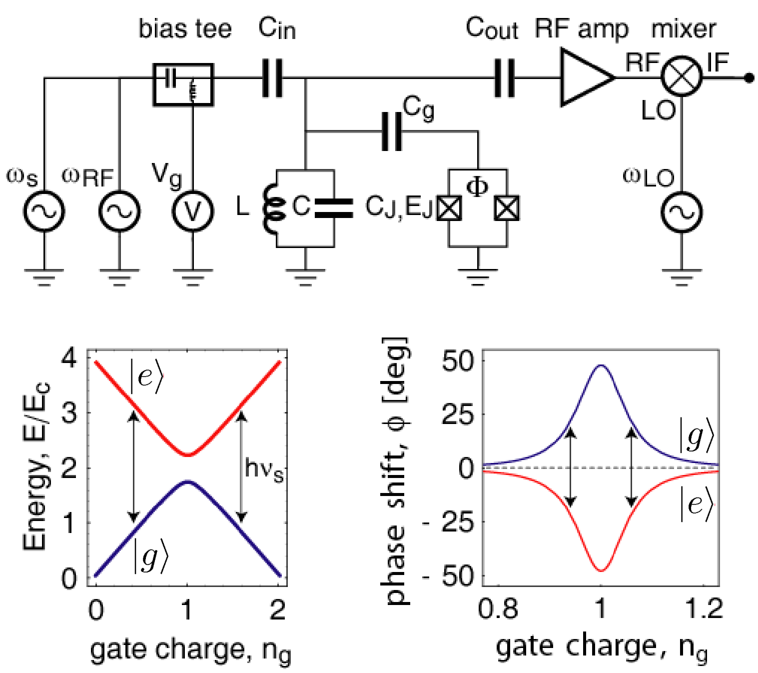
Qubit Spectroscopy with Dispersive Read-Out

Realization



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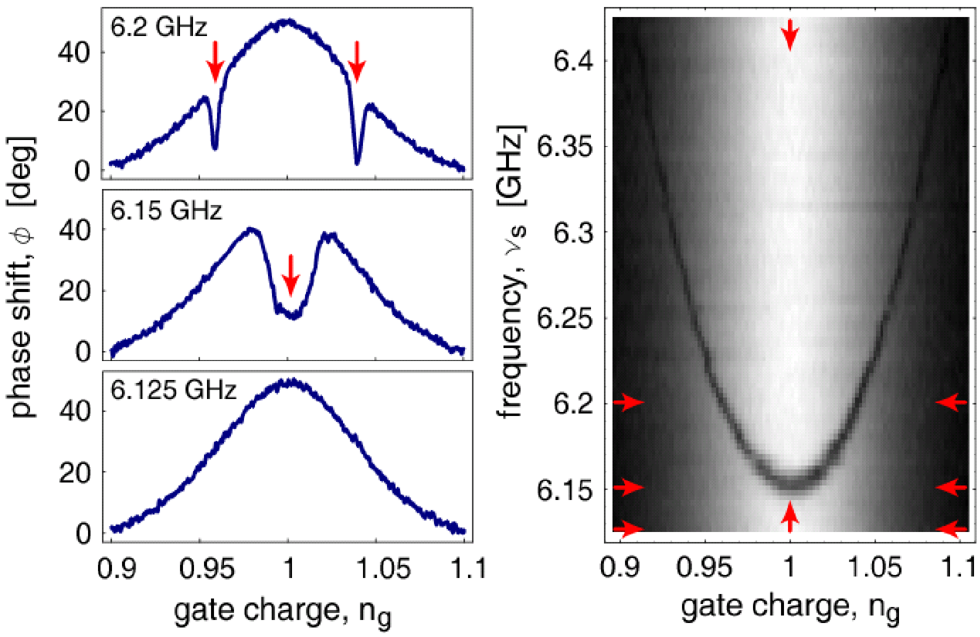
CW Spectroscopy of Cooper Pair Box



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

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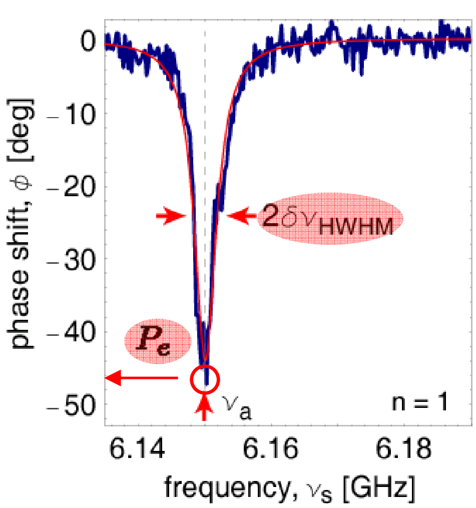
D. I. Schuster *et al.*, *Phys. Rev. Lett.* **94,** 123062 (2005)

Line Shape

excited state population (steady-state Bloch equations):

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



- fixed drive $P_s \propto \Omega_R^2 = n_s \omega_{vac}^2$
- varying $\Delta_{s,a} = \omega_s - \tilde{\omega}_a$
- weak continuous measurement $(n \sim 1)$
- at charge degenracy $(n_g = 1)$

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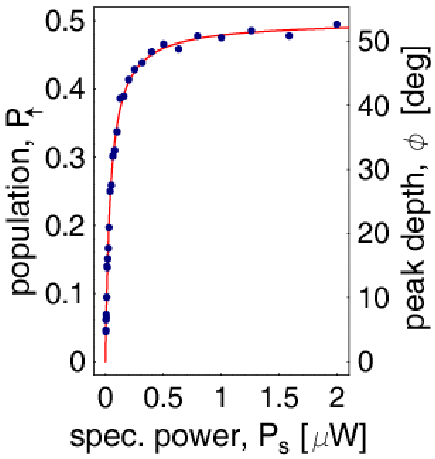
Abragam, Oxford University Press (1961)

Excited State Population

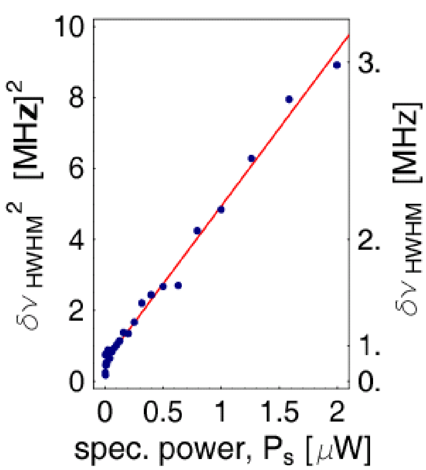


peak depth → population (saturation):

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

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:

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

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

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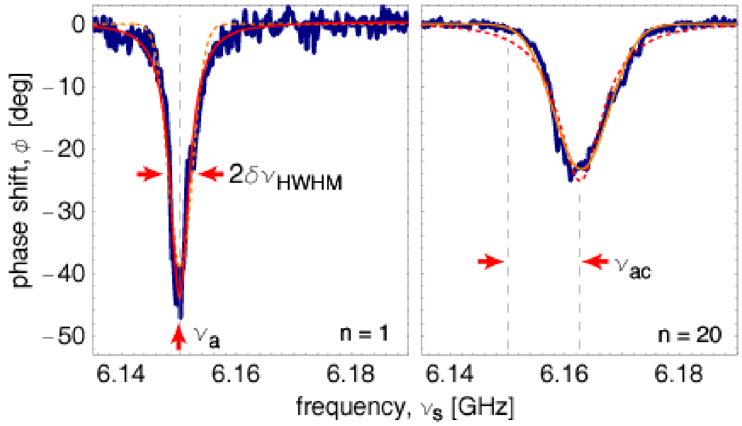
AC-Stark Effect & Measurement Back Action

for $\Delta_{a,r} = \omega_a - \omega_r \gg g$

ac-Stark (light) shift

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

photon number dependence of line position and width



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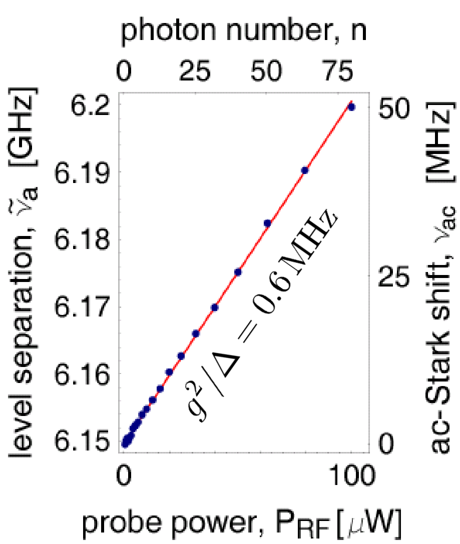
AC-Stark Effect: Line Shift



- ac-Stark (light) shift:

$$\nu_{ac} = \bar{n}\frac{g^2}{\pi\Delta_{a,r}}$$

- here $\nu_{ac}/\bar{n} = 0.6\,\mathrm{MHz}$
- use for photon number calibration

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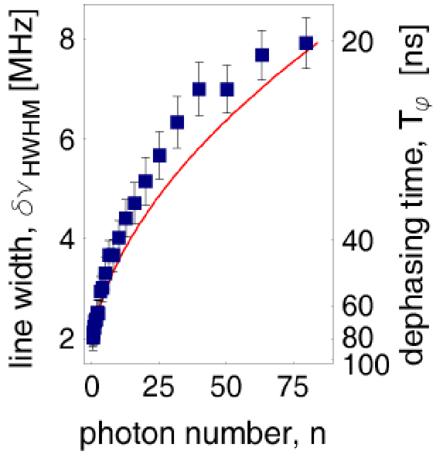
AC-Stark Effect: Line Broadening

photon shot noise:

- quantum fluctuations δn in coherent field with n photons
- random fluctuations in qubit level separation (ac-Stark)



- **for large n gaussian fluctuations in n:**

$$\delta\nu_{\mathrm{HWHM}} = \sqrt{2\ln 2}\,\frac{g^2}{\pi\Delta_{a,r}}\sqrt{\bar{n}}$$

- **characteristic measurement back-action**

D. I. Schuster, A. Wallraff, …, S. Girvin, and R. J. Schoelkopf,
Phys. Rev. Lett. **94,** 123062 (2005)

Coherent Control ...

… of a superconducting charge qubit.

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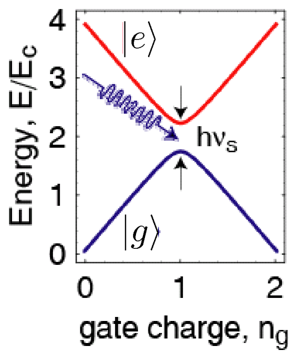
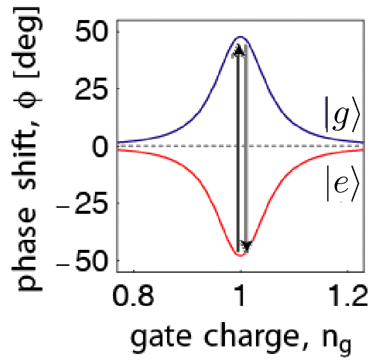
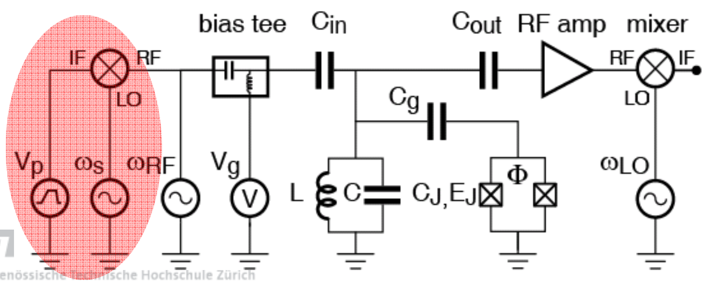
Coherent Control and Read-out in a Cavity





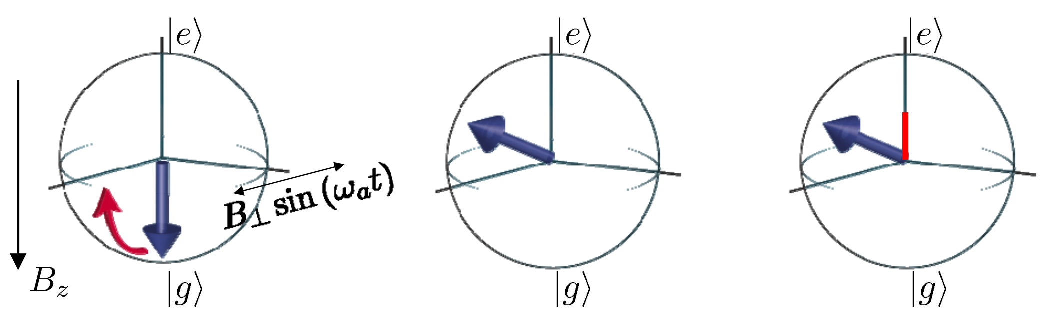
- apply resonant microwave pulse to qubit
- detect change of phase

realization:



- simultaneous control and measurement

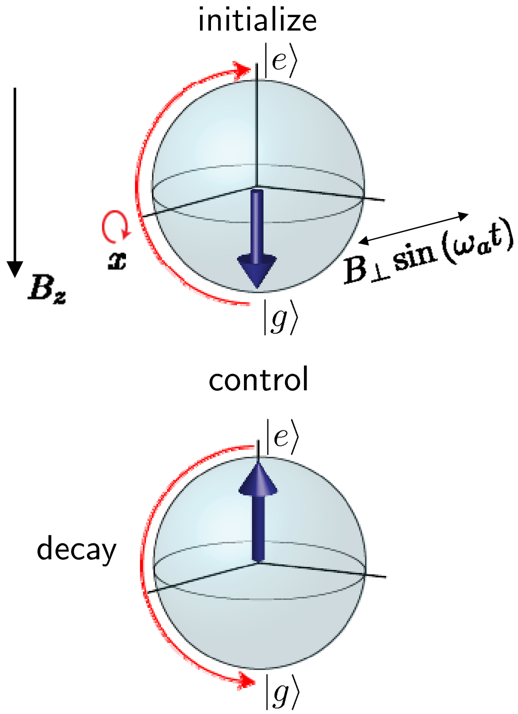
Coherent Control of a Qubit in a Cavity

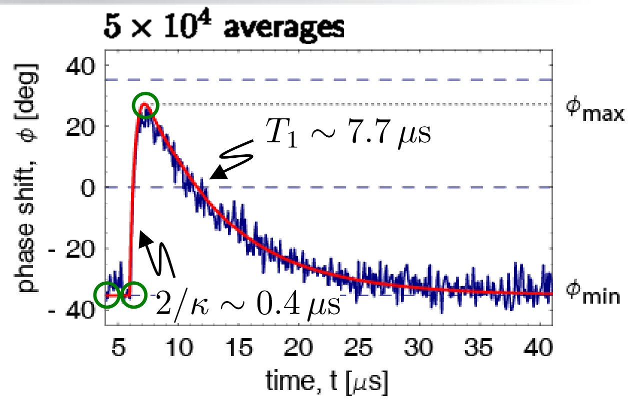


initialize · after operation · measure projection

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

Qubit Control and Readout





measurement properties:

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

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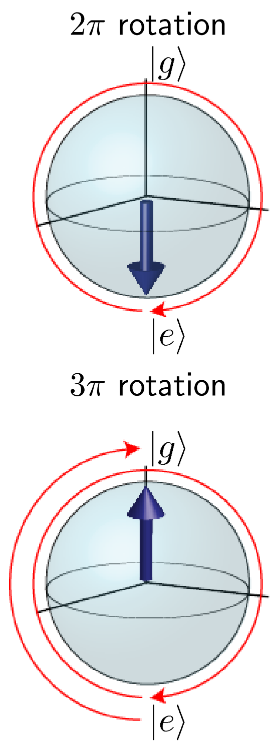
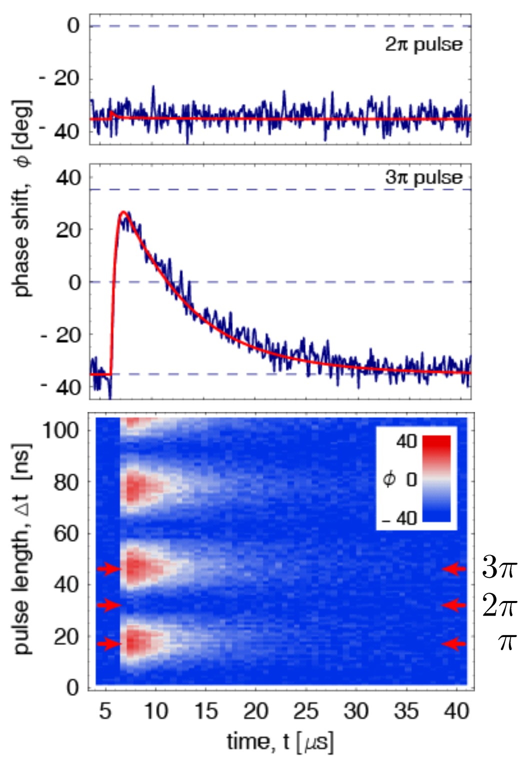
Wallraff, Schuster, Blais, ... Girvin, and Schoelkopf, *Phys. Rev. Lett.* **95**, 060501 (2005)

Varying the Control Pulse Length





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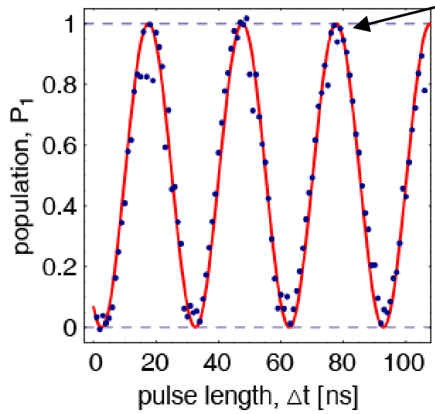
Wallraff, Schuster, Blais, ... Girvin, Schoelkopf, *PRL* **95**, 060501 (2005)

High Visibility Rabi Oscillations

Rabi oscillations:

visibility 95 $\pm$ 5%



for superconducting qubits:

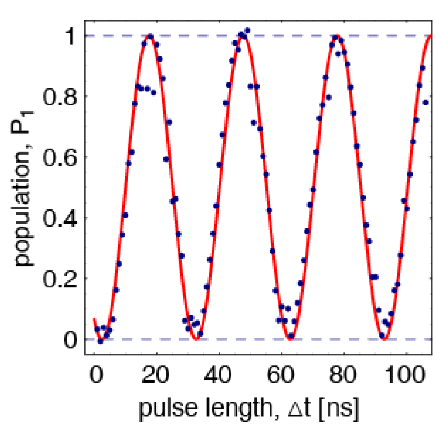
- **high visibility**
- **well characterized and understood measurement**
- **good control accuracy**

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

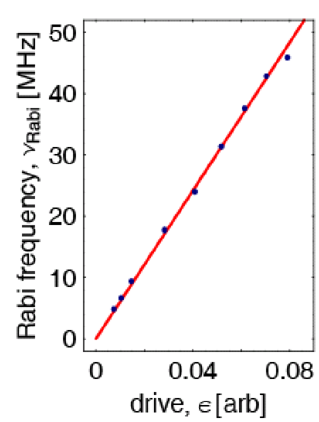
Rabi Frequency

pulse scheme:

Rabi oscillations:



Rabi frequency:

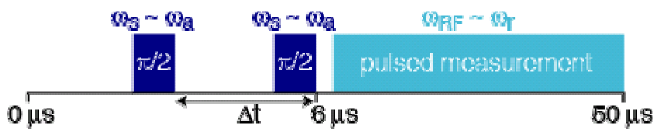


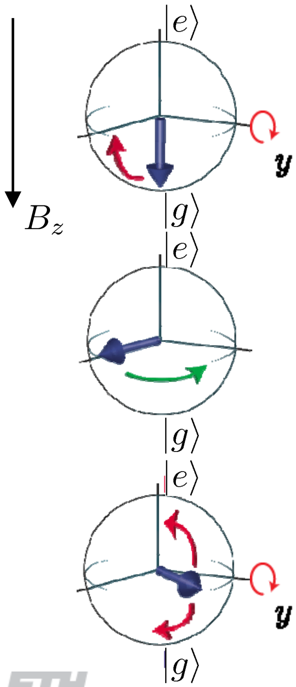
- **linear dependence on drive amplitude**

Measurements of Coherence Time

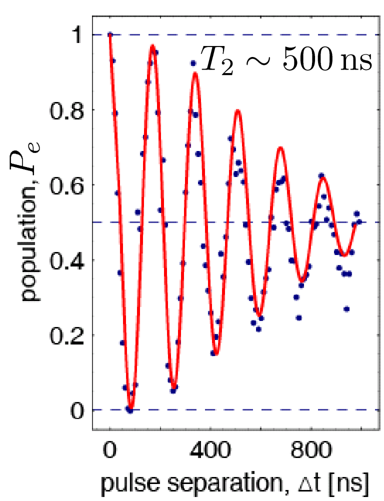
Ramsey Fringes: Coherence Time Measurement

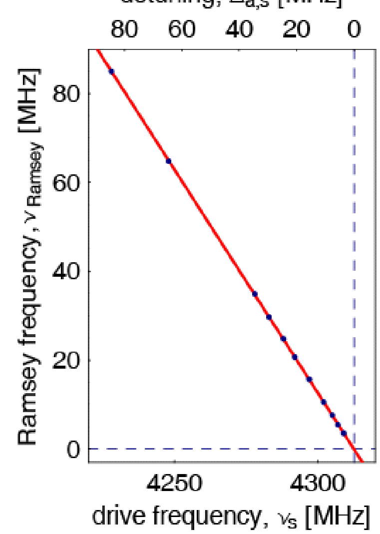
pulse scheme:





Ramsey fringes:





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

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