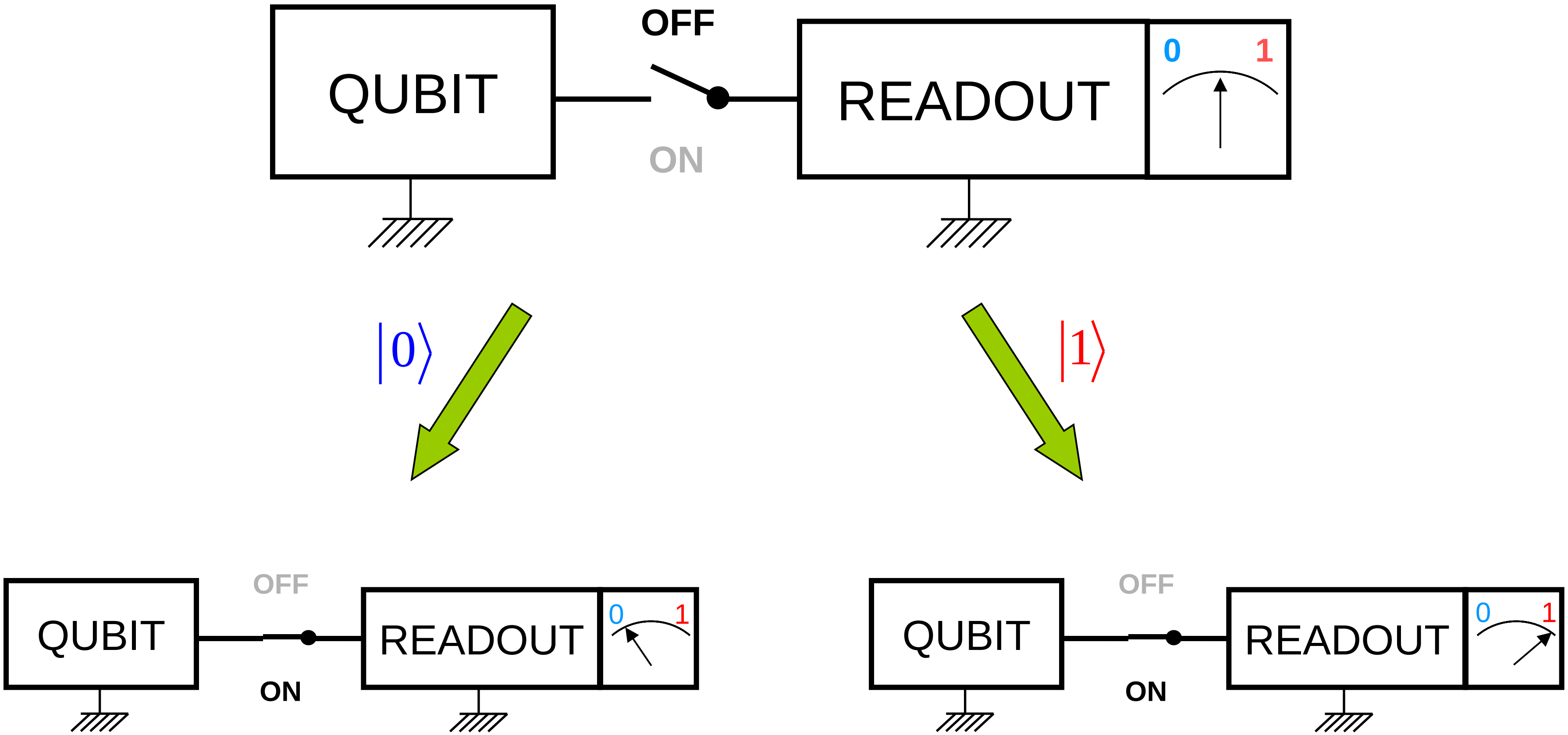
Read-Out …

… of a superconducting charge qubit

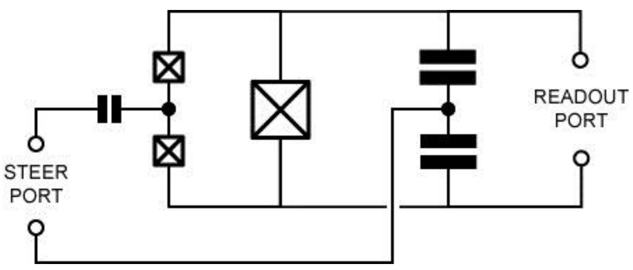
Qubit Read Out



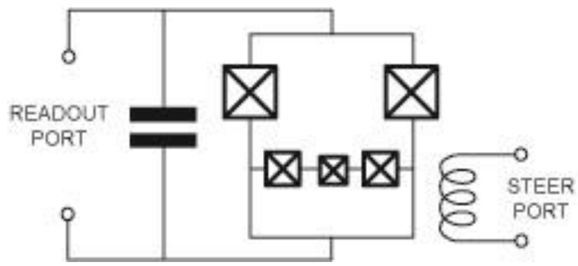
desired: good on/off ratio
no relaxation in on state (QND)

Read Out Strategies

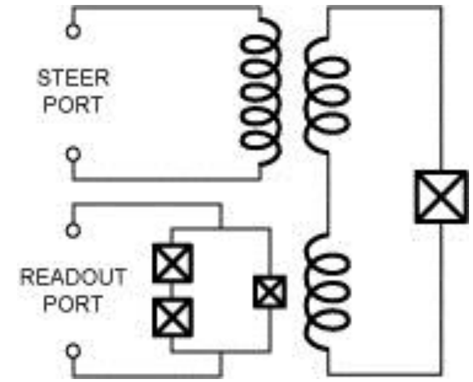
demolition measurements (switching/latching measurements)



Quantronium (Saclay, Yale)

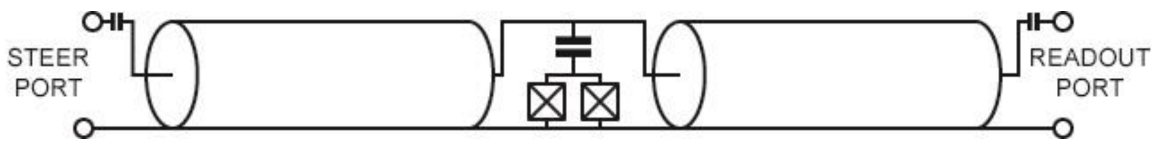


Flux Qubit (TU Delft, NEC)



Phase Qubit (NIST, UCSB)

quantum non-demolition (QND) measurements



Yale (circuit QED)

also: Chalmers, Delft, Yale (JBA)

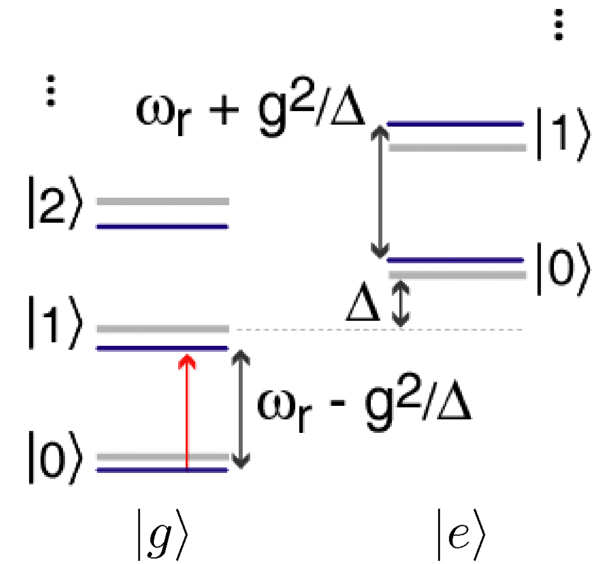
Non-Resonant Qubit-Photon Interaction

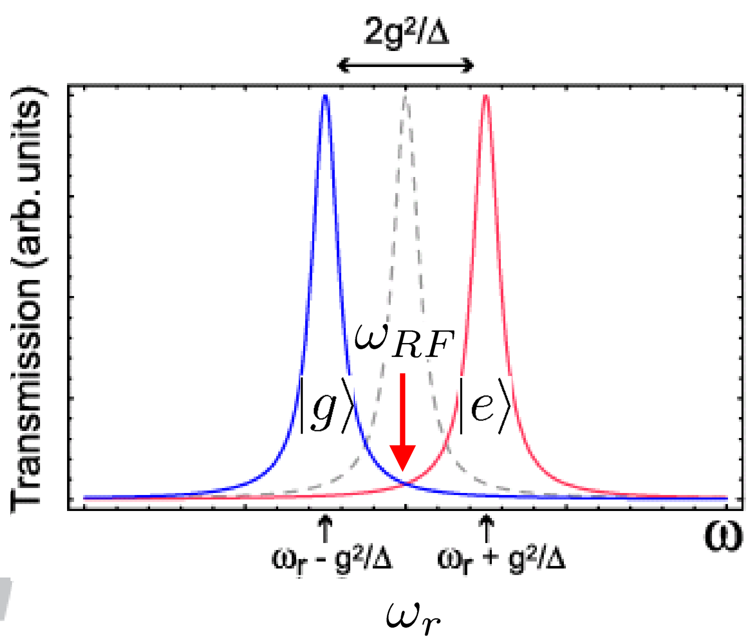
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

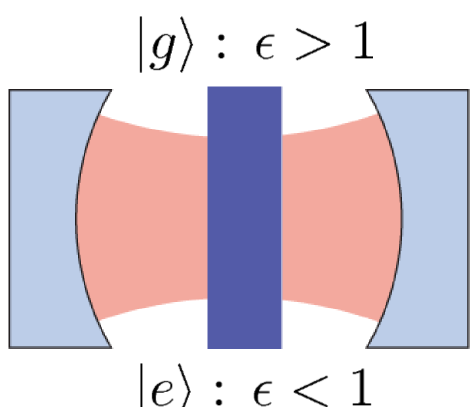
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta}\right) \sigma_z$$

//
cavity frequency shift
and qubit ac-Stark shift

//
Lamb shift







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

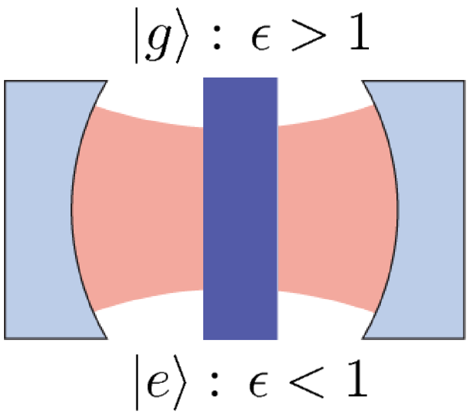
Non-Resonant Qubit-Photon Interaction

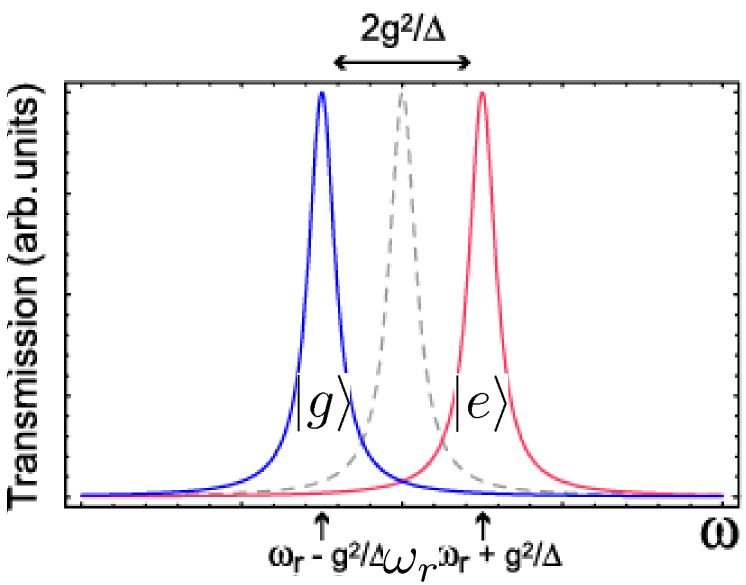
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

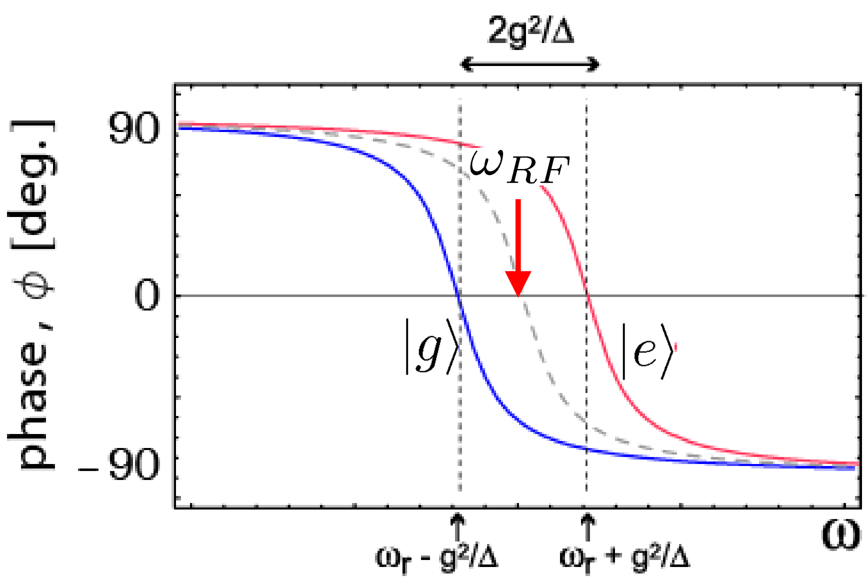
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z \right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

cavity frequency shift
and qubit ac-Stark shift

Lamb shift





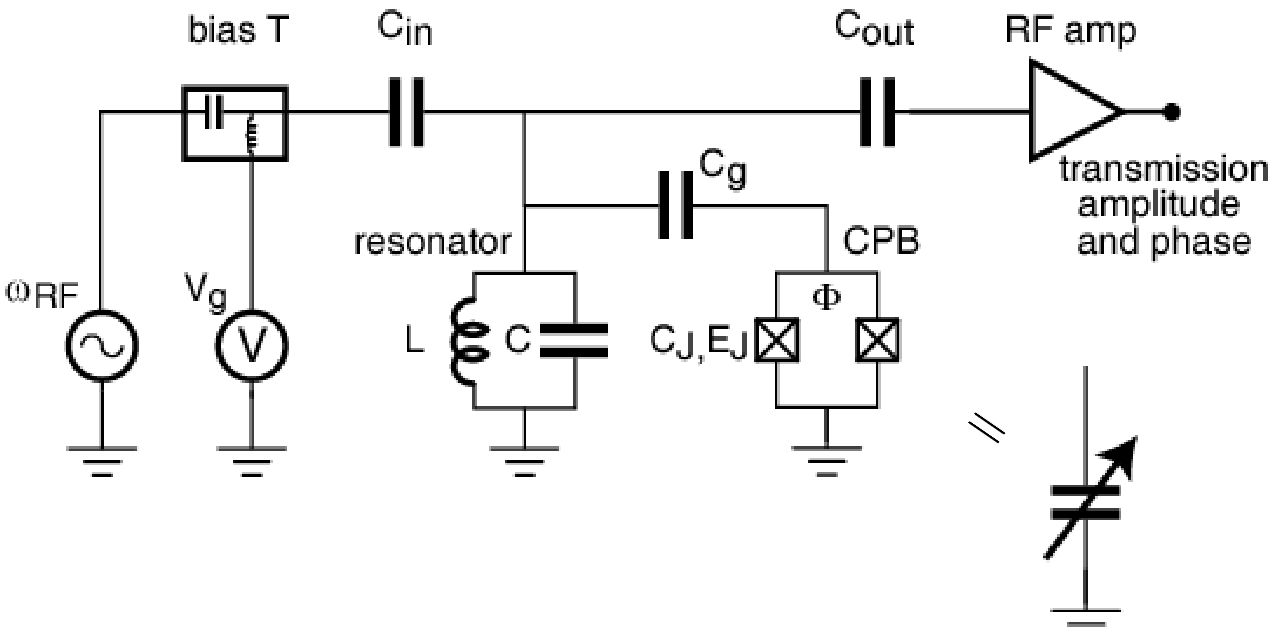


A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Qubit Spectroscopy with Dispersive Read-Out …

… additional material

Measurement Technique

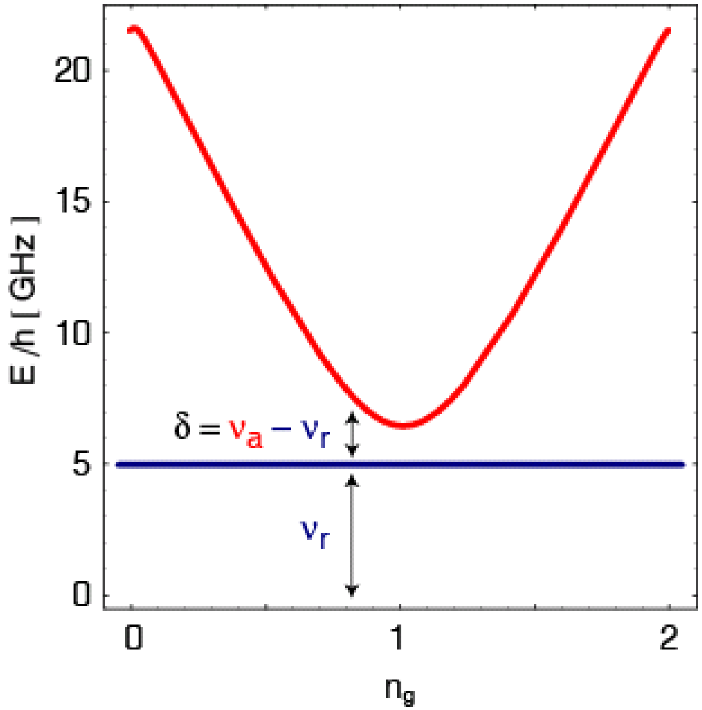


- measurement of microwave transmission amplitude T and phase ϕ
- intra-cavity photon number controllable from $n \sim 10^3$ to $n \ll 1$

Dispersive Shift of Resonance Frequency

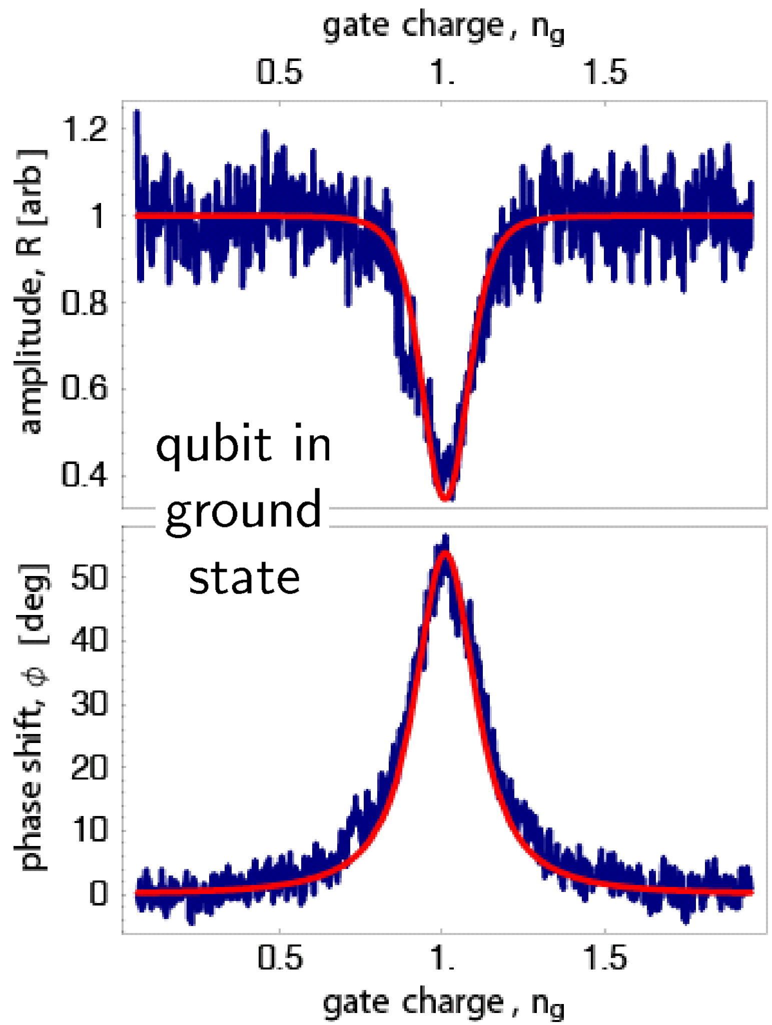
sketch of qubit level separation:

$$\Delta = 2\pi\delta > g$$

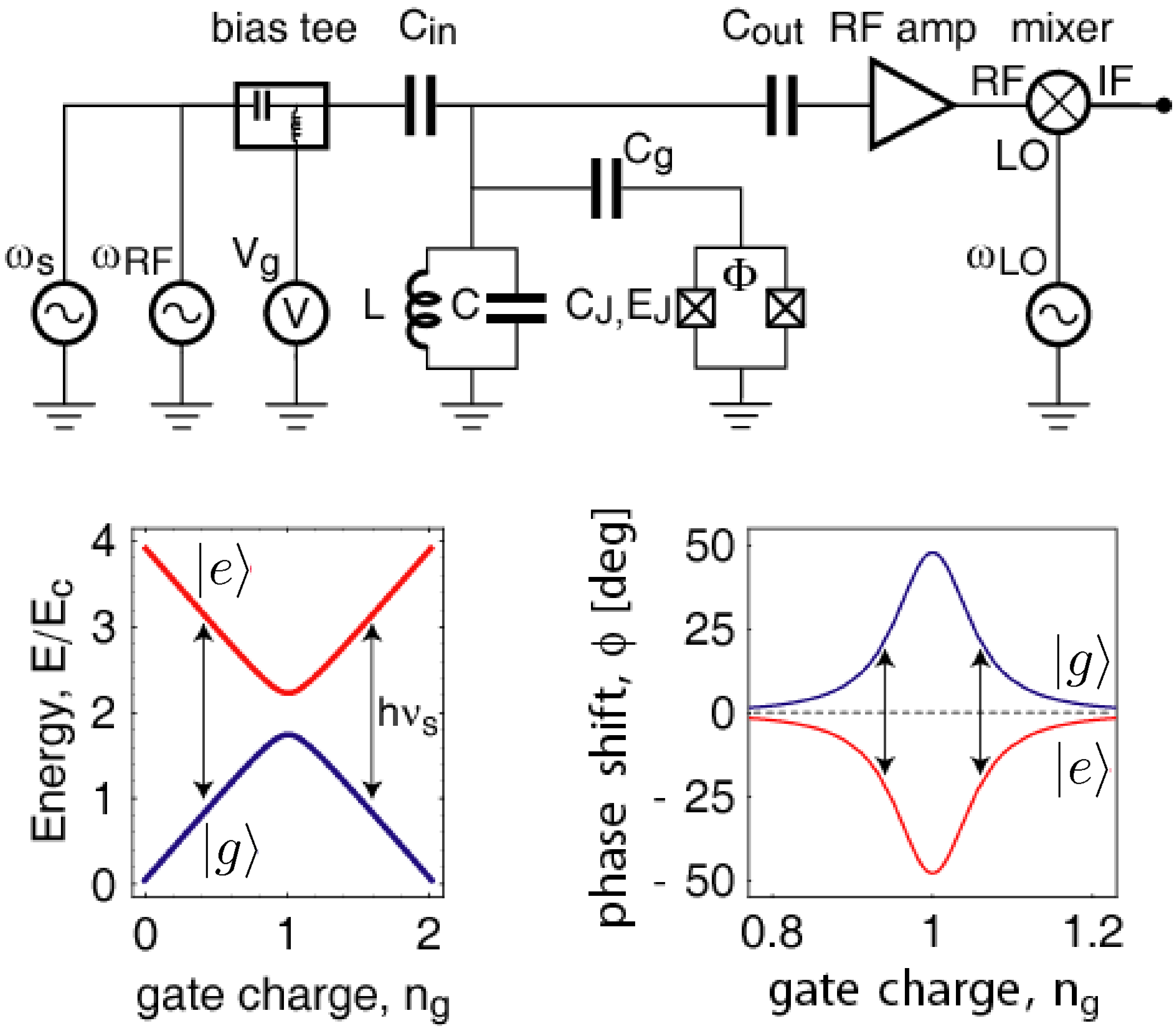


$$\begin{aligned} g/\pi = \nu_{\text{vac}} &= 11\,\text{MHz} \\ \Delta(n_g = 1)/2\pi &= 66\,\text{MHz} \\ n &= 10 \end{aligned}$$

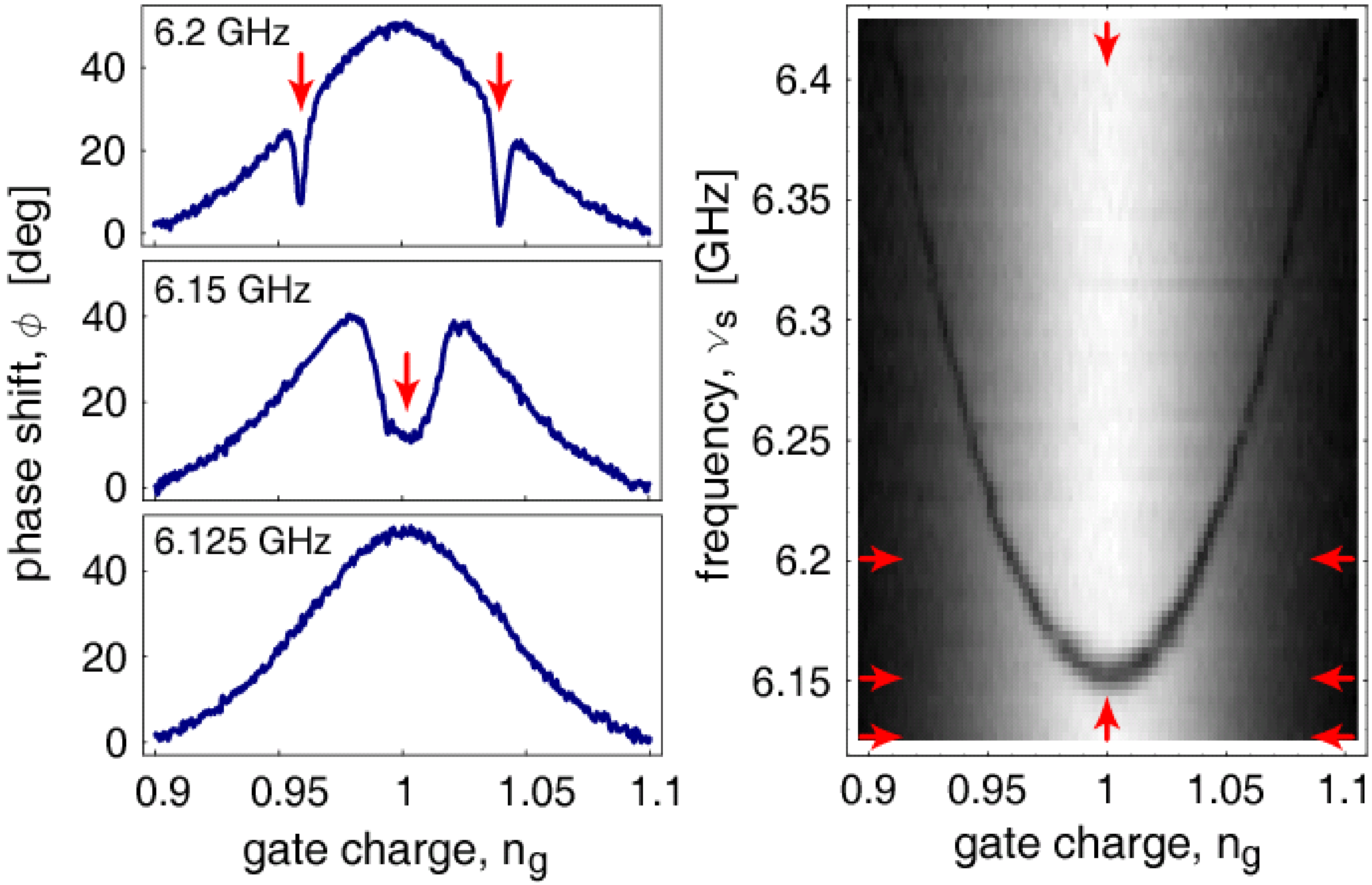
measured resonator transmission amplitude and phase:



Qubit Spectroscopy with Dispersive Read-Out



CW Spectroscopy of Cooper Pair Box



detuning $\Delta_{\mathrm{r,a}}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

ETH
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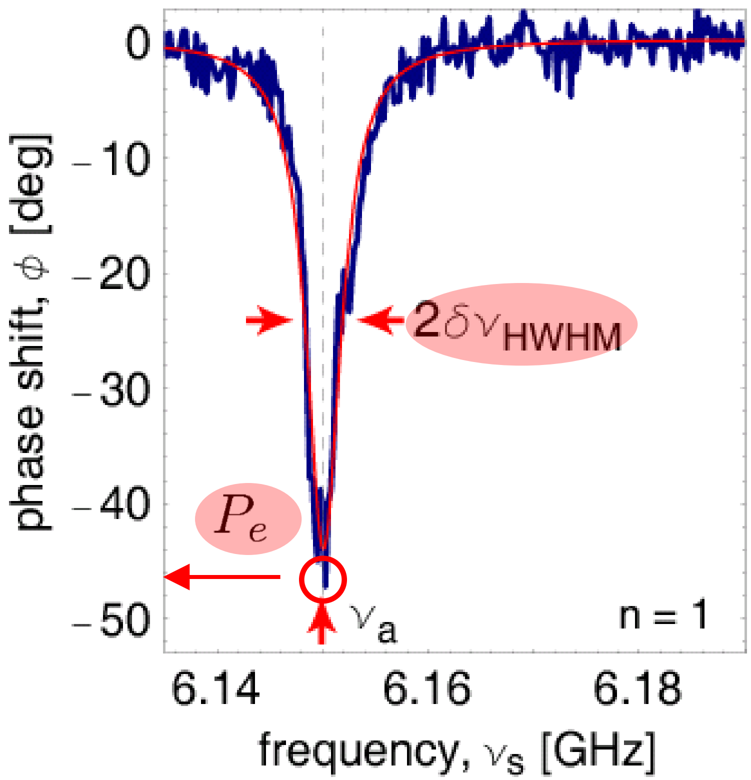
Swiss Federal Institute of Technology Zurich

D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Shape

excited state population (steady-state Bloch equations):

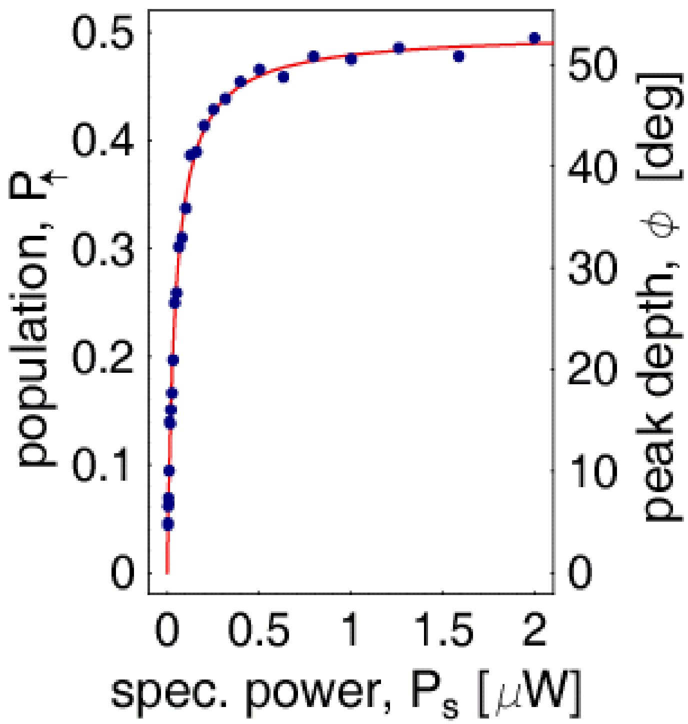
$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + (T_2 \Delta_{\mathrm{s,a}})^2 + \Omega_R^2 T_1 T_2}$$



- fixed drive $P_{\mathrm{s}} \propto \Omega_R^2 = n_{\mathrm{s}} \omega_{\mathrm{vac}}^2$
- varying $\Delta_{\mathrm{s,a}} = \omega_{\mathrm{s}} - \widetilde{\omega}_{\mathrm{a}}$
- weak continuous measurement $(n \sim 1)$
- at charge degenracy $(n_{\mathrm{g}} = 1)$

Abragam, Oxford University Press (1961)

Excited State Population

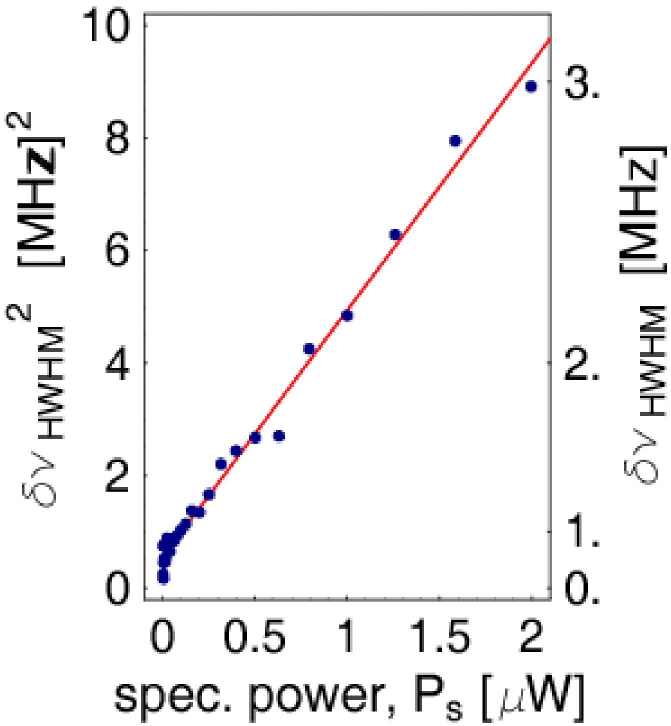


peak depth $\rightarrow$ population (saturation):

$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + \Omega_R^2 T_1 T_2}$$

D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Width



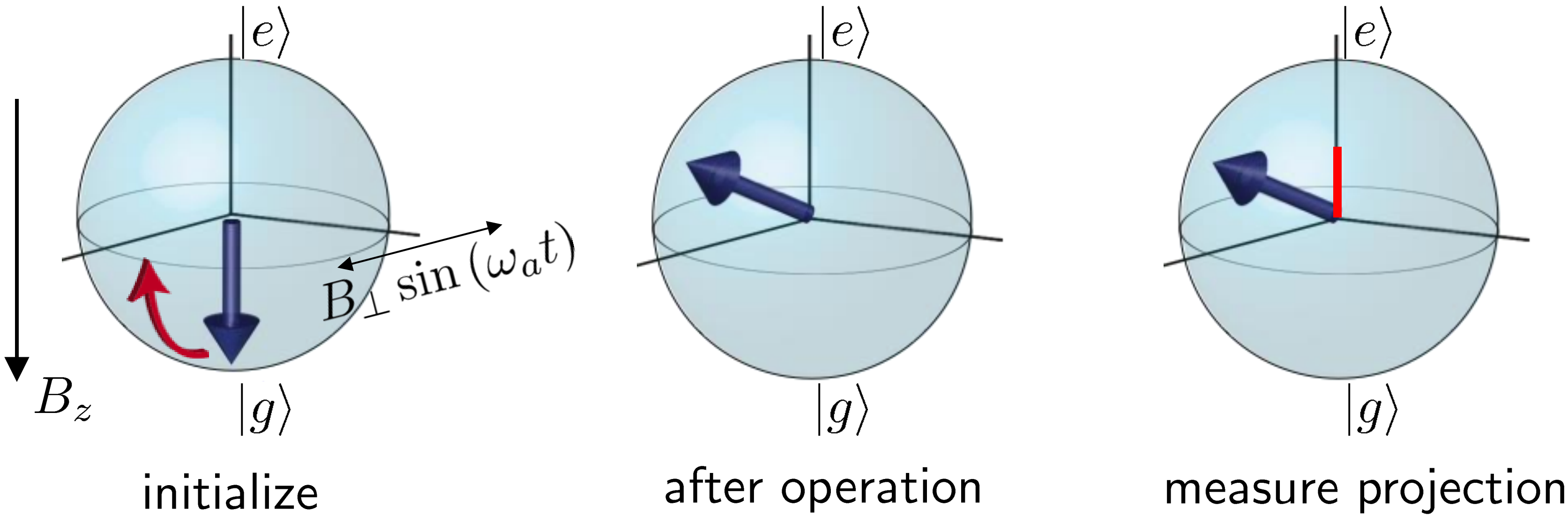
line width $\rightarrow$ coherence time:

$$2\pi\delta\nu_{\mathrm{HWHM}} = \frac{1}{T_2'} = \sqrt{\frac{1}{T_2^2} + \Omega_R^2 \frac{T_1}{T_2}}$$

$$\mathrm{Min}(\delta\nu_{\mathrm{HWHM}}) \sim 750\,\mathrm{kHz} \rightarrow \mathrm{T}_2 > 200\,\mathrm{ns}$$

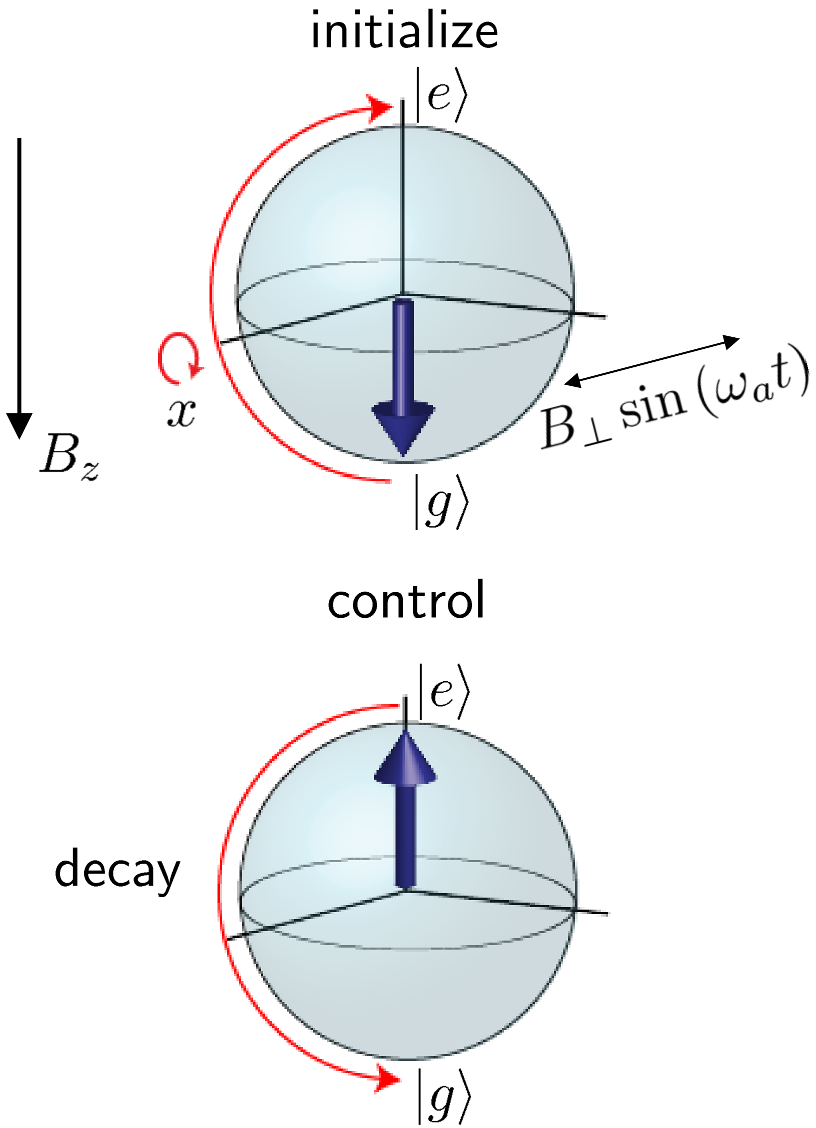
D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **94,** 123062 (2005)

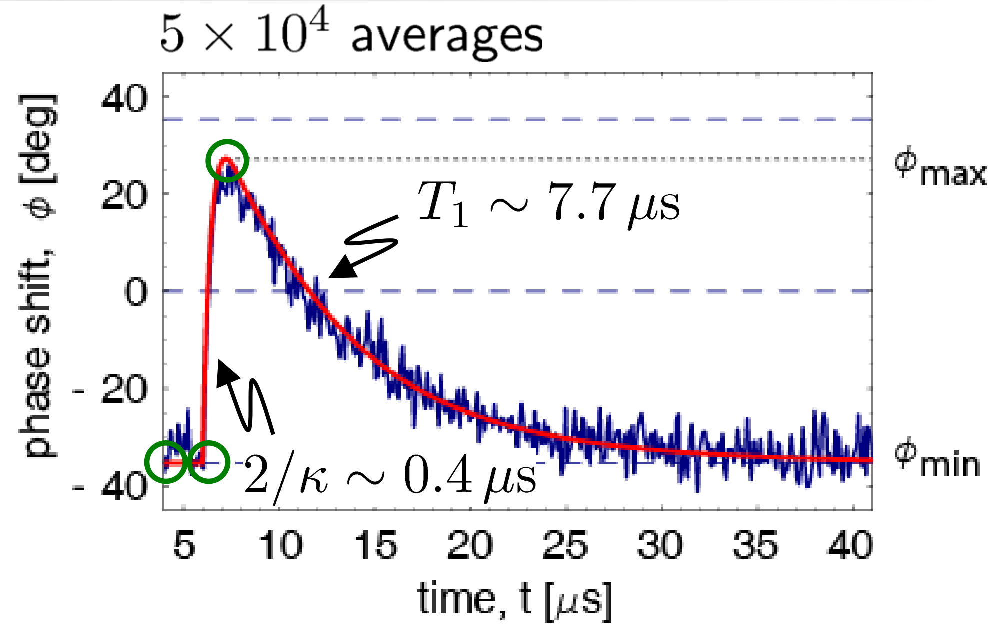
Coherent Control of a Qubit in a Cavity



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

Qubit Control and Readout



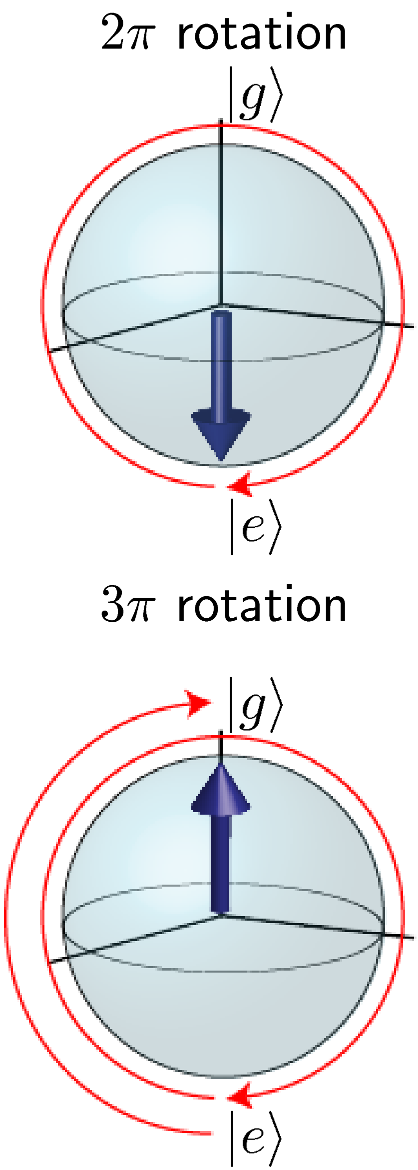


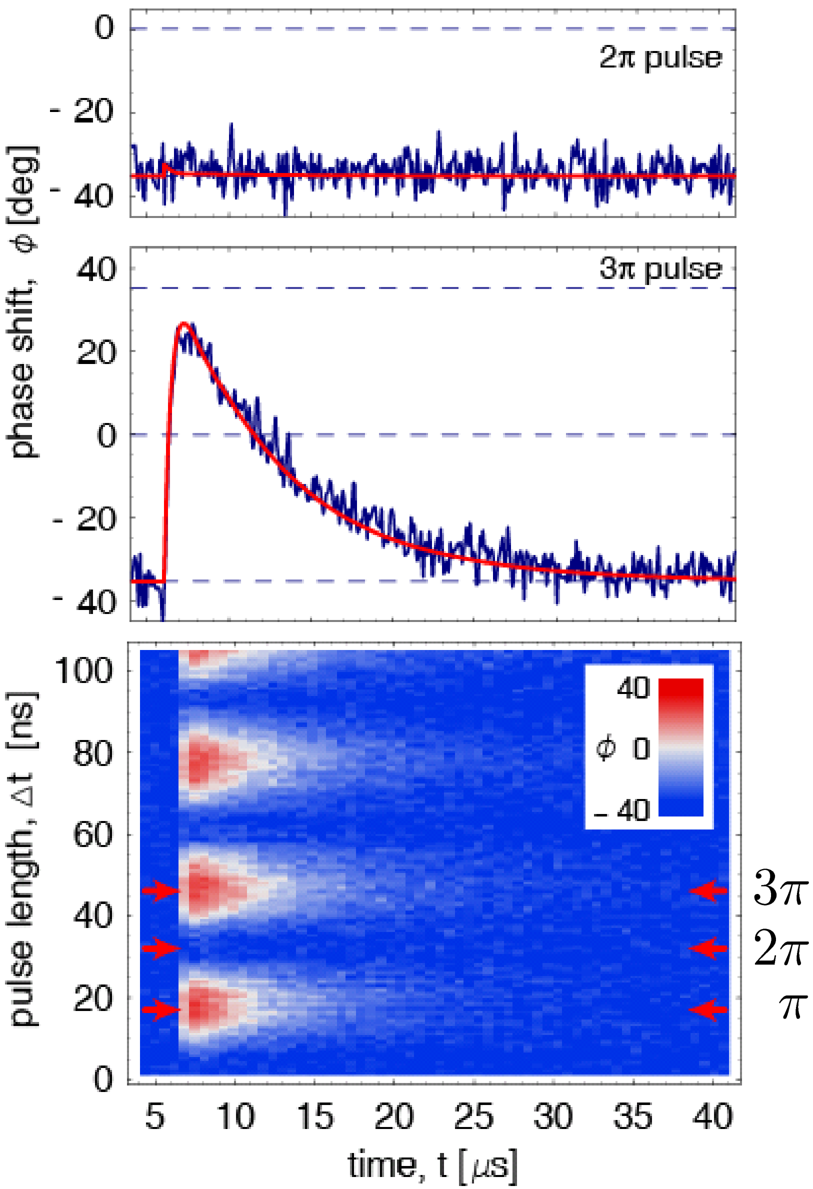
measurement properties:

- continuous
- dispersive
- quantum non-demolition
- in good agreement with predictions

Wallraff, Schuster, Blais, ... Girvin, and Schoelkopf,
Phys. Rev. Lett. **95**, 060501 (2005)

Varying the Control Pulse Length

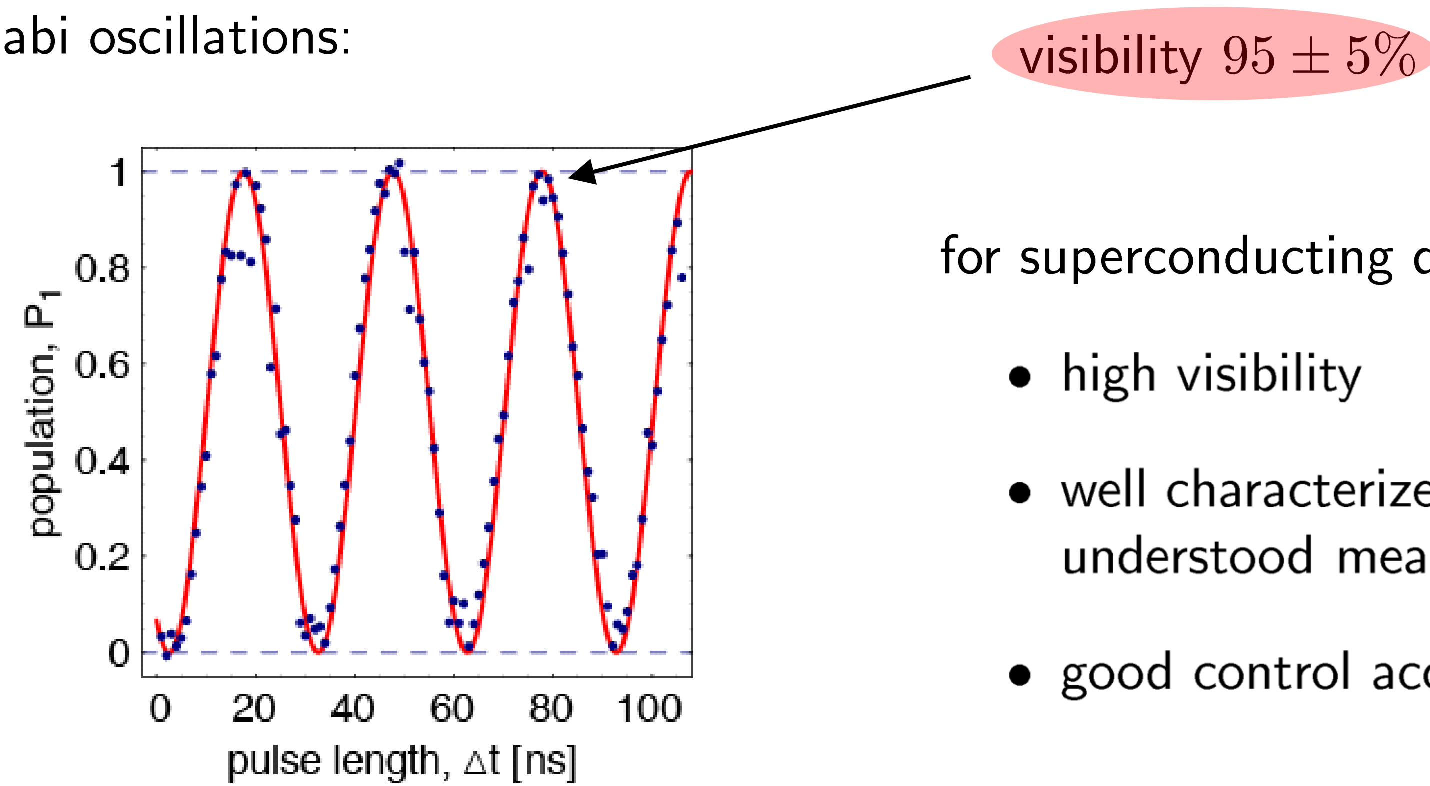




Wallraff, Schuster, Blais, ... Girvin, Schoelkopf, *PRL* **95**, 060501 (2005)

High Visibility Rabi Oscillations

Rabi oscillations:



for superconducting qubits:

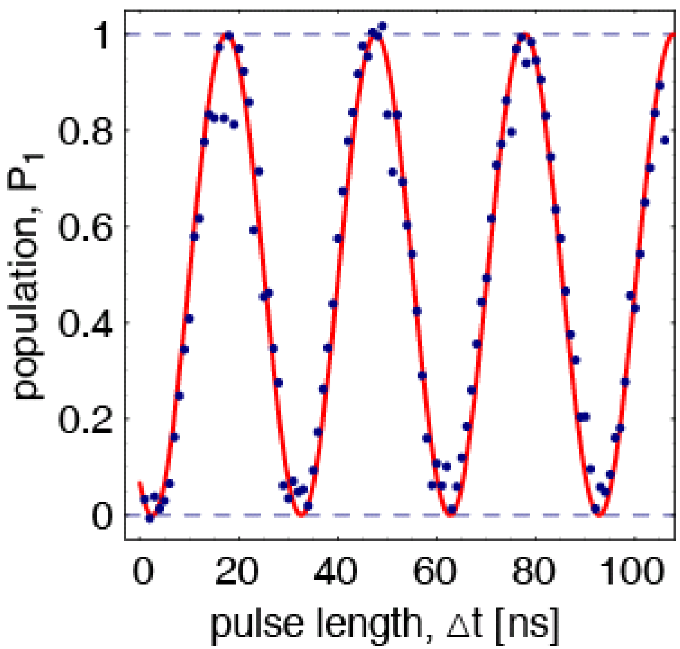
- high visibility
- well characterized and understood measurement
- good control accuracy

A. Wallraff, D. I. Schuster, A. Blais, L. Frunzio, J. Majer, S. M. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005)

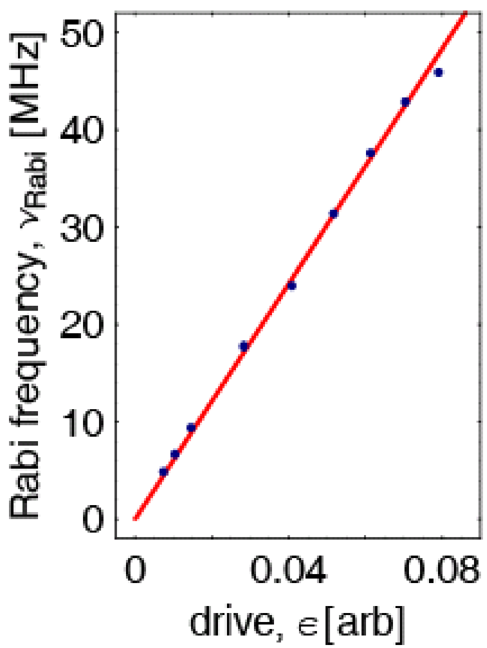
Rabi Frequency

pulse scheme:

Rabi oscillations:



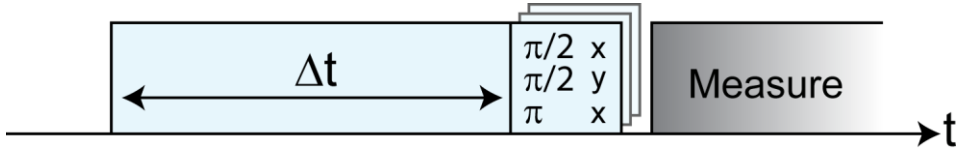
Rabi frequency:



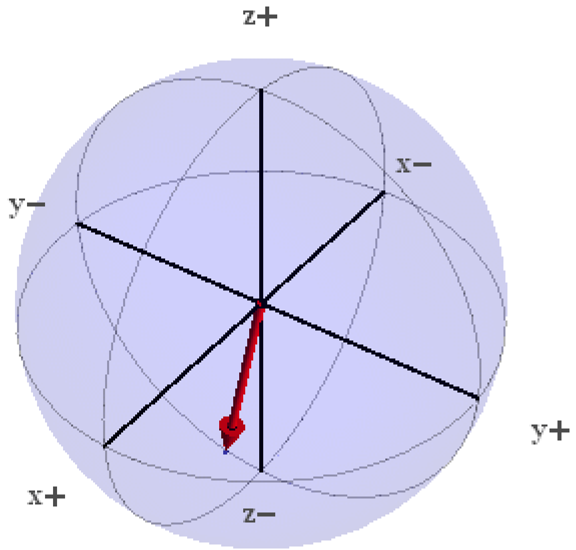
- linear dependence of Rabi frequency on microwave amplitude

Control and Tomographic Read-Out of Single Qubit

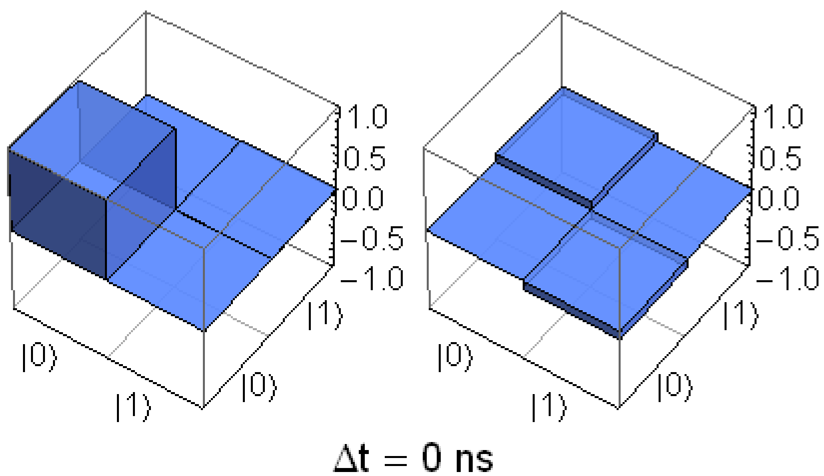
Rabi rotation pulse sequence:



experimental Bloch vector:



experimental density matrix:

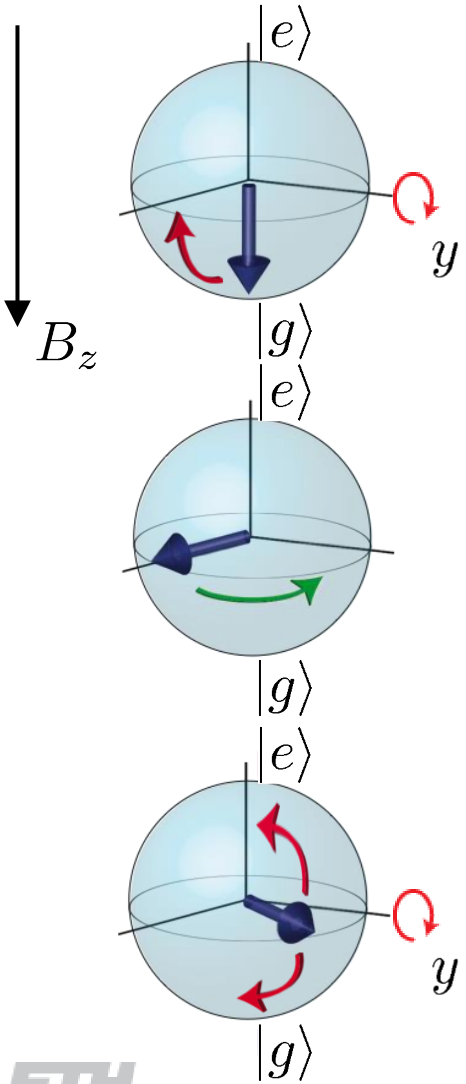


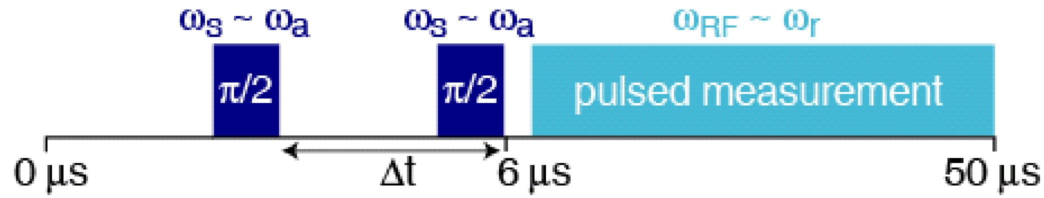
L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Measurements of Coherence Time

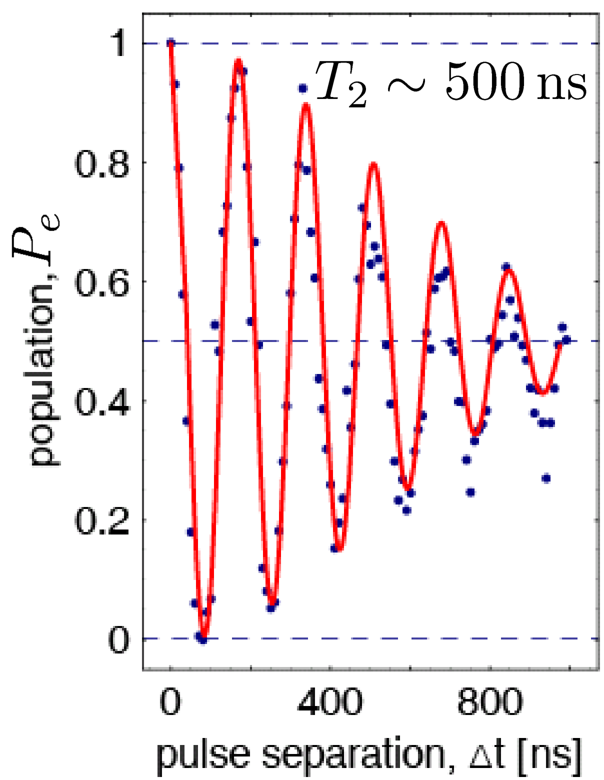
Coherence Time Measurement: Ramsey Fringes

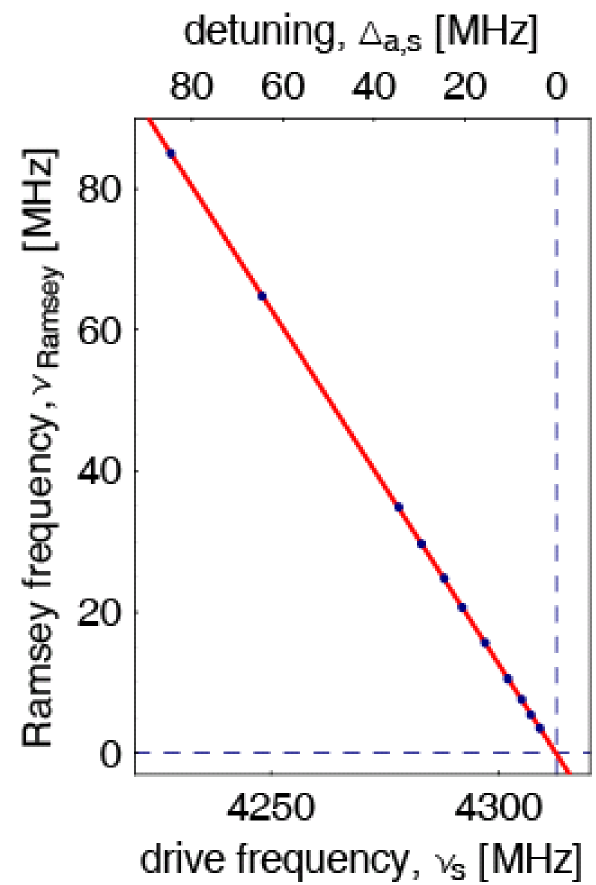
pulse scheme:





Ramsey fringes:





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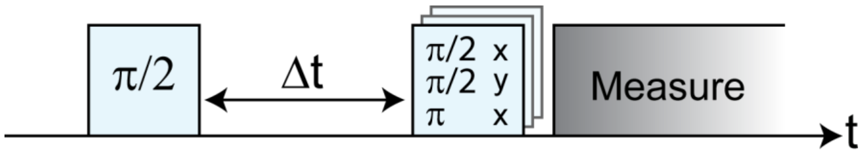
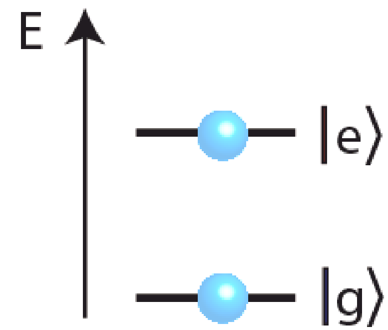
Swiss Federal Institute of Technology Zurich

A. Wallraff *et al.*, *Phys. Rev. Lett.* **95**, 060501 (2005)

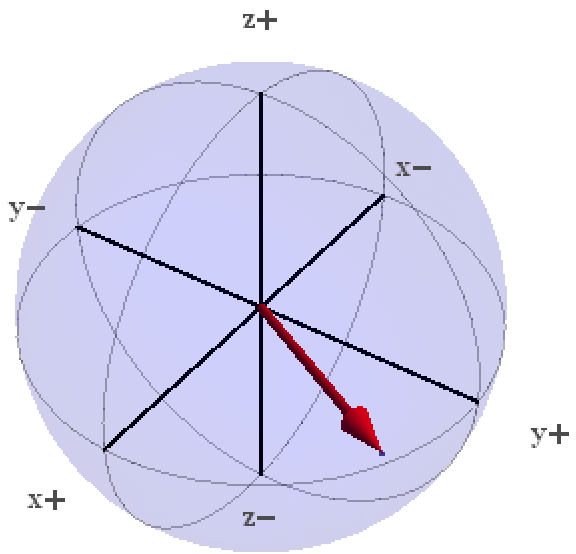
Tomography of Ramsey Experiment

pulse sequence:

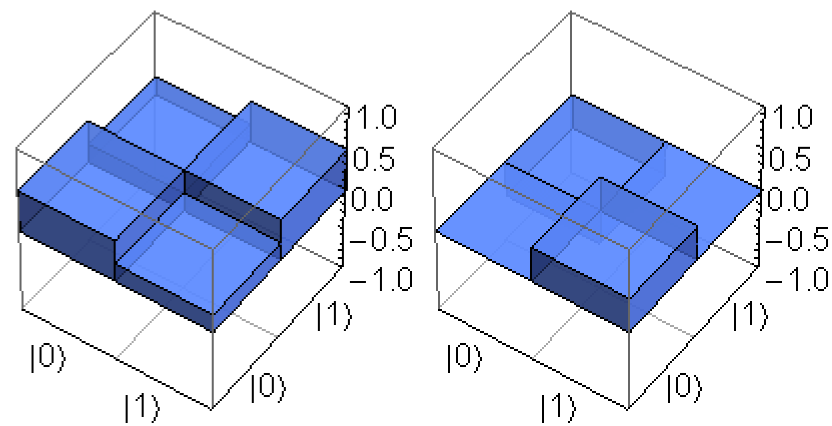




experimental Bloch vector:



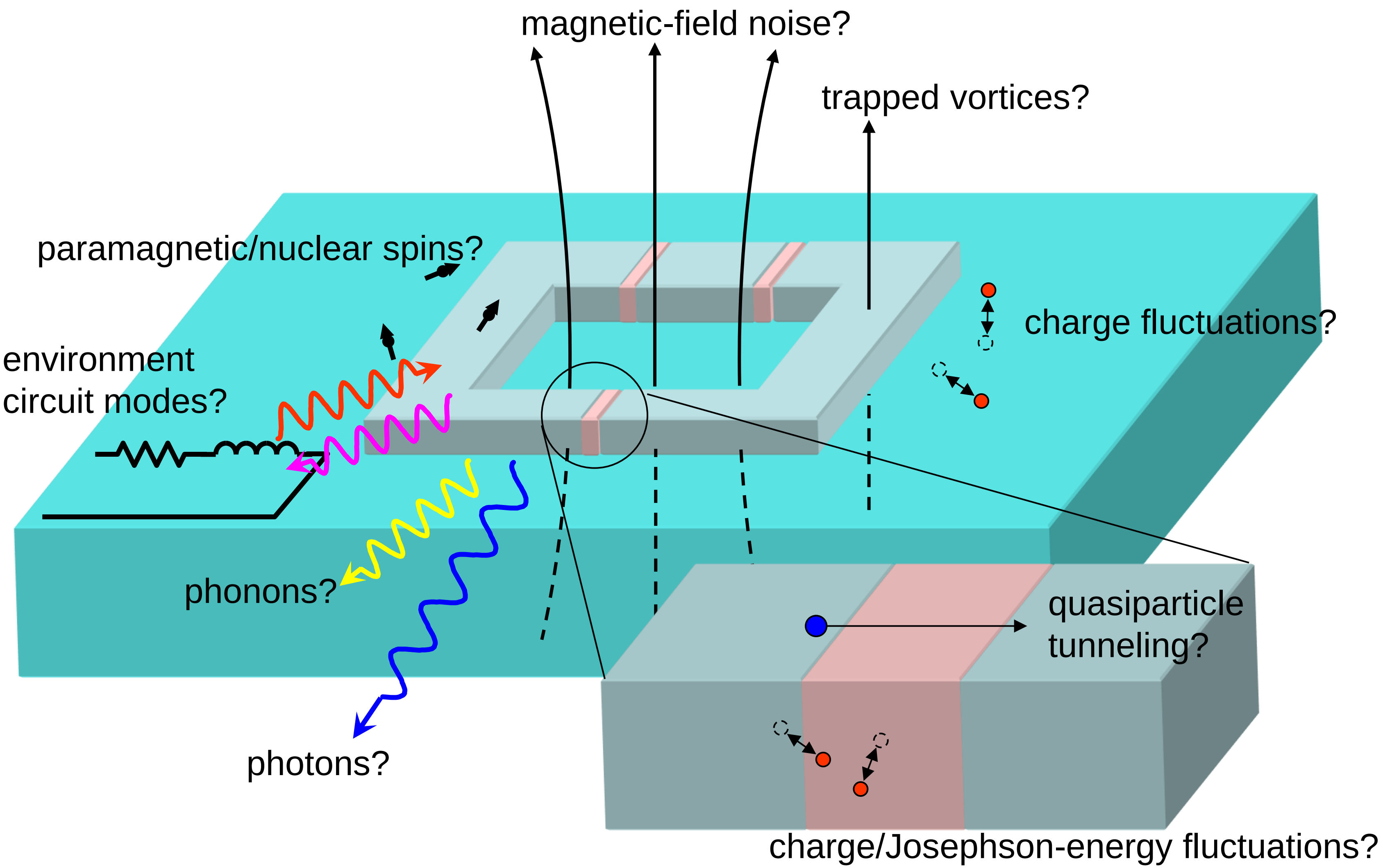
experimental density matrix:



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

Decoherence ...
... additional material

Sources of Decoherence



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

Strategies to Reduce Decoherence

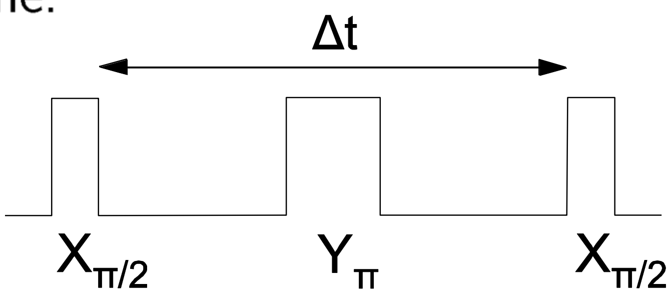
- remove sources of decoherence
    - improve materials

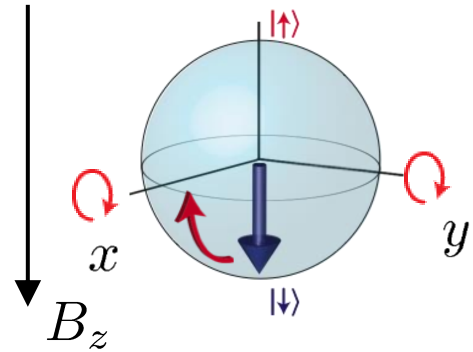
- use dynamic methods to counteract specific sources of decoherence
    - spin echo
    - geometric manipulations

- reduce sensitivity of quantum systems to specific sources of decoherence
    - make use of symmetries in design and operation

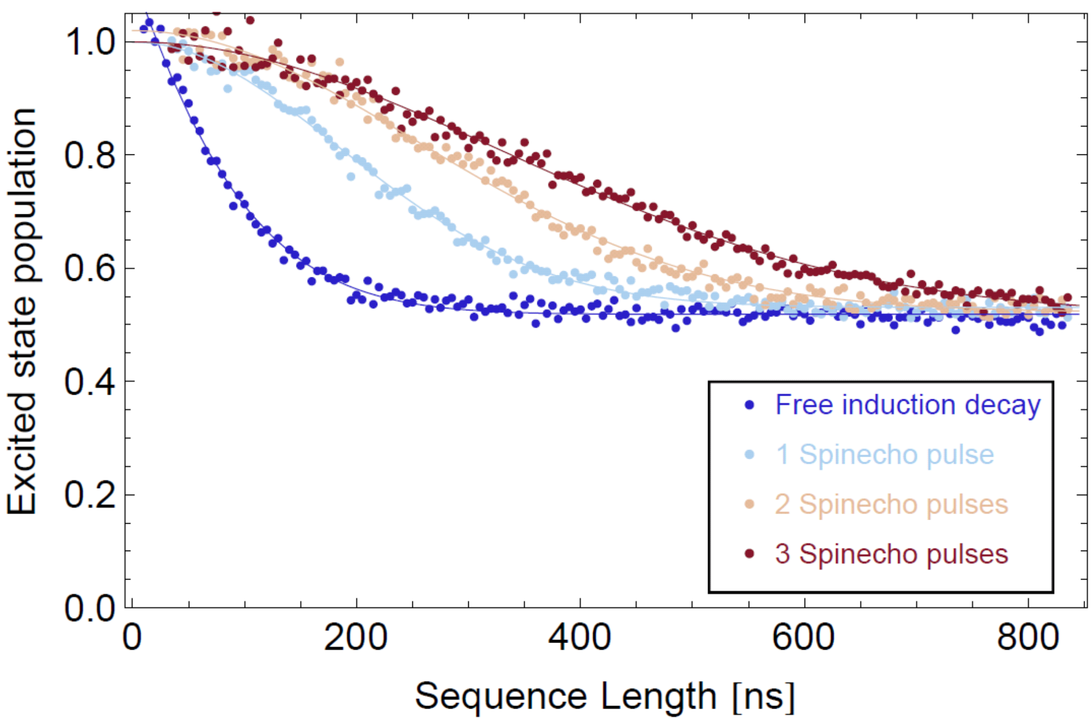
Reduce Decoherence Dynamically: Spin Echo

pulse scheme:





result:



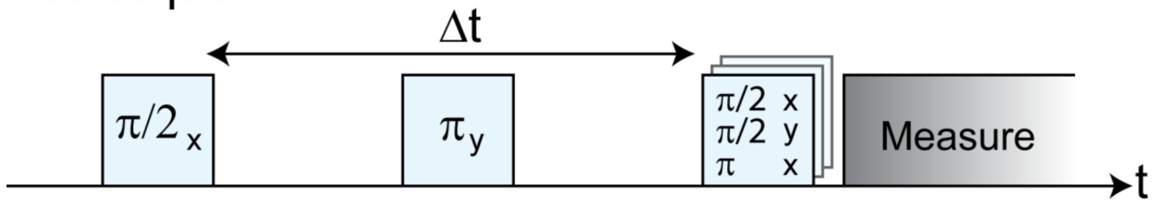
- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

Lars Steffen *et al.* (2009)

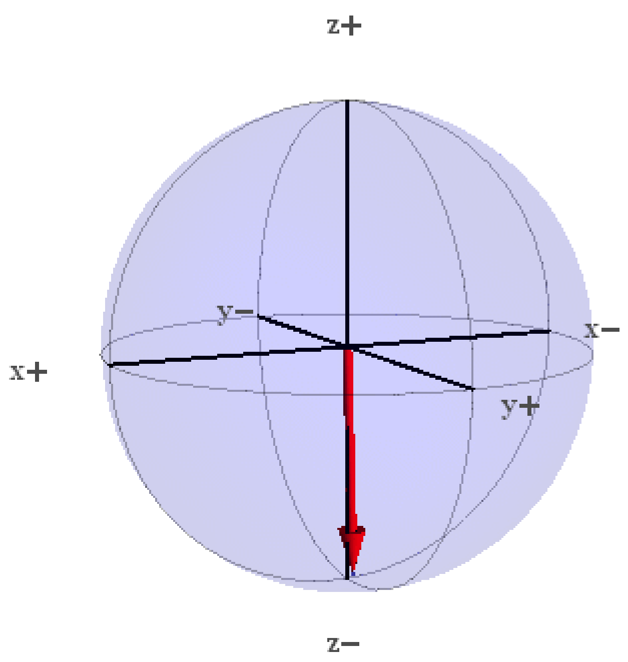
P. J. Leek, J. Fink *et al.*, *Science* **318**, 1889 (2007)

Tomography of a Spin Echo

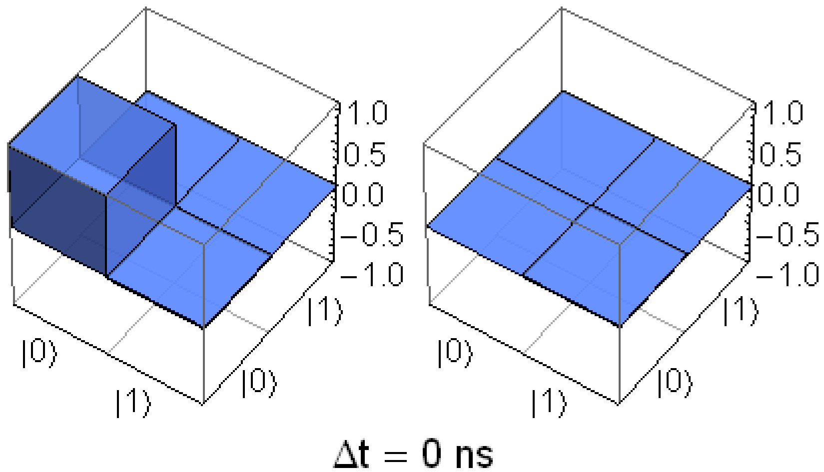
pulse sequence:



experimental Bloch vector:



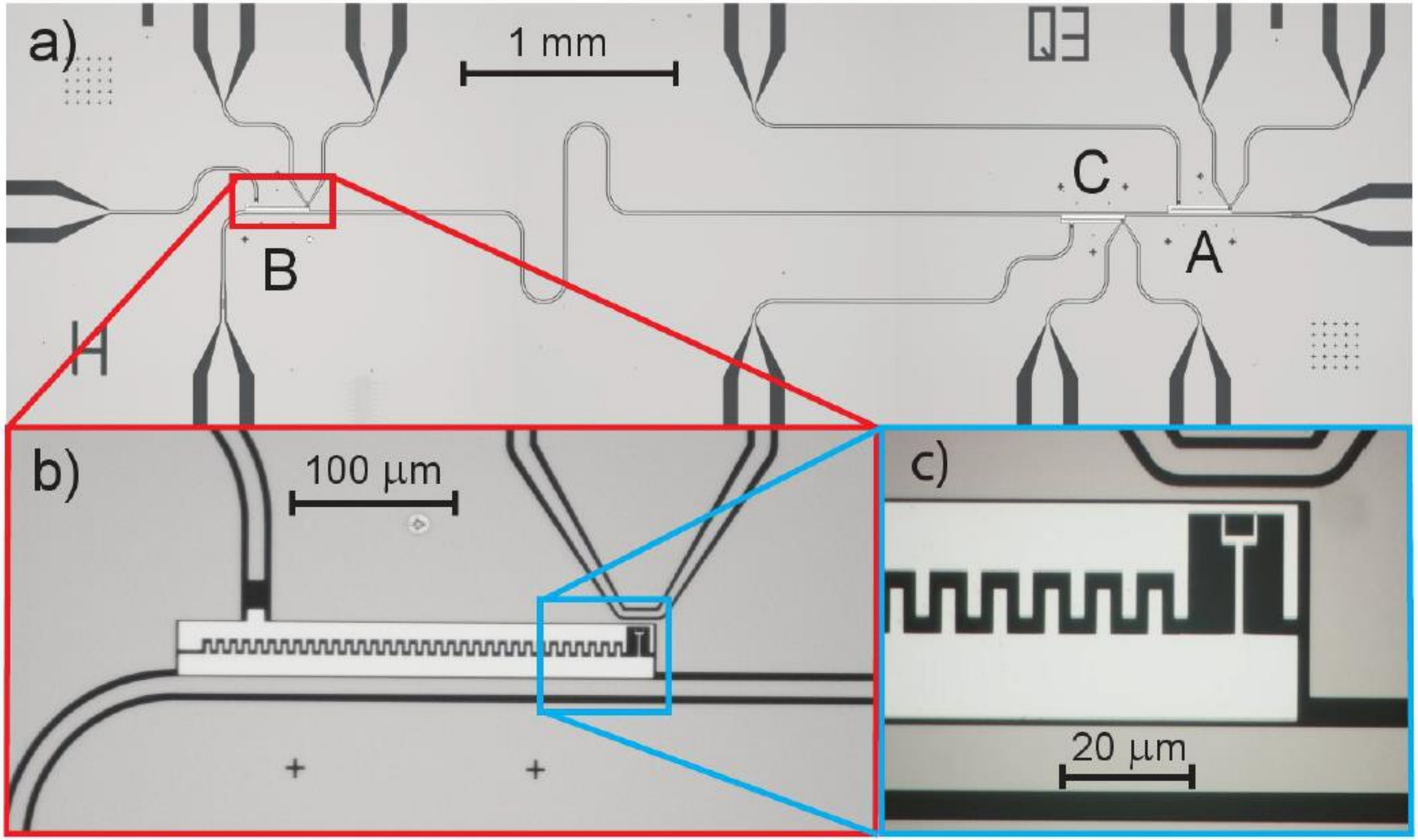
experimental density matrix:



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

Coupling Superconducting Qubits and Generating Entanglement using a Controlled Phase Gate

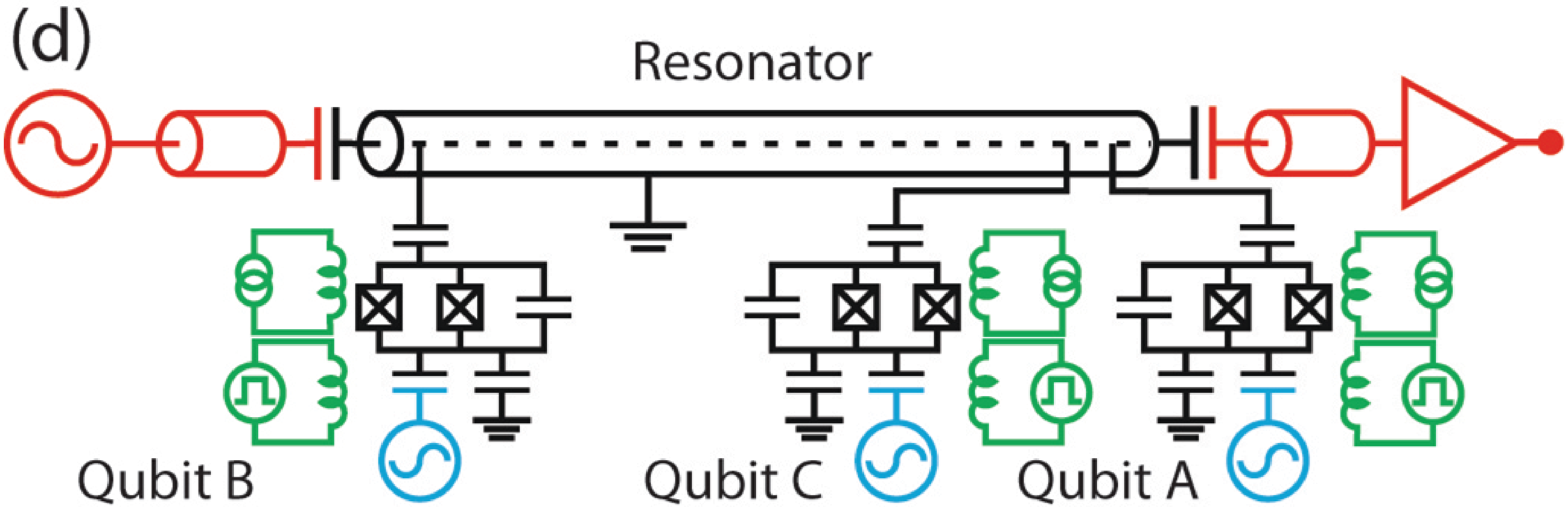
Quantum Processor with 3 Qubits: The Chip



- three transmon qubits: $T_1 \sim 1.0\ \mu s$, $T_2 \sim 0.6\ \mu s$, individual local control
- one resonator: $f_0 \sim 8.625$ GHz, coupling to qubits $g/2\pi \sim 300$ MHz

M. Baur *et al.*, *Phys. Rev. Lett.* **108**, 040502 (2012)

Quantum Processor with 3 Qubits: Circuit Diagram

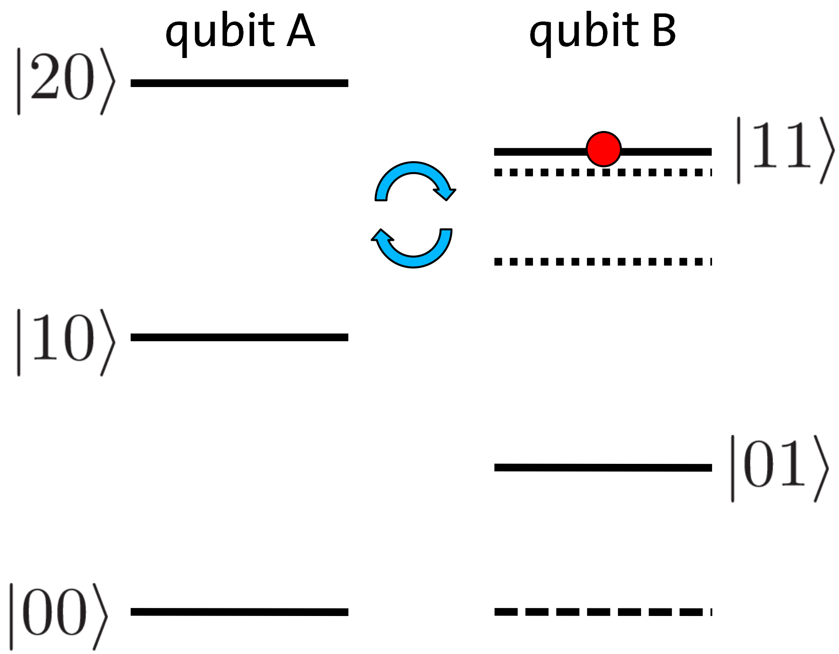


- qubit state measurement through resonator
- individual qubit control through local microwave gates
- two-qubit interactions by tuning qubits into resonance using local flux gates

M. Baur *et al.*, *Phys. Rev. Lett.* **108**, 040502 (2012)

Universal Two-Qubit Controlled Phase Gate

Tune levels into resonance using magnetic field

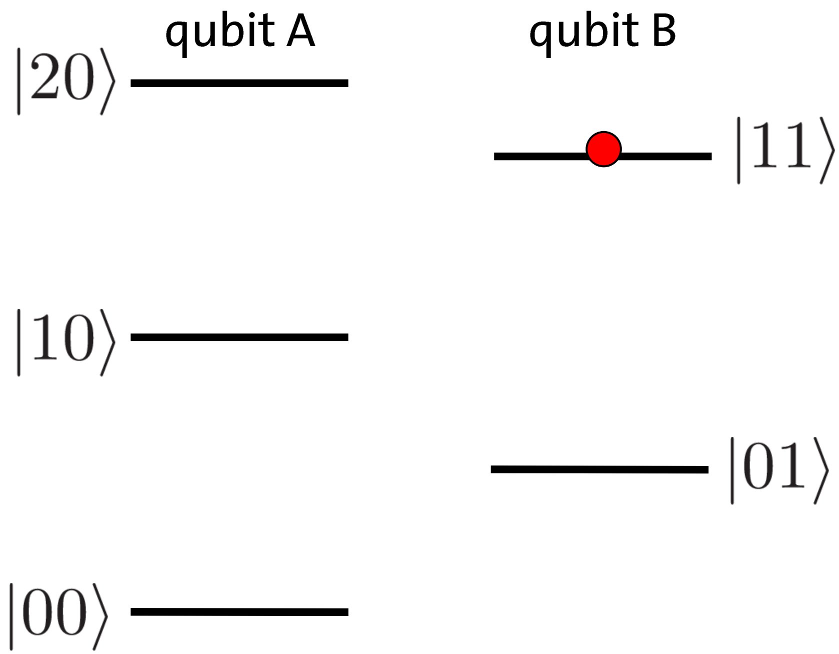


Interaction mediated by virtual photon exchange through resonator

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).
first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

Universal Two-Qubit Controlled Phase Gate



How to verify the operation of this gate?

Universal two-qubit gate. Used together with single-qubit gates to create any quantum operation.

$$|11\rangle \longrightarrow i|20\rangle \longrightarrow -|11\rangle$$

$$|01\rangle \longrightarrow |01\rangle$$

$$|10\rangle \longrightarrow |10\rangle$$

$$|00\rangle \longrightarrow |00\rangle$$

C-Phase gate:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

proposal: F. W. Strauch, *Phys. Rev. Lett.* **91**, 167005 (2003).

first implementation: L. DiCarlo, *Nature* **460**, 240 (2010).

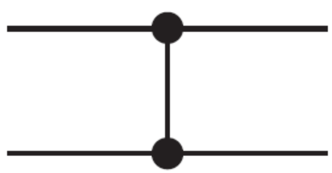
Process Tomography: C-Phase Gate

arbitrary quantum process $\boxed{\rho' = \mathcal{E}(\rho)}$ decomposed into $\boxed{\mathcal{E}(\rho) = \sum_{mn} \tilde{E}_m \rho \tilde{E}_n^\dagger \chi_{mn}}$

$\{\tilde{E}_k\}$ is an operator basis

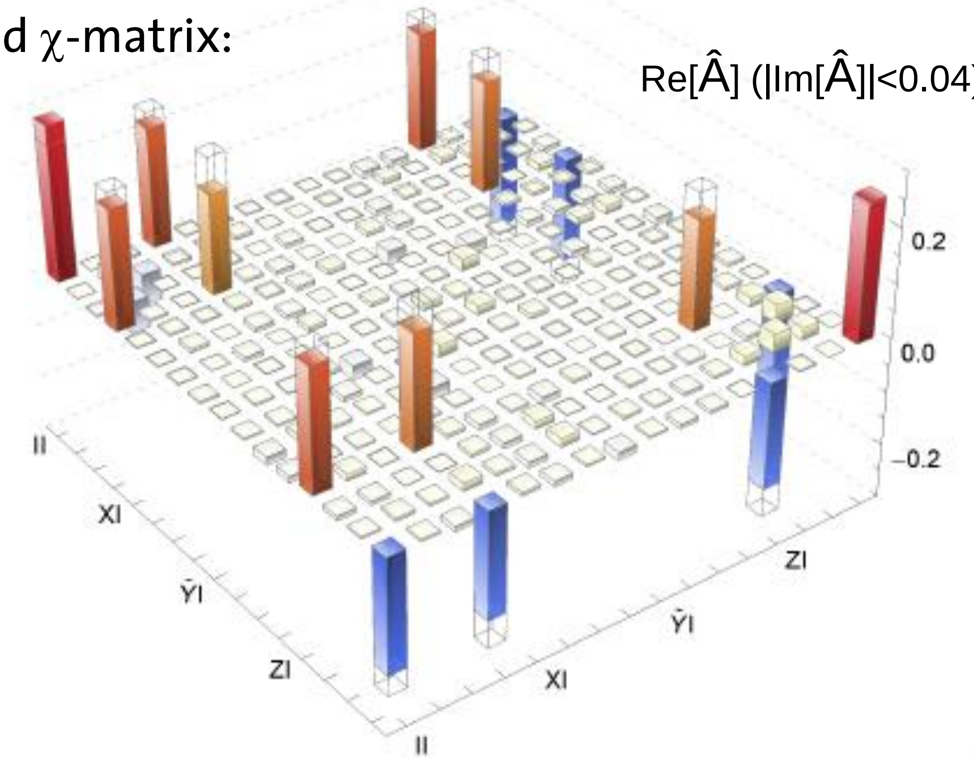
χ is a positive semi definite Hermitian matrix characteristic for the process

Controlled phase gate



$$cZ_{00} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Measured χ-matrix:



$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] = 0.86$

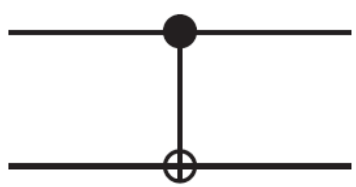
Process Tomography: C-NOT Gate

arbitrary quantum process $\boxed{\rho' = \mathcal{E}(\rho)}$ decomposed into $\boxed{\mathcal{E}(\rho) = \sum_{mn} \tilde{E}_m \rho \tilde{E}_n^\dagger \chi_{mn}}$

$\{\tilde{E}_k\}$ is an operator basis

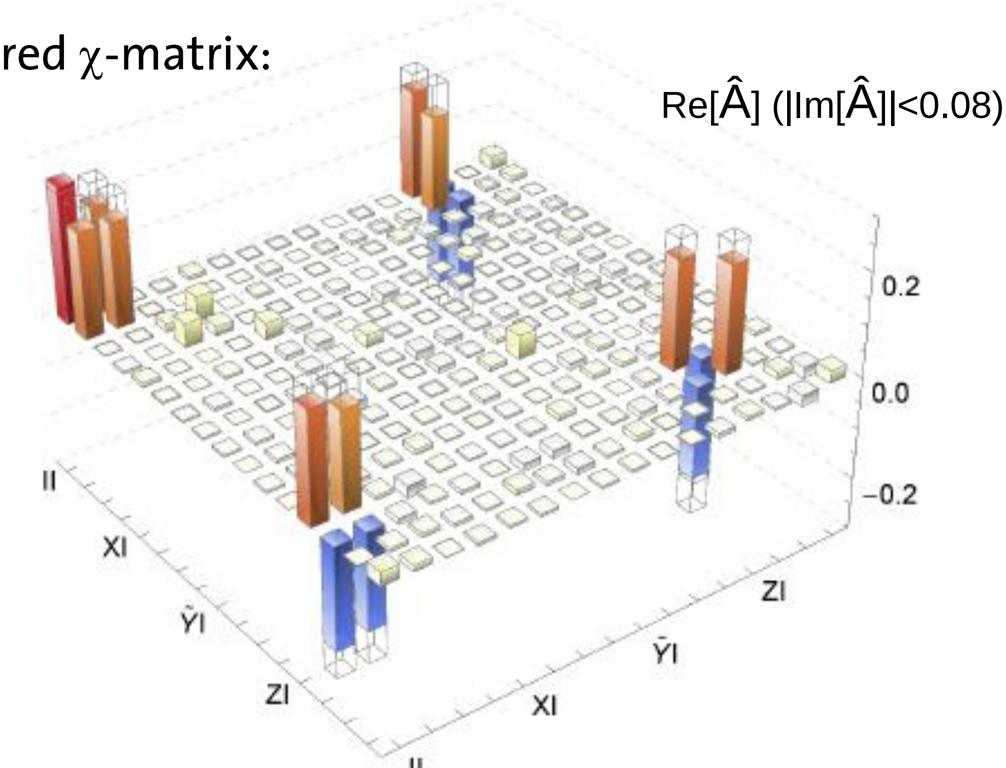
χ is a positive semi definite Hermitian matrix characteristic for the process

Controlled-NOT gate



$$\mathrm{C-NOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Measured χ-matrix:

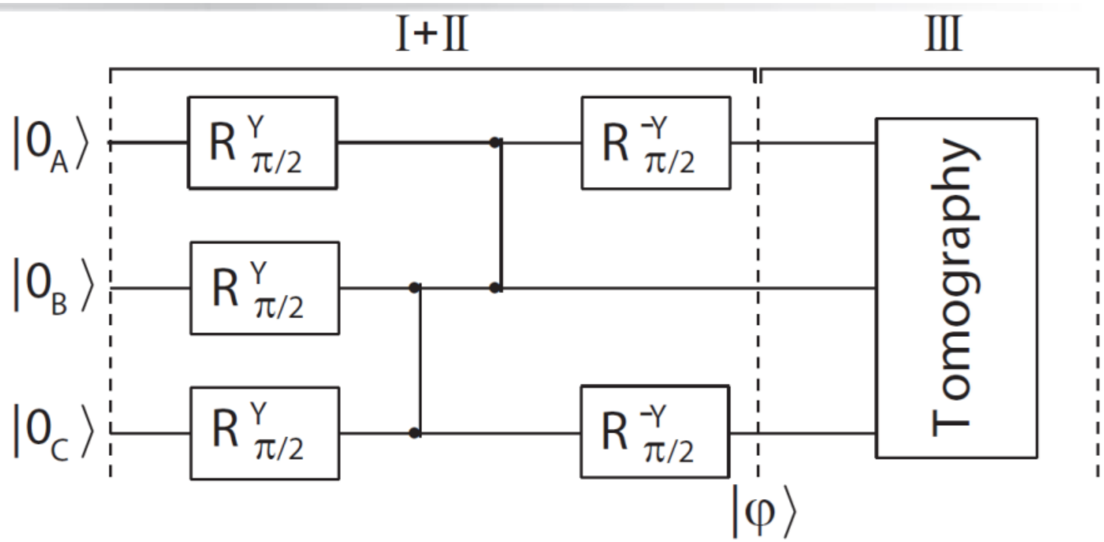


$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] = 0.81$

Maximally Entangled Three Qubit States

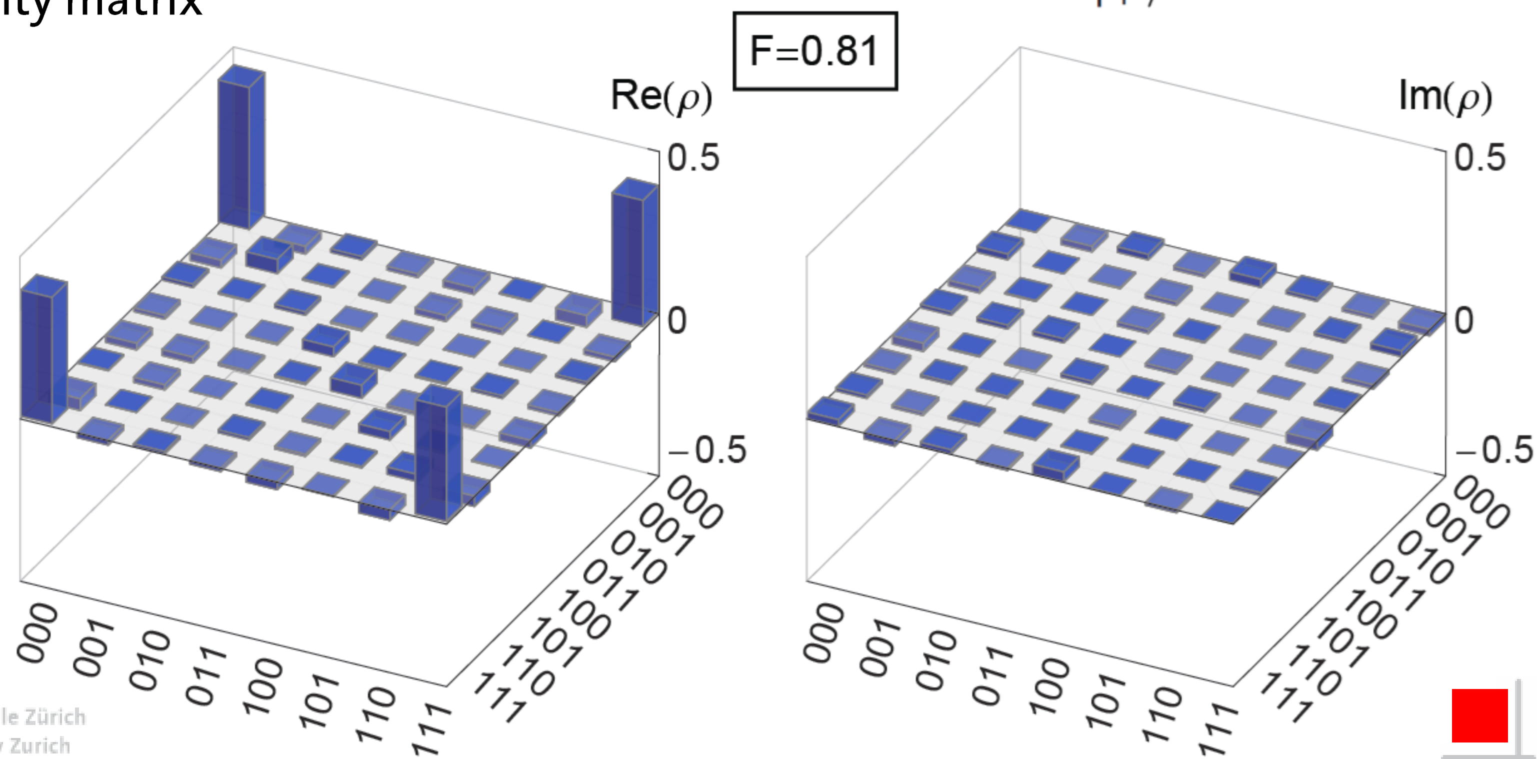
Generation of GHZ class, e.g. |000>+|111>, states:

- single qubit gates
- C-PHASE gates



Measured density matrix

- high fidelity



DiVincenzo Criteria fulfilled for Superconducting Qubits

for Implementing a Quantum Computer in the standard (circuit approach) to quantum information processing (QIP):

#1. A scalable physical system with well-characterized qubits. ✓
#2. The ability to initialize the state of the qubits. ✓
#3. Long (relative) decoherence times, much longer than the gate-operation time. ✓
#4. A universal set of quantum gates. ✓
#5. A qubit-specific measurement capability. ✓

plus two criteria requiring the possibility to transmit information:

#6. The ability to interconvert stationary and mobile (or flying) qubits. ✓
#7. The ability to faithfully transmit flying qubits between specified locations. ✓