Quantum Interfaces based on Superconducting Electronic Circuits

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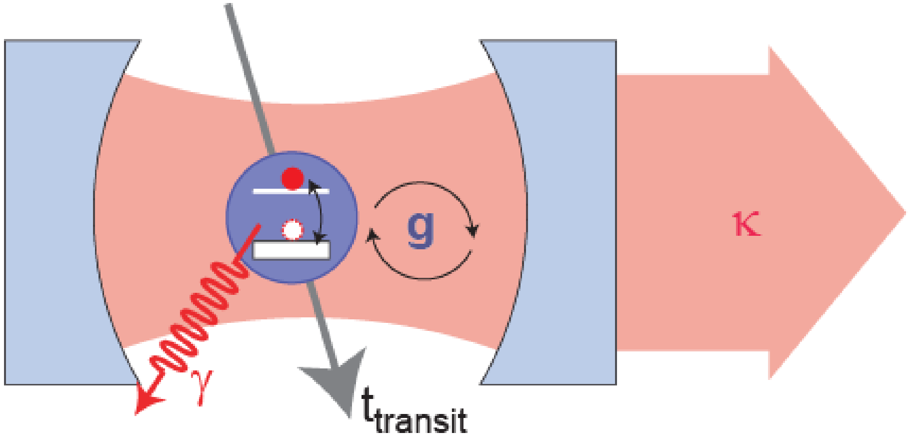
Material from colleagues at:
Yale, CEA Saclay, UCSB, Chalmers, TU Delft

SEVENTH FRAMEWORK PROGRAMME
QED
CIRCUIT AND CAVITY QUANTUM ELECTRODYNAMICS
SOLID
GEOMDISS
aqute
erc
QSIT Quantum Science and Technology
National Centre of Competence in Research
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
FNSNF
Swiss National Science Foundation

Cavity QED with Superconducting Circuits

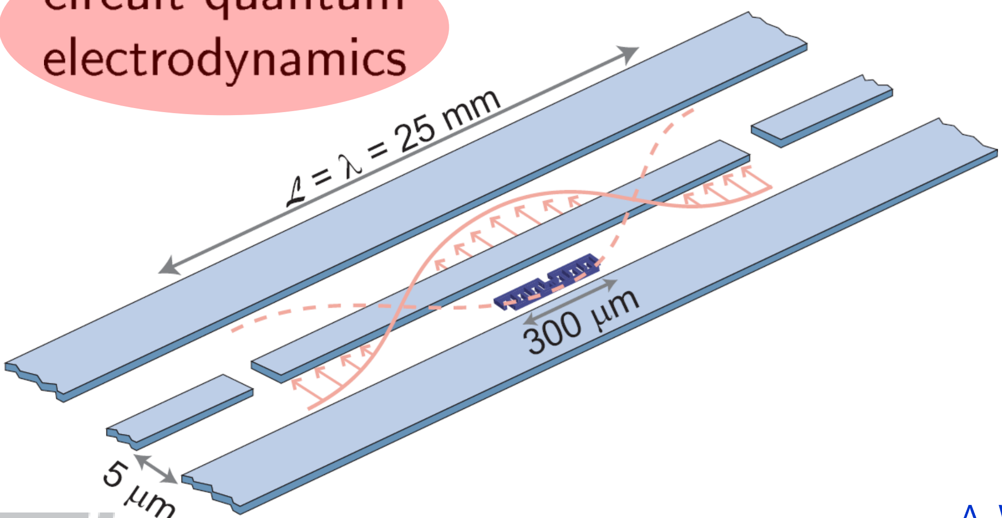


coherent interaction of photons with quantum two-level systems ...

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)

... in superconducting circuits

circuit quantum electrodynamics

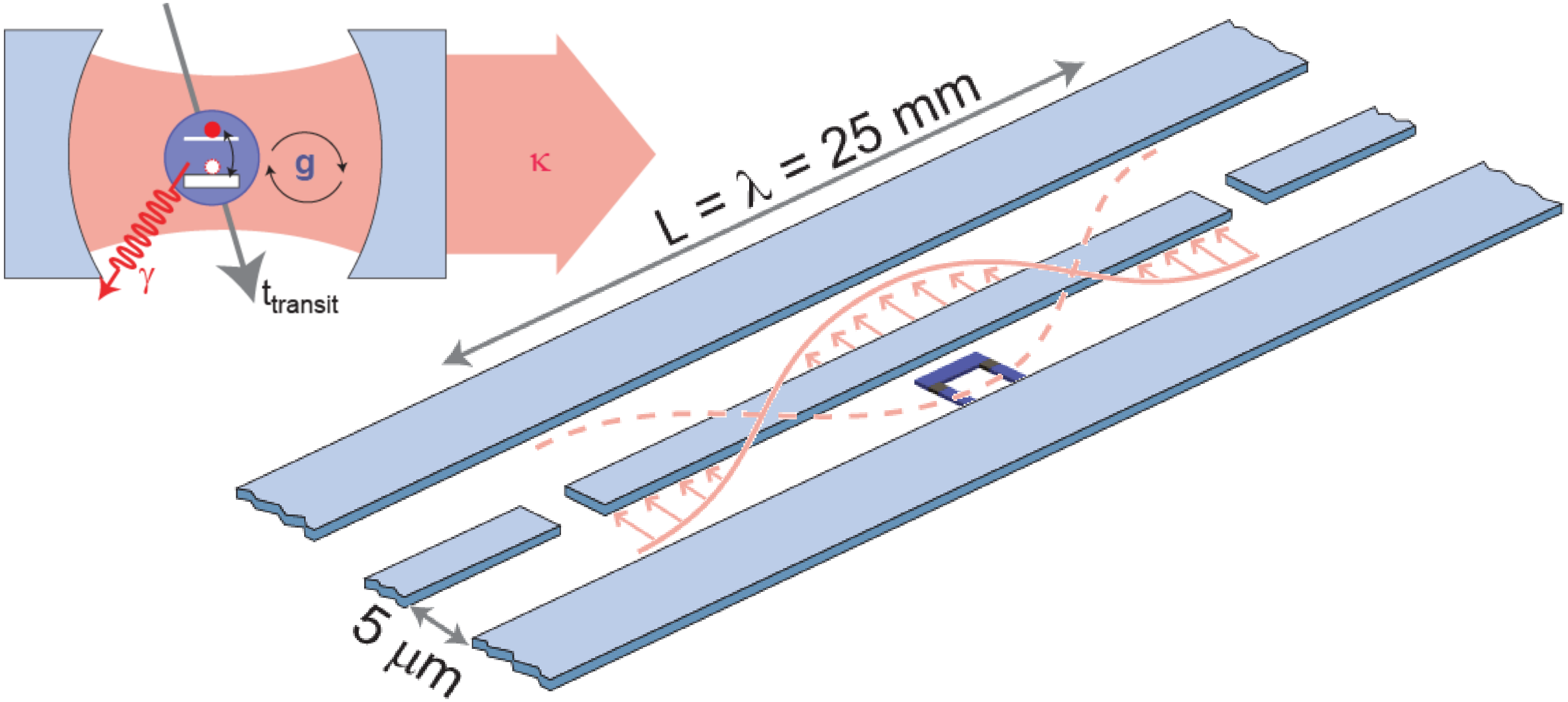


Properties:

- solid state based
- large field per photon
- ‘easy’ to fabricate and integrate
- suitable for quantum interfaces

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)

Circuit Quantum Electrodynamics



elements:

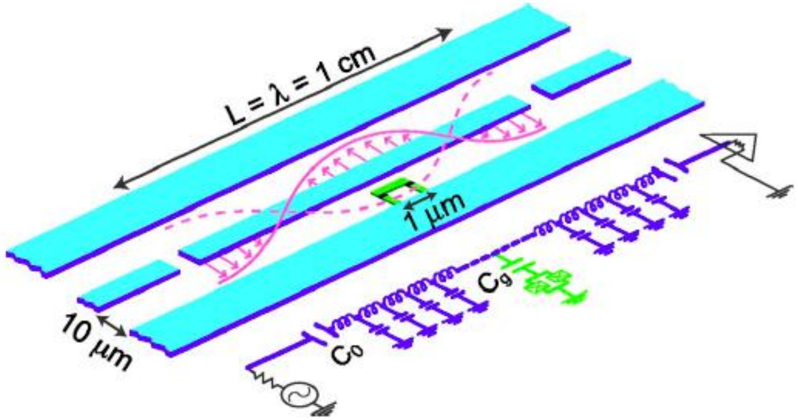
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a superconducting qubit with large dipole moment d and long coherence time $1/\gamma$ and fixed position

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

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

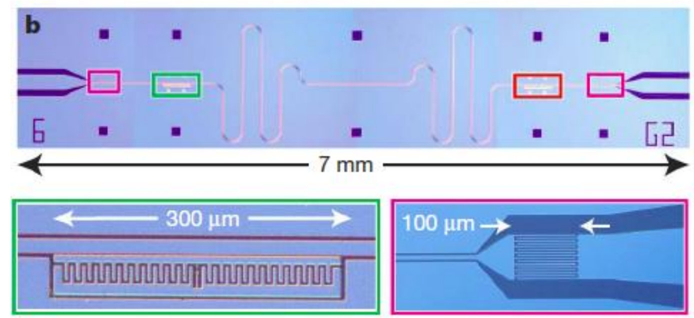
R. J. Schoelkopf, S. M. Girvin, *Nature (London)* **451**, 664 (2008)

Quantum Computing with Superconducting Circuits



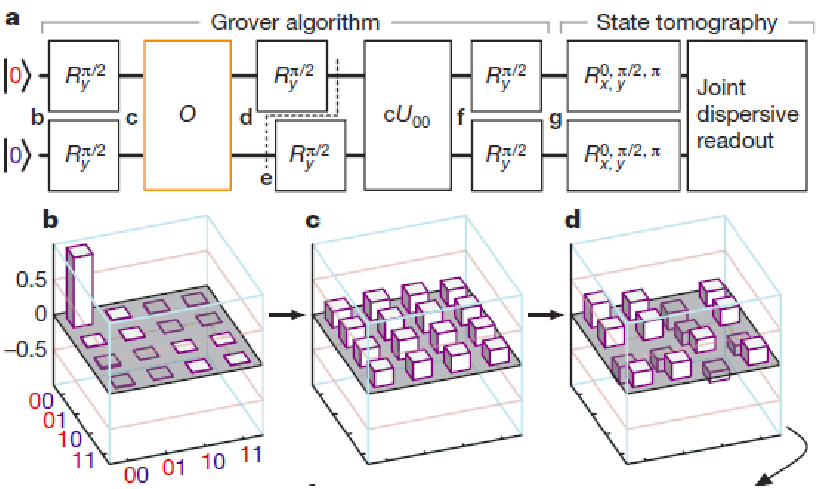
Circuit QED Architecture

A. Blais et al., *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature* **431**, 162 (2004)
M. Mariantoni *et al.*, *Science* **334**, 61 (2011)



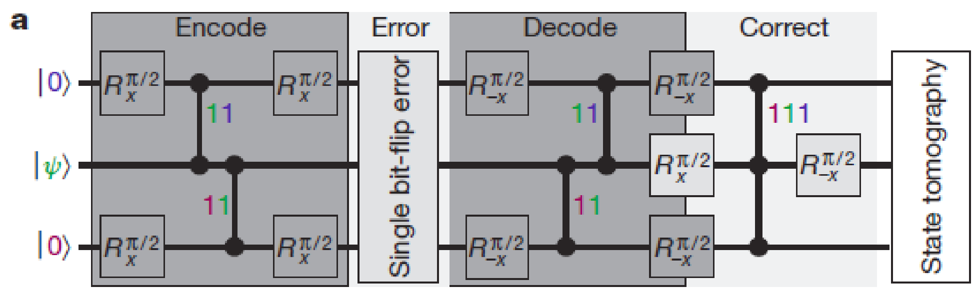
Resonator as a Coupling Bus

M. Sillanpaa *et al.*, *Nature* **449**, 438 (2007)
H. Majer *et al.*, *Nature* **449**, 443 (2007)



Deutsch, Grover Algorithms

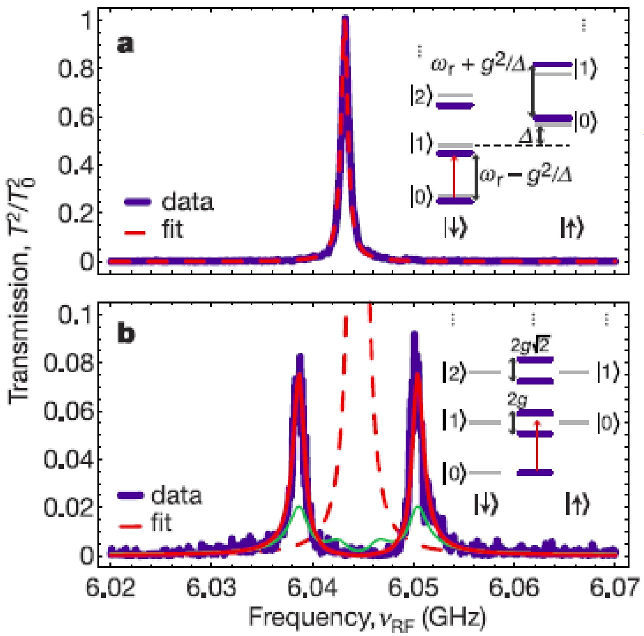
L. DiCarlo *et al.*, *Nature* **460**, 240 (2009)
L. DiCarlo *et al.*, *Nature* **467**, 574 (2010)



Toffoli Gates & Error Correction

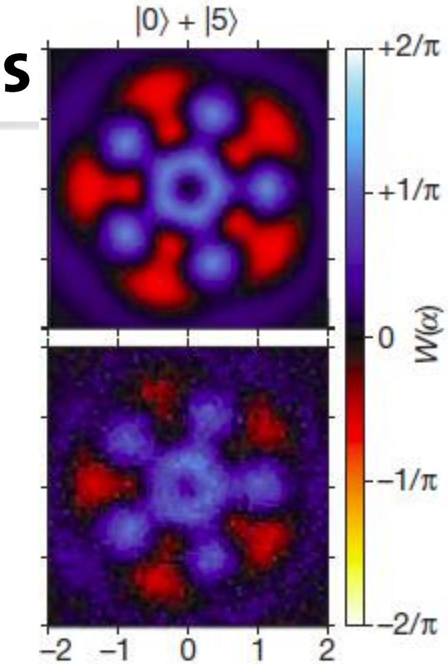
A. Fedorov *et al.*, *Nature* **481**, 170 (2012)
M. Reed *et al.*, *Nature* **481**, 382 (2012)

Quantum Optics with Supercond. Circuits



Strong Coherent Coupling

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

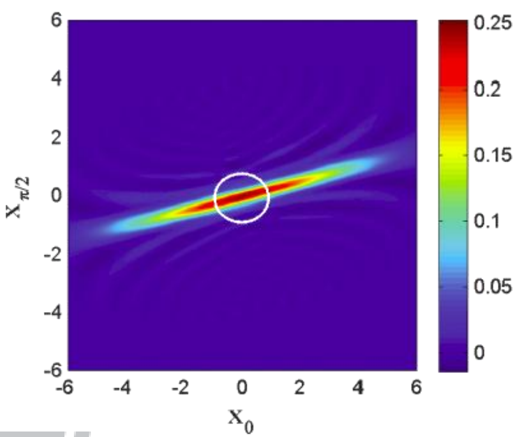


Root n Nonlinearities

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

Fock and Arbitrary Photon States

M. Hofheinz *et al.*, *Nature* **454**, 310 (2008)
M. Hofheinz *et al.*, *Nature* **459**, 546 (2009)

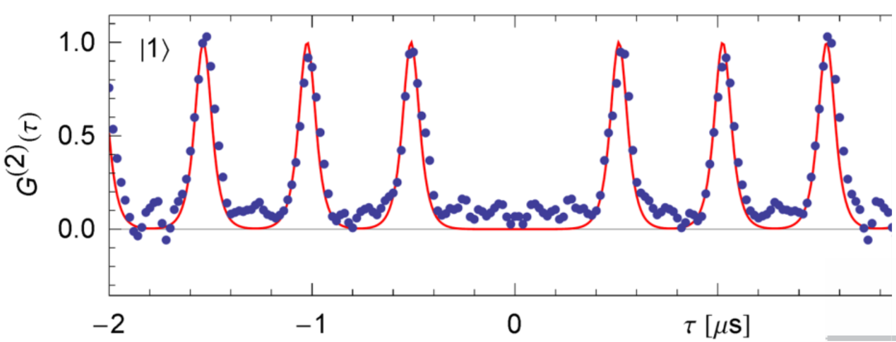


Parametric Amplification & Squeezing

Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 928 (2008)

Single Photons & Correlations

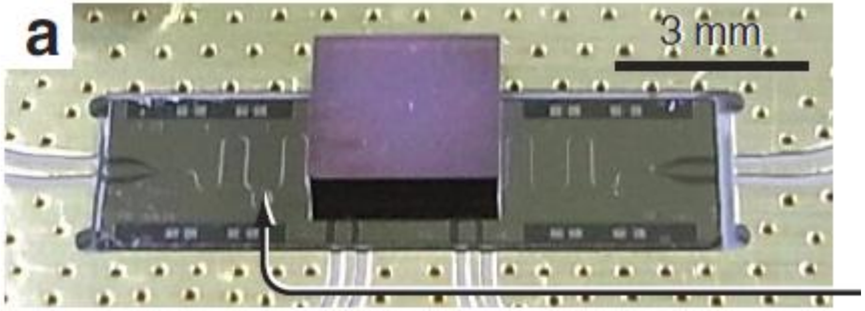
A. Houck *et al.*, *Nature* **449**, 328 (2007)
D. Bozyigit *et al.*, *Nat. Phys.* **7**, 154 (2011)



Hybrid Systems with Superconducting Circuits

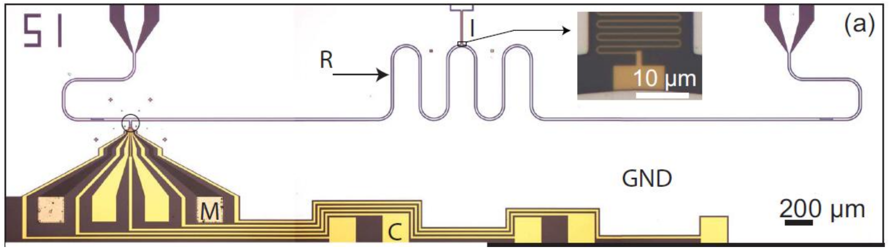
Spin Ensembles: e.g. NV centers

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



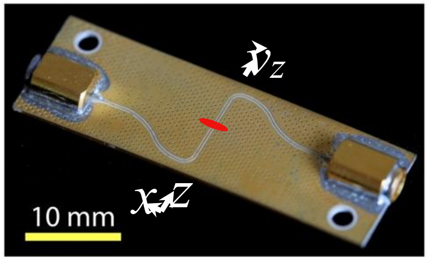
CNT, Gate Defined 2DEG, or nanowire Quantum Dots

M. Delbecq *et al.*, *PRL* **107**, 256804 (2011)
T. Frey *et al.*, *PRL* **108**, 046807 (2012)
K. Petersson *et al.*, *arXiv*:1205.6767 (2012)



Rydberg Atoms

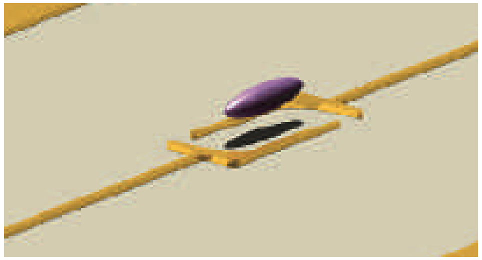
S. Hogan*et al.*, *PRL* **108**, 063004 (2012)



Proposals:

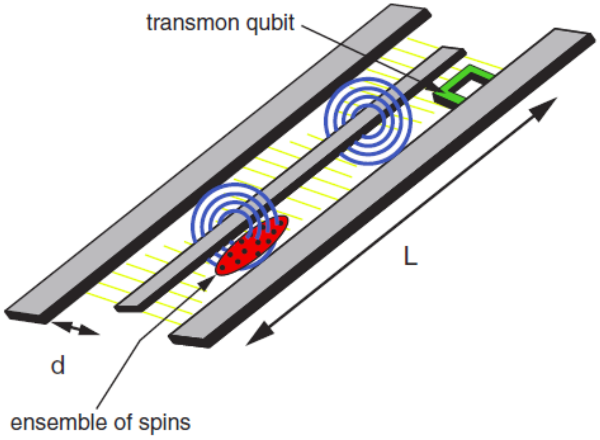
Polar Molecules, Rydberg, BEC

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



Spin Ensembles

A. Imamoglu *et al.*, *PRL* **102**, 083602 (2009)
J. Wesenberg *et al.*, *PRL* **103**, 070502 (2009)



... and many more

Lecture Topics

I. Quantum Mechanics of Superconducting Electronic Circuits

II. Circuit Quantum Electrodynamics (QED)

III. Exploring Matter/Light Interactions in Circuit QED

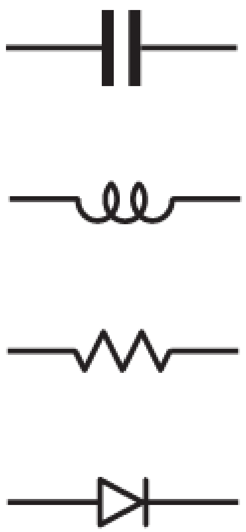
IV. Characterizing Propagating Microwave Photons

V. Interfaces between Superconducting Circuits and Quantum Dots or Rydberg Atoms

Quantum Mechanics of
Superconducting Electronic Circuits

Conventional Electronic Circuits

basic circuit elements:

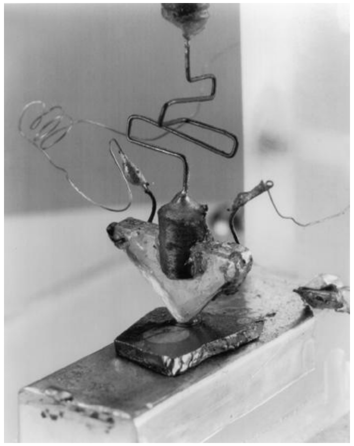


basis of modern information and communication technology

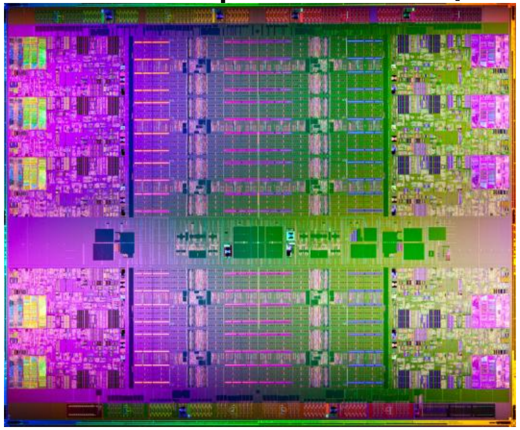
properties :

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

first transistor at Bell Labs (1947)



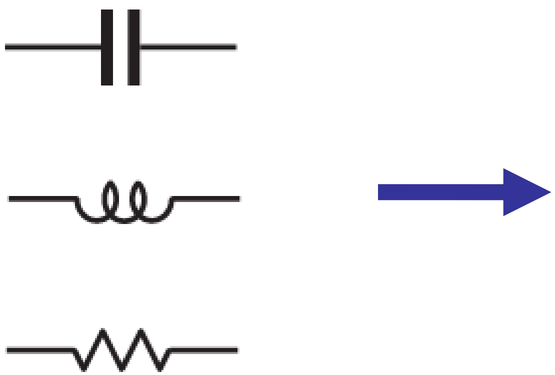
intel xeon processors (2011)



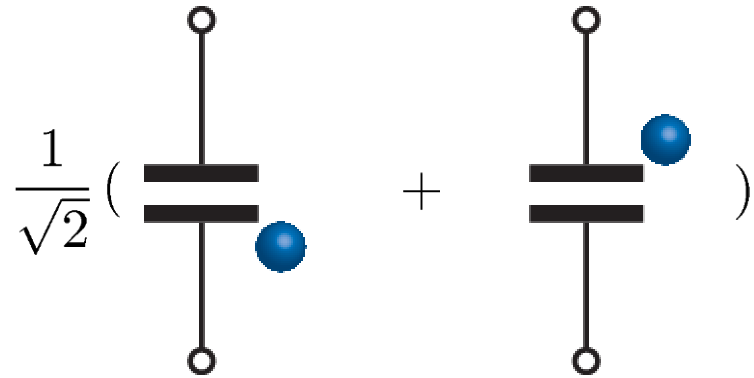
3.000.000.000 transistors
smallest feature size 32 nm
clock speed ~ 3 GHz
power consumption 10 W

Classical and Quantum Electronic Circuit Elements

basic circuit elements:



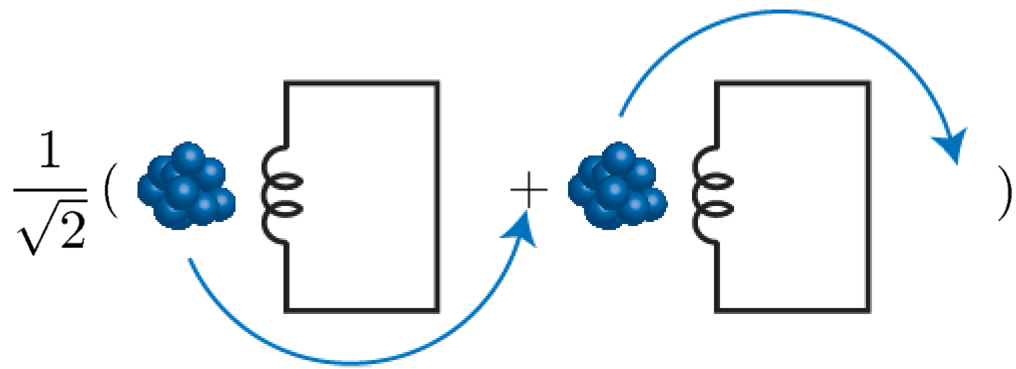
charge on a capacitor:



quantum superposition states of:

- charge q
- flux ϕ

current or magnetic flux in an inductor:

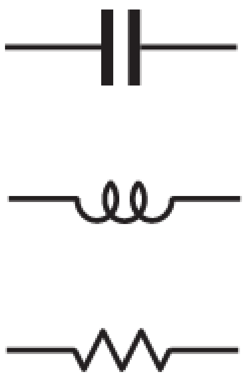


commutation relation (c.f. *x*, *p*):

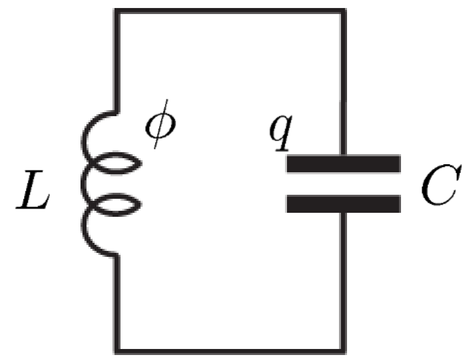
$$\left[\hat{\phi}, \hat{q}\right] = i\hbar$$

Constructing Linear Quantum Electronic Circuits

basic circuit elements:



harmonic LC oscillator:



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

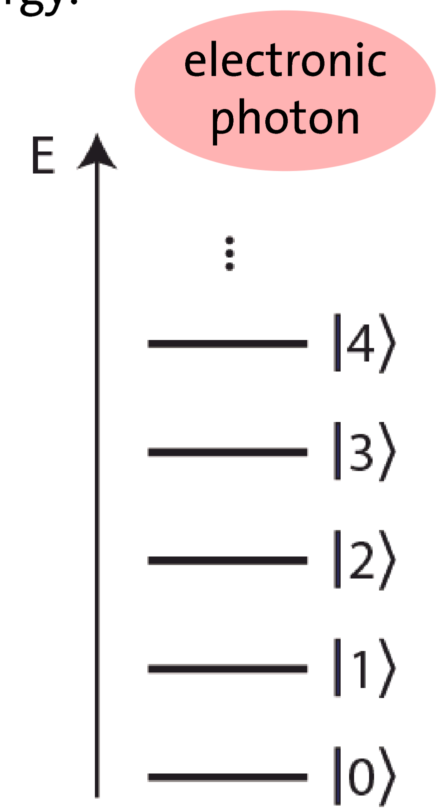
classical physics:

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

quantum mechanics:

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

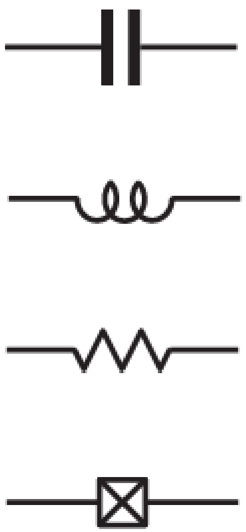
energy:



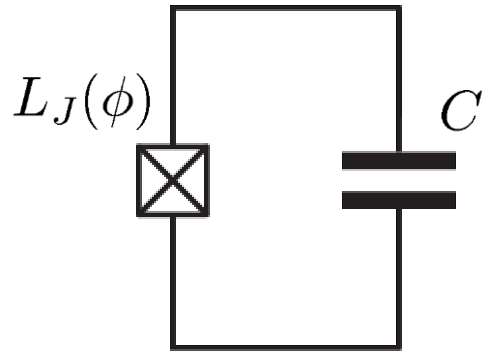
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

Constructing Non-Linear Quantum Electronic Circuits

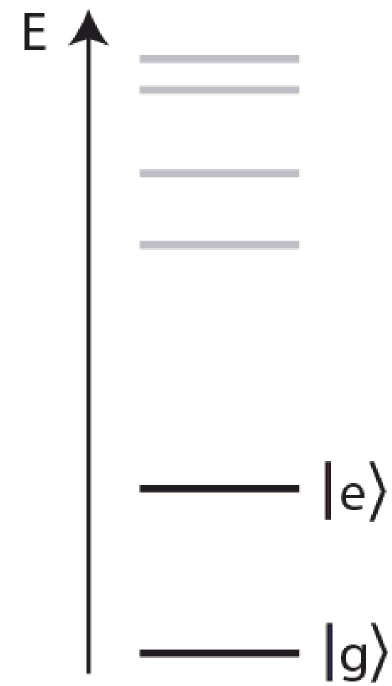
circuit elements:



anharmonic oscillator:



non-linear energy level spectrum:



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

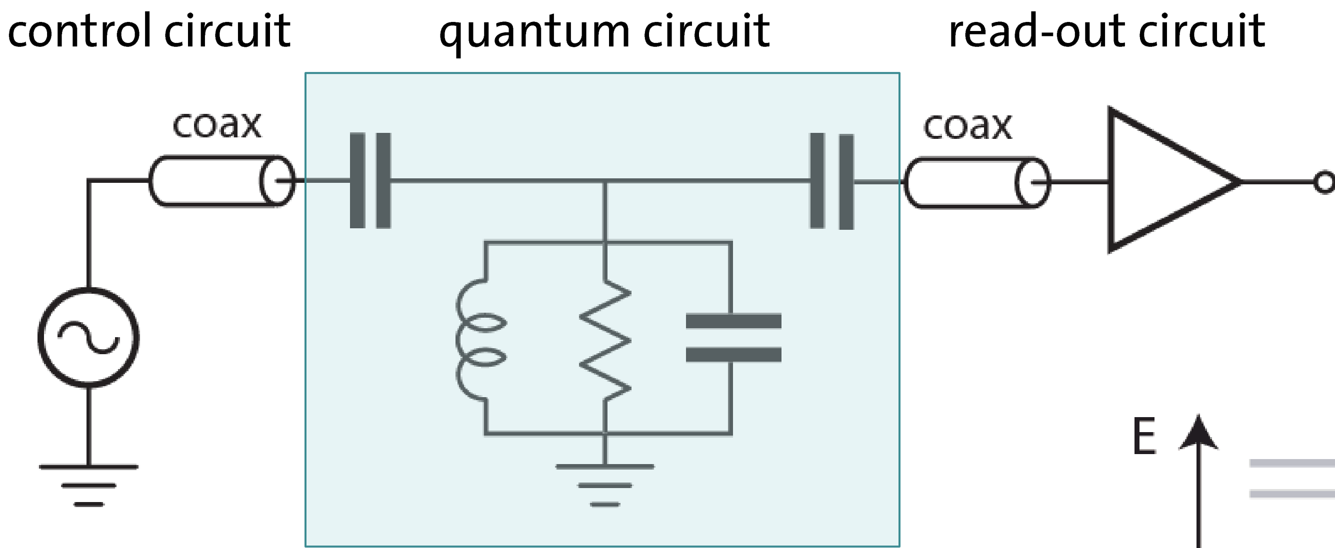
$$L_J(\phi) = \left(\frac{\partial I}{\partial \phi}\right)^{-1}$$

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

electronic artificial atom

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

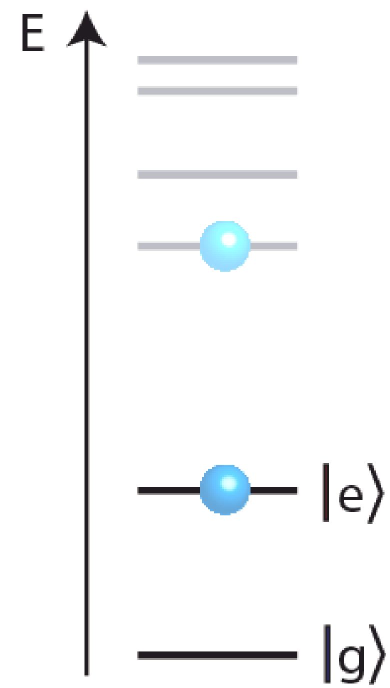
How to Operate Circuits in the Quantum Regime?



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

recipe:

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



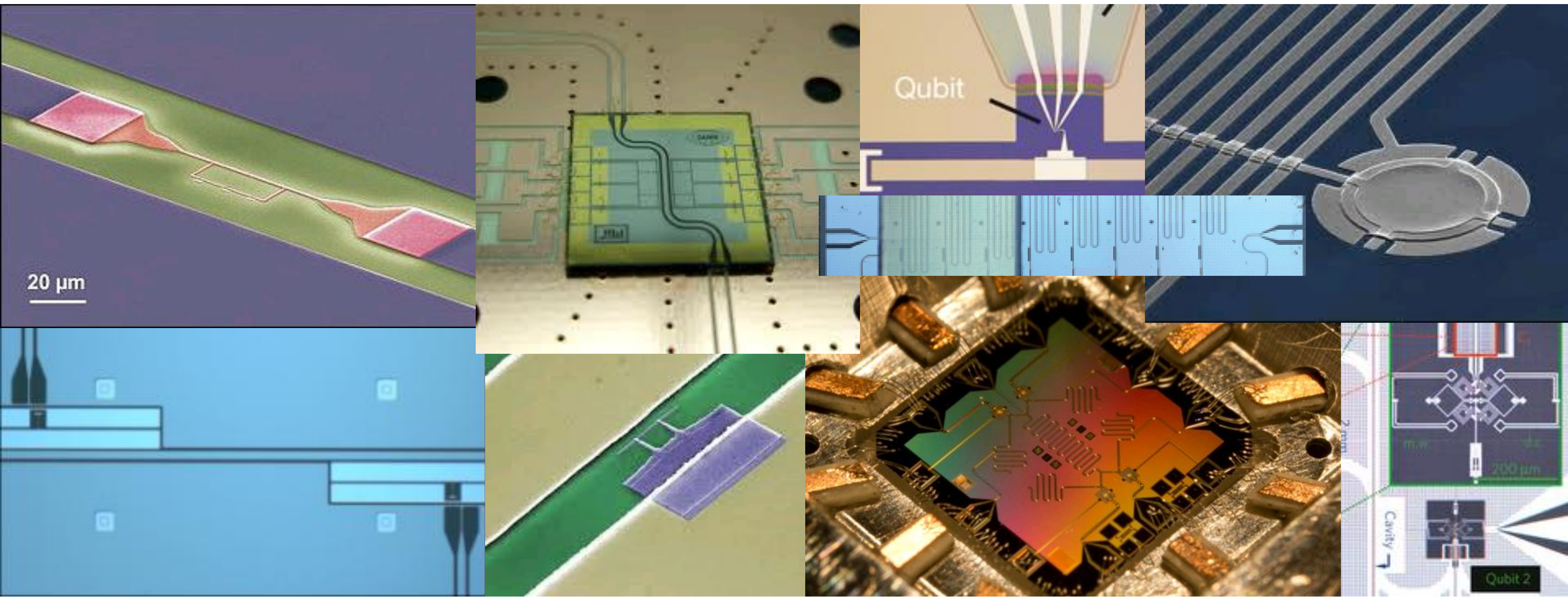
Can one actually build and operate such circuits?

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

Superconducting Quantum Electronic Circuits

single or multiple superconducting qubits coupled to harmonic oscillators

- investigated in a few dozen labs around the world
- for basic science and applications



reviews:

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

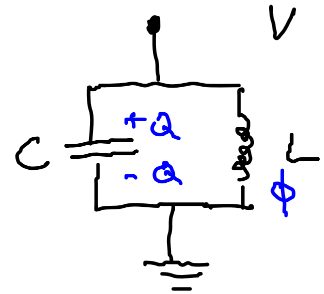
J. Clarke and F. Wilhelm, *Nature* **453**, 1031 (2008)

J. Q. You and F. Nori, *Nature* **474**, 589 (2011)

Electronic Harmonic Oscillators

Quantization of the electrical LC harmonic oscillator:

parallel LC oscillator circuit:



voltage across the oscillator:

$$V = \frac{Q}{C} = -L\frac{\partial I}{\partial t}$$

total energy (Hamiltonian): $H = \frac{1}{2} C V^2 + \frac{1}{2} L I^2 = \frac{1}{2}\frac{Q^2}{C} + \frac{1}{2}\frac{\phi^2}{L}$

with the charge Q stored on the capacitor $\quad Q = VC$

a flux ϕ stored in the inductor $\quad \phi = LI$

properties of Hamiltonian written in variables Q and ϕ:

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

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

Q and ϕ are canonical variables

see e.g.: Goldstein, Classical Mechanics, Chapter 8, Hamilton Equations of Motion

Quantum version of Hamiltonian

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

with commutation relation

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

compare with particle in a harmonic potential:

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2} m \omega^2 \hat{x}^2$$

analogy with electrical oscillator:

- charge Q corresponds to momentum p
- flux ϕ corresponds to position x

$$[\hat{x}, \hat{p}] = [\hat{x}, -i\hbar \frac{\partial}{\partial x}] = i\hbar$$

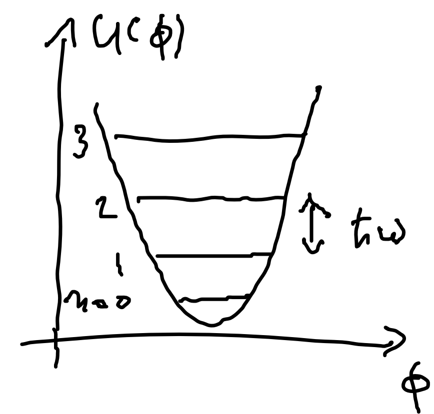
$$[\hat{\phi}, \hat{Q}] = [\hat{\phi}, -i\hbar \frac{\partial}{\partial \phi}] = i\hbar$$

Hamiltonian in terms of raising and lowering operators:

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

with oscillator resonance frequency:

$$\omega = \frac{1}{\sqrt{LC}}$$



Raising and lowering operators:

$$a^\dagger |n\rangle = \sqrt{n+1}\, |n+1\rangle \quad ; \quad \hat{a}\, |n\rangle = \sqrt{n}\, |n-1\rangle$$

$$a^\dagger a\, |n\rangle = n\, |n\rangle$$ number operator

in terms of Q and ϕ:

$$\hat{a} = \frac{1}{\sqrt{2\hbar Z_c}} \left(Z_c \hat{Q} + i \hat{\phi} \right)$$

with Z_c being the characteristic impedance of the oscillator $Z_c = \sqrt{\frac{L}{C}}$

charge Q and flux ϕ operators can be expressed in terms of raising and lowering operators:

$$\hat{Q} = \sqrt{\frac{\hbar}{2 Z_c}} \left(a^\dagger + a \right)$$

$$\hat{\phi} = i \sqrt{\frac{\hbar Z_c}{2}} \left(a^\dagger - a \right)$$

Exercise: Making use of the commutation relations for the charge and flux operators, show that the harmonic oscillator Hamiltonian in terms of the raising and lowering operators is identical to the one in terms of charge and flux operators.