Distributing Quantum Information with Microwave Resonators in Circuit QED

Stefan Filipp *(ETH Zurich)*

M. Baur, A. Fedorov, L. Steffen (Quantum Computation)

J. Fink, A. F. van Loo (Collective Interactions)

T. Thiele, S. Hogan (Hybrid Systems)

PI: A. Wallraff (ETH Zurich)

Theory support:

A. Blais (*Sherbrooke, Canada)*

M. da Silva (Raytheon BBN Tech.)

J. Gambetta *(Waterloo, Canada)*

Grenoble, France,

Juli 29, 2011

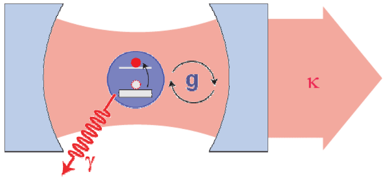
Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung
Fonds national suisse de la recherche scientifique
Swiss National Science Foundation
Fondo nazionale svizzero per la ricerca scientifica

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

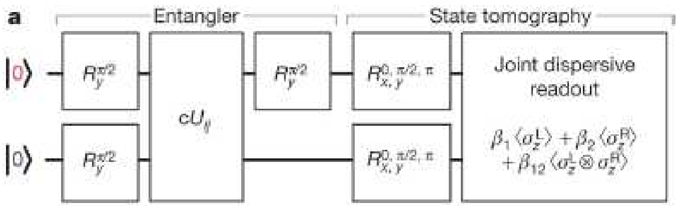
Der Wissenschaftsfonds.

Motivation

- ❖ Investigate new regimes of matter-light interaction in electronic circuits (Quantum optics, cavity quantum electrodynamics)

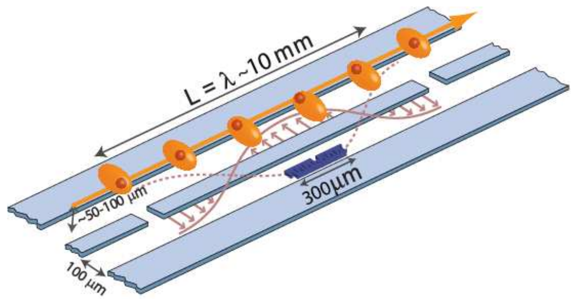


- ❖ Quantum circuits for information processing (Quantum computation)



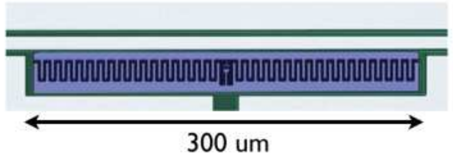
[DiCarlo, Nature (2009)]

- ❖ Interfaces between different physical systems (Quantum hybrids)

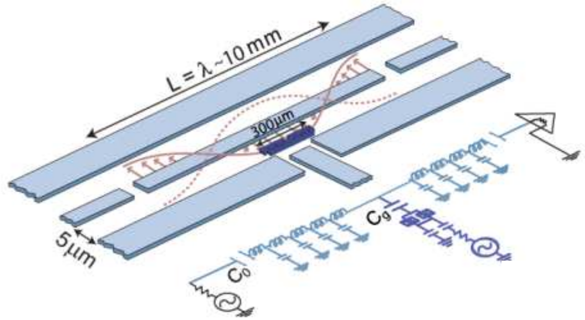


Outline

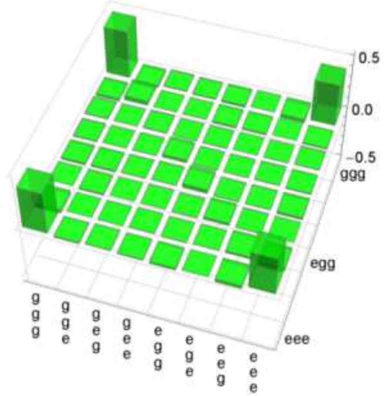
- Quantum Mechanics with Superconducting Circuits (**microresonator in the quantum regime**)



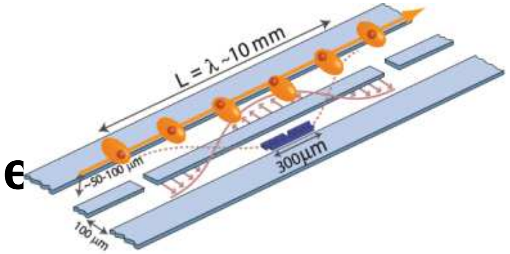
- Circuit QED (**microresonator as noise filter**
  + qubit readout
  + study of matter-light coupling)



- Generation of entangled 2-qubit and 3-qubit states **(microresonator for quantum information distributio**

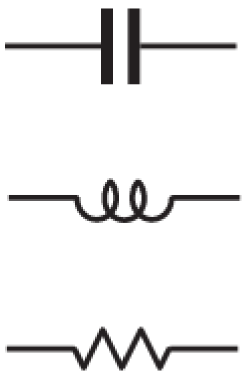


- Hybrid quantum computation with Rydberg atoms and superconducting circuits **(microresonator as interface to other quantum obje**

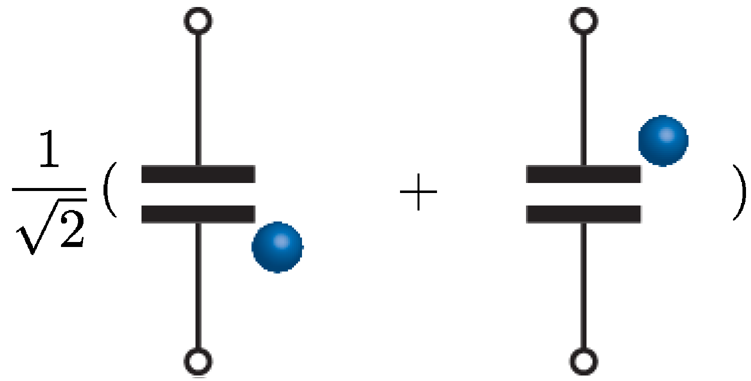


Classical and Quantum Electronic Circuit Elements

basic circuit elements:



charge on a capacitor:

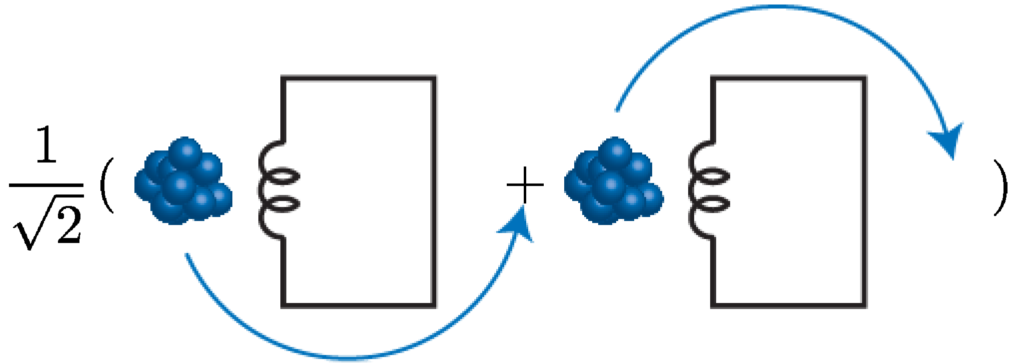


current or magnetic flux in an inductor:

quantum superposition states:

•charge **q**

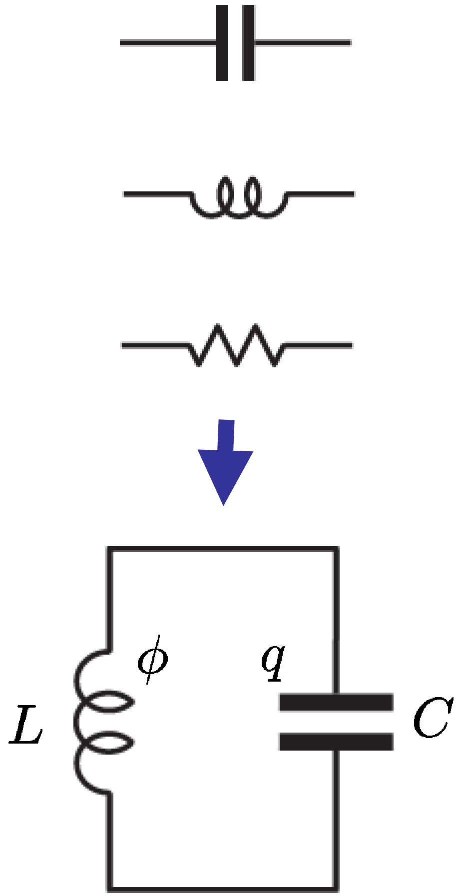
•flux ϕ



[Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)]

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



classical physics:

$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C}$$

quantum mechanics:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C}$$

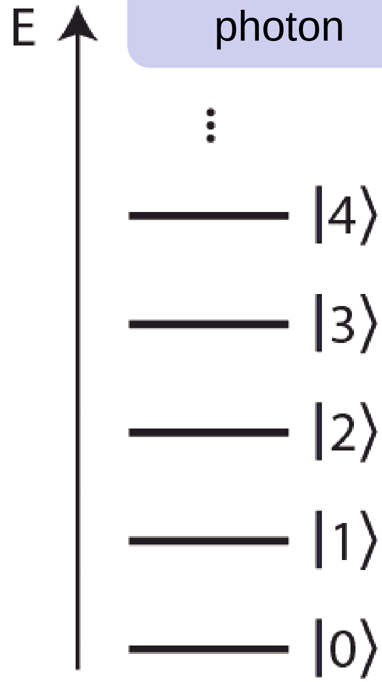
$$= \hbar\omega(\hat{a}^\dagger \hat{a} + \frac{1}{2})$$

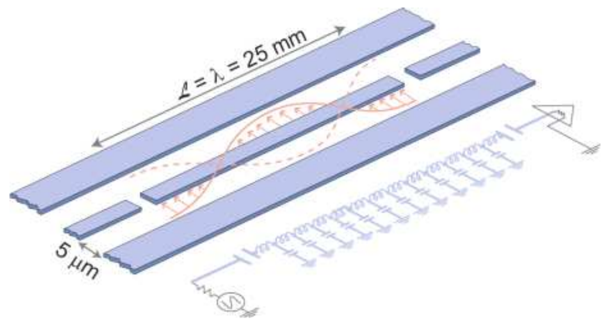
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

harmonic LC oscillator: $\omega = \frac{1}{\sqrt{LC}} \sim 5\,\mathrm{GHz}$

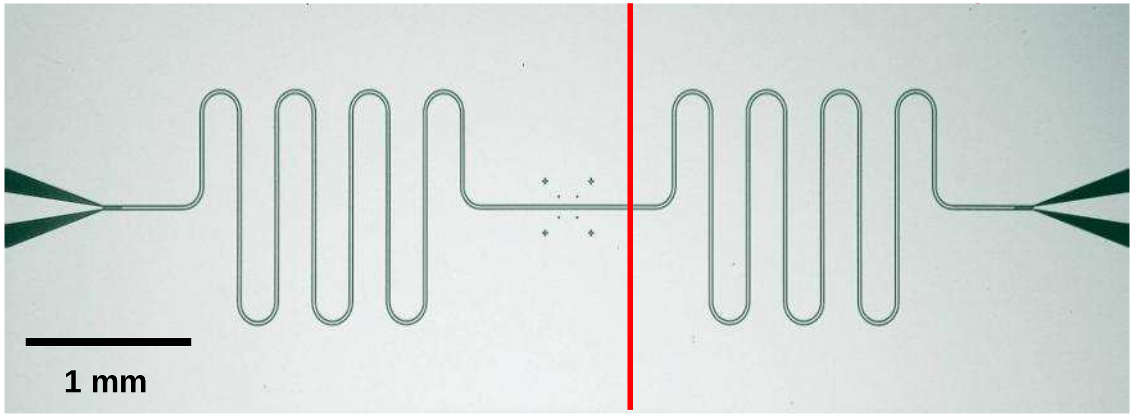
energy:

Electronic photon



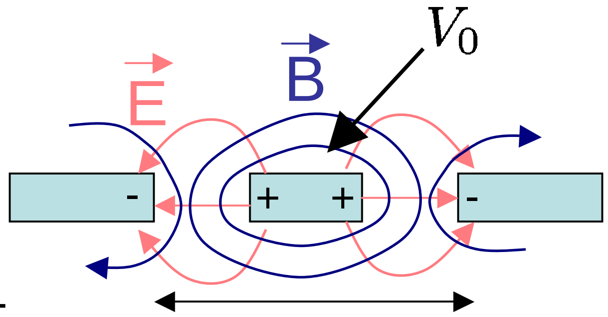


1D Cavity with large Vacuum Field



optical microscope image of sample fabricated at FIRST (Nb on sapphire)

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



electric field across resonator in vacuum state (*n=0*):

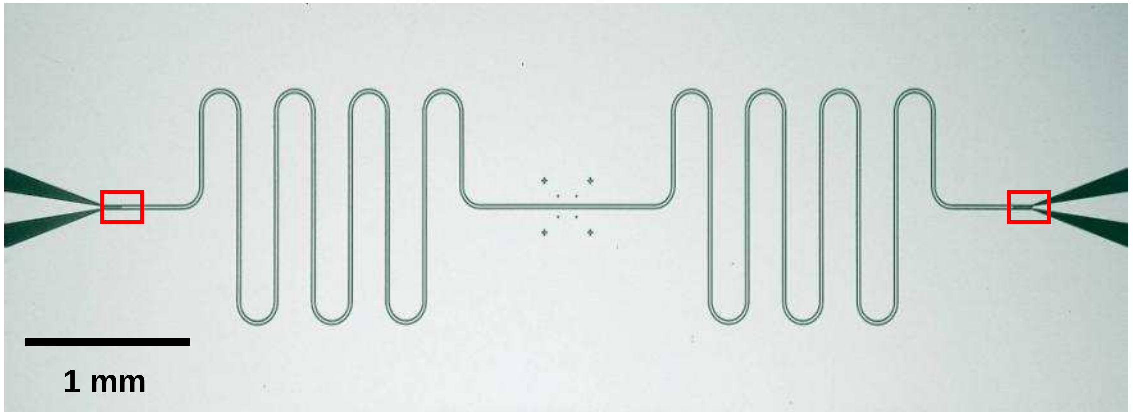
$$E_{0,\mathrm{rms}} \approx 0.2\,\mathrm{V/m} \qquad \text{for } \omega_r/2\pi \approx 6\,\mathrm{GHz}$$

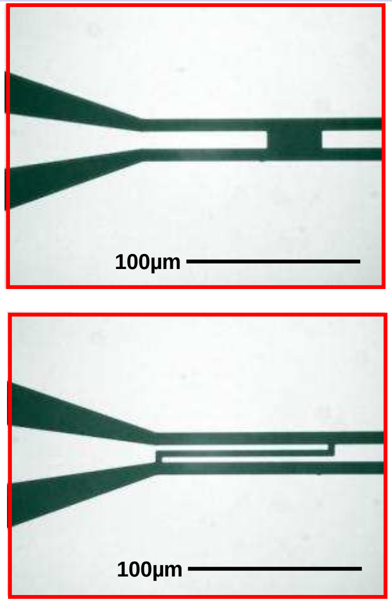
$\times 10^6$ larger than E_0
in 3D microwave cavity

harmonic oscillator

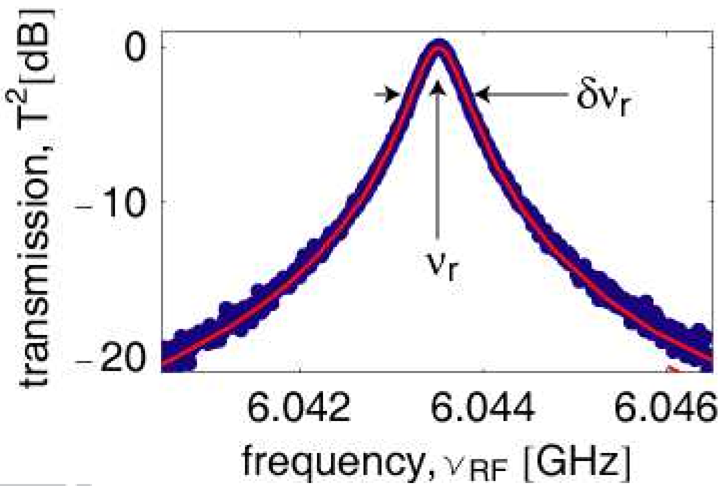
$$H_r = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right)$$

Storing Photons and Controlling their Life Time





measuring the life time:



quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^2 - 10^5$$

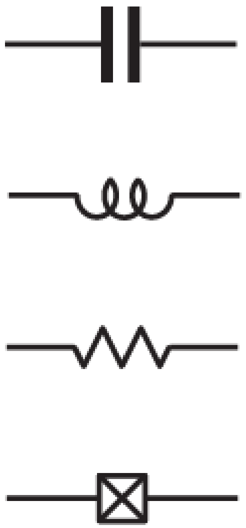
photon lifetime:

$$T_\kappa = 1/\kappa \approx 10\,\mathrm{ns} - 10\,\mu\mathrm{s}$$

[M. Goeppl, *et al. J. Appl. Phys.* **104**, 113904 (2008)]

Constructing Non-Linear Quantum Electronic Circuits

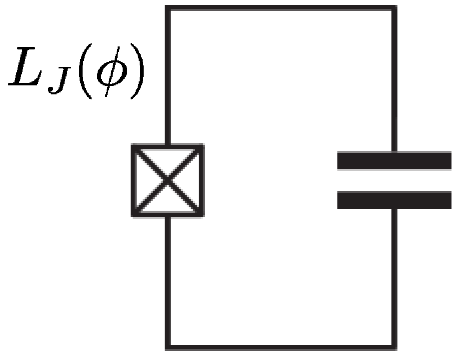
basic circuit elements:



Josephson junction:

a non-dissipative nonlinear element (inductor)

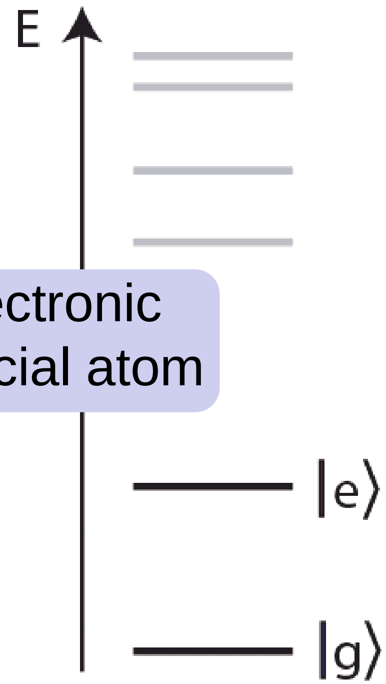
anharmonic oscillator:

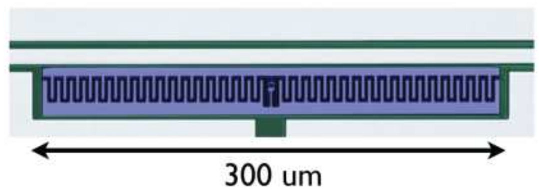


$$L_J(\phi) = \left(\frac{\partial I}{\partial \phi}\right)^{-1}$$

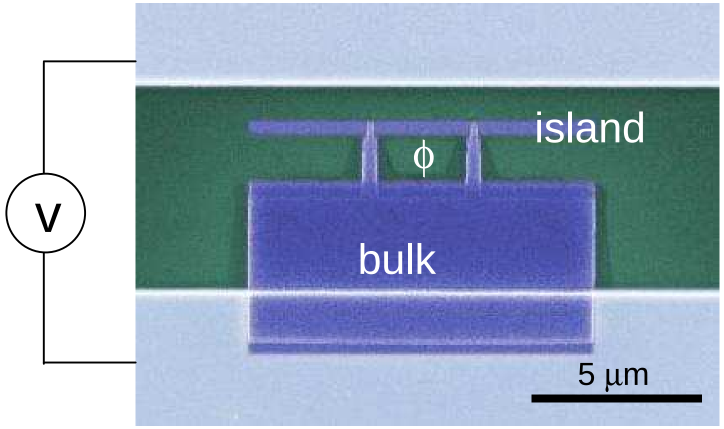
$$= \frac{\phi_0}{2\pi I_c} \frac{1}{\cos(2\pi\phi/\phi_0)}$$

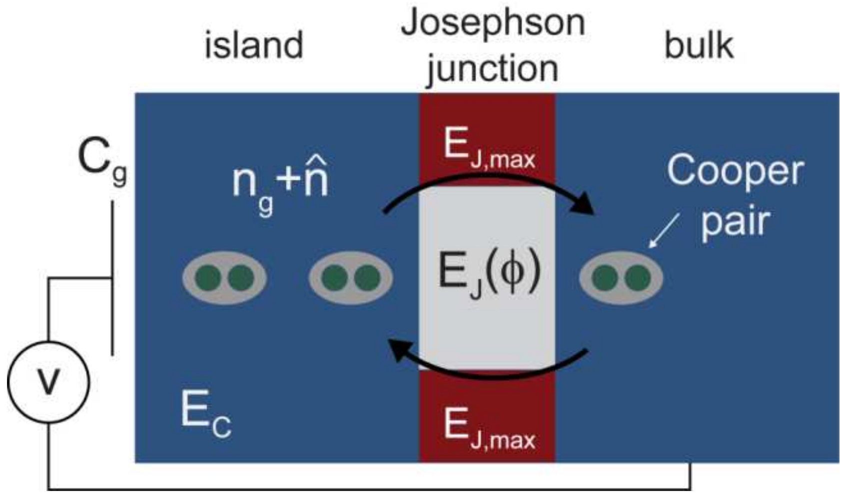
non-linear energy level spectrum:





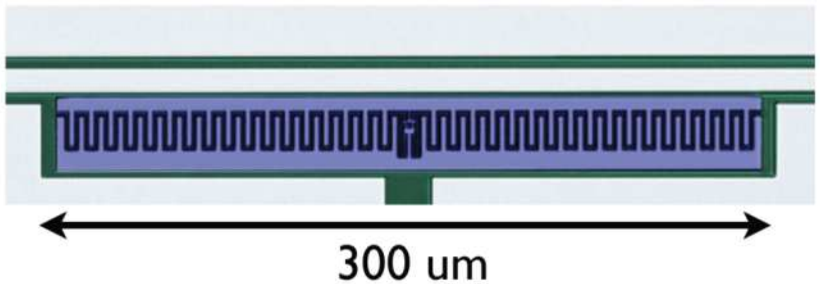
Artificial atom: Cooper Pair Box Qubit

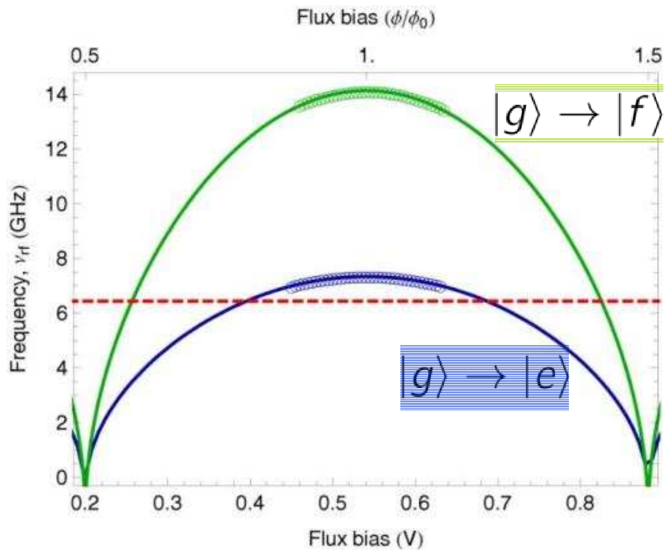




quantum state:
number $\hat{n}$ of Cooper pairs on island

transmon-design for increased
charge noise resilience:

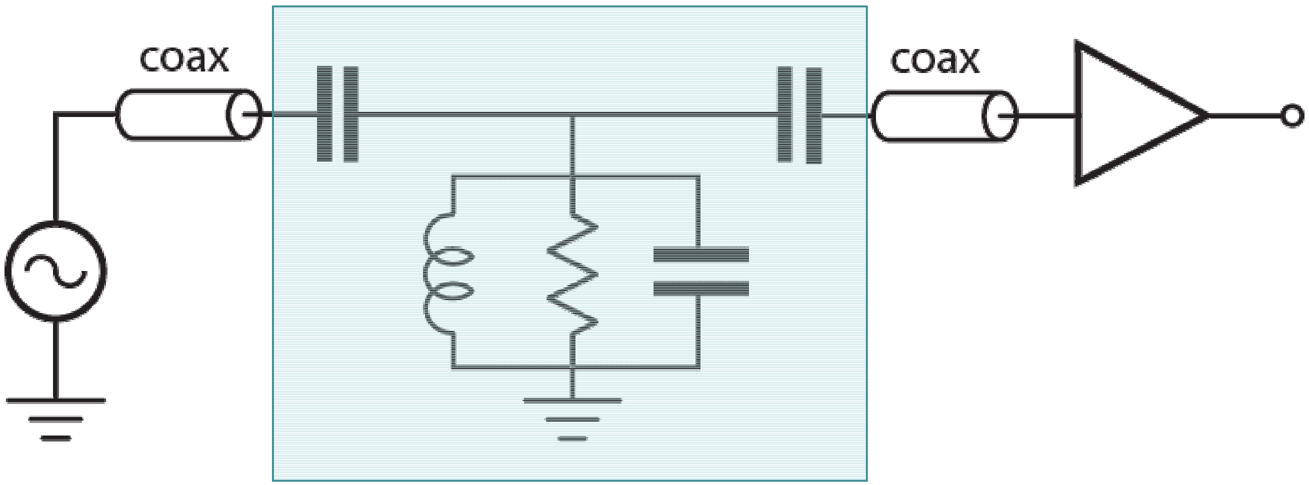




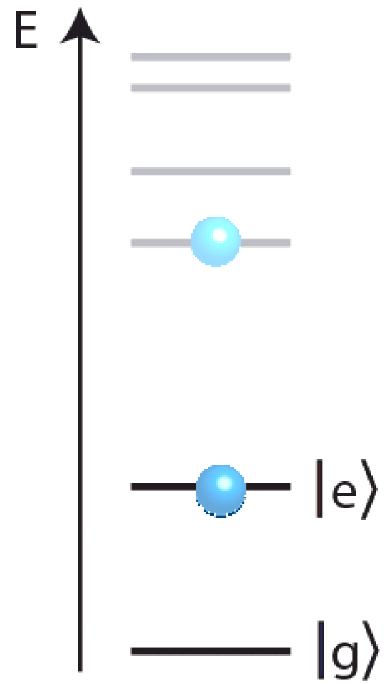
[Bouchiat, Vion, Joyez, Esteve, Devoret, *Physica Scripta* **T76**, 165 (1998);
Koch *et al. PRA* ***76****, 042319 (2007);* Schreier *et al. PRB (2008)]*

How to operate circuits quantum mechanically?

recipe:
- ❖ avoid dissipation
- ❖ work at low temperatures
- ❖ isolate quantum circuit from environment

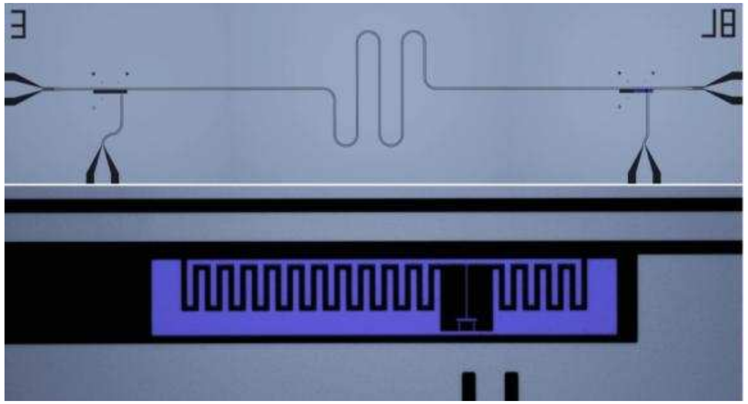


$T \sim 0.01\,\mathrm{K}$

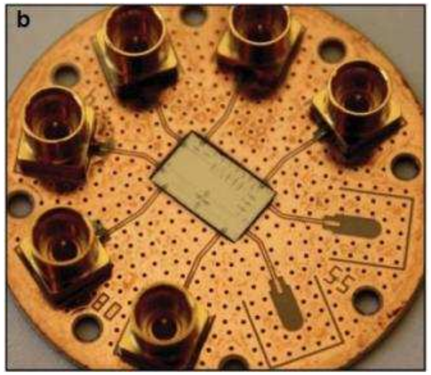


Setup

resonator+ transmon chip:



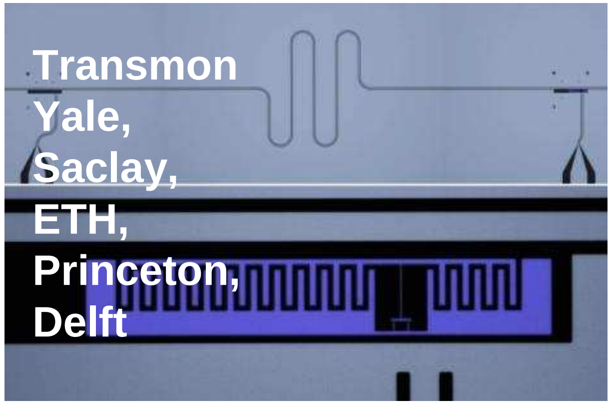
Sampleholder:

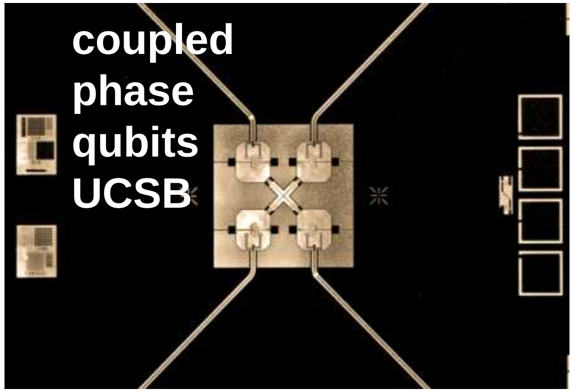


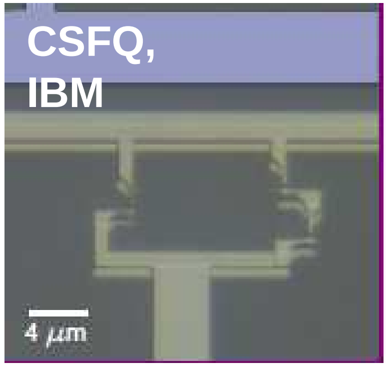
Box with B-field coils:

Dilution fridge (20mk):

Superconducting Artificial Atoms and Molecules



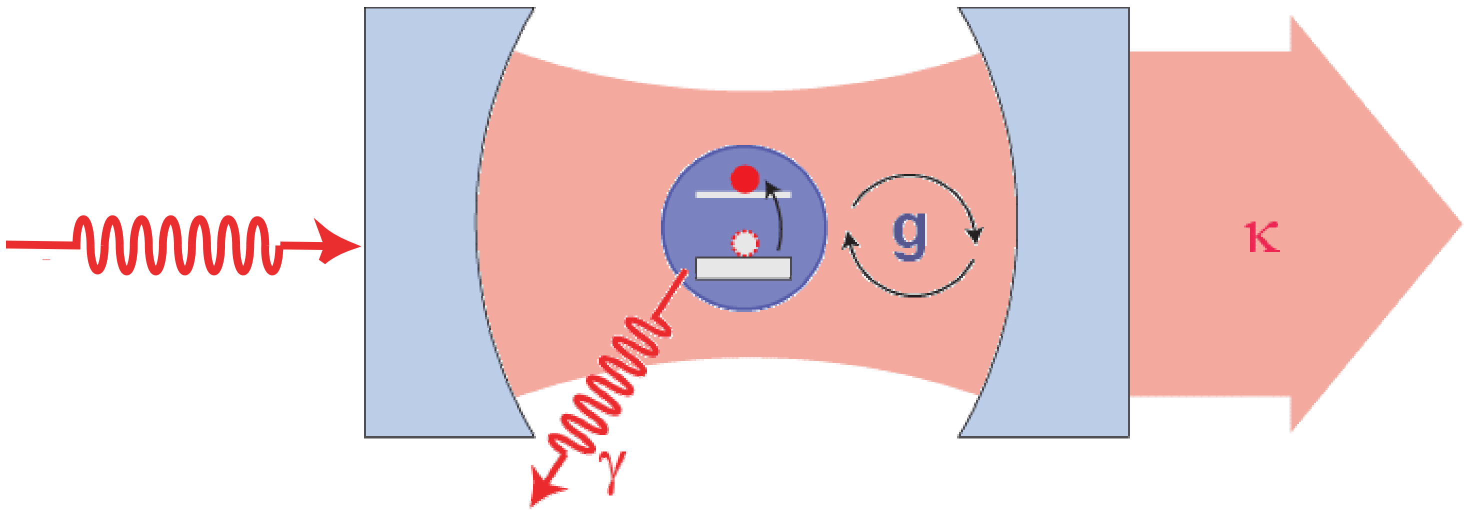




etc…

Cavity Quantum Electrodynamics

interaction of atom and photon in a cavity



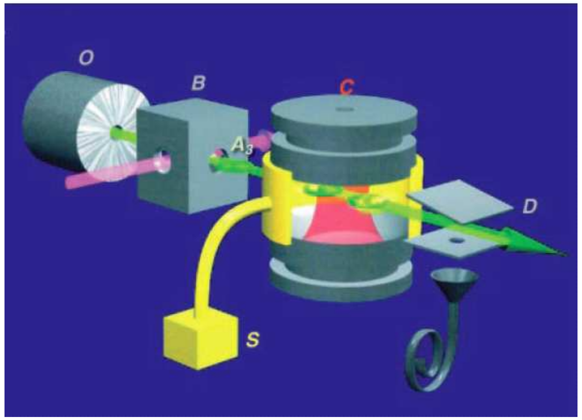
Jaynes-Cummings Hamiltonian

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

strong coupling limit: $g = dE_0/\hbar > \gamma,\ \kappa$

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

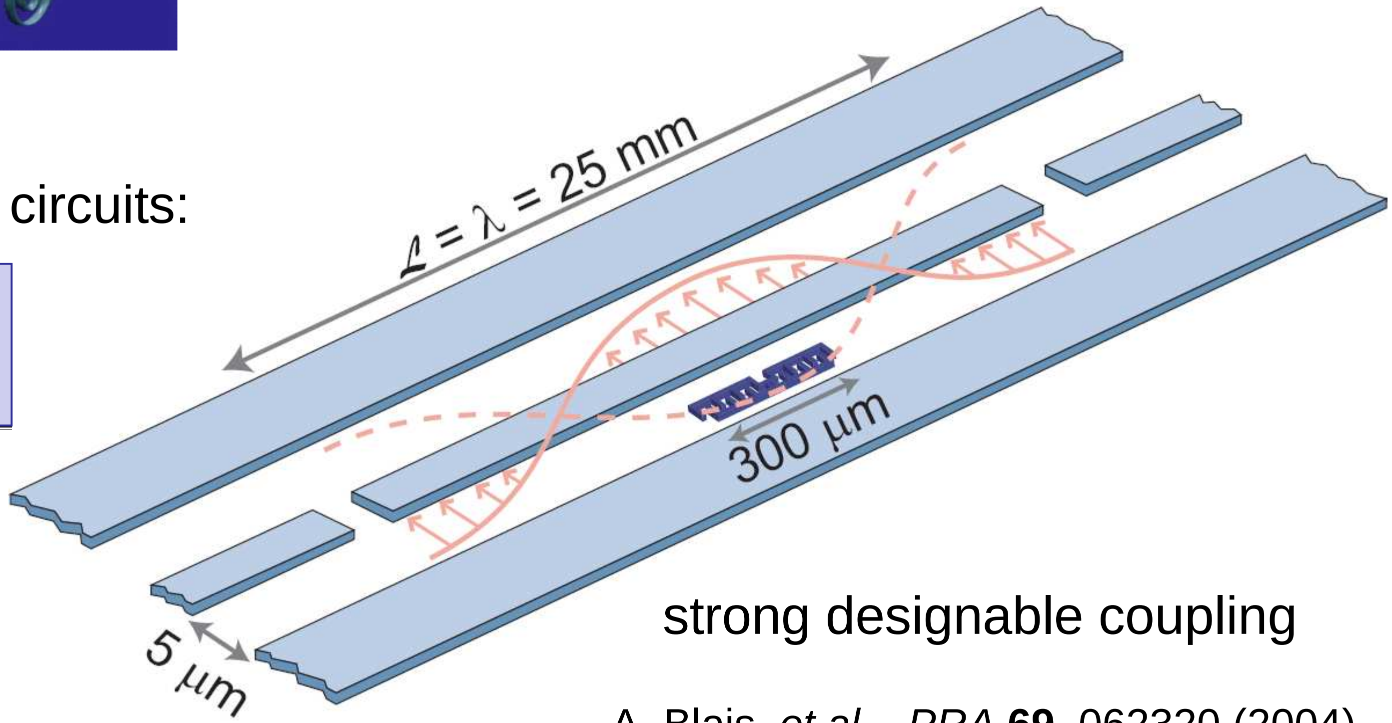
Our Circuit Realization of Cavity QED



Coherent quantum mechanics with individual photons and qubits
[S. Haroche & J. Raimond]

in superconducting circuits:

circuit quantum electrodynamics



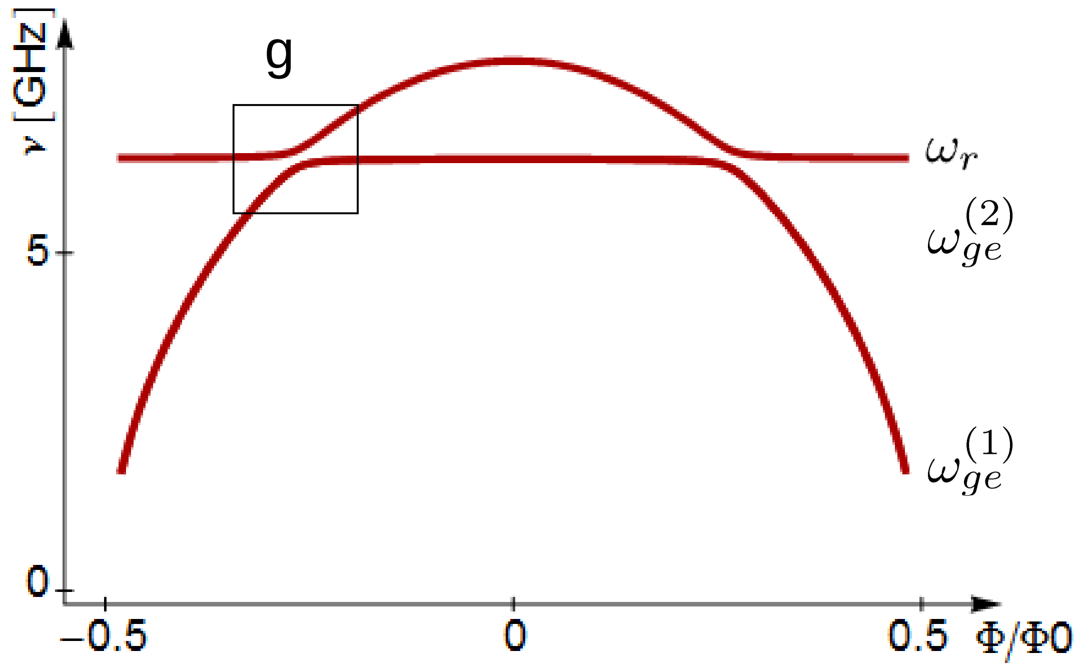
strong designable coupling

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

Resonant coupling

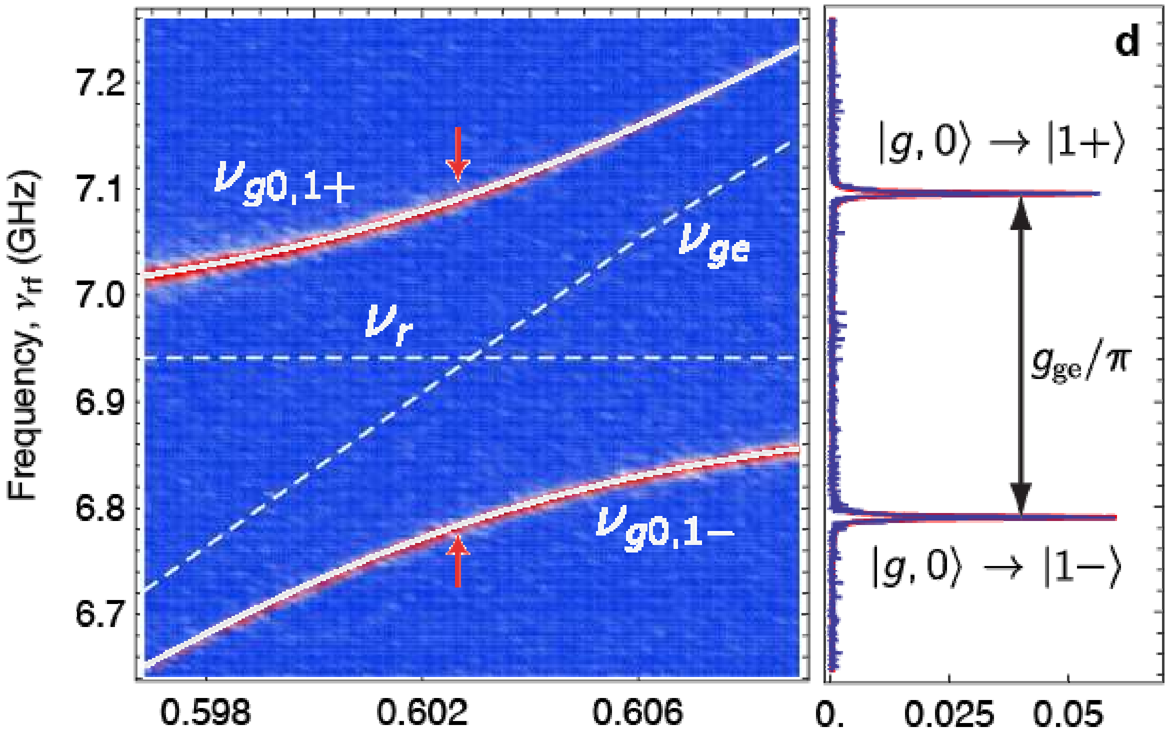
qubit 1: transition frequency: $\omega_{ge} \approx \sqrt{8E_C E_J} = \sqrt{8E_C E_{J,max} \left|\cos(\pi\Phi/\Phi_0)\right|}$

resonator: • direct coupling (g ~ 130 MHz)



Resonant Vacuum Rabi Mode Splitting …

… with one photon ($n = 1$):

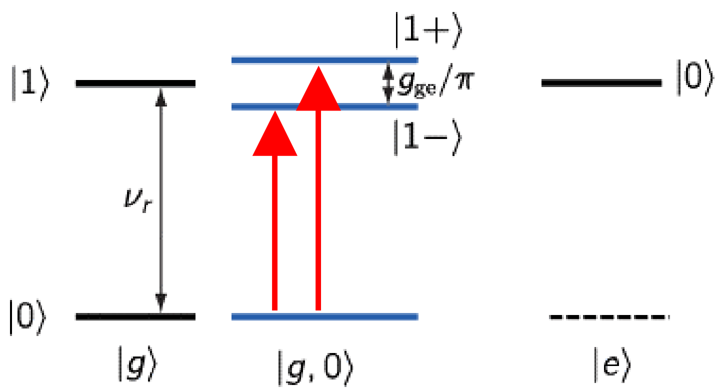


very strong coupling:

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

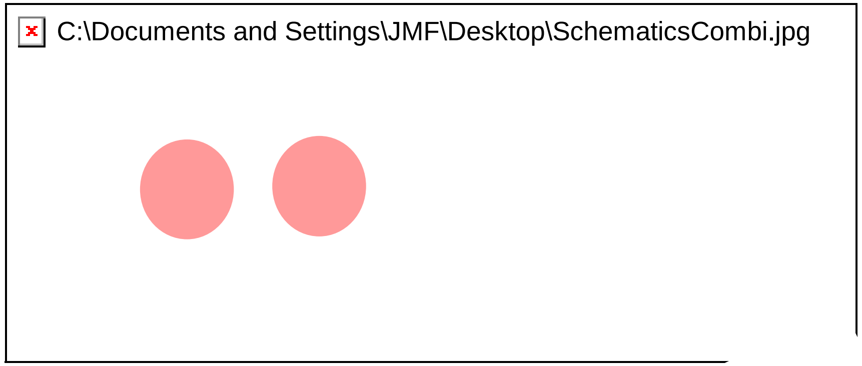
$$\kappa, \gamma < 1\ \mathrm{MHz}$$

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

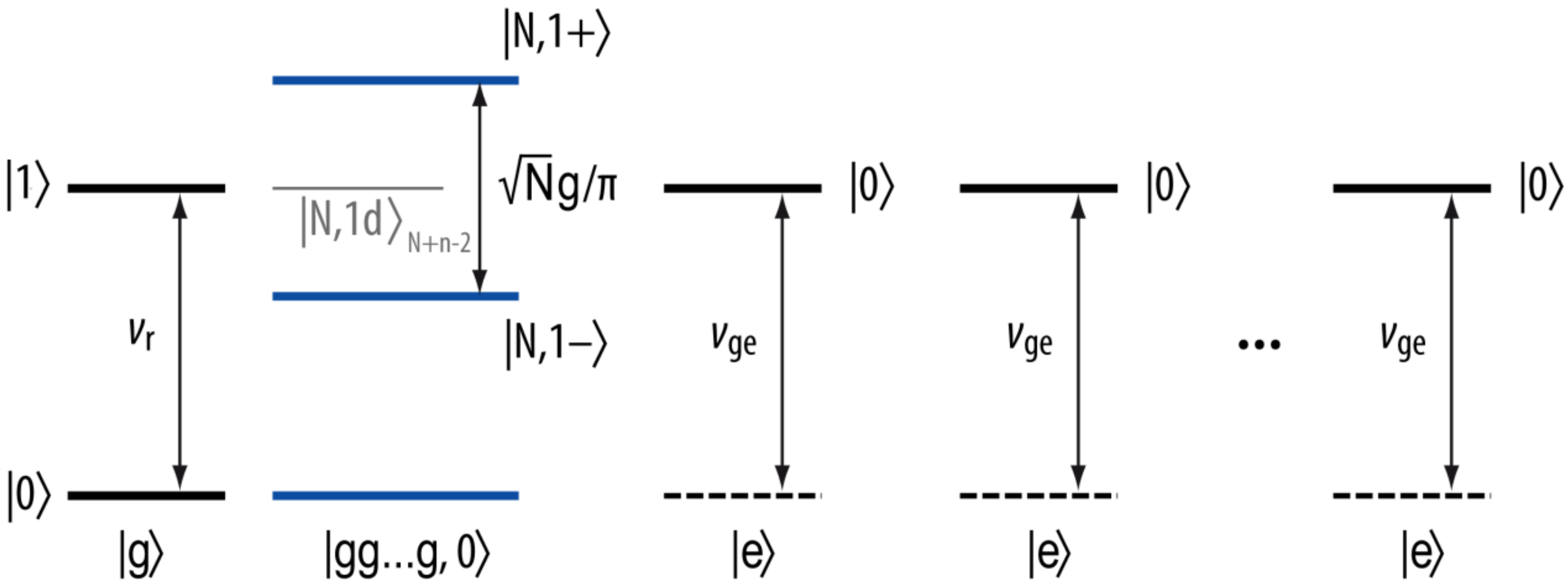


[first demonstration in a solid: A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)
this data: J. Fink et al., *Nature (London)* **454**, 315 (2008)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)]

Tavis-Cummings model: Increase number of qubits

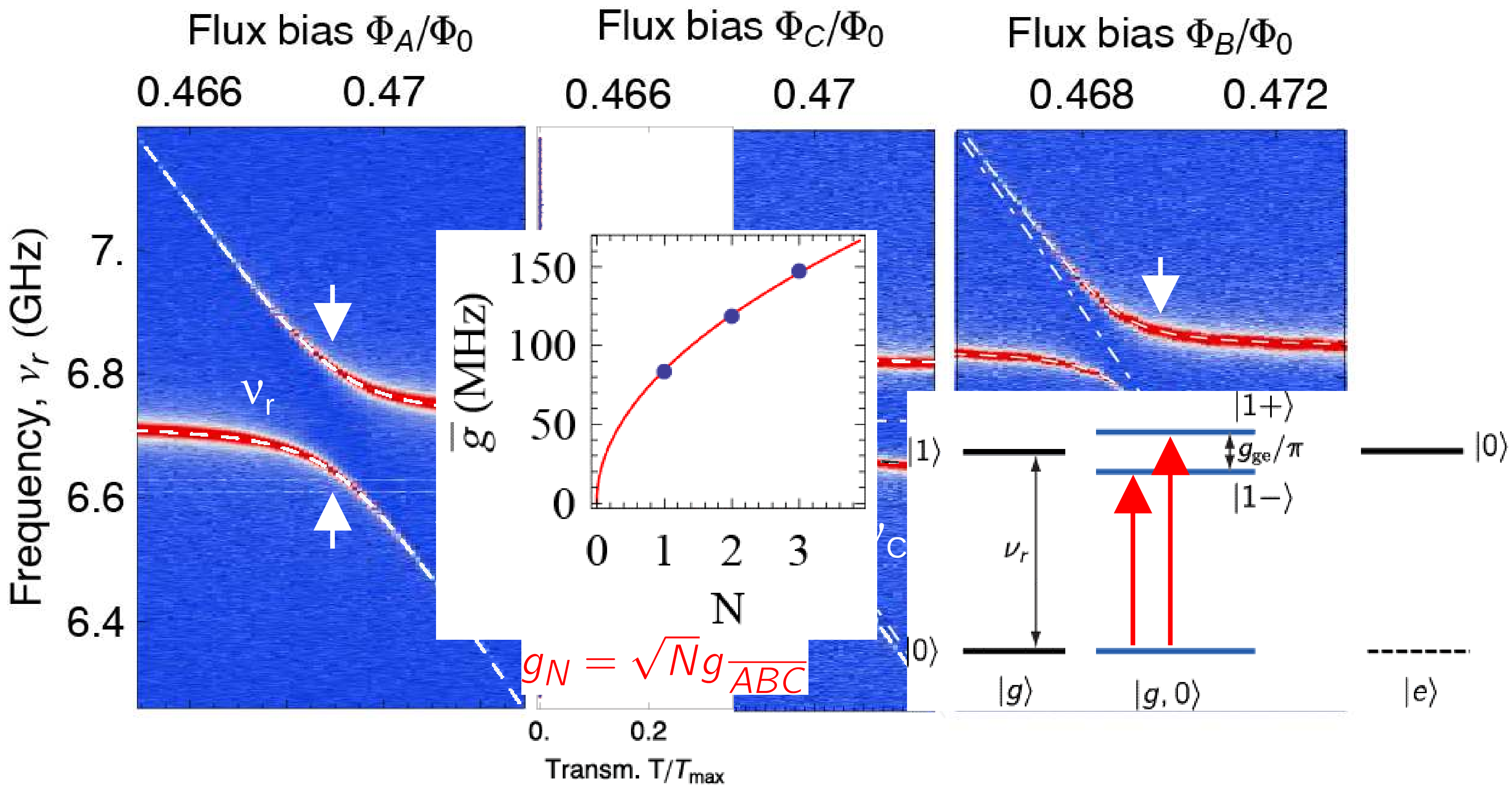


Coupling scales with number ***N*** of atoms $d \propto \sqrt{N}$



[J. M. Fink *et al.*, *PRL* **103**, (2009)]

Rabi Splitting with N = 1, 2, 3 Qubits and 1 Photon

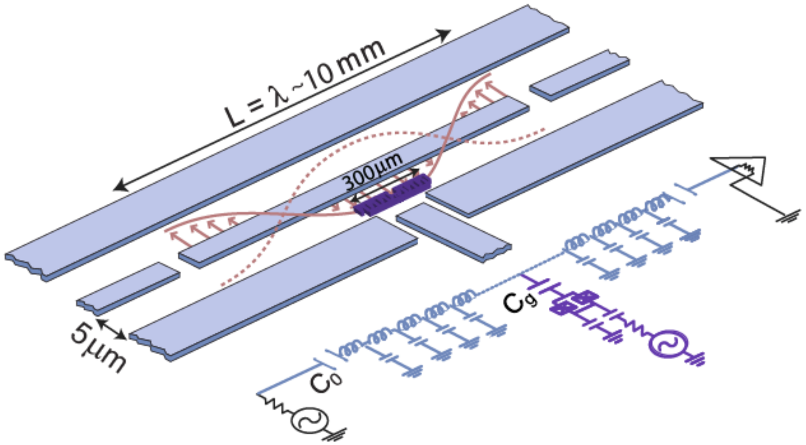


at degeneracy: two bright states, ***N*** - 1 dark states

[J. M. Fink *et al.*, *PRL* **103**, (2009)]

Dispersive regime

resonant:

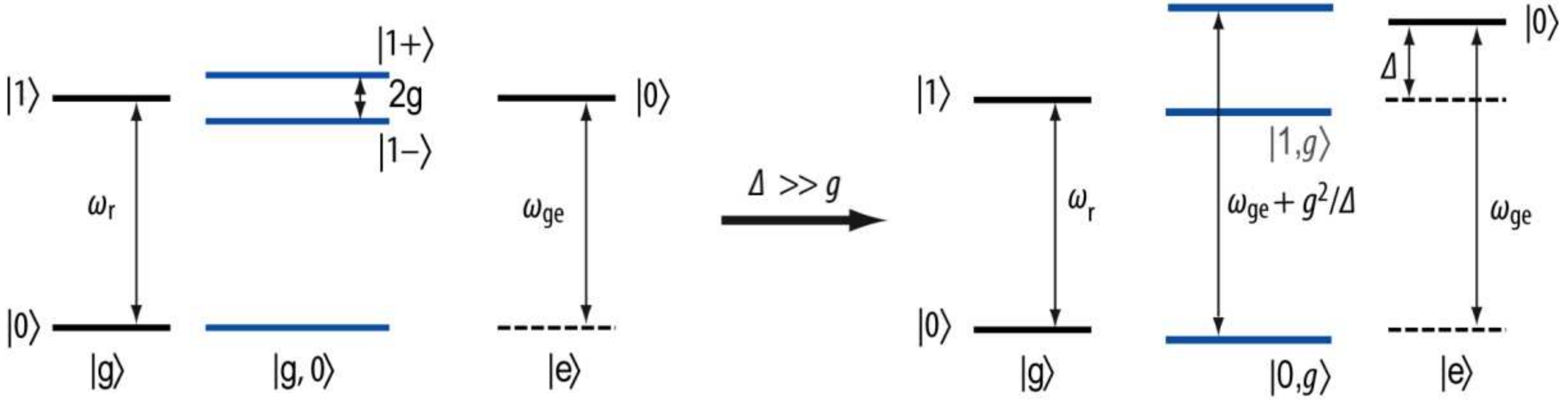


dispersive

(qubit detuned from resonance:

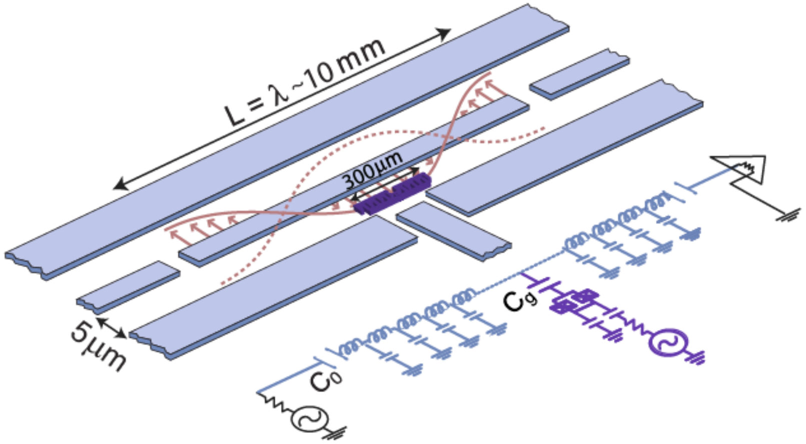
$\Delta = |\omega_{ge} - \omega_r| \gg g$)

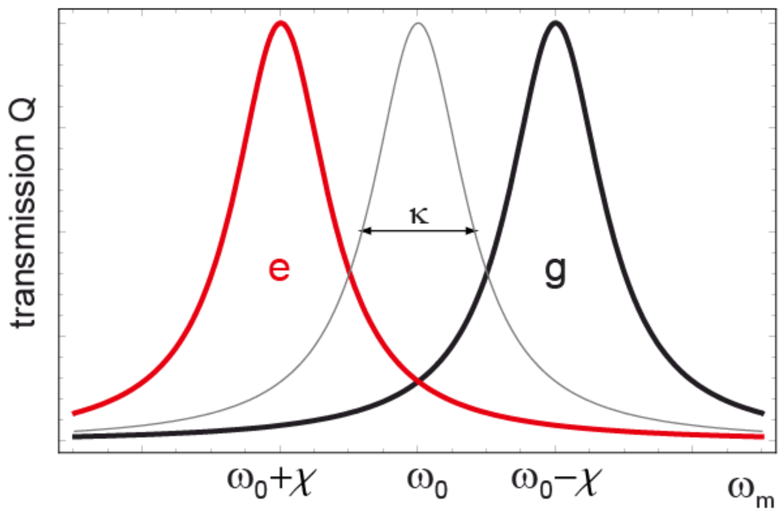
[Blais *et al.*, PRA **69** (2004)]



Circuit QED – read out of qubit state

low power transmission measurement to determine qubit state:





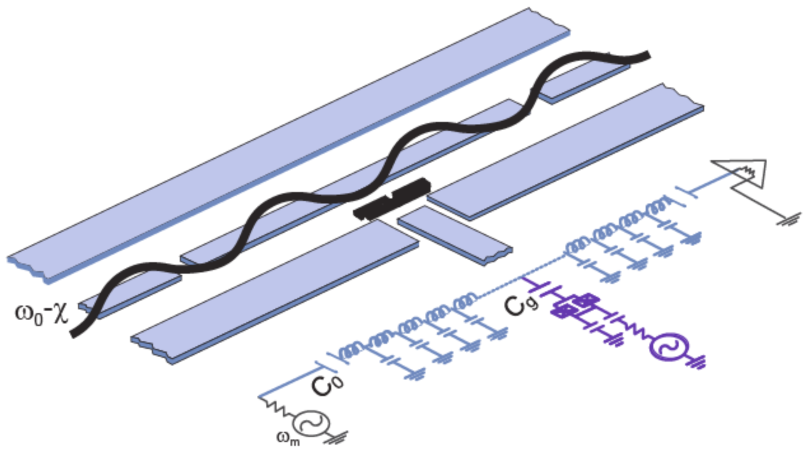
dispersive Hamiltonian:

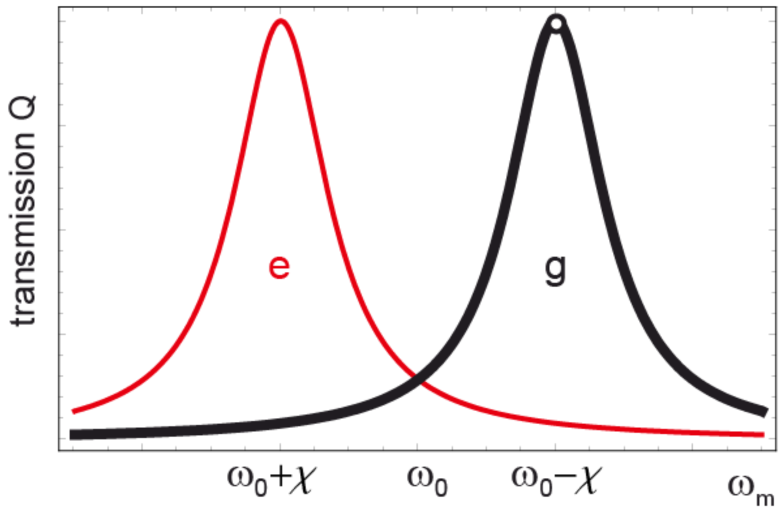
$$H = \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar}{2}(\omega_a + \chi)\sigma_z$$

state-dependent frequency shift

Circuit QED – read out of qubit state

low power transmission measurement to determine qubit state:





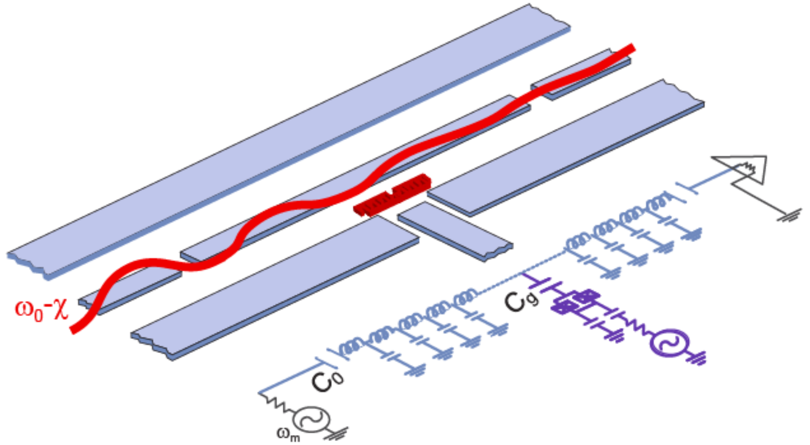
dispersive Hamiltonian:

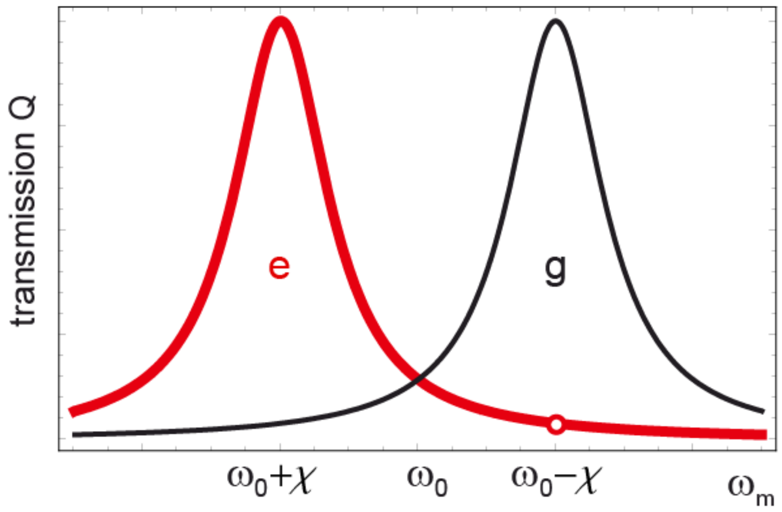
$$H = \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar}{2}(\omega_a + \chi)\sigma_z$$

state-dependent frequency shift

Circuit QED – read out of qubit state

low power transmission measurement to determine qubit state:





dispersive Hamiltonian:

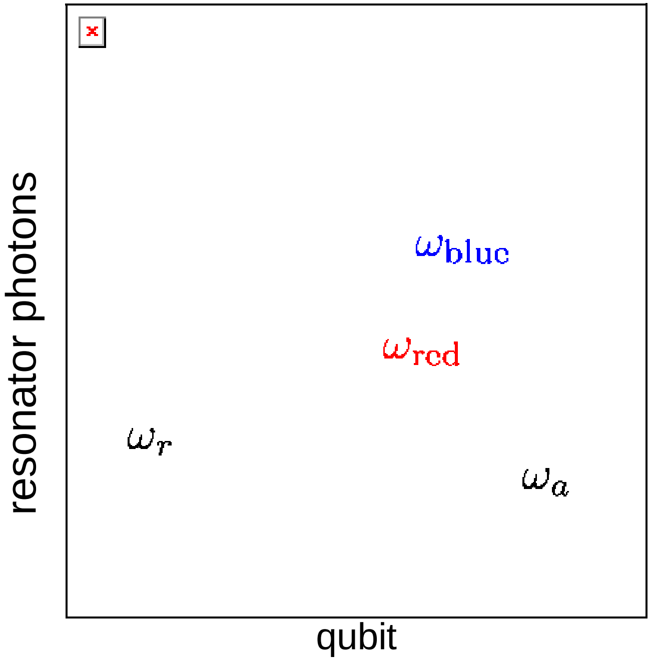
$$H = \hbar(\omega_r + \chi\sigma_z)a^\dagger a + \frac{\hbar}{2}(\omega_a + \chi)\sigma_z$$

state-dependent frequency shift -> σ_z determined

Preparation of non-classical photon states using sideband transitions.

Sideband transitions in circuit QED

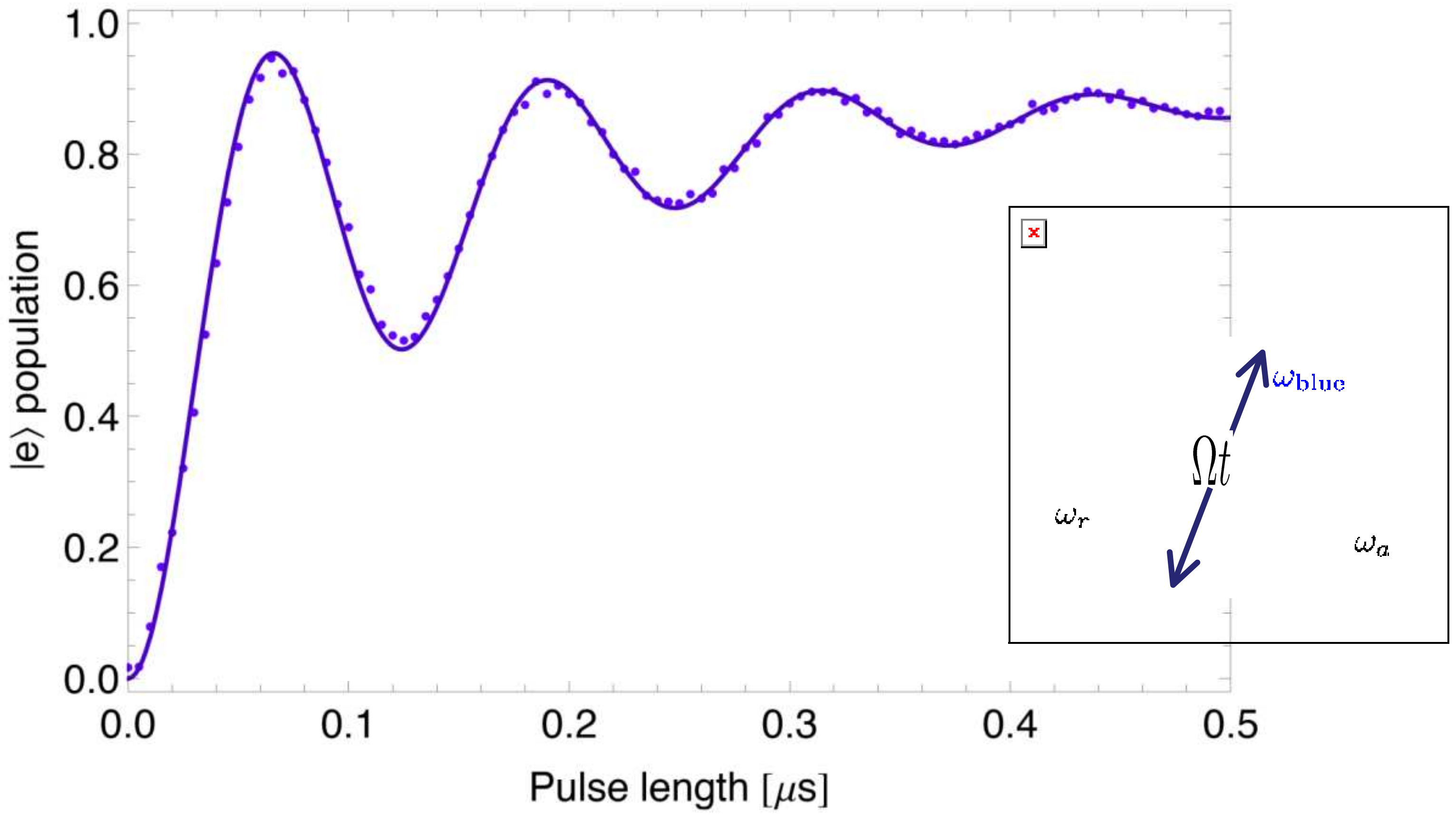
- Qubit & cavity off-resonant: $\Delta = |\omega_r - \omega_a| \gg g$



- Transitions can be driven using strong external fields

[Chiorescu *et al. Nature (2004); Wallraff et al. PRL (2007);*
Blais *et al. PRA (2007); Liu et al. PRB (2007);* P. J. Leek *et al.*, PRB(R) (2009)]

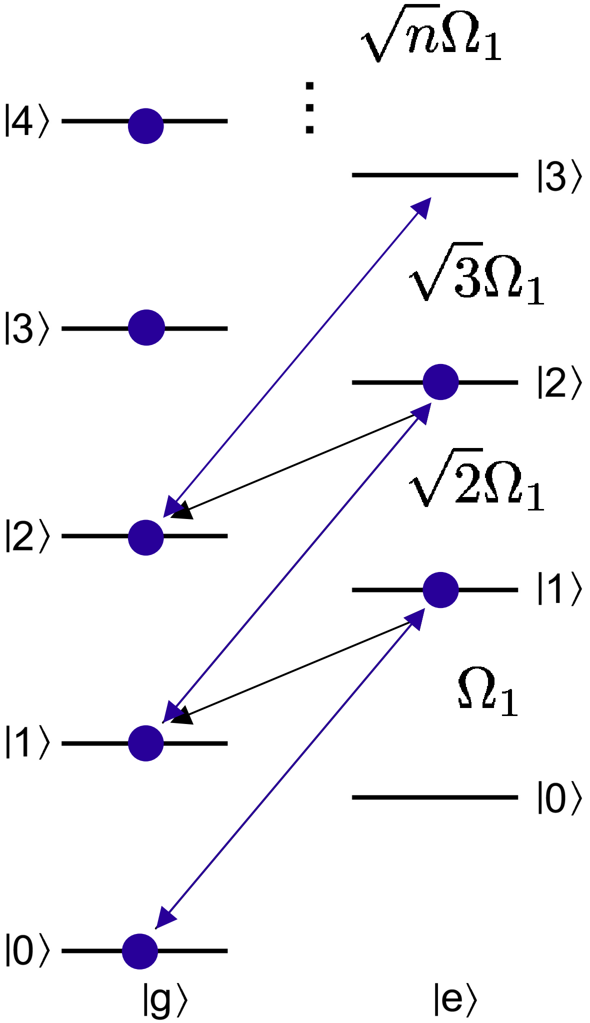
Operations using blue sideband



Sideband can be used for exchange of information between qubit and photon

n photon Fock state Generation up to n=4

Preparation of n photon Fock states with blue sideband transitions



Qubit –

High Q –

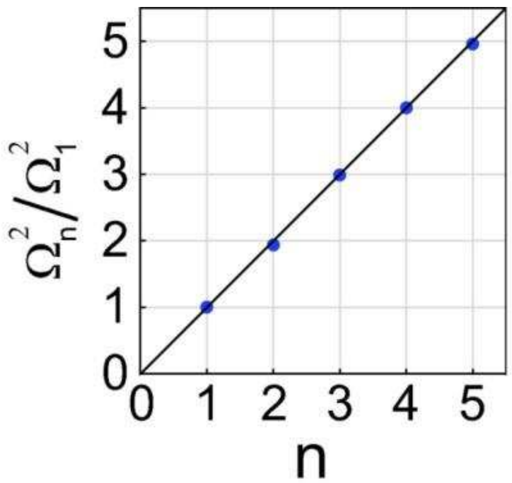
Low Q –

Sideband Rabi frequency scales with $\sqrt{n}$

Sideband Rabi Oscillations with Fock States n=0 to 4

Result: Scaling of Rabi frequency

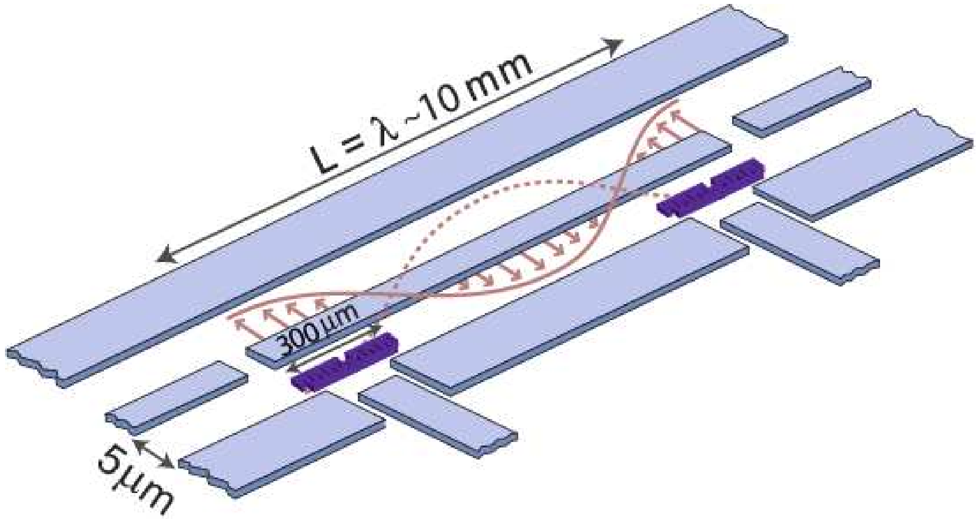
$$\Omega_n = \sqrt{n}\Omega_1$$



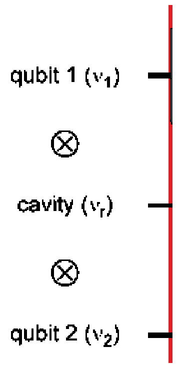
[P. J. Leek *et al.*, PRL **104**, 100504 (2010)]

Entangling two distant qubits

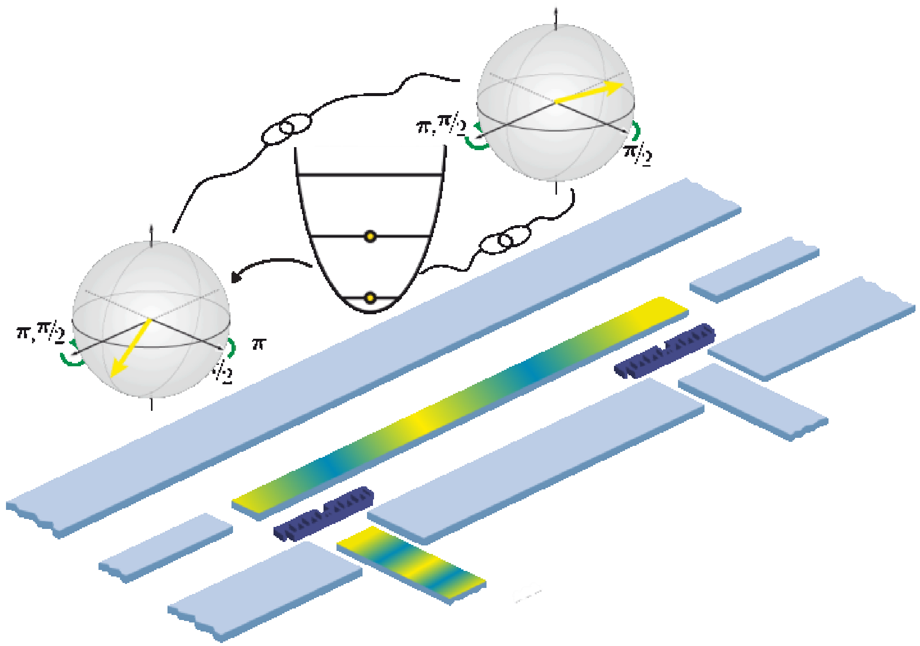
resonator can also be used as a **'quantum bus'** to create an **entangled** state (a quantum state, where the single qubits lose their individuality)



Entangling two qubits using sideband transitions

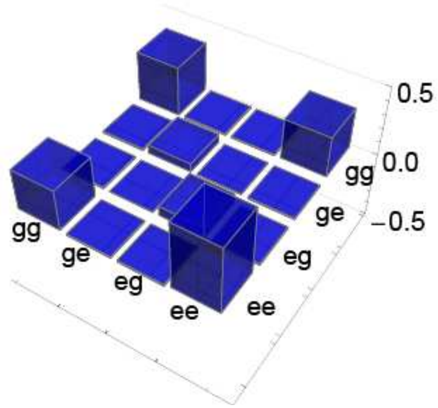


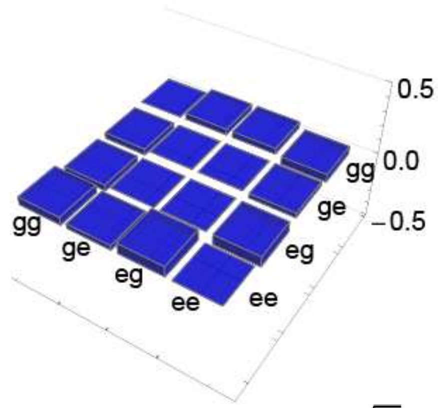
$$|\psi\rangle = (|ge\rangle + |eg\rangle)/\sqrt{2}$$



Entanglement of superconducting qubits

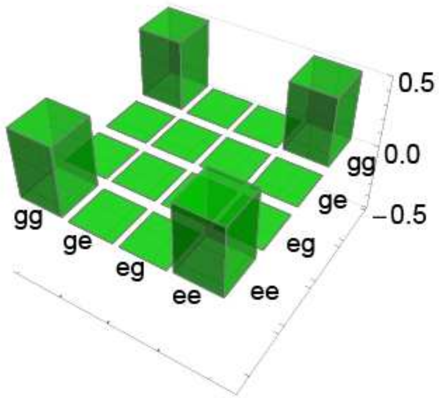
Experiment: Re Ψ_{Bell} Im Ψ_{Bell}

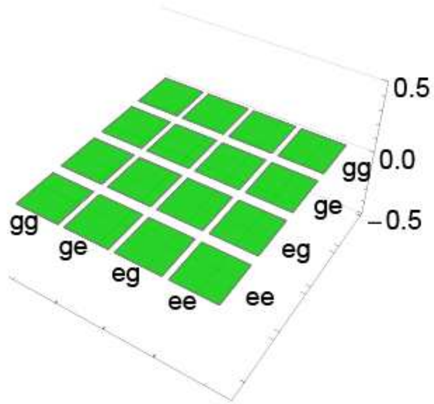




Theory:

$$\Psi_{\mathrm{Bell}} = (|g\rangle \otimes |g\rangle + |e\rangle \otimes |e\rangle)/\sqrt{2}$$





Fidelity: $\left(\mathrm{Tr}\left[(\rho_{\mathrm{exp}}^{1/2}\rho_{\mathrm{th}}\rho_{\mathrm{exp}}^{1/2})^{1/2}\right]\right)$ 86%

[Leek *et al.*, PRB **79**, 180511R (2009);
Filipp *et al.,* PRL **102**, 200402 (2009).]
recent data: M. Baur (ETH Zurich)

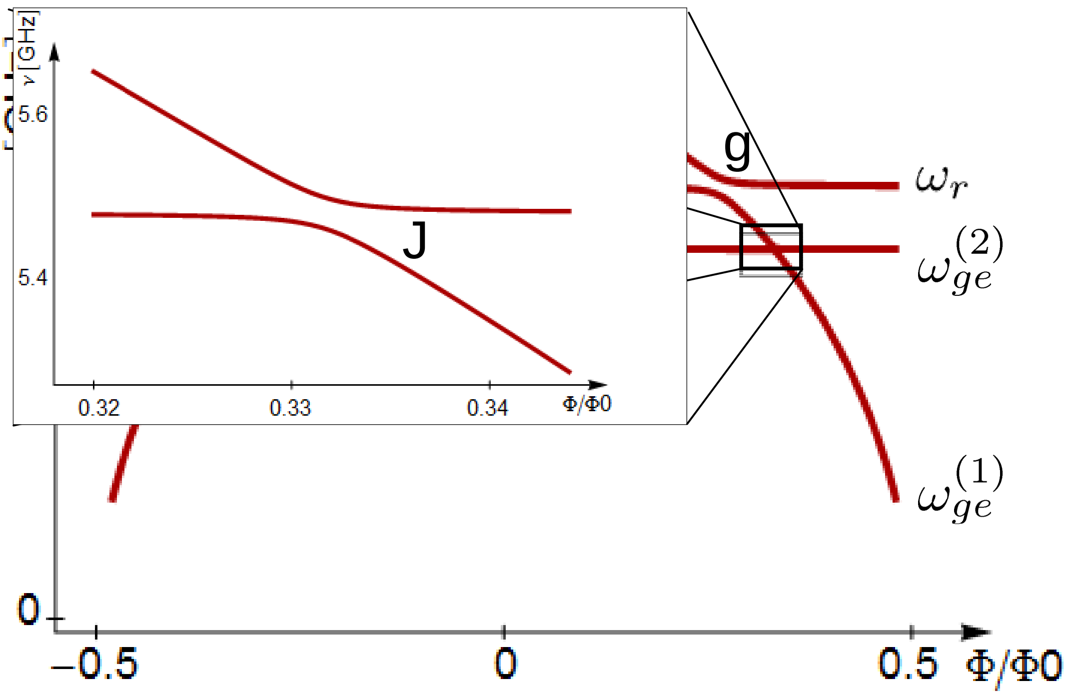
Qubit interactions mediated via virtual photons.

Resonant and dispersive coupling

qubit 1: transition frequency: $\omega_{ge} \approx \sqrt{8E_C E_J} = \sqrt{8E_C E_{J,max} \left|\cos(\pi\Phi/\Phi_0)\right|}$

qubit 2: constant frequency (5.5 GHz)

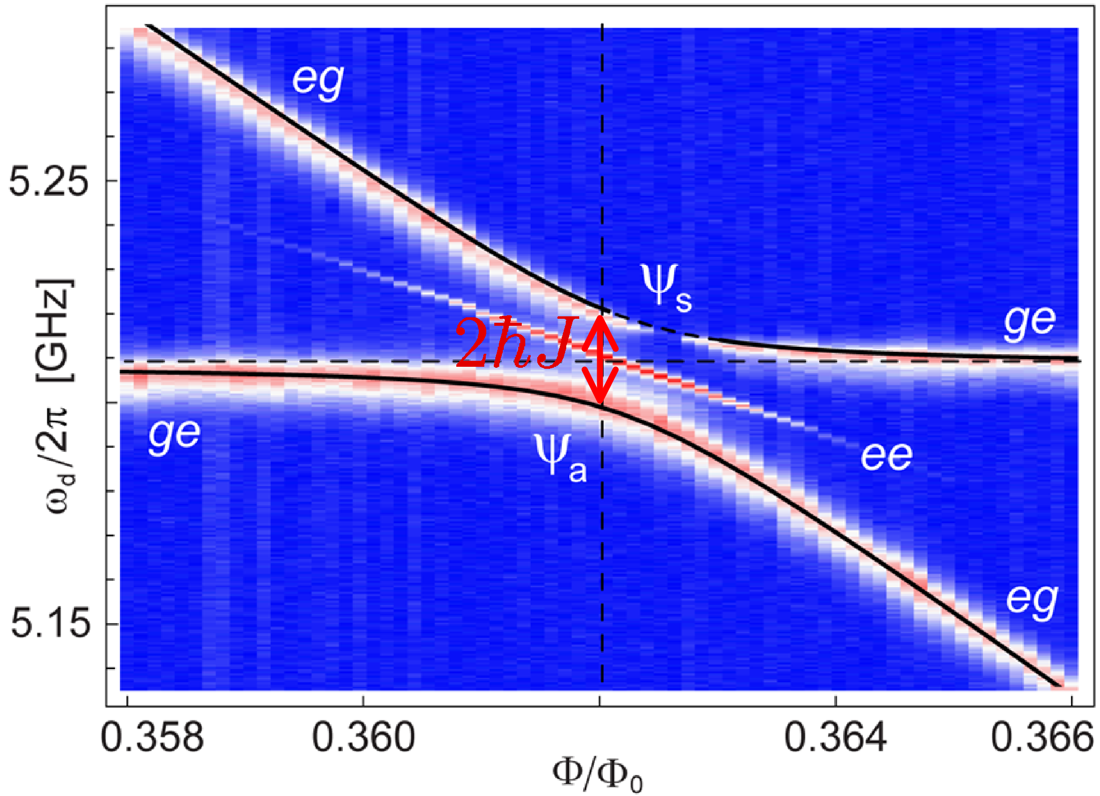
resonator:
- direct coupling (g ~ 130 MHz)
- mediated J-coupling (J ~ 20 MHz)

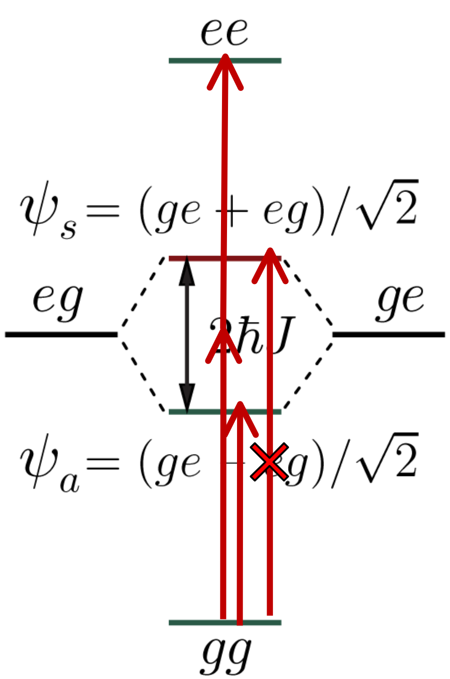


[Majer *et al.*, Nature **449** (2007)]

Avoided level crossing

- cavity mediated coupling leads to an avoided crossing

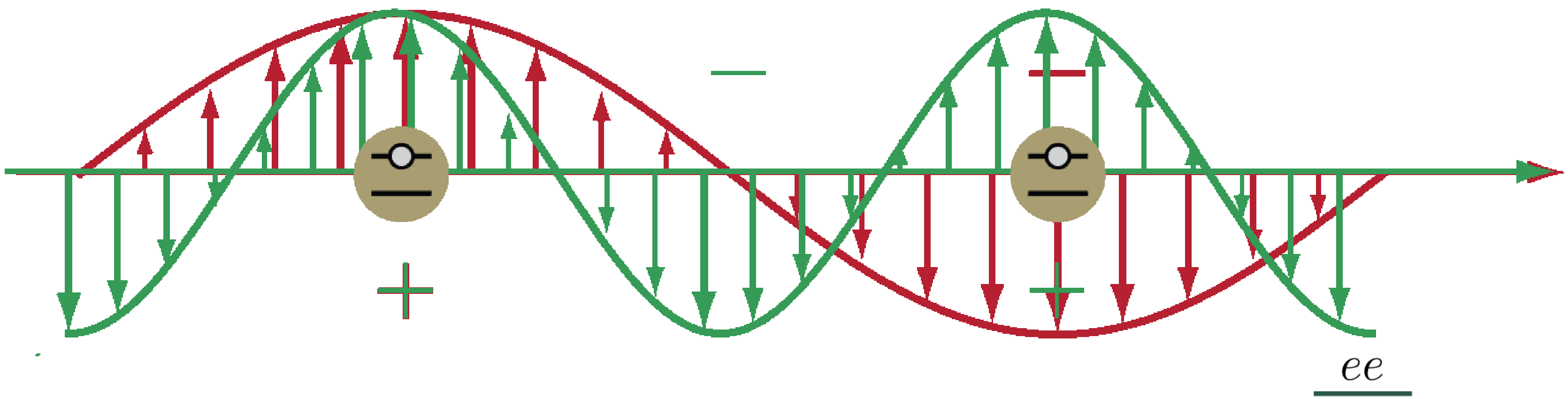




- two-photon transition becomes allowed at avoided crossing
- formation of a darkstate

Formation of dark state – drive symmetry

dark state condition: $\langle gg|H_d|\psi_{\text{dark}}\rangle = 0$

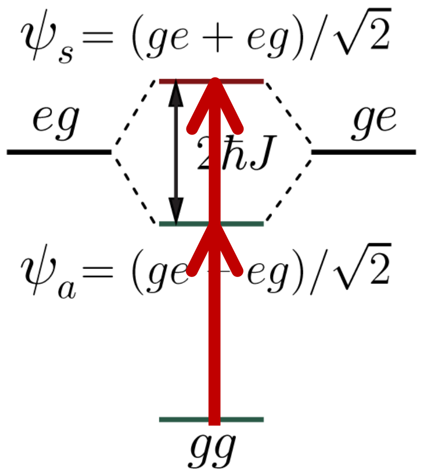


anti-symmetric drive:

$$H_d = \epsilon\left(\frac{|g^{(1)}|}{\Delta}\sigma_+^{(1)} - \frac{|g^{(2)}|}{\Delta}\sigma_+^{(2)}\right) + h.c.$$

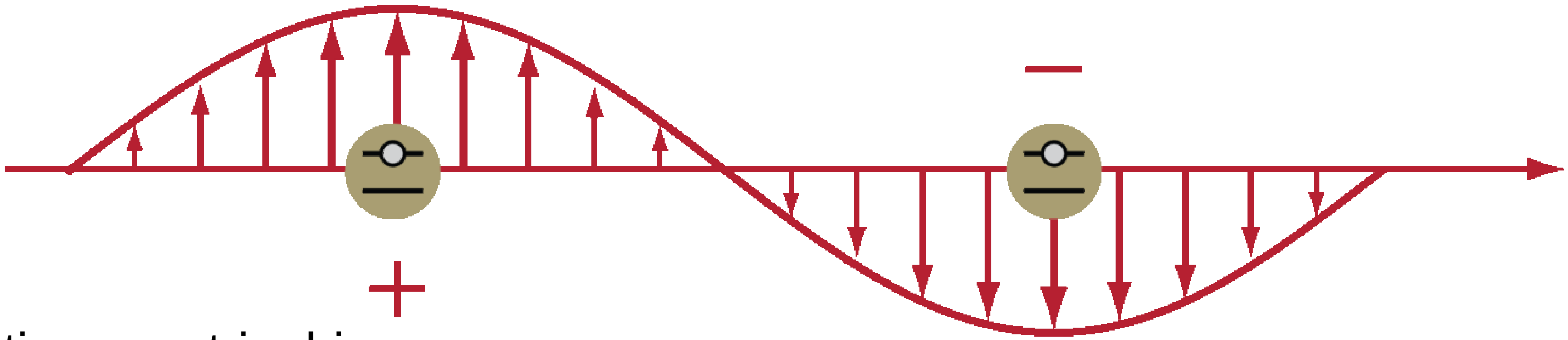
symmetric drive:

$$H_d = \epsilon\left(\frac{|g^{(1)}|}{\Delta}\sigma_+^{(1)} + \frac{|g^{(2)}|}{\Delta}\sigma_+^{(2)}\right) + h.c.$$

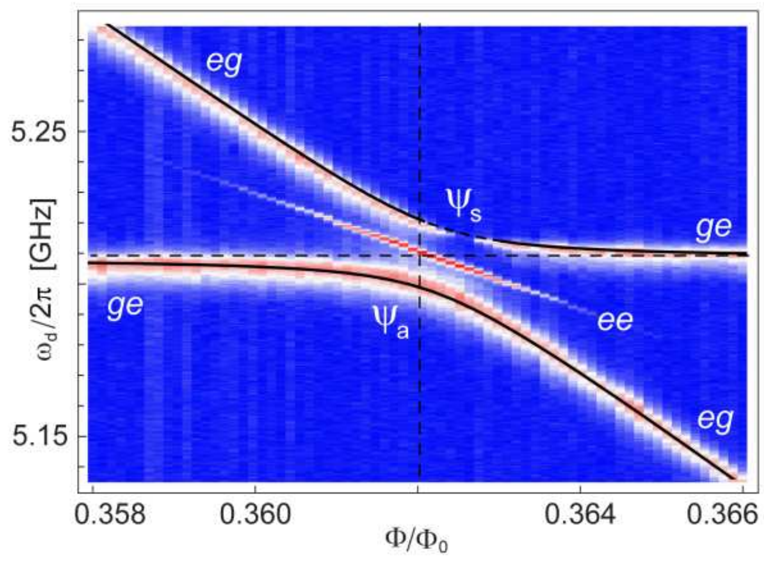


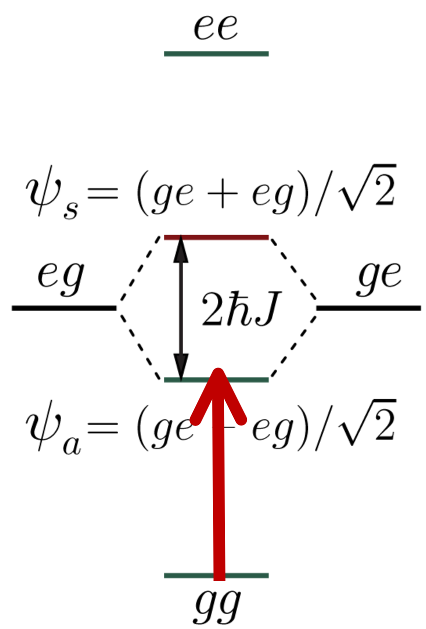
Anti-symmetric drive/symmetric dark state

[S. Filipp, PRA 83, 063827 (2011)]

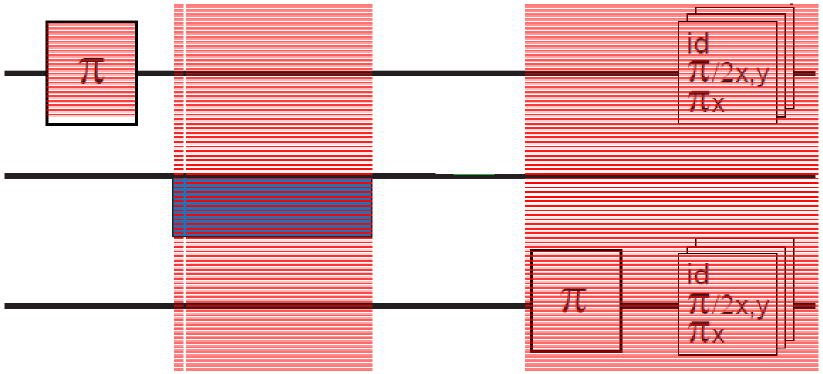


anti-symmetric drive:





J-coupling for Bell-state generation (SWAP gate)

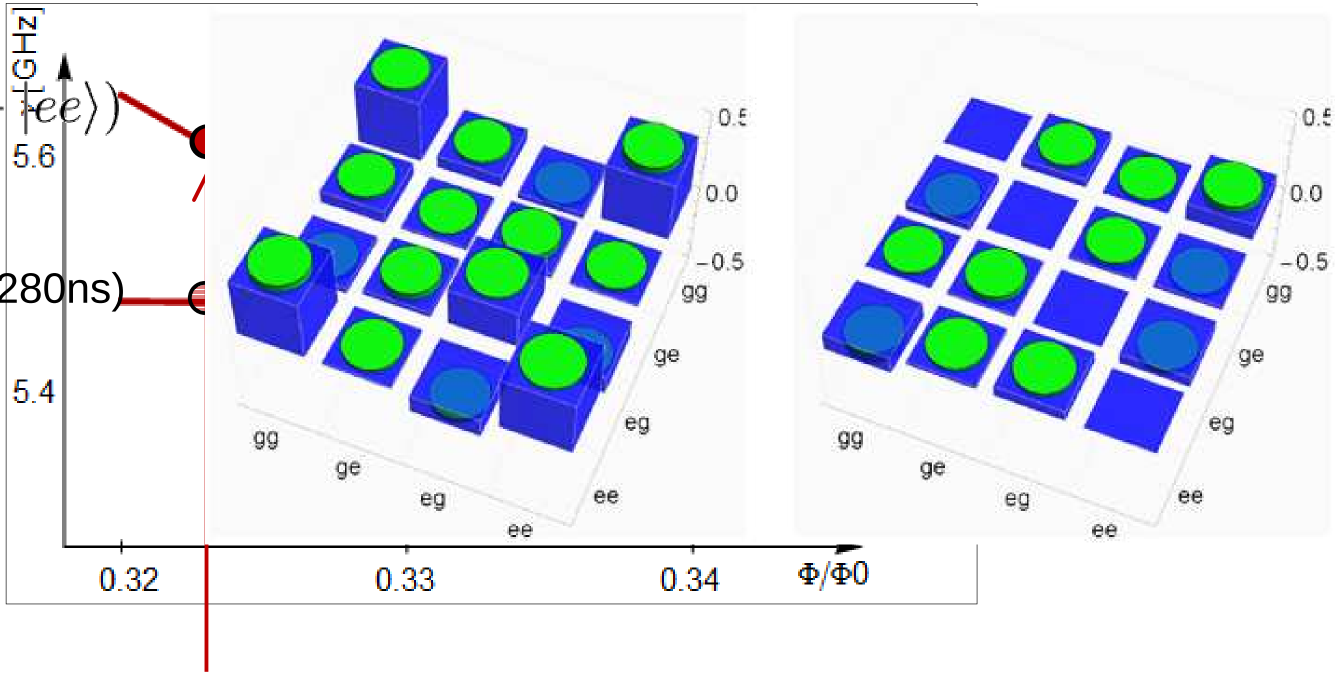


e.g.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|gg\rangle + |ee\rangle\right)$$

fidelity: 74%

(here limited by T1 ~280ns)



3-qubit entanglement for quantum teleportation.

Quantum Teleportation

Alice

No local interaction!

classical communication

Bob

Qubit A:

Qubit B, C:

$|\psi\rangle =$

$|\mathrm{Bell}\rangle = \frac{1}{\sqrt{2}}(\quad + \quad)$

Bell state measurement:

If Bell state 1:

$|\psi\rangle =$

If Bell state 2:

$|\tilde{\psi}\rangle = e^{i\sigma_x/2}|\psi\rangle =$

...

$\overset{U}{\rightarrow}$

Quantum processor platform with 3-Qubits

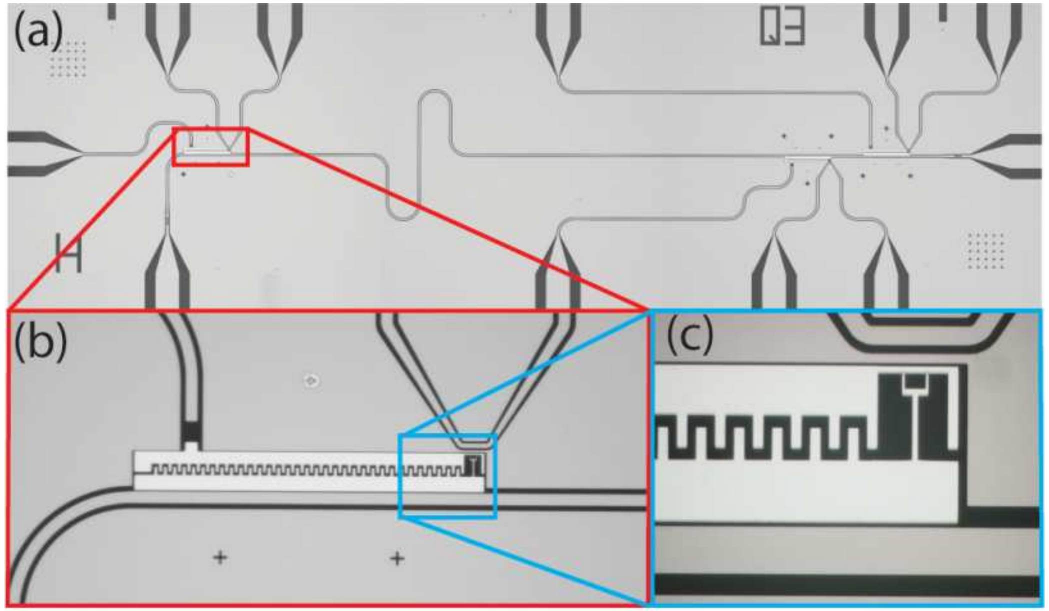
Main parameters

Transmon qubits

- Full individual coherent qubit control via local charge and flux lines
- Large coupling strength to resonator g ~ 300 - 350 MHz
- Coherences times:
  T_1 ~ 0.8 - 1.2 ^{1} s,T_2 ~ 0.4 – 0.7 ^{1} s.

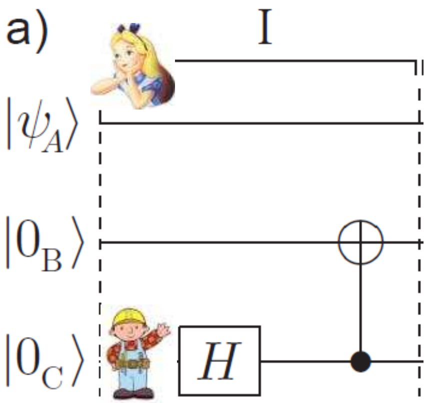
Resonator

- f_0 ~ 8.625 GHz



[M. Baur, et al. arxiv:1107.4774 (201

Teleportation Circuit



Teleportation:
transmission of quantum bit (qubit A) from Alice to Bob using a pair of entangled qubits (qubits B+C)

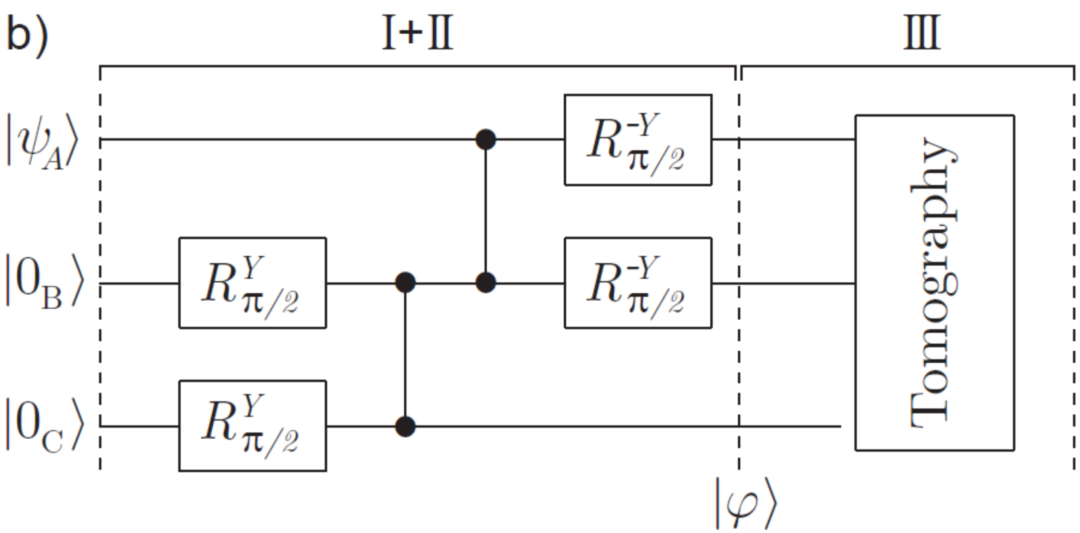
$= |\psi_A\rangle$

Preparation of Bell state

Measurement + classical communication

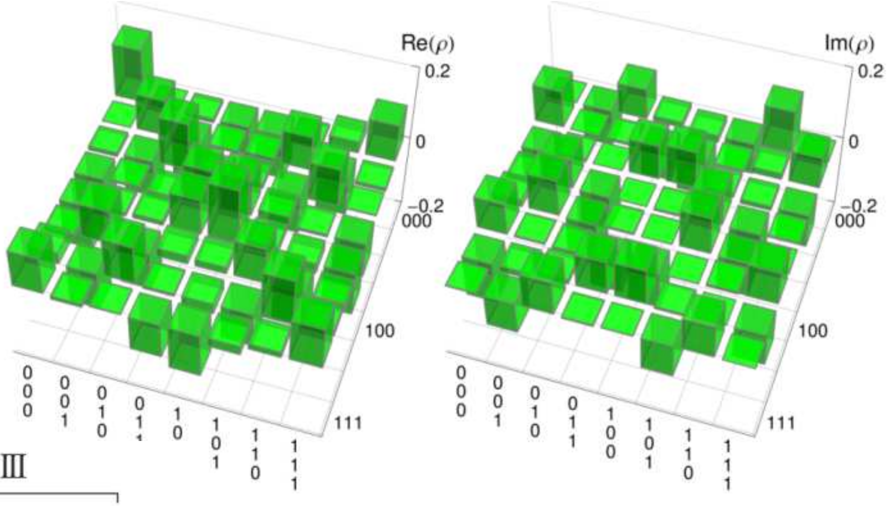
Bell Measurement

implemented three qubit tomography at step III



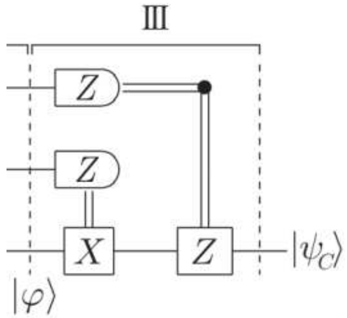
State tomography of the entangled three qubit state

Example: State to be teleported on qubit A is $|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle + i|1\rangle)$

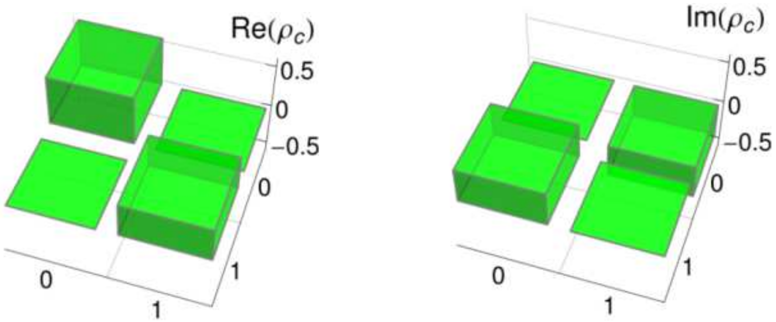


$$|\varphi\rangle = \frac{1}{2}\{|0_A 0_B\rangle \otimes |\Psi\rangle_C + |0_A 1_B\rangle \otimes \sigma_x |\Psi\rangle_C + |1_A 0_B\rangle \otimes \sigma_z |\Psi\rangle_C + |1_A 1_B\rangle \otimes (-\sigma_z \sigma_x)|\Psi\rangle_C\}$$

$$\rho = |\varphi\rangle\langle\varphi|$$



Simulating measurement of qubit A and B with projection onto $|0_A 0_B\rangle$



$$\rho_C = \langle 0_A 0_B | \rho_{ABC} | 0_A 0_B \rangle = |\Psi\rangle\langle\Psi|$$

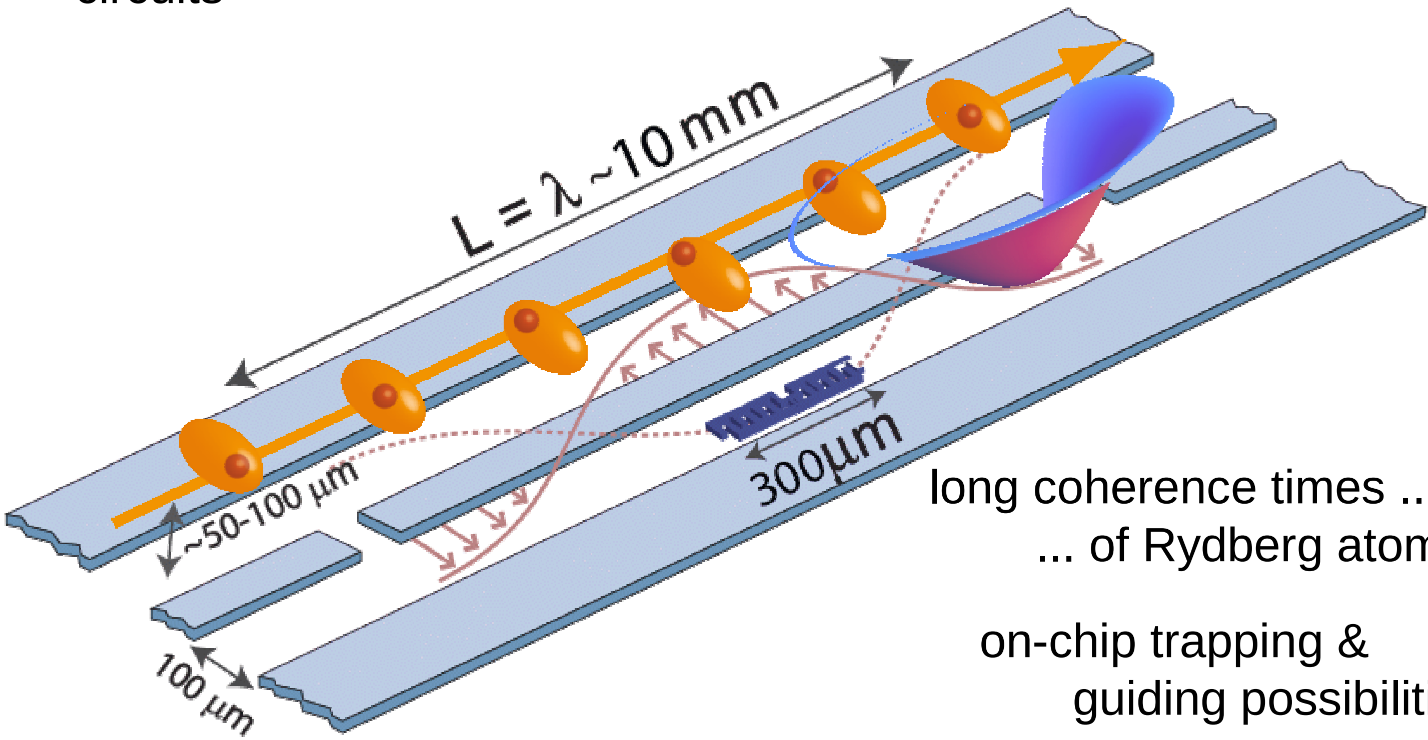
fidelity 88%

Hybrid Quantum Computation.

Hybrid Cavity QED with Atoms and Circuits

combine the best properties of two worlds

very strong dipole interactions ...
... in quantum engineered electronic circuits

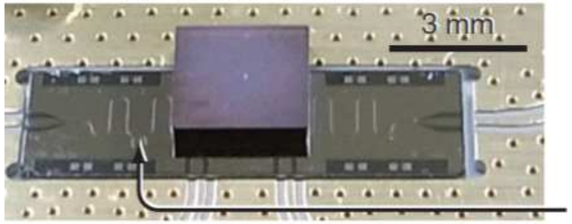


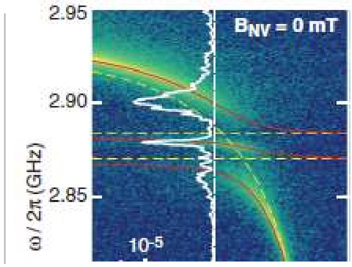
long coherence times ...
... of Rydberg atoms

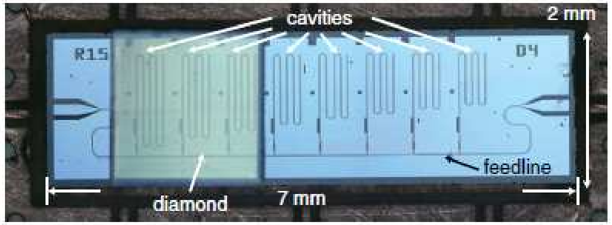
on-chip trapping &
guiding possibilities

Other hybrid (circuit QED) approaches:

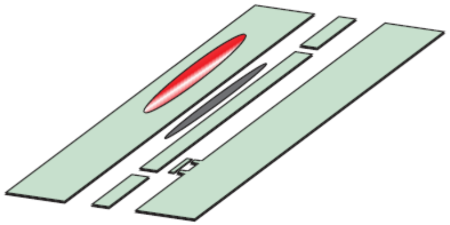
- Spin ensembles (NV centers)
  [Kubo et al., PRL 105, 140502 (2010); Schuster et al., PRL 205, 140501 (2010)]



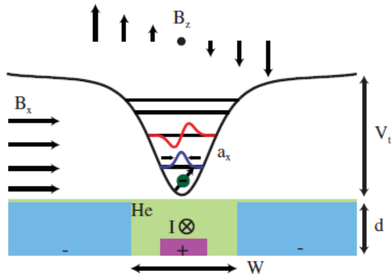




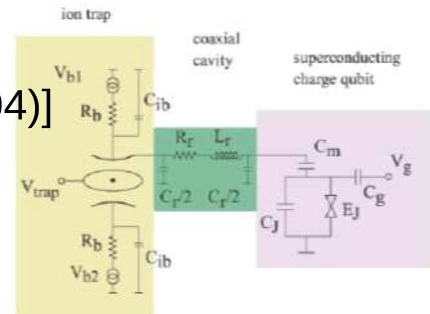
- Atomic ensembles (BEC)
  [Verdu, PRL 103, 043603 (2009)]



- Electrons on Helium
  [Schuster et al., PRL 105, 040503 (2010)]

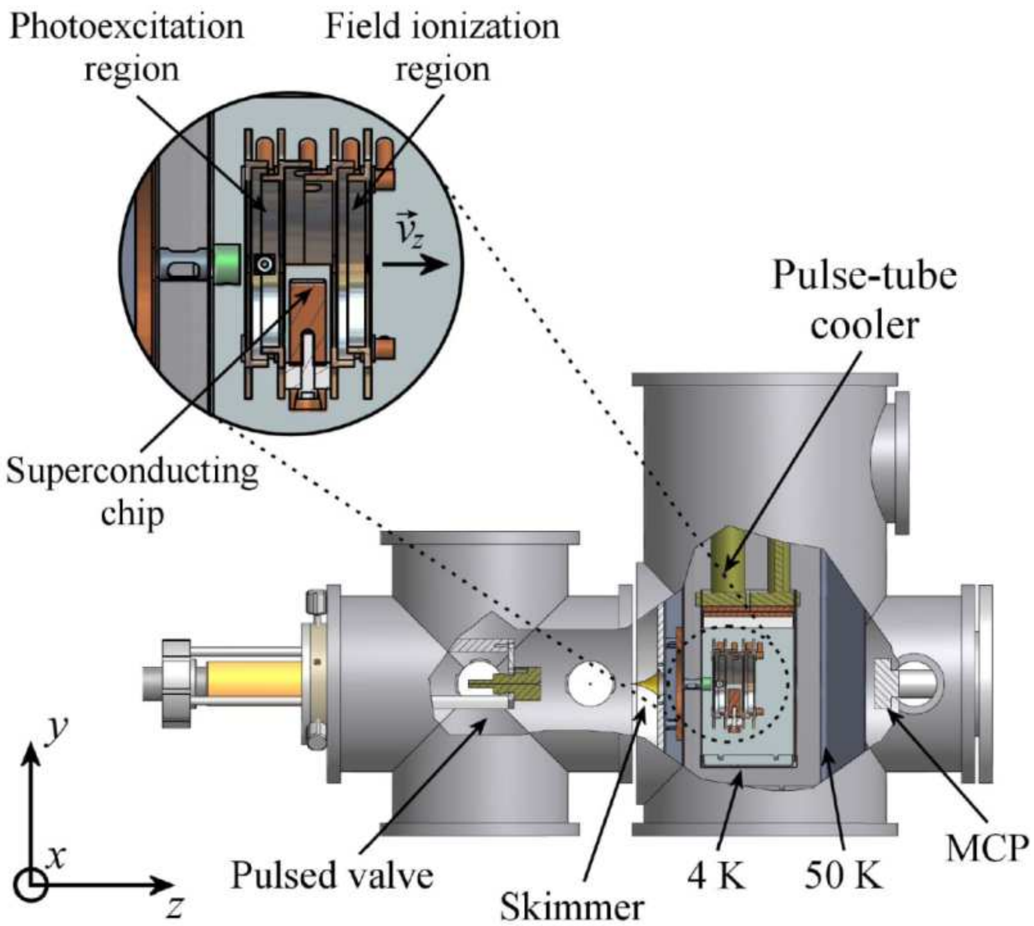


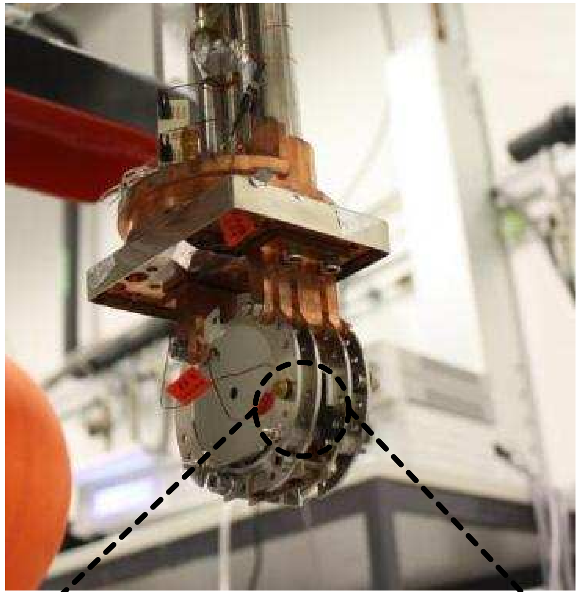
- Charged particles (Ions)
  [Tian et al., PRL 92, 247902 (2004)]

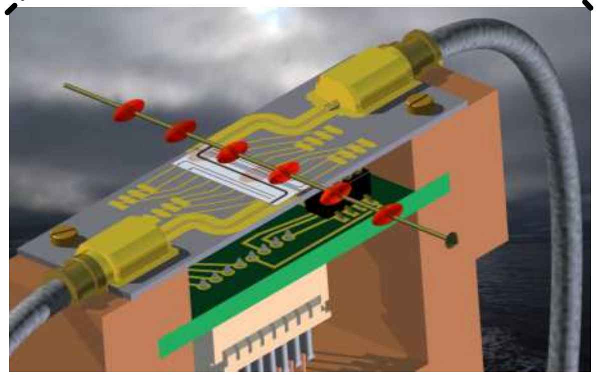


- …

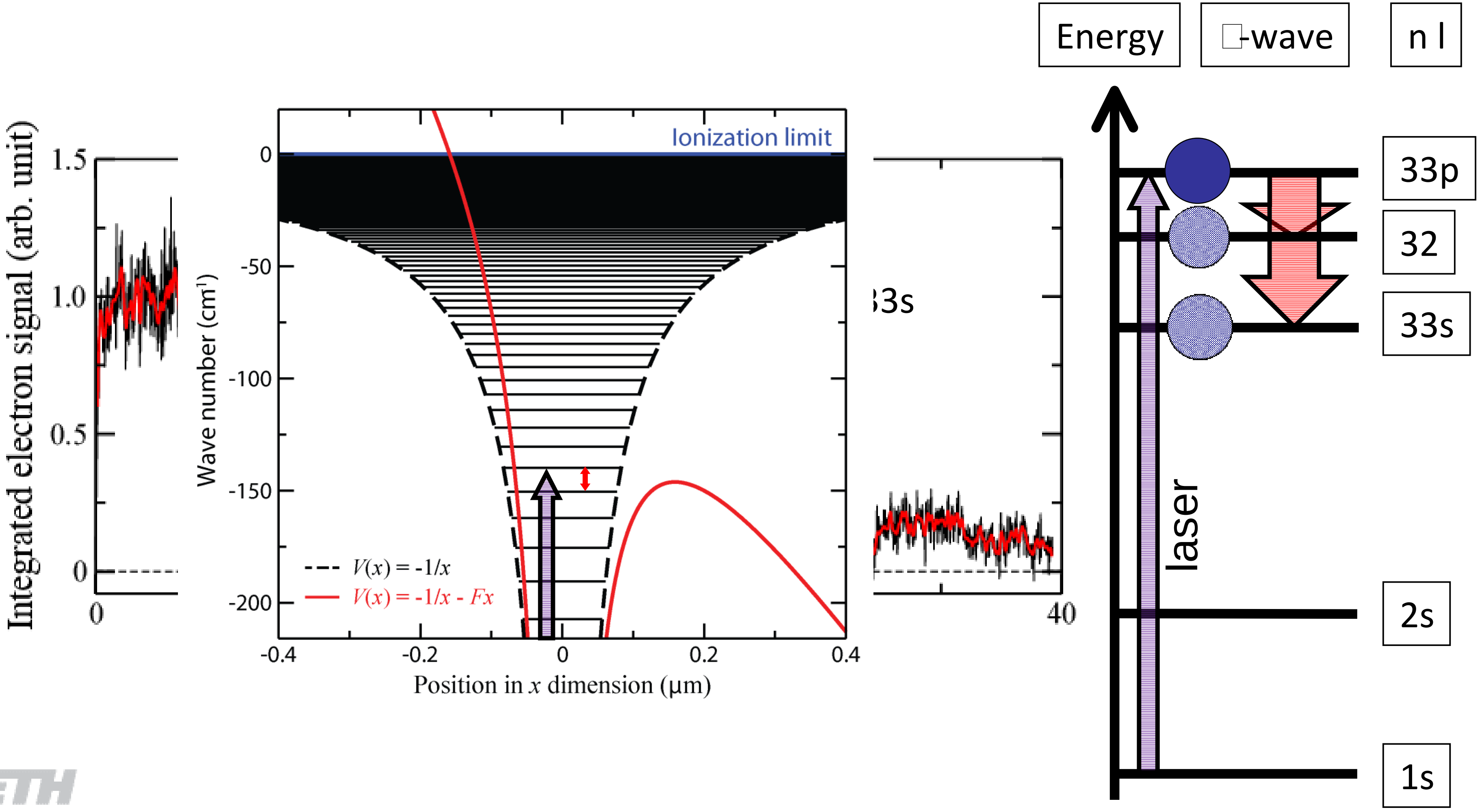
Experimental Setup





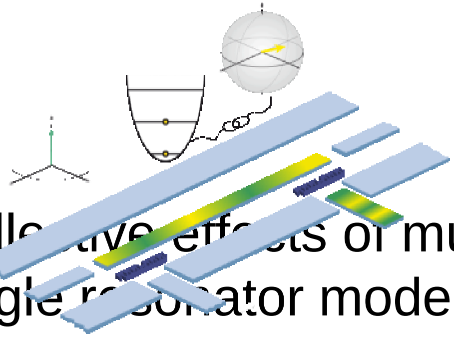


Driving Transitions

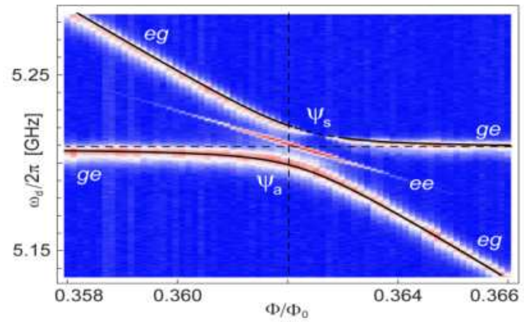


Summary

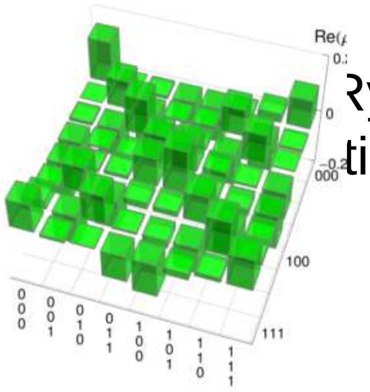
- Photon storage in high-Q mode and entanglement generation using sideband transitions



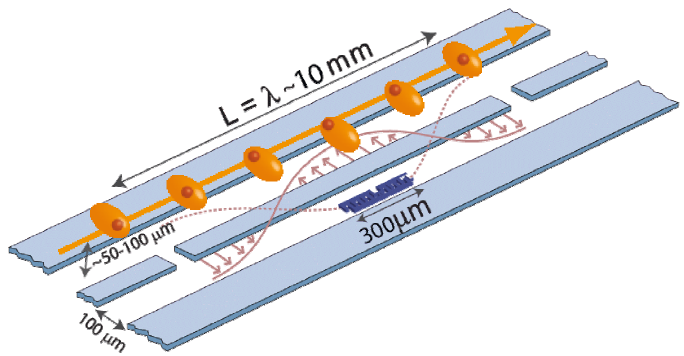
- Collective effects of multi-qubits coupled to a single resonator mode



- Generation of 3-qubit entangled states for quantum teleportation



- Hy… Rydberg atoms and superconducting circuits for future qu…tion



Thanks for your attention.