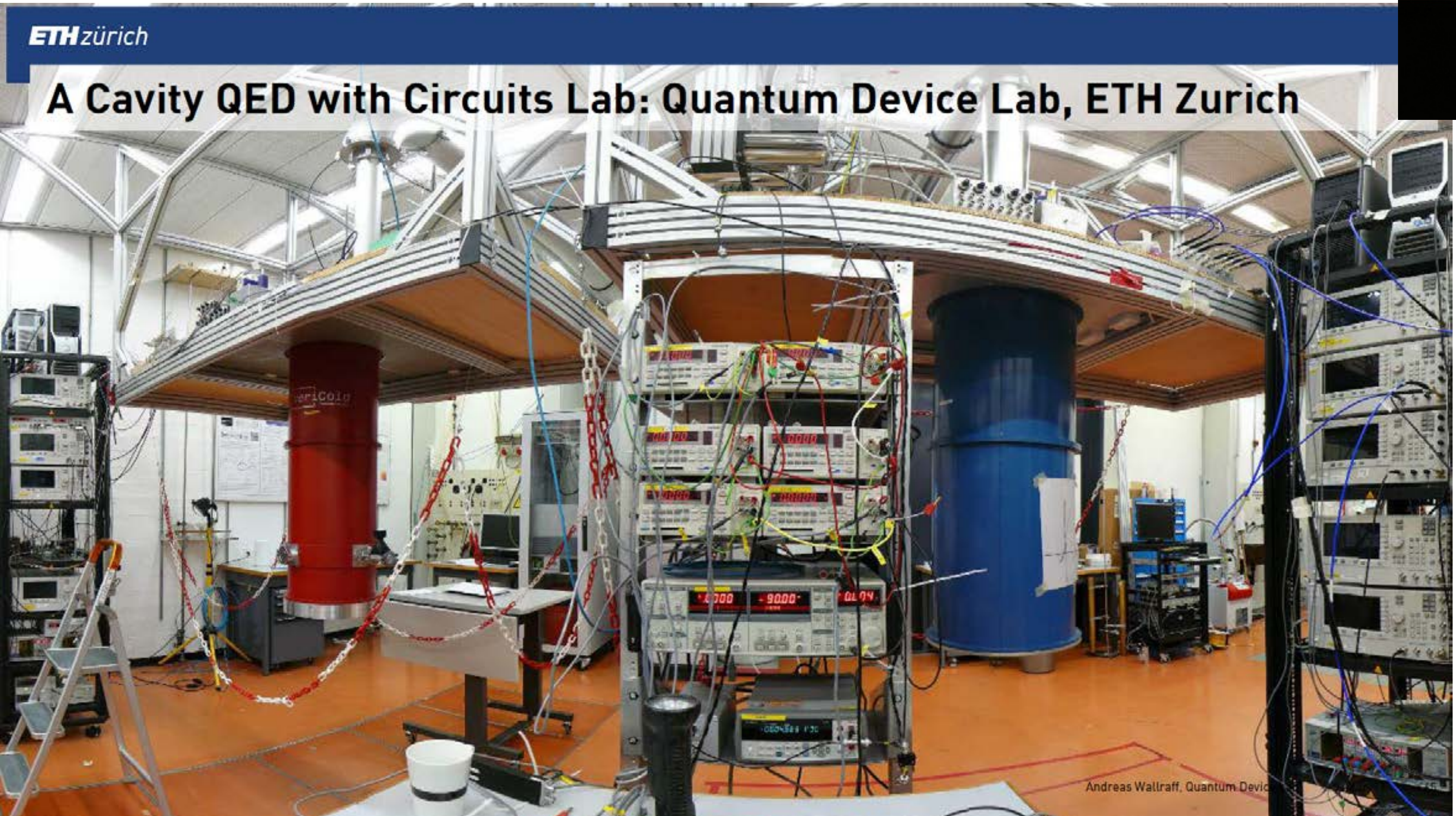
Low temperatures

Fridge: IBM



Ingredients:

- Low temperature (He3-He4 refrigerator)
- Low electrical noise (electron temperature)
- High frequency equipment

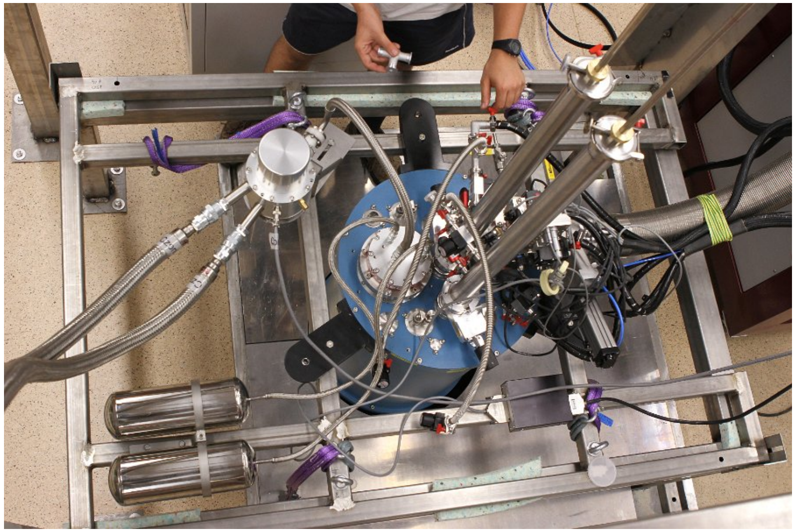


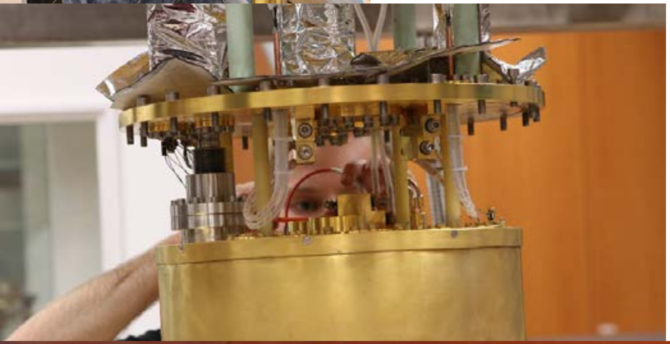
What temperature is needed for a ω_r=5 GHz resonator for average photon number <n> < 0.05 ?

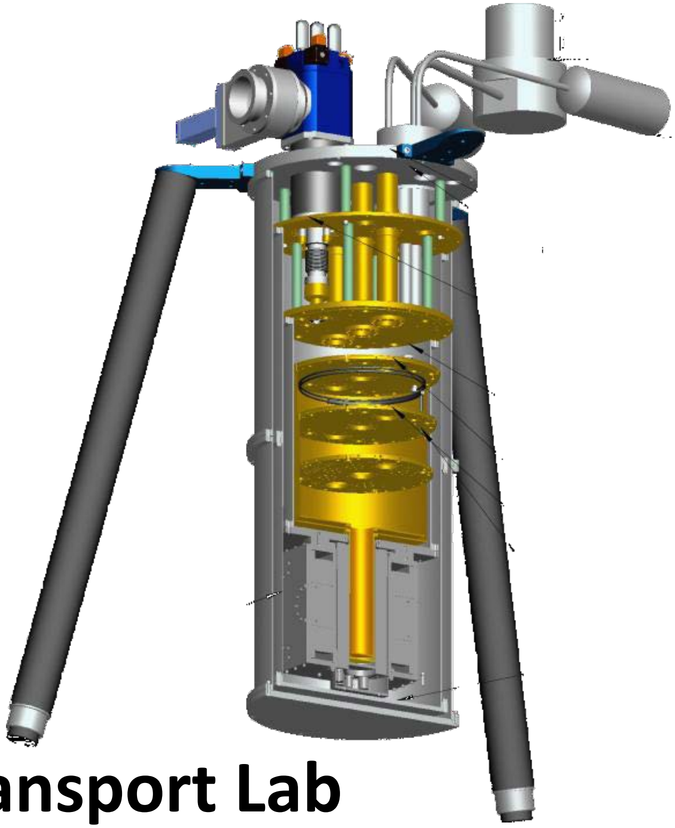
And for a qubit with ω_q=5GHz for a excited state population smaller than 0.05?

Low temperatures

BME quantum transport lab







Transport Lab

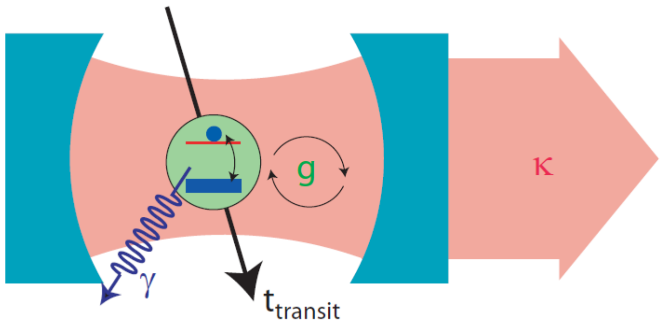
Fridge, $T_{fridge} \approx 7mK$

Vector magnet 9-3T

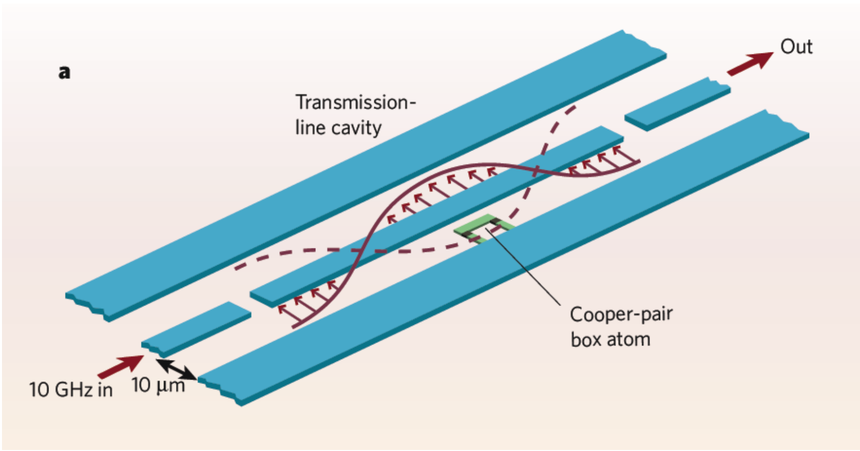
Liquid He facility

Electronics ...

SC circuits

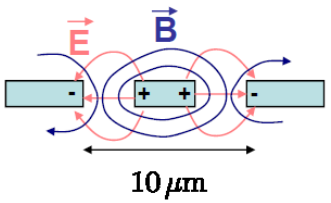


Fabry – Perot cavity for optics – using mirrors

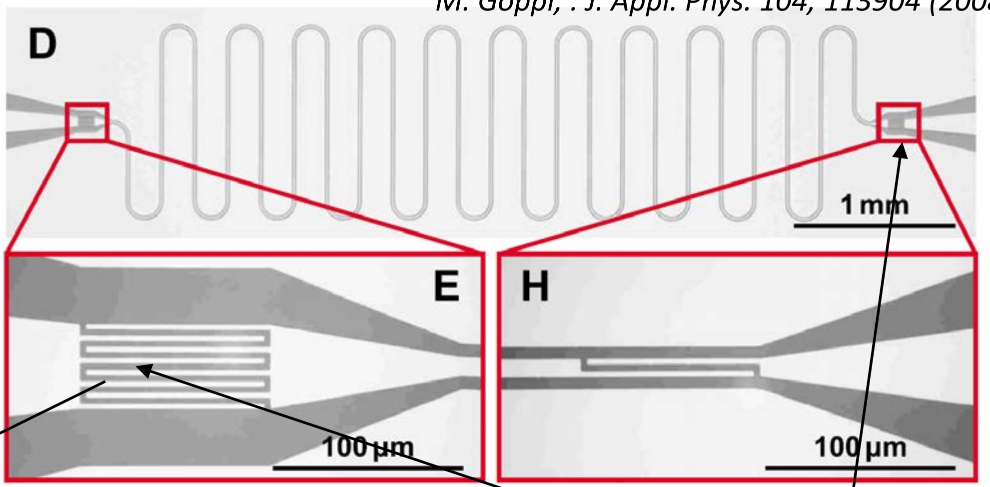


Fabry – Perot cavity for MW photons – capacitive mirrors

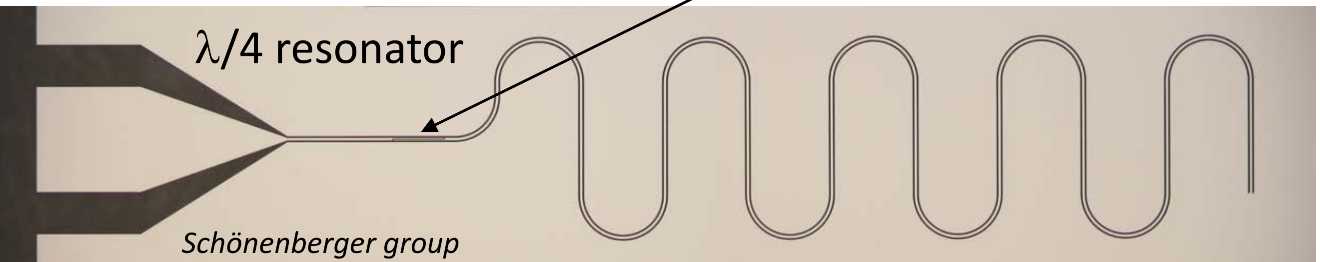
R.J. Schoelkopf et al., Nature 451, 664 (2009)
M. Göppl, : J. Appl. Phys. 104, 113904 (2008)



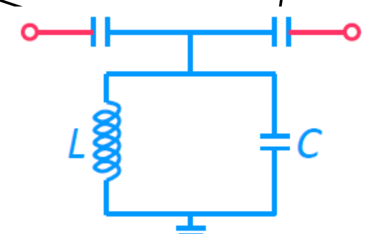
Central conductor and ground plane – essentially a coax



Superconducting circuit to minimize losses (white – SC material, black etched away)
Capacitors: voltage antinodes – zero current – good for electrical dipole coupling
Current antinode (voltage node) - maximal current – good for inductive coupling



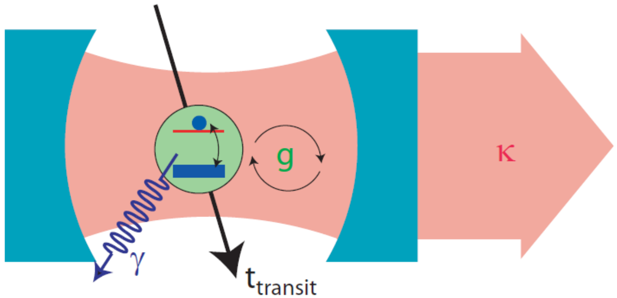
Schönenberger group



Readout: circuit QED

$$\hat{H} = 4E_c\left(N - N_g\right)^2 - E_J \cos\delta + \hbar\omega_r \hat{a}^\dagger \hat{a} + \underbrace{2\frac{C_g}{C_\Sigma} e V^0_{RMS} \hat{N}(\hat{a}^\dagger + \hat{a})}$$

Coupling term – electrical coupling to charge (dipole) – spatial mode profile neglected



$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \qquad V^0_{rms} = \sqrt{\frac{\hbar\omega_r}{2C_r}}$$

Can be mapped to J-C Hamiltonian

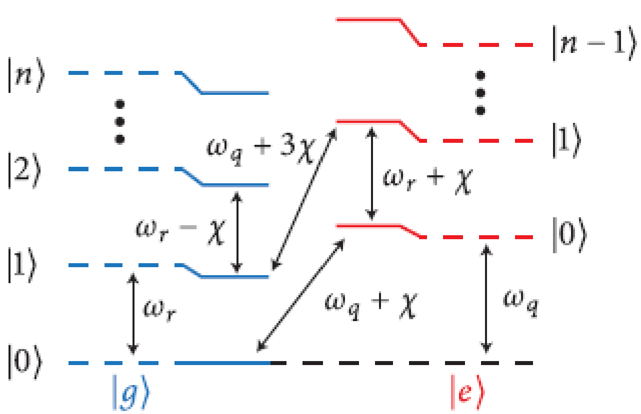
$$\hat{H} = \frac{\hbar\omega_q}{2}\sigma_Z + \hbar\omega_r \hat{a}^\dagger \hat{a} + \hbar g\left(\hat{a}^\dagger \sigma_- + \hat{a}\sigma_+\right) + H_\kappa + H_\gamma$$

Qubit | Resonator | Coupling | Cavity decay | Qubit lifetime

Jaynes Cummings Hamiltonian

$$\hat{H}_{\text{coupling}} = \frac{4E_c C_g V_{\text{rms}}}{e}\hat{n}(\hat{a} + \hat{a}^\dagger)$$

b



$$\hat{H} = \frac{1}{2}\left(\hbar\omega_q + \hbar\frac{g^2}{\Delta}\right)\sigma_Z + \left(\hbar\omega_r + \hbar\frac{g^2}{\Delta}\sigma_Z\right)\hat{a}^\dagger \hat{a}$$

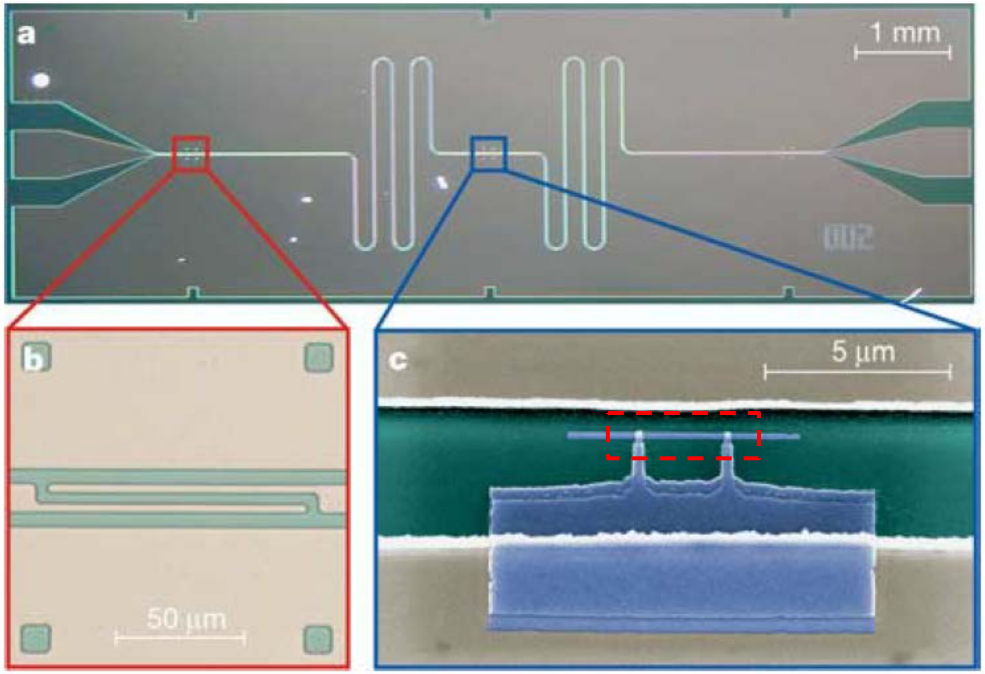
Lamb-shift

Qubit-state dependent resonance shift

$$\Delta = \omega_q - \omega_r$$

Readout: circuit QED

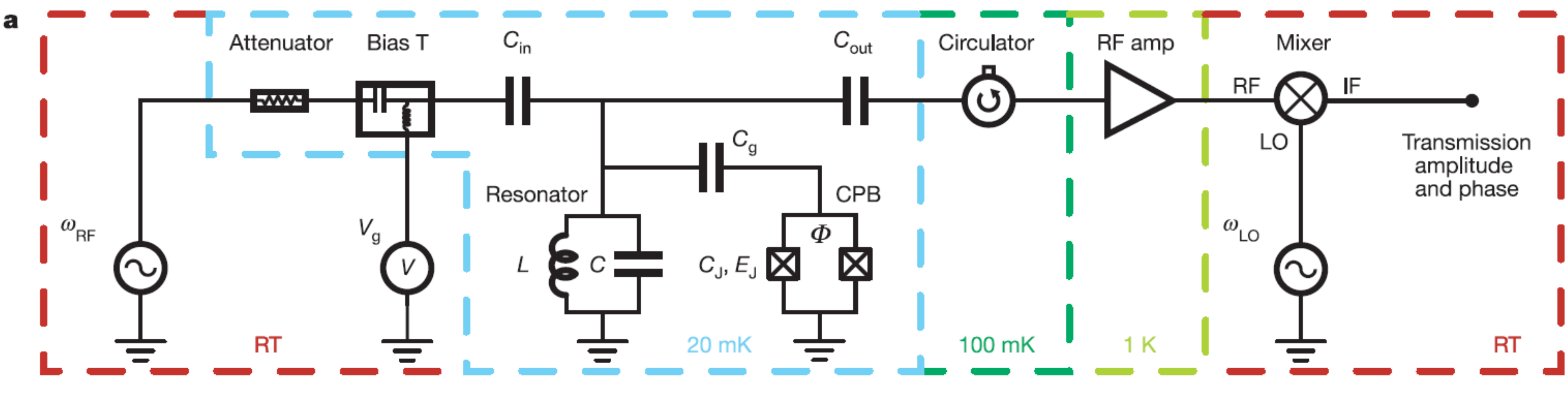
Spectroscopy on resonator



CP-box coupled (capacitively) to a MW cavity

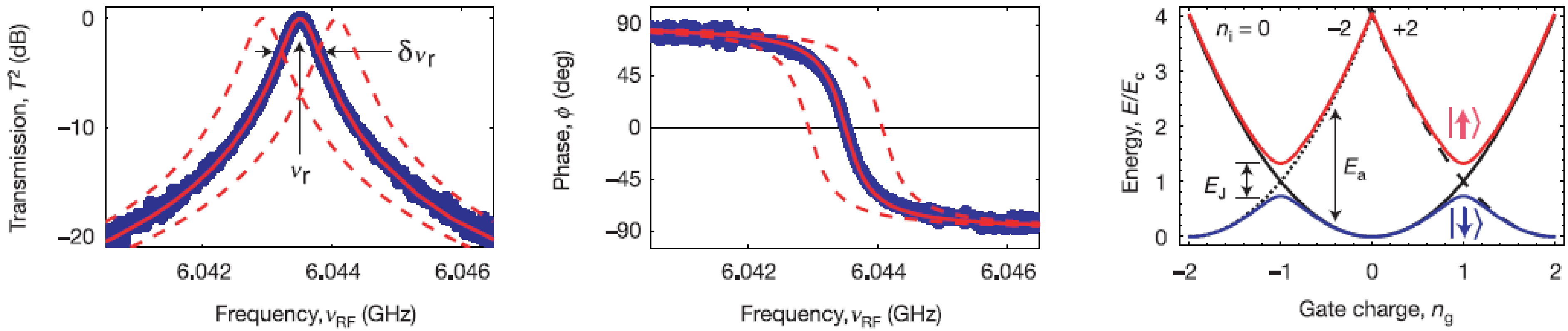
External B field tunes E_J

In the circuit model the qubit is a tunable capacitance which shifts the resonator



Many circuit elements are at low T (amplifier, circulator etc.)

A .Walraff et al., Nature 431, 162 (2004)

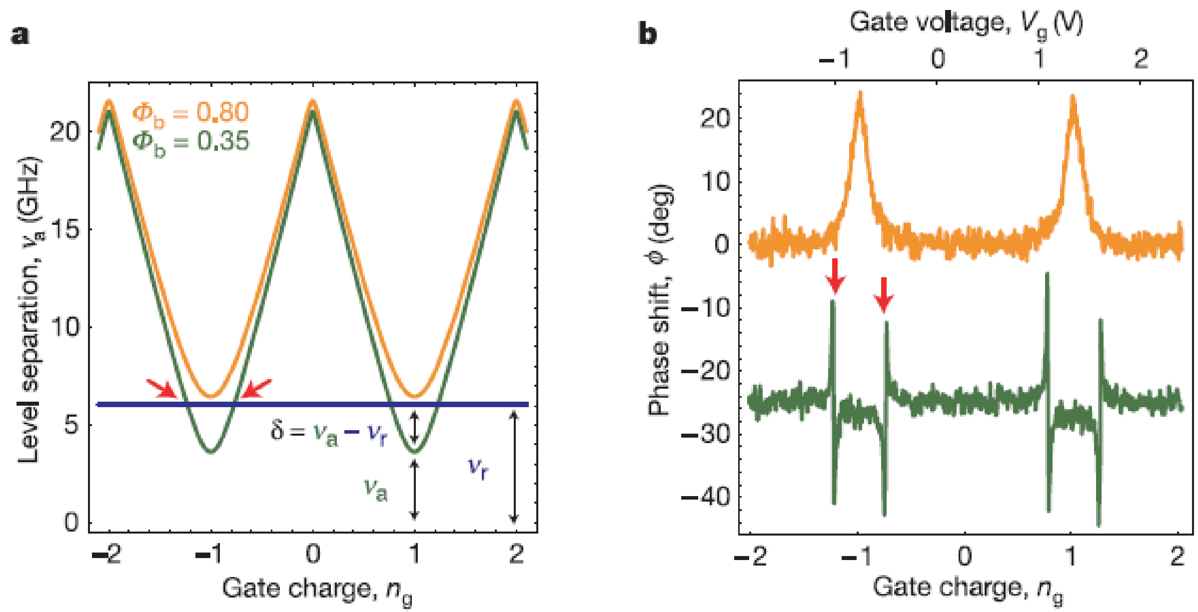


Resonator: Lorentz-like resonance curve with high Q. Phase response is more sensitive
Simulation: shifted curves for the two different qubit states. Idea: measurement at fixed frequency – measure phase response

Reminder:

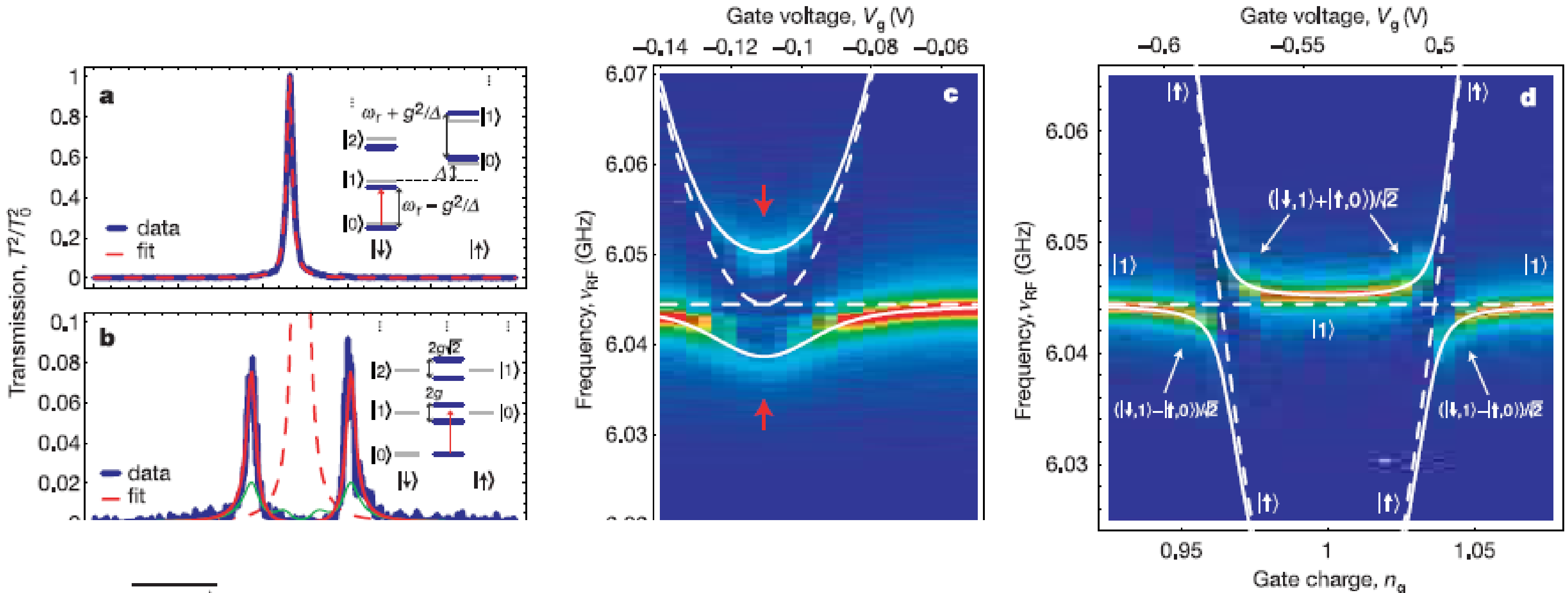
$$\hat{H} = \frac{1}{2}\left(\hbar\omega_q + \hbar\frac{g^2}{\Delta}\right)\sigma_Z + \left(\hbar\omega_r \boxed{+ \hbar\frac{g^2}{\Delta}\sigma_Z}\right)\hat{a}^\dagger\hat{a}$$

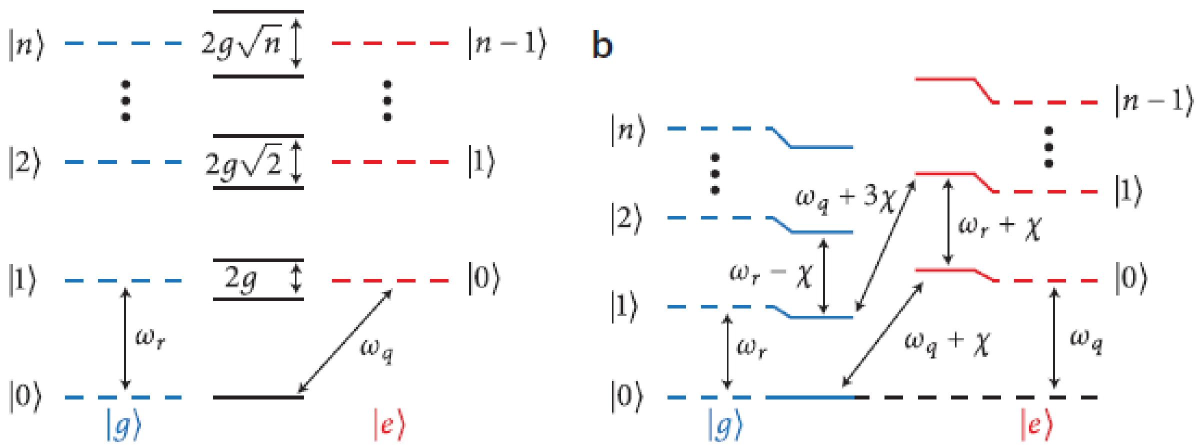
$$\chi = \frac{g^2}{\Delta}$$



Here Qubit is in the ground state, and resonator is probed for different parameters
2 different flux biases: for one it goes through the resonance with the resonator (green), for the other not (orange).
Phase shift decreases by increasing detuning from resonance

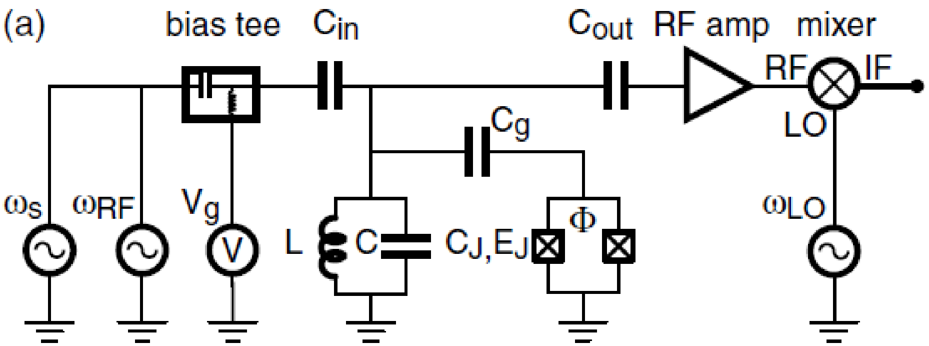
Strong coupling – Spectroscopy measurement





Far away from crossing pure resonator states. Close to resonance an avoided crossing is seen. Bonding and anti-bonding states – entangled states with both photon and qubit character – „phobit" and „quton".

Here the photon number is small n<<1. Vacuum Rabi oscillation with frequency 2g. Continous photon emission and absorbtion.



Spectroscopy

2-tone measurements

2 tone:

ω_S: qubit frequency (here continuous)

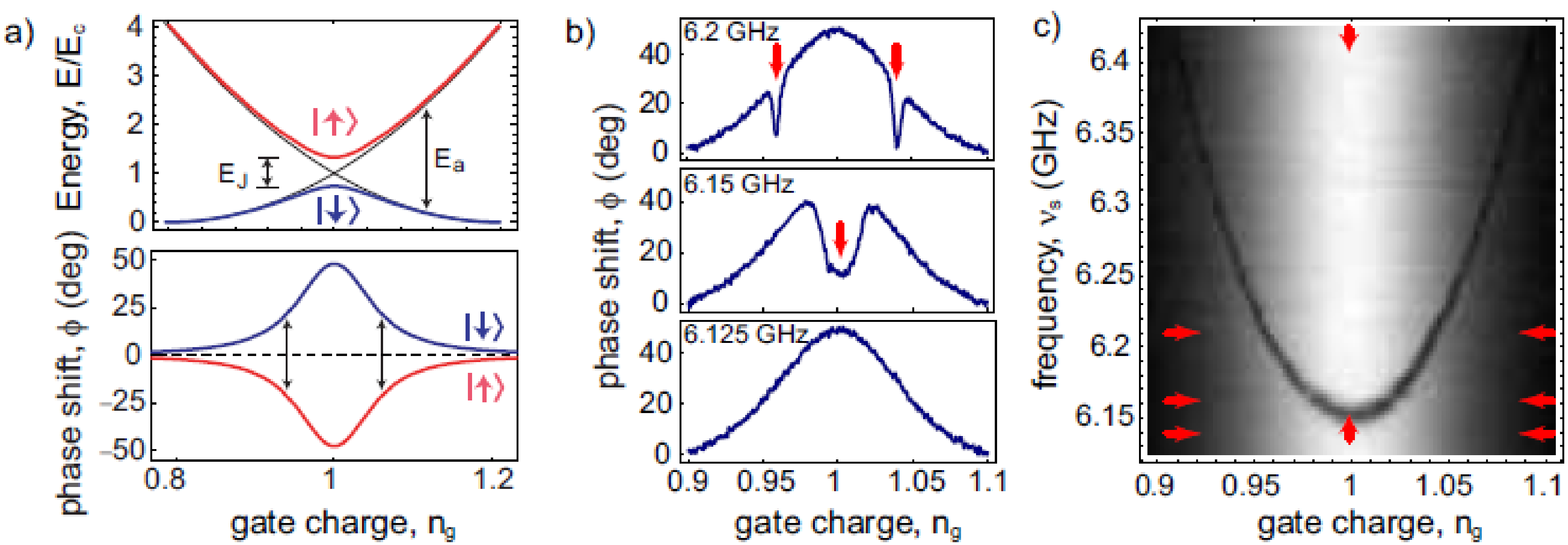
ω_{RF}: cavity frequency (here continuous)

Phase shift: opposite for the two states. If ω_S excites cavity than reduction in phase shift (red arrows). For high power, both states are equally populated and the shift averages to zero.

6.125 GHz- no resonance with qubit, just phase shift observed

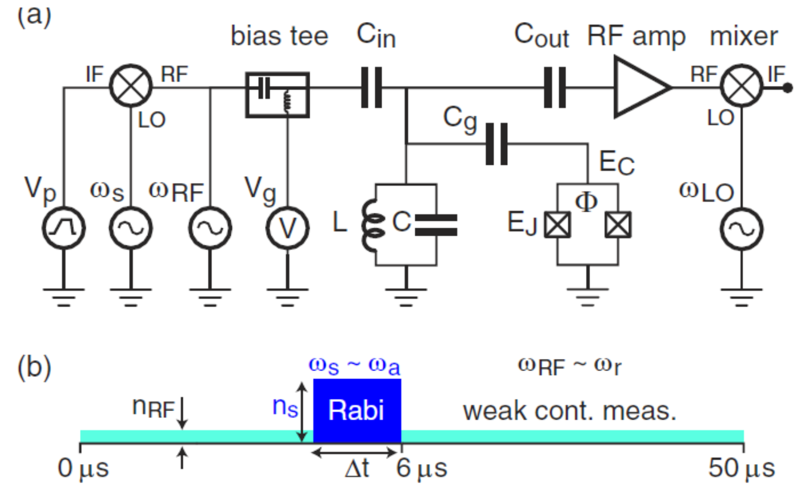
6.15 GHz - at N_g=1 the qubit is driven. Reduction in the phase shift is seen. Similarly at 6.2 GHz.

For Rabi etc. pulsing at ω_S is needed (see later).



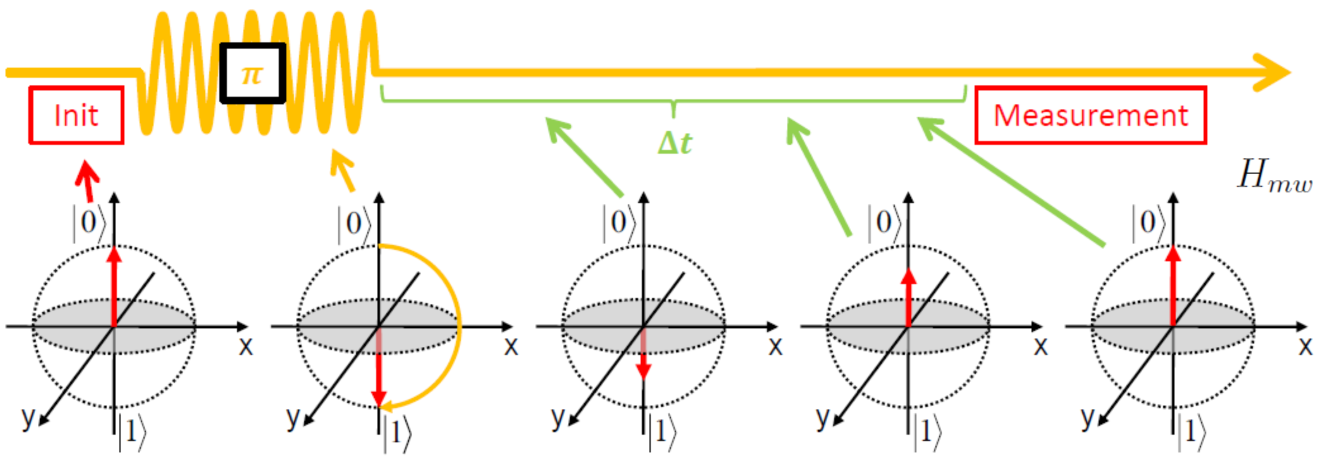
D. I. Schuster et al., PRL 94, 123602 (2005)

Qubit rotations
Two tone measurements

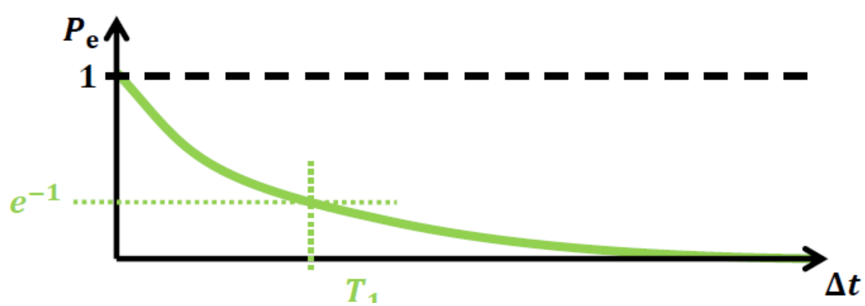


2 tone:
ω_S: qubit frequency (here pulsed)
ω_{RF}: cavity frequency (here continuous)

T1 measurement



Rotating frame & no detuning ($\Delta\omega = \omega - \omega_q = 0$) → no xy-evolution



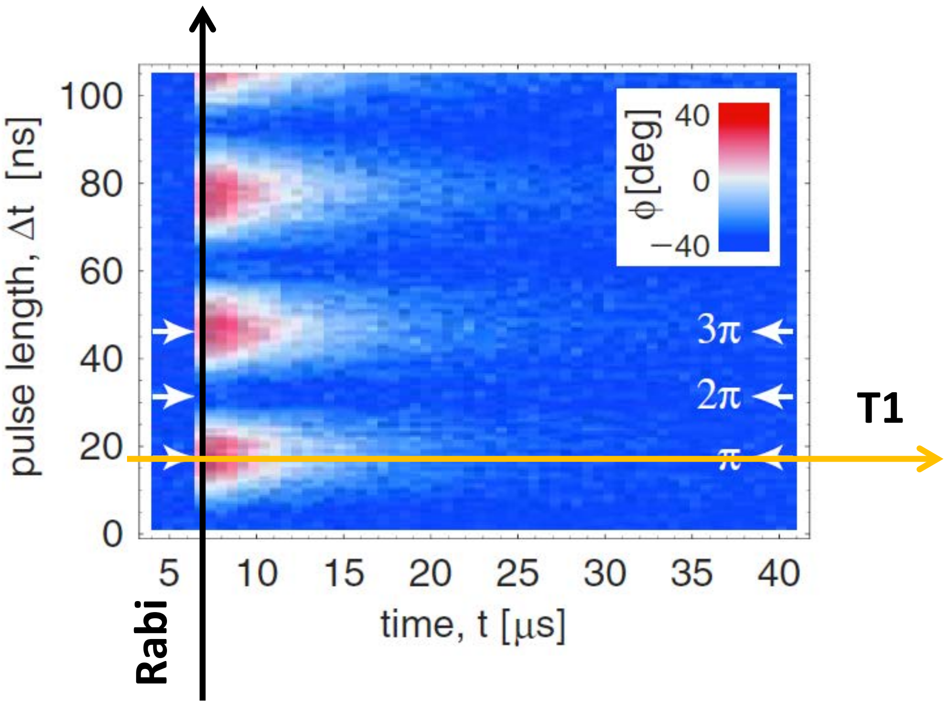
$$H_{mw}(t) = \hbar\epsilon(t)\left(\hat{a}^\dagger e^{i\omega_{mw}t} + \hat{a}e^{-i\omega_{mw}t}\right)$$

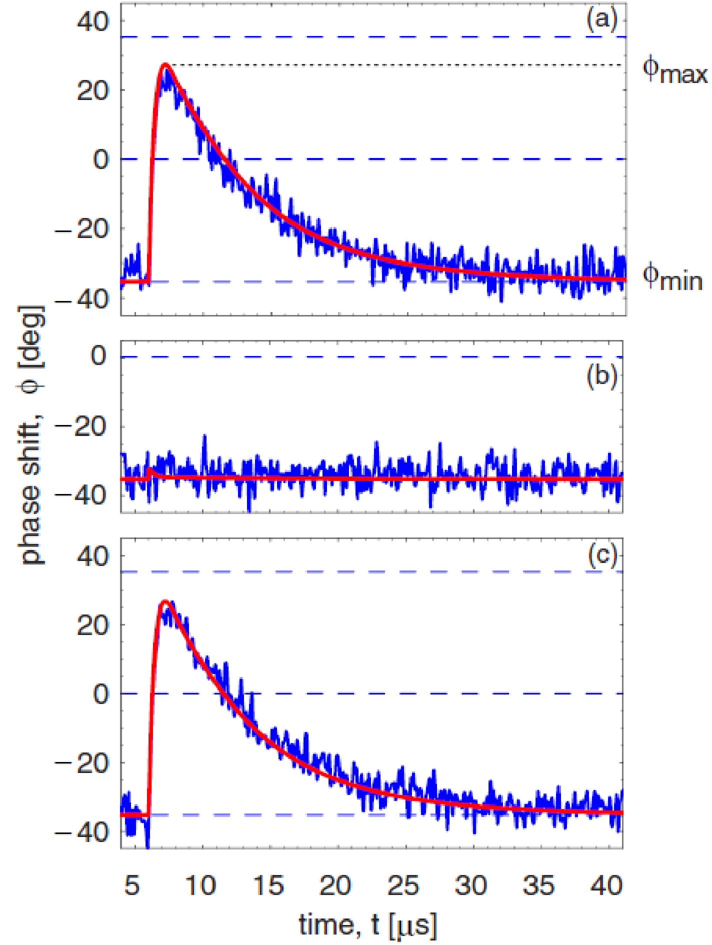
Rotating frame

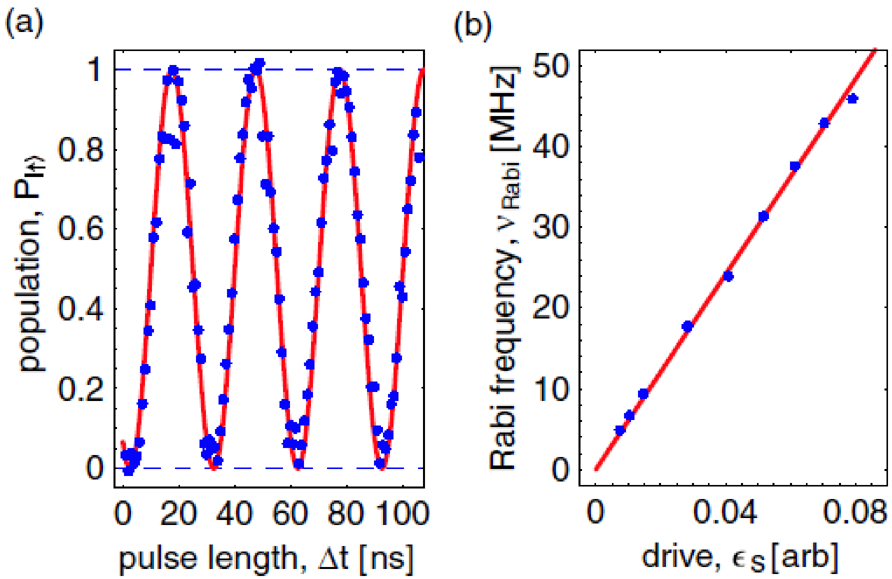
$$\hat{H} = \frac{1}{2}\hbar\left(\omega_q + \frac{2g^2}{\Delta}\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right) - \omega_{mw}\right)\sigma_Z + \hbar(\omega_r - \omega_{mw})\hat{a}^\dagger\hat{a} + \hbar\epsilon(t)\left(\hat{a}^\dagger + \hat{a}\right) + \hbar\frac{g\epsilon(t)}{\Delta}\sigma_X$$

R. Gross, A. Marx, Applied Superconductivity, Lecture notes (Walter-Meissner Institute)

A. Walraff et al., PRL 95, 060501 (2005)







Charge qubit

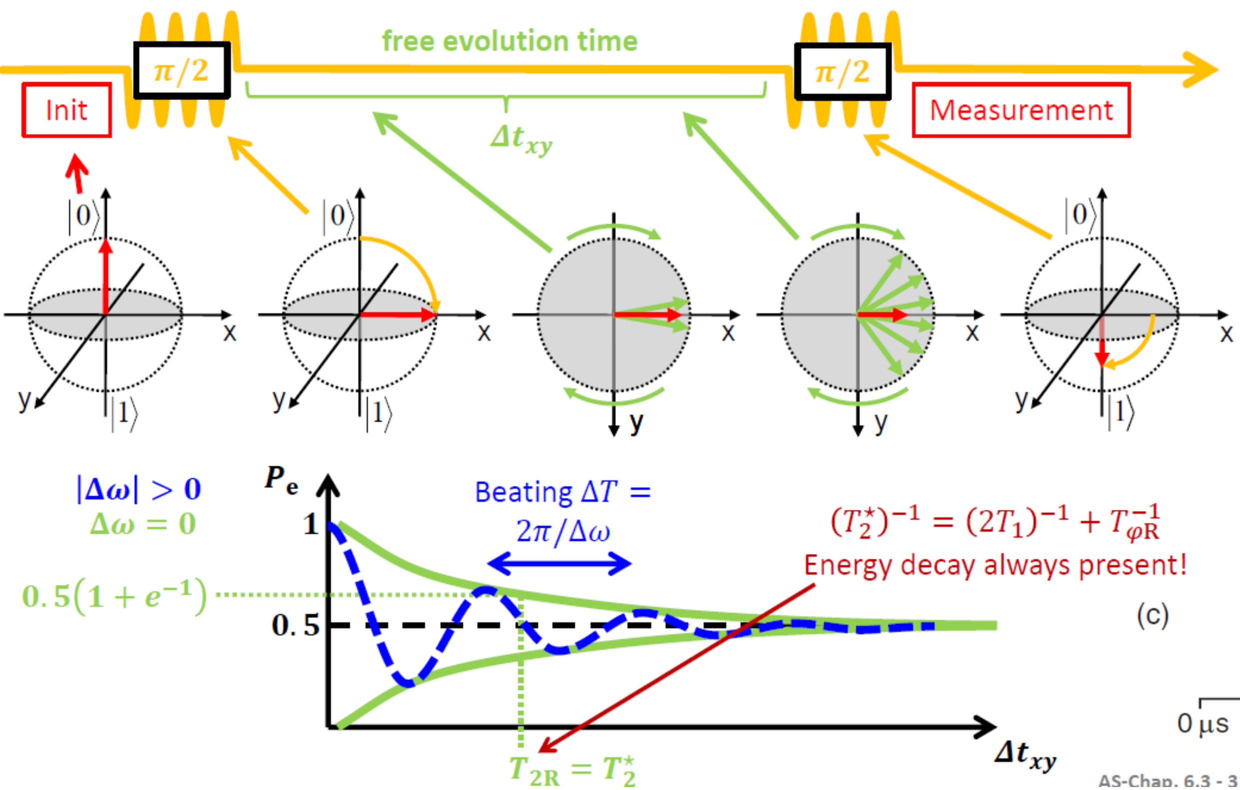
0 phase: if the qubit was not there

GS and ES has opposite shift. In ES does not reach maxima due to finite cavity lifetime

2 π : no relaxation should occur

T1~ 7 µs

A. Walraff et al., PRL 95, 060501 (2005)

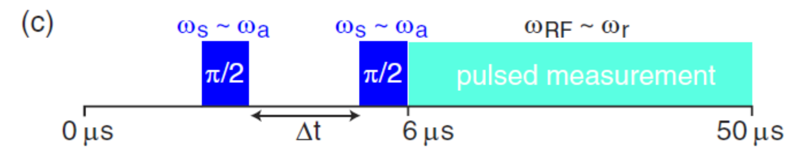


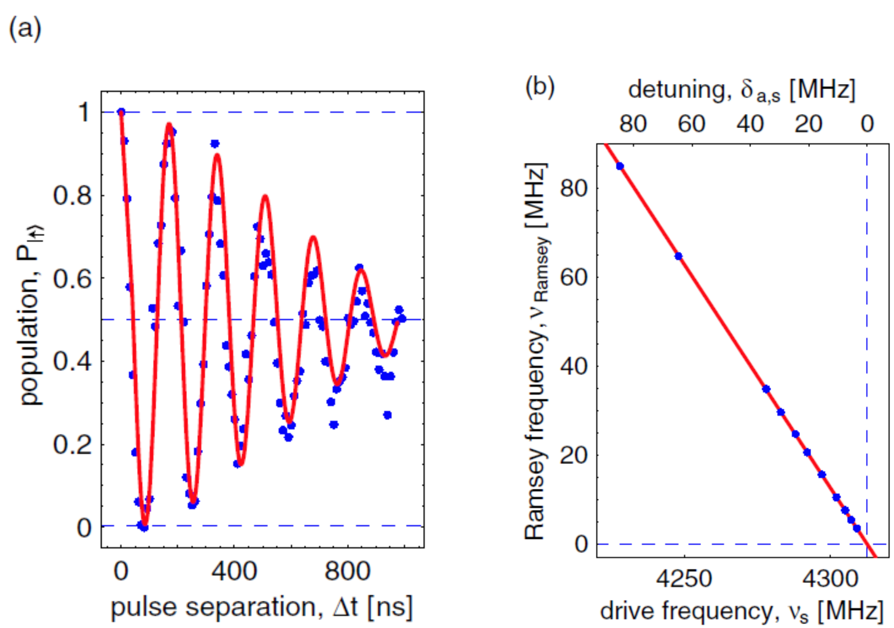
T2 measurement

2 tone:

ω_S: qubit frequency (here pulsed)

ω_{RF}: cavity frequency (here pulsed)



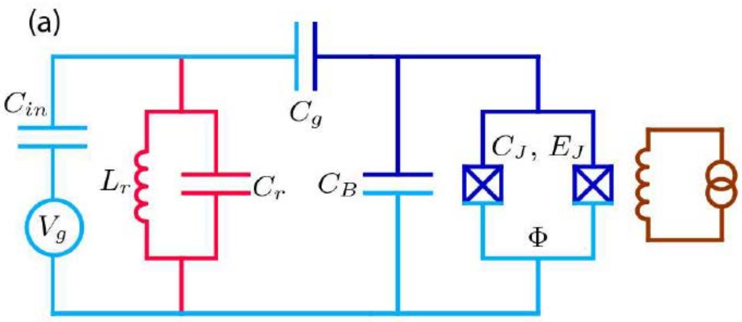


Ramsey measurement for different detunings (detuning – small precession compared to the rotating frame) – decay: T2 ~500 ns

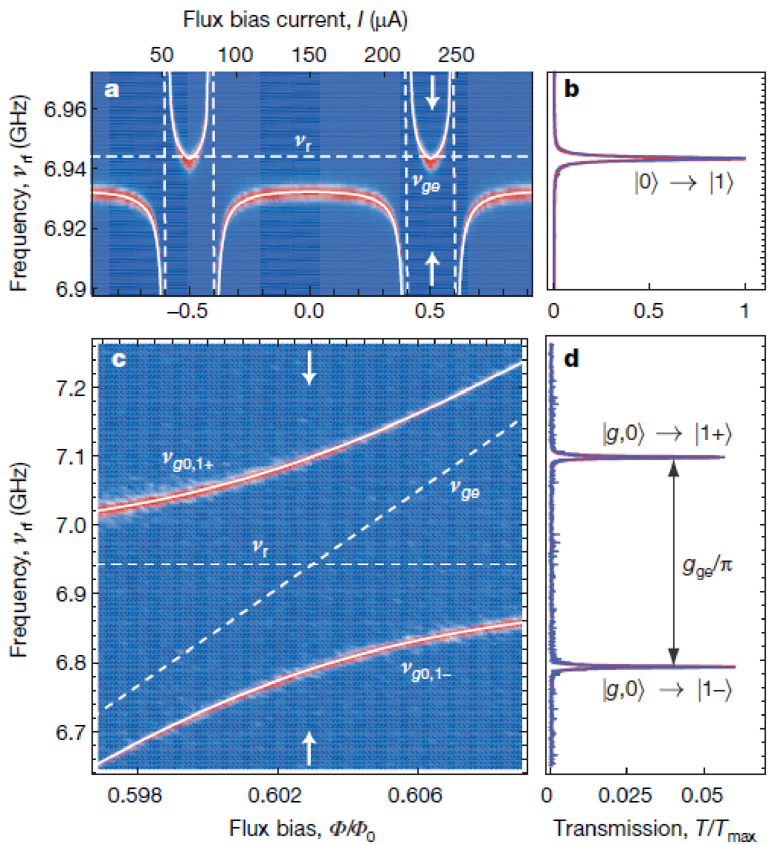
A. Walraff et al., PRL 95, 060501 (2005)

R. Gross, A. Marx, Applied Superconductivity, Lecture notes (Walter-Meissner Institute)

Transmon cQED



Strong coupling



Mostly the same, gate voltage not a useful parameter

Using the transmon wave function, RWA only the following relevant terms remain:

$$\hat{H} = \hbar \sum_j \omega_j |j\rangle\langle j| + \hbar\omega_r \hat{a}^\dagger \hat{a} + \left[\hbar \sum_i g_{i,i+1} |i\rangle\langle i+1| \hat{a}^\dagger + \text{H.C.}\right]$$

Multi level Jaynes Cummings Hamiltonian, where

$$\hbar g_{i,i+1} = 2e\frac{C_g}{C_\Sigma} e V^0_{rms} \langle i|\hat{N}|i+1\rangle \qquad \langle i|\hat{N}|i+1\rangle \sim \left(\frac{E_j}{8E_C}\right)^{1/4}$$

g – coupling term is large, even increases with increasing E_J

$$\hat{H} = \frac{1}{2}\left(\hbar\omega_{01} + \hbar\chi_{01}\right)\sigma_Z + \left(\hbar\omega_r - \hbar\chi_{12} + \hbar\chi\sigma_Z\right)\hat{a}^\dagger\hat{a}$$

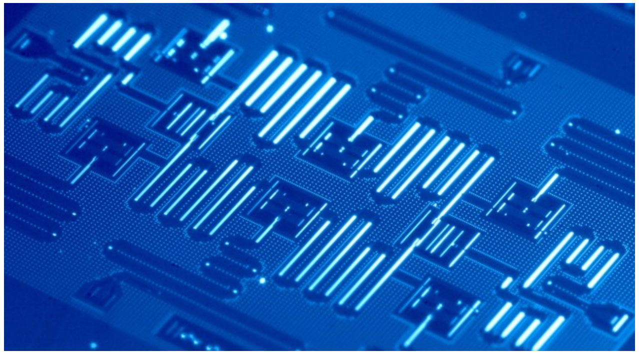
$$\chi = \chi_{01} - \chi_{12}/2 \qquad \chi_{ij} = \frac{g_{ij}}{\omega_{ij} - \omega_r}$$

Higher levels matter a bit, otherwise the same

Strong coupling achieved
For 0-1 state 2g Rabi frequency
For 1-2 state √2*2g as J-C says

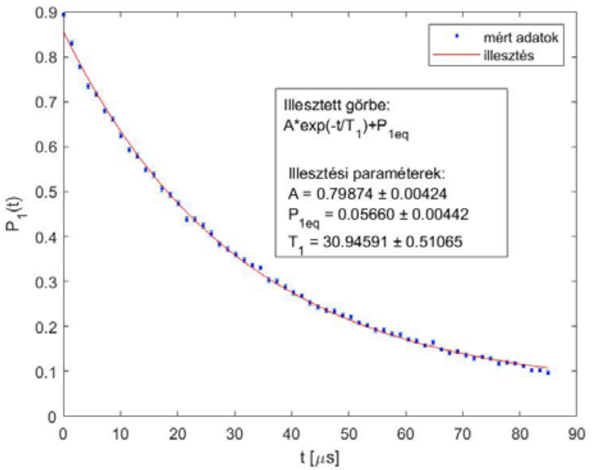
J. M. Fink et al., Nature 454, 315 (2008)

Transmon cQED



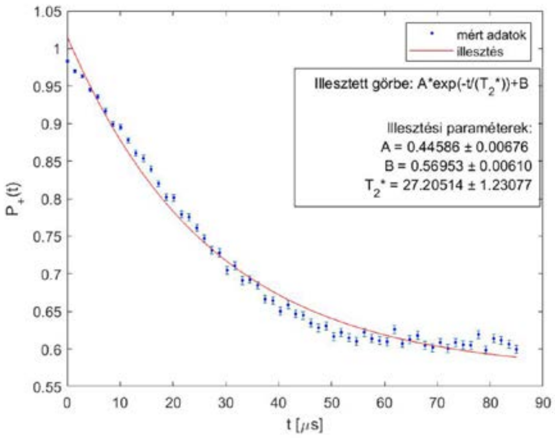
Timescales have evolved
Measurements on IBM experience

T1 measurement



T_1~ 31 μs

T2 measurement



T_2^*~ 27 μs

T2 is T1 limited – relaxation not by decoherence.
Claim T1 comes from spontaneous emission to the cavity – Purcell effect.

Akos Budai, BSc thesis

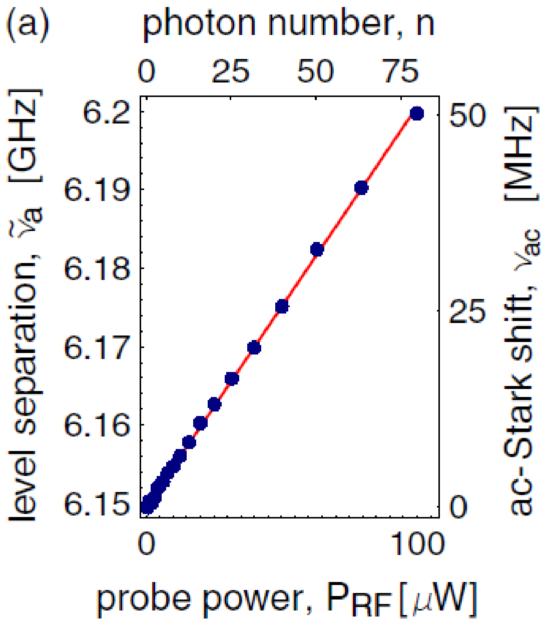
Back-action
Stark-shift

$$\hat{H} = \frac{1}{2}\left(\hbar\omega_q + \hbar\frac{g^2}{\Delta}\right)\sigma_Z + \left(\hbar\omega_r + \hbar\frac{g^2}{\Delta}\right)\hat{a}^\dagger\hat{a}$$

$$\downarrow$$

$$\hat{H} = \frac{1}{2}\left(\hbar\omega_q + \hbar\frac{g^2}{\Delta} + \boxed{\hbar\frac{g^2}{\Delta}\hat{a}^\dagger\hat{a}}\right)\sigma_Z + \hbar\omega_r\hat{a}^\dagger\hat{a}$$

Stark shift

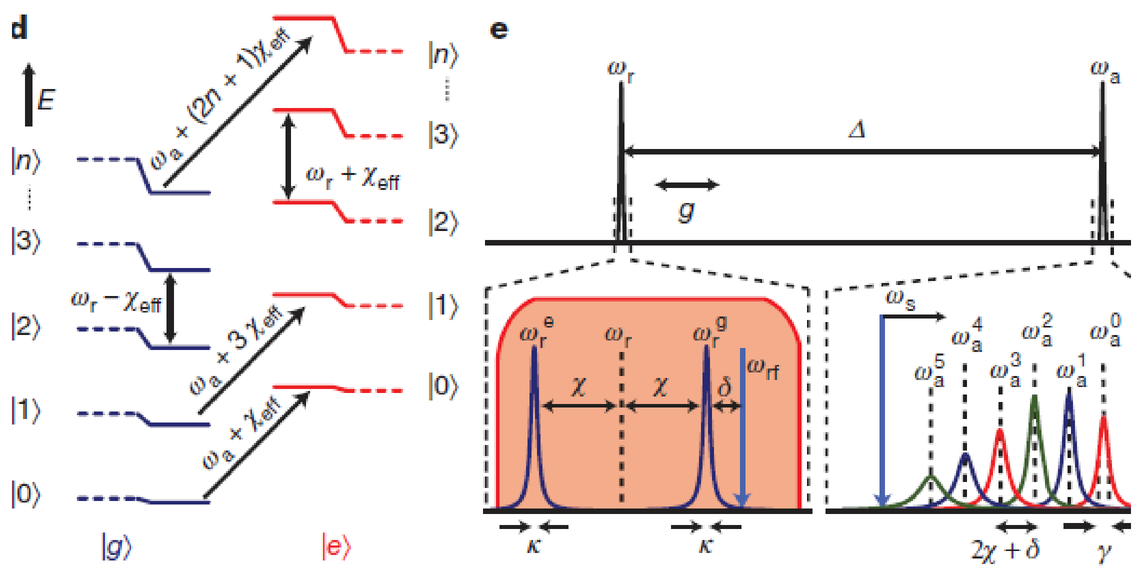


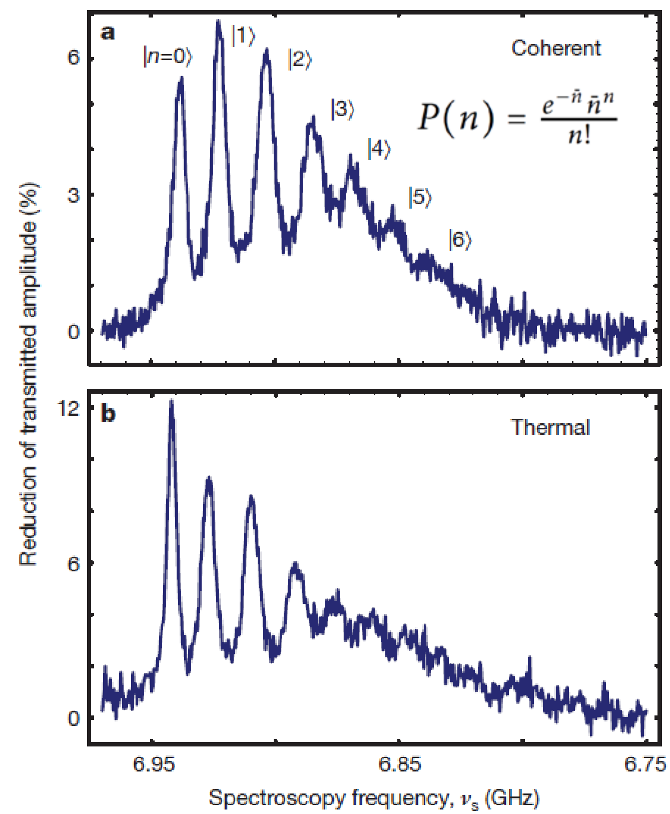
By increasing the resonator power, hence the average photon number, the qubit frequency shifts.

D. I. Schuster et al., PRL 94, 123602 (2005)

$$\hat{H} = \frac{1}{2}\left(\hbar\omega_q + \hbar\frac{g^2}{\Delta} + \boxed{\hbar\frac{g^2}{\Delta}\hat{a}^\dagger\hat{a}}\right)\sigma_Z + \hbar\omega_r\hat{a}^\dagger\hat{a} \qquad \chi = \frac{g^2}{\Delta}$$

In the strong dispersive regime ($\chi >> \gamma, \kappa$) individual photon states resolved:
Populate resonator at ω_{rf}. Than sweep ω_s (qubit frequency). If there were n photons in the cavity the resonance will be at $2n\chi$. If the qubit gets excited can be seen from the resonator frequency shift.
Individual photon states resolved.
Under usual drive close to coherent states observed.
Addig large thermal noise – thermal distribution.





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