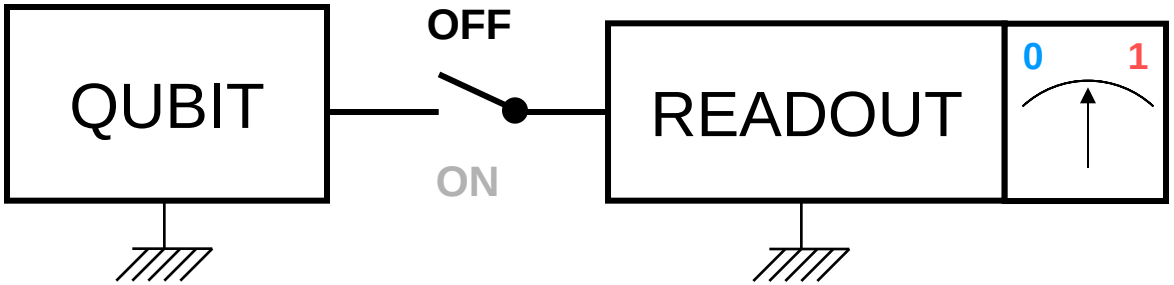
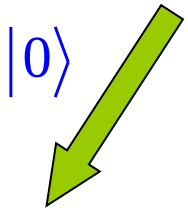
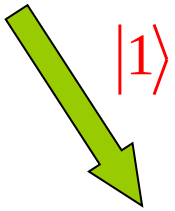
Read-Out ...

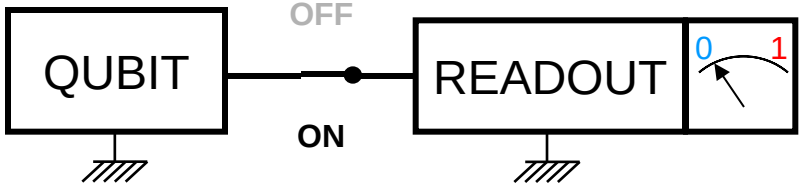
... of superconducting qubits

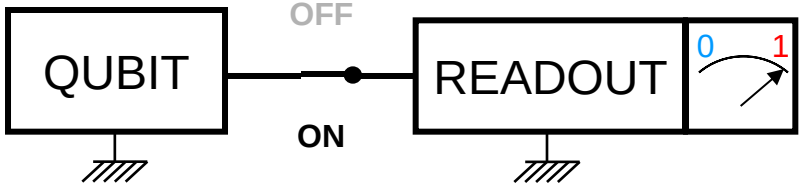
Qubit Read Out







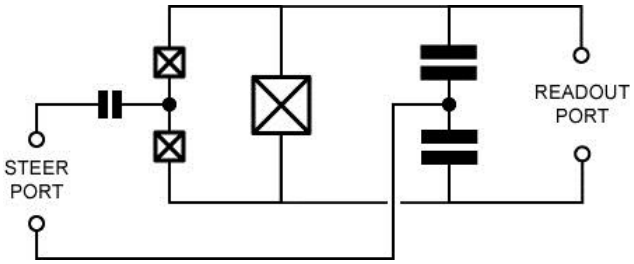




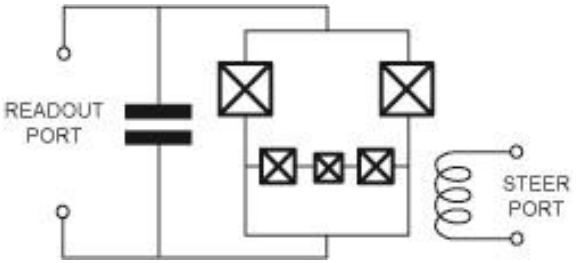
desired: good on/off ratio
no relaxation in on state (QND)

Read Out Strategies

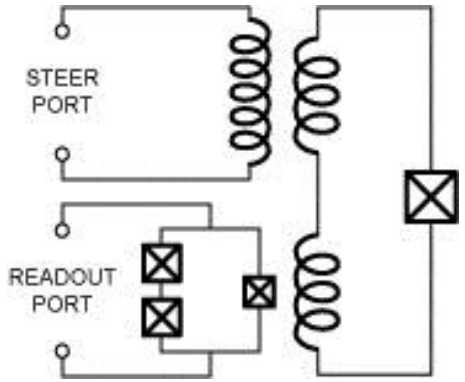
demolition measurements (switching/latching measurements)



Quantronium (Saclay, Yale)

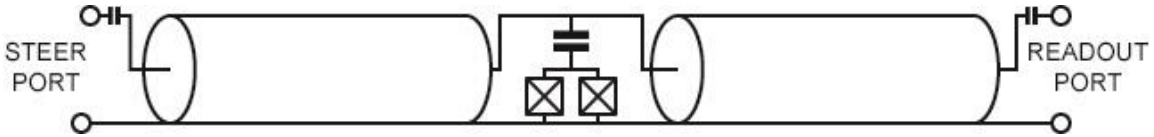


Flux Qubit (TU Delft, NEC)



Phase Qubit (NIST, UCSB)

quantum non-demolition (QND) measurements



Yale (circuit QED)

also: Chalmers, Delft, Yale (JBA)

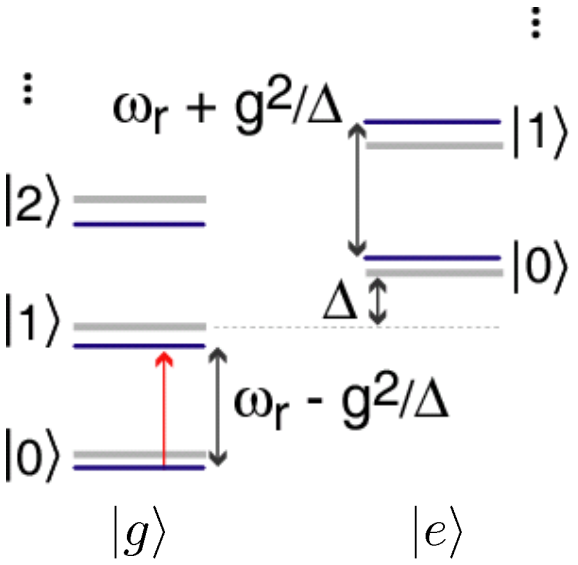
Non-Resonant Qubit-Photon Interaction

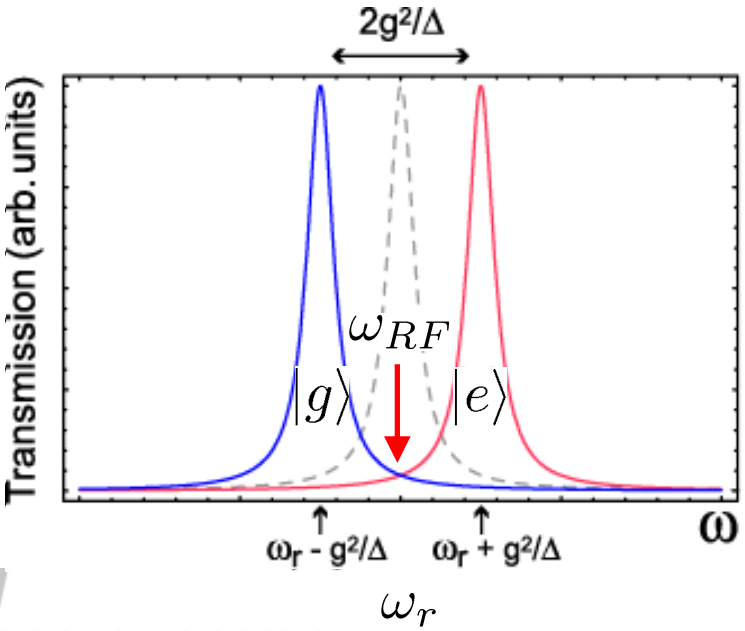
approximate diagonalization in the dispersive limit $|\Delta| = |\omega_a - \omega_r| \gg g$

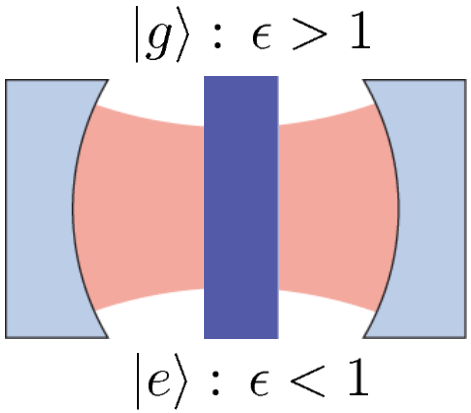
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z \right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

cavity frequency shift *and* qubit ac-Stark shift

Lamb shift







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

Non-Resonant Qubit-Photon Interaction

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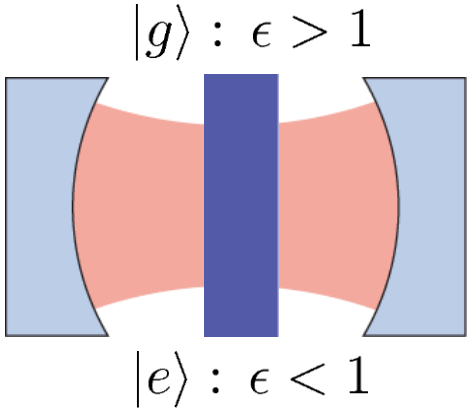
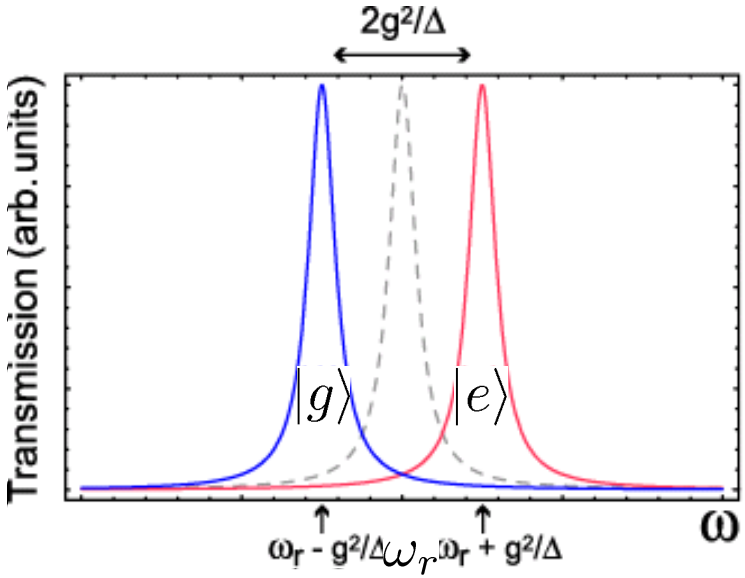
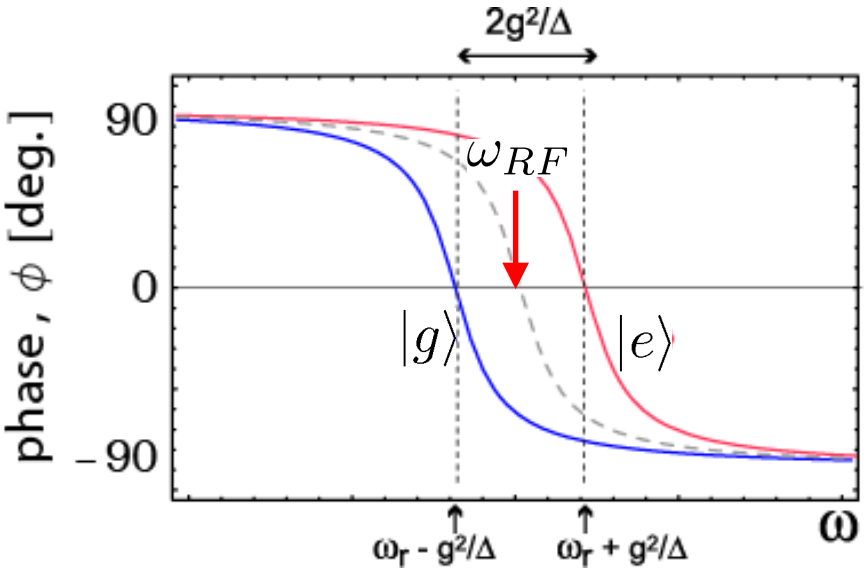


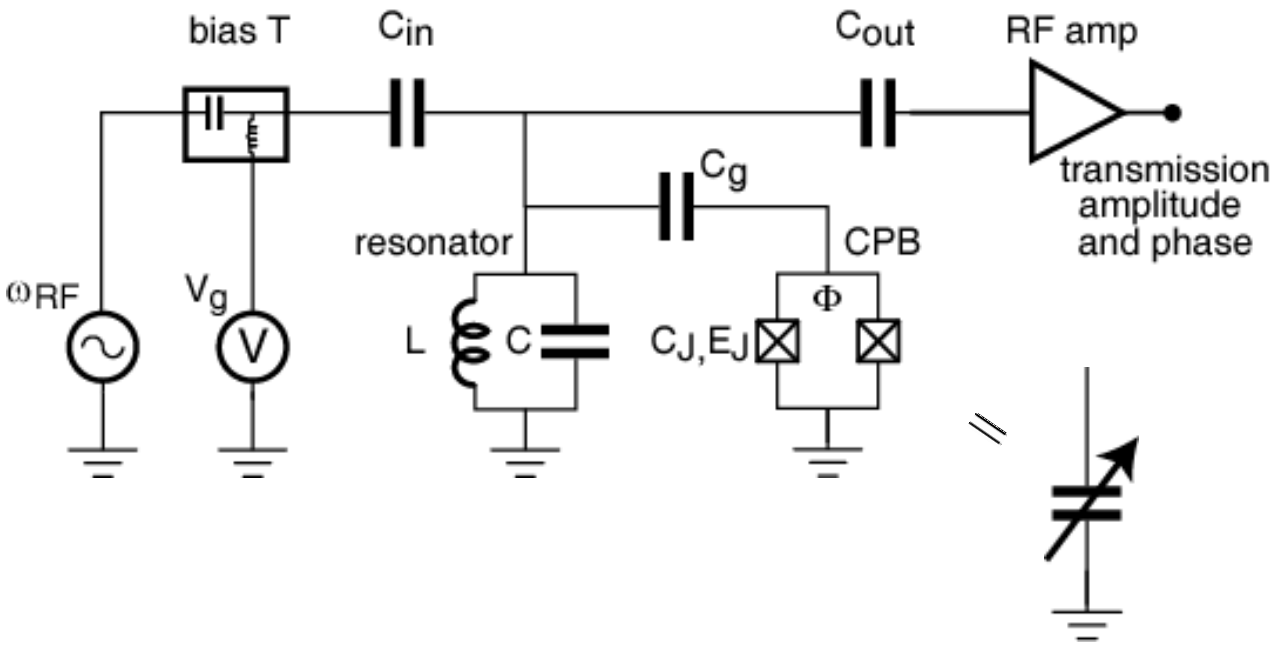




A. Blais *et al.*, *PRA* **69,** 062320 (2004)

Qubit Spectroscopy with Dispersive Read-Out

Measurement Technique

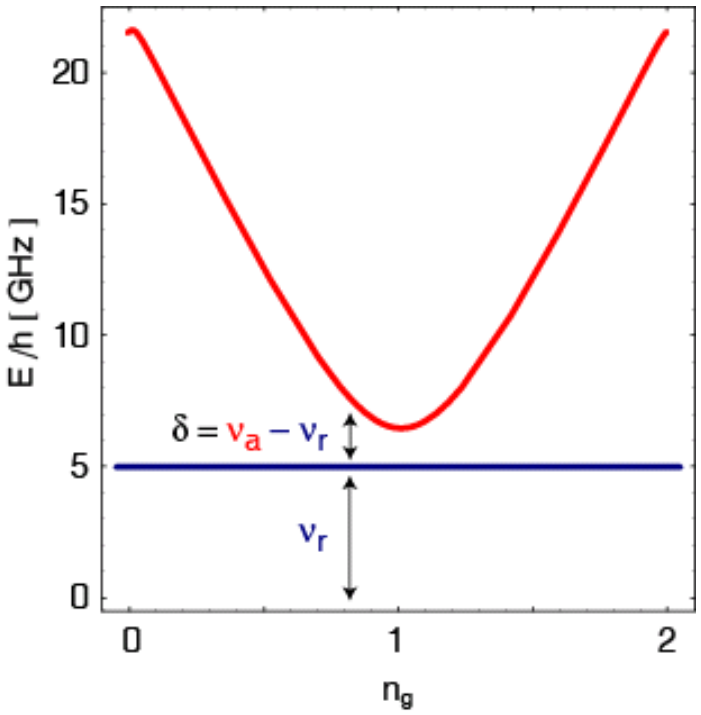


- measurement of microwave transmission amplitude T and phase ϕ
- intra-cavity photon number controllable from $n \sim 10^3$ to $n \ll 1$

Dispersive Shift of Resonance Frequency

sketch of qubit level separation:

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

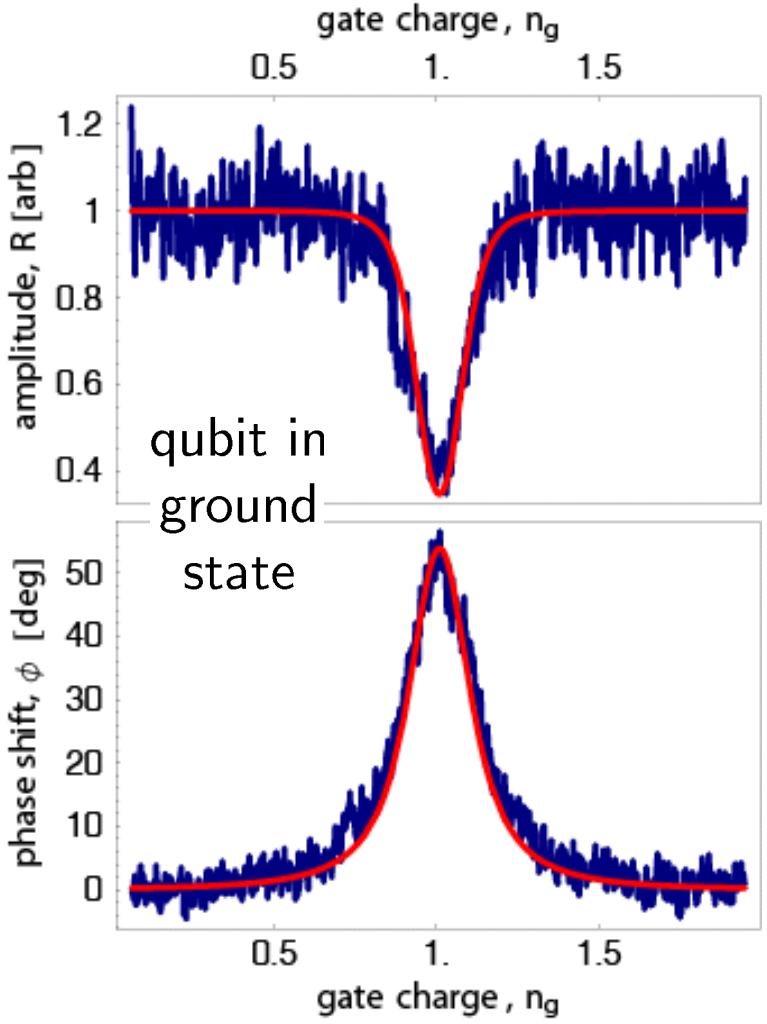


$$g/\pi = \nu_{\mathrm{vac}} = 11\,\mathrm{MHz}$$

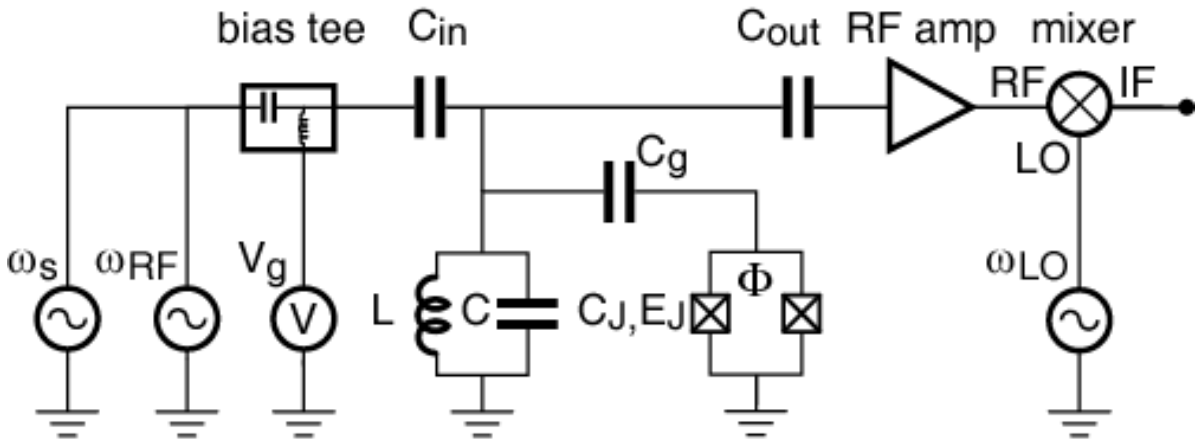
$$\Delta(n_g = 1)/2\pi = 66\,\mathrm{MHz}$$

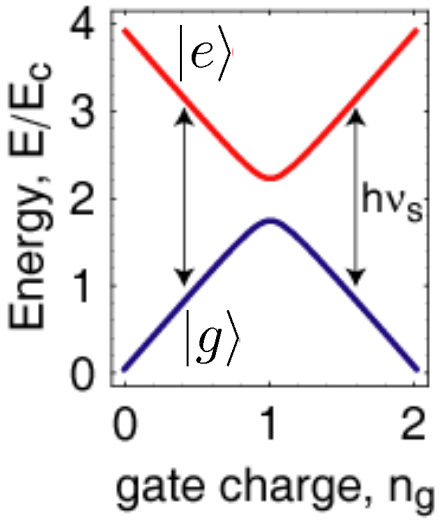
$$n = 10$$

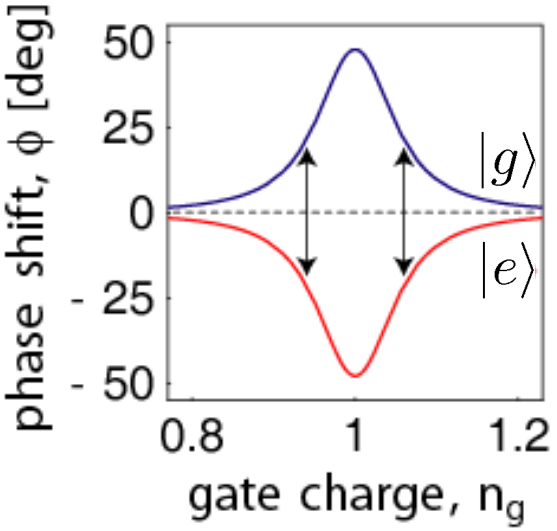
transmission amplitude and phase at bare resonator frequency



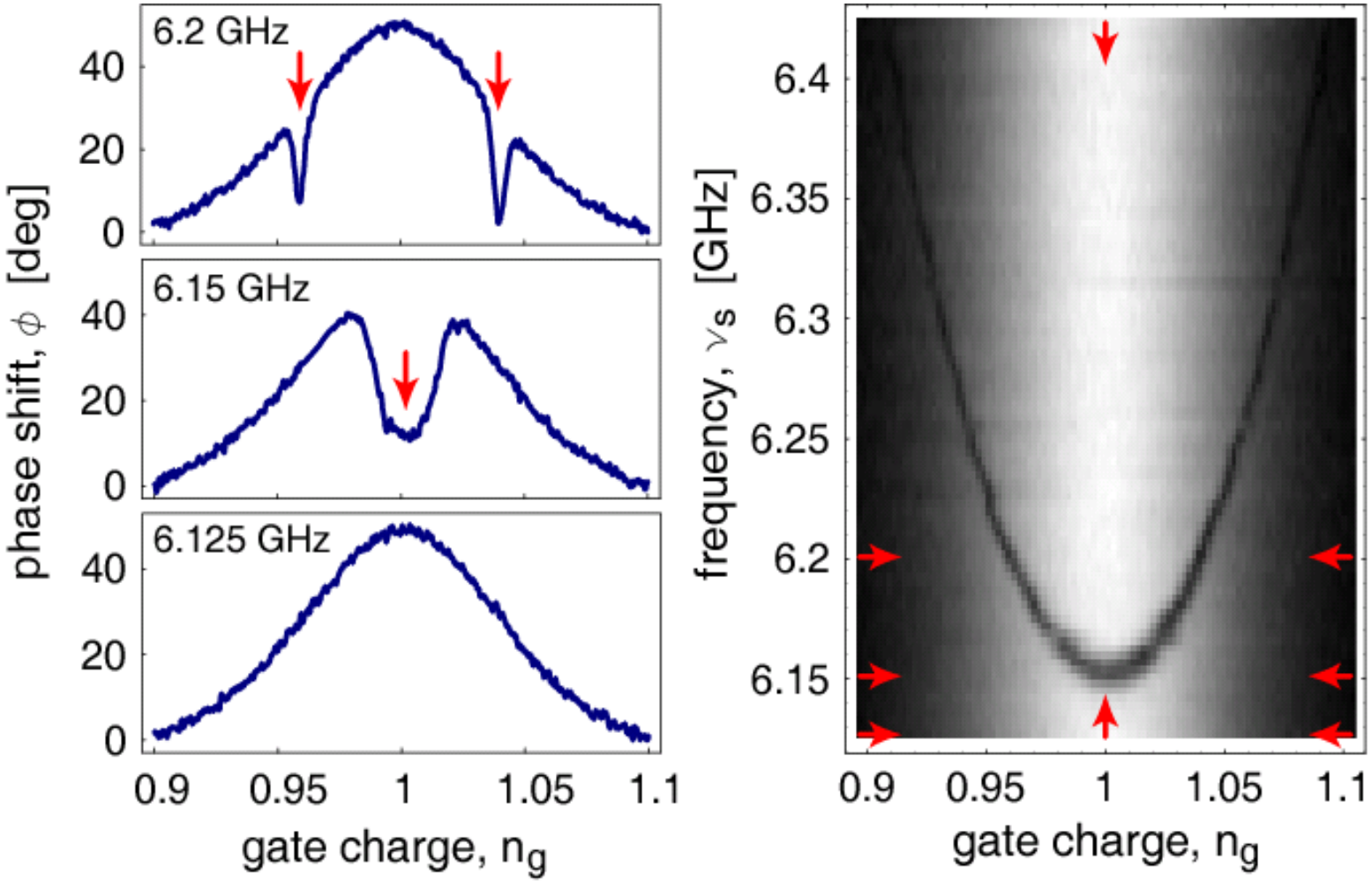
Qubit Spectroscopy with Dispersive Read-Out







CW Spectroscopy of Cooper Pair Box



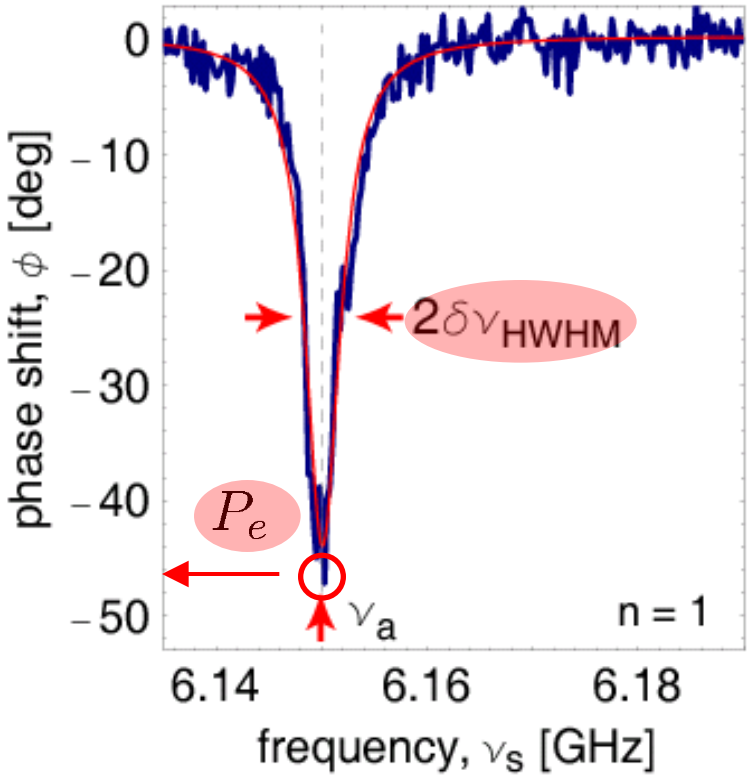
detuning $\Delta_{r,a}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

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

Line Shape

excited state population (steady-state Bloch equations):

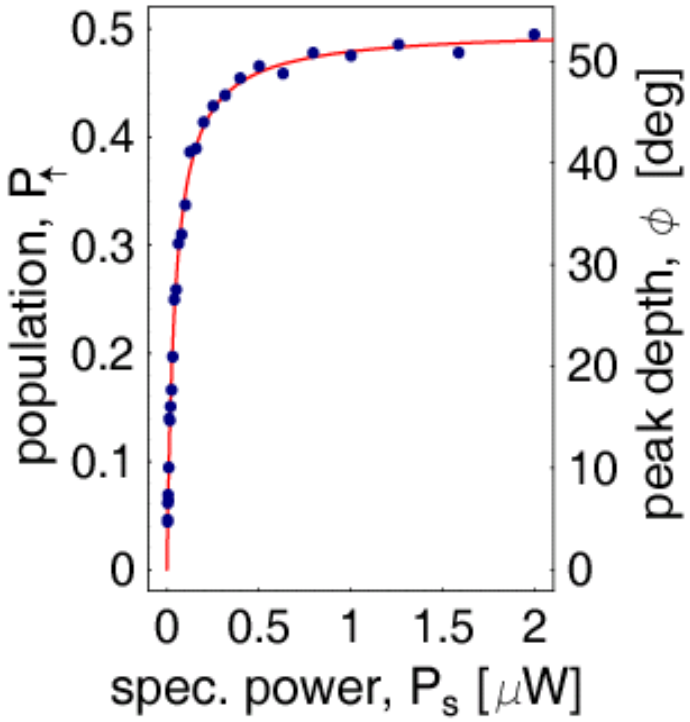
$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + (T_2 \Delta_{\mathrm{s,a}})^2 + \Omega_R^2 T_1 T_2}$$



- 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

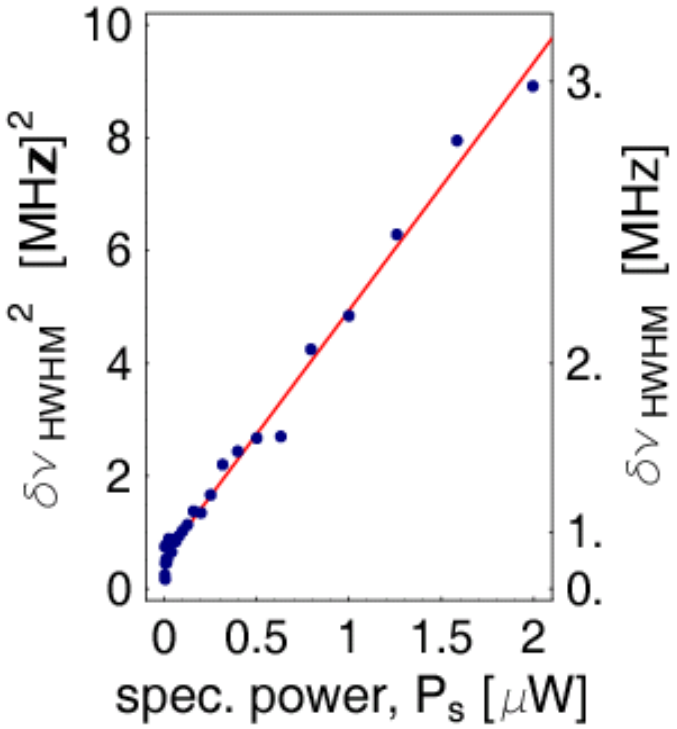


peak depth $\rightarrow$ population (saturation):

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

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:

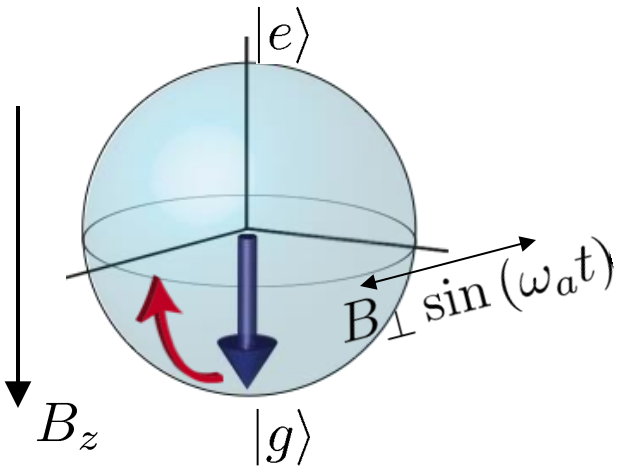
$$2\pi\delta\nu_{\mathrm{HWHM}} = \frac{1}{T_2'} = \sqrt{\frac{1}{T_2^2} + \Omega_R^2 \frac{T_1}{T_2}}$$

$$\mathrm{Min}(\delta\nu_{\mathrm{HWHM}}) \sim 750\,\mathrm{kHz} \rightarrow \mathrm{T_2} > 200\,\mathrm{ns}$$

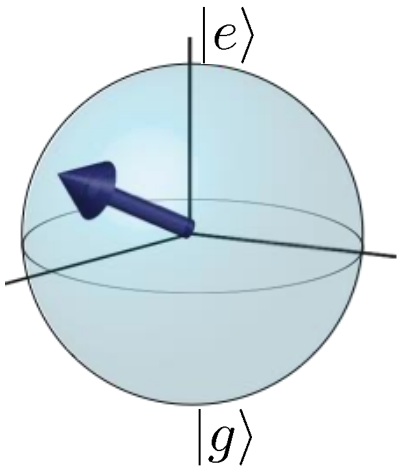
D. I. Schuster, A. Wallraff, A. Blais, L. Frunzio, R.-S. Huang, J. Majer, S. Girvin, and R. J. Schoelkopf, *Phys. Rev. Lett.* **94,** 123062 (2005)

Time Resolved Measurements

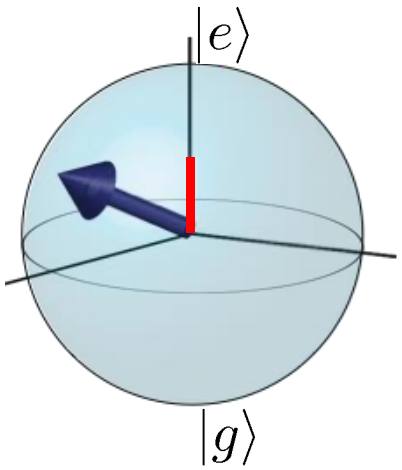
Coherent Control of a Qubit in a Cavity



initialize



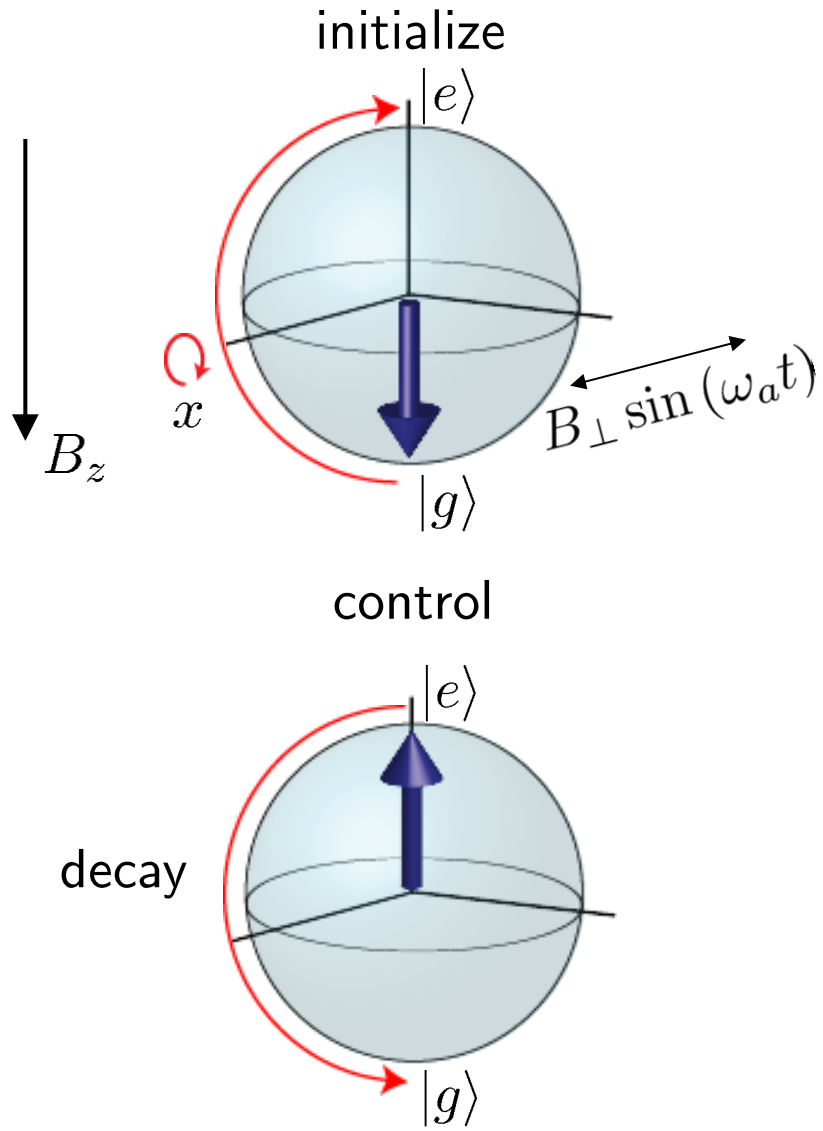
after operation

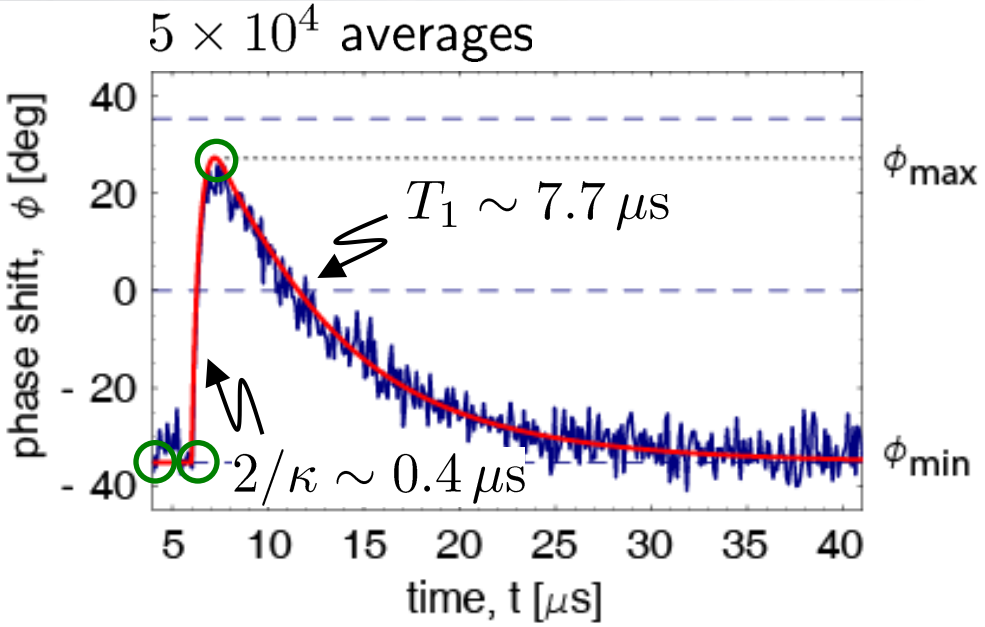


measure projection

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

Qubit Control and Readout



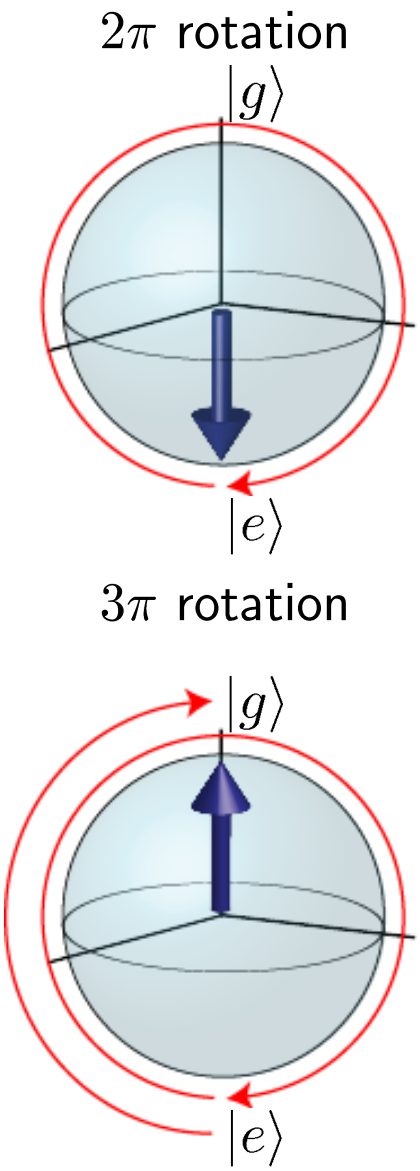


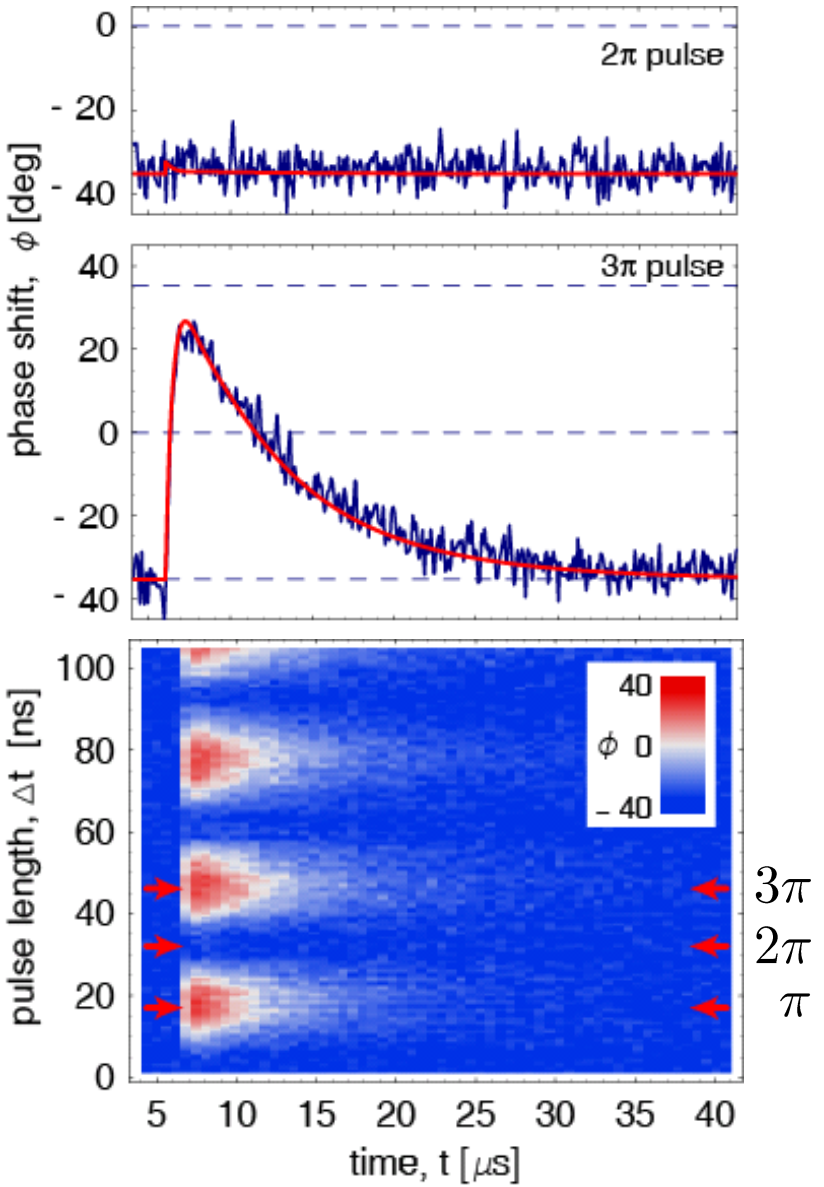
measurement properties:

- 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

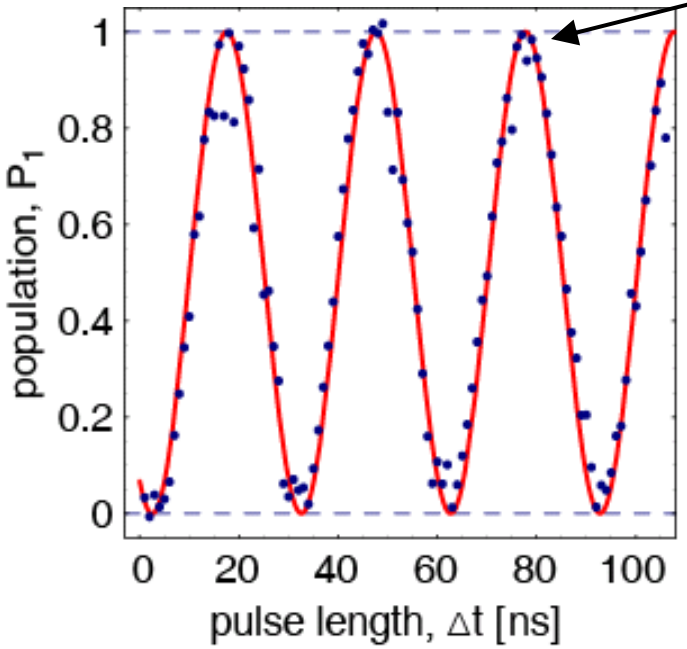




Wallraff, Schuster, Blais, ... Girvin, Schoelkopf, *PRL* **95**, 060501 (2005)

High Visibility Rabi Oscillations

Rabi oscillations:



visibility $95 \pm 5\%$

for superconducting qubits:

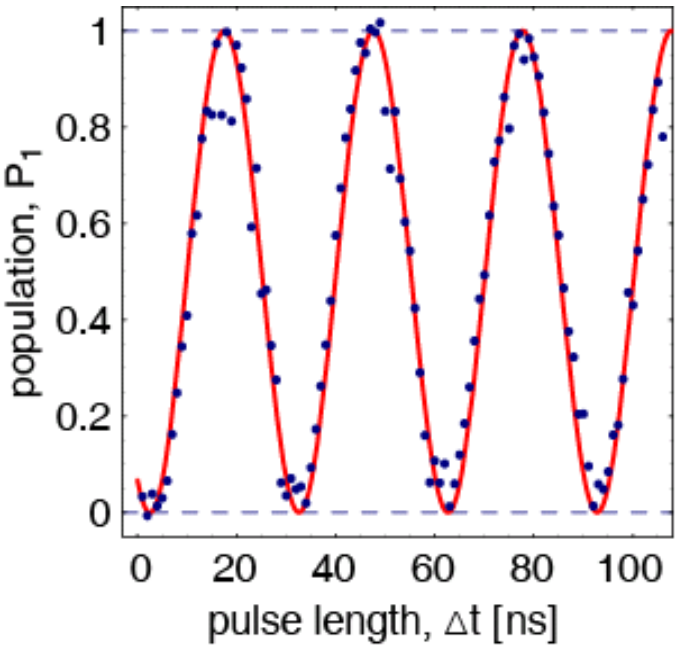
- high visibility
- well characterized and understood measurement
- good control accuracy

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

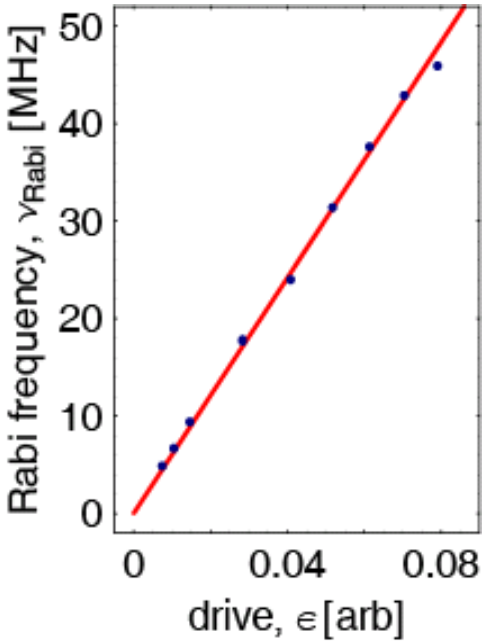
Rabi Frequency

pulse scheme:

Rabi oscillations:



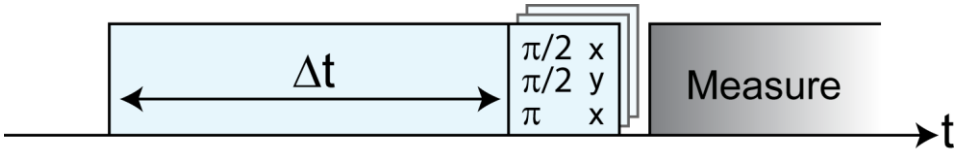
Rabi frequency:



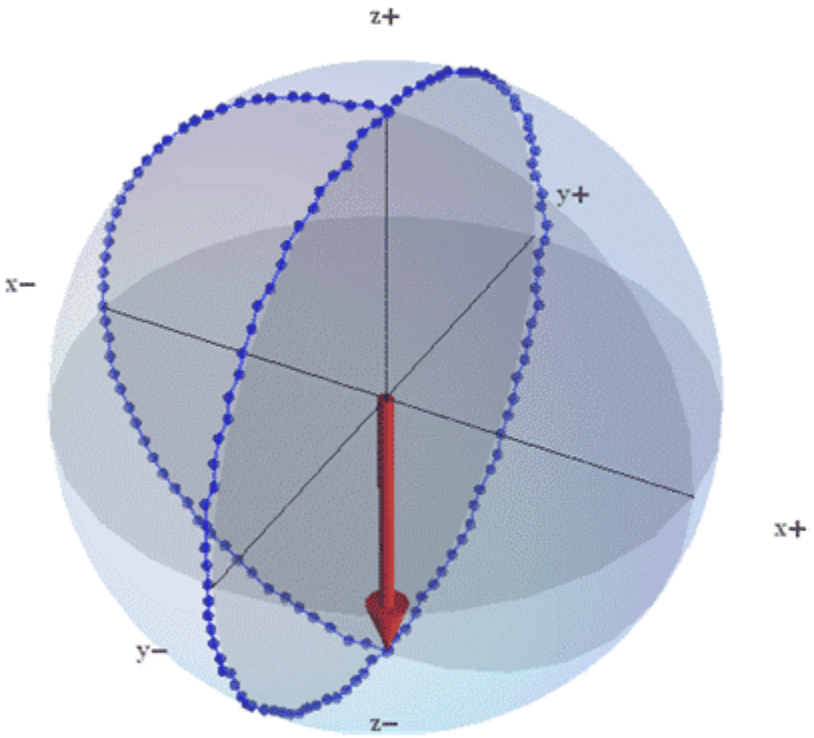
- linear dependence of Rabi frequency on microwave amplitude

Single Qubit Gates

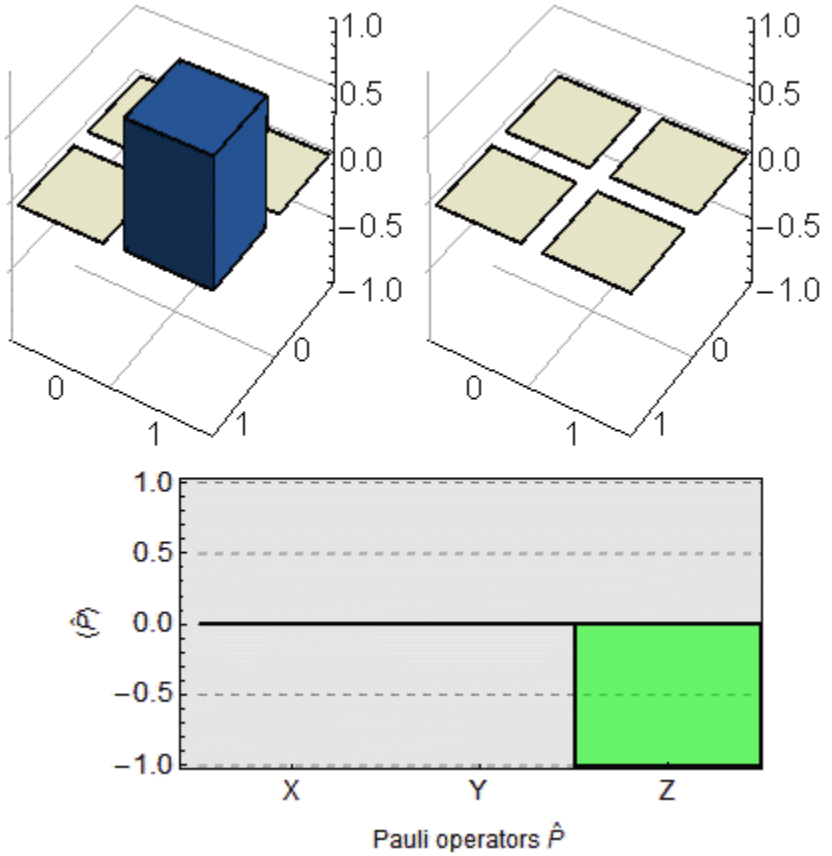
Pulse sequence for qubit rotation and readout:



experimental Bloch vector:



experimental density matrix and Pauli set:

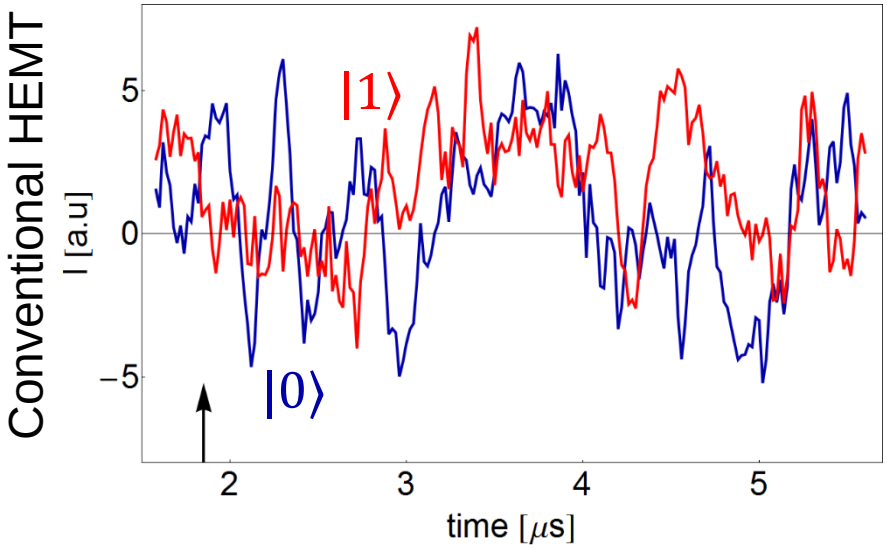


L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

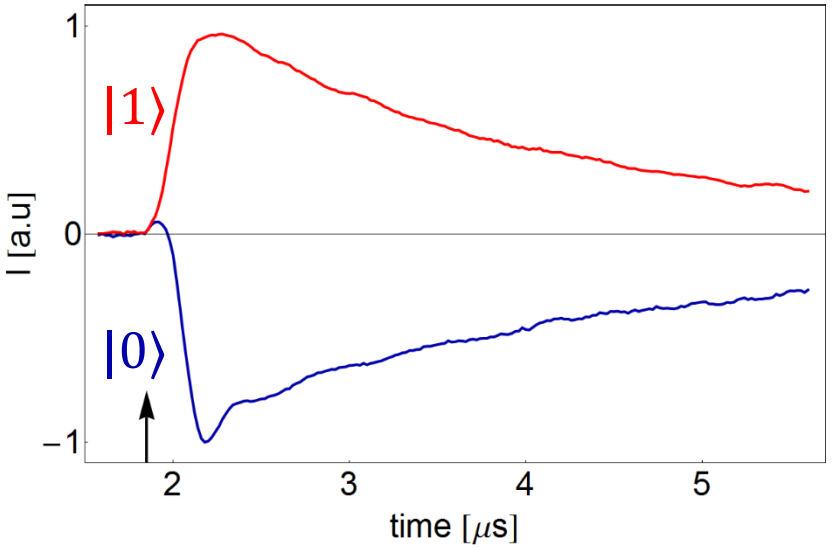
Single Shot Read-Out

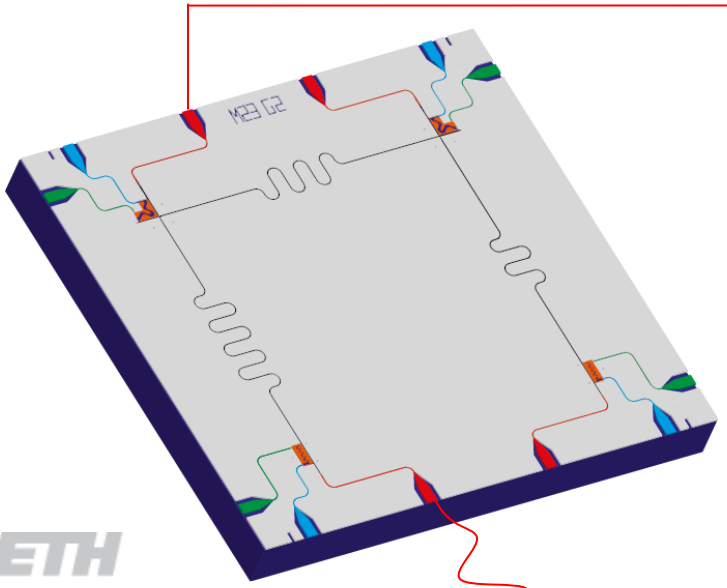
Single-Shot Single-Qubit Readout

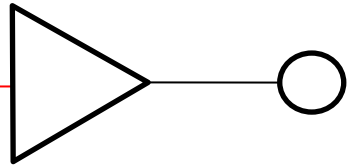
single-shot measurements:



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





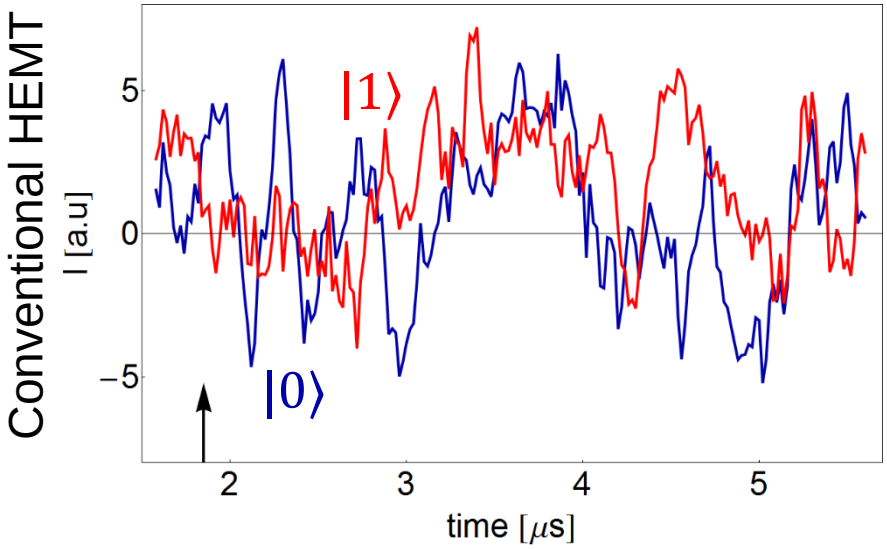


HEMT amplifier 4 K

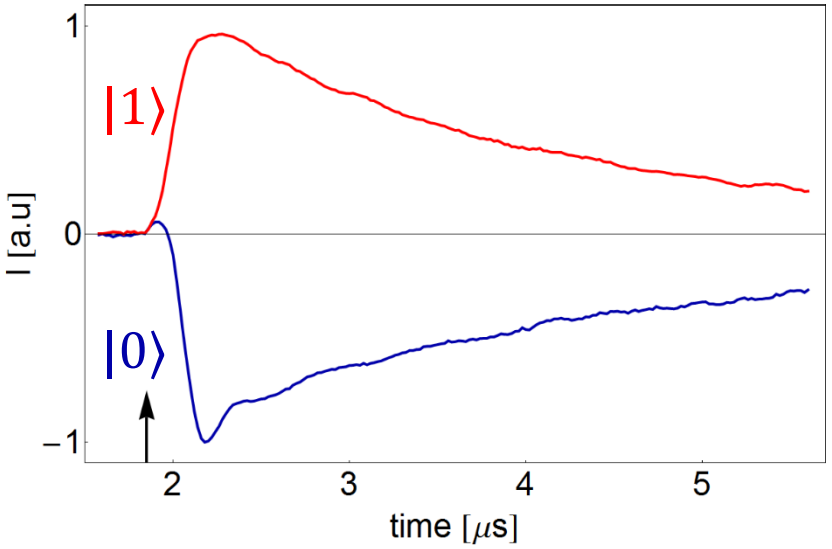
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* **106**, 110502 (2011)

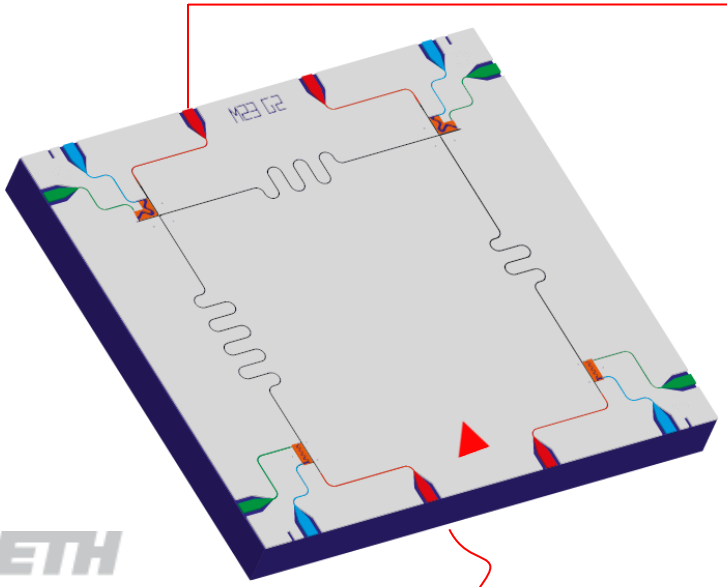
Single-Shot Single-Qubit Readout

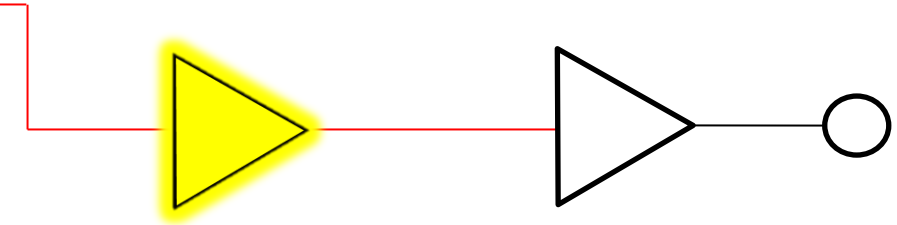
single-shot measurements:



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







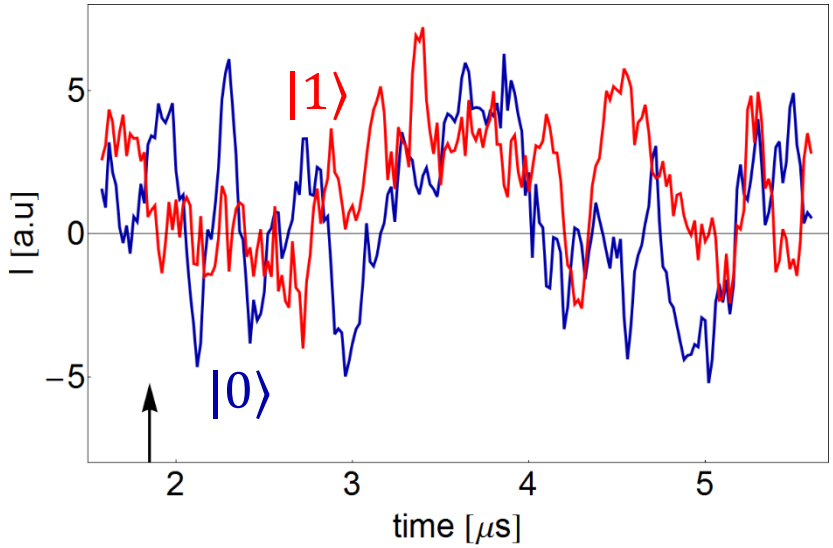
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)
R. Vijay *et al.*, *PRL* **106**, 110502 (2011)

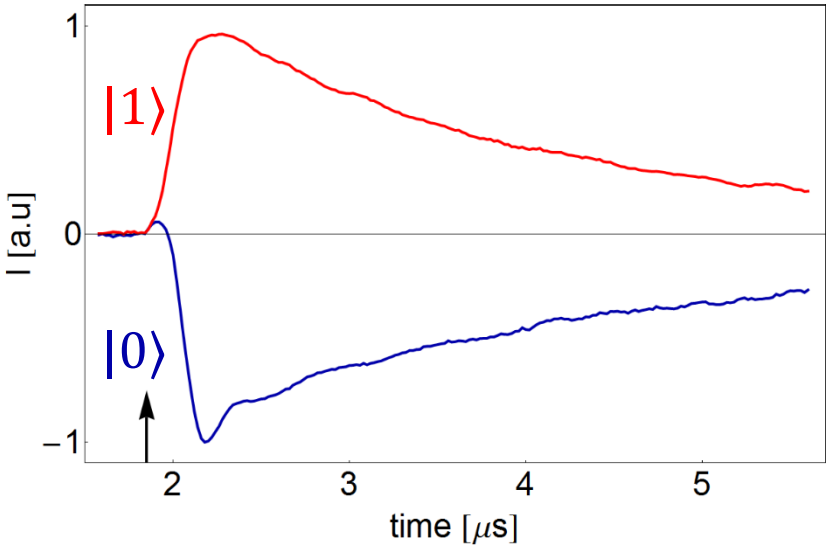
Single-Shot Single-Qubit Readout

single-shot measurements:

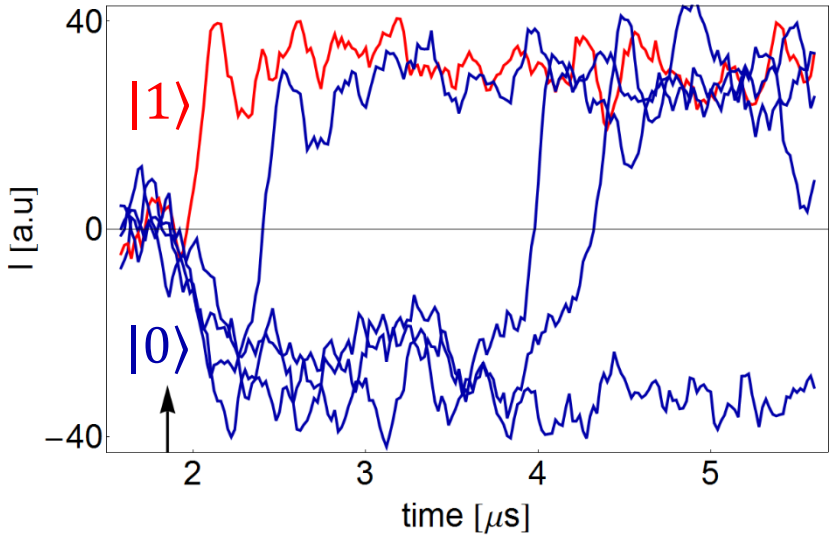
averaged measurements ($8\ 10^4$):

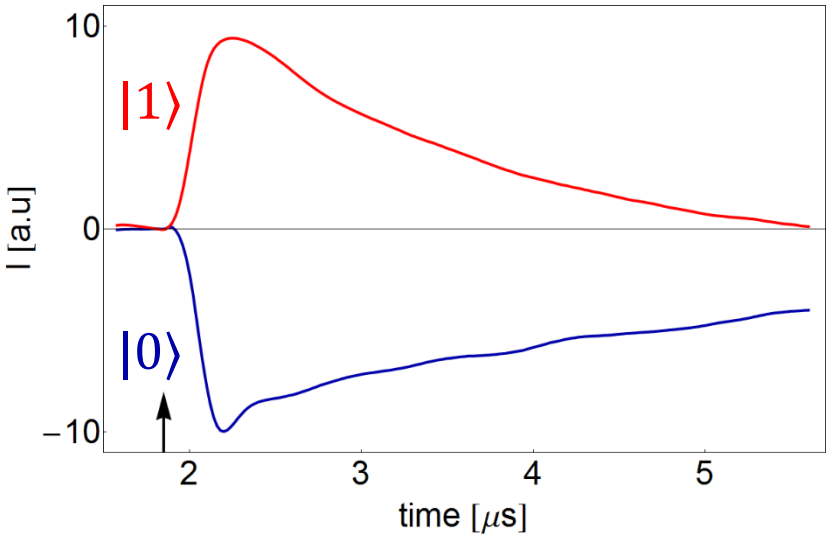
Conventional HEMT





Parametric Amplifier





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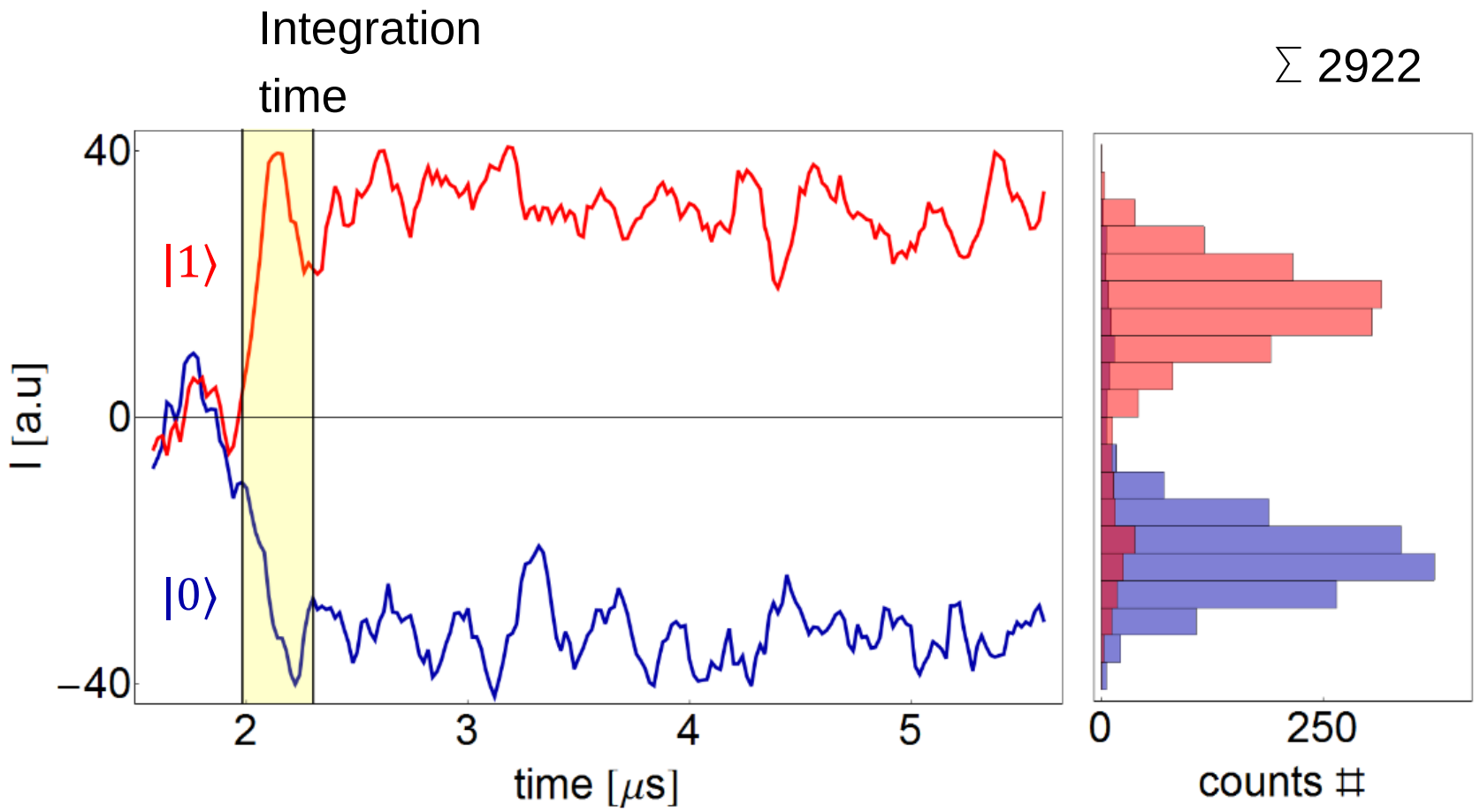
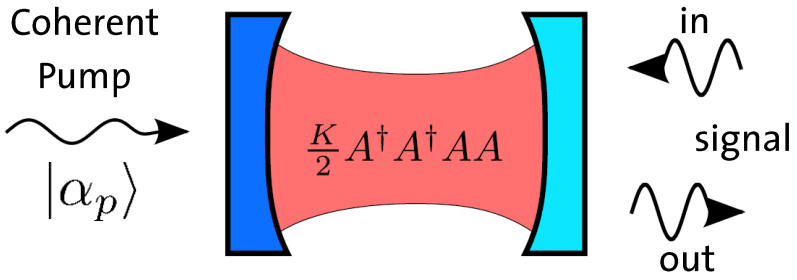
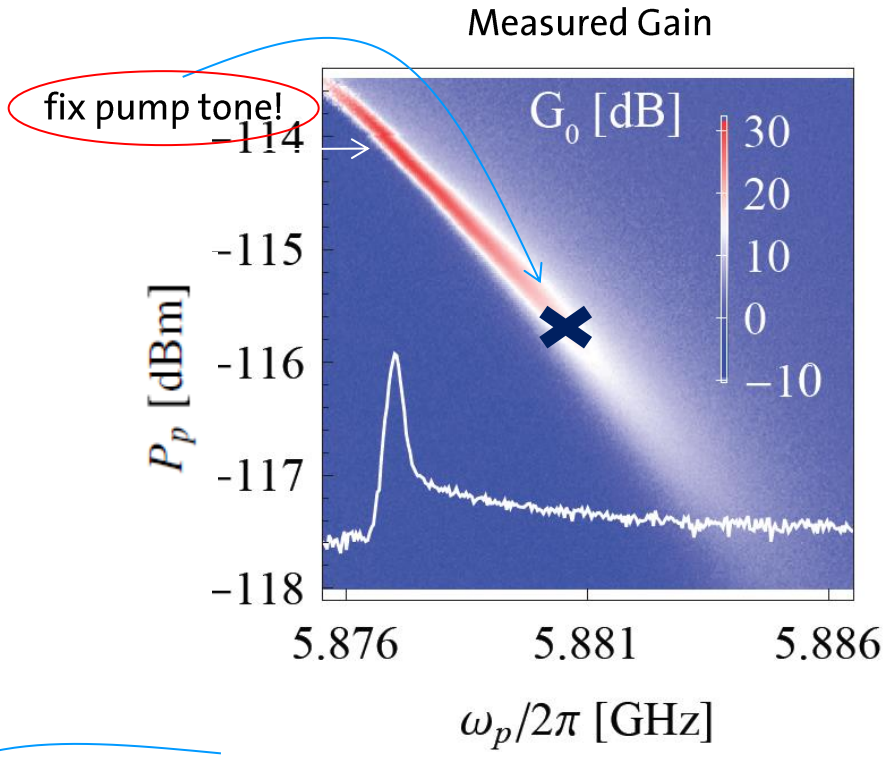
Statistics of Integrated Single-Shot Readout



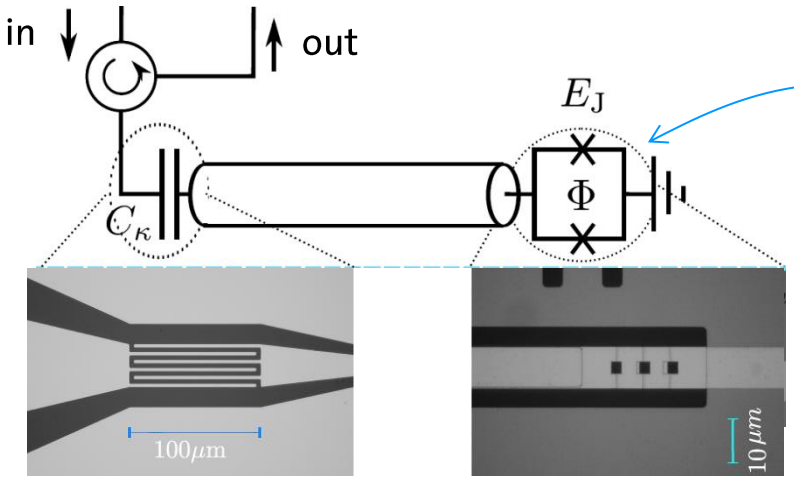
P. Kurpiers, Y. Salathe *et al*, *ETH Zurich* (2013)

Near Quantum-Limited Parametric Amplifier





Circuit QED implementation:



SQUID(-array) provides required nonlinearity

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