Cavity Quantum Electrodynamics with Superconducting Circuits

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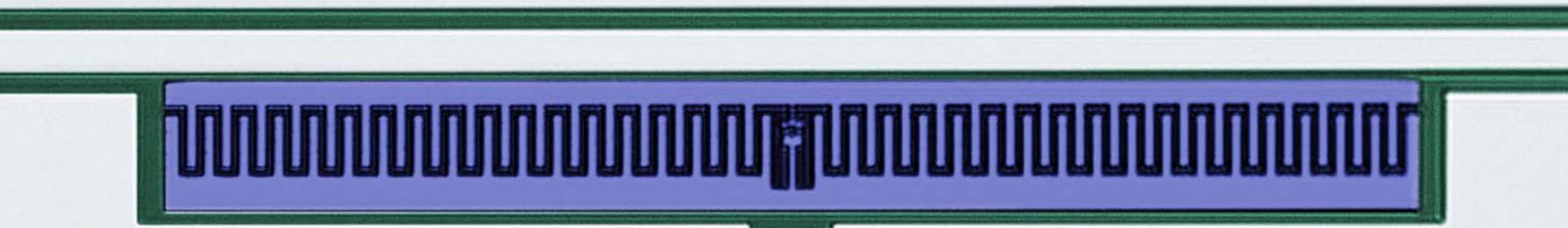
www.qudev.ethz.ch



M. Baur, R. Bianchetti, S. Filipp, J. Fink,
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L. Steffen, P. Studer
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J. Schreier, J. Chow, J. Majer, L. Frunzio,
M. Devoret, S. Girvin, R. Schoelkopf
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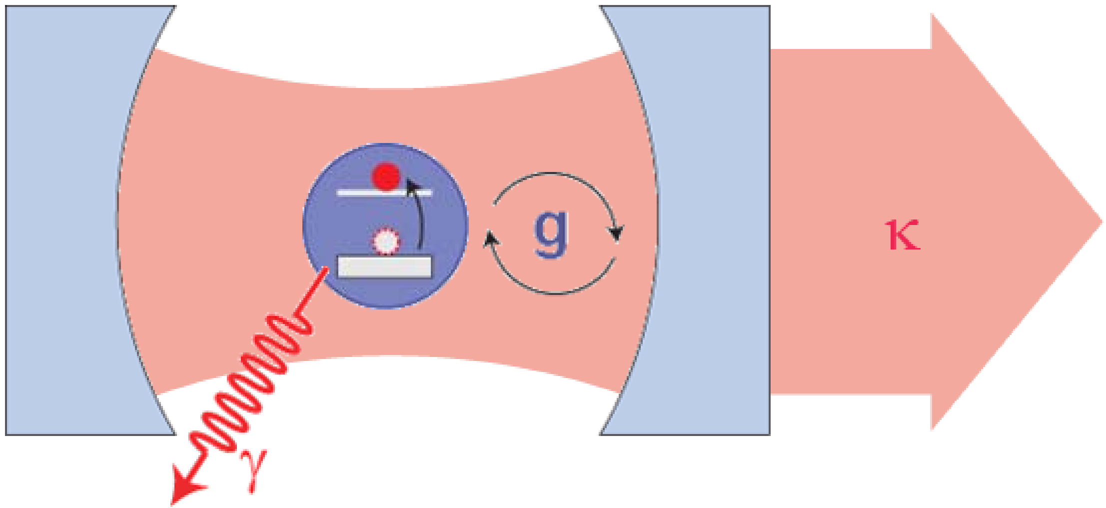
Outline

- Cavity Quantum Electrodynamics
- Quantum Electrical Circuits
  - Harmonic Oscillators
  - Qubits
- Circuit Quantum Electrodynamics
  - The Basics
  - Resonant and Dispersive Circuit QED Experiments
- Quantum Information Processing
  - Single Qubit Control and Read-Out in Circuit QED
  - Quantum Geometric Phases
  - Two-Qubit Gates

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

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

Dressed States Energy Level Diagram

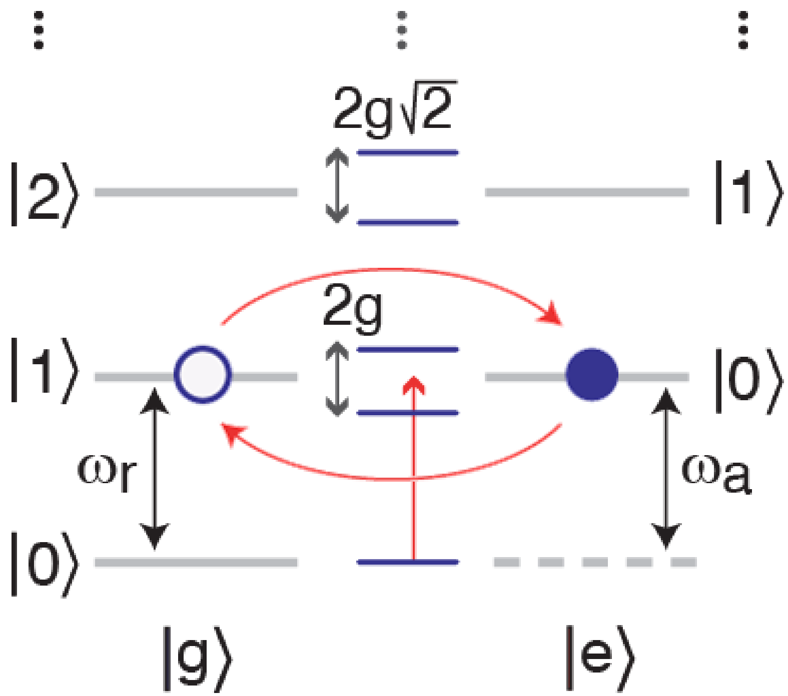
$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

in resonance:

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

strong coupling limit:

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



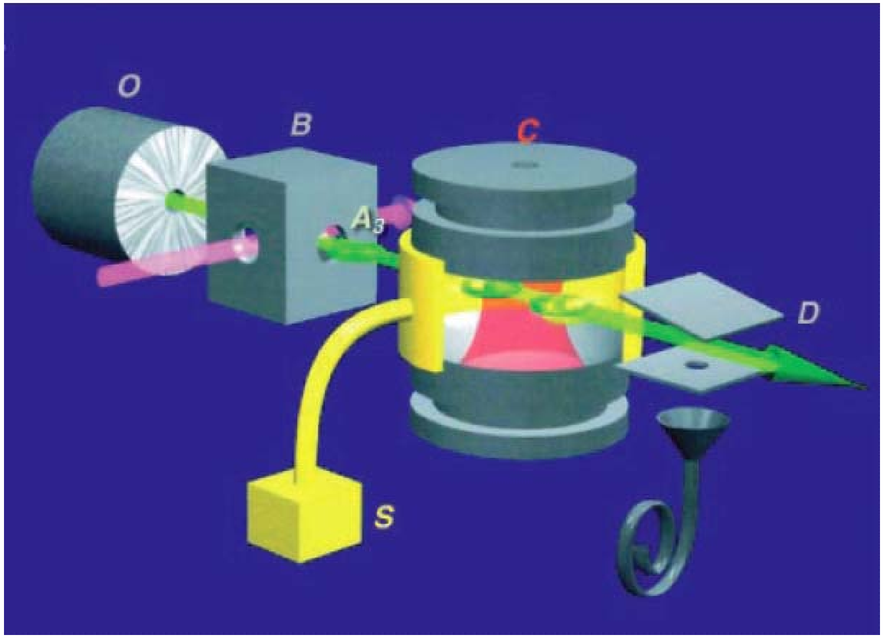
Jaynes-Cummings Ladder

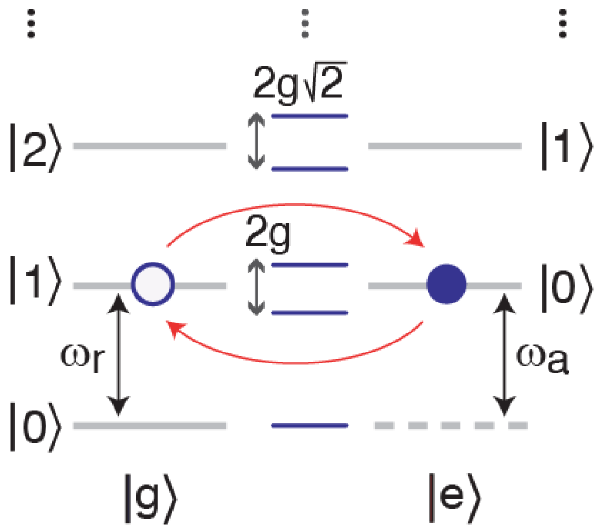
Atomic cavity quantum electrodynamics reviews:

H. Mabuchi, A. C. Doherty *Science* **298**, 1372 (2002)

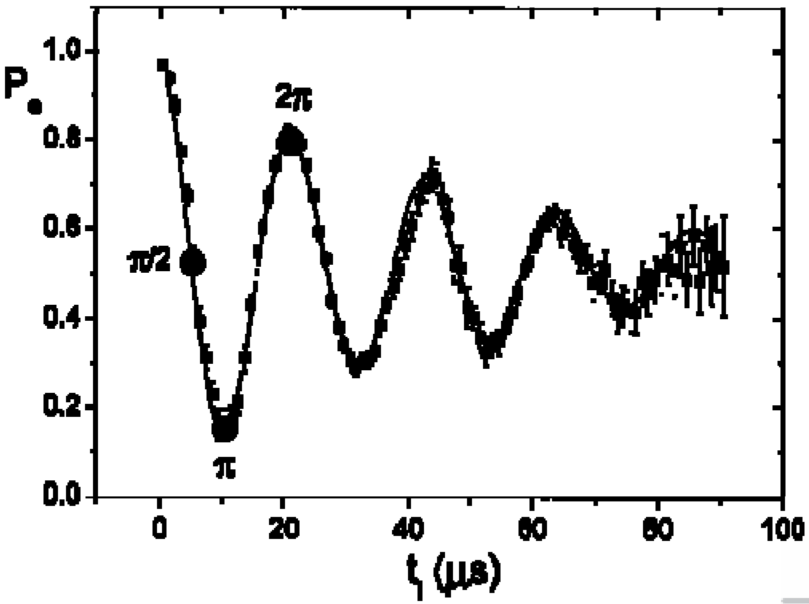
J. M. Raimond, M. Brune, & S. Haroche *Rev. Mod. Phys.* **73**, 565 (2001)

Vacuum Rabi Oscillations with Rydberg Atoms

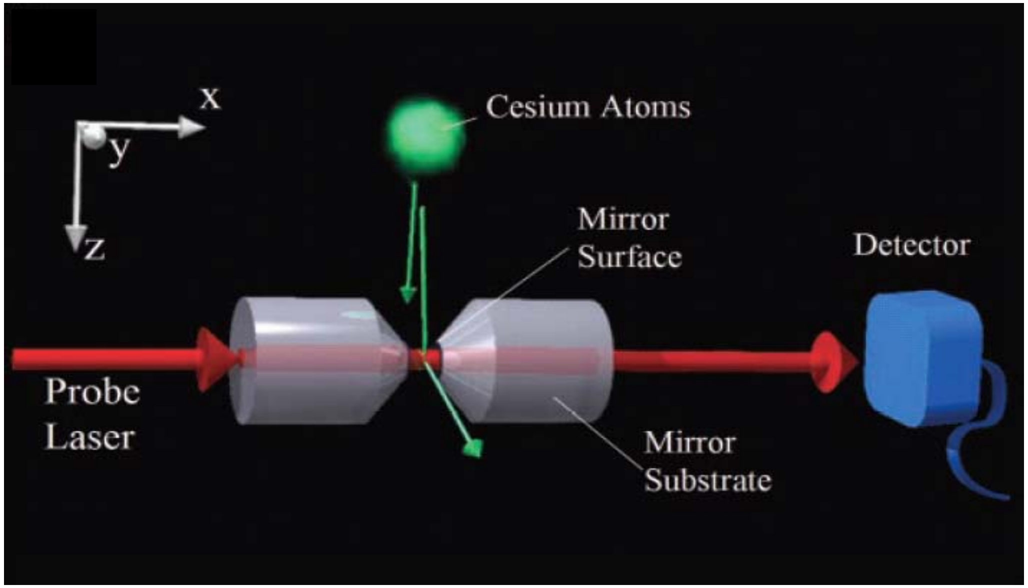


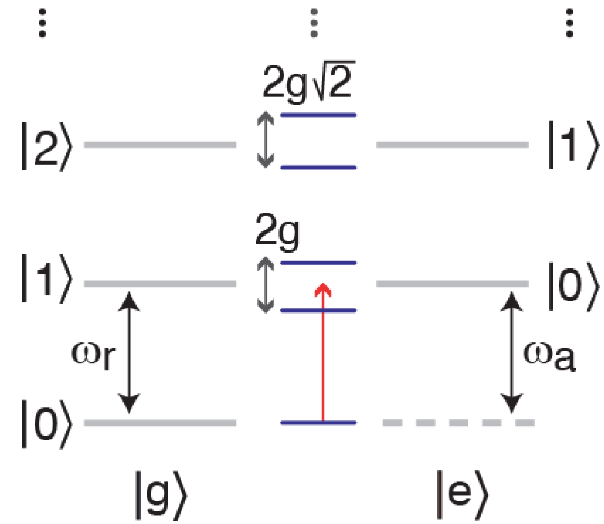


Review: J. M. Raimond, M. Brune, and S. Haroche
Rev. Mod. Phys. **73**, 565 (2001)
P. Hyafil, ..., J. M. Raimond, and S. Haroche,
Phys. Rev. Lett. **93**, 103001 (2004)

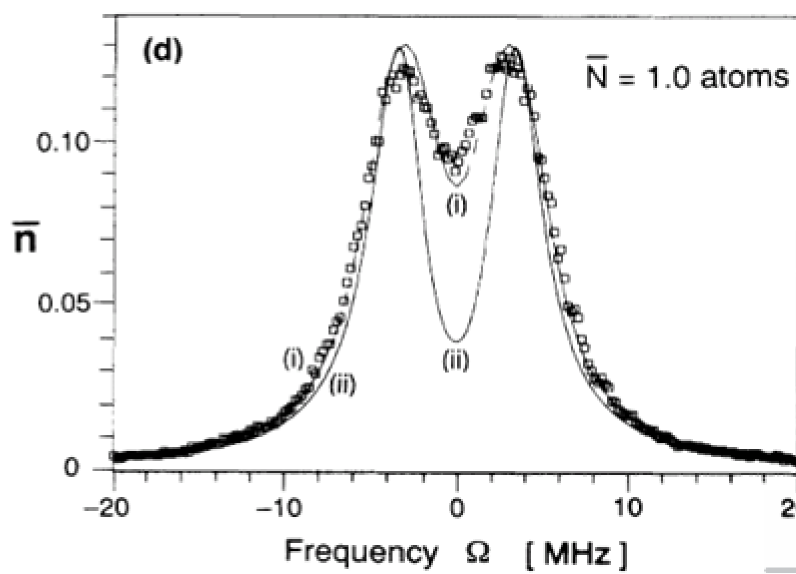


Vacuum Rabi Mode Splitting with Alkali Atoms

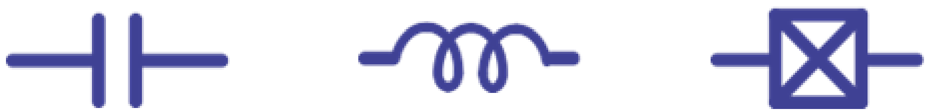




R. J. Thompson, G. Rempe, & H. J. Kimble,
Phys. Rev. Lett. **68** 1132 (1992)
A. Boca, ... , J. McKeever, & H. J. Kimble
Phys. Rev. Lett. **93**, 233603 (2004)



Quantum Electronic Circuits:
Artificial Atoms and Photons on a Chip



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The Quantum Electronic Circuit Toolkit

Capacitor

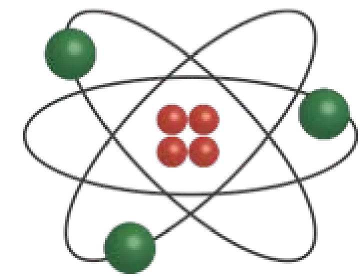
Inductor

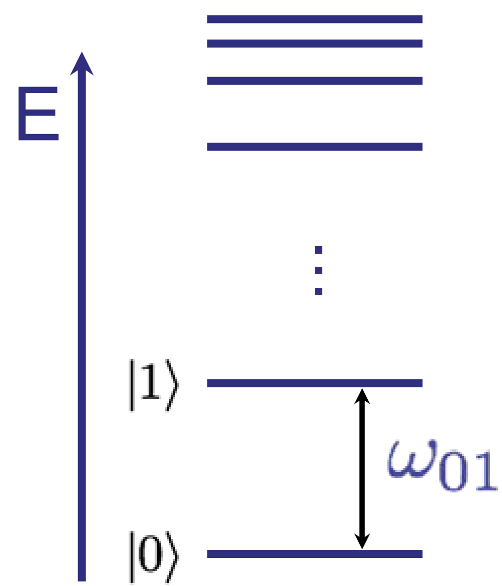
Resistor

Voltage source

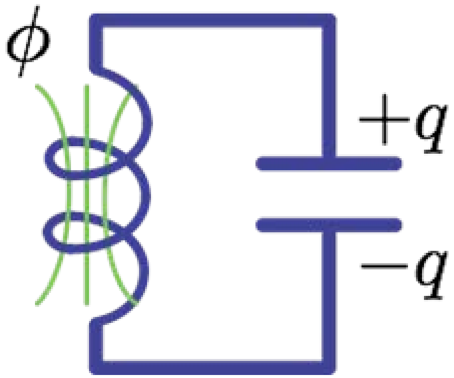
Current source

?



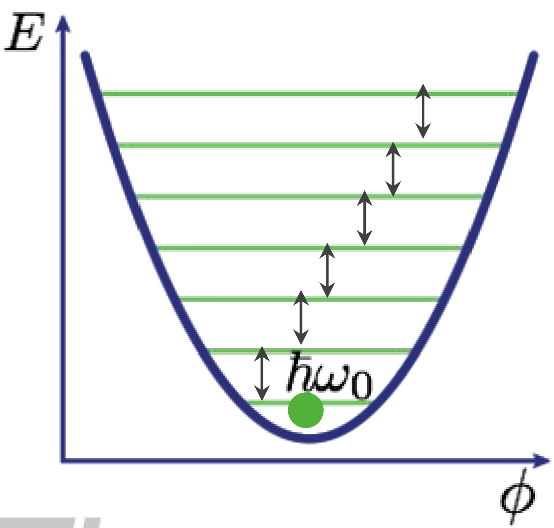


Electrical Harmonic Oscillators



$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C} \rightarrow \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C} \qquad [\hat{\phi}, \hat{q}] = i$$

$$\hat{H} = \hbar\omega_0 \left(a^\dagger a + \frac{1}{2} \right) \qquad \omega_0 = 1/\sqrt{LC}$$



Typical parameters for microfabricated LC:

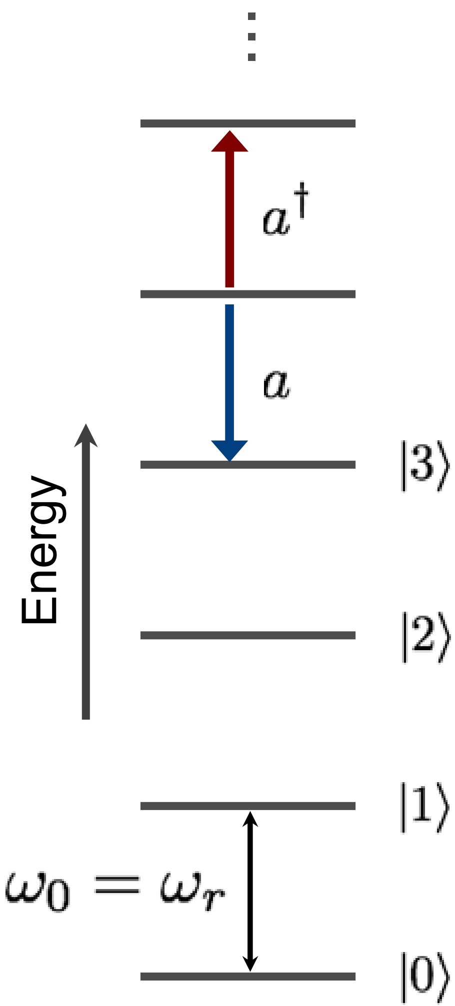
$$L \sim 0.1\,\mathrm{nH} \quad C \sim 1\,\mathrm{pF} \rightarrow \omega_0/2\pi \sim 15\ \mathrm{GHz}$$

$1\ \mathrm{GHz} \sim 50\ \mathrm{mK}$

Problem #1: Linear

M. Devoret,
Quantum fluctuations in electrical circuits, Elsevier Science (1997)

Harmonic Oscillator: A Linear Many-Level System



Infinitely many ***linearly*** spaced energy levels

Ladder operators: $a, a^\dagger$

Product of ladder operators:

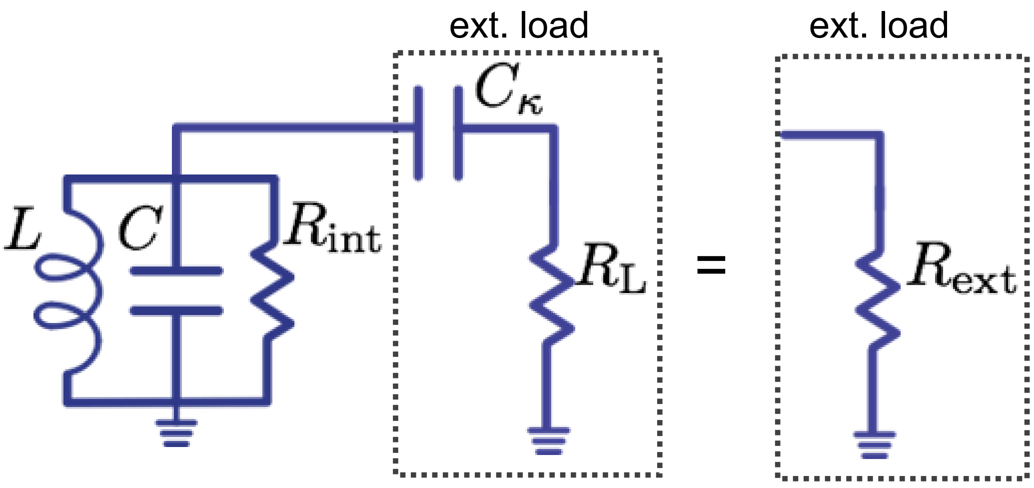
$$a^\dagger a = \begin{pmatrix} 0 & & & & \\ & 1 & & & \\ & & 2 & & \\ & & & 3 & \\ & & & & \ddots \end{pmatrix}$$

Contains information about which "step" of the ladder the oscillator is on

Hamiltonian of a harmonic oscillator (the total energy):

$$H = \omega_0 a^\dagger a$$

Electrical Harmonic Oscillators: Dissipation



Internal losses: R_{int}

conductor, dielectric

External losses: R_{ext}

radiation, coupling

Total losses: $$\frac{1}{R} = \frac{1}{R_{\mathrm{int}}} + \frac{1}{R_{\mathrm{ext}}}$$

Quality factor: $$Q = \frac{R}{Z} = \omega_0 RC$$

Relaxation rate: $$\Gamma_1 = \frac{\omega_0}{Q} = \frac{1}{RC}$$

Characteristic impedance: $$Z = \sqrt{\frac{L}{C}} \sim 10\ \Omega$$

Problem #2: Avoid internal and external dissipation

Artificial Atom Toolkit

Capacitor

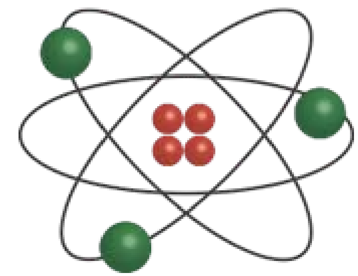
Inductor

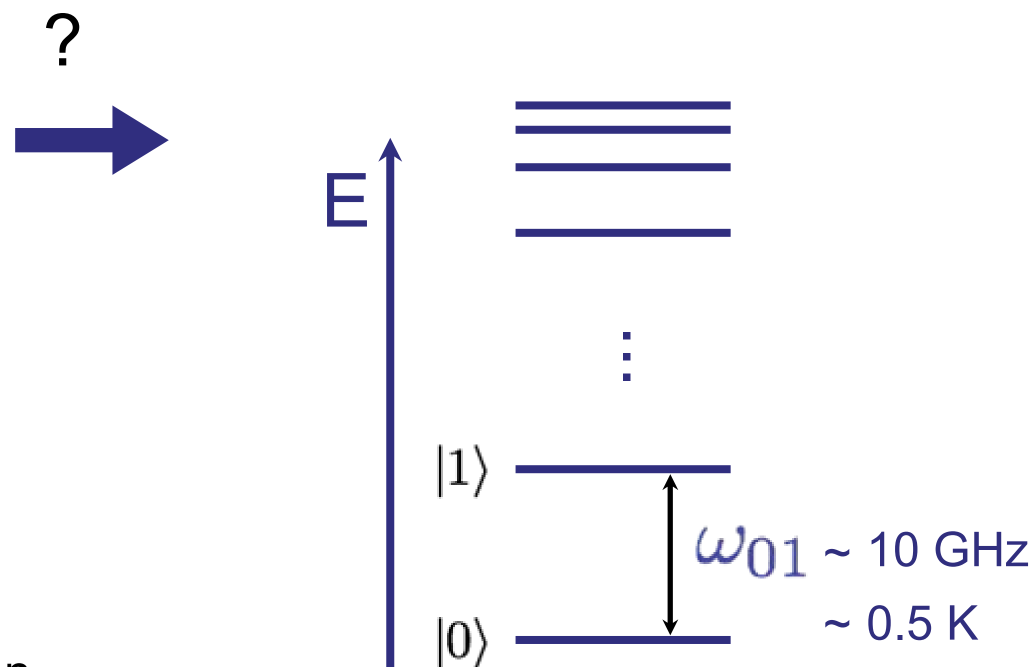
Resistor

Voltage source

Current source

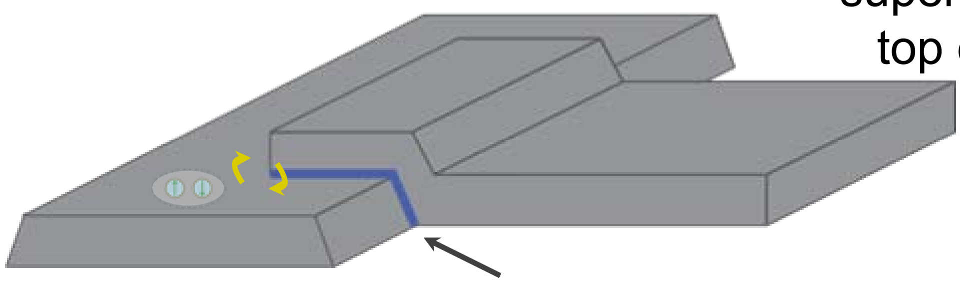
Transistor
Josephson Junction





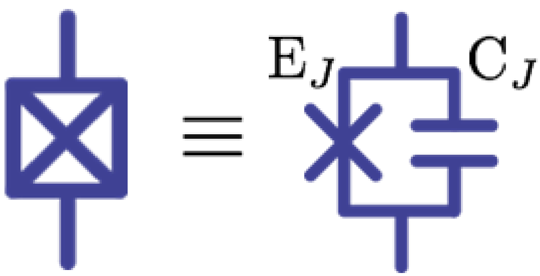
Josephson Junctions …

… superconducting non-linear elements:



superconductors: Al, Nb

tunnel barrier: AlOx



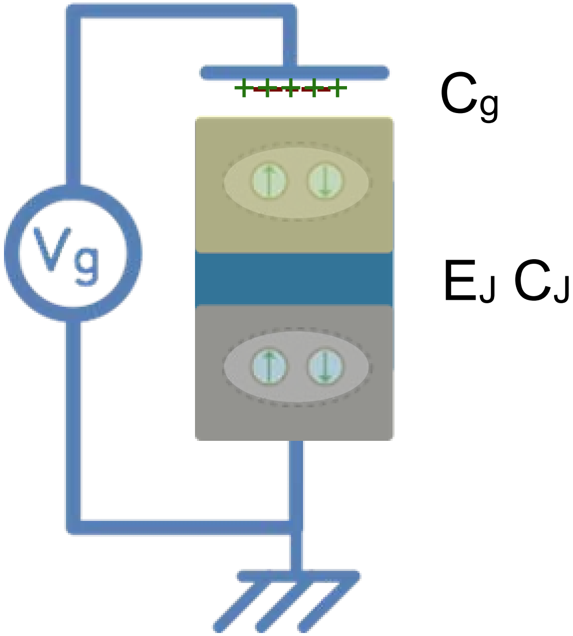
Josephson energy :
(tunneling amplitude) E_J

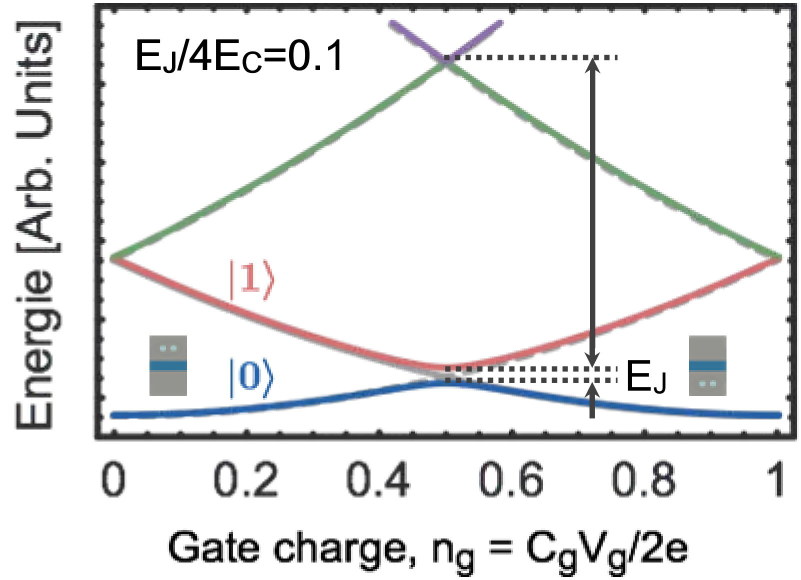
junction capacitance: C_J

nonlinear

dissipation-less

A Superconducting Qubit: The Cooper Pair Box





First theoretically suggested:

Shnirman et al. Phys. Rev. Lett. **79**, 2371 (1997)
Bouchiat et al. Physica Scripta **176**, 165 (1998)

First experimental realization:

Y. Nakamura et al. Nature (London) **398**, 786 (1999)

The Cooper Pair Box Hamiltonian (for Theorists)

- generic Hamiltonian for an electrical oscillator

$$\mathbf{H} = \mathbf{H}_{\mathrm{el}} + \mathbf{H}_{\mathrm{J}} = \frac{1}{2C} q^2 + \frac{1}{2L} \Phi^2$$

- CPB Hamiltonian

$$\mathbf{H}_{\mathrm{CPB}} = \mathbf{H}_{\mathrm{el}} + \mathbf{H}_{\mathrm{J}} = 4E_{C0}(N - n_g)^2 - E_{J0}\cos\Theta$$

$$E_{C0} = (2e^2)/2C_{\Sigma} \qquad E_J = \Phi_0 I_c/2\pi$$

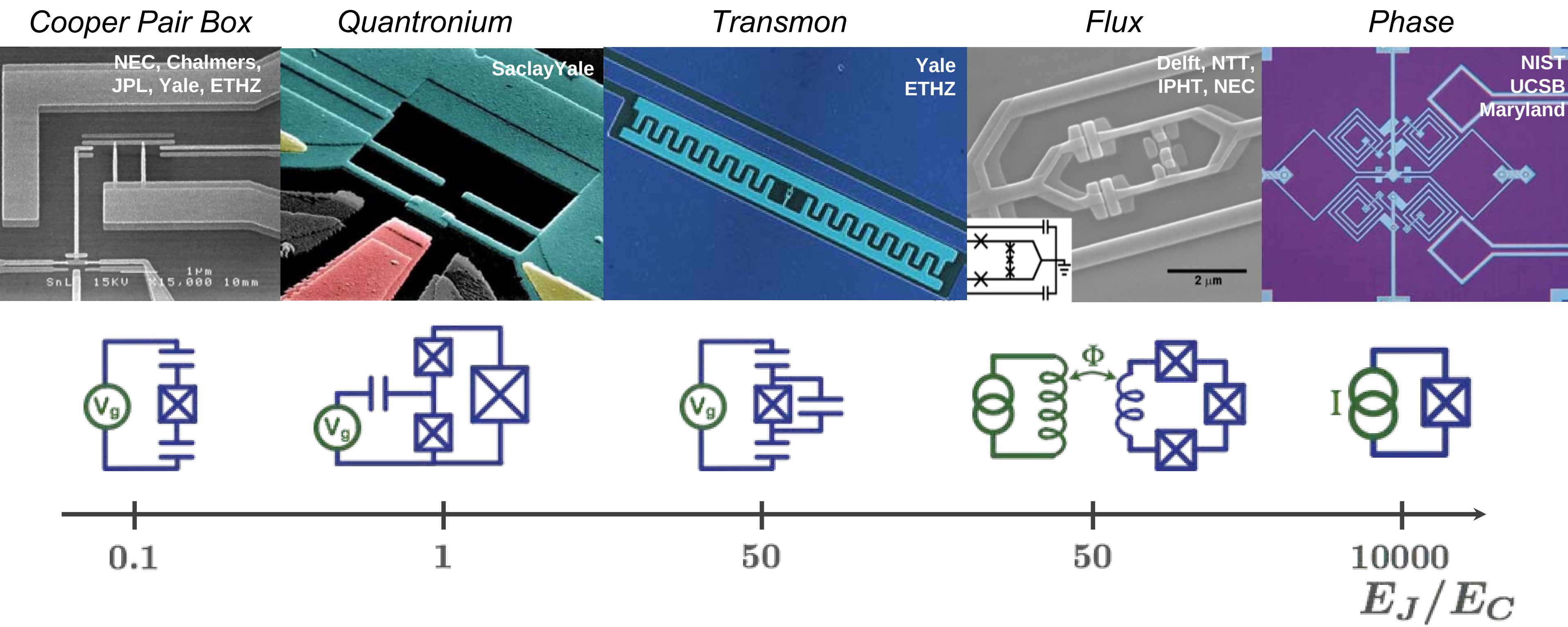
- pick a basis

$$[\Theta, N] = i \qquad \text{and} \qquad N = i\frac{\partial}{\partial\theta} \quad , \quad \Theta = -i\frac{\partial}{\partial n}$$

- in the charge basis

$$\mathbf{H}_{\mathrm{CPB}} = \sum_n \left[4E_{C0}(N - n_g)^2 \left|n\right\rangle \left\langle n\right| - \frac{E_{\mathrm{J}}}{2} \left(\left|n\right\rangle \left\langle n+1\right| + \left|n+1\right\rangle \left\langle n\right| \right) \right]$$

Many Superconducting Qubits

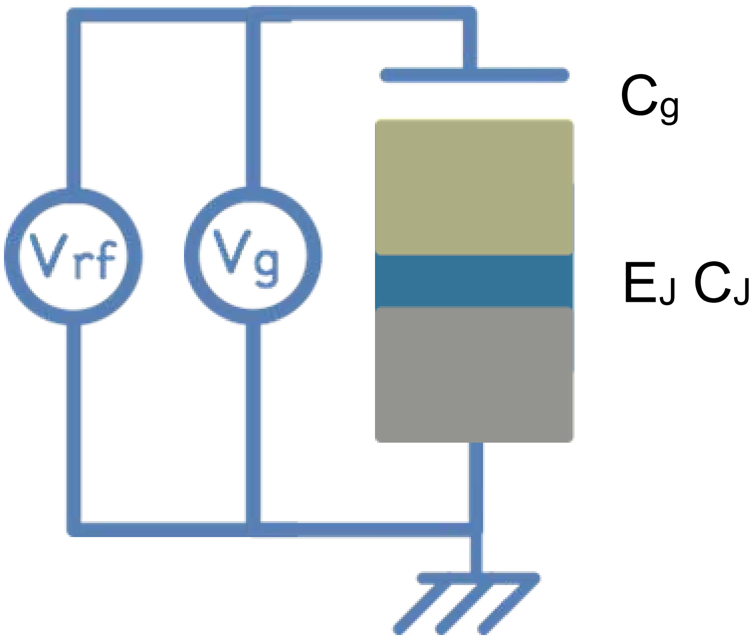


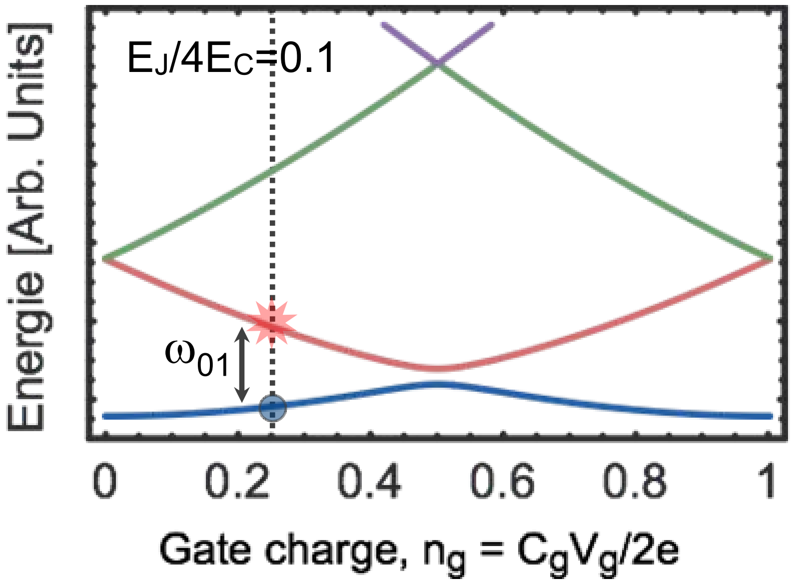
concepts review: M. H. Devoret, A. Wallraff and J. M. Martinis, condmat/0411172 (2004)
realizations review: G. Wendin and V.S. Shumeiko, *cond-mat/0508729* (2005)

Thousandfold increase in dephasing times:

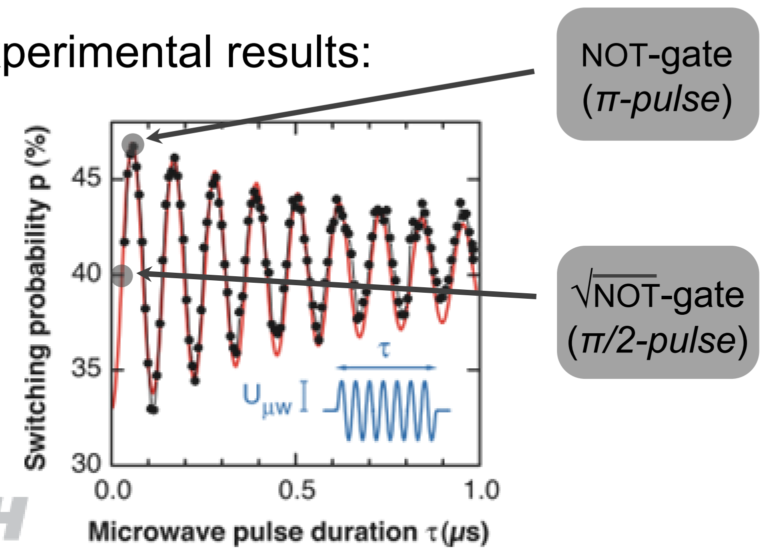
- First coherent oscillations (NEC, 1999) ⟶ T_2 ~ 1 ns
- “Sweet spot” (Saclay, 2002) ⟶ T_2 ~ 500 ns
- Transmon (Yale, 2007) ⟶ T_2 ~ 2000 ns

How to do Control: Single-Qubit Gates à la NMR





Experimental results:



Single qubit Hamiltonian, with drive:

$$H = \frac{\omega_{01}}{2}\sigma_z + \Omega_R \cos(\omega t)\sigma_x$$

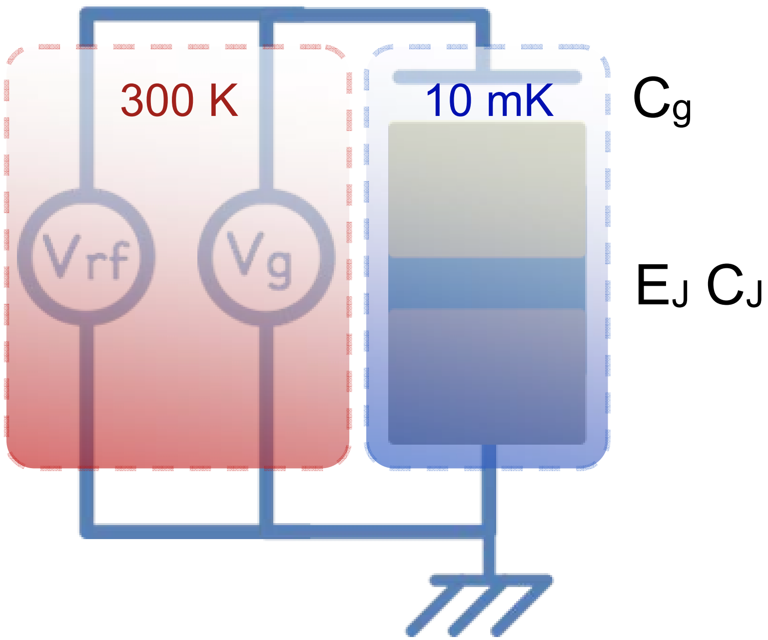
Relaxation and dephasing times:

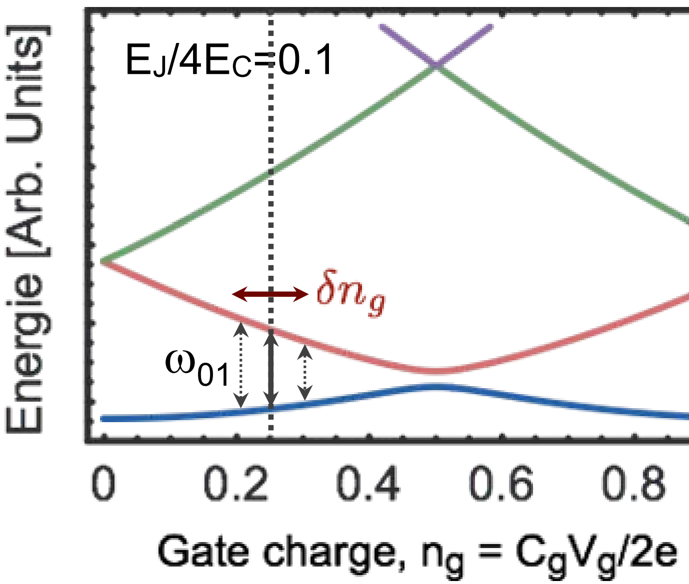
$T_1 \sim 1.8\ \mu s$ *(Bit flip)*

$T_2^* \sim 500ns$ *(Phase randomization)*

Vion *et al.*, *Science* **296** 886 (2002)

Problem: Charge (and other types of) Noise





Charge fluctuations:

$$n_g \rightarrow n_g + \delta n_g$$

Golden rule:

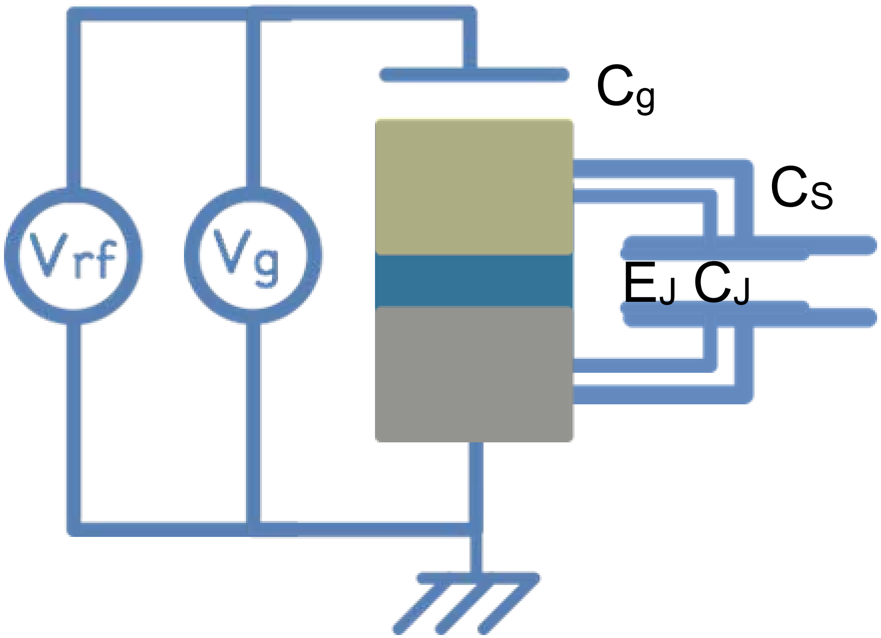
$$\gamma_1 = T_1^{-1} \propto S_{n_g}(\omega_{01}) + S_{n_g}(-\omega_{01})$$

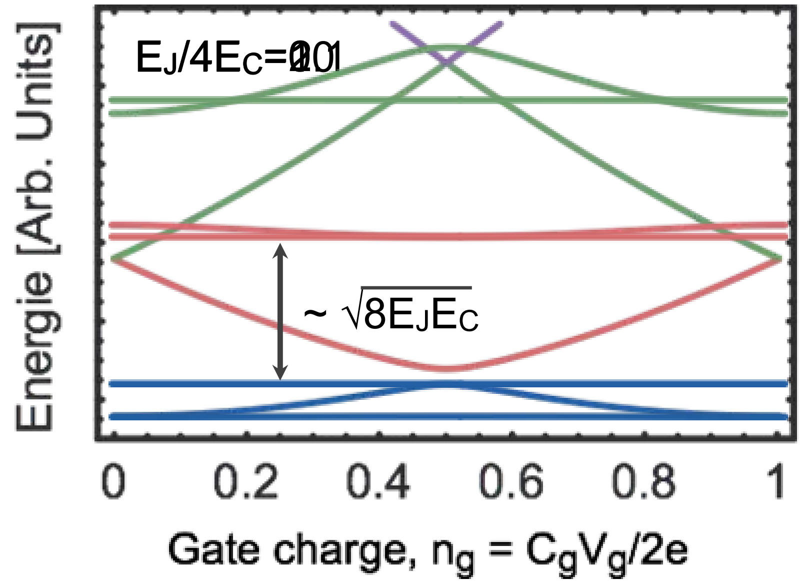
$$\gamma_\phi = T_\phi^{-1} \propto S_{n_g}(\omega \rightarrow 0)$$

Solutions:

- Suppress relaxation by suppressing noise at qubit frequency (circuit QED)
- Suppress phase randomization with flat energy bands (Transmon)

Solution: Reduce Charge Noise Sensitivity





Charge dispersion decreases more rapidly than anharmonicity:

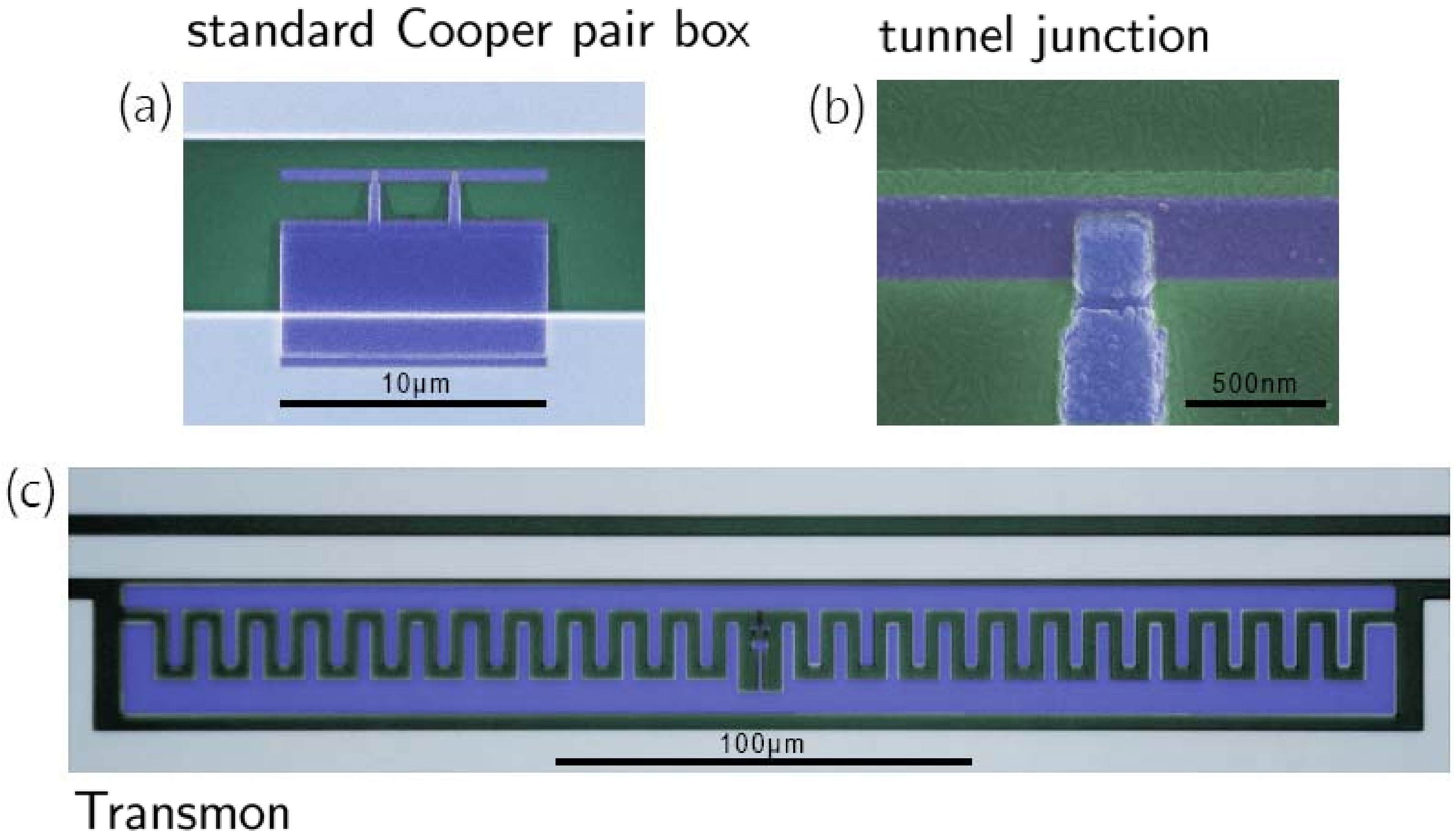
$$\epsilon_m \equiv E_m(n_g = 1/2) - E_m(n_g = 0)$$
$$\simeq (-1)^m E_C \frac{2^{4m+5}}{m!} \sqrt{\frac{2}{\pi}} \left(\frac{E_J}{2E_C}\right)^{\frac{m}{2}+\frac{3}{4}} e^{-\sqrt{8E_J/E_C}}$$

$$\alpha_r(n_g = 1/2) \equiv (E_{12} - E_{01})/E_{01}$$
$$\simeq -(8E_J/E_C)^{-1/2}$$

Predicted long dephasing times: J. Koch *et al.*, *PRA* **76**, 042319 (2007)

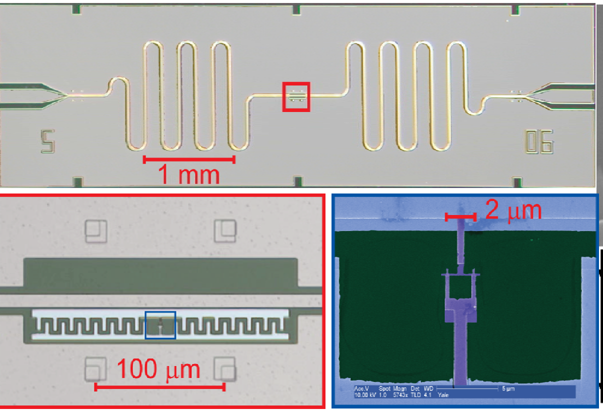
Measured long dephasing times: J. A. Schreier *et al. PRB* **77**, 180502 (2008)

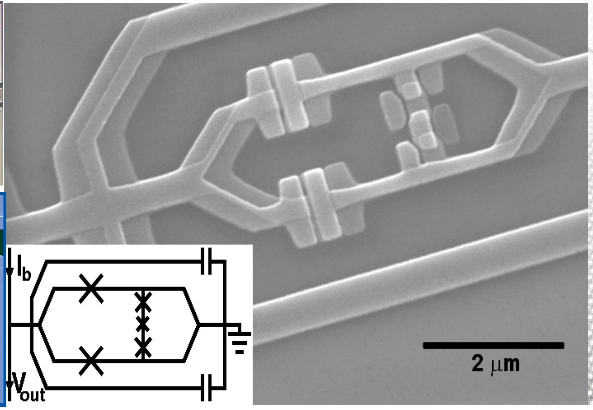
Two Versions of the Cooper Pair Box

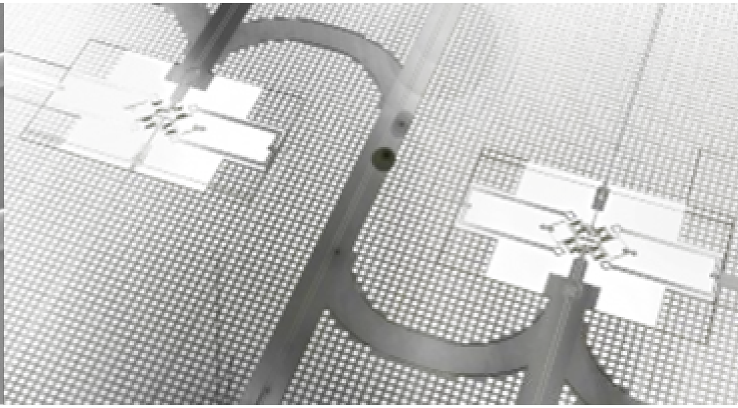


M. Goppl, P. Leek (Quantum Device Lab, ETHZ, 2007)

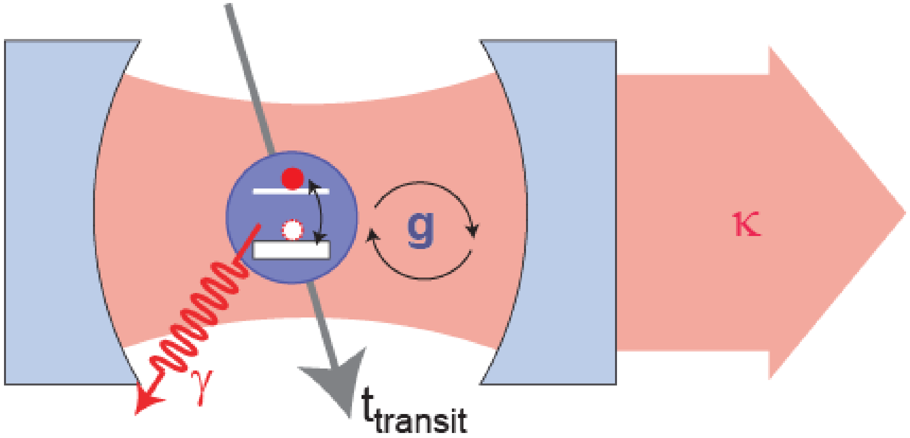
Circuit Quantum Electrodynamics







Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

... in superconducing circuits:

many proposals:

discrete LC circuits:

- Y. Makhlin, G. Schön, and A. Shnirman, Rev. Mod. Phys. **73**, 357 (2001).
- O. Buisson and F. Hekking, in *Macroscopic Quantum Coherence and Quantum Computing*, edited by D. V. Averin, B. Ruggiero, and P. Silvestrini (Kluwer, New York, 2001).

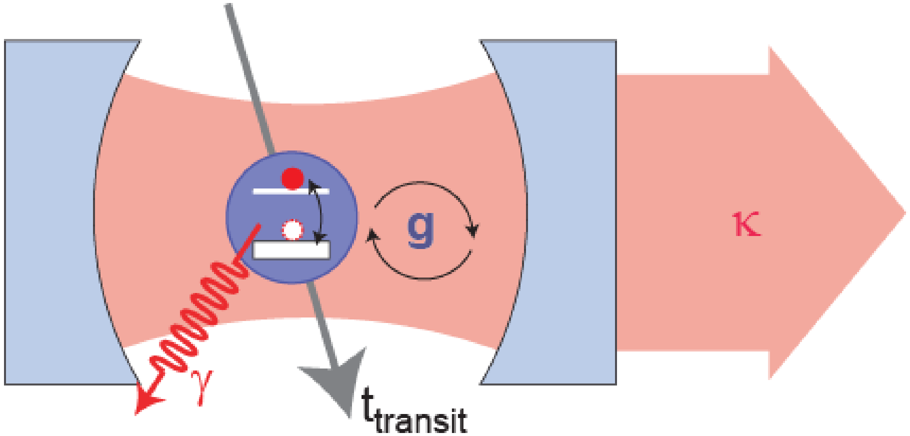
large junctions:

- F. Marquardt and C. Bruder, Phys. Rev. B **63**, 054514 (2001).
- F. Plastina and G. Falci, Phys. Rev. B **67**, 224514 (2003).
- A. Blais, A. Maassen van den Brink, and A. Zagoskin, Phys. Rev. Lett. **90**, 127901 (2003).

3D cavities:

- W. Al-Saidi and D. Stroud, Phys. Rev. B **65**, 014512 (2001).
- C.-P. Yang, S.-I. Chu, and S. Han, Phys. Rev. A **67**, 042311 (2003).
- J. Q. You and F. Nori, Phys. Rev. B **68**, 064509 (2003).

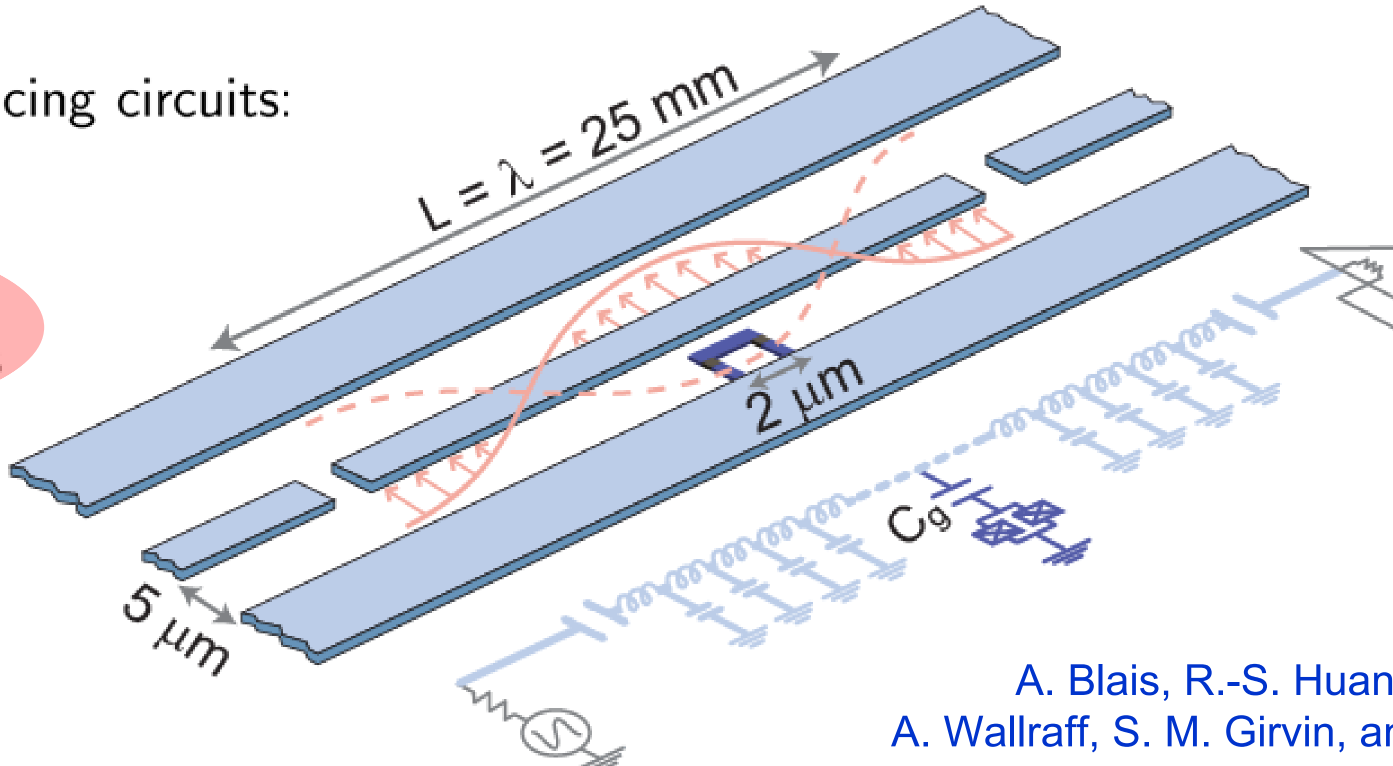
Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

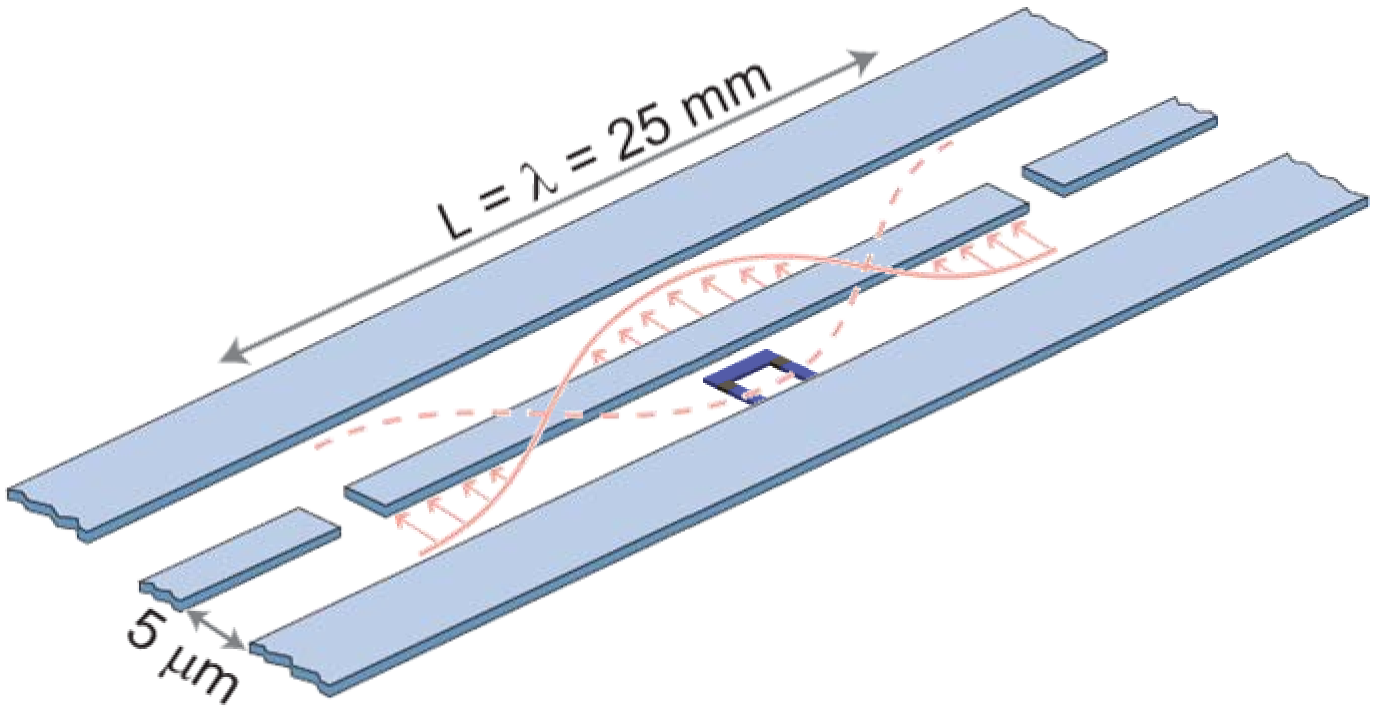
... in superconducing circuits:

circuit quantum electrodynamics



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

Circuit Quantum Electrodynamics

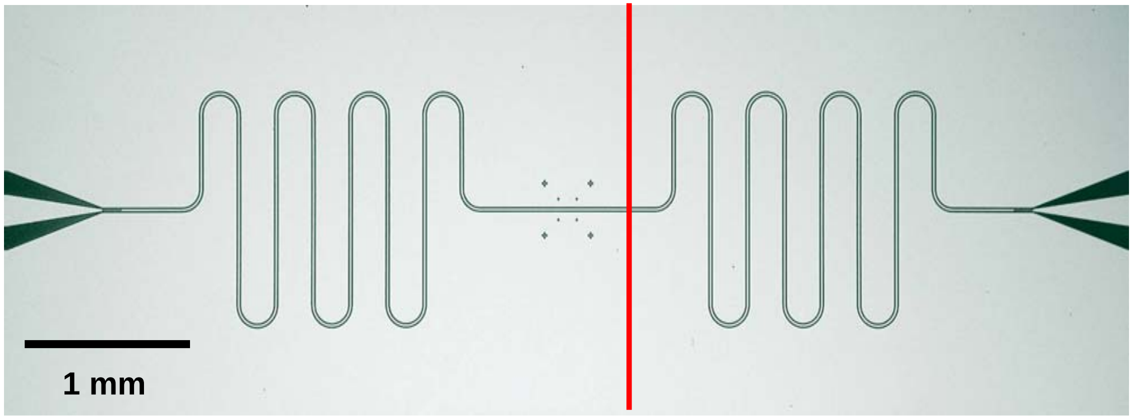


elements

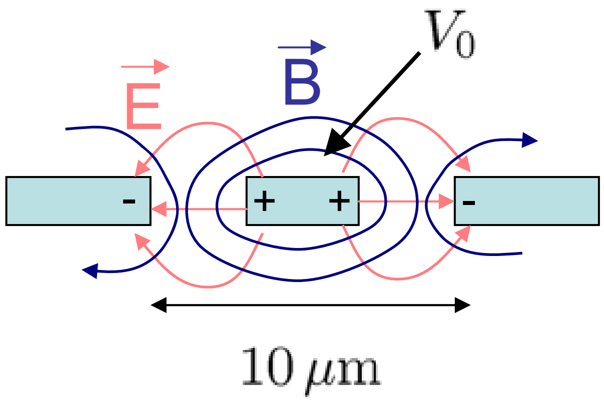
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box with large dipole moment d and long coherence time $1/\gamma$

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

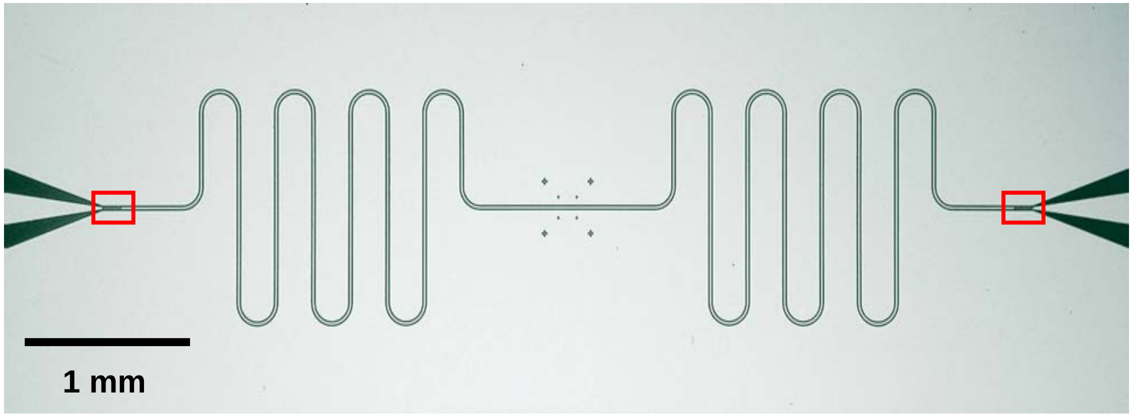
$$H_r = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$$

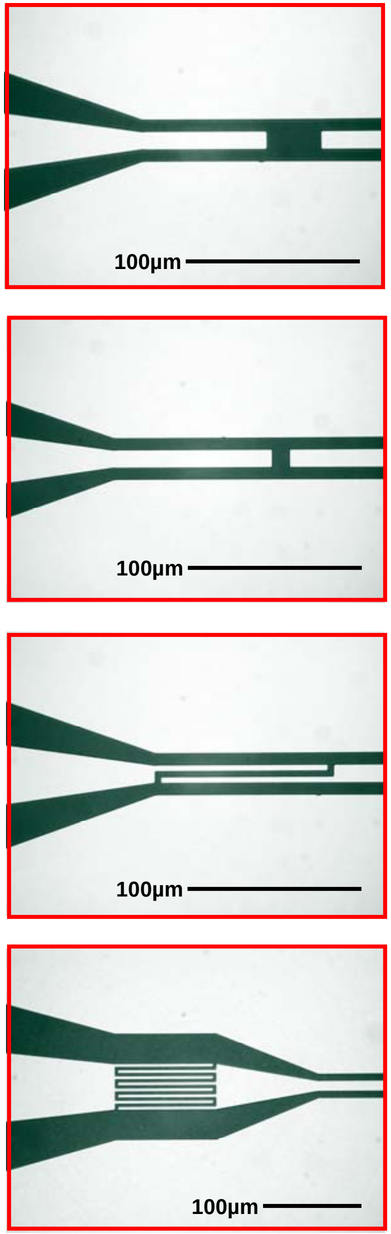
$$E_0 = \frac{V_{0,\mathrm{rms}}}{b} \approx 0.2\,\mathrm{V/m}$$

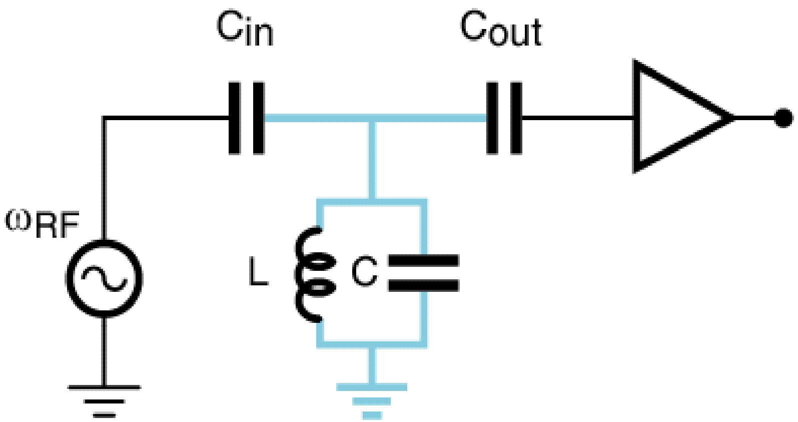
$\times 10^6$ larger than E_0 in 3D microwave cavity

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

Storing Photons and Controlling their Life Time

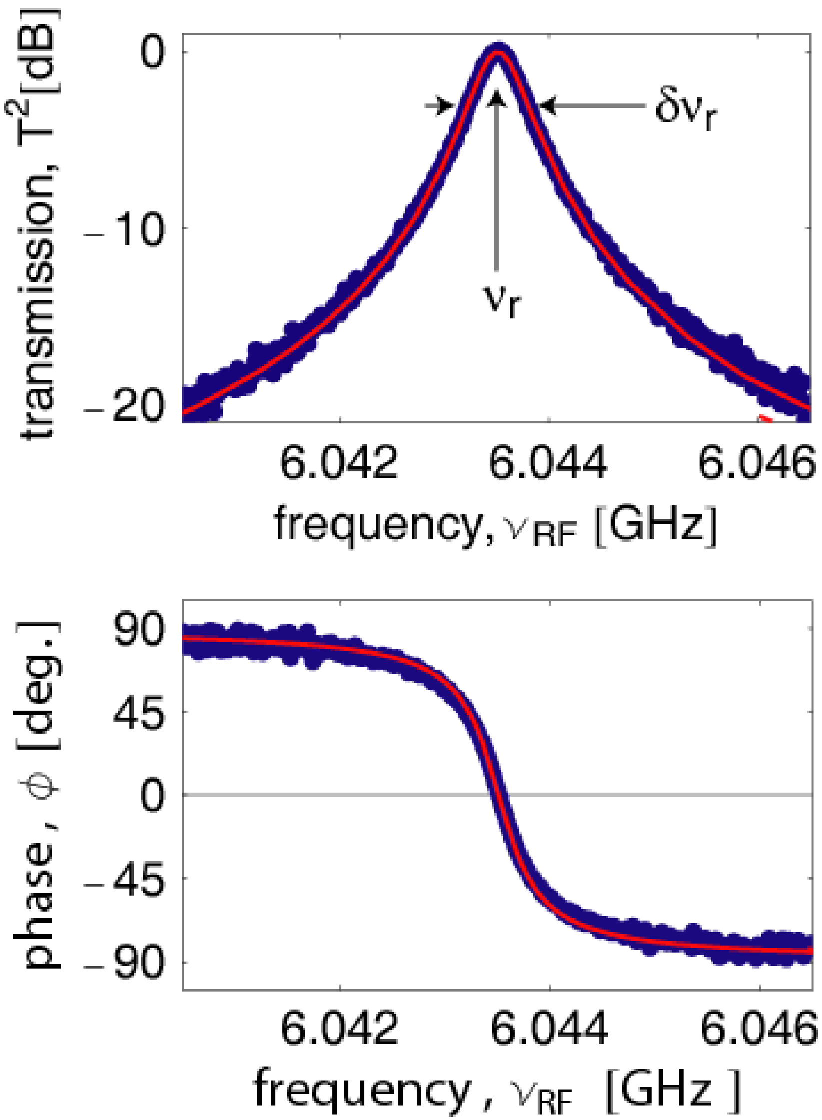






photon lifetime (quality factor)
controlled by coupling capacitor $C_{in/out}$

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:

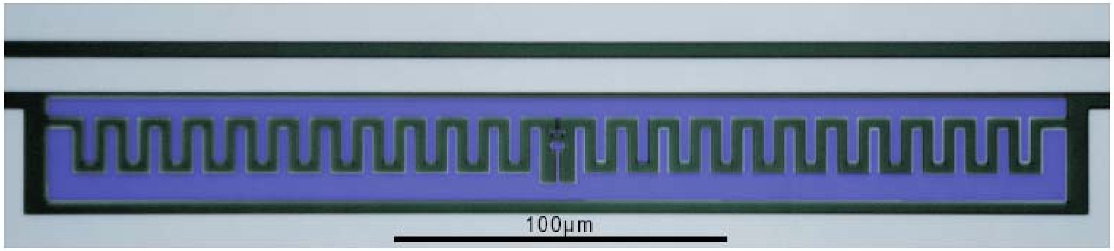
$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\mathrm{MHz}$$

photon lifetime:

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

Energy Levels of a Superconducting Qubit

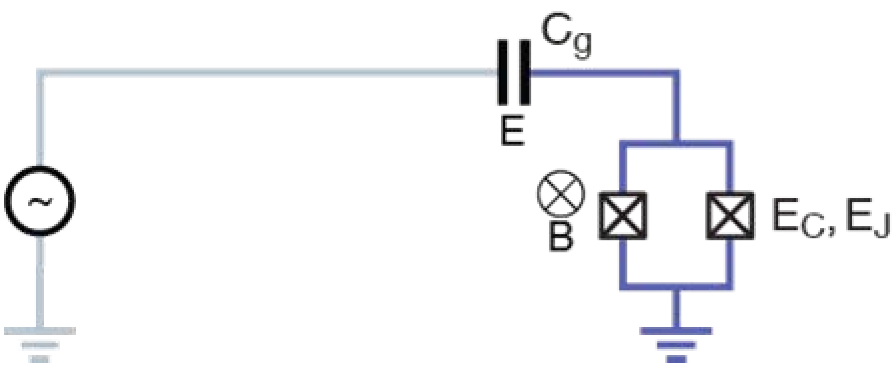
transmon:



controllable by:

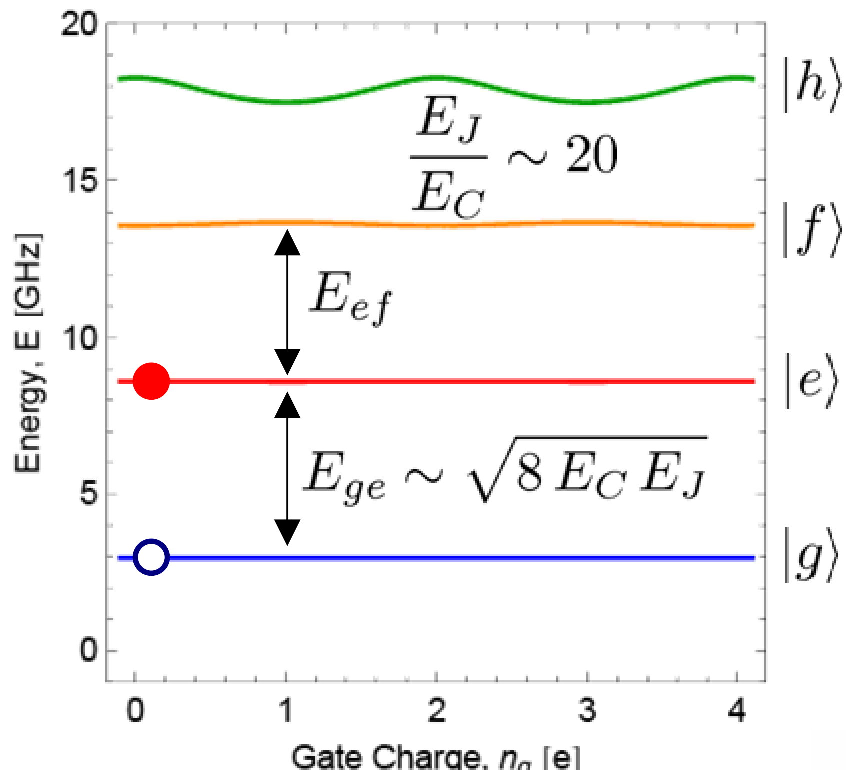
- electric fields E
- magnetic fields B

circuit diagram:



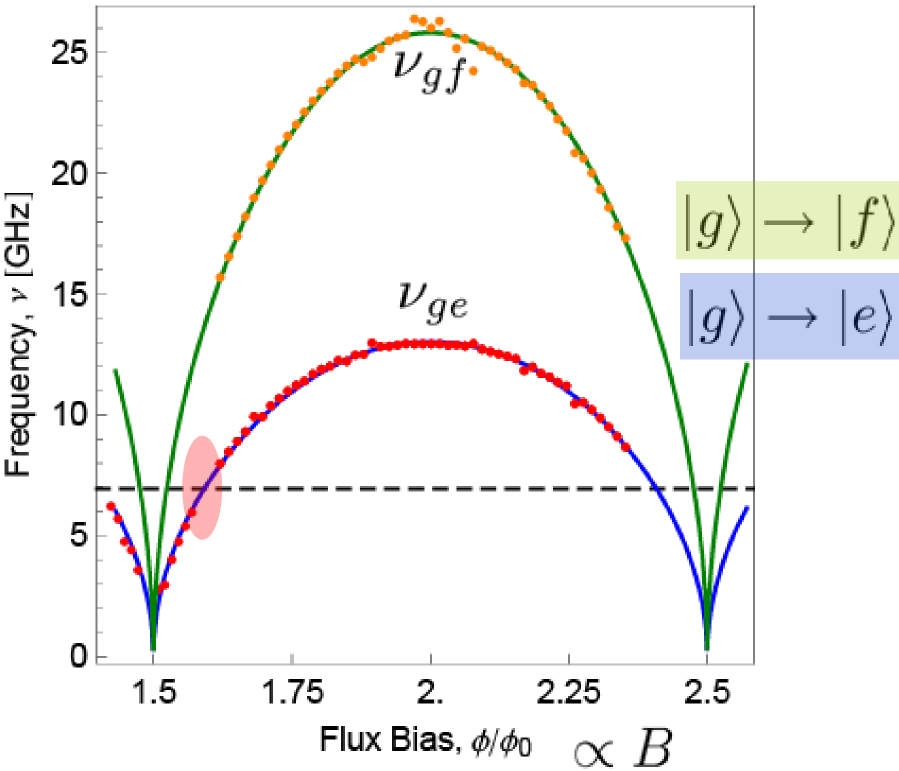
long excited state life time $T_1 = 1/\gamma$

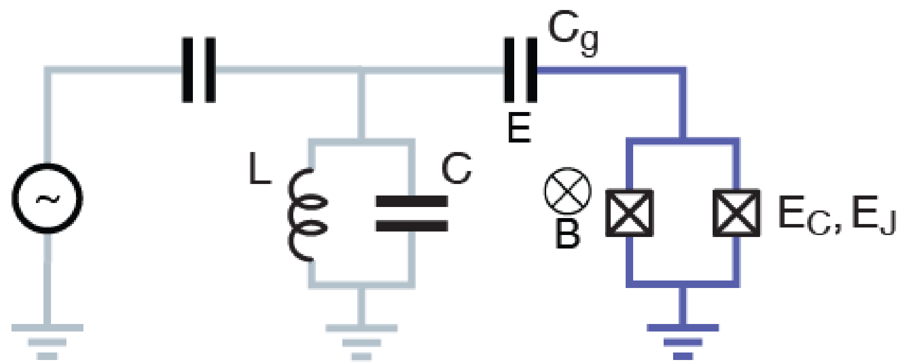
Transmon energy levels vs. E



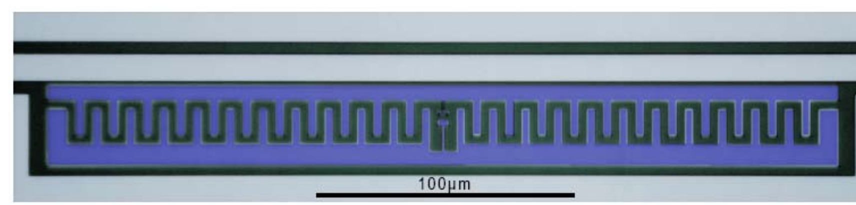
B-Field Dependence of Energy Levels

spectroscopic measurement of transition frequency vs. magnetic field B:





qubit coupled to resonator



tune qubit into resonance

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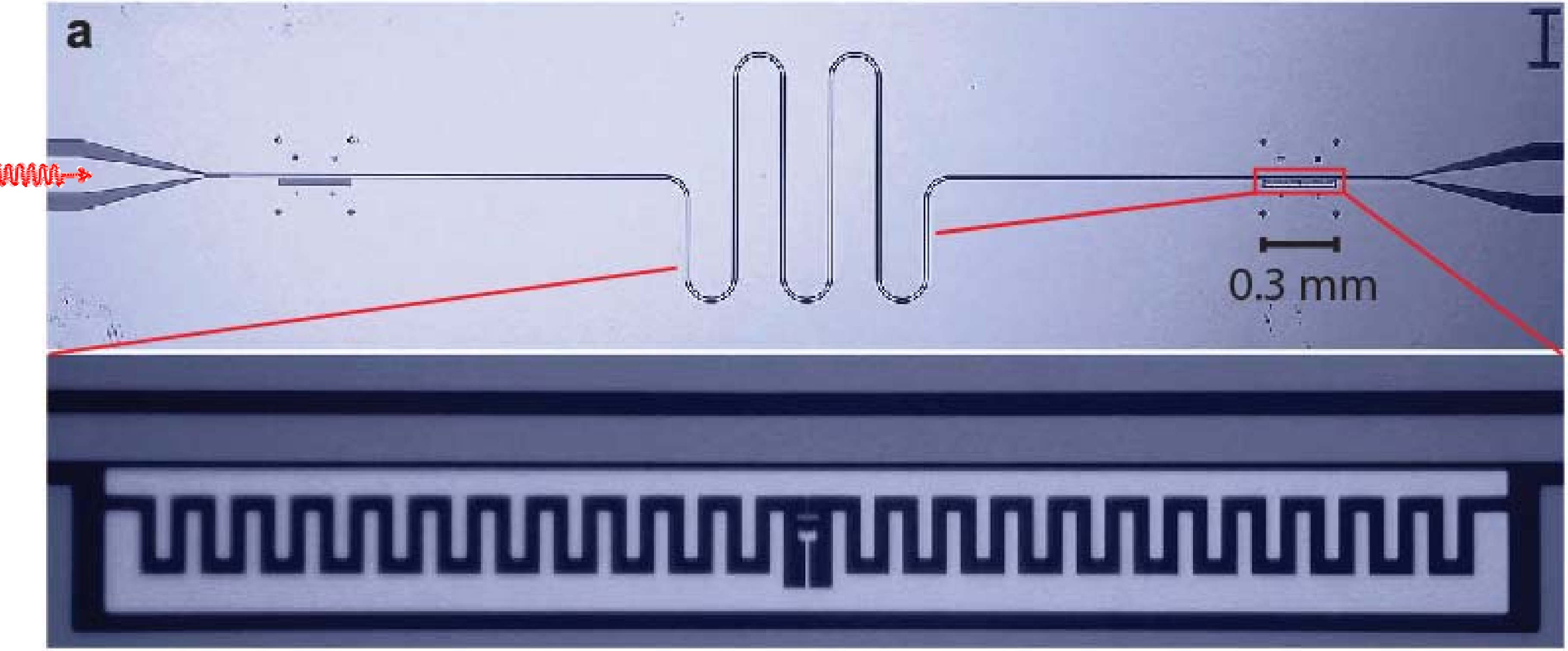
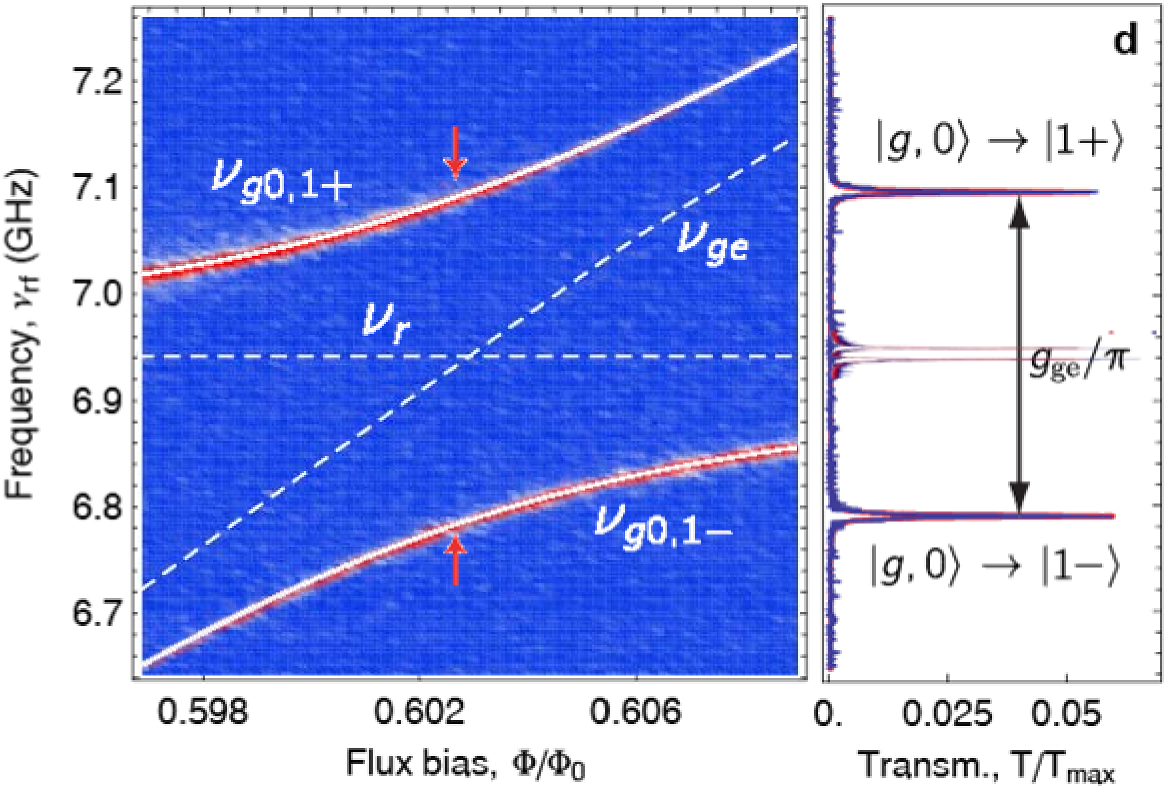
J. Koch *et al.*, Phys. Rev. A **76**, 042319 (2007)

Strong Coupling Cavity QED Circuit



Resonant Vacuum Rabi Mode Splitting ...

... with one photon ($n = 1$):

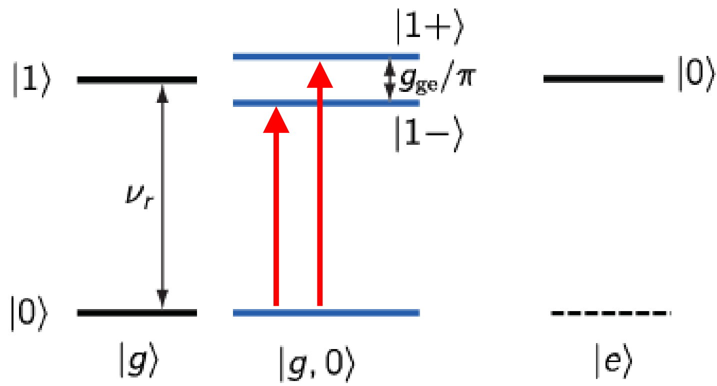


very strong coupling:

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

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

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



forming a 'molecule' of a qubit and a photon

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Swiss Federal Institute of Technology Zurich

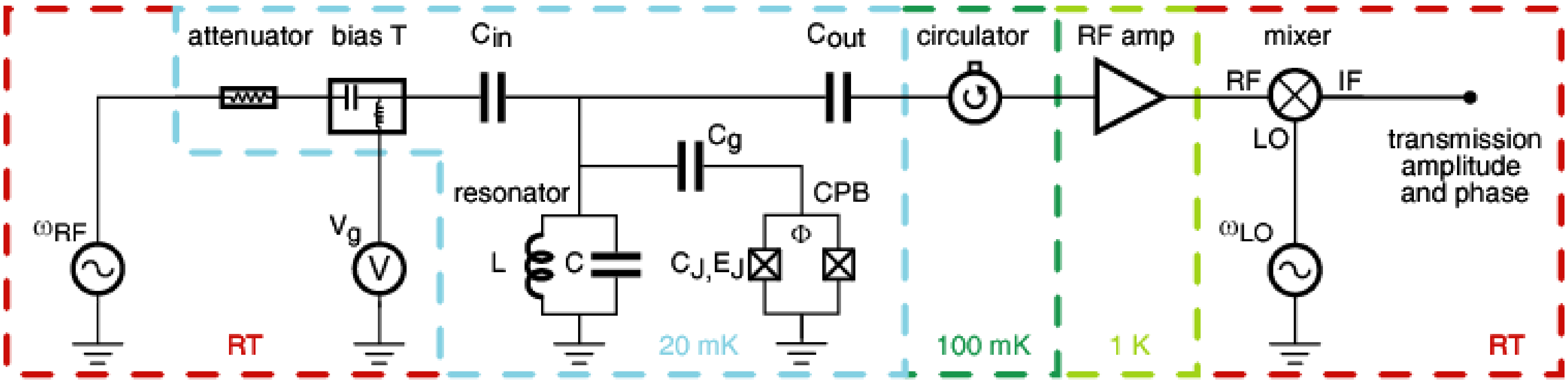
first demonstration: A. Wallraff, … and R. J. Schoelkopf, *Nature (London)* **431**, 162 (2004)

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

How to Measure Single Microwave Photons

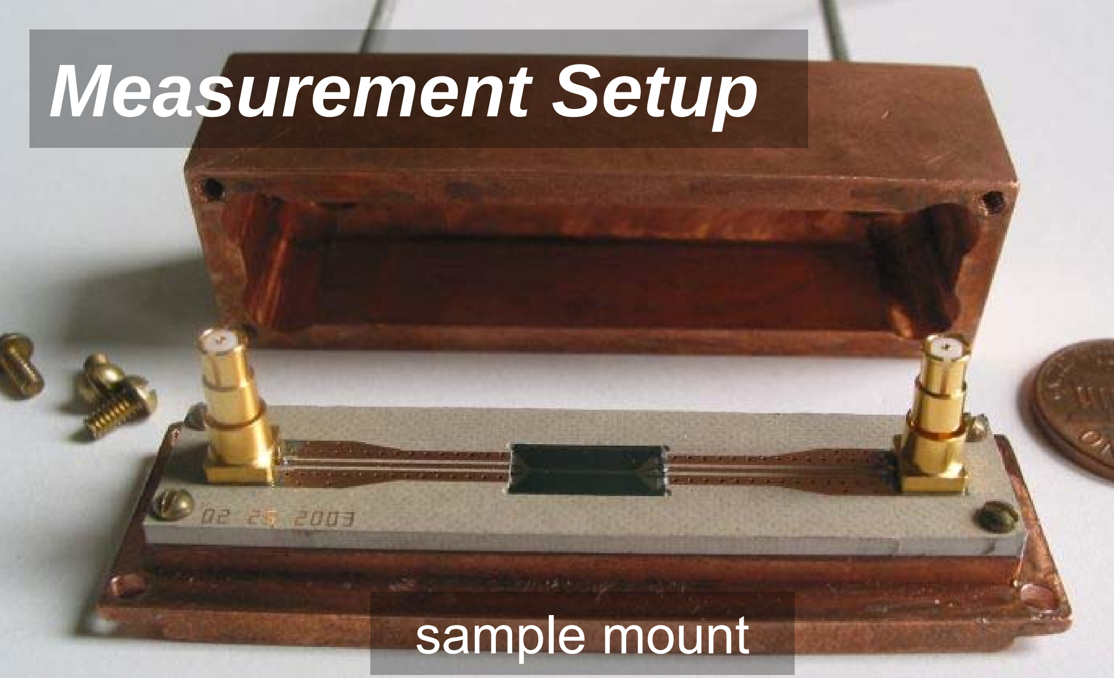
- average power to be detected

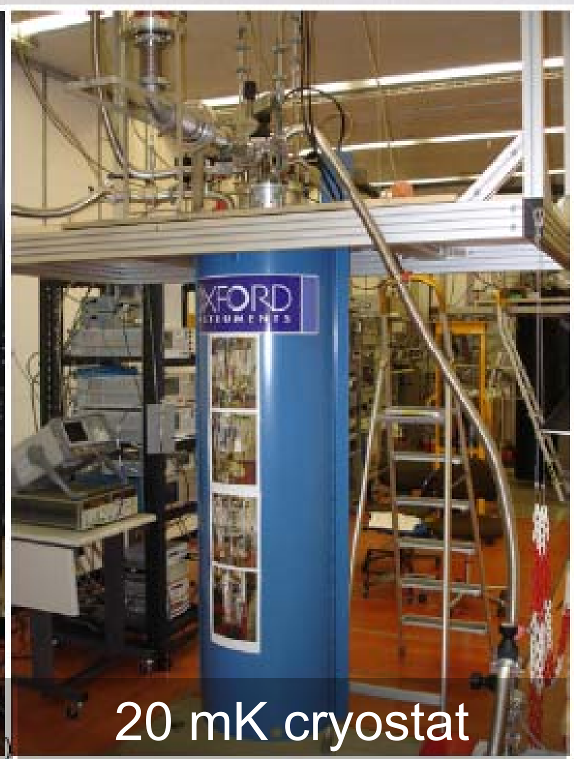
$$\rightarrow \langle n=1\rangle \hbar\omega_r\kappa/2 \approx P_{RF} = -140\,\text{dBm} = 10^{-17}\,\text{W}$$



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

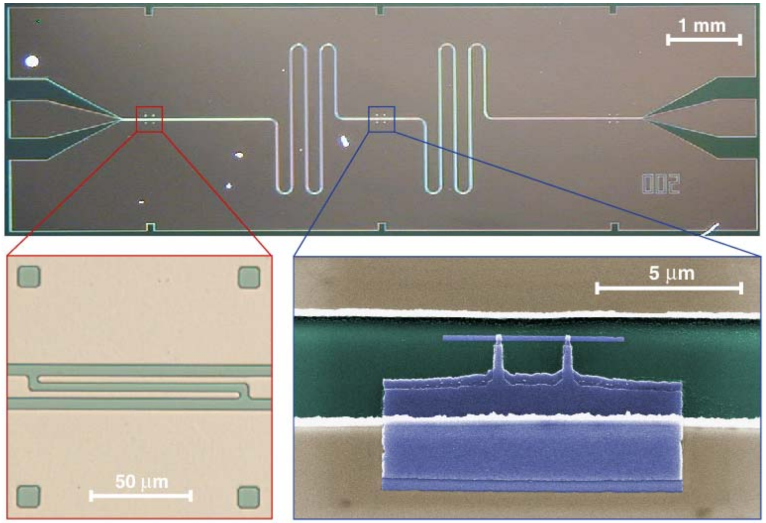
Measurement Setup





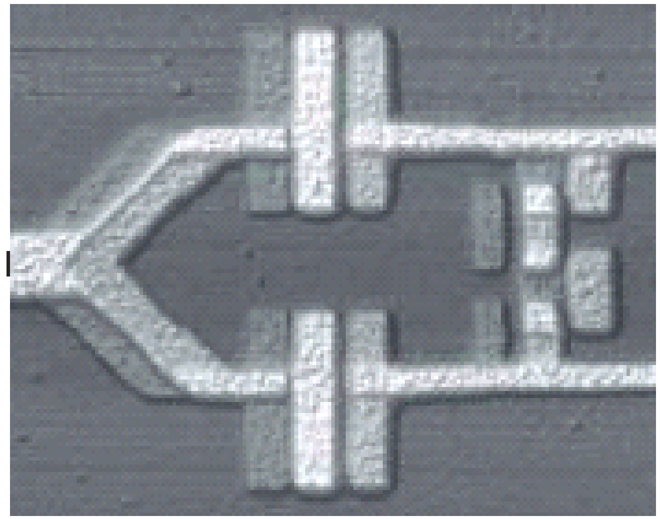
Strong Coupling with Superconducting Circuits

circuit quantum electrodynamics (QED) experiments since 2004:



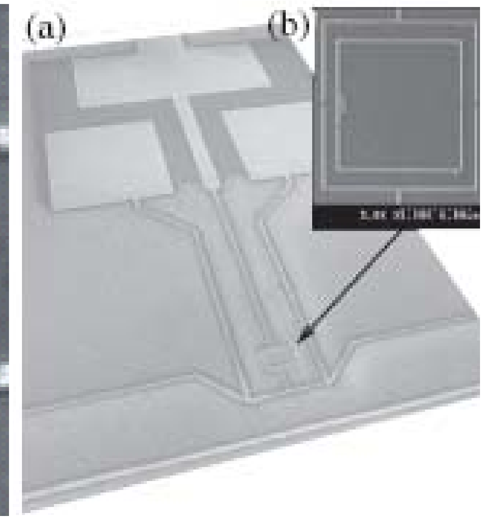
Yale University (now also ETH Zurich)

Nature (London) **431**, 162 (2004)



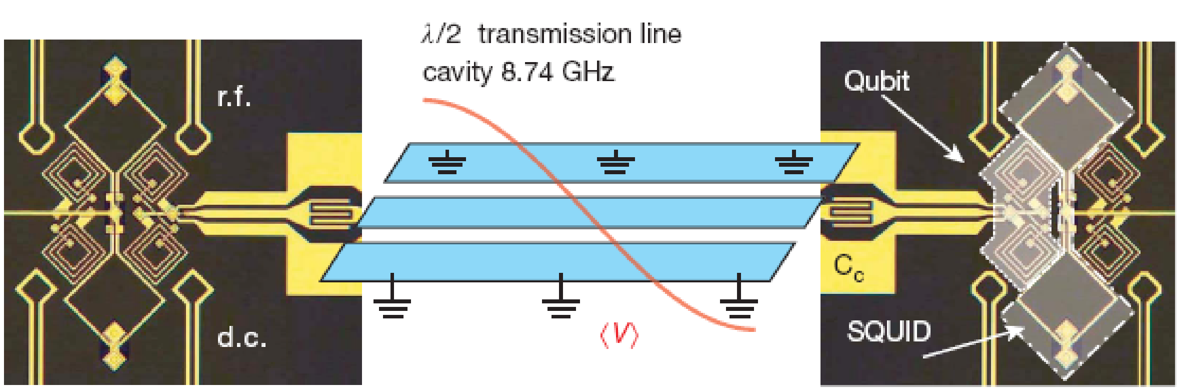
TU Delft.

Nature (London) **431**, 159 (2004)



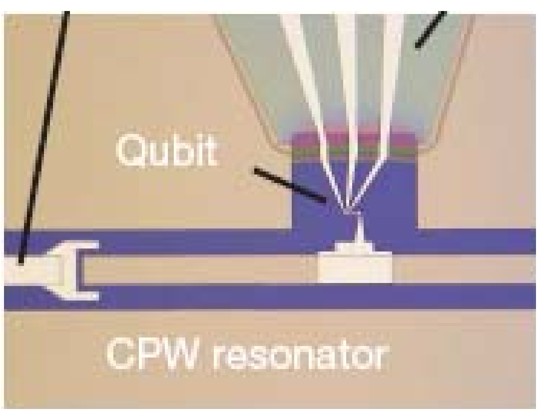
NTT

PRL **96**, 127006 (2006)



NIST Boulder (now also at UCSB)

Nature (London) **449**, 438 (2007)



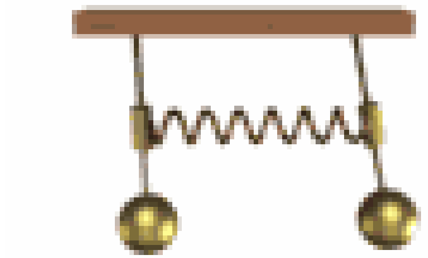
NEC

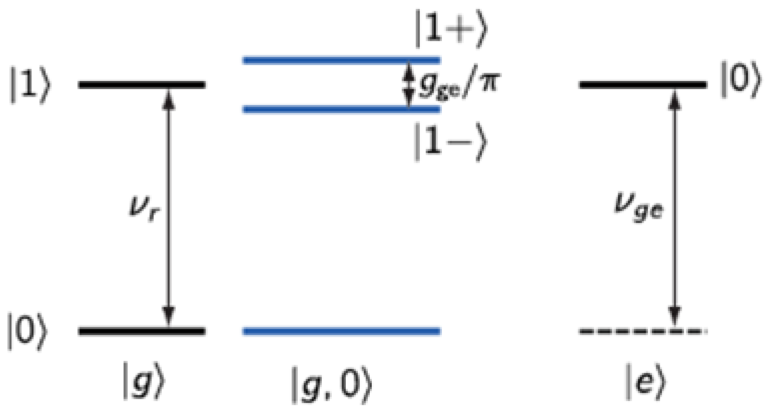
Nature (London) **449**, 588 (2007)

The Quantum Nonlinearity of the J-C Ladder

Why to probe the nonlinearity?

- classical interpretation of first doublet
- quantum effects
  - scaling of coupling rate g_{eff} with amplitude (square root of photon number n)
- $\sqrt{n}$-scaling is a pure quantum effect
  - direct evidence for field quantization
  - studied in time-resolved measurements of the atom but until recently not in spectroscopic experiments





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

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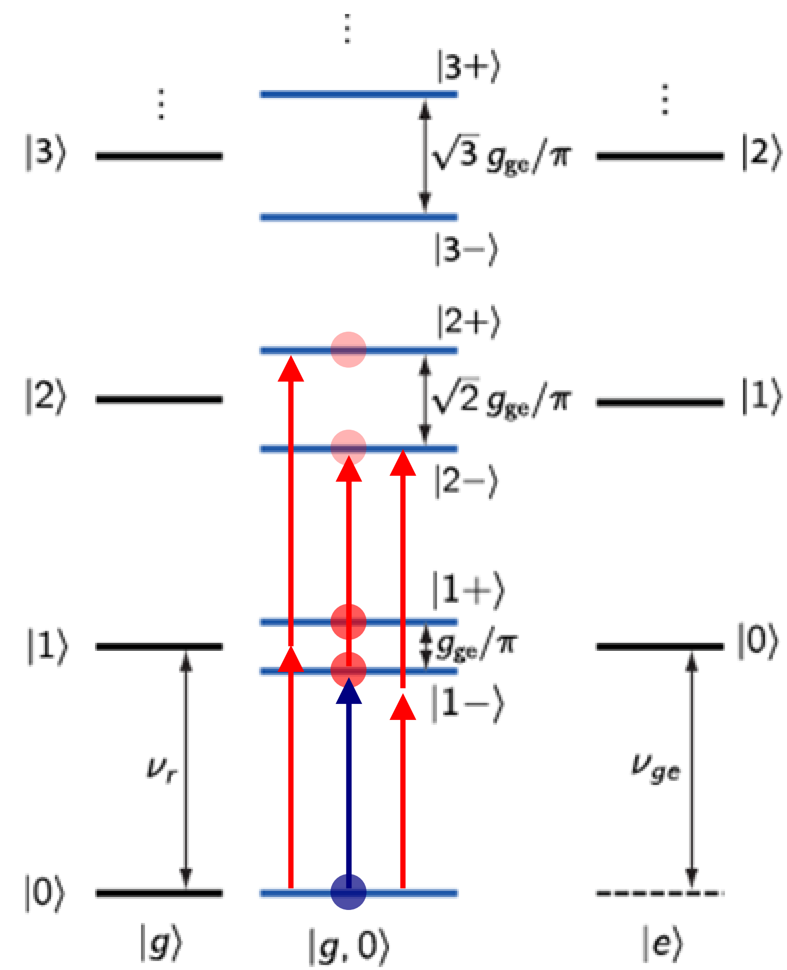
Climbing the Jaynes-Cummings Ladder

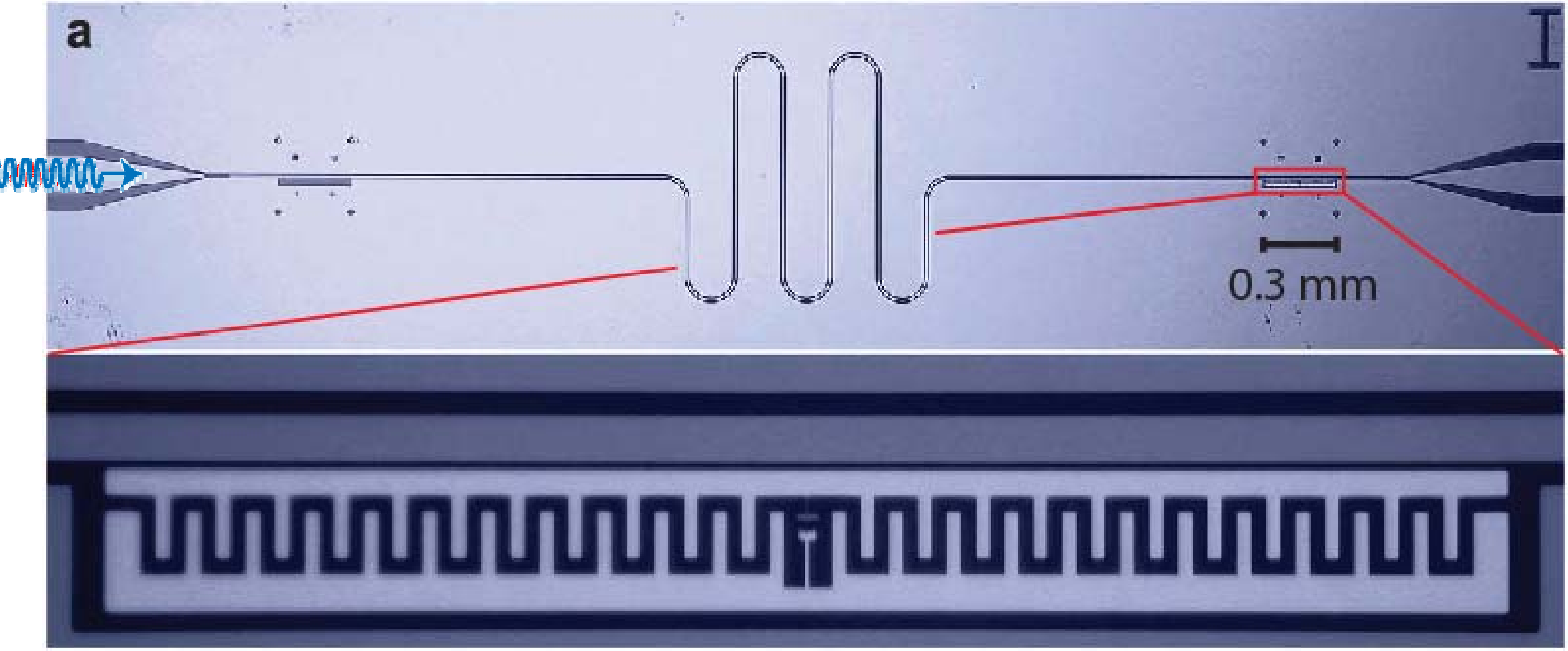
How to climb the ladder?

- cool to ground state $|g, 0\rangle$
- Controllably increase $\#\ n$ of excitations
  - thermal population
  - multi photon transitions
  - pump and probe spectroscopy



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

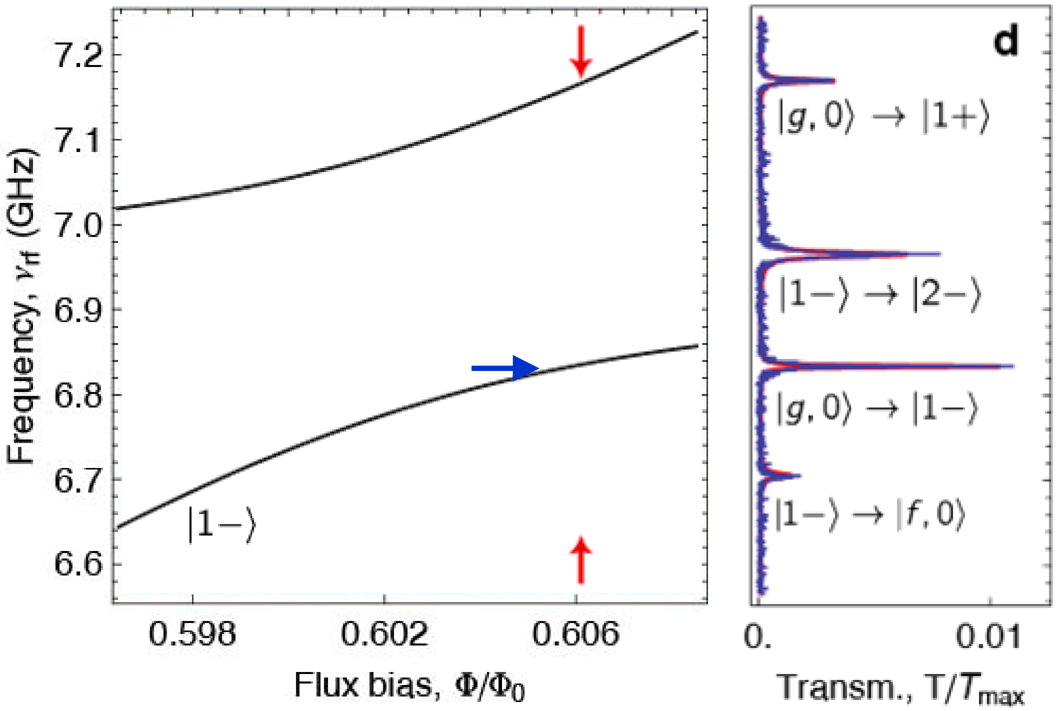
Two-Photon Pump and Probe Spectroscopy



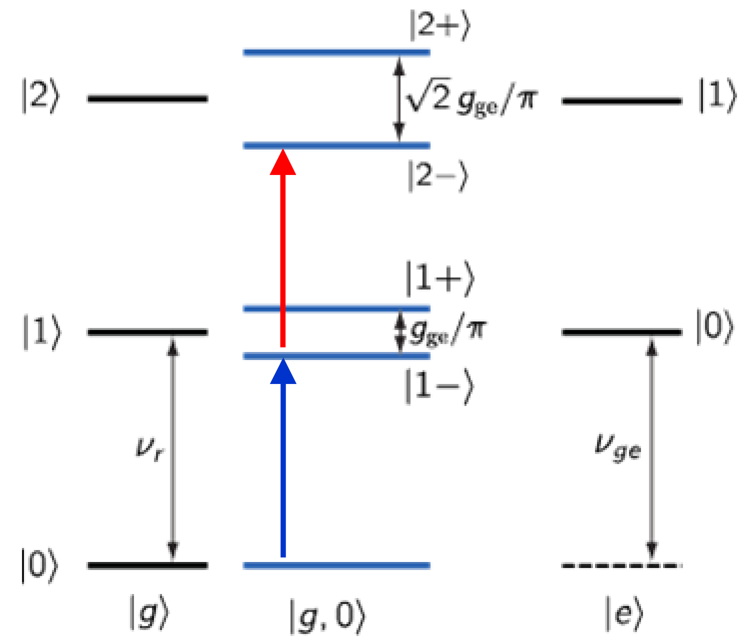
J. Fink, M. Goeppl, M. Baur, R. Bianchetti, P. Leek, A. Blais, A. Wallraff,
Nature (London) **454**, 315 (2008)

Resonant Vacuum Rabi Mode Splitting ...

... with two photons ($n = 2$):



pump and probe: $|n-\rangle$



- $|n-\rangle \rightarrow |n+\rangle$ is weak

J. Fink, M. Goeppl, M. Baur, R. Bianchetti, P. Leek, A. Blais, A. Wallraff, *Nature (London)* **454**, 315 (2008)

Resonant Vacuum Rabi Mode Splitting ...

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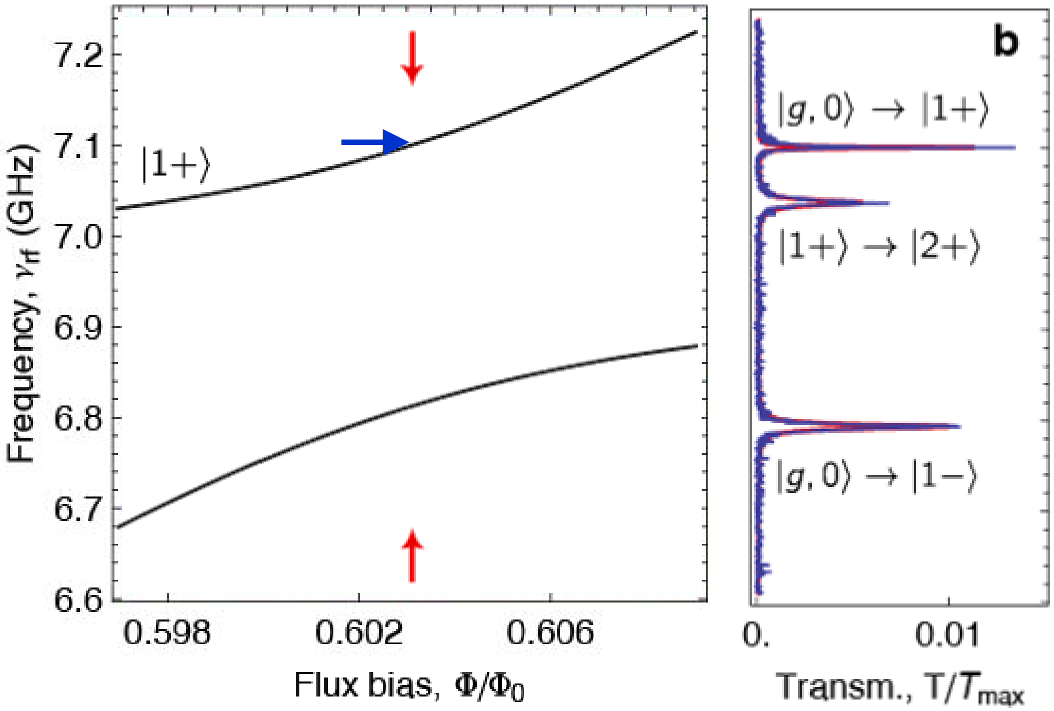
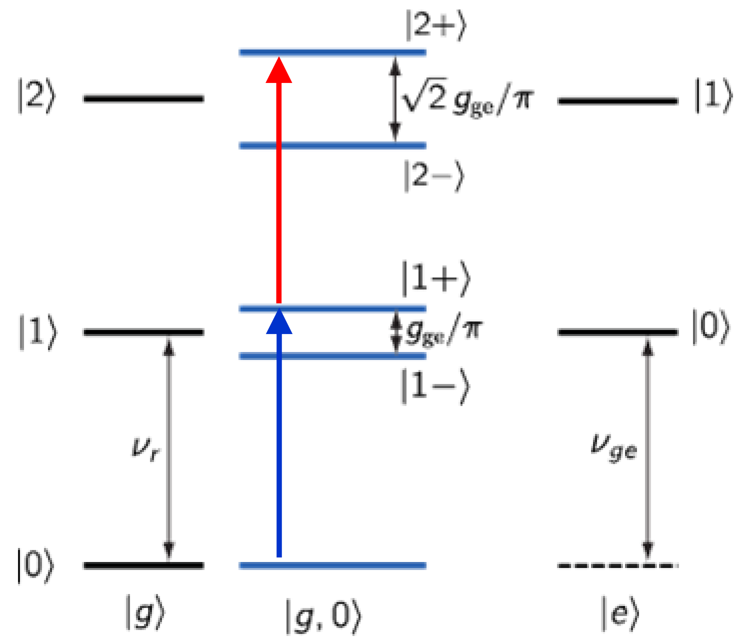


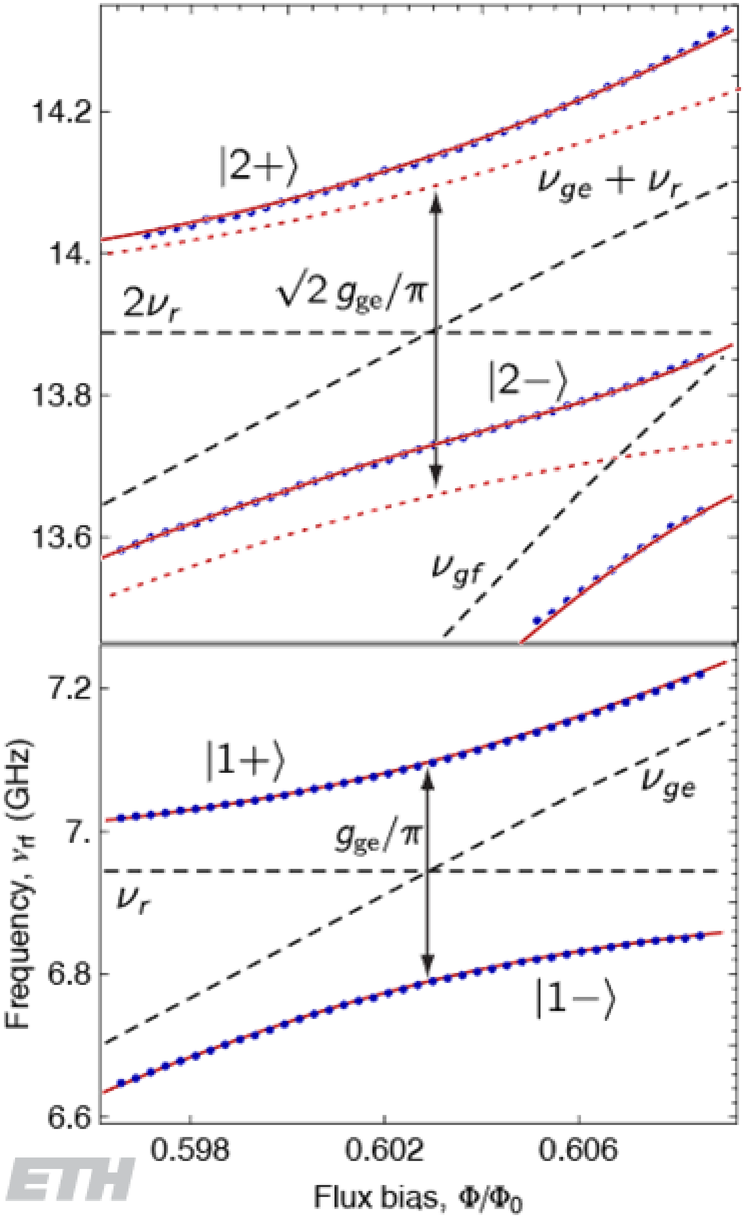
pump and probe: $|n+\rangle$



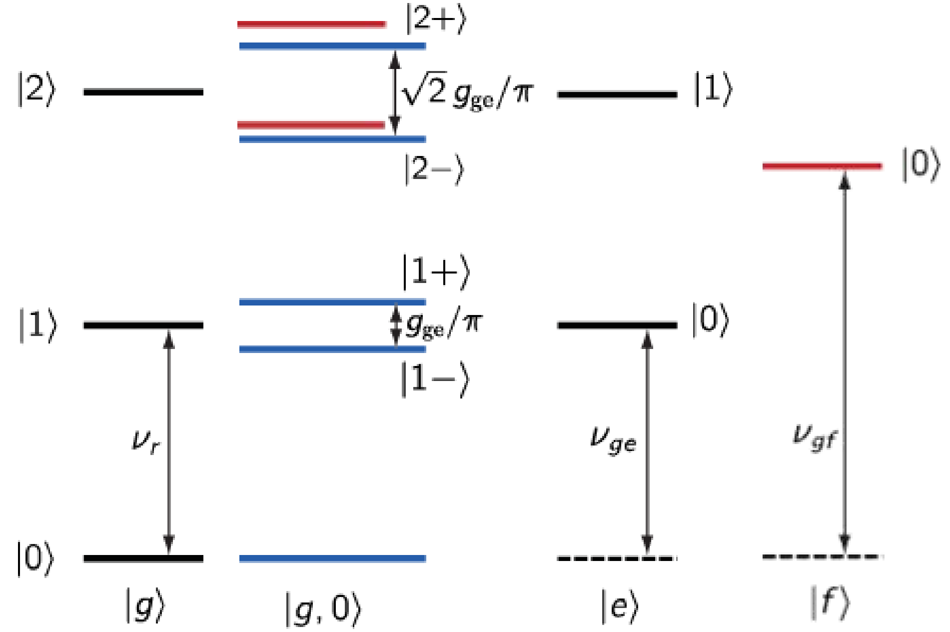
- $|n+\rangle \rightarrow |n-\rangle$ is weak

J. Fink, M. Goeppl, M. Baur, R. Bianchetti, P. Leek, A. Blais, A. Wallraff, *Nature (London)* **454**, 315 (2008)

Sqrt(n) Quantum Nonlinearity



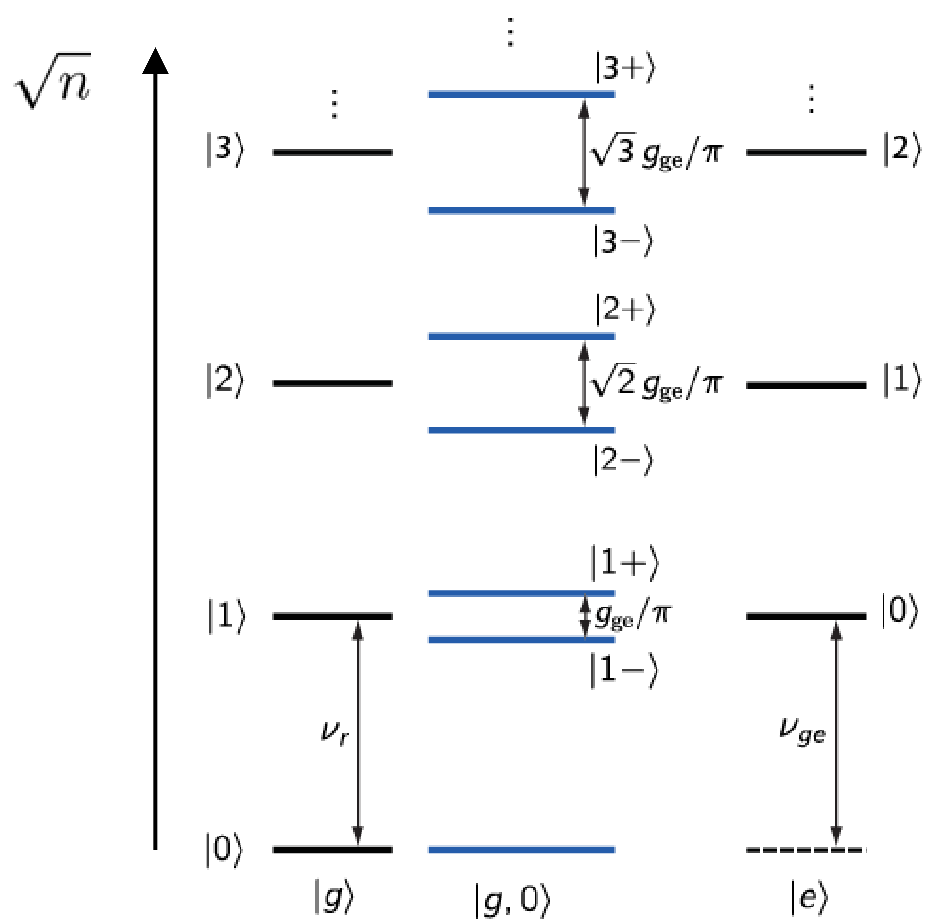
- energies reconstructed from pump + probe
- shifts due to 3rd qubit level $|f\rangle$
- full Hamiltonian yields good agreement
- clear spectroscopic demonstration of field quantization in cavity QED



J. Fink, … , A. Wallraff, *Nature (London)* **454**, 315 (2008)

Cavity QED with Multiple Atoms

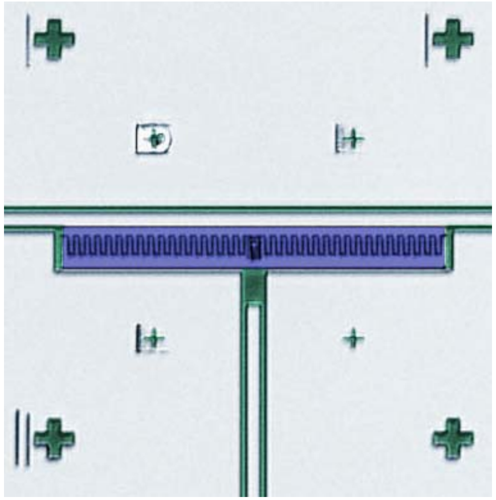
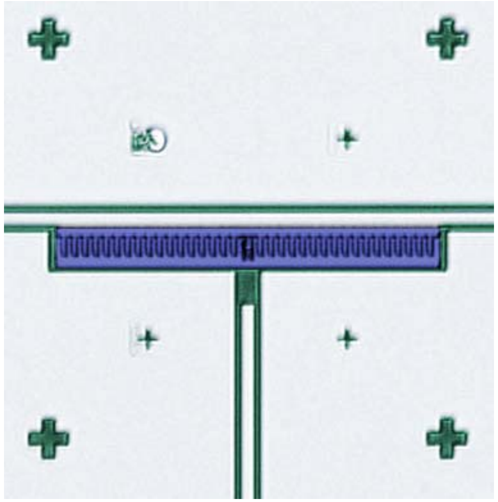
coupling scales with number n of photons



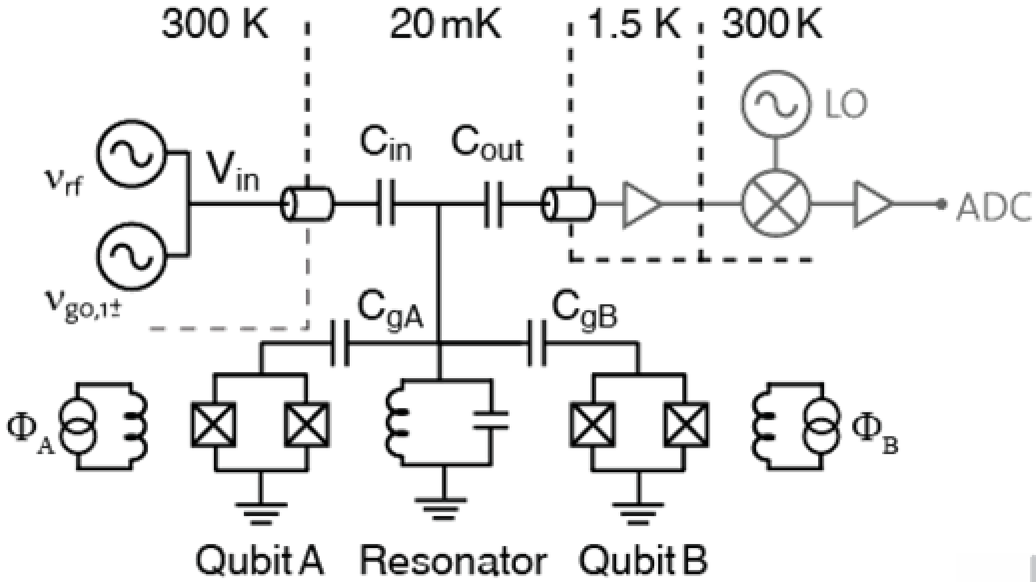
coupling scales with number m of atoms

$\sqrt{m}$

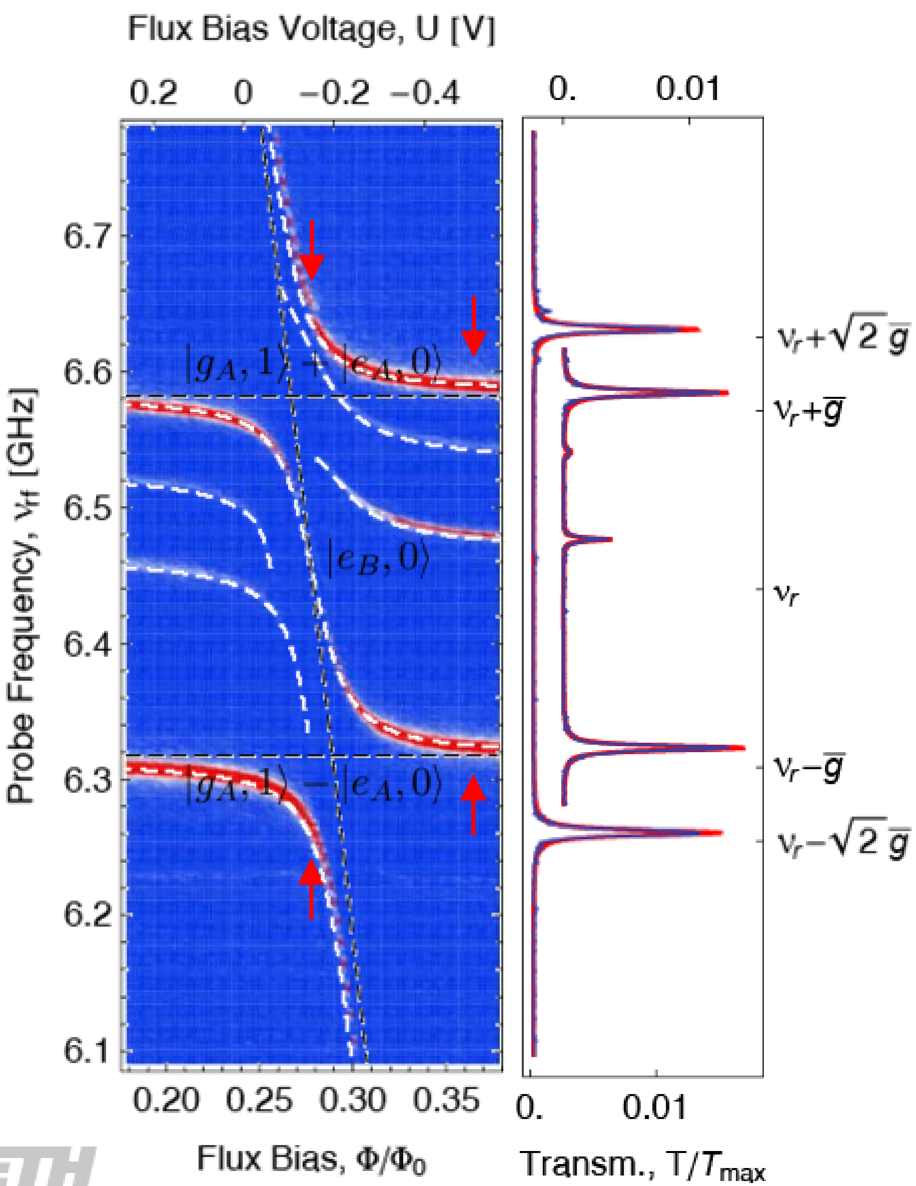
Two-'Atom' Cavity QED

qubit A:  qubit B: 

- two almost identical qubits
- two almost identical coupling constants $g_{A,B}$
- local flux control $\Phi_{A,B}$



Two Qubit Vacuum-Rabi Mode Splitting



- qubit A in resonance with resonantor ($\nu_{ge} = \nu_r$)

$$|g_A, 1\rangle \pm |e_A, 0\rangle$$

- qubit B tuned into resonance with local flux Φ_B
- two qubit & resonator coupled states

$$|g_A g_B 1\rangle \pm |e_A g_B 0\rangle \pm |g_A e_B 0\rangle$$

- multi-qubit splitting scales as $\sqrt{m}\,\bar{g}$, where m is the number of qubits
- and a little bit of a two-photon ($n = 2$) state

Dispersive Qubit-Photon Interaction

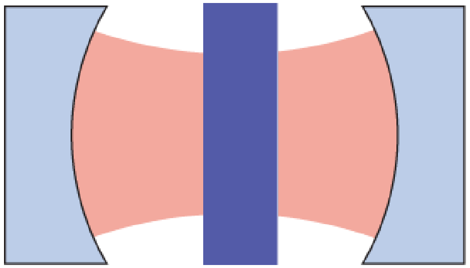
approximate diagonalization in the dsipersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

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

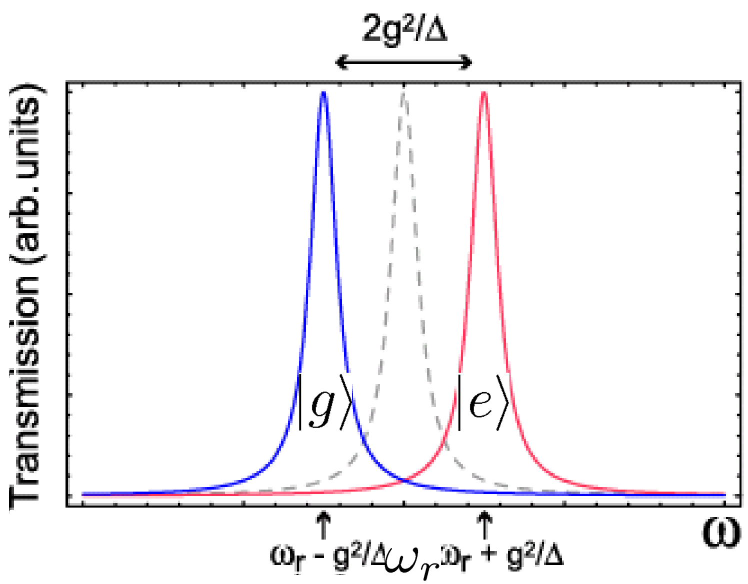
// cavity frequency shift *and* qubit ac-Stark shift

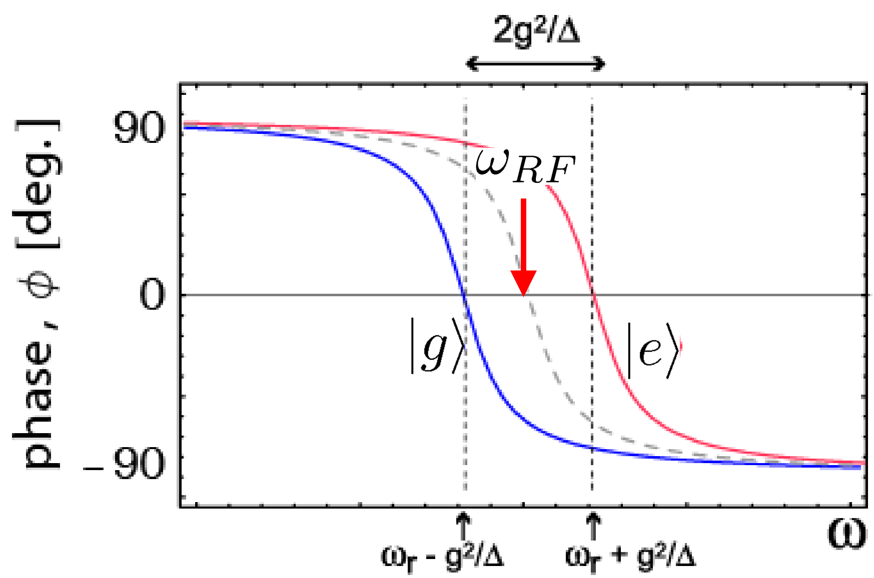
// Lamb shift

$|g\rangle : \epsilon > 1$



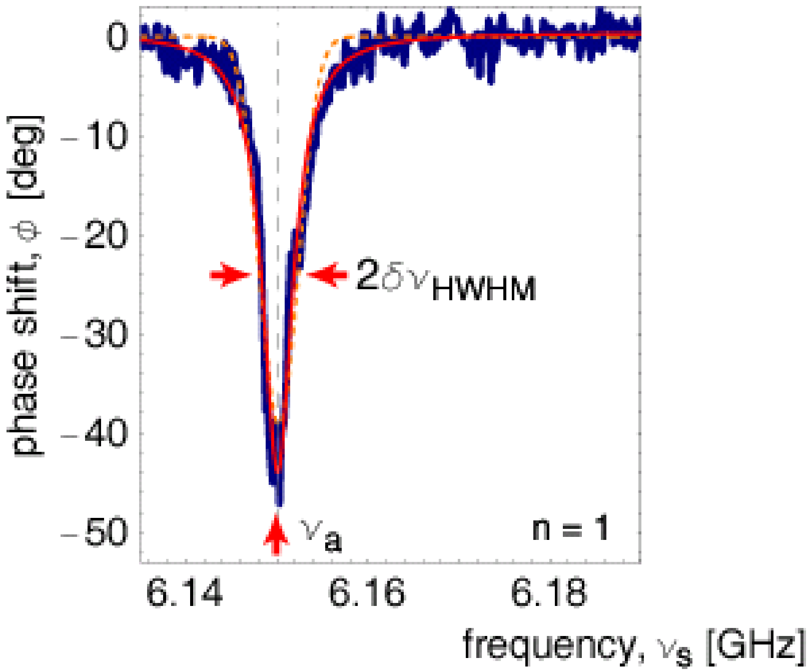
$|e\rangle : \epsilon < 1$

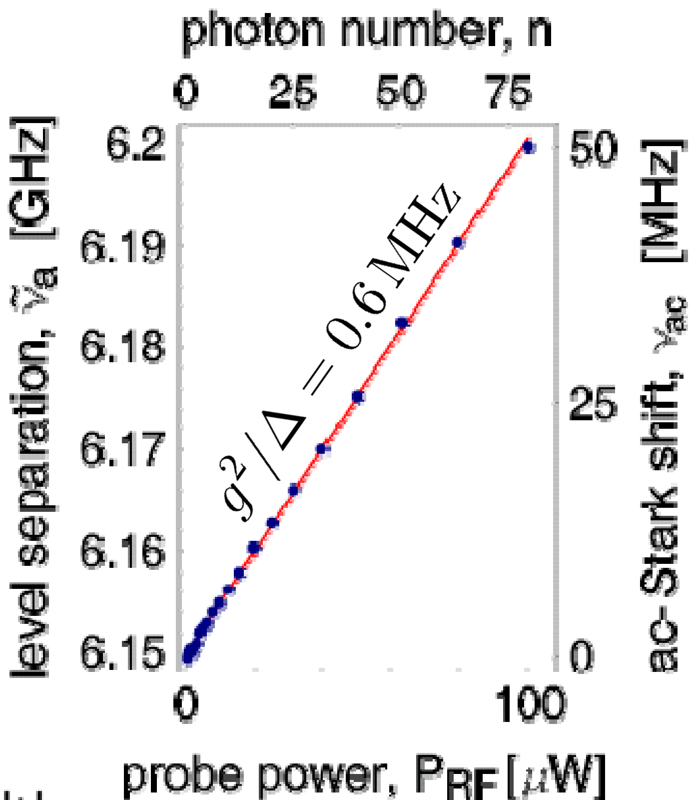




A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Qubit Spectroscopy & AC-Stark Effect





photon number dependence of line position and width

for $\Delta_{\mathrm{a,r}} = \omega_a - \omega_r \gg g$

ac-Stark (light) shift

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

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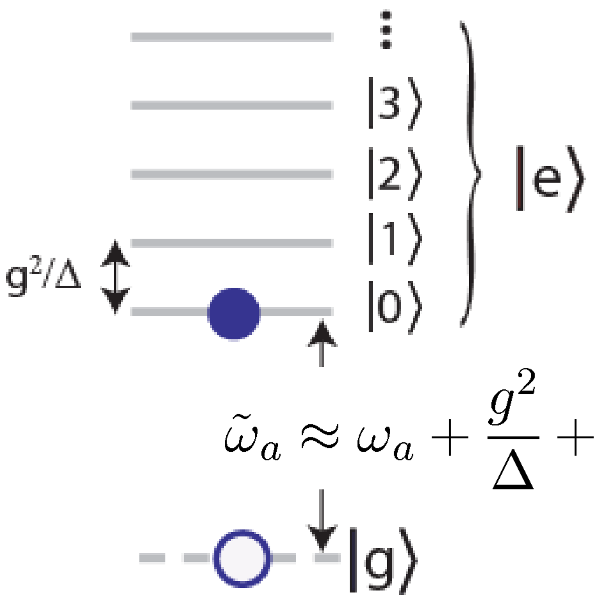
D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Photon Number Dependent 'Quantum' Light Shift

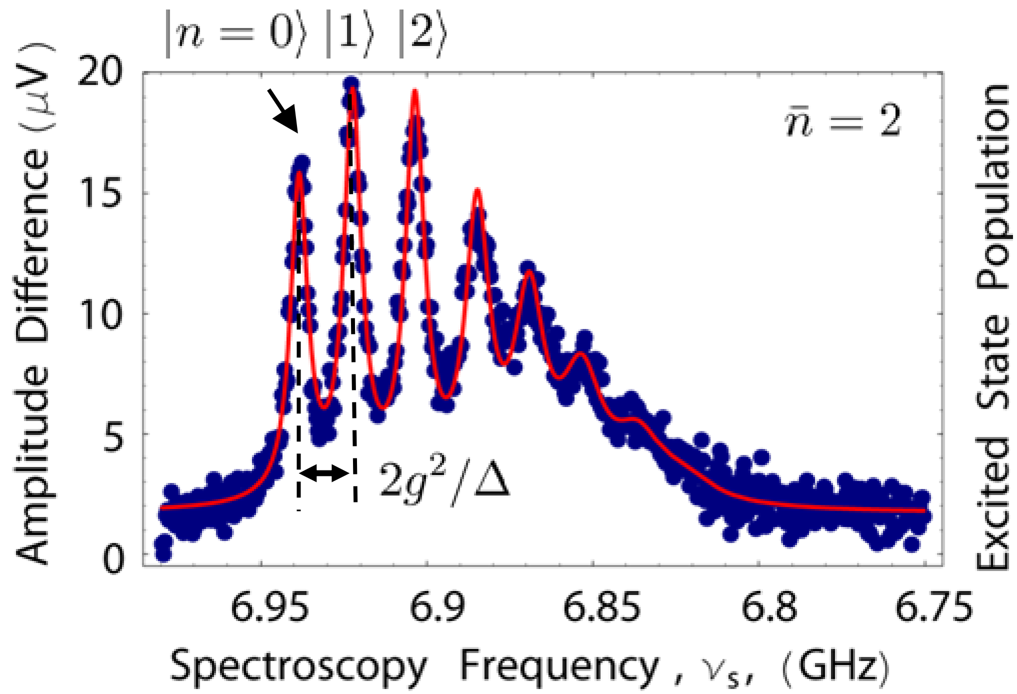
for $\Delta_{\mathrm{a,r}} = \omega_a - \omega_r \gg g$

ac-Stark (light) shift

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

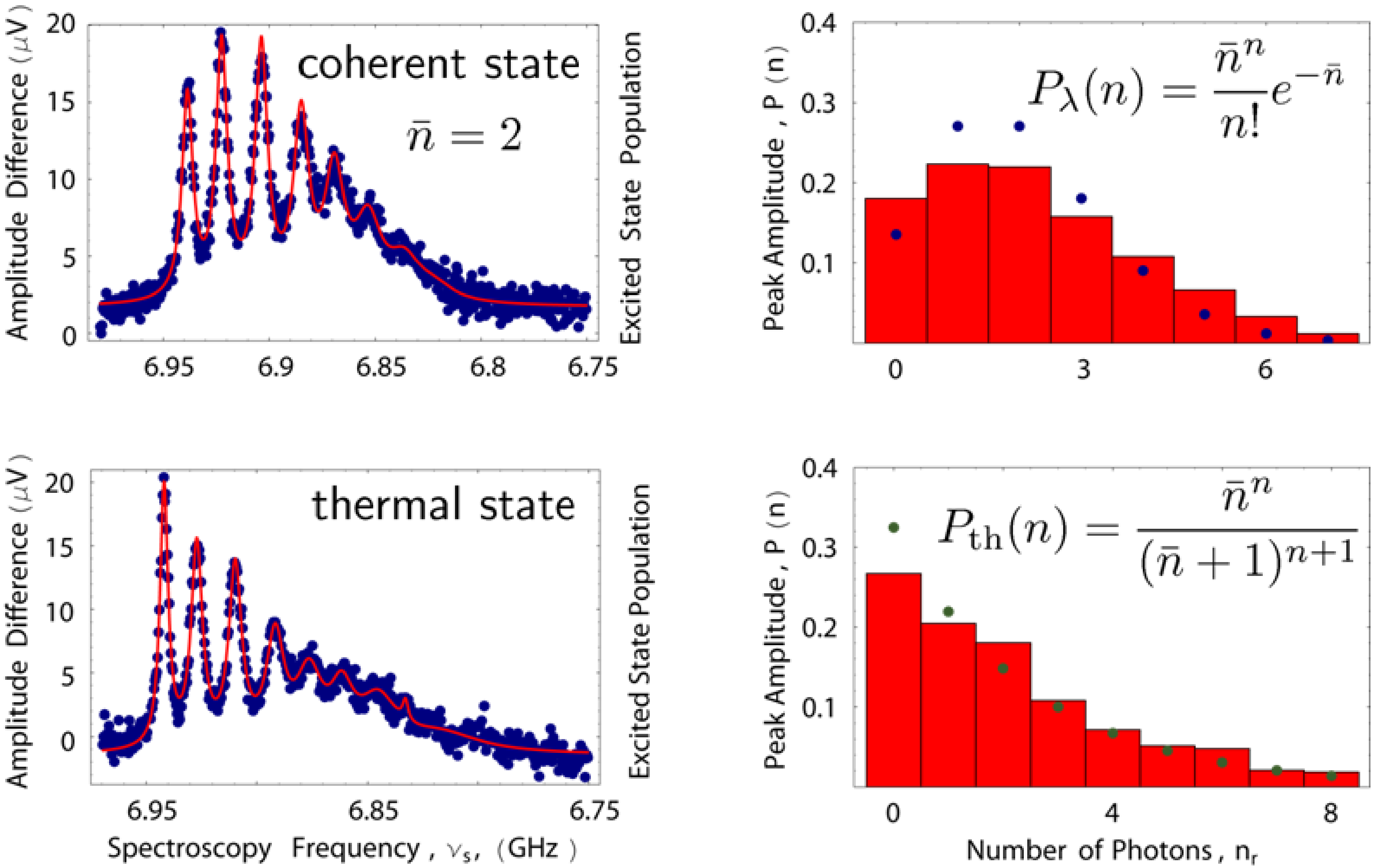


$$\tilde{\omega}_a \approx \omega_a + \frac{g^2}{\Delta} + \frac{2g^2}{\Delta}n$$



weight of spectroscopic peaks relate to probability $P(n)$ of photon number states

Measuring Photon Number Statistics



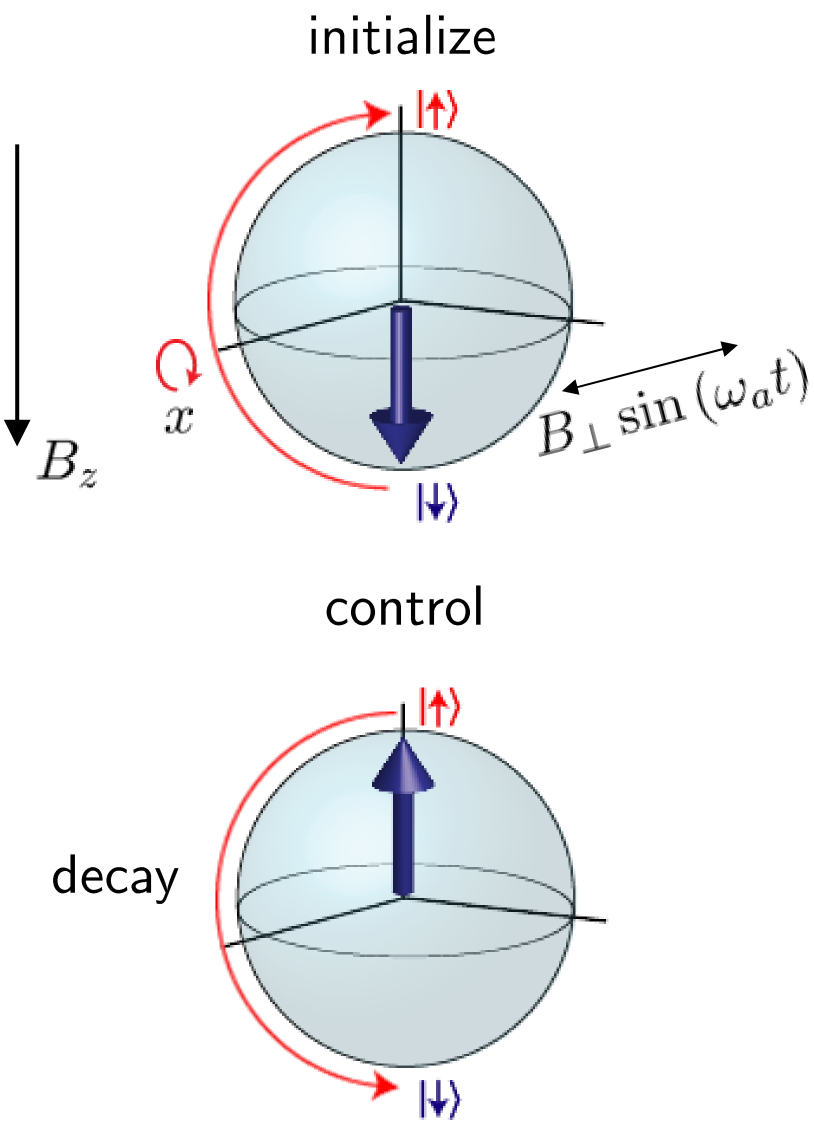
distinguish between coherent and thermal states

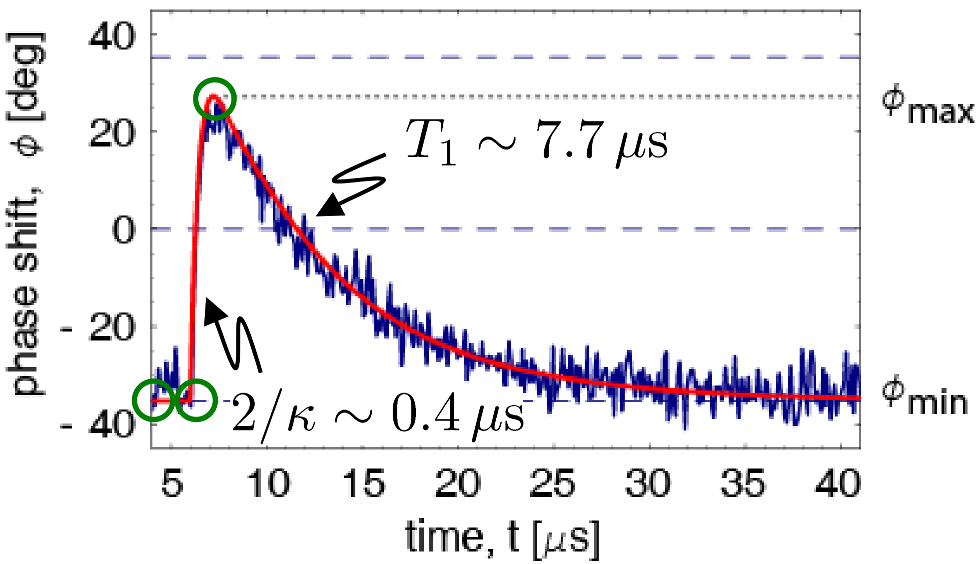
Schuster, Houck, Schreier, Wallraff, Gambetta, Blais, Frunzio, Johnson, Devoret, Girvin, Schoelkopf, *Nature* **445**, 515 (2007)

Qubit Control and Time Resolved Measurements

Rabi Oscillations, Ramsey Fringes, Tomography …

Qubit Control and Readout



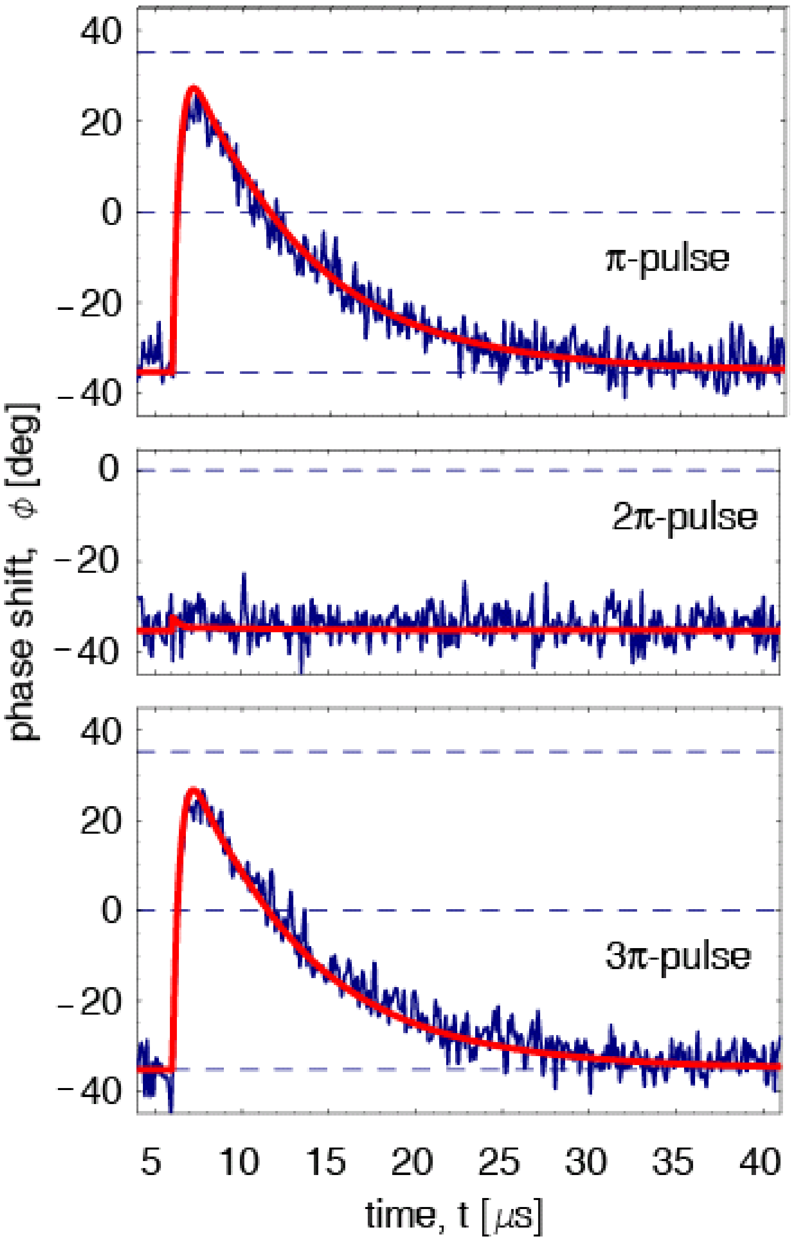


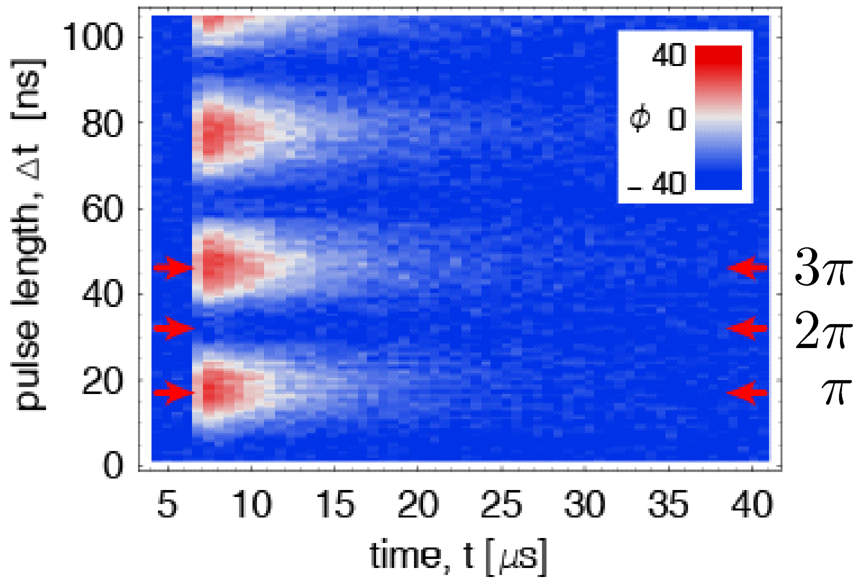
measurement properties:

- continuous
- dispersive
- quantum non-demolition
- in good agreement with predictions

Wallraff, Schuster, Blais, ... Girvin, and Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005)

Rabi Oscillations (weak cont. measurement)



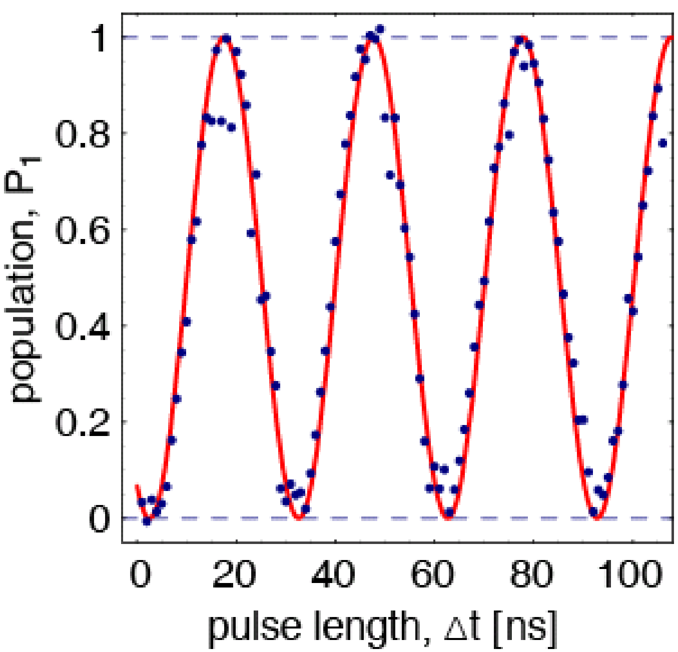


- high control fidelity
- high read-out fidelity
- good understanding of field-qubit interaction

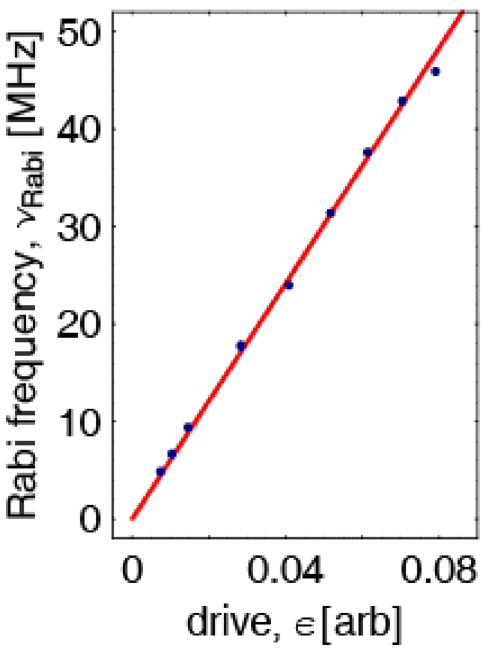
High Fidelity Control & Read Out

pulse scheme:

Rabi oscillations:

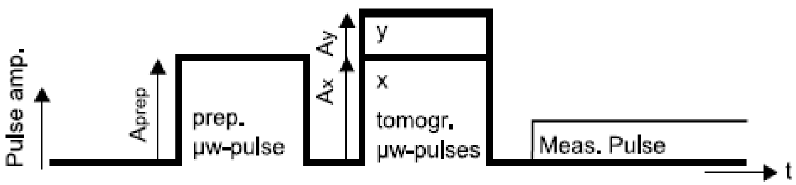


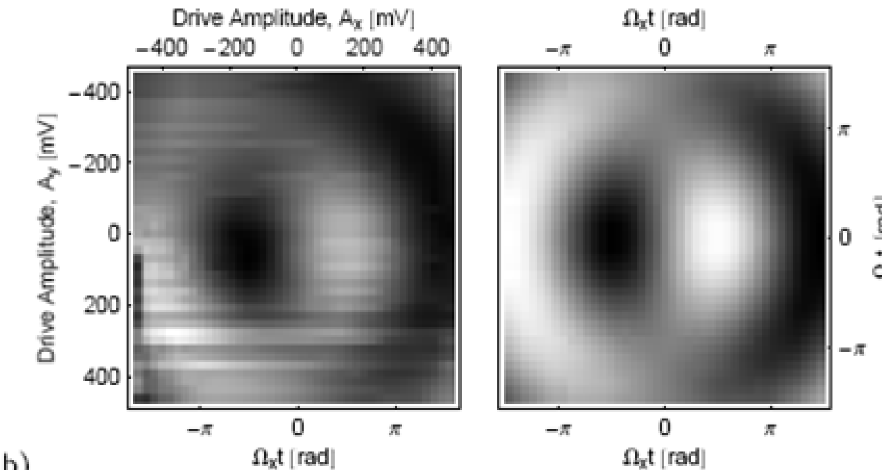
Rabi frequency:



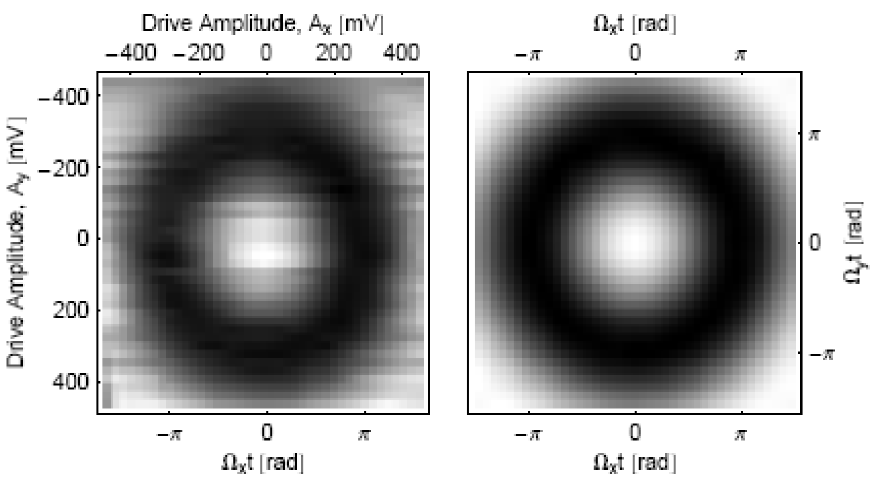
- high visibility $95 \pm 5\%$
- detailed understanding of qubit/read-out interaction

Quantum State Tomography

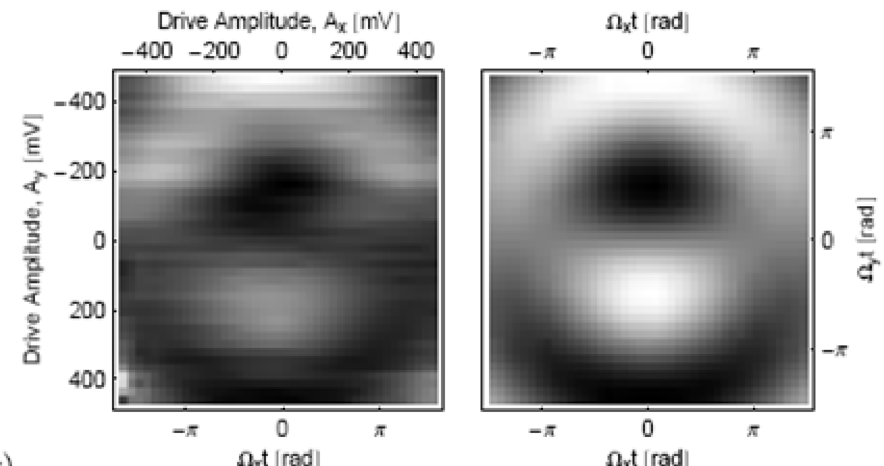




b)



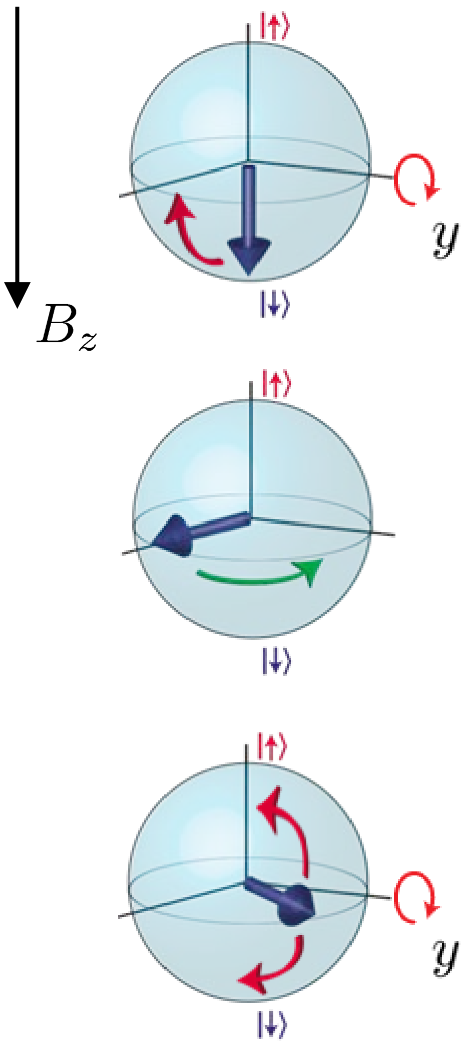
a)

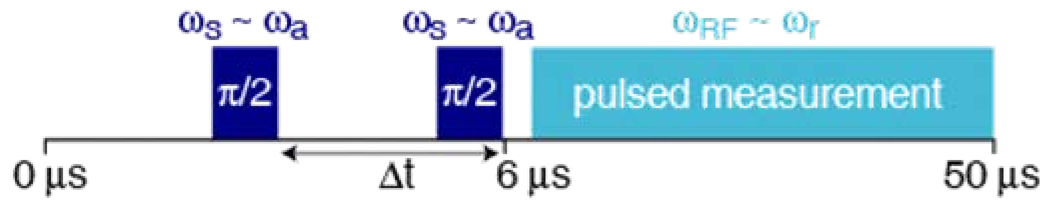


c)

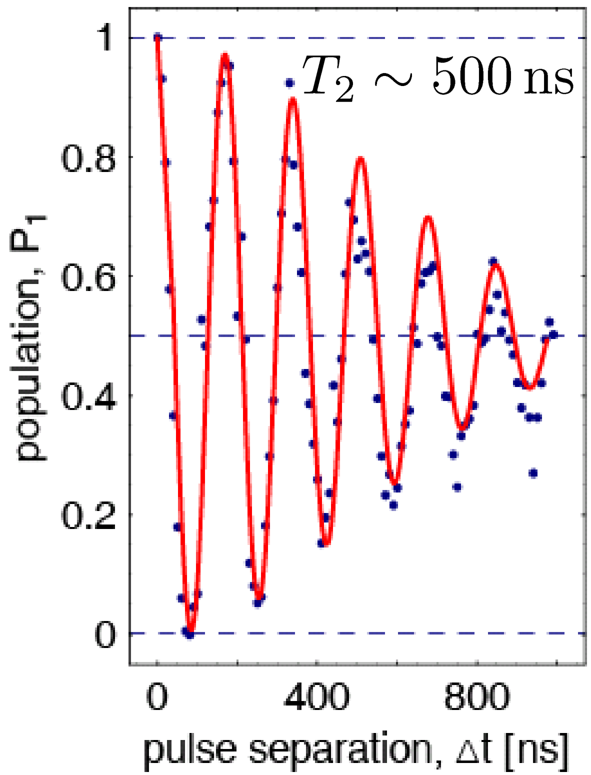
Single Qubit Coherence: Ramsey Fringes

pulse scheme:





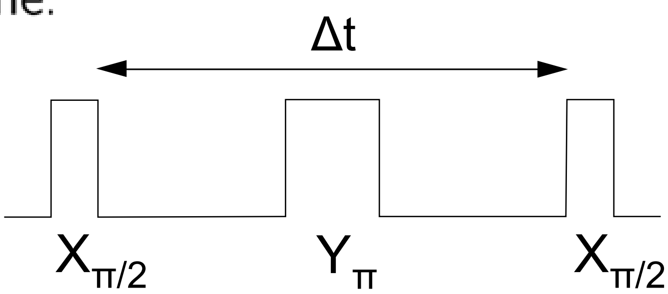
Ramsey fringes:

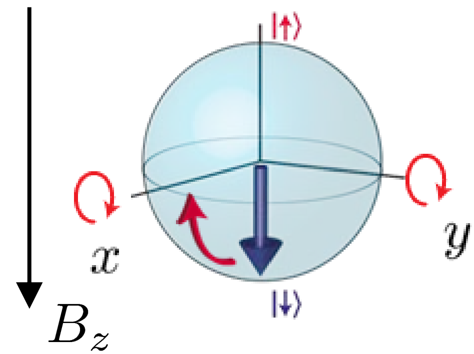


A. Wallraff *et al., Phys. Rev. Lett.* **95**, 060501 (2005)

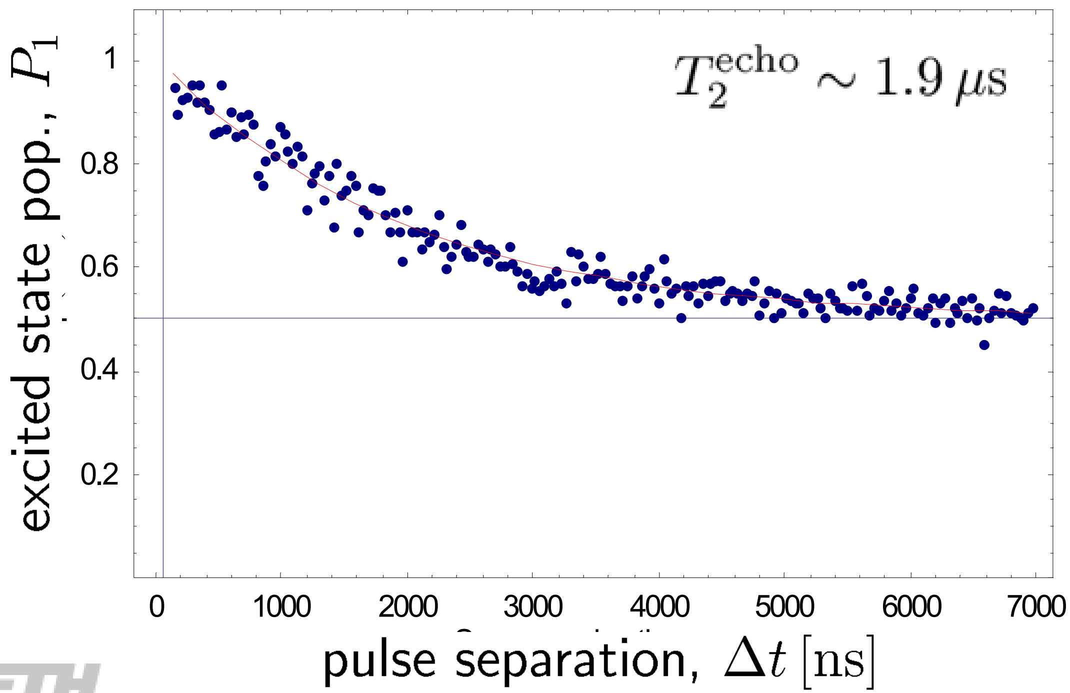
Spin Echo Experiment

pulse scheme:





result:



- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lars Steffen *et al.* (2007)

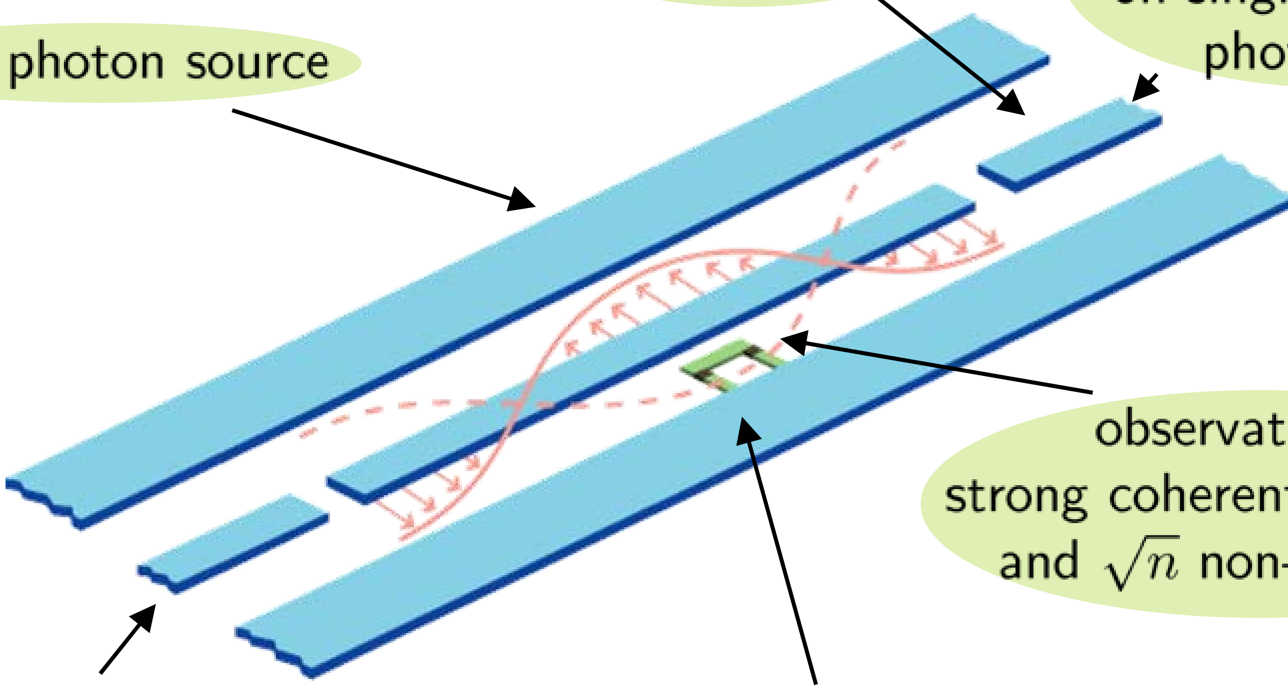
Circuit QED and Quantum Optics

in the future:
single photon detector
squeezed states

photon statistics:
coherent and
thermal states

measurements in solid
on single microwave
photon level

single photon source



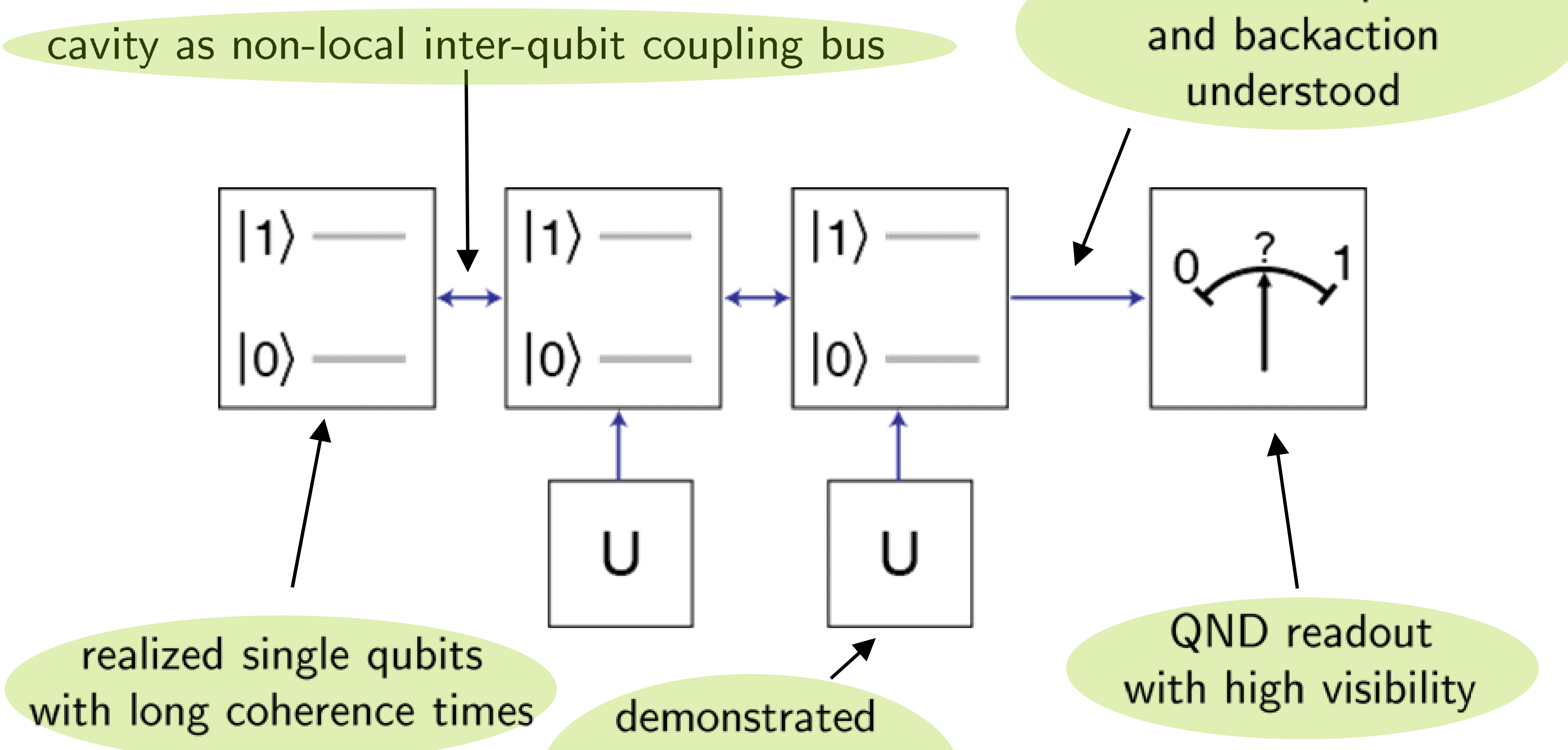
observation of
strong coherent interaction
and $\sqrt{n}$ non-linearities

realized cavities
with large vacuum fields
long photon lifetimes

artificial atom
with large dipole moment
long coherence time

Quantum Computation with Circuit QED

next steps:
realize single shot read-out
demonstrate 2 bit gate and quantum algorithm



The ETH Zurich Quantum Device Lab

with funding from:

ETH
Eidgenössische Technische Hochschule Zürich
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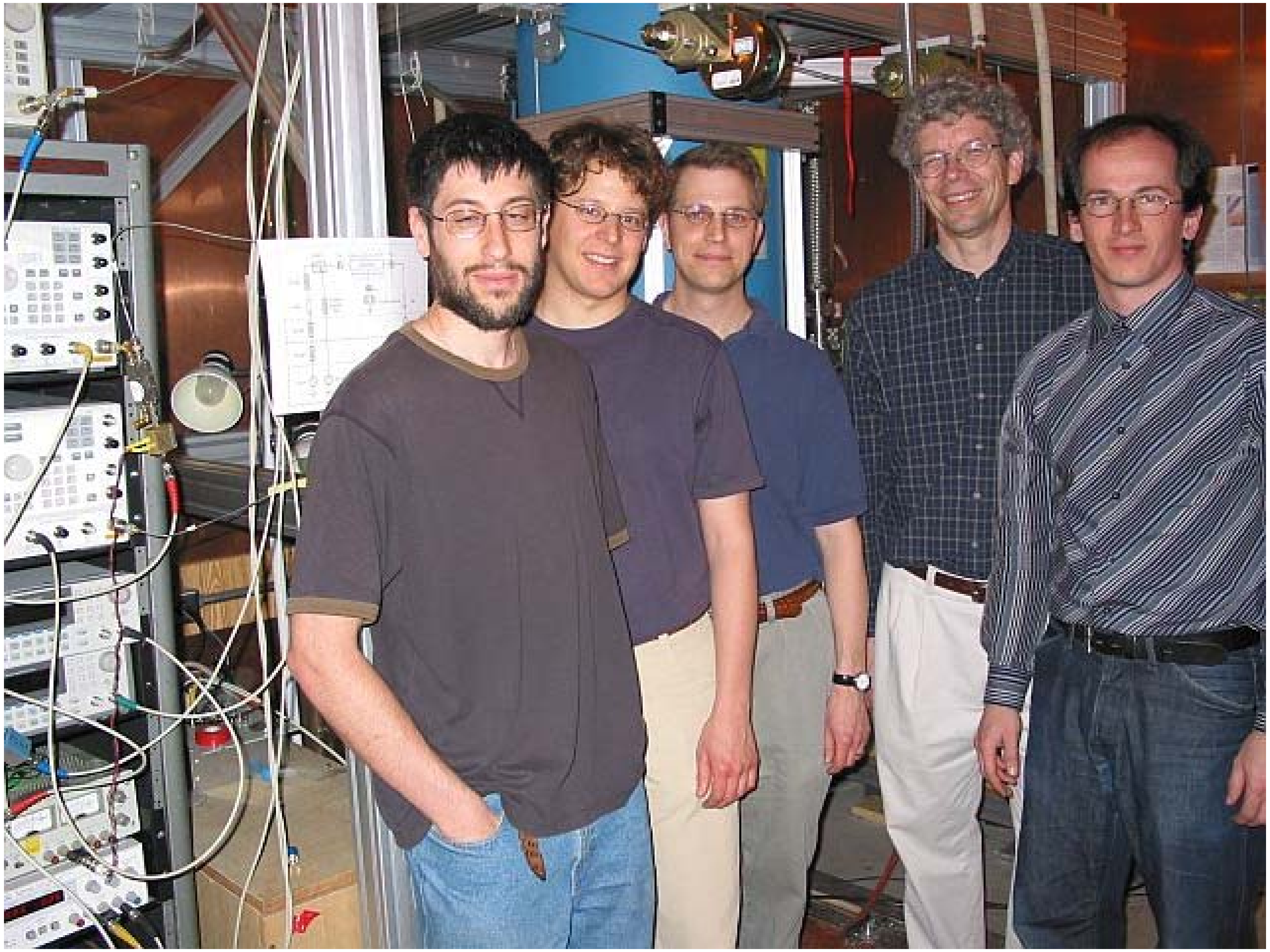
MARIE CURIE
FELLOWSHIPS

lab started in April 2006

The Yale Circuit QED Team



David Schuster
Alexandre Blais
Rob Schoelkopf
Steve Girvin
Andreas Wallraff

and also:
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Andrew Houck
Joseph Schreier
Blake Johnson
Jerry Chow
Hannes Majer
Luigi Frunzio
Michel Devoret

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Circuit QED Publications

circuit QED proposal:

- Blais, Huang, Wallraff, Girvin, Schoelkopf, *PRA* **69,** 062320 (2004)

strong coupling & vacuum Rabi mode splitting:

- Wallraff, Schuster, Blais, Frunzio, Huang, Majer, Kumar, Girvin, Schoelkopf, *Nature* **431**, 162 (2004)
- Fink, Goeppl, Baur, Bianchetti, Leek, Blais, Wallraff, *Nature* **454**, 315 (2008)

high visibility Rabi oscillations & coherence time measurements:

- Wallraff, Schuster, Blais, Frunzio, Majer, Girvin, and Schoelkopf, *PRL* **95**, 060501 (2005)

ac Stark shift, number splitting & measurement induced dephasing:

- Schuster, Wallraff, Blais, Frunzio, Huang, Majer, Girvin, Schoelkopf, *PRL* **94,** 123062 (2005)
- Gambetta, Blais, Schuster, Wallraff, Frunzio, Majer, Devoret, Girvin, Schoelkopf, *PRA* **74**, 042318 (2006)
- Schuster, Houck, Schreier, Wallraff, Gambetta, Blais, Frunzio, Johnson, Devoret, Girvin, Schoelkopf, *Nature* **445**, 515 (2007)

circuit QED gates, side band transitions:

- Blais, Gambetta, Wallraff, Schuster, Devoret, Girvin, Schoelkopf, *PRA* **75**, 032329 (2007)
- Wallraff, Schuster, Blais, Gambetta, … , Frunzio, Devoret, Girvin, Schoelkopf, *PRL* **99**, 050501 (2007)
- Majer, Chow, Gambetta, Koch, Johnson, Schreier, Frunzio, Schuster, Houck, Wallraff, Blais, Devoret, Girvin, Schoelkopf, *Nature* **449**, 443 (2007)
- Leek, Fink, Blais, Bianchetti, Goeppl, Gambetta, Schuster, Frunzio, Schoelkopf, Wallraff, *Science* **318**, 1889 (2007)

circuit QED device fabrication:

- Frunzio, Wallraff, Schuster, Majer, Schoelkopf, *IEEE Trans. Appl. Supercond.* **15**, 860 (2005)