Strongly Driven Semiconductor Double Quantum Dots

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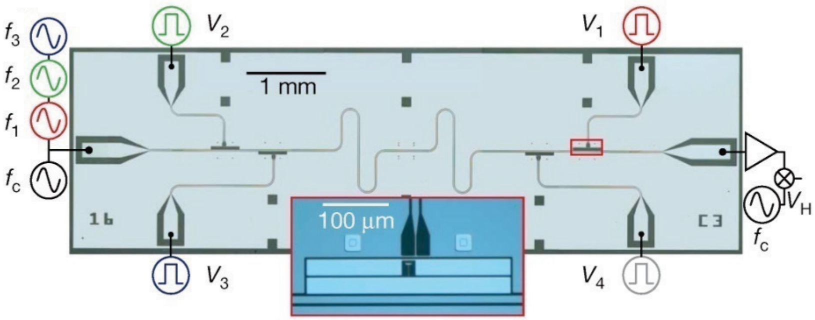
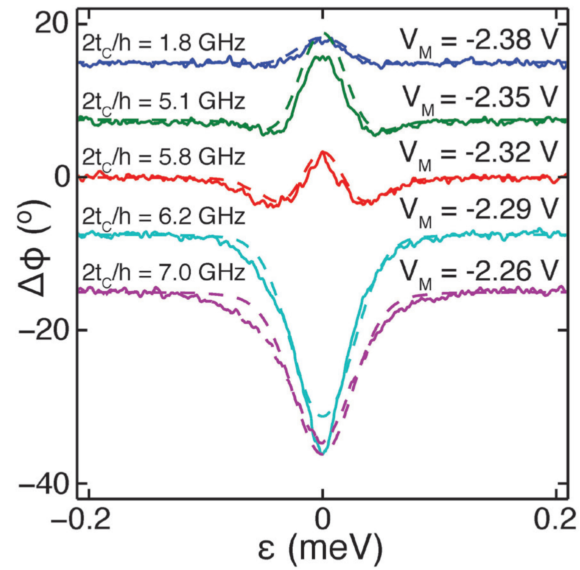
Lecture 3: Cavity-Coupled Double Quantum Dots

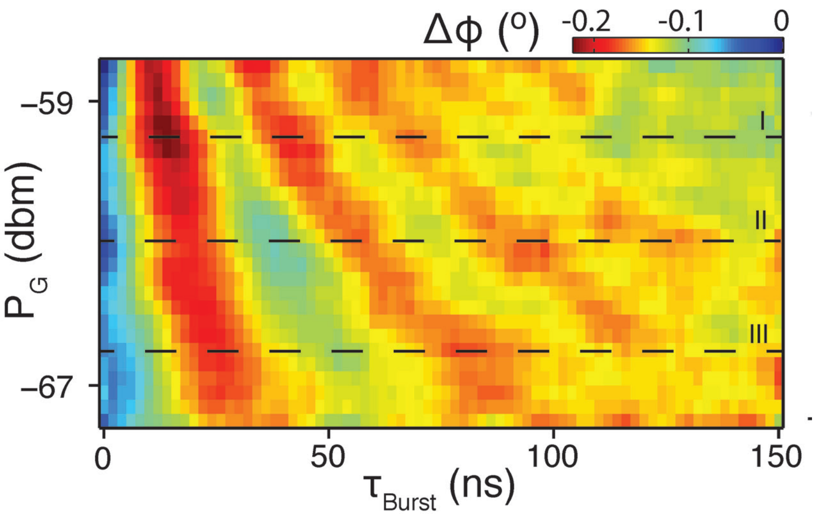
Circuit QED



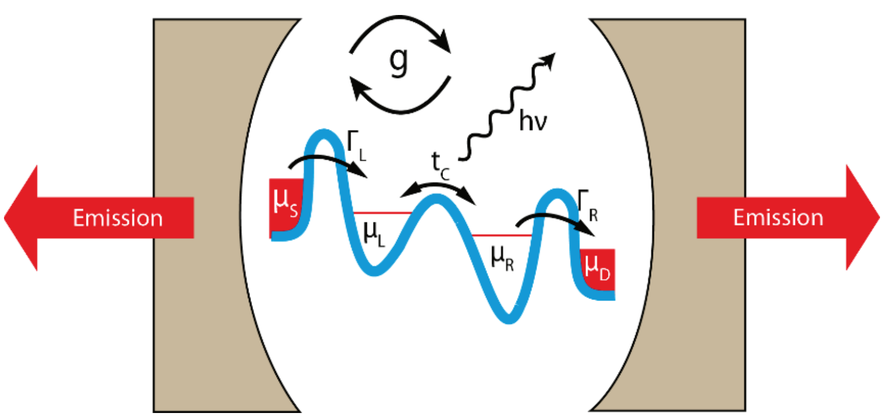
Charge-Cavity Coupling



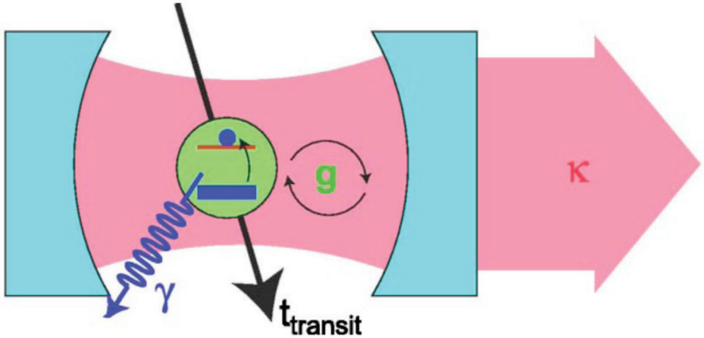
Towards Spin-Cavity Coupling



Quantum Dot Maser

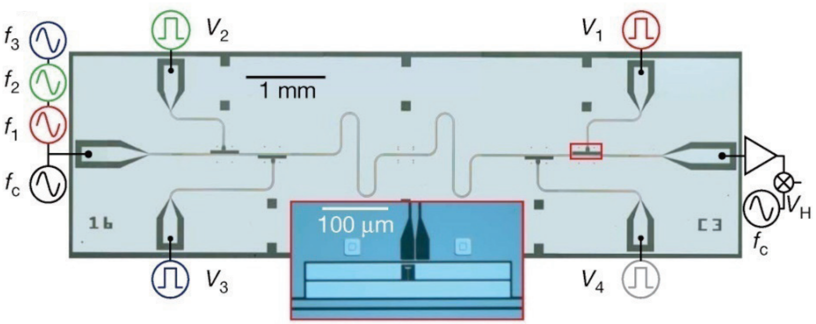


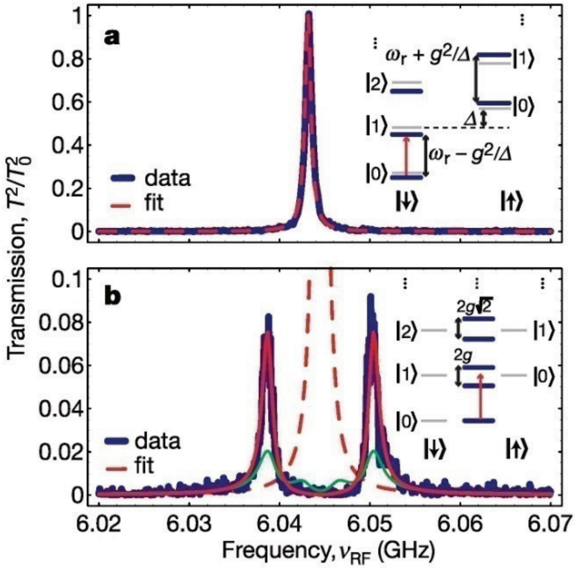
Cavity Quantum Electrodynamics



Kimble Group, Caltech

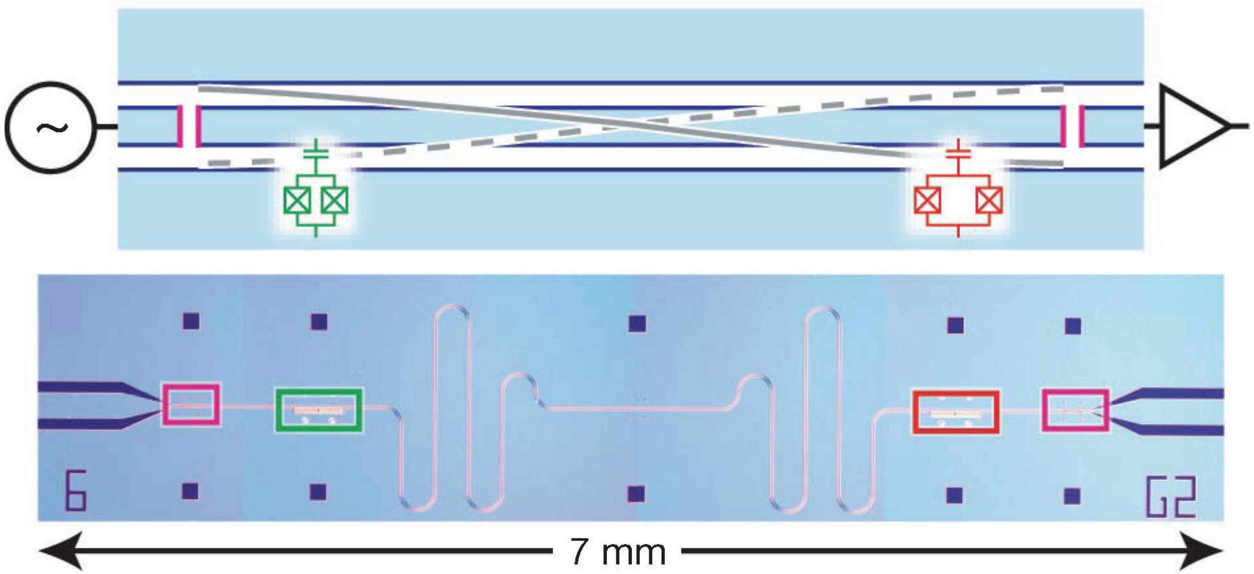
Circuit Quantum Electrodynamics (cQED)



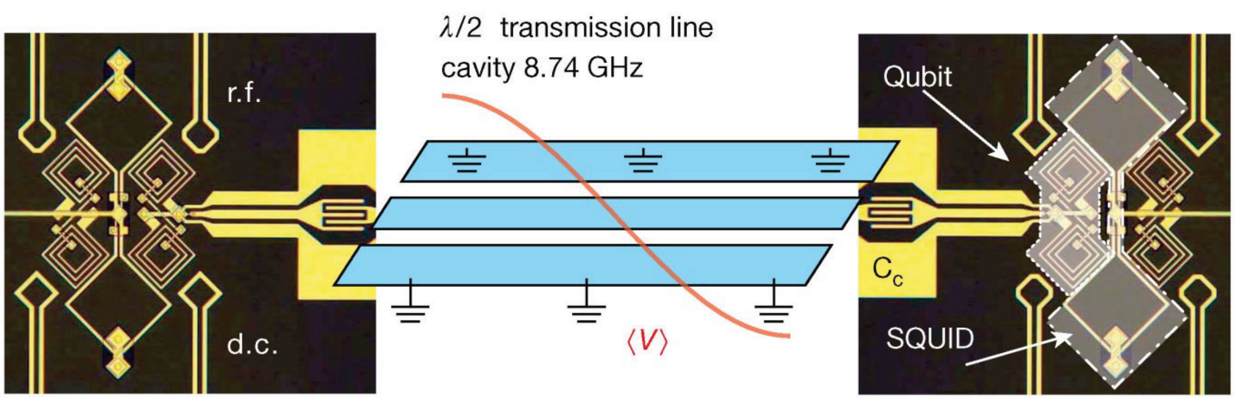


Blais (2004), Wallraff (2004), DiCarlo (2010)

Coupling Superconducting Qubits Via a Cavity Bus



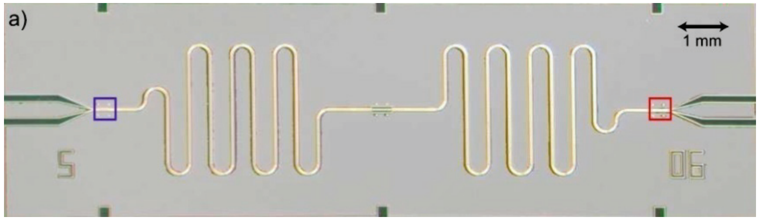
Majer *et al.* Nature (2007)



Sillanpää *et al.* Nature (2007)

Spin Qubit Analog to cQED?

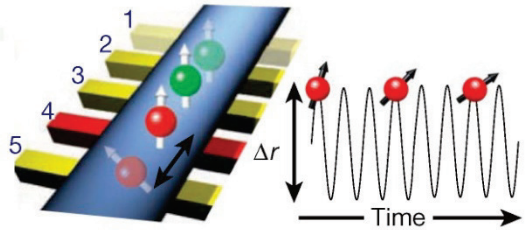
superconducting resonator



Schuster (2007)

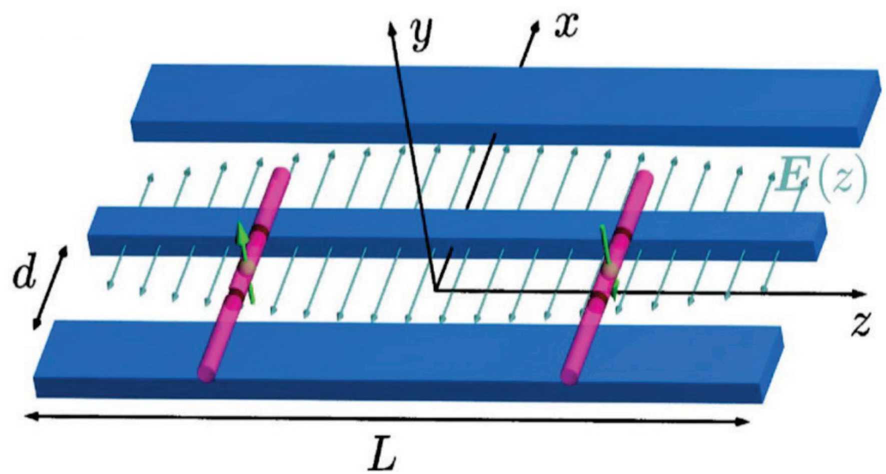
+

spin-orbit qubit



Nadj-Perge (2010)

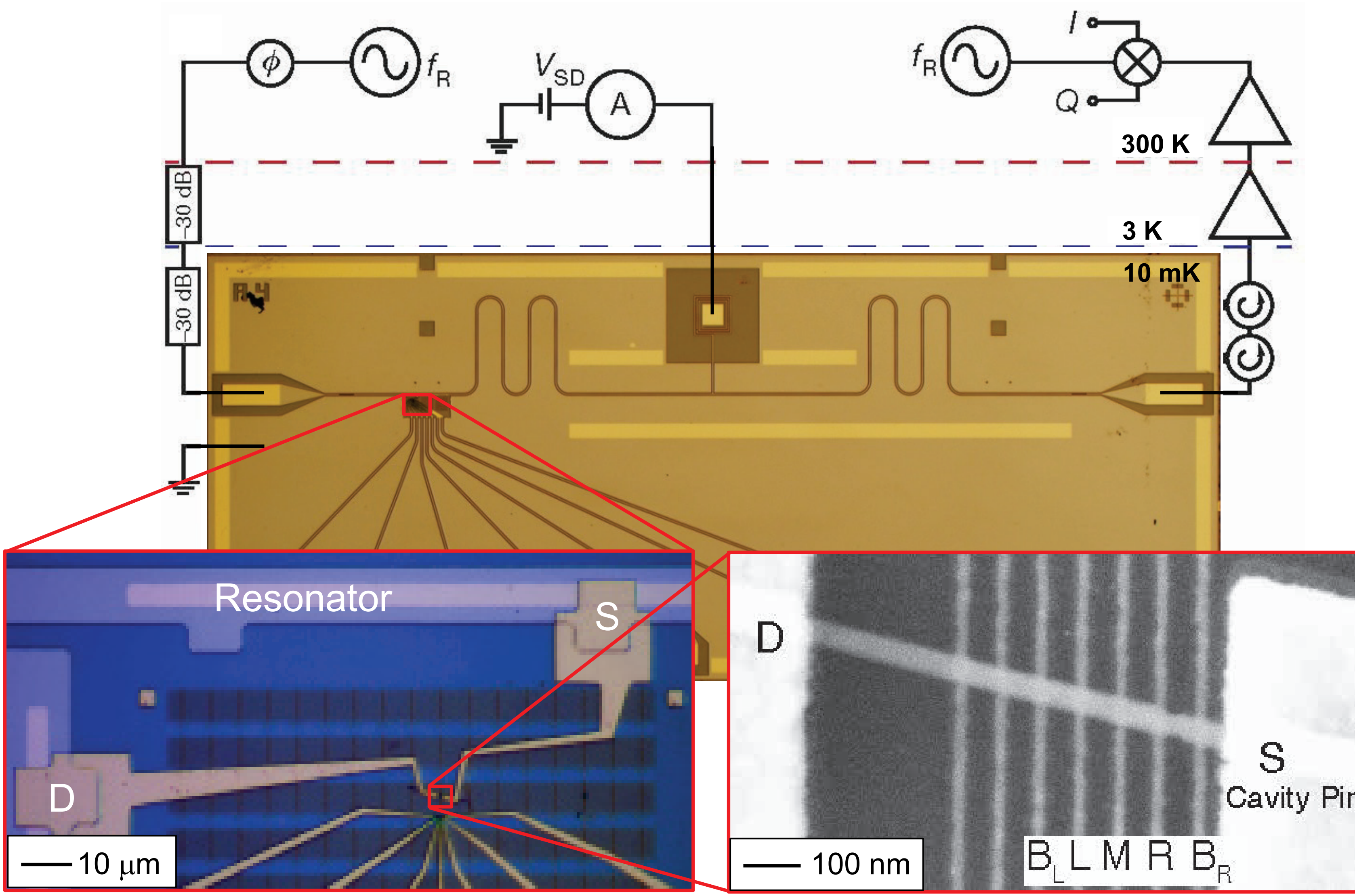
= ?



$$J = \nu_1 \nu_2 \left(\frac{1}{\Delta_1} + \frac{1}{\Delta_2} \right)$$

Trif, Golovach, Loss (2008)

Quantum Dot-Superconductor Hybrid System: Circuit

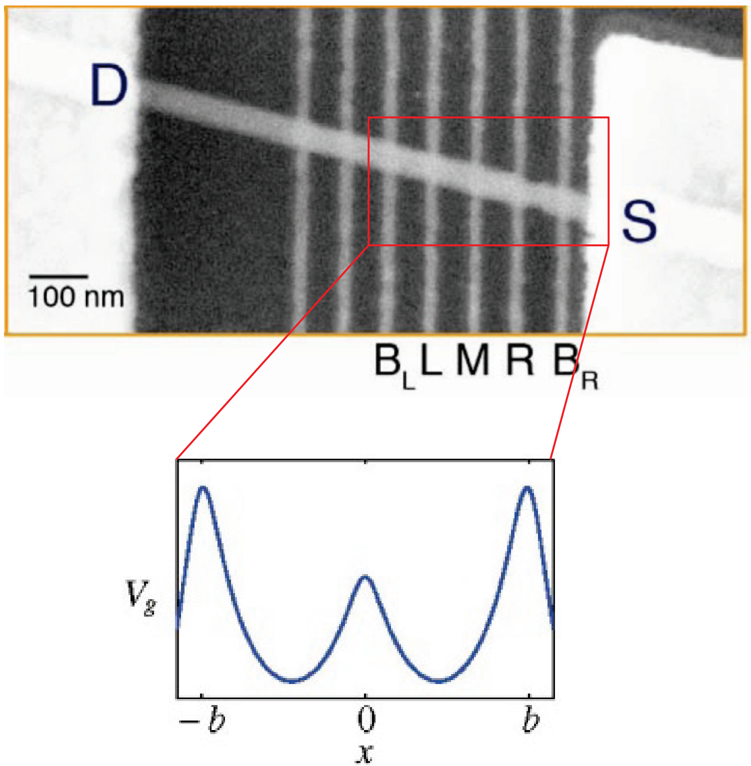


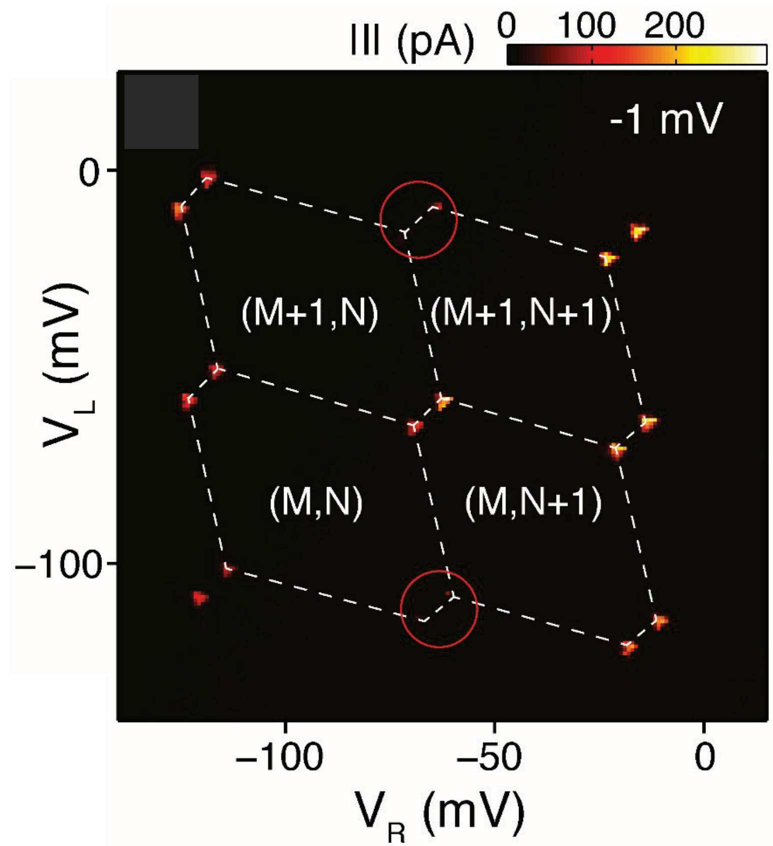
dc biased cavity: Chen *et al*., APL (2011)

GaAs: Frey *et al*., PRL (2012), Toida *et al*., PRL (2013), CNT: Delbecq *et al*., PRL (2011)

K. D. Petersson, L. W. McFaul, J. M. Taylor, A. A. Houck, J. R. Petta, Nature (2012)

Bottom Gated InAs Nanowire Double Dots

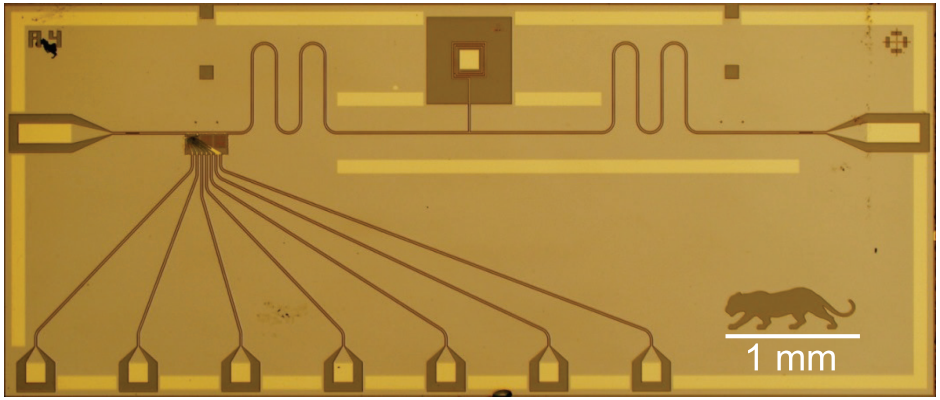




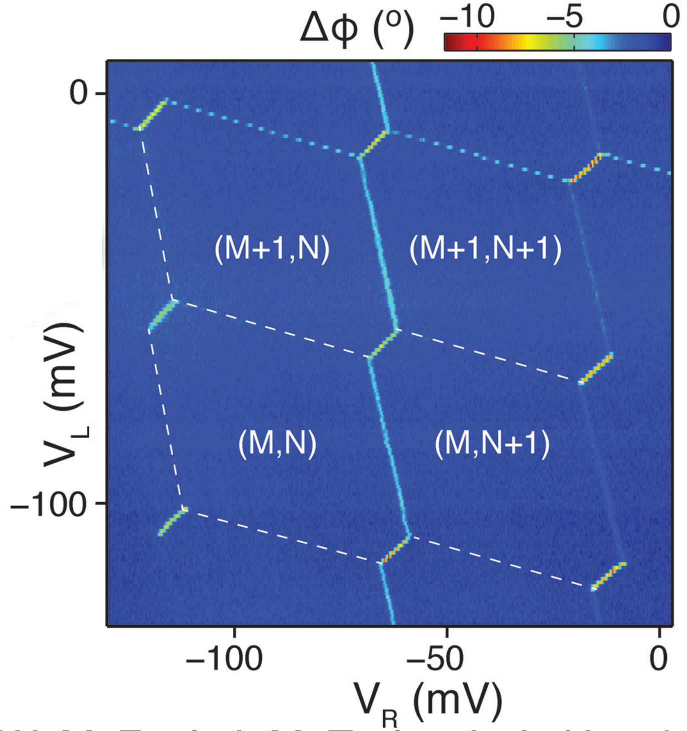
Nadj-Perge *et al.*, Nature (2010)

Schroer, Petersson, Jung, Petta, PRL (2011)

Charge Sensing Via the Cavity

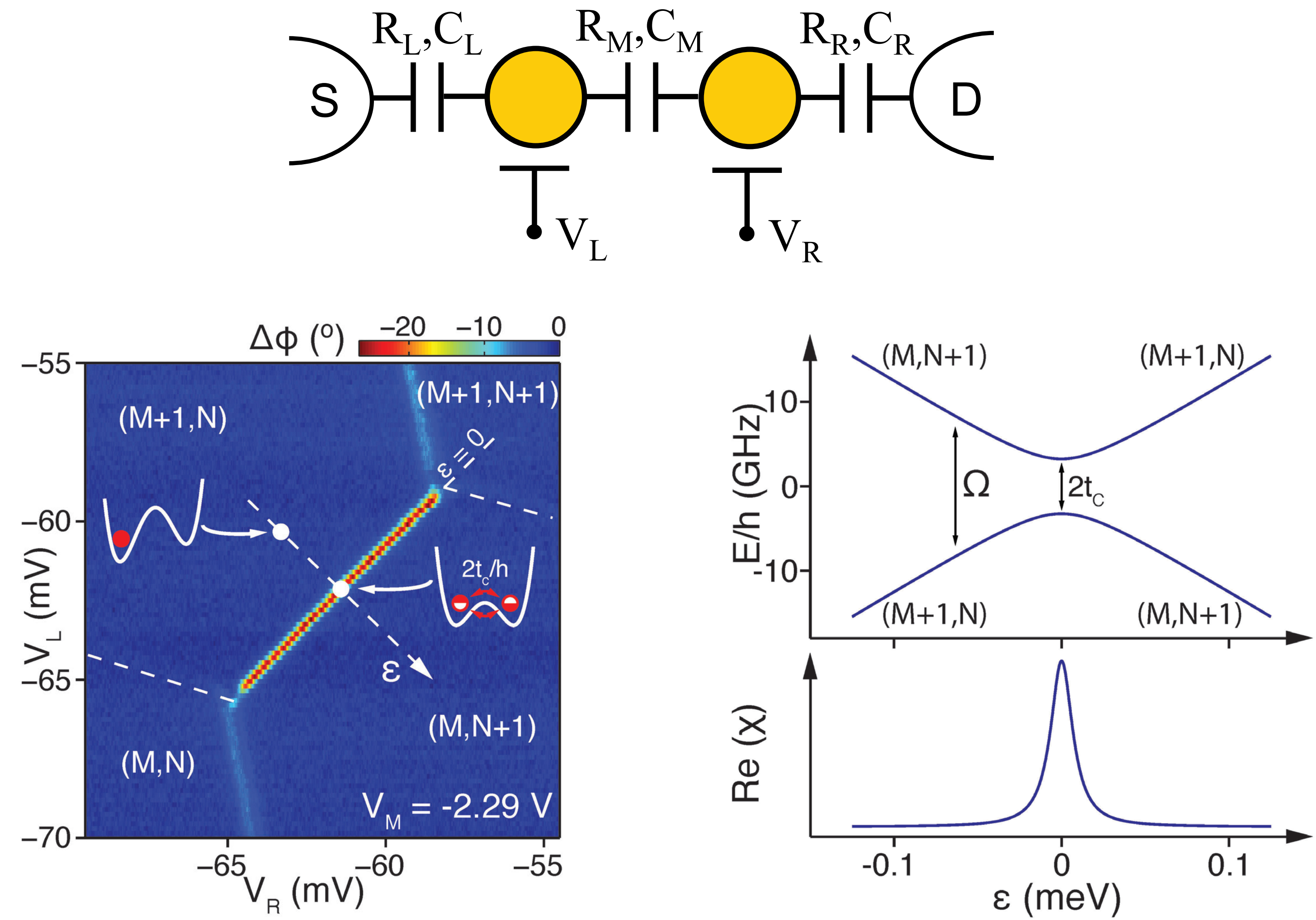


resonator phase response



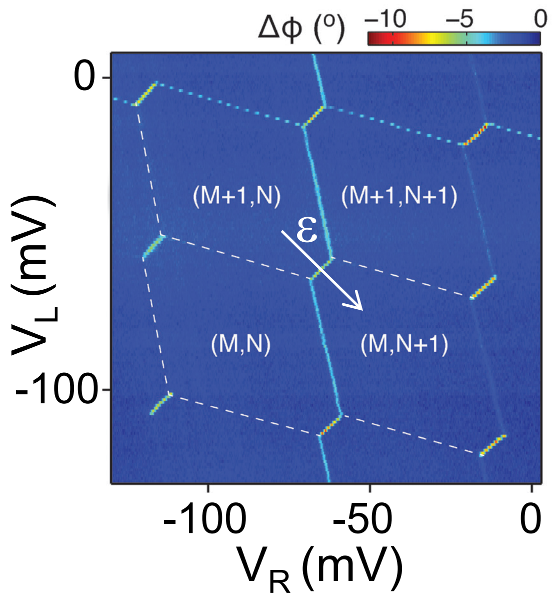
K. D. Petersson, L. W. McFaul, J. M. Taylor, A. A. Houck, J. R. Petta, Nature (2012)

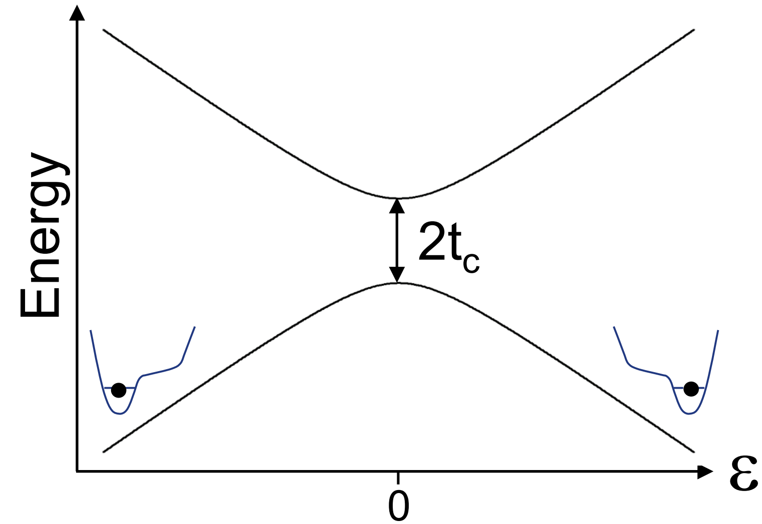
Interdot Charge Transitions



K. D. Petersson, L. W. McFaul, J. M. Taylor, A. A. Houck, J. R. Petta, Nature (2012)

Cavity Response at Interdot Charge Transitions





Charge qubit

$$H_0 = \frac{\varepsilon}{2}\tilde{\sigma}_Z + t_C\tilde{\sigma}_X$$

$$H_U = \frac{\Omega}{2}\sigma_Z, \ \Omega = \sqrt{\varepsilon^2 + 4t_C^2}$$

Resonator dipole coupling

$$H_D = \frac{\delta\varepsilon}{2}\cos(\omega_r t)\tilde{\sigma}_Z$$

$$H_{U,D} = \frac{\delta\varepsilon}{2}\cos(\omega_r t)\left(\frac{\varepsilon}{\Omega}\sigma_Z + \frac{2t_C}{\Omega}\sigma_X\right)$$

Total Hamiltonian

$$H_{U,T} = \frac{\Omega}{2}\sigma_Z + \frac{\delta\varepsilon}{2}\cos(\omega_r t)\left(\frac{\varepsilon}{\Omega}\sigma_Z + \frac{2t_C}{\Omega}\sigma_X\right)$$

Jaynes-Cummings Hamiltonian

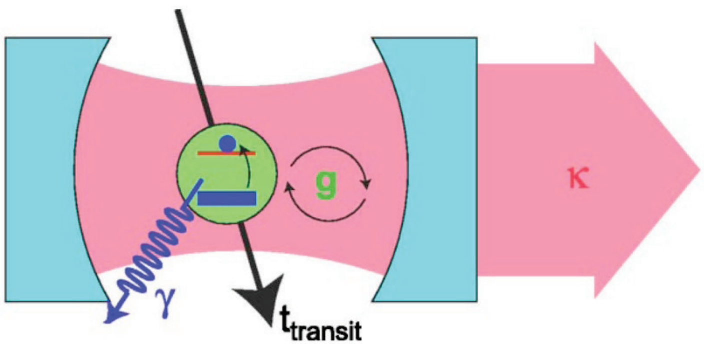
Transform to rotating frame and quantize the field:

$$H_{tot} = \hbar\Delta_0 a^\dagger a + \frac{\hbar\Delta}{2}\sigma_Z + \hbar g_{eff}(a\sigma_+ + a^\dagger\sigma_-)$$

with $\Delta_0 = \omega_0 - \omega_r,\quad \Delta = \frac{\Omega}{\hbar} - \omega_r,\quad g_{eff} = g_0\frac{2t_C}{\Omega}$

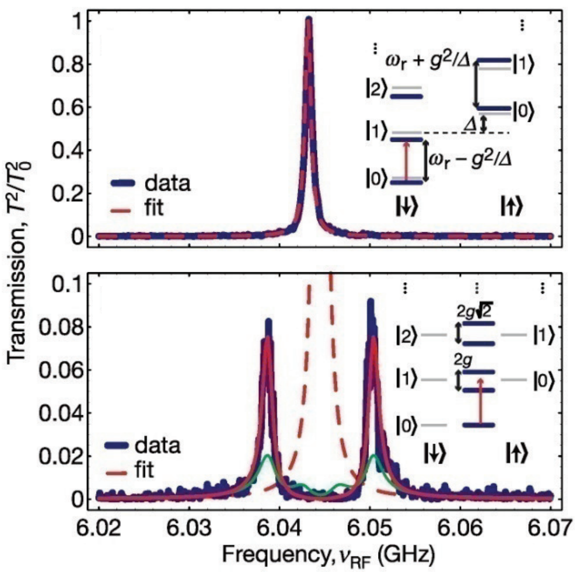
See: "Quantum Optics" by Walls and Milburn, Springer 2008

Cavity QED (CQED)



Kimble Group

Circuit QED (cQED)

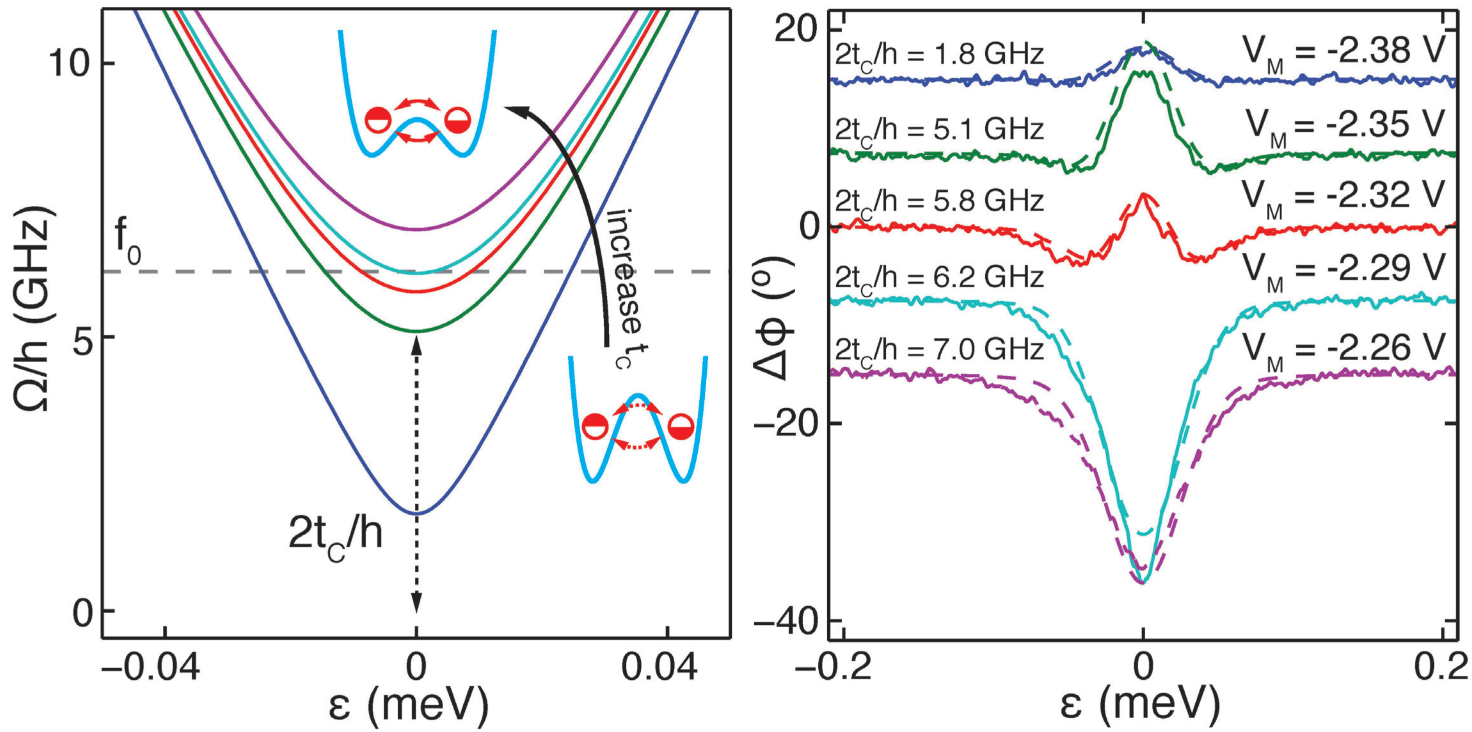


Blais (2004), Wallraff (2004)

Charge-Cavity Coupling Rate, $g/2\pi \sim 30$ MHz

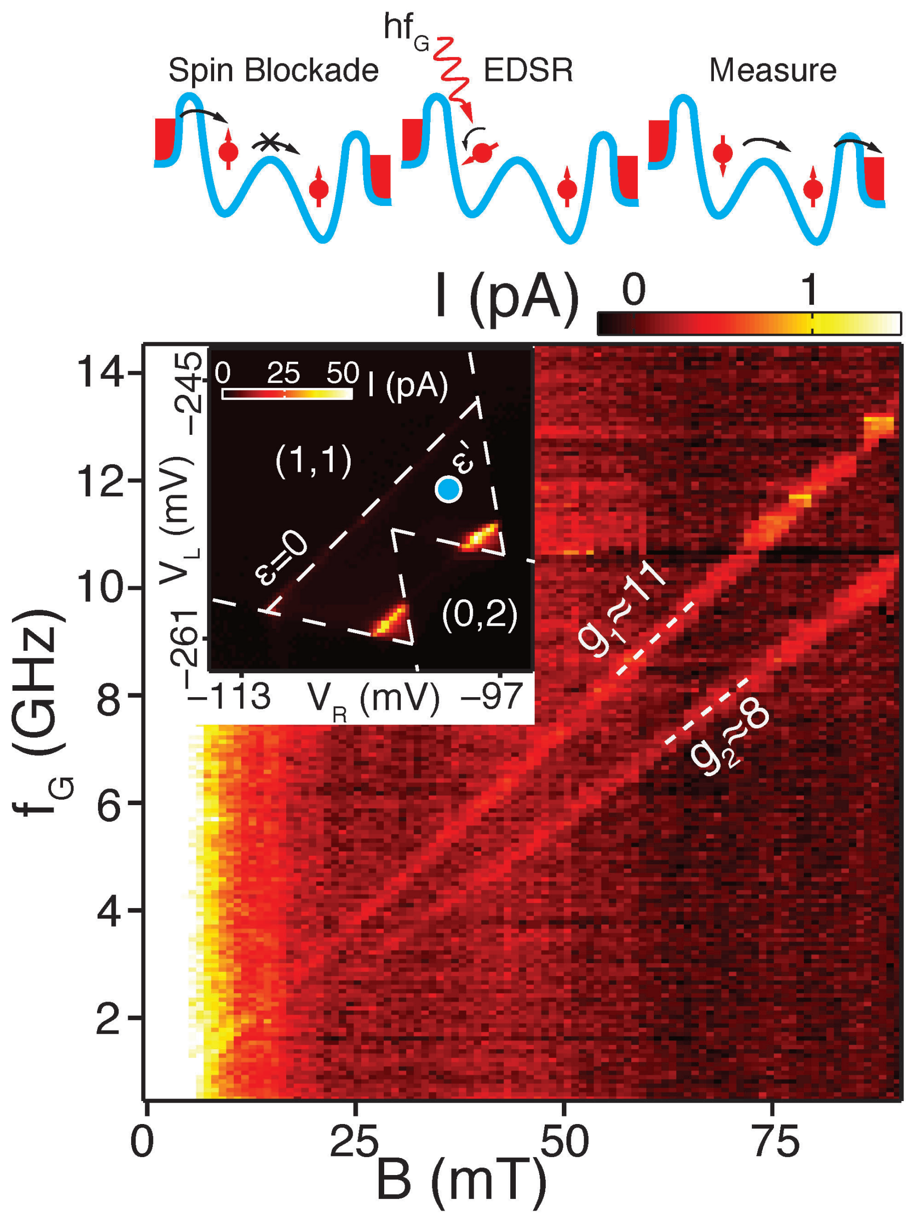
$$H \approx \hbar\left(\omega_\mathrm{r} + \frac{g^2}{\Delta}\sigma_\mathrm{z}\right)(a^\dagger a + 1/2) + \hbar\omega_\mathrm{a}\,\sigma_\mathrm{z}/2$$

atom-cavity detuning $\Delta = \omega_a - \omega_r$



K. D. Petersson, L. W. McFaul, J. M. Taylor, A. A. Houck, J. R. Petta, Nature (2012)

Transport: EDSR



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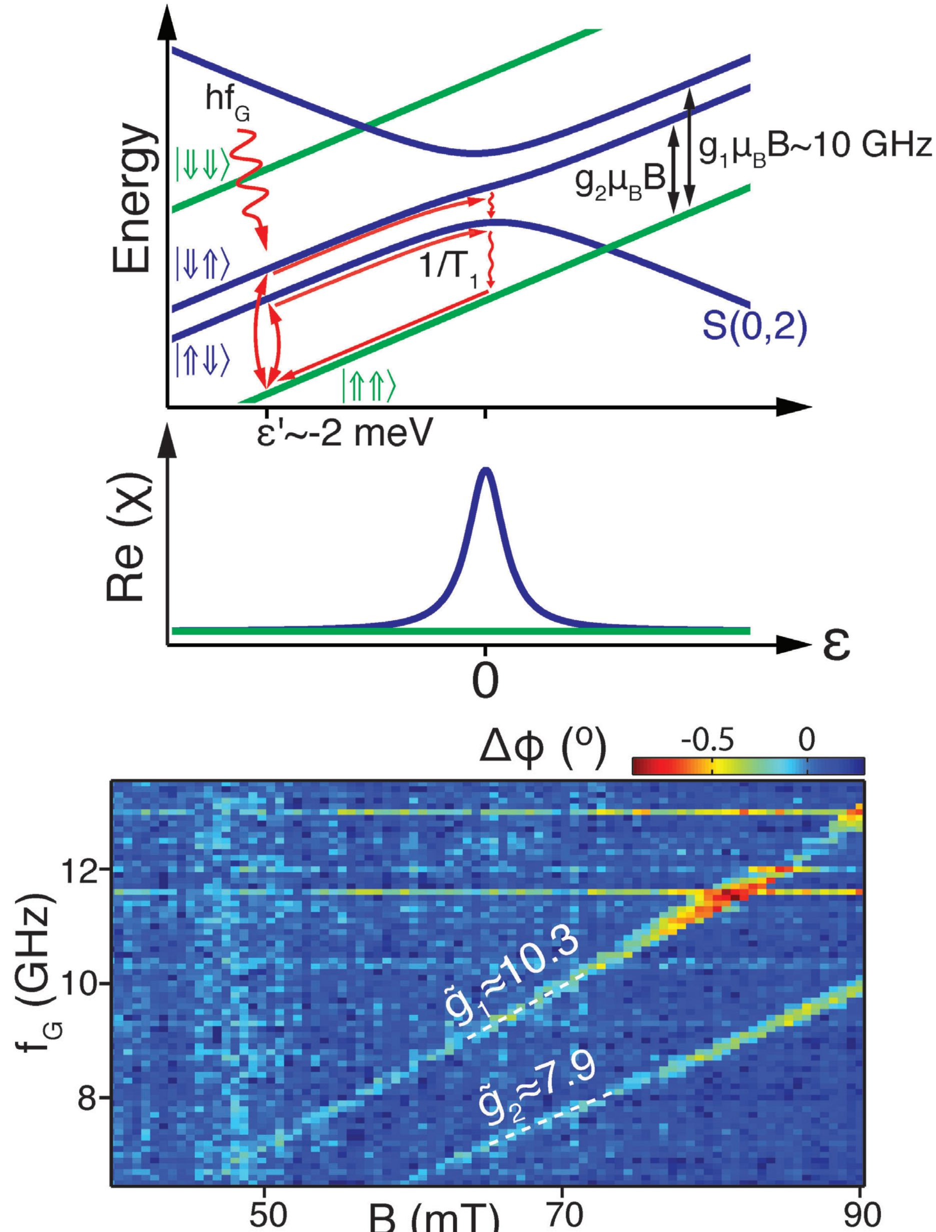
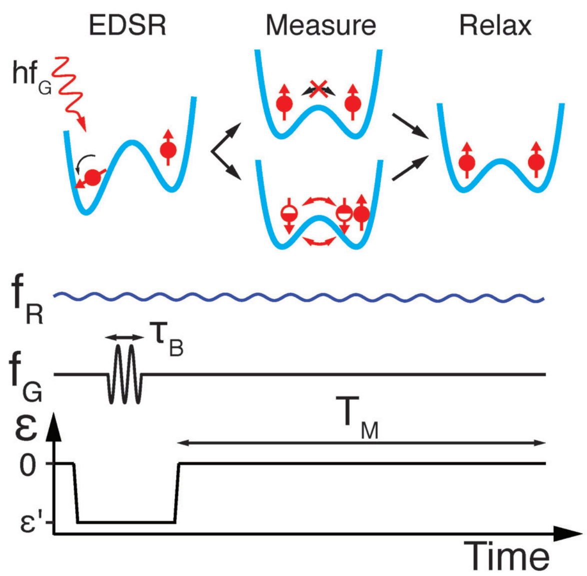
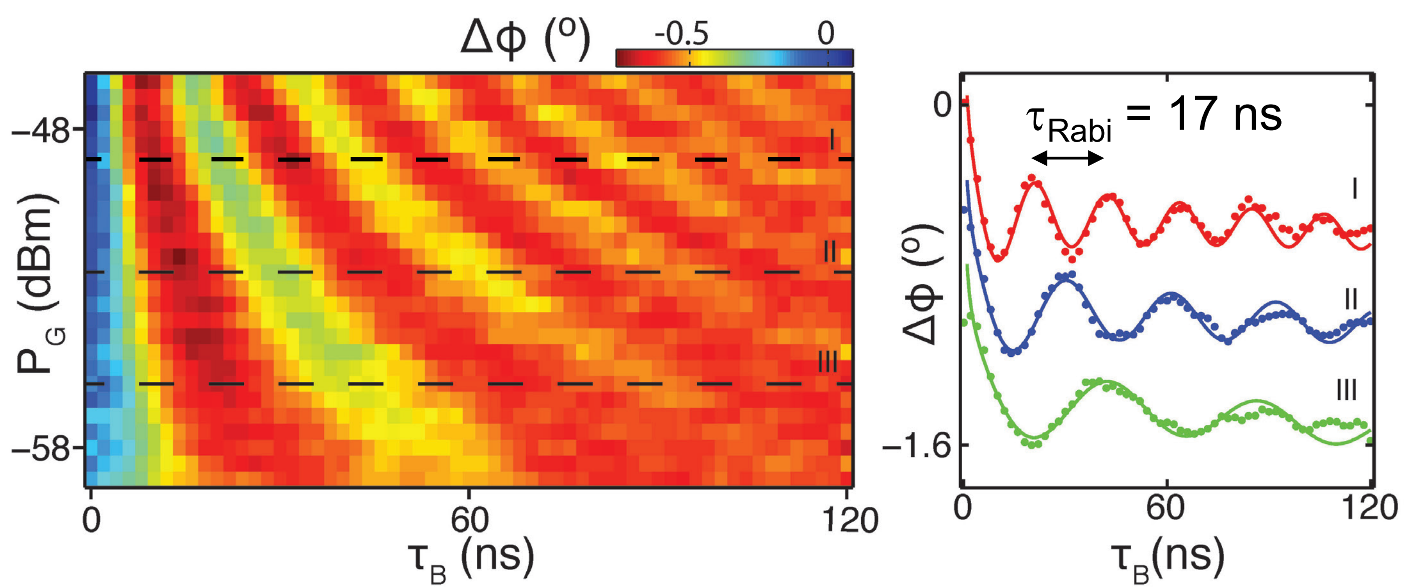
Spin State Readout



Coherent Spin Control and Readout

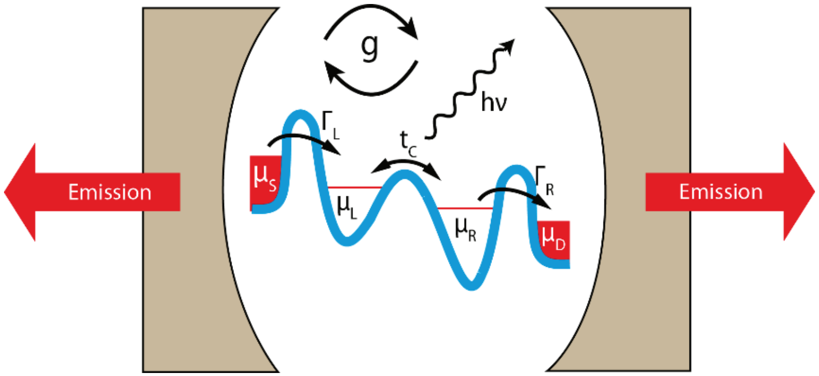




K. D. Petersson, L. W. McFaul, J. M. Taylor, A. A. Houck, J. R. Petta, Nature (2012)

Inelastic Charge Transport in a Cavity-Coupled Semiconductor Double Quantum Dot

Quantum Dot Micromaser



Key Elements

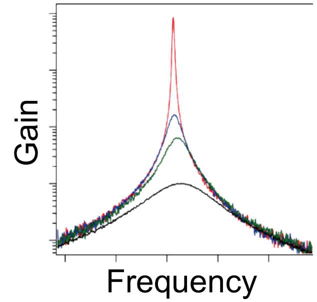
Gain medium: double quantum dot

Cavity: microwave resonator

Energy supply: V_{SD} (battery)

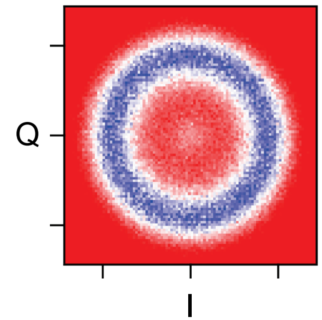
Theory: Childress *et al*., PRA (2004)
Hauss *et al*., PRL (2008); Andre *et al*., PRA (2009)
Cottet *et al*., PRB (2011); Jin *et al*., PRB (2011)
Bergenfeldt *et al*., PRB (2012)

Main Results:



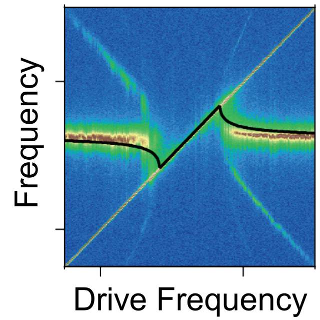
- Single electron tunneling results in microwave amplification with gain $G \sim 1000$.

Experiment: Liu *et al*., PRL (2014)
Liu *et al*., Science (2015)



- Free-running photon emission statistics are consistent with an above threshold maser.

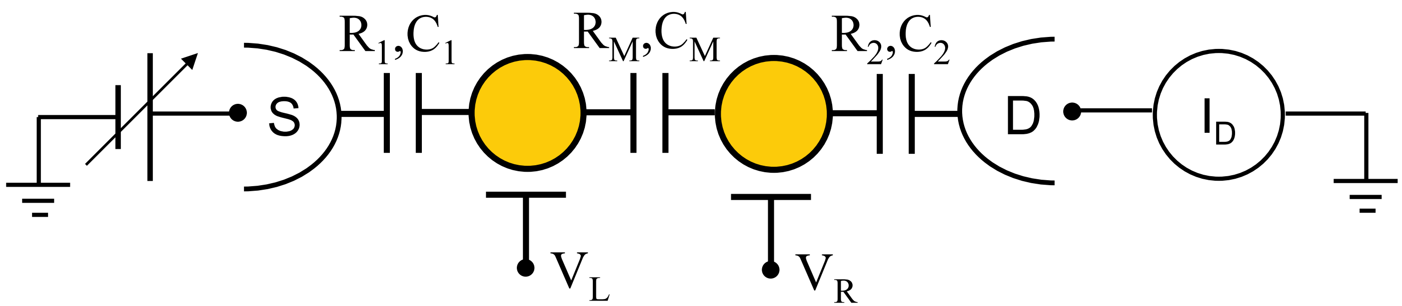
Experiment: Liu *et al*., Science (2015)
Theory: Gullans *et al*., PRL (2015)

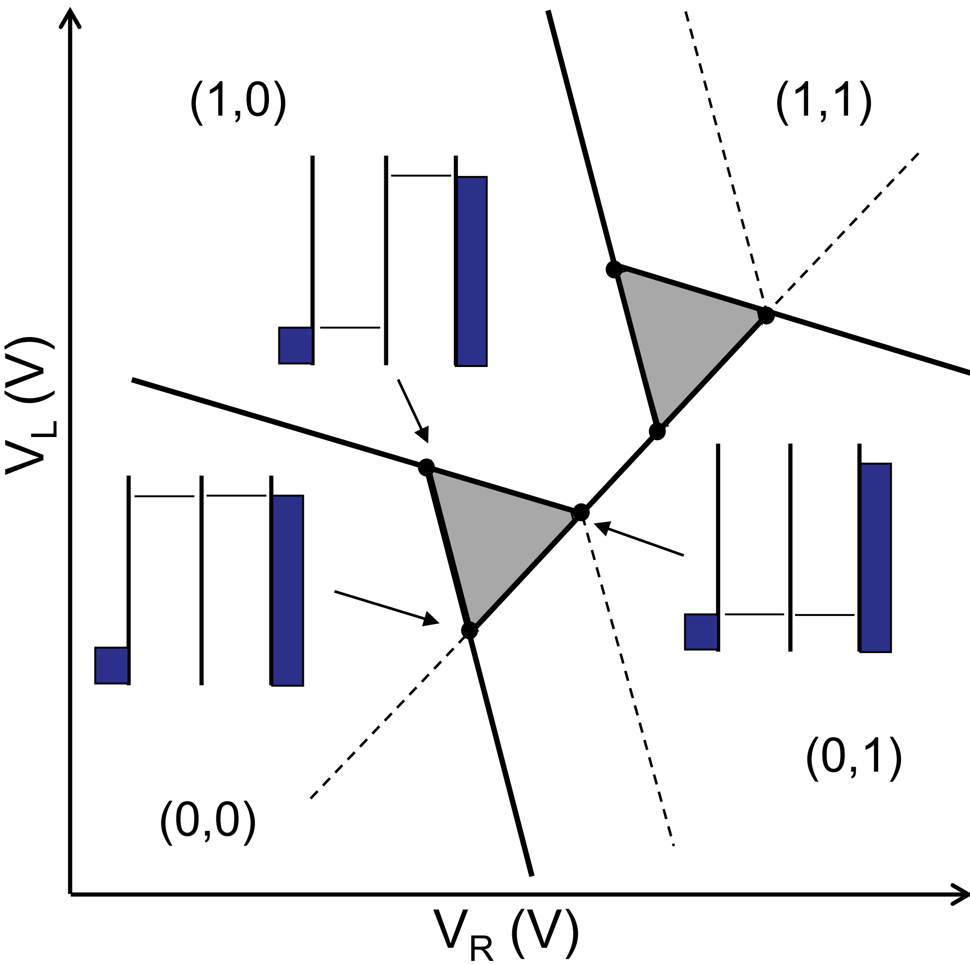


- The free-running emission can be injection-locked to an input tone.

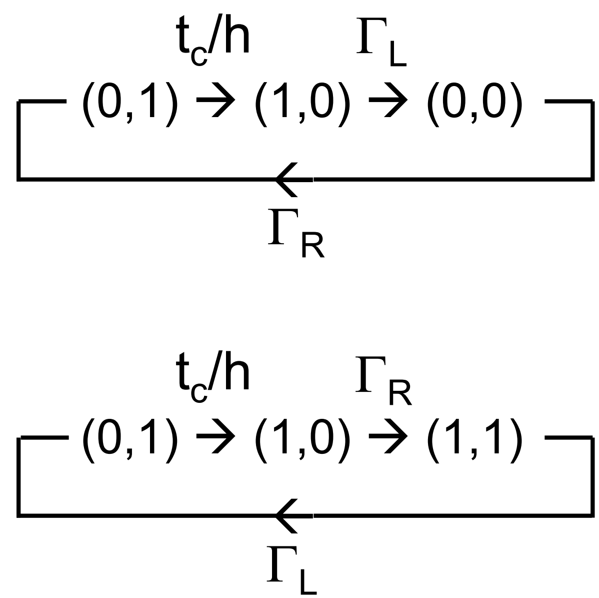
Experiment: Liu *et al*., PRA (2015)

DC Transport in Double Quantum Dots

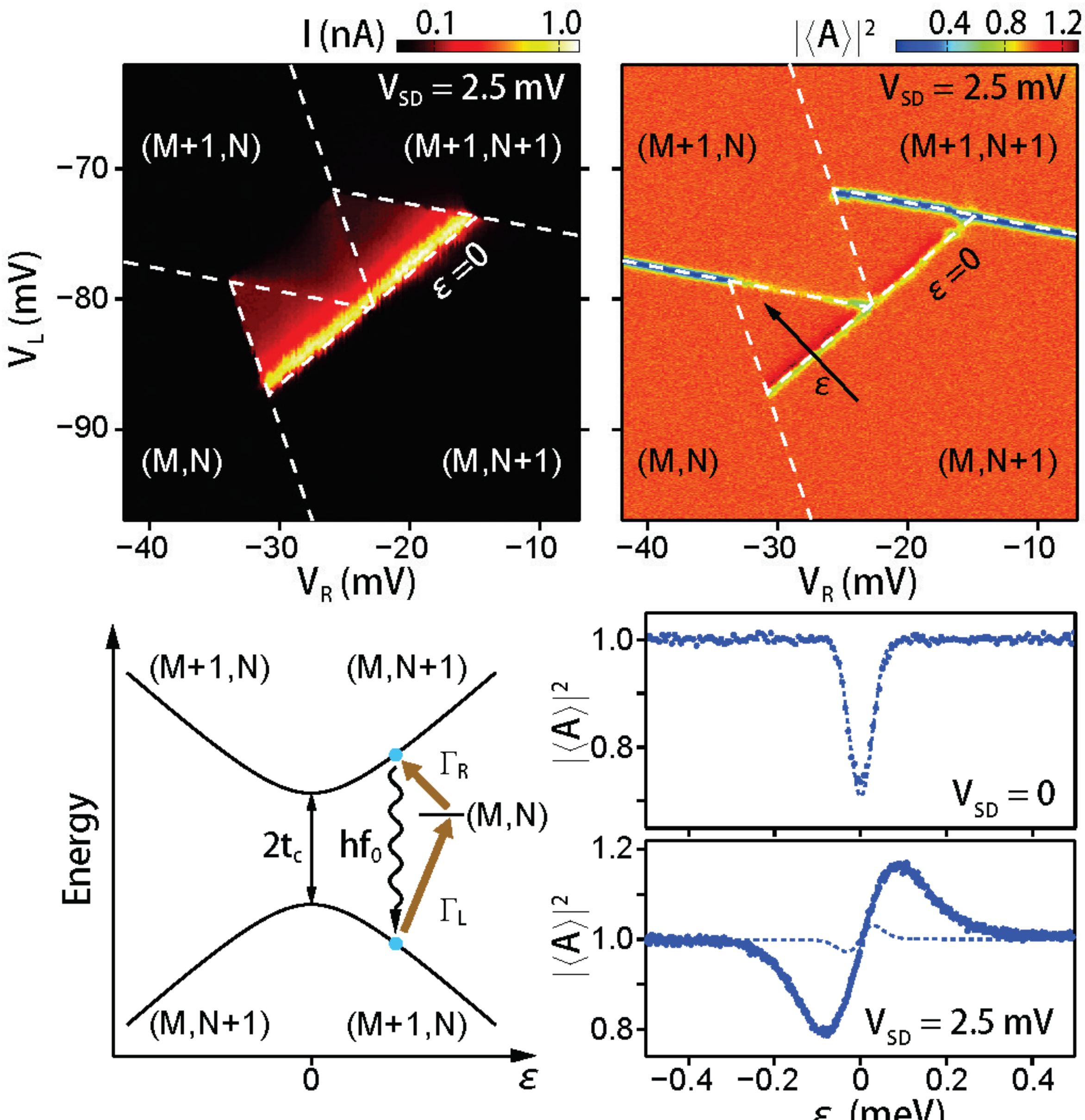




Finite bias "triangles"

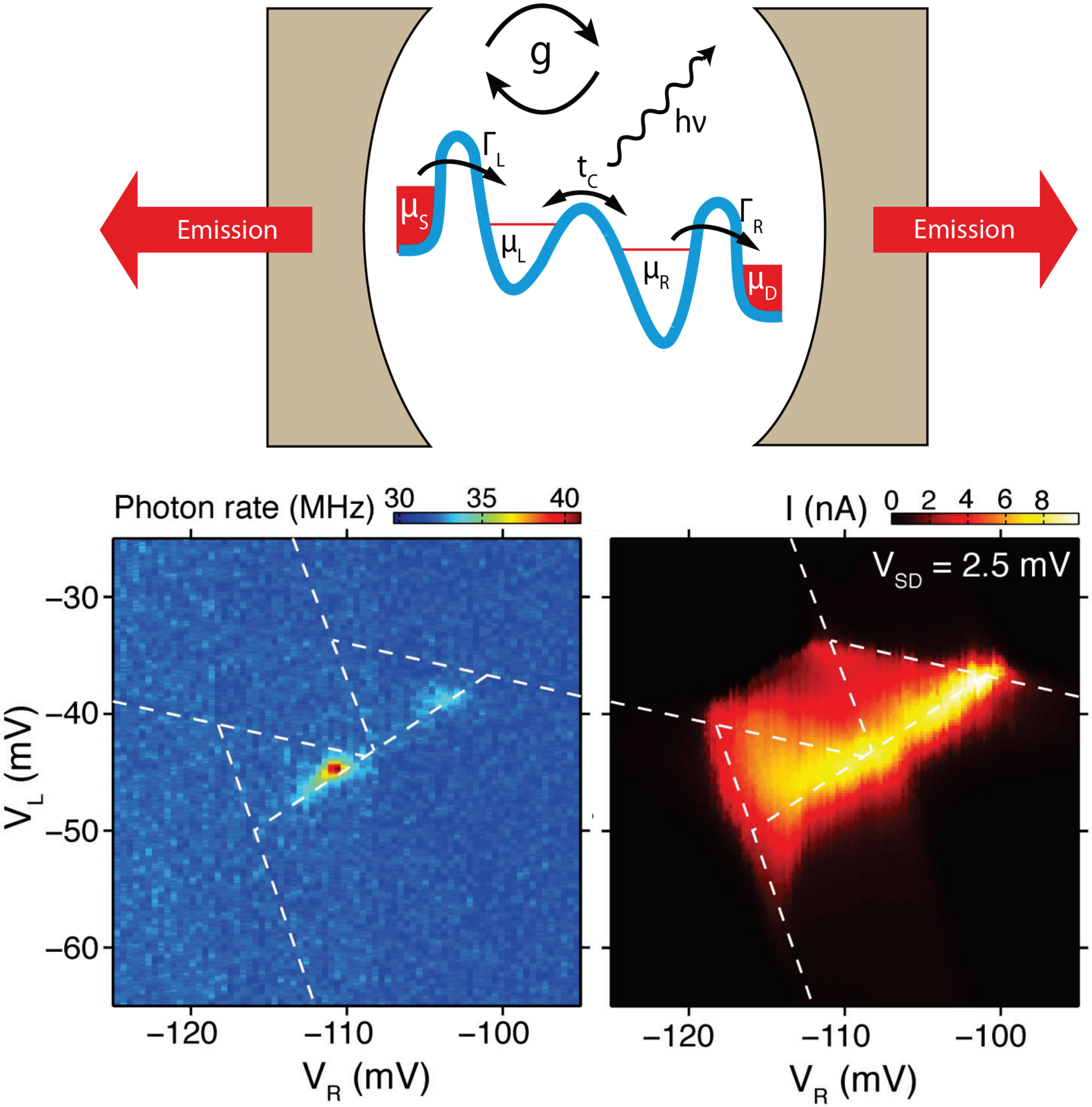


Microwave Amplification

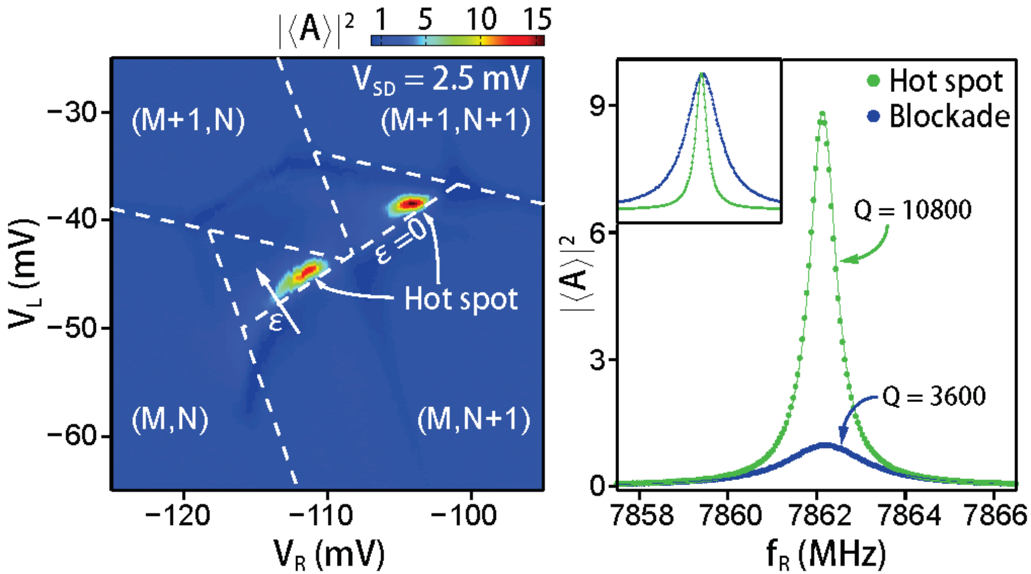


Repumping Mechanism: P.-Q. Jin *et al*., PRB (2011)

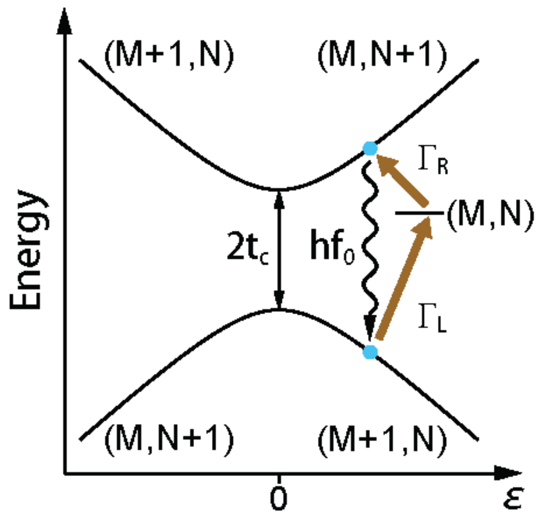
Photon Emission (High Current)



Narrowing of the Cavity Resonance



Y.-Y. Liu, K. D. Petersson, J. Stehlik, J. M. Taylor, J. R. Petta, PRL (2014)
Related work: Viennot *et al.*, PRB (2014); Stockklauser *et al.*, PRL (2015)



Repumping Mechanism: P.-Q. Jin *et al.*, PRB (2011)

Cooperativity Parameter

$$C = \frac{\text{Good Coupling}}{\text{Bad Coupling}} = \frac{g^2}{\kappa\gamma}$$

$g =$ vacuum Rabi frequency ~ 30 MHz

$\kappa =$ cavity decay rate ~ 3 MHz

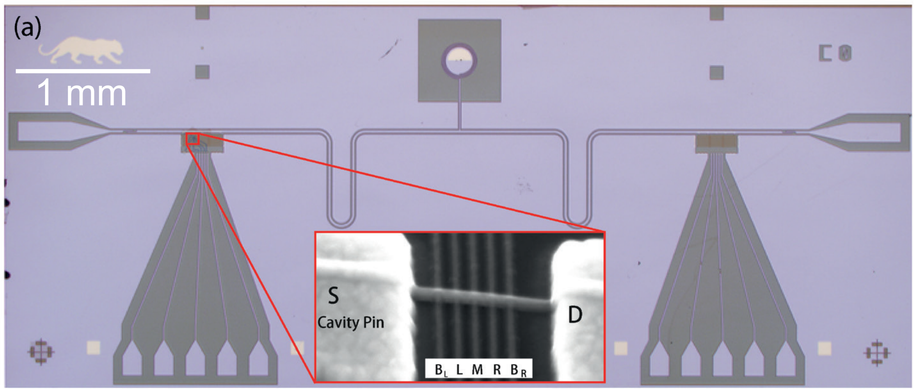
$\gamma =$ qubit decay rate ~ 500 MHz

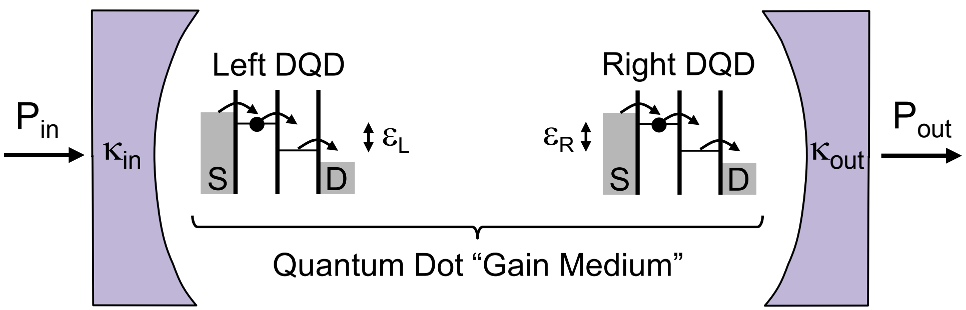
$C \sim 0.6$

"Anything will lase if you hit it hard enough"

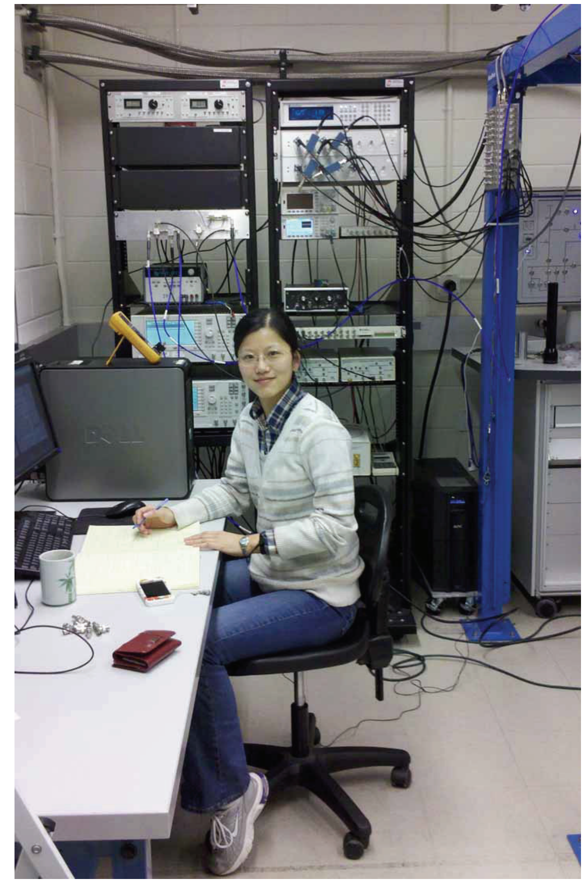
Arthur Schawlow
Nobel Prize in 1981
Photo: Wikipedia

Two Atoms in a Cavity: "Double-Double"



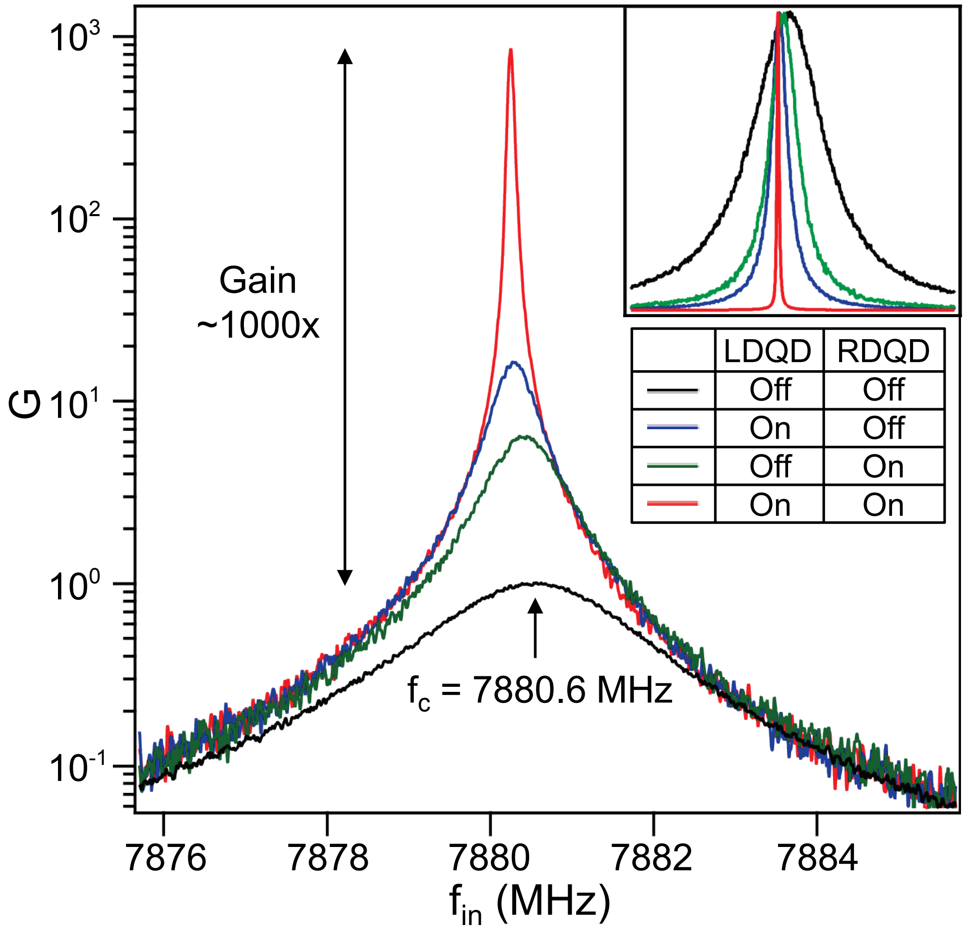


Cavity gain $G = P_{out}/P_{in}$



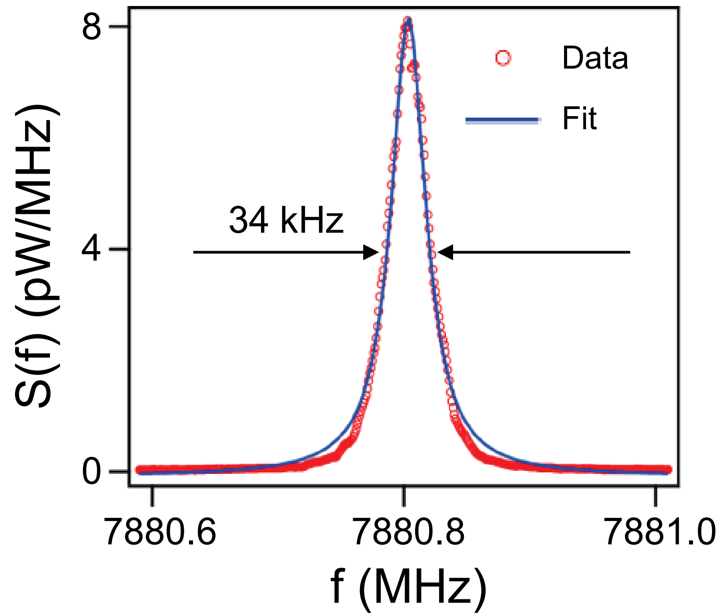
Yinyu Liu

Maser Action?



Gain peak ~100 times narrower than the bare cavity resonance!

Free Running Maser Emission: Temporal Coherence

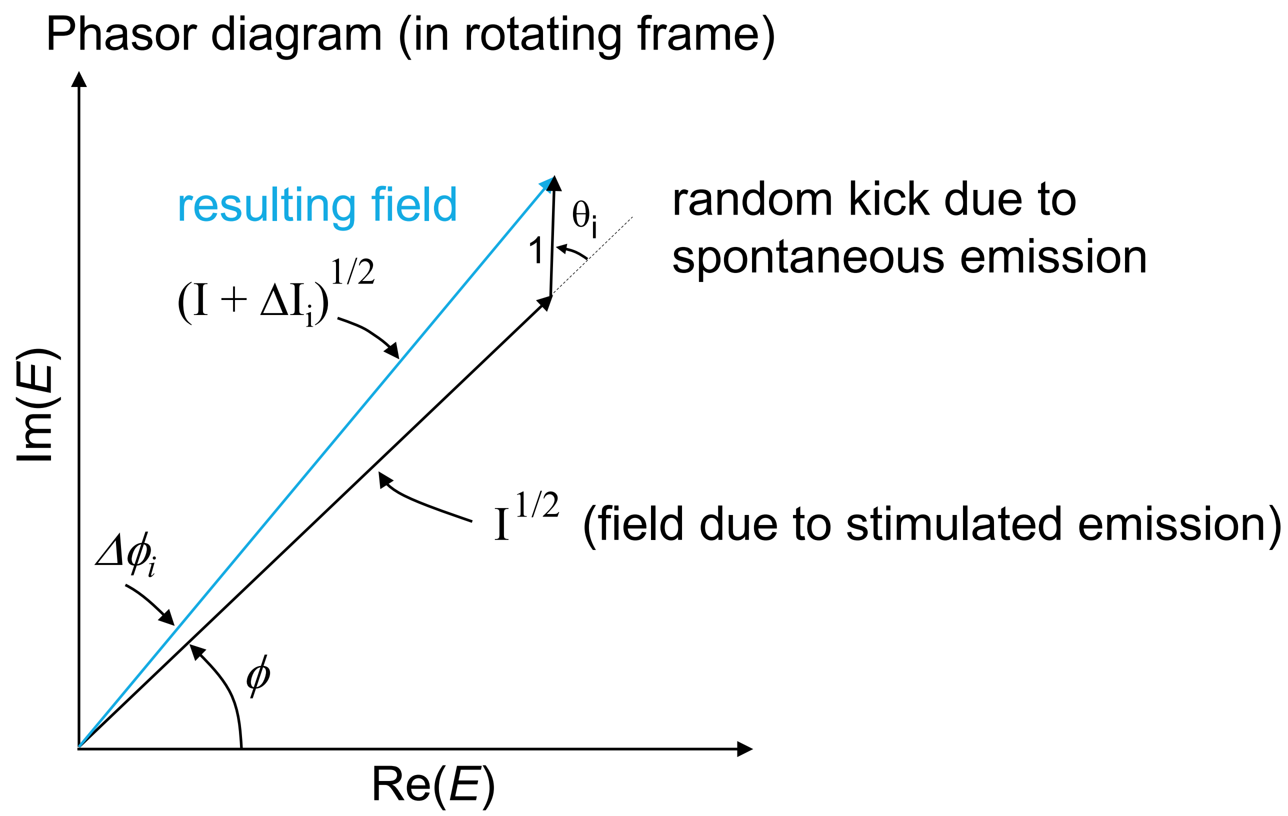


Peak full-width at half-maximum Δ_f = 34 kHz

Coherence time $\tau_{coh} = 1/(\pi \, \Delta_f) = 9.4\ \mu s$

Coherence length $l_{coh} = c\ \tau_{coh} = 2.8$ km

Comparison with the Schawlow-Townes Limit

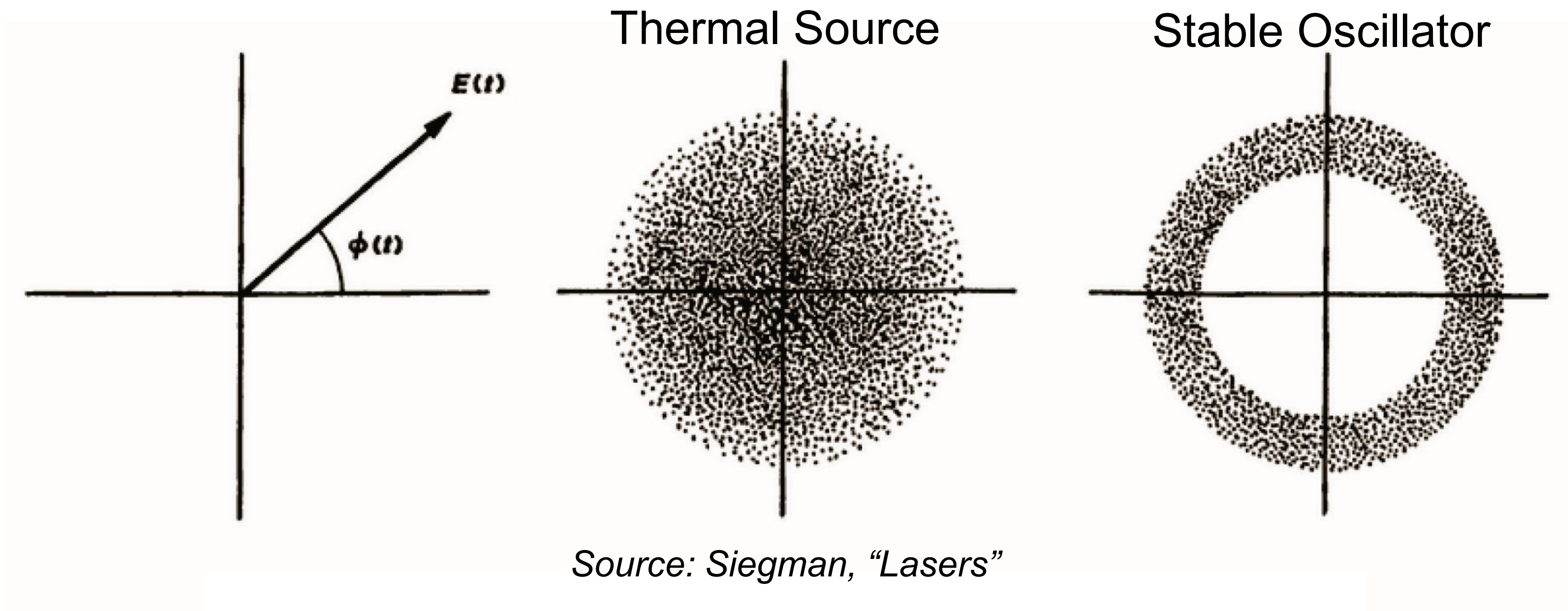


Schawlow-Townes linewidth prediction $\Delta_f = \frac{\pi h f_c \left(\frac{\kappa}{2\pi}\right)^2}{P_{tot}} = 0.4$ kHz

Measured linewidth $\Delta_f = 34$ kHz

Schawlow and Townes, Phys. Rev. **112**, 1940 (1958)
Henry, IEEE Quant. Elec. **18**, 259 (1982)

Statistics of the Emitted Radiation

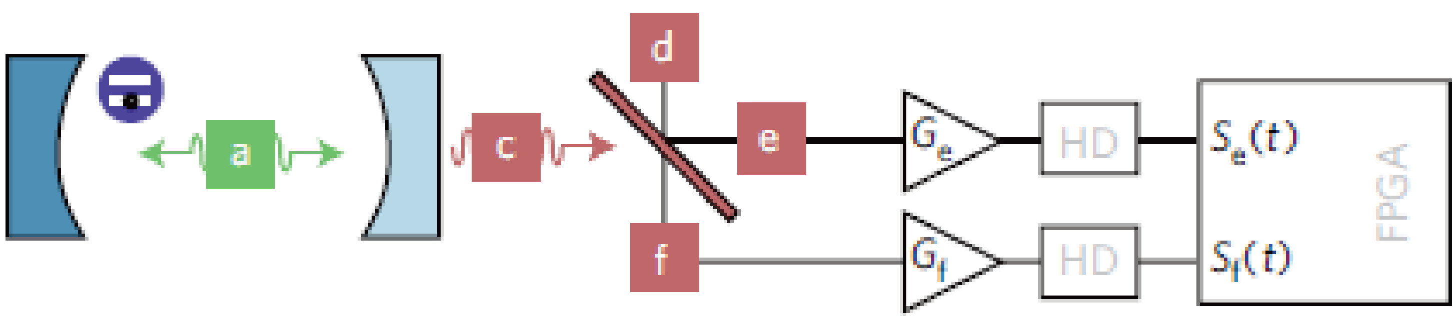


Source: Siegman, "Lasers"

<u>Experimental Challenges</u>

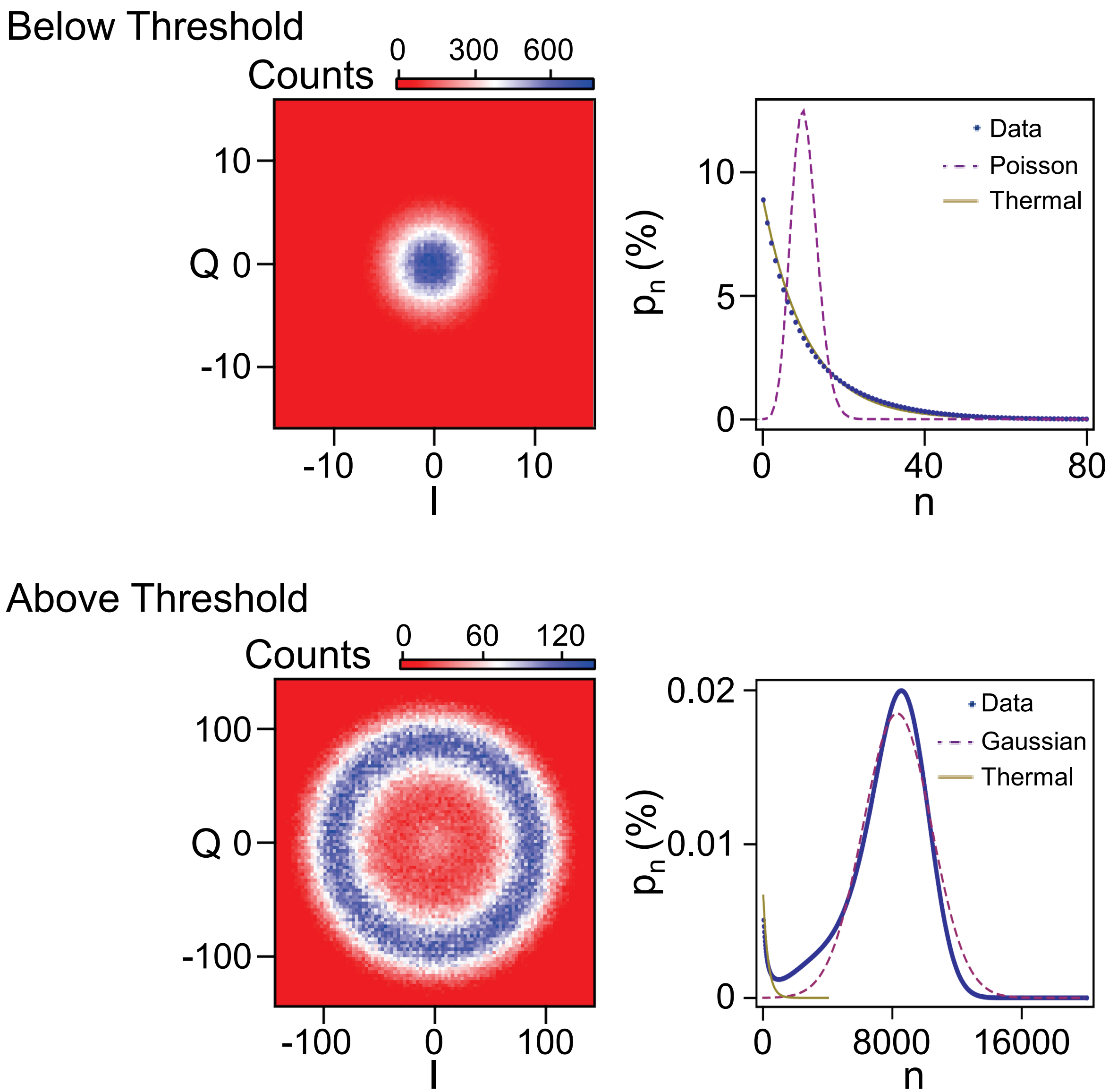
Optical photon energy $E = h\nu \sim 2$ eV >> $k_B T$ (use "off the shelf" detectors)

Microwave photon energy $E = h\nu = 30$ μeV << $k_B T$ (no "off the shelf" detectors)

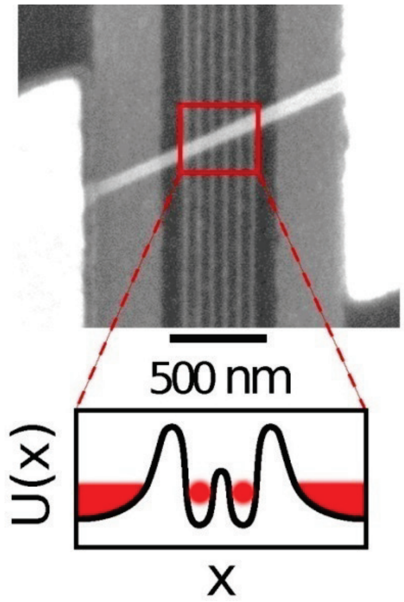


Leading effort by the Wallraff Group: Bozyigit *et al.*, Nature (2011)

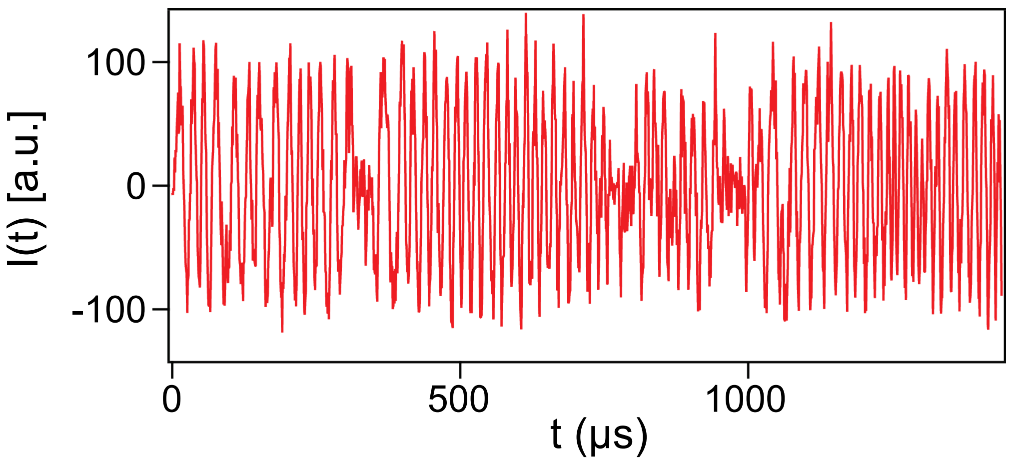
Statistics of the Emitted Radiation



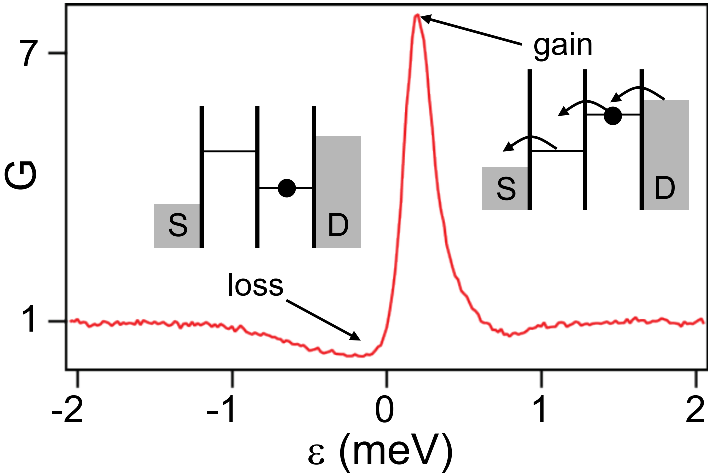
Other Characteristics of the Double Dot Micromaser



- charge noise
- phonons (lattice vibrations)

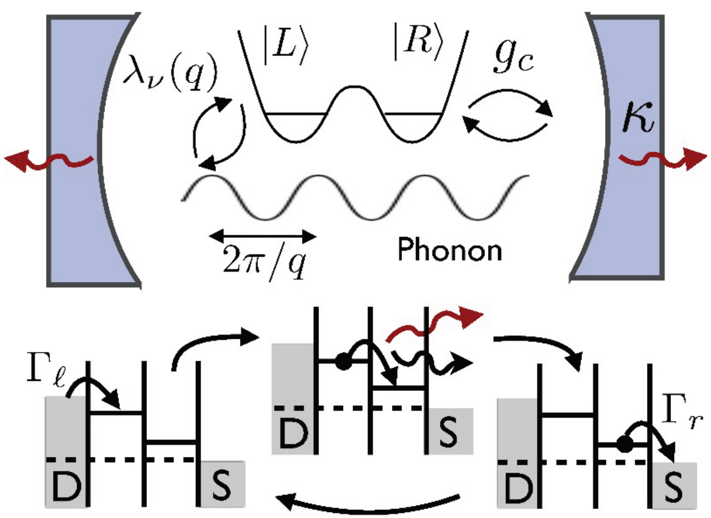


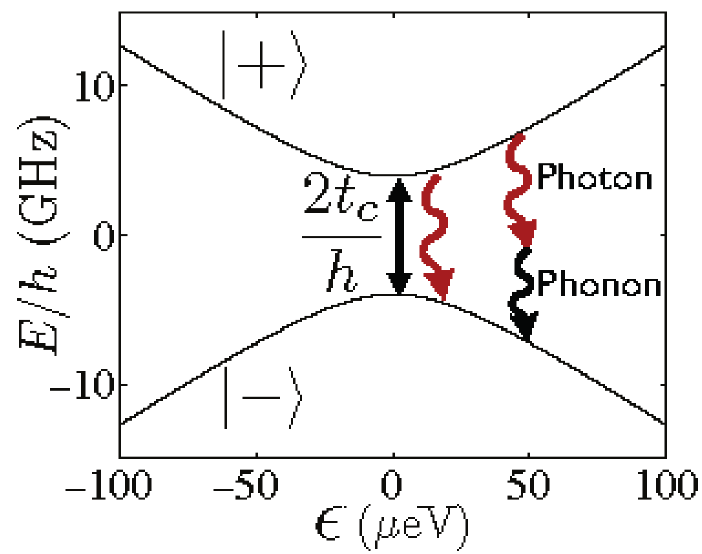
Electric-Dipole + Electron-Phonon Interaction



Gain feature is very broad
100 μeV ~ 25 GHz

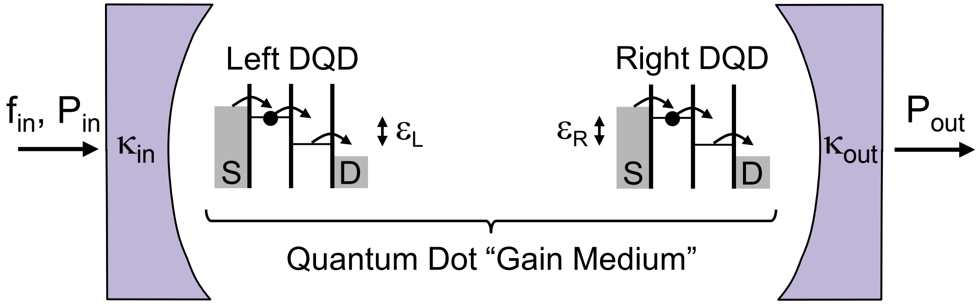
Liu *et al.*, Science (2015)





Theory: Gullans *et al.*, PRL (2015)
Related work: Brandes, Phys. Rep. (2005); Kulkarni *et al.*, PRB (2014)

Injection Locking



Liu *et al.*, PRA (2015)

<u>Adler equations:</u>

$$\frac{d\phi}{dt} + 2\pi(f_{in} - f_e) = -\pi\Delta f_{in} \sin\phi$$

$$\Delta f_{in} \propto \sqrt{P_{in}/P_e}$$

P_e = free running emission power

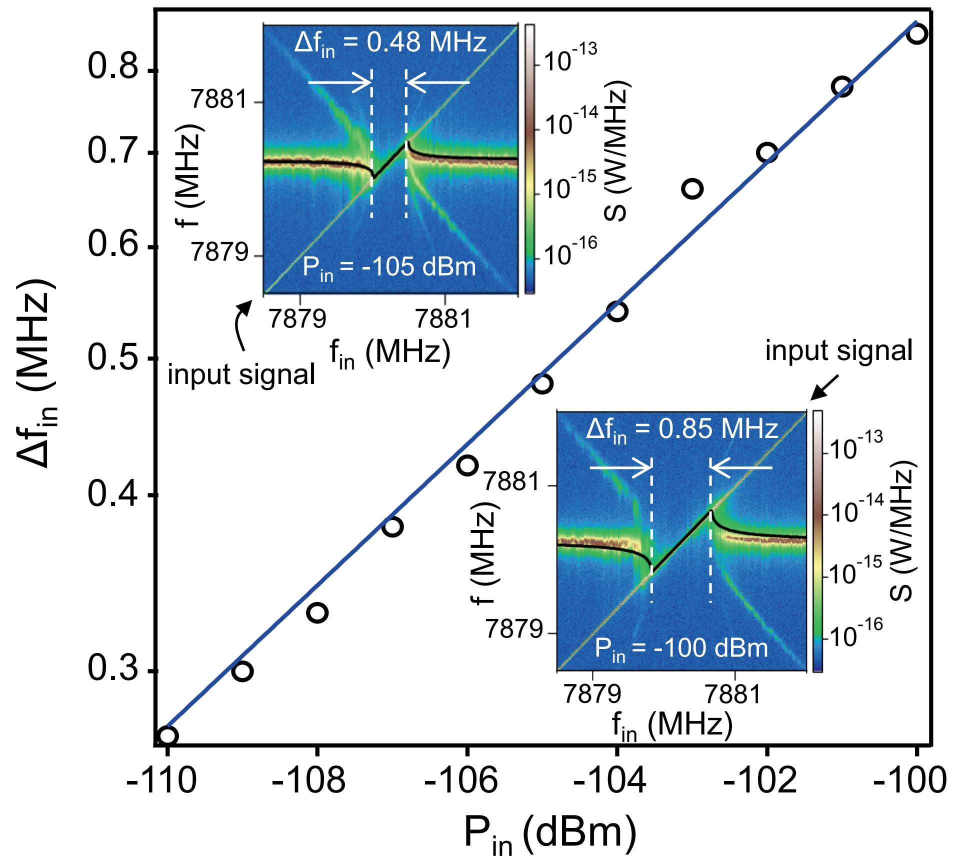
f_e = free running emission frequency

P_{in} = input power

f_{in} = input frequency

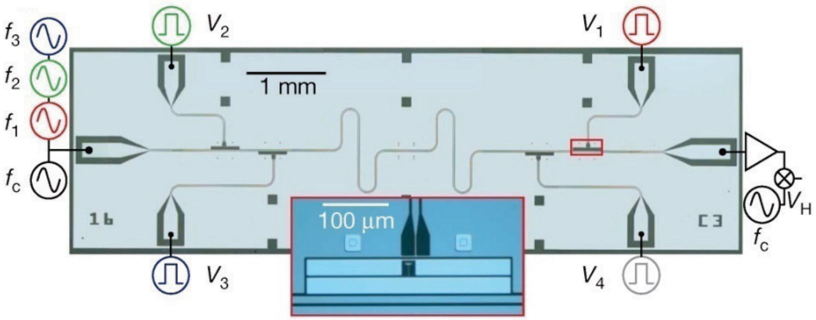
$\phi = \phi_{out} - \phi_{in}$

Adler, Proc. IRE **34**, 351 (1946)

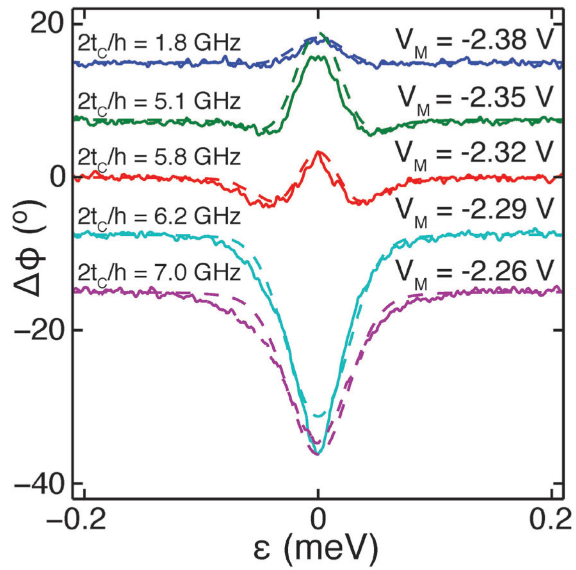


Summary

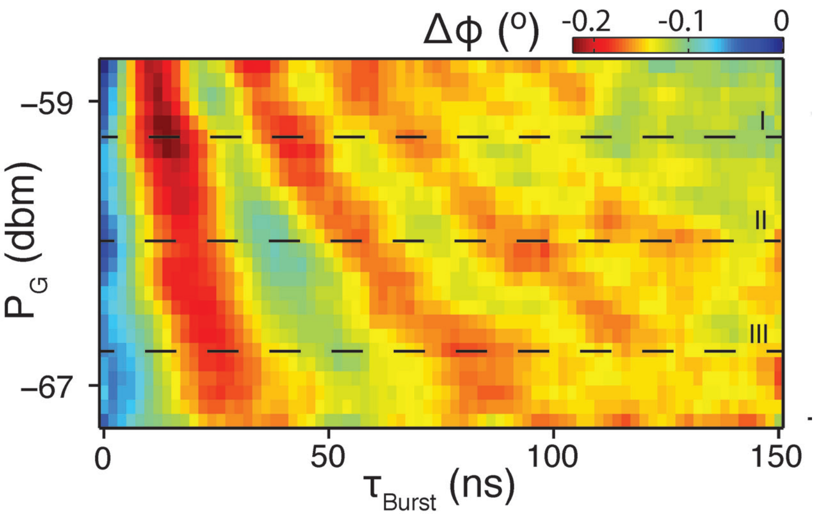
Circuit QED



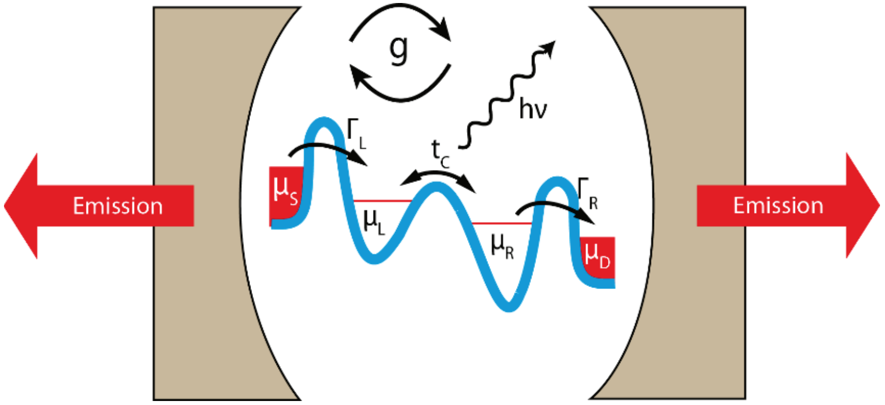
Charge-Cavity Coupling



Towards Spin-Cavity Coupling



Quantum Dot Maser



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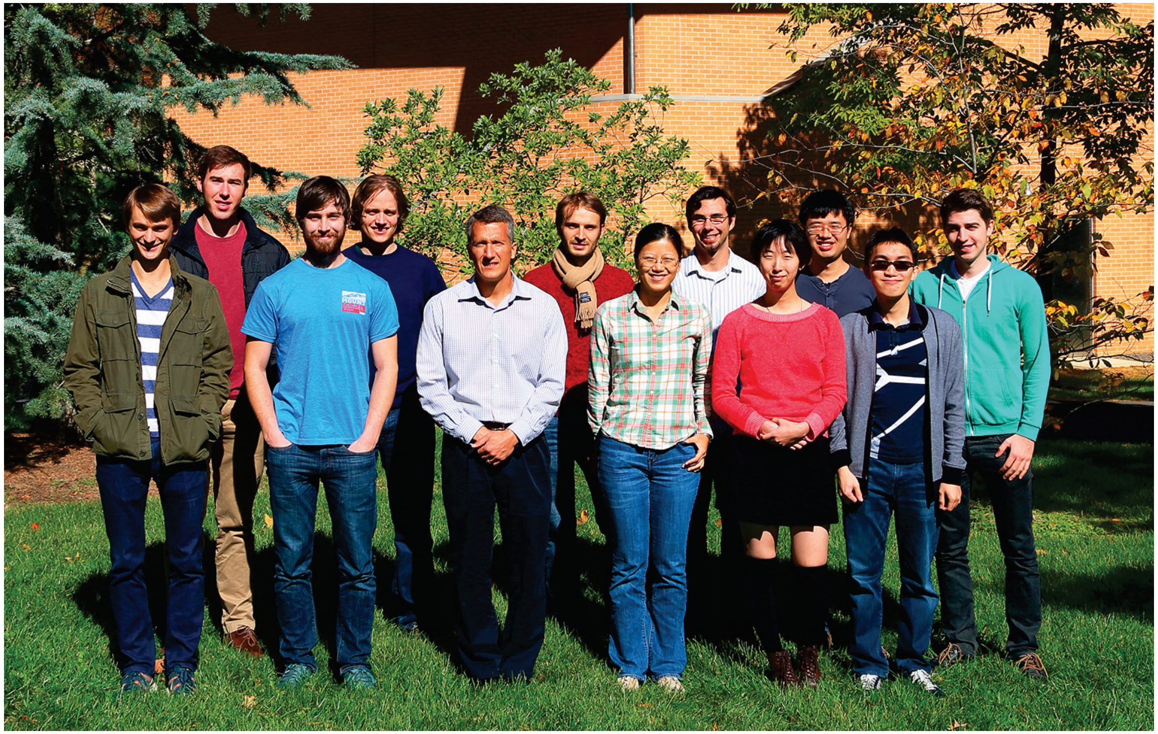

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