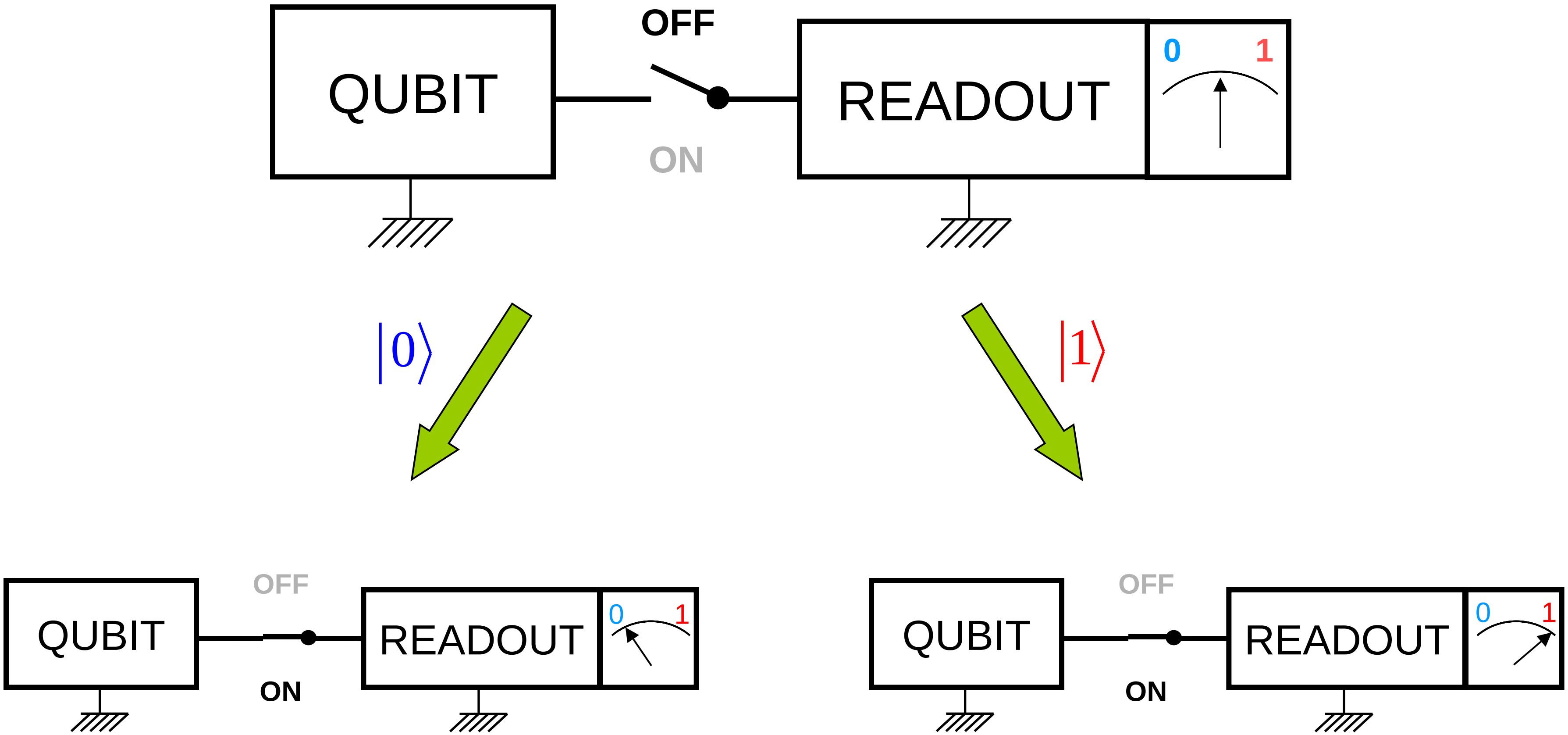
Read-Out …

… of superconducting qubits

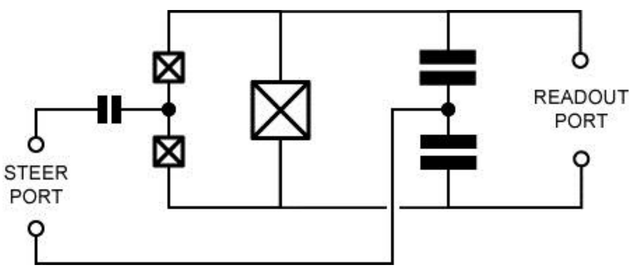
Qubit Read Out



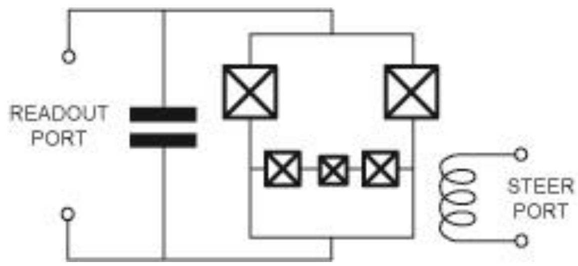
desired: good on/off ratio
no relaxation in on state (QND)

Read Out Strategies

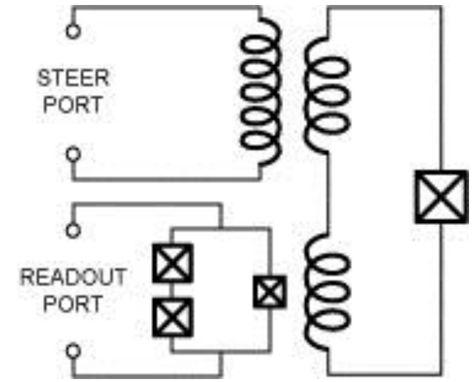
demolition measurements (switching/latching measurements)



Quantronium (Saclay, Yale)

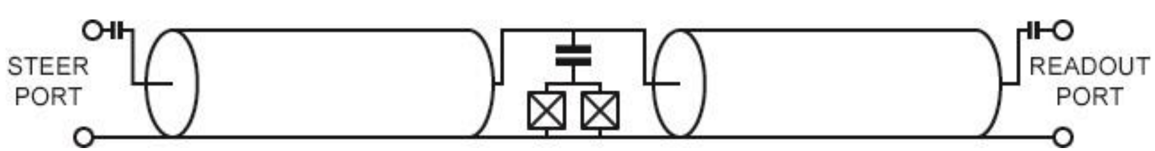


Flux Qubit (TU Delft, NEC)



Phase Qubit (NIST, UCSB)

quantum non-demolition (QND) measurements



Yale (circuit QED)

also: Chalmers, Delft, Yale (JBA)

Dispersive Approximation of the J-C Hamiltonian

Jaynes-Cummings Hamiltonian

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

Unitary transformation

$$\tilde{H} = UHU^\dagger \quad \text{with} \quad U = \exp\frac{g}{\Delta}(a\sigma^+ - a^\dagger\sigma^-)$$

$$\text{and} \quad \Delta = \omega_a - \omega_r$$

Results in dispersive approximation up to 2[nd] order in g

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

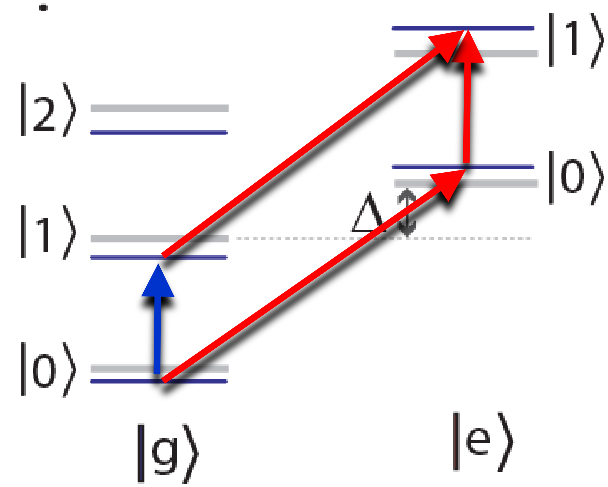
A. Blais, *et al.*, *PRA* **69**, 062320 (2004)

Non-Resonant (Dispersive) Interaction

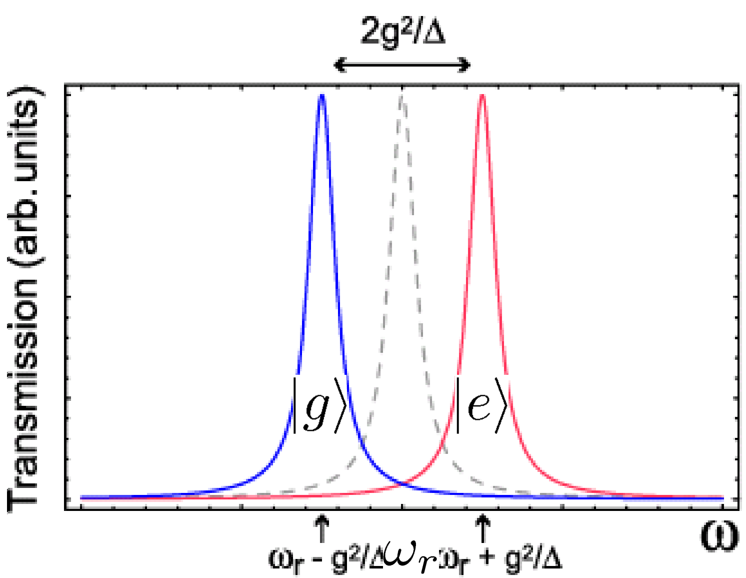
approximate diagonalization for $|\Delta| = |\omega_a - \omega_r| \gg g$

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

cavity frequency shift



qubit detuned by Δ from resontaor



A. Blais *et al.*, *PRA* **69**, 062320 (2004)
A. Wallraff *et al.*, *Nature (London)* **431**, 162 (2004)
D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94**, 123062 (2005)
A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Dispersive Read-Out

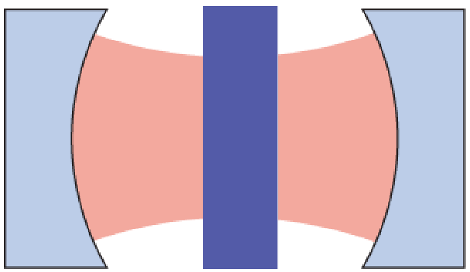
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

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

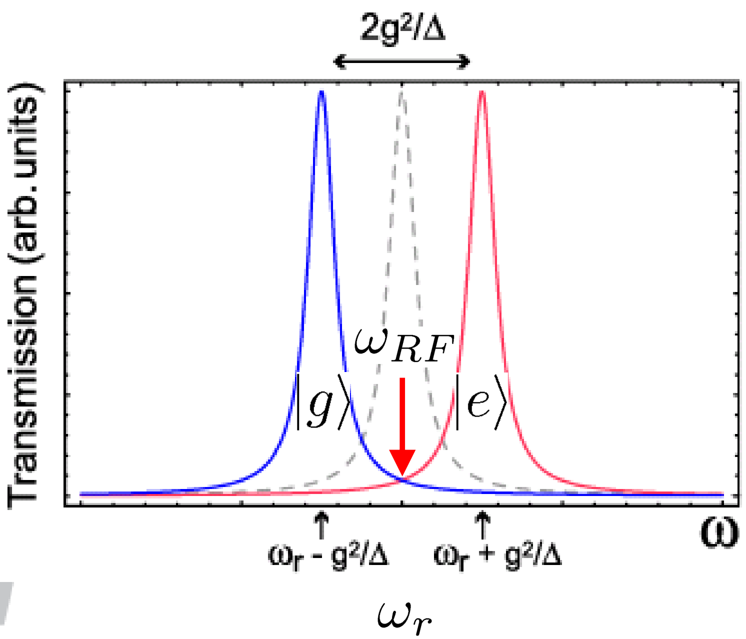
//

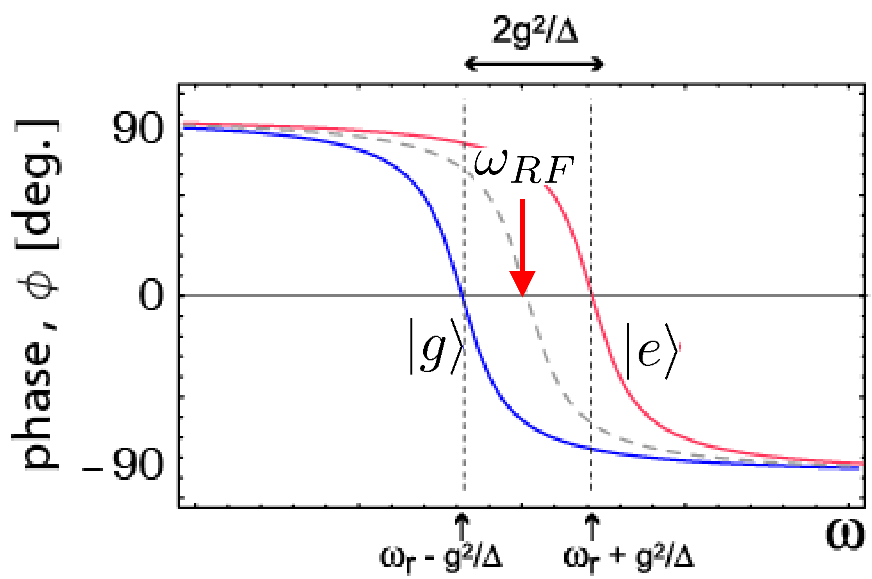
cavity frequency shift

$|g\rangle : \epsilon > 1$



$|e\rangle : \epsilon < 1$

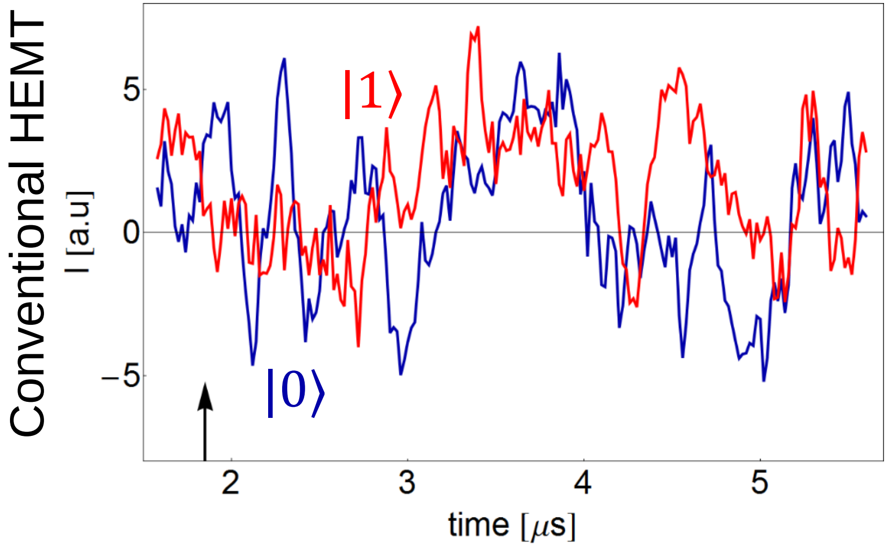




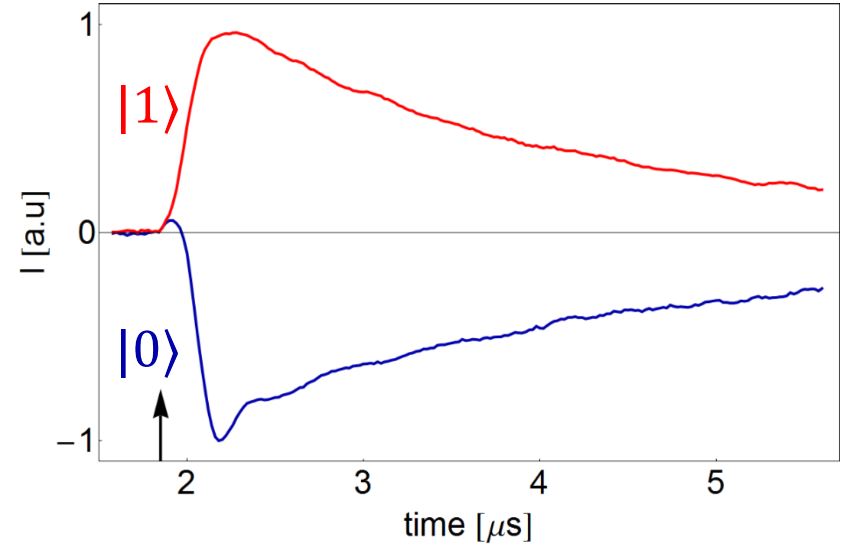
A. Blais *et al.*, *PRA* **69,** 062320 (2004)

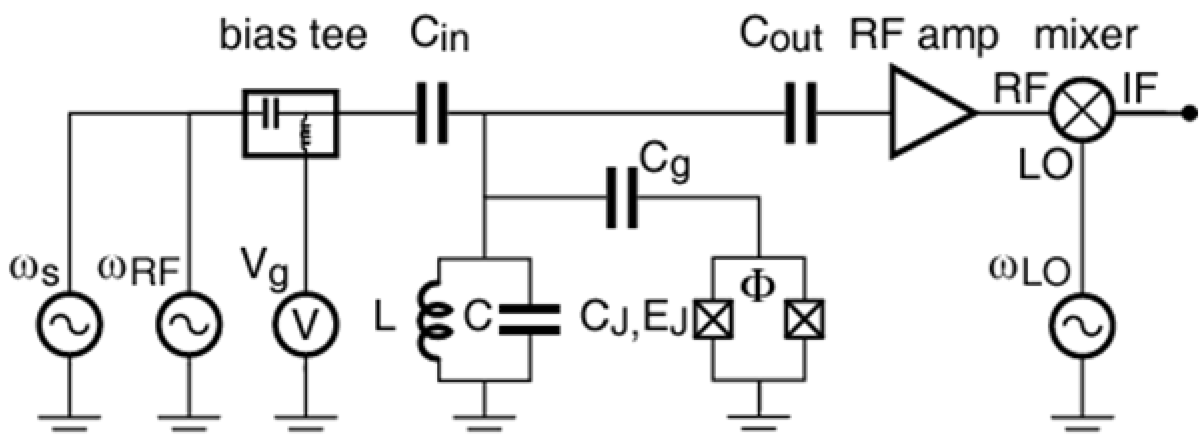
Qubit-Readout (Averaged)

single-shot measurements:



averaged measurements ($8\ 10^4$):

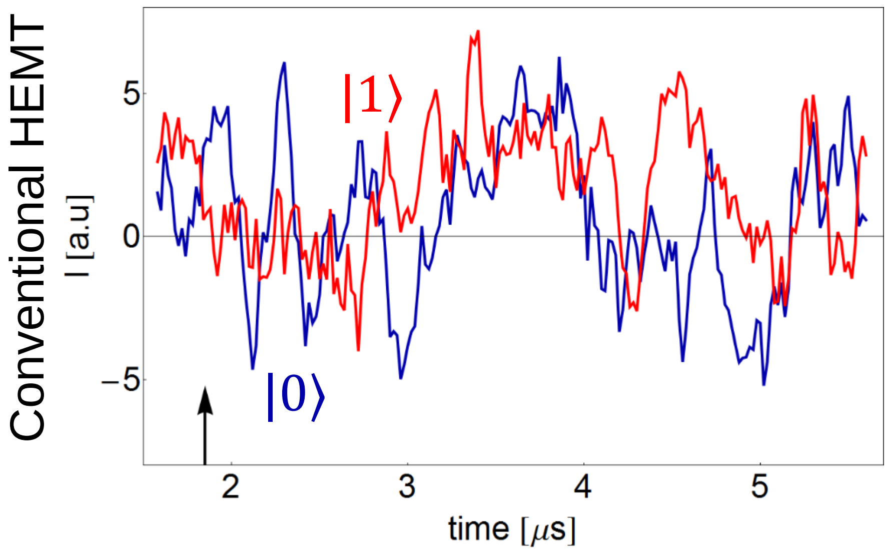




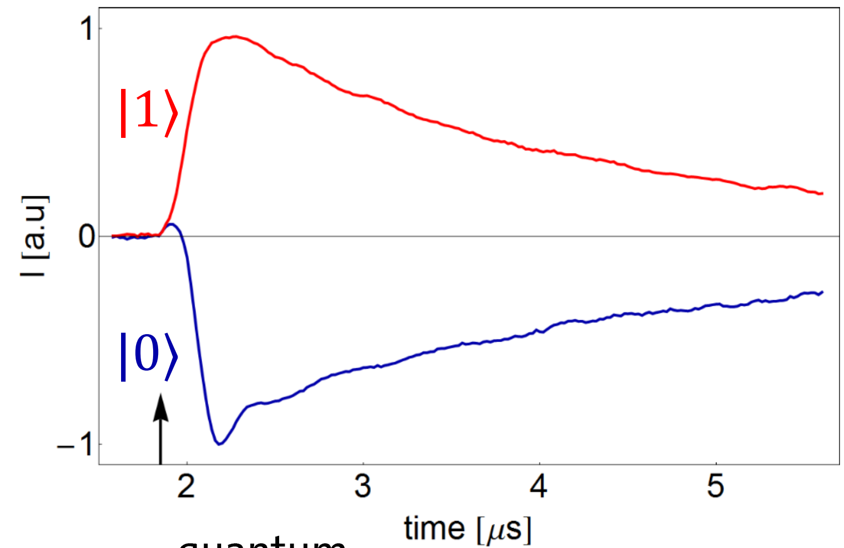
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* **106**, 110502 (2011)

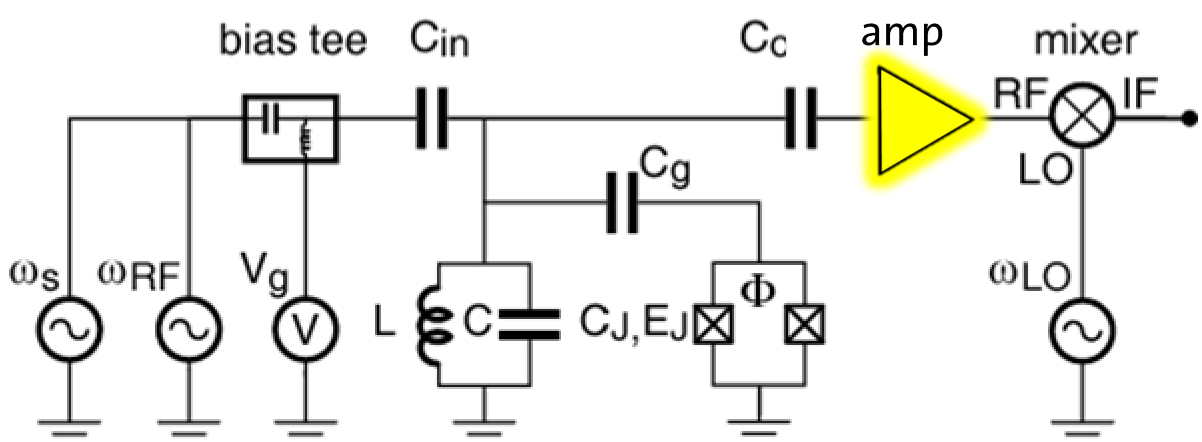
Improved using a Quantum Limited Amplifier

single-shot measurements:



averaged measurements (8 10^4):



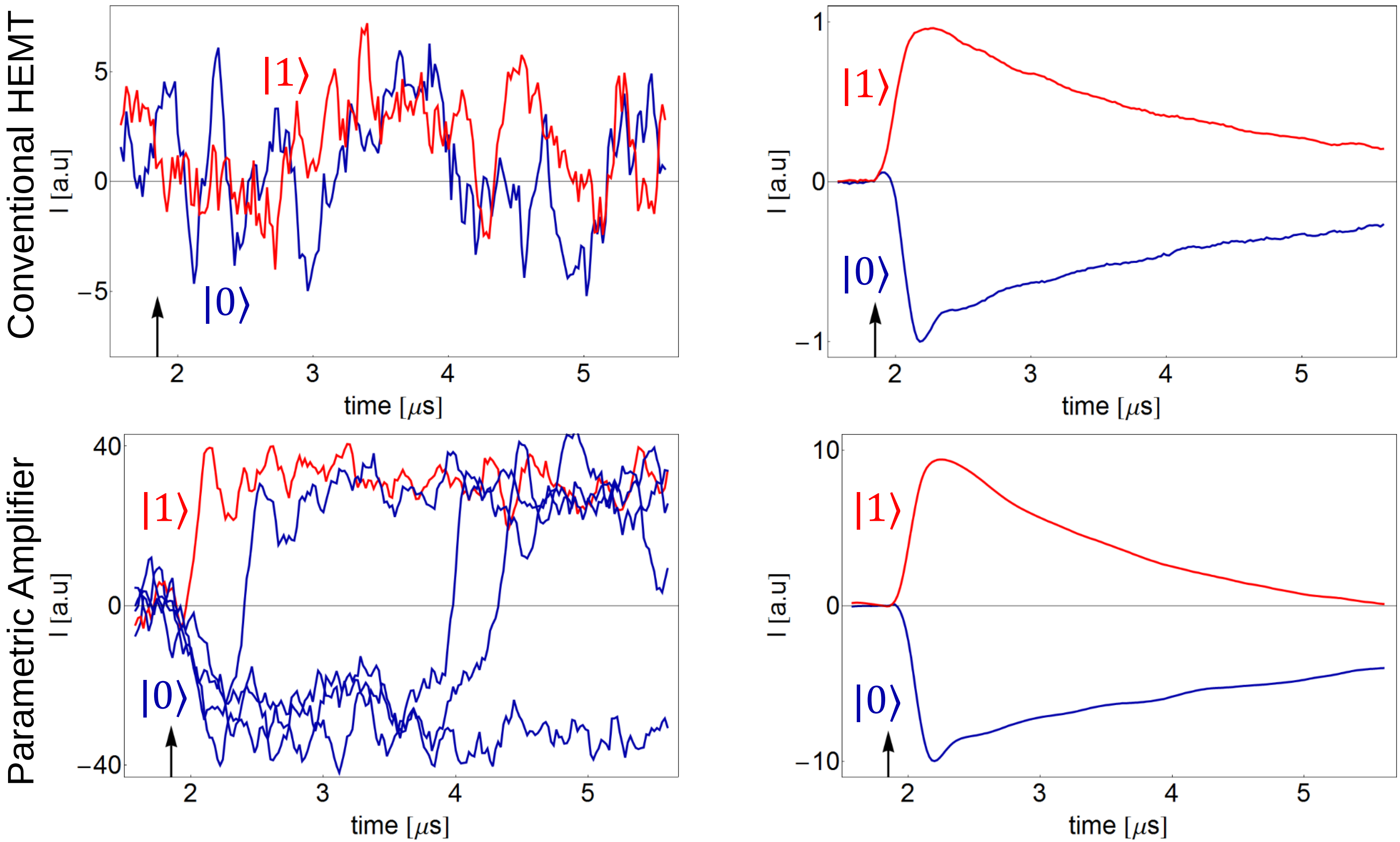


P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* **106**, 110502 (2011)

Single-Shot Single-Qubit Readout

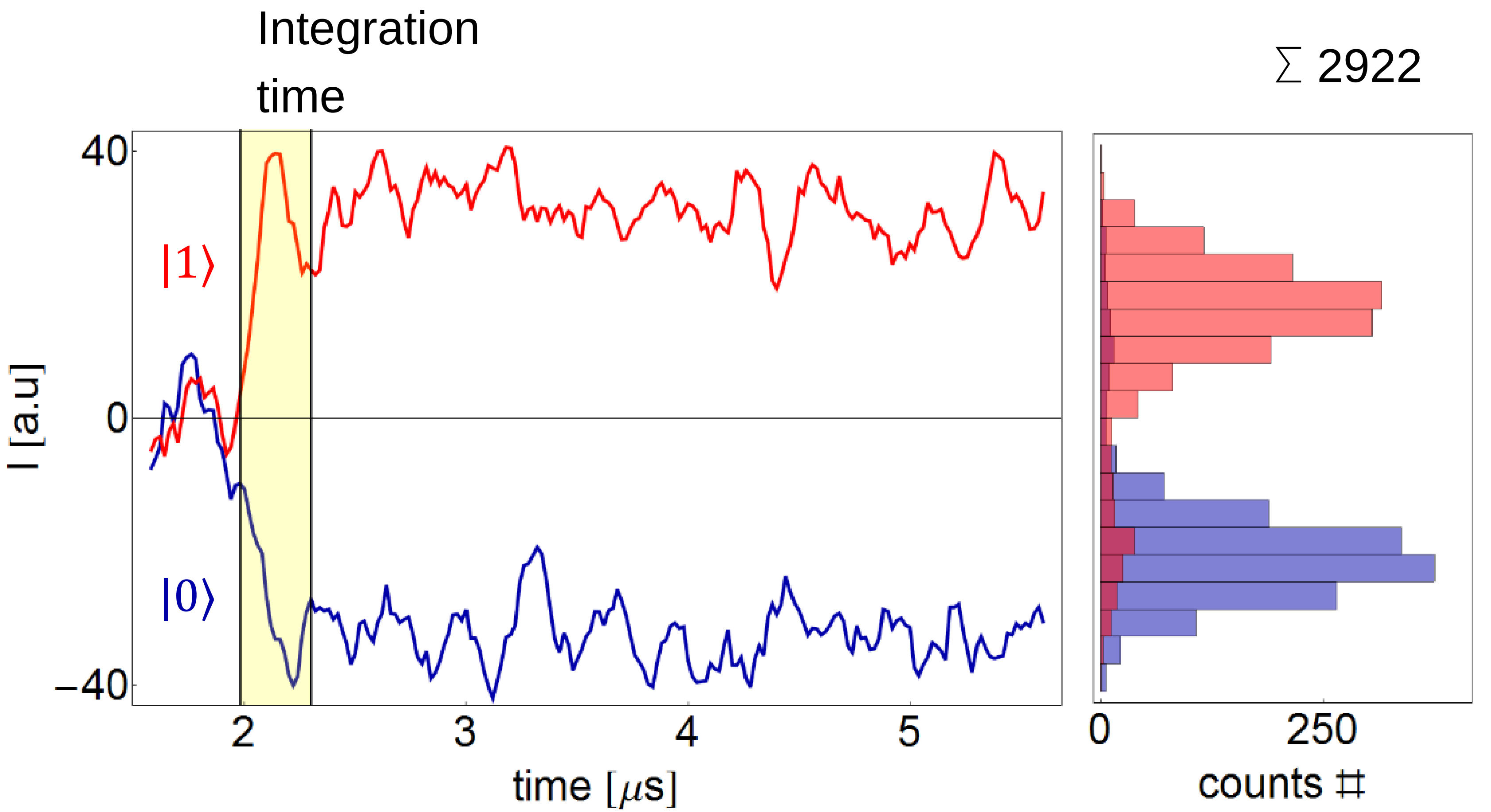
single-shot measurements:

averaged measurements ($8\ 10^4$):



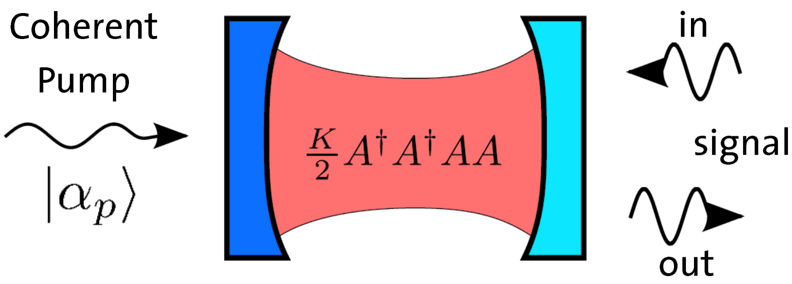
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* **106**, 110502 (2011)

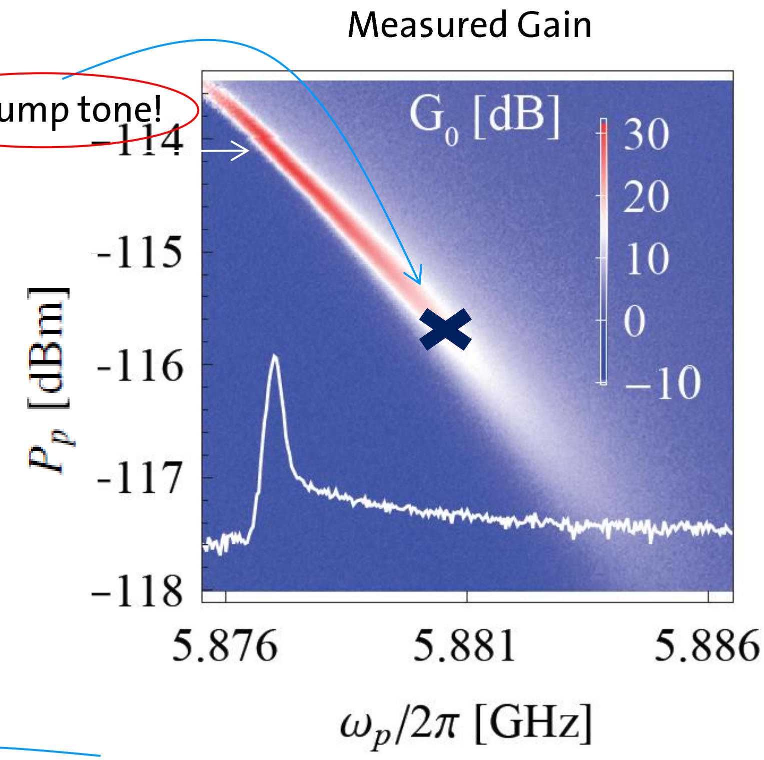
Statistics of Integrated Single-Shot Readout



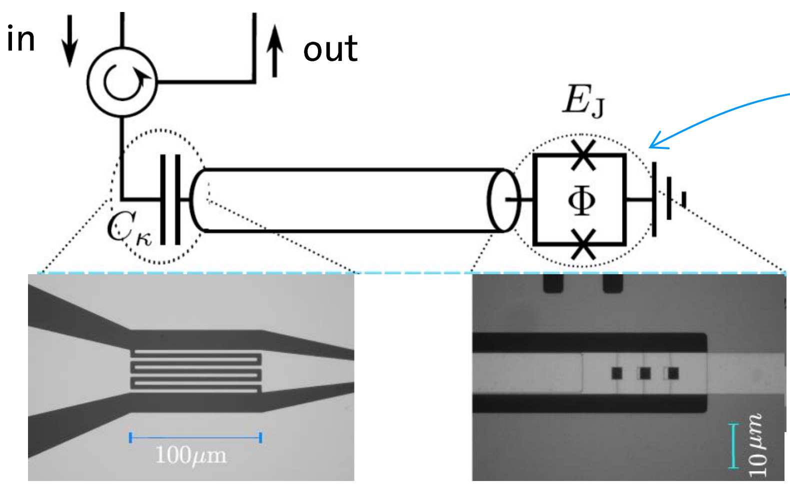
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)

Near Quantum-Limited Parametric Amplifier





Circuit QED implementation:



SQUID(-array) provides required nonlinearity

Eichler *et al.*, EPJ Quantum Technology **1**, 2 (2014)
Eichler *et al.*, *Phys. Rev. Lett.* **107**, 113601 (2011)

Caves, *Phys. Rev. D* **26**, 1817 (1982)
Yurke and Buks, *J. Lightwave Tech.* **24**, 5054 (2006)
Castellanos-Beltran *et al.*, *Nat. Phys.* **4**, 929 (2008)

The Lamb and AC-Stark Shifts

signatures of the dispersive interaction with a quantum field

for $\Delta = \omega_a - \omega_r \gg g$

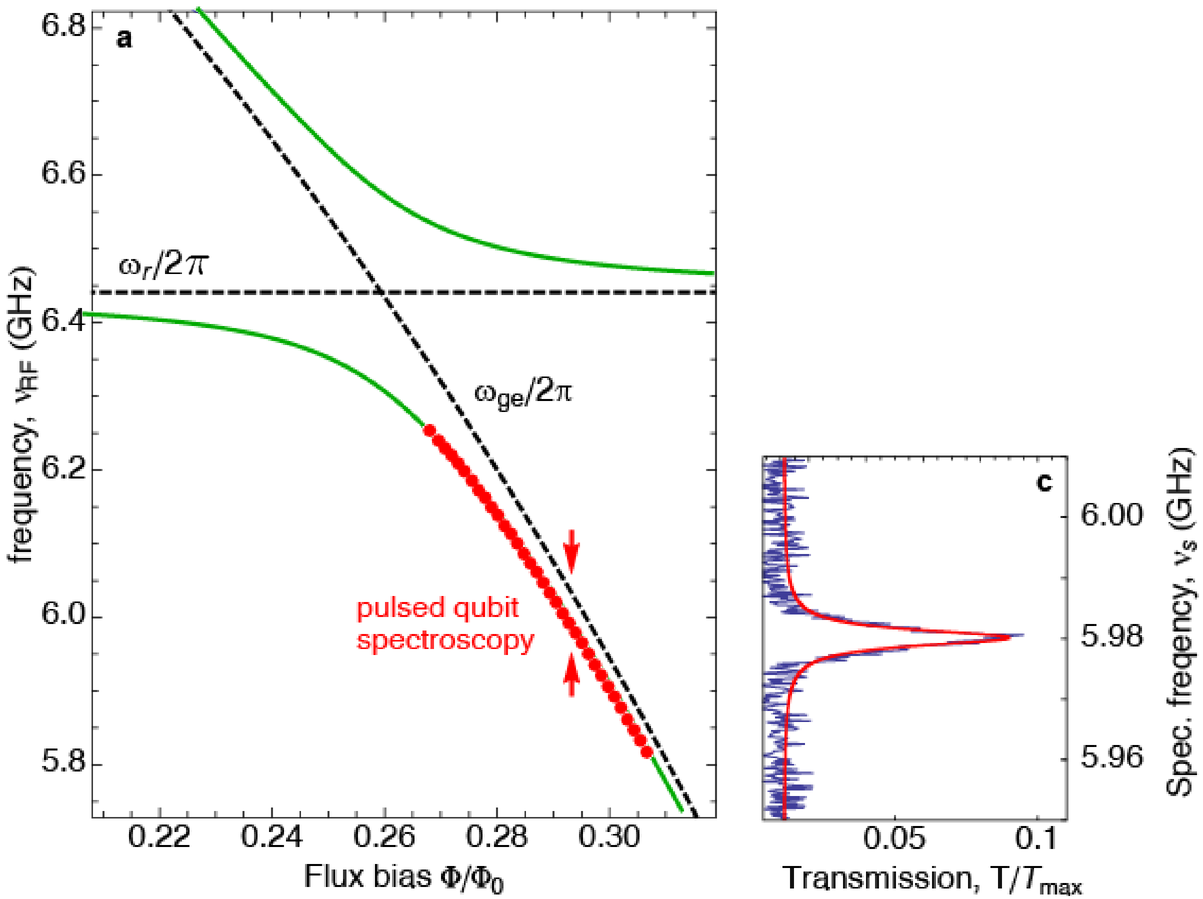
Lamb shift AC Stark shift

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

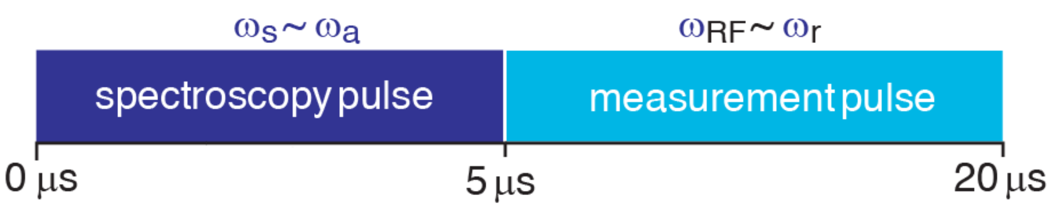
$$\tilde{\omega}_a \approx \omega_a + \frac{g^2}{\Delta} + \frac{2g^2}{\Delta}n$$

M. Brune *et al.*, *Phys. Rev. Lett.* **72**, 3339 (1994)
A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Measurements of the Lamb and Quantized Stark Shifts



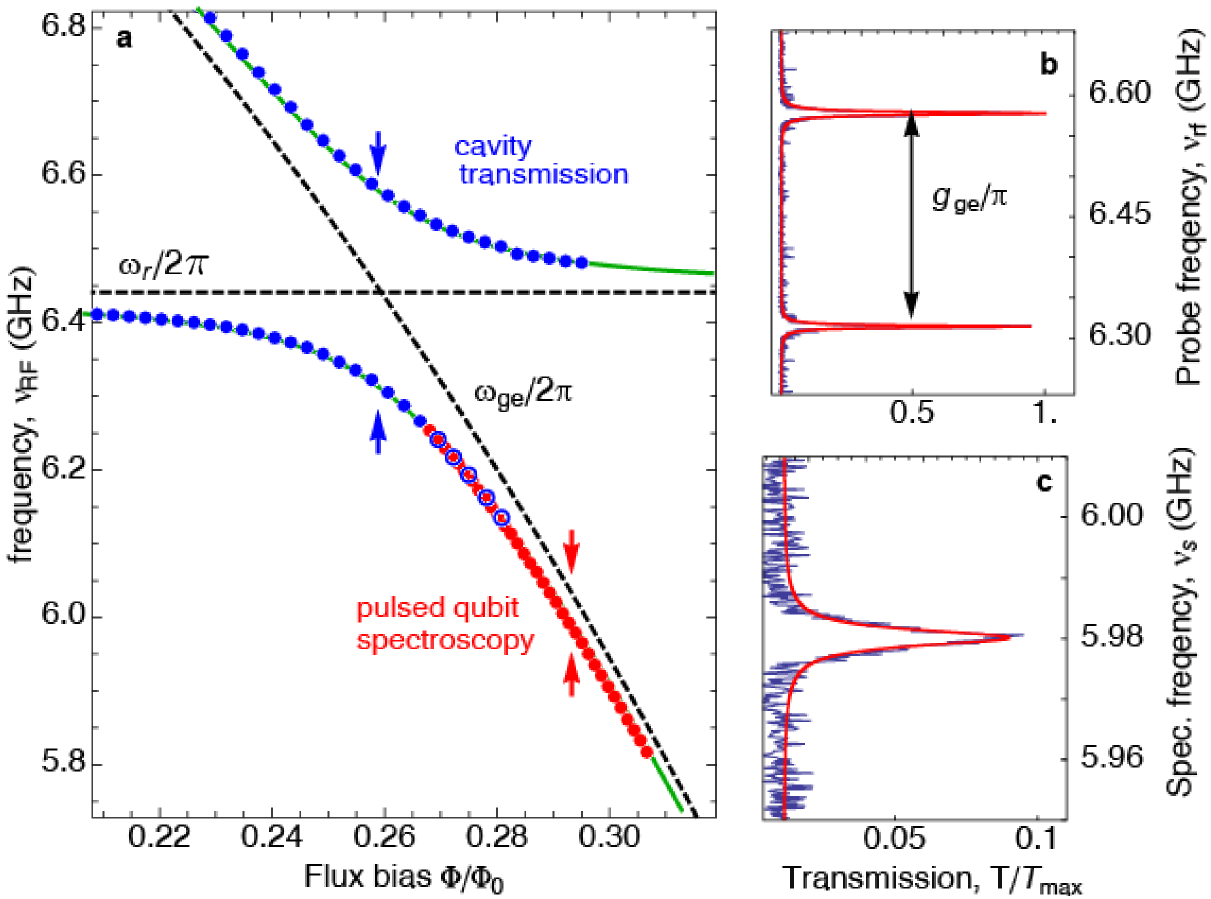
pulsed dispersive qubit spectroscopy



pulsed spectroscopy scheme

A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Measurement of the Lamb Shift



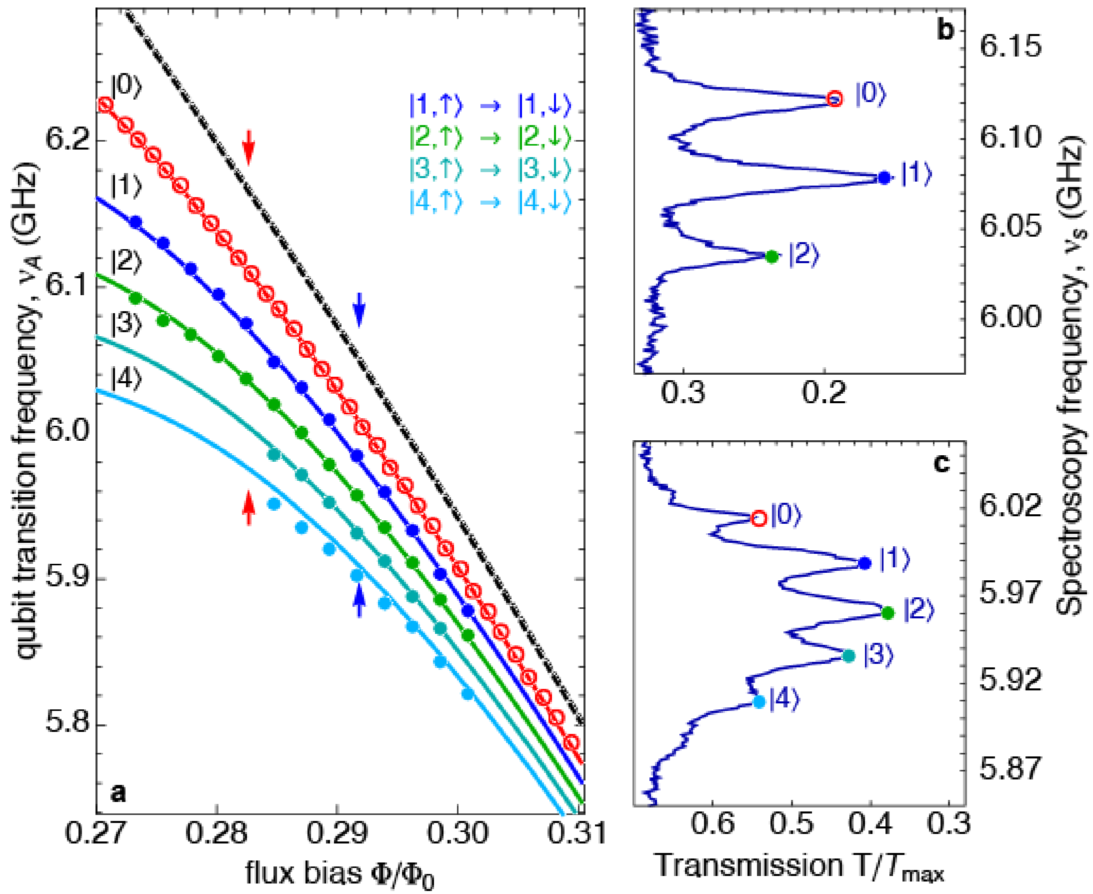
resonator transmission spectrum

pulsed dispersive qubit spectroscopy

- qubit and photon component of joint state are measured
- accurate knowledge of qubit parameters possible

A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Quantum AC-Stark Shift and Lamb Shift



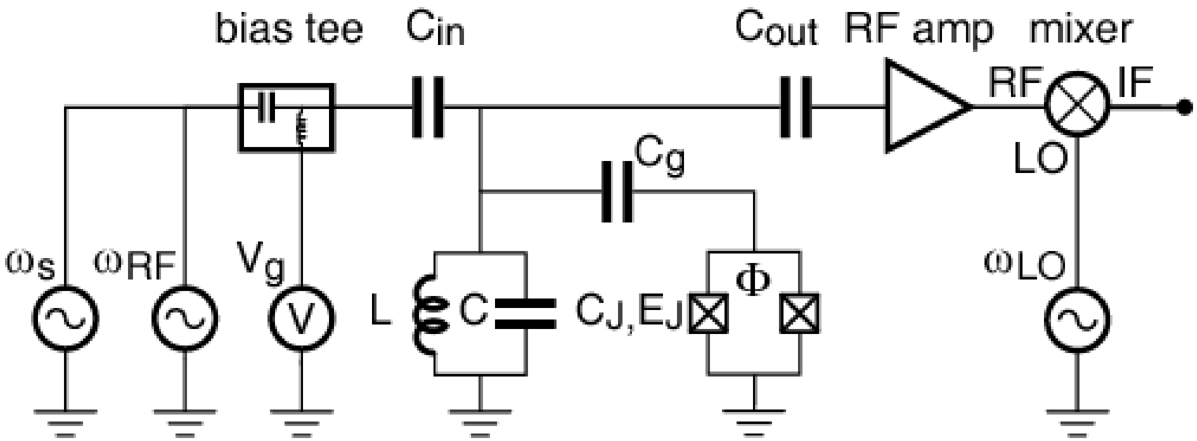
- populate resonator with small coherent field (Poisson distribution of photon number)
- spectroscopic measurement of qubit line shape
- qubit frequencies ac-Stark shifted by quantized cavity field

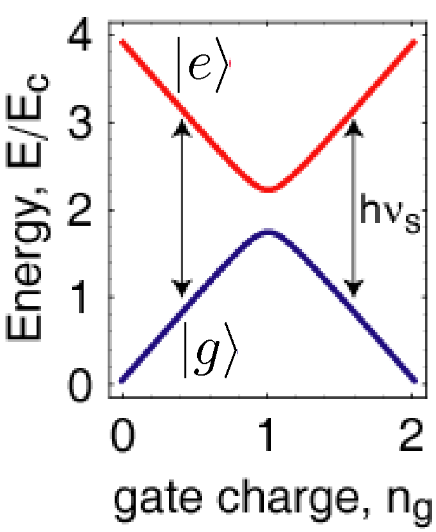
D. Schuster *et al.*, *Nature* **445**, 515 (2007)

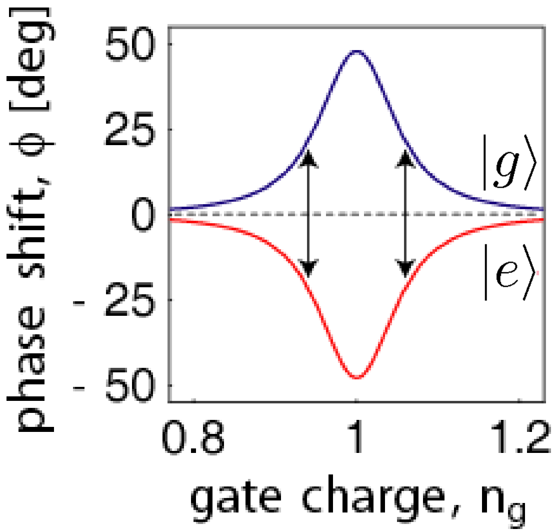
A. Fragner *et al.*, *Science* **322**, 1357 (2008)

Qubit Control

Qubit Spectroscopy with Dispersive Read-Out







Driving Qubit Transitions in J-C Hamiltonian

Hamiltonian for microwave drive

$$H_d = \hbar\epsilon(t)\left(a^\dagger e^{-i\omega_d t} + a e^{i\omega_d t}\right)$$

Unitary transform

$$\tilde{H} = U(H_{\mathrm{JC}} + H_d)U^\dagger \quad \text{with} \quad U = \exp\frac{g}{\Delta}(a\sigma^+ - a^\dagger\sigma^-)$$

$$\text{and} \quad \Delta = \omega_a - \omega_r$$

Results in dispersive approximation up to 2nd order in g

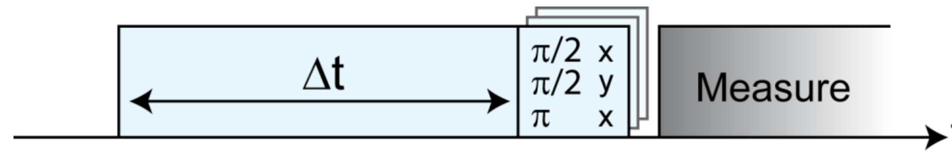
$$\tilde{H} \approx \frac{\hbar}{2}\left(\omega_q + \frac{2g^2}{\Delta}(a^\dagger a + \frac{1}{2}) - \omega_d\right)\sigma_z + \hbar\frac{g\epsilon(t)}{\Delta}\sigma_x$$
$$+\hbar(\omega_r - \omega_d)a^\dagger a + \hbar\epsilon(t)(a^\dagger + a)$$

Drive induces Rabi oscillations in qubit when in resonance with dispersively shifted qubit frequency

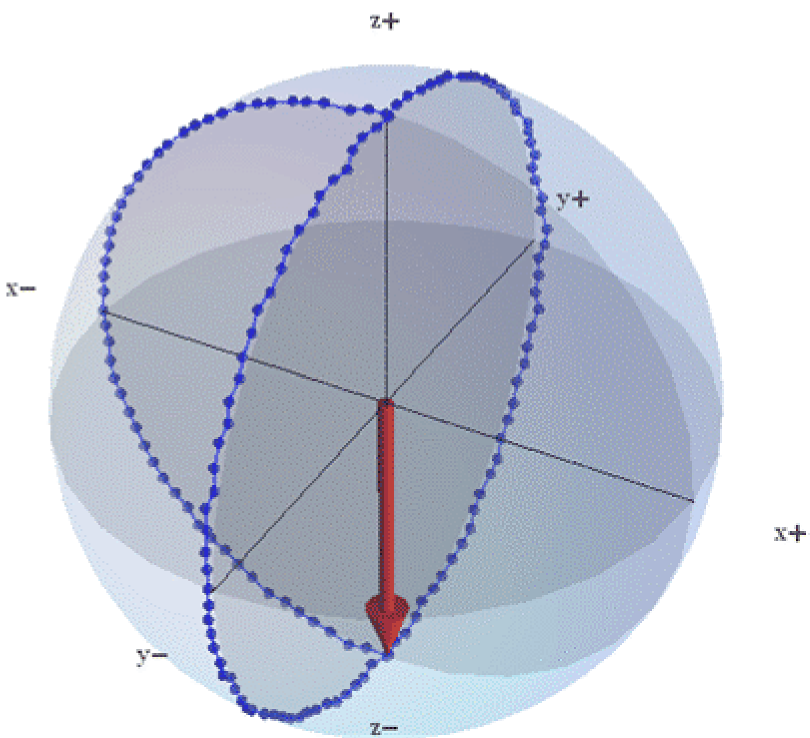
A. Blais, *et al.*, *PRA* **69**, 062320 (2004)

Single Qubit Gates

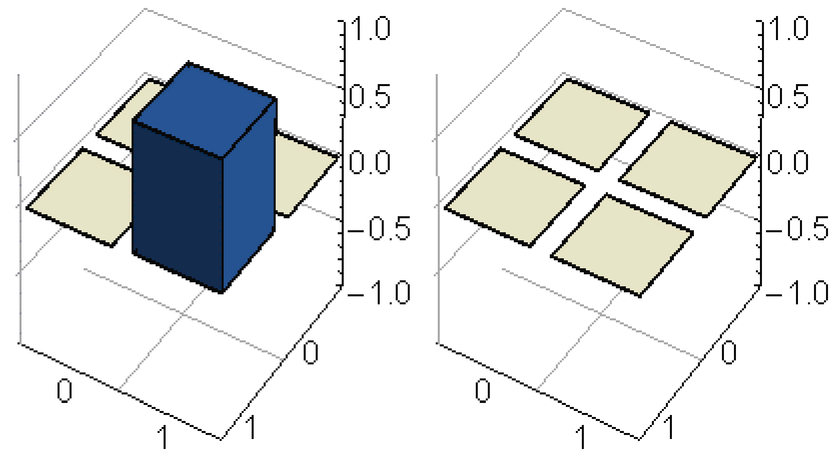
Pulse sequence for qubit rotation and readout:

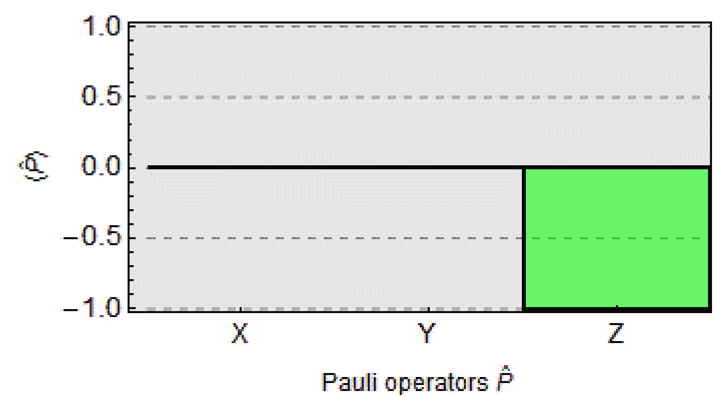


experimental Bloch vector:



experimental density matrix and Pauli set:

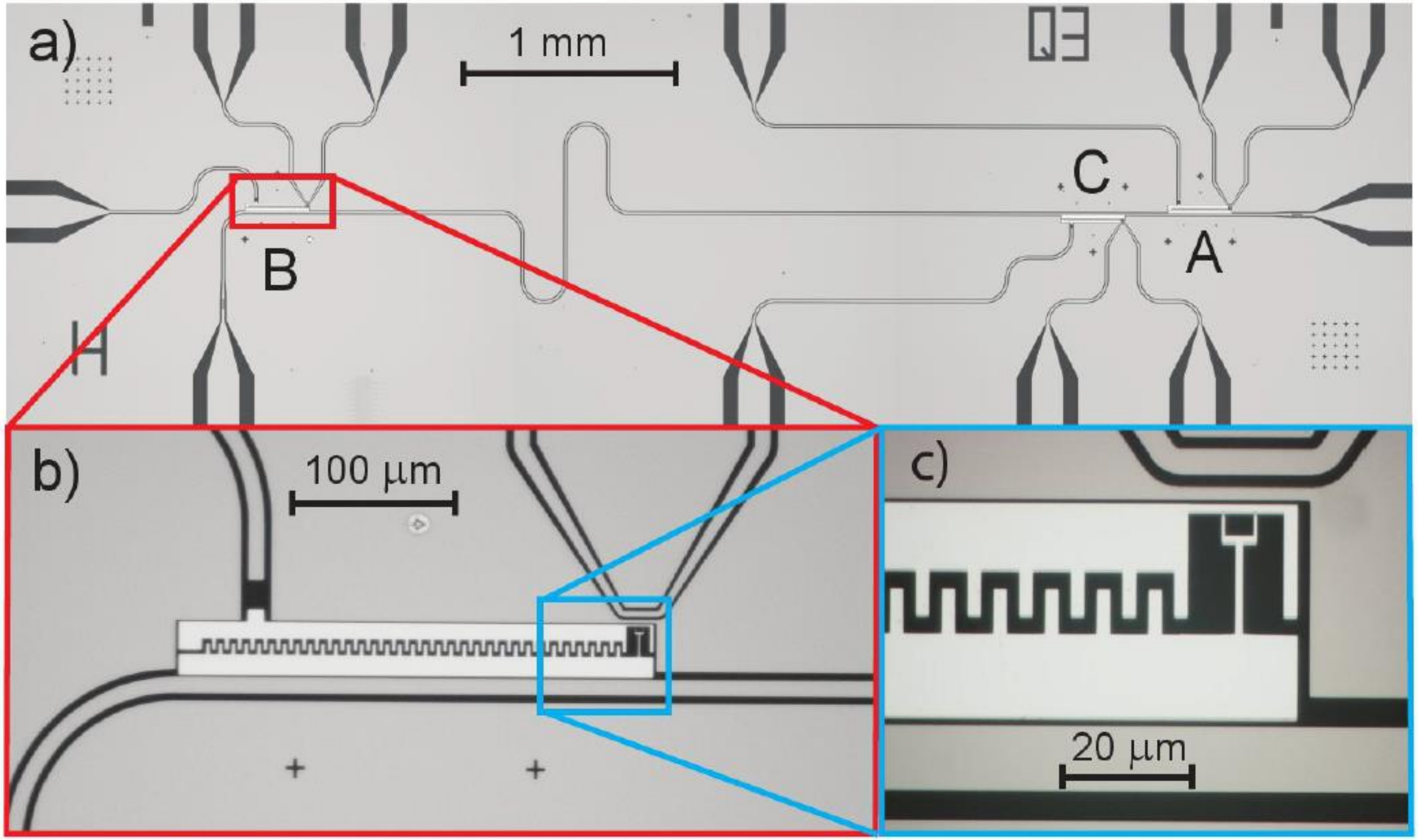




L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Coupling Superconducting Qubits and Generating Entanglement using a Controlled Phase Gate

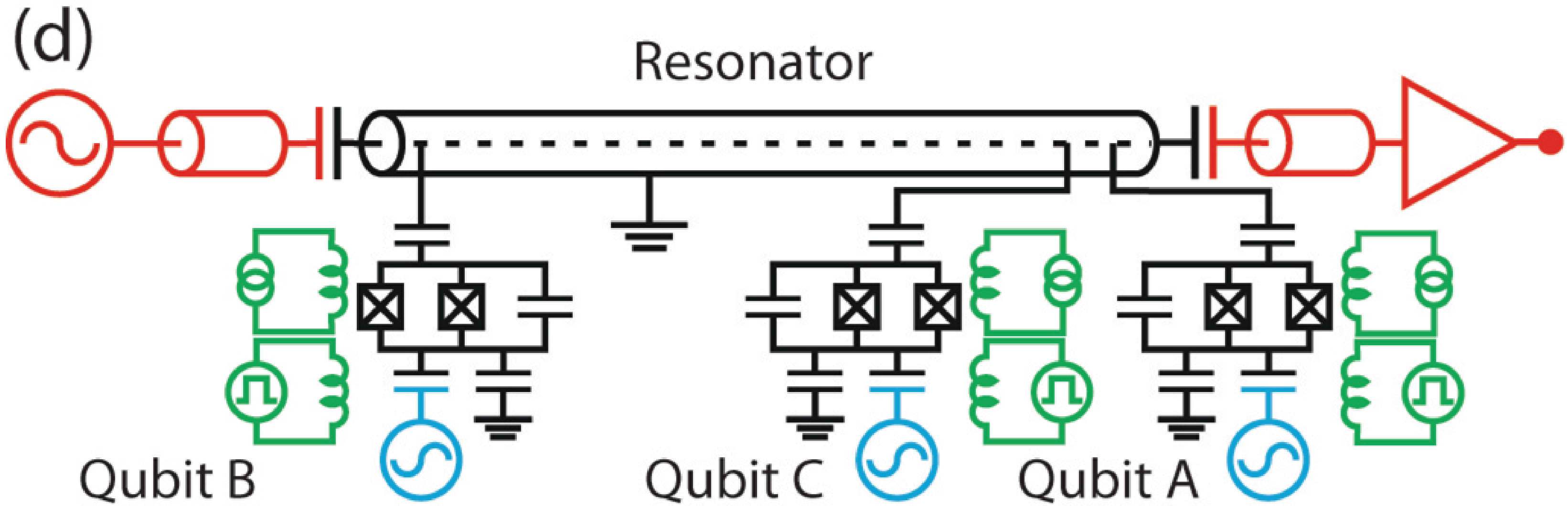
Quantum Processor with 3 Qubits: The Chip



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

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

Quantum Processor with 3 Qubits: Circuit Diagram

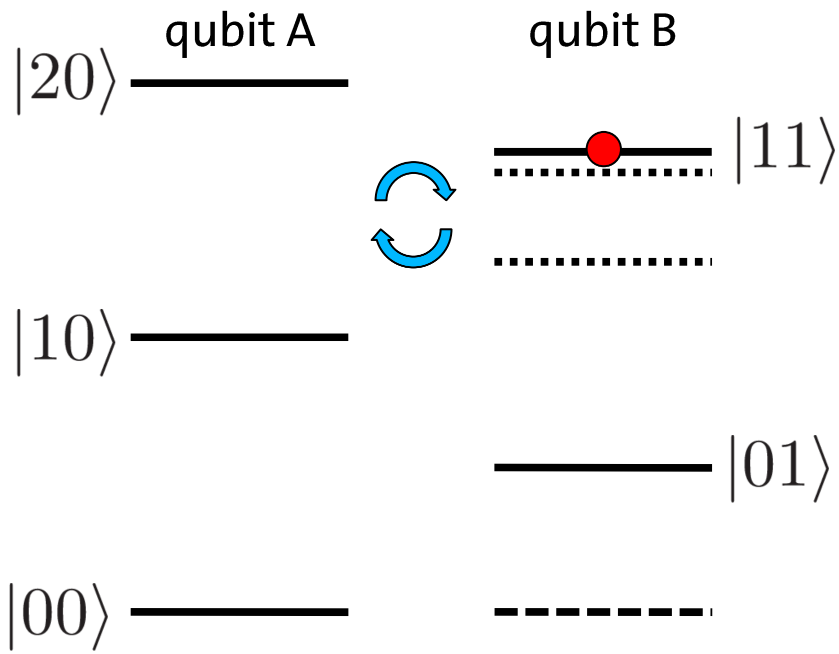


- qubit state measurement through resonator
- individual qubit control through local microwave gates
- two-qubit interactions by tuning qubits into resonance using local flux gates

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

Universal Two-Qubit Controlled Phase Gate

Tune levels into resonance using magnetic field

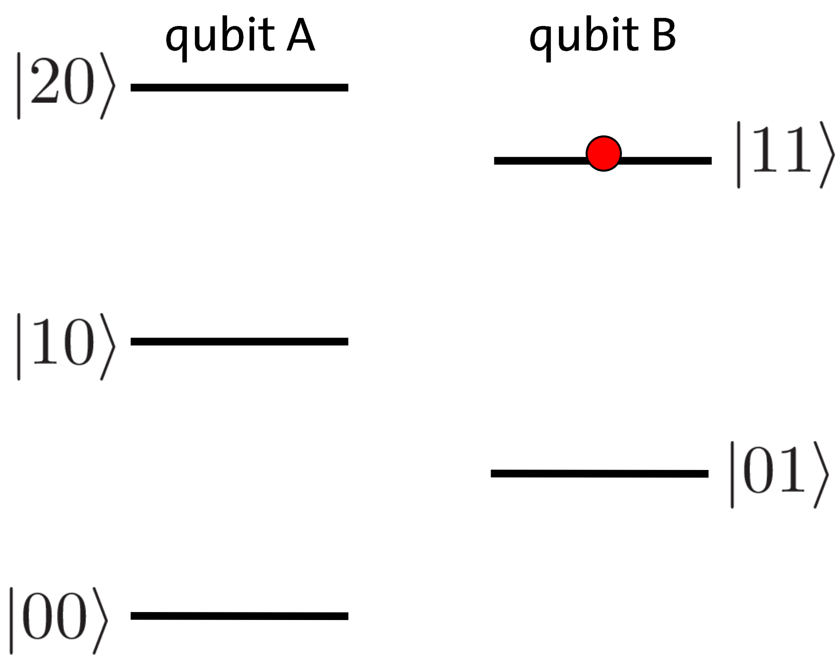


Interaction mediated by virtual photon exchange through resonator

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

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).

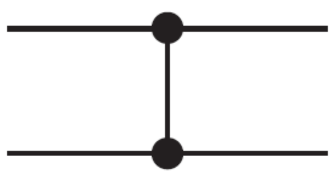
Process Tomography: C-Phase Gate

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

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

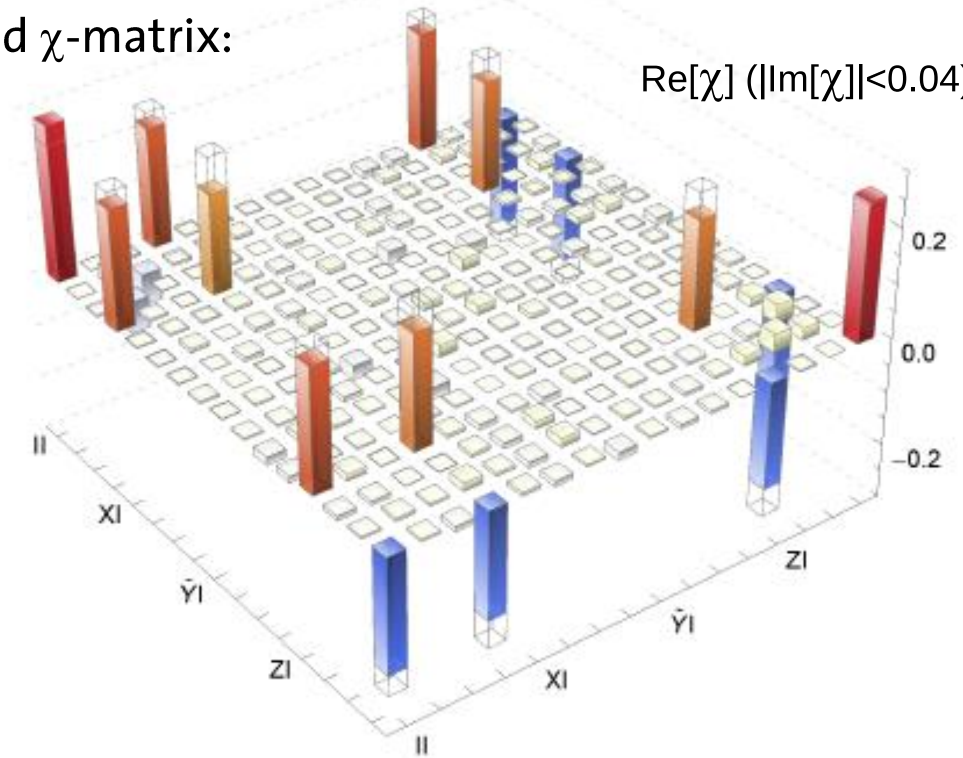
χ is a positive semi definite Hermitian matrix characteristic for the process

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:



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

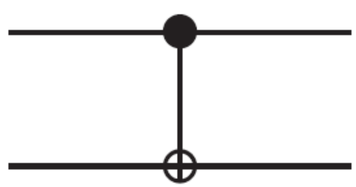
Process Tomography: C-NOT Gate

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

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

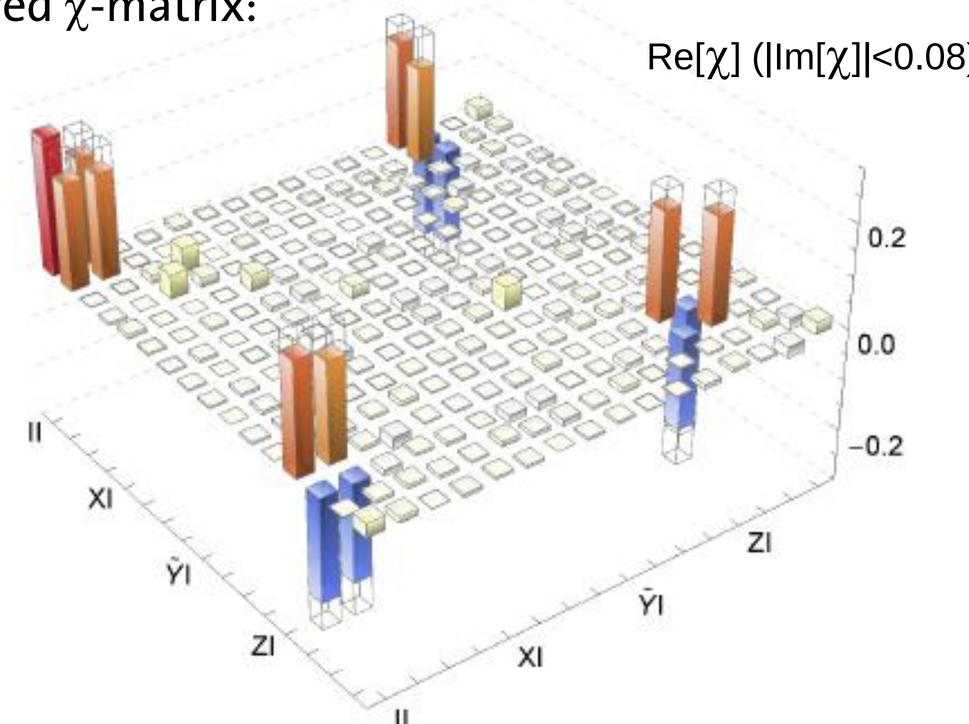
χ is a positive semi definite Hermitian matrix characteristic for the process

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:

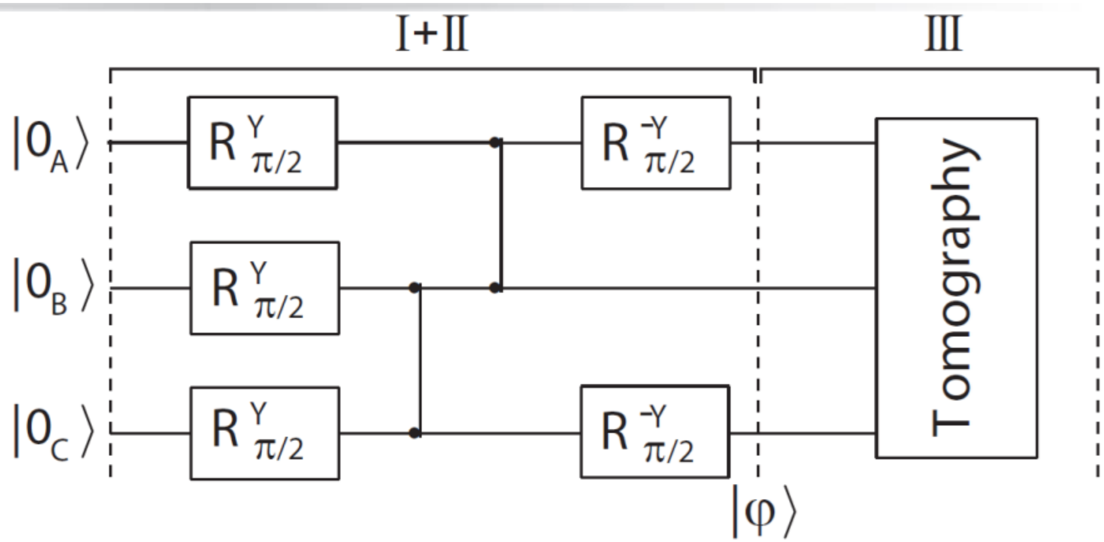


$$F = \mathrm{Tr}[\chi_{\mathrm{meas}}\chi_{\mathrm{ideal}}] = 0.81$$

Maximally Entangled Three Qubit States

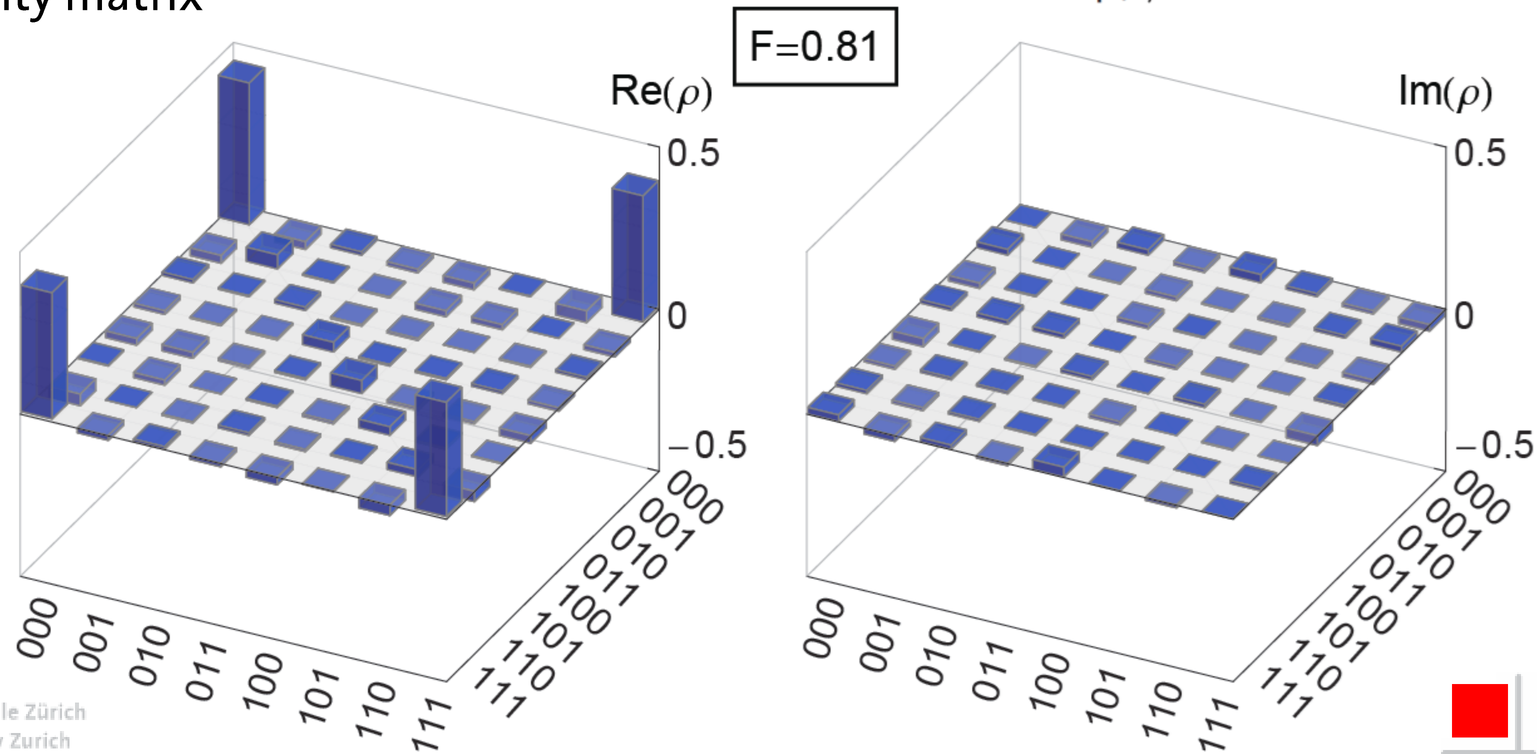
Generation of GHZ class, e.g. |000>+|111>, states:

- 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. ✓