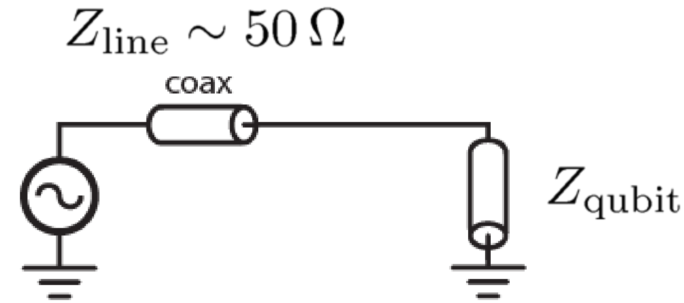
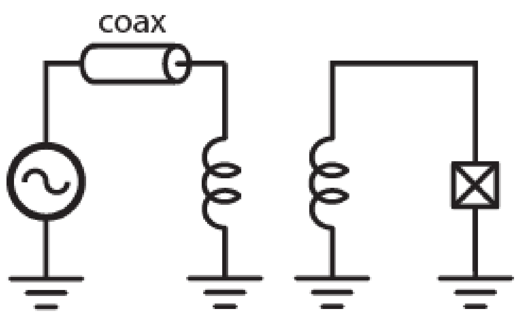
Controlling Coupling to the E.M. Environment

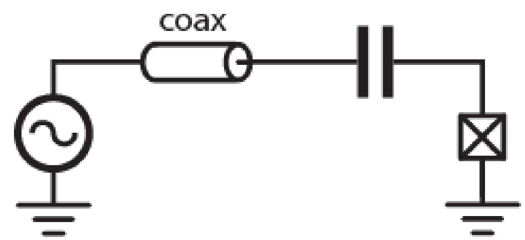
coupling to environment (bias wires):

decoherence
from energy relaxation
(spontaneous emission)

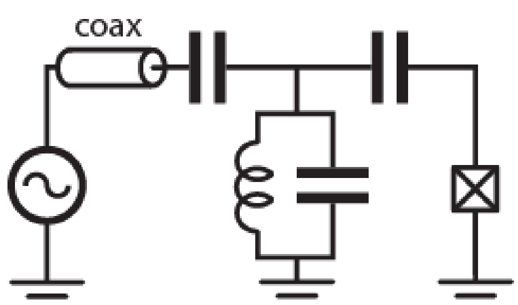


decoupling using non-resonant impedance transformers:





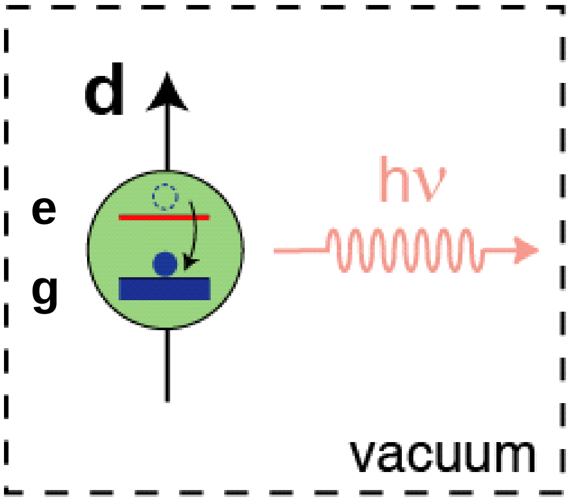
using resonant impedance transformers

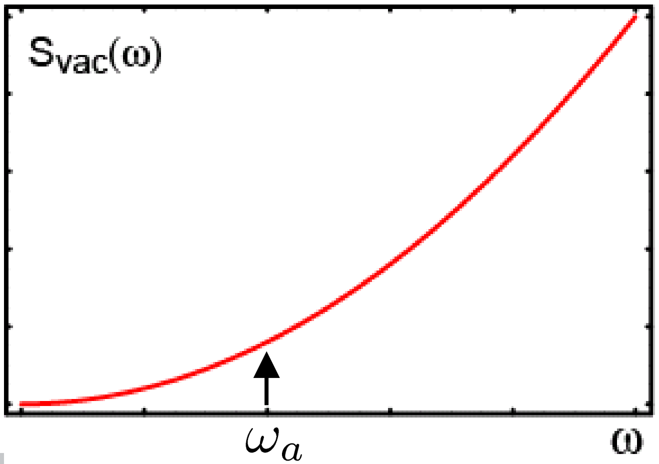


control spontaneous emission
by circuit design

Cavity QED with Electronic Circuits

Spontaneous Emission



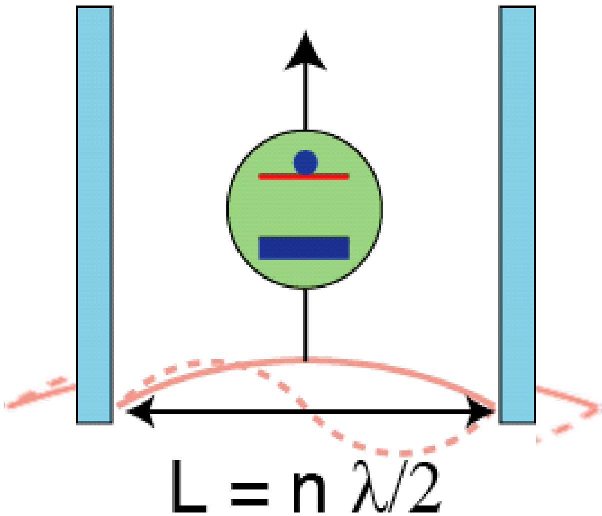


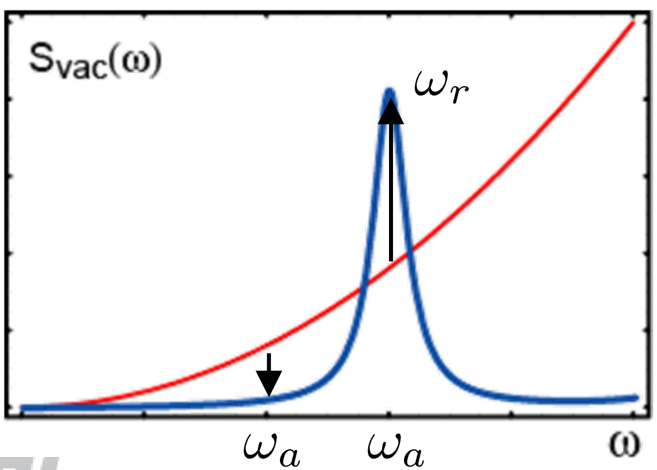
decay by dipole interaction with vacuum fluctuations

$$\gamma \sim \Omega^2 S_{\rm vac}(\omega_a)$$

Review: D. Kleppner and S. Haroche *Physics Today* **Jan.**, 24 (1989)

Suppression and Enhancement of Emission





engineering the vacuum

$$\gamma \sim \Omega^2 S_{\mathrm{vac}}(\omega_a)$$

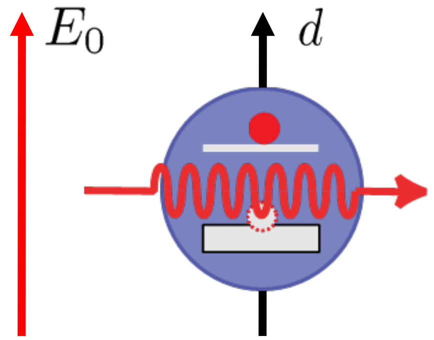
suppression of emission

enhancement of emission

Review: D. Kleppner and S. Haroche *Physics Today* **Jan.**, 24 (1989)

Free Atom

weak interaction with single photons:

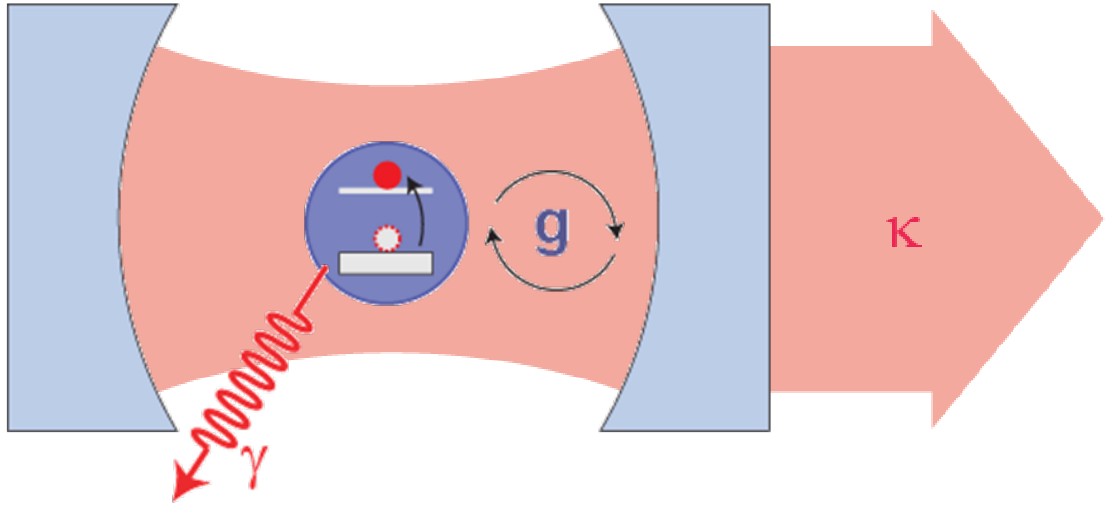


- dipole moment d (usually small in atoms ~ ea_o)
- single photon fields E_o (small in 3D)
- photon/atom interaction $\hbar g \sim dE_0$ (usually small)

[D. Walls, G. Milburn, Quantum Optics (Springer-Verlag, Berlin, 1994)]

Cavity Quantum Electrodynamics

coupling single photons to single qubits:



Jaynes-Cummings Hamiltonian

$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+) + H_\kappa + H_\gamma$$

strong coupling limit $(g = dE_0/\hbar > \gamma,\, \kappa\,,\, 1/t_{\text{transit}})$

D. Walls, G. Milburn, Quantum Optics (Spinger-Verlag, Berlin, 1994)

Dressed States Energy Level Diagram

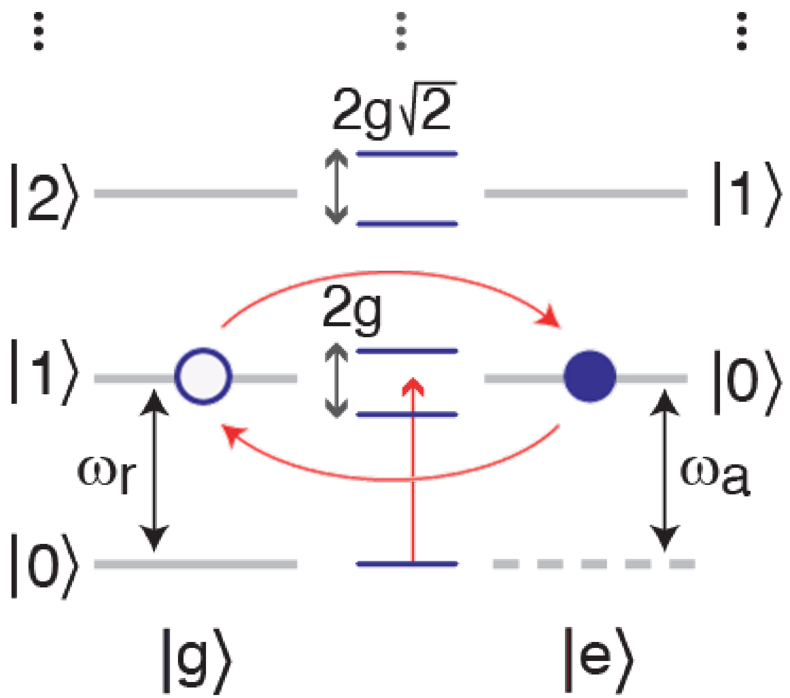
$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

in resonance:

$$\omega_a - \omega_r = \Delta = 0$$

strong coupling limit:

$$g = \frac{dE_0}{\hbar} > \gamma,\, \kappa$$



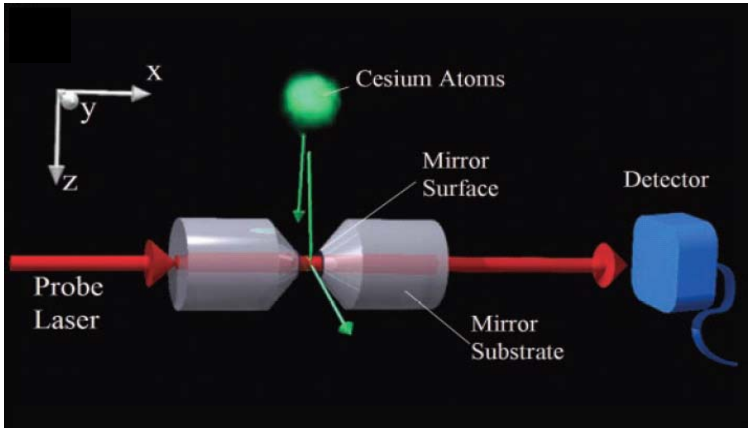
Jaynes-Cummings Ladder

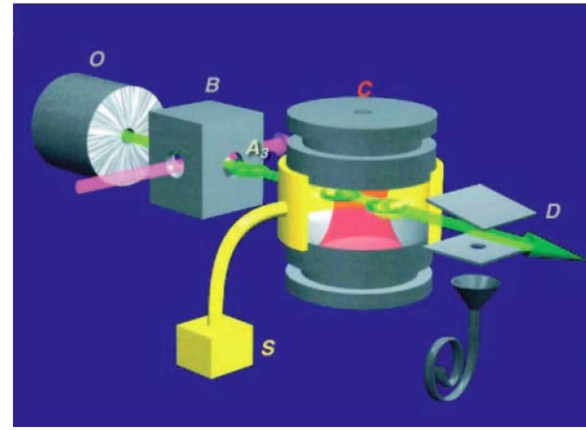
Atomic cavity quantum electrodynamics reviews:

J. Ye., H. J. Kimble, H. Katori, *Science* **320**, 1734 (2008)

S. Haroche & J. Raimond, Exploring the Quantum, *OUP Oxford* (2006)

Cavity Quantum Electrodynamics (QED)



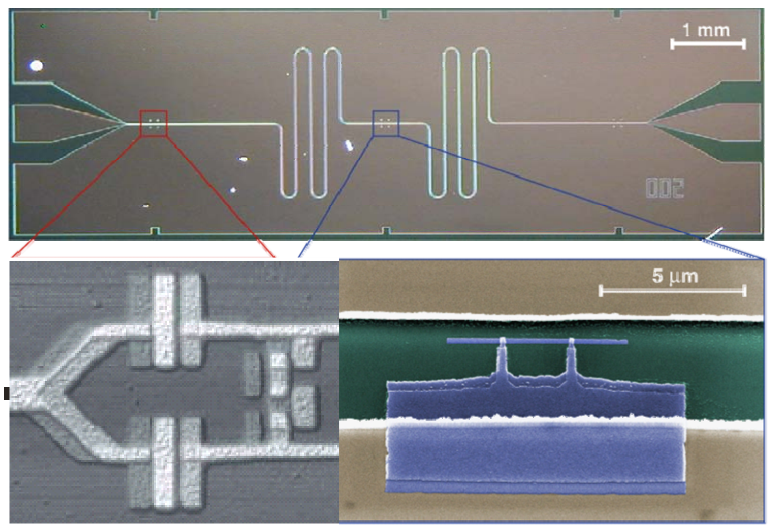


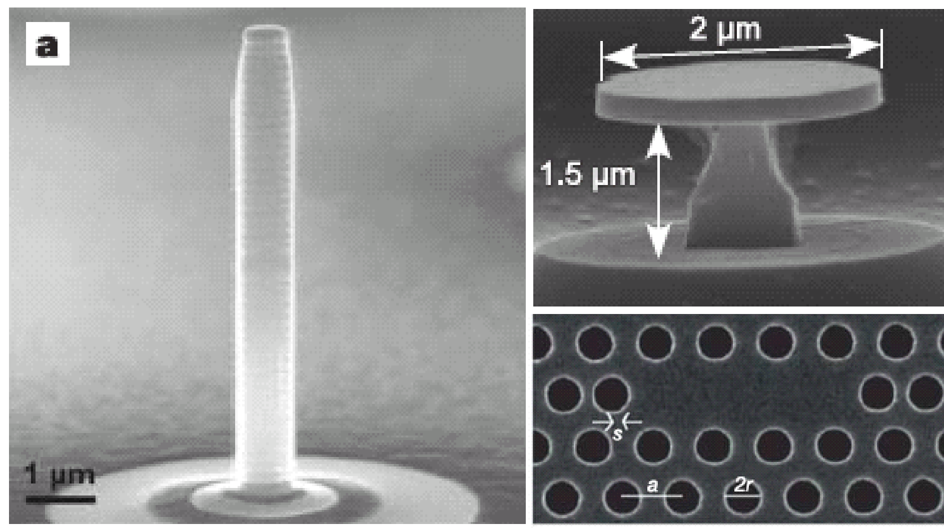
alkali atoms

MPQ, Caltech, ...

Rydberg atoms

ENS, MPQ, ...





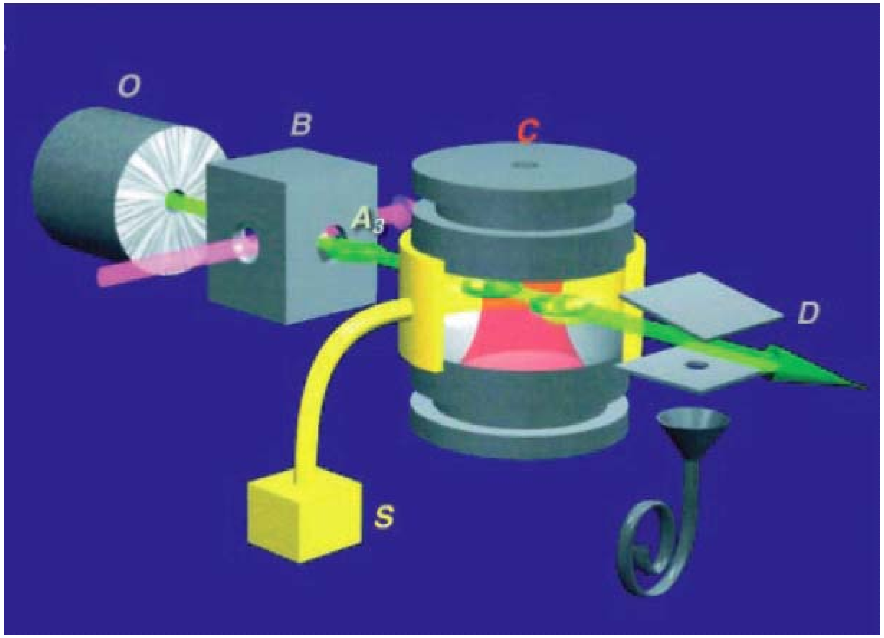
superconductor circuits

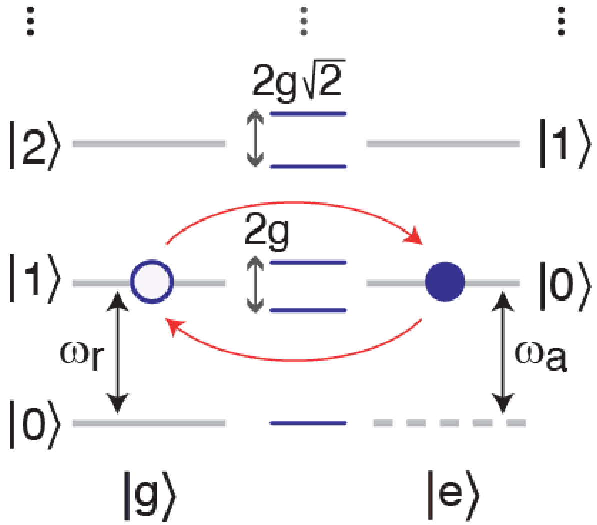
Yale, Delft, NTT, ETHZ, NIST, …

semiconductor quantum dots

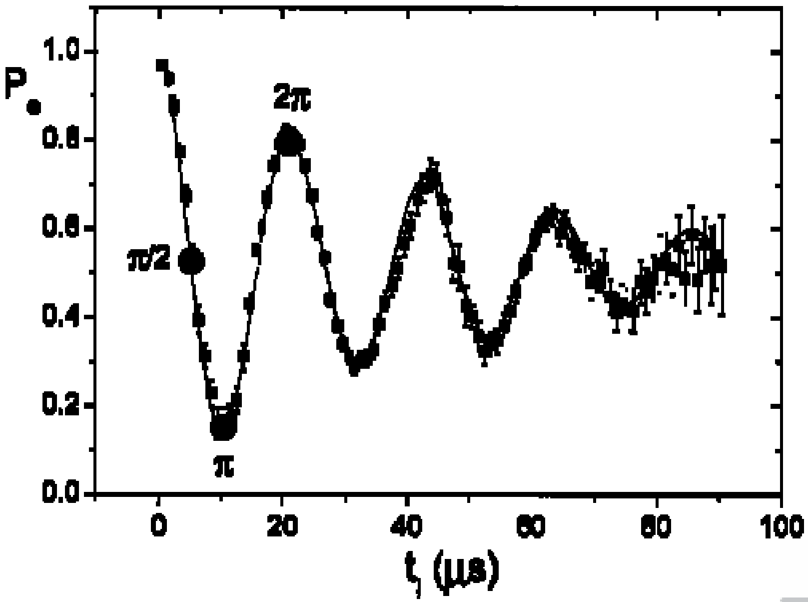
Wurzburg, ETHZ, Stanford …

Vacuum Rabi Oscillations with Rydberg Atoms

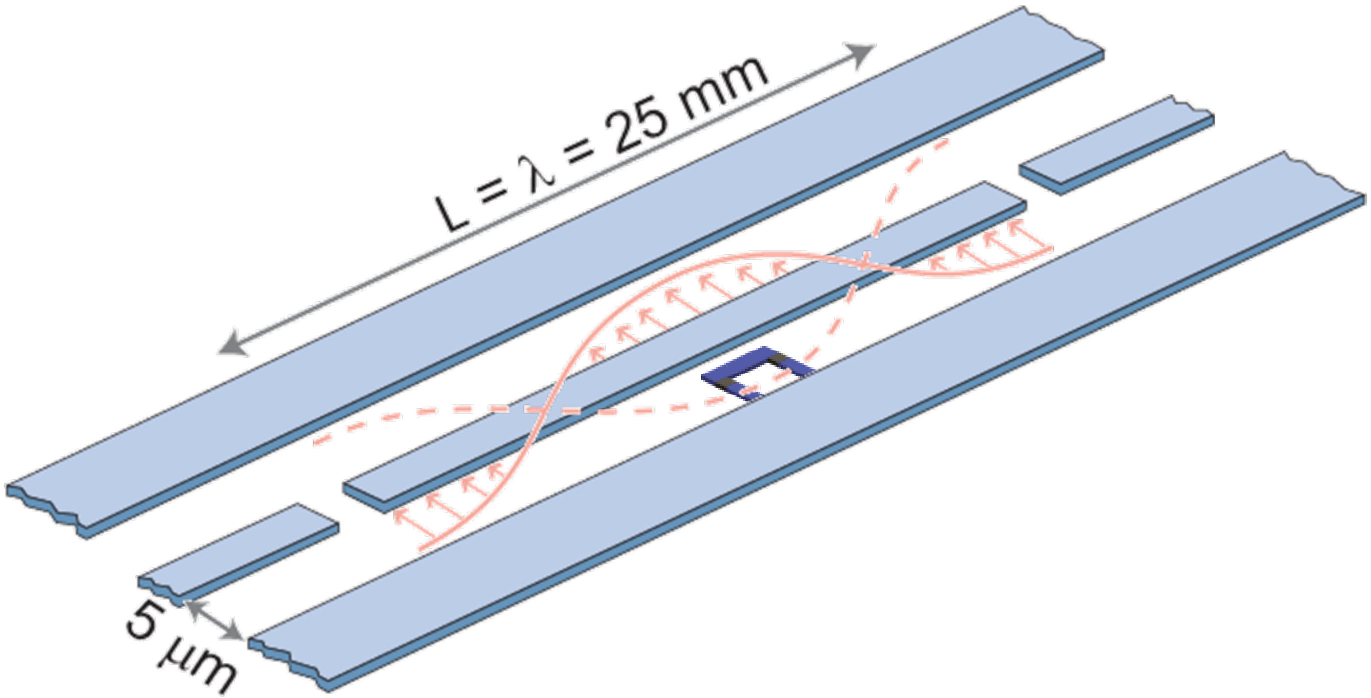




Review: J. M. Raimond, M. Brune, and S. Haroche
Rev. Mod. Phys. **73**, 565 (2001)
P. Hyafil, ..., J. M. Raimond, and S. Haroche,
Phys. Rev. Lett. **93**, 103001 (2004)



Circuit Quantum Electrodynamics

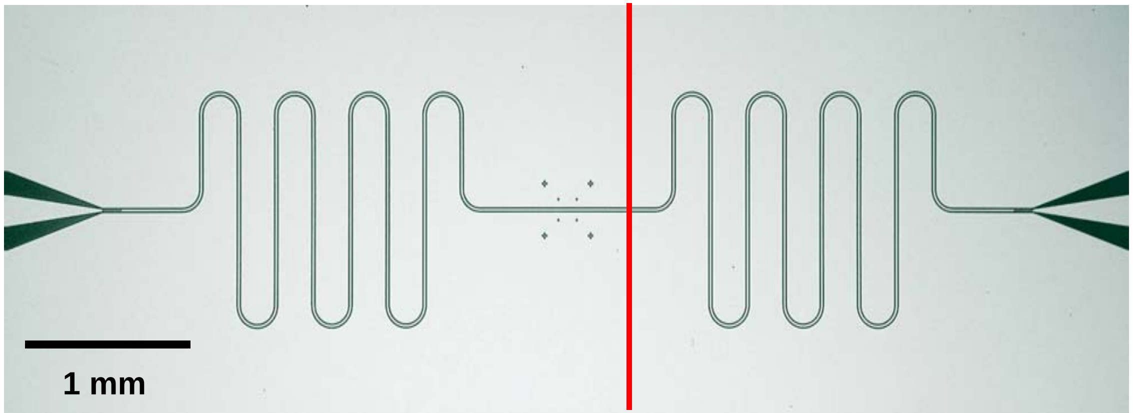


elements

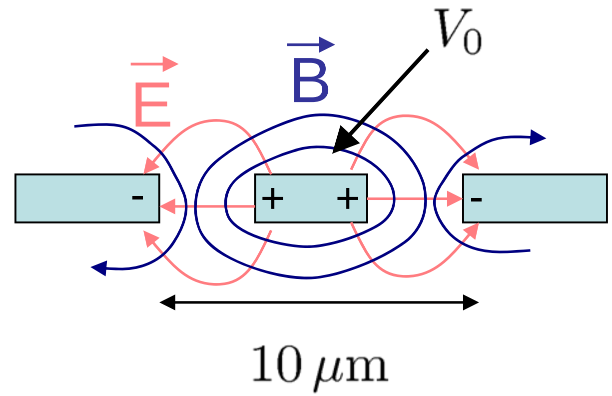
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box with large dipole moment *d* and long coherence time $1/\gamma$

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

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

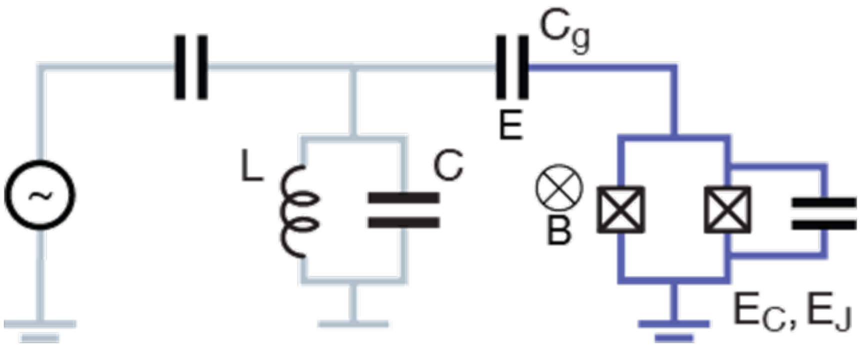
$$H_r = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$$

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

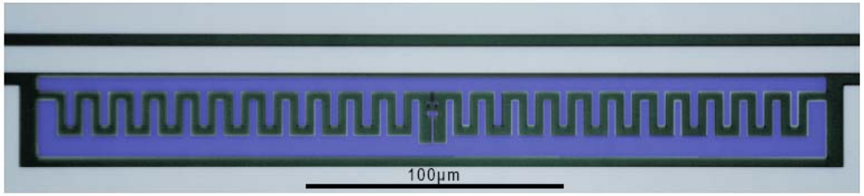
10^3 larger than in 3D cavity

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

Qubit/Photon Coupling in a Circuit



qubit coupled to resonator



coupling strength:

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

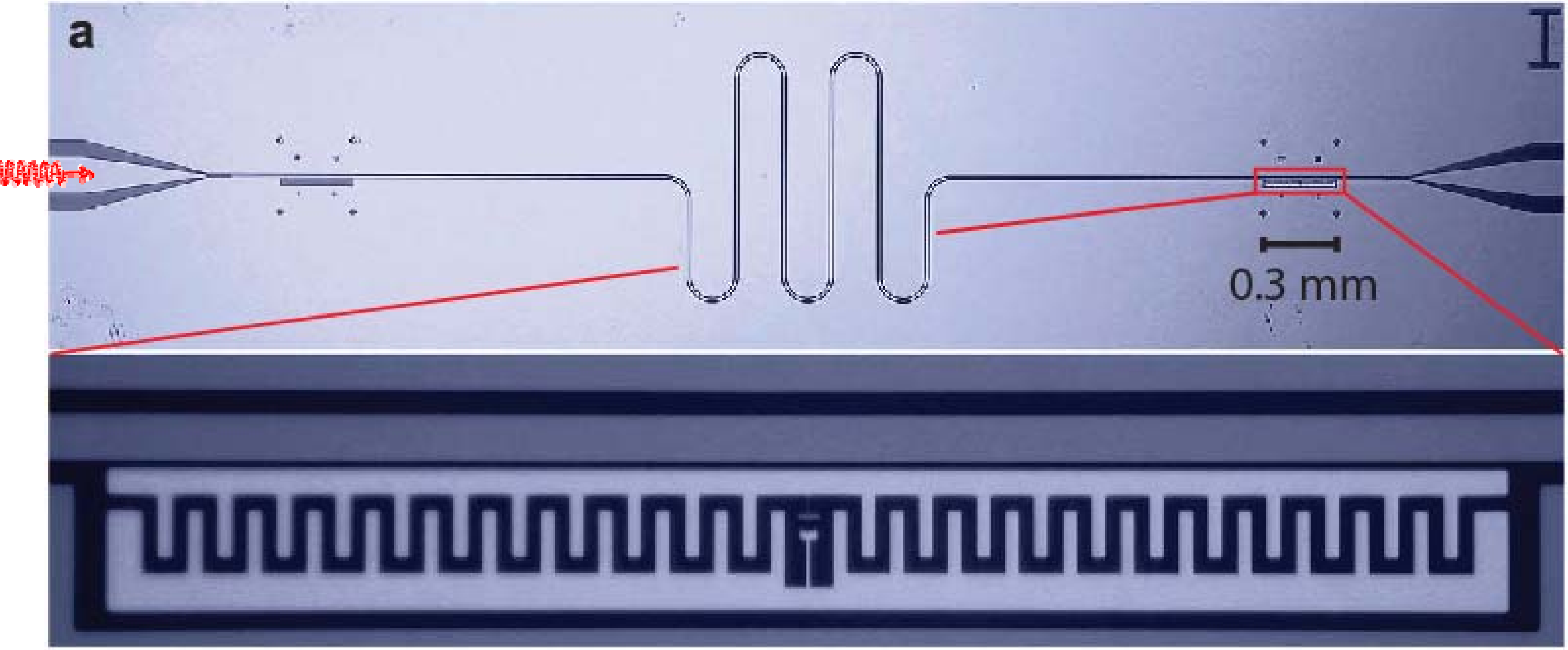
$$\Longrightarrow \nu_{\mathrm{vac}} = \frac{g}{\pi} \approx 1 \ldots 300\,\mathrm{MHz}$$

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

large effective dipole moment

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

Circuit QED with One Photon

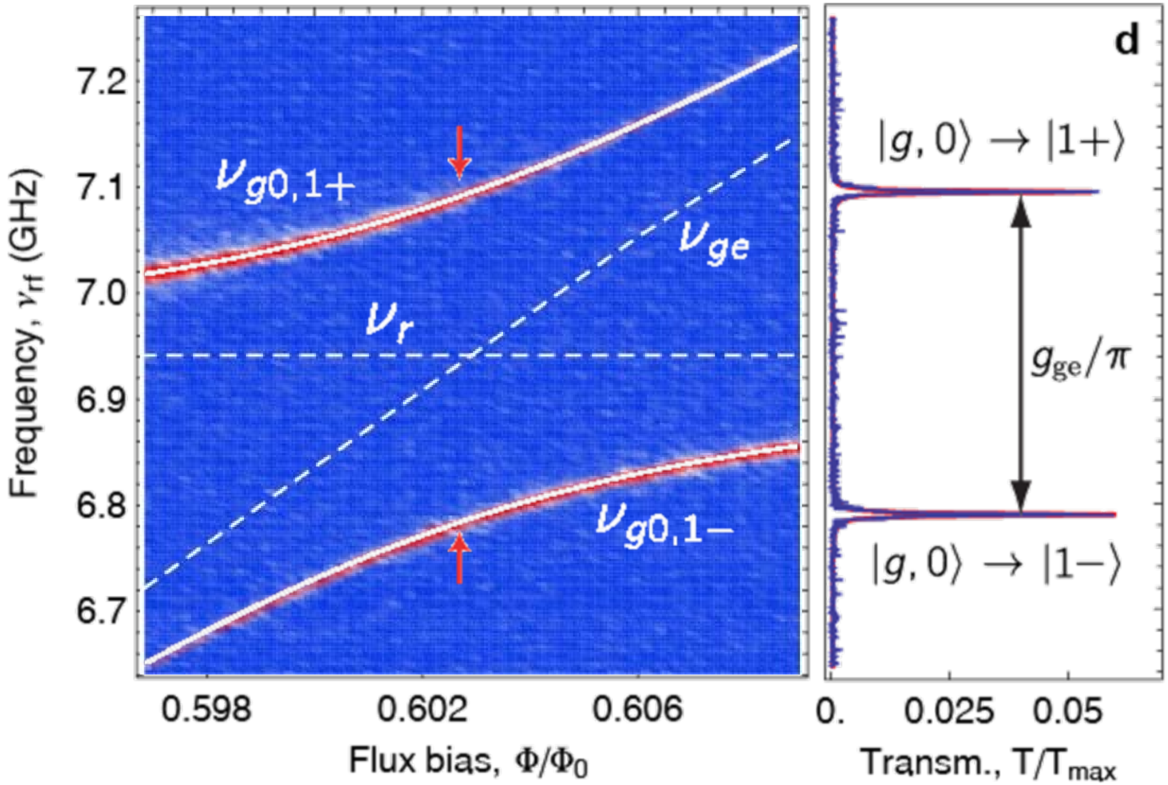


superconducting cavity QED circuit

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

Resonant Vacuum Rabi Mode Splitting …

… with one photon ($n = 1$):

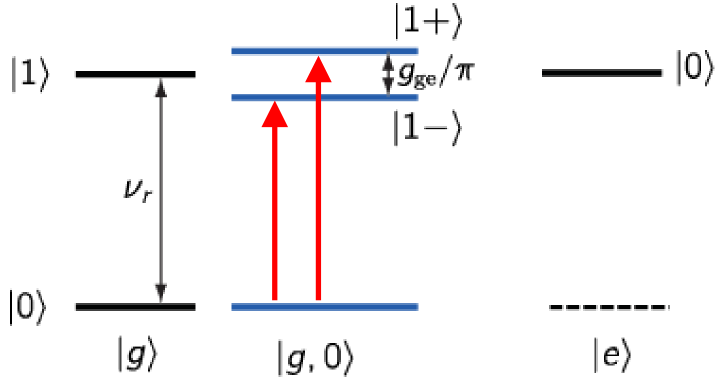


very strong coupling:

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

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

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



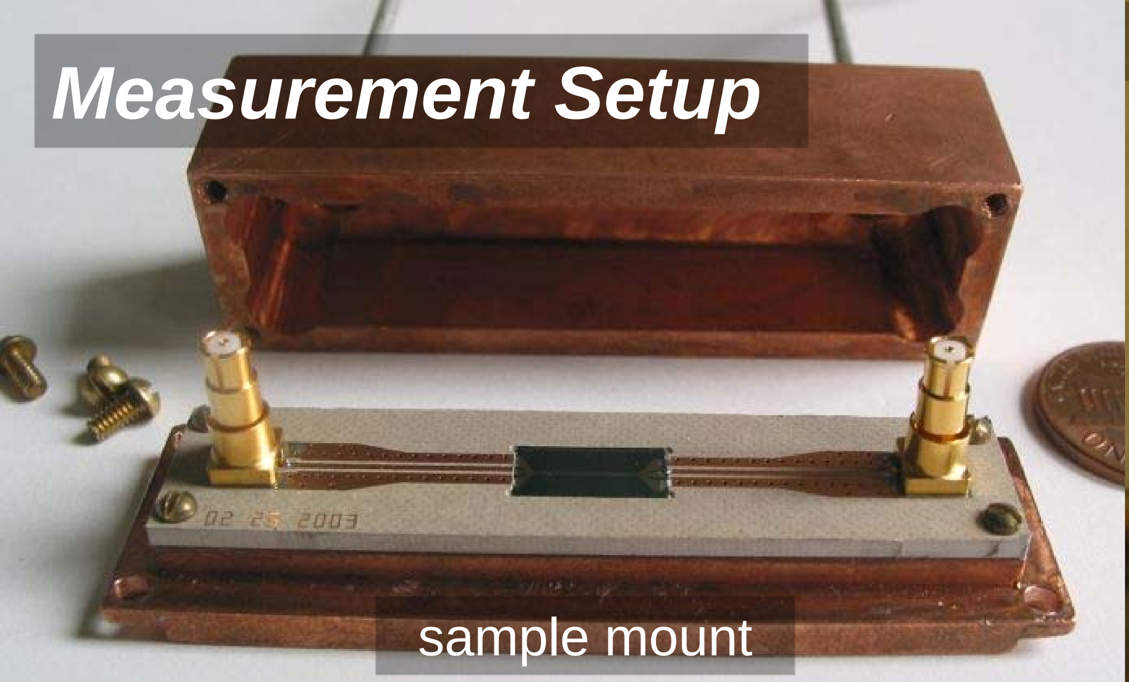
forming a 'molecule' of a qubit and a photon

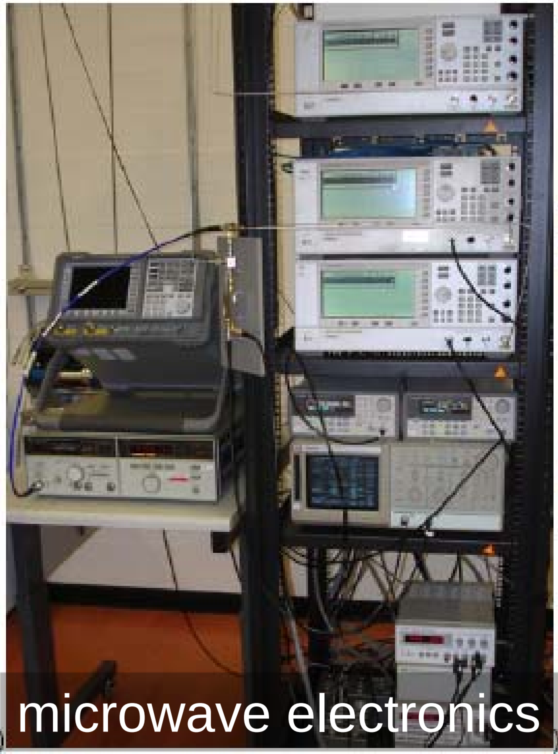
$$|1\pm\rangle = (|g,1\rangle \pm |e,0\rangle)\,/\sqrt{2}$$

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

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

Measurement Setup

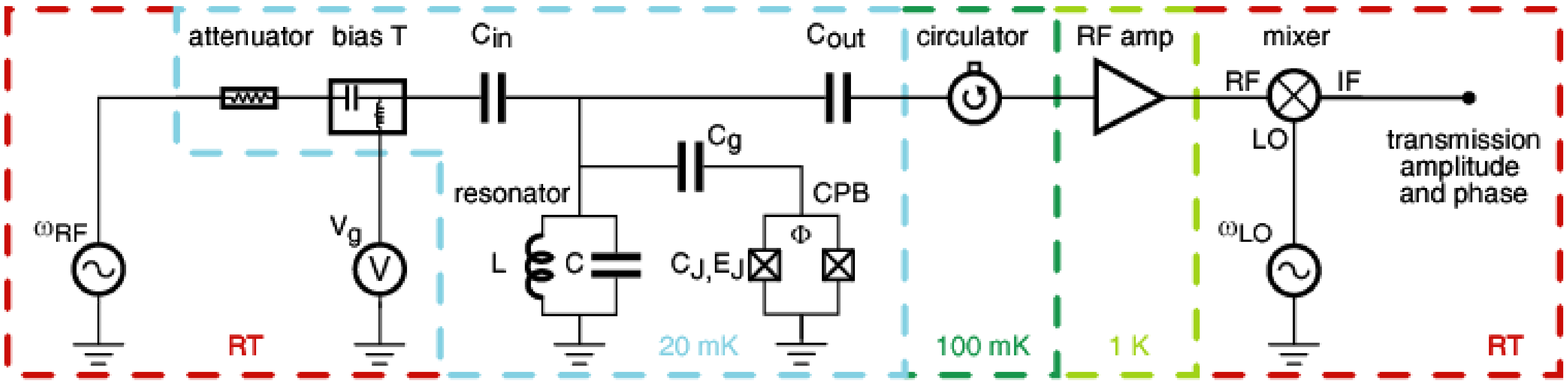




How to Measure Single Microwave Photons

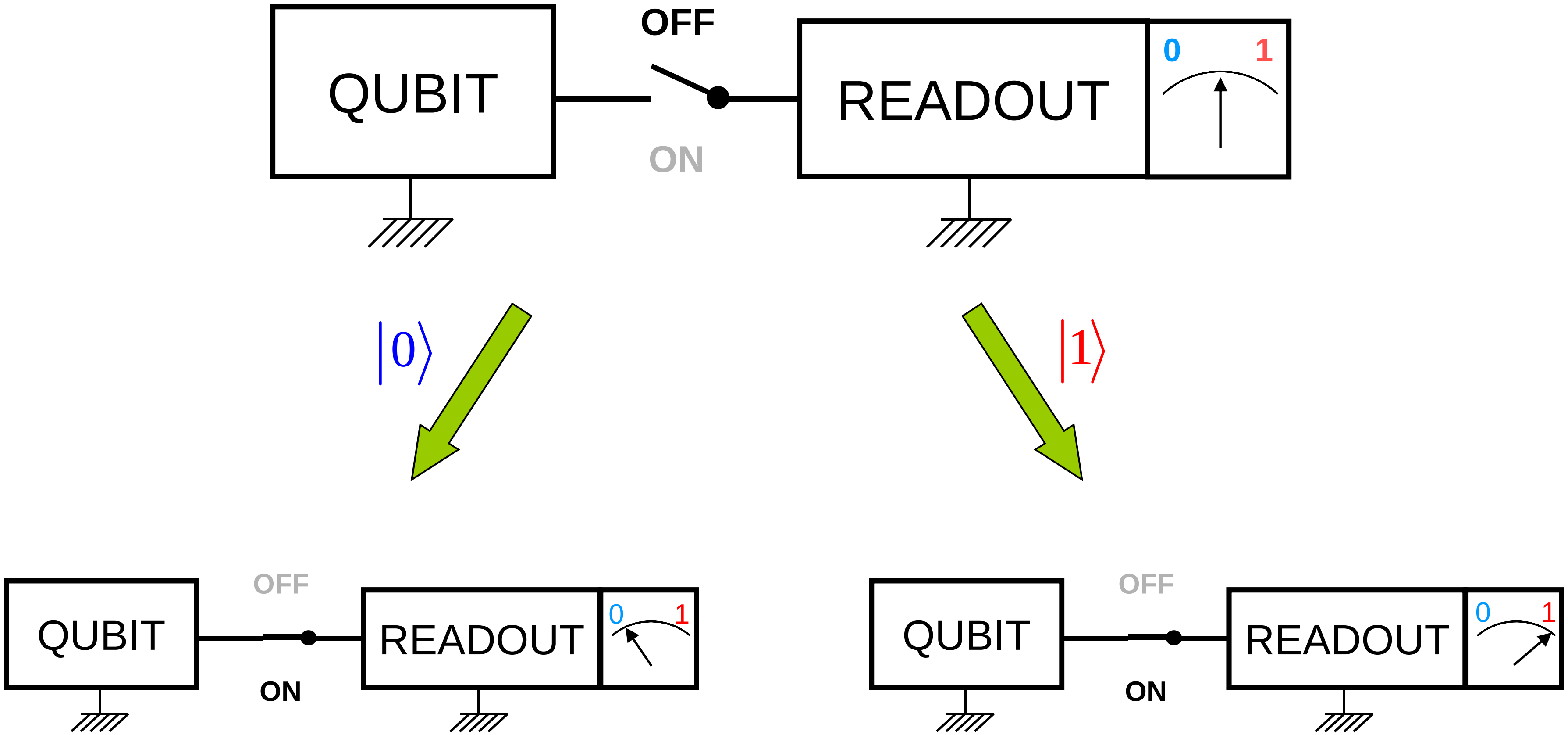
- average power to be detected

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



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

Qubit Read Out



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

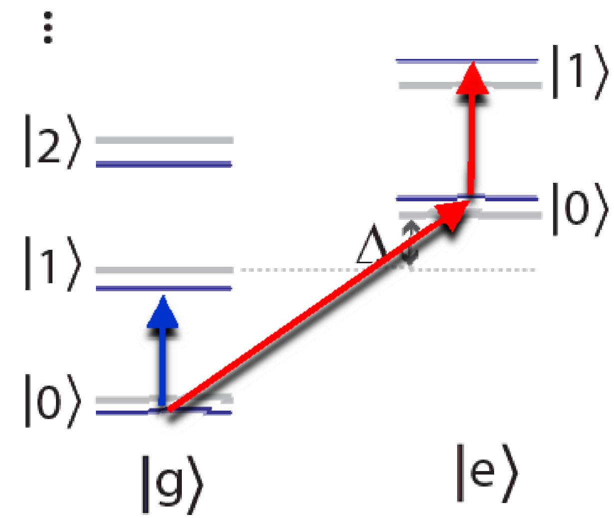
Non-Resonant (Dispersive) Interaction

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

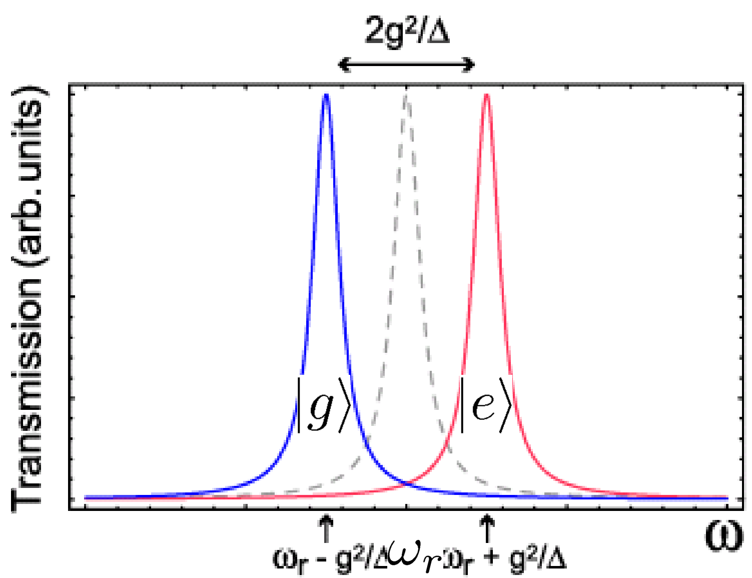
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{\hbar}{2}\left(\omega_a + \frac{g^2}{\Delta}\right)\sigma_z$$

cavity frequency shift
and qubit ac-Stark shift

Lamb Shift



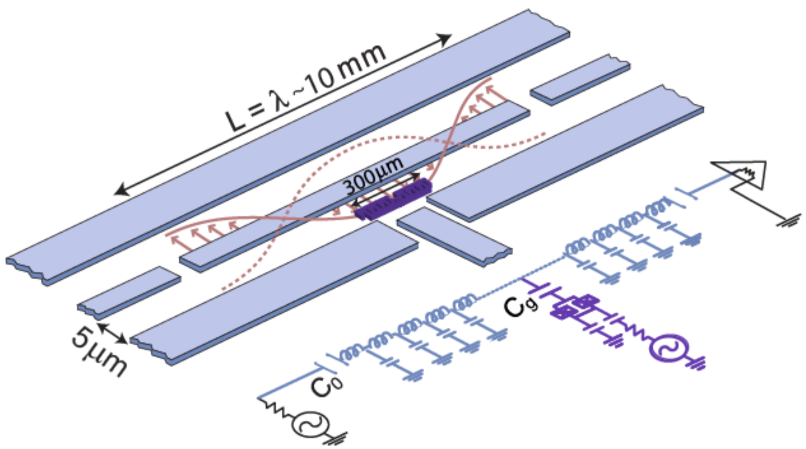
qubit detuned by Δ
from resonaator



A. Blais *et al., PRA* 69, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* 431, 162 (2004)
D. I. Schuster *et al., Phys. Rev. Lett.* 94, 123062 (2005)
A. Fragner *et al., Science* 322, 1357 (2008)

Circuit QED – read out of qubit state

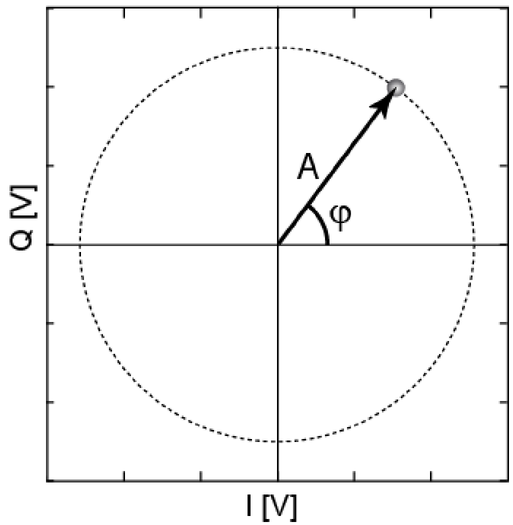
- transmission measurement to determine qubit state:



Phase sensitive measurement of transmitted microwave:

Voltage signal:

$$A(t)\sin(\omega_m t + \phi(t)) \equiv I(t)\sin\omega_m t + Q(t)\cos\omega_m t$$



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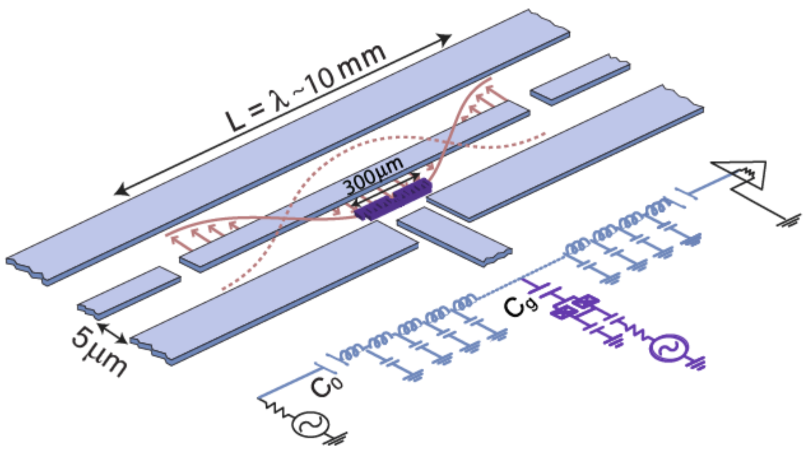
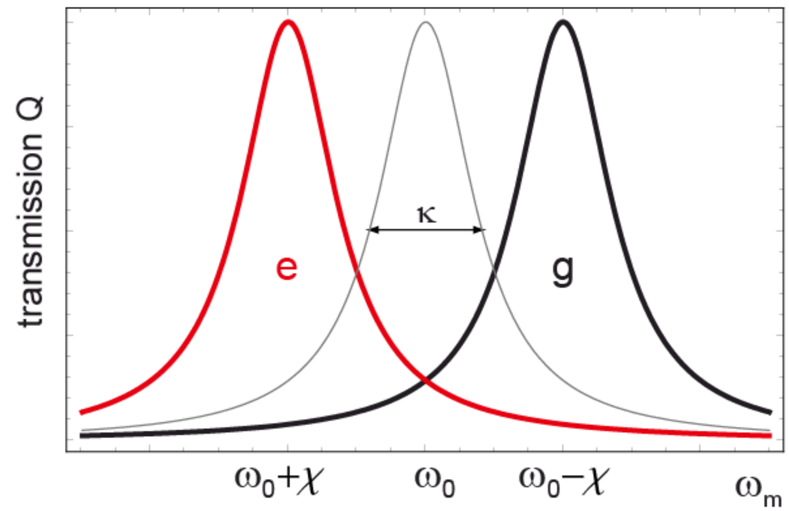




qubit far from resonance ($\Delta_{ar} = |\omega_a - \omega_r| \gg g$) – dispersive Hamiltonian:

$$H = \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar}{2}(\omega_a + \chi)\sigma_z$$

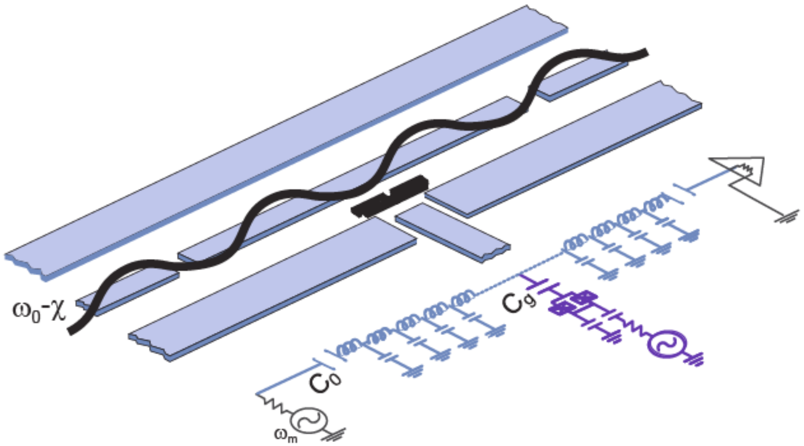
[Blais *et al.*, PRA 69 (2004)]

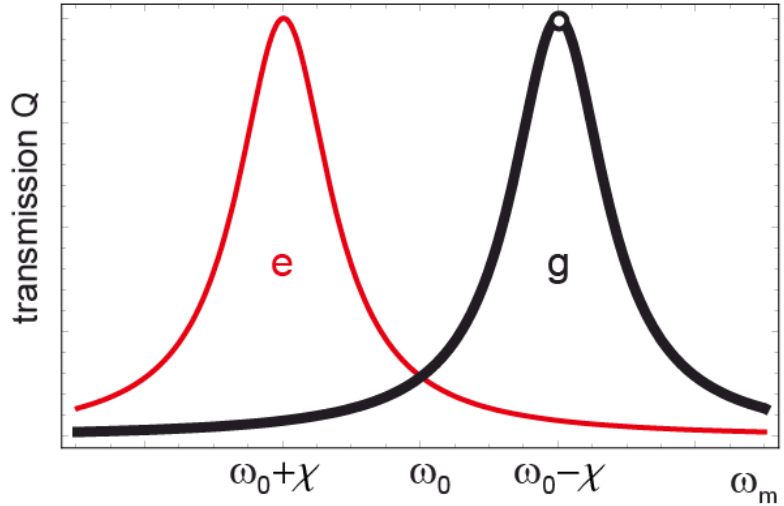
state-dependent frequency shift

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Circuit QED – read out of qubit state

- transmission measurement to determine qubit state:





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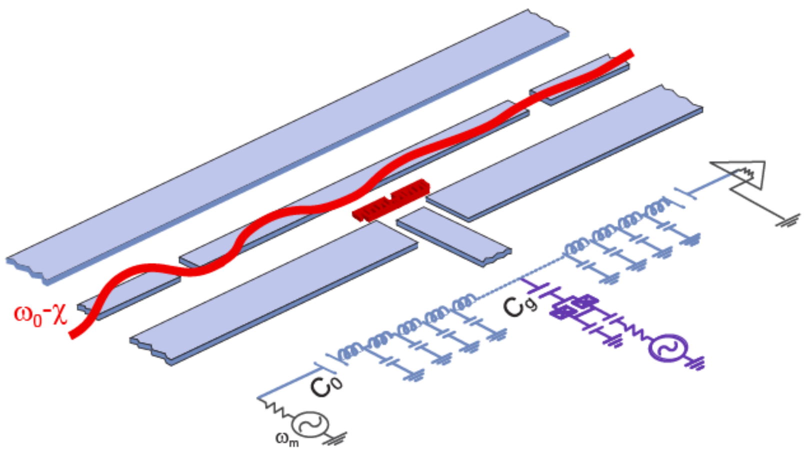
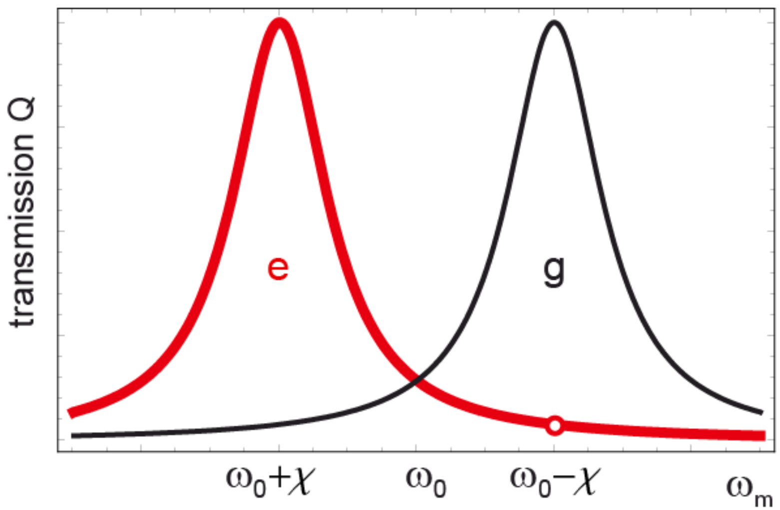
[Blais *et al.*, PRA 69 (2004)]

state-dependent frequency shift

Circuit QED – read out of qubit state

- transmission measurement to determine qubit state:





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$$H = \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar}{2}(\omega_a + \chi)\sigma_z$$

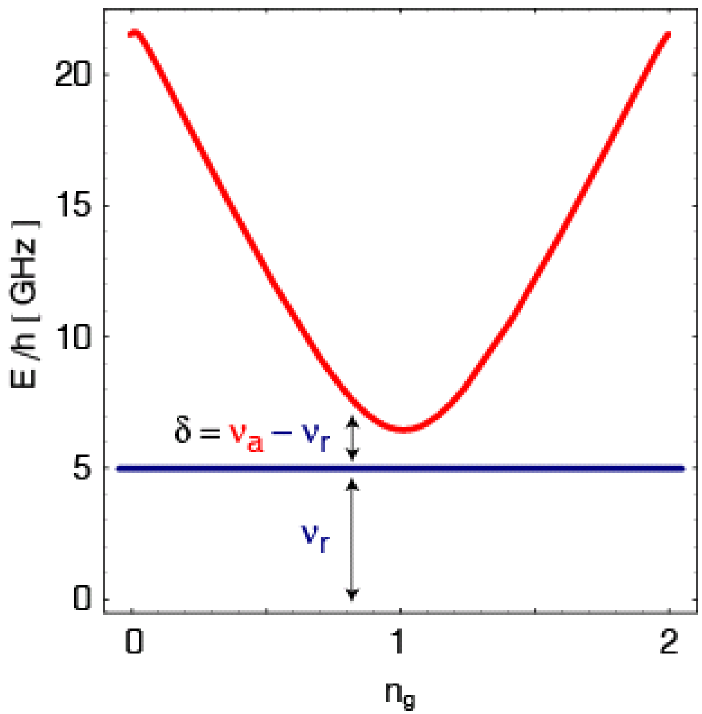
[Blais *et al.*, PRA 69 (2004)]

state-dependent frequency shift -> σ_z determined

Dispersive Shift of Resonance Frequency

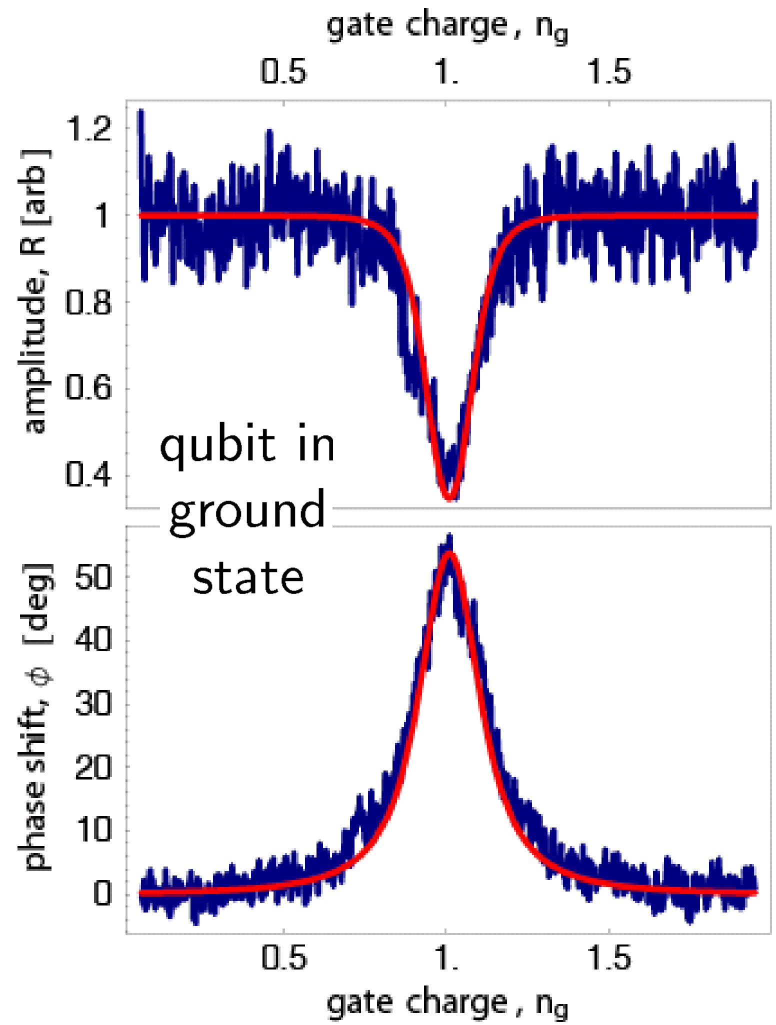
sketch of qubit level separation:

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



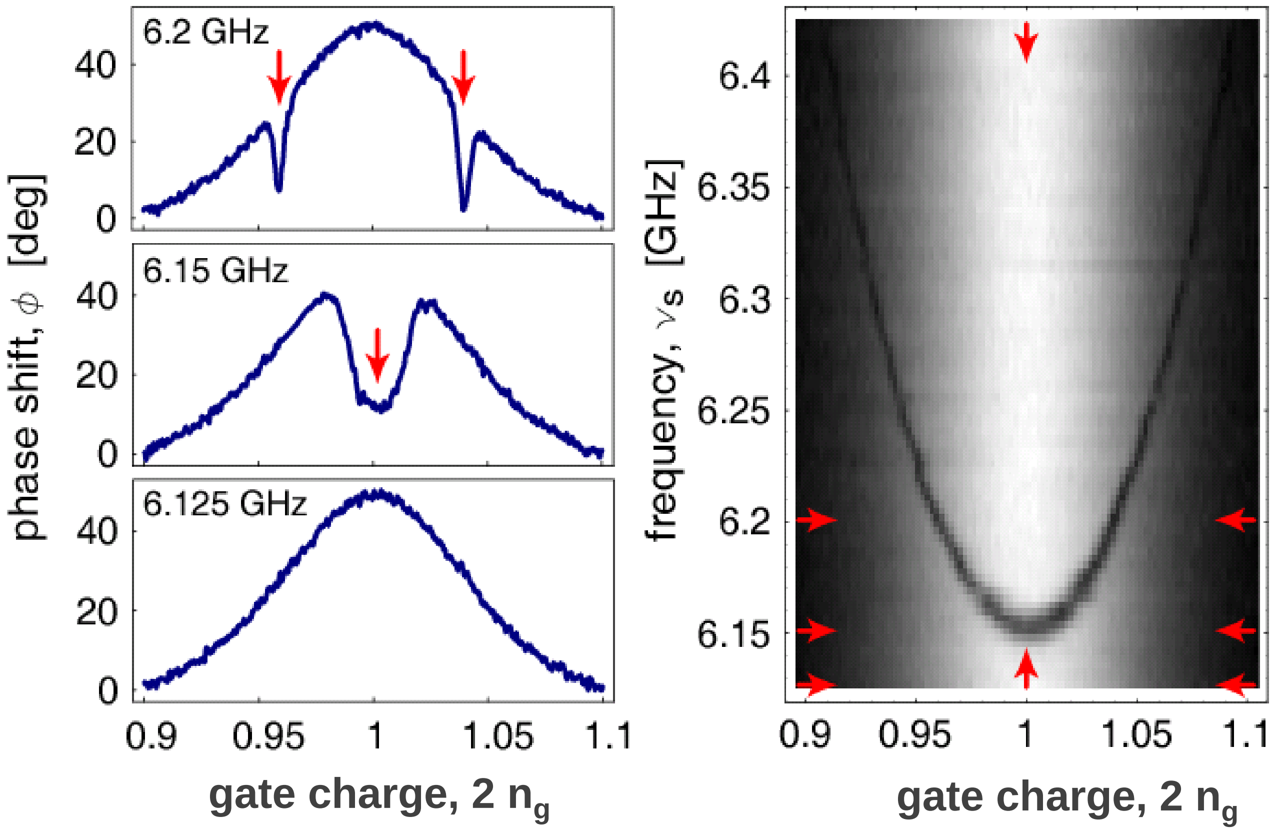
$$\begin{aligned} g/\pi = \nu_{\text{vac}} &= 11\,\text{MHz} \\ \Delta(n_g = 1)/2\pi &= 66\,\text{MHz} \\ n &= 10 \end{aligned}$$

measured resonator transmission amplitude and phase:



CW Spectroscopy of Cooper Pair Box

drive qubit transition at frequency ν_s



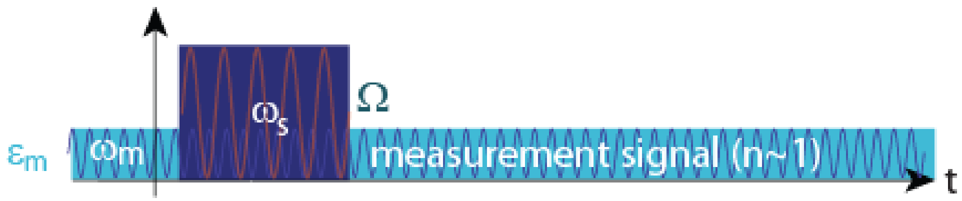
detuning $\Delta_{r,a}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

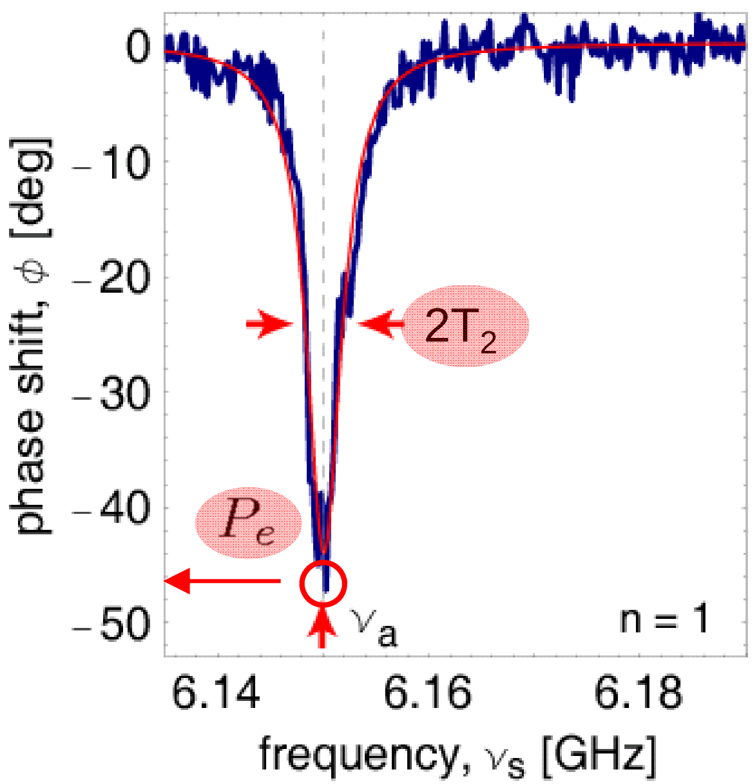
D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Shape

excited state population (steady-state Bloch equations):

equilibrium between emission and absorption processes





$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega^2 T_1 T_2}{1 + (T_2 \Delta_{s,a})^2 + \Omega^2 T_1 T_2}$$

- drive strength Ω
- varying $\Delta_{s,a} = \omega_s - \widetilde{\omega}_a$
- weak continuous measurement (approx. 1 photon in resonator)

[Abragam, Oxford University Press (1961)]