Hybrid Systems for Quantum Information

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A nascent collaboration with the Gisin group at University of Geneva:

Nicolas Sangouard, Mikael Afzelius

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Hybrid Quantum Network

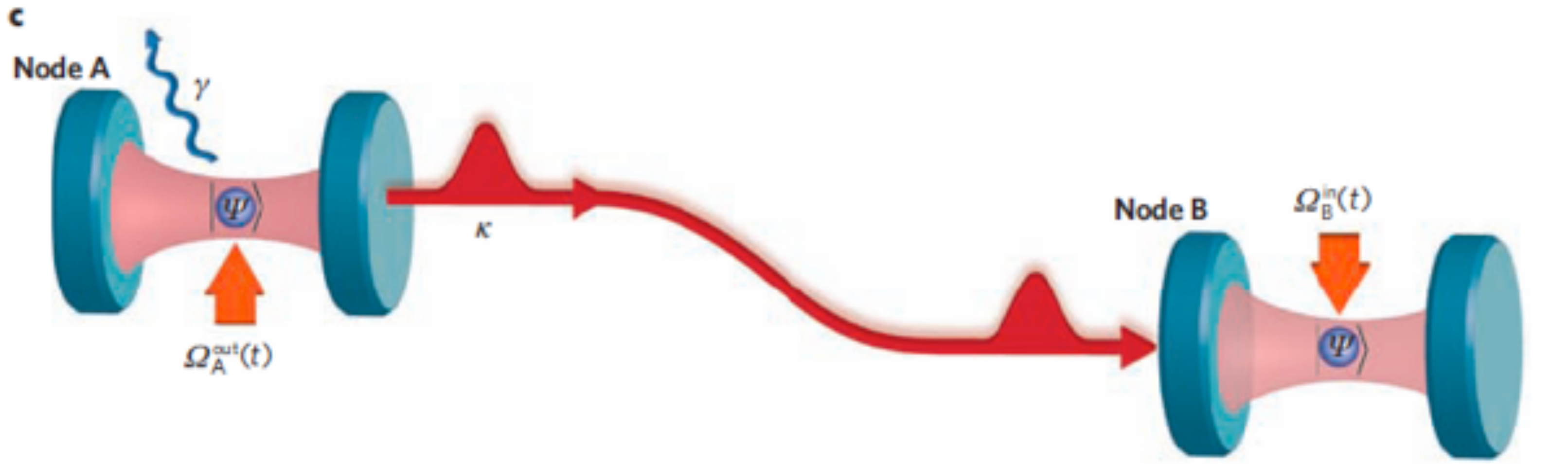

Fig: Kimble, Nature (2008)

- Telecom photons to distribute quantum information
- Superconducting circuits to process at nodes

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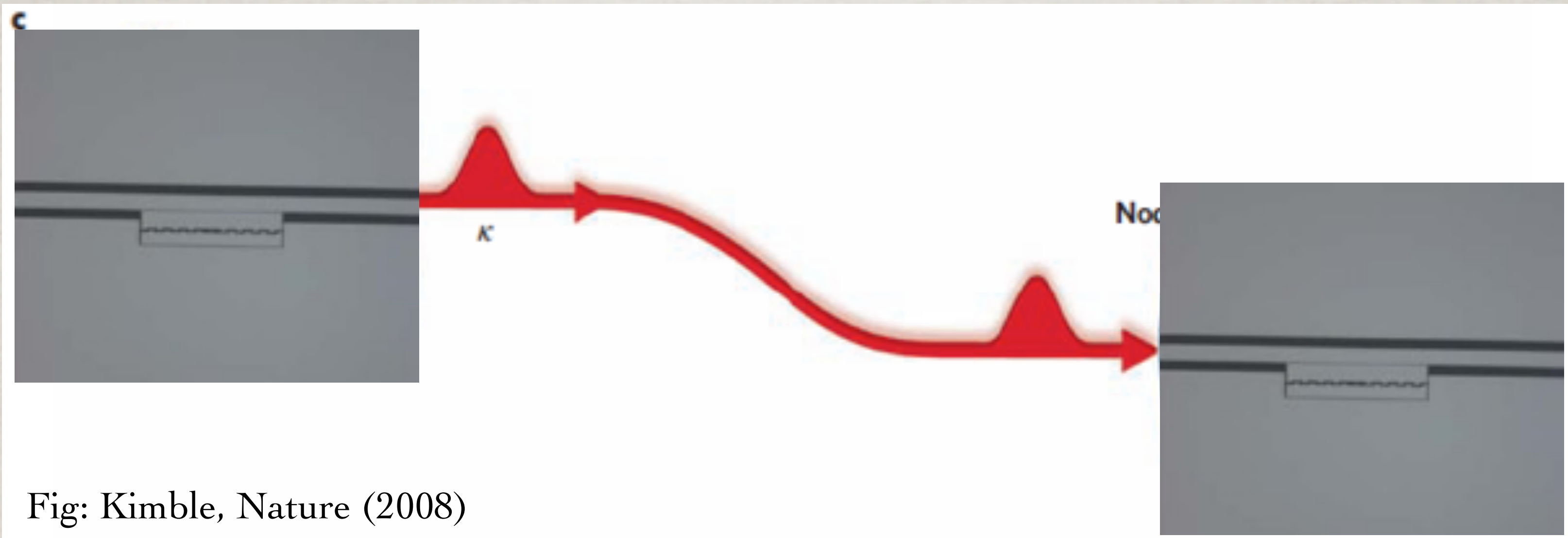
Hybrid Quantum Network



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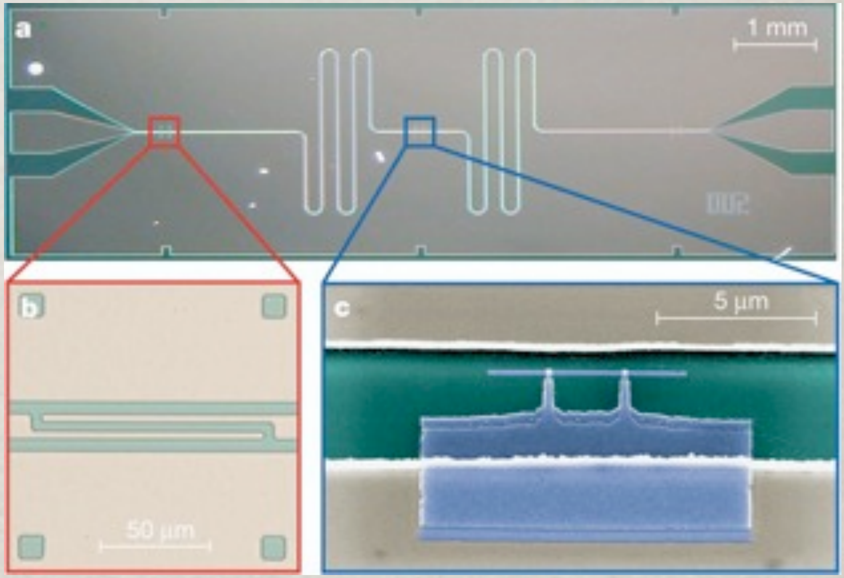
- Telecom photons to distribute quantum information
- Superconducting circuits to process at nodes

Quantum Circuits and Artificial Atoms

Circuit quantum electrodynamics

Atoms ⇒ Qubits
3D Cavity ⇒ 1D on-chip resonator

- In 2004, Wallraff et. al. introduced circuit QED
- Coupling strengths not accessible in cavity QED are possible.
- "Atoms" can be engineered.



Wallraff *et. al.* Nature, 2004.

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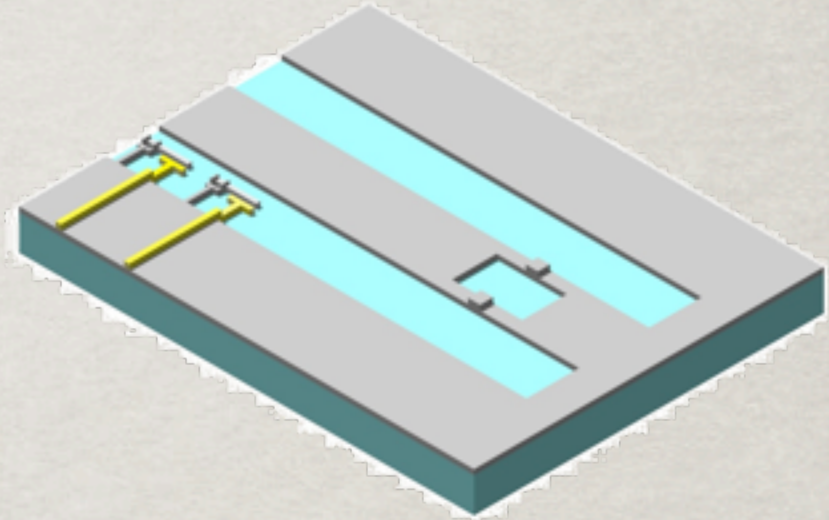
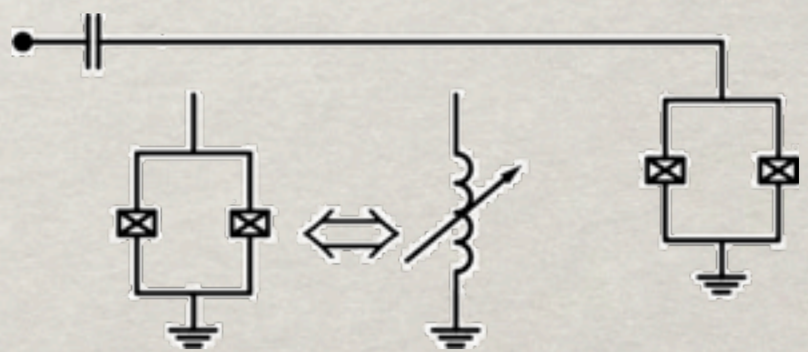
Circuit quantum electrodynamics

- Vacuum Rabi splitting. Wallraff, Nature, 2004.
- Photon number distribution. Schuster, Nature, 2007.
- Entanglement between two qubits. Majer, Nature, 2007.
- Resolving Vacuum fluctuations. Fragner, Science, 2008.
- Generation and resolving of number states. Hoffheinz, Nature, 2008,2009.
- Simple quantum algorithms. DiCarlo Nature, 2009.
- And more…

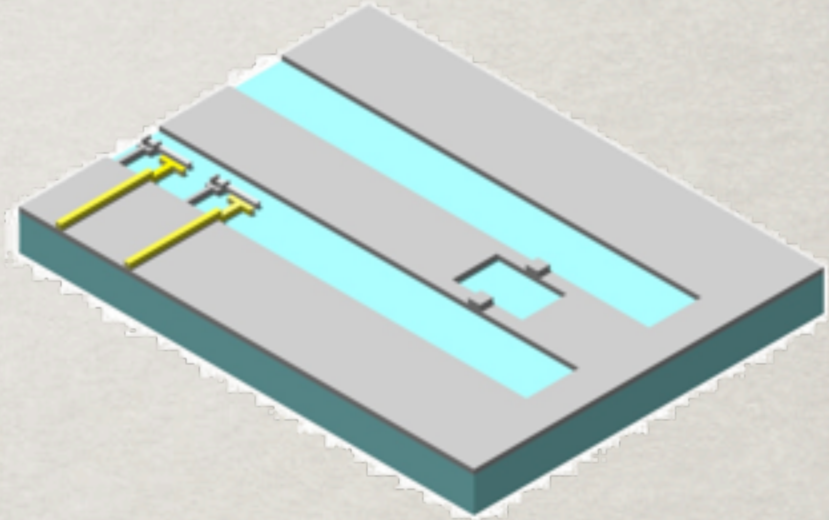
Tunable transmission line resonator



- Transmission line terminated in a tunable impedance.
- Tunable impedance: the Josephson inductance of a SQUID.
- M. Wallquist et al. constructed a control-phase gate protocol



Tunable transmission line resonator



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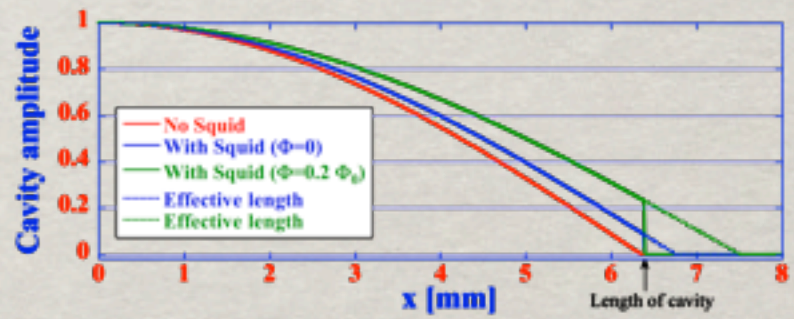

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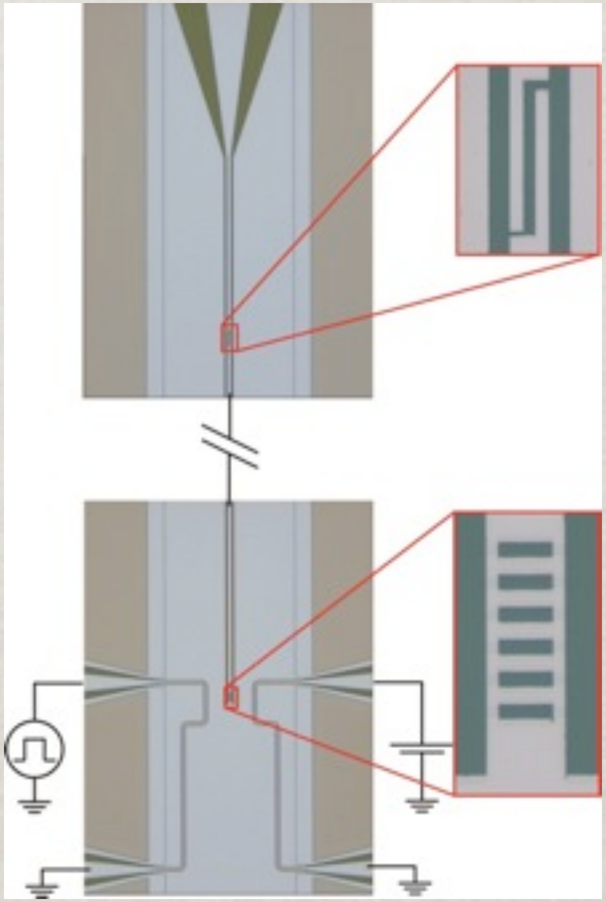
Device fabrication

Transmission line and SQUID fabricated in Al. Tunnel junctions fabricated from native Al_2O_3.

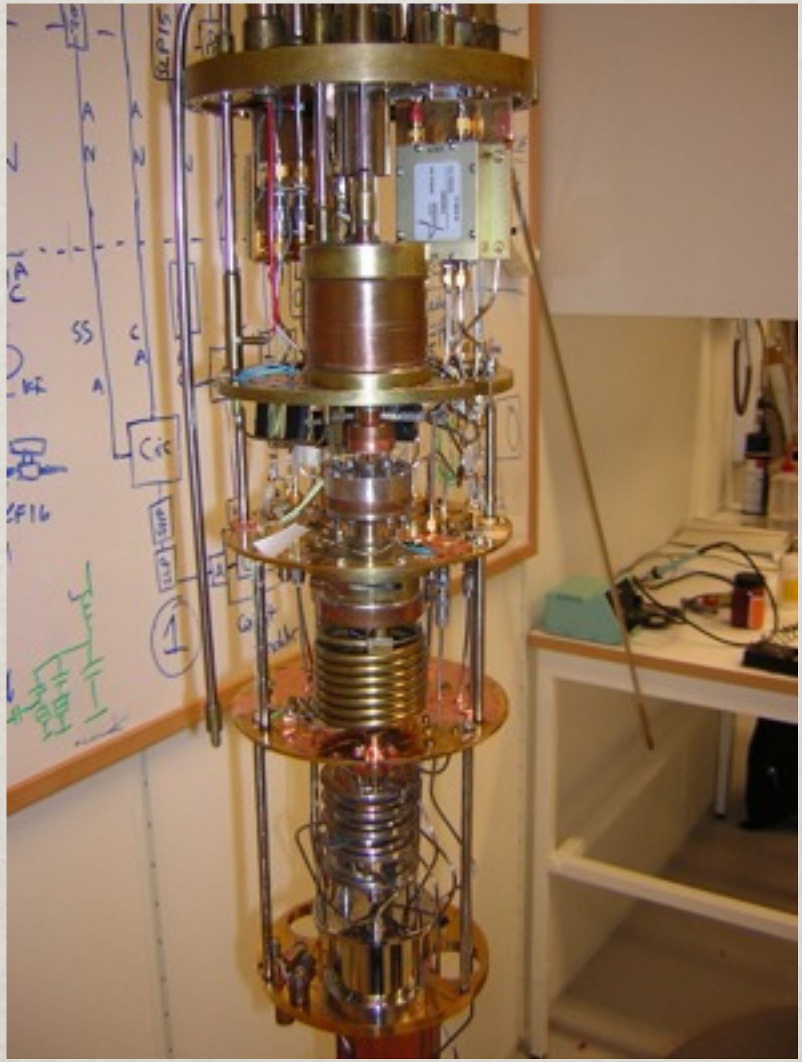


Coupling capacitance

Array of SQUIDs

On-chip tuning lines for fast tuning

Dilution Fridge



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Dilution Fridge

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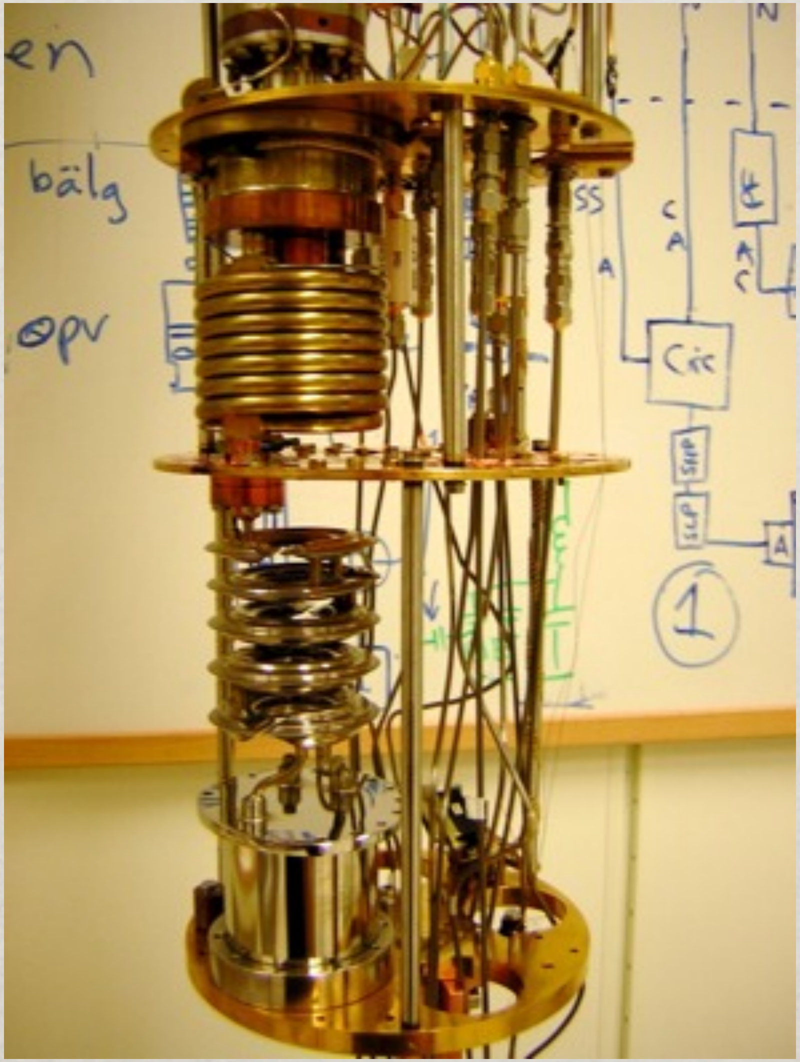

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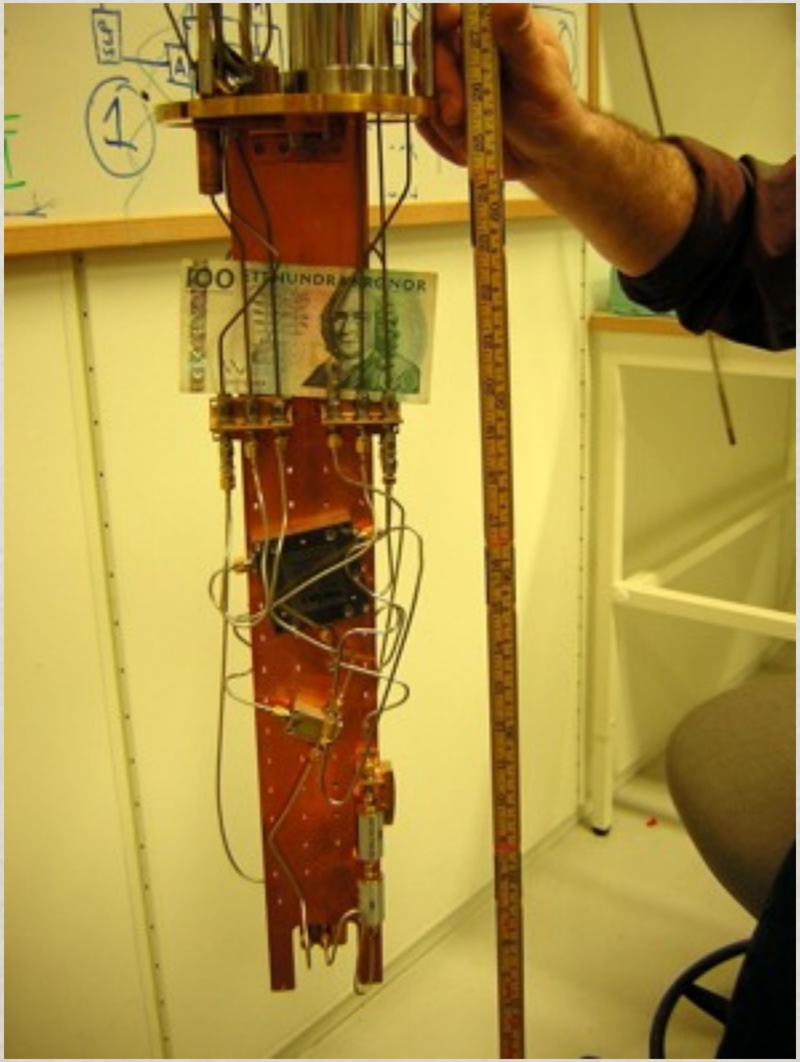

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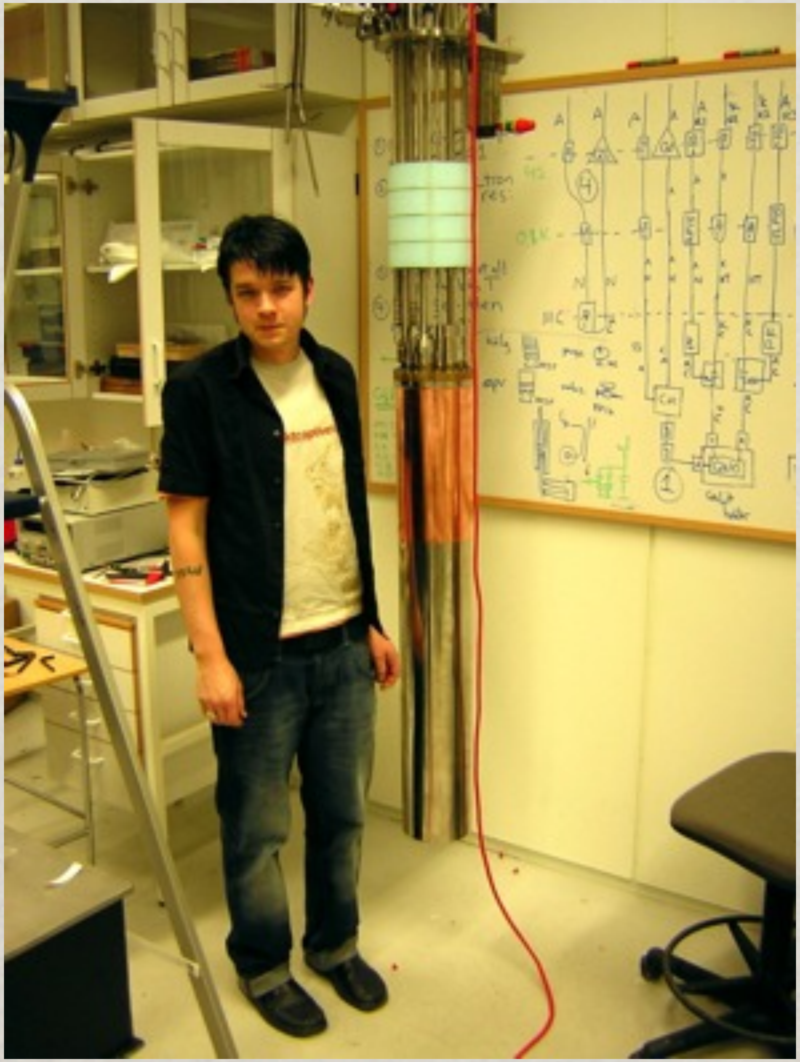

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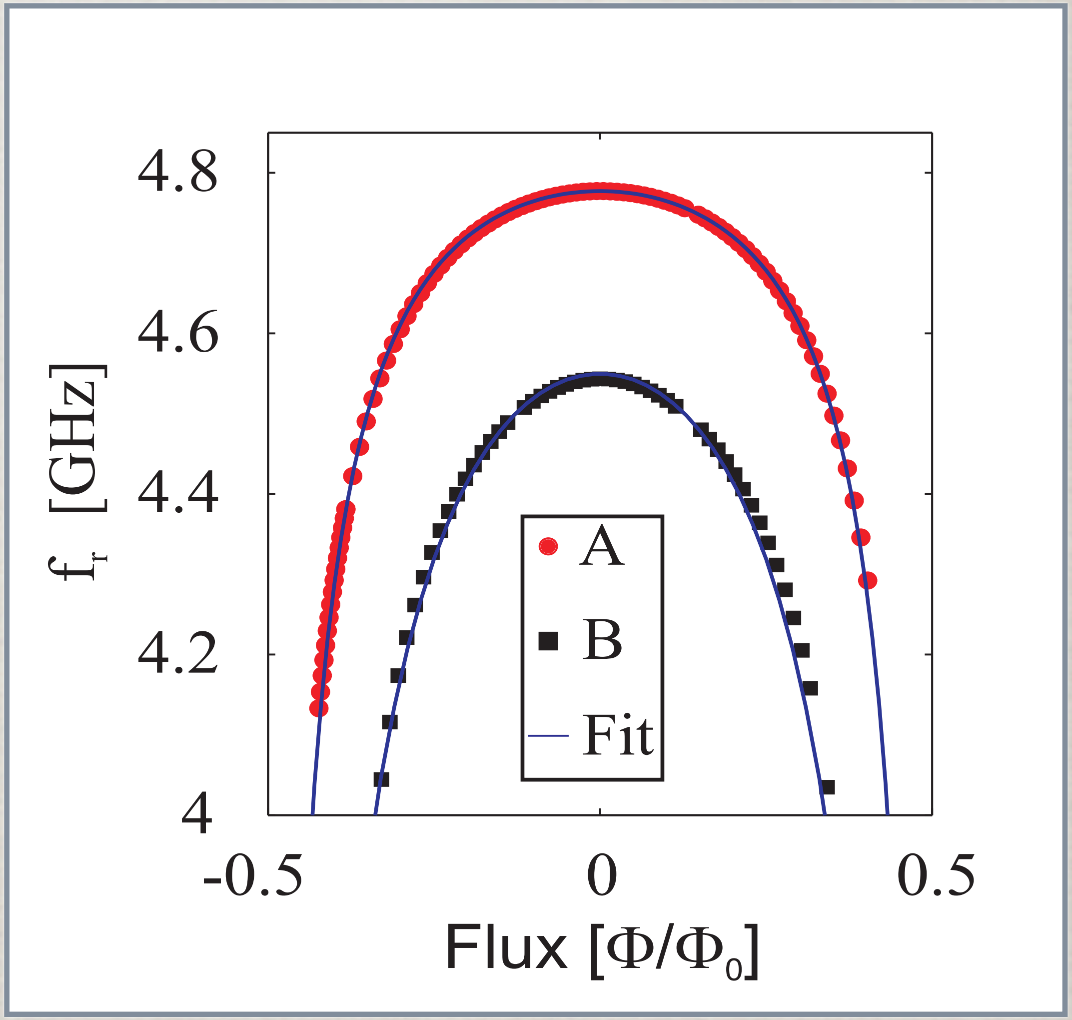
Tunability

- Frequency tuning explained well by Josephson ind.

$$f(\Phi) = \frac{f_0}{1 + \frac{L_s(\Phi)}{Ll}}$$

Sandberg, et al. *APL*, **92** (2008)

Yamamoto, et al. *APL*, **93** (2008)



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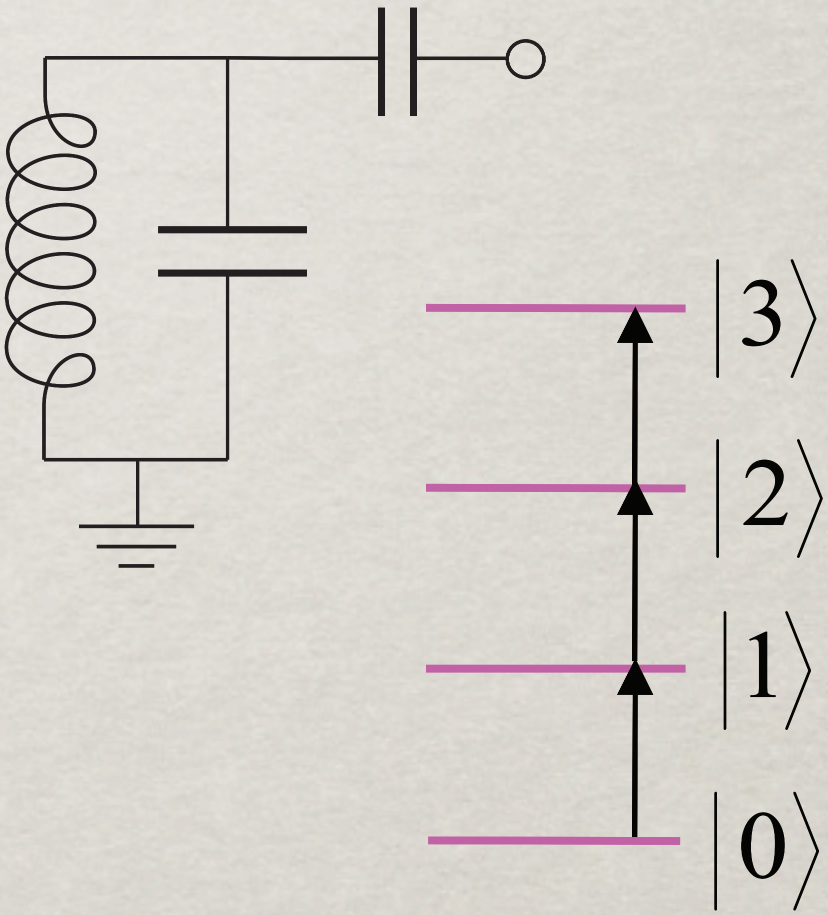
Artificial Atoms

- Quantized electrical circuit
- Harmonic oscillator is not a qubit
- Nonlinearity makes the circuit anharmonic and addressable
- Small JJ is a good nonlinear inductor



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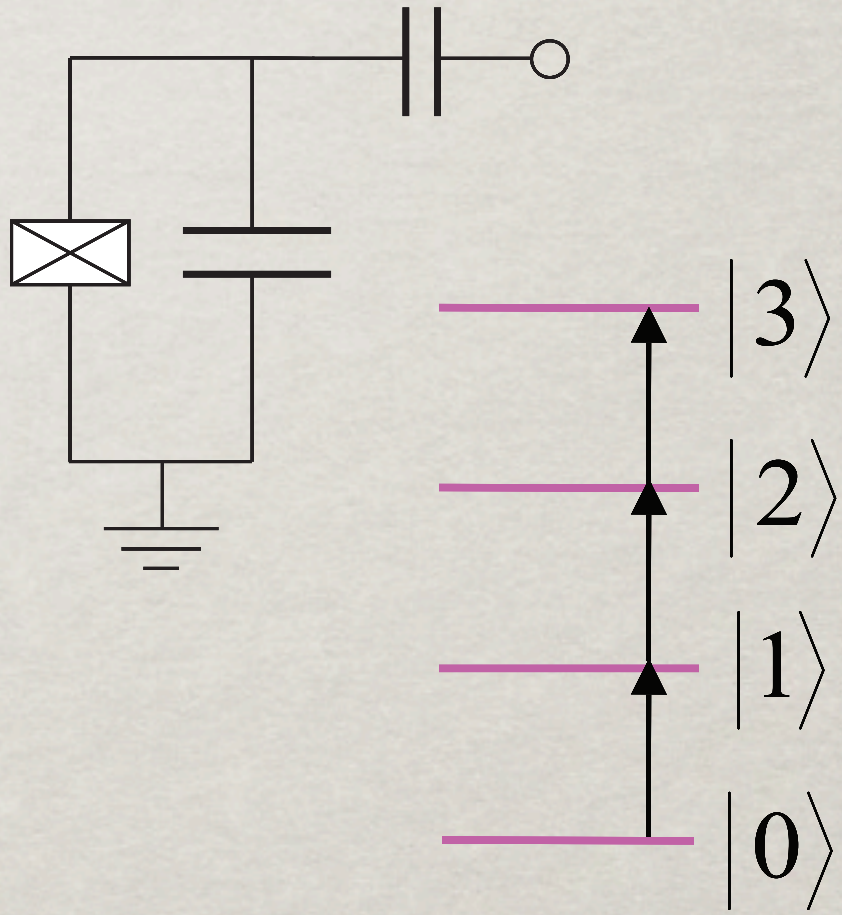

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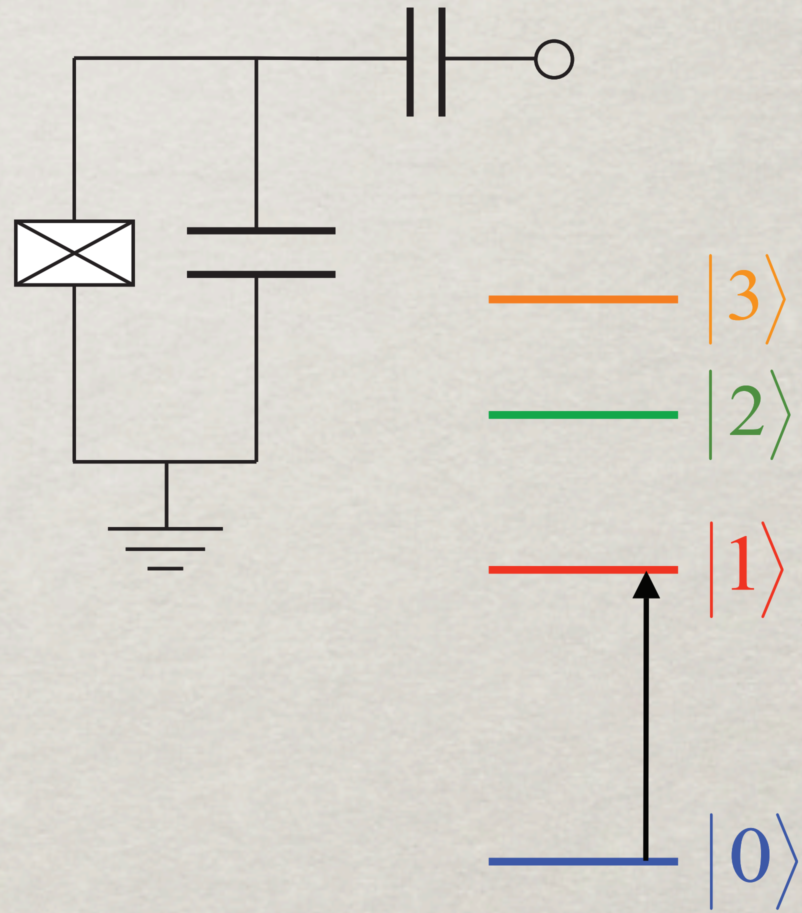
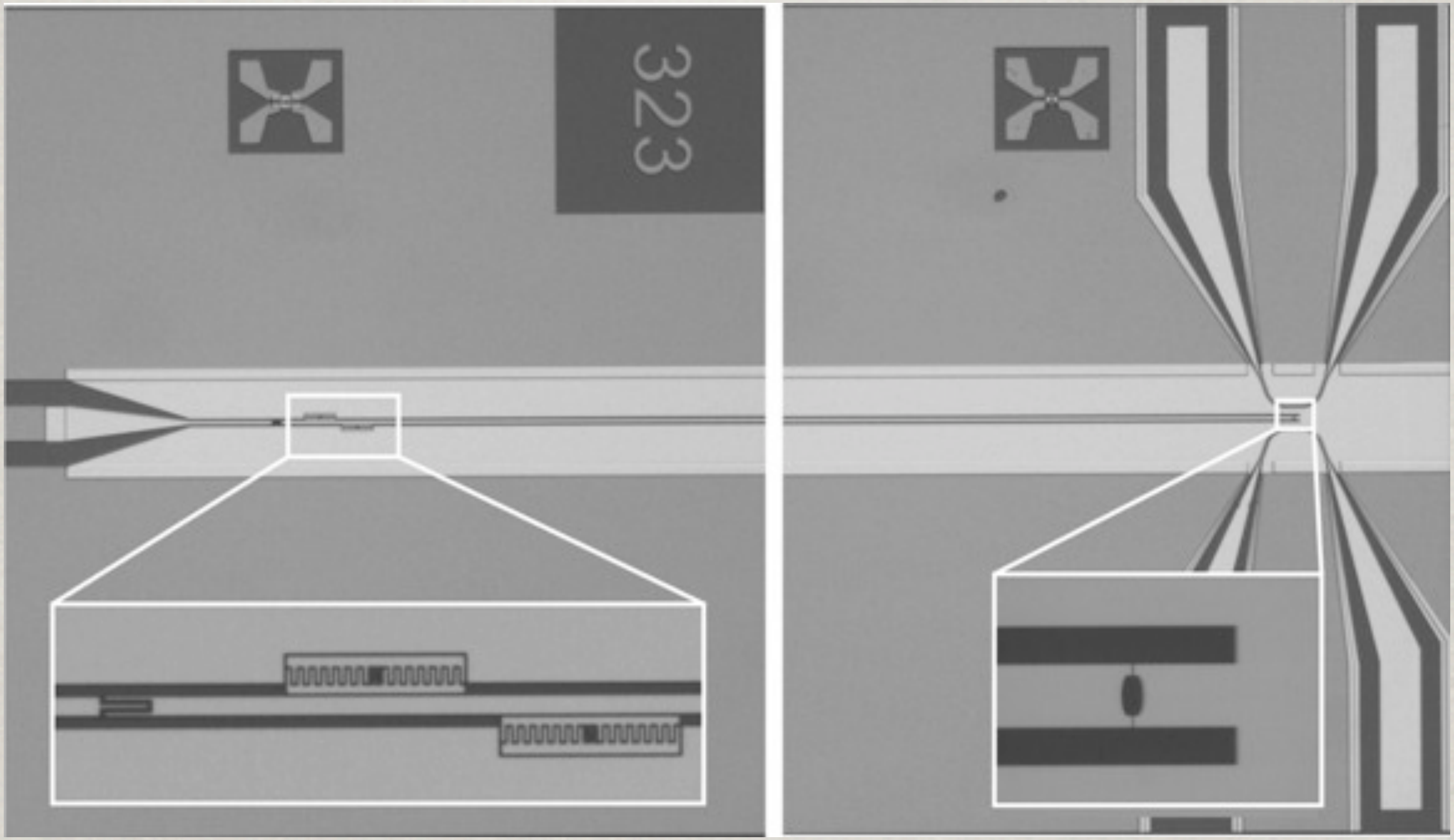
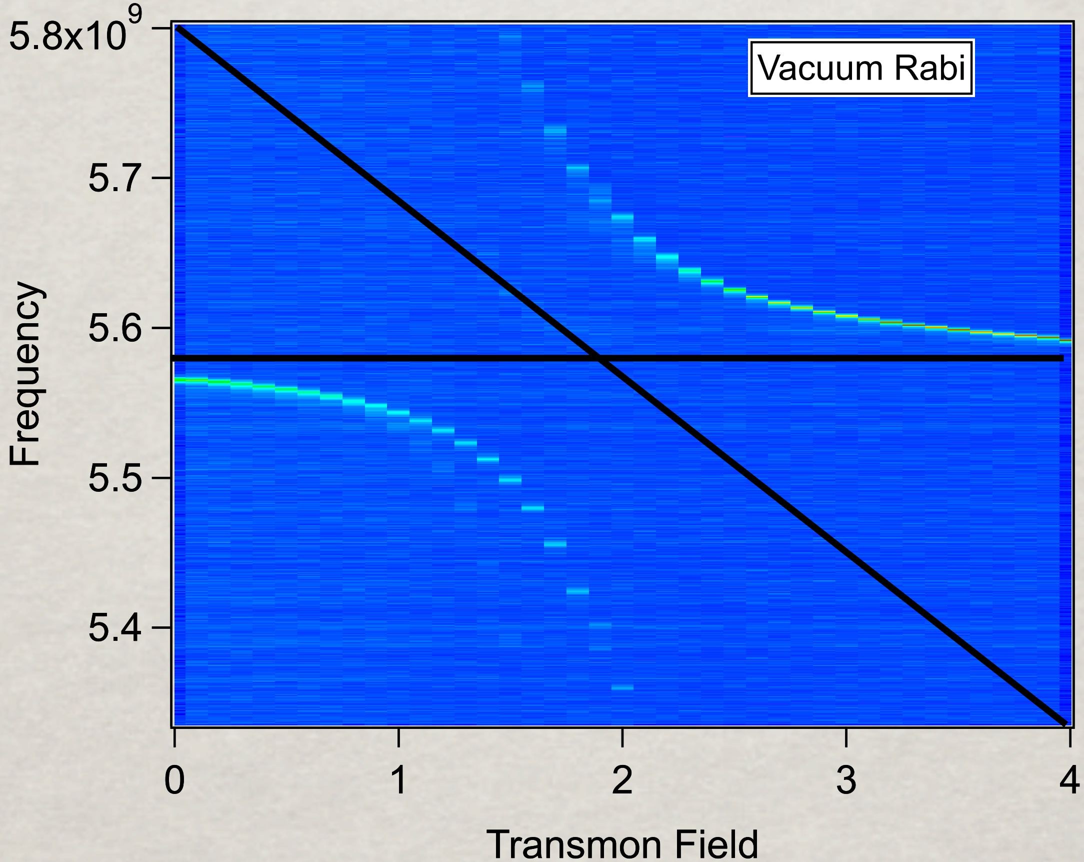


Circuit QED



Wallraff et al, Nature **431** (2004) (and many more)
Chiorescu et al, Nature **431** (2004)

Circuit QED



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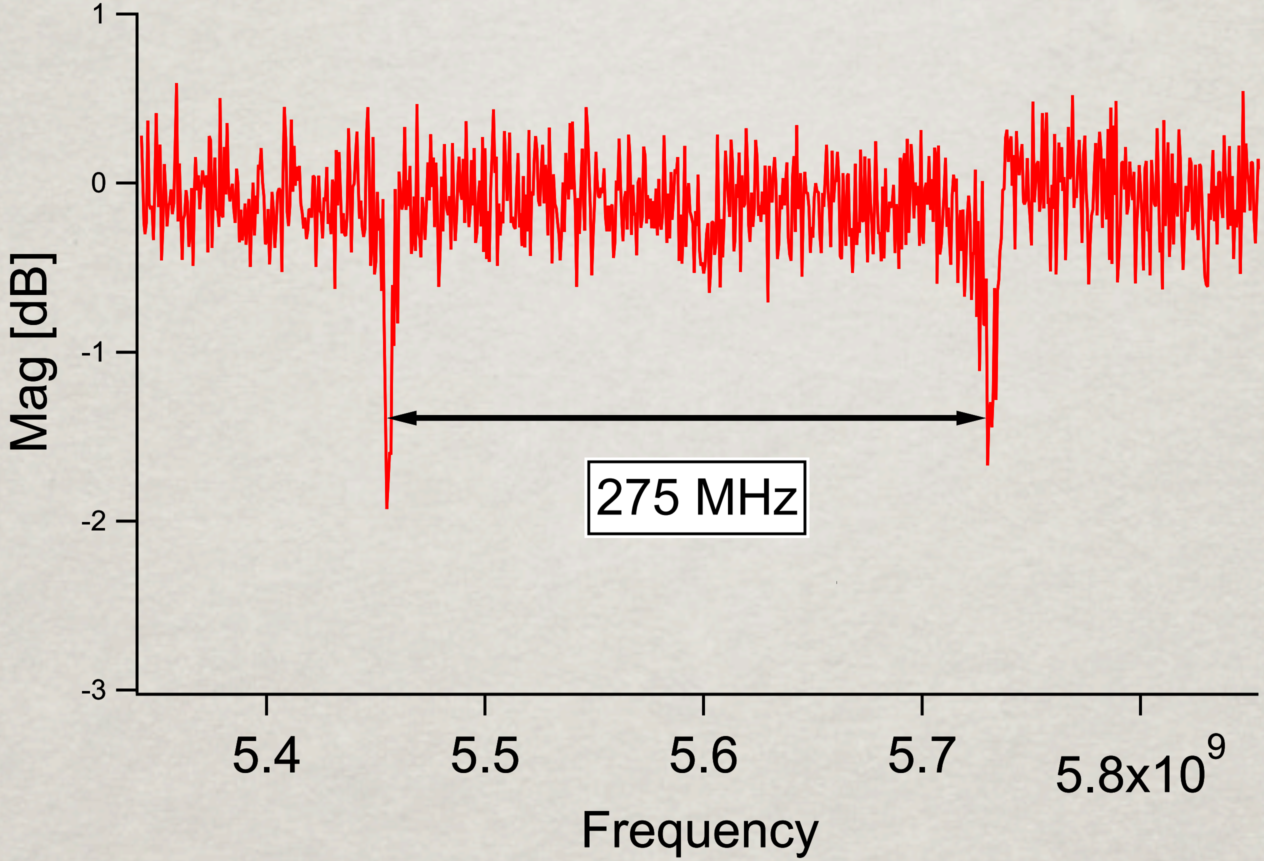

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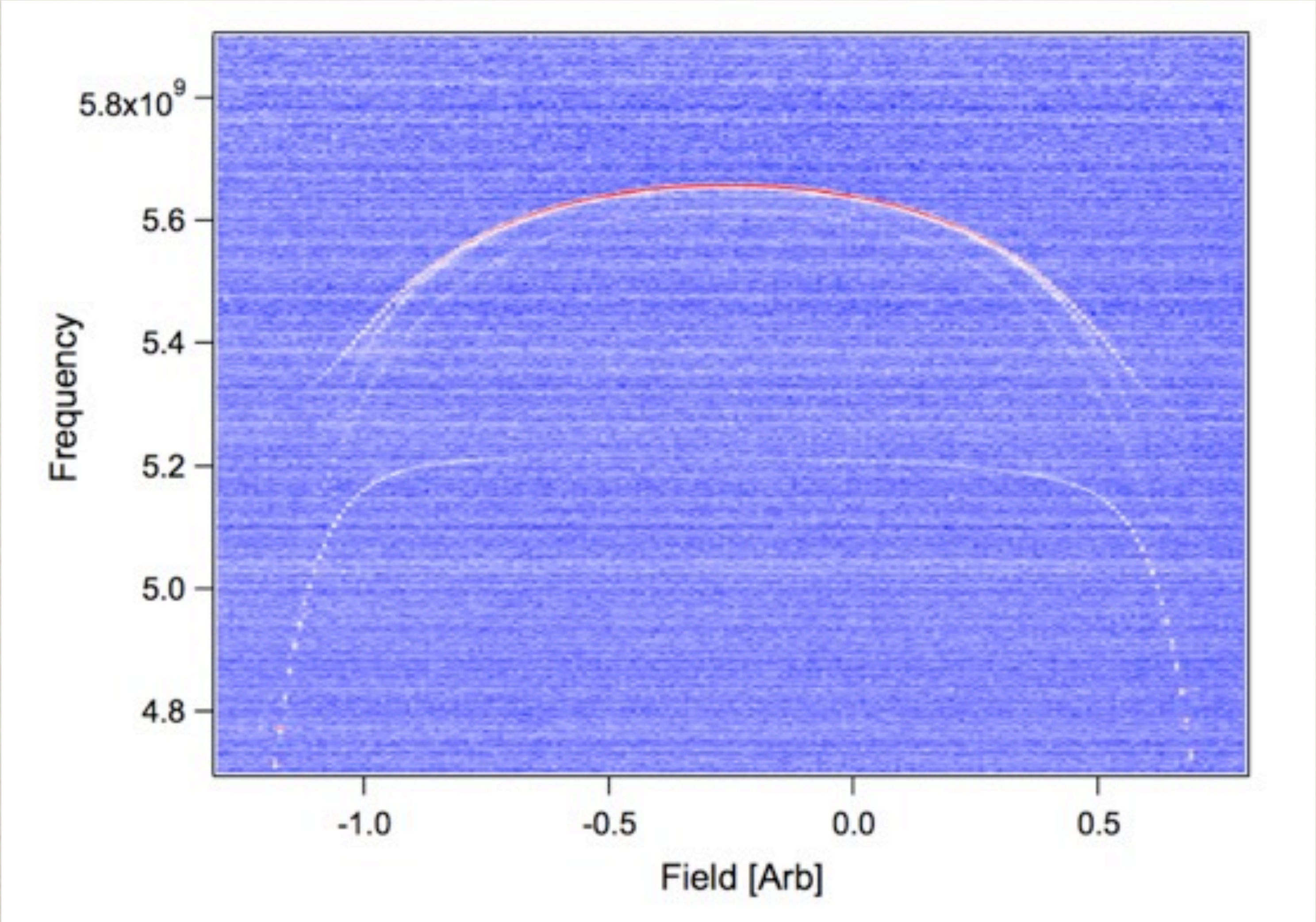
Vacuum Rabi

- Tuning the resonator



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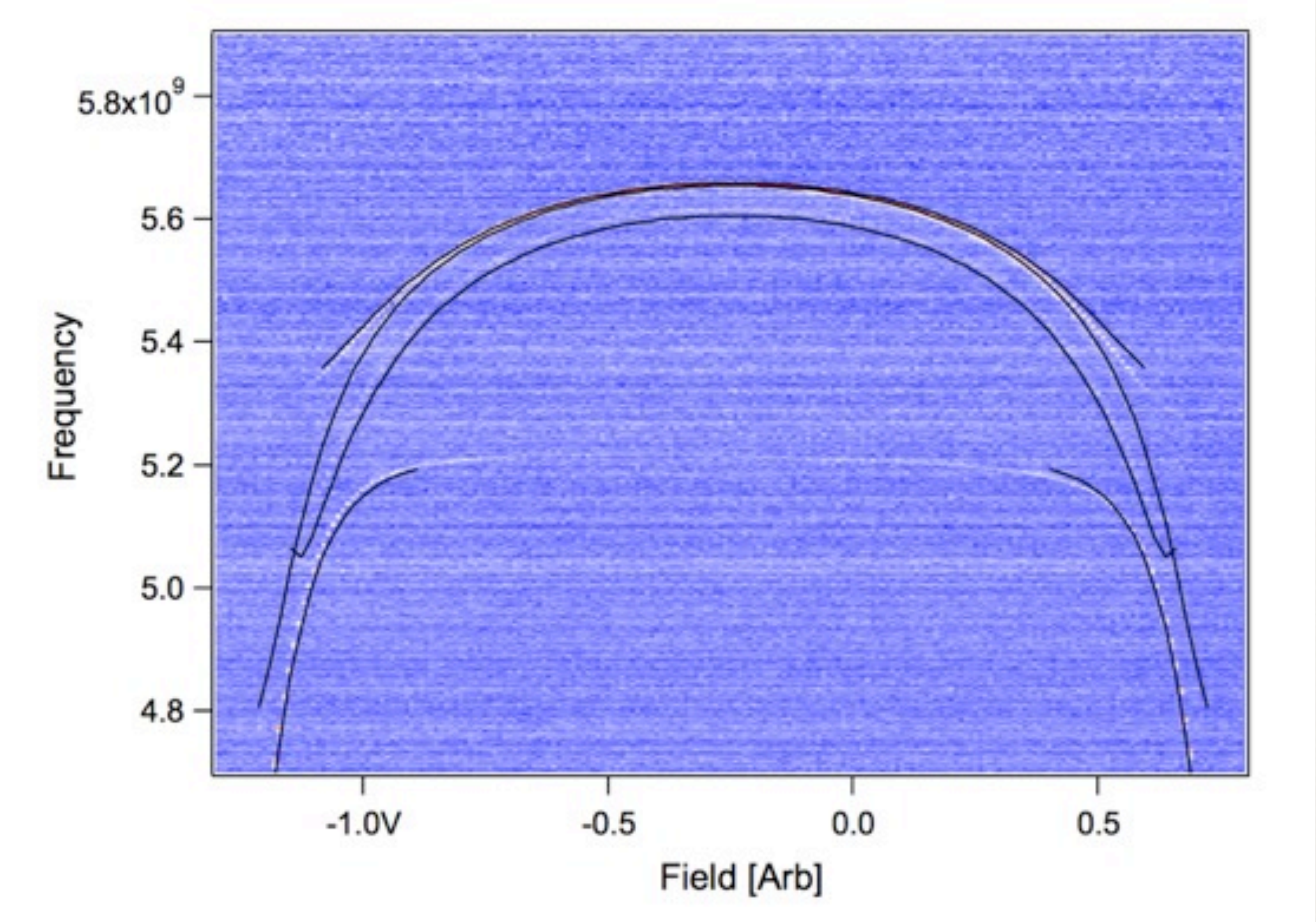

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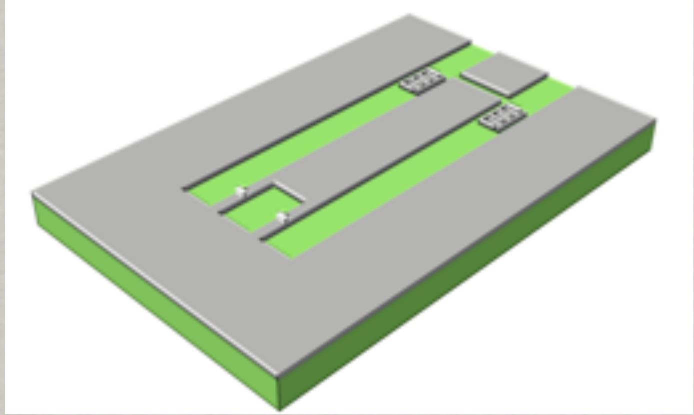
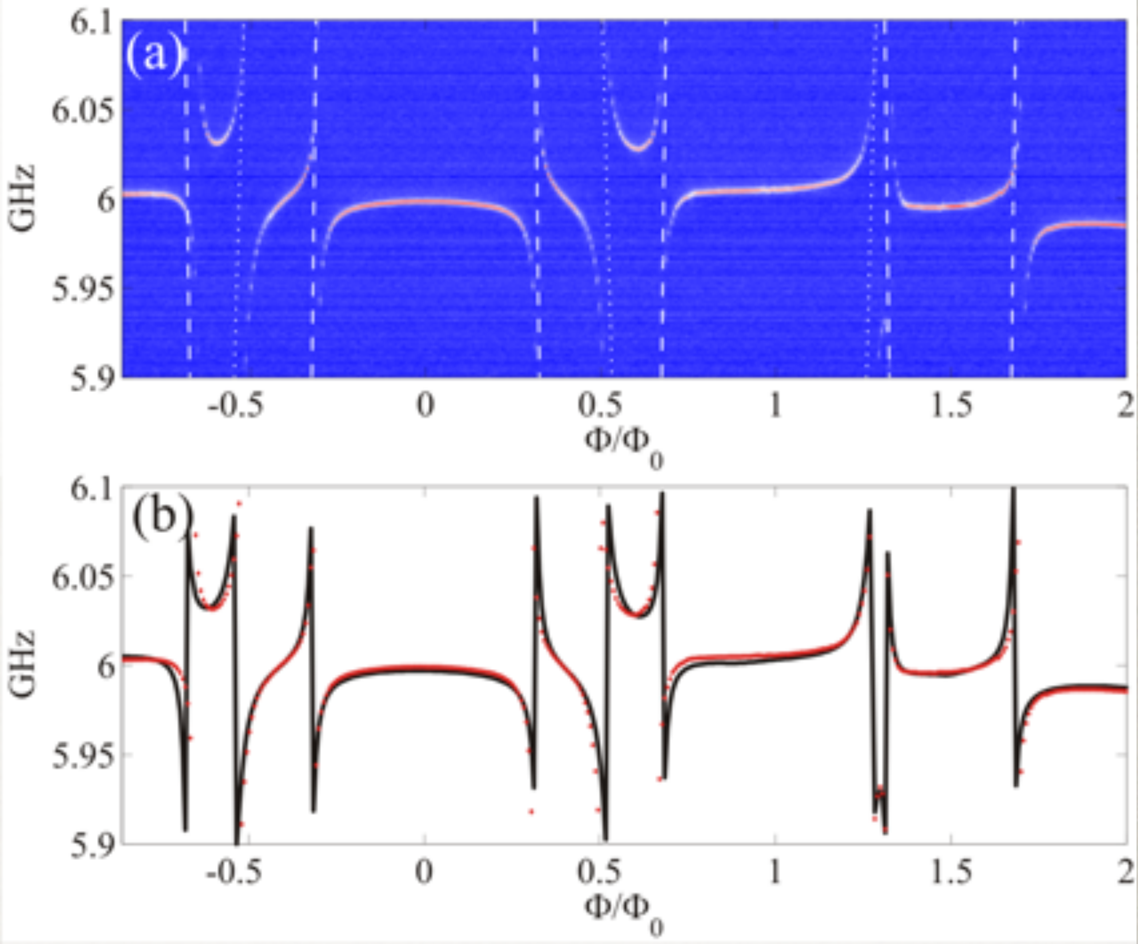
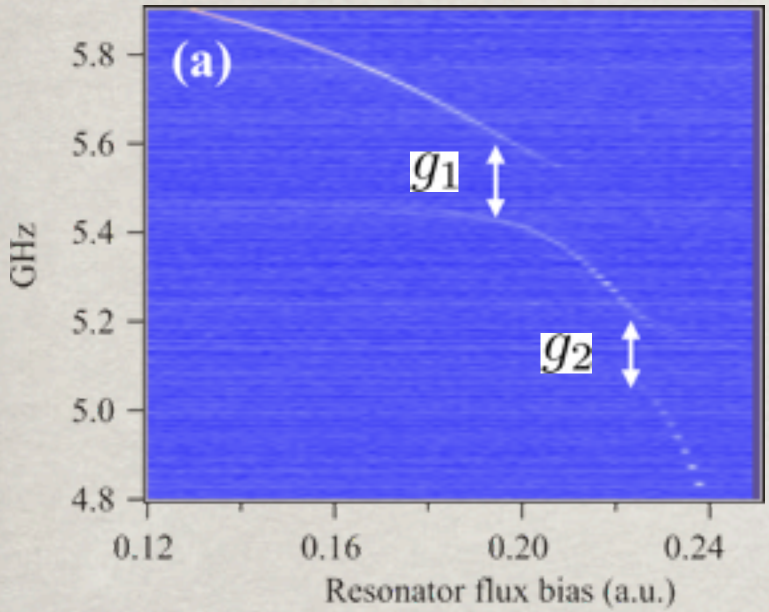
2-Qubit Circuit QED

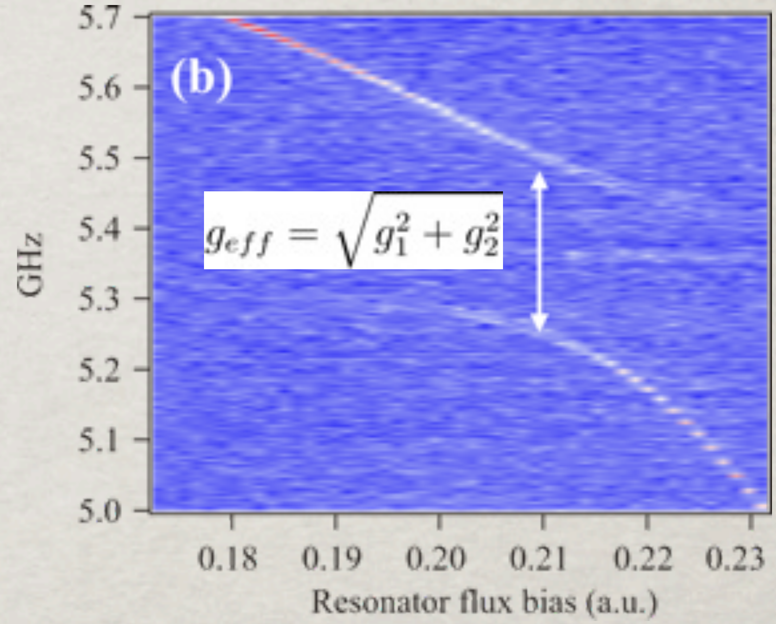




- Fit only the flux coupling, others parameters from spectroscopy

2-Qubit Circuit QED





- Tune resonator with qubits detuned

- Now with qubits on resonance
- Qubits acts as one collective system: Tavis-Cummings model

Fink, PRL (2009).

Single-Atom Scattering and 1D QED

Single-Atom Scattering

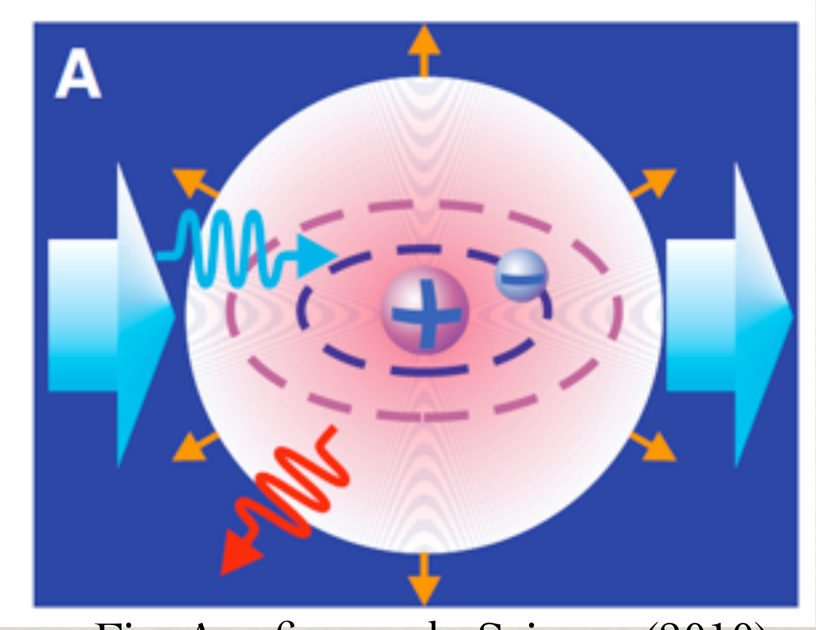
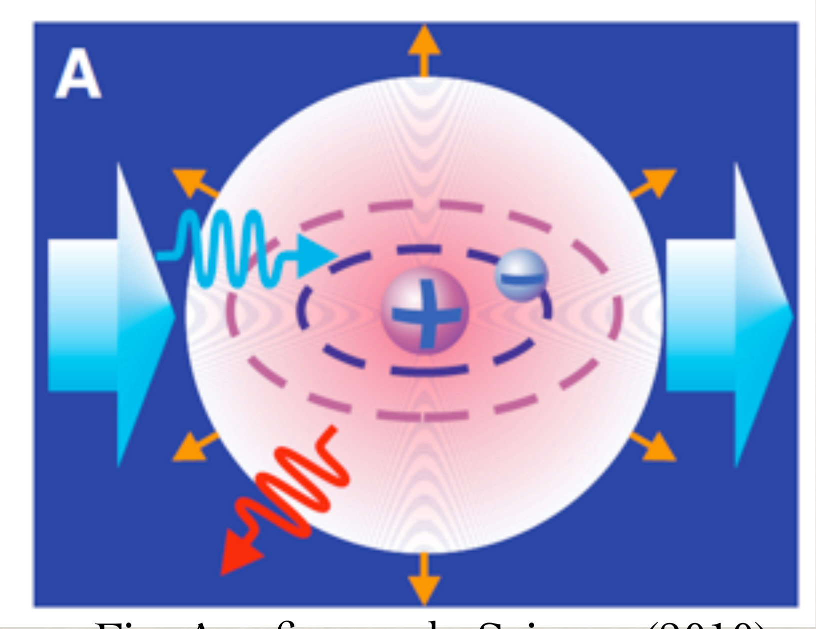


Fig: Astafiev et al., Science (2010).

Single-Atom Scattering



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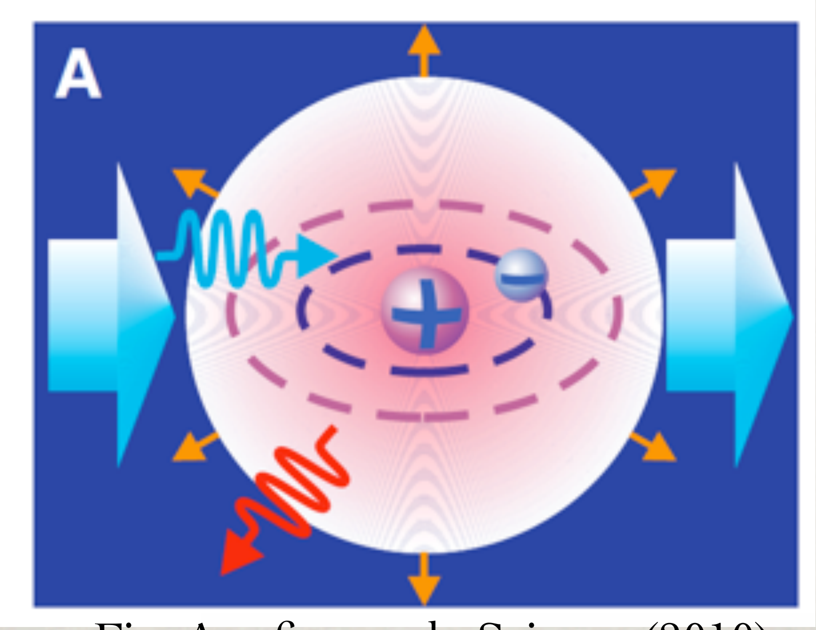
- What is the maximum reflection from a single atom?

Single-Atom Scattering



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- What is the maximum reflection from a single atom?
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Single-Atom Scattering

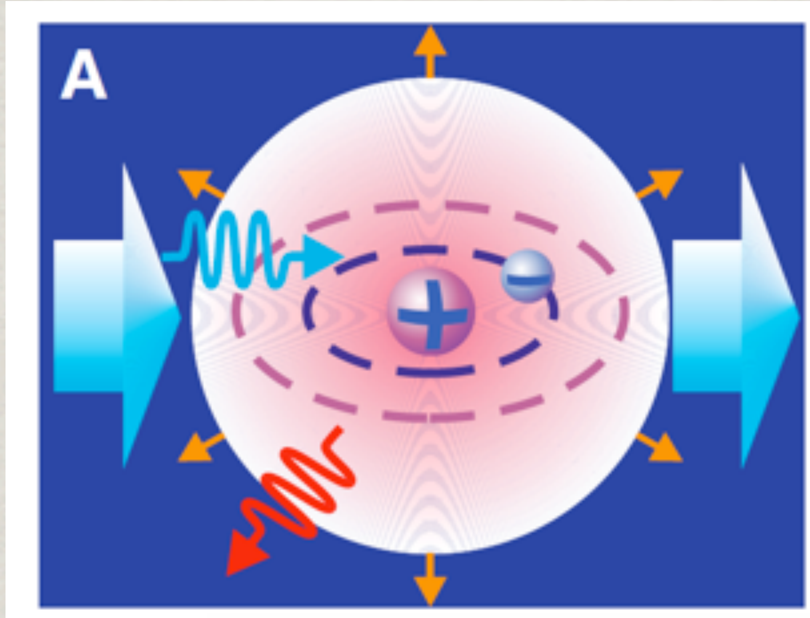
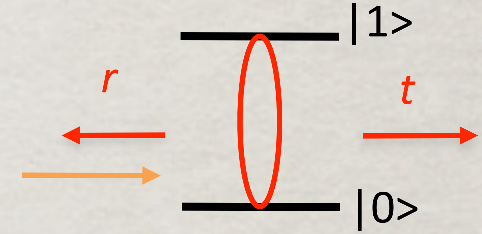


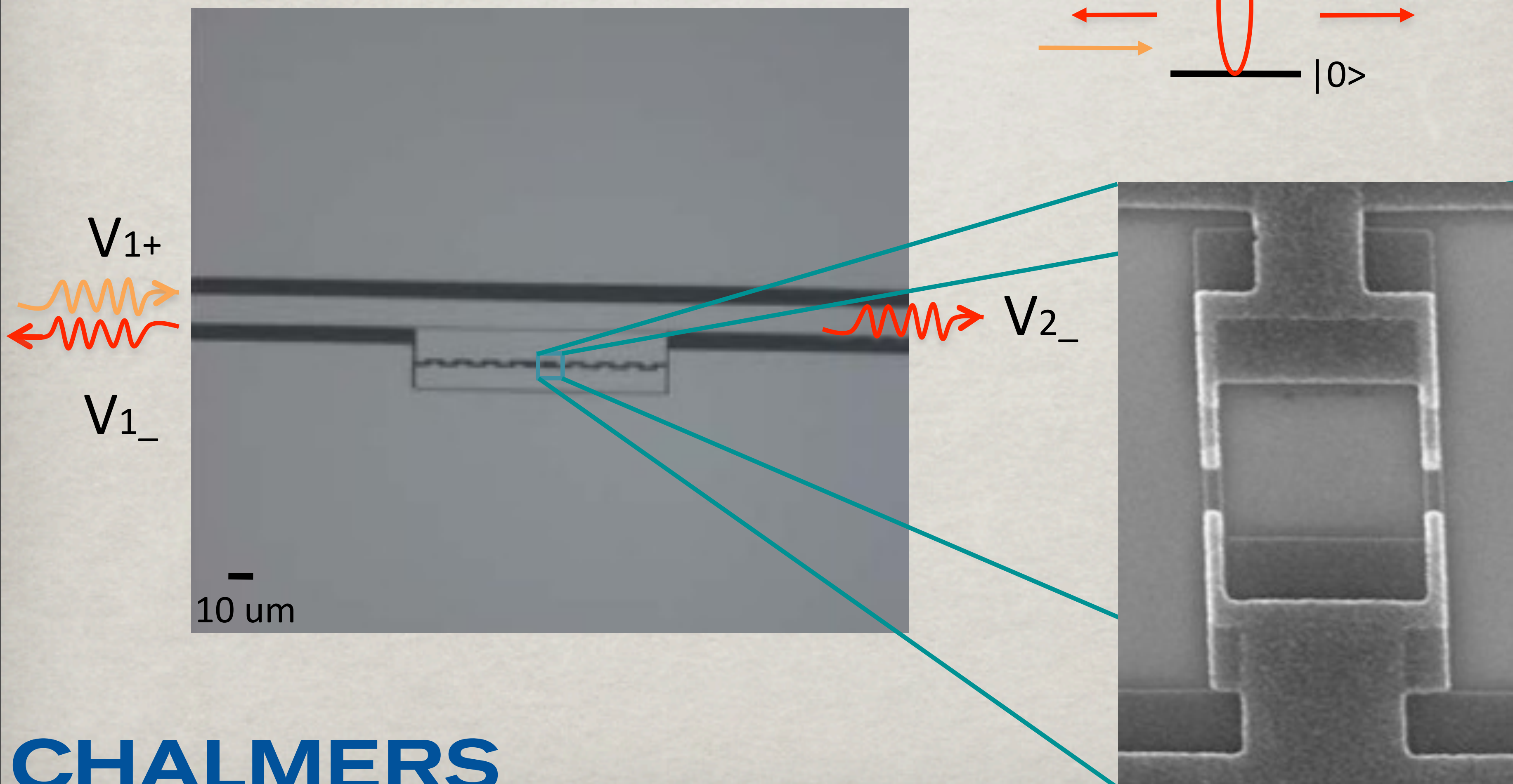
Fig: Astafiev et al., Science (2010).

- What is the maximum reflection from a single atom?
  - First guess: 50% because 1/2 of spontaneous emission goes forward, 1/2 back
  - Fully coherent: 100% because forward scattering destructively interferes with incoming wave

Atom in a Transmission Line

Astafiev,et al., Science (2010).





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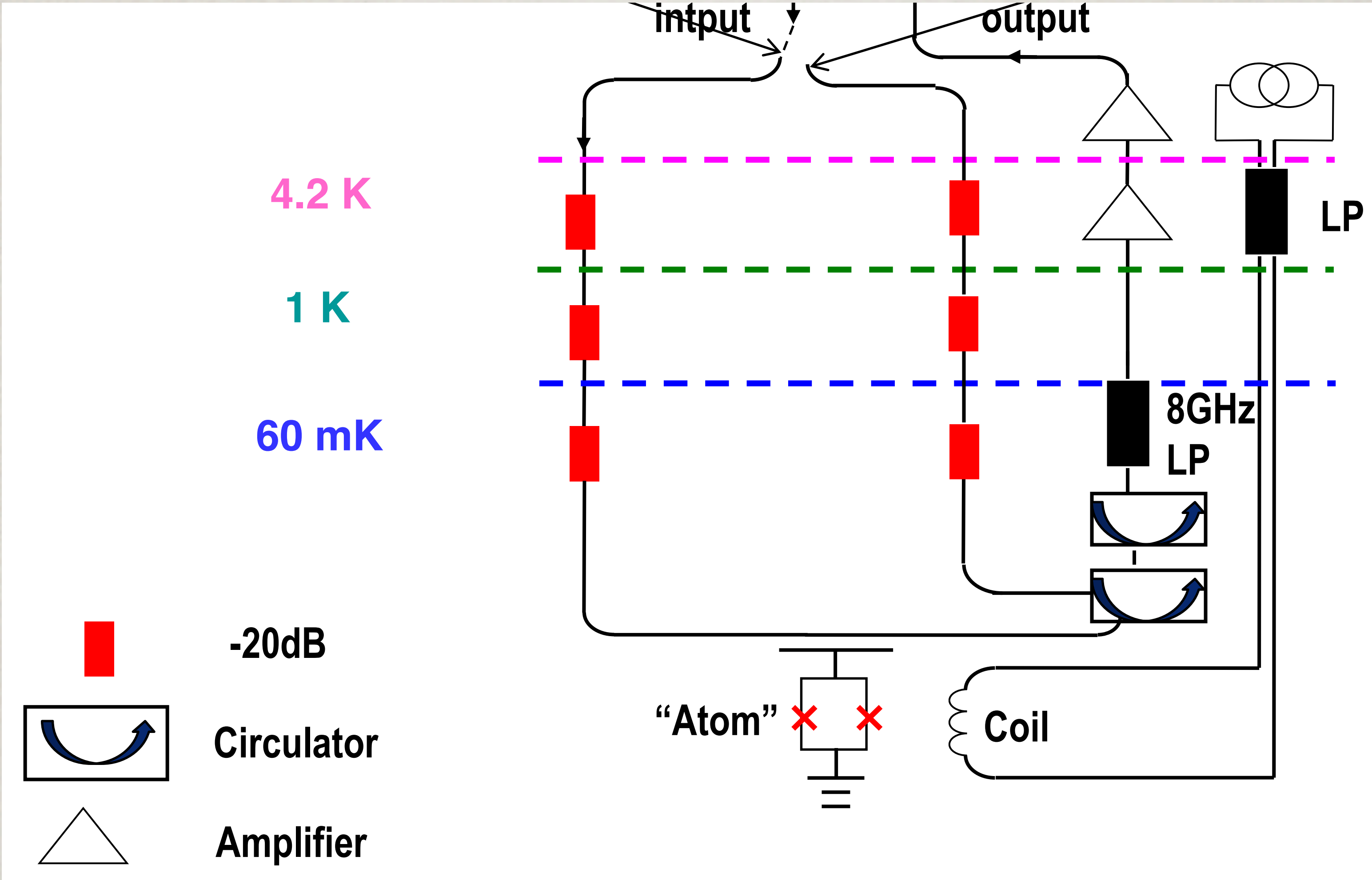
Measurement Setup



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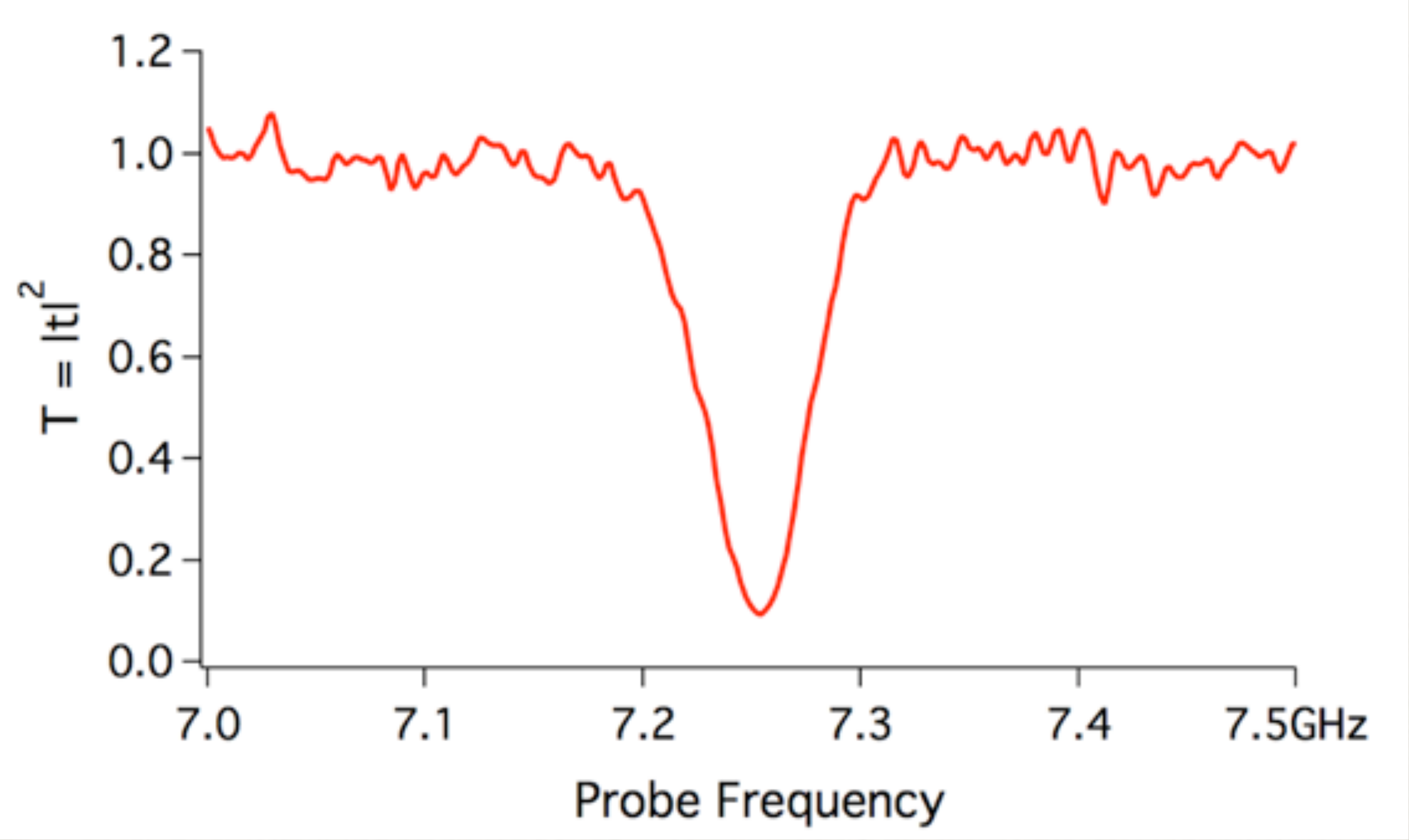
Strong Extinction



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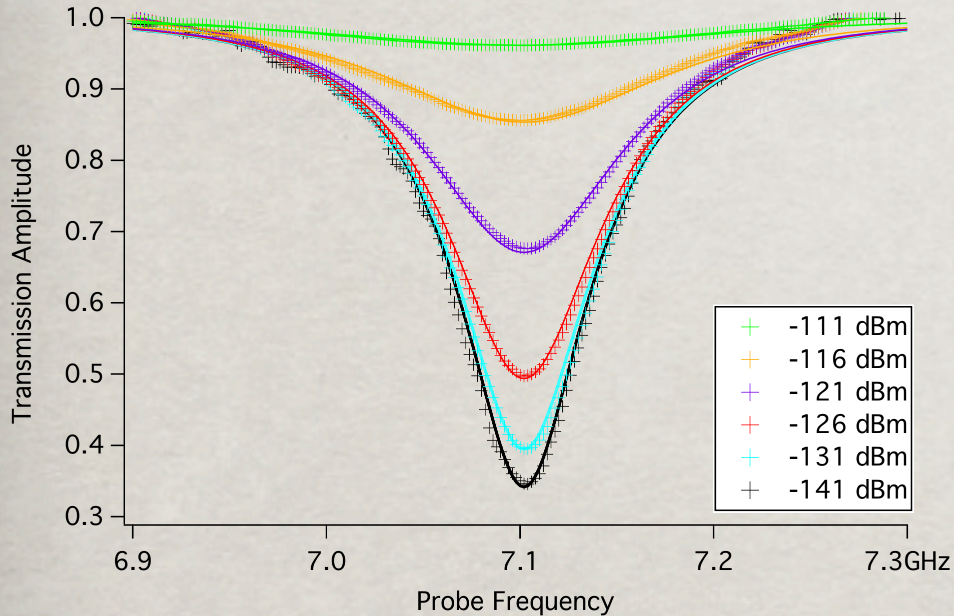
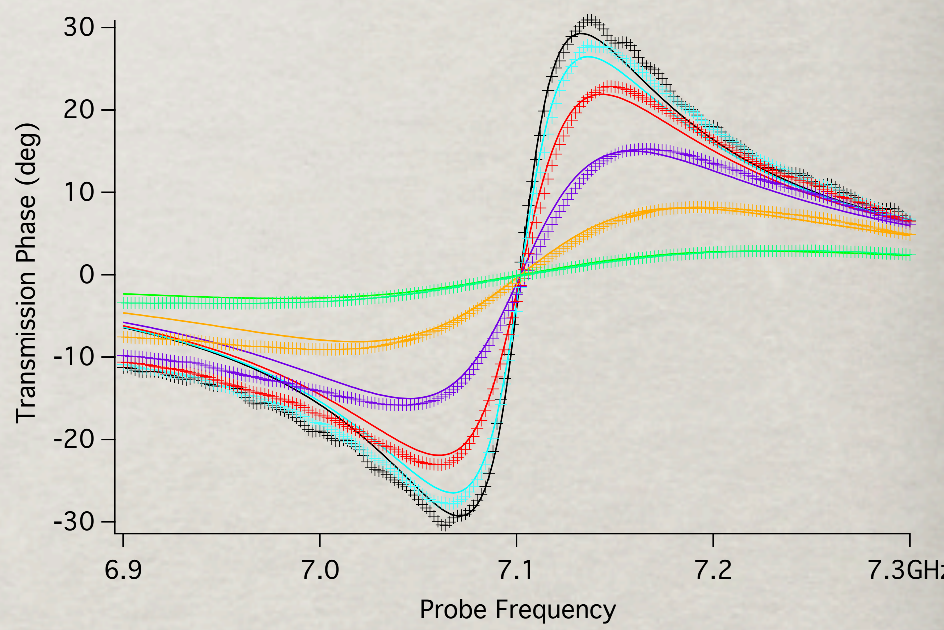
Strong Saturation





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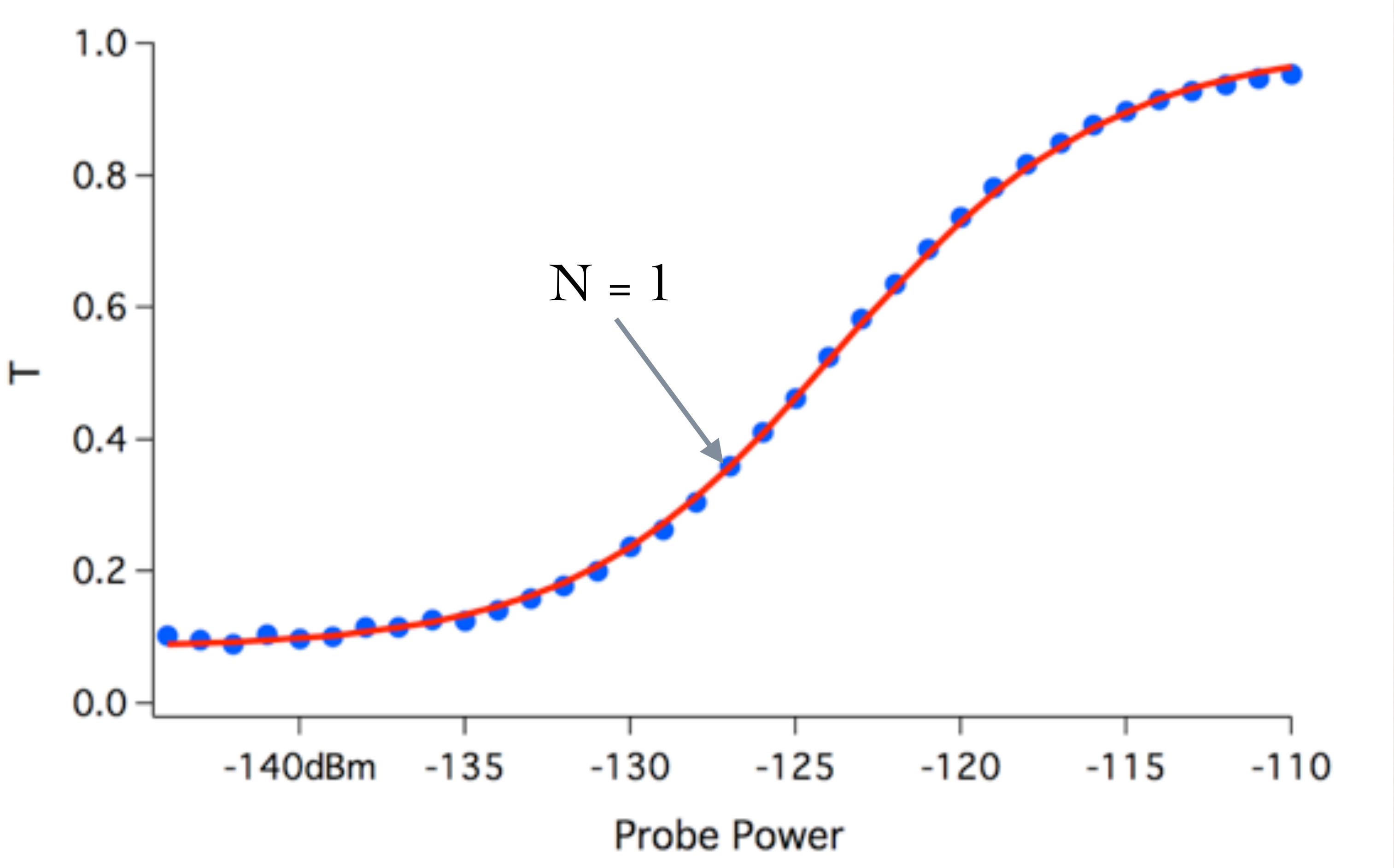

$$N = \frac{P}{h f_0 \Gamma_1}$$

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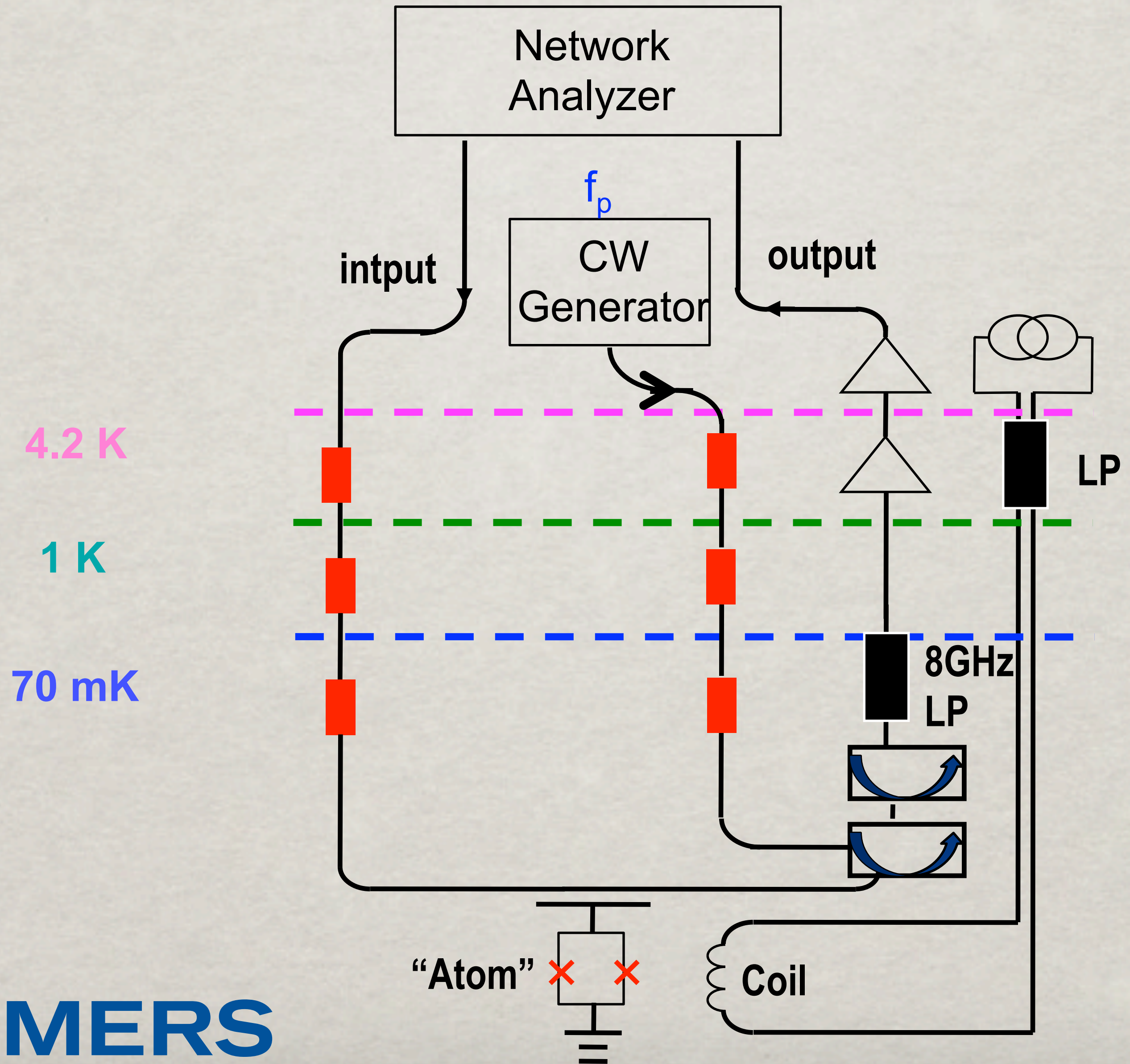
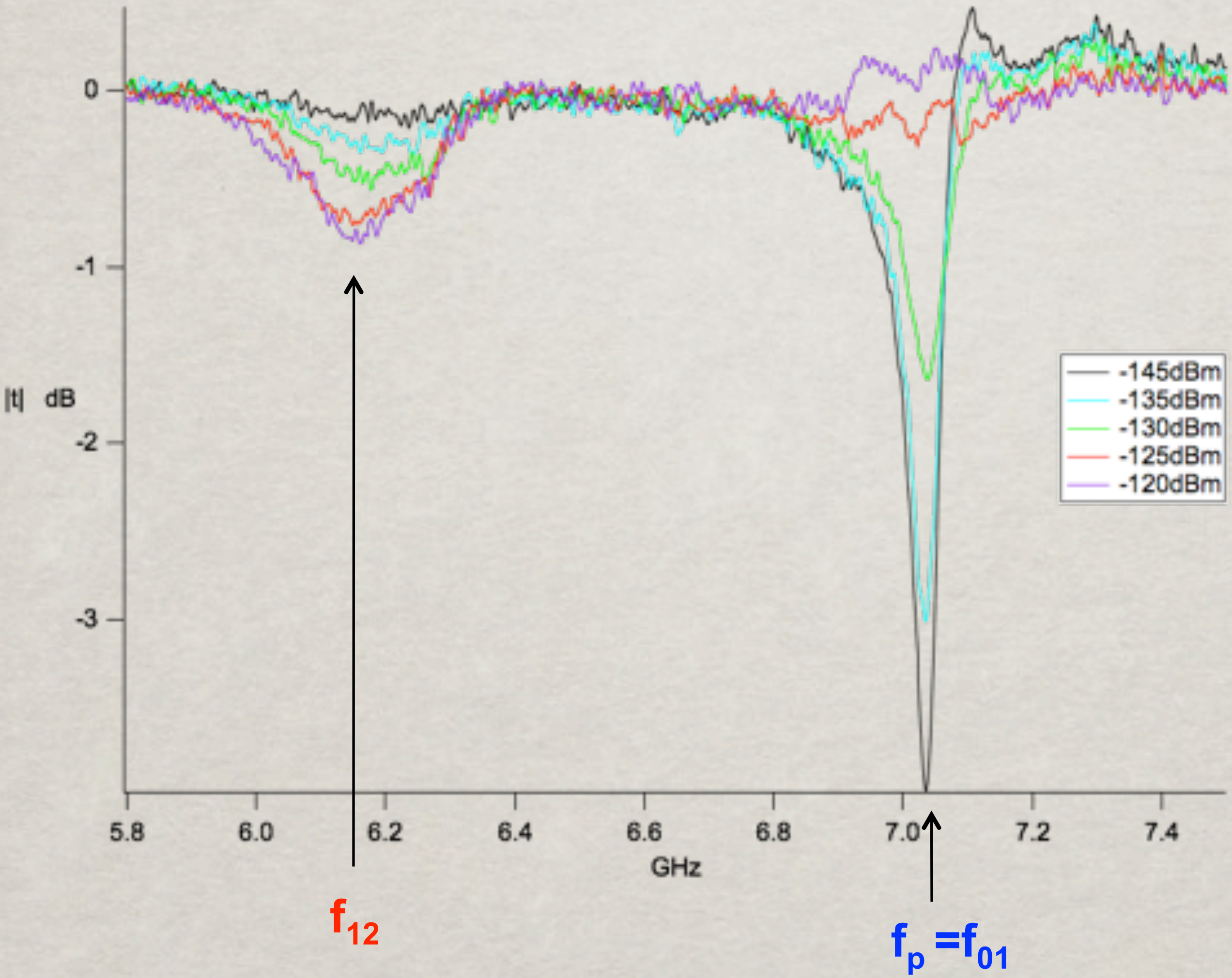
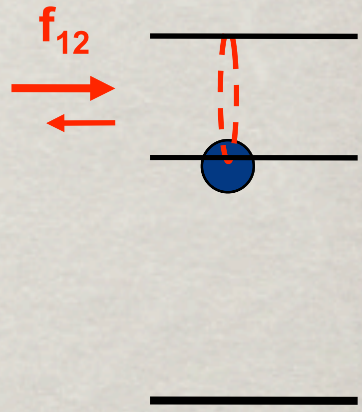
Two-Tone Spectroscopy



Excited Extinction





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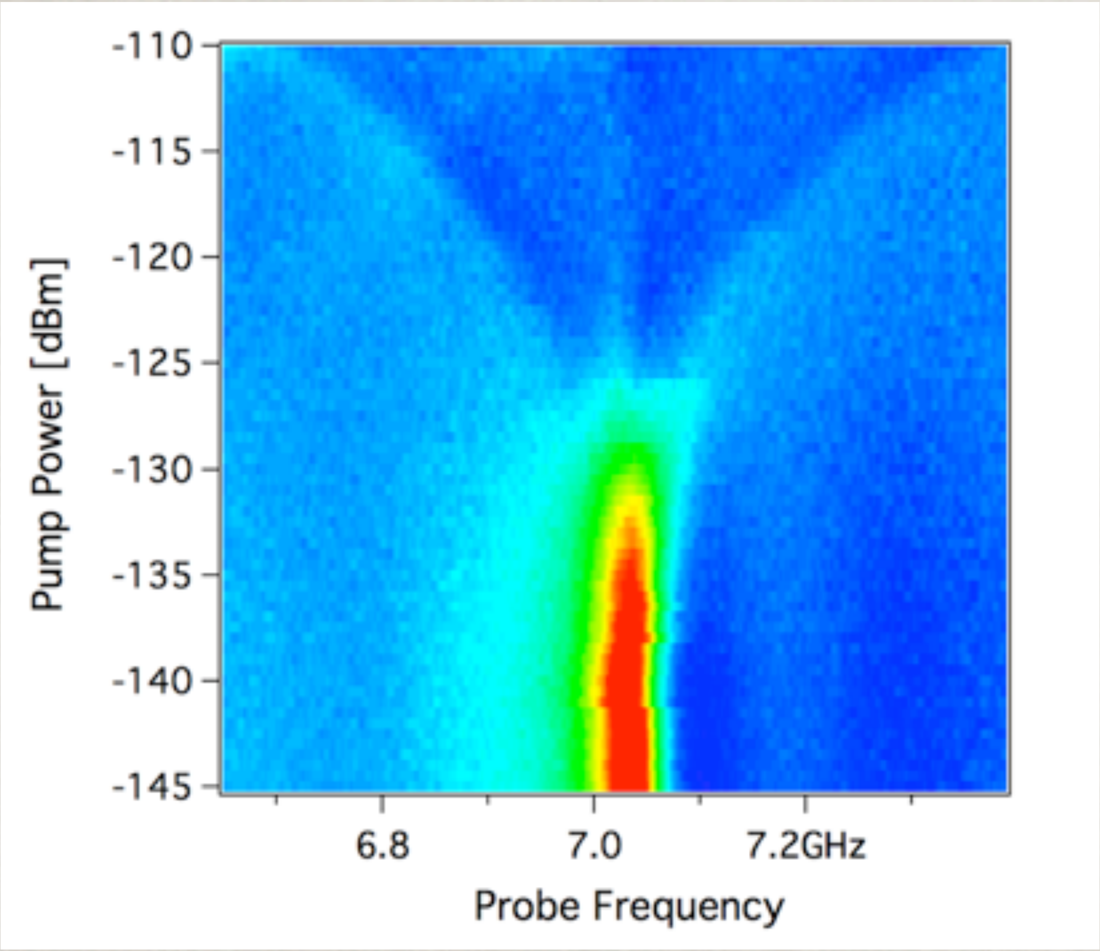
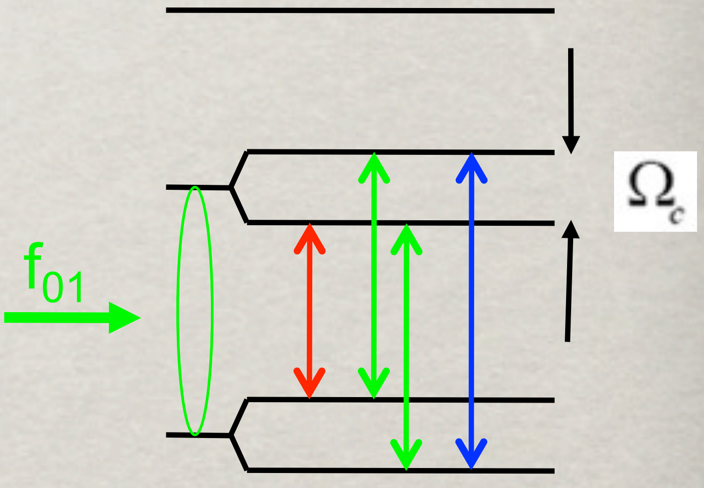
Mollow Triplet





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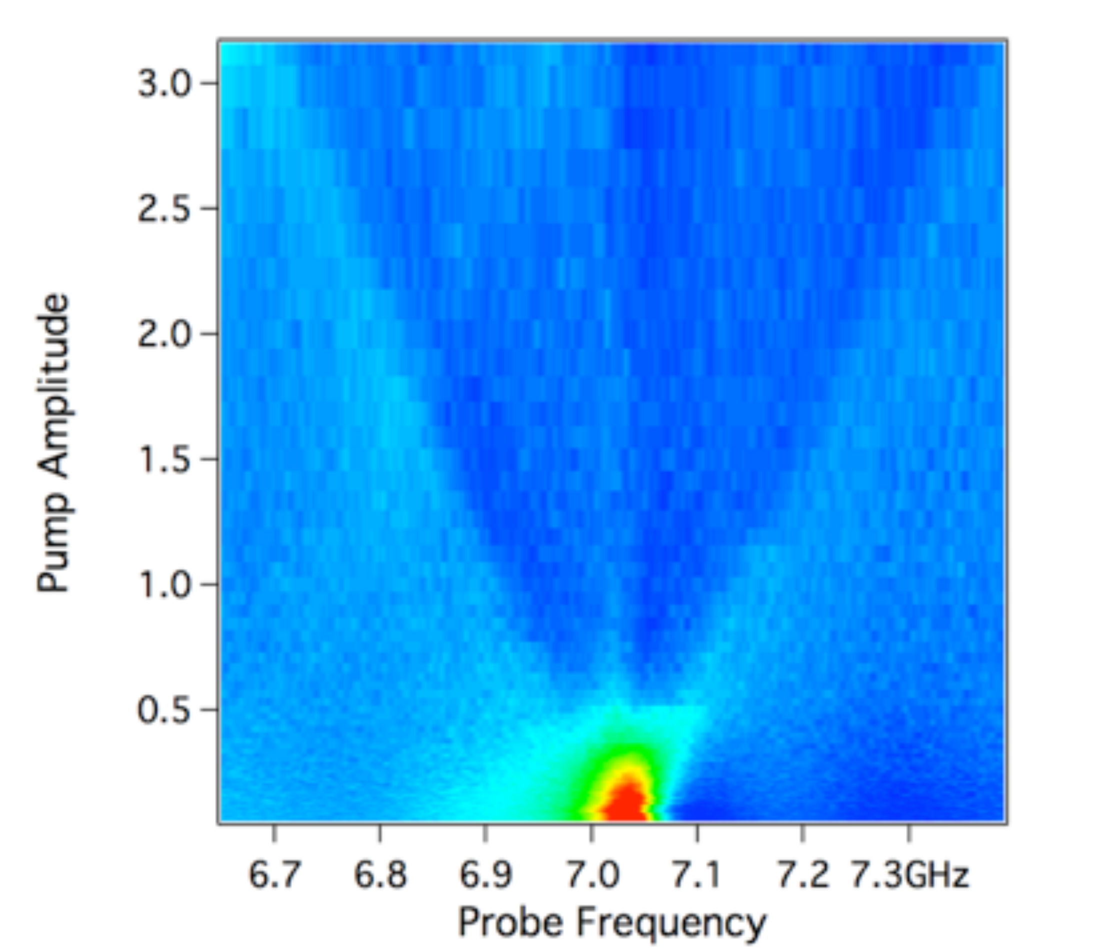

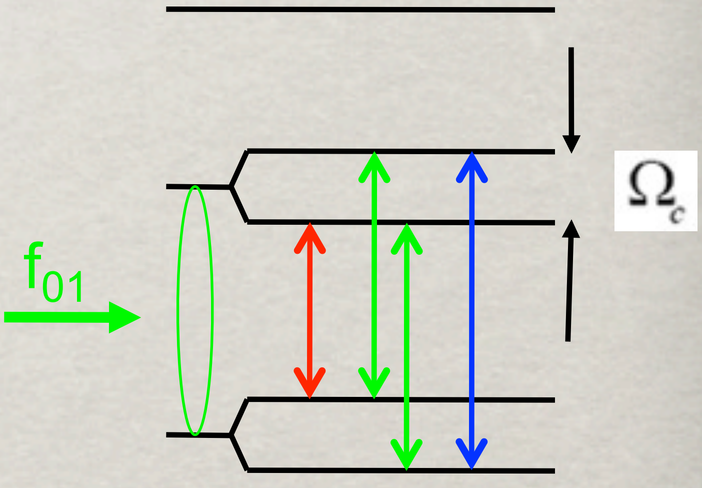

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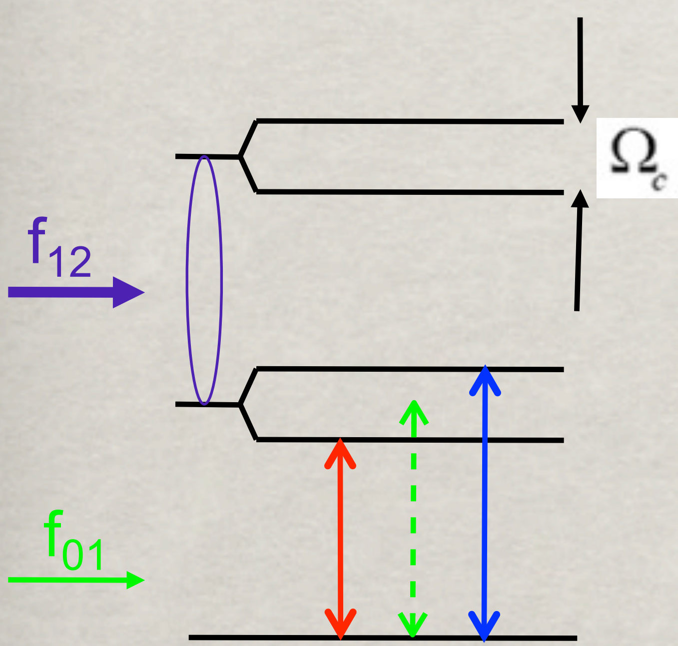
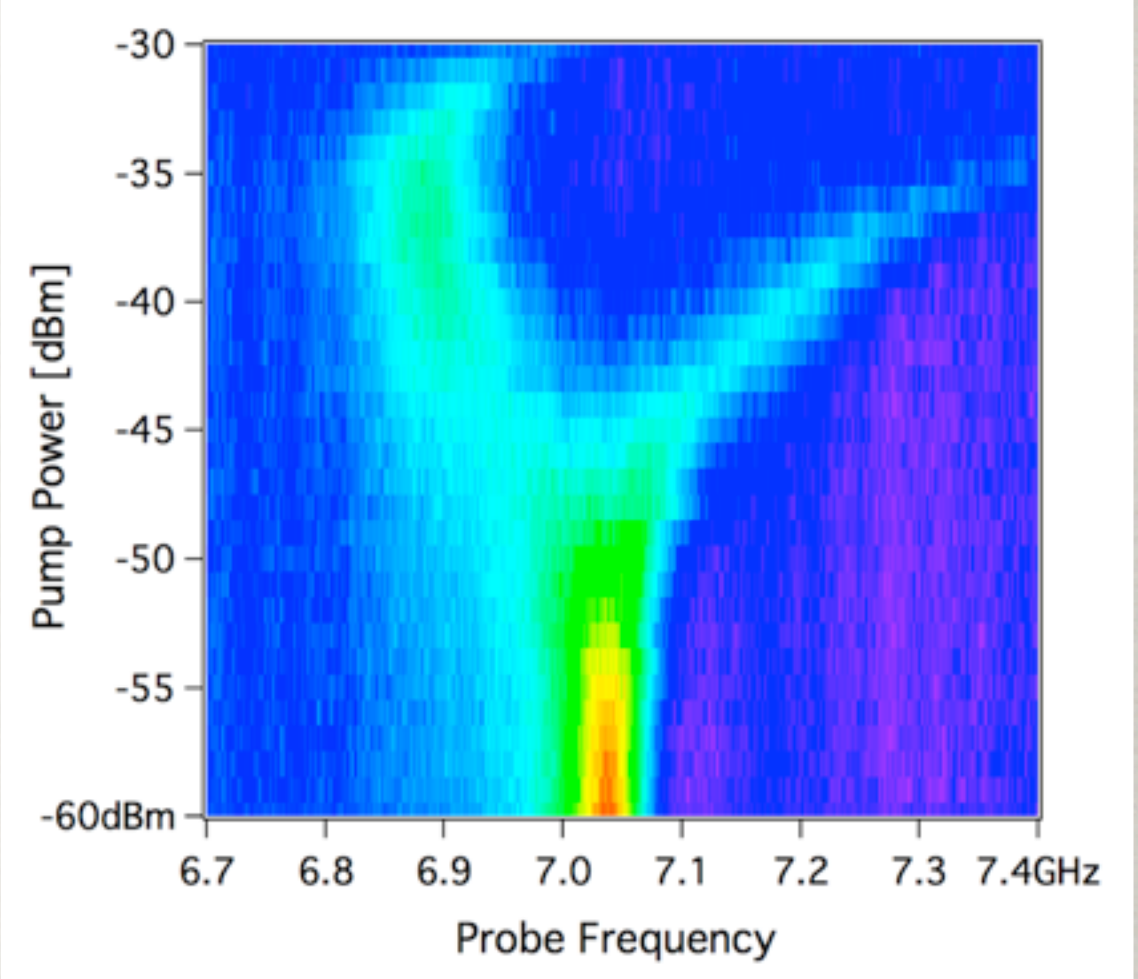
Electromagnetically Induced Transparency

- Pump 1-2 transition





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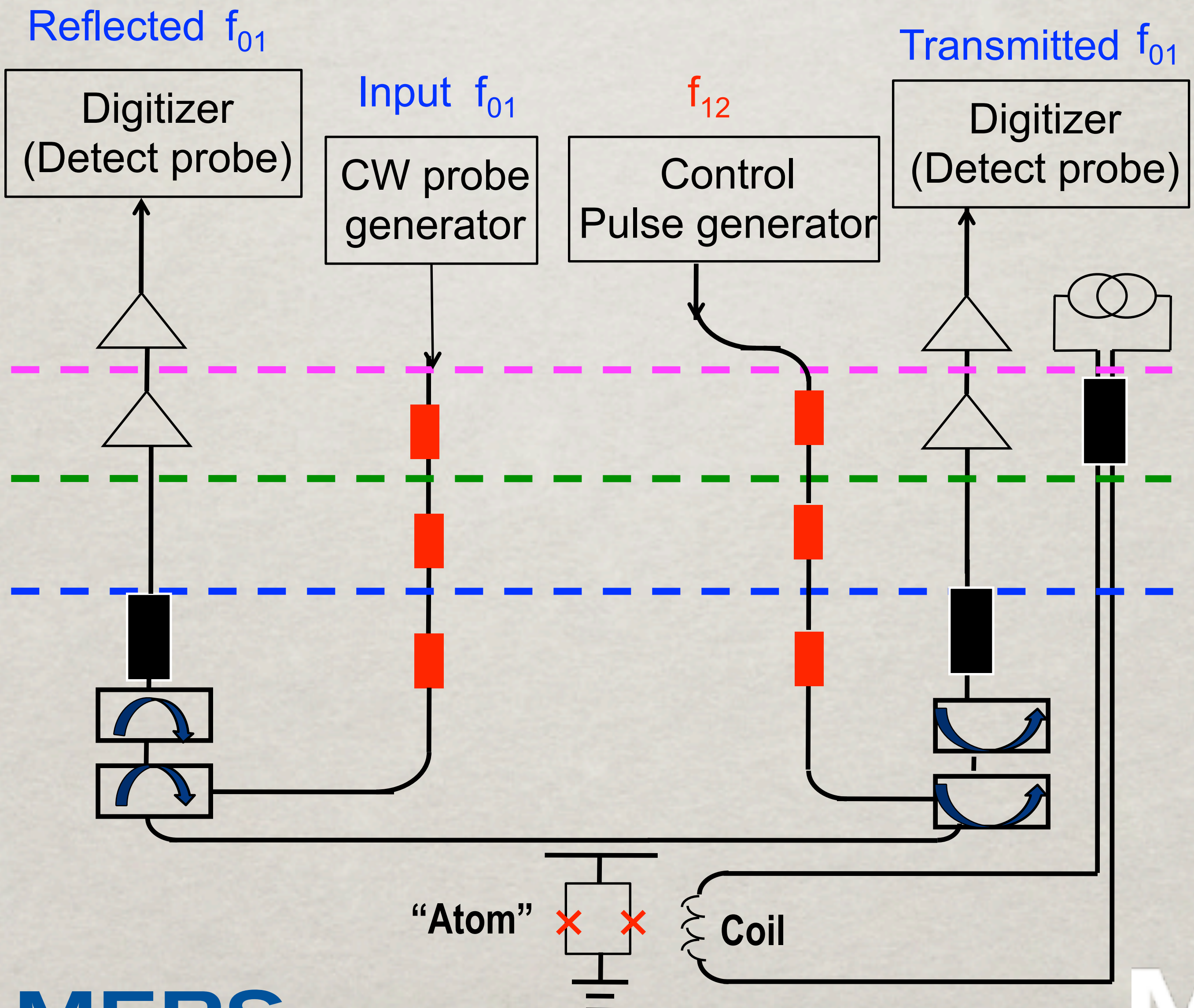
Single-Photon Router



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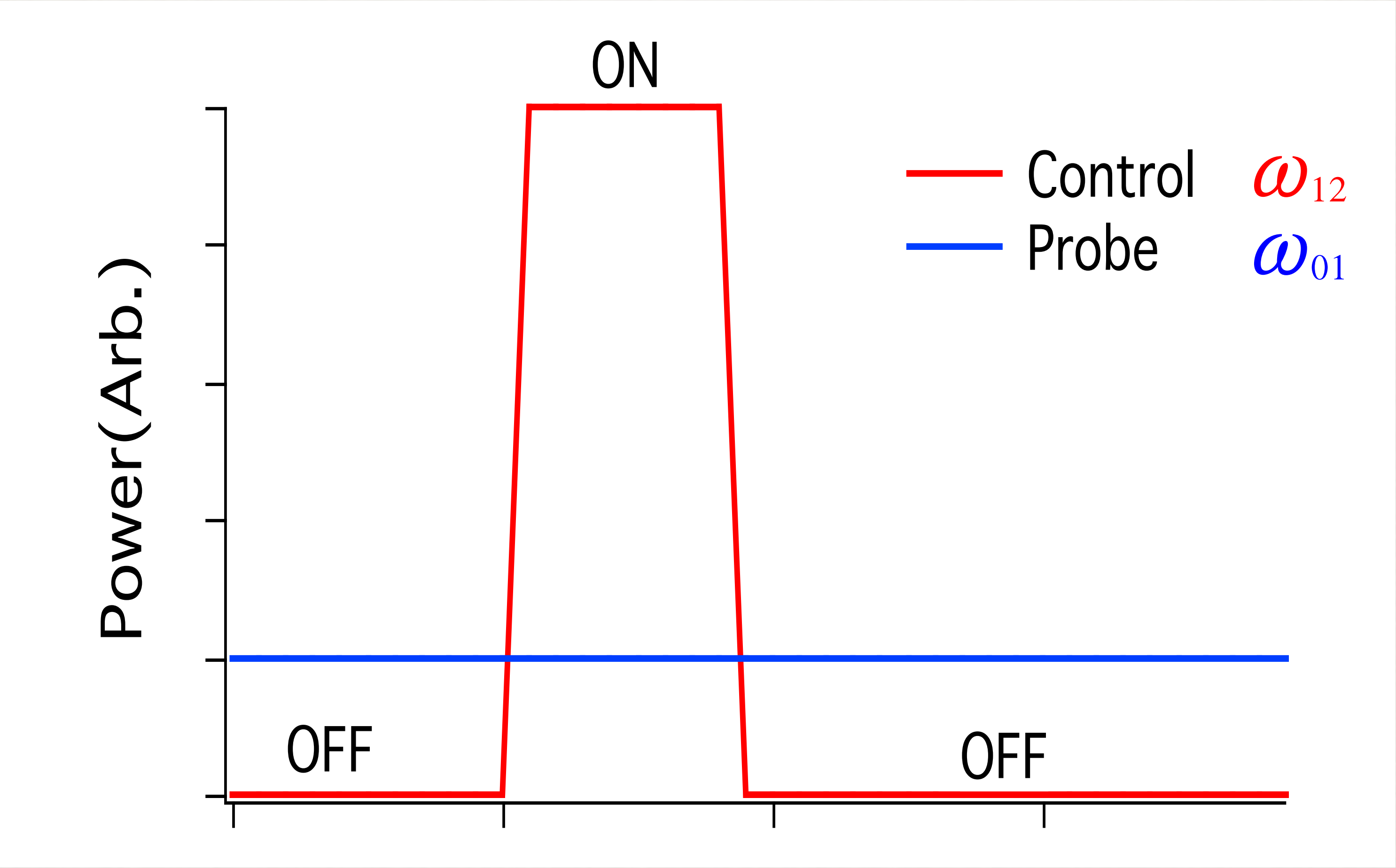

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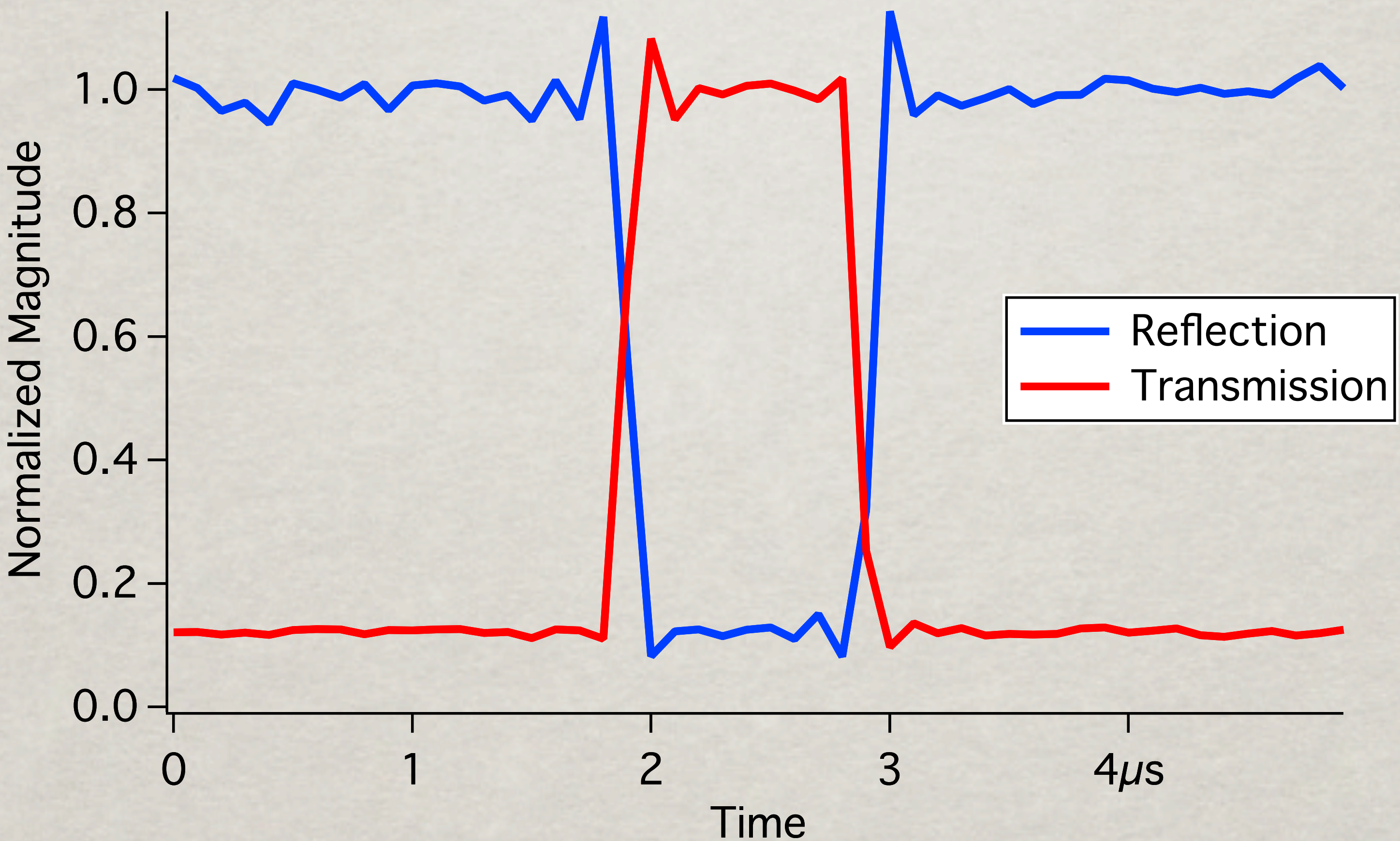

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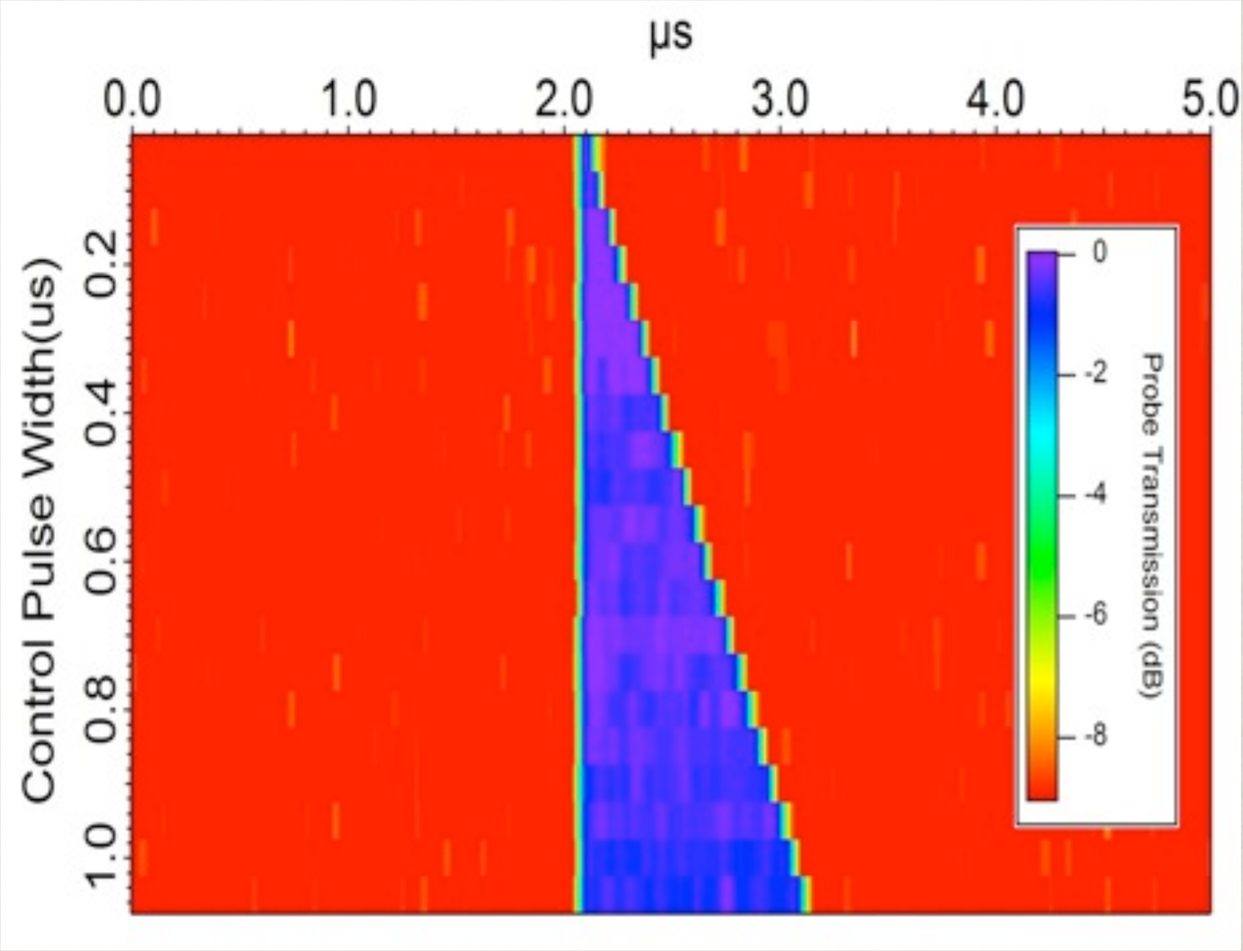
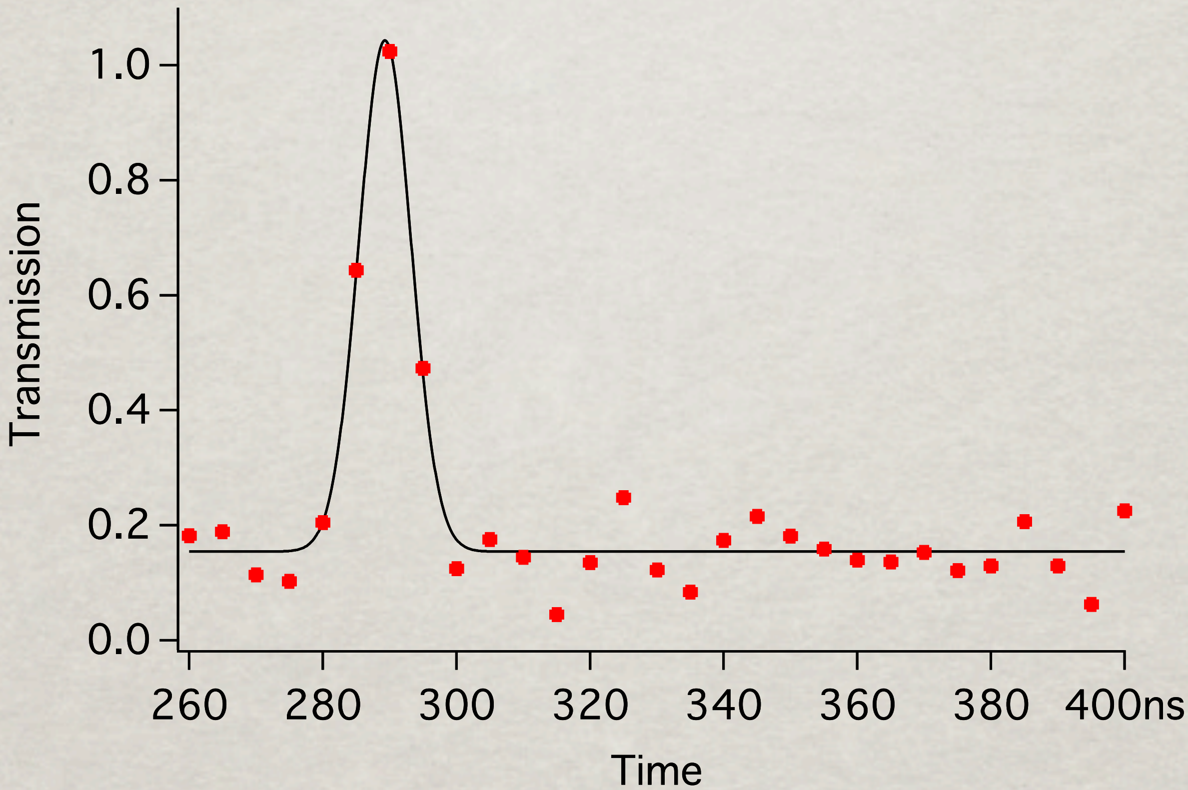


- Operation time down to ~ 10 ns

Single-Photon Router



- Operation time down to ~ 10 ns

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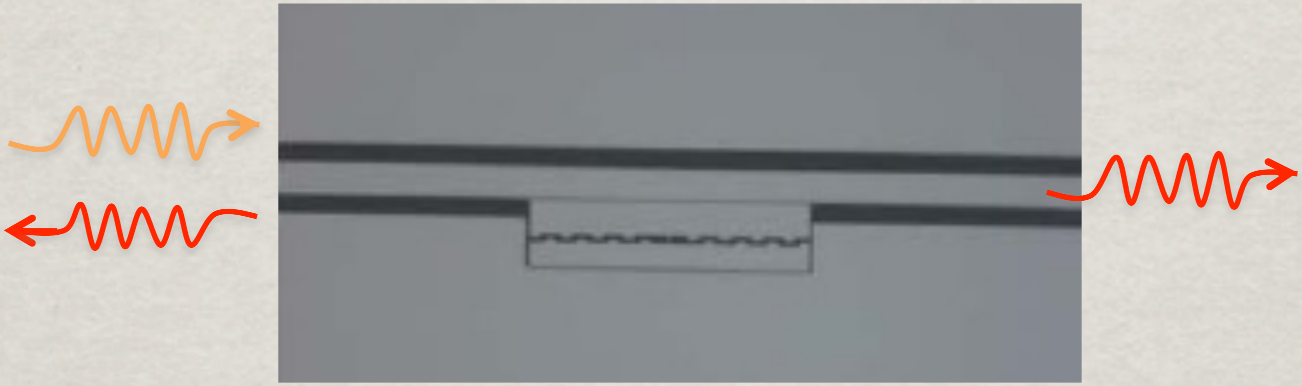
Quantum-State Filter

Quantum-State Filter

$$|\Phi_{in}\rangle = a_0\,|0\rangle + a_1\,|1\rangle + a_2\,|2\rangle + \dots$$



$$|\Phi_R\rangle = r_0\,|0\rangle + r_1\,|1\rangle$$

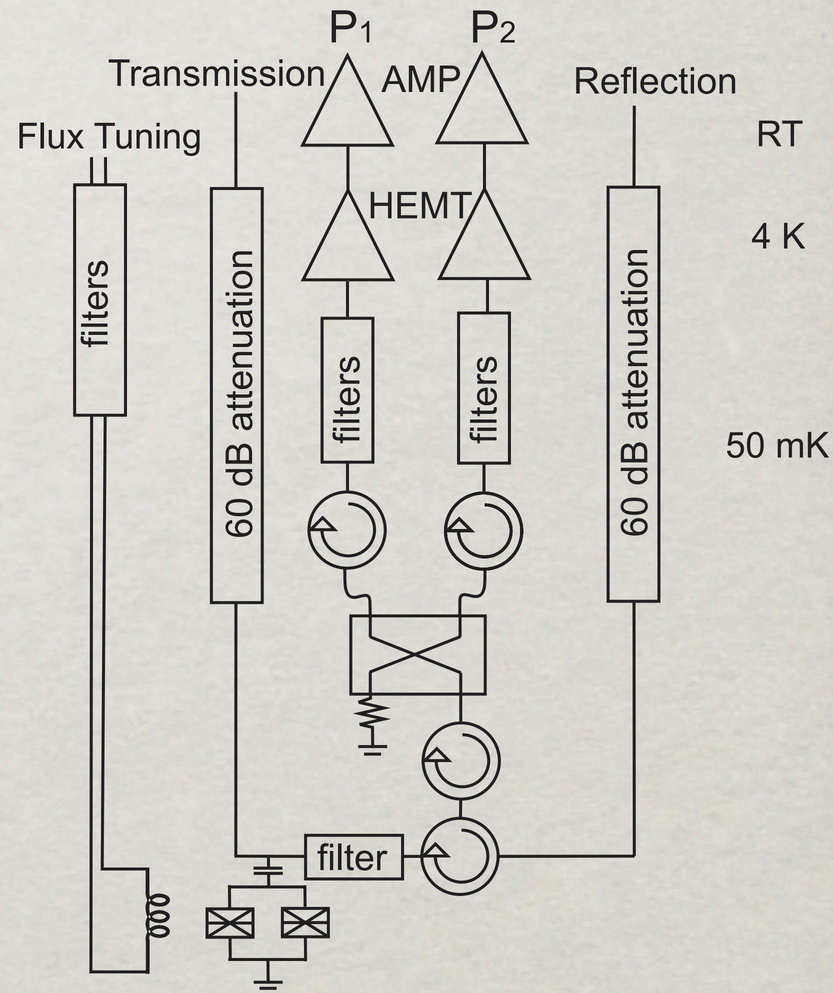
$$|\Phi_T\rangle = t_0\,|0\rangle + t_2\,|2\rangle + t_3\,|3\rangle \dots$$

- Atom selectively reflects 1-photon state
- Input coherent state converted to nonclassical state

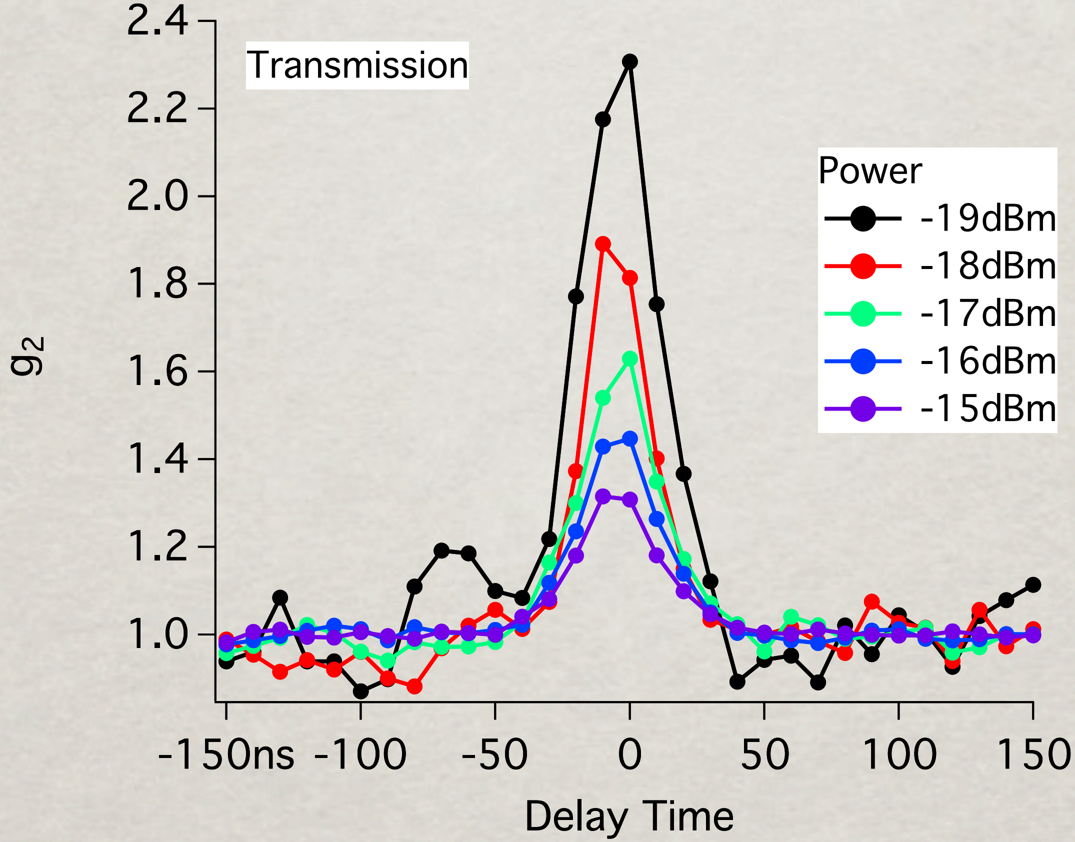
Chang et al., Nature Physics (2007)

Fourth Moment ($g^{(2)}$)

- HBT measurements of output state
- Commercial "beamsplitter"
- Gabelli et al., **PRL** (2004)



Superbunching



- Observe superbunching of transmitted mode
  - n = 1 state “filtered out”

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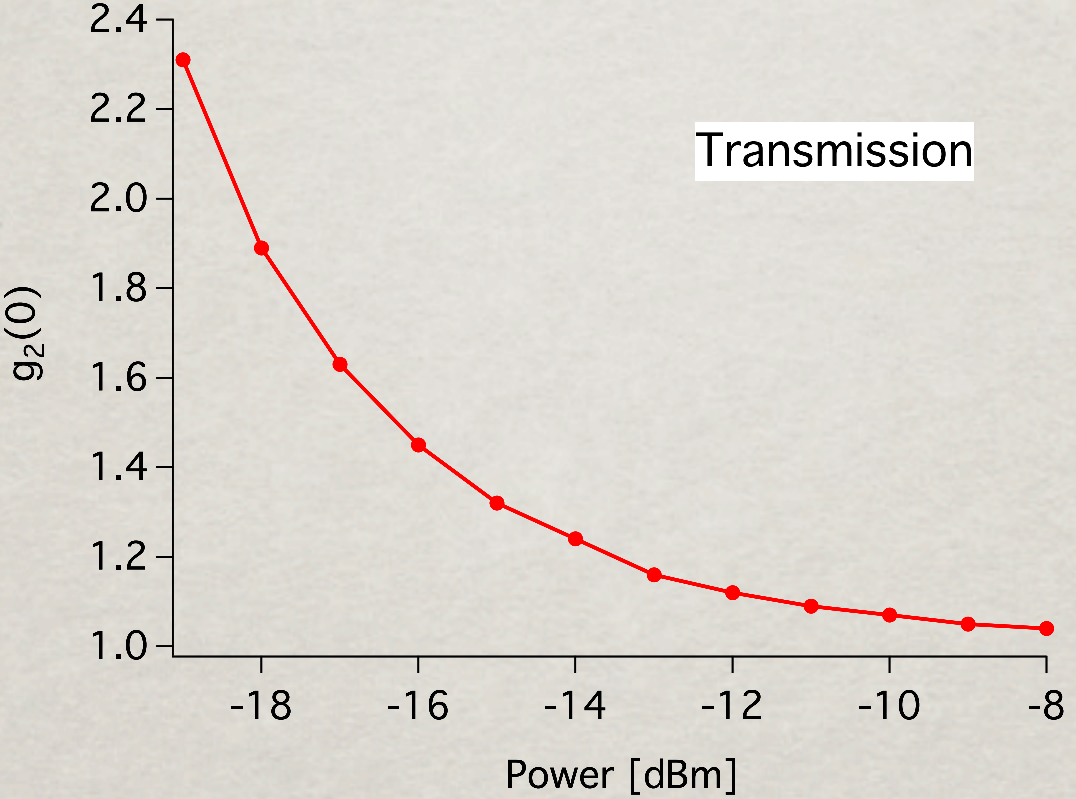
Superbunching



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Summary

- Demonstrated strong extinction caused by a single “atom”
- Demonstrated single-photon router using EIT
- Measured nonclassical statistics produce by a novel quantum-state filter

Towards an Optical-Microwave Quantum Interface

Hybrid Quantum Network

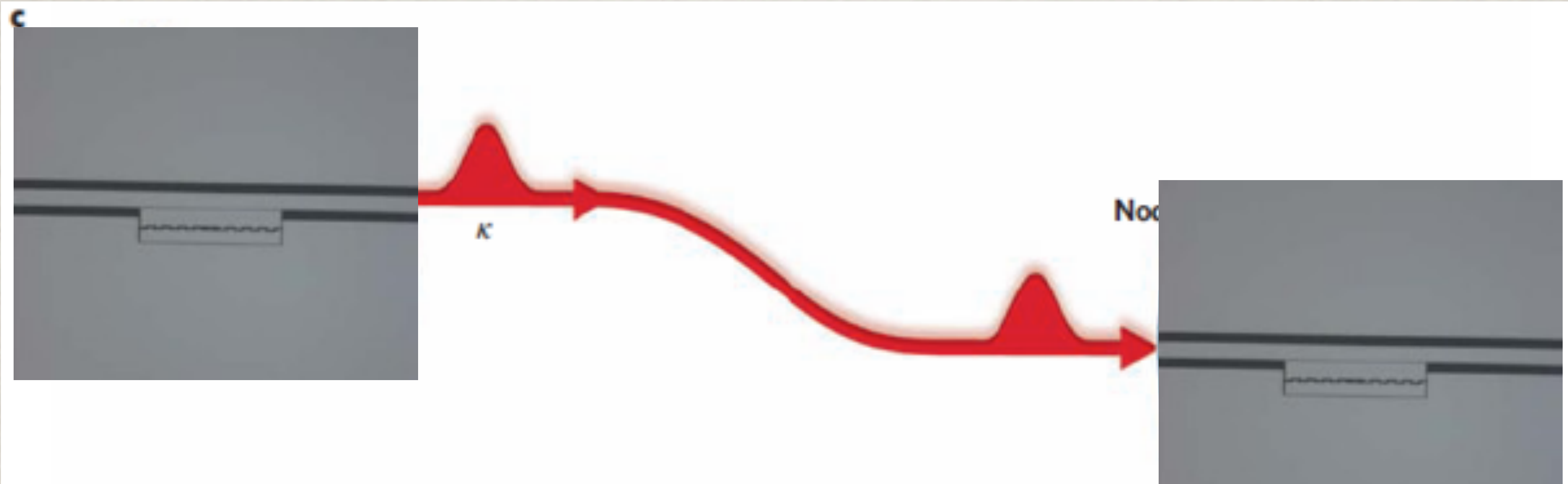

Fig: Kimble, Nature (2008)

- Telecom photons to distribute quantum information
- Superconducting circuits to process at nodes
- Need to coherently convert frequency by factor of 10^4!

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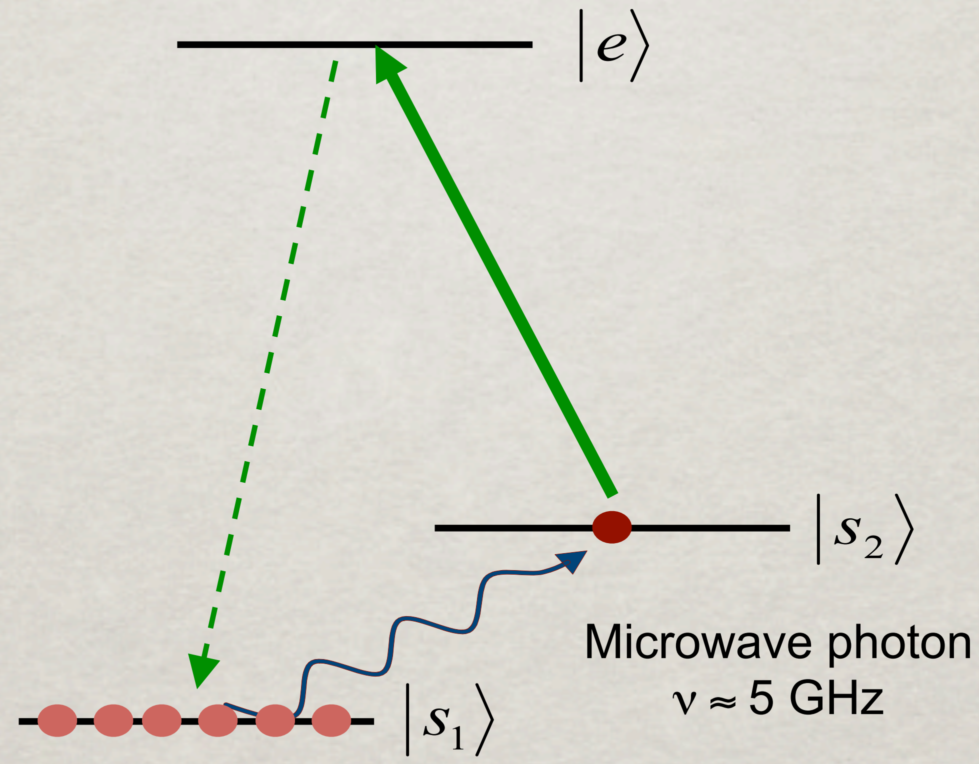
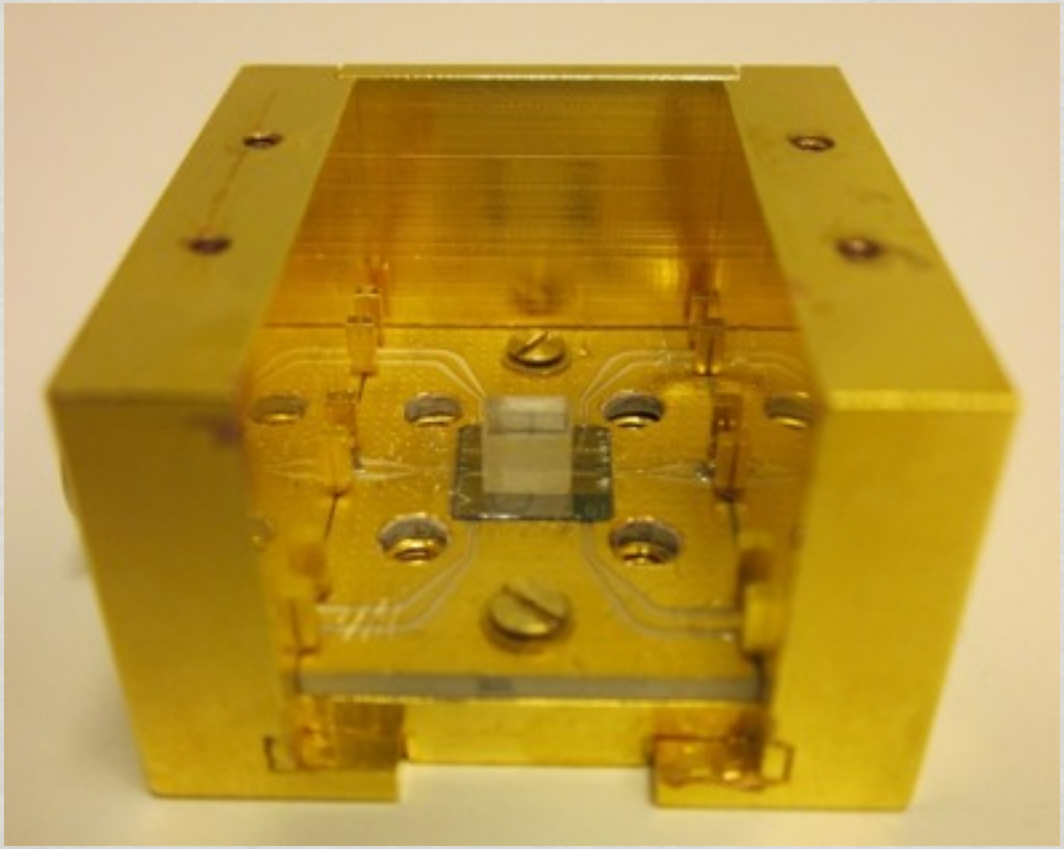
Quantum Interface

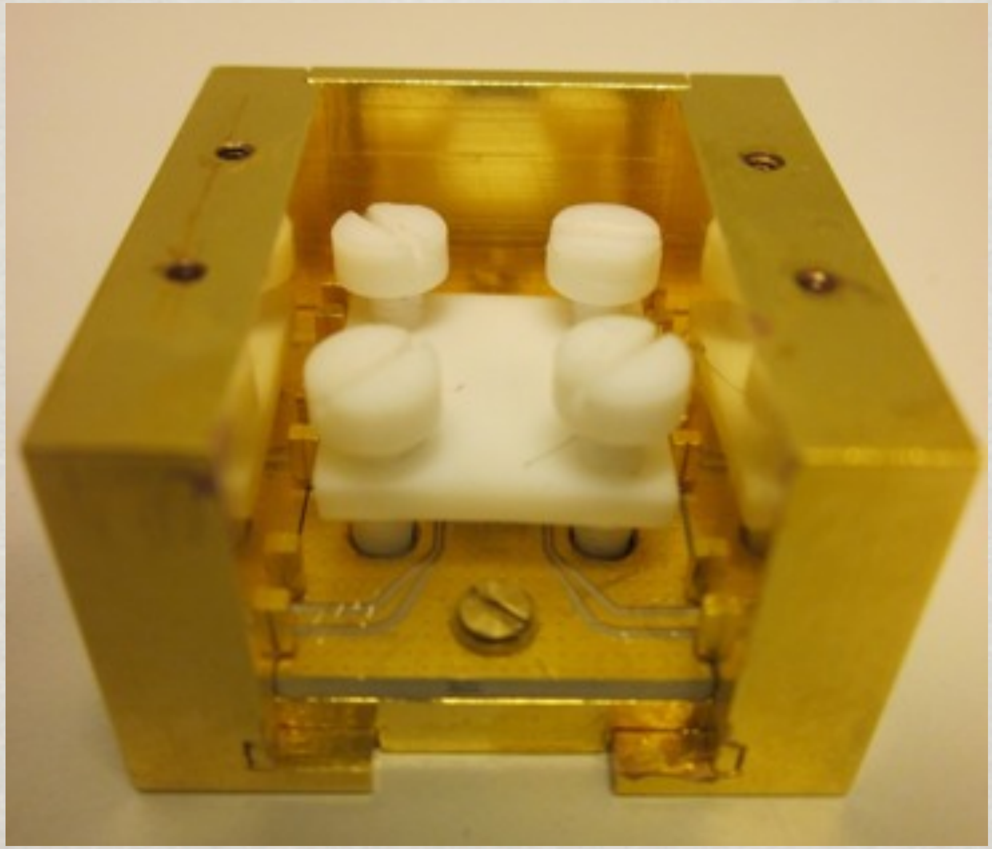


Microwave Coupling



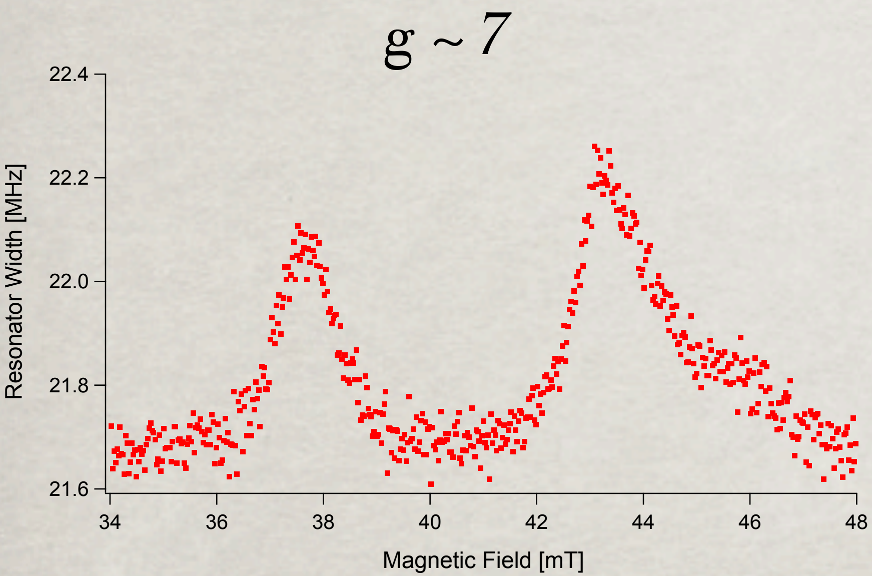
- Erbium doped crystal coupled to low-Q Nb CPW
- Pressed contact

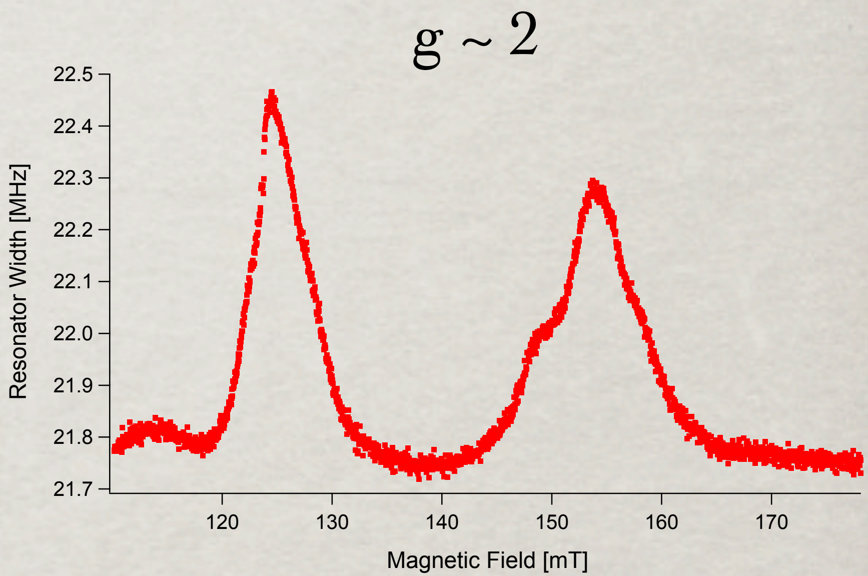
Microwave Coupling



- Erbium doped crystal coupled to low-Q Nb CPW
- Pressed contact

Planar ESR





- Magnetic field tunes Zeeman splitting of spin levels
- On resonances, ensemble damps the resonator
- Measure resonance width vs. magnetic field
- Collective coupling $g_c \sim 5$ MHz, implying $N \sim 10^{12}$

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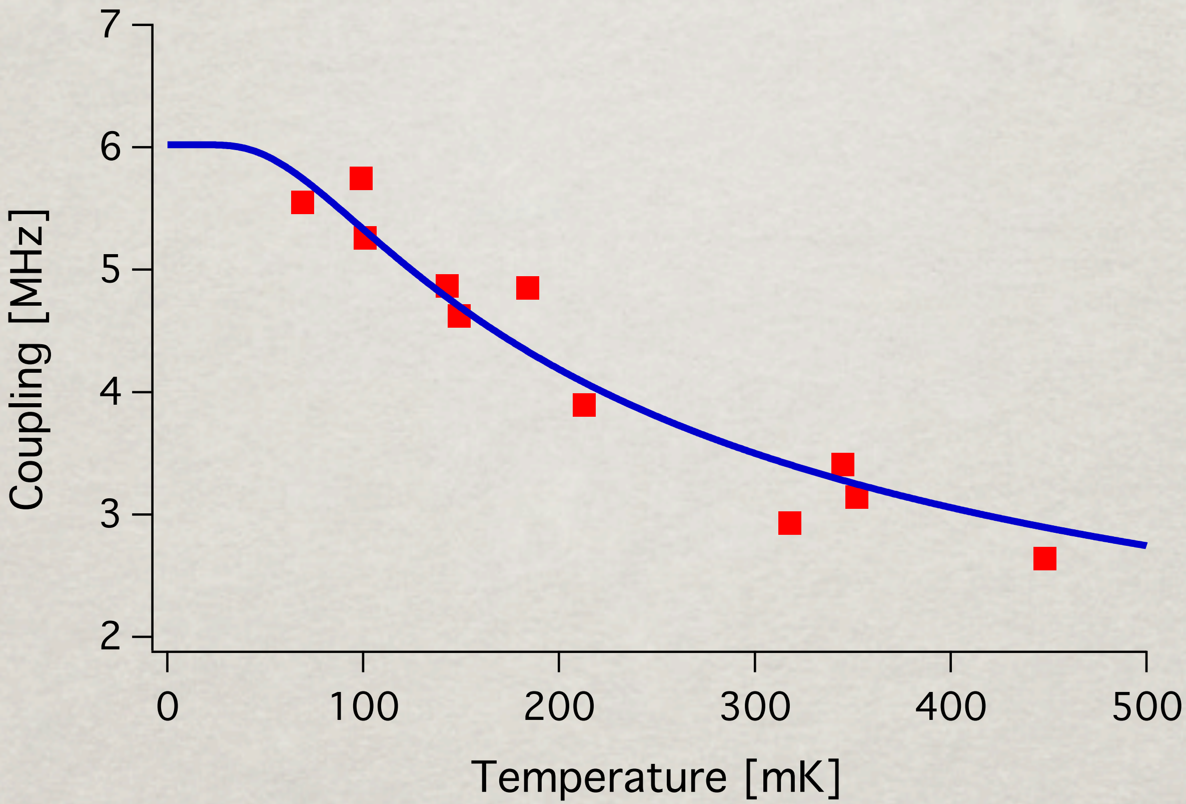
Temp. Dependence



- g_c declines with temp as the spins depolarize

$$g_c = g\sqrt{N(T)} = g_0\sqrt{\tanh\left(\frac{\hbar\omega}{k_B T}\right)}$$

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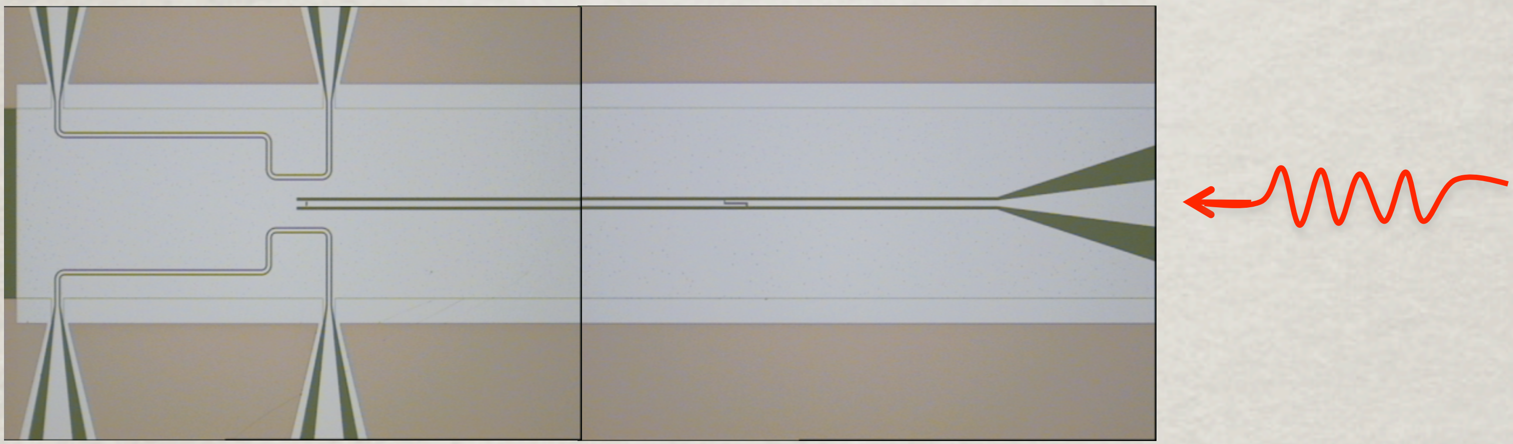
Propagating Photons



- Necessary to catch propagating photons originating outside of the cavity
- "Strong coupling" is not a requirement

Future Work

- Tunable resonator to measure zero field lines
- Compare with Nd
- Impedance matching and photonic memory...