Quantenmechanik mit Schaltkreisen: Photonen und Qubits auf einem supraleitenden Mikrochip

Andreas Wallraff *(ETH Zurich)*

www.qudev.ethz.ch

Team: R. Buijs, M. Collodo, S. Gasparinetti, J. Heinsoo, P. Kurpiers, M. Mondal, M. Oppliger, M. Pechal, A. Potocnik, Y. Salathe, M. Stammeier, A. Stockklauser, T. Thiele, T. Walter *(ETH Zurich)*

SEVENTH FRAMEWORK PROGRAMME

scaleQIT

erc

QSIT Quantum Science and Technology

National Centre of Competence in Research

ETH

Eidgenössische Technische Hochschule Zürich

Swiss Federal Institute of Technology Zurich

FNSNF

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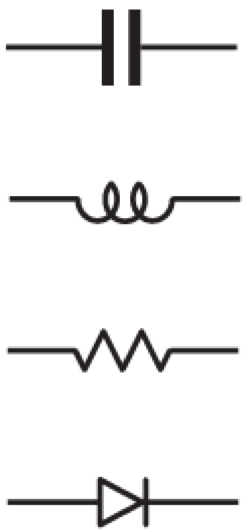
Conventional Electronic Circuits

basic circuit elements:

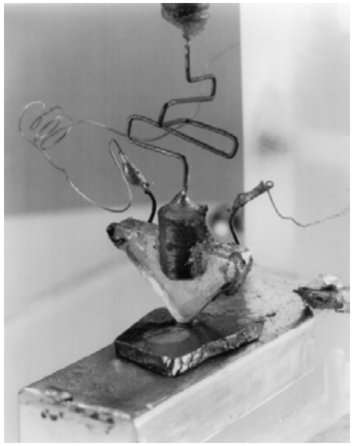


basis of modern information and communication technology

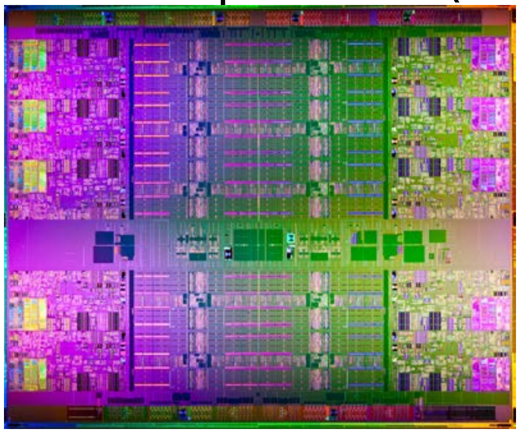
properties :

- classical physics
- no quantum mechanics
- no superposition principle
- no quantization of fields

first transistor at Bell Labs (1947)



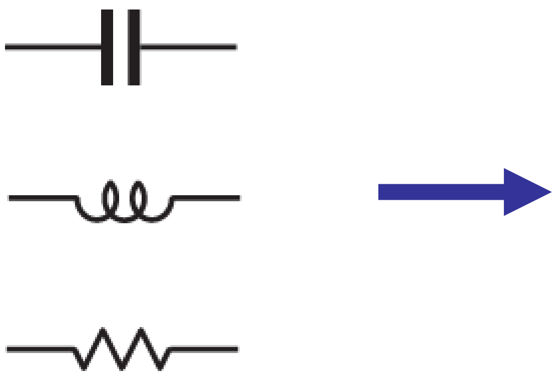
intel xeon processors (2011)



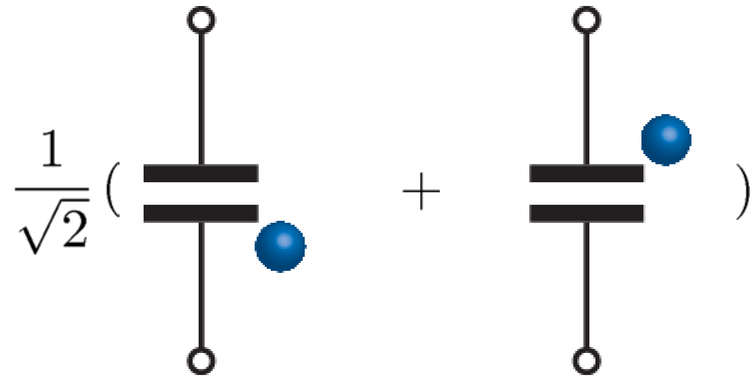
3.000.000.000 transistors
smallest feature size 32 nm
clock speed ~ 3 GHz
power consumption ~ 10 W

Classical and Quantum Electronic Circuit Elements

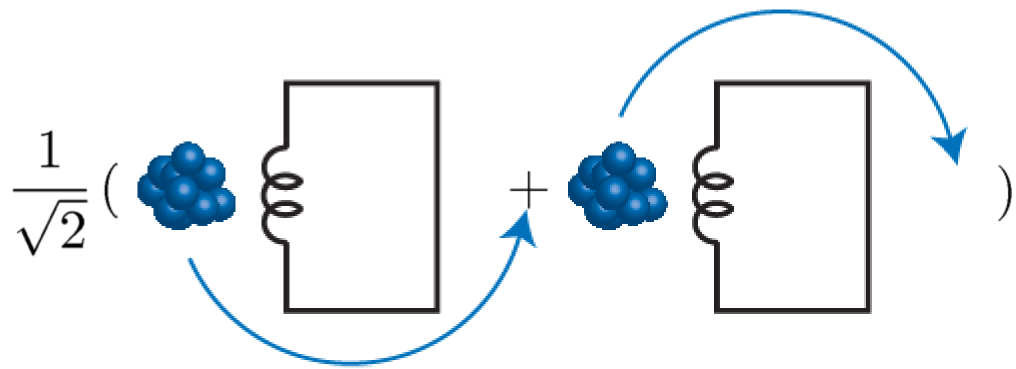
basic circuit elements:



charge on a capacitor:



current or magnetic flux in an inductor:

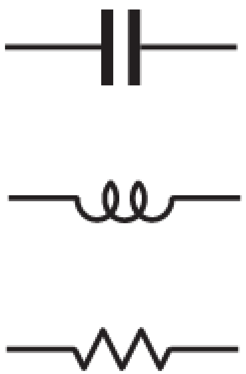


quantum superposition states:

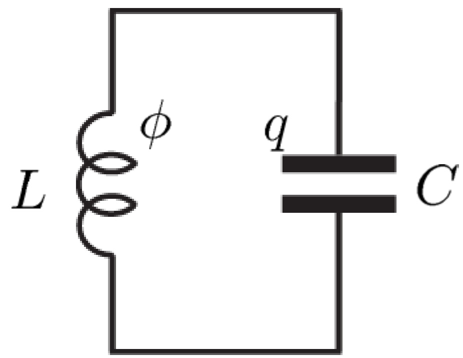
- charge q
- flux ϕ

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



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

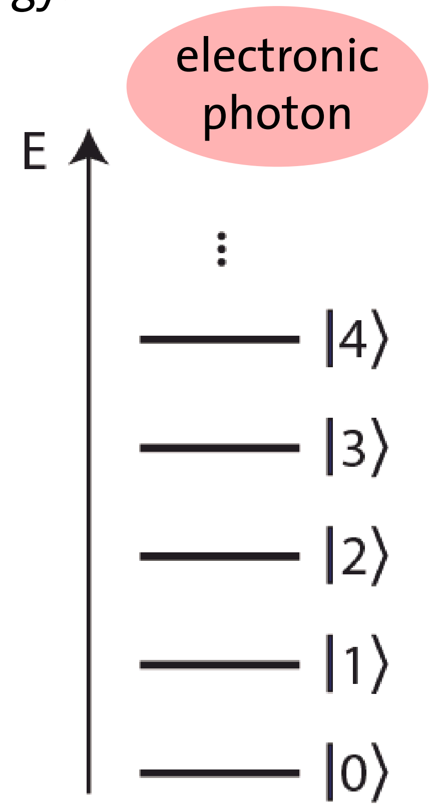
classical physics:

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

quantum mechanics:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{q}^2}{2C} = \hbar\omega(\hat{a}^\dagger \hat{a} + \frac{1}{2}) \qquad \left[\hat{\phi}, \hat{q}\right] = i\hbar$$

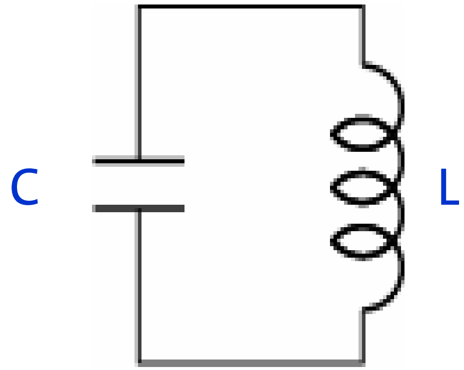
energy:



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

Superconducting Harmonic Oscillators

a simple electronic circuit:



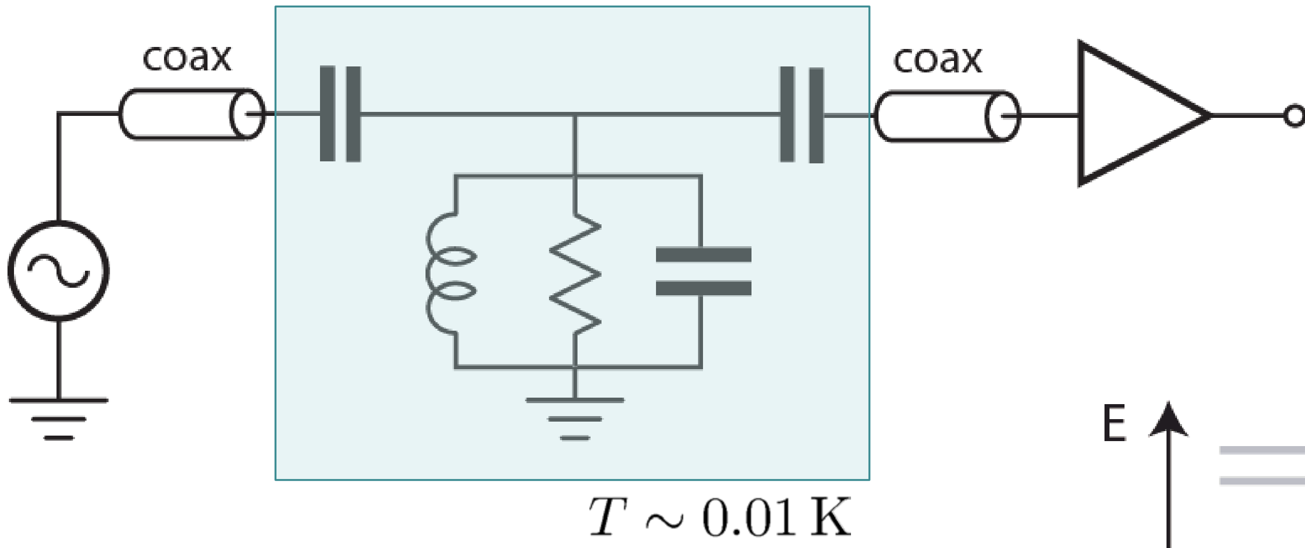
- typical inductor: $L = 1$ nH
- a wire in vacuum has inductance ~ 1 nH/mm

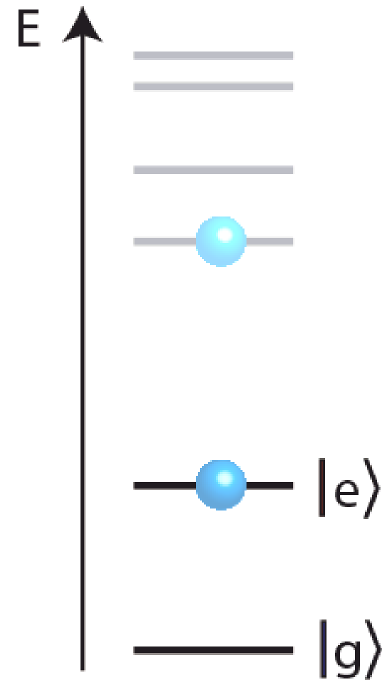
- typical capacitor: $C = 1$ pF
- a capacitor with plate size 10 μm x 10 μm and dielectric AlOx ($\varepsilon = 10$) of thickness 10 nm has a capacitance $C \sim 1$ pF

- resonance frequency

$$\frac{1}{2\pi\sqrt{LC}} \sim 5\ \text{GHz}$$

How to Operate Circuits Quantum Mechanically?





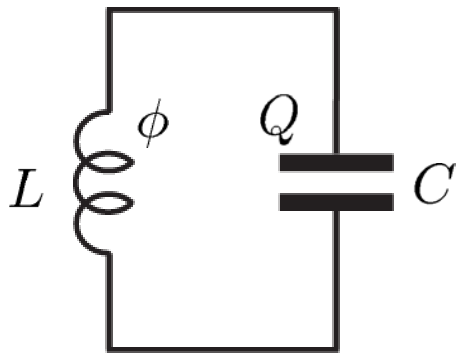
recipe:

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

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

Quantization of an Electronic Harmonic Oscillator

Harmonic LC oscillator:



$$Q = CV \quad \text{Charge on capacitor}$$
$$\phi = LI \quad \text{Flux in inductor}$$
$$V = -L\dot{I} = -\dot{\phi} \quad \text{Voltage across inductor}$$

Classical Hamiltonian:

$$H = \frac{CV^2}{2} + \frac{LI^2}{2} = \frac{Q^2}{2C} + \frac{\phi^2}{2L}$$

Conjugate variables:

$$\frac{\partial H}{\partial \phi} = \frac{\phi}{L} = I = \dot{Q}$$
$$\frac{\partial H}{\partial Q} = \frac{Q}{C} = V = -L\dot{I} = -\dot{\phi}$$

Hamilton operator:

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

Flux and charge operator:

$$\hat{\phi} = \phi$$
$$\hat{Q} = -i\hbar\frac{\partial}{\partial \phi}$$

Commutation relation:

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

Creation and Annihilation Operators for Circuits

Hamilton operator of harmonic oscillator in second quantization:

$$\hat{H} = \frac{\hat{\phi}^2}{2L} + \frac{\hat{Q}^2}{2C} = \hbar\omega(\hat{a}^\dagger\hat{a} + 1/2)$$

$$\hat{a}^\dagger |n\rangle = \sqrt{n+1}\,|n+1\rangle$$ Creation operator

$$\hat{a} |n\rangle = \sqrt{n}\,|n-1\rangle$$ Annihilation operator

$$\hat{a}^\dagger\hat{a} |n\rangle = n\,|n\rangle$$ Number operator

$$\hat{Q} = \sqrt{\frac{\hbar}{2Z_C}}(\hat{a}^\dagger + \hat{a})$$ Charge/voltage operator $$\hat{V} = \frac{\hat{Q}}{C}$$

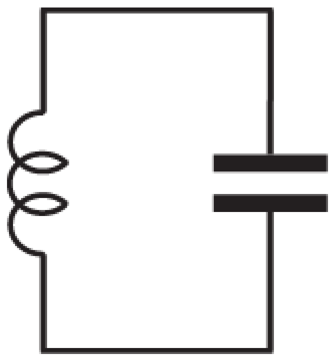
$$\hat{\phi} = i\sqrt{\frac{\hbar Z_C}{2}}(\hat{a}^\dagger - \hat{a})$$ Flux/current operator $$\hat{I} = \frac{\hat{\phi}}{L}$$

With characteristic impedance:

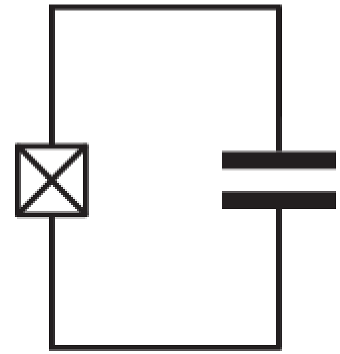
$$Z_C = \sqrt{\frac{L}{C}}$$

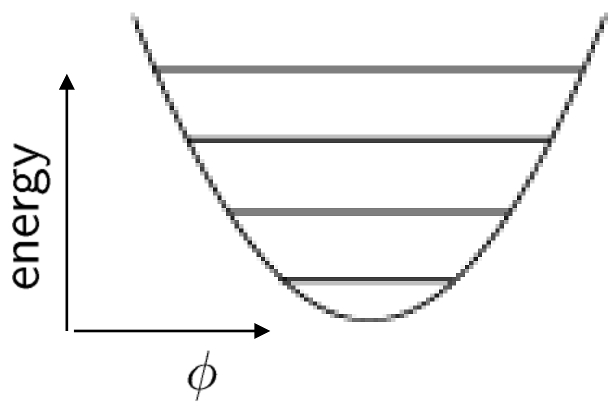
Linear vs. Nonlinear Superconducting Oscillators

LC resonator:

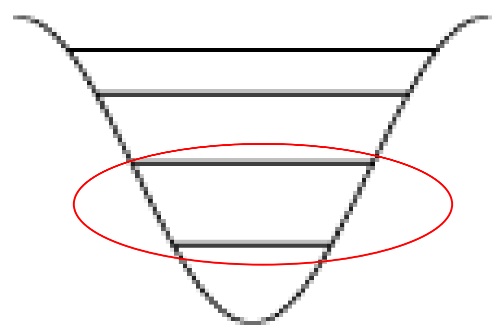


Josephson junction resonator:
Josephson junction = nonlinear inductor



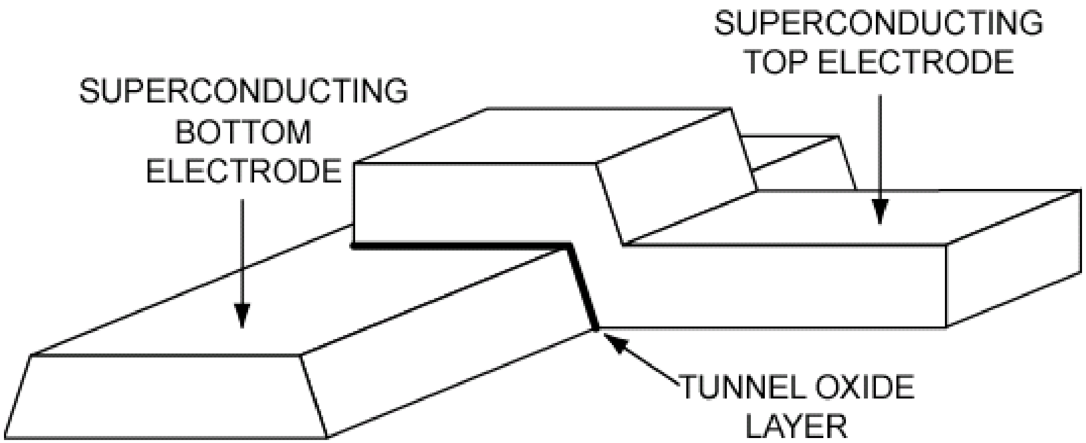


anharmonicity defines effective two-level system



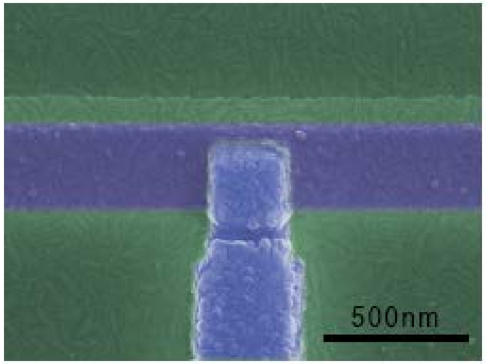
A Low-Loss Nonlinear Element

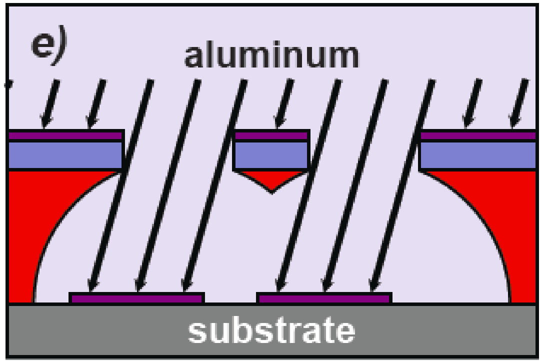
a (superconducting) Josephson junction:

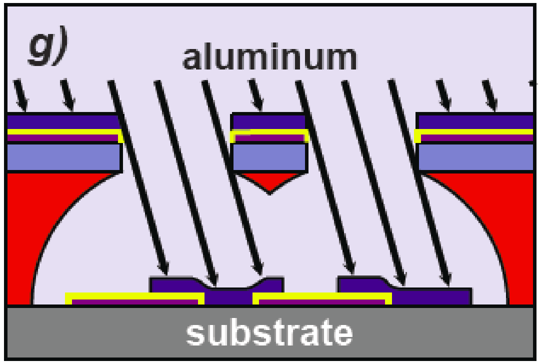


- superconductors: Nb, Al
- tunnel barrier: AlO_x

Josephson junction fabricated by shadow evaporation:





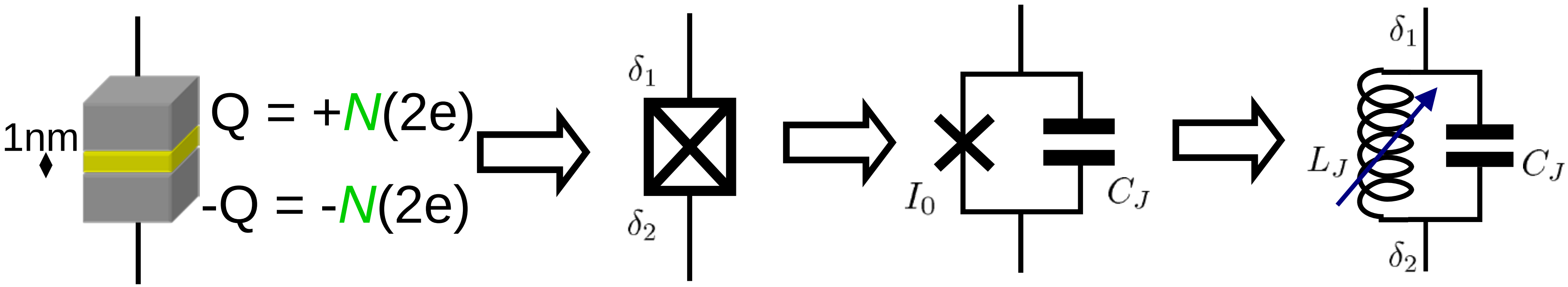


ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

M. Tinkham, *Introduction to Superconductivity* (Krieger, Malabar, 1985).

Josephson Tunnel Junction

The only non-linear resonator with no dissipation (BCS, $k_B T < \Delta$)



Tunnel junction parameters:

- Critical current I_o
- Junction capacitance C_J
- Internal resistance R_J

Josephson relations:

$$I = I_0 \sin\delta$$

$$V = \frac{\phi_0}{2\pi}\dot{\delta}$$

Flux quantum:

$$\phi_0 = \frac{h}{2e}$$

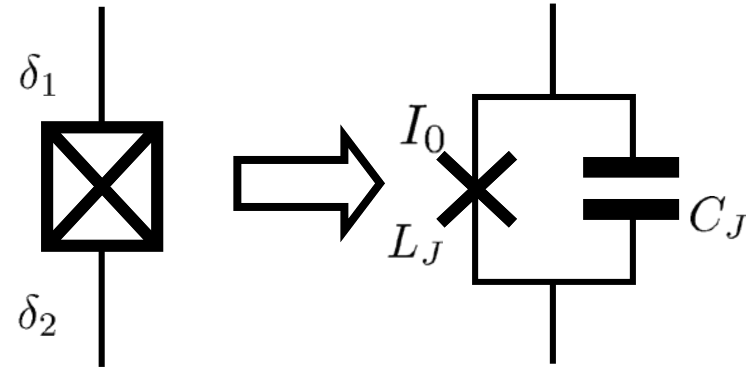
Phase difference:

$$\delta = \delta_2 - \delta_1$$

derivation of Josephson effect, see e.g.: chap. 21 in R. A. Feynman: Quantum mechanics, The Feynman Lectures on Physics. Vol. 3 (Addison-Wesley, 1965)

The Josephson Junction as an ideal Non-Linear Inductor

a nonlinear inductor without dissipation



Josephson relations:

$$I = I_0 \sin \delta = I_0 \sin \left[2\pi \phi(t)/\phi_0 \right]$$

nonlinear current/phase relation

$$V = \frac{\phi_0}{2\pi} \dot{\delta} = \dot{\phi}$$

gauge inv. phase difference:

$$\delta = \delta_2 - \delta_1 = 2\pi \phi(t)/\phi_0$$

Josephson inductance:

$$V = -L_J \dot{I} = \frac{\phi_0}{2\pi I_0} \frac{1}{\cos \delta} \dot{I}$$

specific Josephson inductance L_{J0}

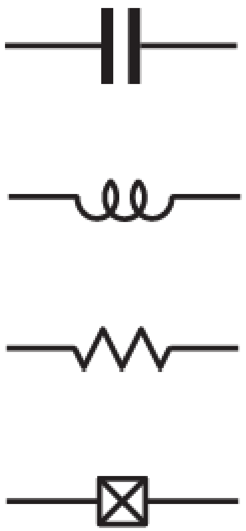
Josephson energy:

$$E_J = \int V I dt = -\frac{I_0 \phi_0}{2\pi} \cos \delta$$

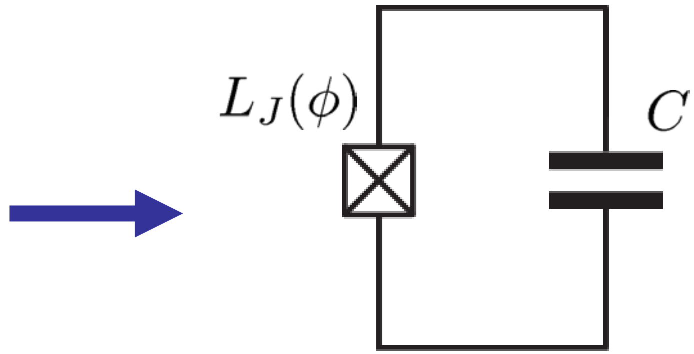
specific Josephson energy E_{J0}

Constructing Non-Linear Quantum Electronic Circuits

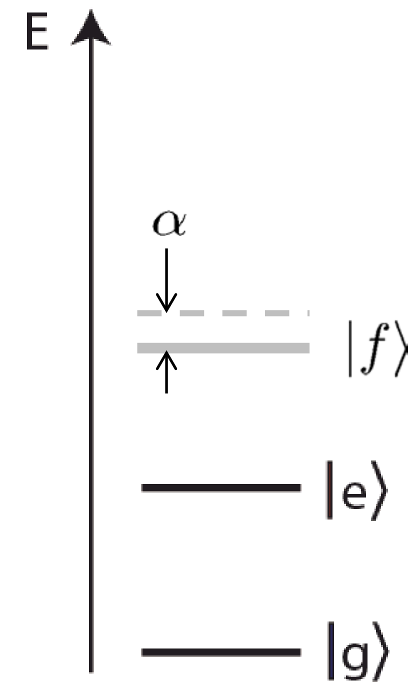
circuit elements:



anharmonic oscillator:



non-linear energy level spectrum:



Josephson junction:
a non-dissipative nonlinear element (inductor)

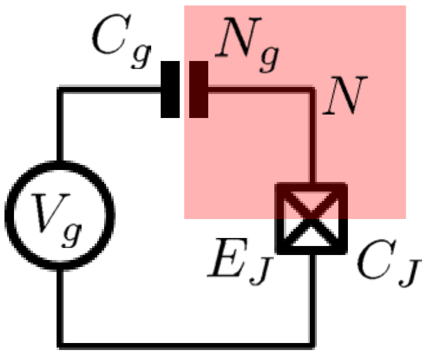
$$H \approx \hbar(\omega_{ge}\, \hat{b}^\dagger \hat{b} - \frac{\alpha}{2}\, \hat{b}^{\dagger 2} \hat{b}^2)$$

electronic artificial atom

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

The Cooper Pair Box Qubit

A Charge Qubit: The Cooper Pair Box



discrete charge on island: $N = \frac{Q}{2e}$

continuous gate charge: $N_g = \frac{C_g V_g}{2e}$

total box capacitance $C_\Sigma = C_g + C_J$

Hamiltonian: $H = H_{\text{el}} + H_{\text{mag}}$

electrostatic part:

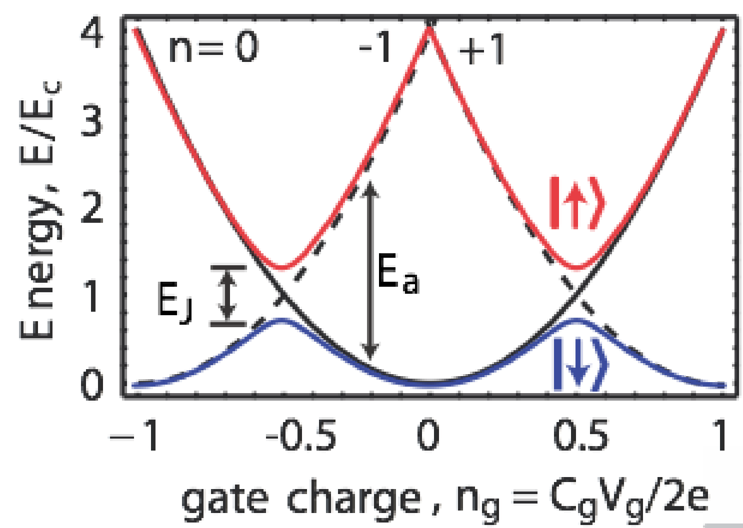
$$H_{\text{el}} = \frac{Q^2}{2C} = \frac{(2e)^2}{2C_\Sigma}(N - N_g)^2$$

charging energy E_C

magnetic part:

$$H_{\text{mag}} = -E_J \cos\delta \approx \frac{\phi^2}{2L_{J0}}$$

Josephson energy



Hamilton Operator of the Cooper Pair Box

Hamiltonian:
$$\hat{H} = \hat{H}_{\mathrm{el}} + \hat{H}_{\mathrm{mag}} = E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\delta}$$

$$\cos\hat{\delta} = \frac{1}{2}(e^{i\hat{\delta}} + e^{-i\hat{\delta}})$$

commutation relation:
$$[\hat{\delta}, \hat{N}] = i$$

charge number operator:

$$\hat{N}|N\rangle = N|N\rangle$$ eigenvalues, eigenfunctions

$$\sum_N |N\rangle\langle N| = 1$$ completeness

$$\langle N|M\rangle = \delta_{NM}$$ orthogonality

phase basis:

$$|\delta\rangle = \frac{1}{\sqrt{2\pi}}\sum_N e^{iN\delta}|N\rangle$$ basis transformation

$$e^{\pm i\hat{\delta}}|N\rangle = |N \pm 1\rangle$$

Solving the Cooper Pair Box Hamiltonian

Hamilton operator in the charge basis N:

$$\hat{H} = \sum_N \left[E_C (N - N_g)^2 |N\rangle\langle N| - \frac{E_J}{2} (|N\rangle\langle N+1| + |N+1\rangle\langle N|) \right]$$

solutions in the charge basis:

$$\hat{H}|\psi_n(N)\rangle = E_n|\psi_n(N)\rangle$$

Hamilton operator in the phase basis δ:

$$\hat{H} = E_C(\hat{N} - N_g)^2 - E_J \cos\hat{\delta} = E_C(-i\frac{\partial}{\partial\delta} - N_g)^2 - E_J \cos\hat{\delta}$$

transformation of the number operator:

$$\hat{N} = \frac{\hat{Q}}{2e} = -i\hbar\frac{1}{2e}\frac{\partial}{\partial\phi} = -i\frac{\partial}{\partial\delta}$$

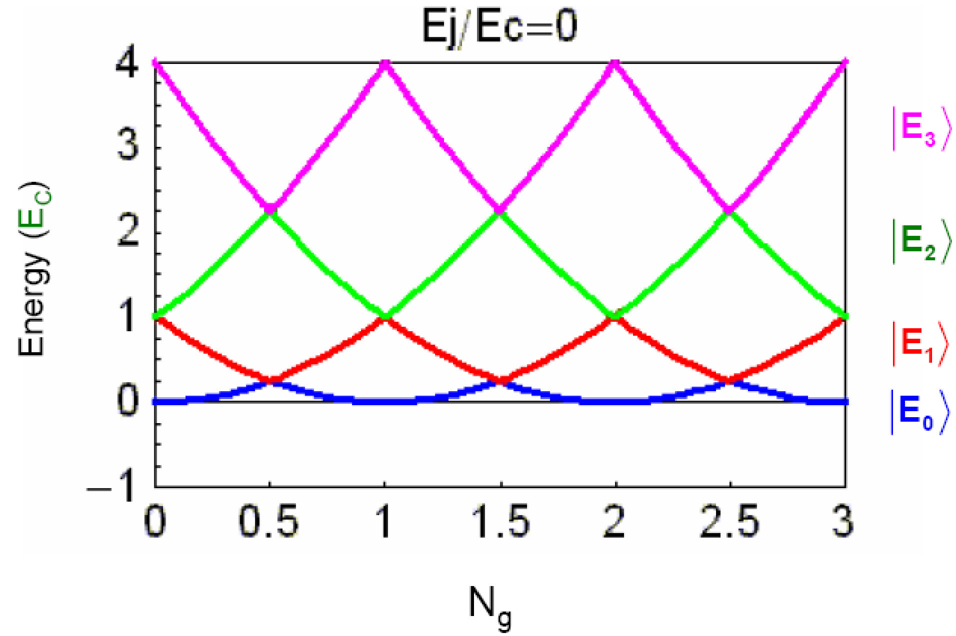
solutions in the phase basis:

$$\hat{H}|\psi_n(\delta)\rangle = E_n|\psi_n(\delta)\rangle$$

Energy Levels

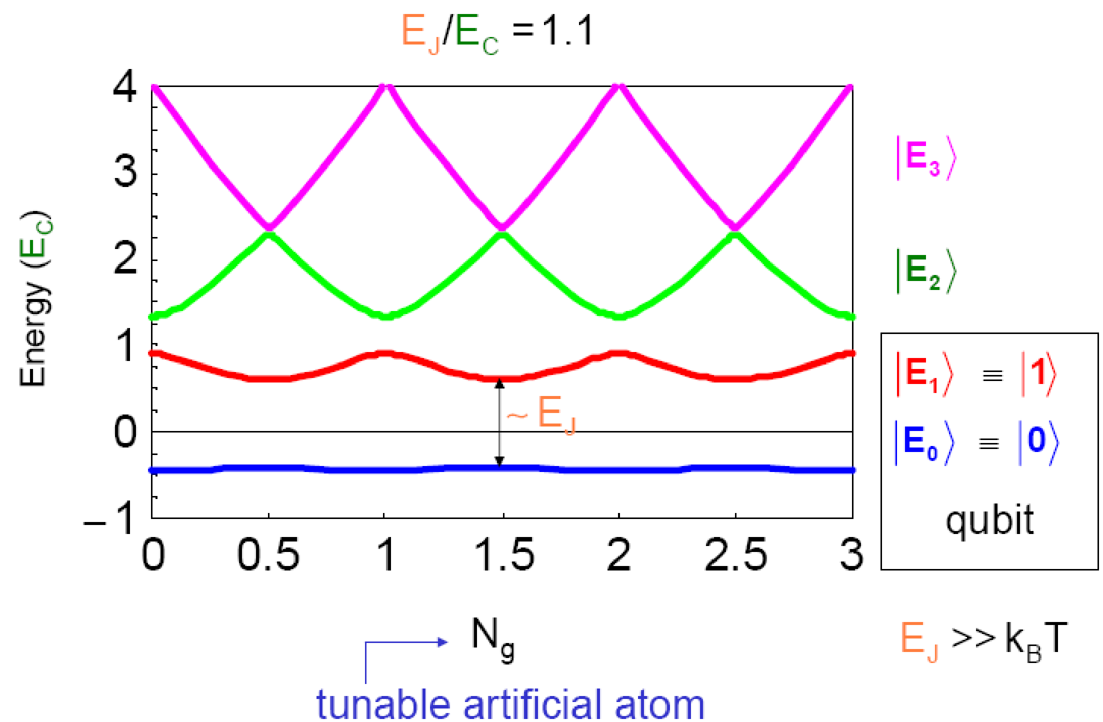
energy level diagram for $E_J=0$:

- energy bands are formed
- bands are periodic in N_g

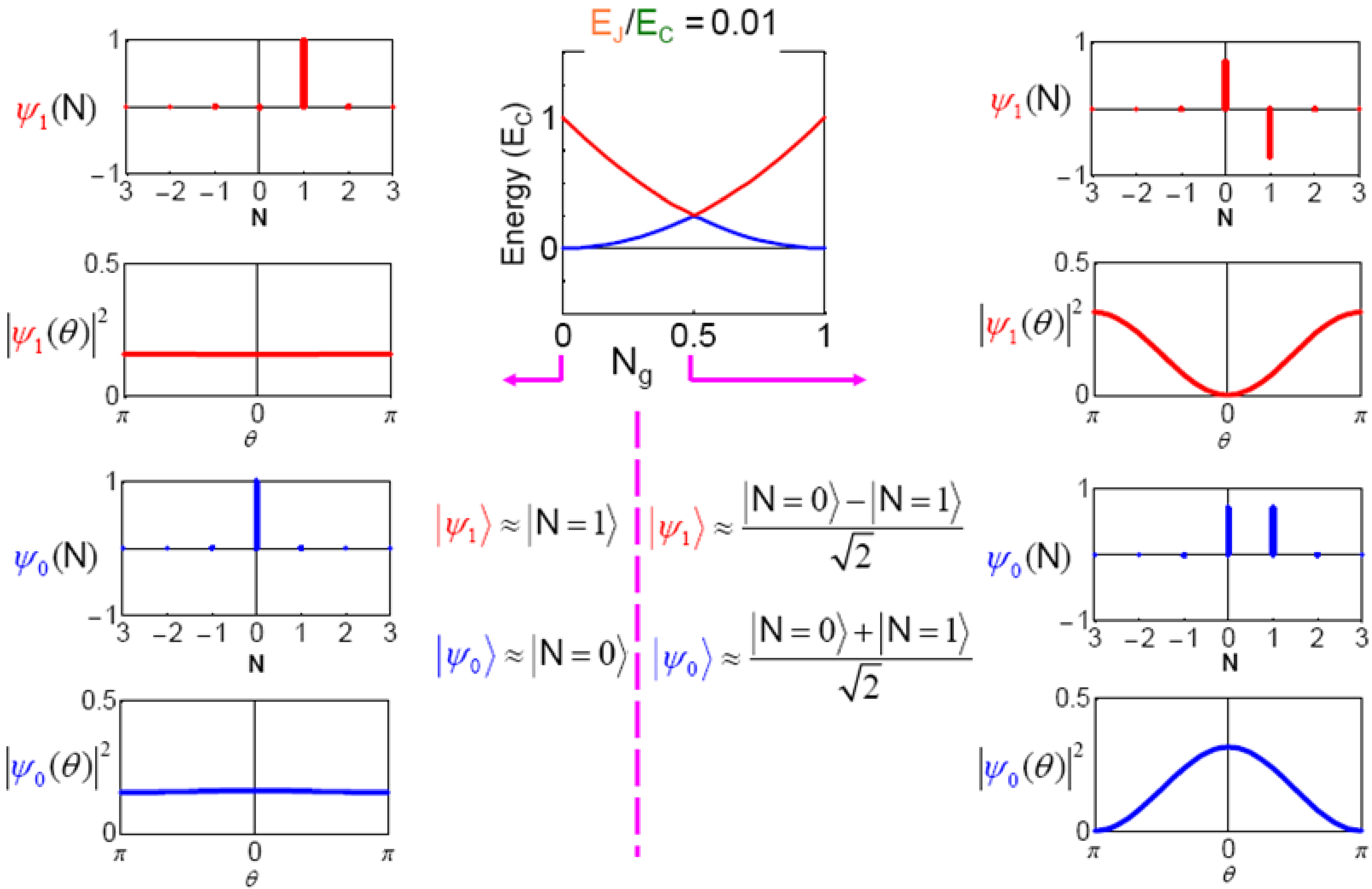


energy bands for finite E_J

- Josephson coupling lifts degeneracy
- E_J scales level separation at charge degeneracy



Charge and Phase Wave Functions ($E_J \ll E_C$)

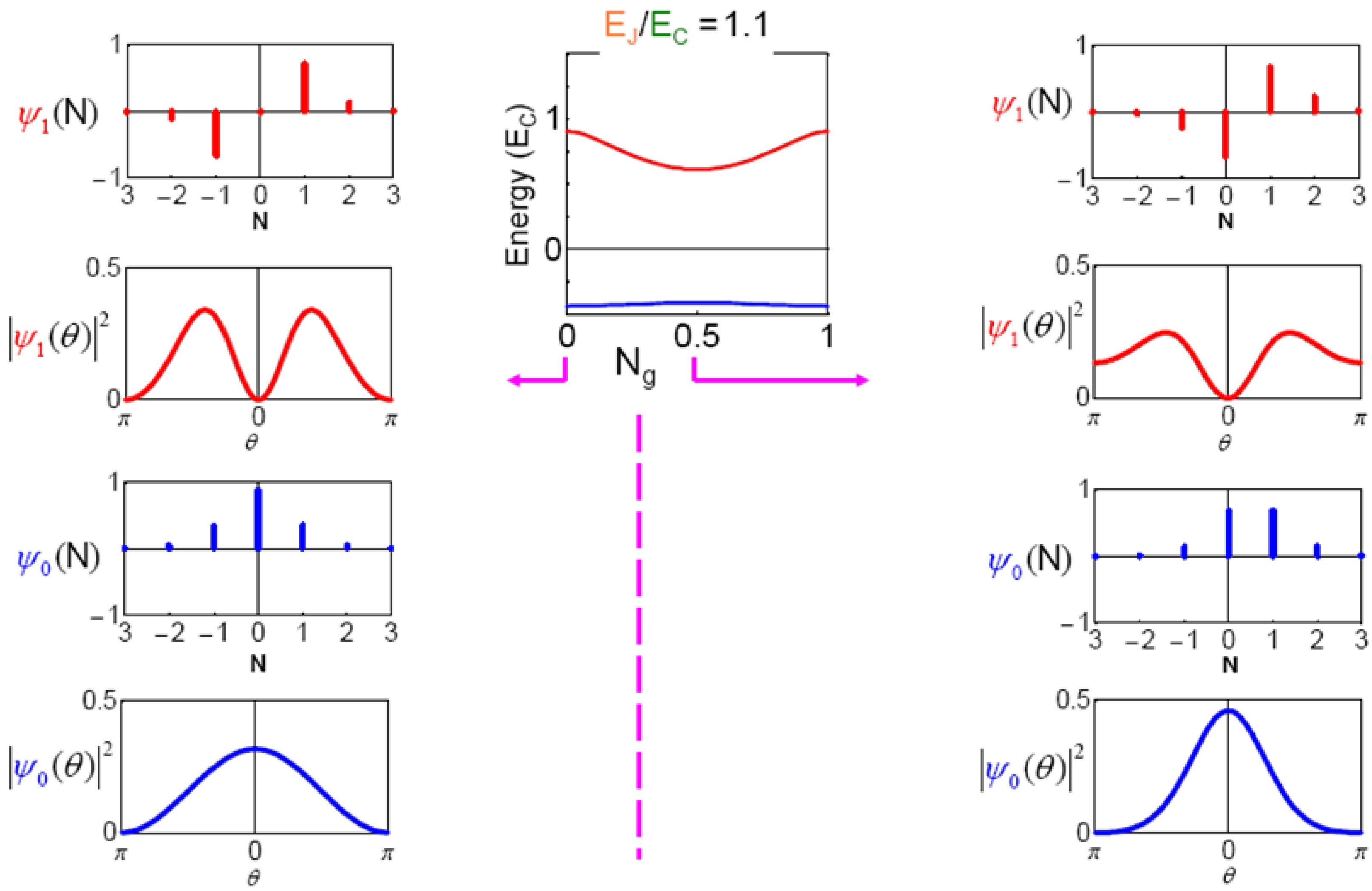


$$|\psi_1\rangle \approx |N=1\rangle \qquad |\psi_1\rangle \approx \frac{|N=0\rangle - |N=1\rangle}{\sqrt{2}}$$

$$|\psi_0\rangle \approx |N=0\rangle \qquad |\psi_0\rangle \approx \frac{|N=0\rangle + |N=1\rangle}{\sqrt{2}}$$

courtesy CEA Saclay

Charge and Phase Wave Functions ($E_J \sim E_C$)

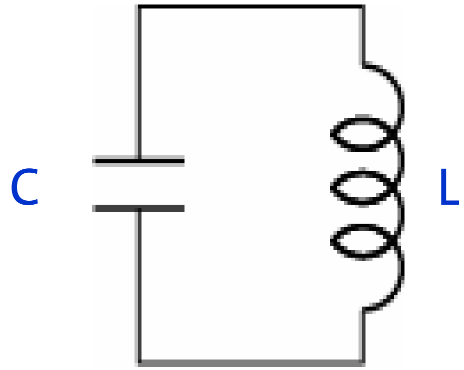


courtesy CEA Saclay

Realizations of Harmonic Oscillators

Superconducting Harmonic Oscillators

a simple electronic circuit:



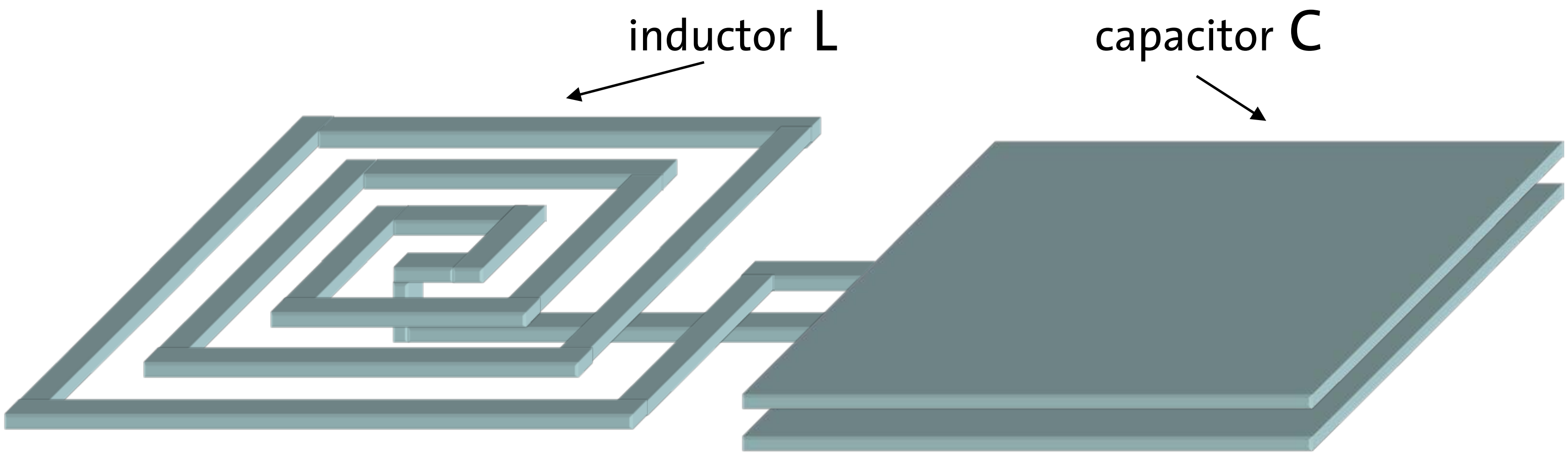
- typical inductor: L = 1 nH
- a wire in vacuum has inductance ~ 1 nH/mm

- typical capacitor: C = 1 pF
- a capacitor with plate size 10 μm x 10 μm and dielectric AlOx (ε = 10) of thickness 10 nm has a capacitance C ~ 1 pF

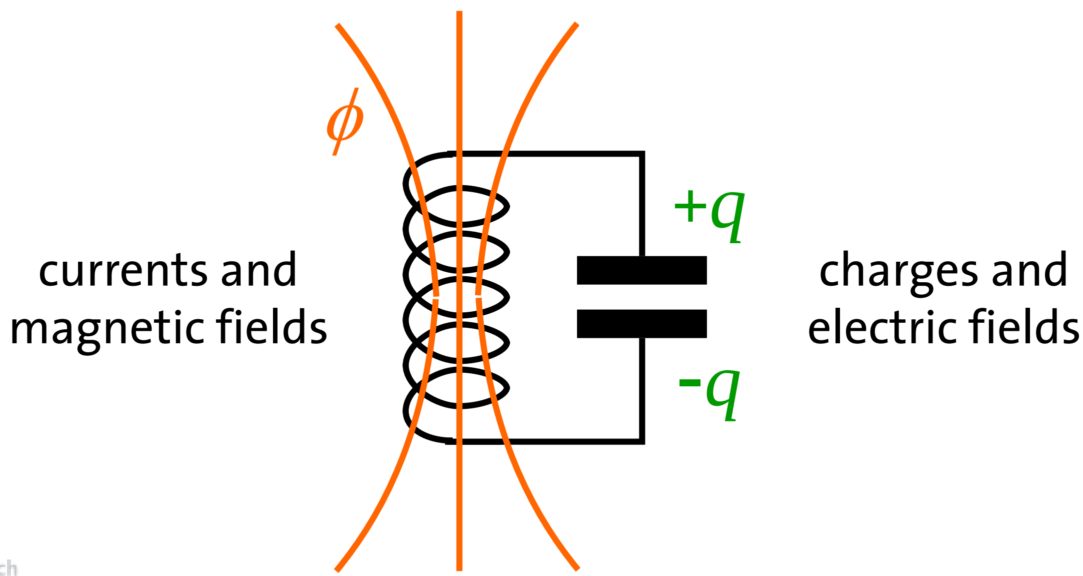
- resonance frequency

$$\frac{1}{2\pi\sqrt{LC}} \sim 5\,\text{GHz}$$

Realization of H.O.: Lumped Element Resonator

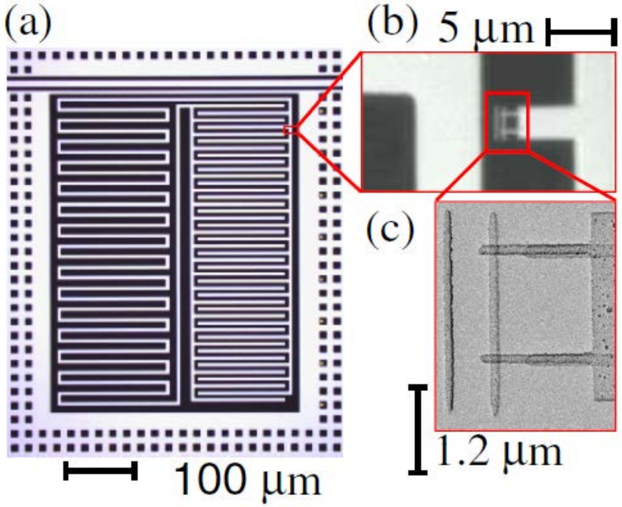


a harmonic oscillator



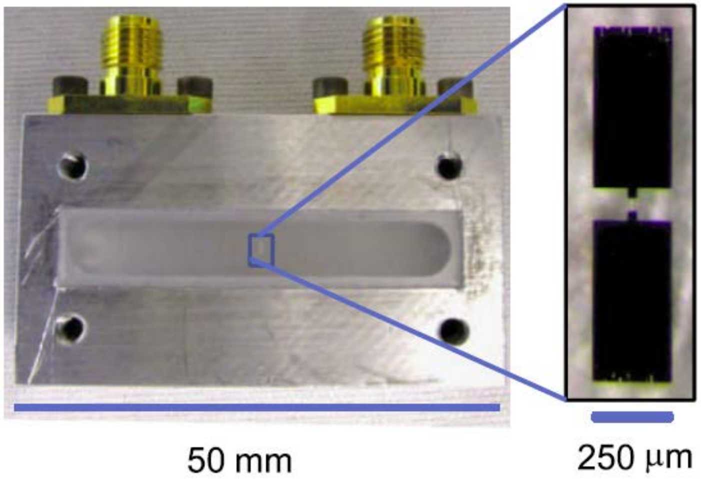
Types of Superconducting Harmonic Oscillators

lumped element resonator:



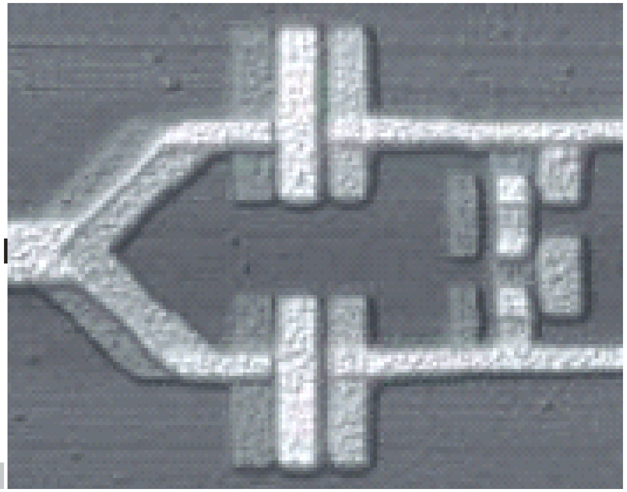
Z. Kim *et al.*, *PRL* 106, 120501 (2011)

3D cavity:



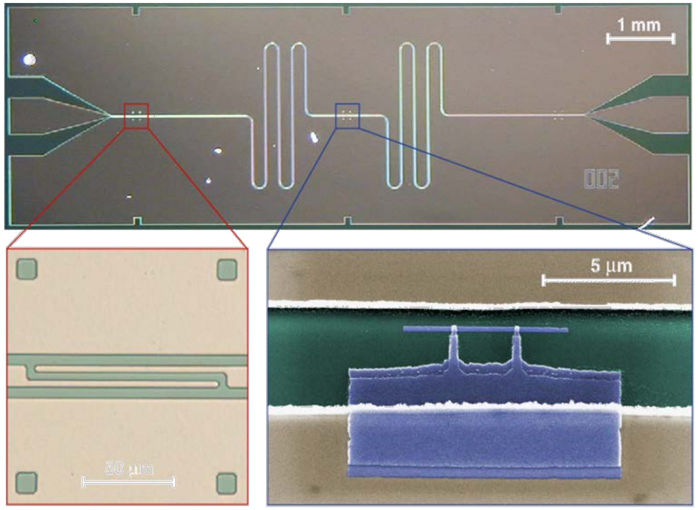
H. Paik *et al.*, *PRL* 107, 240501 (2011)

weakly nonlinear junction:



I. Chiorescu *et al.*, *Nature* 431, 159 (2004)

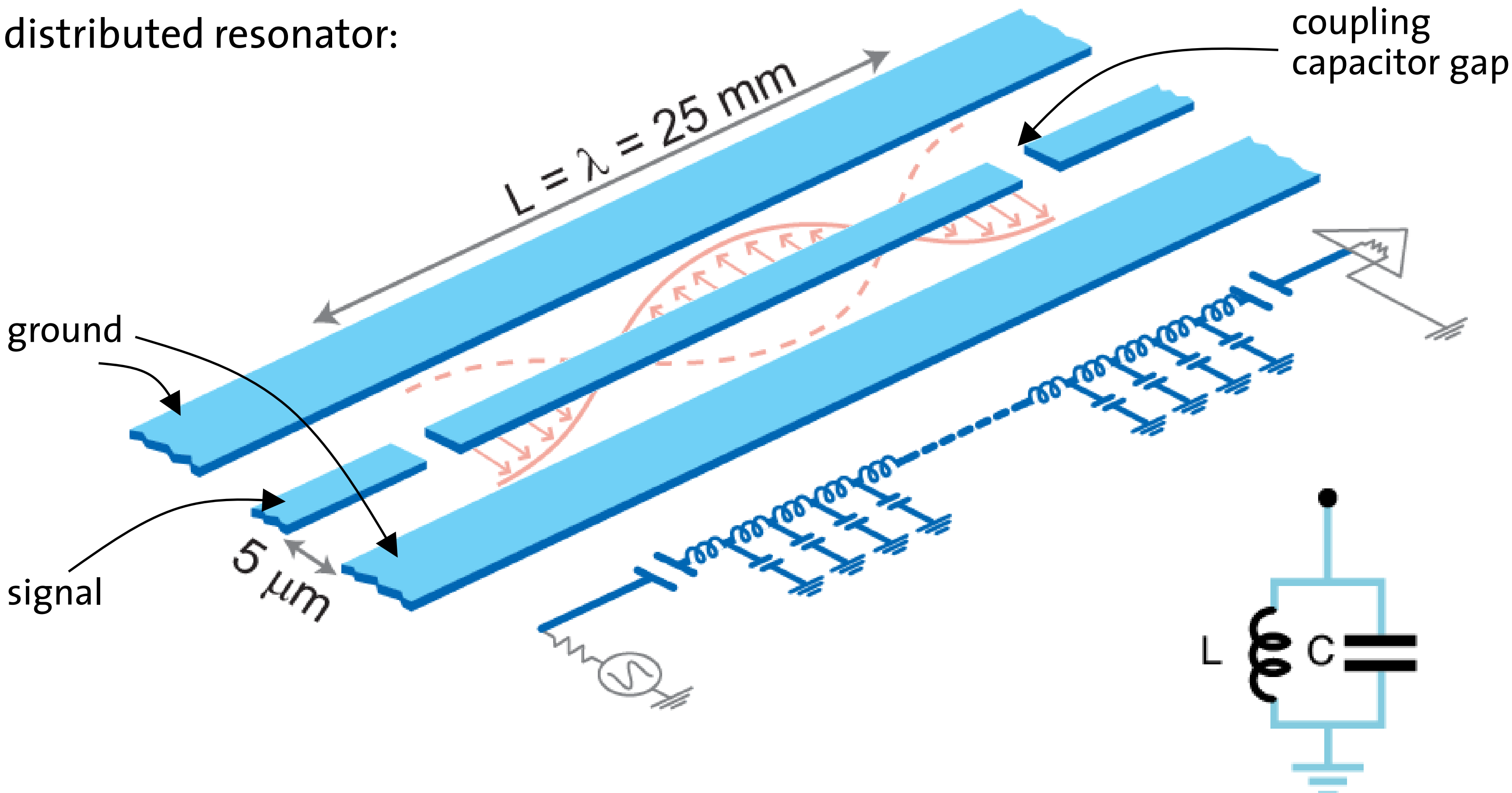
planar transmission line resonator:



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

Realization of H.O.: Transmission Line Resonator

distributed resonator:

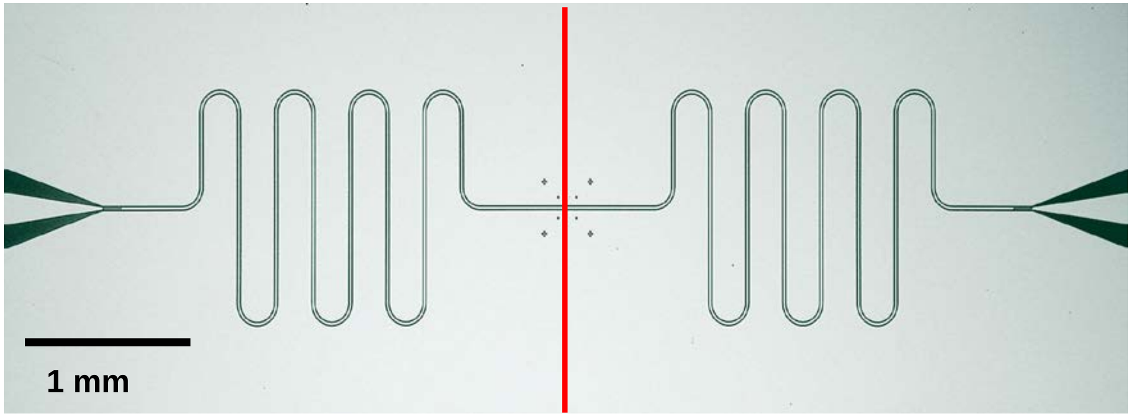


- coplanar waveguide resonator
- close to resonance: equivalent to lumped element LC resonator

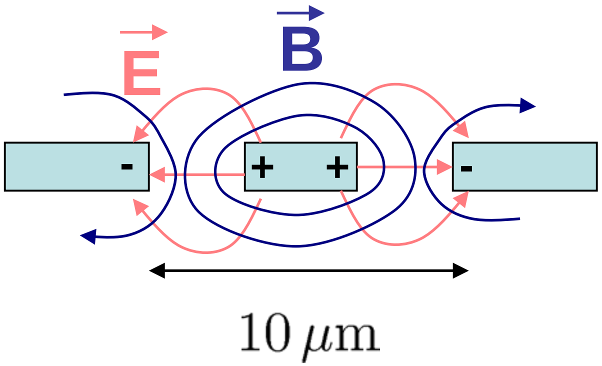
M. Goeppl *et al.*, Coplanar Waveguide Resonators for Circuit QED, *Journal of Applied Physics* 104, 113904 (2008)

Realization of Transmission Line Resonator

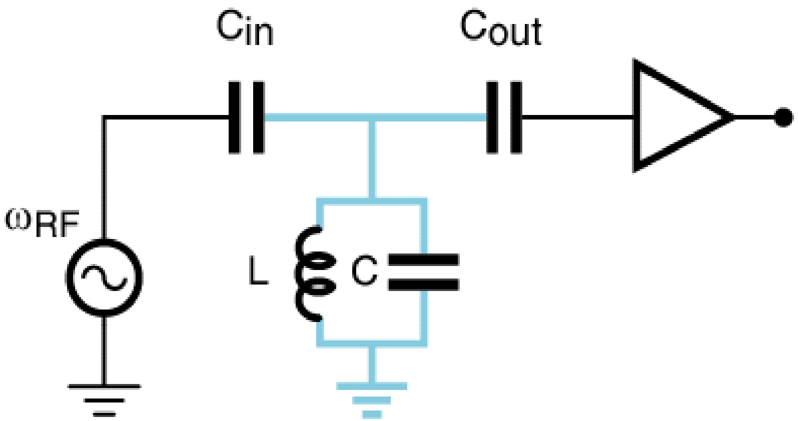
coplanar waveguide:



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

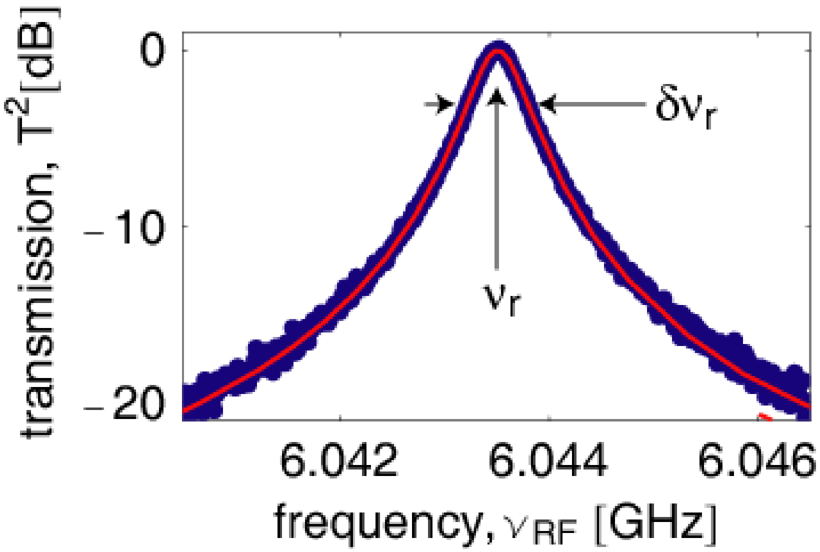


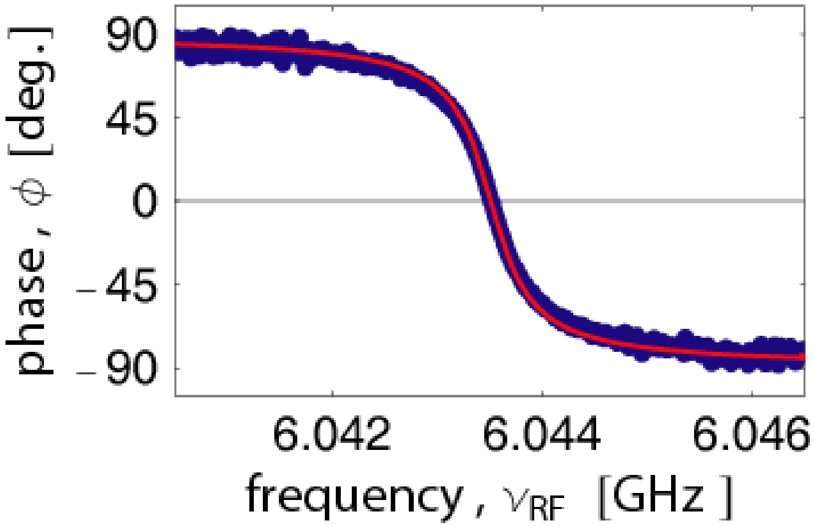
measuring the resonator:



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

Resonator Quality Factor and Photon Lifetime





resonance frequency:

$$\nu_r = 6.04\,\mathrm{GHz}$$

quality factor:

$$Q = \frac{\nu_r}{\delta\nu_r} \approx 10^4$$

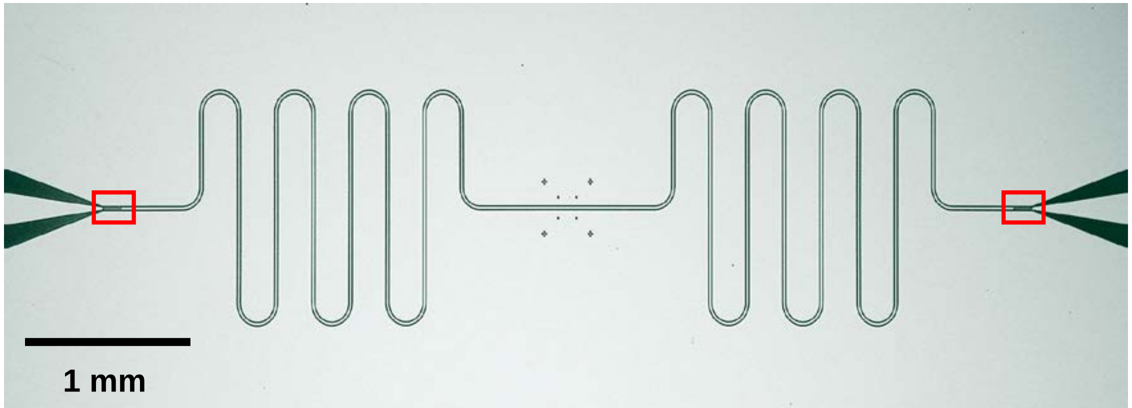
photon decay rate:

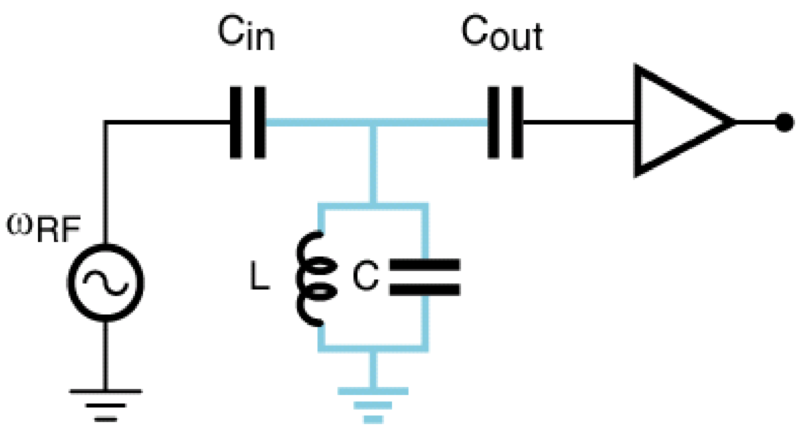
$$\frac{\kappa}{2\pi} = \frac{\nu_r}{Q} \approx 0.8\,\mathrm{MHz}$$

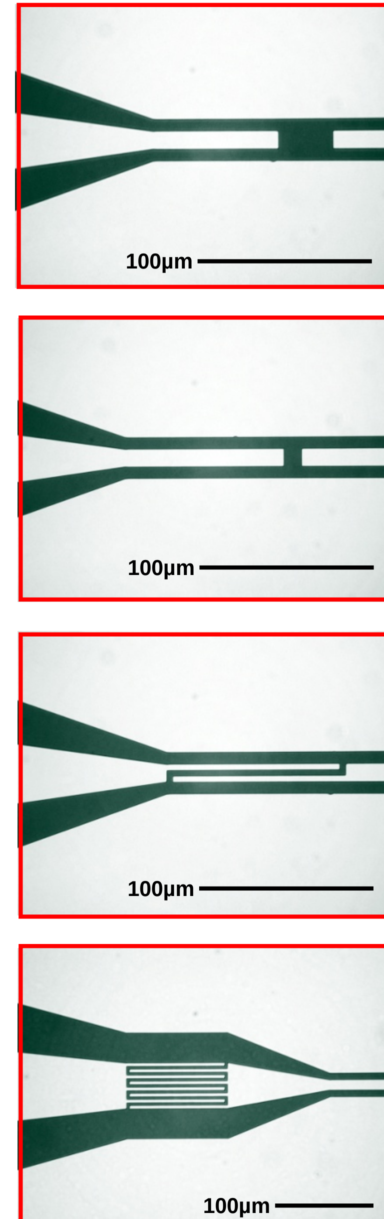
photon lifetime:

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

Controlling the Photon Life Time

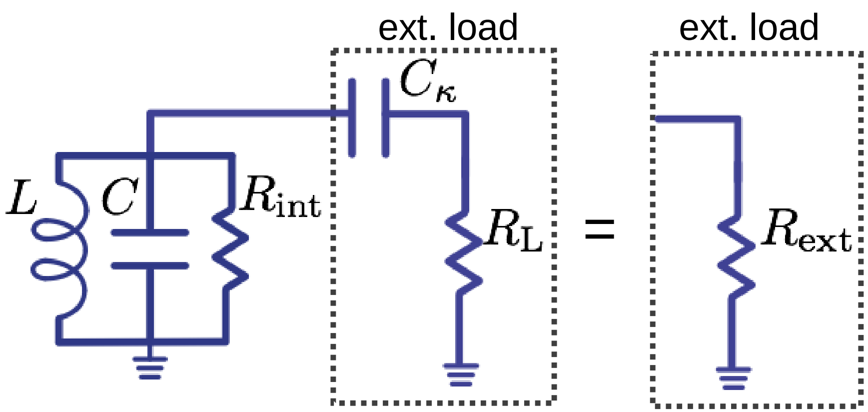


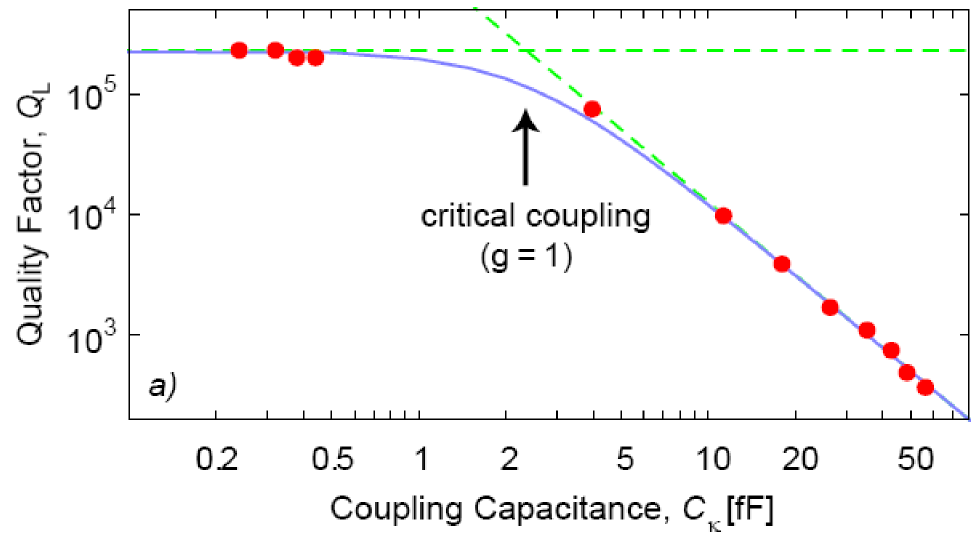


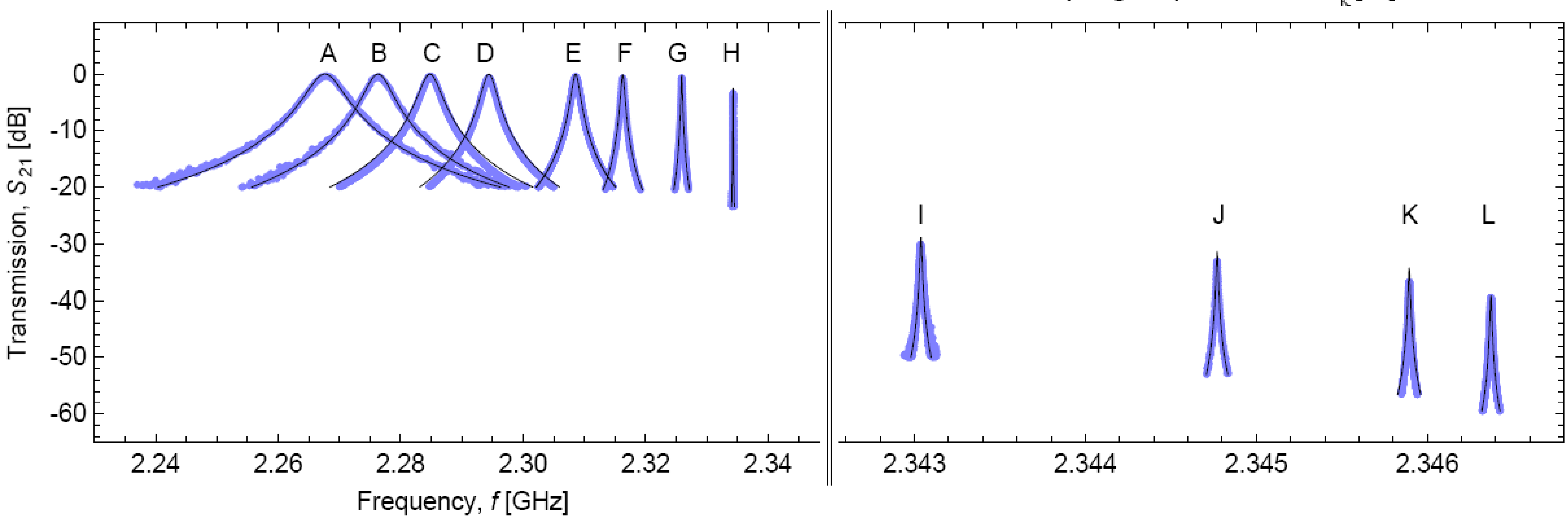


photon lifetime (quality factor)
controlled by coupling capacitor $C_{in/out}$

Quality Factor Measurement





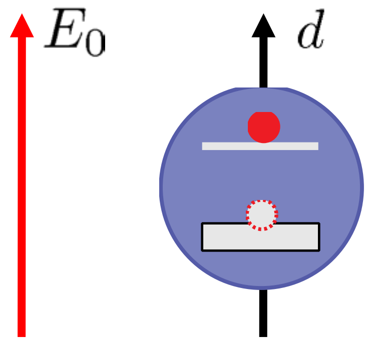


M. Goeppl *et al., J. Appl. Phys.* 104, 113904 (2008)

Cavity Quantum Electrodynamics (QED): Coupling a Harmonic Oscillator to a Qubit

Investigating the Interaction of Light and Matter

challenging on the level of single (artificial) atoms and single photons



- mode-matching (controlling the absorption probability)
- single photon fields E_o (small in 3D)
- dipole moment d (usually small ~ ea_o)
- photon/dipole interaction $\hbar g \sim dE_0$ (usually small)

What to do?

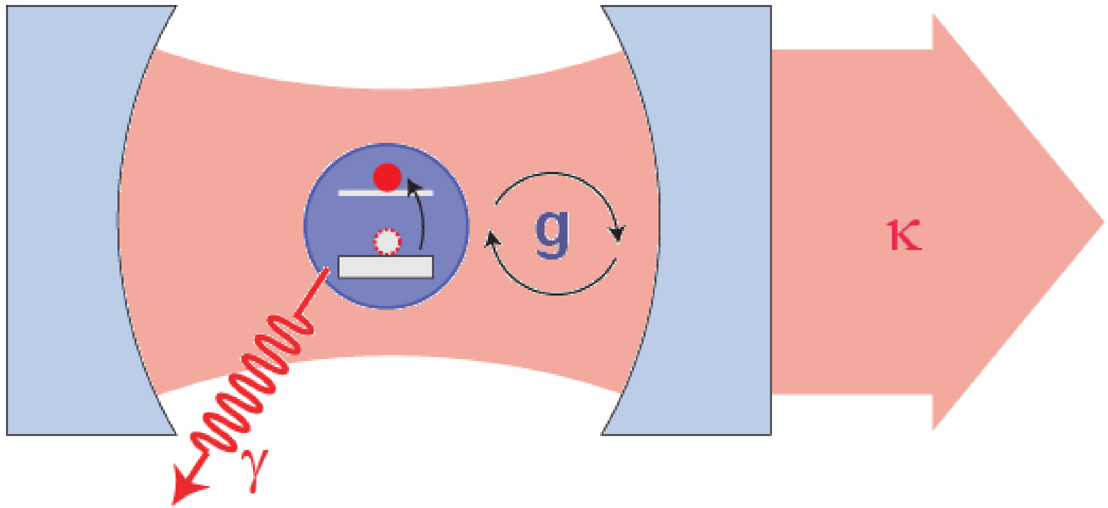
- confine atom and photon in a cavity (cavity QED)
- engineer matter/light interactions, e.g. in solid state circuits

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

Cavity Quantum Electrodynamics

coupling photons to qubits:



Jaynes-Cummings Hamiltonian

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

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

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

Dressed States Energy Level Diagram

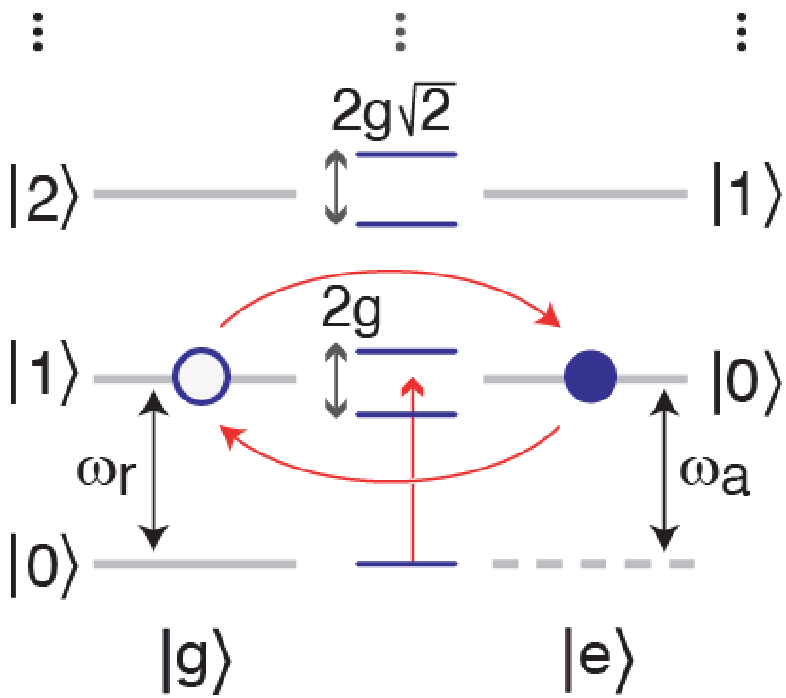
$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

in resonance:

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

strong coupling limit:

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



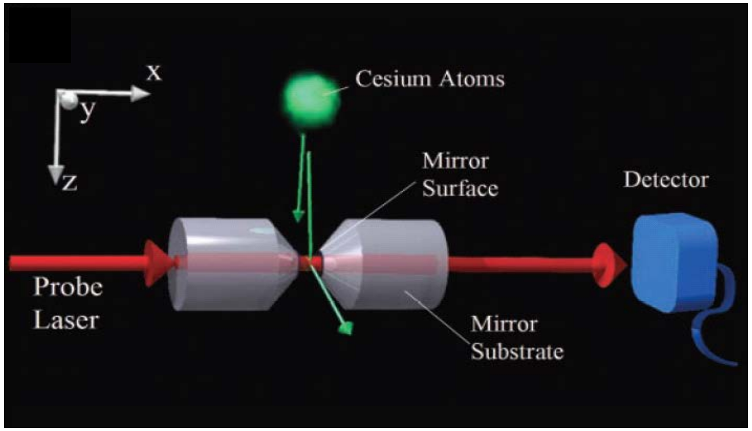
Jaynes-Cummings Ladder

Atomic cavity quantum electrodynamics reviews:

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

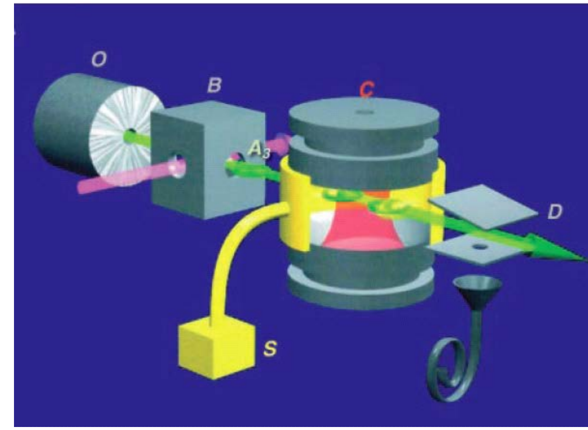
S. Haroche & J. Raimond, Exploring the Quantum, *OUP Oxford* (2006)

Systems for Exploring Cavity QED



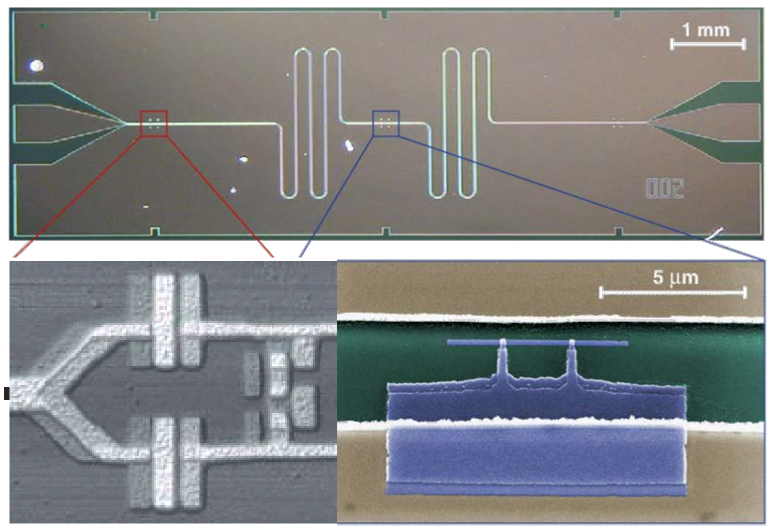
alkali atoms

MPQ, Caltech, ...



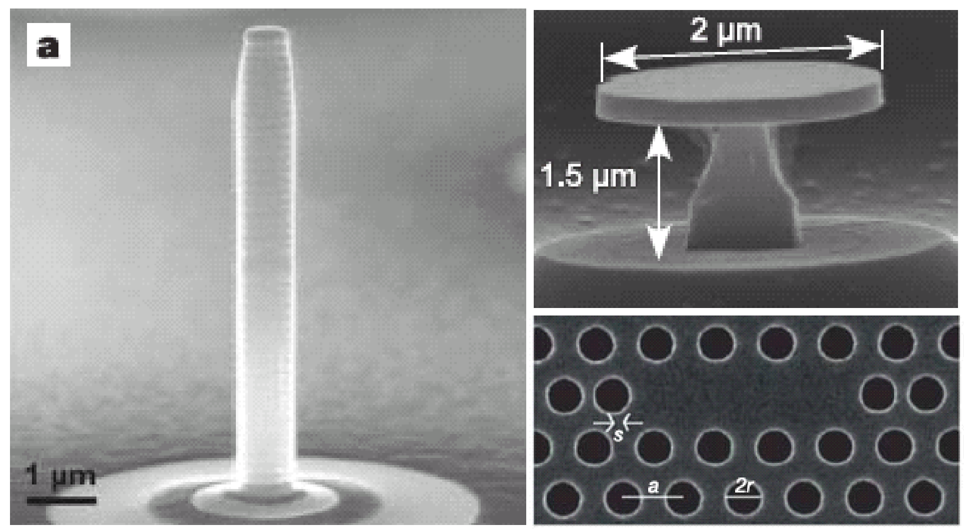
Rydberg atoms

ENS, MPQ, ...



superconductor circuits

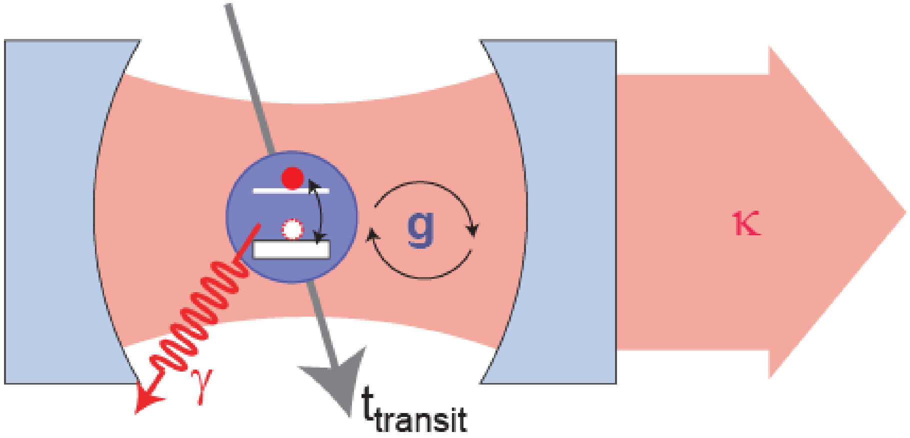
Yale, Delft, NTT, ETHZ, NIST, …



semiconductor quantum dots

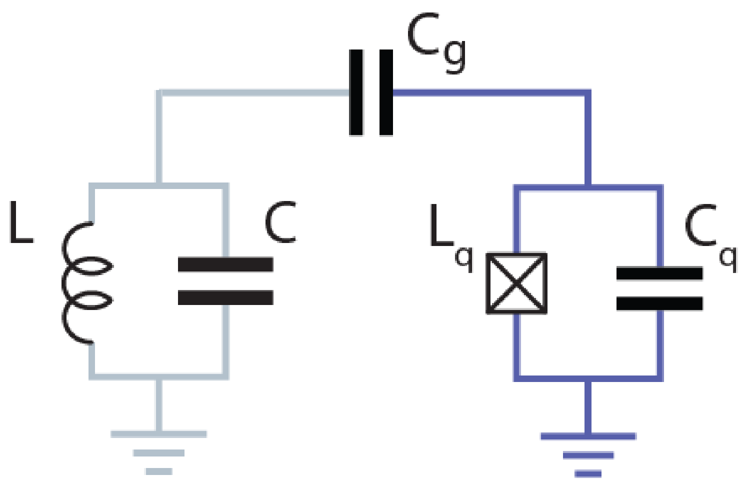
Wurzburg, ETHZ, Stanford …

Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

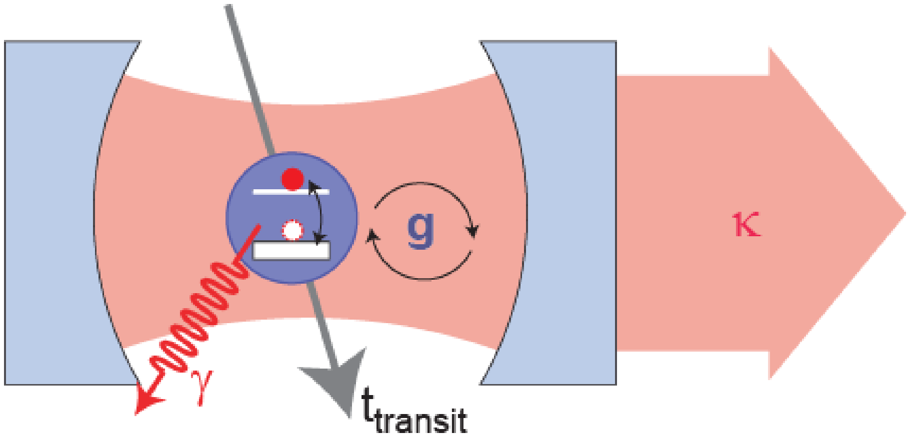
... basic approach:



What is this good for?

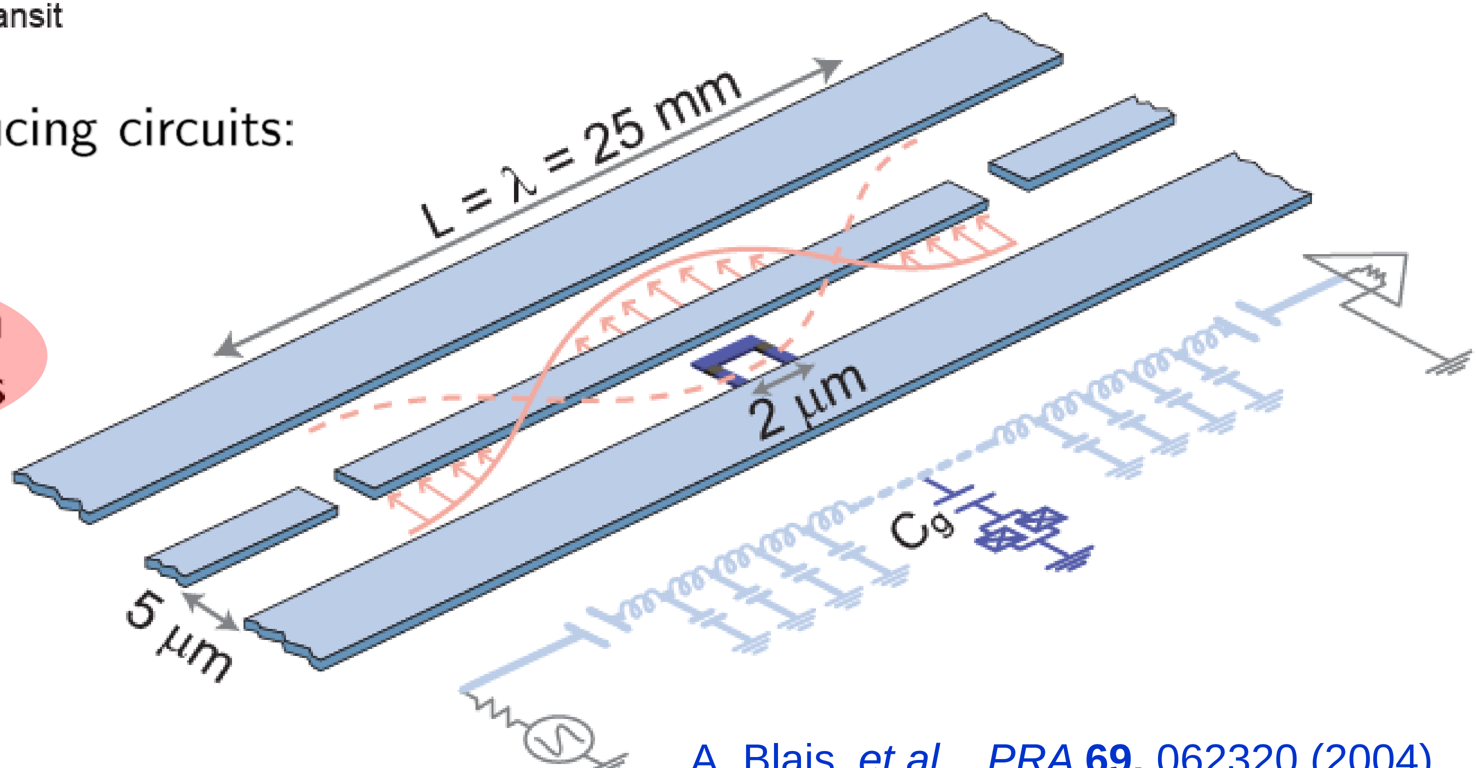
- Study matter light interaction
- Convert qubit states to photon states
- Use concepts to ...
  - ... build single photon sources and detectors
  - ... build quantum computers

Cavity QED with Superconducting Circuits



coherent quantum mechanics
with individual photons and qubits ...

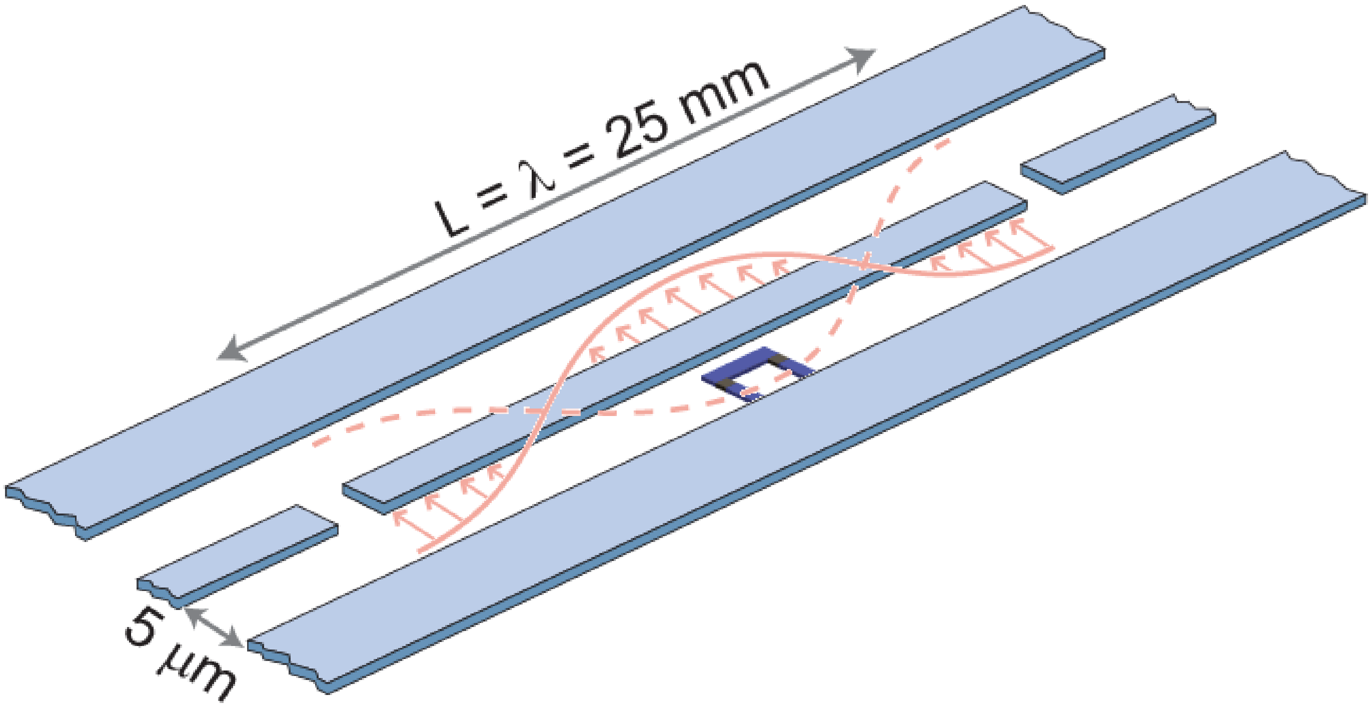
... in superconducing circuits:



circuit quantum electrodynamics

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

Circuit Quantum Electrodynamics

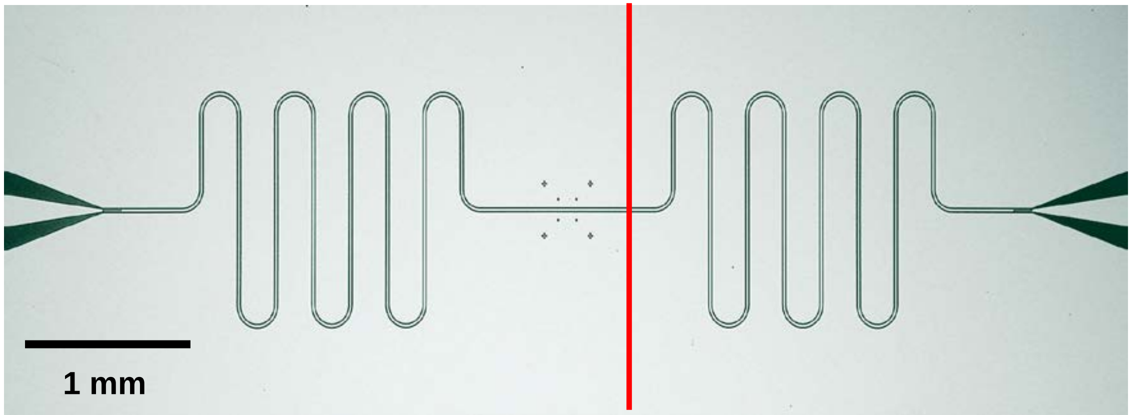


elements

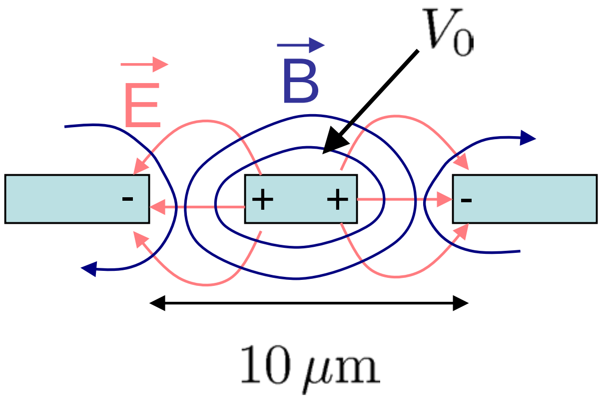
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box with large E_J/E_C with large dipole moment d and long coherence time $1/\gamma$

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

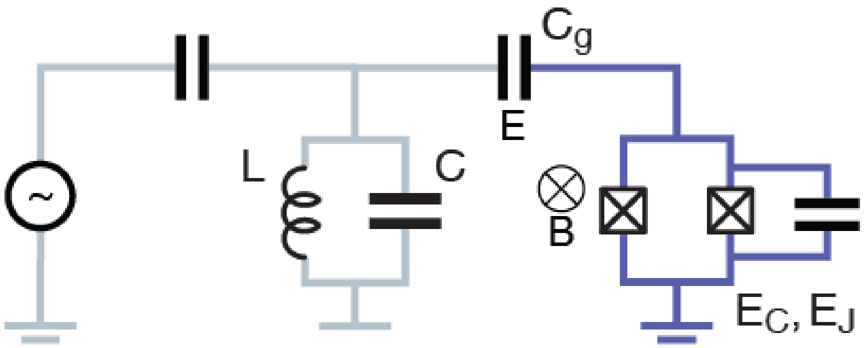
$$H_r = \hbar\omega_r \left(a^\dagger a + \frac{1}{2} \right)$$

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

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

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

Qubit/Photon Coupling



Hamilton operator of qubit (2-level approx.) coupled to resonator:

$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\phi}^2}{2L} + \frac{E_C}{2}(1 - 2(N_g + \hat{N}_g))\hat{\sigma}_z - \frac{E_J}{2}\hat{\sigma}_x$$

quantum part of gate voltage due to resonator

$$\hat{N}_g = \frac{C_g}{2e}\hat{V}_g = \frac{C_g}{2e}\sqrt{\frac{\hbar\omega_r}{2C}}(\hat{a}^\dagger + \hat{a})$$

Jaynes-Cummings Hamiltonian

Consider bias at charge degeneracy N_g = 1/2 and change of qubit basis (*z* to *x*, *x* to *-z*)

$$\hat{H} \quad = \quad \hbar\omega_r(\hat{a}^\dagger\hat{a} + 1/2) + \frac{E_J}{2}\hat{\sigma}_z + \frac{E_C}{2}\frac{C_g}{2e}\sqrt{\frac{\hbar\omega_r}{2C}}(\hat{a}^\dagger + \hat{a})\hat{\sigma}_x$$

Use qubit raising and lowering operators $\hat{\sigma}_x = \hat{\sigma}^+ + \hat{\sigma}^-$

Coupling term in the rotating wave approximation (RWA)

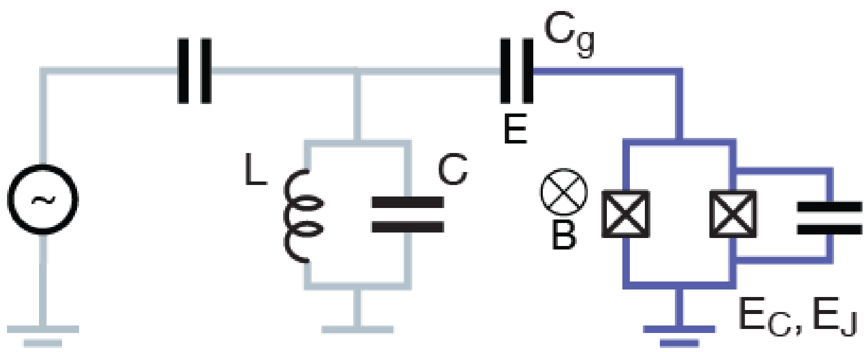
$$\hat{H}_g \quad = \quad \frac{E_C}{2}\frac{C_g}{2e}\sqrt{\frac{\hbar\omega_r}{2C}}(\hat{a}^\dagger\hat{\sigma}^- + \cancel{\hat{a}\hat{\sigma}^-} + \cancel{\hat{a}^\dagger\hat{\sigma}^+} + \hat{a}\hat{\sigma}^+) \approx \hbar g(\hat{a}^\dagger\hat{\sigma}^- + \hat{a}\hat{\sigma}^+)$$

Coupling strength of the Jaynes Cummings Hamiltonian $\hbar g = \frac{C_g}{C_\Sigma}2e\sqrt{\frac{\hbar\omega_r}{2C}}$

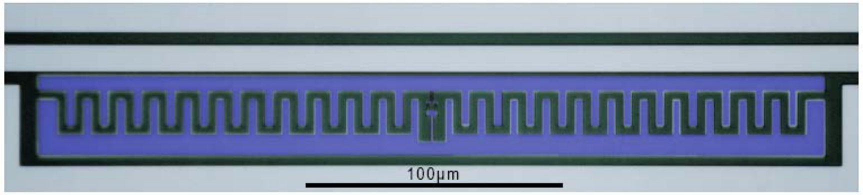
Vacuum-Rabi frequency $\nu_R = \frac{2g}{2\pi} \approx 1\ldots300\,\mathrm{MHz}$

$$g \gg [\kappa, \gamma] \text{ possible!}$$

Qubit/Photon Coupling in a Circuit



qubit coupled to resonator



coupling strength:

$$\hbar g \quad = \quad eV_{0,\mathrm{rms}} \frac{C_g}{C_\Sigma}$$

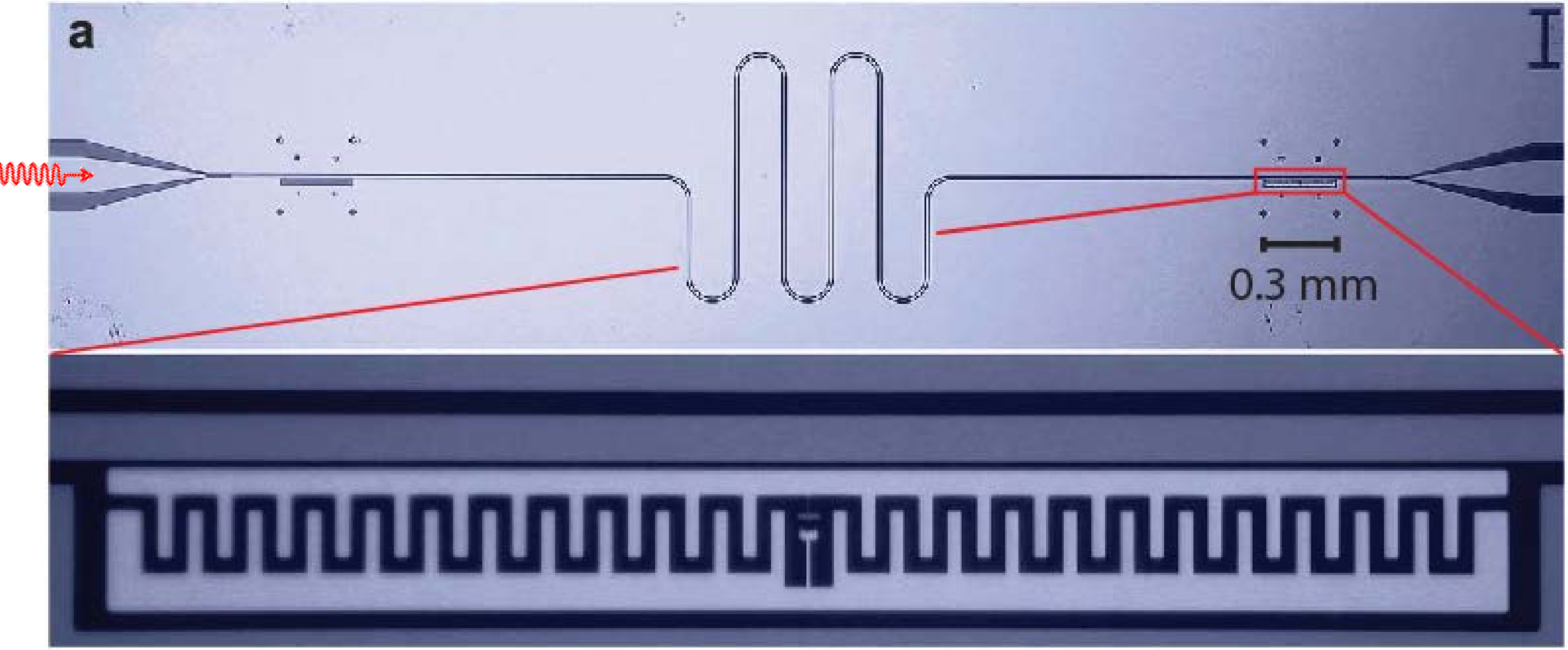
$$\Longrightarrow \nu_{\mathrm{vac}} \quad = \quad \frac{g}{\pi} \approx 1 \ldots 300\,\mathrm{MHz}$$

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

large effective dipole moment

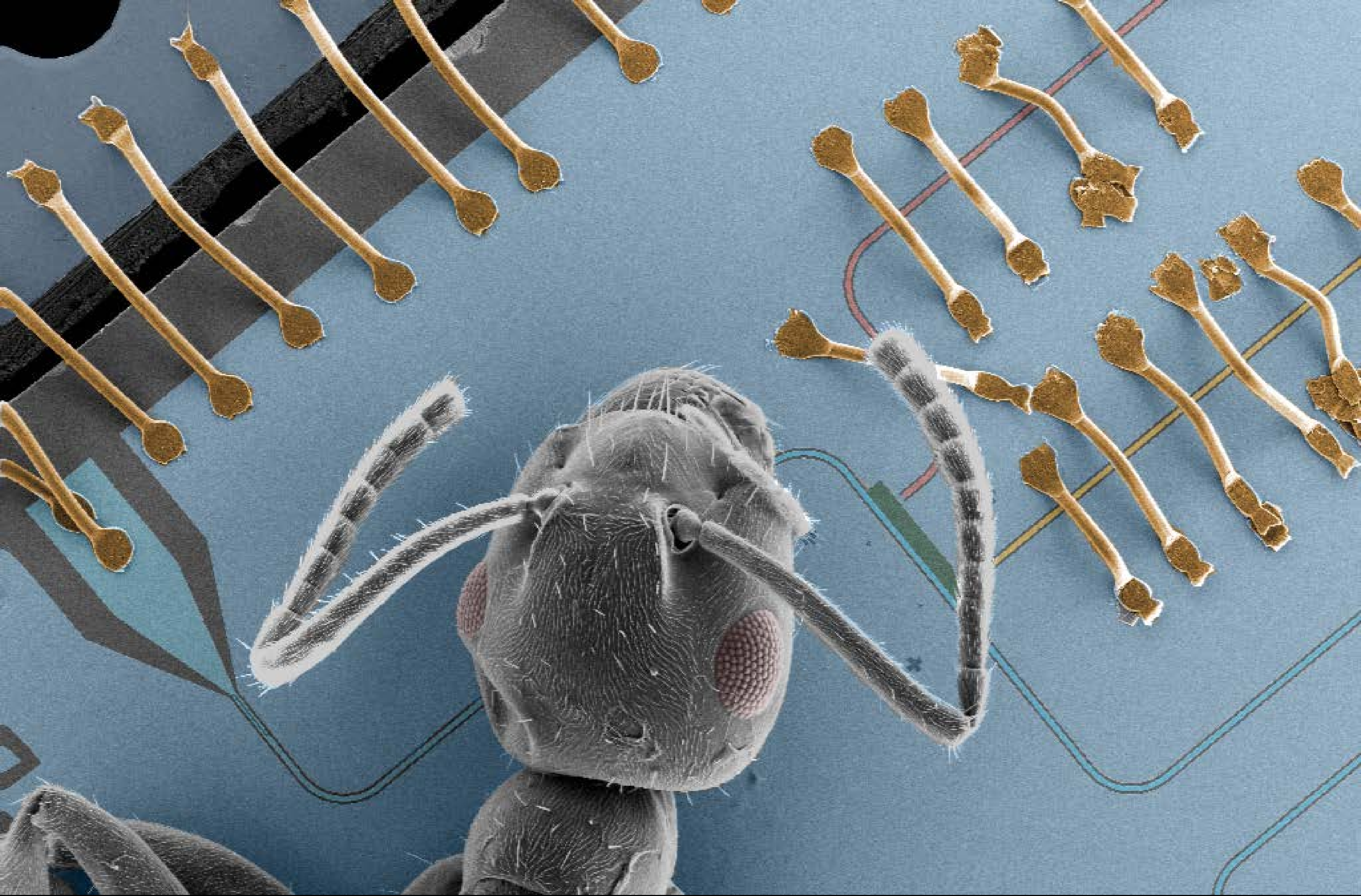
$$d = \frac{\hbar g}{E_0} \sim 10^2 \ldots 10^4\, e a_0$$

Circuit QED with One Photon



superconducting cavity QED circuit

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



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

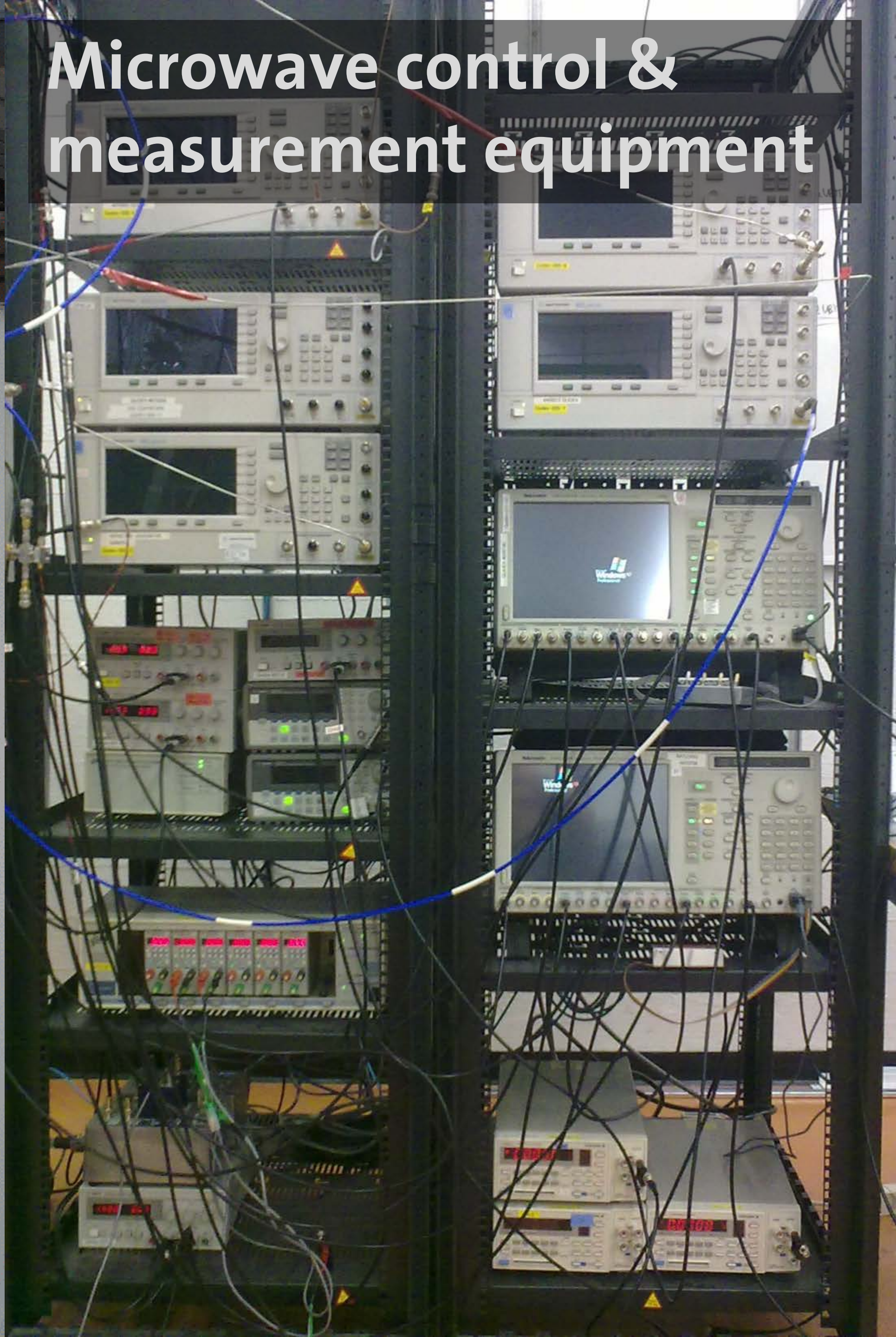
J. Mlynek *et al.,* Quantum Device Lab, ETH Zurich (2012)

Sample Mount

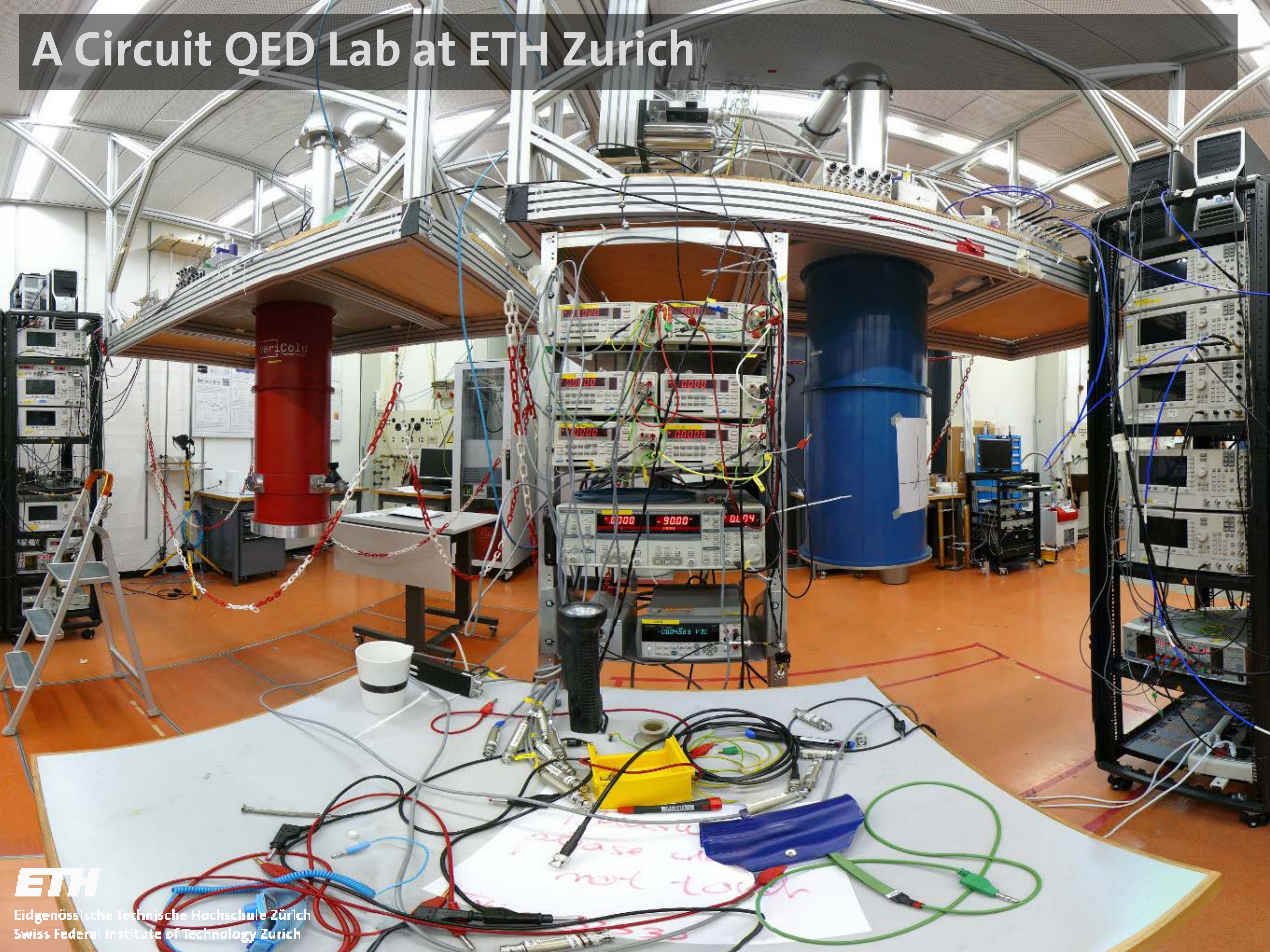
M. Peterer *et al.*, Quantum Device Lab, ETH Zurich (2012)

Cryostate for temperatures down to 0.02 K

Microwave control & measurement equipment

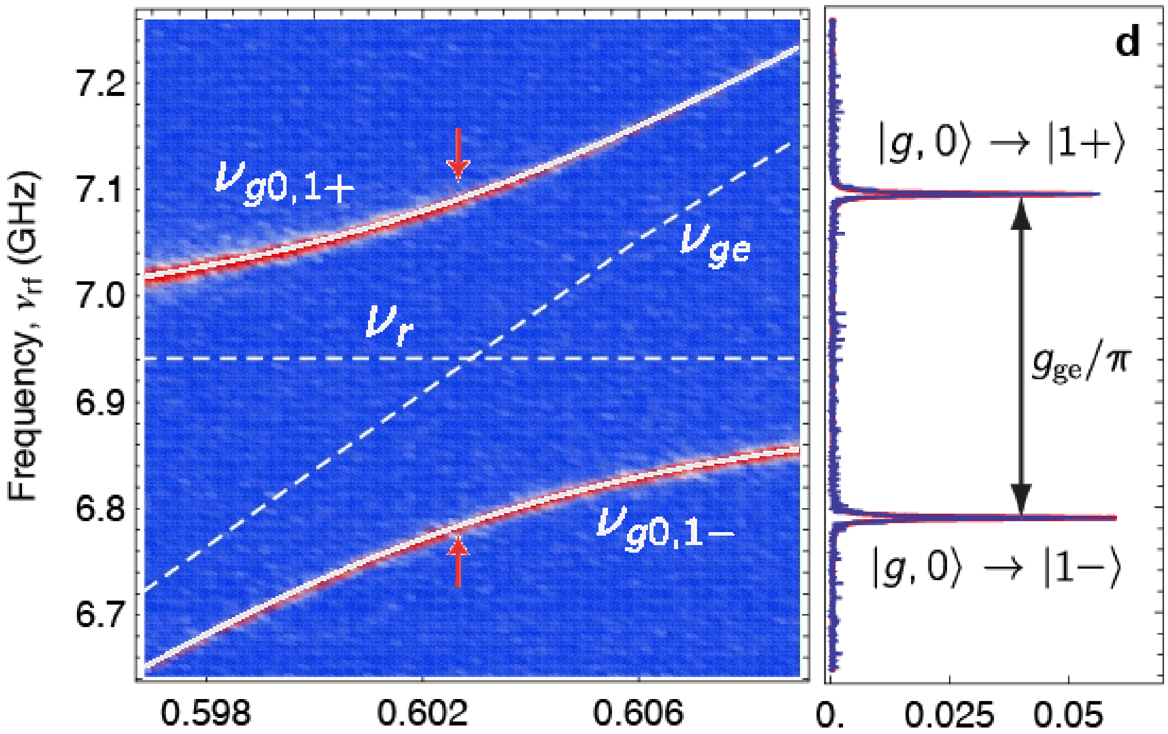


A Circuit QED Lab at ETH Zurich



Resonant Vacuum Rabi Mode Splitting ...

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

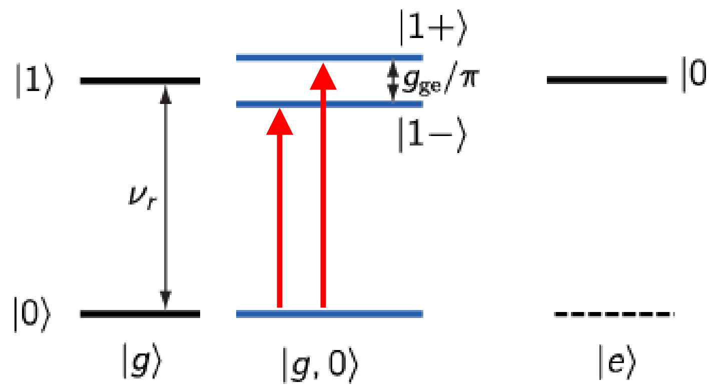


very strong coupling:

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

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

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



forming a 'molecule' of a qubit and a photon

first demonstration in a solid: A. Wallraff e*t 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)

Resonant Vacuum Rabi Mode Splitting ...

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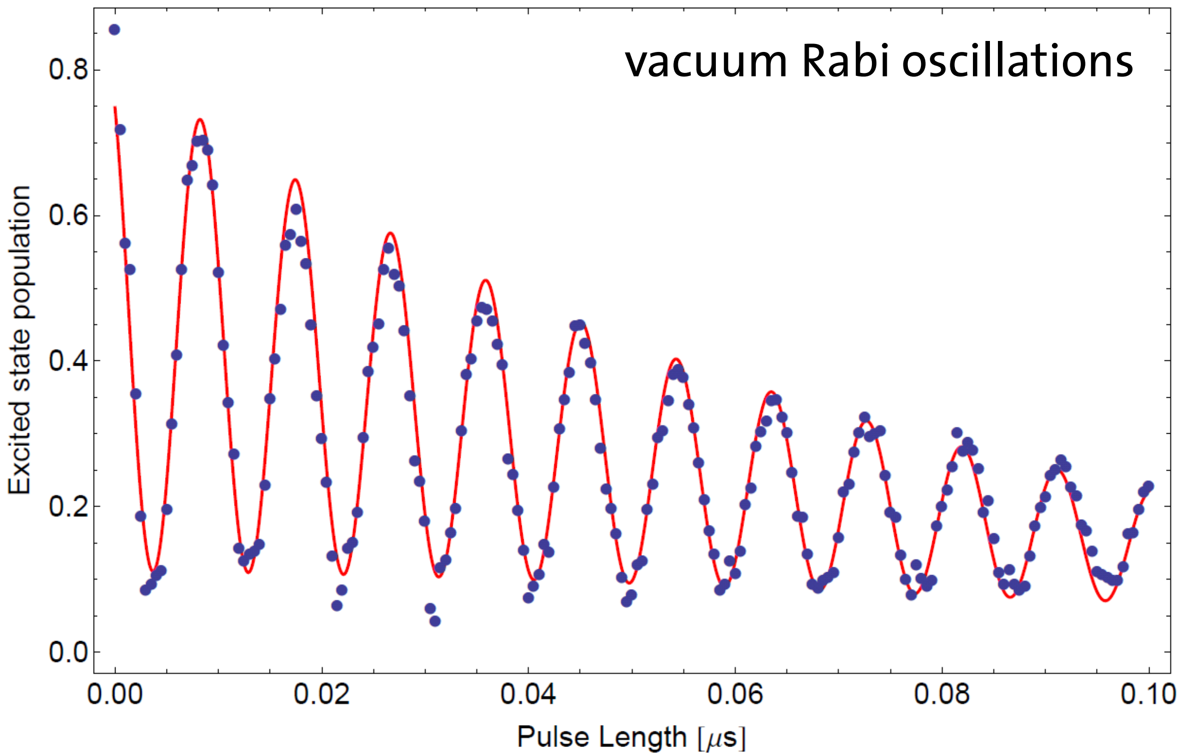

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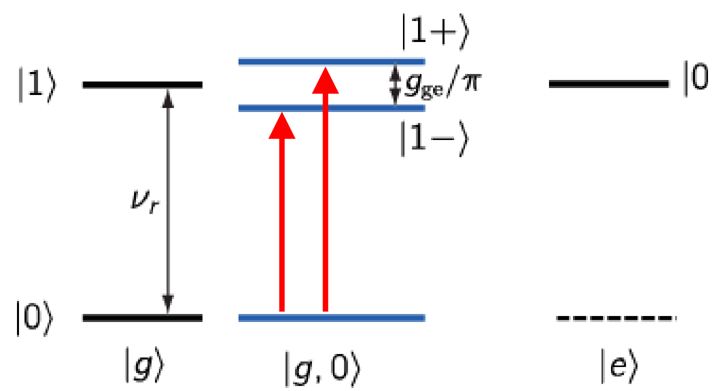

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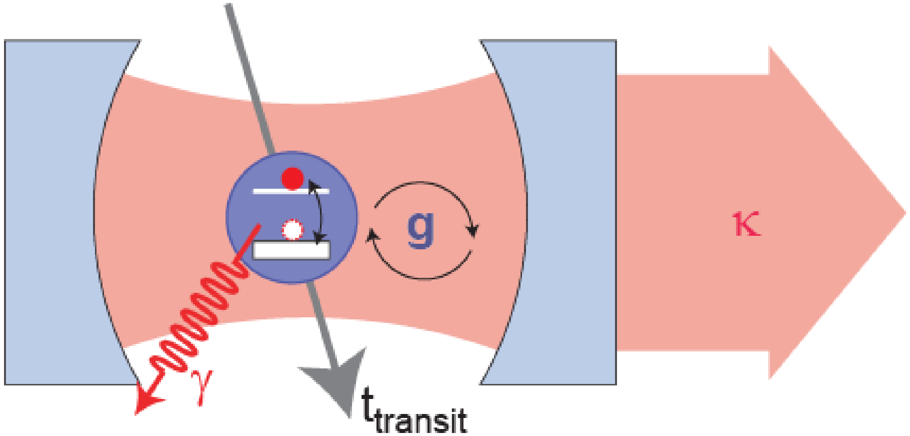
this data: J. Fink et al., *Nature (London)* 454, 315 (2008)

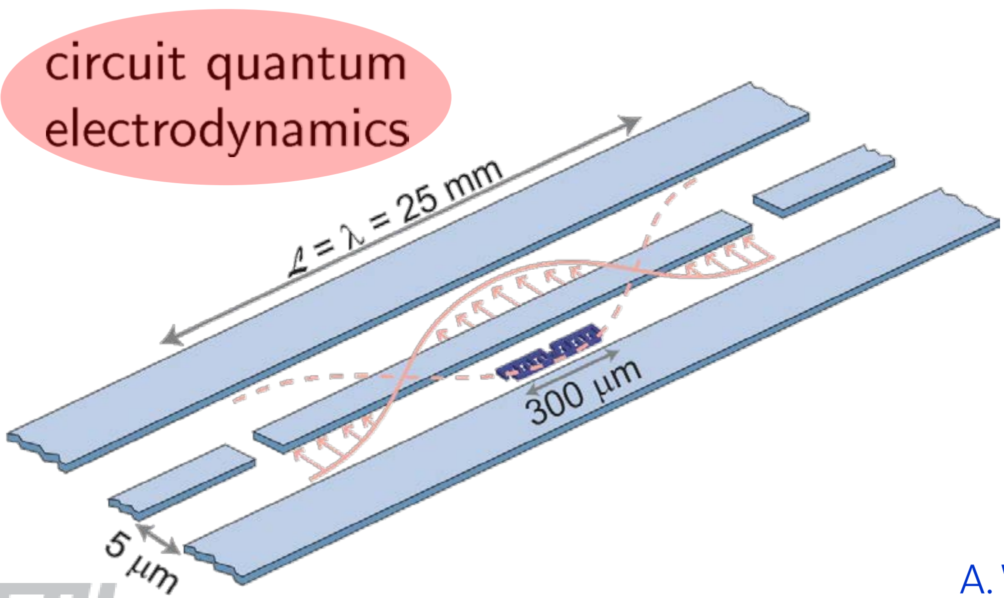
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

Cavity QED with Superconducting Circuits



coherent interaction of photons with quantum two-level systems ...

J. M. Raimond *et al., Rev. Mod. Phys.* 73, 565 (2001)
S. Haroche & J. Raimond, *OUP Oxford* (2006)
J. Ye., H. J. Kimble, H. Katori, *Science* 320, 1734 (2008)



Properties:

- strong coupling in solid state sys.
- 'easy' to fabricate and integrate

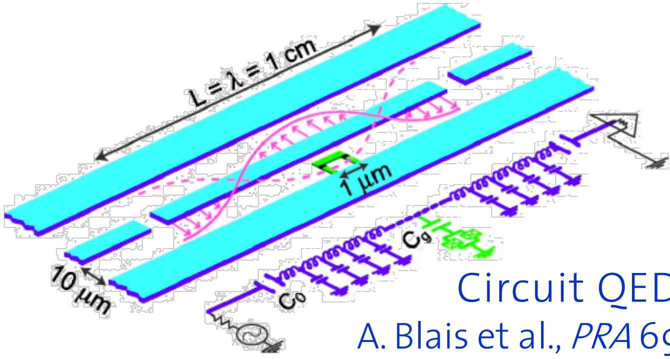
Research directions:

- quantum optics
- hybrid quantum systems
- quantum information

A. Blais, *et al., PRA* 69, 062320 (2004)
A. Wallraff *et al., Nature (London)* 431, 162 (2004)
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* 451, 664 (2008)

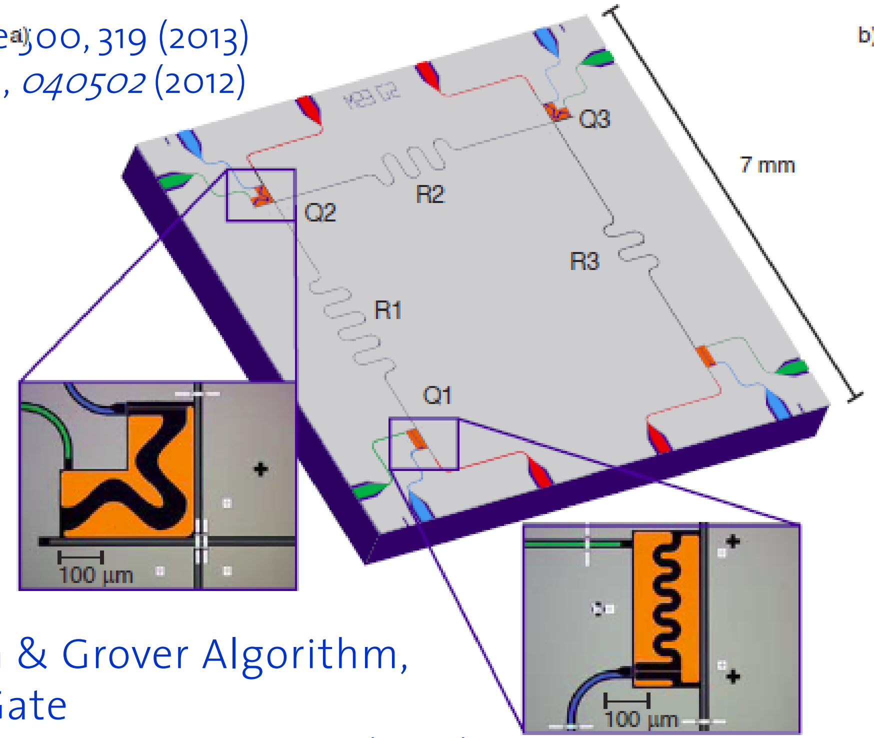
Research Directions & Applications

Quantum Computing with Superconducting Circuits



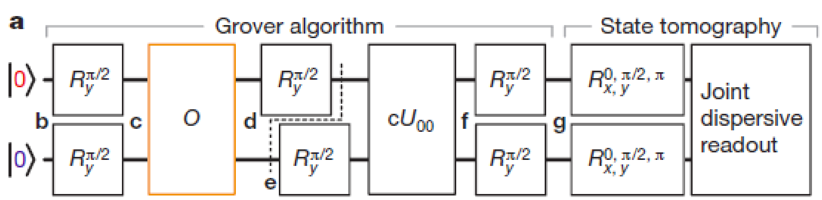
Teleportation

L. Steffen *et al.*, *Nature* 500, 319 (2013)
M.. Baur *et al.*, *PRL* 108, *040502* (2012)



Circuit QED Architecture

A. Blais et al., *PRA* 69, 062320 (2004)
A. Wallraff *et al.*, *Nature* 431, 162 (2004)
M. Sillanpaa *et al.*, *Nature* 449, 438 (2007)
H. Majer *et al.*, *Nature* 449, 443 (2007)
M. Mariantoni *et al.*, *Science* 334, 61 (2011)
R. Barends *et al.*, *Nature* 508, 500 (2014)

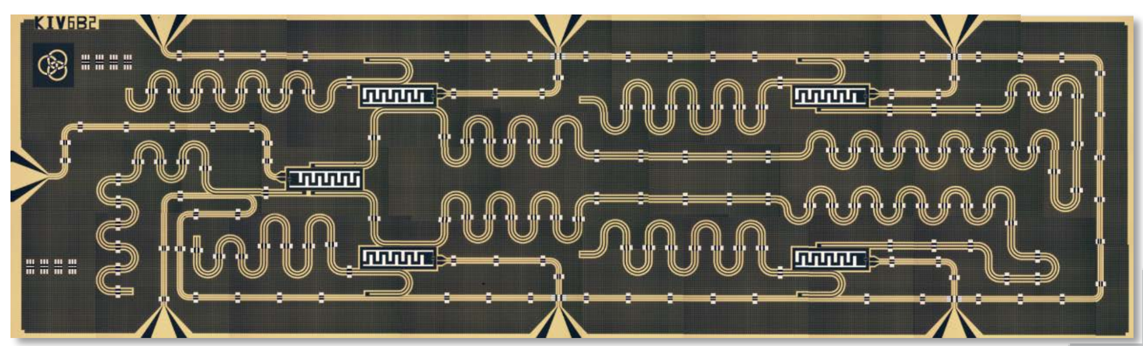


Deutsch & Grover Algorithm, Toffoli Gate

L. DiCarlo *et al.*, *Nature* 460, 240 (2009)
L. DiCarlo *et al.*, *Nature* 467, 574 (2010)
M. Reed *et al.*, *Nature* 481, 382 (2012)

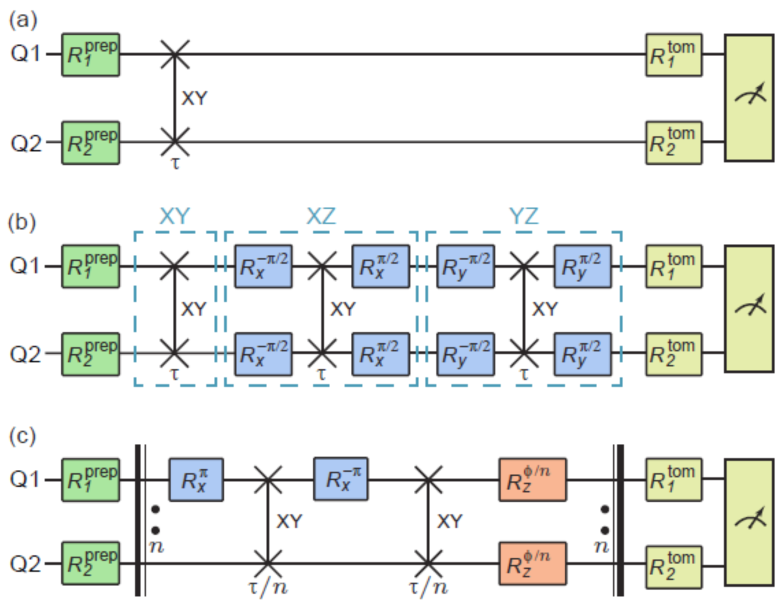
Error Correction

M. Reed *et al.*, *Nature* 481, 382 (2012)
Corcoles et al., *Nat. Com.* 6, 6979 (2015)
Ristè et al., *Nat. Com.* 6, 6983 (2015)
Kelly et al., *Nature* 519, 66-69 (2015)



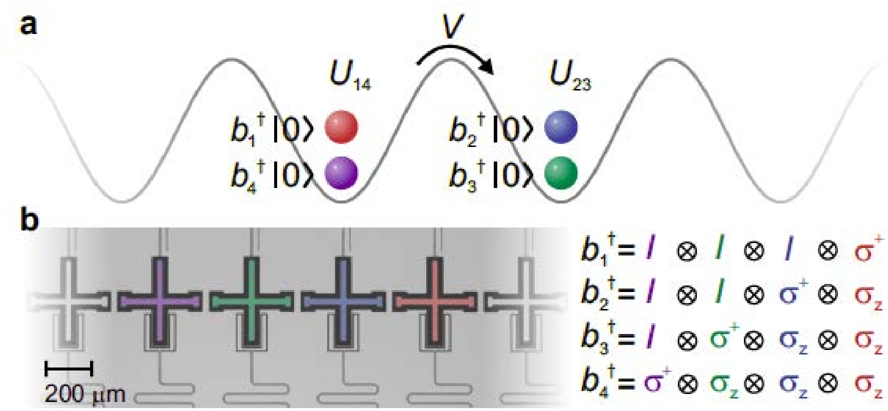
Quantum Simulation with Superconducting Circuits

Digital simulation of exchange, Heisenberg, Ising spin models

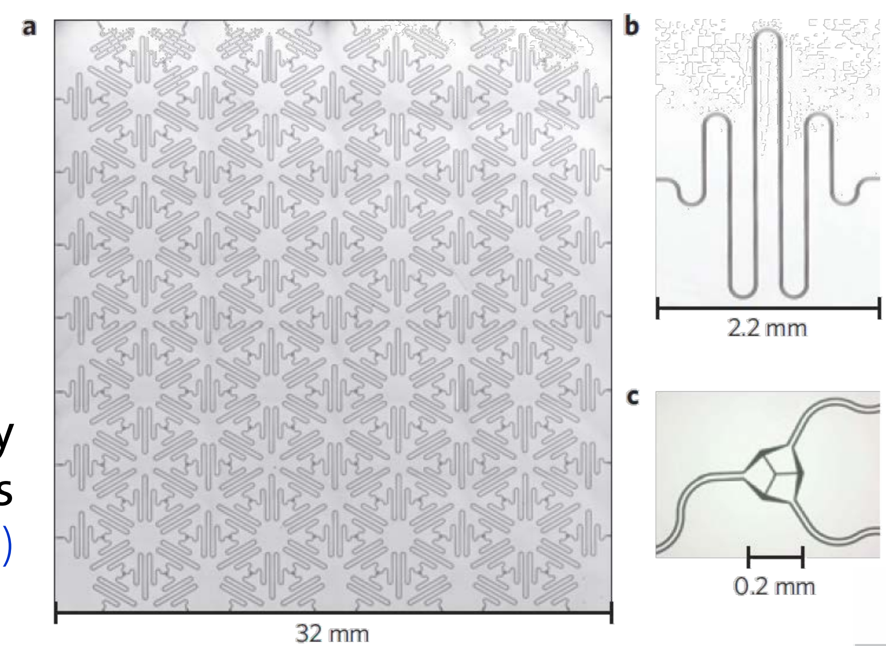


Salathe *et al.*, *PRX* 5, 021027 (2015)
arXiv:1502.06778

... two-mode fermionic Hubbard models

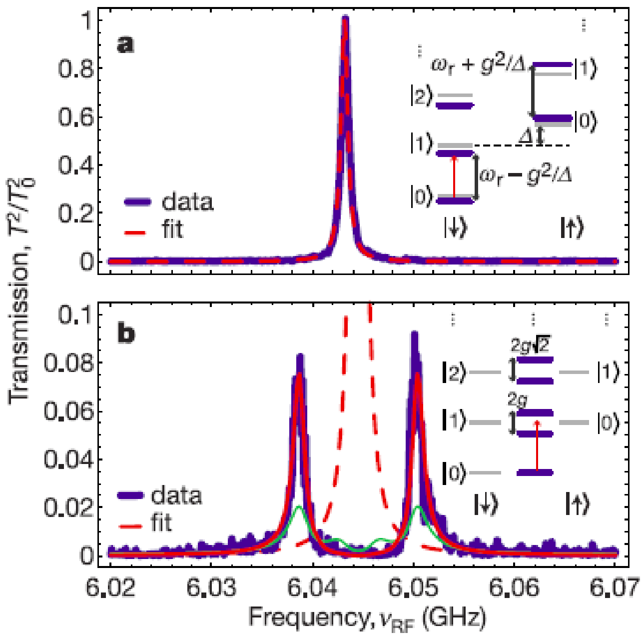


Barends *et al.*, *arXiv:1501.07703*, (2015)



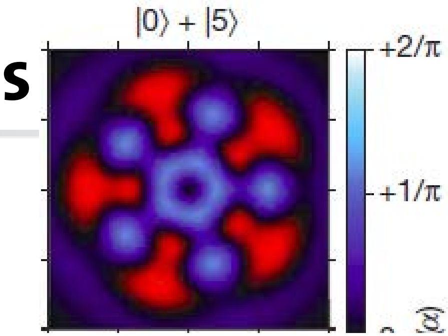
Analog simulations with cavity and/or qubit arrays
Houck *et al.*, *Nat Phys.* 8, 292 (2012)

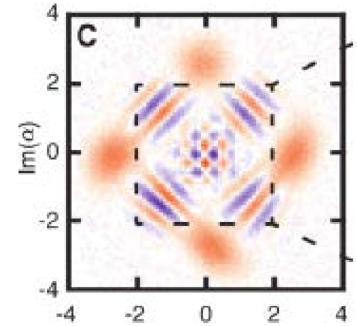
Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

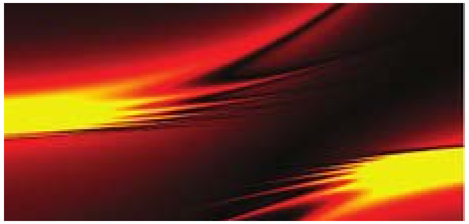
Chiorescu *et al.*, *Nature* 431, 159 (2004)
Wallraff *et al.*, *Nature* 431, 162 (2004)
Schuster *et al.*, *Nature* 445, 515 (2007)





Root n Nonlinearities

Fink *et al.*, *Nature* 454, 315 (2008)
Deppe *et al.*, *Nat. Phys.* 4, 686 (2008)
Bishop *et al.*, *Nat. Phys.* 5, 105 (2009)



Microwave Fock and Cat States

Hofheinz *et al.*, *Nature* 454, 310 (2008)
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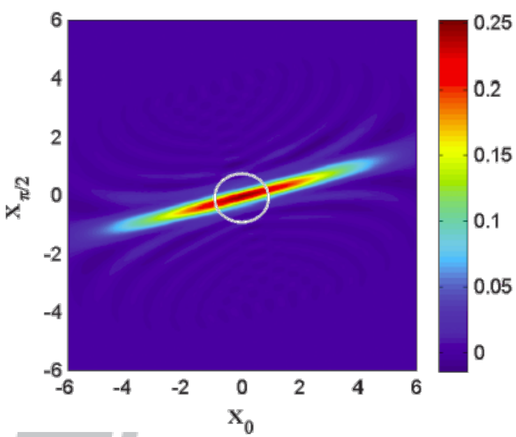
Kirchmair *et al.*, *Nature* 495, 205 (2013)
Vlastakis *et al.*, *Science* 342, 607 (2013)

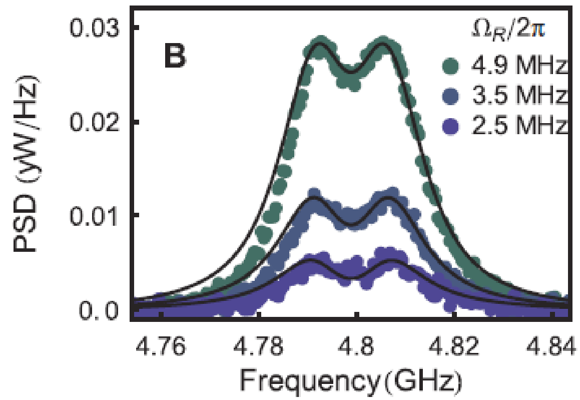


Parametric Amplification & Squeezing

Castellanos-Beltran *et al.*, *Nat. Phys.* 4, 928 (2008)
Abdo *et al.*, *PRX* 3, 031001 (2013)

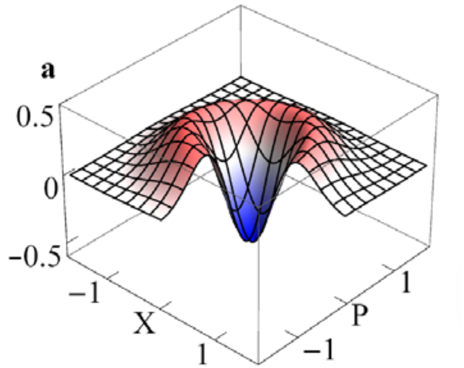
Waveguide QED – Qubit Interactions in Free Space

Astafiev *et al.*, *Science* 327, 840 (2010)
van Loo *et al.*, *Science* 342, 1494 (2013)



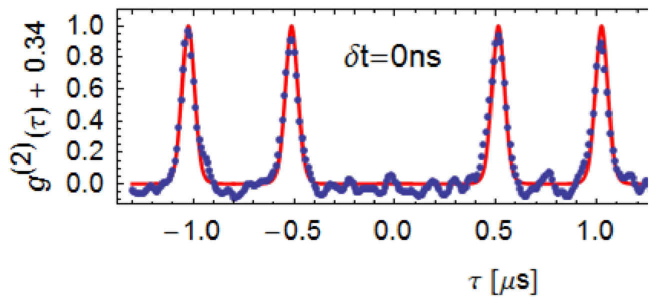
Experiments with Propagating Microwaves in 1D

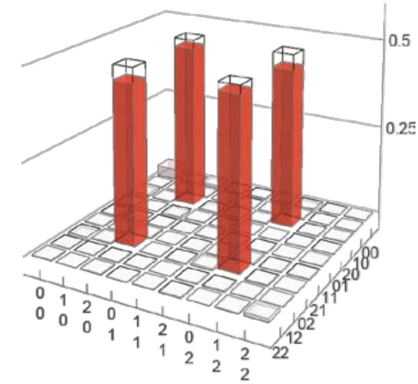
Full state tomography and Wigner functions of propagating photons



Eichler *et al., PRL* 106, 220503 (2011)

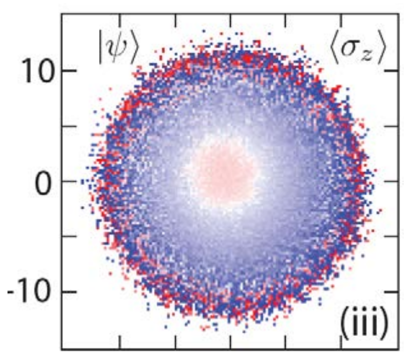
Hong-Ou-Mandel: Two-photon interference incl. msrmnt of coherences at microwave freq.

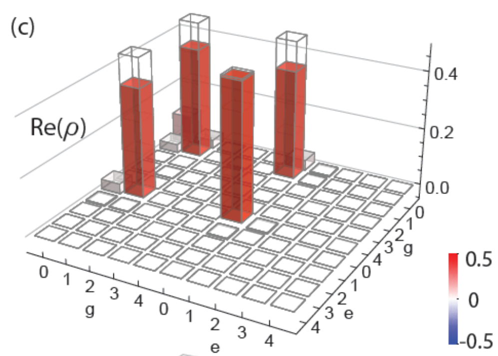




Lang *et al.*, *Nat. Phys.* 9, 345 (2013)

Preparation and characterization of qubit-propagating photon entanglement

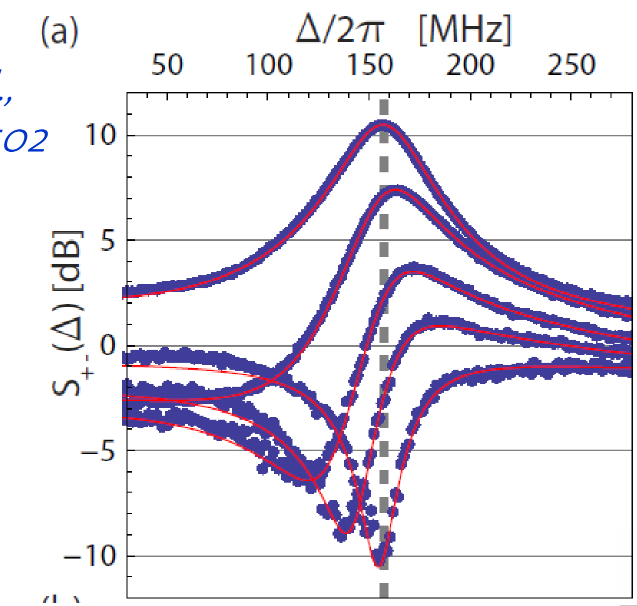




Eichler *et al., PRL* 109, *240501* (2012)
Eichler *et al., PRA* 86, 032106 (2012)

Squeezing in a Josephson parametric dimer

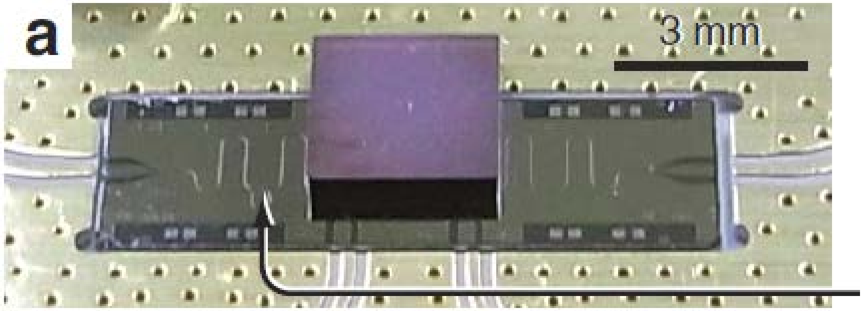
Eichler *et al., PRL* 113, *110502* (2014)



Hybrid Systems with Superconducting Circuits

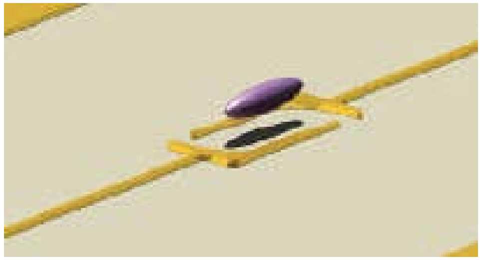
Spin Ensembles: e.g. NV centers

D. Schuster *et al.*, *PRL* 105, 140501 (2010)
Y. Kubo *et al.*, *PRL* 105, 140502 (2010)



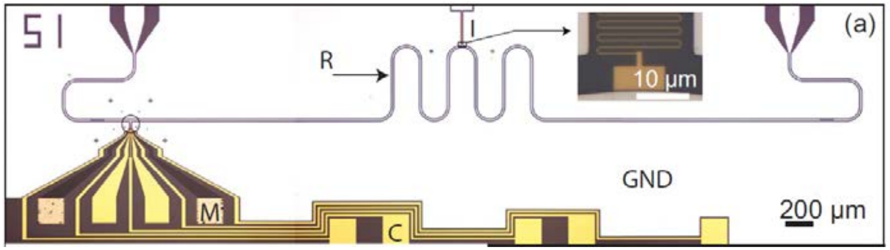
Polar Molecules, Rydberg, BEC

P. Rabl *et a*l, *PRL* 97, 033003 (2006)
A. Andre *et a*l, *Nat. Phys.* 2, 636 (2006)
D. Petrosyan *et al*, *PRL* 100, 170501 (2008)
J. Verdu *et al*, *PRL* 103, 043603 (2009)



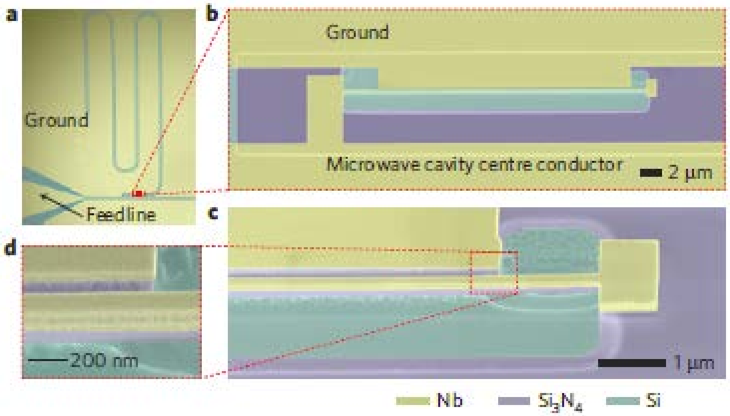
CNT, Gate Defined 2DEG, or nanowire Quantum Dots

M. Delbecq *et al.*, *PRL* 107, 256804 (2011)
T. Frey *et al.*, *PRL* 108, 046807 (2012)
K. Petersson *et al.*, *Nature* 490, 380 (2013)



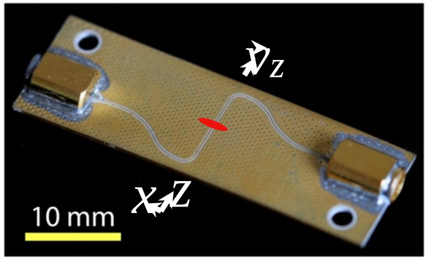
Nano-Mechanics

J. Teufel *et al.*, *Nature* 475, 359 (2011)
X. Zhou *et al.*, *Nat. Phys.* 9, 179(2013)



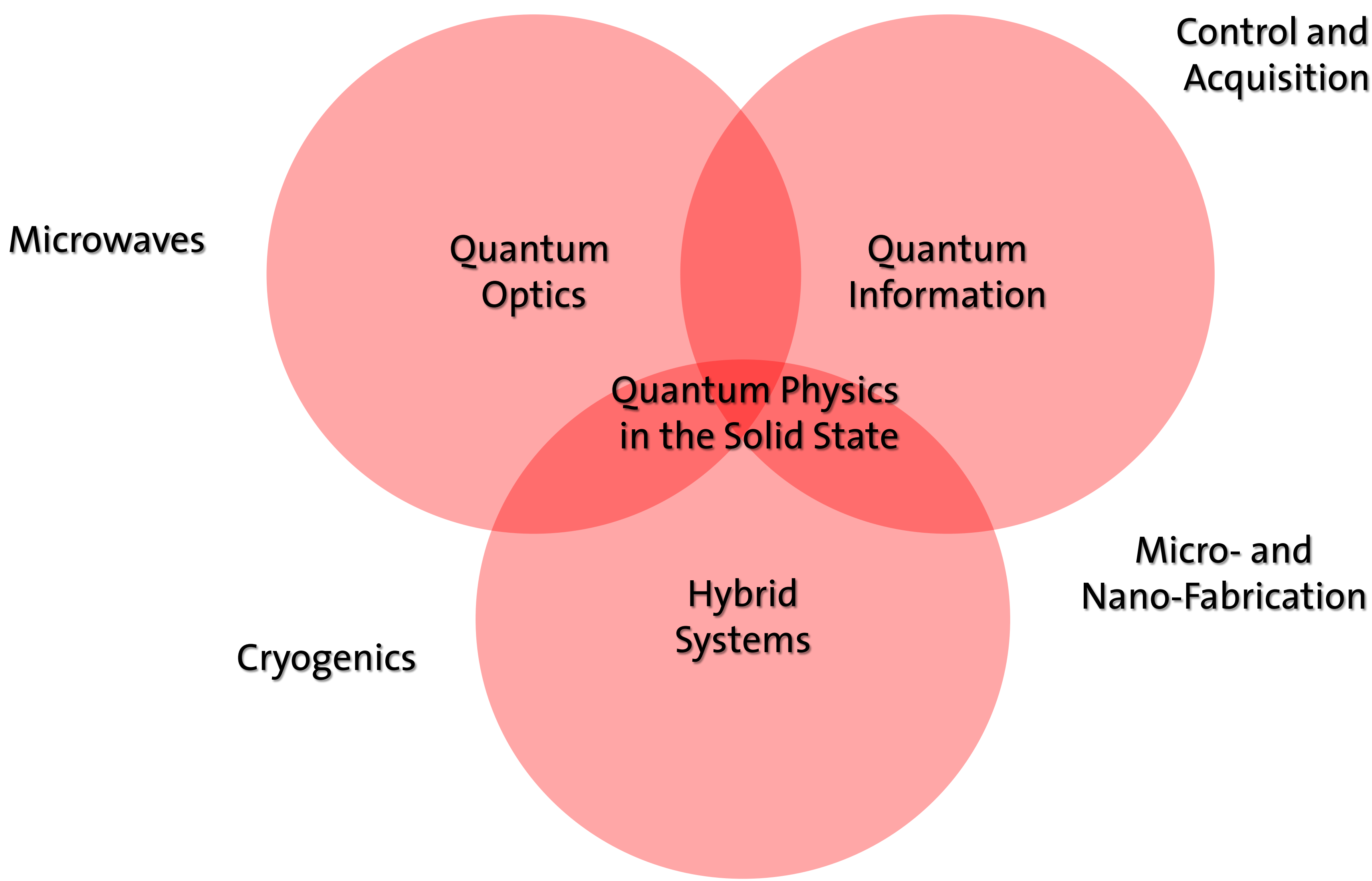
Rydberg Atoms

S. Hogan *et al.*, *PRL* 108, 063004 (2012)



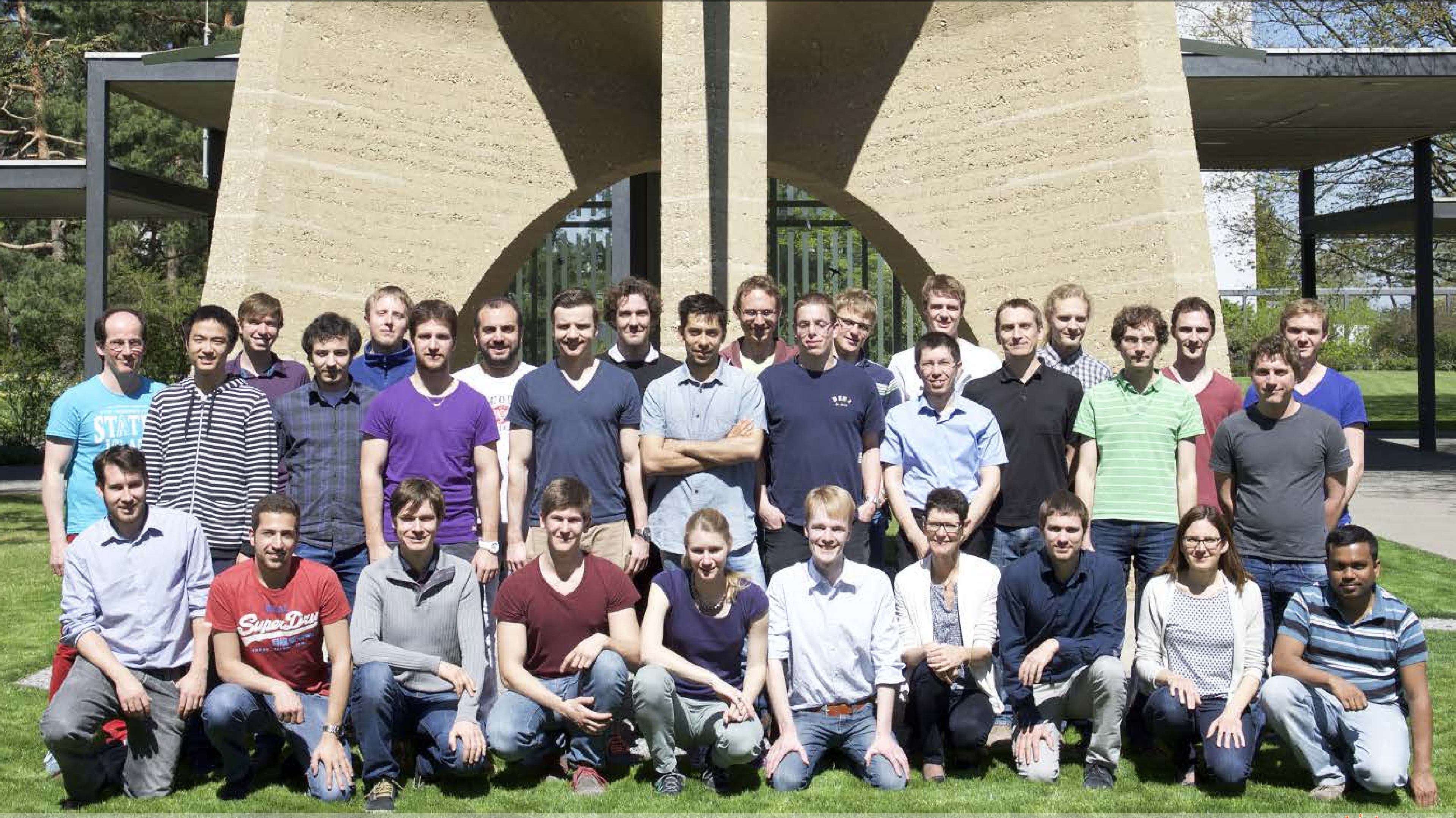
... and many more

Circuit QED Research



The ETH Zurich Quantum Device Lab

incl. undergrad and summer students



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