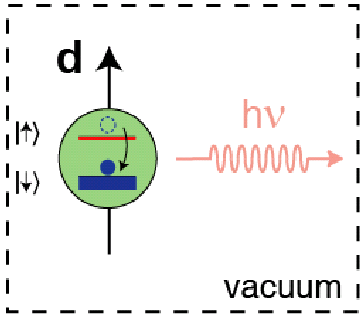
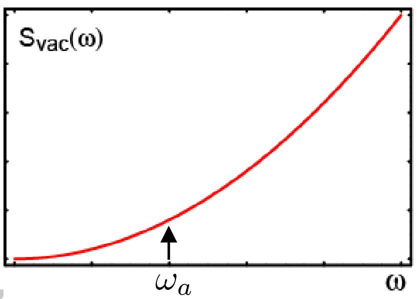
Spontaneous Emission



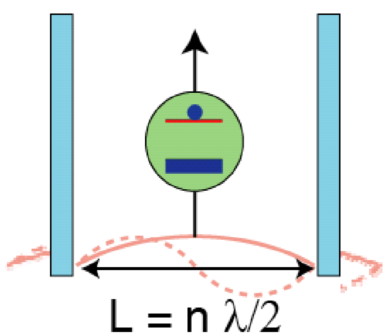


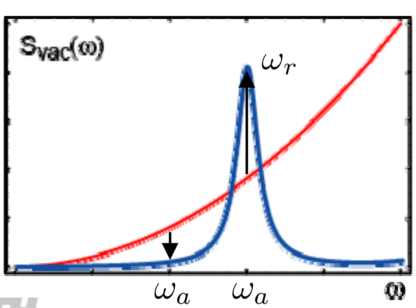
decay by dipole interaction with vacuum fluctuations

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

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

Suppression and Enhancement of Emission





engineering the vacuum

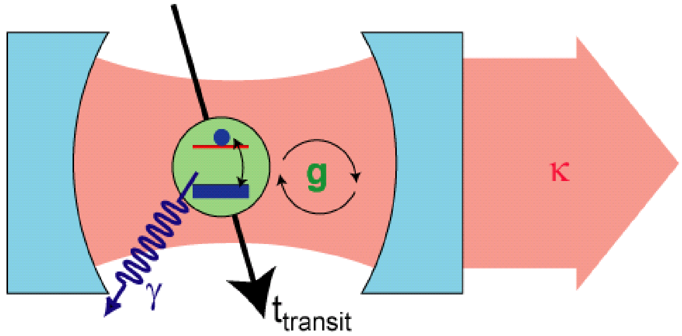
$$\gamma \sim \Omega^2 S_{\rm vac}(\omega_a)$$

suppression of emission

enhancement of emission

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

Photons: Cavity Quantum Electrodynamics



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 $(g = dE_0/\hbar > \gamma,\ \kappa\,, 1/t_{\mathrm{transit}})$

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

Dressed States Energy Level Diagram

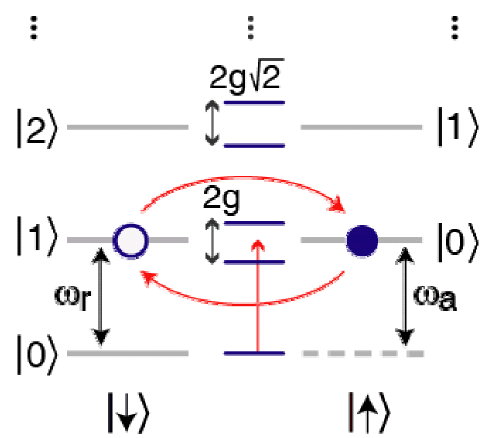
$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2} \right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger \sigma^- + a\sigma^+)$$

in resonance:

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

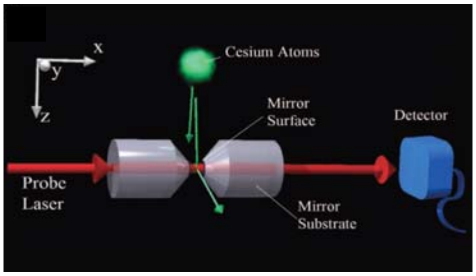
strong coupling limit:

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

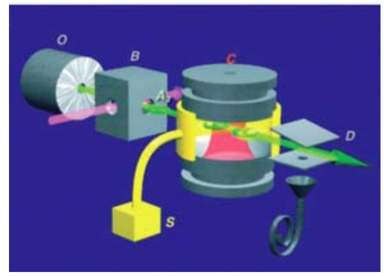


Atomic cavity quantum electrodynamics reviews:
H. Mabuchi, A. C. Doherty *Science* **298**, 1372 (2002)
J. M. Raimond, M. Brune, & S. Haroche *Rev. Mod. Phys.* **73**, 565 (2001)

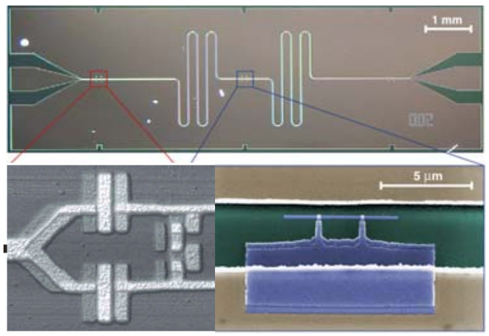
Cavity Quantum Electrodynamics (QED)



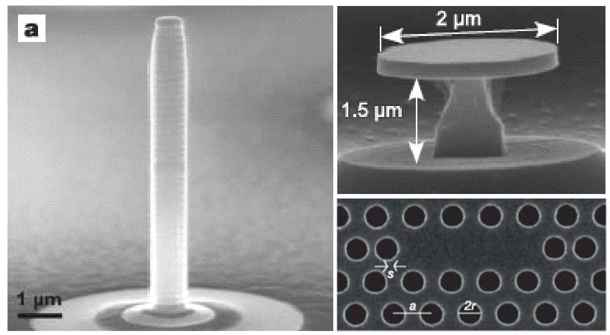
alkali atoms
MPQ, Caltech, ...



Rydberg atoms
ENS, MPQ, ...

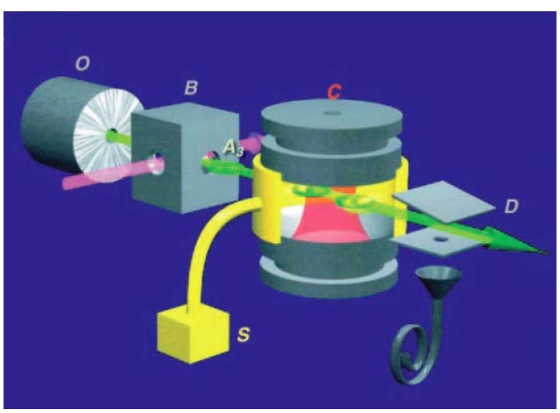


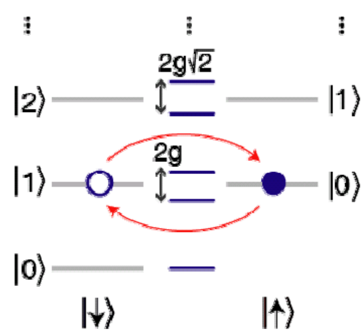
superconductor circuits
Yale, Delft, NTT, ETHZ, NIST, …

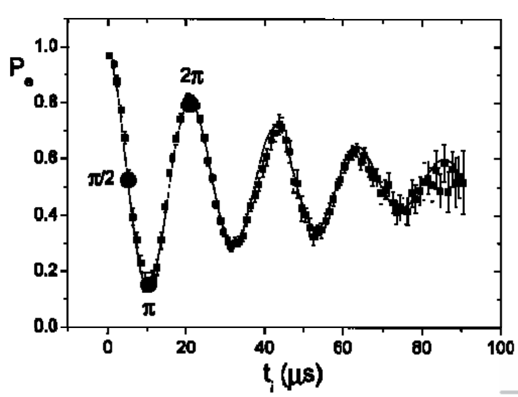


semiconductor quantum dots
Wurzburg, ETHZ, Stanford …

Vacuum Rabi Oscillations with Rydberg Atoms

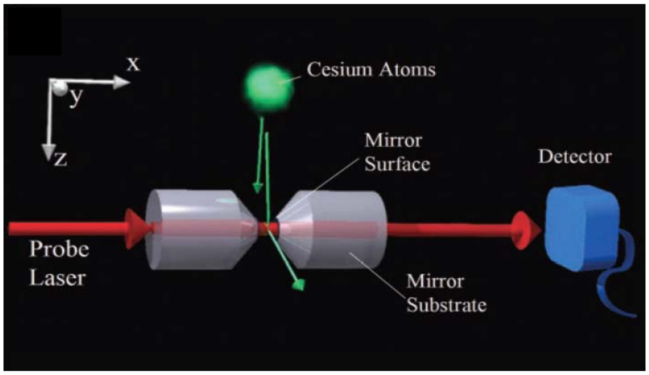


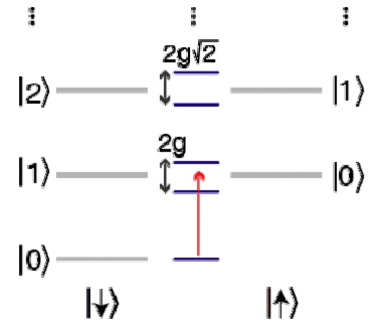




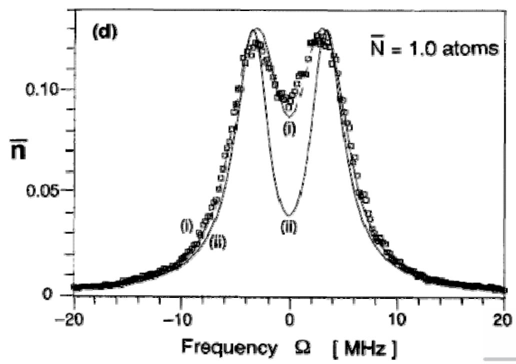
Review: J. M. Raimond, M. Brune, and S. Haroche
Rev. Mod. Phys. **73**, 565 (2001)
P. Hyafil, ..., J. M. Raimond, and S. Haroche,
Phys. Rev. Lett. **93**, 103001 (2004)

Vacuum Rabi Mode Splitting with Alkali Atoms

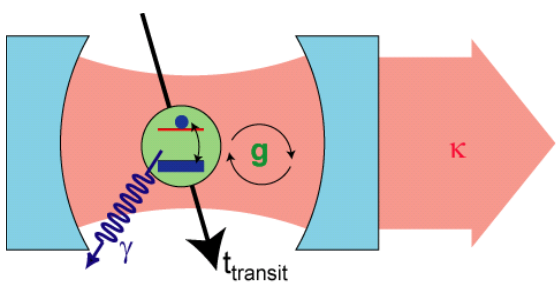




R. J. Thompson, G. Rempe, & H. J. Kimble,
Phys. Rev. Lett. **68** 1132 (1992)
A. Boca, ... , J. McKeever, & H. J. Kimble
Phys. Rev. Lett. **93**, 233603 (2004)



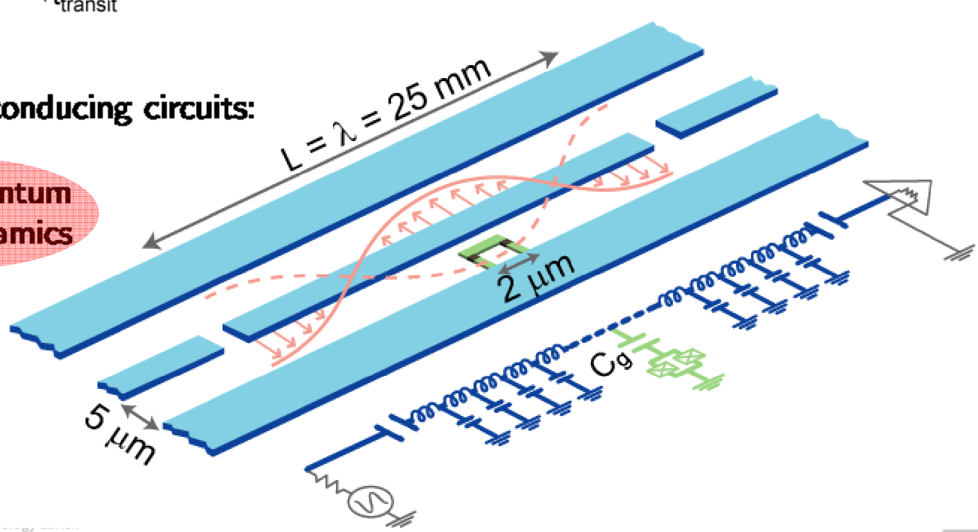
Photons and Qubits



cavity quantum electrodynamics:
coherent quantum mechanics
with individual photons and qubits ...

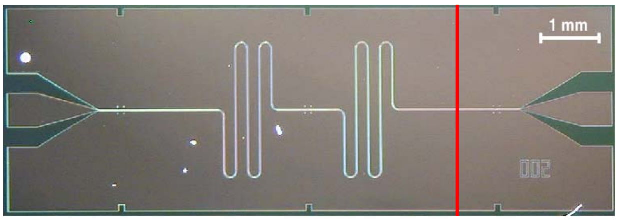
... in superconducing circuits:

circuit quantum electrodynamics

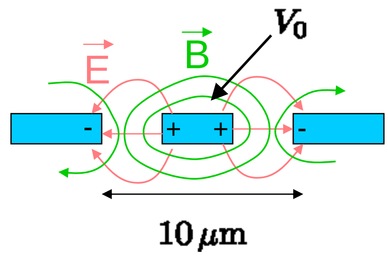


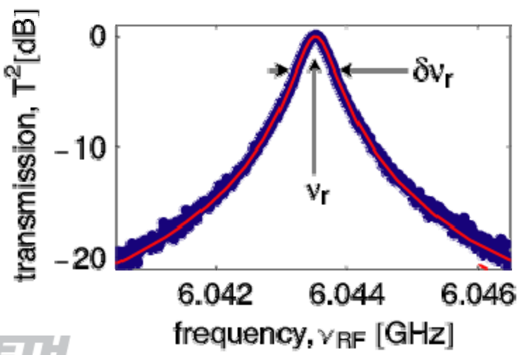
Large Single Photon Fields and Lifetimes

transmission line resonator:



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





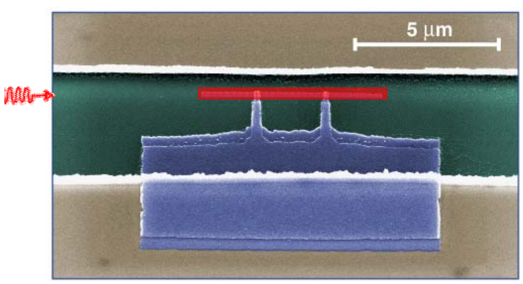
electric field strength per photon

$$E_0 \approx 0.2\,\mathrm{V/m}$$

quality factor: $Q \sim 10^4 - 10^6$

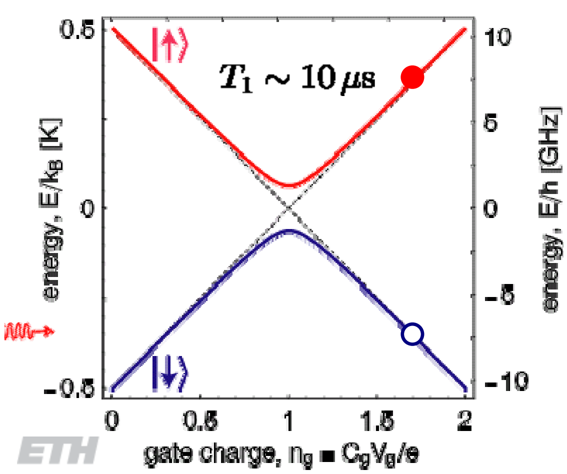
photon lifetime: $T_\kappa \approx 100\,\mathrm{ns} - 10\,\mu s$

Superconducting Qubit with Large Dipole Moment



large effective dipole moment

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

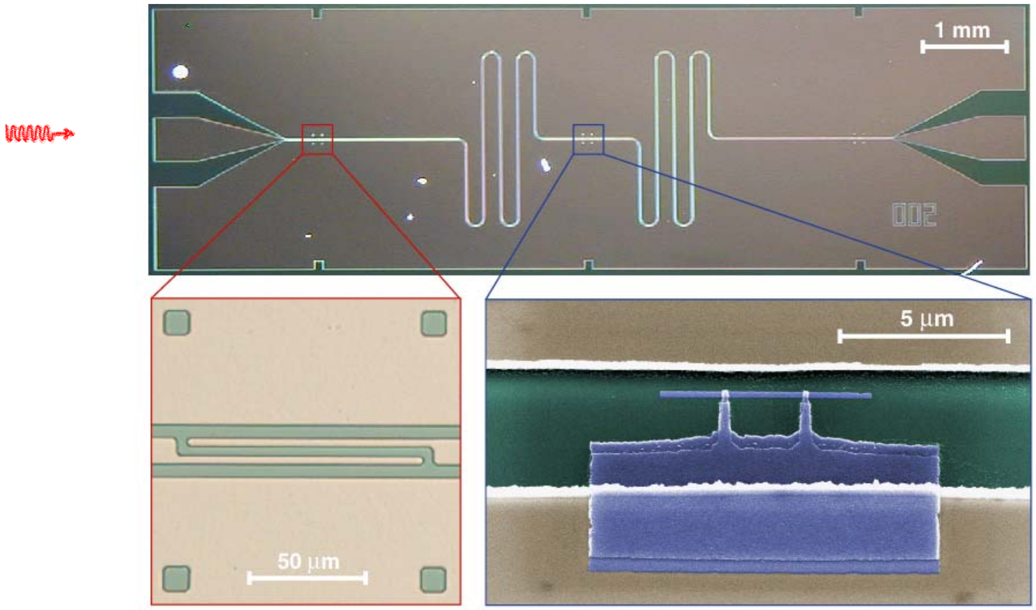


coupling strength to light:

$$\Longrightarrow \nu_{vac} = \frac{g}{\pi} \approx 1 \ldots 100\,\mathrm{MHz}$$

expressed as how often a qubit would absorb and reemit a photon per second

Integration in a Circuit QED Device

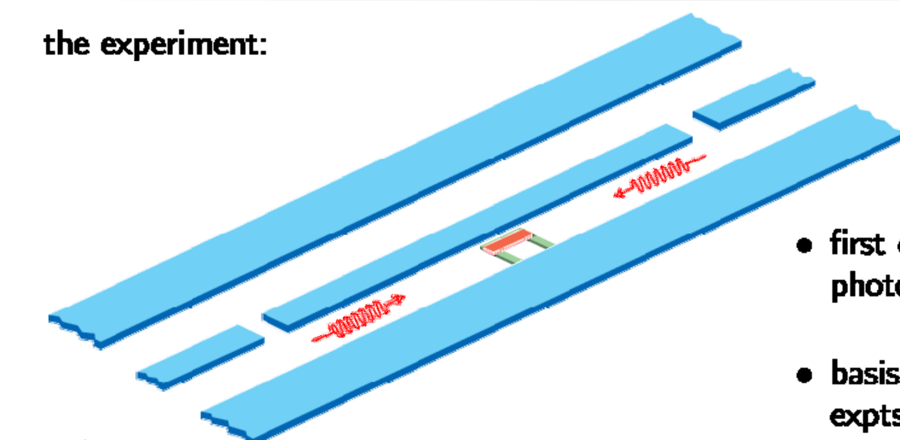


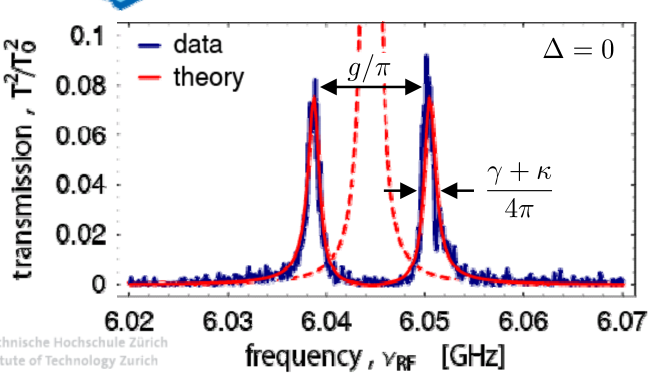
superconducting cavity QED circuit

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

Coherent Dynamics of a Single Photon and a Qubit

the experiment:

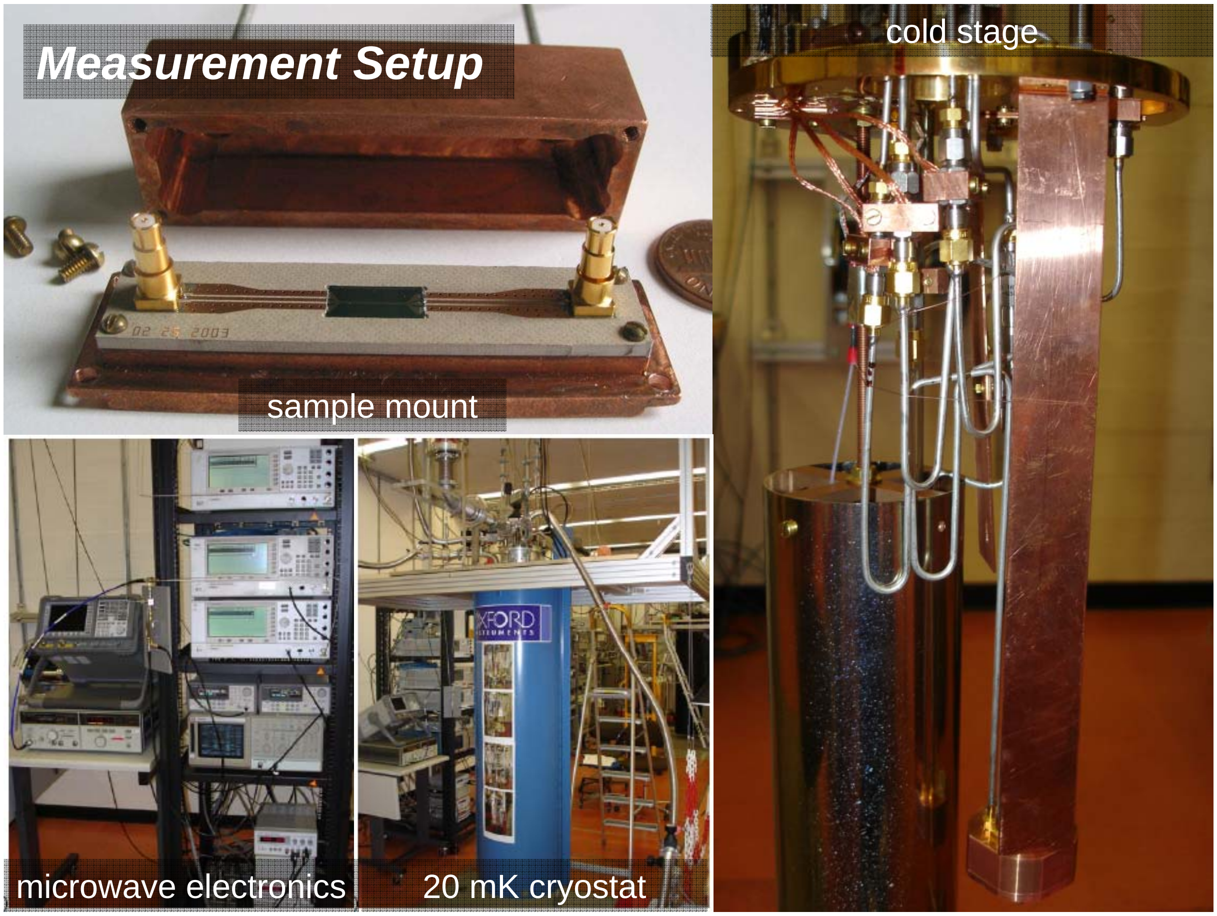




- first coherent single photon in a solid
- basis for quantum optics expts. in a solid
- architecture for quantum information processing

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

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich



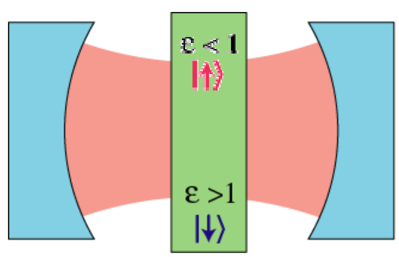
Non-Resonant Interaction

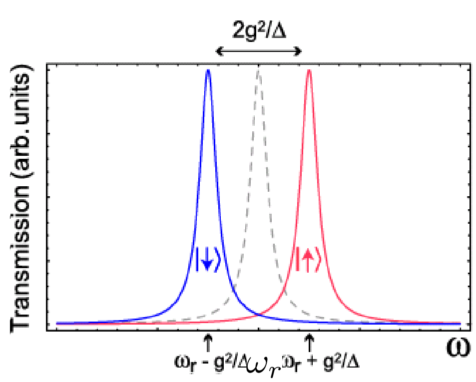
approximate diagonalization in the dsipersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

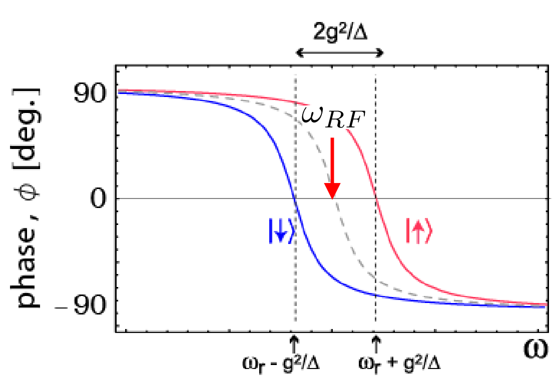
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta}\right)\sigma_z$$

// cavity frequency shift *and* qubit ac-Stark shift

// Lamb shift





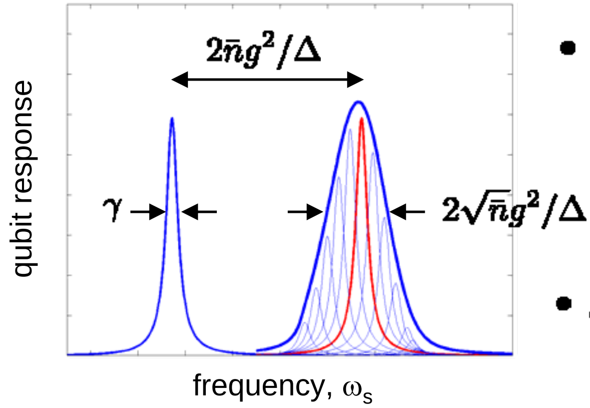


ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

Fluctuations of the Photon Number: Shot Noise

ac-Stark induced fluctuations of the qubit transition frequency:



- Poisson distributed photon number of coherent field

$$P_\lambda(n) = \frac{\bar{n}^n}{n!}e^{-\bar{n}}$$

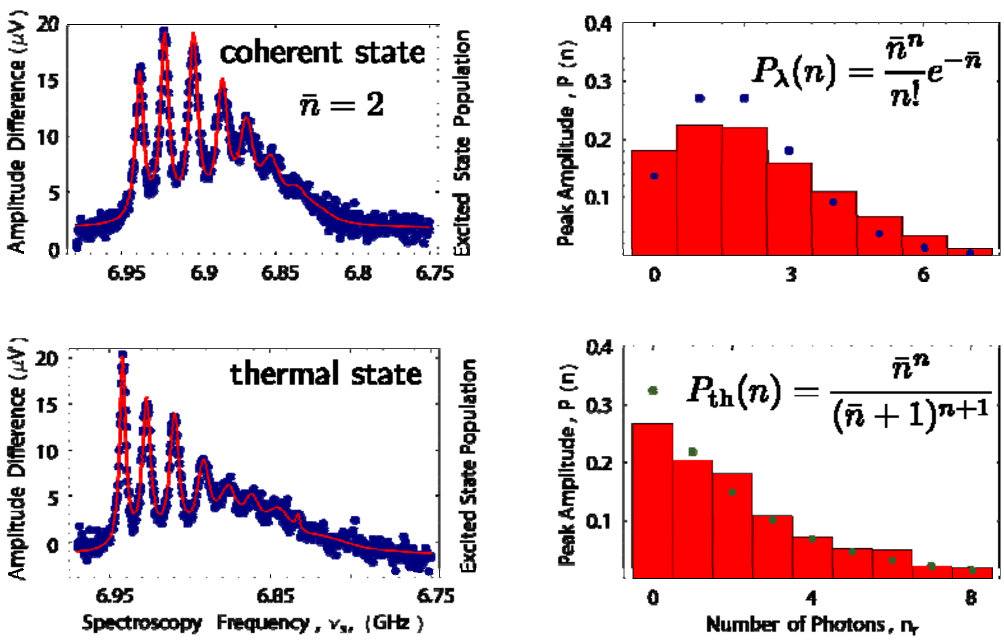
- gaussian line is sum of Lorentzians

What if the Stark shift per photon is larger than an intrinsic qubit line width?

$$2g^2/\Delta > \gamma$$

$\rightarrow$ resolving individual photon number states

Measuring Photon Statistics



distinguish between coherent and thermal states

Schuster, Houck, Schreier, Wallraff, Gambetta, Blais, Frunzio, Johnson, Devoret, Girvin, Schoelkopf, *Nature* **445**, 515 (2007)

Summary Cavity QED

- strong coupling between individual photon and qubit
- interface between light and matter
- bus for quantum communication
- interesting fundamental physics of quantum light matter interaction