超伝導量子回路における開放量子系の制御

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http://www.qc.rcast.u-tokyo.ac.jp

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General picture as non-equilibrium system

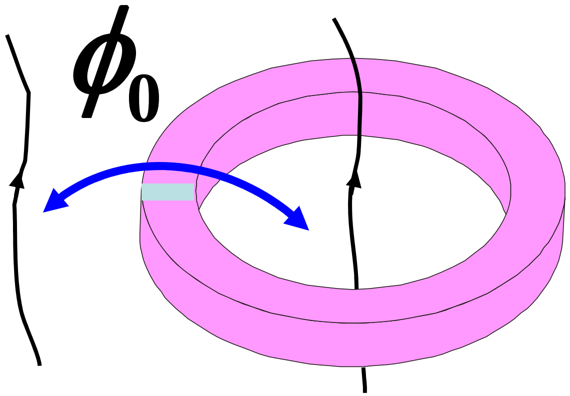
Outline

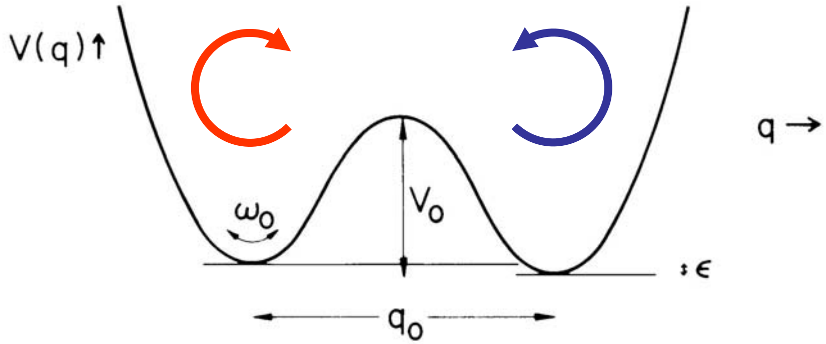
- Superconducting qubits as an artificial atom
- Decoherence and environment
  - Qubit as quantum spectrum analyzer
- Microwave quantum optics
  - Atoms in cavity
  - Atoms in 1D waveguide

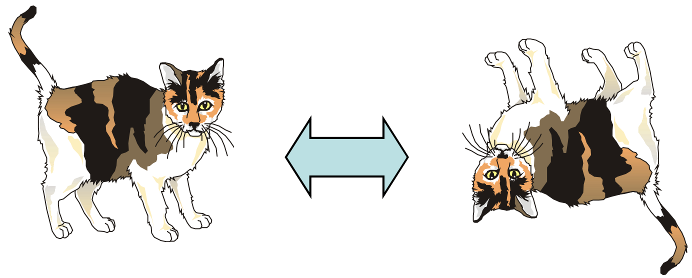
Macroscopic quantum coherence

A.J. Leggett, Prog. Theor. Phys. Suppl. 69, 80 (1980); Phys. Scr. T102, 69 (2002).

Does quantum mechanics hold in macroscopic systems?



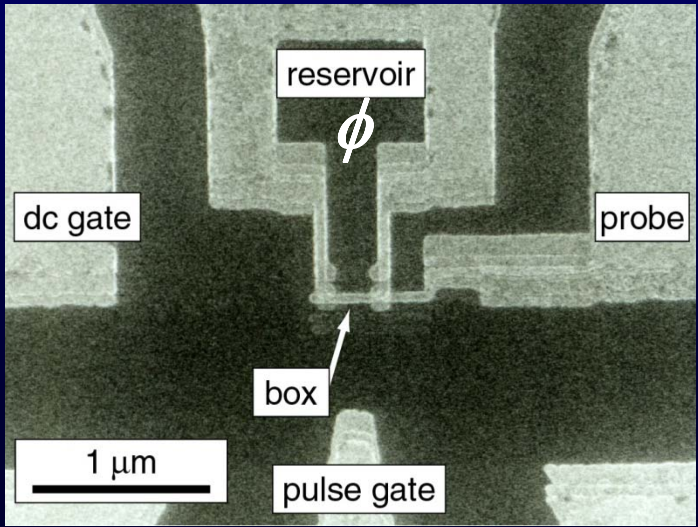


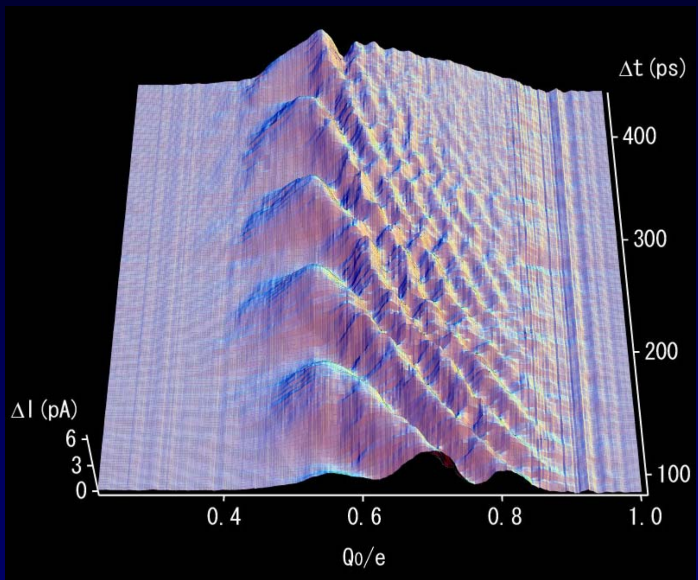


Schrödinger 1935

Superconducting qubits

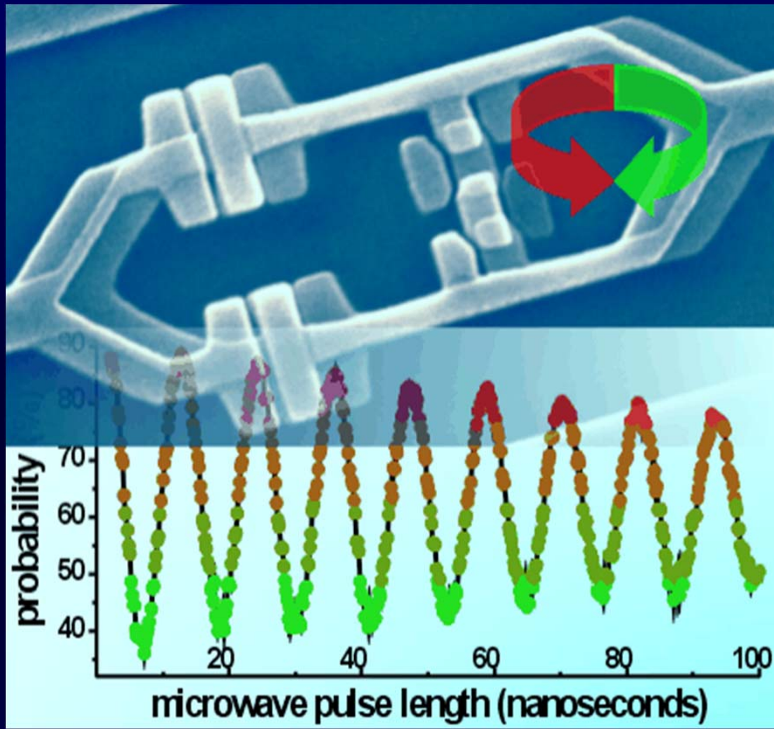
Charge qubit





Y. Nakamura et al. Nature (1999)

Flux qubit



Chiorescu, Nakamura, Harmans, Mooij, Science (2003)

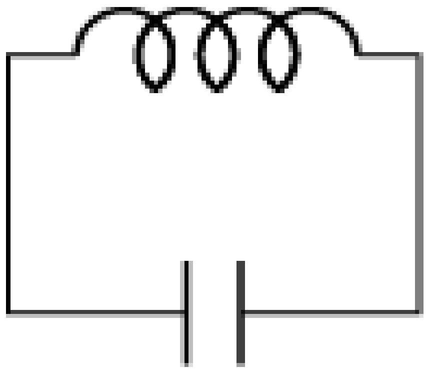
- Artificial two-level system in electric circuits
- Coherent control of quantum states in macroscopic systems

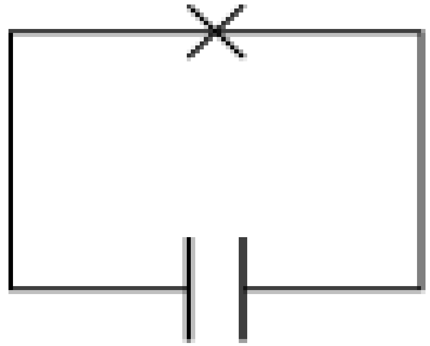
Superconducting qubit – nonlinear resonator

LC resonator

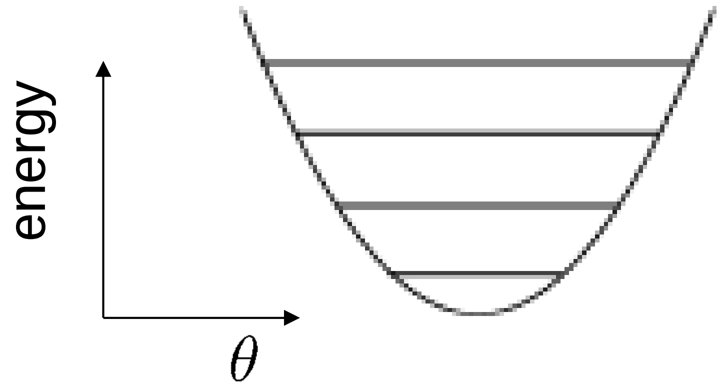
Josephson junction resonator

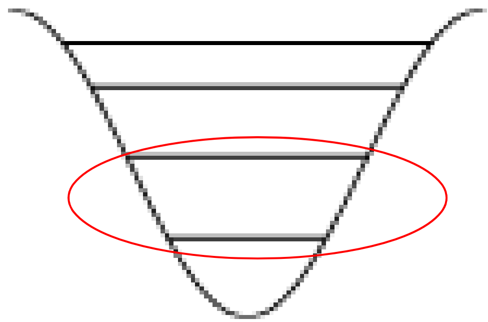
Josephson junction = nonlinear inductor





anharmonicity $\Rightarrow$ effective two-level system



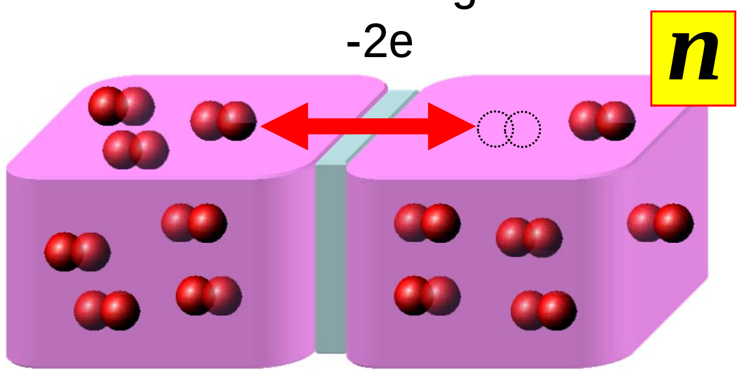


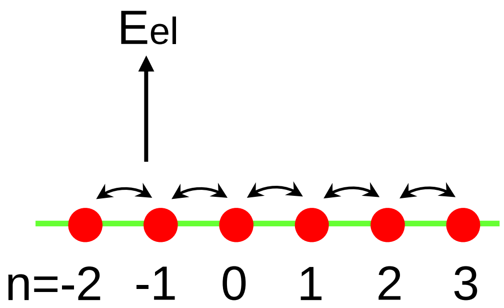
inductive energy = confinement potential
charging energy = kinetic energy $\Rightarrow$ quantized states

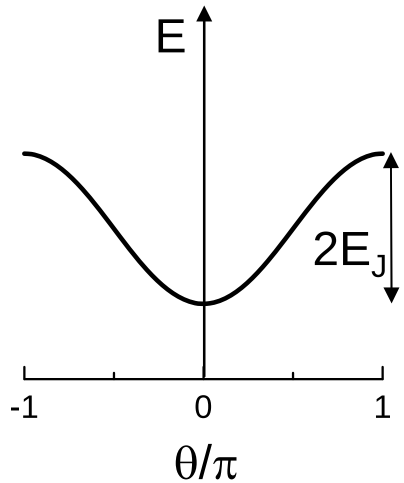
Josephson effect

B. D. Josephson 1962

number ***n*** ⇔ phase difference ***θ*** $[n, \theta] = -i$







$$H = -\frac{E_J}{2}\sum_n \{|n\rangle\langle n+1| + |n+1\rangle\langle n|\} = -\int_0^{2\pi} d\theta E_J \cos\theta |\theta\rangle\langle\theta|$$

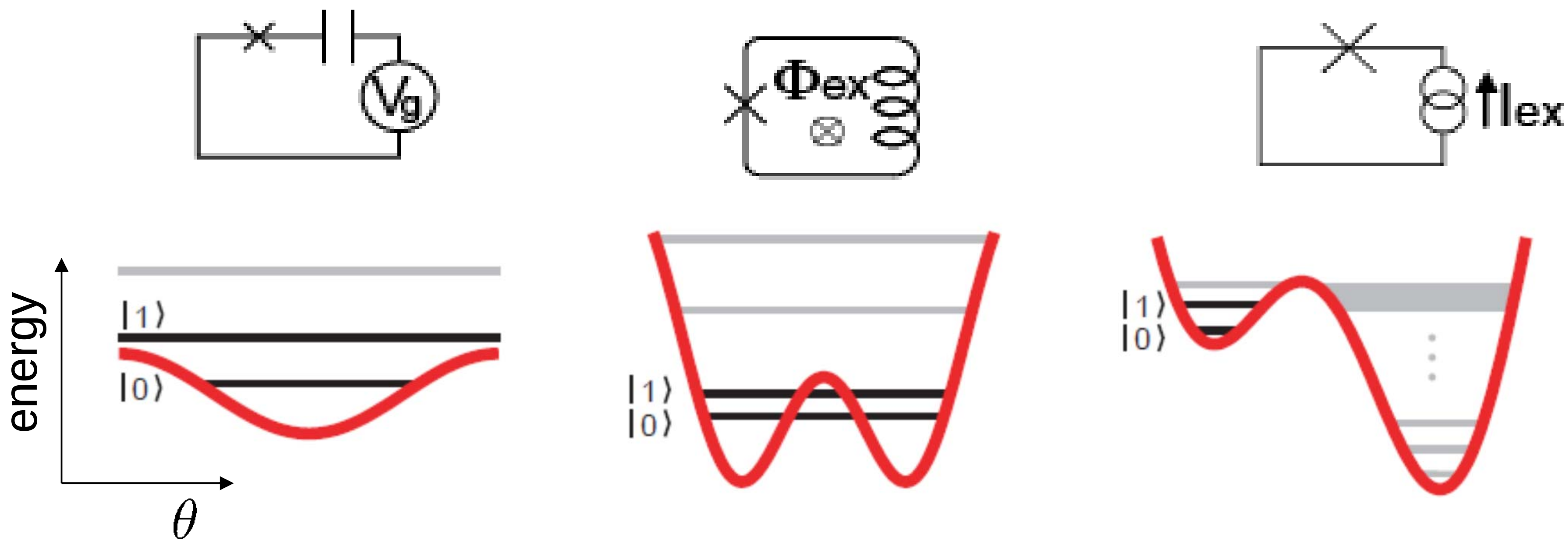
Tight-binding model in 1d lattice ⇒ Bloch band

$$|\theta\rangle = \sum_n e^{in\theta}|n\rangle$$

Superconducting qubits – artificial atoms in electric circuit

small ← E_J/E_C → large

Charge qubit | Flux qubit | Phase qubit



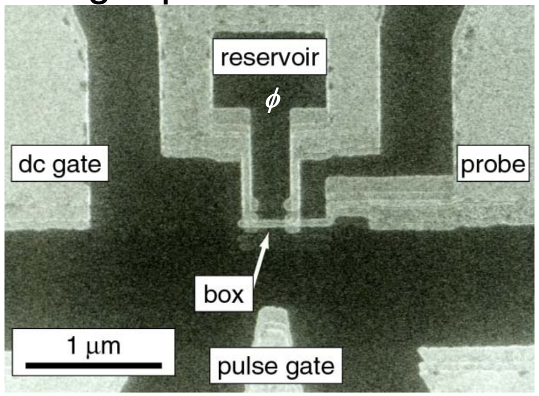
Josephson energy E_J = confinement potential
charging energy E_C = kinetic energy ⇒ quantized states

typical qubit energy $E_{01} \sim 10\,\mathrm{GHz} \sim 0.5\,\mathrm{K}$

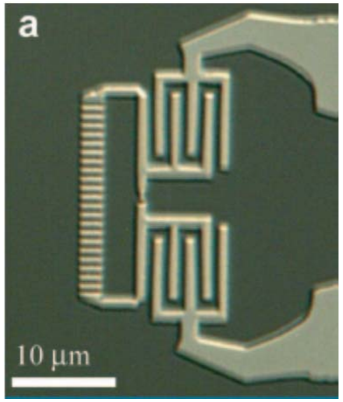
typical experimental temperature $T \sim 0.02\,\mathrm{K}$

Superconducting qubits – macroscopic artificial atom in circuits

charge qubit/NEC $E_J/E_C \sim 0.3$

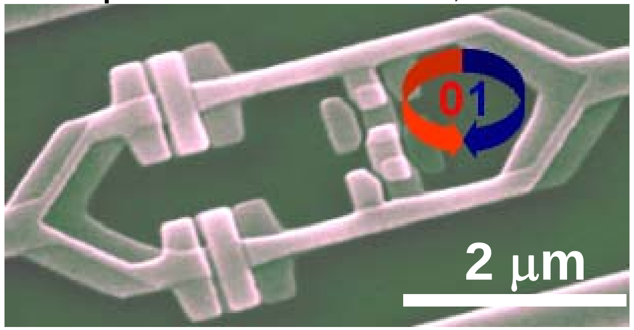


"fluxonium"/Yale

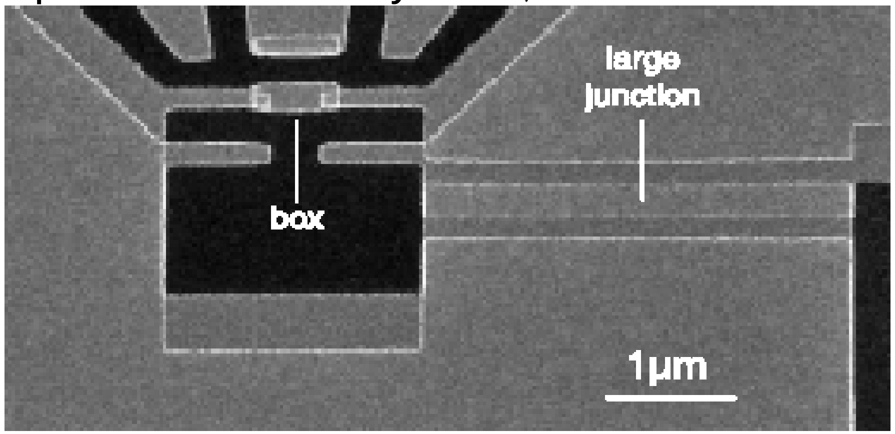


$E_J/E_C \sim 3$

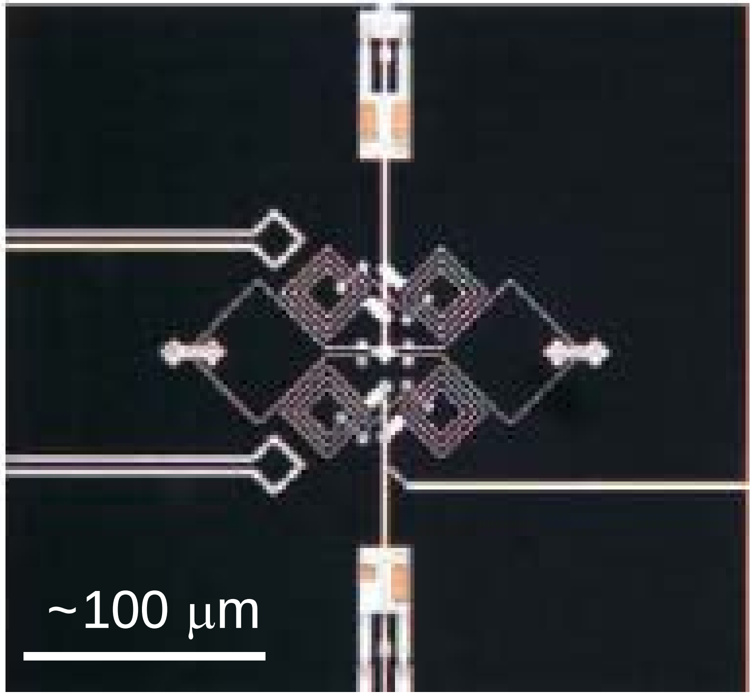
flux qubit/Delft $E_J/E_C \sim 40$



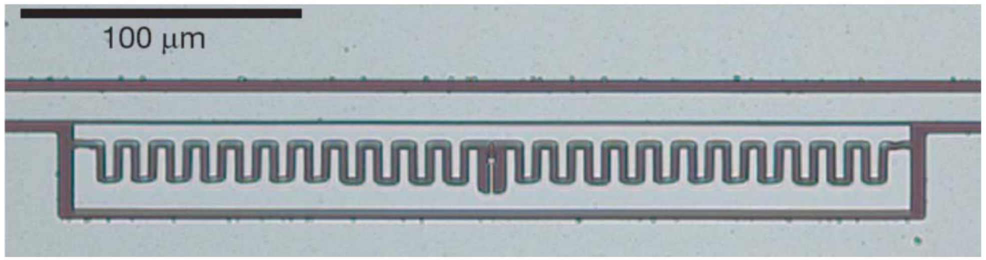
"quantronium"/Saclay $E_J/E_C \sim 5$



phase qubit/NIST/UCSB $E_J/E_C \sim 10^4$



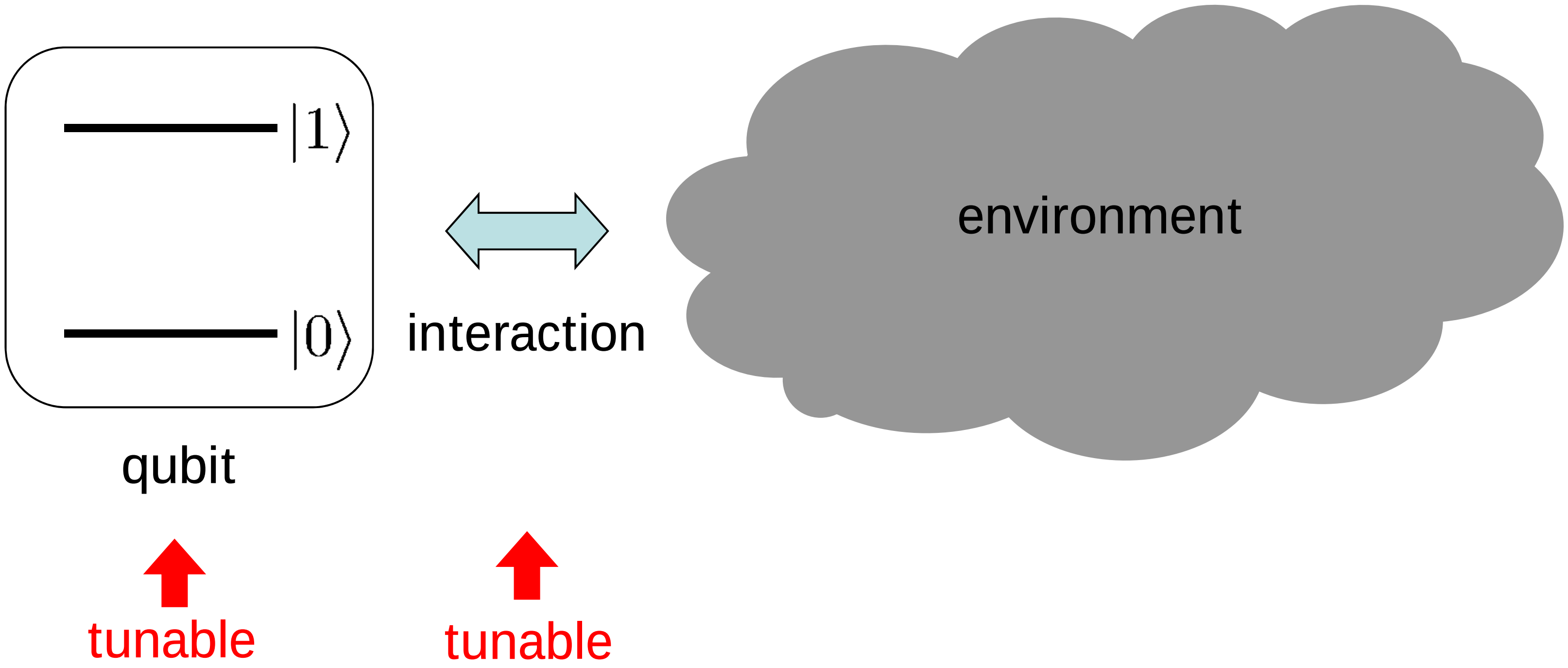
"transmon"/Yale $E_J/E_C \sim 50$



Decoherence

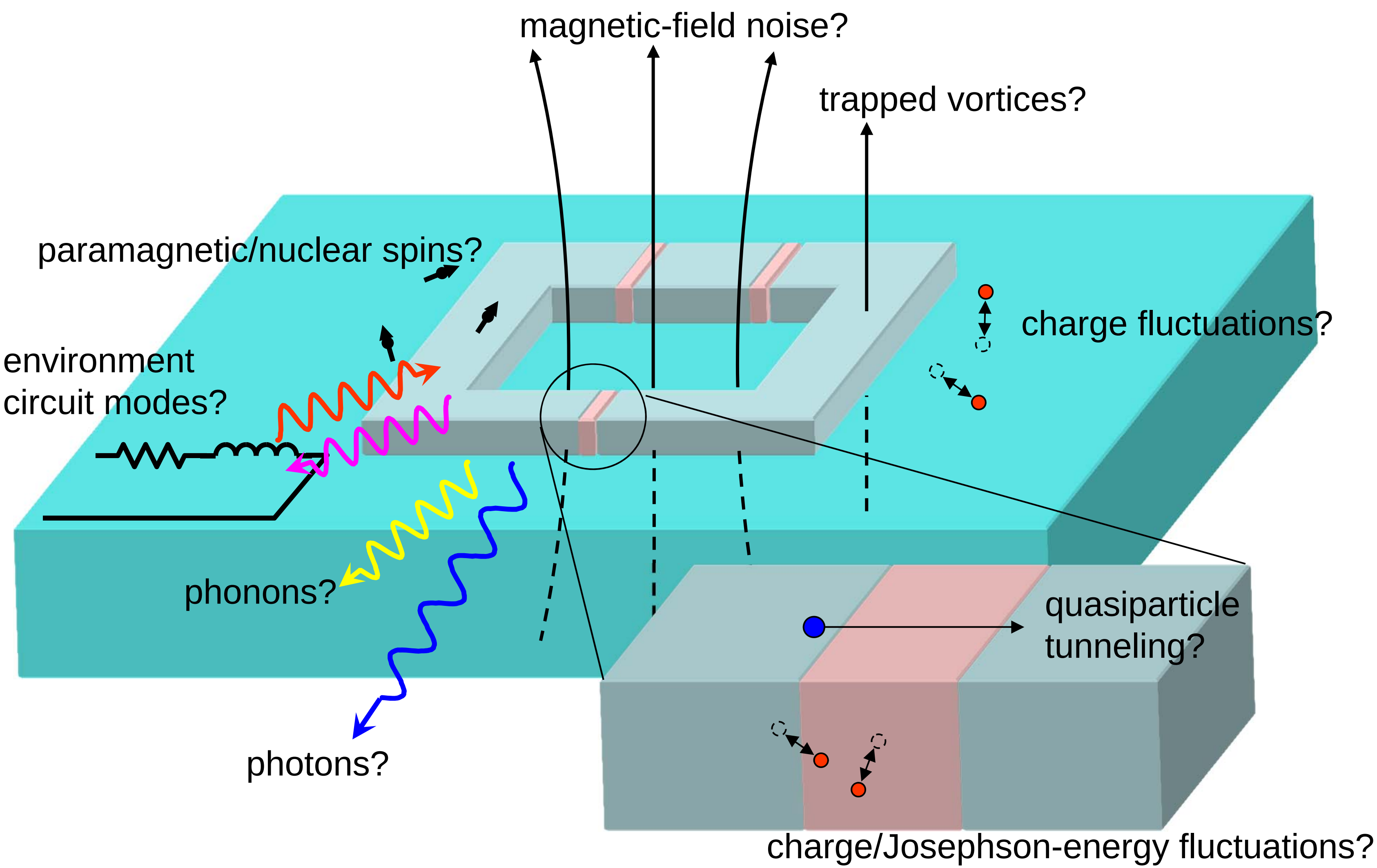
Loss of coherence due to coupling with uncontrolled environment

- dissipation
- dephasing



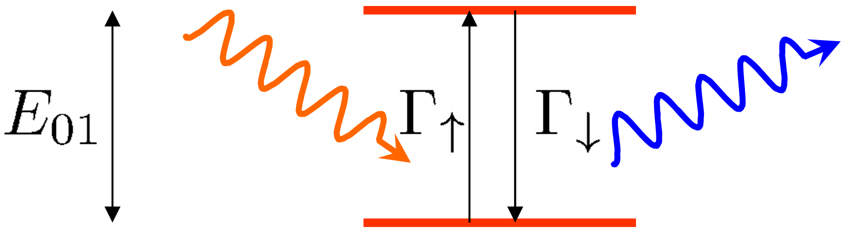
Qubit as a tool for characterization of environment

Possible decoherence sources



Energy relaxation

relaxation and excitation



$$\Gamma_\downarrow = \frac{2\pi}{\hbar^2}\left|\left\langle 0\left|\frac{\partial H_q}{\partial\lambda}\right|1\right\rangle\right|^2 S_\lambda\left(\frac{E_{01}}{\hbar}\right)$$

$$\Gamma_\uparrow = \frac{2\pi}{\hbar^2}\left|\left\langle 0\left|\frac{\partial H_q}{\partial\lambda}\right|1\right\rangle\right|^2 S_\lambda\left(-\frac{E_{01}}{\hbar}\right)$$

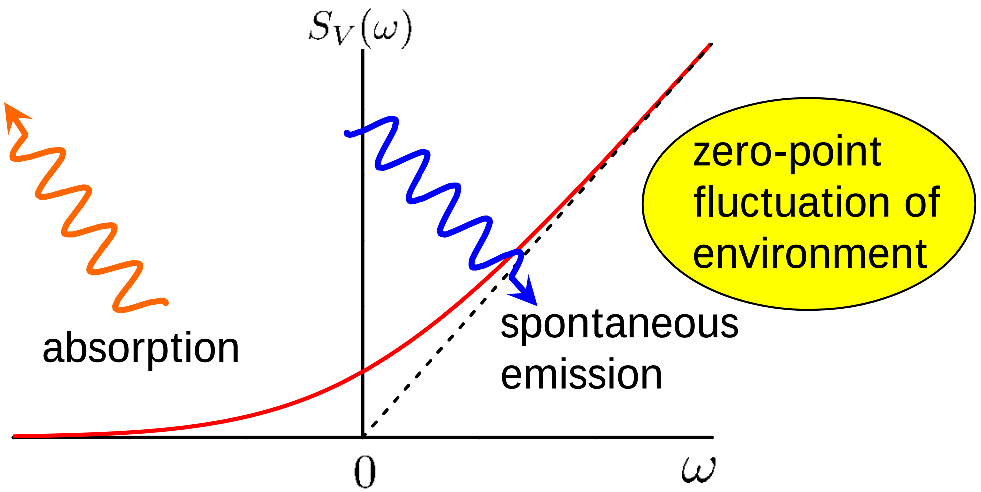
for weak perturbation: Fermi's golden rule

- qubit energy E_{01} variable
- relaxation $\propto$ S(+$E_{01}/\hbar$) and excitation $\propto$ S(-$E_{01}/\hbar$)

$\Rightarrow$ quantum spectrum analyzer

ex. Johnson noise in Ohmic resistor R

$$S_V(\omega) = \frac{|\hbar\omega|}{2\pi} R\left(\coth\frac{|\hbar\omega|}{2k_B T} + 1\right)$$



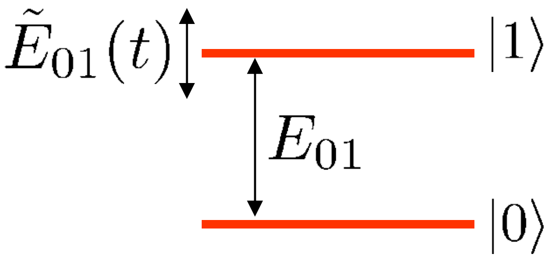
Dephasing

free evolution of the qubit phase

$$\alpha|0\rangle + \beta|1\rangle \Longrightarrow \alpha|0\rangle + \beta e^{i\varphi(t)}|1\rangle$$

$$\varphi(t) = \bar{\varphi}(t) + \tilde{\varphi}(t) \qquad \bar{\varphi}(t) = \frac{\overline{E_{01}}}{\hbar} t$$

dephasing



$$\langle \exp i\tilde{\varphi}(t) \rangle = \left\langle \exp\left(\frac{i}{\hbar} \int_0^\tau dt \tilde{E}_{01}(t) \right) \right\rangle$$

$$= \exp\left[-\frac{1}{2\hbar^2} \left(\frac{\partial E_{01}}{\partial \lambda} \right)^2 \int_{-\infty}^{\infty} d\omega S_\lambda(\omega) \left(\frac{\sin(\omega t/2)}{\omega/2} \right)^2 \right]$$

for Gaussian fluctuations

tunable

tunable

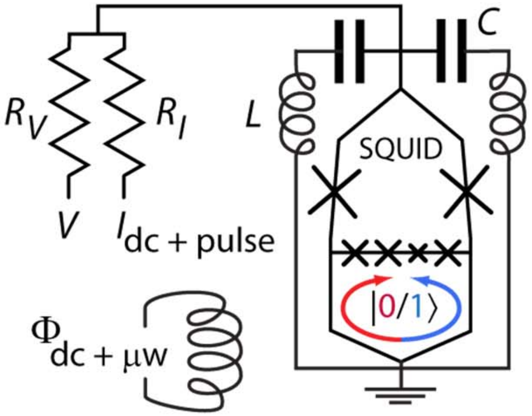
sensitivity of qubit energy to the fluctuations of external parameter

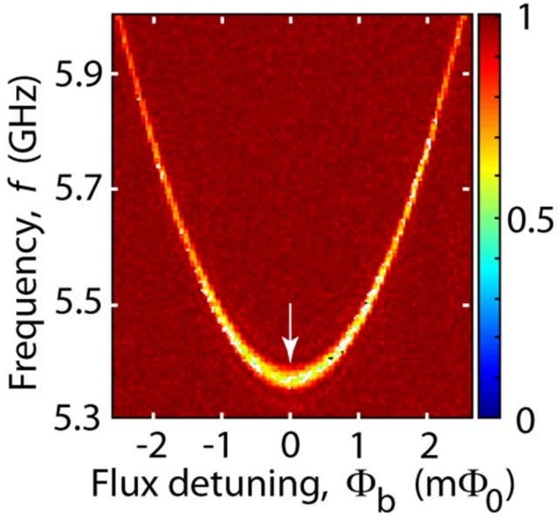
information of S(ω) at low frequencies

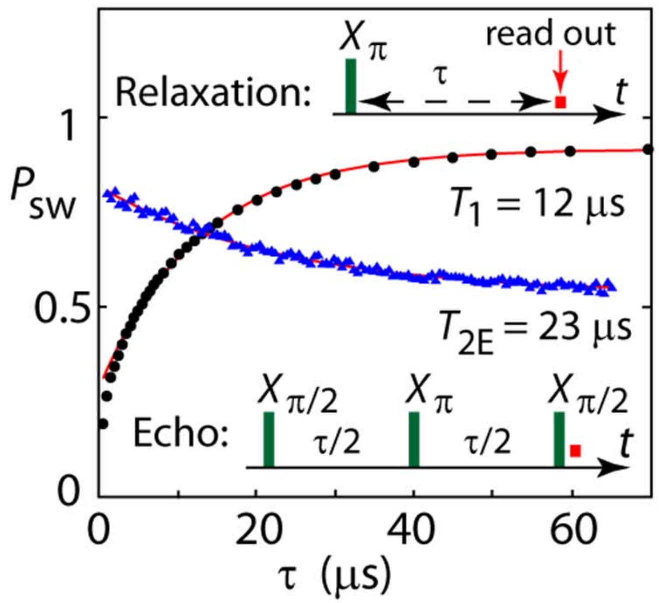
A long-lived flux qubit

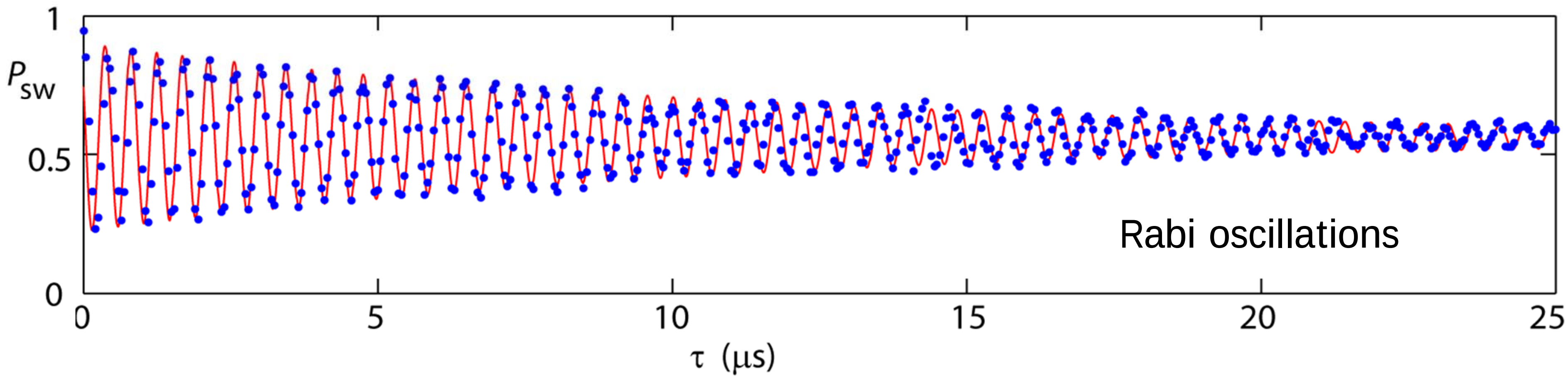
Aluminum 4JJ flux qubit on SiO_2/Si

$$Q = \omega_{01} T_1 \approx 400,000$$



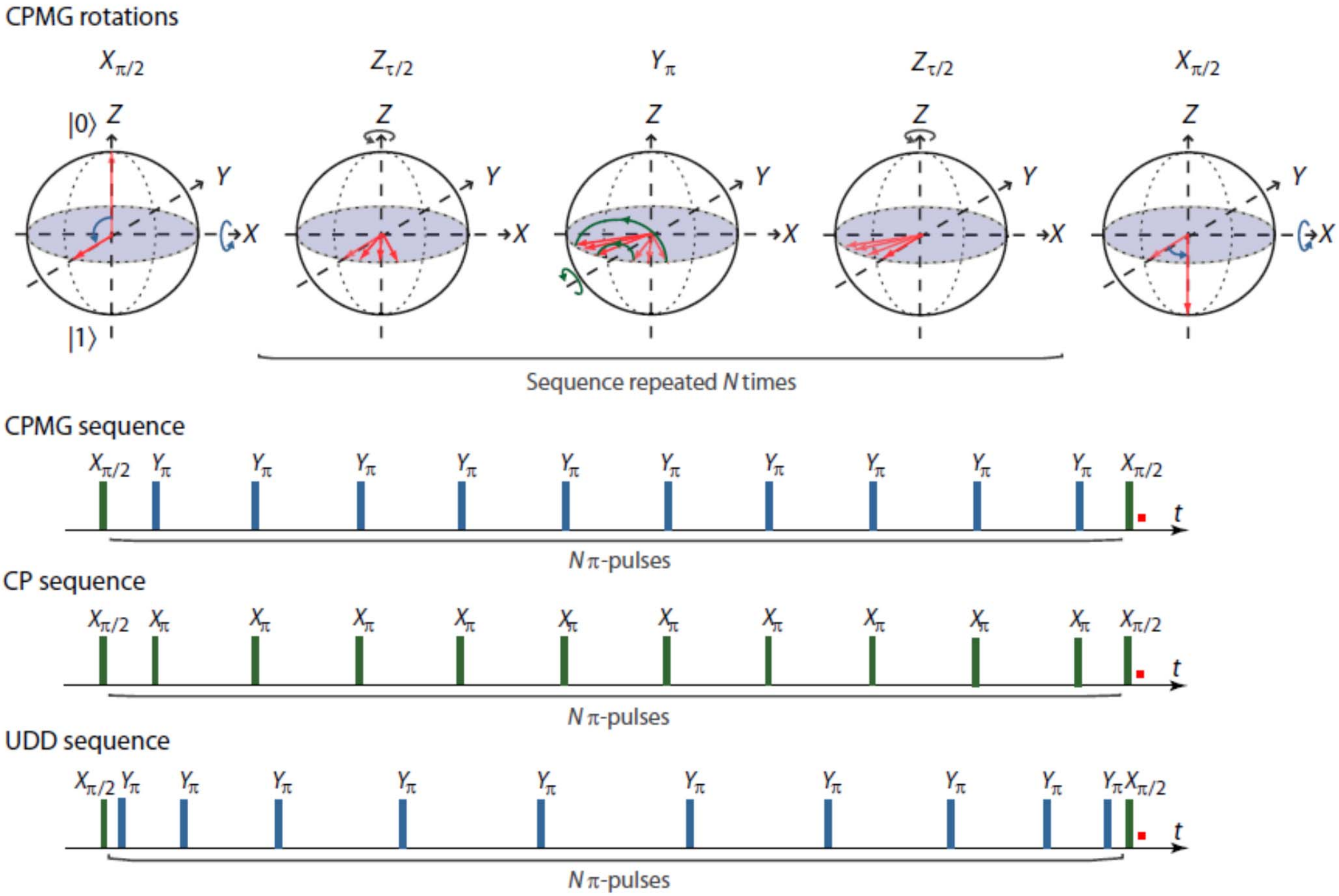






In collaboration with Jonas Bylander, Simon Gustavsson, Fei Yan, Will Oliver (MIT)

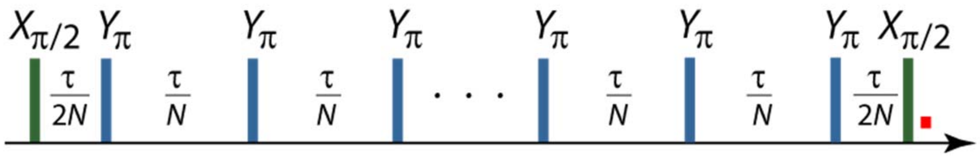
Dynamical decoupling pulse sequences

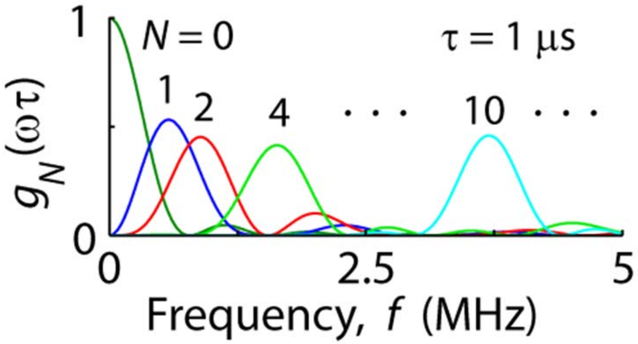


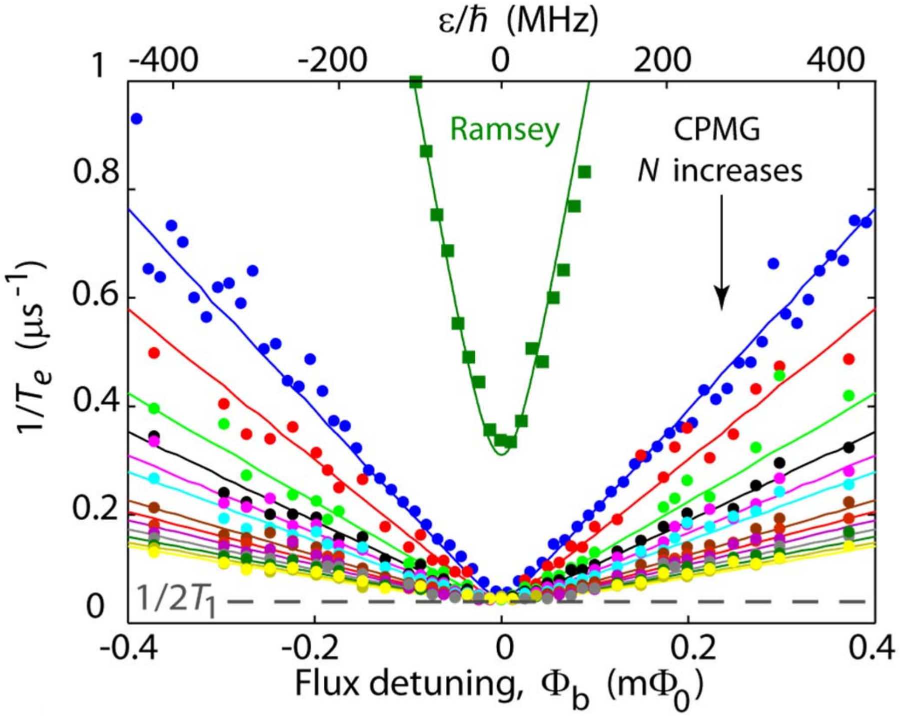
Carr and Purcell, PR 94, 630 (1954); Meiboom and Gill, RSI 29, 688 (1958); Uhrig et al., NJP 10, 083024 (2008)

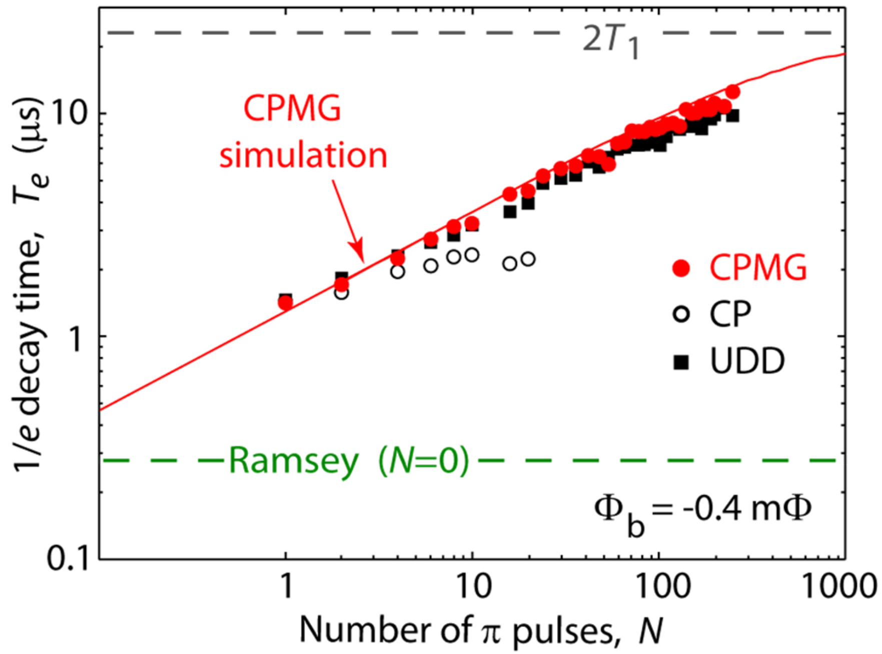
Recovery of dephasing time

CPMG

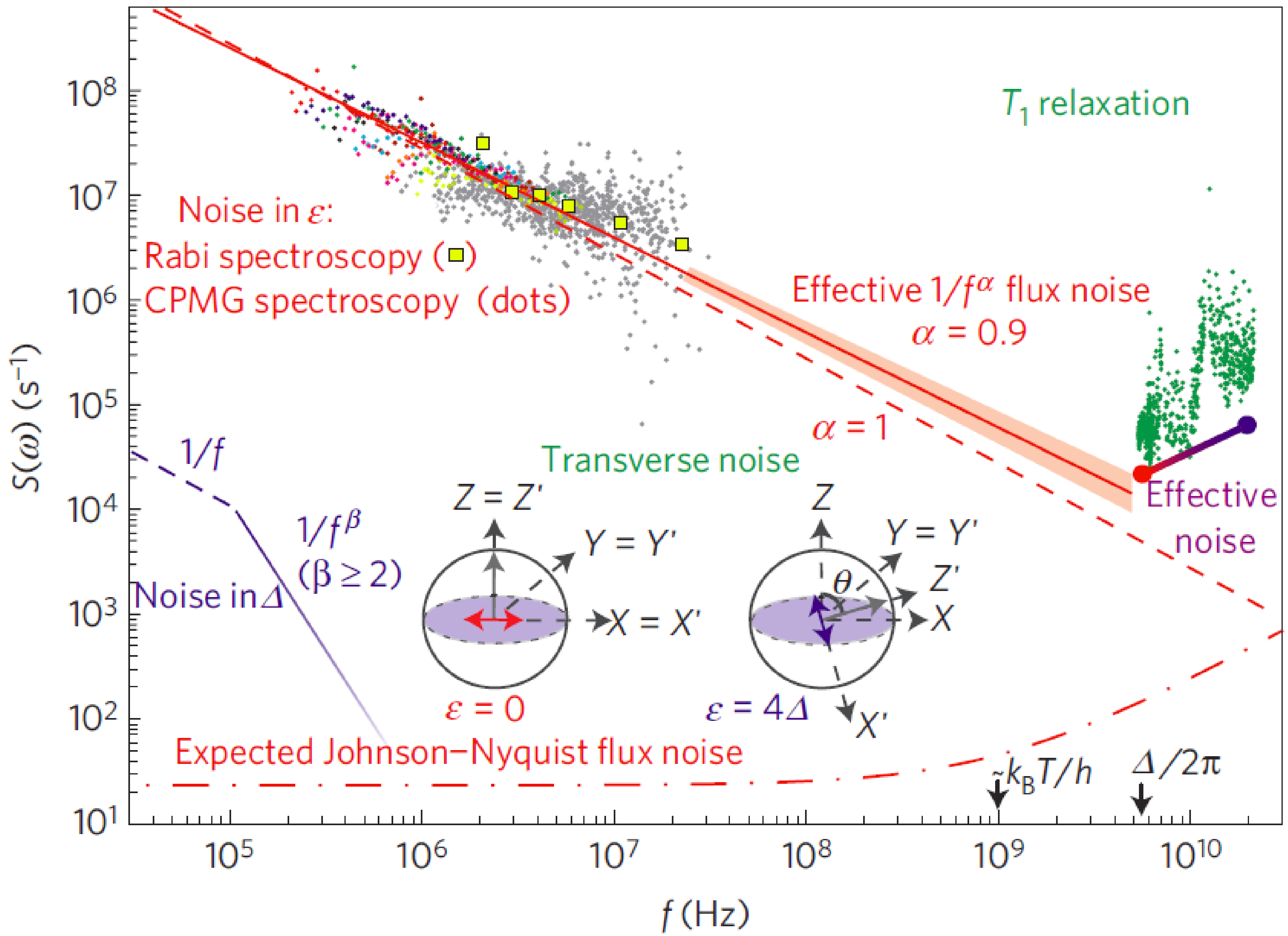






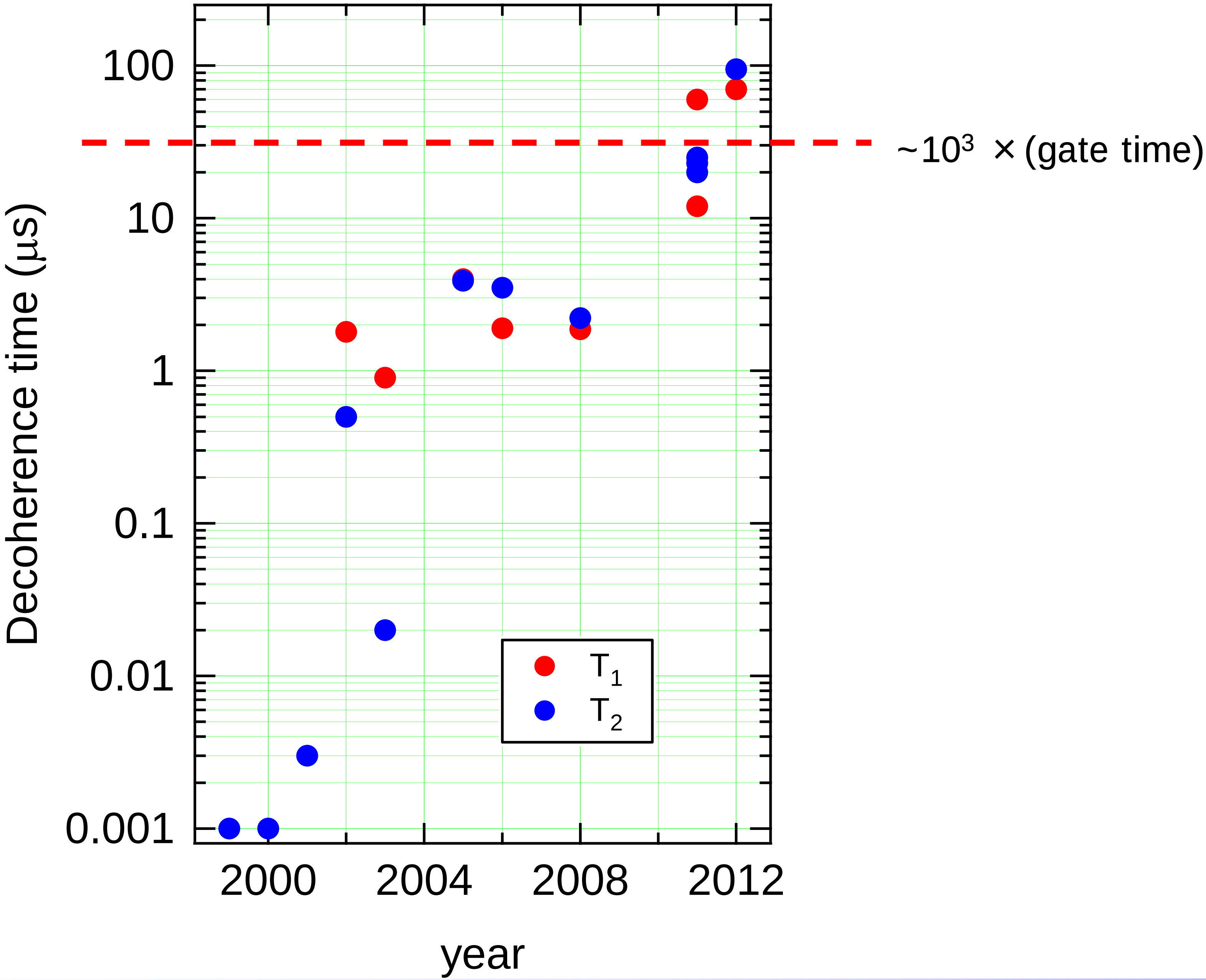


Noise spectrum



J. Bylander et al. Nature Phys. 7, 565 (2011)

Decoherence time of superconducting qubits

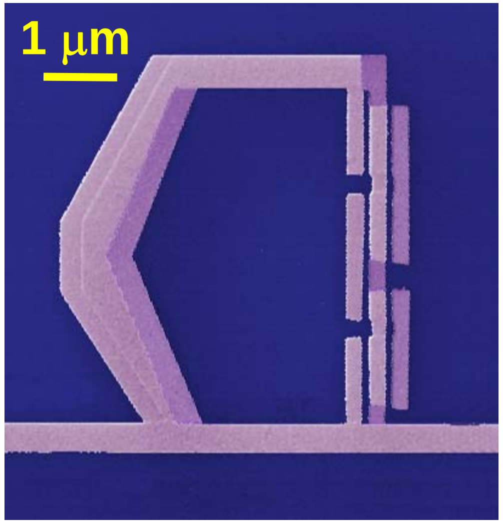


Atoms

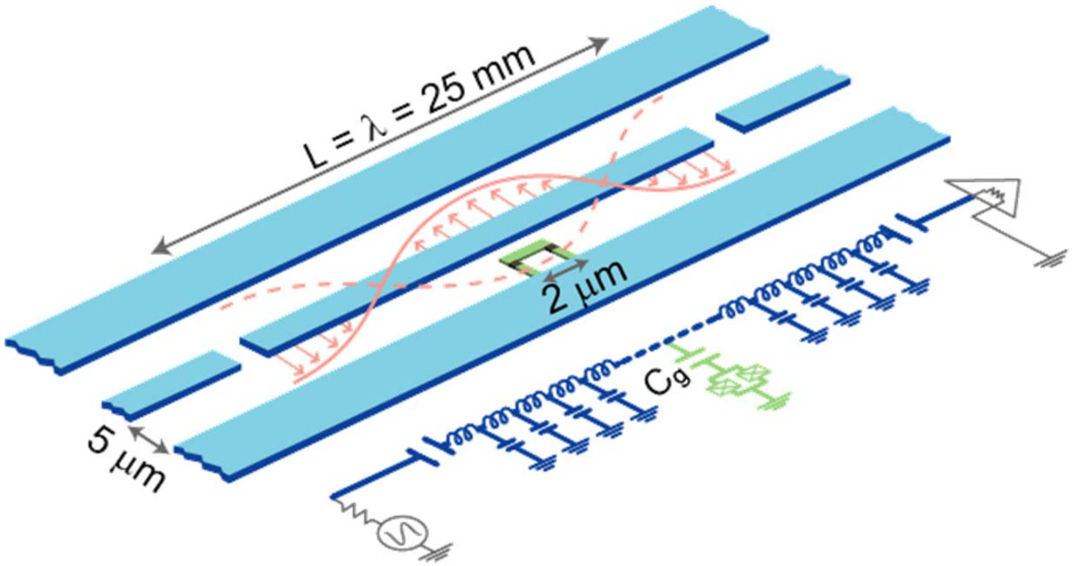
(a stereotype of) atom

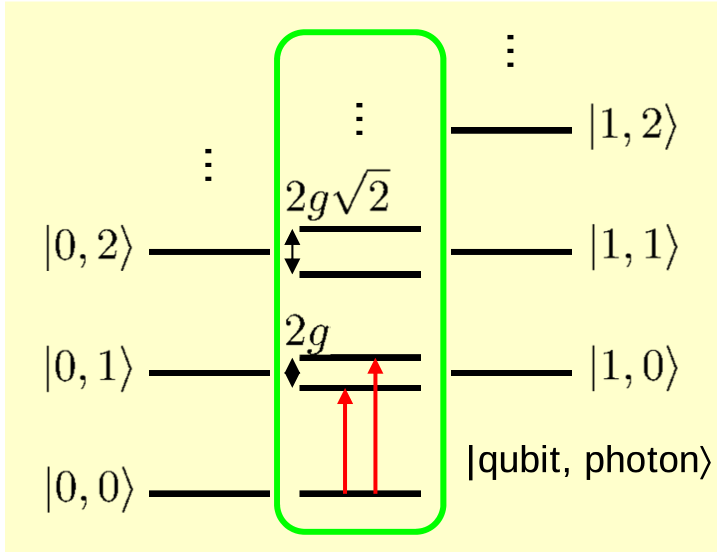
Our artificial atom

$\sim$ Å

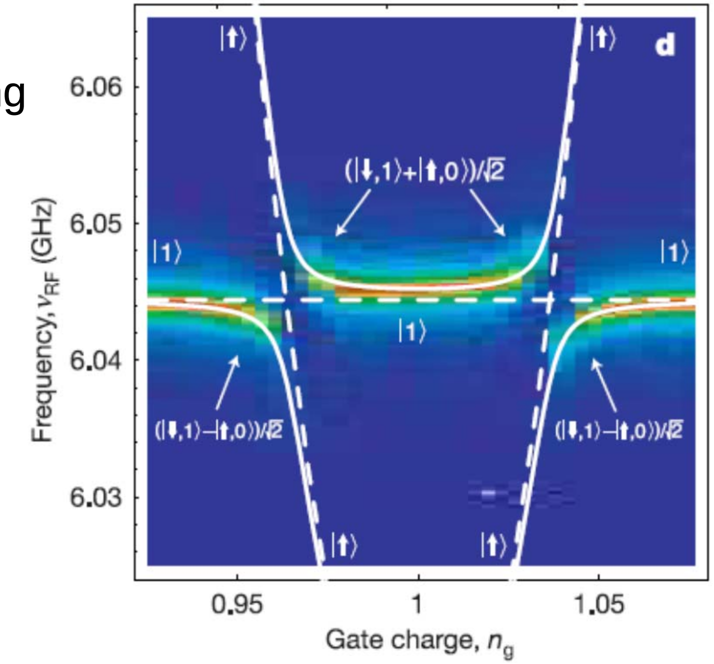


Circuit quantum electrodymanics (circuit QED)





vacuum Rabi splitting



Jaynes-Cummings Hamiltonian:

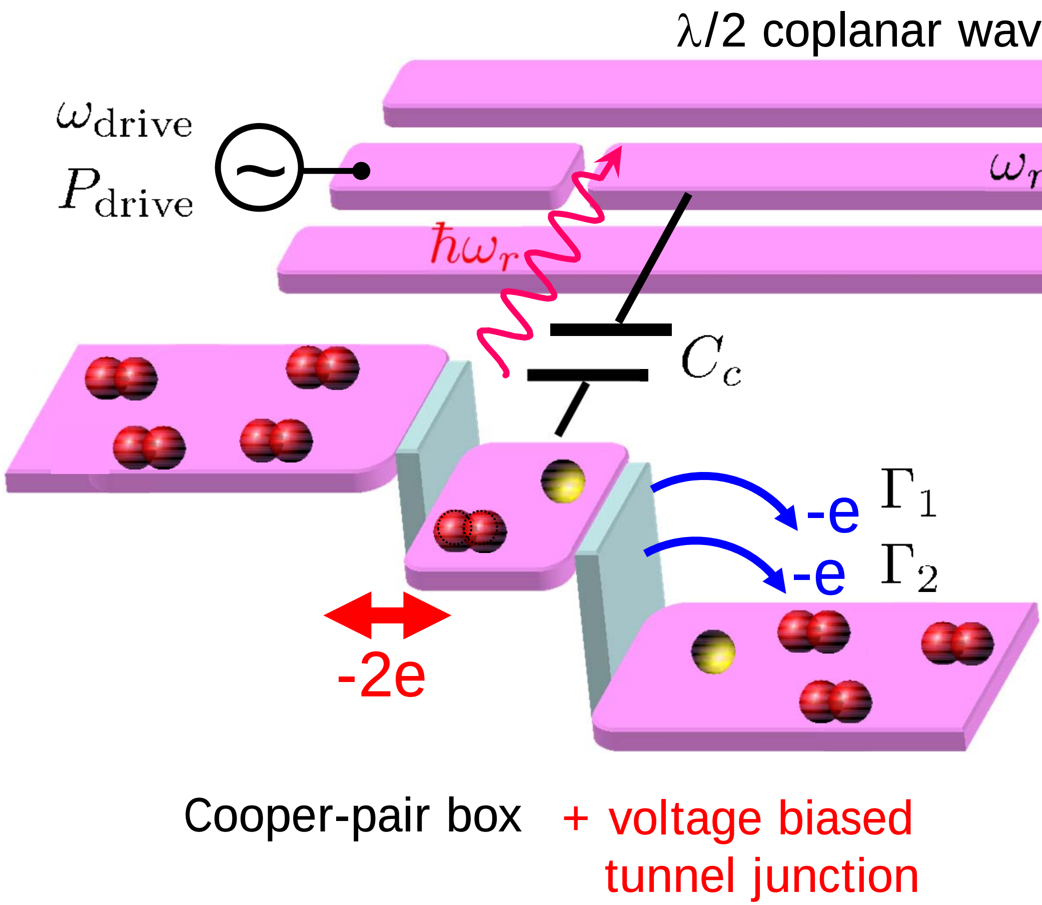
$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) - \frac{\hbar\omega_q}{2}\sigma_z + \hbar g(a^\dagger\sigma_- + a\sigma_+)$$

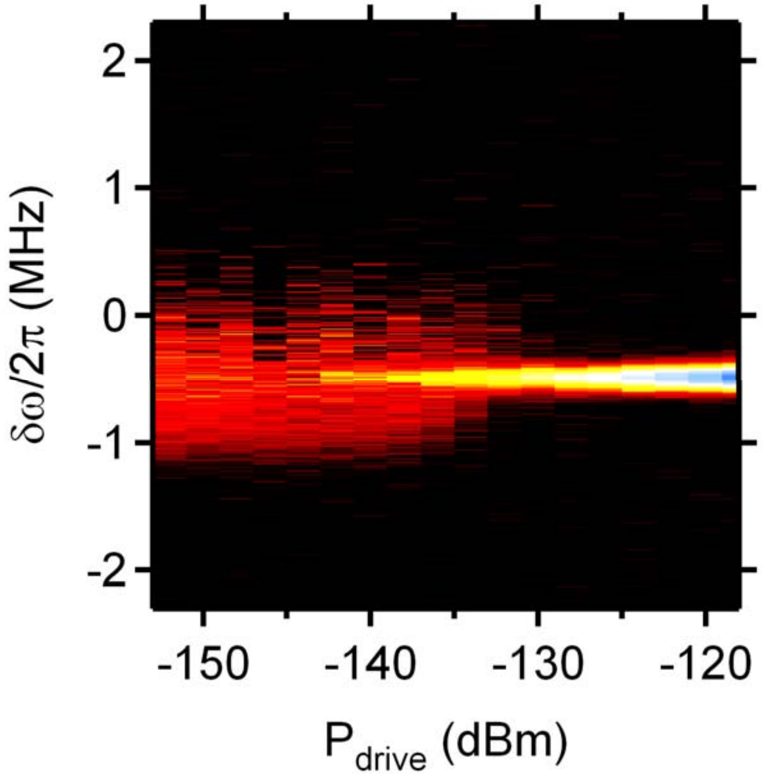
Strong coupling: $g \gg \gamma, \kappa$

$g/2\pi \sim 10$ MHz $\quad (\gamma,\kappa)/2\pi \sim 1$ MHz

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

Single artificial-atom maser





- Population inversion generated by current injection
- Capacitive coupling with cavity mode

O. Astafiev et al. Nature 449, 588 (2007)

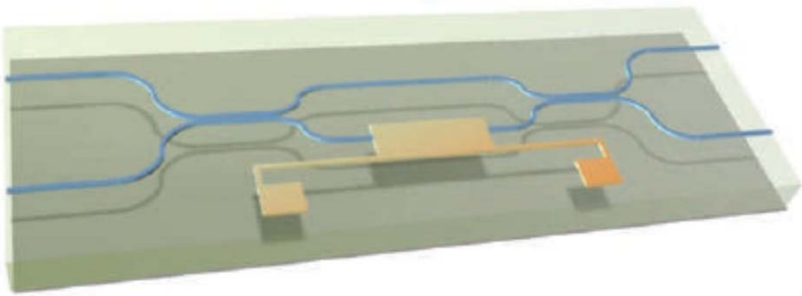
Photons in transmission line

Optics

Frequency 100-1000 THz
Wavelength 3 μm – 300 nm

Optical fiber, low loss ~0.2 dB/km
Photonic on-chip circuits, ~0.1 dB/cm

Weak nonlinearity

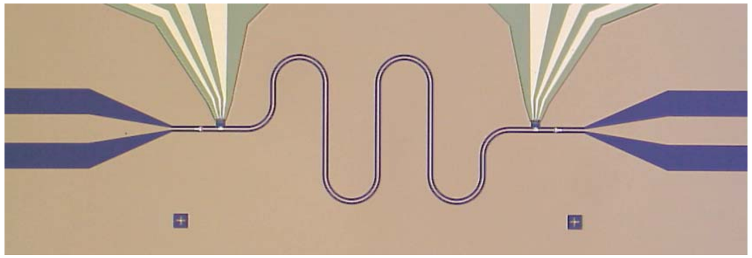


Microwave

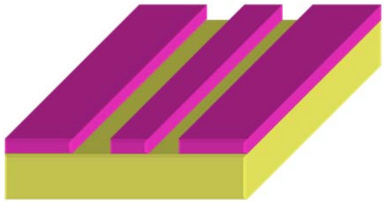
Frequency 1-10 GHz
Wavelength 30 cm – 3 cm

Microwave on-chip circuits, ~0.3 dB/km(?)

Strong nonlinearity available



coplanar waveguide



J. L. O'Brien et al. Nature Photonics 3, 687 (2009) Bristol

Superconducting transmission line

$Z = \sqrt{l/c}$

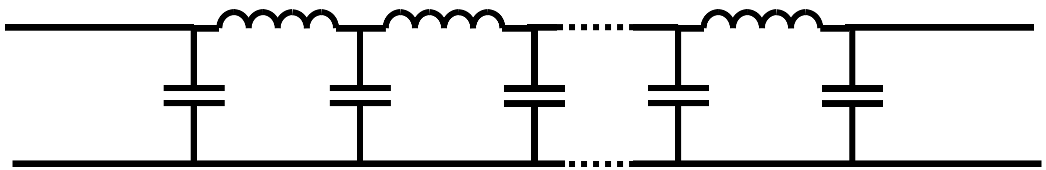
$v = 1/\sqrt{lc}$

$\omega = vk$

distributed element

↕

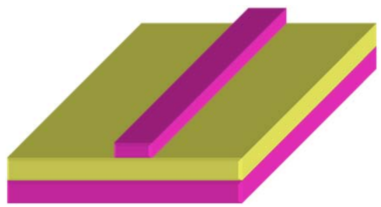
lumped element



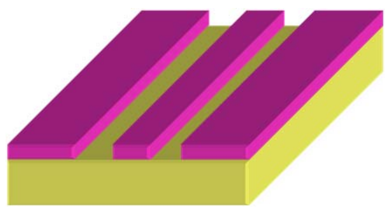
- small dissipation for $\hbar\omega_r, k_B T \ll \Delta$
- 1D transmission mode
- Photon life time ~ 100 μs, 10 km (?)

Variety of transmission lines:

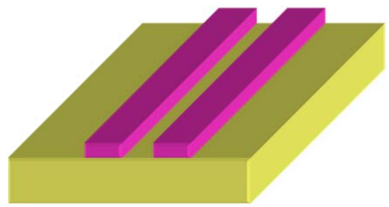
microstrip line



coplanar waveguide

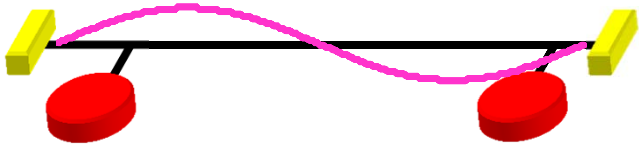


slot line



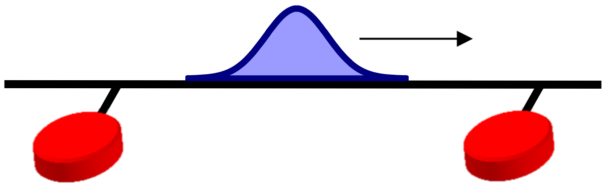
Confined photon and flying photon

- in resonator (confined “0D” photon; single-mode)



$$H = \hbar\omega_r a^\dagger a$$

- through transmission line (flying photon; multi-mode; continuum)

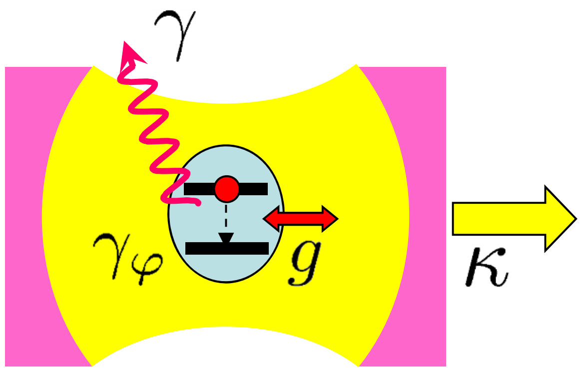


$$H = \hbar \int_0^\infty d\omega\, \omega a^\dagger(\omega) a(\omega)$$

Atom-photon strong coupling

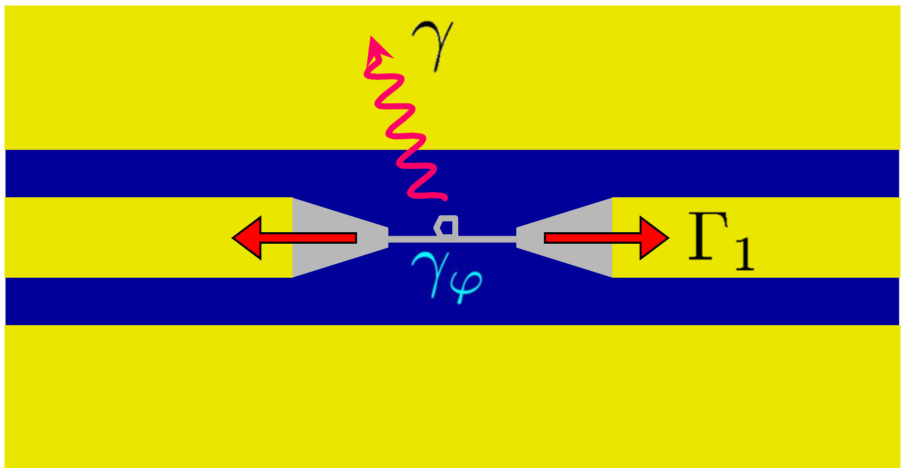
Strong coupling in cavity QED

$$g \gg \kappa,\ \gamma, \gamma_\varphi$$



“Strong coupling” in 1D waveguide

$$\Gamma_1 \gg \gamma,\ \gamma_\varphi$$



Superconducting qubits coupled to a transmission line

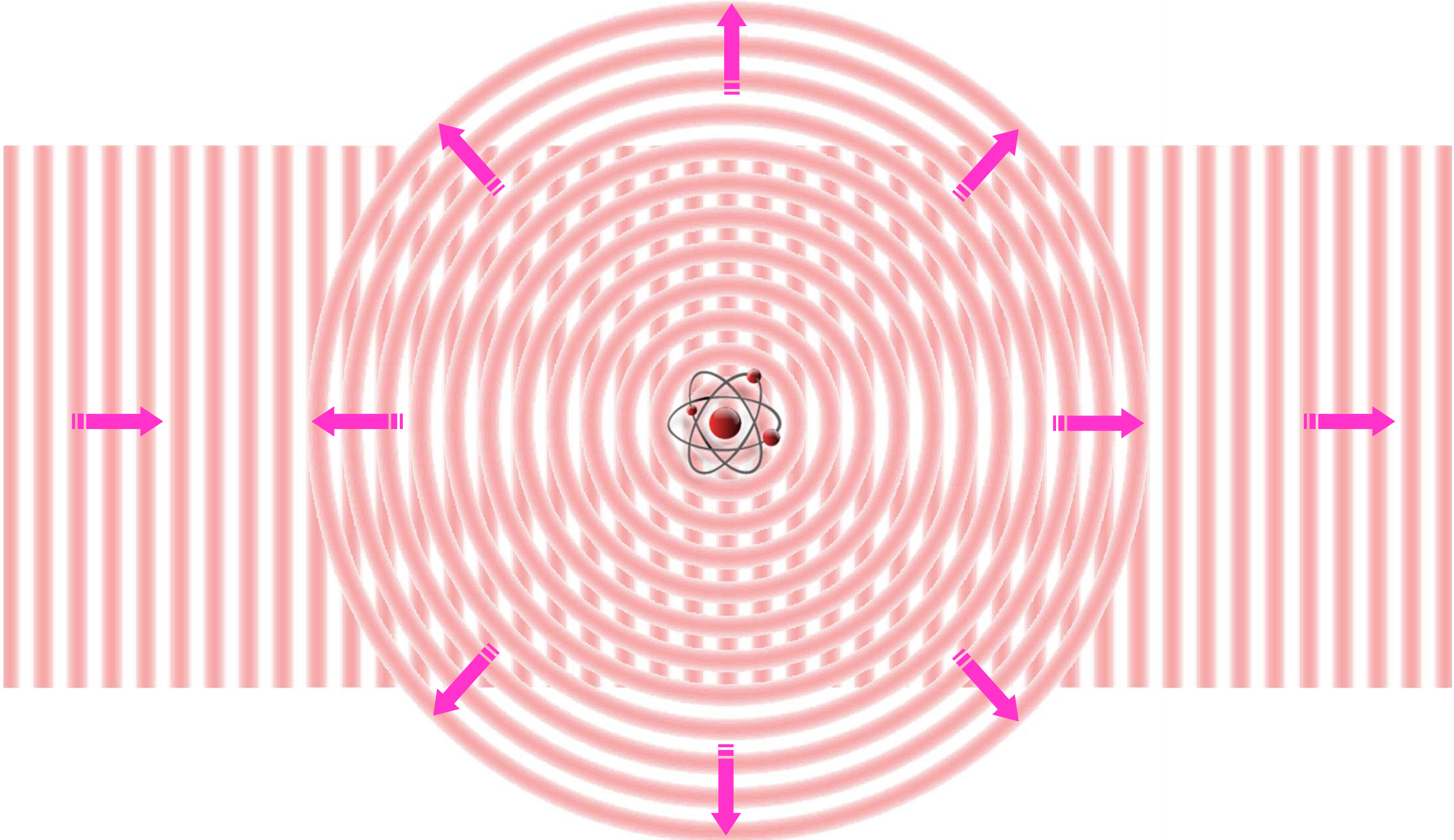
- Superconducting qubits as artificial atoms
  - Fixed on chip
  - Strong coupling
  - Multi levels, selection rules

- Beauty of 1D
  - Microwave transmission line as 1D channel
  - Perfect spatial mode matching

- Use of interference
  - Importance of temporal modes
  - Limitation with bandwidth

- Spontaneous emission – coherent process

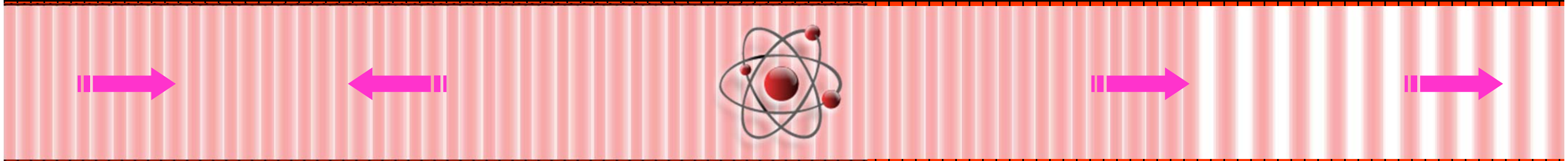
Resonant scattering in 3D space

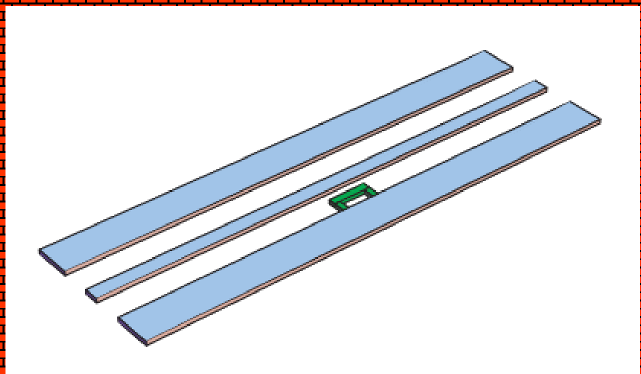


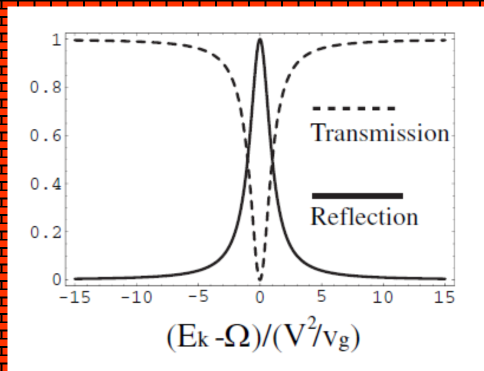
- Small scattering cross section
- Spatial mode mismatch between incident and radiated waves

Resonant scattering in 1D waveguide

Destructive interference of transmitted wave
⇒ Extinction of transmittance
⇒ Perfect reflection



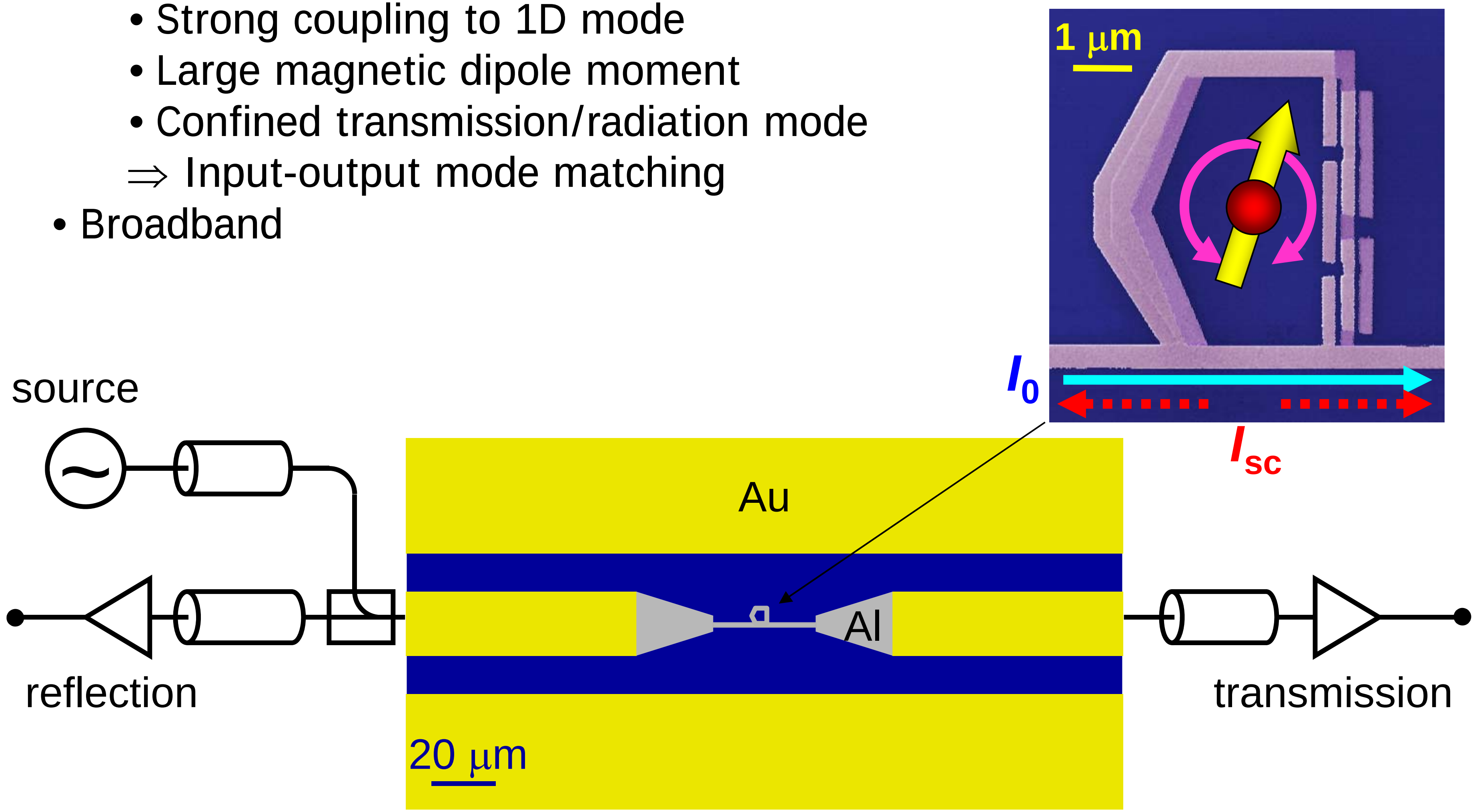




Shen and Fan, PRL 95, 213001 (2005) Stanford; Chang et al. PRL 97, 053002 (2006) Harvard

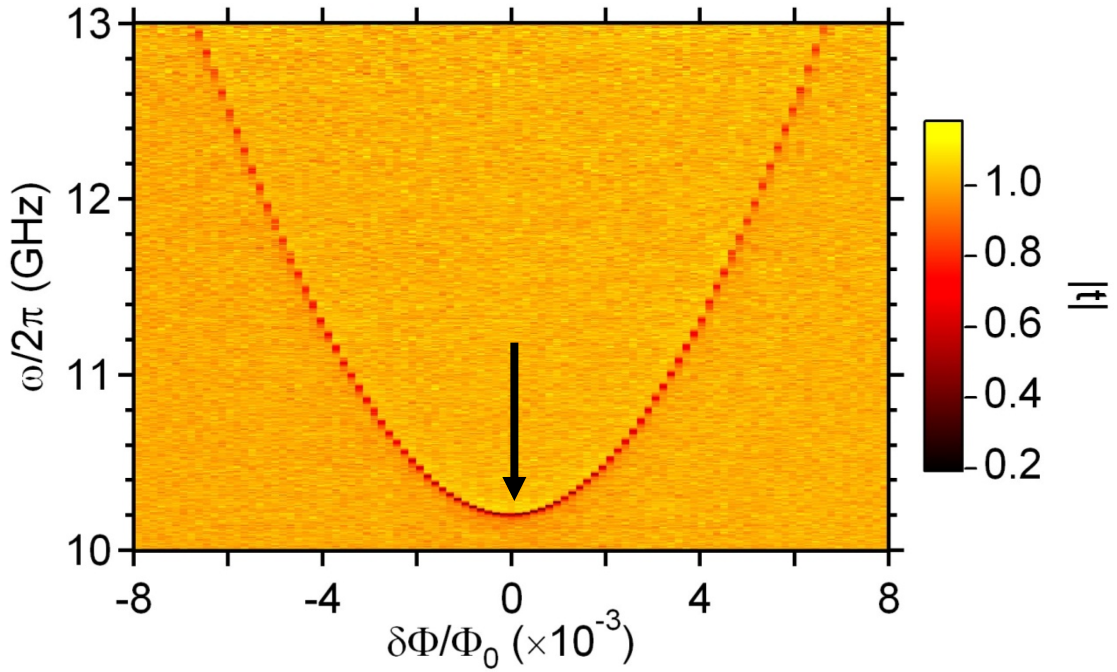
Artificial atom in 1D open space

- Flux qubit coupled to transmission line via kinetic inductance
  - Strong coupling to 1D mode
  - Large magnetic dipole moment
  - Confined transmission/radiation mode
  - $\Rightarrow$ Input-output mode matching
- Broadband



Transmission spectroscopy — elastic scattering

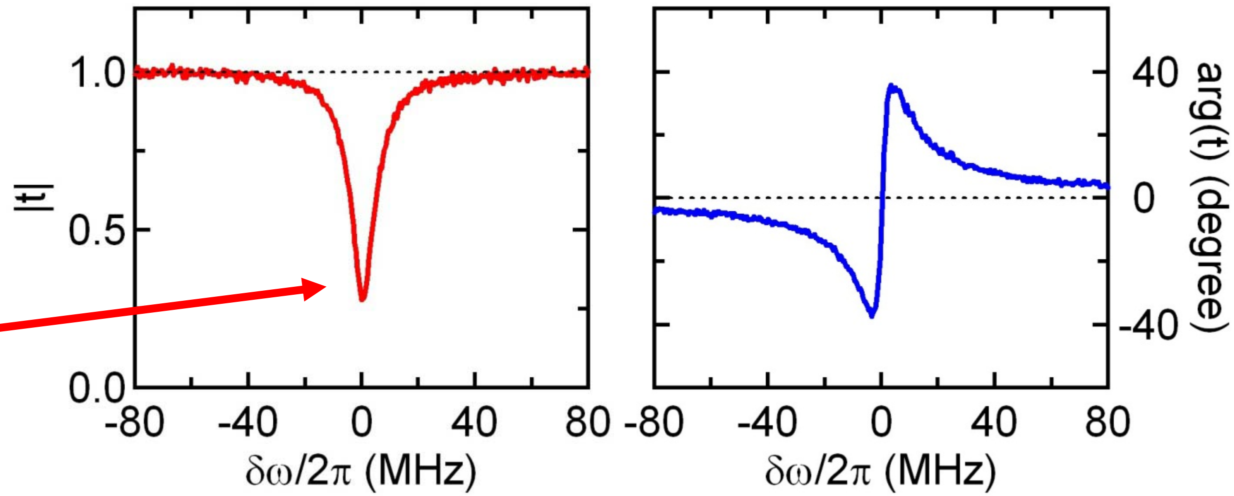
$$\Delta/h = 10.20\ \mathrm{GHz}$$
$$I_p = 195\ \mathrm{nA}$$



At degeneracy point

$$\delta\Phi/\Phi_0 = 0$$

Strong extinction of transmitted wave



O. Astafiev et al. Science 327, 840 (2010)

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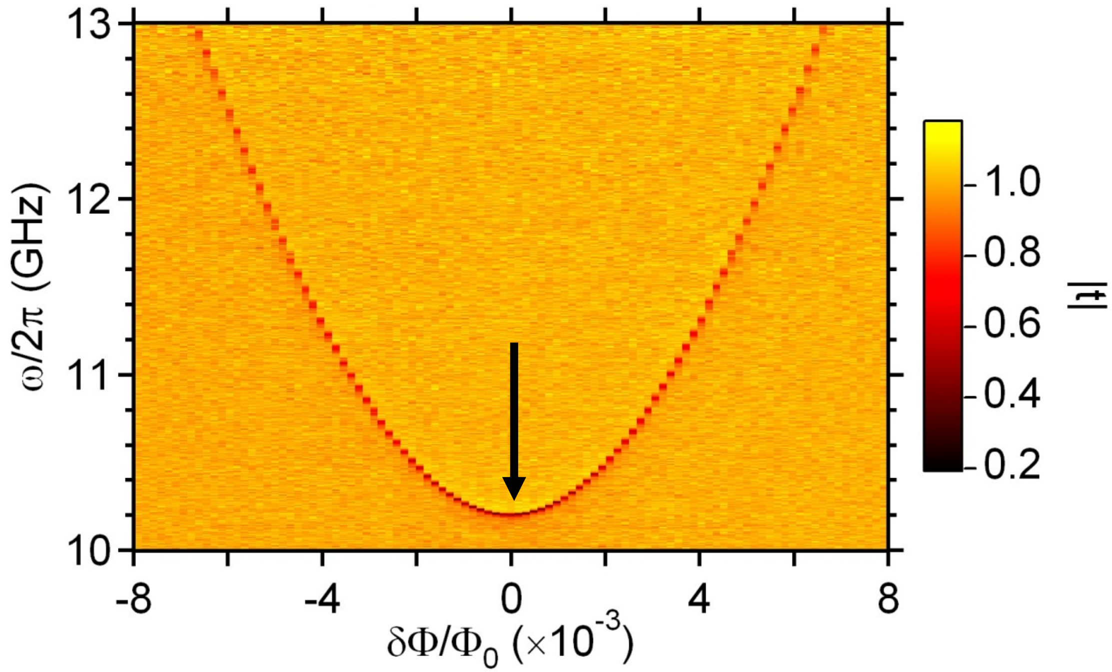
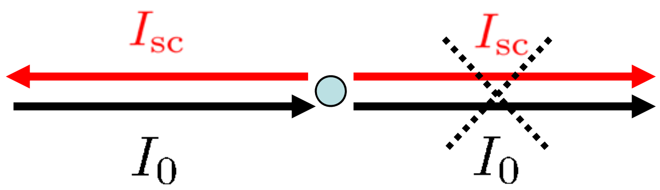
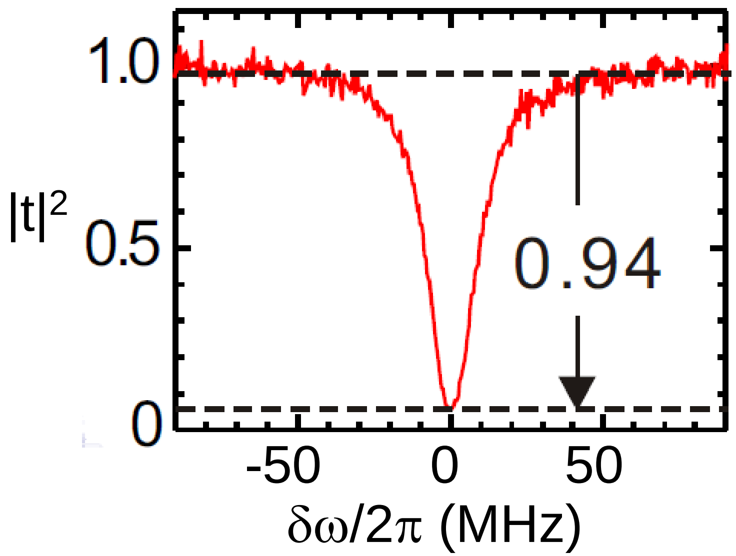




Perfect reflection



$$|r_0|^2 = \left(\frac{\Gamma_1}{2\Gamma_2}\right)^2$$

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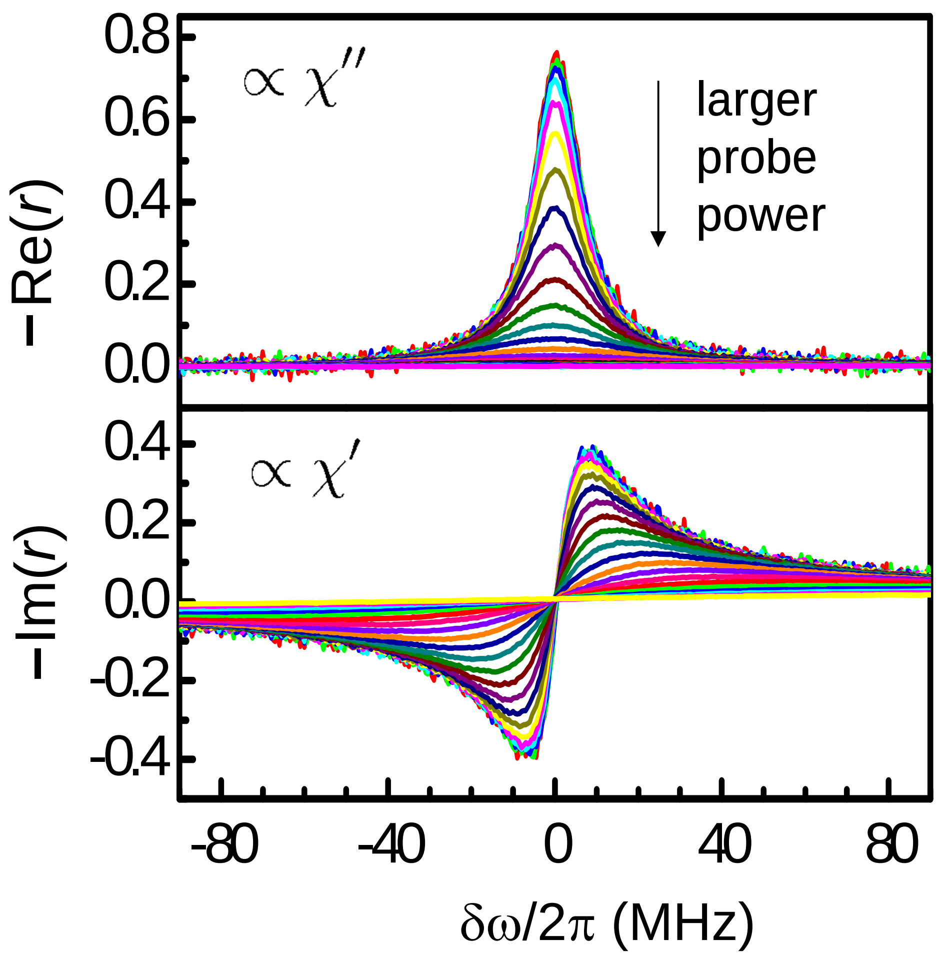
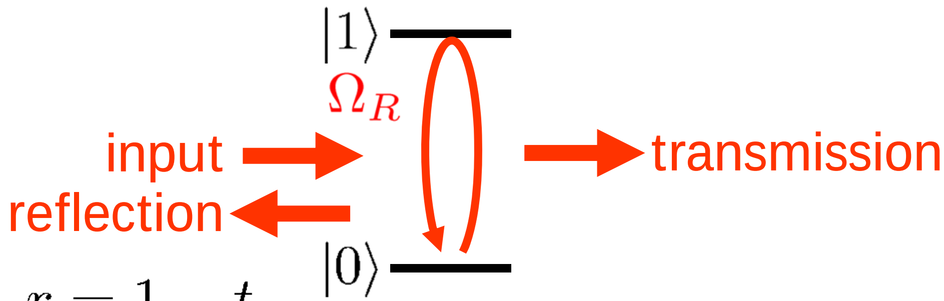
Power dependence — saturation of atom





$$-r = 1 - t$$

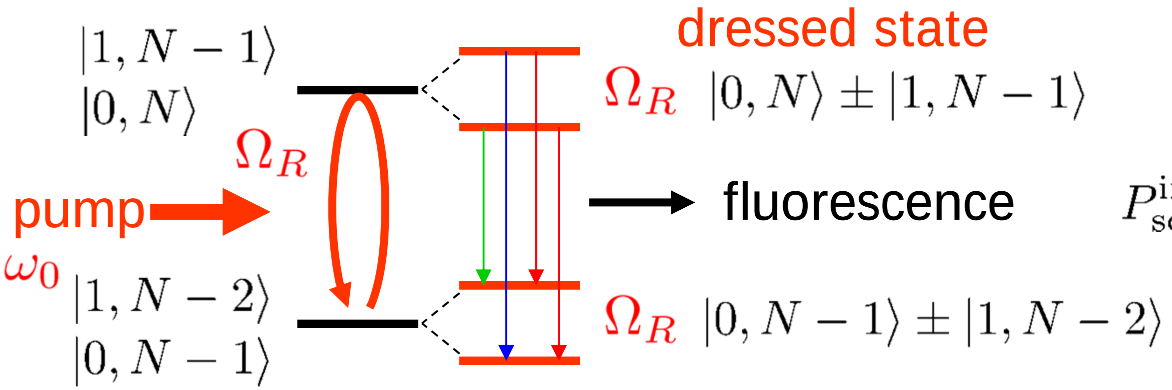
$$r = -r_0 \frac{1 + i\delta\omega/\Gamma_2}{1 + (\delta\omega/\Gamma_2)^2 + \Omega_R^2/\Gamma_1\Gamma_2}$$

$$r_0 = \frac{\Gamma_1}{2\Gamma_2} = \frac{\Gamma_1}{\Gamma_1 + 2\Gamma_\varphi}$$

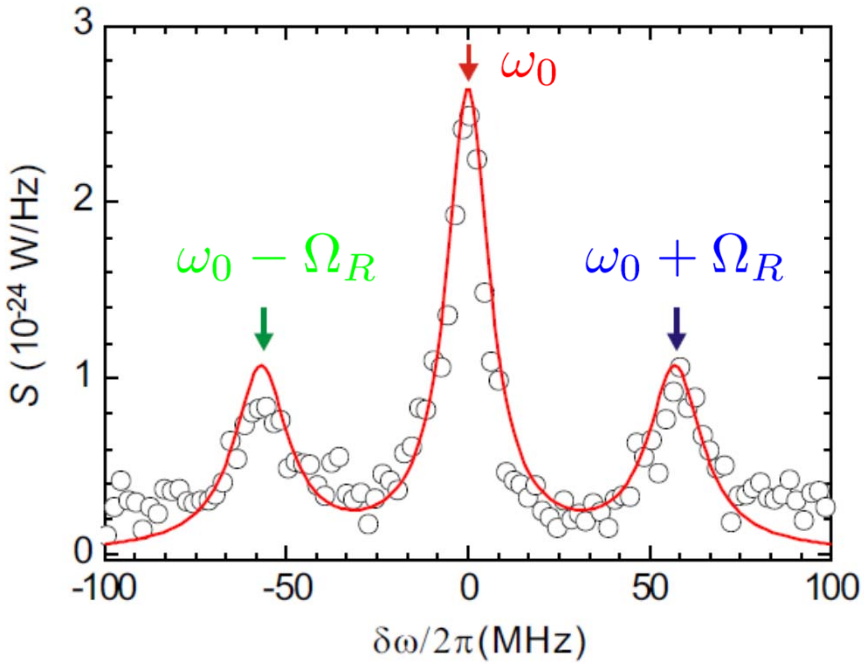
$$\Gamma_1/2\pi = 11.0\ \mathrm{MHz}$$
$$\Gamma_\varphi/2\pi = 1.7\ \mathrm{MHz}$$
$$M = 12.2\ \mathrm{pH}$$

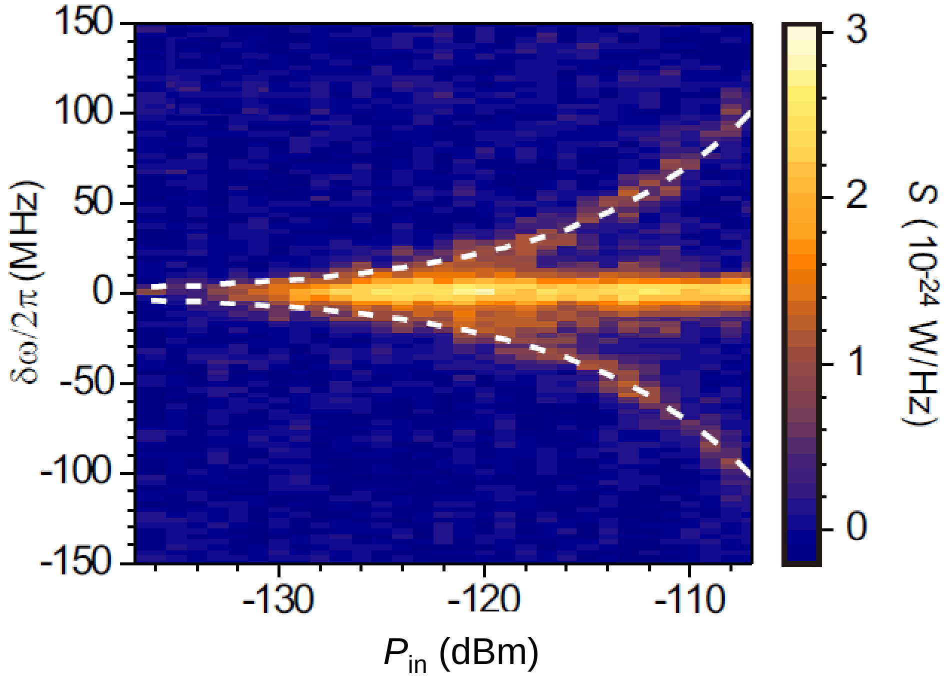
Inherent nonlinearity of the two-level atom

Resonance fluorescence: inelastic scattering



$$P_{\rm sc}^{\rm inel.}/P_{\rm in} = 1 - |r|^2 - |t|^2$$



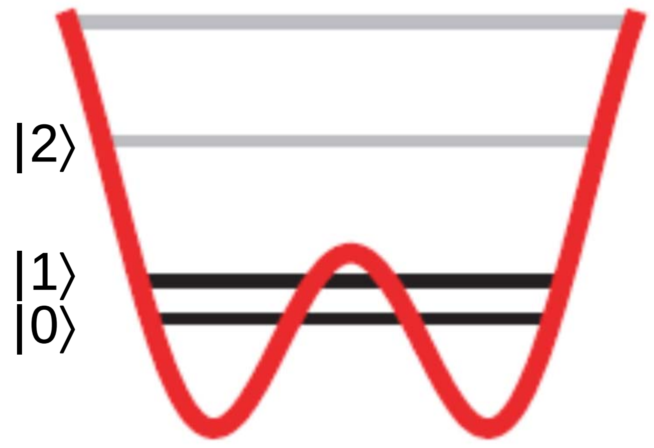


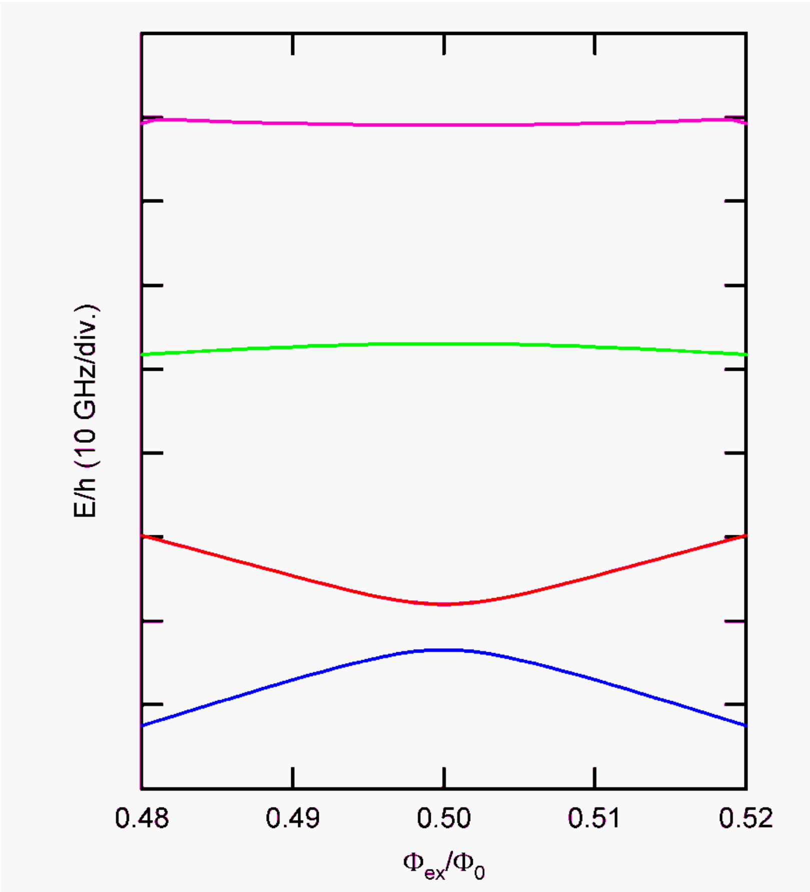
Mollow triplet: $S(\omega) \approx \frac{1}{2\pi}\frac{\hbar\omega\Gamma_1}{8}\left(\frac{\gamma_s}{(\delta\omega+\Omega)^2+\gamma_s^2} + \frac{2\gamma_c}{\delta\omega^2+\gamma_c^2} + \frac{\gamma_s}{(\delta\omega-\Omega)^2+\gamma_s^2}\right)$

O. Astafiev et al. Science 327, 840 (2010)

$\gamma_s = (\Gamma_1 + \Gamma_2)/2 \qquad \gamma_c = \Gamma_2 = \Gamma_1/2 + \Gamma_\varphi$

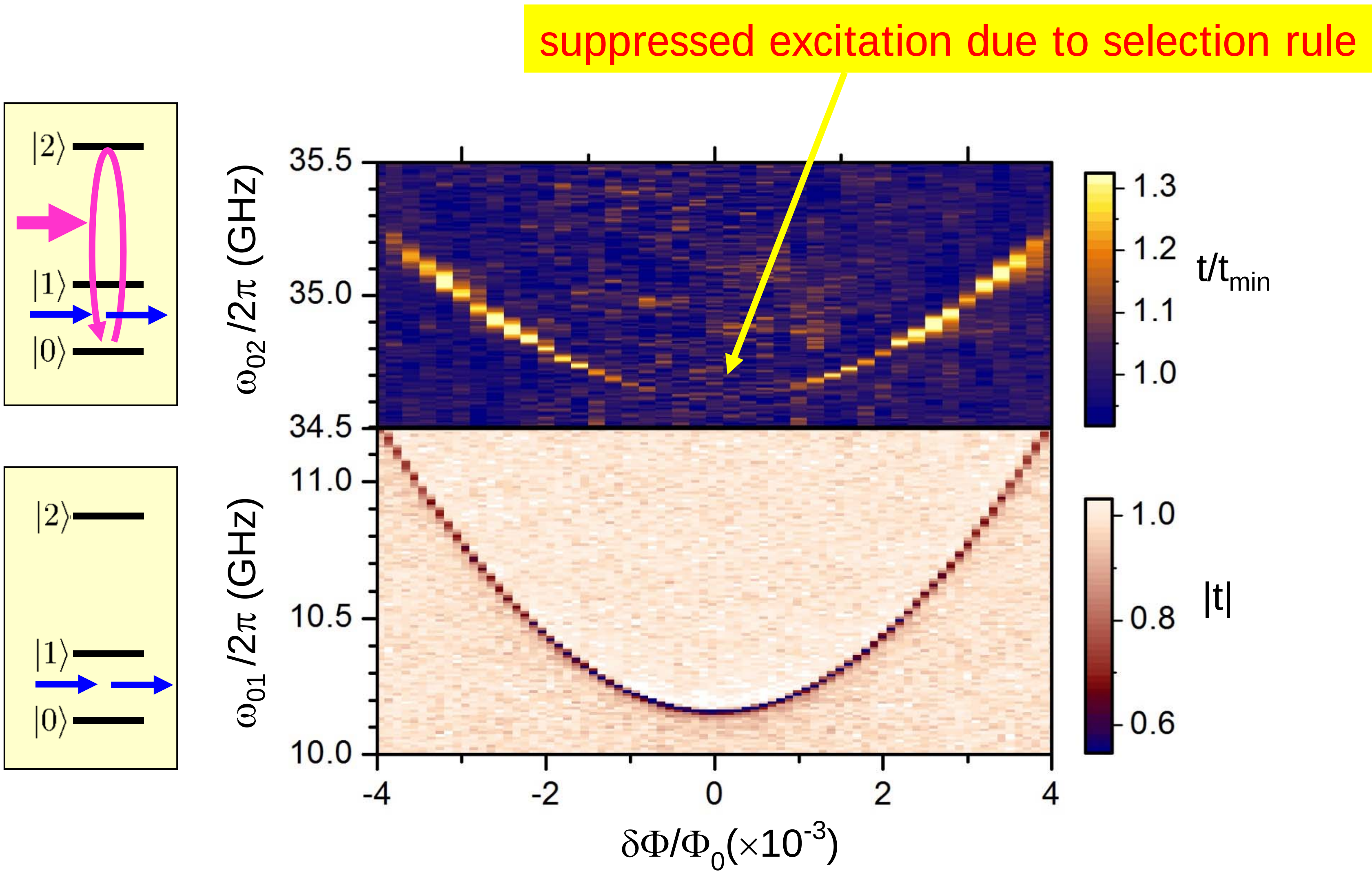
Flux qubit as a three-level artificial atom



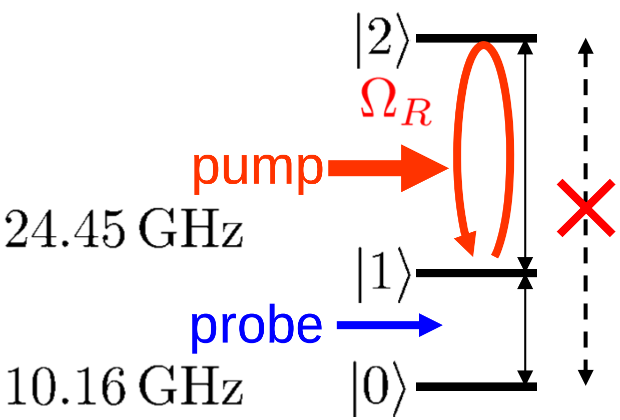


- Josephson junction qubits = effective two-level system
- presence of auxiliary states
- large anharmonicity/nonlinearity
- selection rule due to symmetry when flux bias $\delta\Phi$=0

Spectroscopy of a three-level atom



Ladder system at degeneracy point: induced transparency

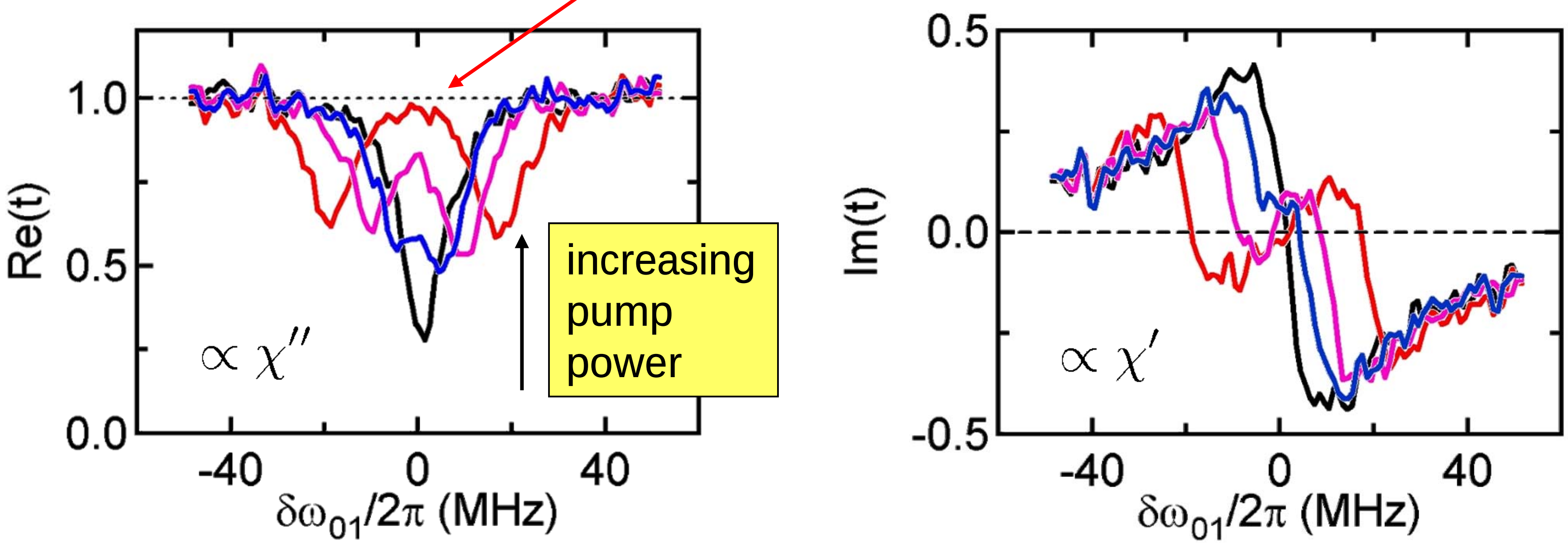


Biased at degeneracy point
Transition 0 ↔ 2 not allowed

ladder-type

"Electromagnetically-induced transparency"

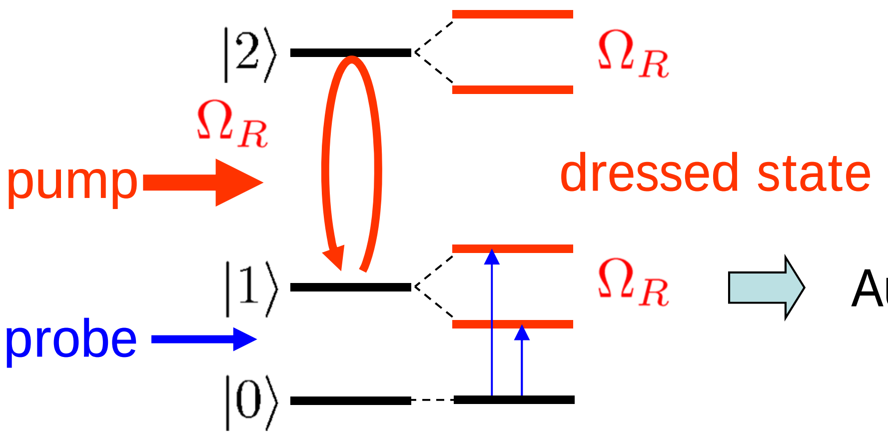
$$\Gamma_{10} < \Gamma_{21} < \Omega_R$$



A. A. Abdumalikov et al. PRL 104, 193601 (2010)

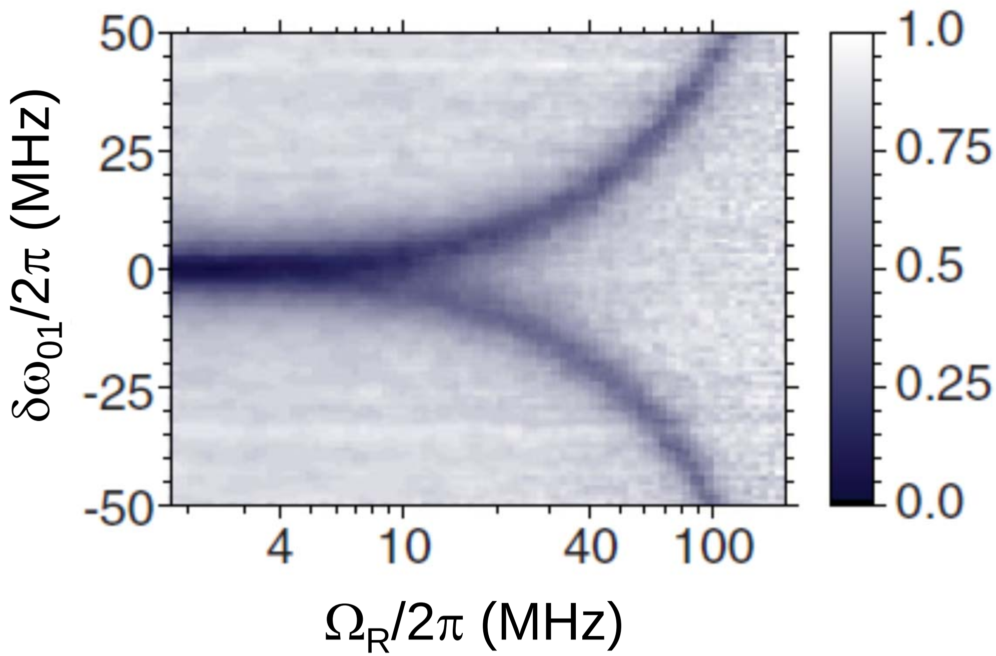
Ladder system at degeneracy point: induced transparency

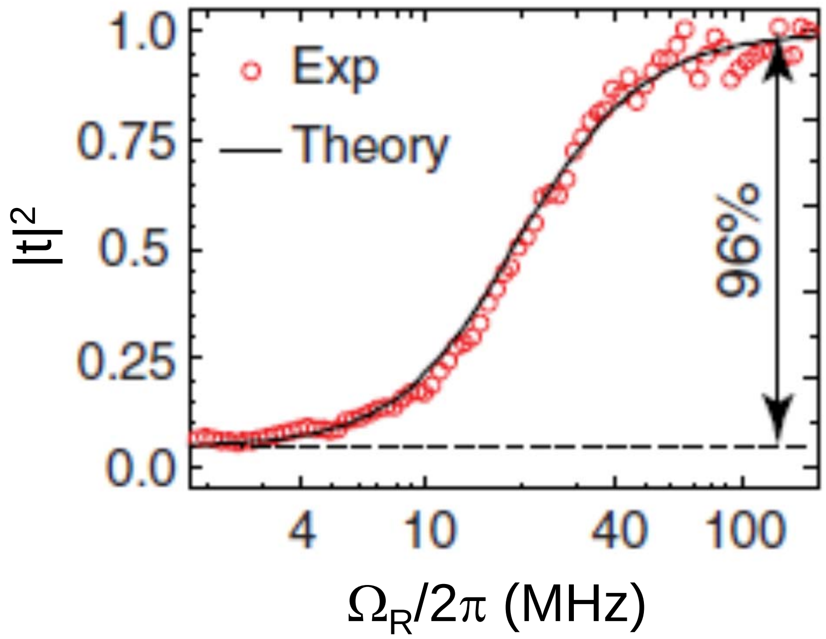
A. A. Abdumalikov et al. PRL 104, 193601 (2010)
See also, I.-C. Hoi et al. PRL 107, 073601 (2011) (Chalmers)



Autler-Townes doublet

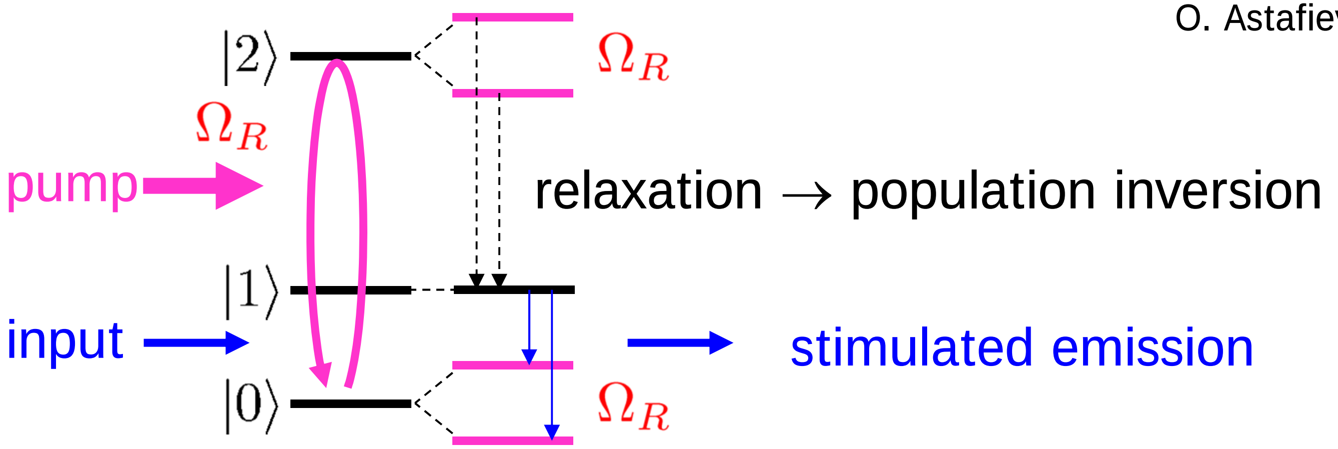
Transmission of probe signal

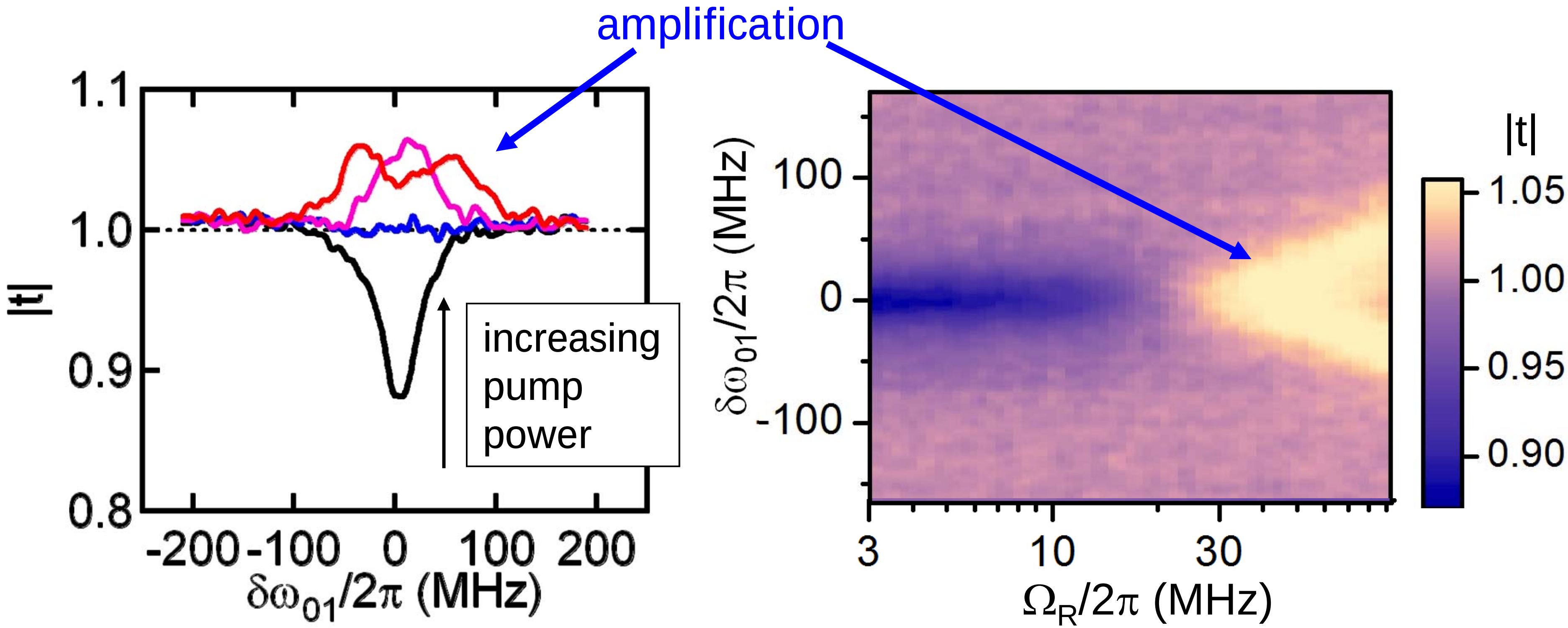




Stimulated emission and amplification

O. Astafiev et al. PRL 104, 183603 (2010)





Summary

- Superconducting qubits as artificial atoms
  - Electrical circuits fixed on chip
  - Gigantic dipole, strong coupling with EM modes
  - Multiple levels, selection rules
  - Qubit as quantum spectrum analyzer

- Coupling to 1D channel
  - Microwave transmission line as 1D channel
  - Perfect spatial mode matching
  - Interference between transmitted and scattered fields
  - Design and control of modes

- Future: quantum-optics tools in microwave domain
  - Single photon source/detectors
  - Squeezed state generators
  - Parametric amplifiers