Quantum Optics with Electrical Circuits: ‘Circuit QED’

Experiment

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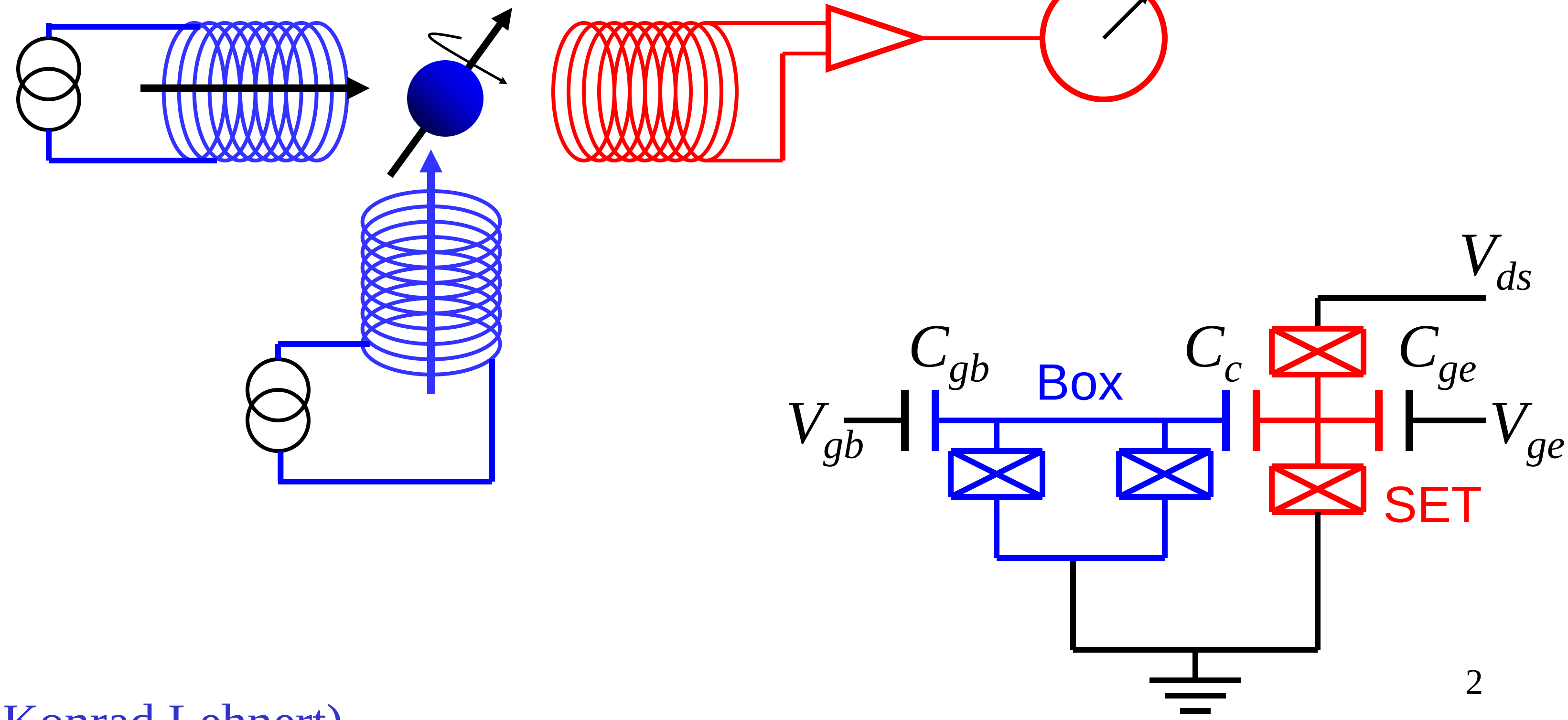
CRSNG NSERC

Quantum Computation and NMR of a Single „Spin"

Single „Spin" ½

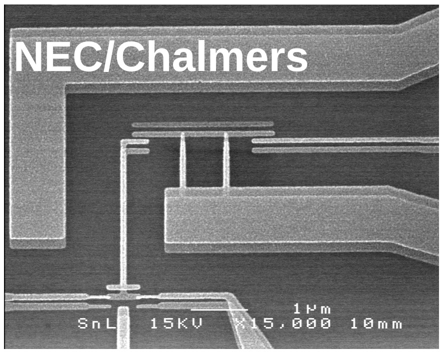
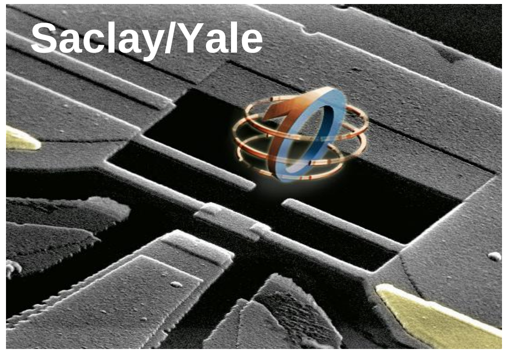
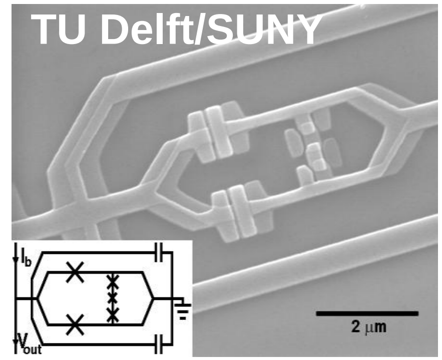
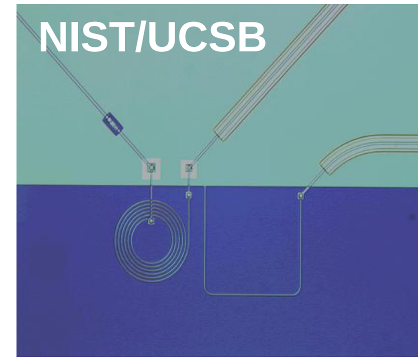
Quantum Measurement



(After Konrad Lehnert)

State of the Art in Superconducting Qubits

• Nonlinearity from Josephson junctions (Al/AlO_x/Al)

Charge	Charge/Phase	Flux	Phase
			

Junction size ⟶ $E_J = E_C$ ⟵ # of Cooper pairs

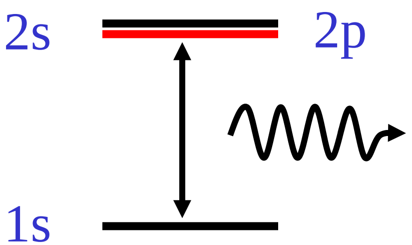
- 1^{st} qubit demonstrated in 1998 (NEC Labs, Japan)
- “Long” coherence shown 2002 (Saclay/Yale)
- Several experiments with two degrees of freedom
- C-NOT gate (2003 NEC, 2006 Delft and UCSB)
- Bell inequality tests being attempted (2006, UCSB)

So far only classical E-M fields: atomic physics with circuits

Our goal: interaction w/ quantized fields ⇒ Quantum optics with circuits

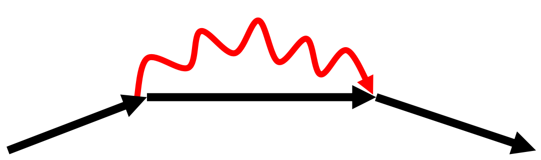
Communication between discrete photon states and qubit states

Atoms Coupled to Photons

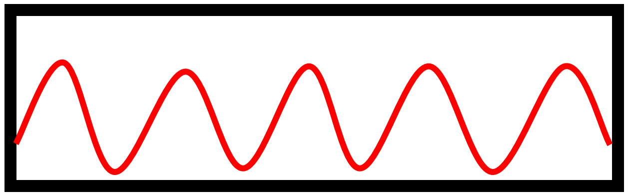


Irreversible spontaneous decay into the photon continuum:

$2p \quad 1s \qquad\qquad T_1 \sim 1\ \text{ns}$



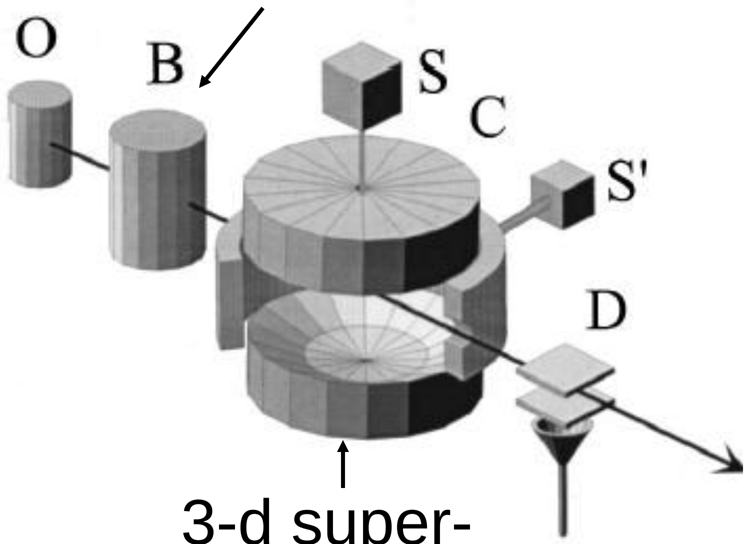
Vacuum Fluctuations:
(Virtual photon emission and reabsorption)
Lamb shift lifts 1s 2p degeneracy



Cavity QED: What happens if we trap the photons as discrete modes inside a cavity?

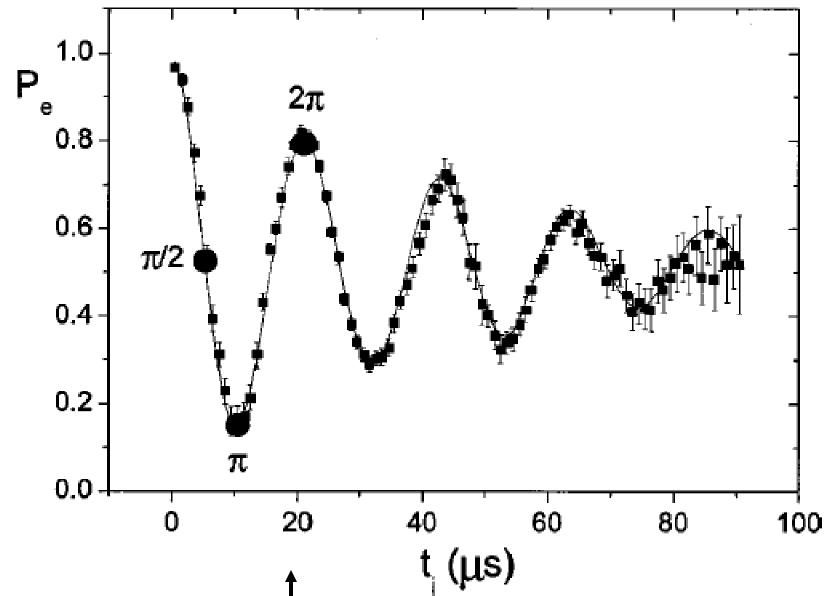
Microwave cQED with Rydberg Atoms

beam of atoms;
prepare in |e>



3-d super-
conducting
cavity (50 GHz)

vacuum Rabi oscillations

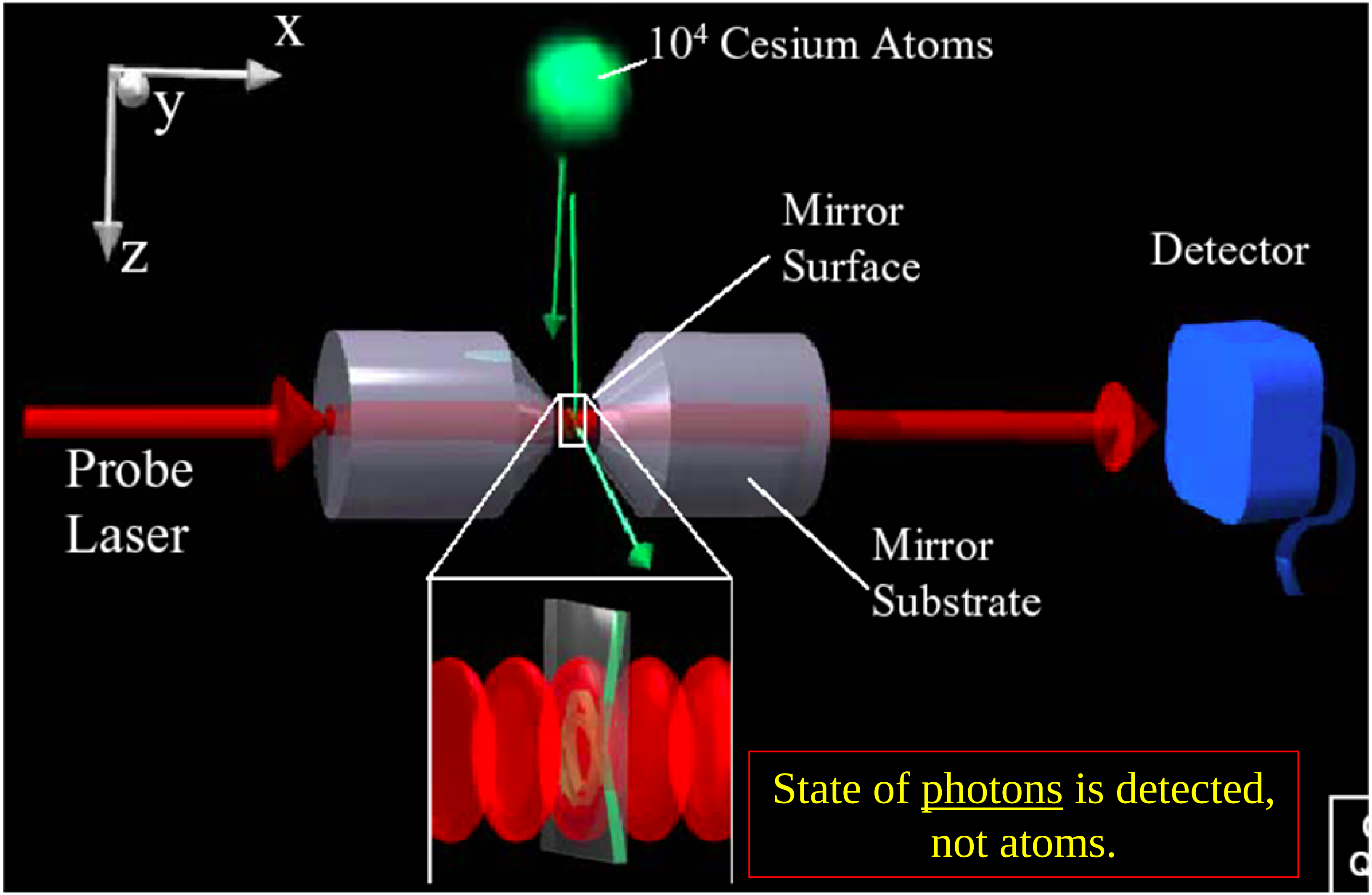


observe dependence of atom final
state on time spent in cavity

measure atomic state, or …

Review: S. Haroche et al., *Rev. Mod. Phys.* **73** 565 (2001)

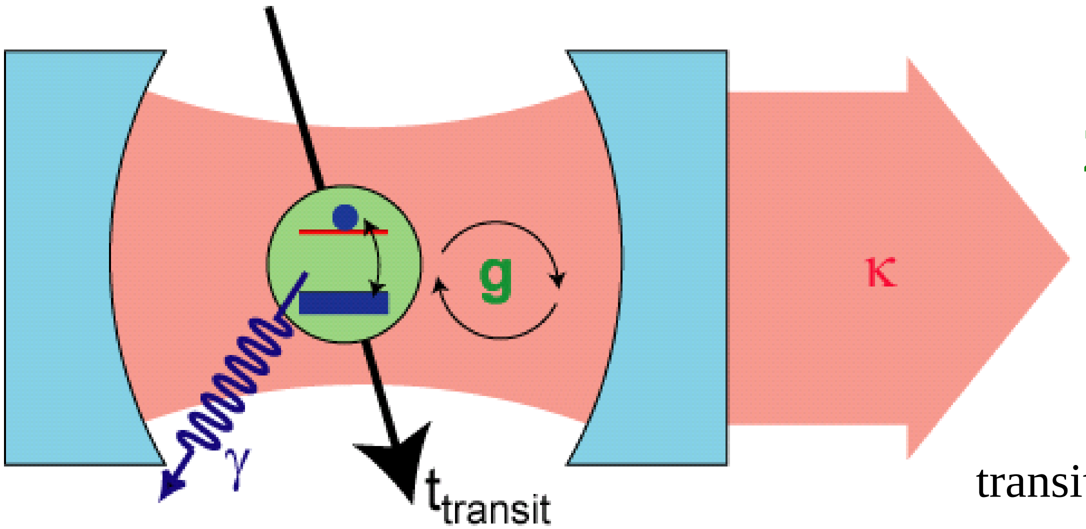
cQED at Optical Frequencies



… measure changes in transmission of optical cavity

(Caltech group H. J. Kimble, H. Mabuchi)

Cavity Quantum Electrodynamics (CQED)



2g = vacuum Rabi freq.

k = cavity decay rate

= “transverse” decay rate

transition dipole   vacuum field

$\hbar g \;\; d E_{RMS}$

$E \;\; E_{RMS}(a \;\; a^{\dagger})$

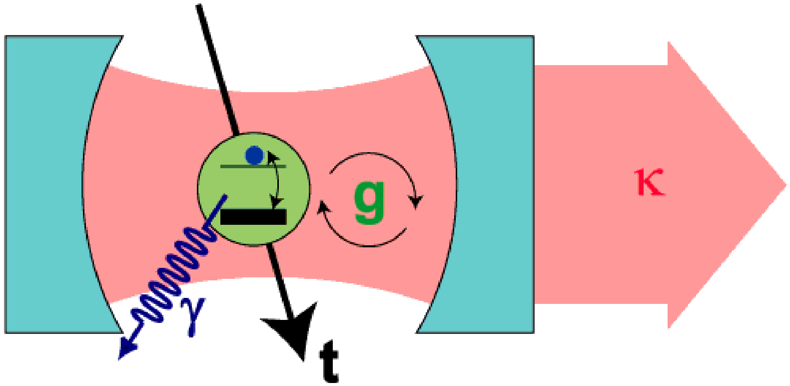
Jaynes-Cummings Hamiltonian

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

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

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

A Circuit Analog for Cavity QED



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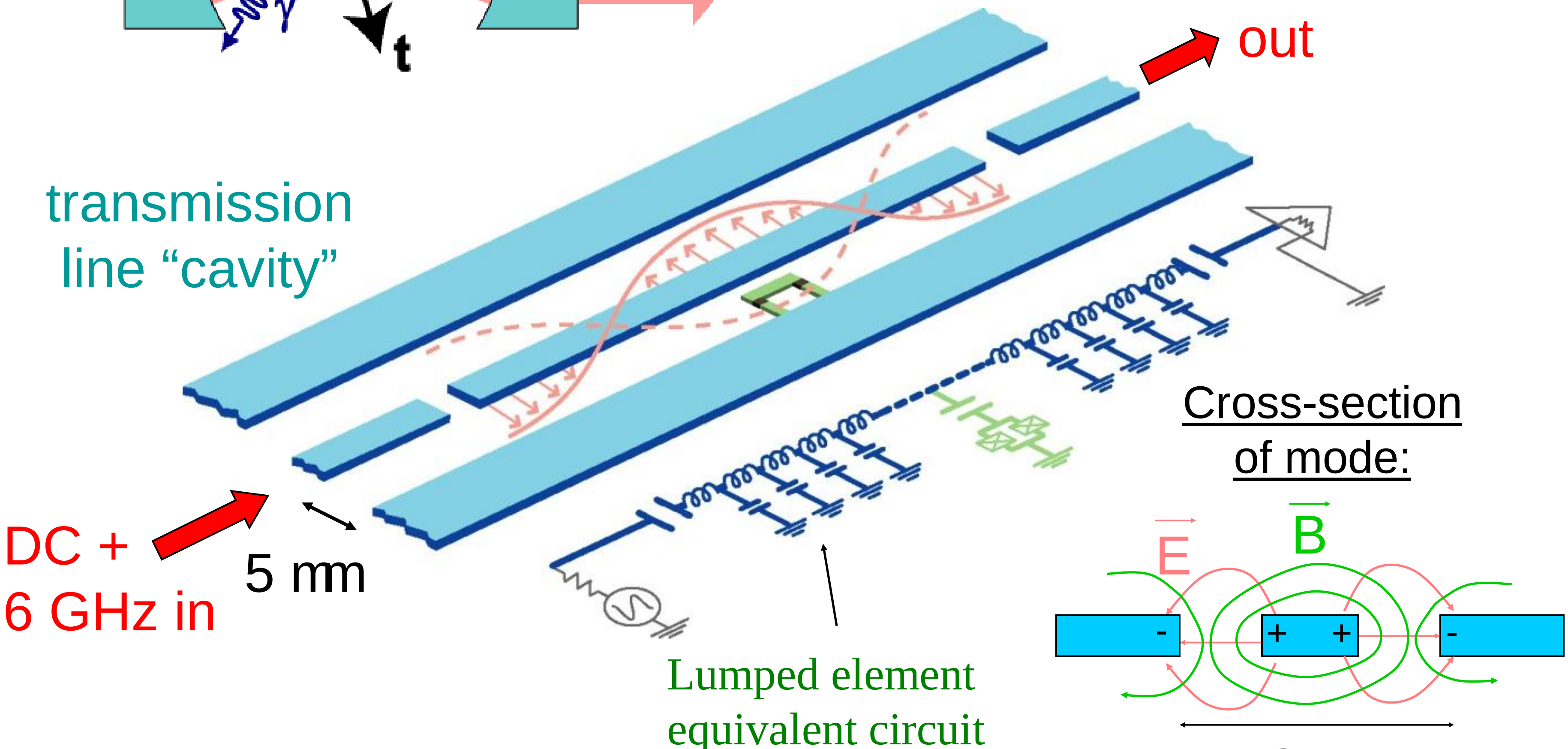
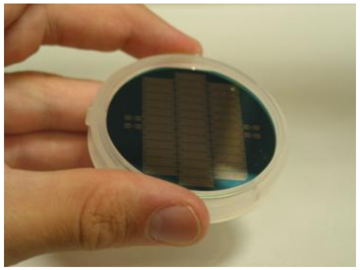


Blais, Huang, Wallraff, SMG & RS, PRA 2004

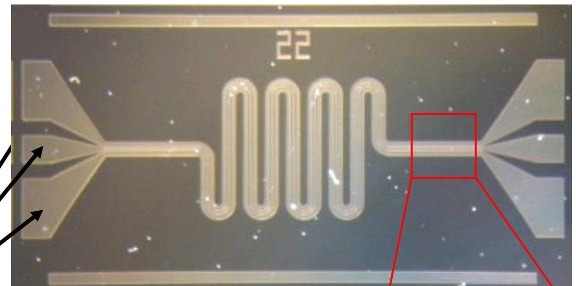
Implementation of Cavities for cQED

Superconducting coplanar waveguide transmission line

Q > 600,000 @ 0.025 K



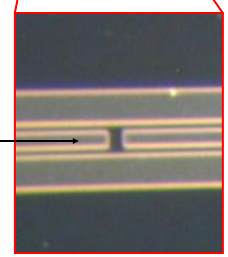
Optical lithography at Yale

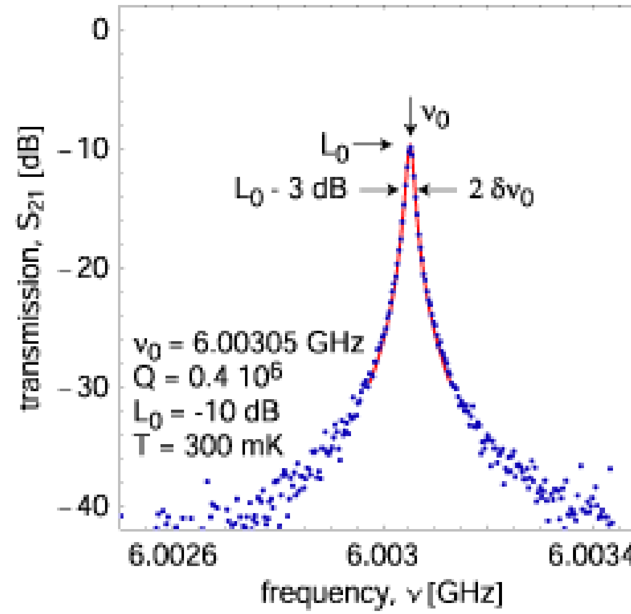


Niobium films

1 cm

gap = mirror



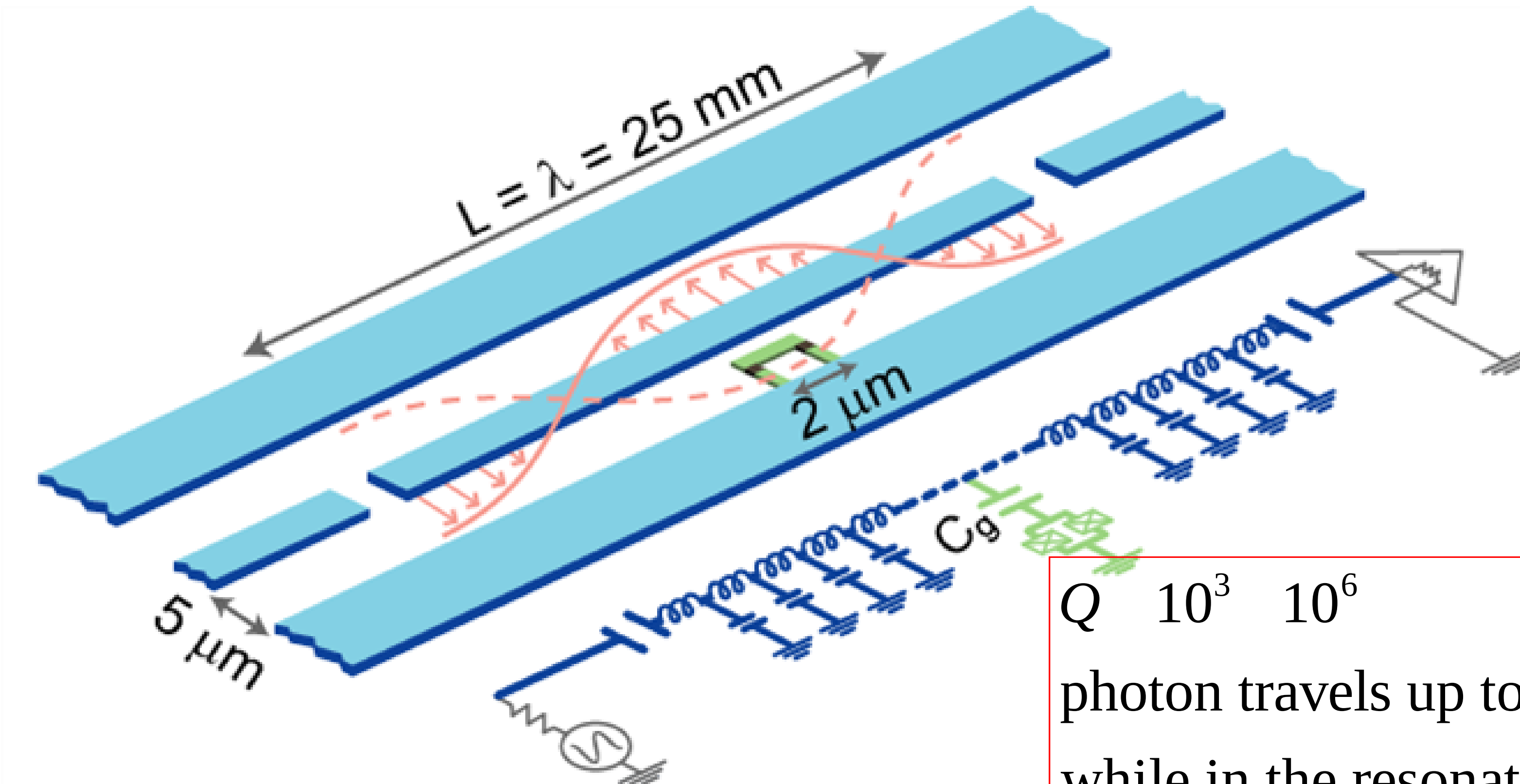


<u>6 GHz:</u>

$$\hbar \qquad 300\,mK \quad \Rightarrow \quad \langle\, n \,\rangle \ll 1 \quad @20\,mK$$

- Internal losses negligible – Q dominated by coupling

Circuit Quantum Electrodynamics



Q 10^3 10^6

photon travels up to 10 km

while in the resonator!

CPW optical fiber

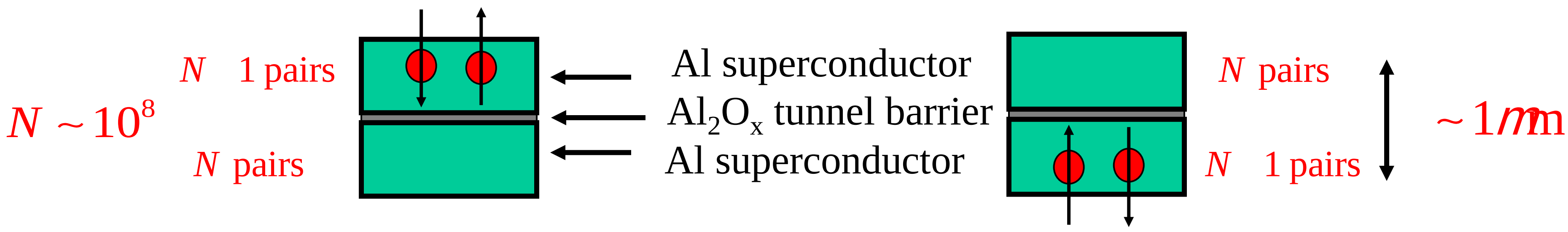
elements

- cavity: a superconducting 1D transmission line resonator
- artificial atom: a Cooper pair box (large *d*)

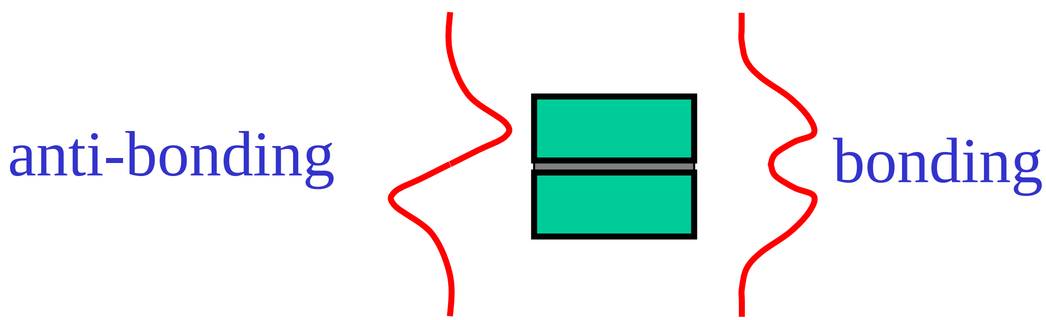
A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *PRA* **69,** 062320 (2004)

Artificial Atom
Superconducting Tunnel Junction

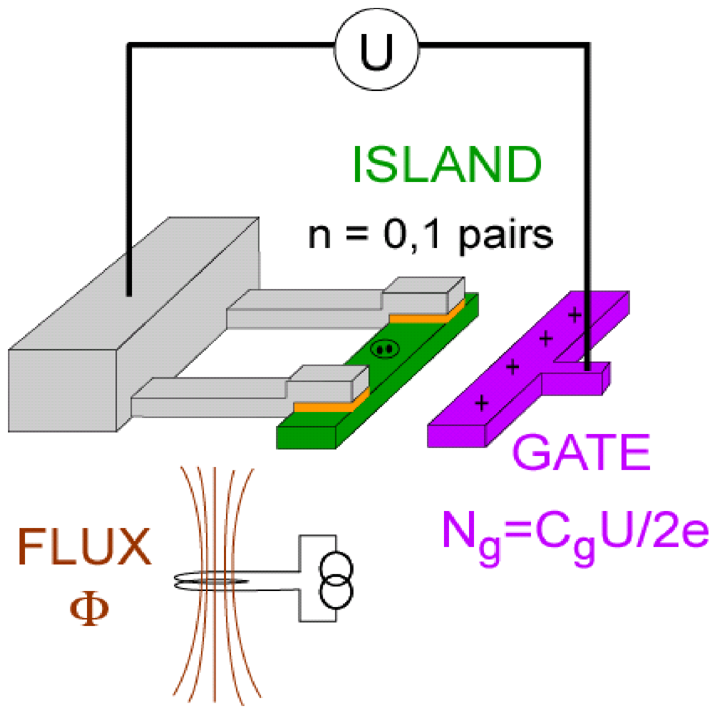
(The <u>only</u> non-linear dissipationless circuit element.)

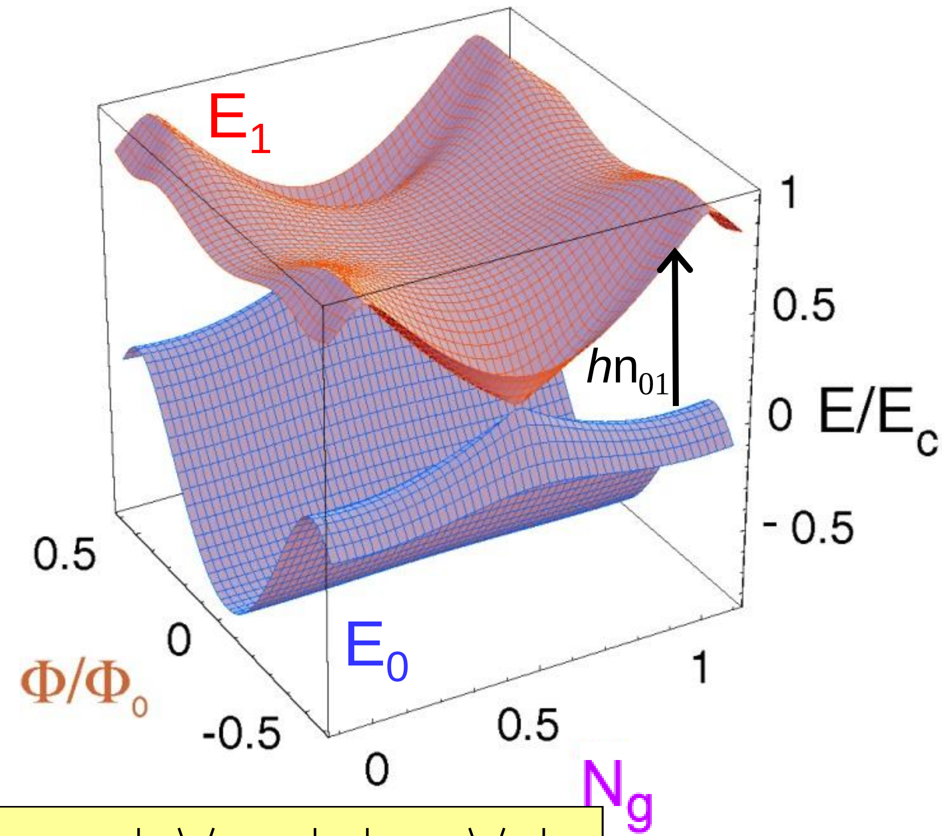


Josephson Tunneling Splits
the Bonding and Anti-bonding „Molecular Orbitals“
<u>Covalently</u> Bonded Diatomic „Molecule“



SPLIT COOPER PAIR BOX QUBIT:
THE “ARTIFICIAL ATOM”
with two control knobs



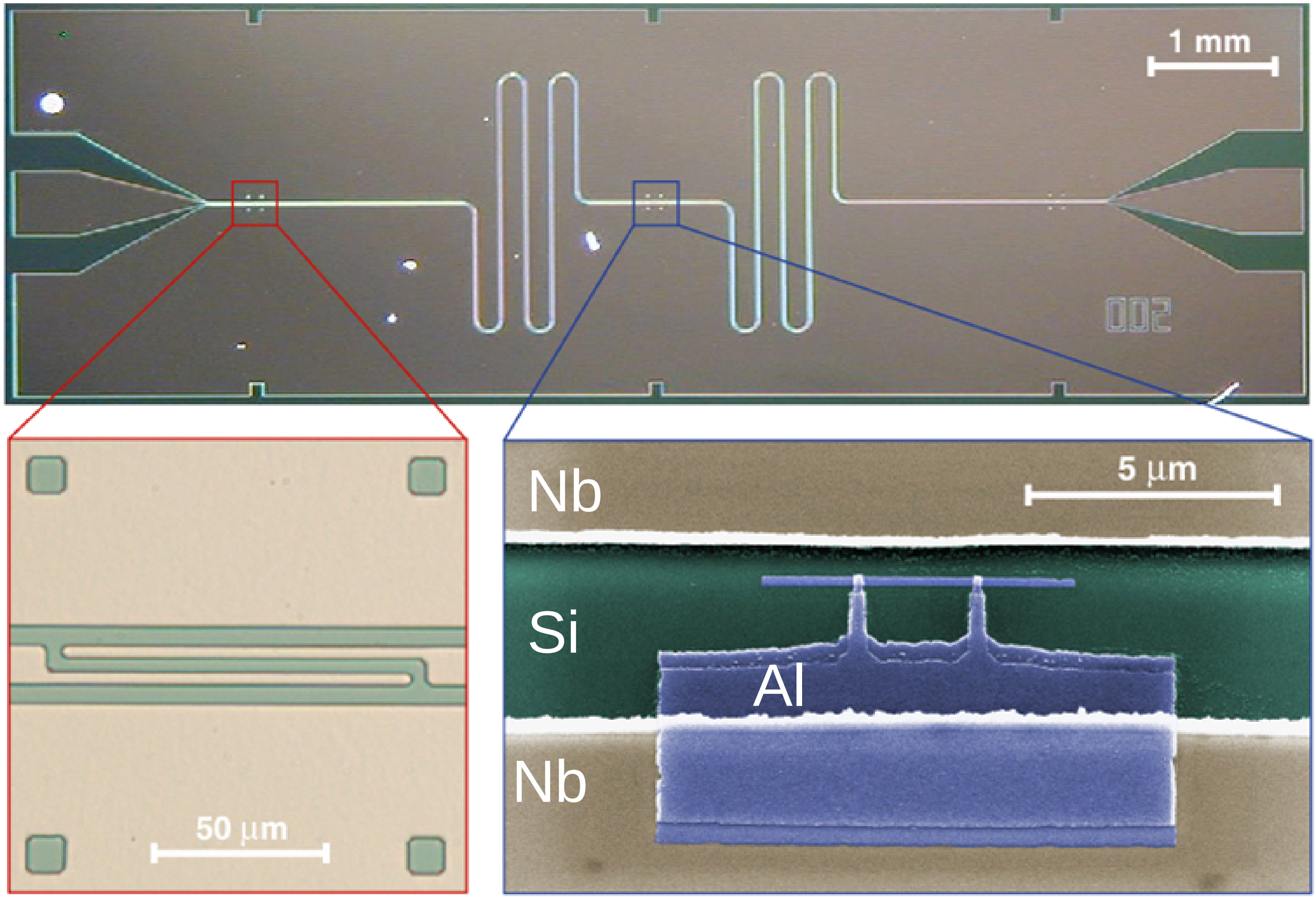


$$\hat{H} \quad {}_{n} \quad E_C(n \quad N_g)^2|n\rangle\langle n| \quad E_j \cos \frac{}{{}_0} \quad \frac{|n\rangle\langle n \quad 1| \quad |n \quad 1\rangle\langle n|}{2}$$

THE Hamiltonian

*[Devoret & Martinis, QIP, **3**, 351-380(2004)]*

First Generation Chip for Circuit QED



No wires attached to qubit!

<u>First coherent coupling of solid-state qubit to single photon:</u>

A. Wallraff, et al., *Nature (London)* **431**, 162 (2004)

<u>*Theory:*</u> Blais et al., *Phys. Rev. A* **69**, 062320 (2004)

Advantages of 1d Cavity and Artificial Atom

$g \quad \vec{d}\bullet\vec{E}_{\mathrm{RMS}}/\hbar$

$\hbar g \quad dE_{\mathrm{RMS}}$

$E \quad E_{\mathrm{RMS}}(a \quad a^{\dagger})$

quantized electric field

<u>Vacuum fields:</u>

mode volume $10^{6 \quad 3}$

zero-point energy density

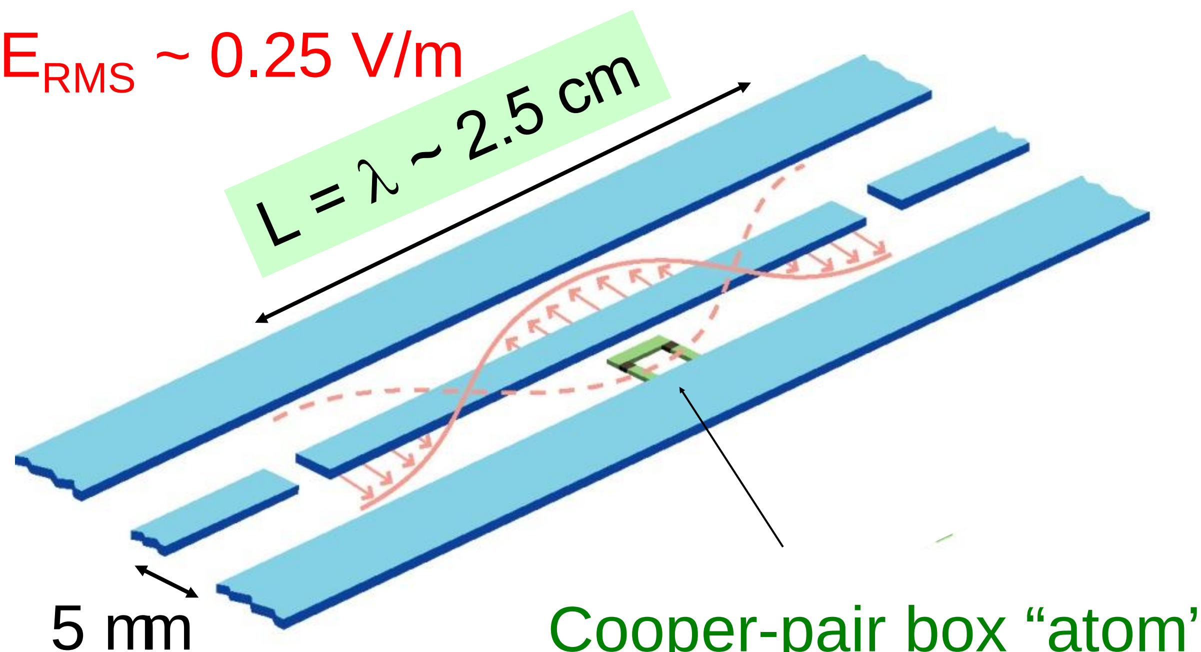
enhanced by 10^{6}

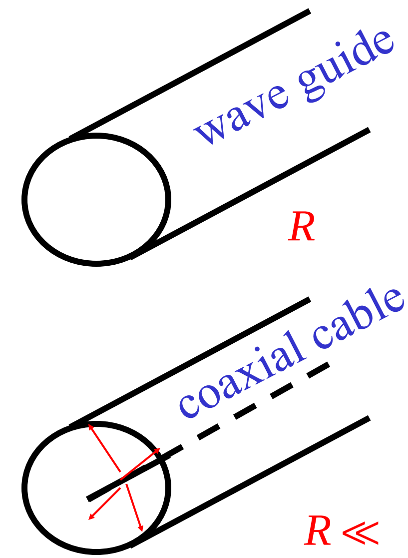
<u>Transition dipole:</u>

$d \sim 40{,}000\, ea_0$

$\sim 10 d_{\mathrm{Rydberg\ n=50}}$

E_{RMS} ~ 0.25 V/m





Extreme Strong Coupling Limit

$$g \quad \vec{d} \bullet \vec{E}_{\mathrm{RMS}} / \hbar$$

Maximum dipole moment: $2e\frac{d}{2} \quad ed$

energy density

mode volume

Vacuum electric field: $\frac{{}_{0} \quad {}_{r}}{2} E_{\mathrm{rms}}^{2} \quad d^{2} \quad \frac{1}{2} \; \frac{1}{2}\hbar$

Vacuum Rabi coupling:
(independent of *d* !)

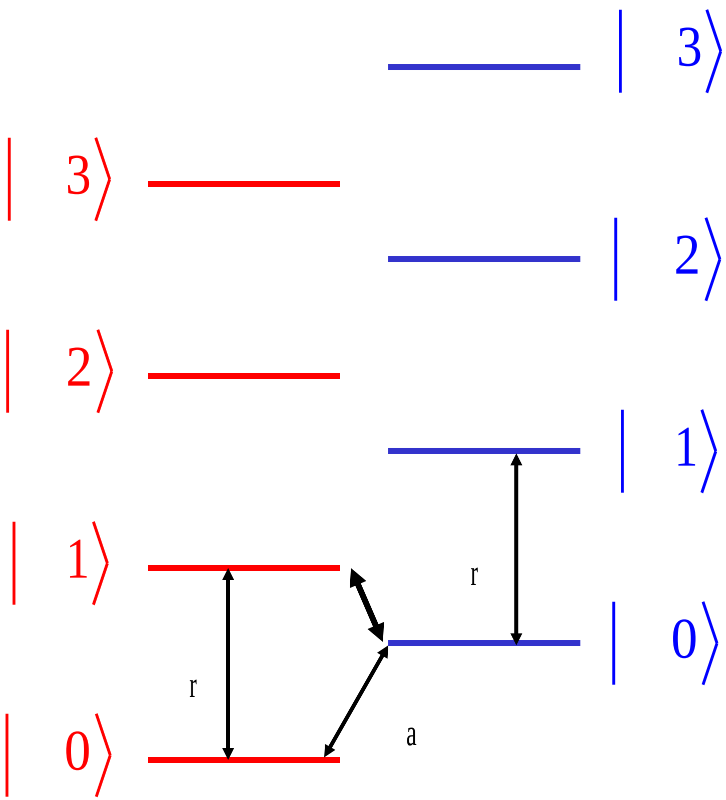
$$\frac{g}{} \quad \sqrt{\frac{}{{}_{r}}} \quad 0.04$$

Present experiments: $\frac{g}{} \quad \frac{2 \quad 100\ \mathrm{MHz}}{2 \quad 5\ \mathrm{GHz}} \quad 0.02$

Jaynes Cummings Hamiltonian: “dressed atom” picture

cavity qubit dipole coupling

$$H \quad \hbar \;{}_{r}\, a^{\dagger} a \quad \frac{\hbar \quad {}_{01}}{2} \quad {}^{z} \quad \hbar g \;\; a^{\dagger} \qquad a \qquad H_k \quad H$$



Dispersive case:
Atom is strongly detuned from the cavity

a r

Photons do not cause „real“ transitions in the qubit.. only level repulsion.

Cavity and atom frequencies shift.
Second order p.t. $\frac{g^2}{}$

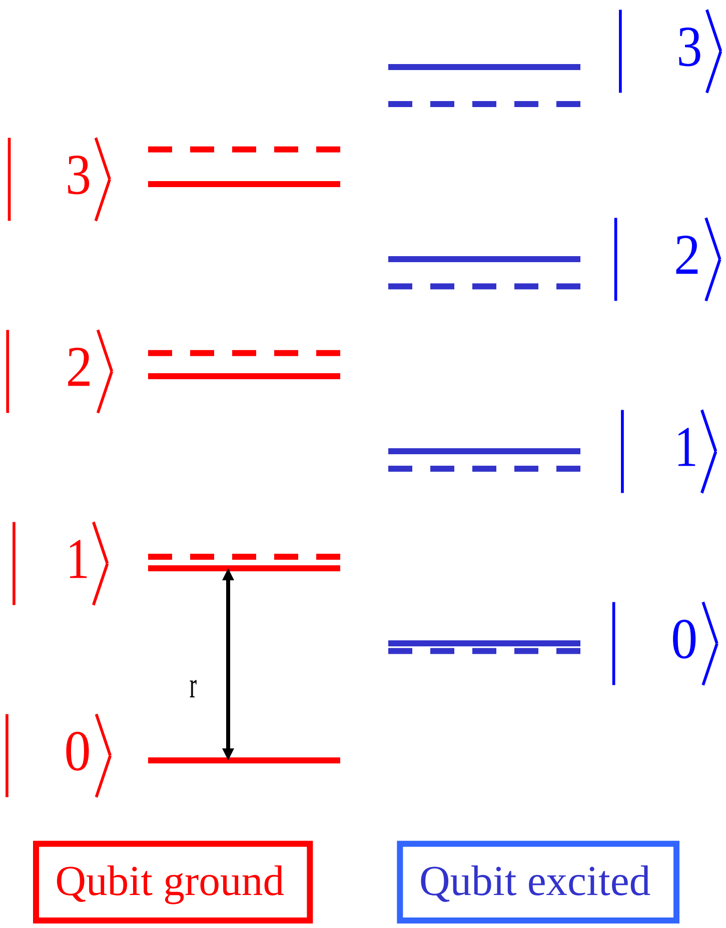
Qubit ground

Qubit excited

"dressed atom" picture: 2nd order perturbation theory

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 shifts up if qubit is in ground state; down if qubit in excited state.

(0)

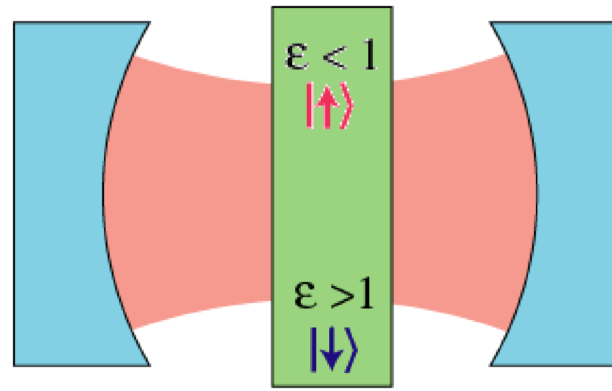
cQED Dispersive Measurement I: atom strongly detuned from cavity

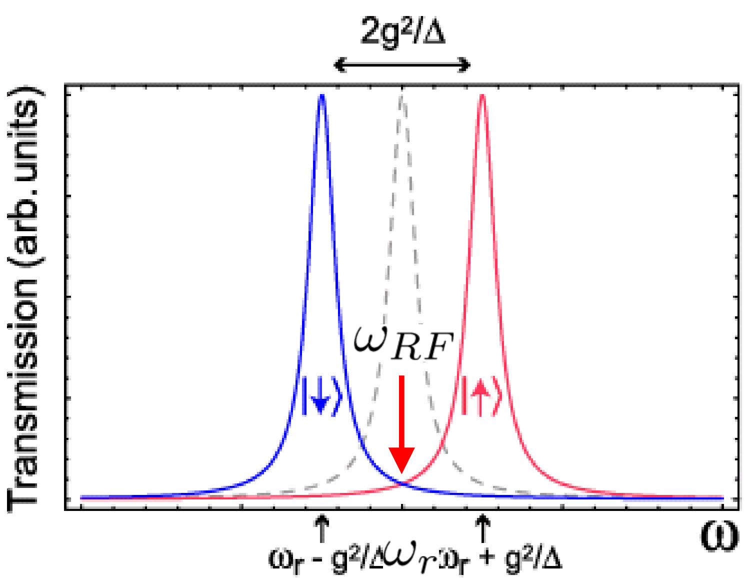
approximate diagonalization for $|\Delta| = |\omega_a - \omega_r| \gg g$

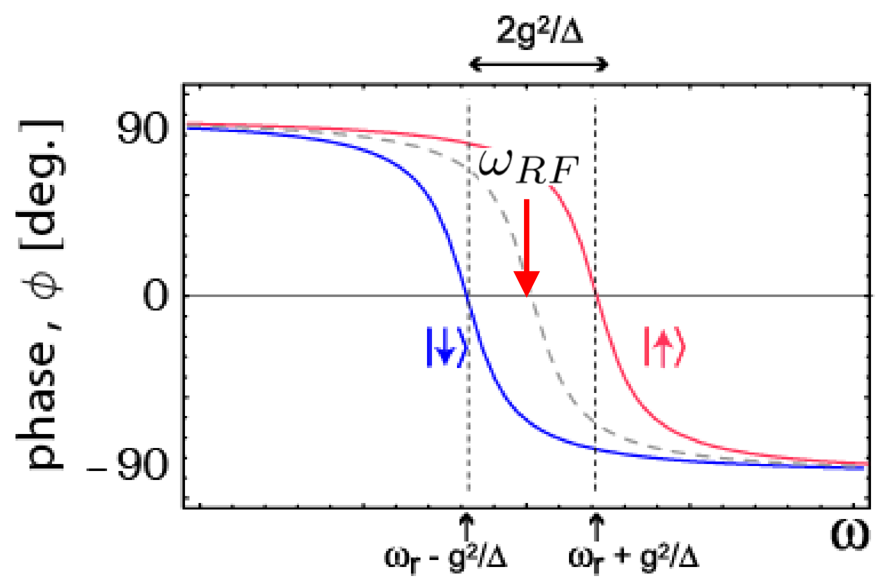
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta}\right) \sigma_z$$

cavity frequency shift *and* qubit ac-Stark shift

Lamb shift





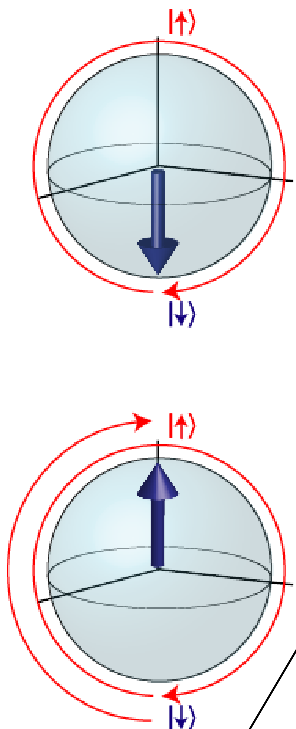


A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and RS, *PRA* **69,** 062320 (2004)

Coherent Control of Qubit in Cavity

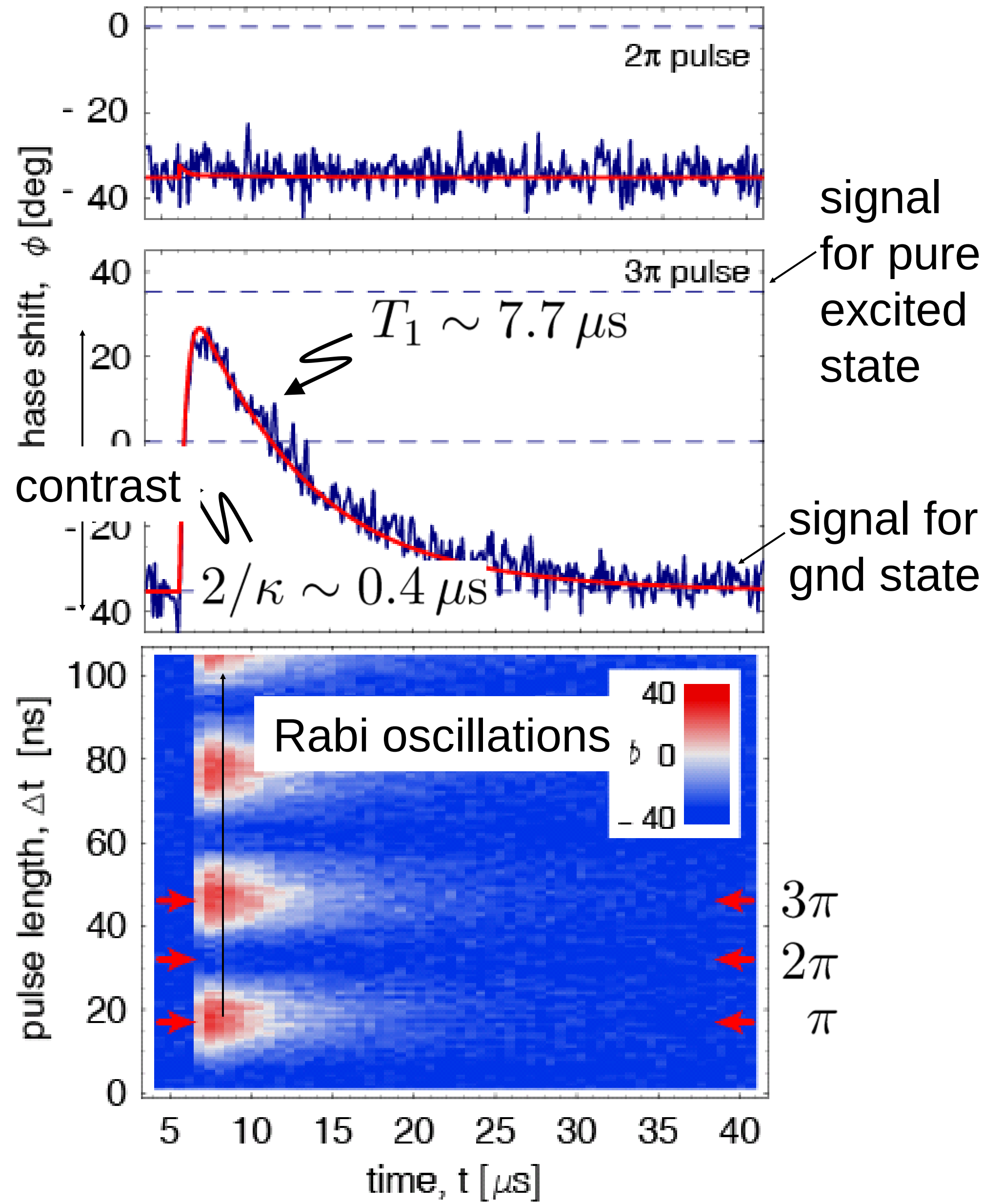
2π rotation

3π rotation



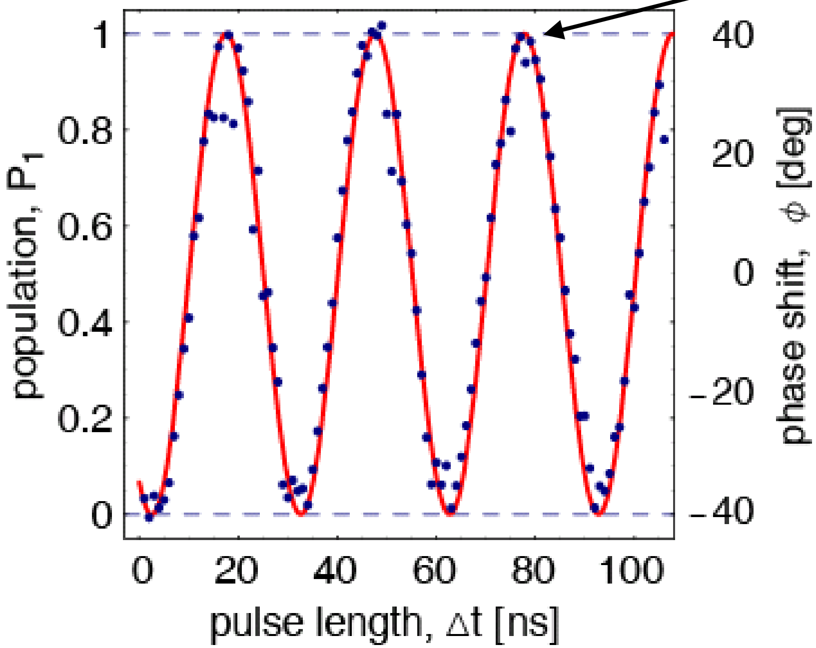
85 % contrast

consistent with 100% fidelity of qubit rotation



High Visibility Rabi Oscillations

Rabi oscillations:



visibility $95 \pm 5\%$

(i.e. inferred fidelity of operation)

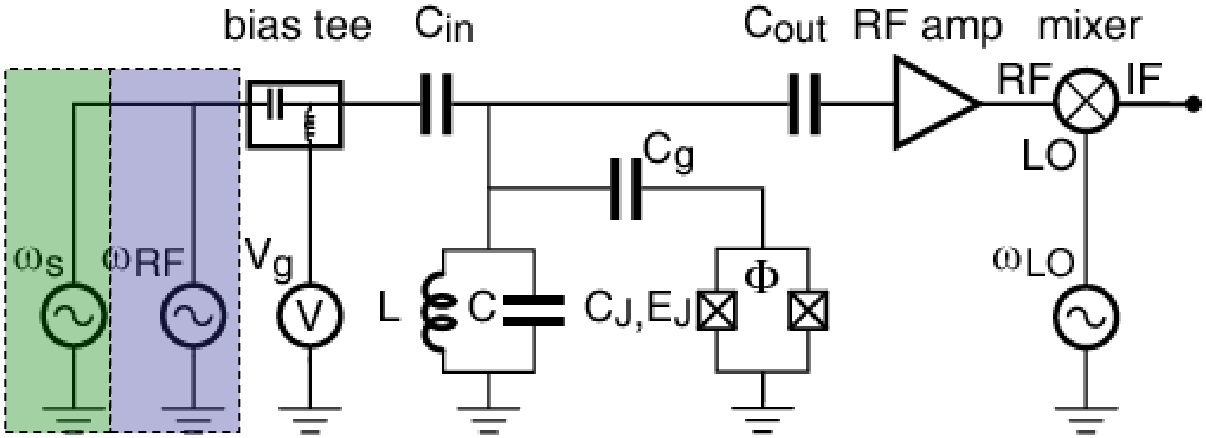
for superconducting qubits:

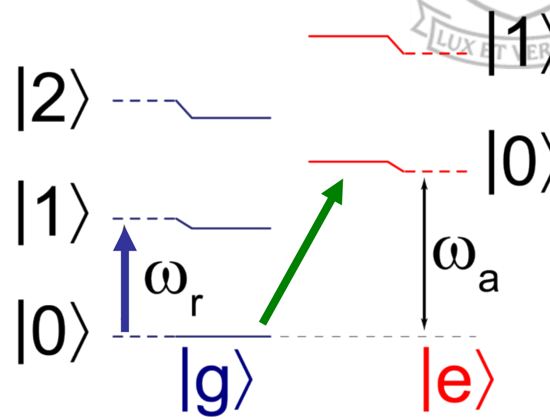
- first high visibility
- well characterized and understood measurement
- good control accuracy

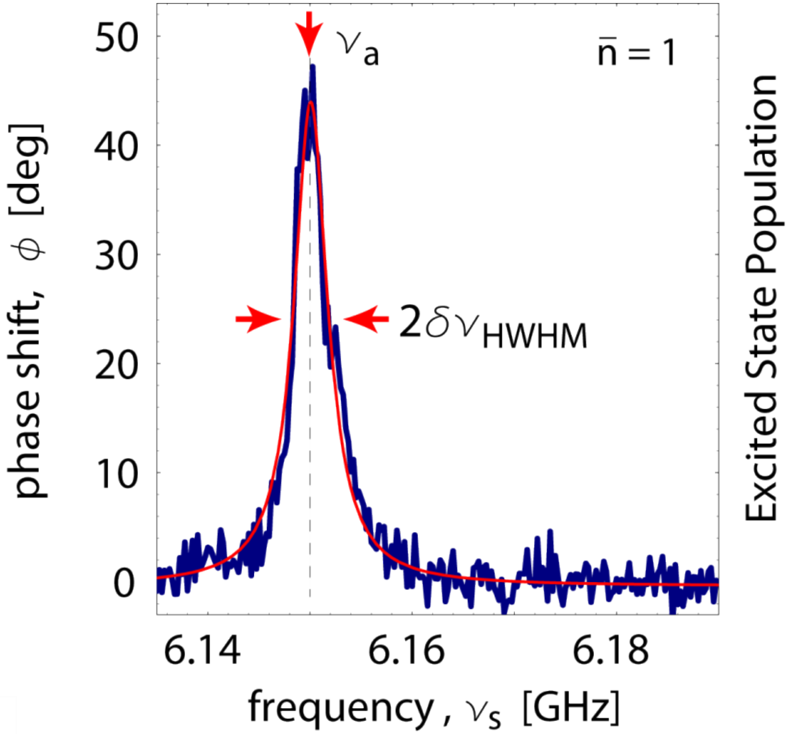
Indicates no undesired entanglement with environment during operations.

A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, MHD, SMG, and RJS, Phys. Rev. Letters **95**, 060501 (2005).

Spectroscopy of the qubit







When qubit is excited cavity responds

n 3 MHz ~ dephasing rate

Q > 20,000 !!!

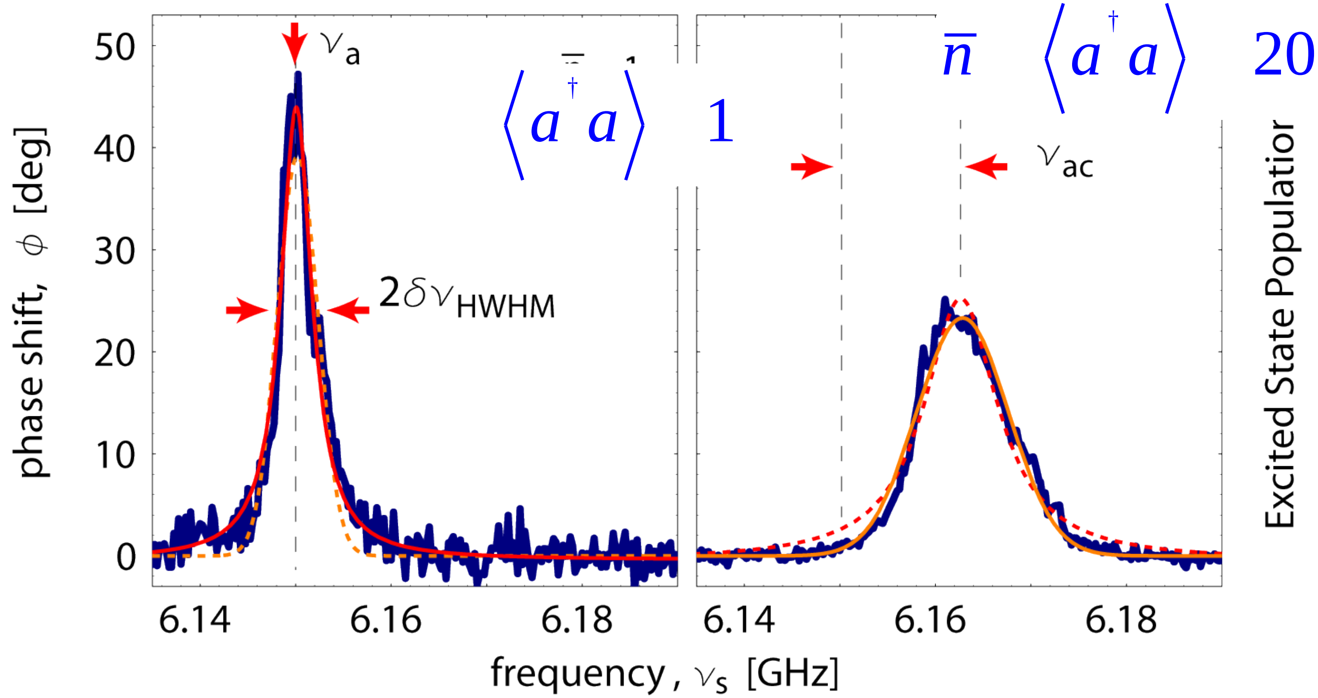
Backaction of QND Measurement

$\gg g:$

$$H_{\text{eff}} \quad \hbar \quad {}_{r}a^{\dagger}a \quad \frac{\hbar}{2} \quad {}_{01} \quad \hbar\frac{g^{2}}{\ }a^{\dagger}a \quad {}_{z}$$

\

AC Stark shift of qubit by photons



$\langle a^{\dagger}a\rangle \quad 1$

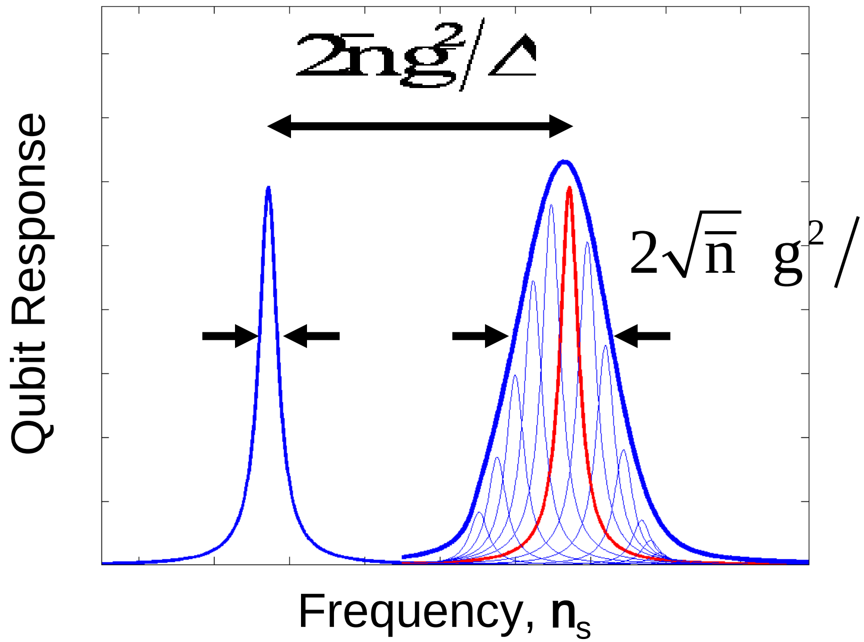
$\bar{n} \quad \langle a^{\dagger}a\rangle \quad 20$

AC Stark measurements: Schuster et al., PRL 94, 123602 (2005).

Measurement induced dephasing (back action)

- Measurement dephasing from Stark random shifts
- Gaussian lineshape at strong coupling is sum of Lorentzians

$$H_{\mathrm{eff}} \quad {}_{\mathrm{r}} a^{\dagger} a \quad \frac{1}{2} \quad {}_{01} \quad 2\frac{g^{2}}{\quad} \; a^{\dagger} a \quad \frac{1}{2} \quad {}_{z}$$



- Coherent state has shot noise
- Peaks are Poisson distributed

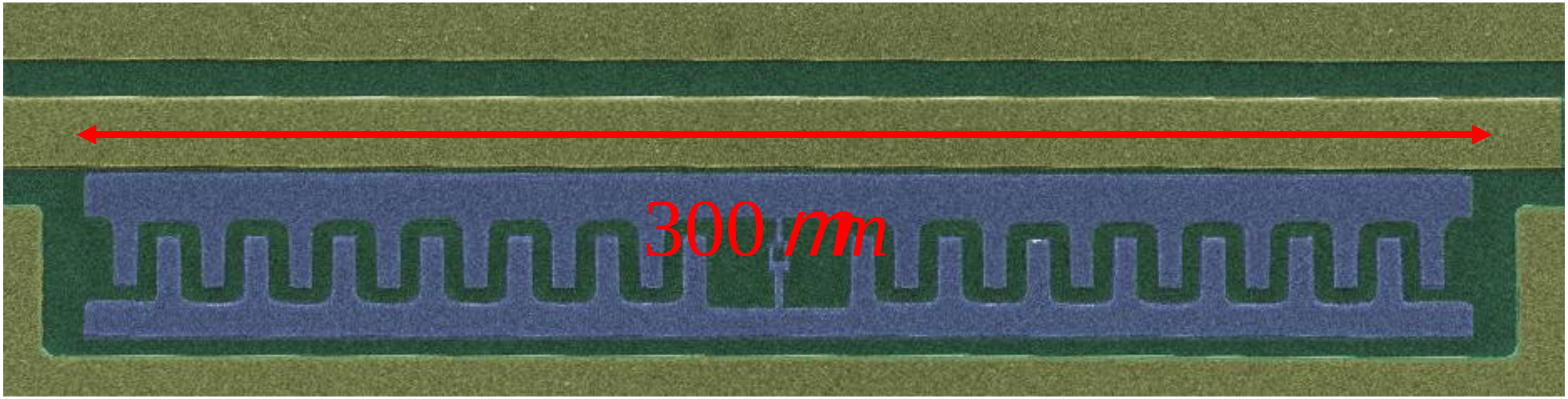
$$P(n) \quad \frac{(\bar{n})^{n}}{n!} e^{\;\bar{n}}$$

“Strong Dispersive Regime”:

What if 2g²/   >   ?

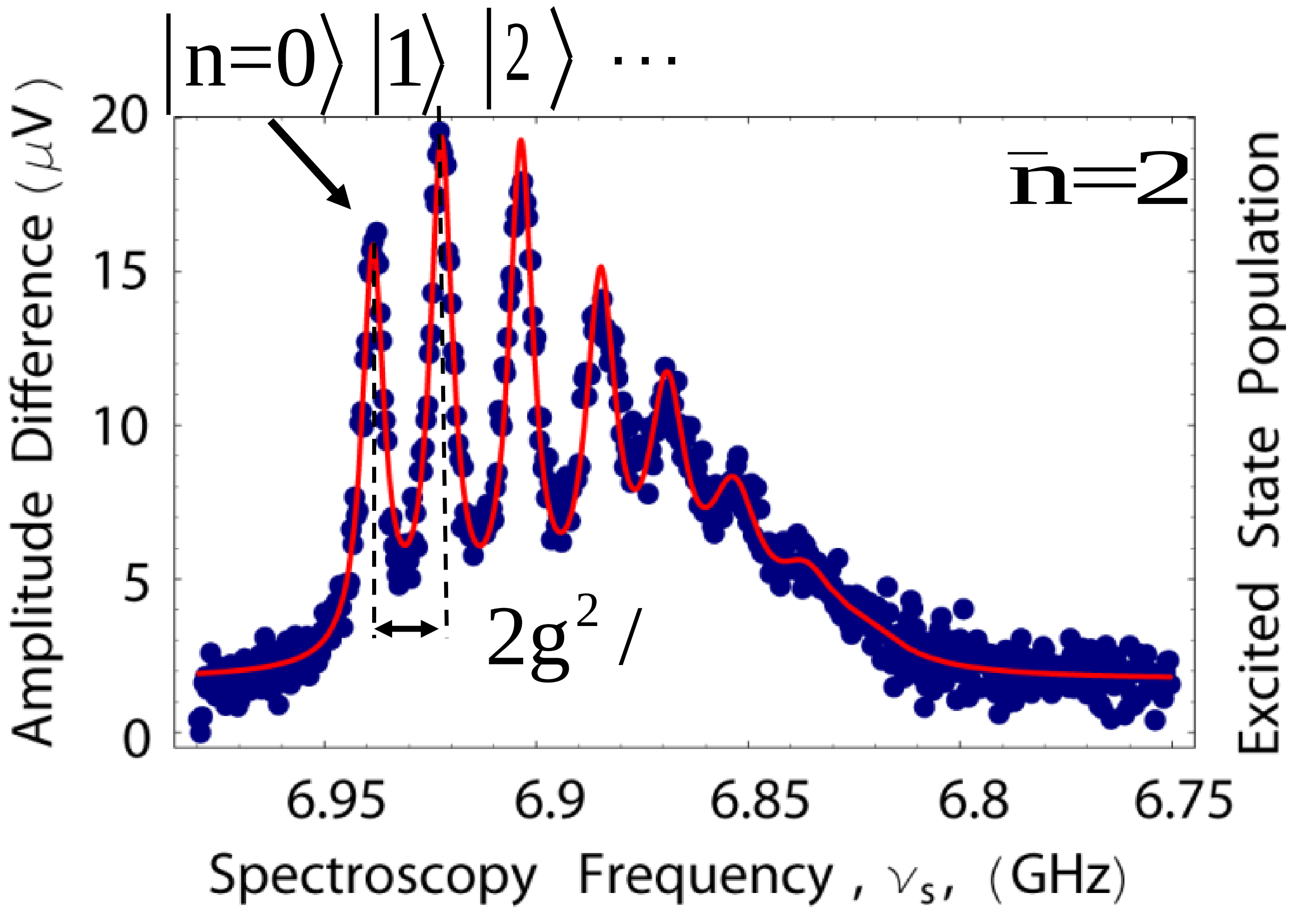
Need to increase coupling strength

Want bigger coupling… Make a bigger atom !



	Old	**New**
Resonant	$g \quad 12\ \text{MHz} > \quad , k$	$g \quad 115\ \text{MHz} > \quad , k$
Dispersive	$\frac{g^2}{\ } \quad , k$	$\frac{g^2}{\ } \quad , k$

Resolving Photon States in a Circuit



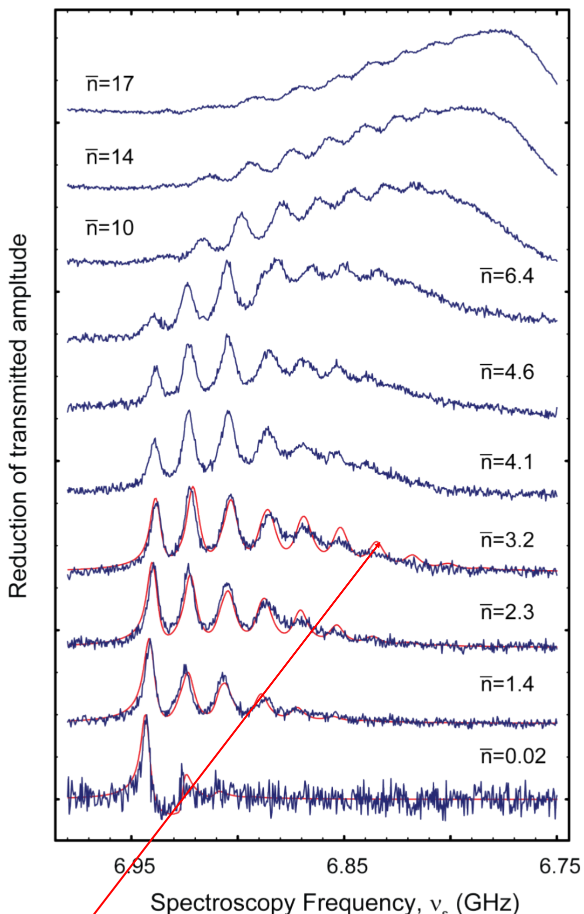
$g = 100$ MHz

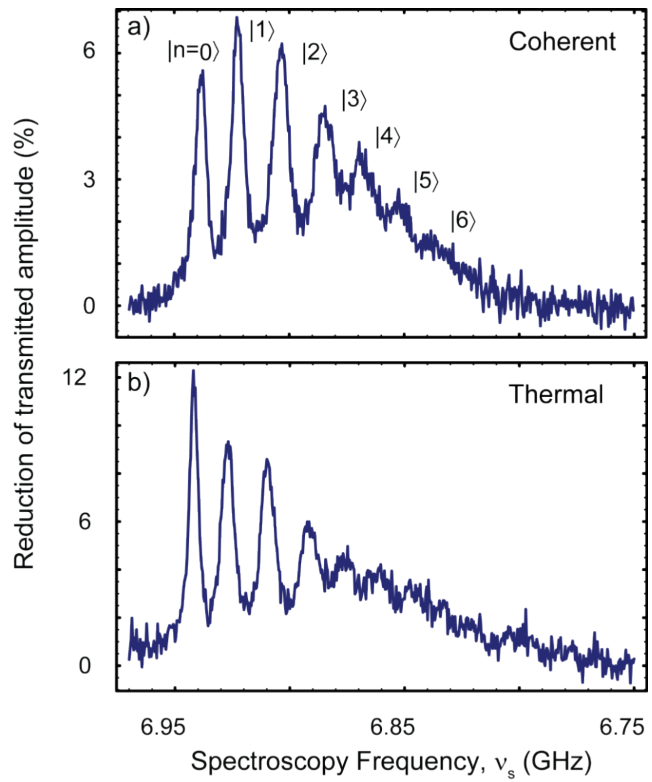
$2g^2/\quad = 20$ MHz

- # distribution visible in spectroscopy
- Peaks well separated $\frac{2g^2}{\quad} \gg$
- Well into dispersive limit $\frac{g}{\quad} \ll 1$

Resolving individual photon numbers using ac Stark shift of qubit transition frequency

coherent input power = 10 ^{17} Watts





Coherent state
$\bar{n} \quad 2$
Poisson distribution

$$P(n) \quad \frac{(\bar{n})^n}{n!} e^{\bar{n}}$$

Thermal state
$\bar{n} \quad 2$
Bose-Einstein distribution

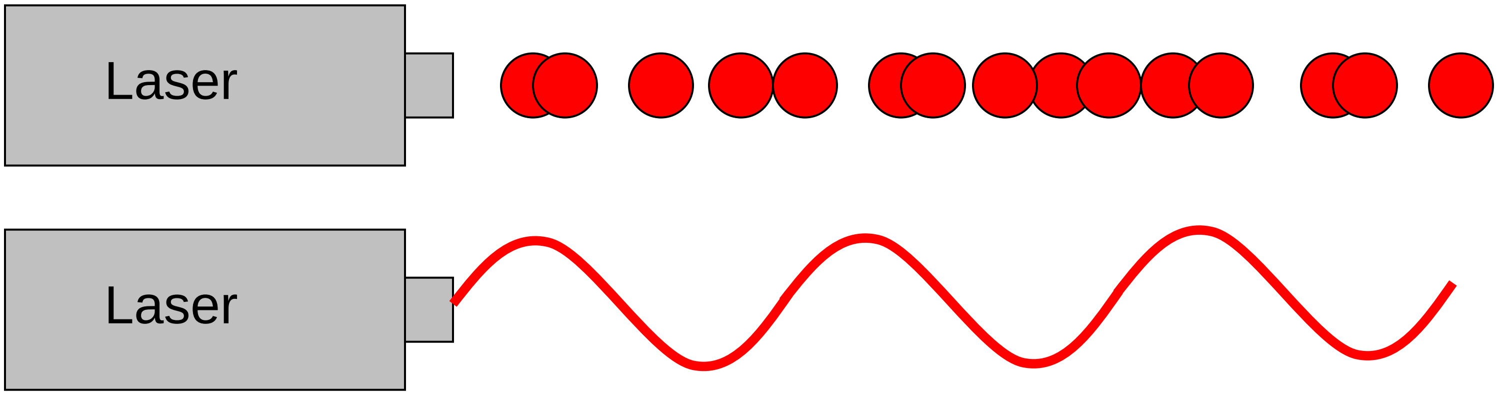
$$P_{th}(n) \quad \frac{(\bar{n})^n}{\bar{n} \quad 1^{\, n \quad 1}}$$

— Master Eqn. Simulations

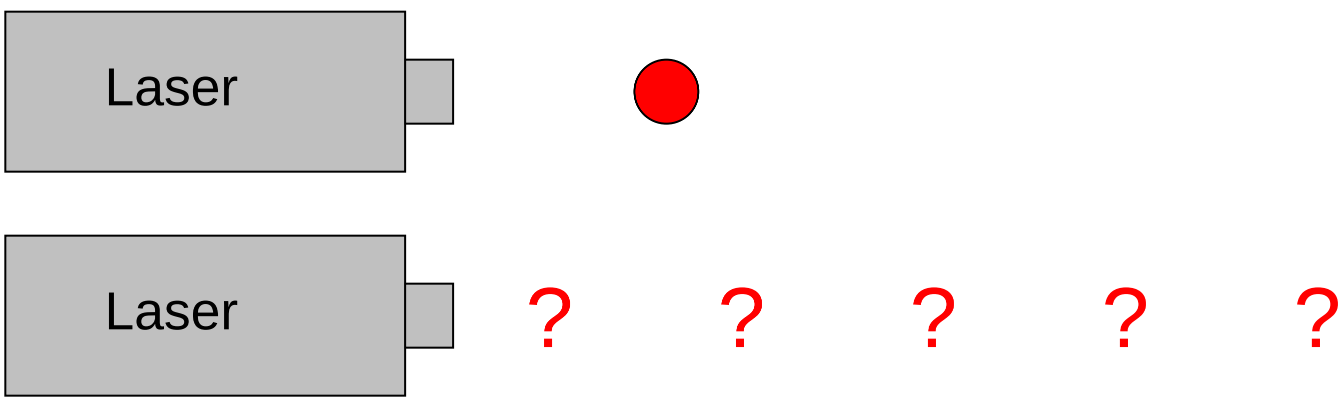
Master eqn. simulations show that homodyne signal is an <u>approximate</u> proxy for cavity photon number distribution.

Waves and Particles

Coherent State: Many Photons

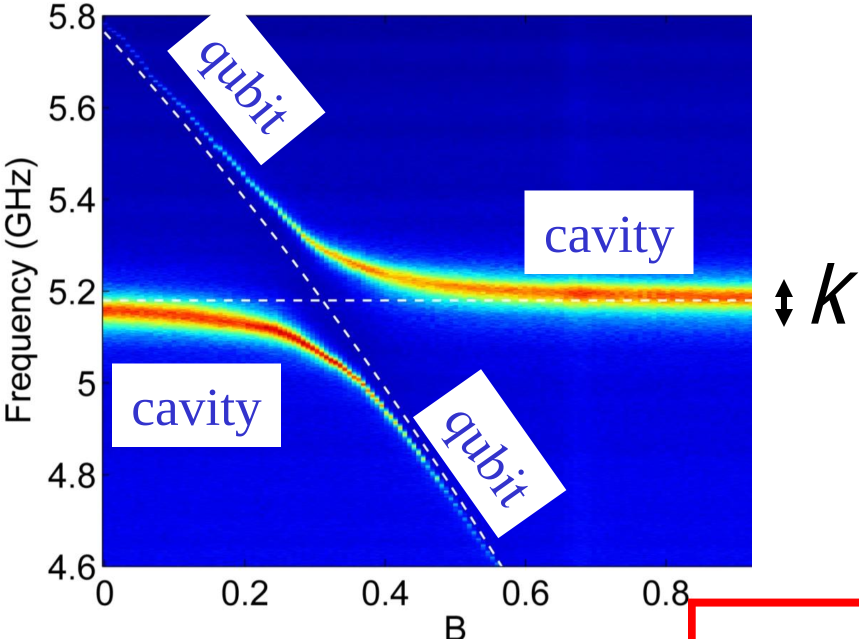


Single Photons



What is the electric field of a single photon?

Purcell Effect:
Low Q cavity can enhance rate of spontaneous emission of photon from qubit



Photon emission becomes dominate decay channel. Maps qubit state onto state of flying qubit (photon field):

$$|\mathrm{IN}\rangle \quad |\ \rangle \quad |\ \rangle|0\rangle$$

$$|\mathrm{OUT}\rangle \quad |\ \rangle \quad a^{\dagger}\ |0\rangle$$

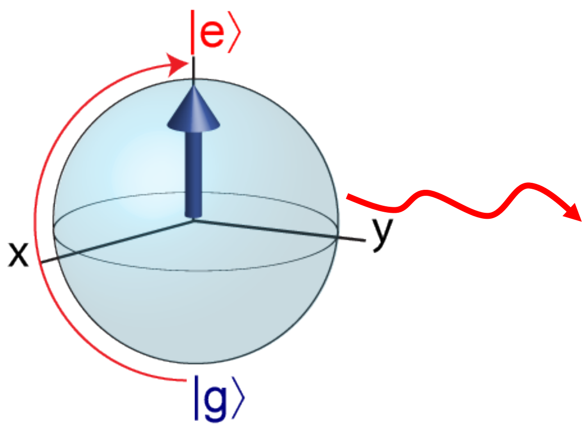
$$\frac{g}{\ }^{2}\ k$$

Intrinsic non-radiative decay rate

Cavity enhanced decay rate

Oscillations in Electric Field?

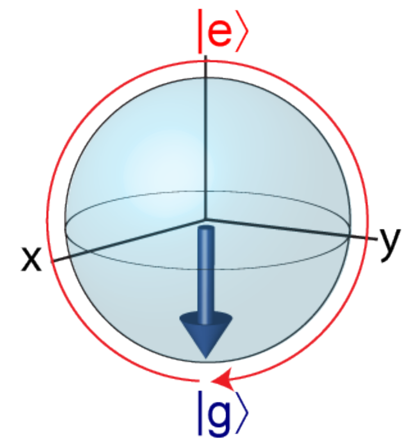
pulse



$|0e\rangle \quad |1g\rangle$

$\langle 1|a^{\dagger} \quad a|1\rangle \quad 0$

2 pulse



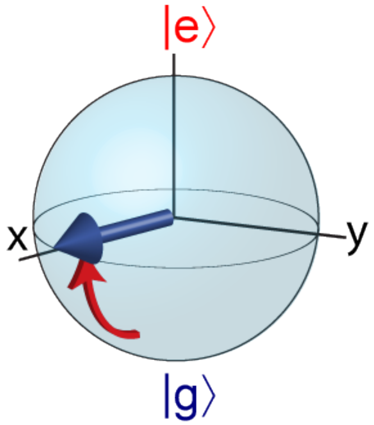
$|0g\rangle \quad |0g\rangle$

$\langle 0|a^{\dagger} \quad a|0\rangle \quad 0$

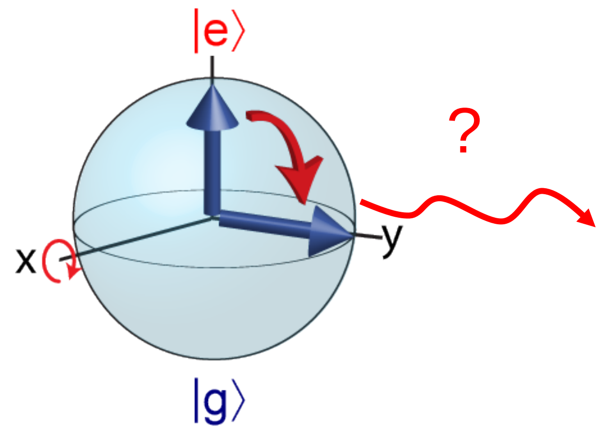
No average voltage for Fock states!
Phase completely uncertain!

Oscillations in Electric Field?

/2 pulse



Arbitrary pulse

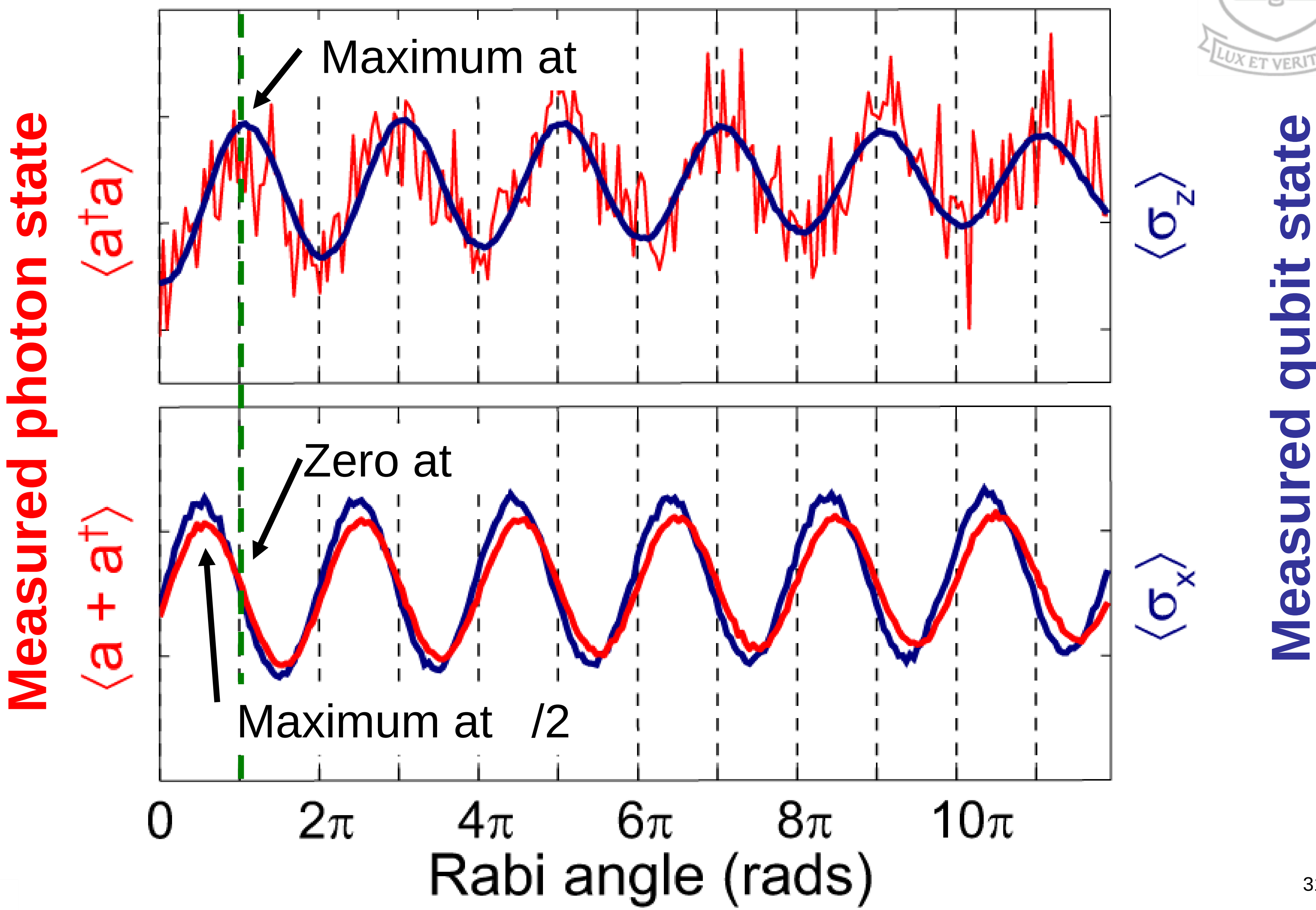


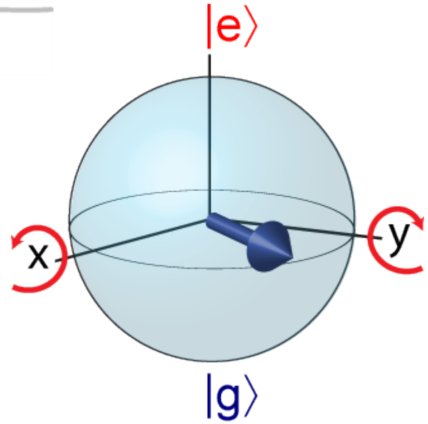
$\frac{1}{\sqrt{2}}|0\rangle \;\; |g\rangle \;\;\; |e\rangle$ $\qquad\qquad |0g\rangle \qquad |0e\rangle$

$\frac{1}{\sqrt{2}} \;\; |0\rangle \;\;\; |1\rangle \;\; |g\rangle$ $\qquad\qquad |0\rangle \qquad |1\rangle \;\; |g\rangle$

$\frac{1}{2}\langle 0 \;\;\; 1|a^\dagger \;\;\; a|0 \;\;\; 1\rangle \;\;\; 1 \;\;\; \langle a^\dagger \;\;\; a\rangle \qquad {}^* \qquad {}^* \qquad \langle \;\;\; {}_x \rangle$

Mapping the qubit state on to a photon

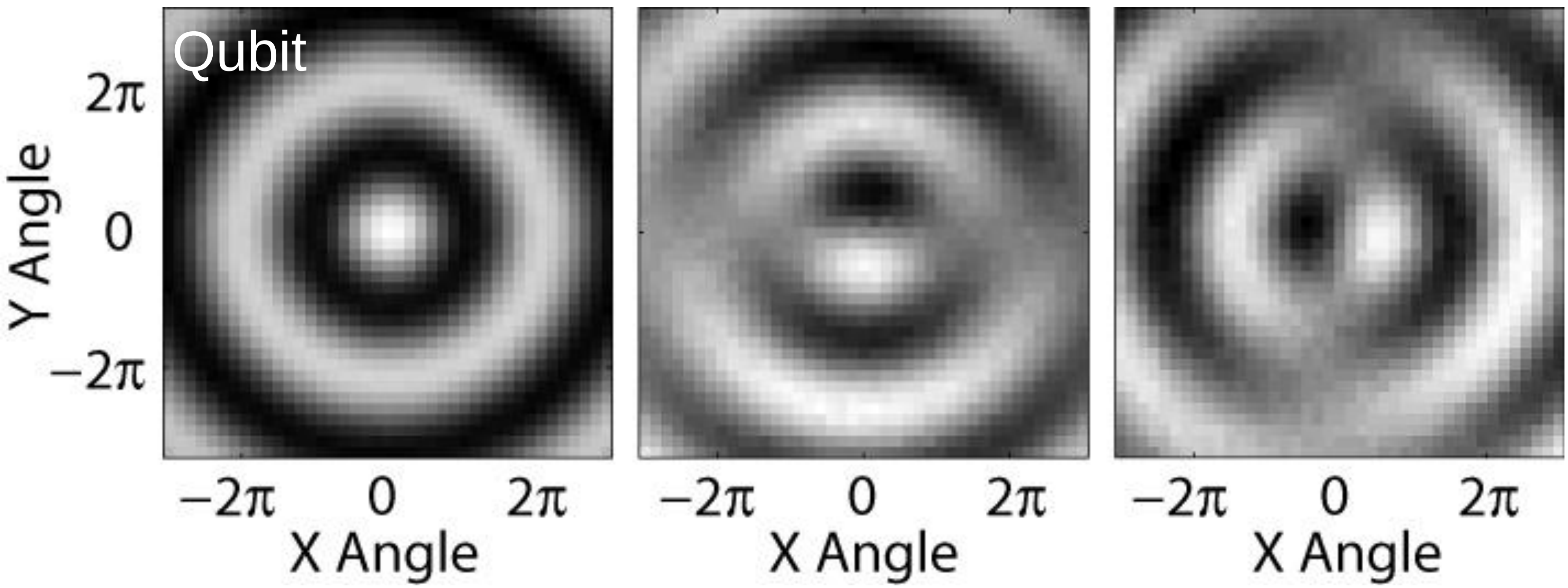




"Fluorescence Tomography"

- Apply pulse about arbitrary qubit axis
- Qubit state mapped on to photon superposition

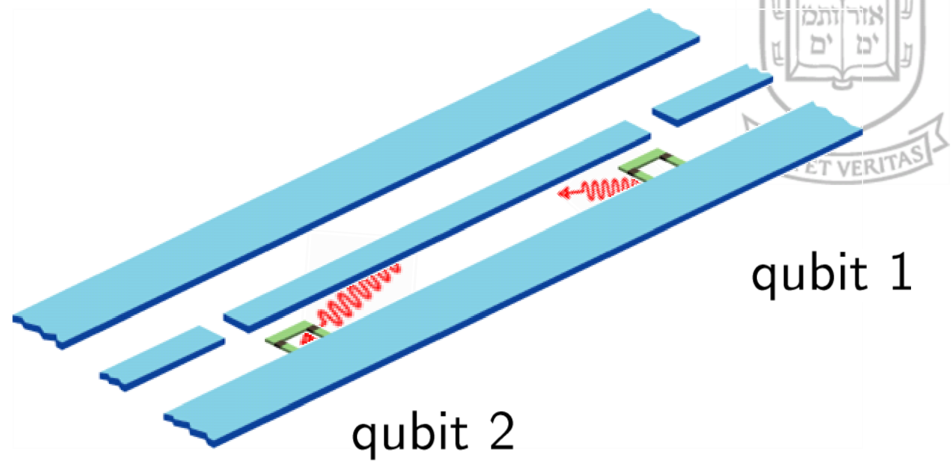
$\langle \hat{\ }_z \rangle$ $\langle a \quad a^\dagger \rangle$ $\langle a \quad a^\dagger \rangle$



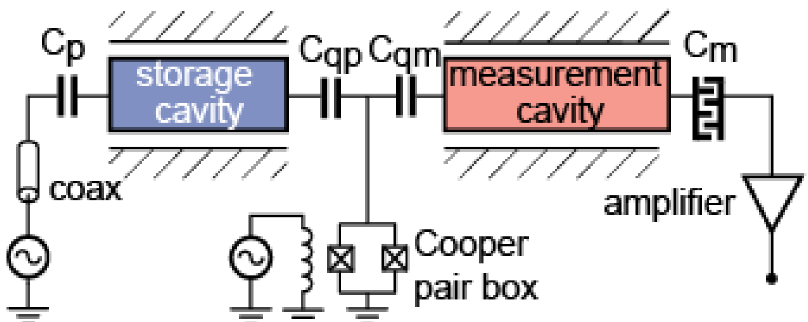
<u>all of the above are data!</u>

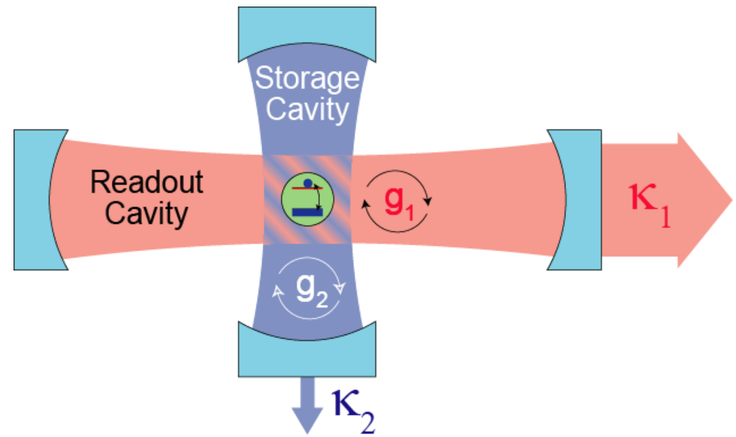
Future Possibilities

Cavity as quantum bus
for two qubit gates

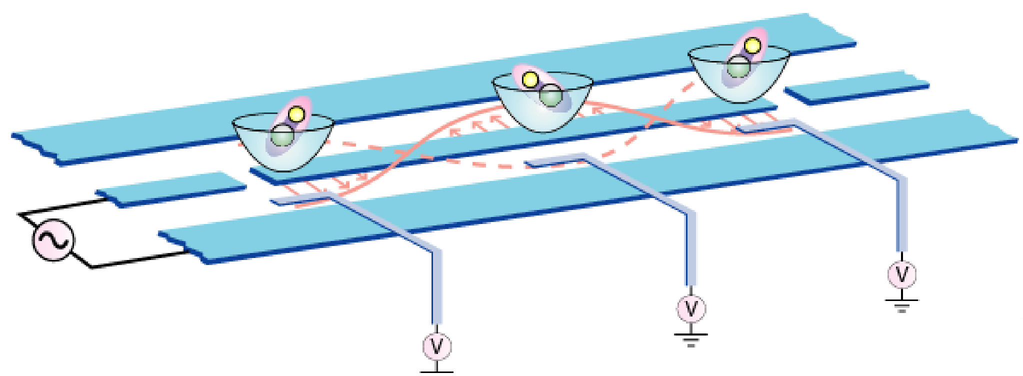


High-Q cavity as quantum memory





Cavities to cool
and manipulate
single molecules?



SUMMARY

Cavity Quantum Electrodynamics

cQED

"circuit QED"

Coupling a Superconducting Qubit to a Single Photon

- first observation of vacuum Rabi splitting
- initial quantum control results
- QND dispersive readout
- detection of particle nature of microwave photons
- single microwave photons on demand

„Circuit QED"
Strong Coupling of a Single Photon to a Cooper Pair Box

http://pantheon.yale.edu/~smg47
http://www.eng.yale.edu/rslab/cQED

- "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: an Architecture for Quantum Computation," A. Blais et al., Phys. Rev. A **69**, 062320 (2004).

- "Coherent Coupling of a Single Photon to a Superconducting Qubit Using Circuit Quantum Electrodynamics," A. Wallraff et al., Nature **431**, 162 (2004).

- "AC Stark Shift and Dephasing in a Superconducting Qubit Strongly Coupled to a Cavity Field," D.I. Schuster, et al., Phys. Rev. Lett. **94**, 123602 (2005).

- "Approaching Unit Visibility for Control of a Superconducting Qubit with Dispersive Readout," A. Wallraff et al., Phys. Rev. Lett. **95**, 060501 (2005).

- "Resolving Photon Number States in a Superconducting Circuit", Nature (Feb. 1, 2007)