Superconducting Qubits
Lecture 4

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

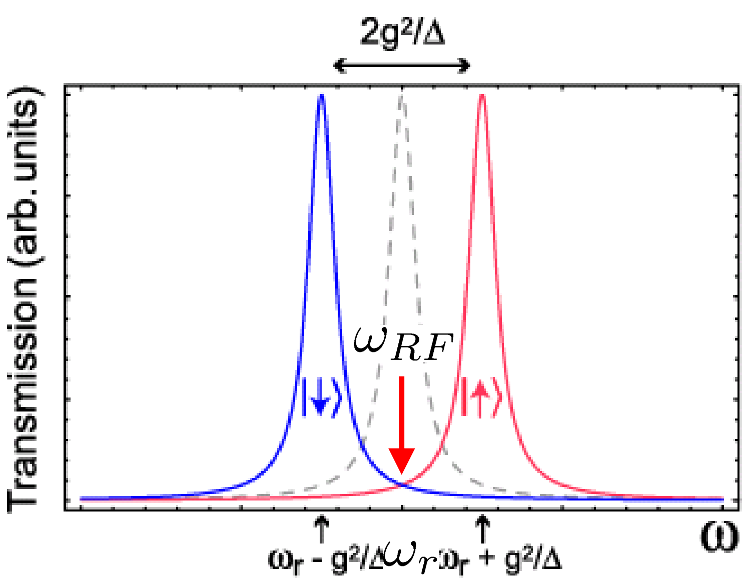
Non-Resonant Coupling for Qubit Readout

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

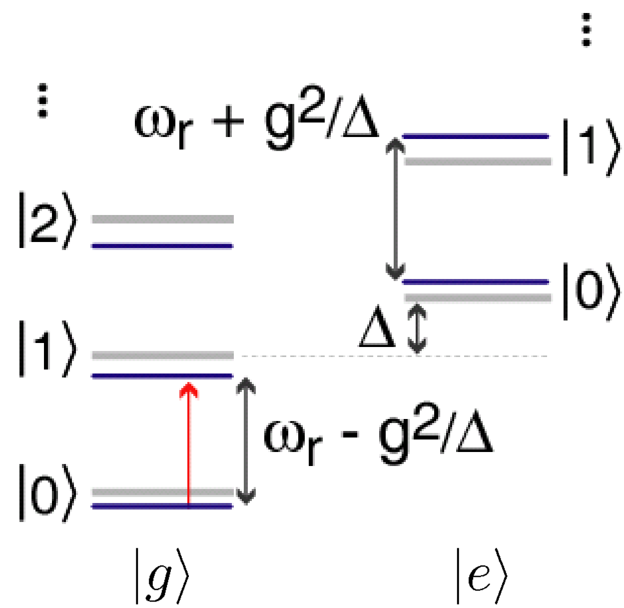
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z \right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

//

cavity frequency shift
and qubit ac-Stark shift

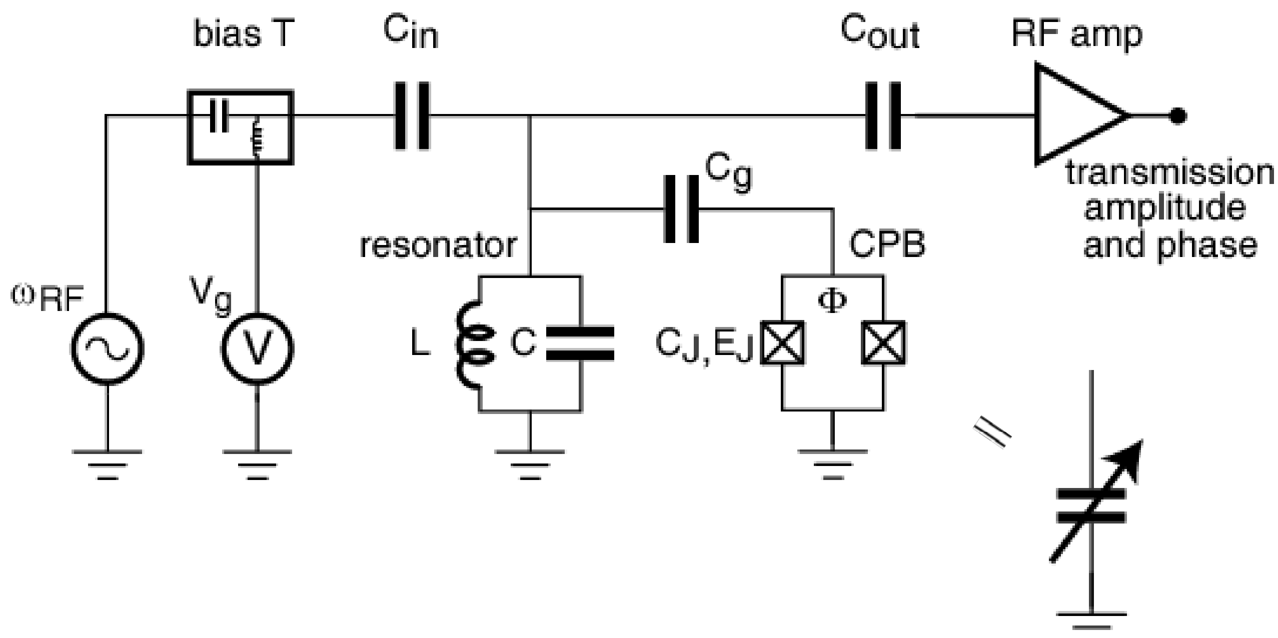


dispersive level diagram:



A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *PRA* **69,** 062320 (2004)

Measurement Technique

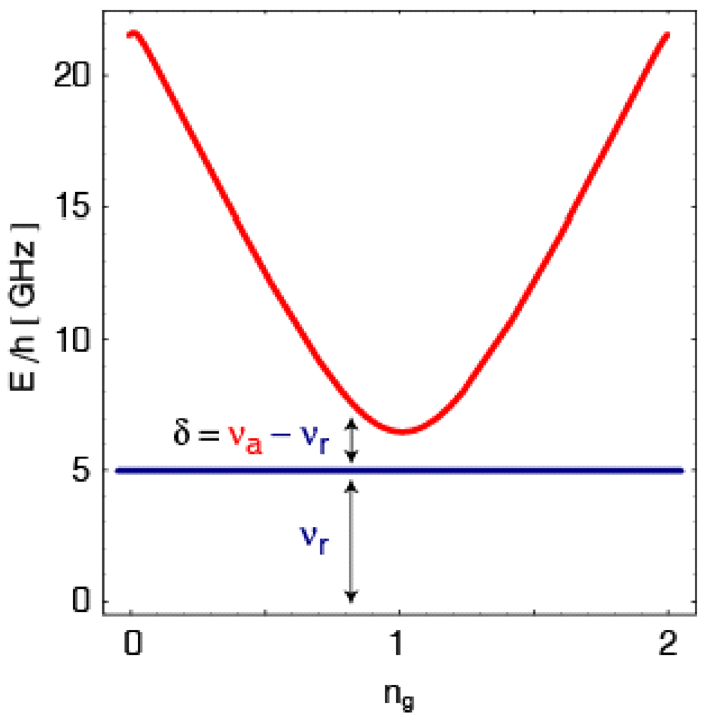


- measurement of microwave transmission amplitude T and phase ϕ
- intra-cavity photon number controllable from $n \sim 10^3$ to $n \ll 1$

Dispersive Shift of Resonance Frequency

sketch of qubit level separation:

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

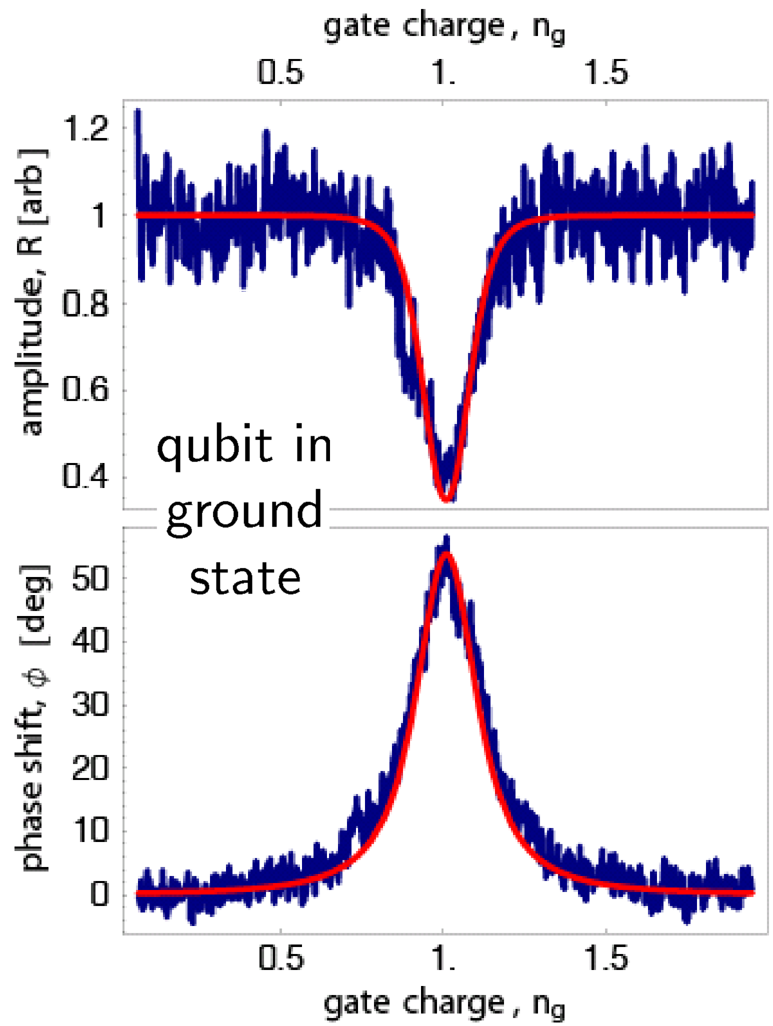


$$g/\pi = \nu_{\mathbf{vac}} = 11\,\mathrm{MHz}$$

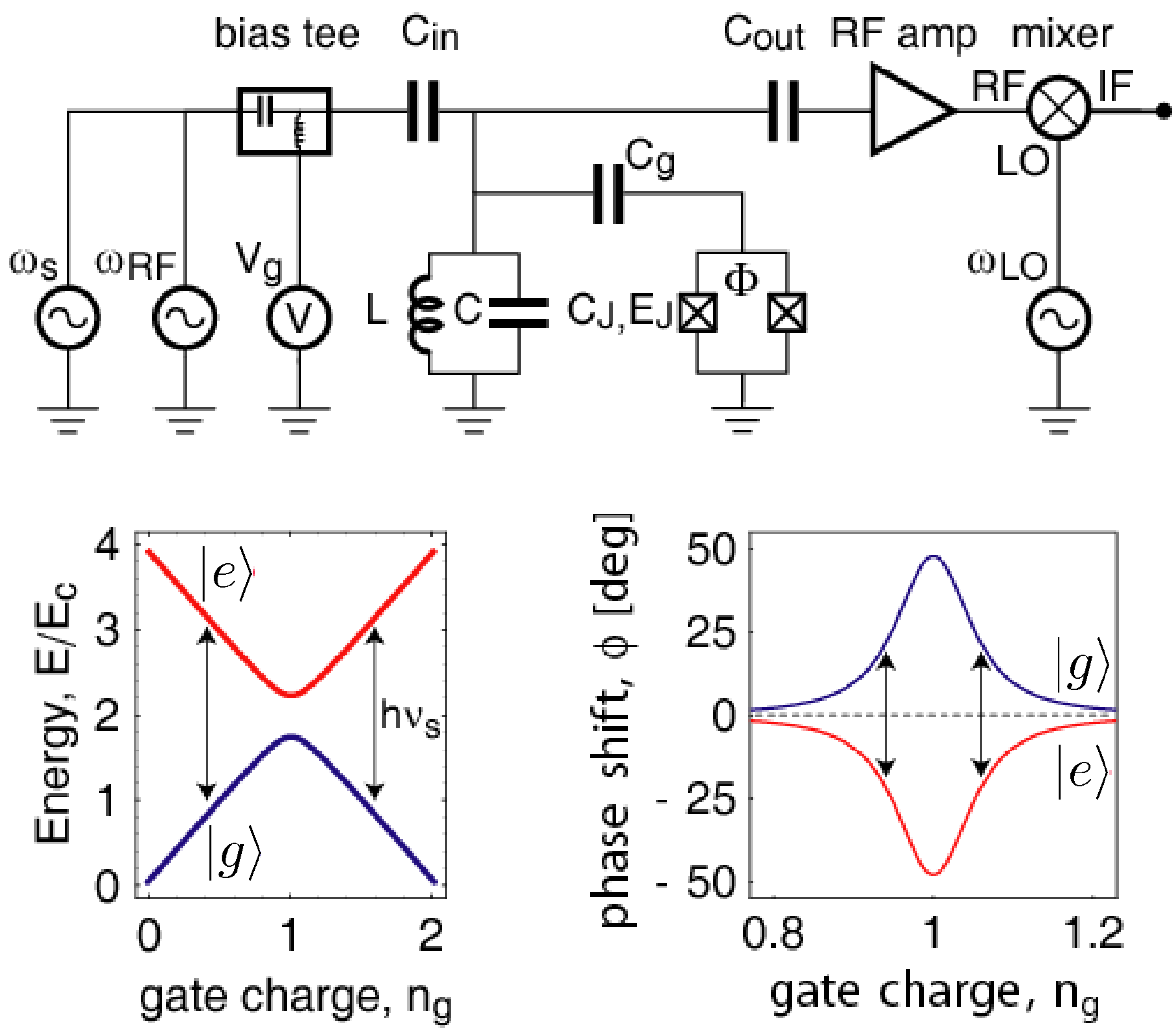
$$\Delta(n_g = 1)/2\pi = 66\,\mathrm{MHz}$$

$$n = 10$$

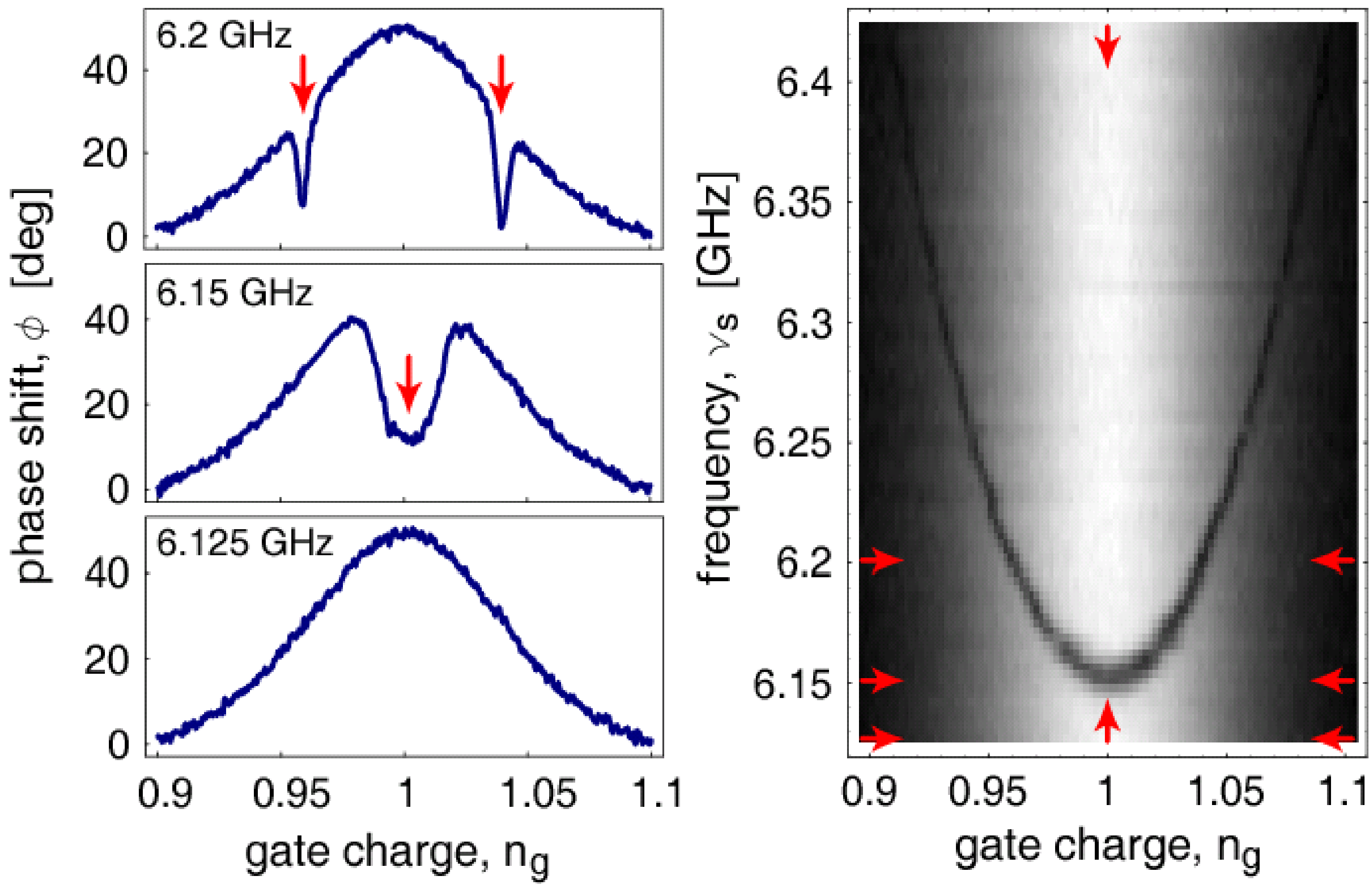
measured resonator transmission amplitude and phase:



Qubit Spectroscopy with Dispersive Read-Out



CW Spectroscopy of Cooper Pair Box



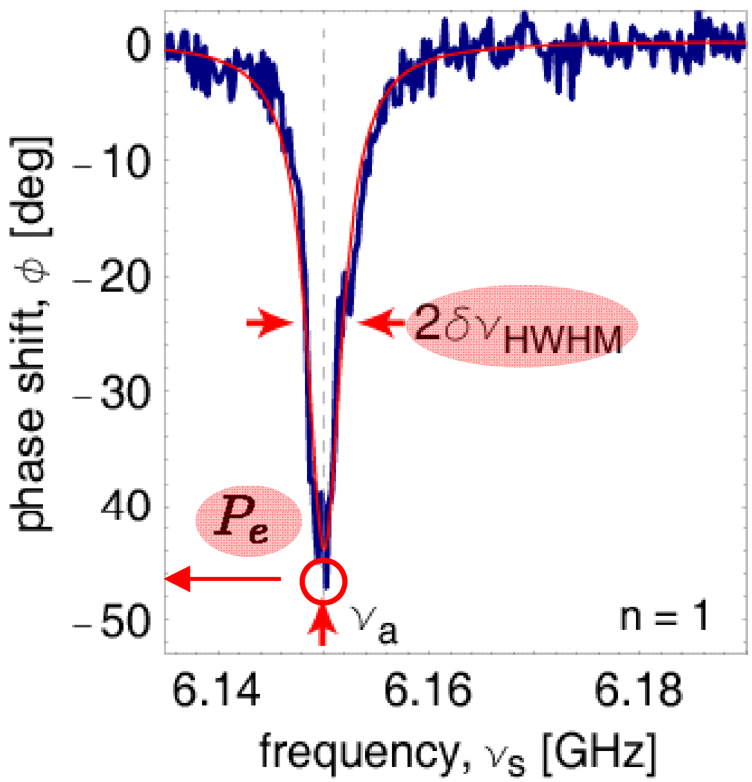
detuning $\Delta_{\mathrm{r,a}}/2\pi \sim 100\,\mathrm{MHz}$ extracted: $E_J = 6.2\,\mathrm{GHz},\ E_C = 4.8\,\mathrm{GHz}$

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

Line Shape

excited state population (steady-state Bloch equations):

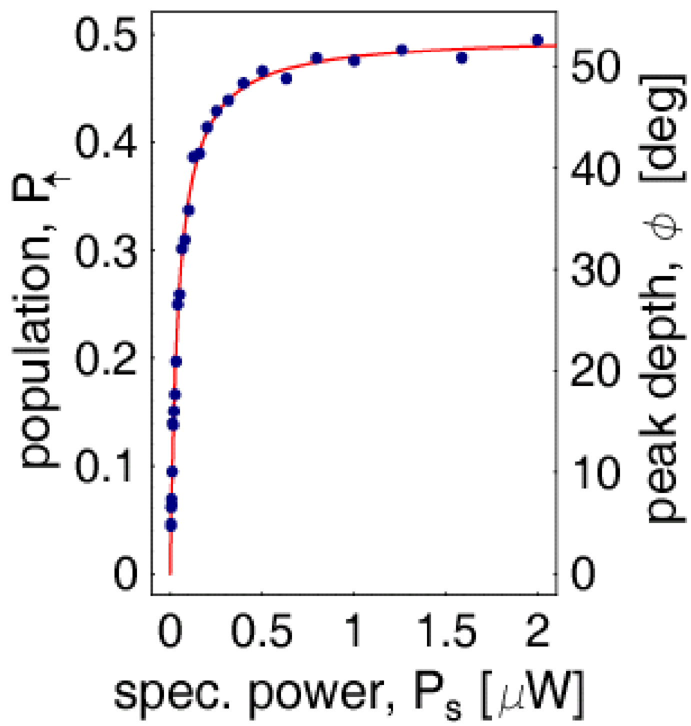
$$P_e = 1 - P_g = \frac{1}{2}\frac{\Omega_R^2 T_1 T_2}{1 + (T_2\Delta_{\mathrm{s,a}})^2 + \Omega_R^2 T_1 T_2}$$



- 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

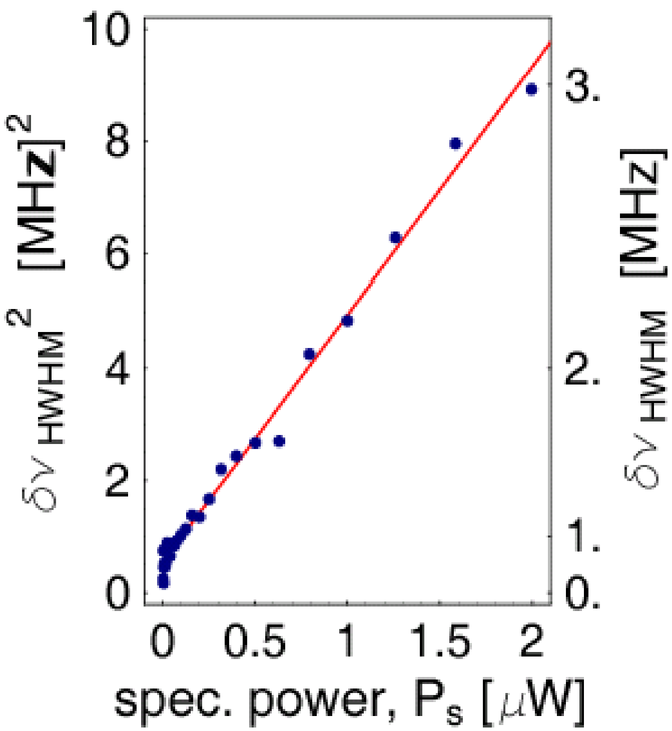


peak depth → population (saturation):

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

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



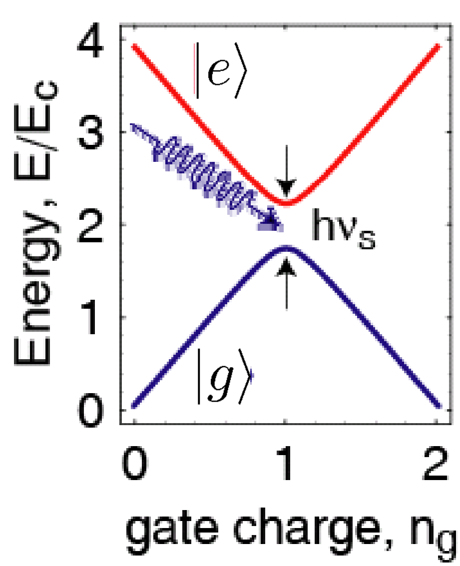
line width → coherence time:

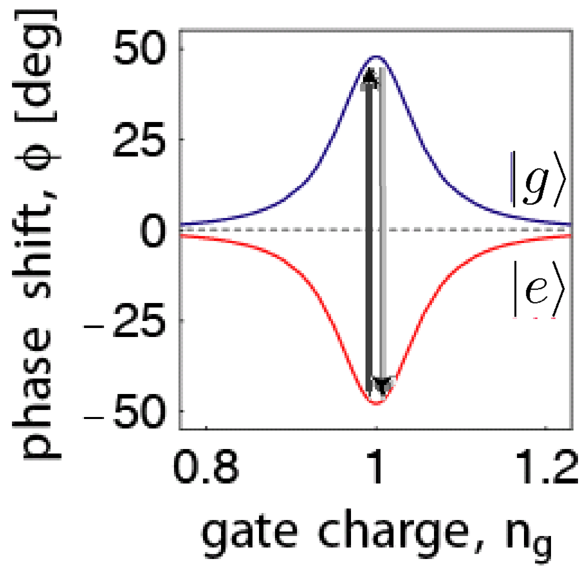
$$2\pi\delta\nu_{\mathrm{HWHM}} = \frac{1}{T_2'} = \sqrt{\frac{1}{T_2^2} + \Omega_R^2\frac{T_1}{T_2}}$$

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

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)

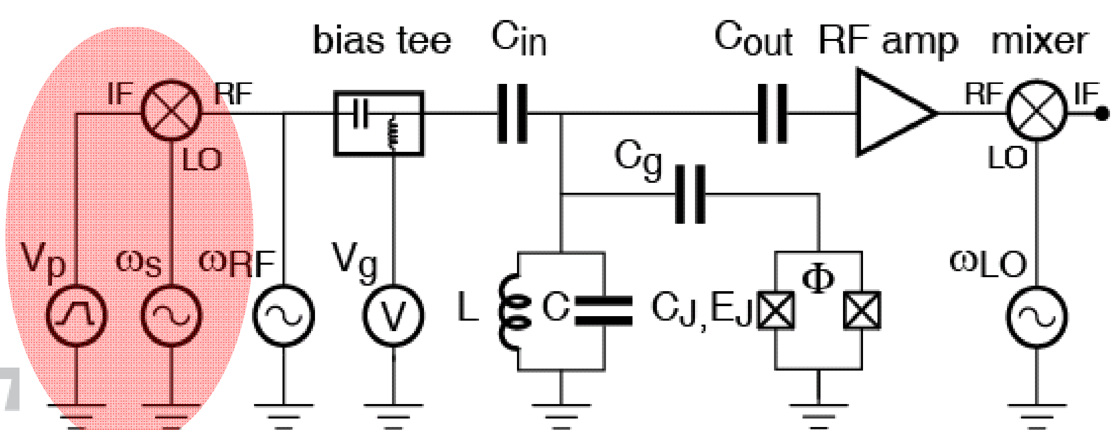
Coherent Control and Readout in a Cavity





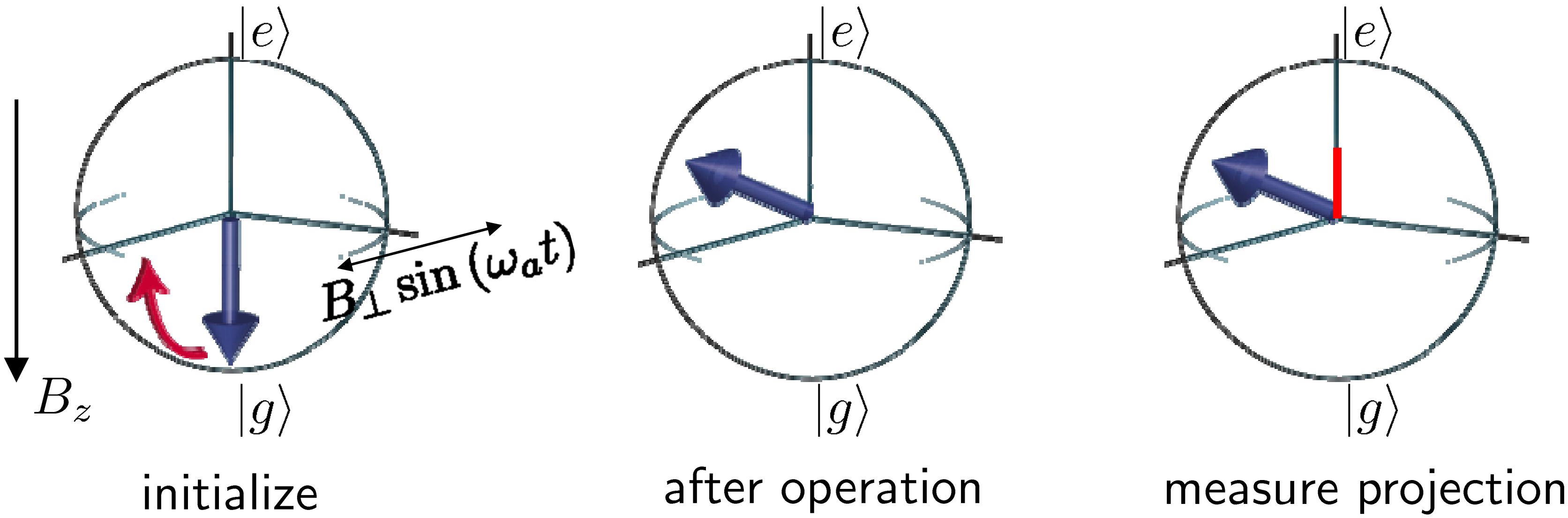
- apply resonant microwave pulse to qubit
- detect change of phase

realization:



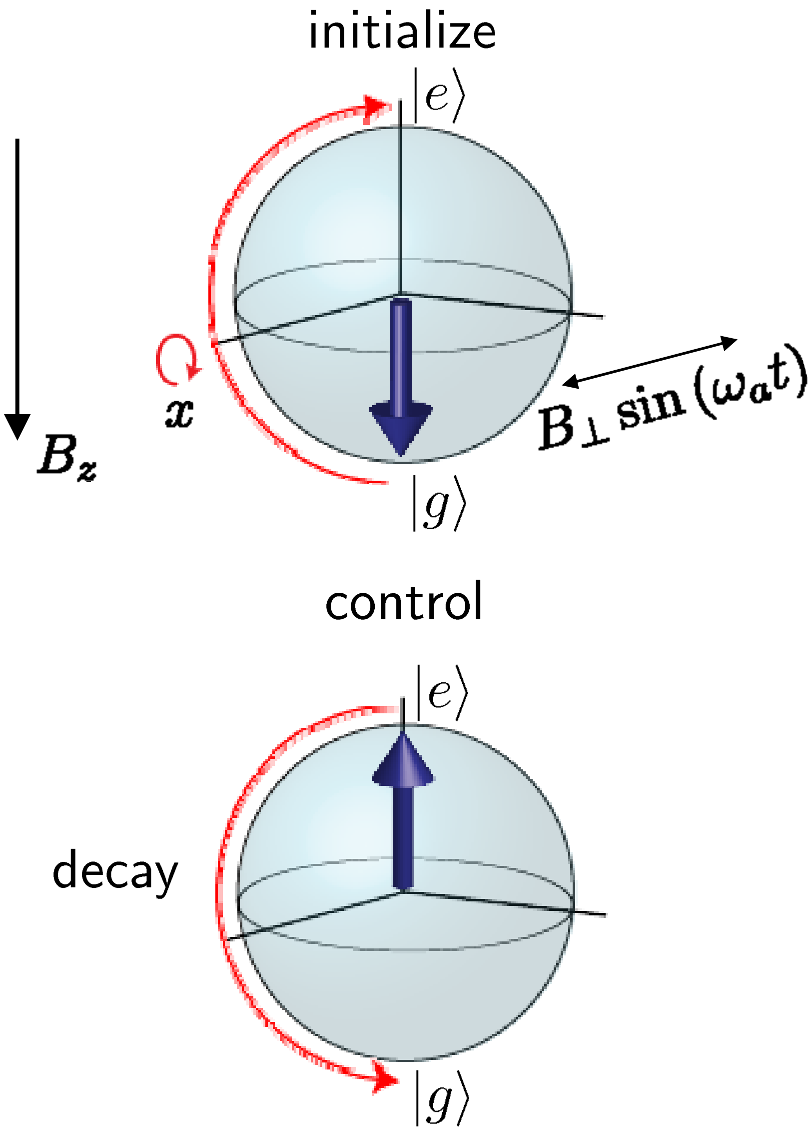
- simultaneous control and measurement

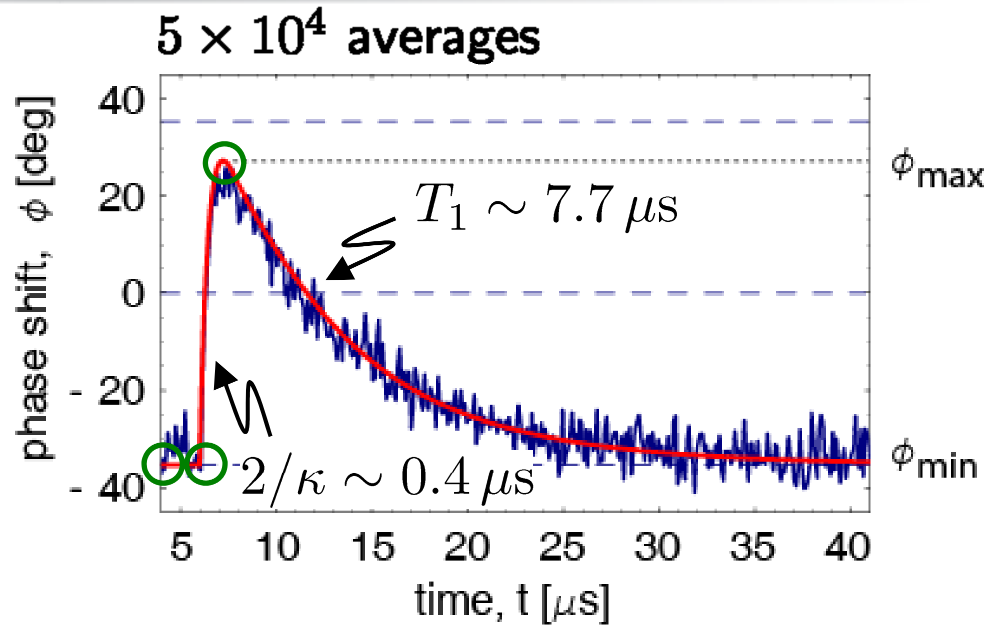
Coherent Control of a Qubit in a Cavity



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

Qubit Control and Readout



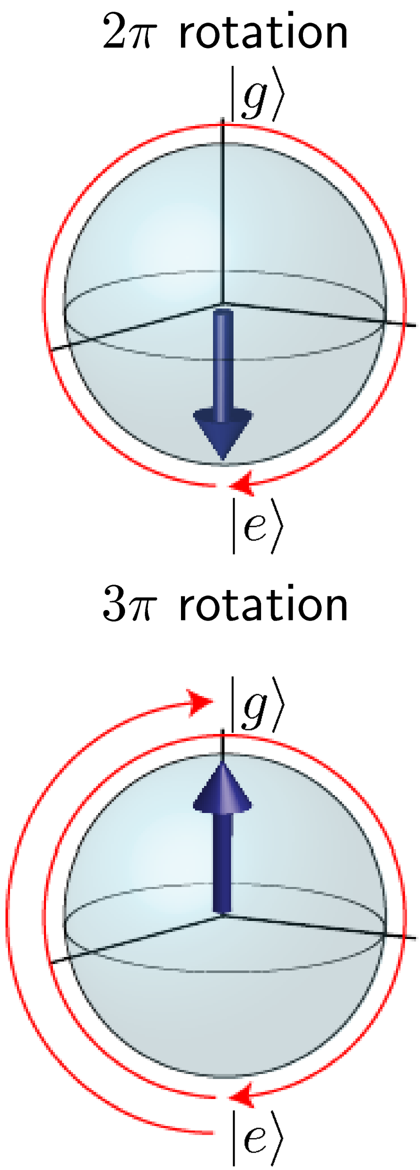


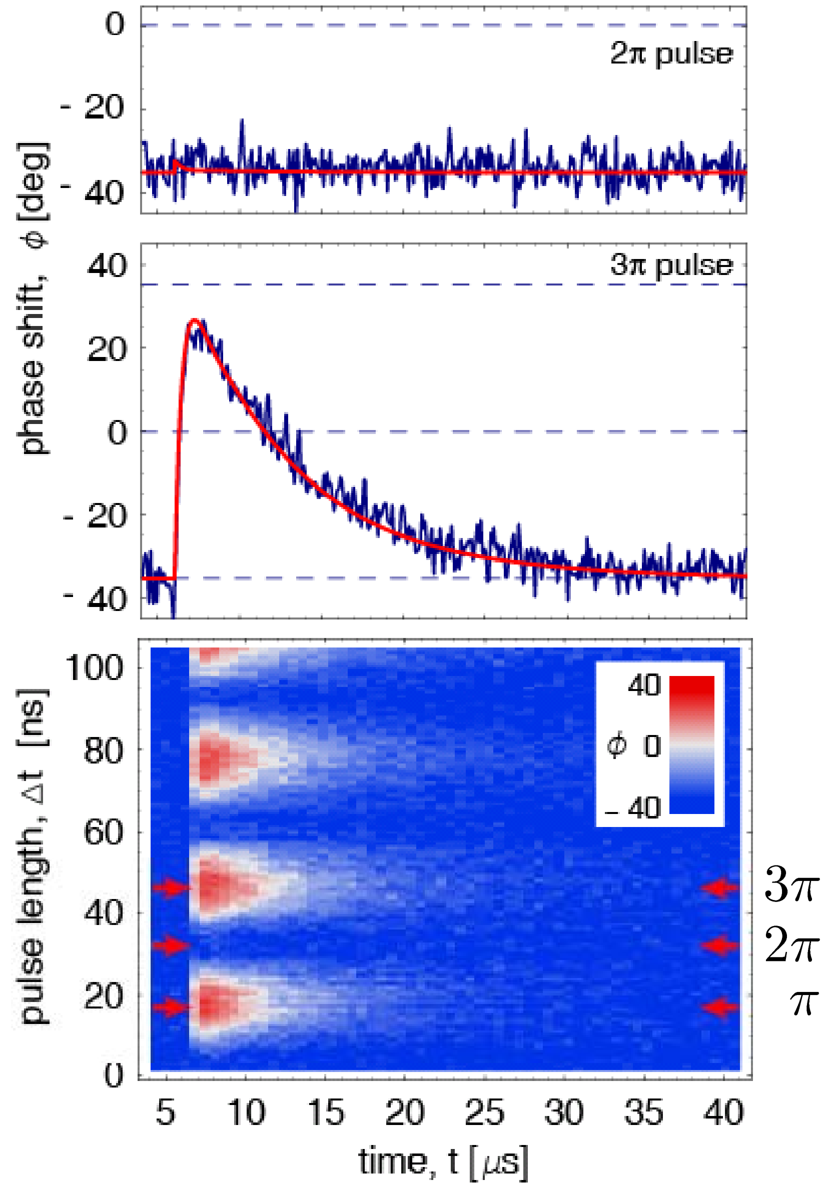
measurement properties:

- 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



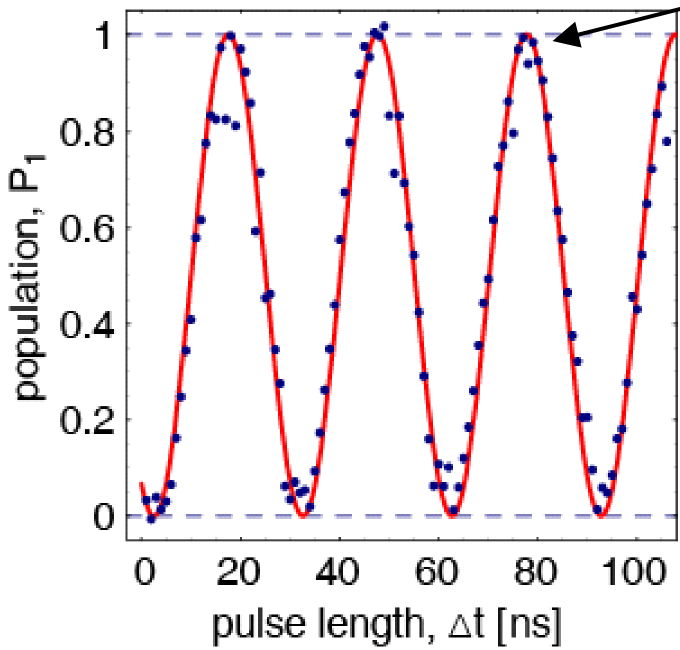


Wallraff, Schuster, Blais, ... Girvin, Schoelkopf, *PRL* **95**, 060501 (2005)

High Visibility Rabi Oscillations

Rabi oscillations:

visibility $95 \pm 5\%$



for superconducting qubits:

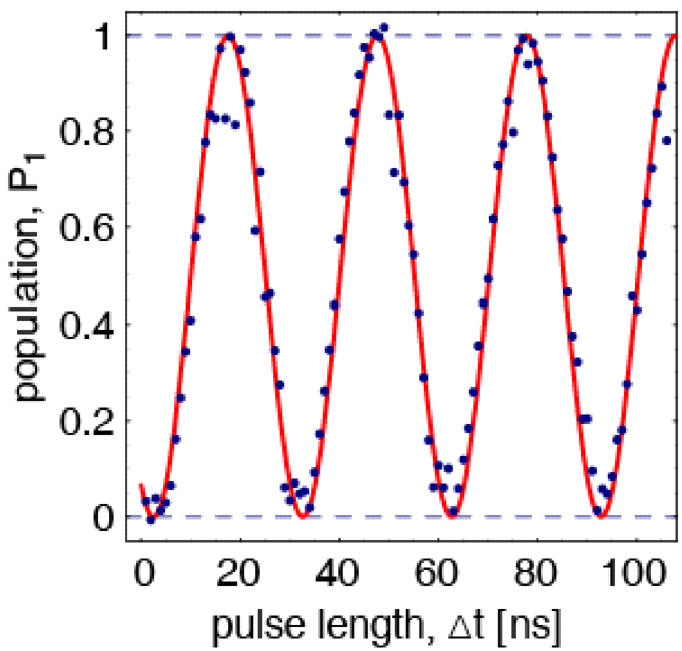
- **high visibility**
- **well characterized and understood measurement**
- **good control accuracy**

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

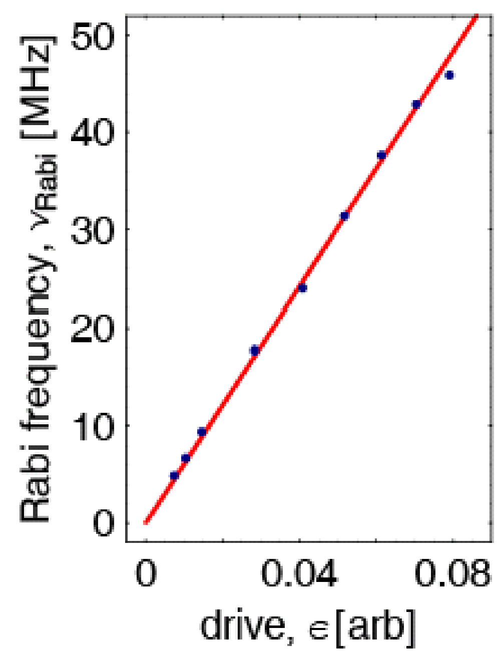
Rabi Frequency

pulse scheme:

Rabi oscillations:

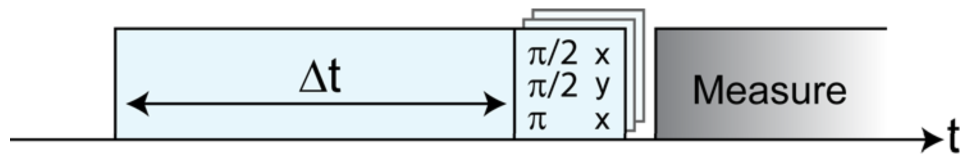


Rabi frequency:

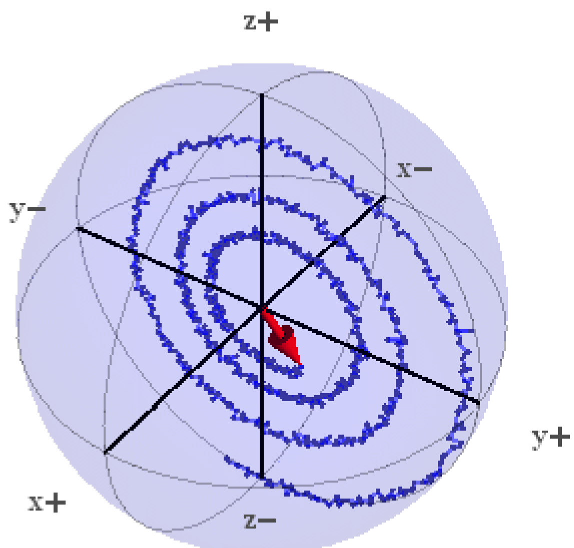


- linear dependence of Rabi frequency on microwave amplitude

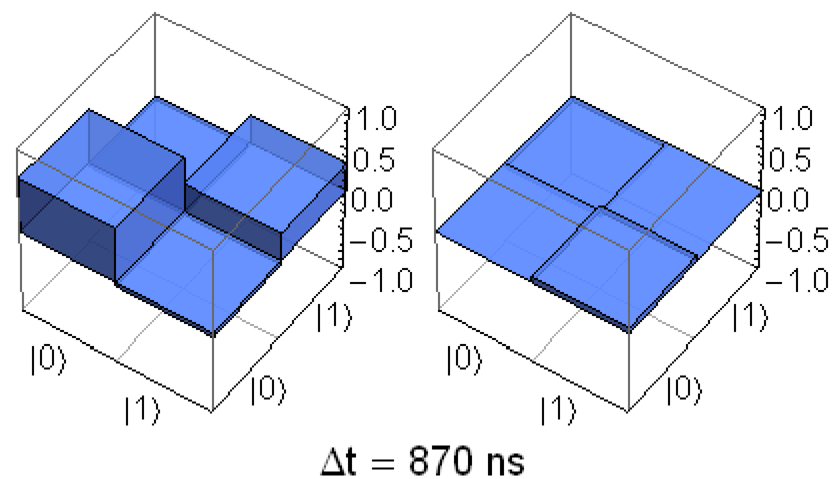
Rabi rotation pulse sequence:



experimental Bloch vector:



experimental density matrix:

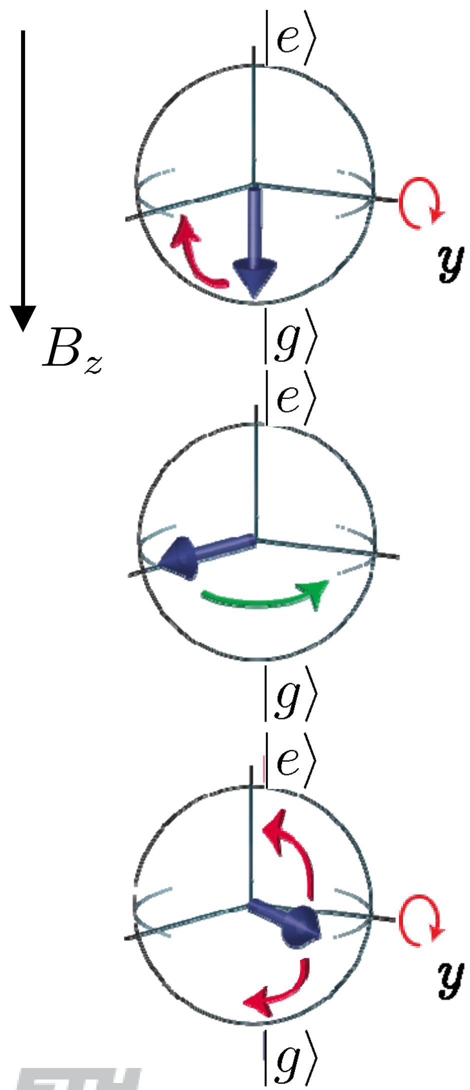


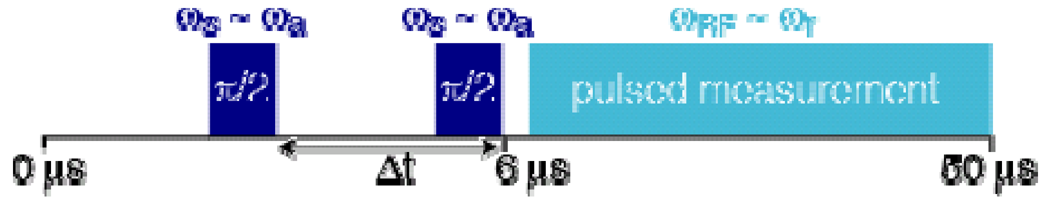
L. Steffen *et al.*, Quantum Device Lab, ETH Zurich (2008)

Measurements of Coherence Time

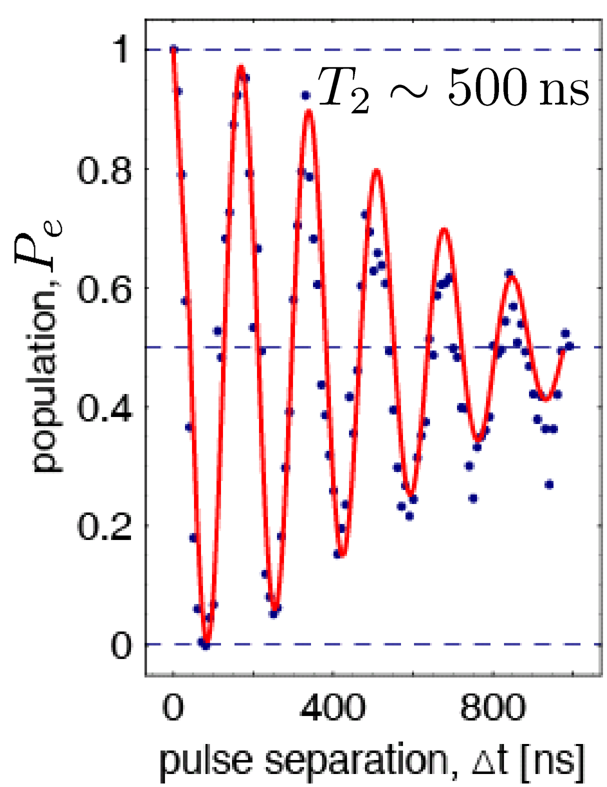
Coherence Time Measurement: Ramsey Fringes

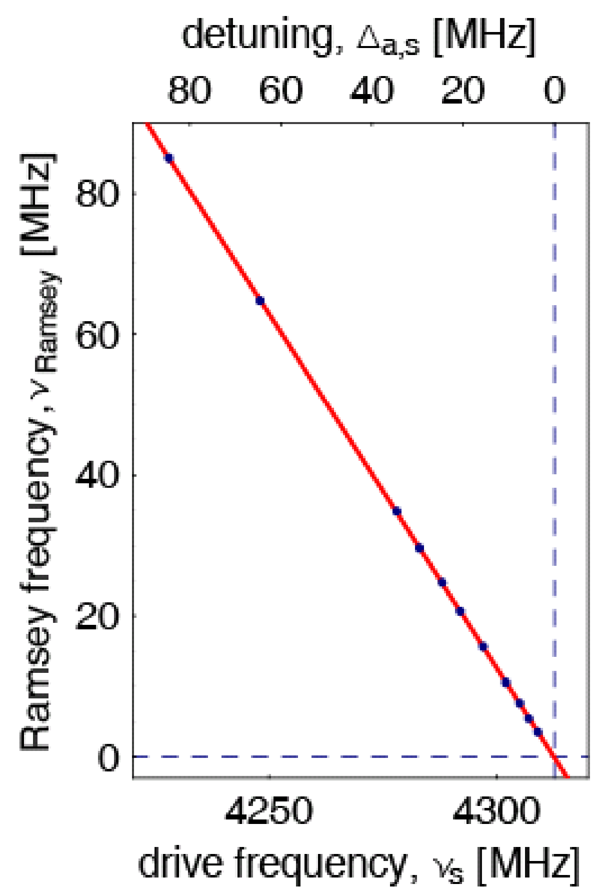
pulse scheme:





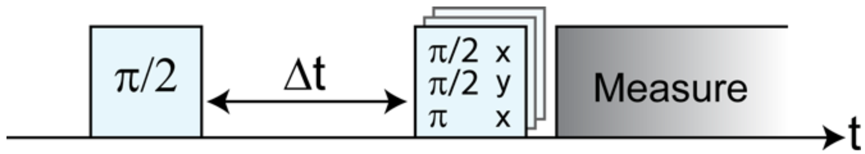
Ramsey fringes:

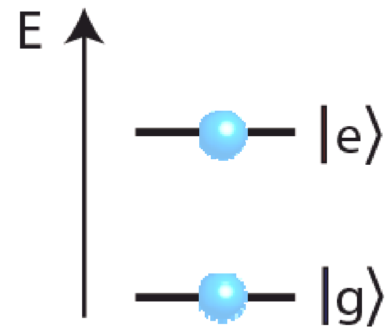




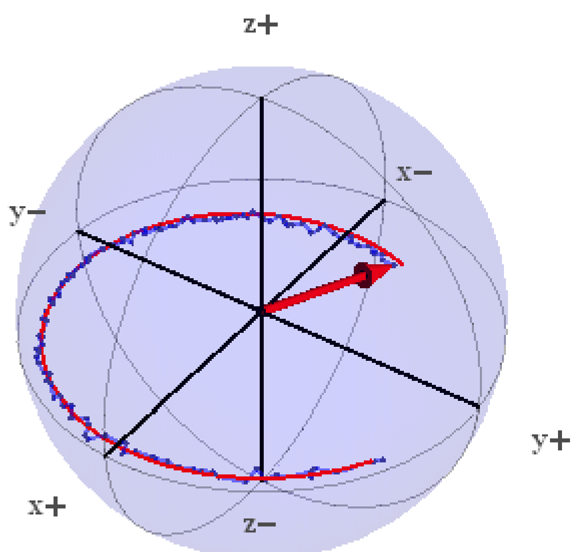
A. Wallraff *et al.*, *Phys. Rev. Lett.* **95**, 060501 (2005)

pulse sequence:

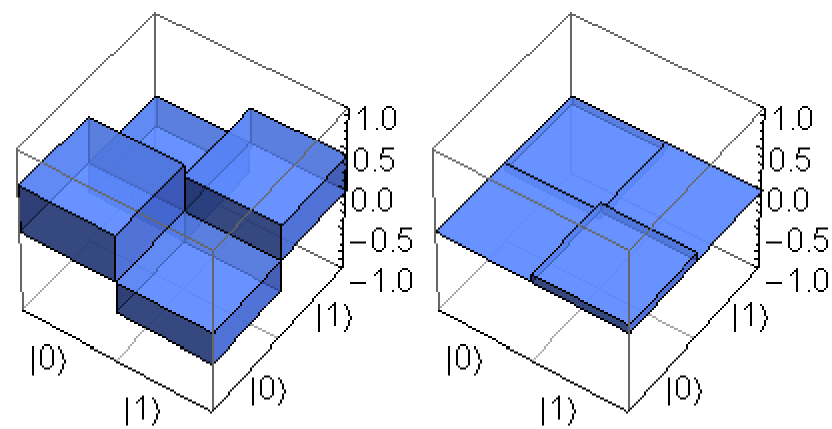




experimental Bloch vector:



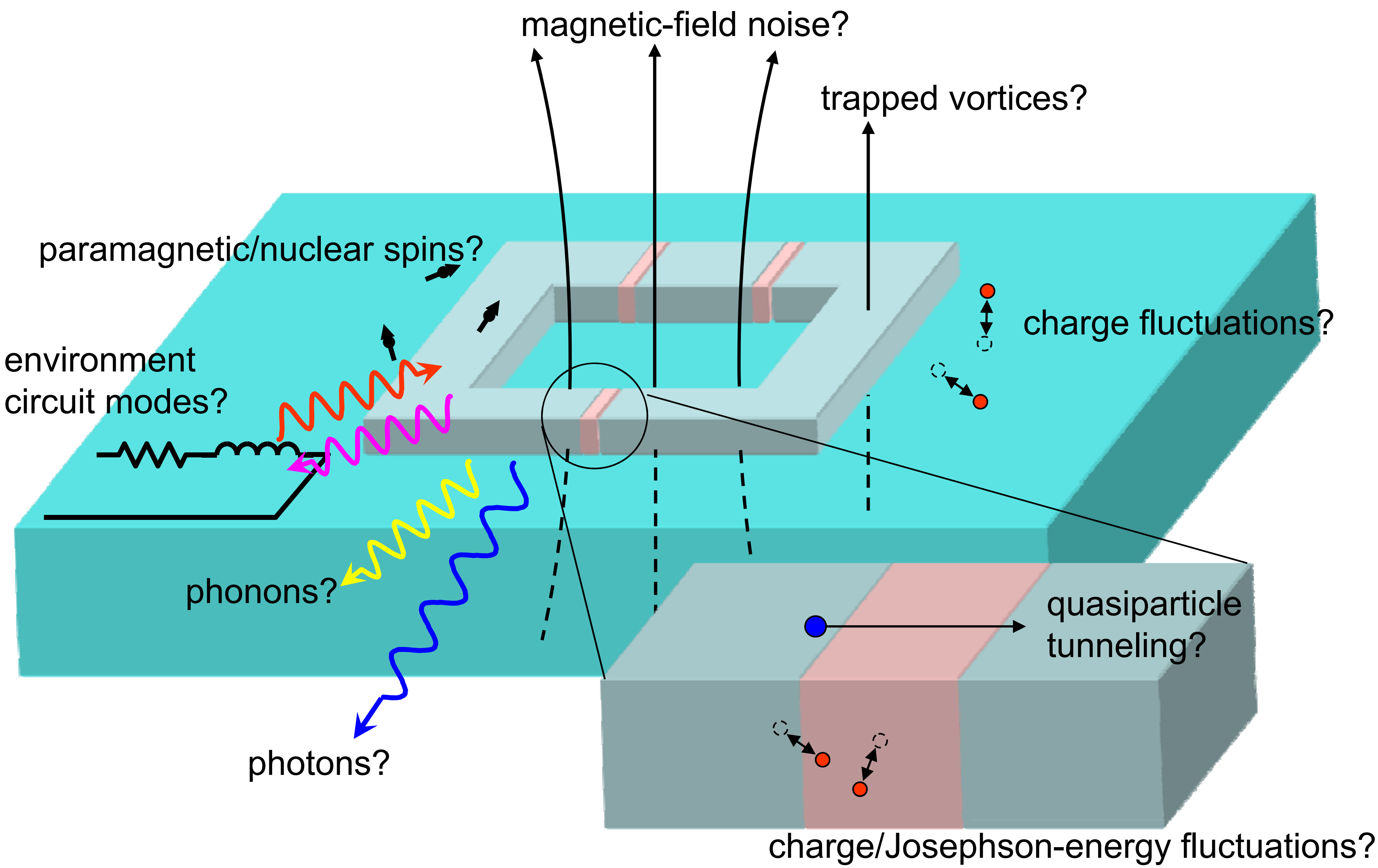
experimental density matrix:



$\Delta t = 114$ ns

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

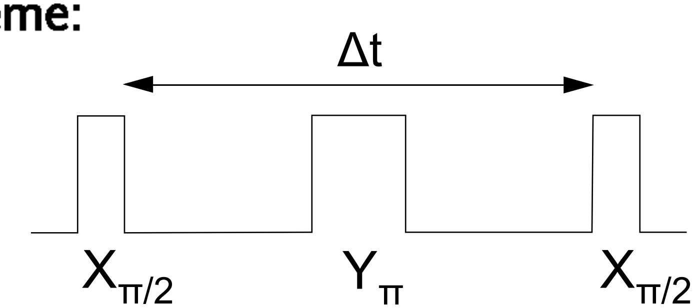
Sources of Decoherence

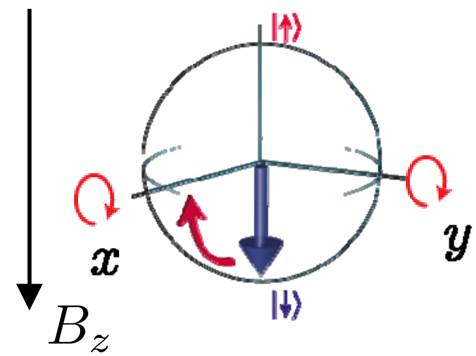


G. Ithier *et al.*, *Phys. Rev. B* **72**, 134519 (2005)

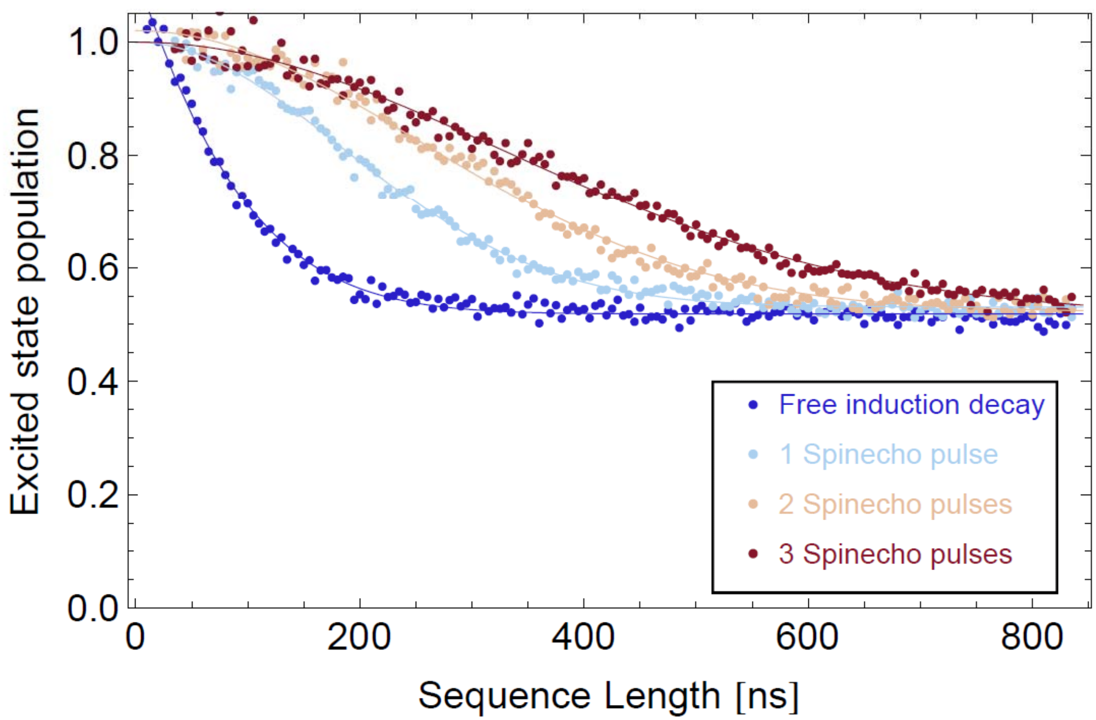
- remove sources of decoherence
    - improve materials
- use dynamic methods to counteract specific sources of decoherence
    - spin echo
    - geometric manipulations
- reduce sensitivity of quantum systems to specific sources of decoherence
    - make use of symmetries in design and operation

pulse scheme:





result:



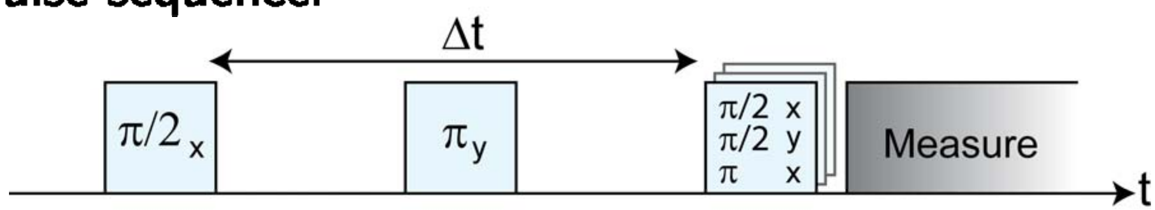
- refocusing
- elimination of low frequency fluctuations
- increased effective coherence time

Lars Steffen *et al.* (2009)

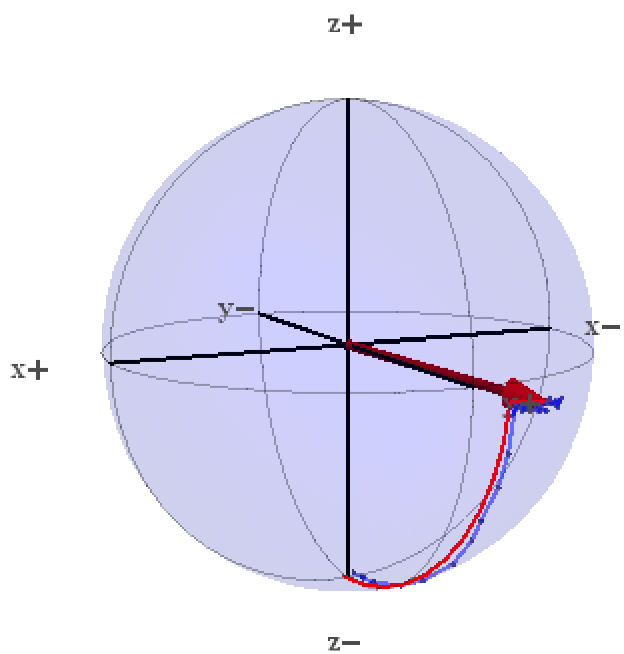
P. J. Leek, J. Fink *et al.*, *Science* **318**, 1889 (2007)

Tomography of a Spin Echo

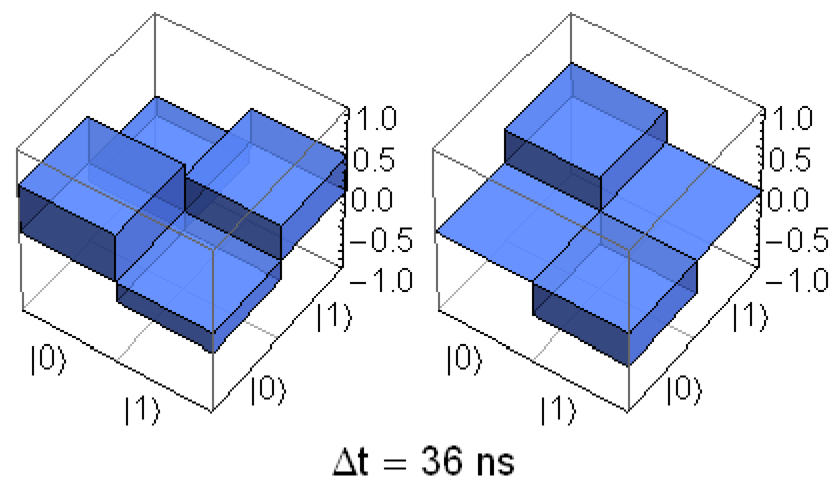
pulse sequence:



experimental Bloch vector:



experimental density matrix:



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

Coupling Superconducting Qubits and Generating Entanglement using Sideband Transitions

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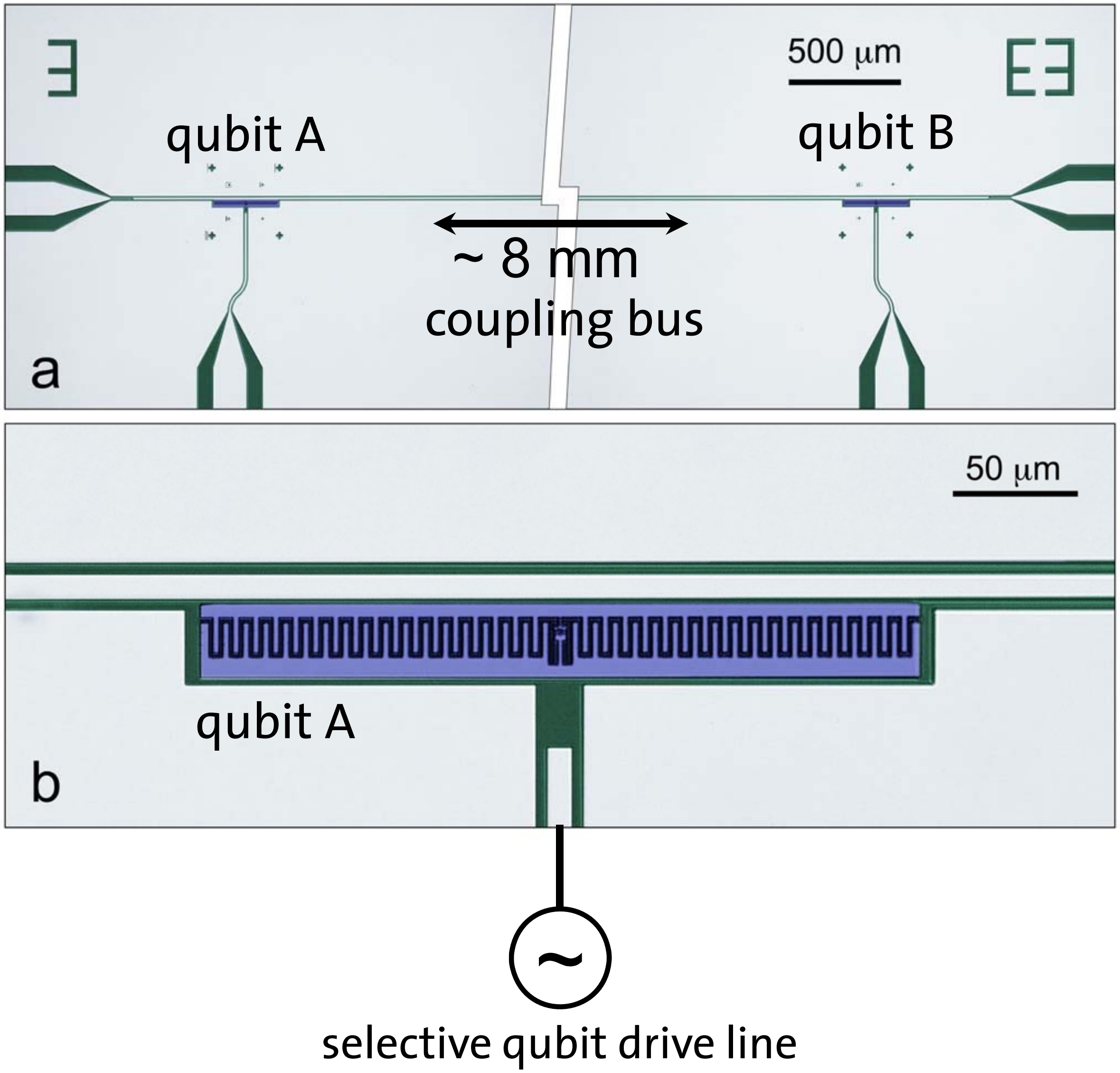
2-Qubit Chip

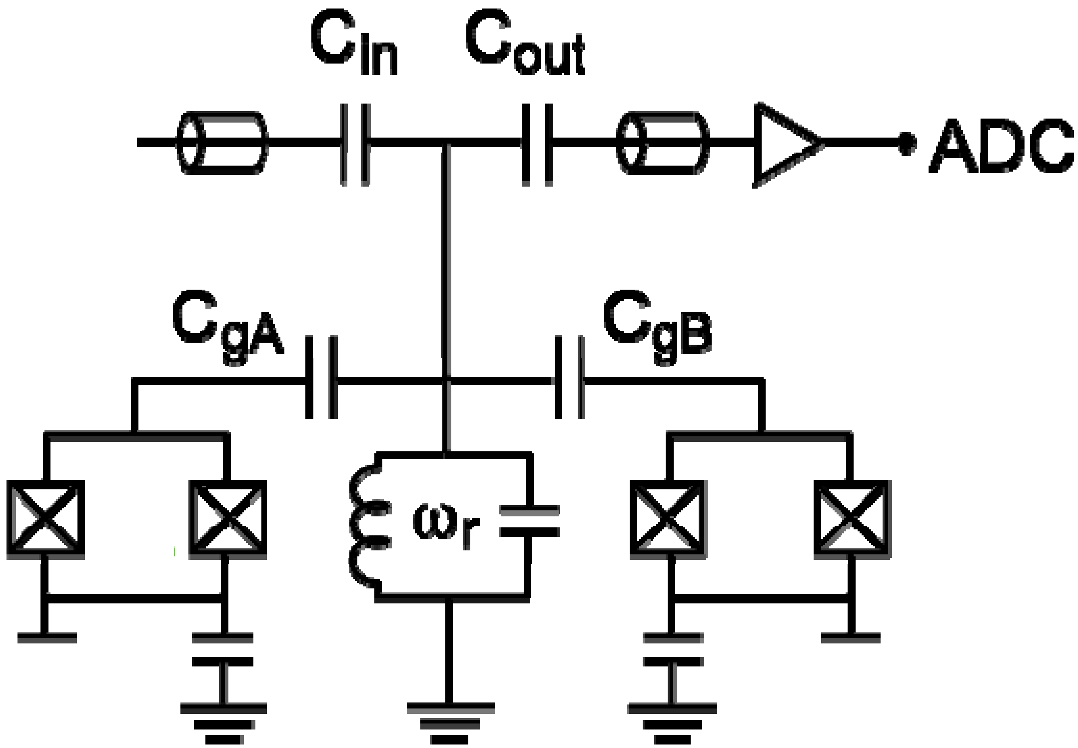


- Two near identical superconducting qubits
- Local control of magnetic flux allows independent selection of qubit transition frequencies
- Local drive lines allow selective excitation of individual qubits

et al., Phys. Rev. B **79**, 180511(R) (2009)

2-Qubit Circuit with Selective Control

joint dispersive read-out

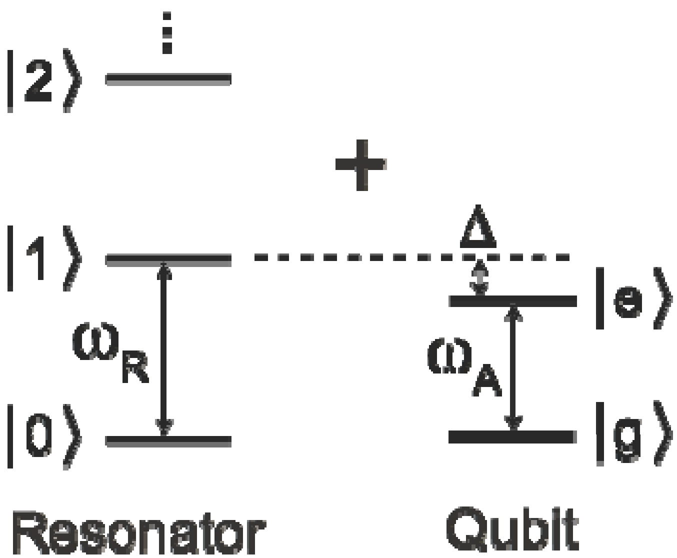


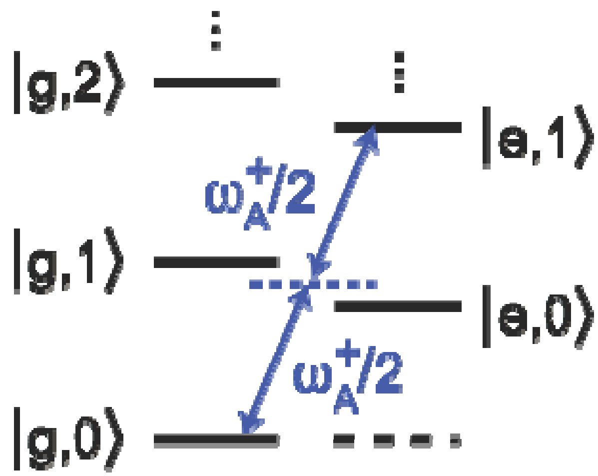
Local magnetic fields created using small inductively coupled coils

Selective qubit excitation using locally capacitively coupled drive lines

P. Leek *et al., Phys. Rev. B* **79**, 180511(R) (2009)

Sideband Transitions in Circuit QED



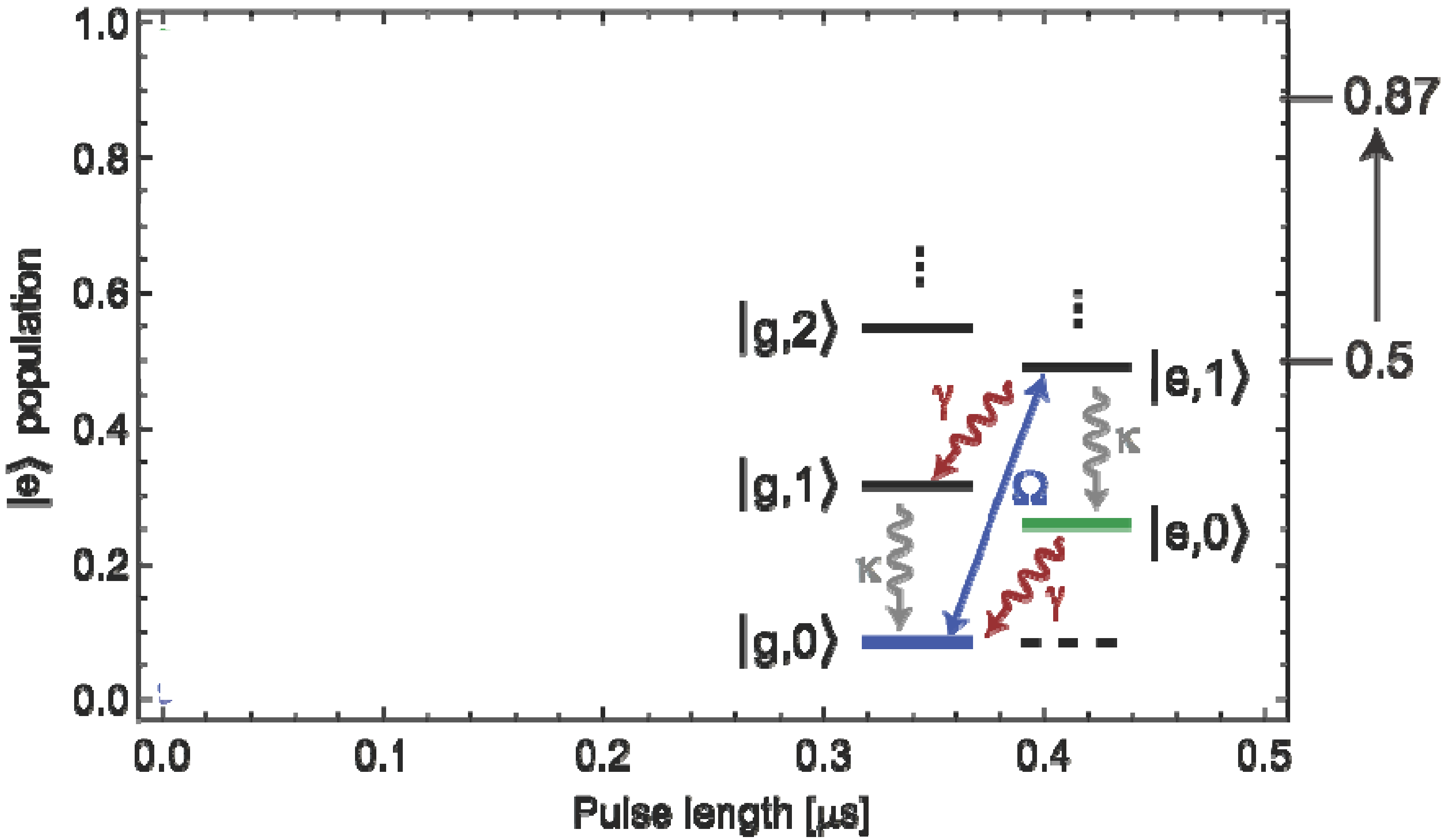


$$\omega_A/2 = (\omega_R + \omega_A)/2$$

- dispersive coupling allows joint excitations to be driven
- sideband transitions forbidden to first order: use two photon transition

Wallraff et al., *PRL* **99**, 050501 (2007)

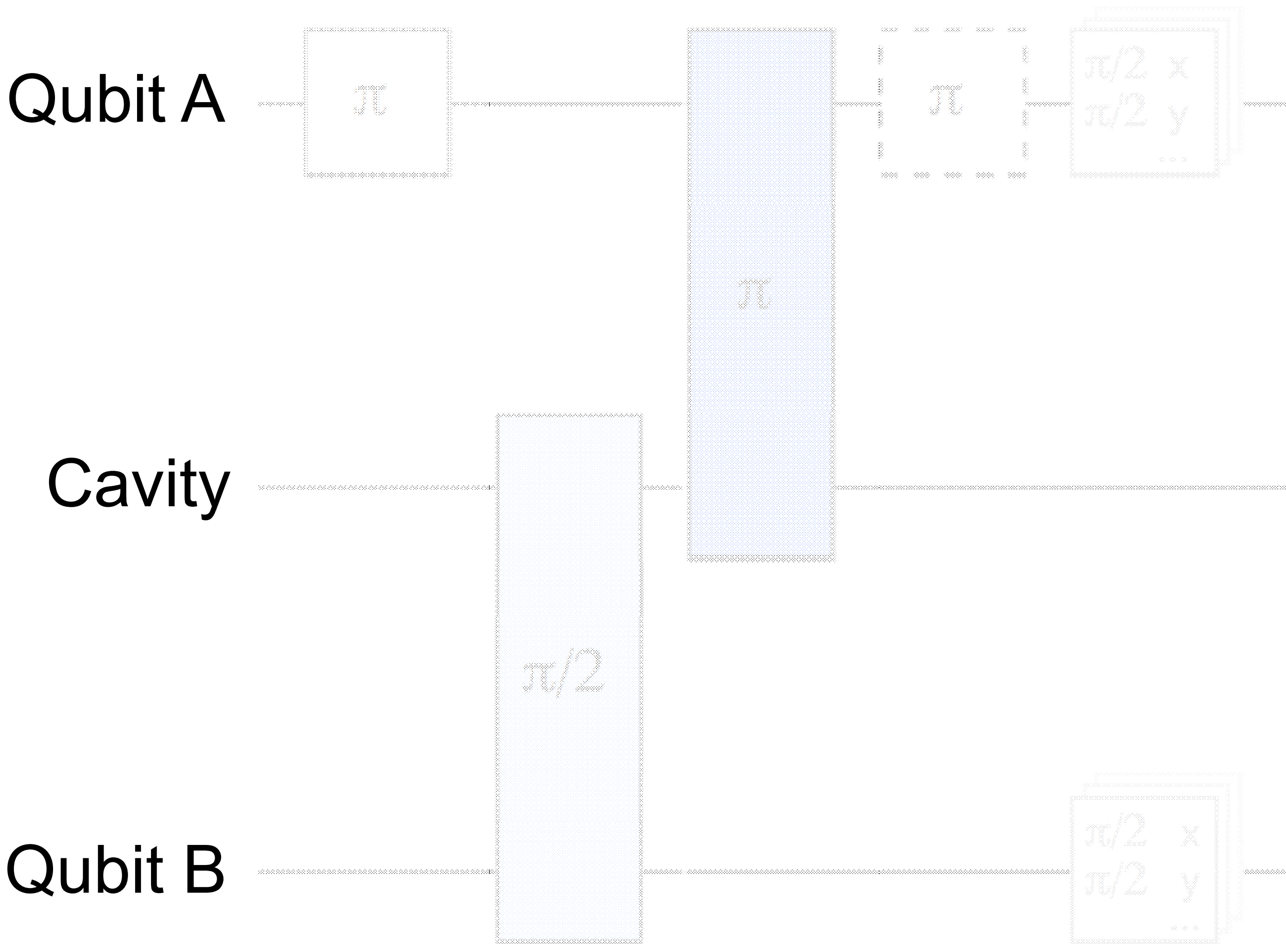
/Resonator Sideband Transitions



simultaneous excitation of qubit and resonator: |g,0> → |e,1>

entangle a qubit with a photon on the bus: |g,0> → |g,0> + |e,1>

Bell State Preparation



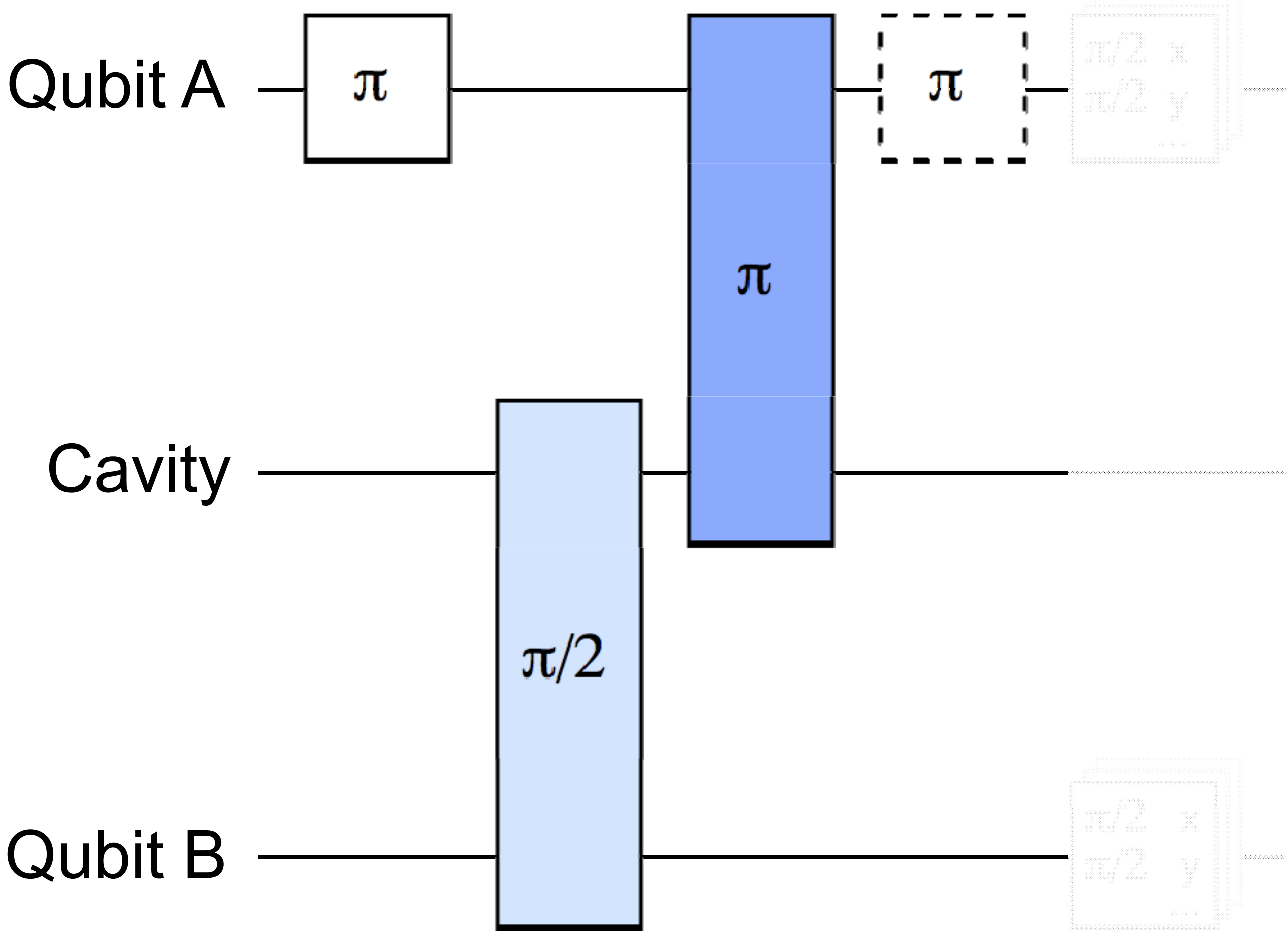
π pulse qubit A

Transfer entanglement to qubits to create Ψ Bell state

Entangle qubit B with cavity using blue sideband B

$$|gg0\rangle \longrightarrow |eg0\rangle \longrightarrow \frac{1}{\sqrt{2}}(|eg0\rangle + |ee1\rangle) \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)} \otimes |0\rangle$$

Bell State Preparation



π pulse qubit A to convert to Φ Bell state

π pulse qubit A

Transfer entanglement to qubit A to create Ψ Bell state

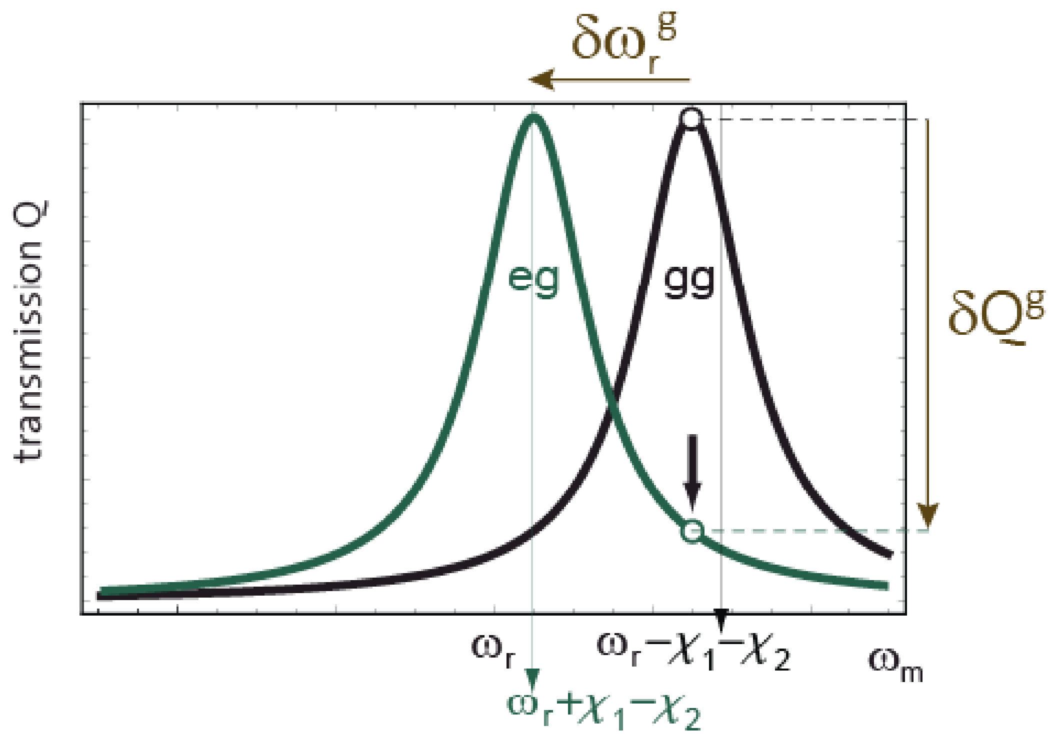
Characterise the final state using quantum state tomography with joint msrmnt

Entangle qubit B with cavity using blue sideband

$$\ldots \longrightarrow \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle) \otimes |0\rangle \longrightarrow \boxed{\frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)} \otimes |0\rangle$$

Joint Two Qubit Readout

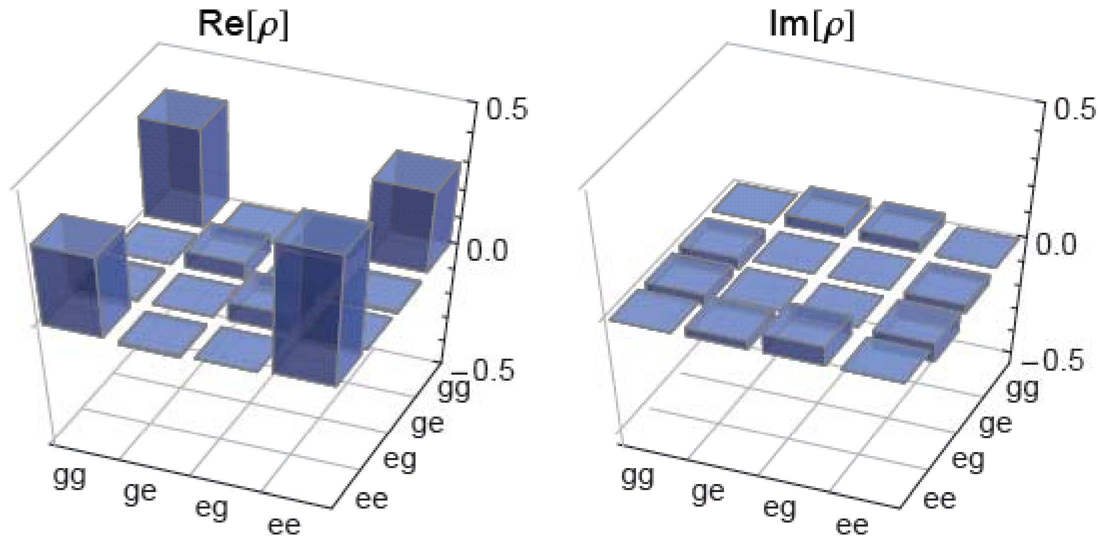
Amplitude difference (δQ) depends on state of both qubits:



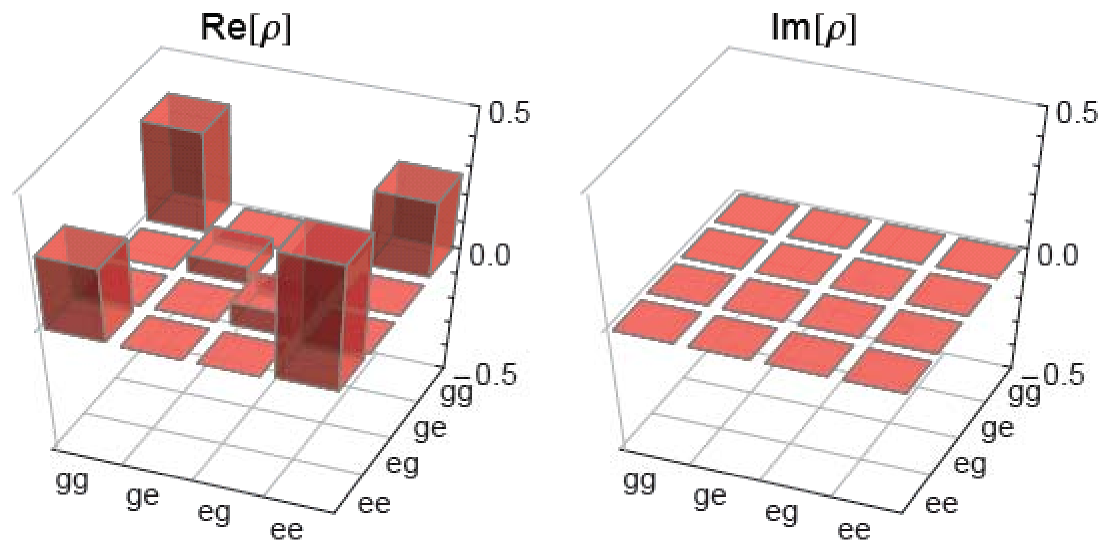
➡ qubit-qubit correlations can be determined from transmission measurement

Filipp *et al., Phys. Rev. Lett.* **102**, 200402 (2009)
Majer *et al., Nature (London)* **445**, 443 (2007)
Blais, Huang, Wallraff, Girvin & Schoelkopf, *PRA* **69**, 062320 (2004)

$$|\Phi_+\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)$$

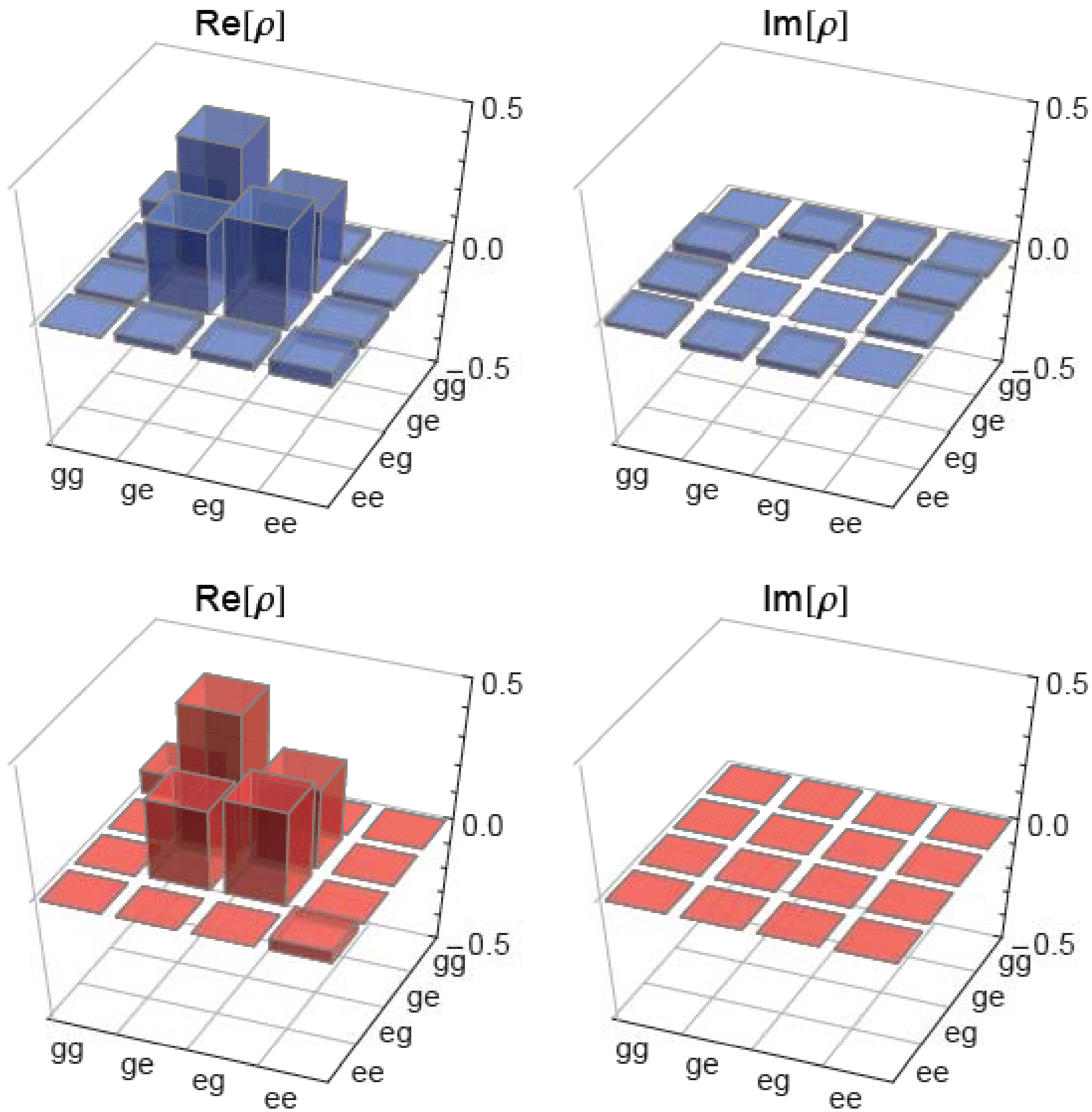


experimental state fidelity:
F = 86%
concurrence:
0.541
entanglement of formation :
0.371



overlap with calculation
F = 99%

$$|\Psi_+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$$



experimental state fidelity:
F = 86%

concurrence:
0.518

entanglement of formation :
0.374

overlap with calculation
F = 99%

P. Leek *et al., Phys. Rev. B* **79**, 180511(R) (2009)
S. Filipp *et al., Phys. Rev. Lett.* **102**, 200402 (2009)

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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. ✓