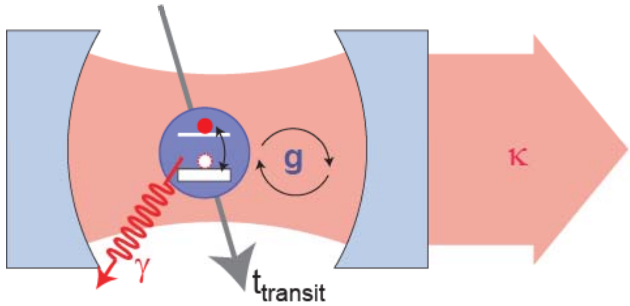
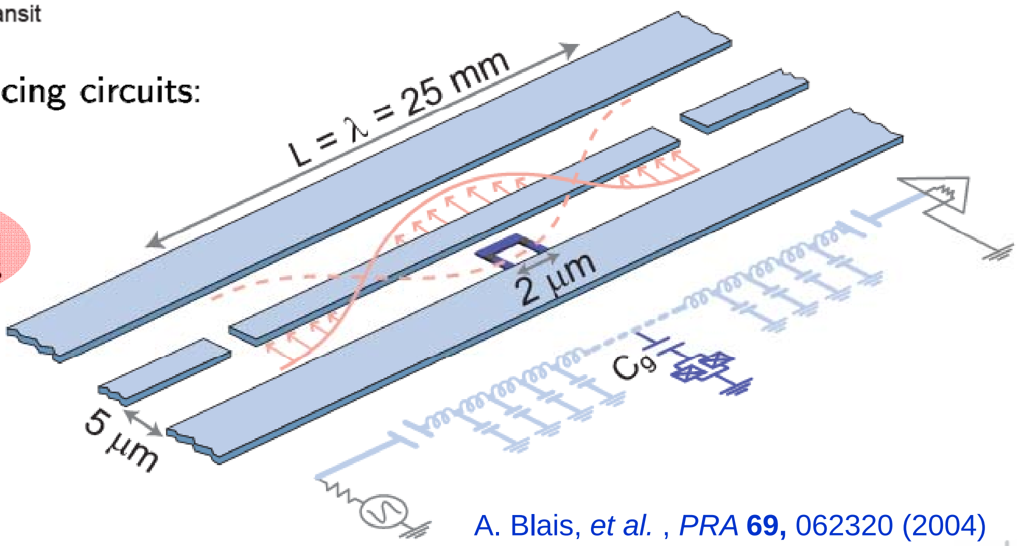
Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

... in superconducing circuits:

circuit quantum electrodynamics



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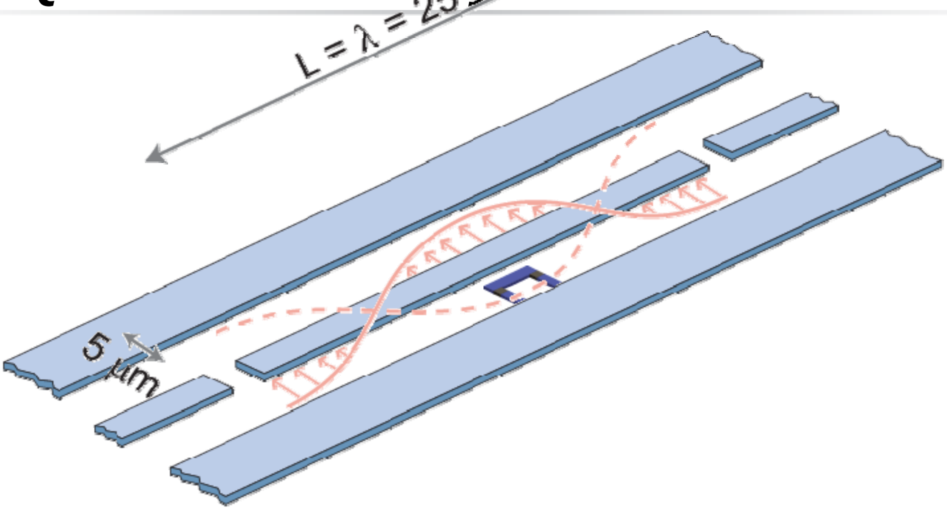
A. Blais, *et al.* , *PRA* **69,** 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)

Circuit Quantum Electrodynamics



elements

- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box with large dipole moment *d* and long coherence time $1/\gamma$

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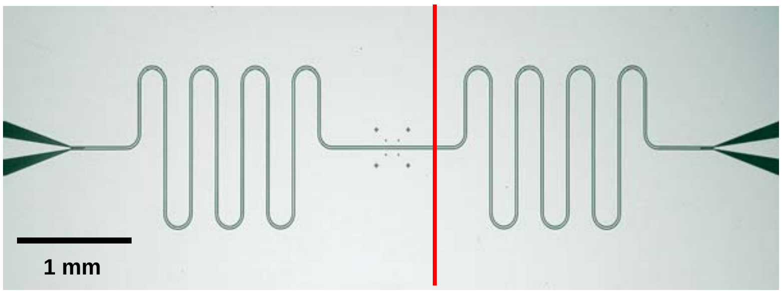
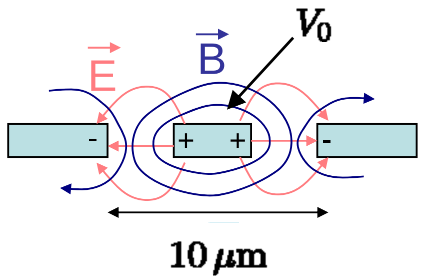
Vacuum Field in 1D Cavity



cross-section of transm. line (TEM mode):



voltage across resonator in vacuum state $(n = 0)$

$$V_{0,\mathrm{rms}} = \sqrt{\frac{\hbar\omega_r}{2C}} \approx 1\,\mu\mathrm{V}$$

harmonic oscillator

$$H_r = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$$

$$E_0 = \frac{V_{0,\mathrm{rms}}}{b} \approx 0.2\,\mathrm{V/m}$$

10^3 larger than in 3D cavity

for $\omega_r/2\pi \approx 6\,\mathrm{GHz}$ $(C \sim 1\,\mathrm{pF})$, $b \approx 5\,\mu\mathrm{m}$

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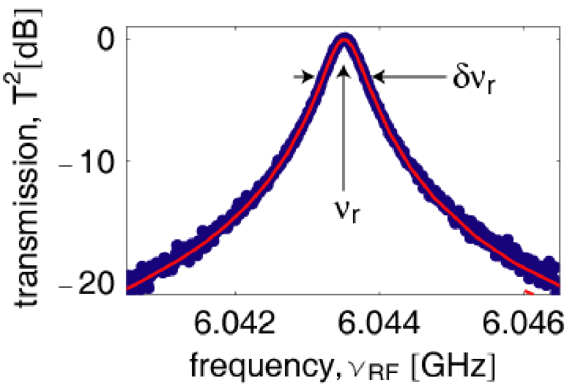
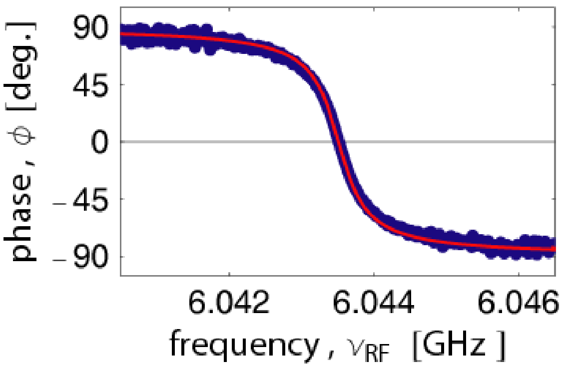
Resonator Quality Factor and Photon Lifetime





resonance frequency:

$$\nu_r = 6.04\,\mathrm{GHz}$$

quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^4$$

photon decay rate:

$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\mathrm{MHz}$$

photon lifetime:

$$T_\kappa = 1/\kappa \approx 200\,\mathrm{ns}$$

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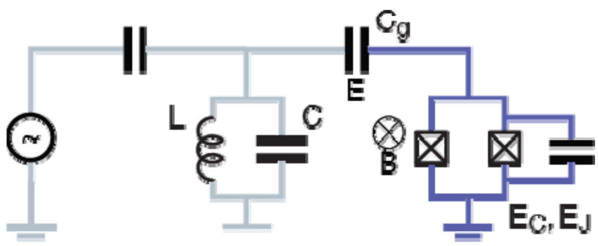
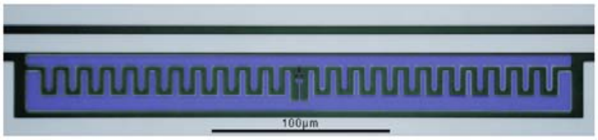
Qubit/Photon Coupling in a Circuit



qubit coupled to resonator



coupling strength:

$$\hbar g = e V_{0,\mathrm{rms}} \frac{C_g}{C_\Sigma}$$

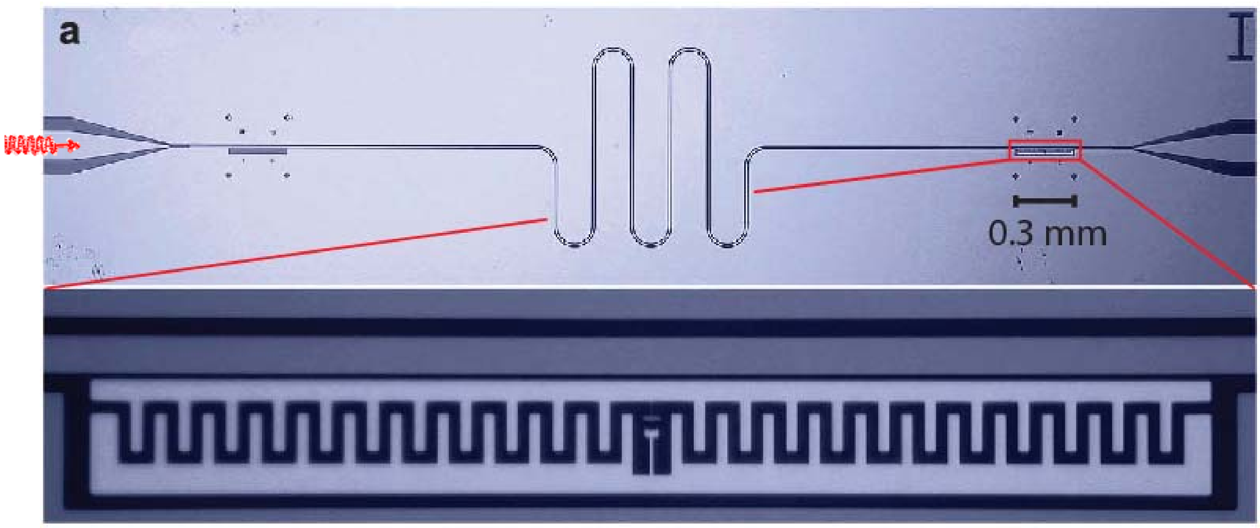
$$\Longrightarrow \nu_{\mathrm{vac}} = \frac{g}{\pi} \approx 1 \dots 300\,\mathrm{MHz}$$

$g \gg [\kappa, \gamma]$ possible!

large effective dipole moment

$$d = \frac{\hbar g}{E_0} \sim 10^2 \dots 10^4\, e a_0$$

Circuit QED with One Photon

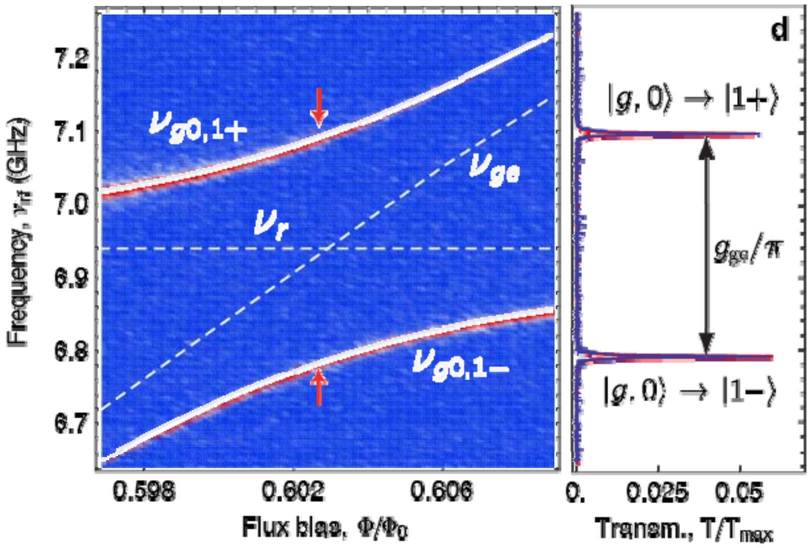


superconducting cavity QED circuit

A. Wallraff, …, R. J. Schoelkopf, *Nature (London)* **431**, 162 (2004)

Resonant Vacuum Rabi Mode Splitting …

… with one photon ($n = 1$):

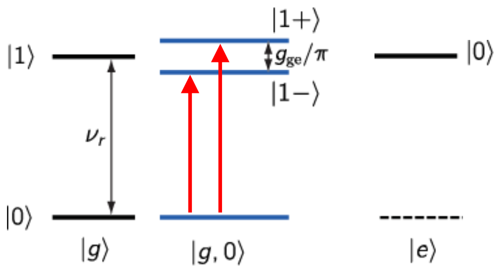


very strong coupling:

$$g_{ge}/\pi = 308\,\mathrm{MHz}$$

$$\kappa, \gamma < 1\ \mathrm{MHz}$$

$$g_{ge} \gg \kappa, \gamma$$



forming a 'molecule' of a qubit and a photon

$$|1\pm\rangle = \left(|g,1\rangle \pm |e,0\rangle\right)/\sqrt{2}$$

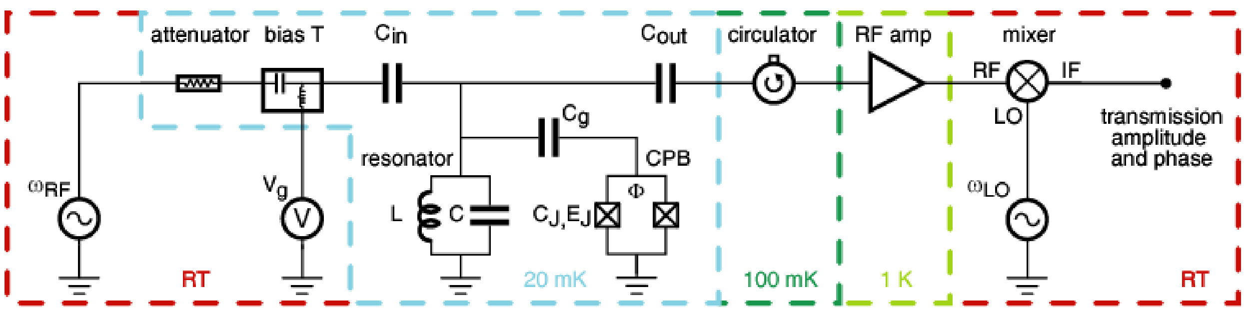
first demonstration: A. Wallraff, … and R. J. Schoelkopf, *Nature (London)* **431**, 162 (2004)

this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)

How to Measure Single Microwave Photons

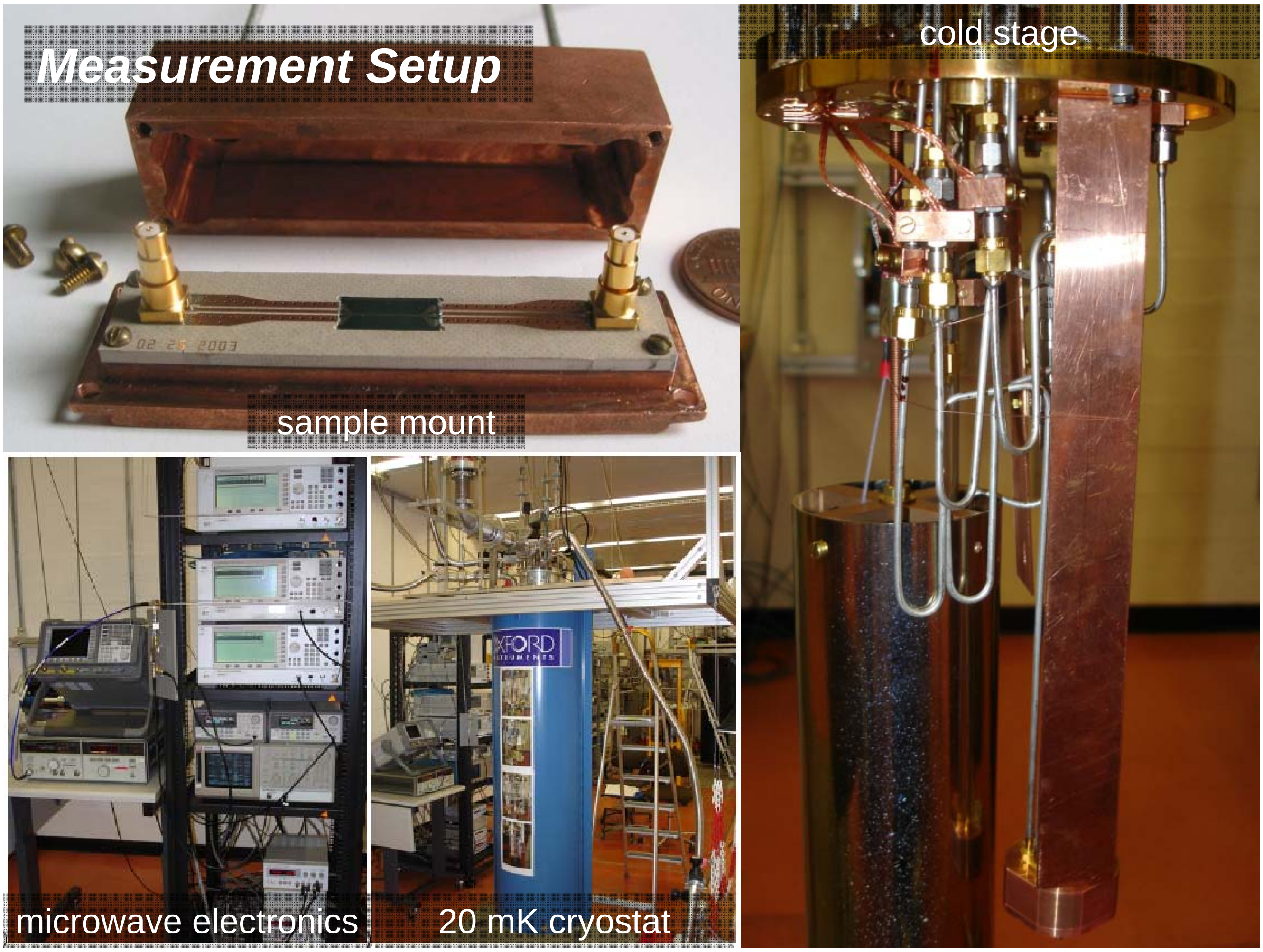
- average power to be detected

$$\rightarrow \langle n=1\rangle \hbar\omega_r\kappa/2 \approx P_{RF} = -140\,\mathrm{dBm} = 10^{-17}\,\mathrm{W}$$

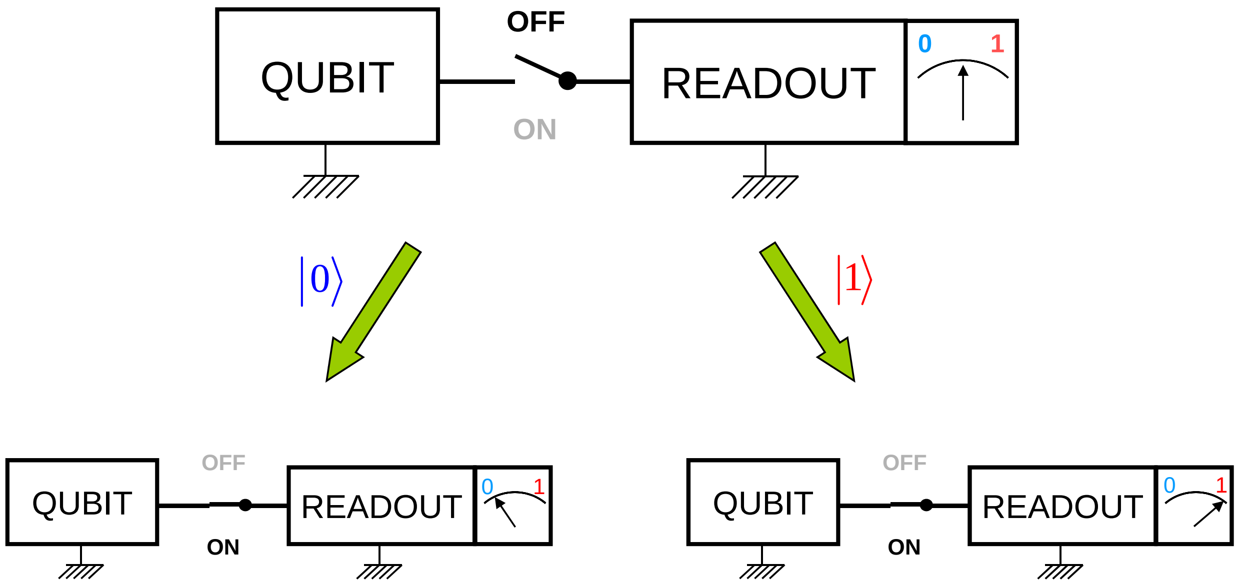


- efficient with cryogenic low noise HEMT amplifier ($T_N = 6\,\mathrm{K}$)
- prevent leakage of thermal photons (cold attenuators and circulators)

Measurement Setup



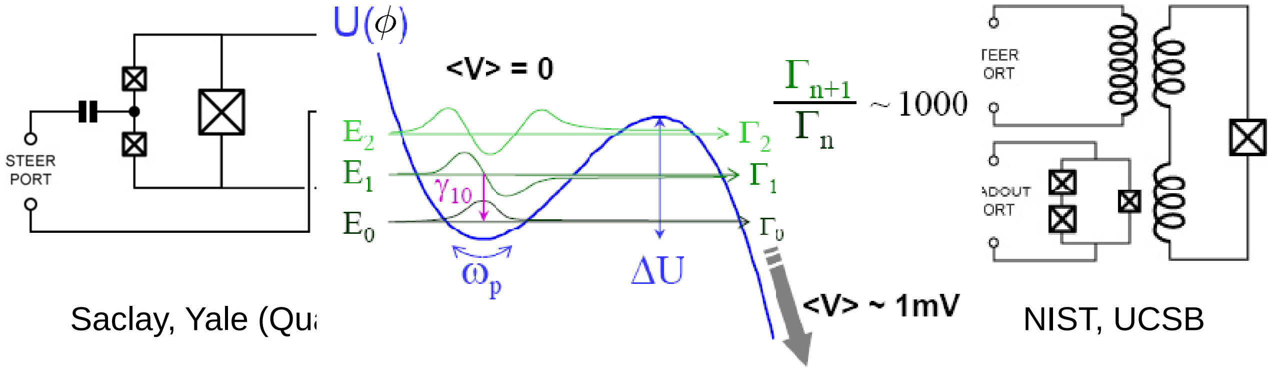
Qubit Read Out



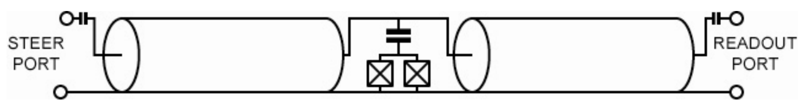
desired: good on/off ratio
no relaxation in on state (QND)

Read Out Strategies

demolition measurements (switching/latching measurements)



quantum non-demolition (QND) measurements



Yale (circuit QED)

now also: Chalmers, Delft, Yale (JBA)

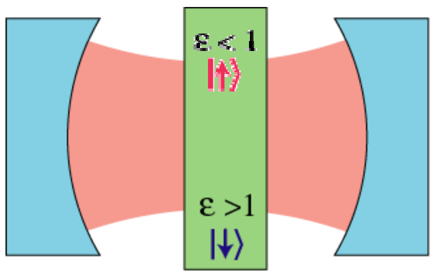
Non-Resonant Interaction: Qubit Readout

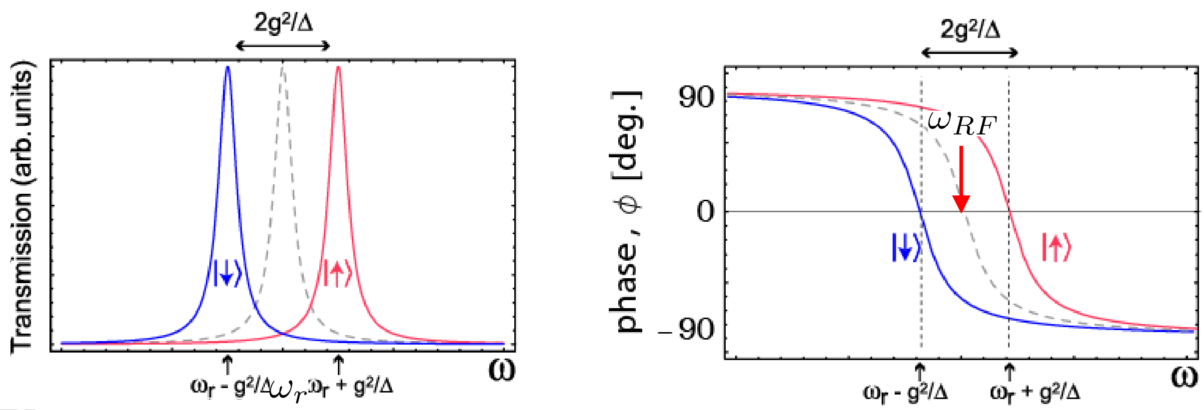
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta}\right) \sigma_z$$

cavity frequency shift *and* qubit ac-Stark shift

Lamb shift





A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Non-Resonant Coupling for Qubit Readout

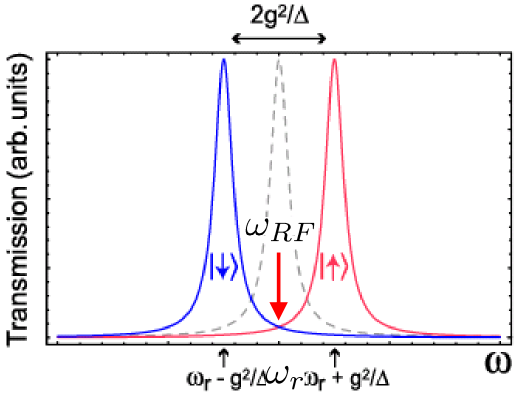
approximate diagonalization for $|\Delta| = |\omega_a - \omega_r| \gg g$

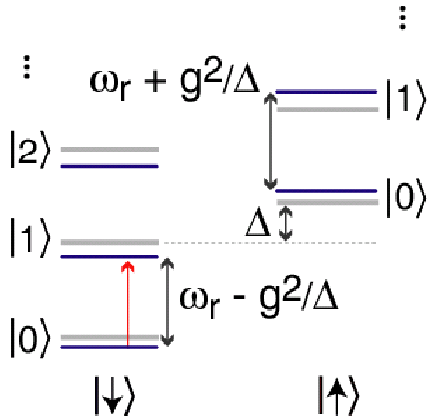
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\hbar\left(\omega_a + \frac{g^2}{\Delta}\right)\sigma_z$$

cavity frequency shift *and* qubit ac-Stark shift

Lamb shift

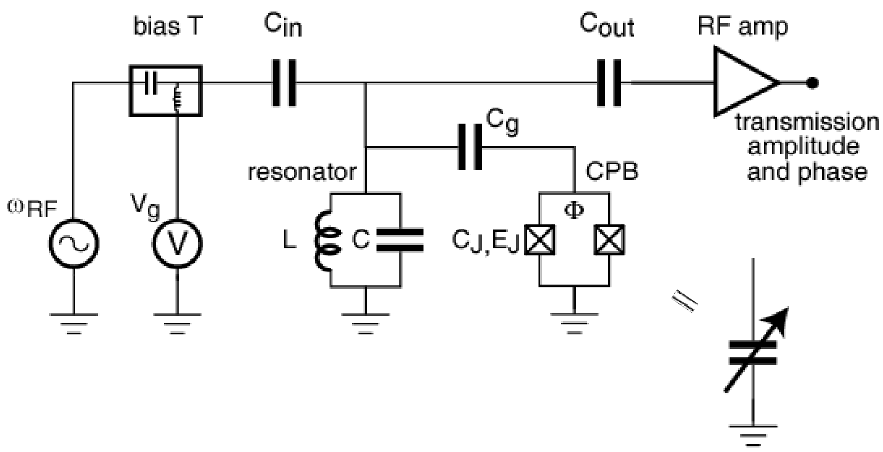
dispersive level diagram:





A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *PRA* **69,** 062320 (2004)

Measurement Technique

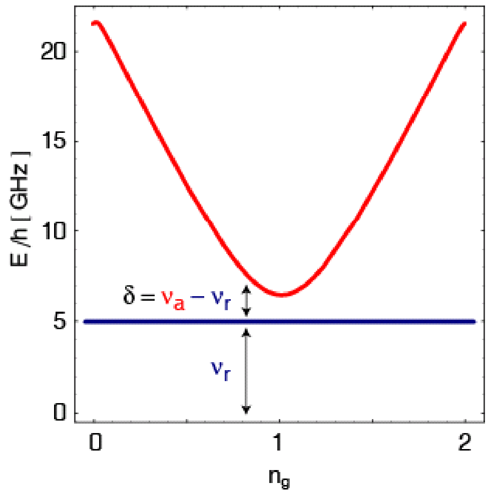


- measurement of microwave transmission amplitude T and phase ϕ
- intra-cavity photon number controllable from $n \sim 10^3$ to $n \ll 1$

Dispersive Shift of Resonance Frequency

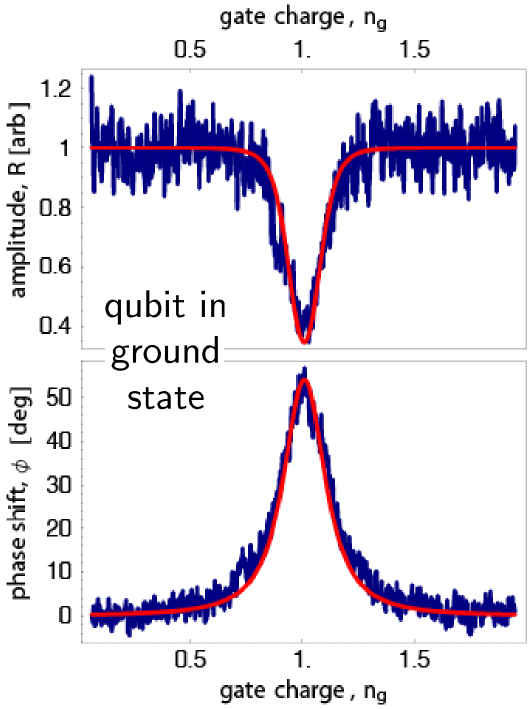
sketch of qubit level separation:

$$\Delta = 2\pi\delta > g$$



$$g/\pi = \nu_{\text{vac}} = 11\,\text{MHz}$$
$$\Delta(n_g = 1)/2\pi = 66\,\text{MHz}$$
$$n = 10$$

measured resonator transmission amplitude and phase:



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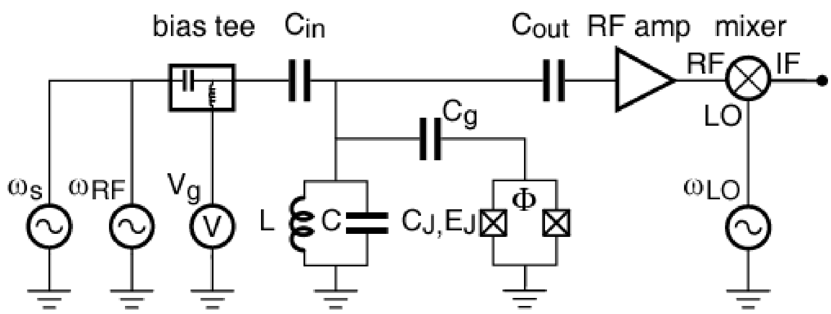
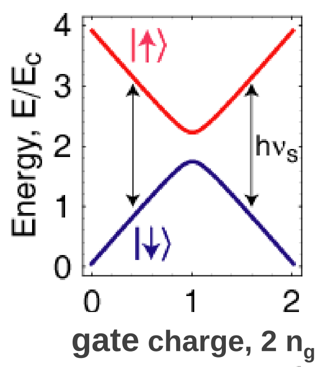
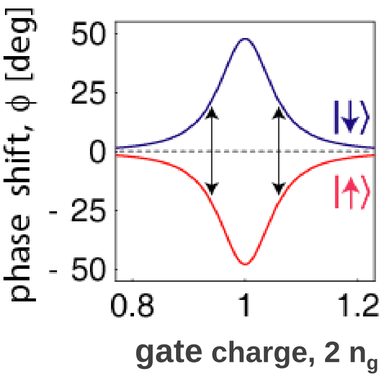
Realization of qubit spectroscopy







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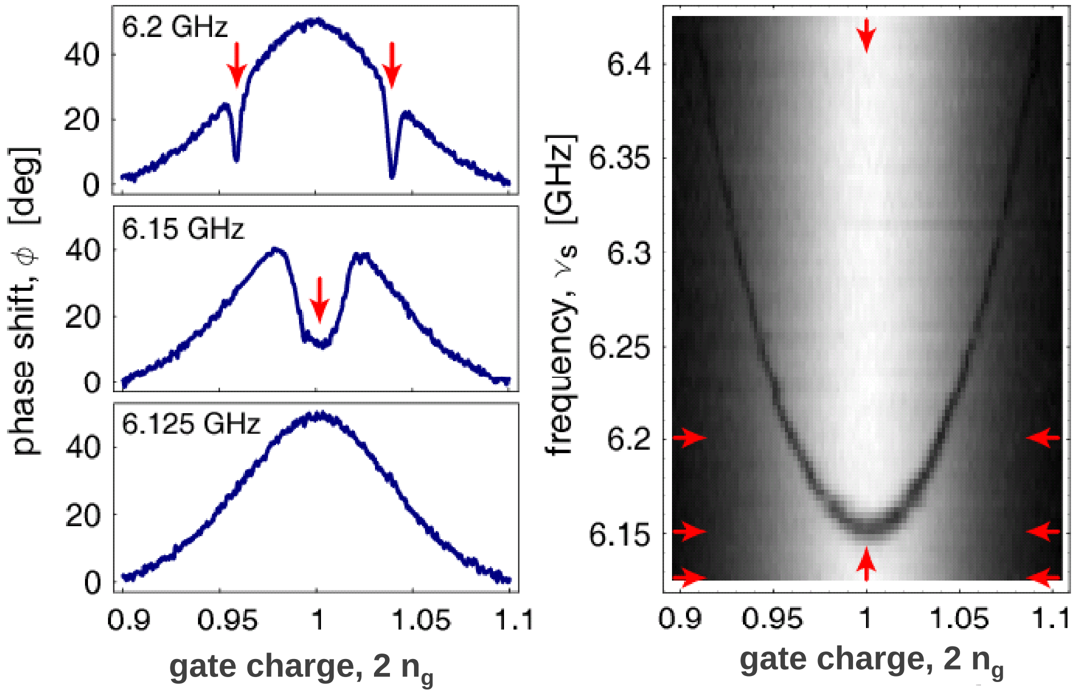
CW Spectroscopy of Cooper Pair Box



detuning $\Delta_{\mathrm{r,a}}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

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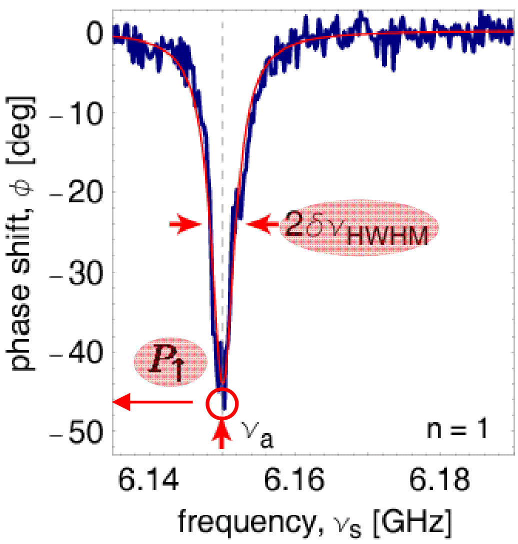
D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Shape

excited state population (steady-state Bloch equations):

$$P_\uparrow = 1 - P_\downarrow = \frac{1}{2}\frac{n_s \omega_{\mathrm{vac}}^2 T_1 T_2}{1 + (T_2 \Delta_{\mathrm{s,a}})^2 - n_s \omega_{\mathrm{vac}}^2 T_1 T_2}$$



- fixed drive $P_\mathrm{s} \propto n_\mathrm{s} \omega_{\mathrm{vac}}^2$
- varying $\Delta_{\mathrm{s,a}} = \omega_\mathrm{s} - \widetilde{\omega}_\mathrm{a}$
- weak continuous measurement $(n \sim 1)$
- at charge degenracy $(n_\mathrm{g} = 1)$

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Abragam, Oxford University Press (1961)