Cavity QED with Electronic Circuits

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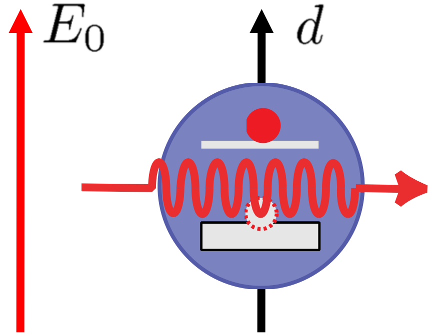
Free Atom

weak interaction with single photons:

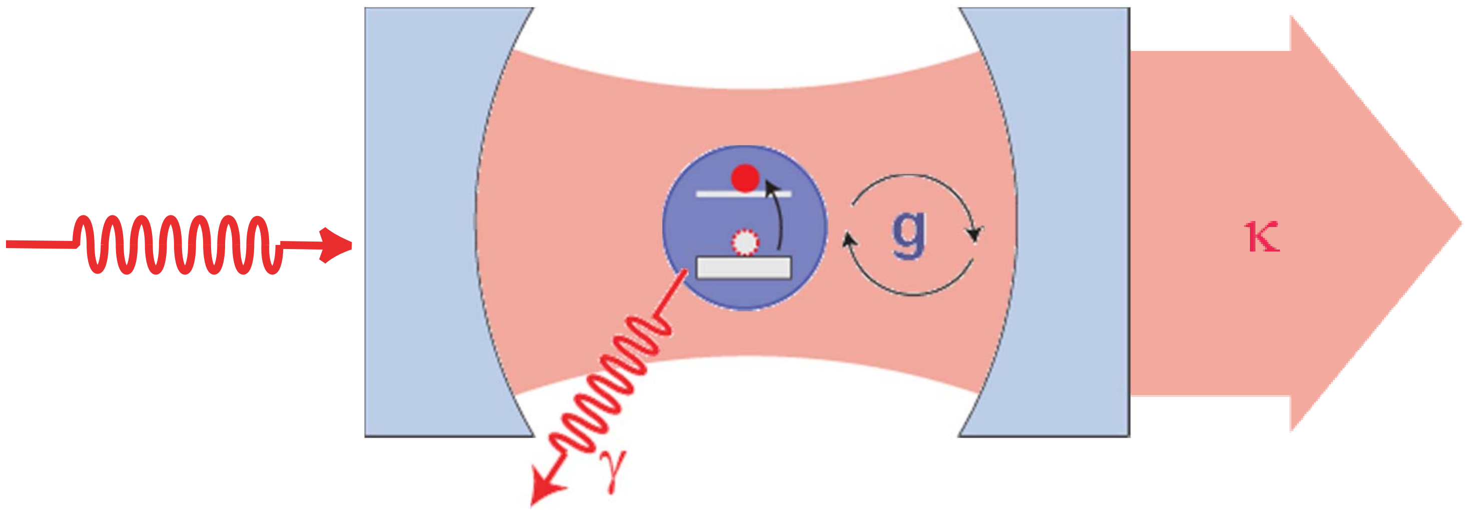


- dipole moment *d* (usually small in atoms ~ ea_o)
- single photon fields E_o (small in 3D)
- photon/atom interaction $\hbar g \sim dE_0$ (usually small)

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

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)]

Dressed States Energy Level Diagram

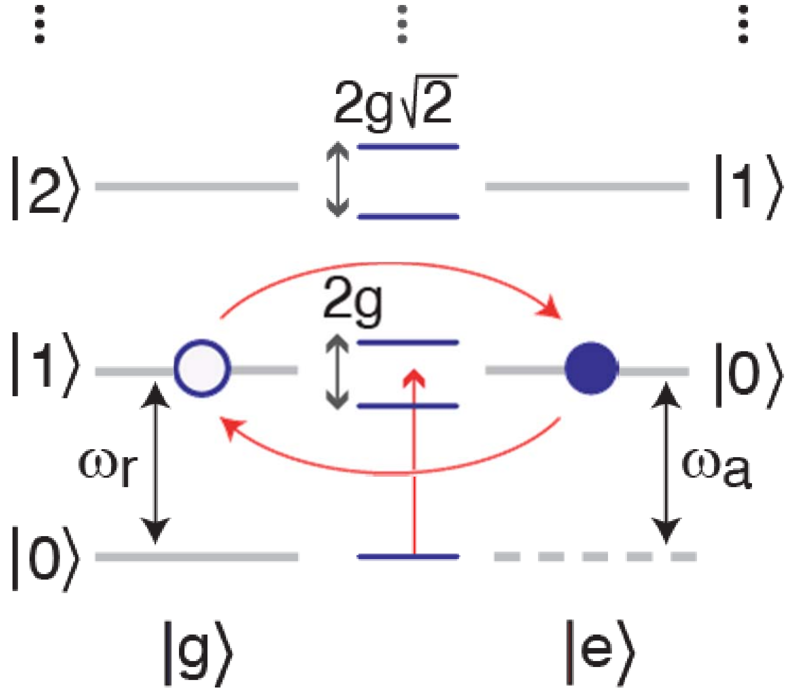
$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

in resonance:

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

strong coupling limit:

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



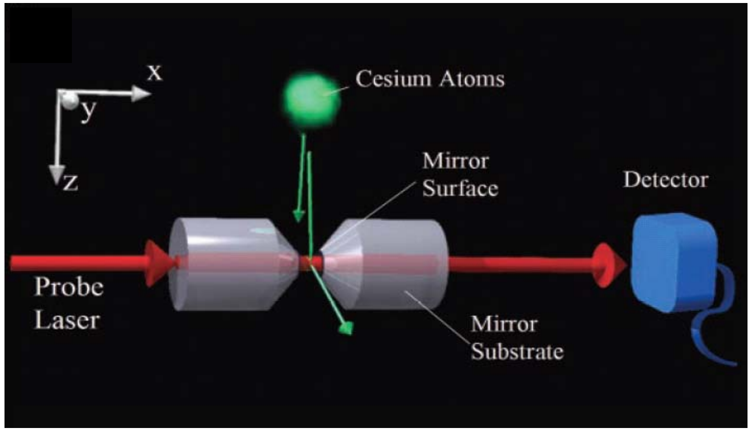
Jaynes-Cummings Ladder

Atomic cavity quantum electrodynamics reviews:

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

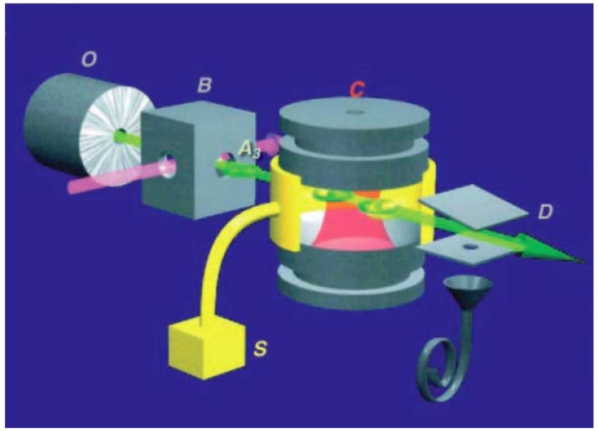
S. Haroche & J. Raimond, Exploring the Quantum, *OUP Oxford* (2006)

Cavity Quantum Electrodynamics (QED)



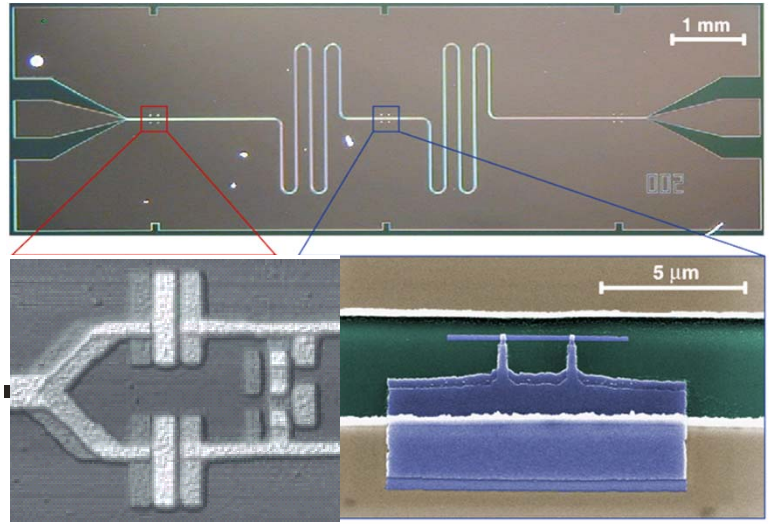
alkali atoms

MPQ, Caltech, ...



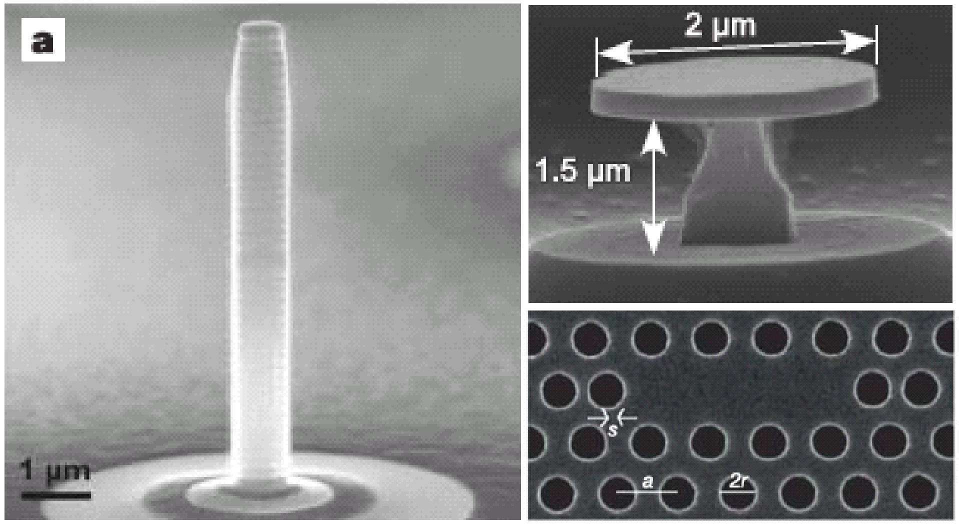
Rydberg atoms

ENS, MPQ, ...



superconductor circuits

Yale, Delft, NTT, ETHZ, NIST, …



semiconductor quantum dots

Wurzburg, ETHZ, Stanford …

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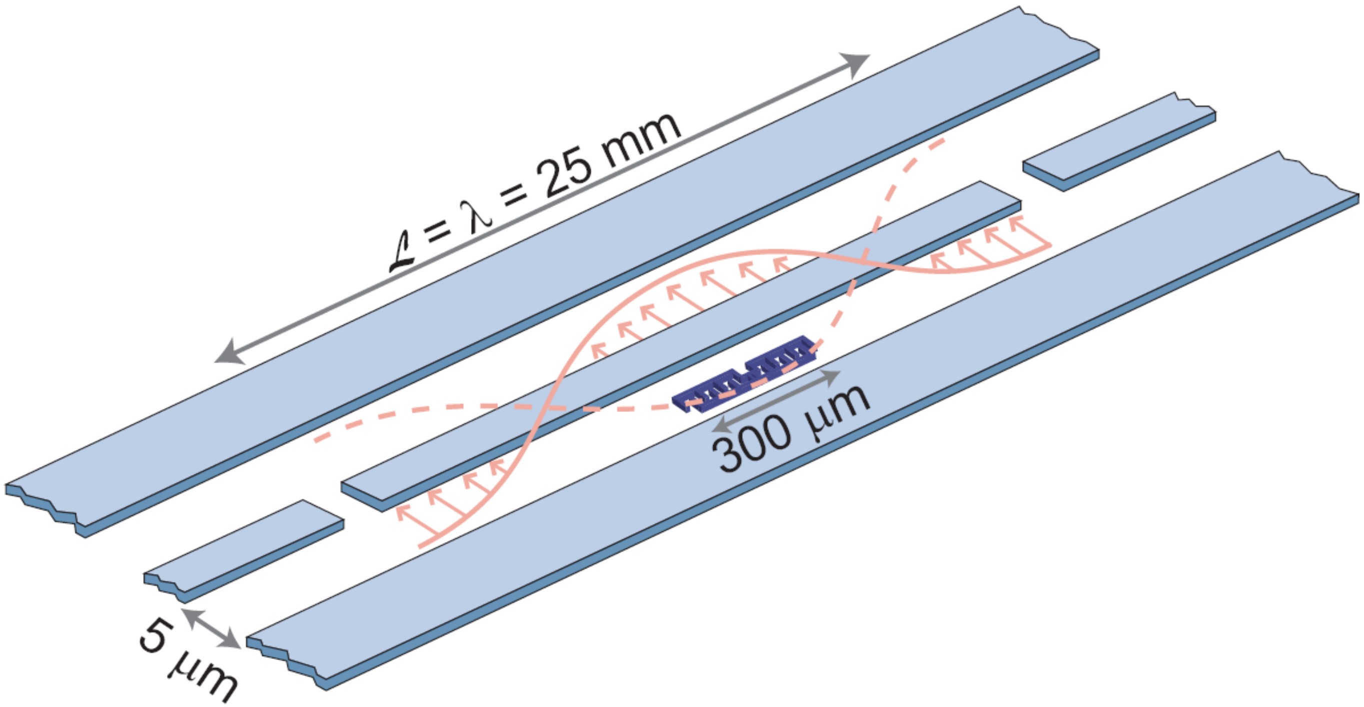
Circuit Quantum Electrodynamics

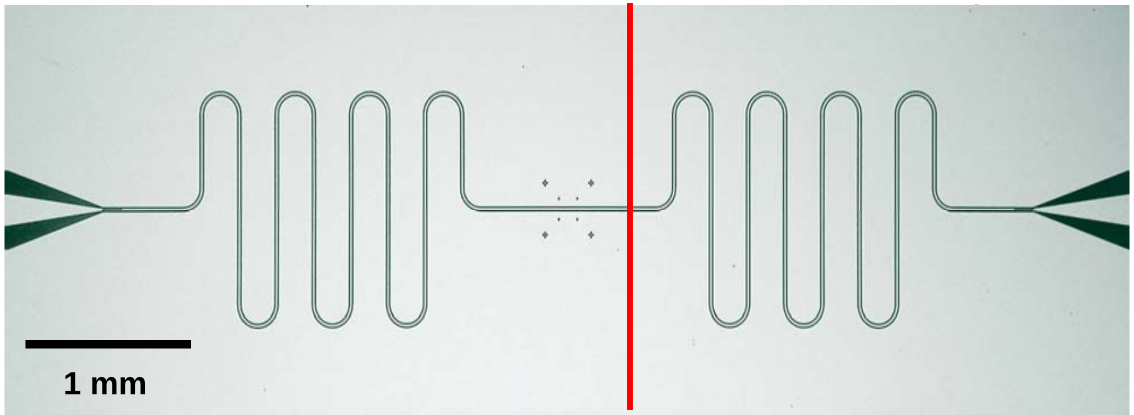


elements

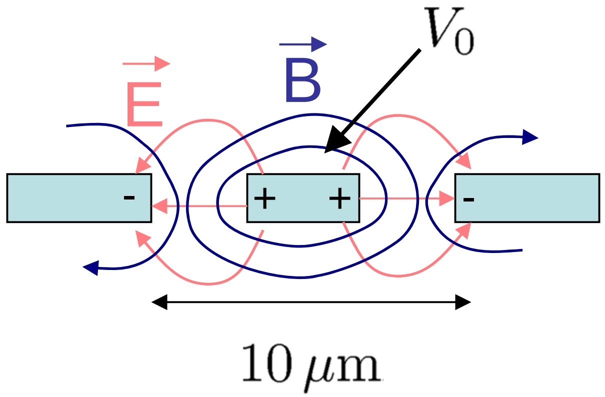
- the cavity: a superconducting 1D transmission line resonator with large vacuum field E_0 and long photon life time $1/\kappa$
- the artificial atom: a Cooper pair box (Transmon) with large dipole moment d and long coherence time $1/\gamma$

[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

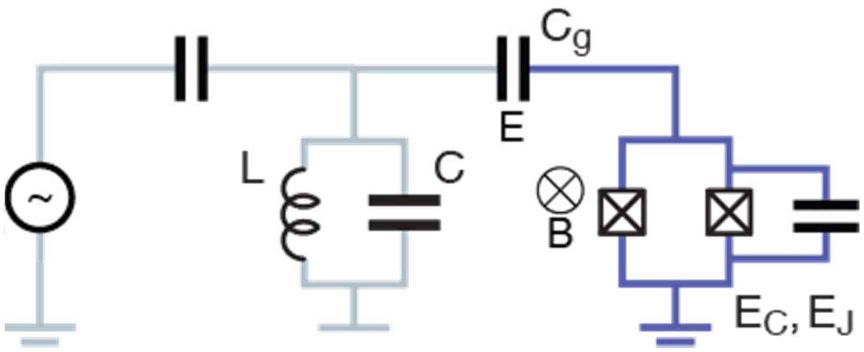
$$H_r = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right)$$

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

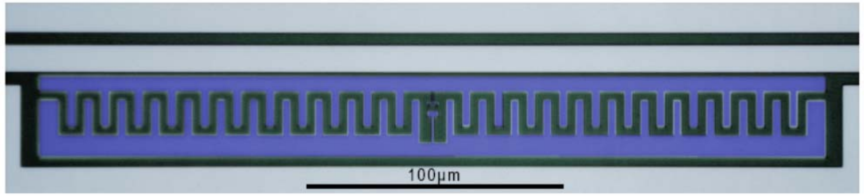
10^3 larger than in 3D cavity

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

Qubit/Photon Coupling in a Circuit



qubit coupled to resonator



coupling strength:

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

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

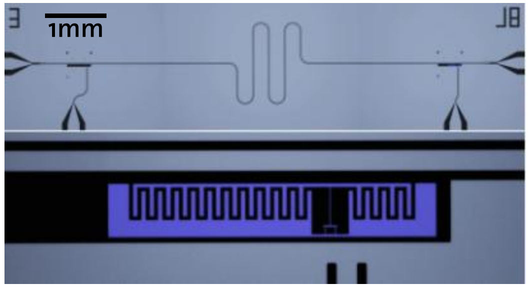
$g \gg [\kappa, \gamma]$ possible!

large effective dipole moment

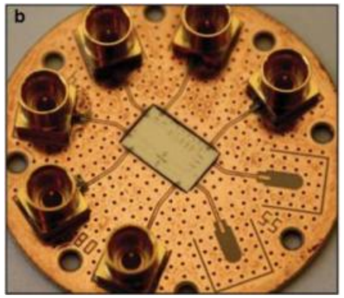
$$d = \frac{\hbar g}{E_0} \sim 4 \times 10^2 \ldots 10^5\, e a_0$$

Experimental Setup

Resonator+ transmon chip:



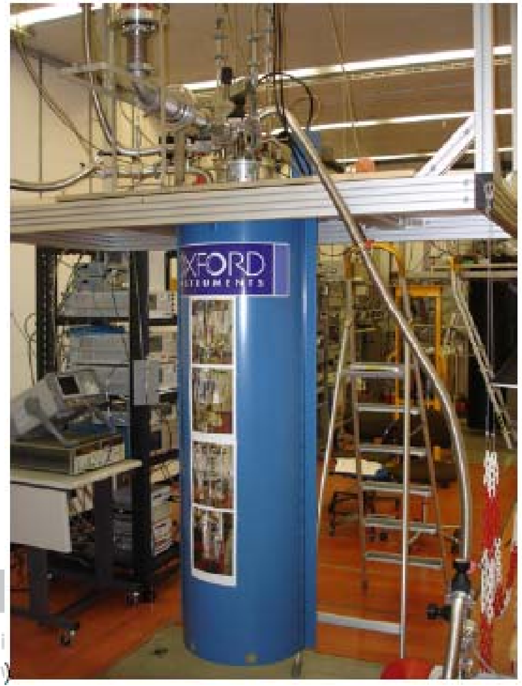
Sample holder:



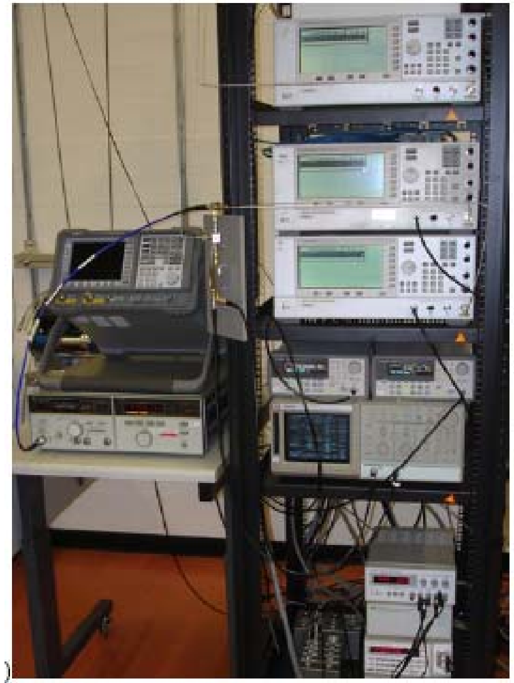
Box with B-field coils:

Cold stage 20 mK:

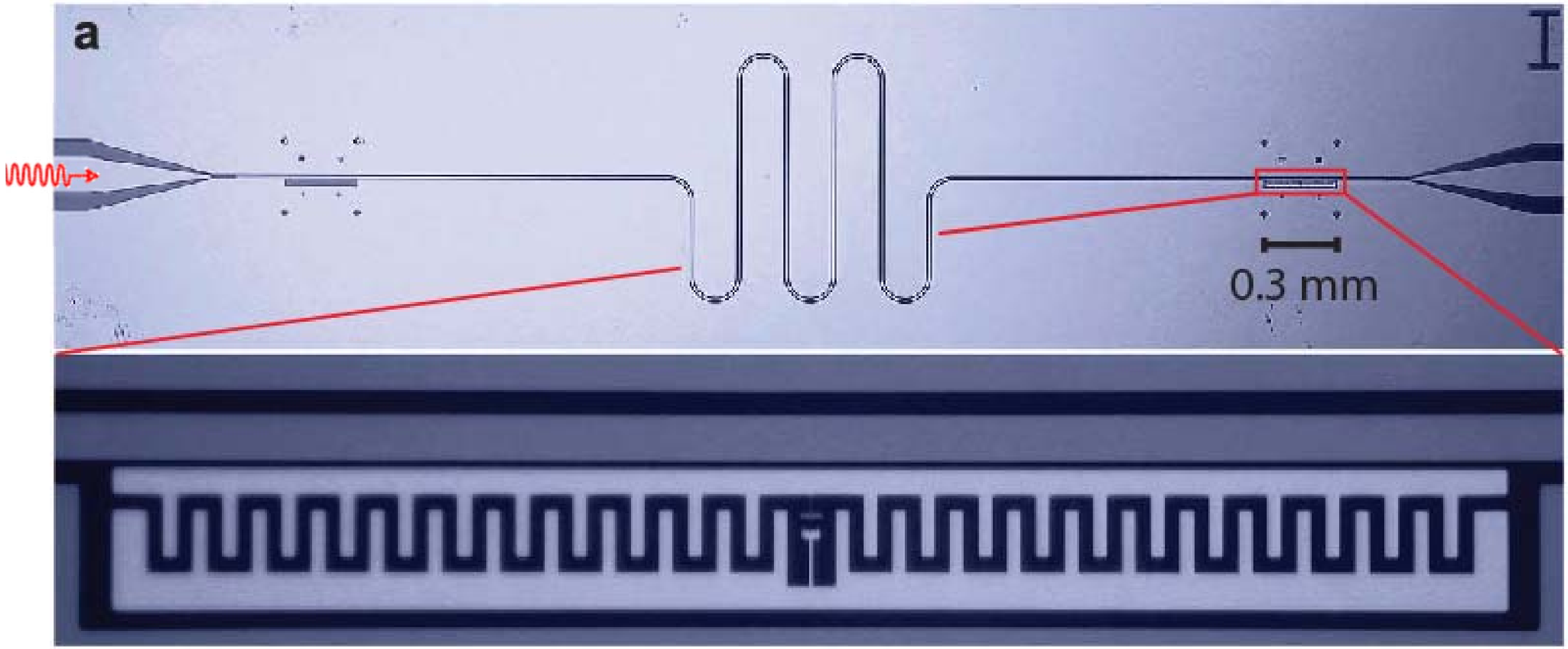
Dilution cryostat:



Microwave electronics:



Circuit QED with One Photon

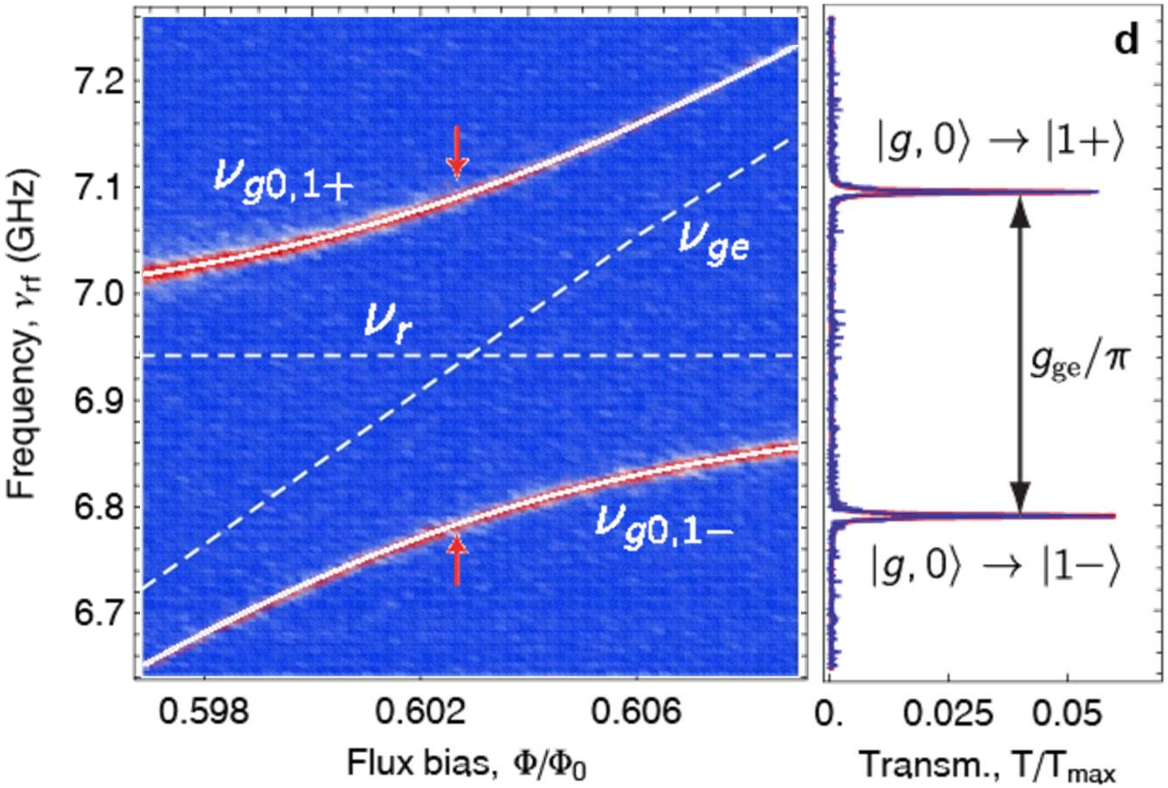


superconducting cavity QED circuit

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

Resonant Vacuum Rabi Mode Splitting …

… with one photon ($n = 1$):

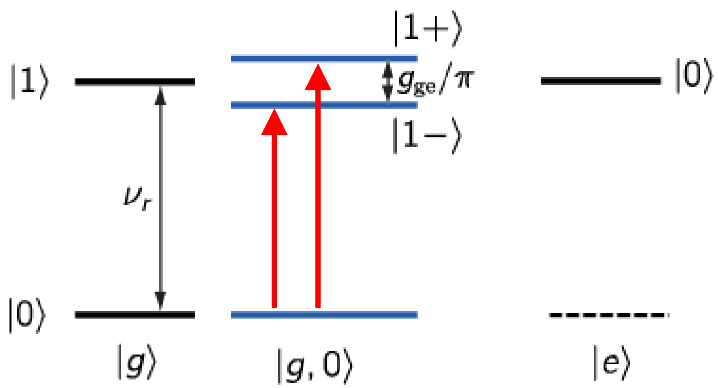


very strong coupling:

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

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

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



forming a 'molecule' of a qubit and a photon

$$|1\pm\rangle = \left(|g,1\rangle \pm |e,0\rangle\right)/\sqrt{2}$$

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

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

Dispersive Regime for Quantum Computation

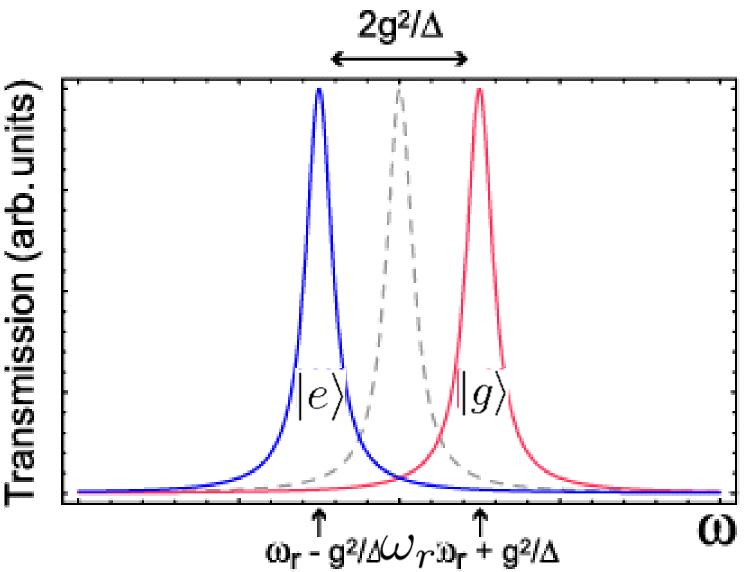
Non-Resonant (Dispersive) Interaction

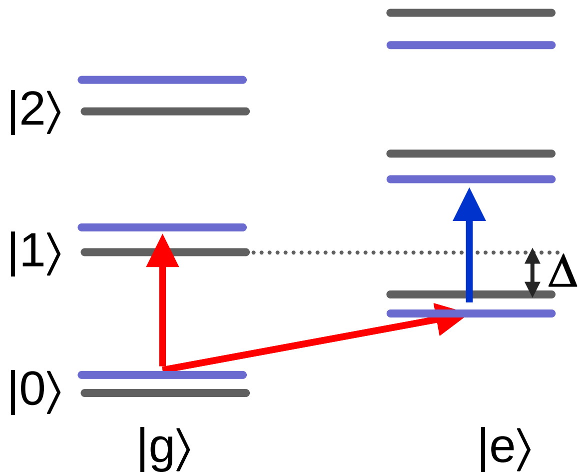
approximate diagonalization: $|\Delta| = |\omega_a - \omega_r| \gg g$:

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

// cavity frequency shift and qubit ac-Stark shift

// Lamb Shift





qubit detuned by Δ from resonator

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

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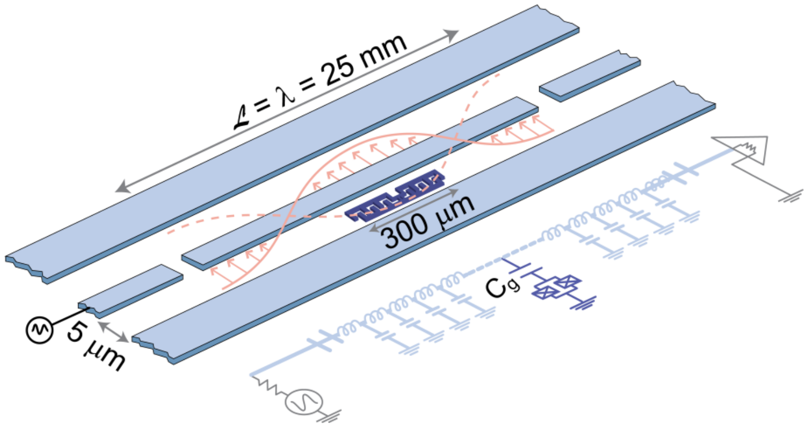
Circuit QED – read out of qubit state

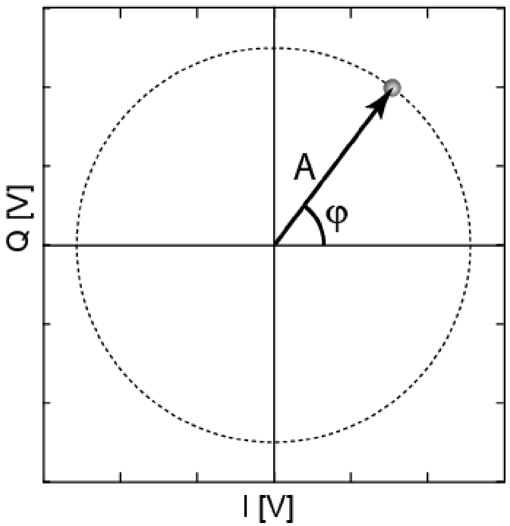
- transmission measurement to determine qubit state:



Phase sensitive measurement of transmitted microwave:

Voltage signal:

$$A(t)\sin(\omega_m t + \phi(t)) \equiv I(t)\sin\omega_m t + Q(t)\cos\omega_m t$$



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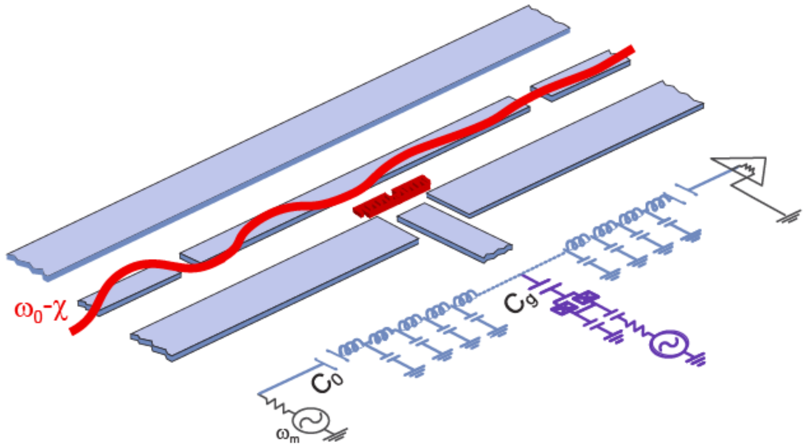

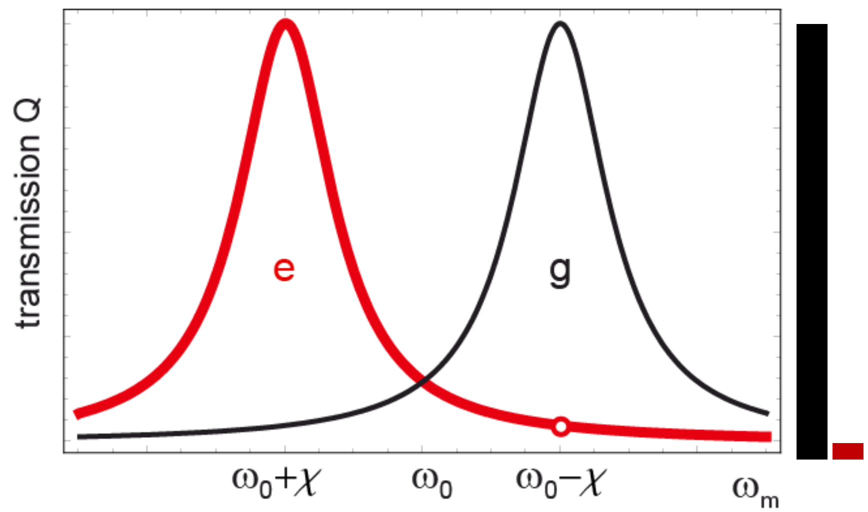

dispersive Hamiltonian:

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

state-dependent frequency shift -> σ_z determined

extendable to more qubits

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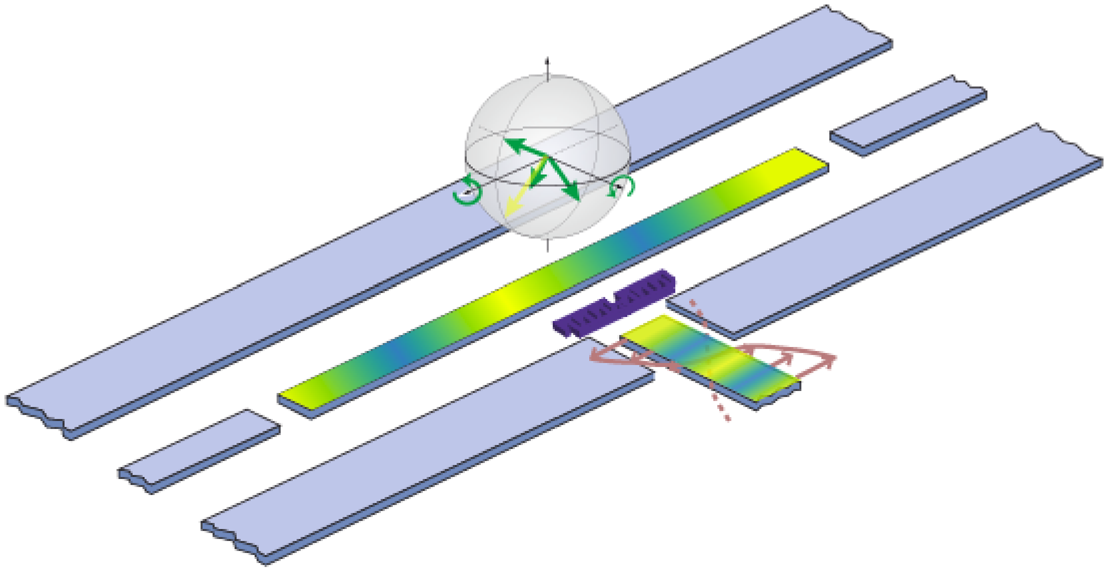
Qubit control

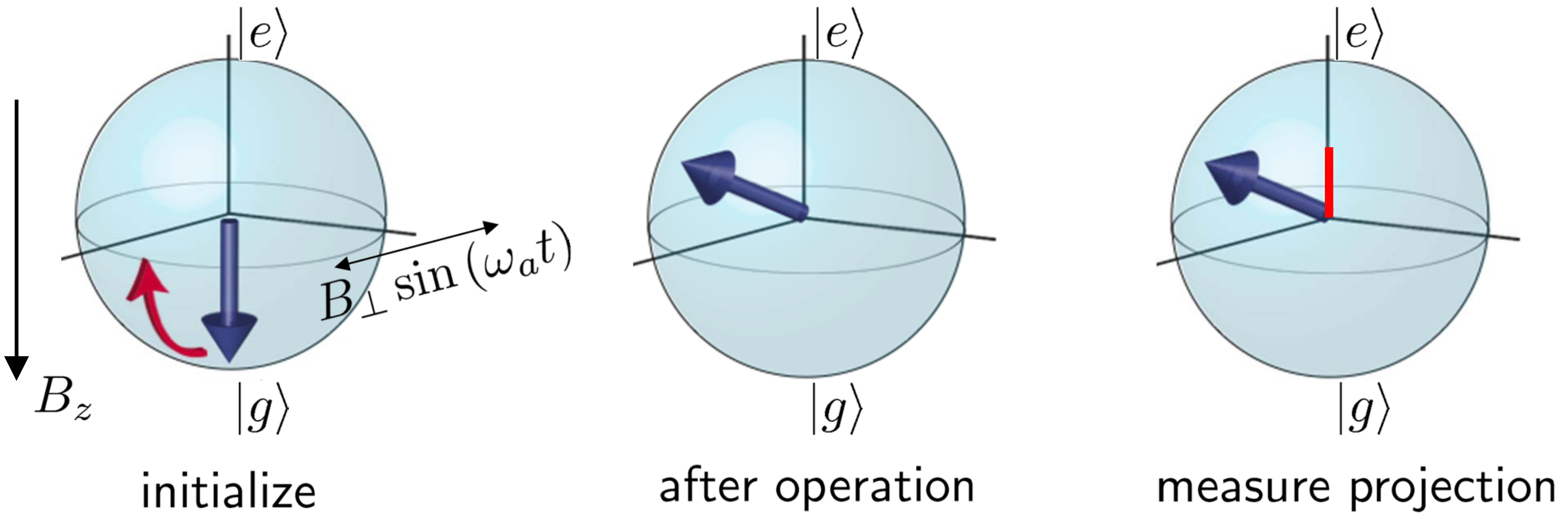
- apply microwave signal through resonator input
- or through side-gate



- time-dependent Hamiltonian for state manipulation

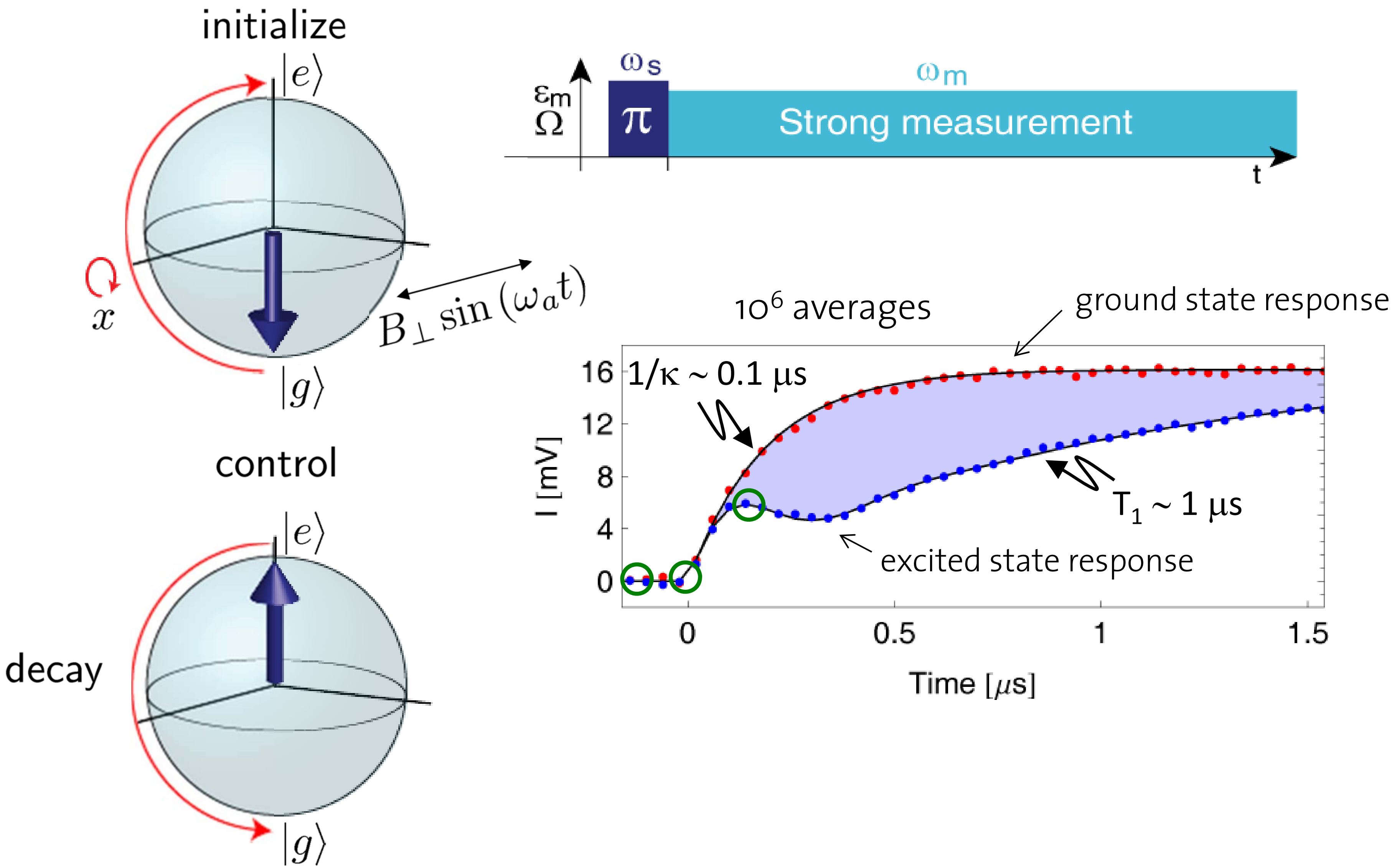
$$\hat{H} = \frac{1}{2}\hbar\omega_a\hat{\sigma}_z + \hbar\Omega_R\cos(\omega_b t + \phi_R)\hat{\sigma}_x$$

Coherent Control of a Qubit in a Cavity



- qubit state represented on a Bloch sphere
- vary length, amplitude and phase of microwave pulse to control qubit state

Qubit Control and Readout



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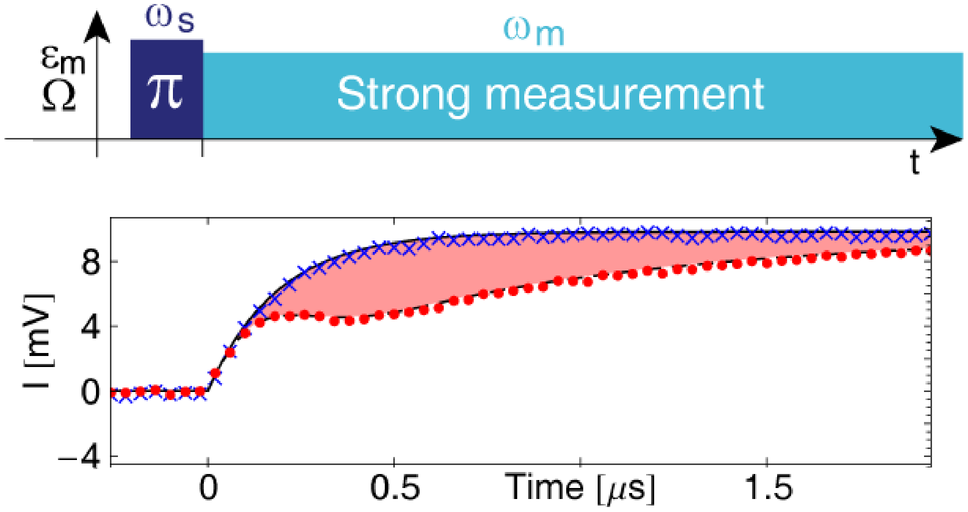
Time dependent measurements

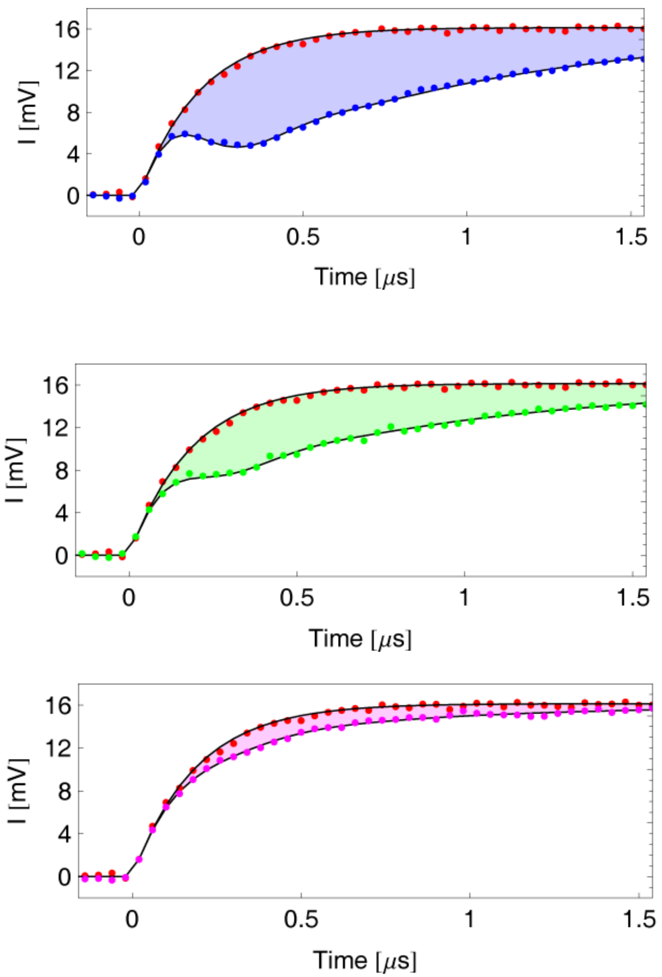
- excite qubit at t<o
- measure transmitted field quadratures (I, Q) with microwave drive at resonance ($\omega_m = \omega_r - \chi$)
- qubit in ground state: full resonator transmission (rise time given by κ)
- qubit in excited state: only partial transmission until qubit decays to ground state

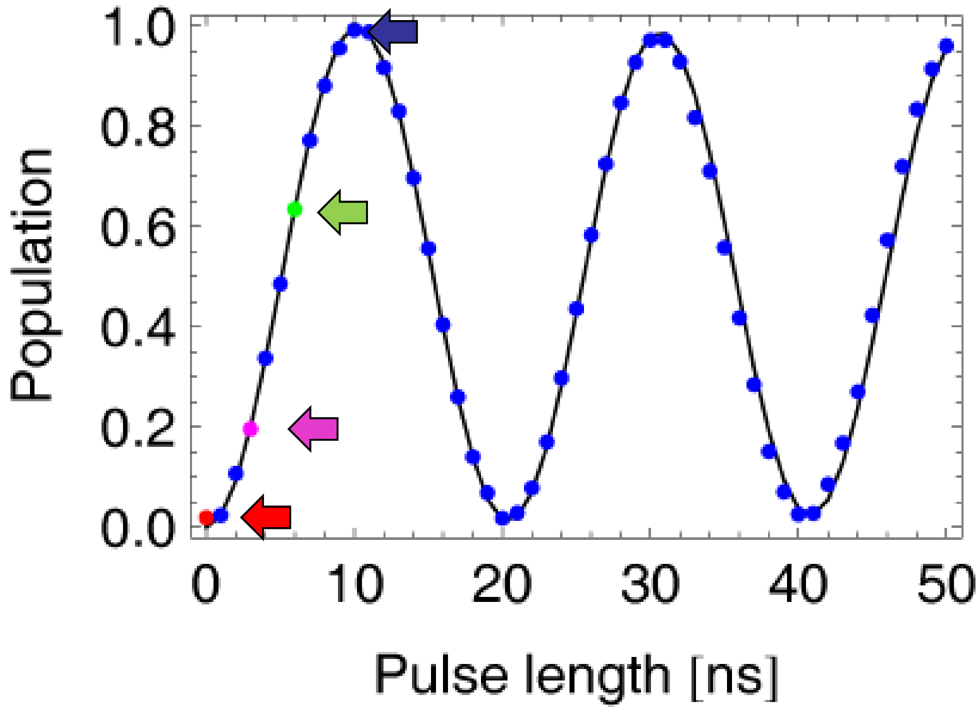


[Bianchetti *et al*. PRA 80 (2009)]

Population reconstruction

Area between curves is proportional to qubit state population:

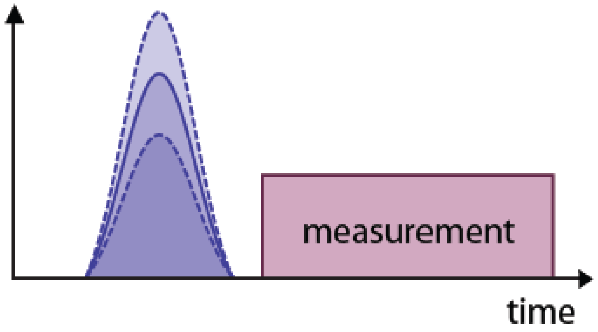


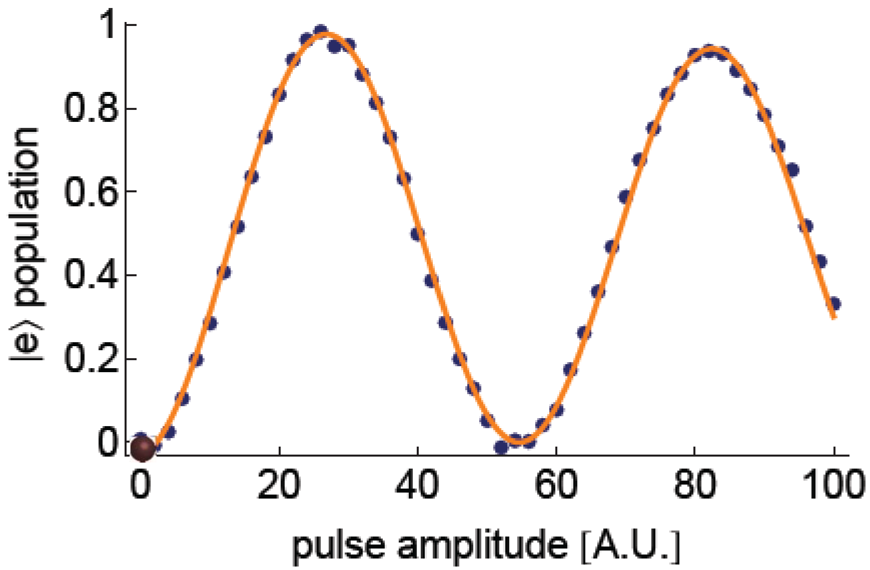


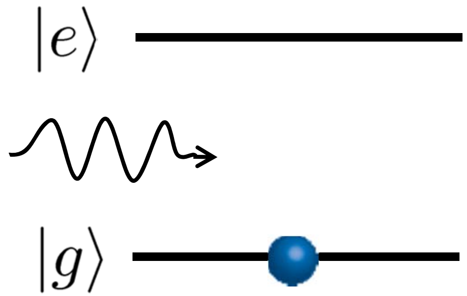
typical pulse length for π-pulse: 10ns

Coherent population transfer – Rabi Oscillations

drive system at its resonance frequency with varying drive strength:





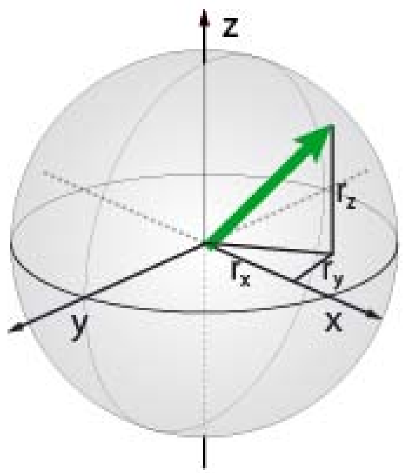


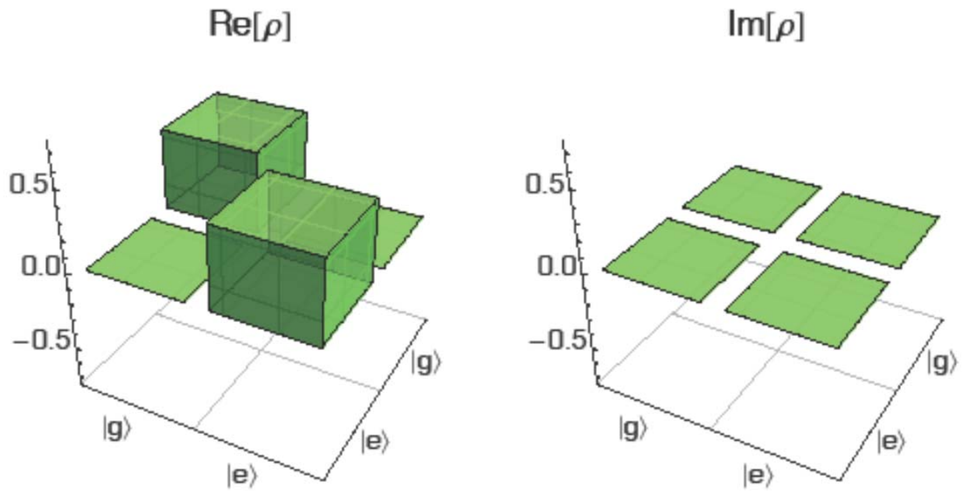
- high visibility (~ 99%)
- well characterized and understood measurement
- good control accuracy

State reconstruction single qubit

3 measurements for 3 coefficients r_x, r_y, r_z of

$$\rho = \frac{1}{2}(\mathrm{id} + r_x\sigma_x + r_y\sigma_z + r_z\sigma_z)$$





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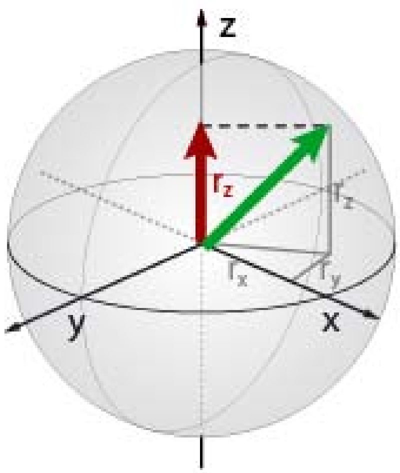
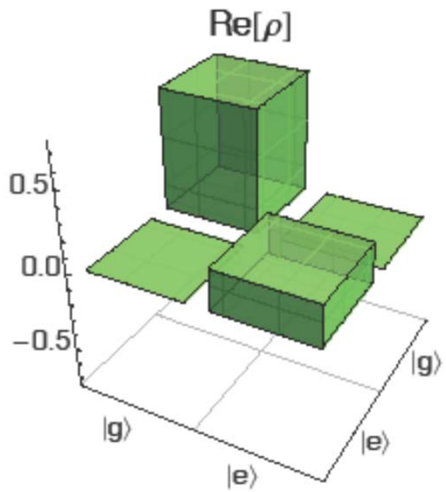
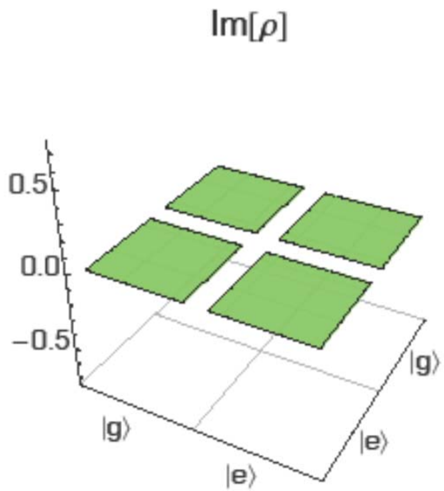
Measurement along z-axis: $r_z = \langle\sigma_z\rangle = \mathrm{Tr}[\rho\sigma_z]$







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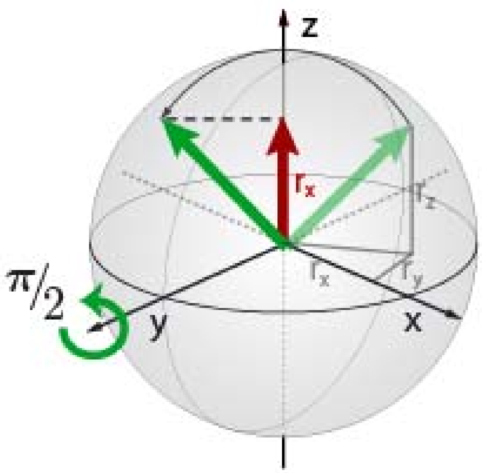
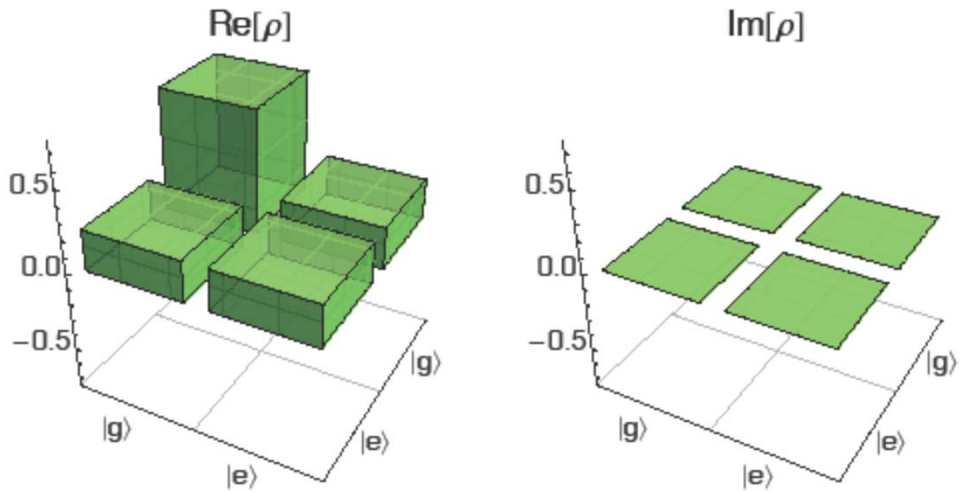
Measurement along z-axis: $r_z = \langle\sigma_z\rangle = \mathrm{Tr}[\rho\sigma_z]$

Rotation + measurement: $r_x = \langle\sigma_x\rangle = \mathrm{Tr}[\left(\frac{\pi}{2}\right)_y \rho \left(\frac{\pi}{2}\right)_{-y} \sigma_z]$





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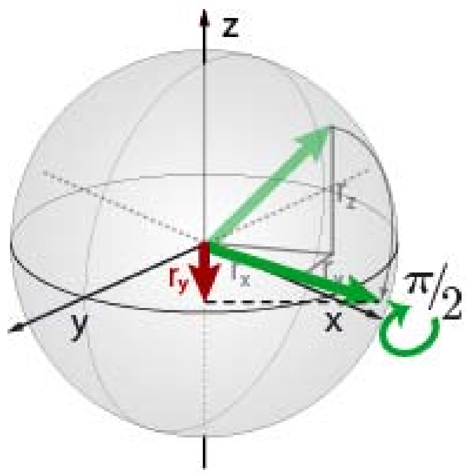
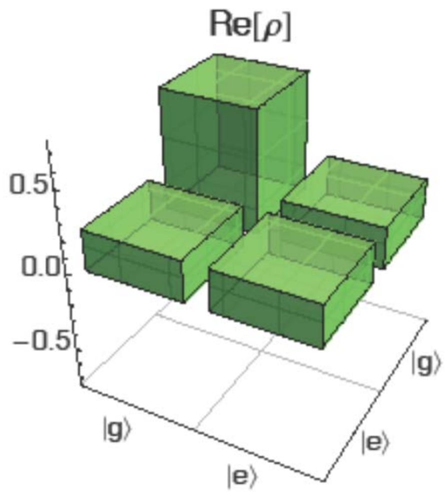
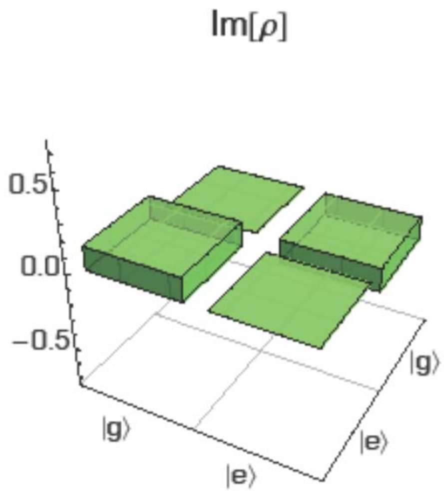
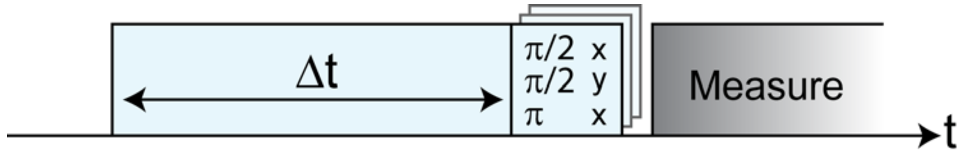




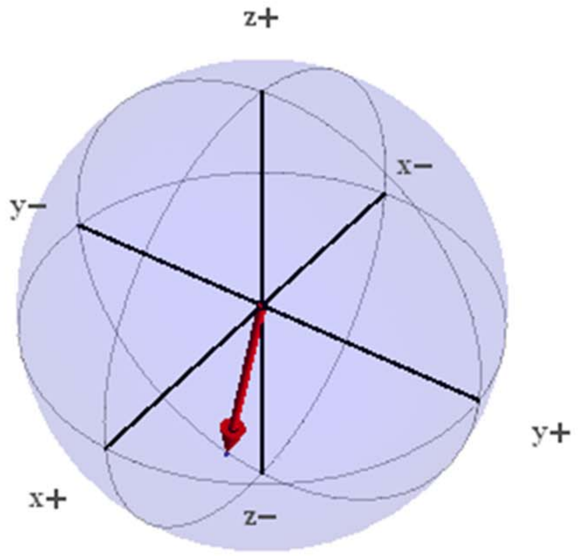


Control and Tomographic Read-Out of Single Qubit

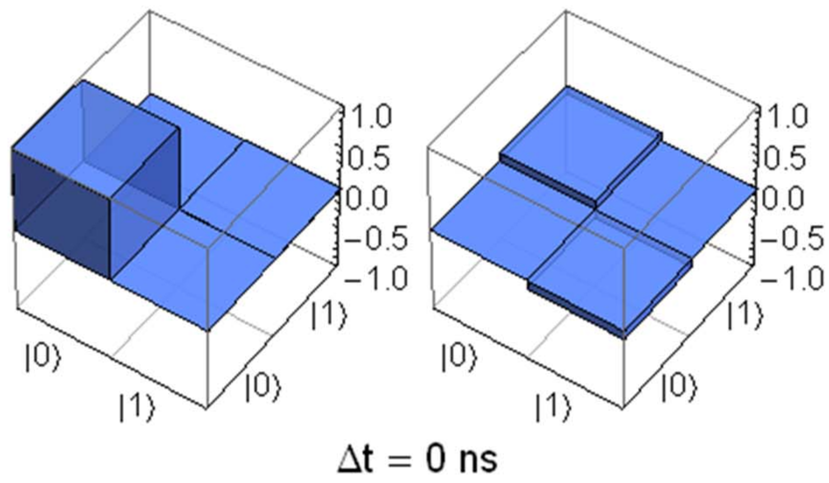
Rabi rotation pulse sequence:



experimental Bloch vector:



experimental density matrix:



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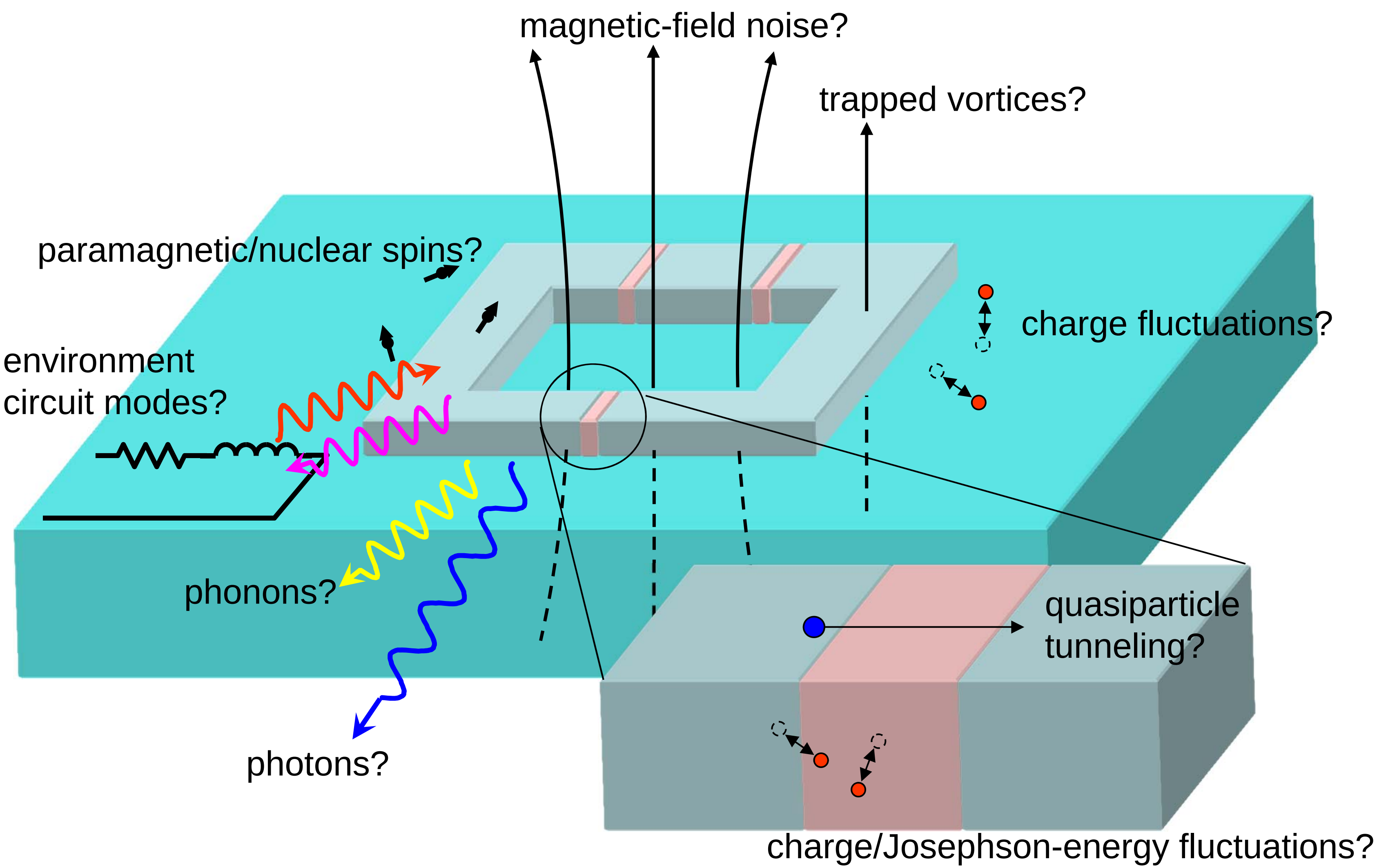
L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Sources of Decoherence

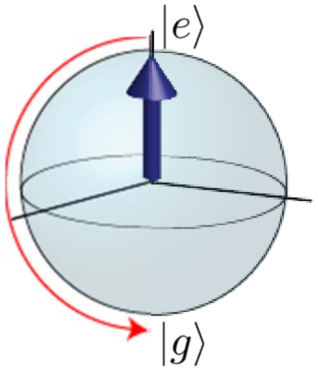


G. Ithier *et al.*, *Phys. Rev. B* **72**, 134519 (2005)

Relaxation and dephasing (T_1 and T_2)

- T_1: energy relaxation time

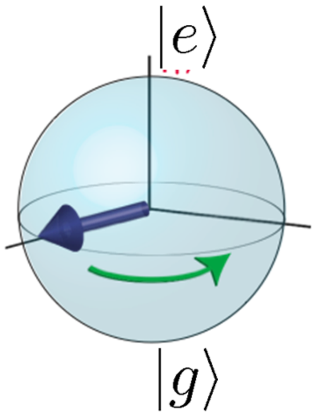
depolarization, decay



perturbation orthogonal to quantization axis ($\propto \sigma_{x,y}$); e.g. fast charge fluctuations causing transitions

- T_2: dephasing time

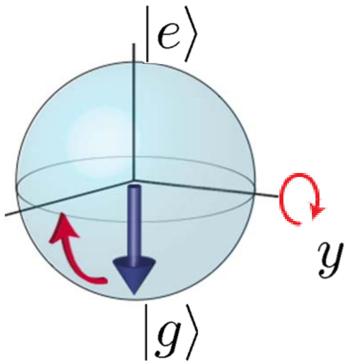
dephasing

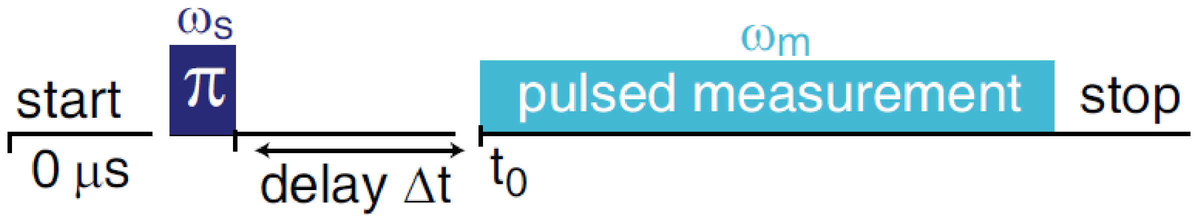


slow perturbation along quantization axis ($\propto \sigma_z$); e.g. magnetic flux noise causing phase randomization

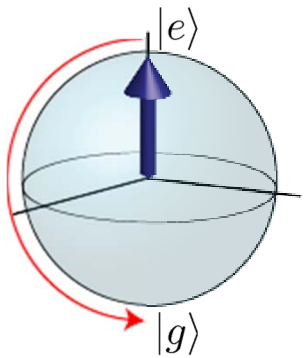
Relaxation Time (T1) Measurement

pulse scheme:

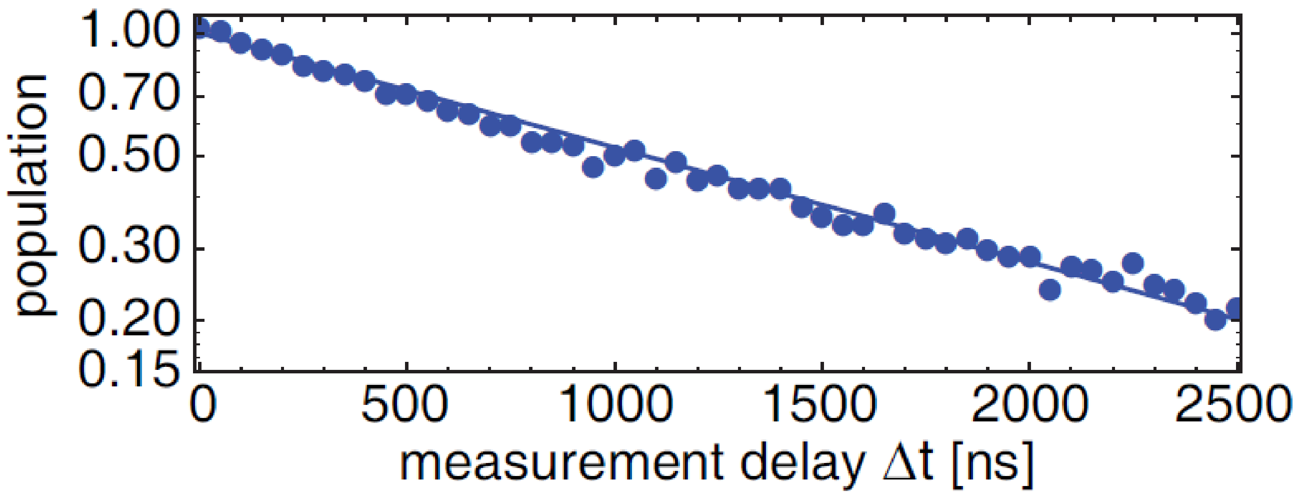




decay



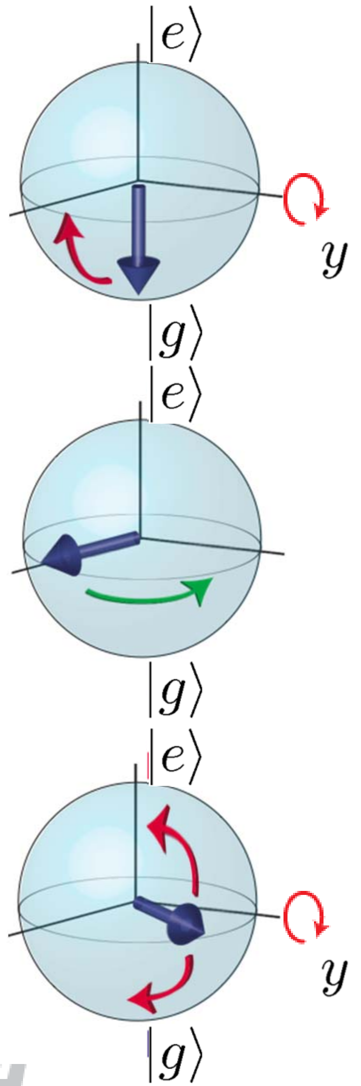
T_1=1.2 us

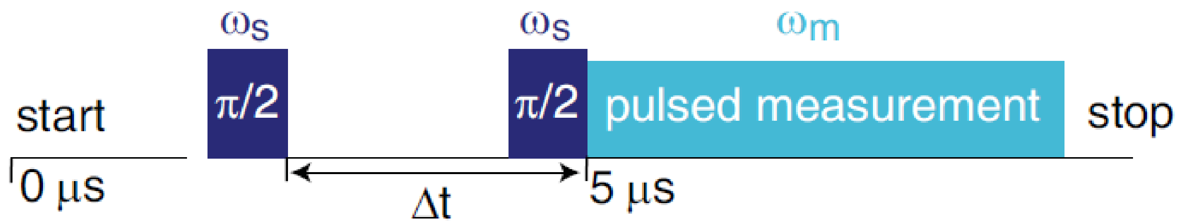


R. Bianchetti, QUDEV, ETH Zurich (2010)

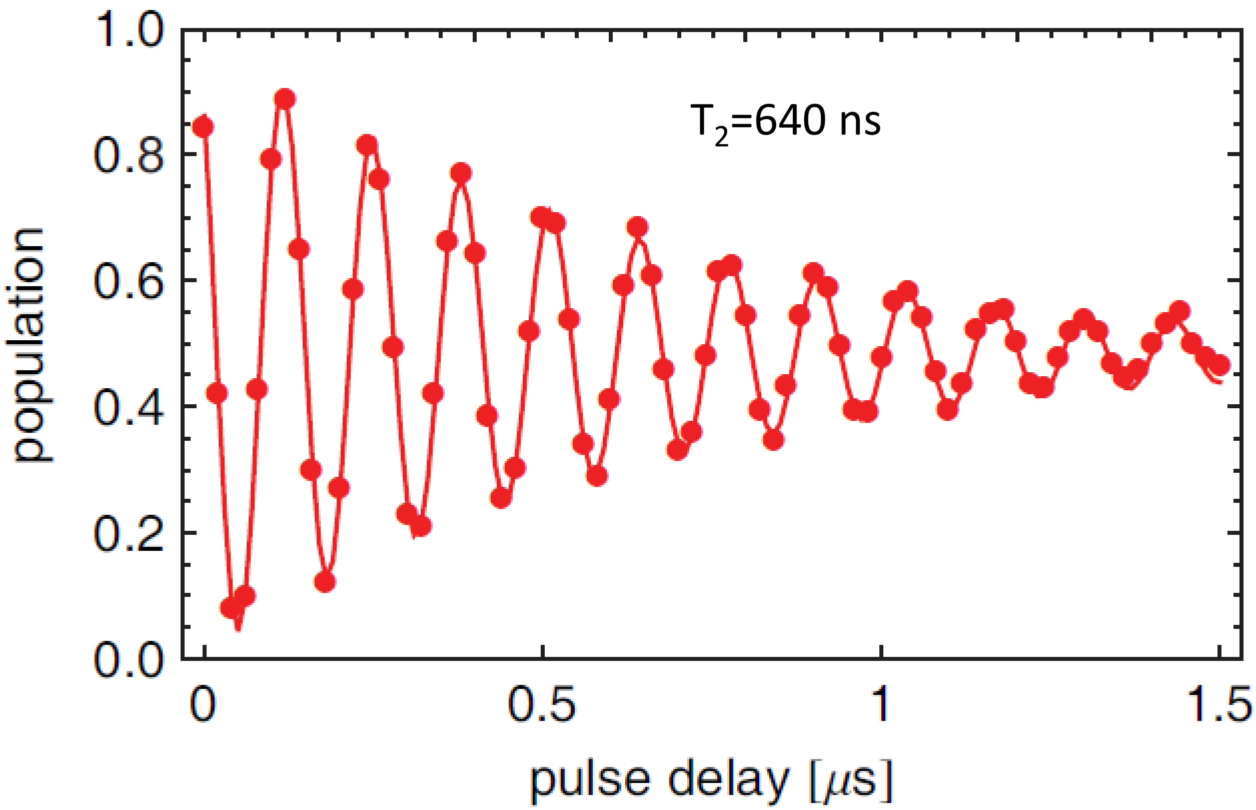
Coherence Time (T2) Measurement: Ramsey Fringes

pulse scheme:





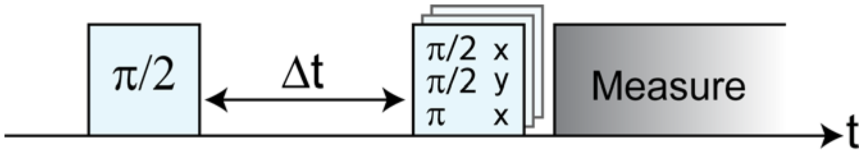
Ramsey fringes:

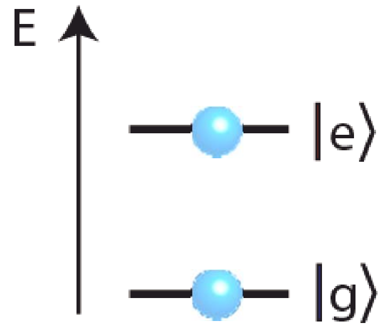


R. Bianchetti, QUDEV, ETH Zurich (2010)

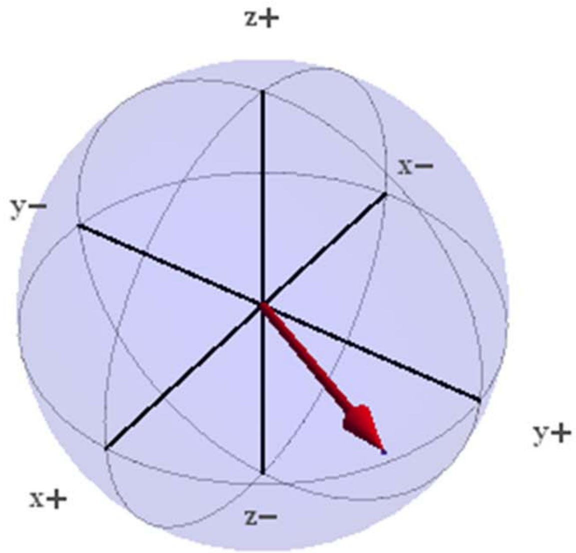
Tomography of Ramsey Experiment

pulse sequence:

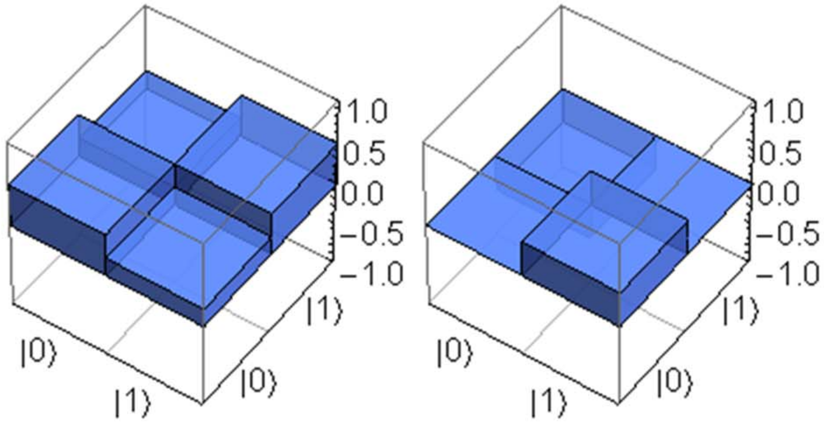




experimental Bloch vector:



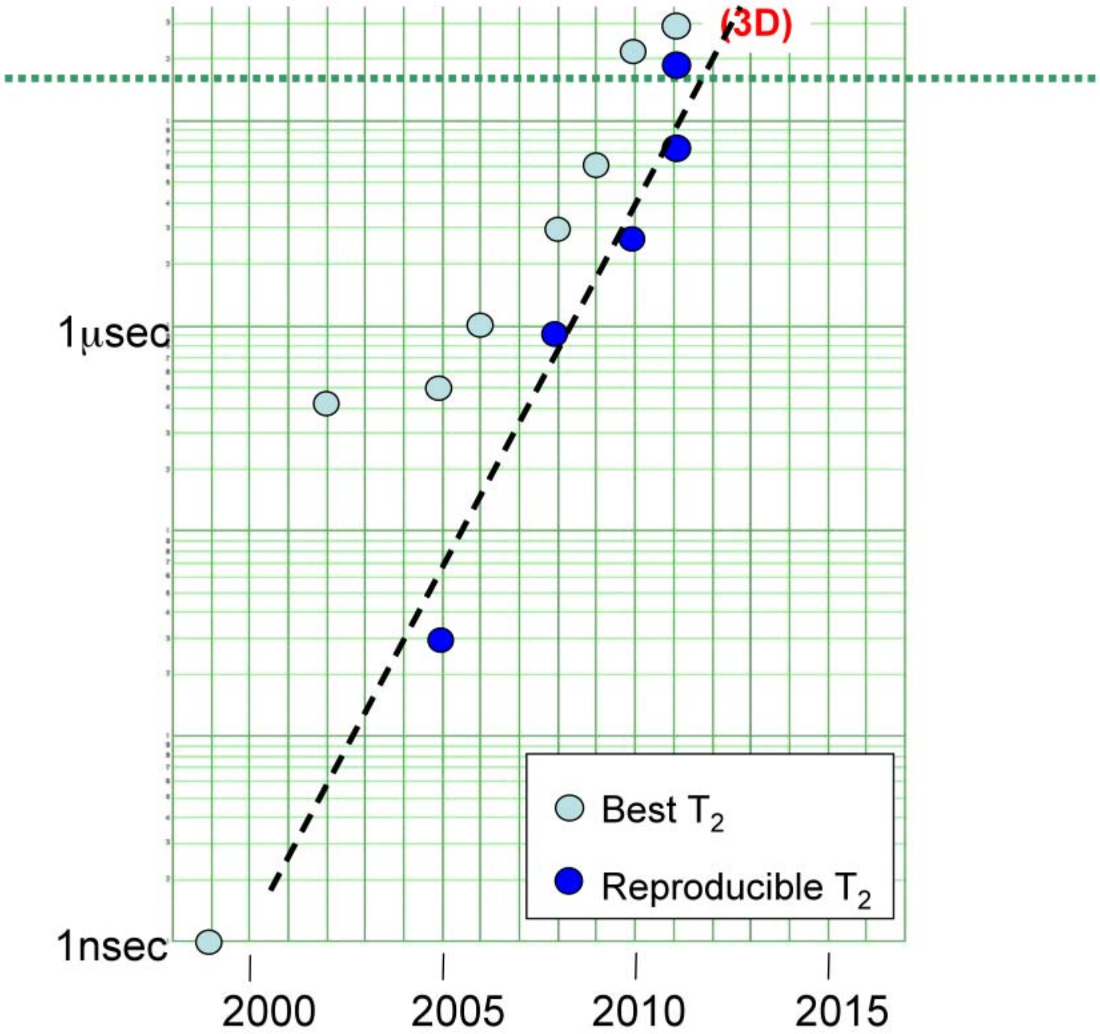
experimental density matrix:



$\Delta t = 0$ ns

L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Evolution of T2 – coherence of superconducting qubits



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