Quasiparticles in Superconducting Quantum Circuits

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Acknowledgements

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Superconducting Electronics

- Quantum bits and artificial atoms
  - Quantum computing: Shor's algorithm, Grover's algorithm
  - Quantum simulation: Simulate dynamics, QVE
  - Large-N systems
- Quantum-limited amplifiers
  - Ultra-low-noise amplification of microwave signals
  - Squeezed light, light-matter interactions
- Sensitive detectors

Challenges

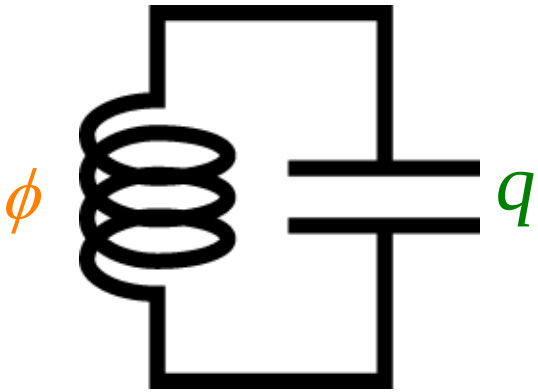
- Decoherence: I know $|\psi(0)\rangle$, what's $|\psi(t)\rangle$?
- Fidelity: want to store, transfer, and read out information without loss
- Scalability: more is different!

Improve technology → do new experiments → discover new limiting factors → figure out how to fix → improve technology…

First, the basics!

Building Blocks: Superconducting Resonator

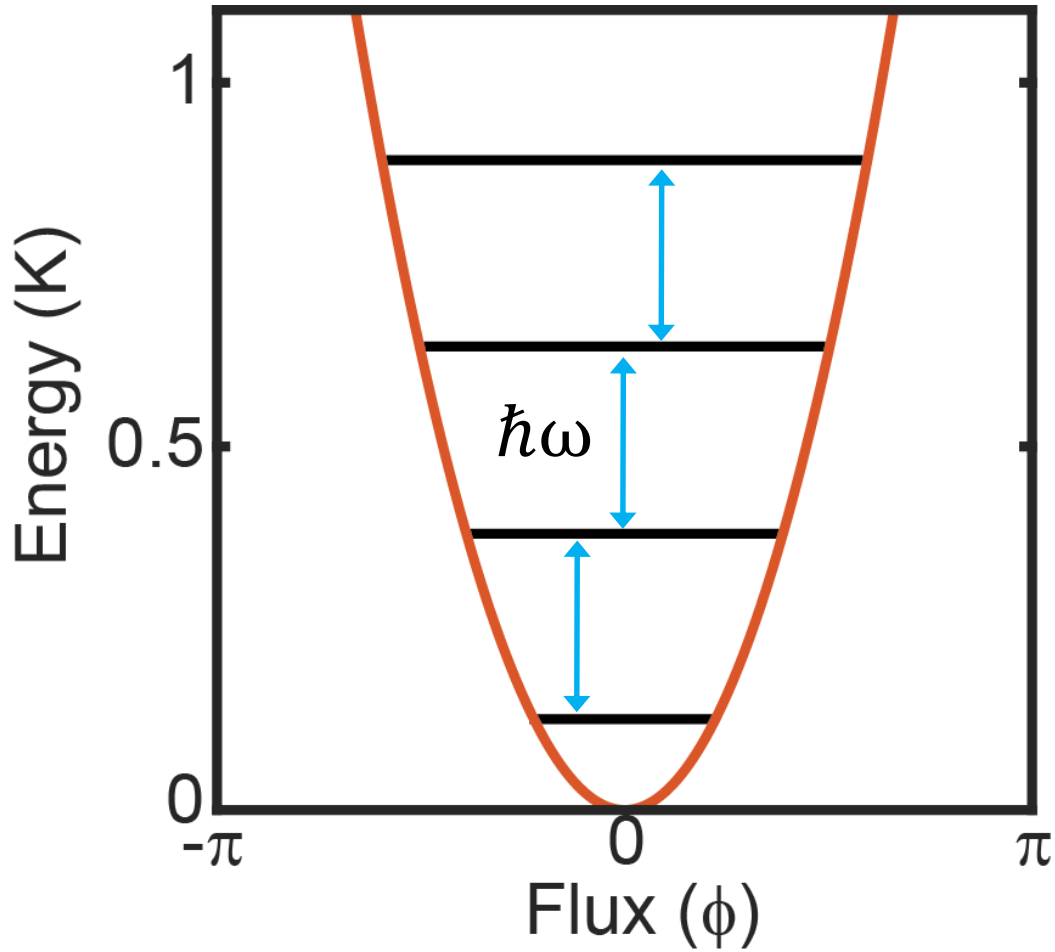
(a.k.a. Griffiths Chapter 2)



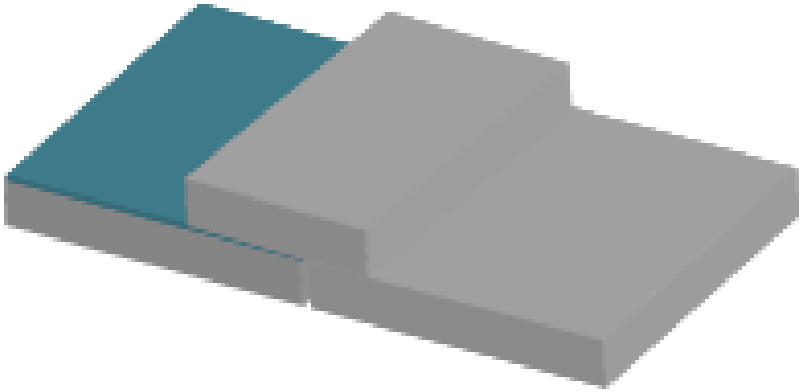
$$[\phi, q] = i\hbar$$

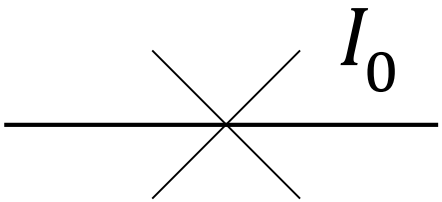
$$\phi = LI$$

$$q = CV$$



Building Blocks: Josephson Junction



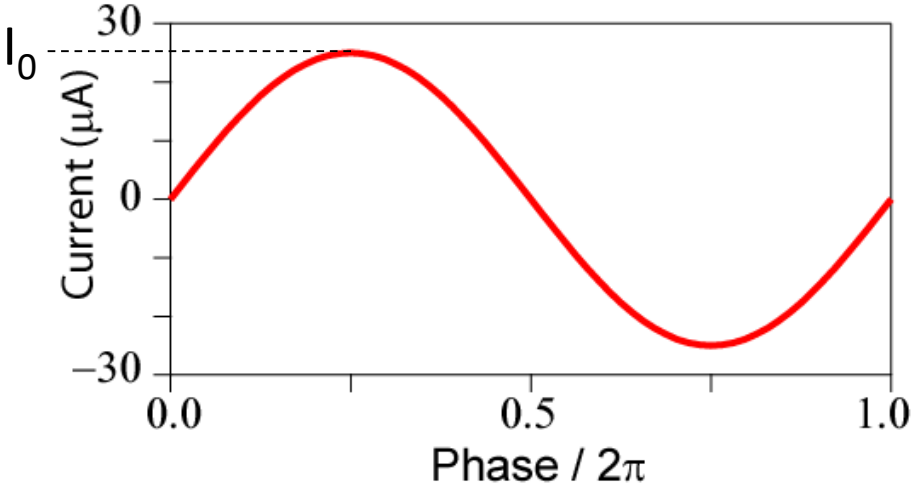


$$I = I_0 \sin\delta$$

$$V = \frac{\hbar}{2e}\frac{d\delta}{dt}$$

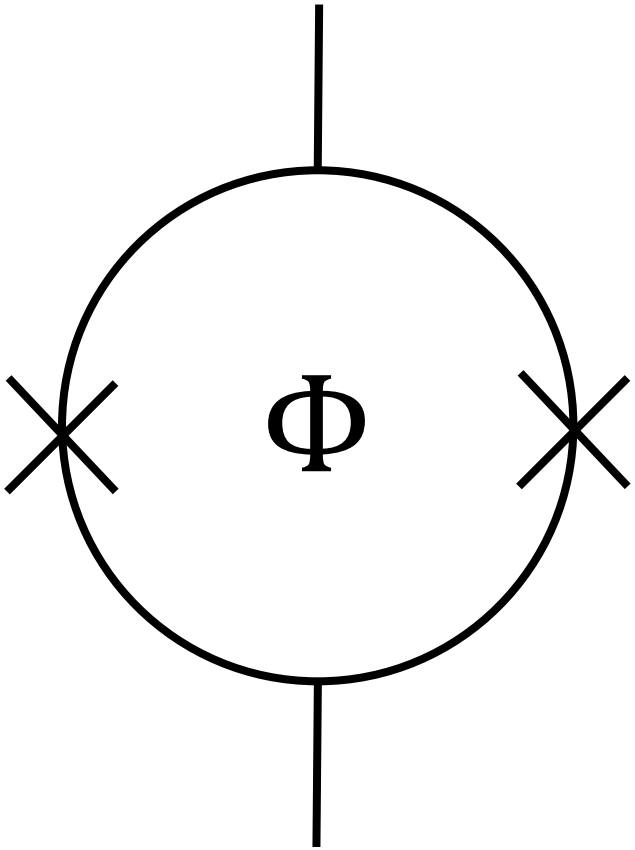
$$V = \frac{\hbar}{2eI_0\cos\delta}\frac{dI}{dt}$$

$$L_J = \frac{\hbar}{2eI_0\cos\delta} = \frac{L_0}{\cos\delta}$$



Nonlinear inductor

Building Blocks: SQUID

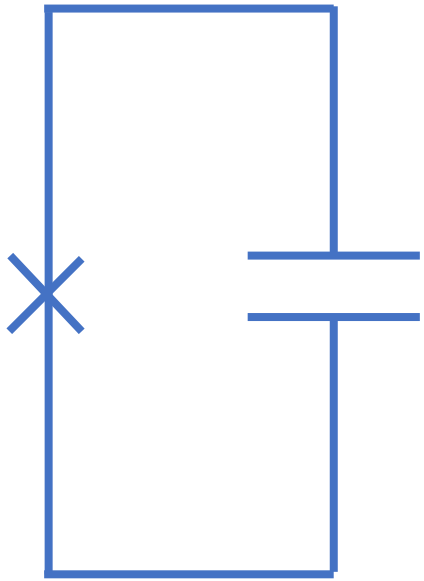


$$I_C = 2\, I_0\, \left|\cos\frac{\pi\Phi}{\Phi_0}\right|$$

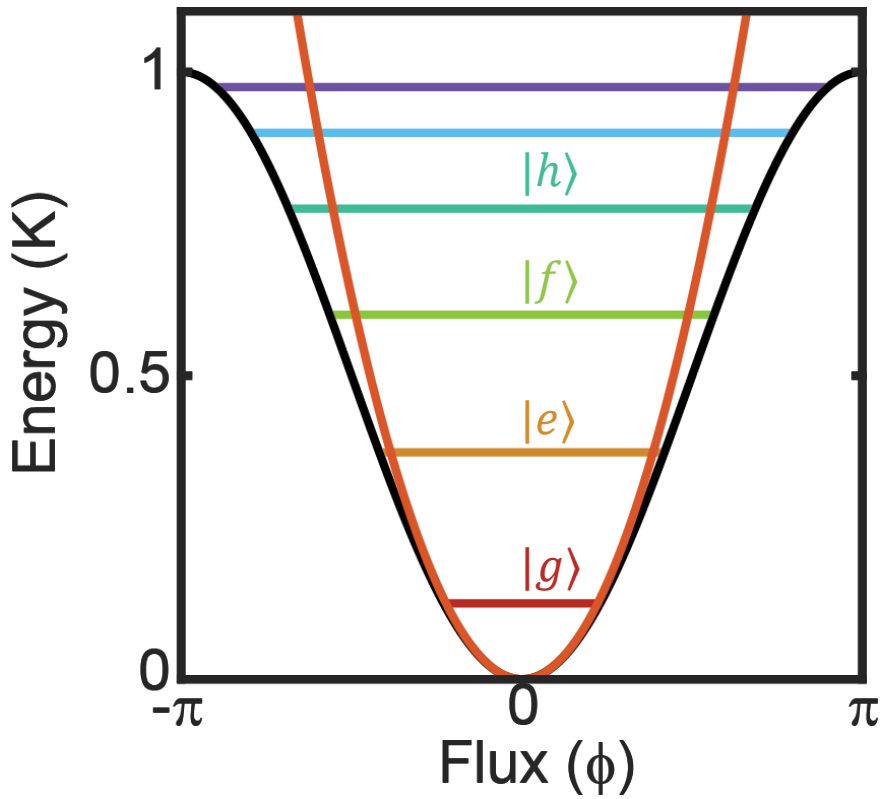
$$L_S = \frac{L_J}{2\, \left|\cos\frac{\pi\Phi}{\Phi_0}\right|}$$

For our purposes: SQUID acts as flux-tunable JJ

Transmon Qubit / AA

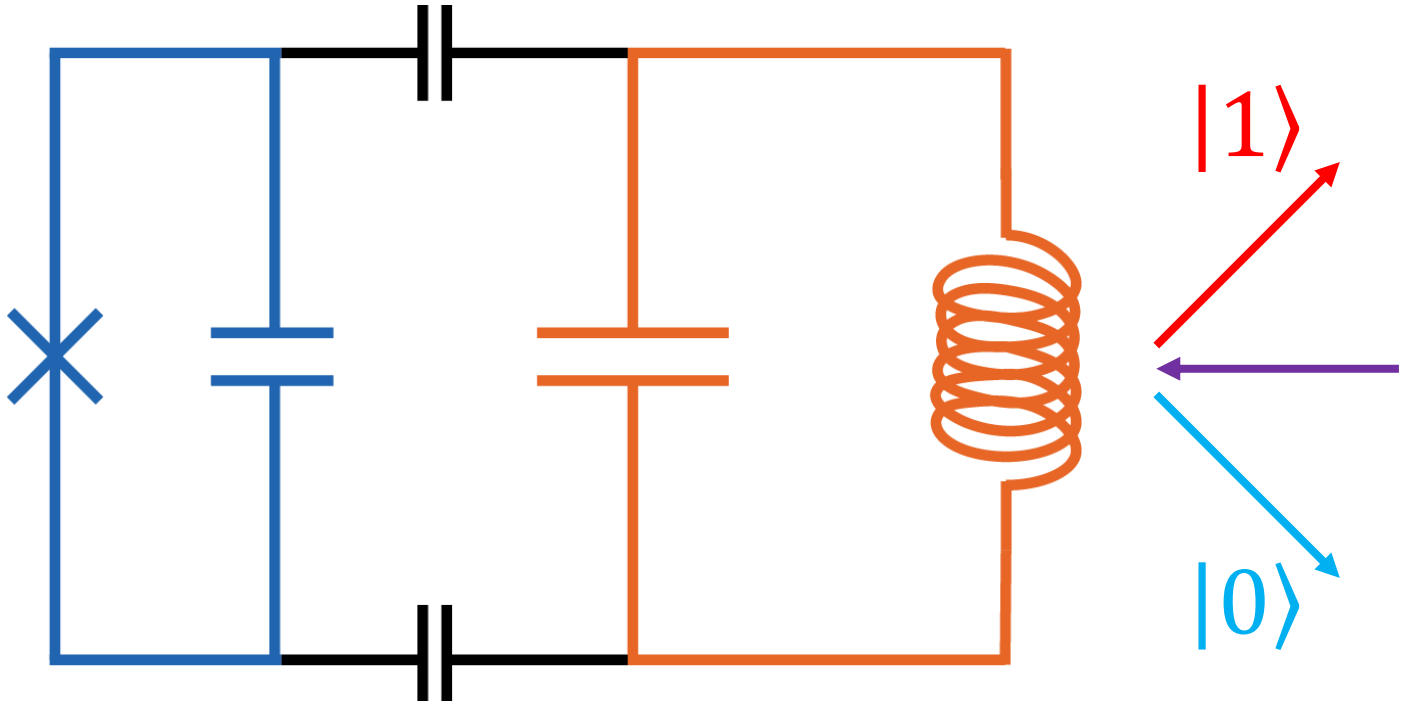


(JJ could be SQUID)



- Weakly anharmonic oscillator (1-10% anharmonicity typical)
- Wavefunctions are harmonic oscillator states, 1-20 GHz
- Isolate $|g\rangle$, $|e\rangle$ as $|0\rangle, |1\rangle$
- Simple, coherent, easy to couple

Readout: cQED



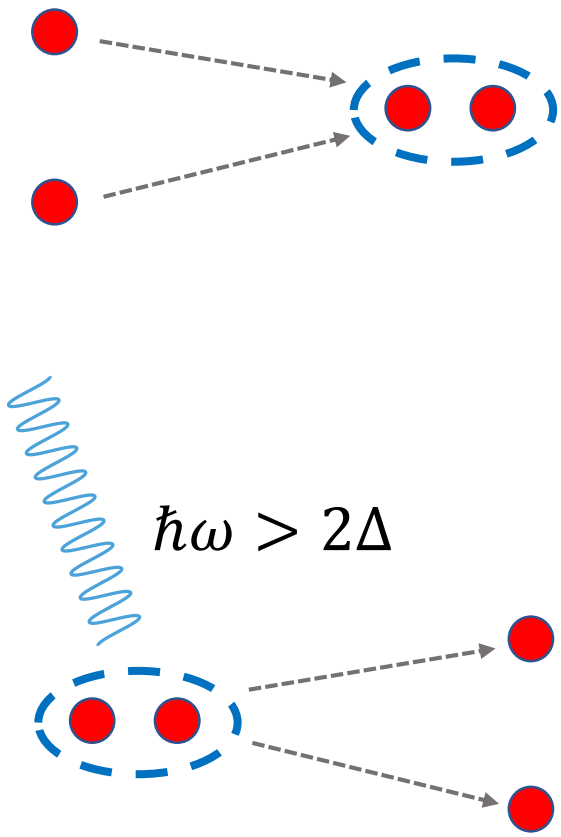
- Couple qubit to linear resonator / cavity
- Qubit can exchange E with cavity or modify cavity resonance
- Cavity protects qubit from environment
- Can be used for coupling, storage, as qubit, quantum optics, etc.

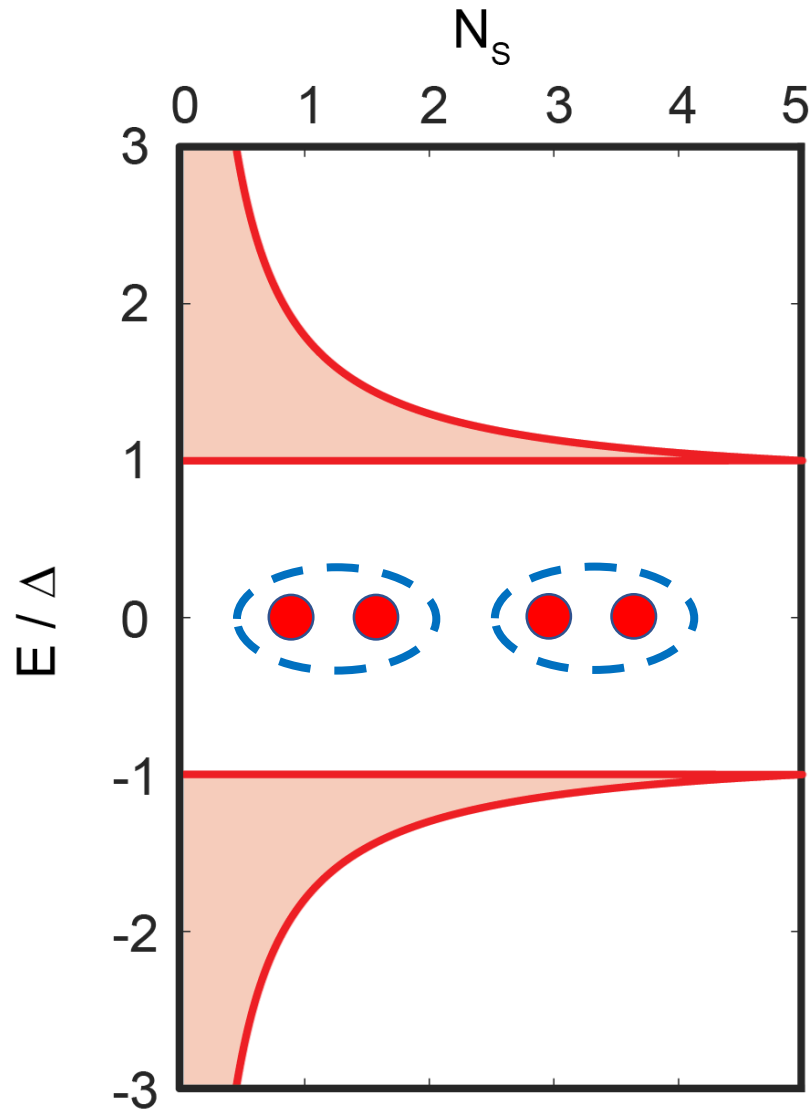
Decoherence

I know $|\psi(0)\rangle$, what's $|\psi(t)\rangle$?

- Relaxation: $|1\rangle \rightarrow |0\rangle$ (a.k.a. T_1)
  - Dielectric loss
  - Purcell decay
  - Quasiparticles
- Spurious excitation: $|0\rangle \rightarrow |1\rangle$
  - "Hot Purcell"
  - Quasiparticles
- Dephasing: $a|0\rangle + be^{i\phi}|1\rangle$, scrambles ϕ (a.k.a. $T_\phi \rightarrow T_2$)
  - "Hot cavity"
  - Flux noise
  - Quasiparticles

Superconducting Quasiparticles





Superconducting Quasiparticles

- Tunnel across junction → relaxation and spurious excitation (T_1)
- Transport in bulk → relaxation (weak) (T_1)
- Trap in junction → dephasing (T_2)

Too cold for thermal QPs, but QPs exist!

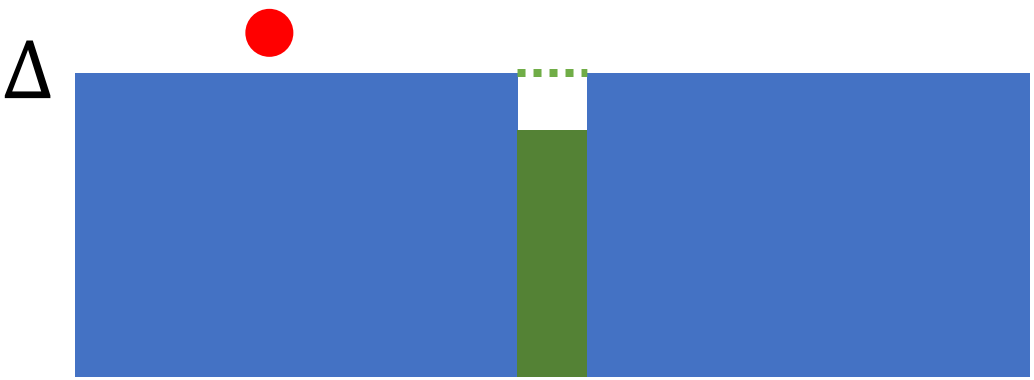
Hot spots? Thermal radiation? Cosmic rays? Defects?

Need to better understand behavior

Use trapping measurements

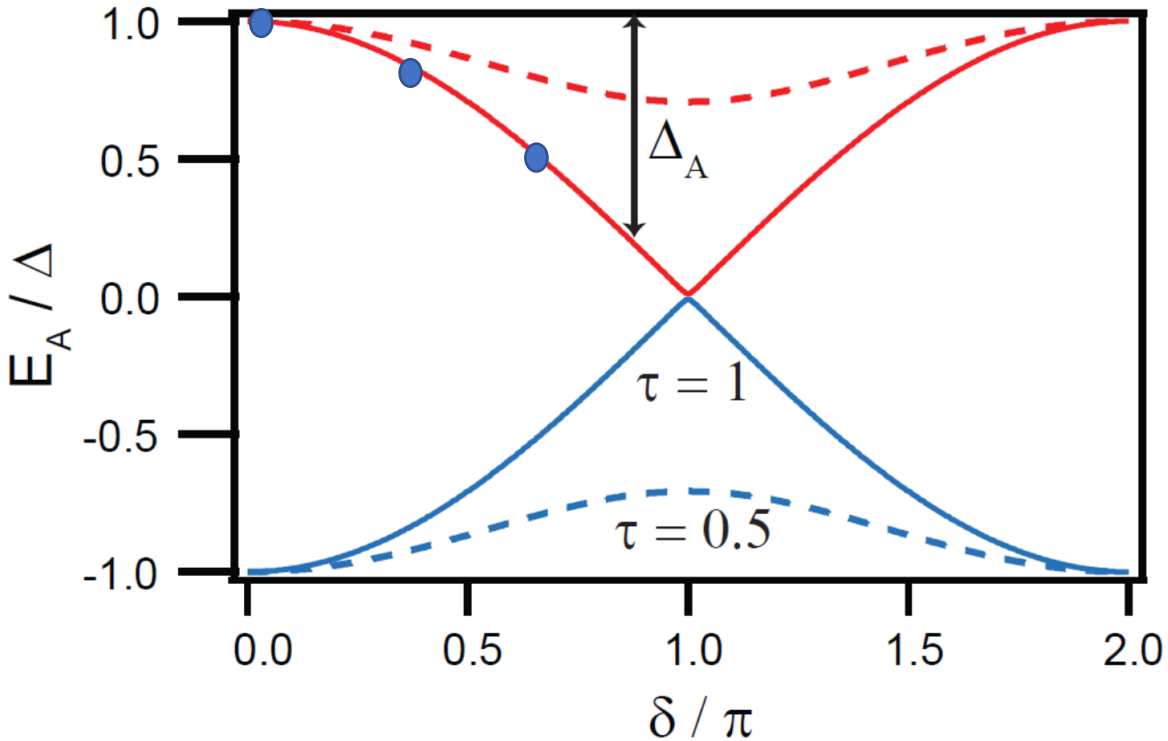
Taupin 2016, Vool 2014, Wang 2014, **Levenson-Falk 2014**, Ristè 2013, Wenner 2013, Bretheau 2013, Olivares 2013, Barends 2011, Lelander 2011, Zgirski 2011

How to Trap Your Quasiparticles

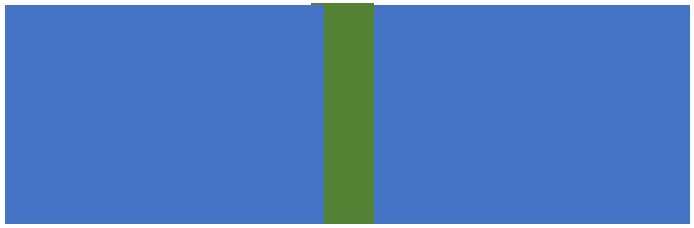


- QP falls into subgap state, gets stuck (deeper than $k_B T$)
- Need to be able to measure → circuit sensitive to trap!
- Ideally, we can:
  1. Tune trap energy
  2. Reset trap on demand
  3. Measure single trapped QP
  4. Measure dynamics

Andreev States

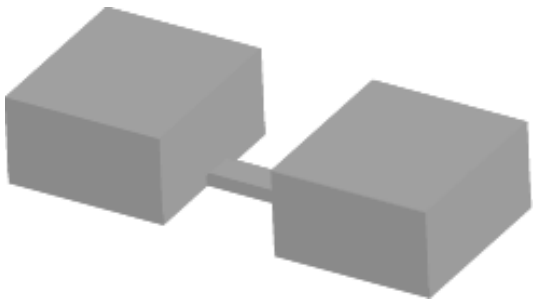


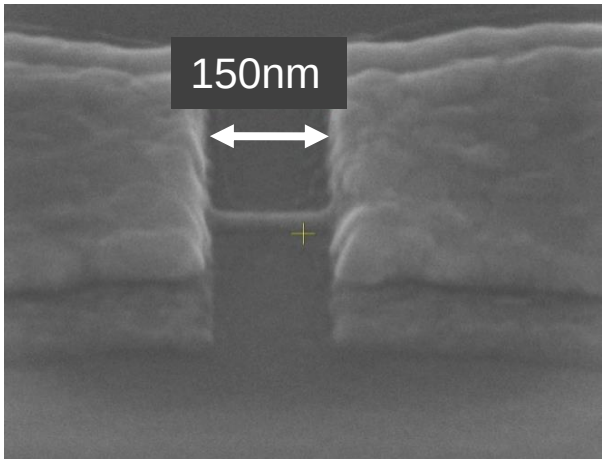
$$E_{A\pm} = \pm\Delta\sqrt{1 - \tau \sin^2 \frac{\delta}{2}}$$

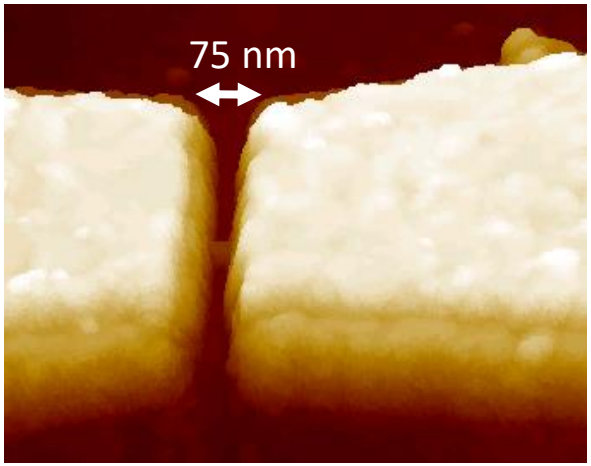


- Semiconductor picture: 1D conduction channels
- Trap forms in transmissive channel
- Trap depth tuned by phase bias
- Trapped QP detectable by effect on I_c (i.e. on L_J)

Nanobridge Junction



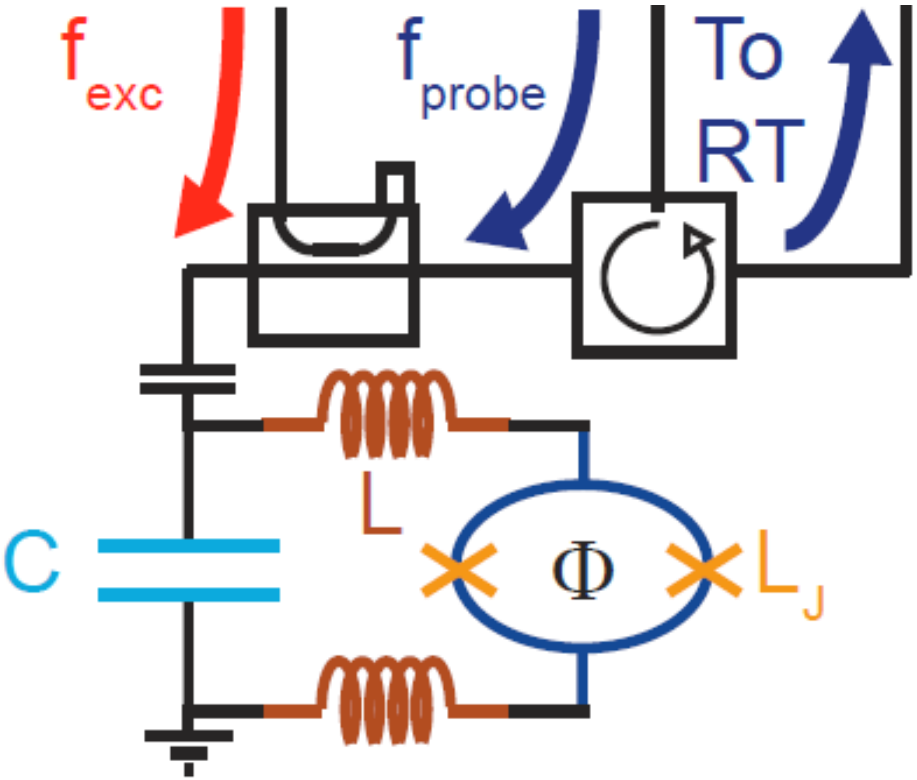


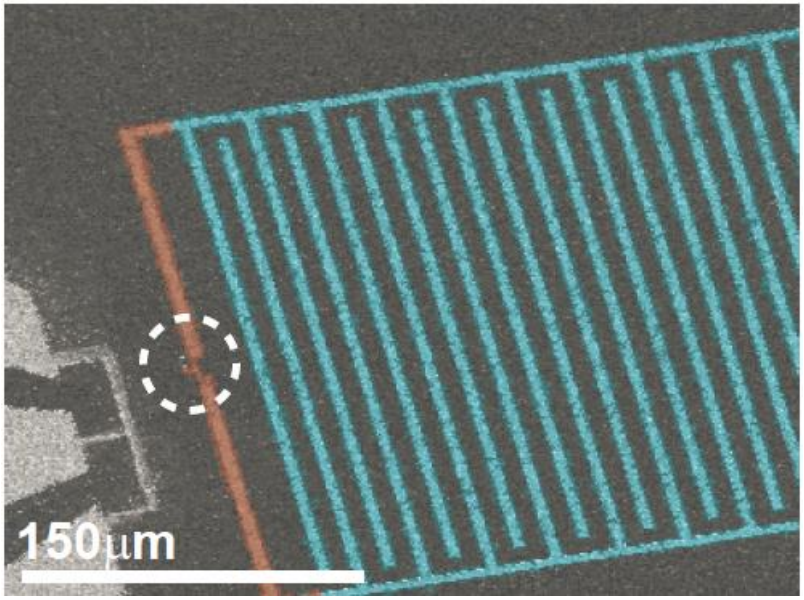


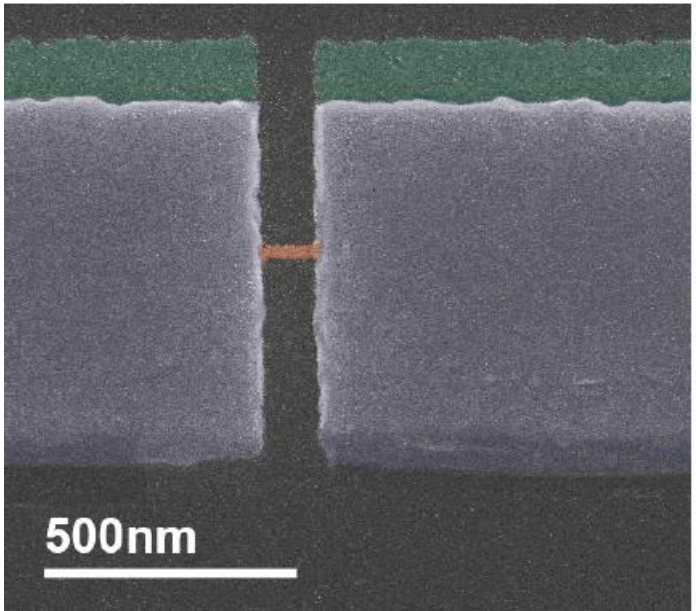
- 3D: thin bridge, thick banks → acts like ideal weak link
- All superconducting → trapping only due to Andreev states
- Many channels (100 – 1000 typical)
- Known distribution of transmittivity τ: $\rho(\tau) \sim \frac{1}{\tau\sqrt{1-\tau}}$

Vijay, Levenson-Falk, and Siddiqi 2010
Levenson-Falk, Vijay, and Siddiqi 2011

NanoSQUID Resonator



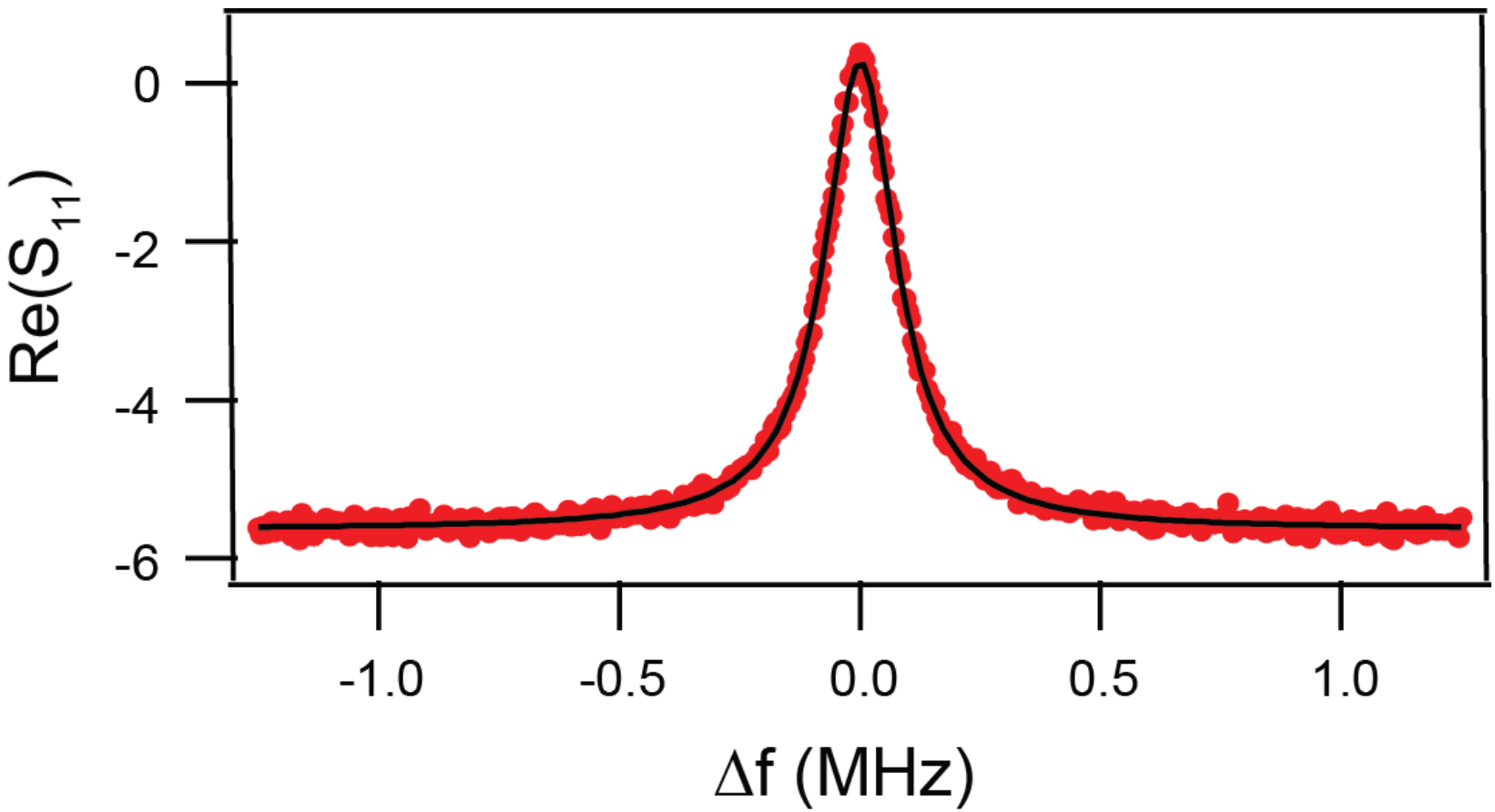




Model system, similar QP behavior to qubit

Levenson-Falk 2014

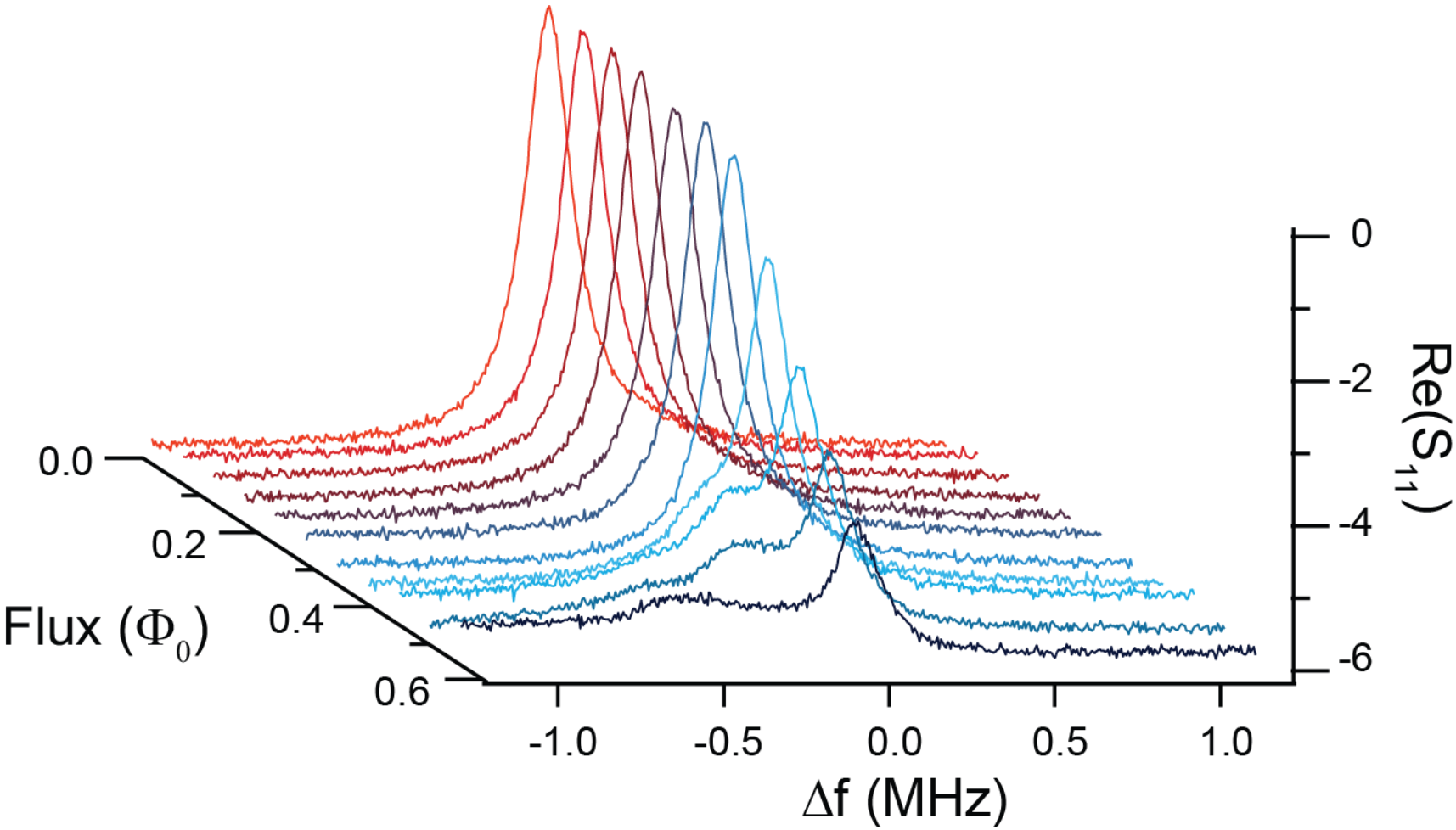
Resonance Lineshapes



No flux (phase) bias, no trap → ordinary resonance

Levenson-Falk 2014

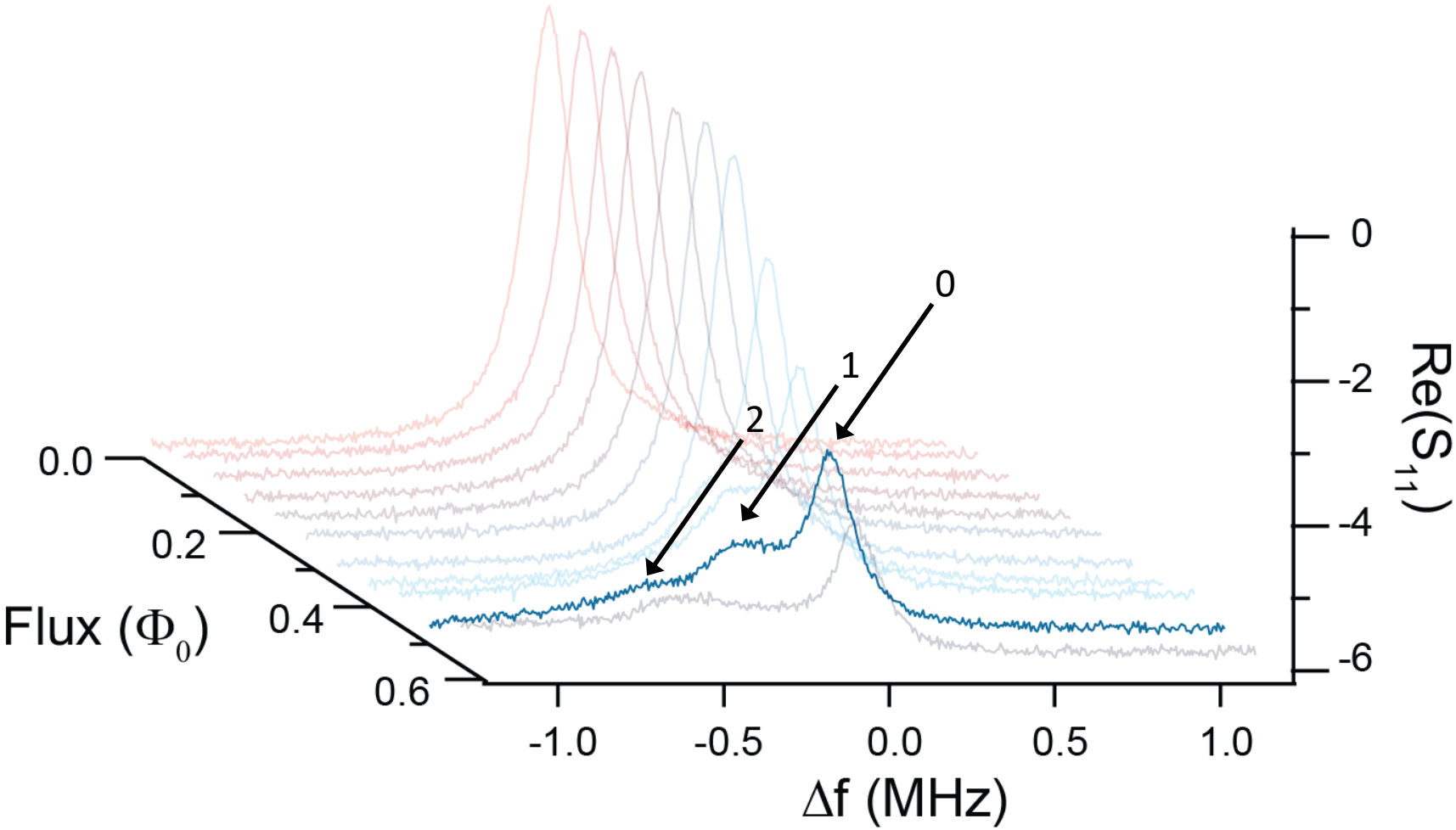
Resonance Lineshapes



Multiple resonances at finite flux!

Levenson-Falk 2014

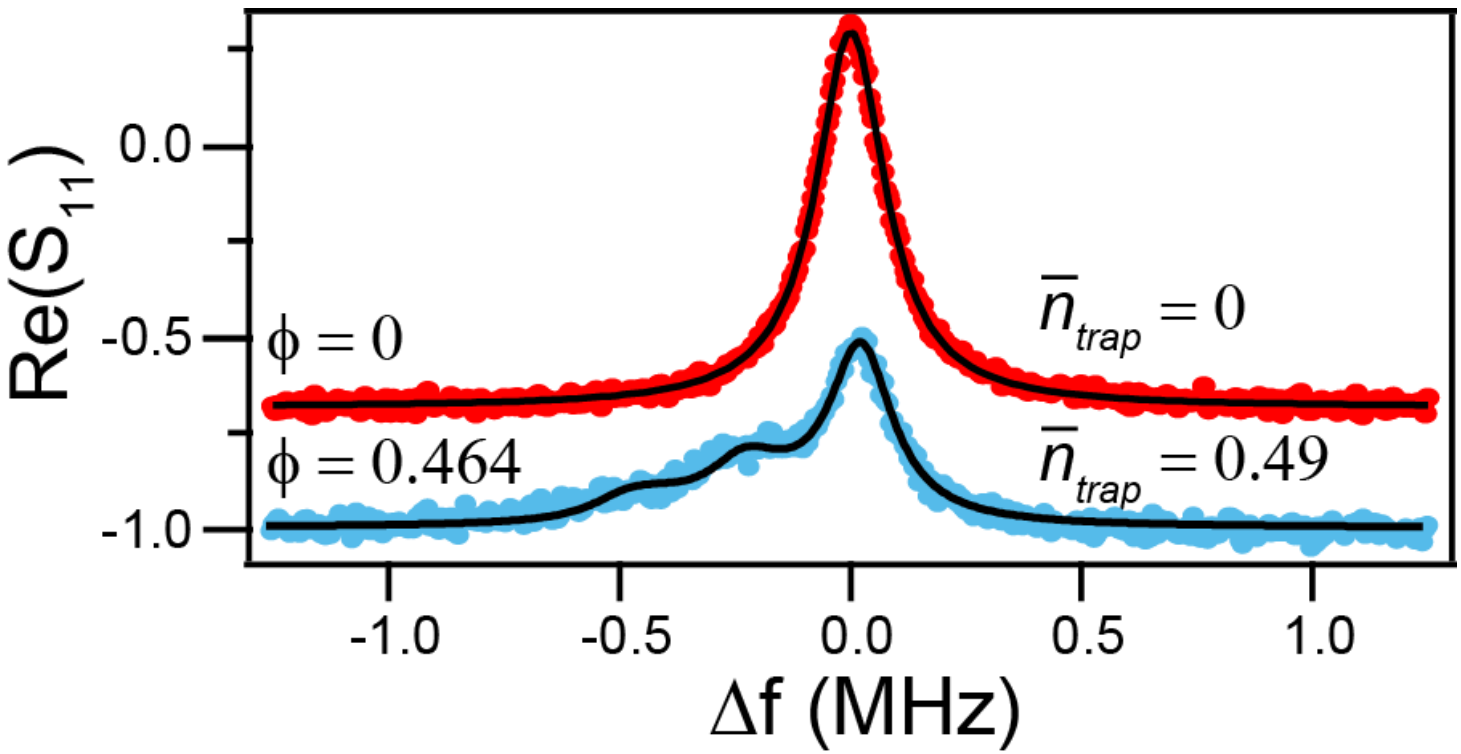
Resonance Lineshapes



Multiple resonances at finite flux!

Levenson-Falk 2014

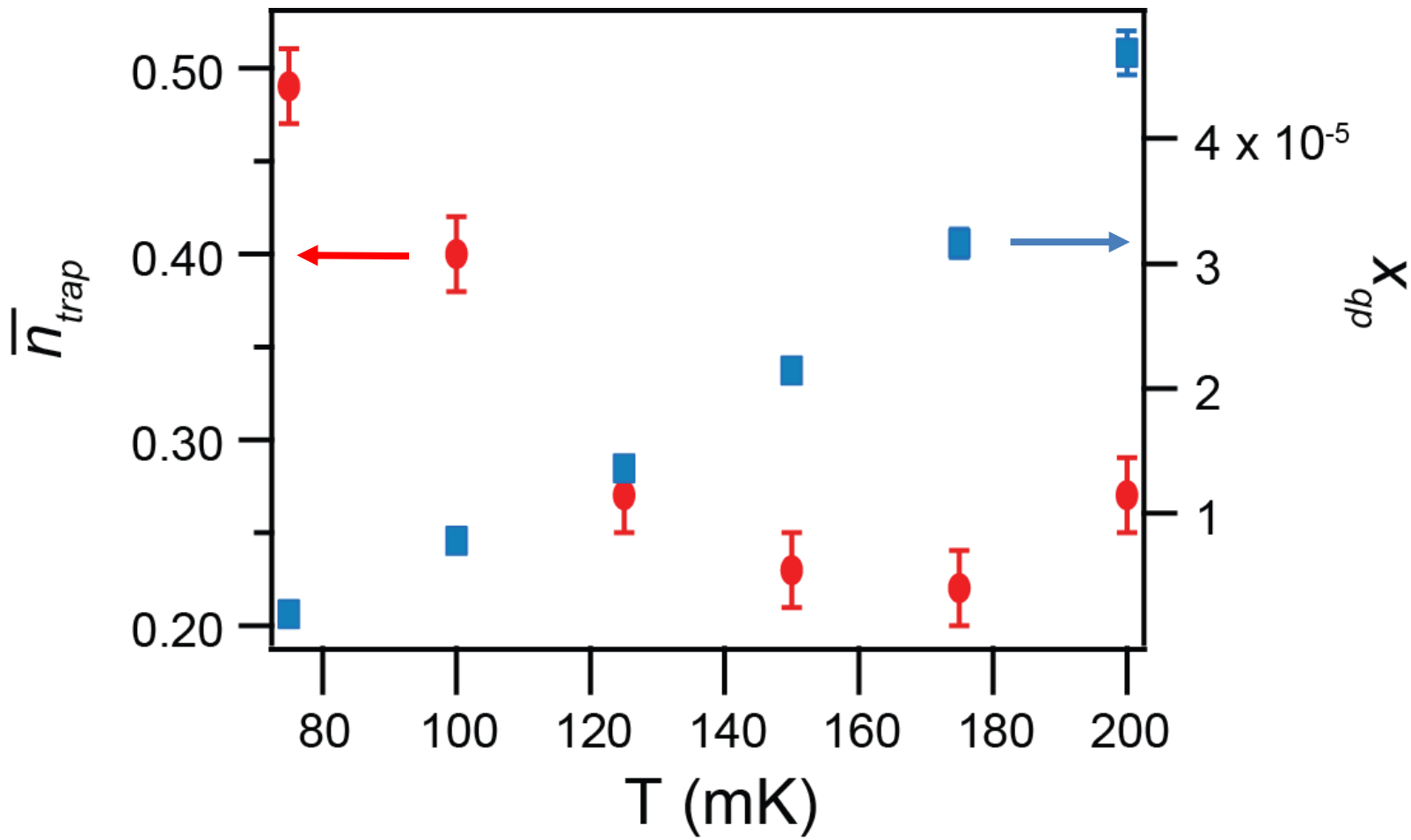
Fits to Resonance Lineshapes



- Ensemble measurement—averages over all configurations
- Thermal above 75 mK
- Not Poisson-distributed; P(n=2) higher than predicted from measured P(n=0)

Levenson-Falk 2014

Number of QPs

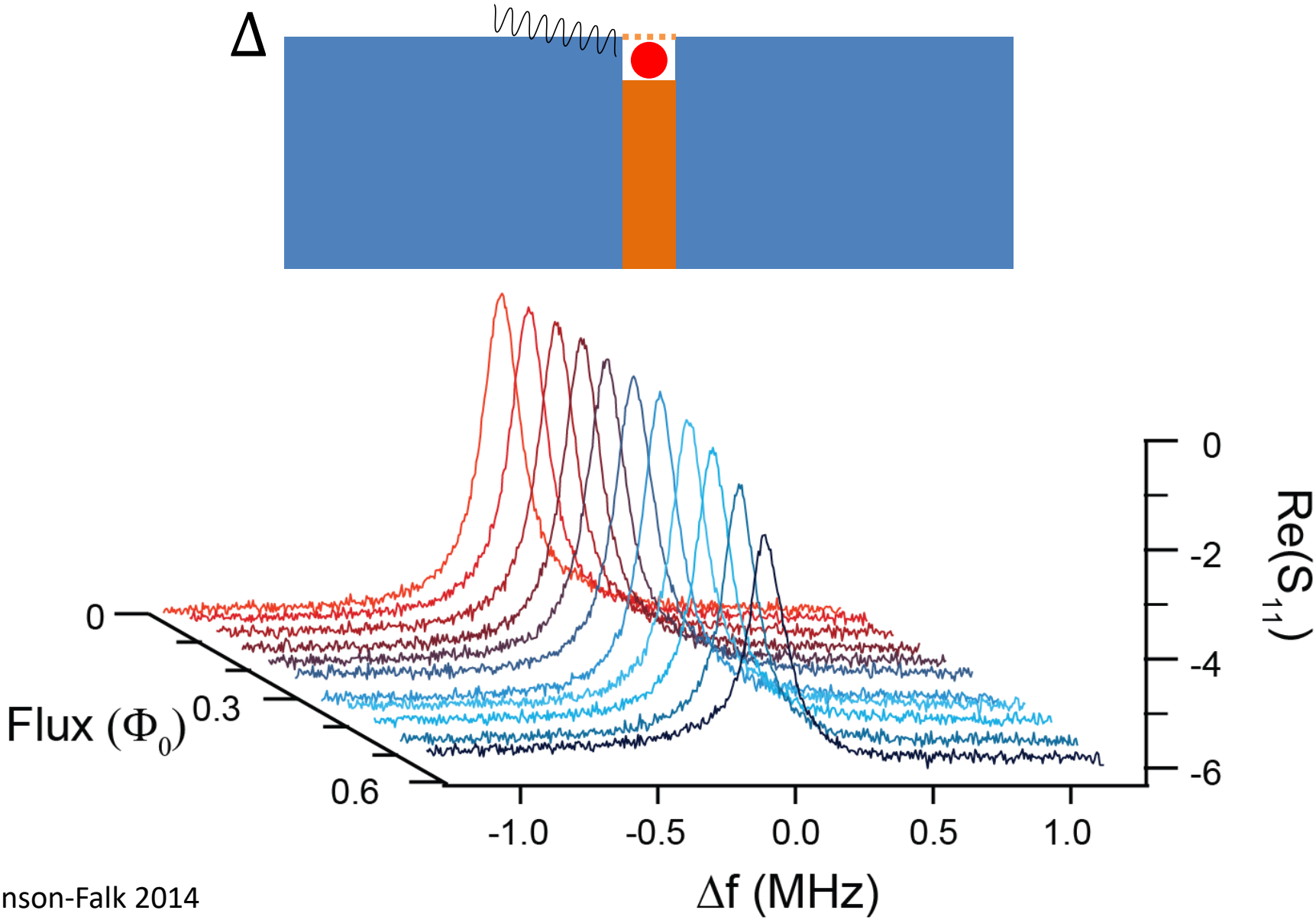


As T rises:

-Each individual QP less likely to trap (thermally excited)

-QP density rises (thermal population)

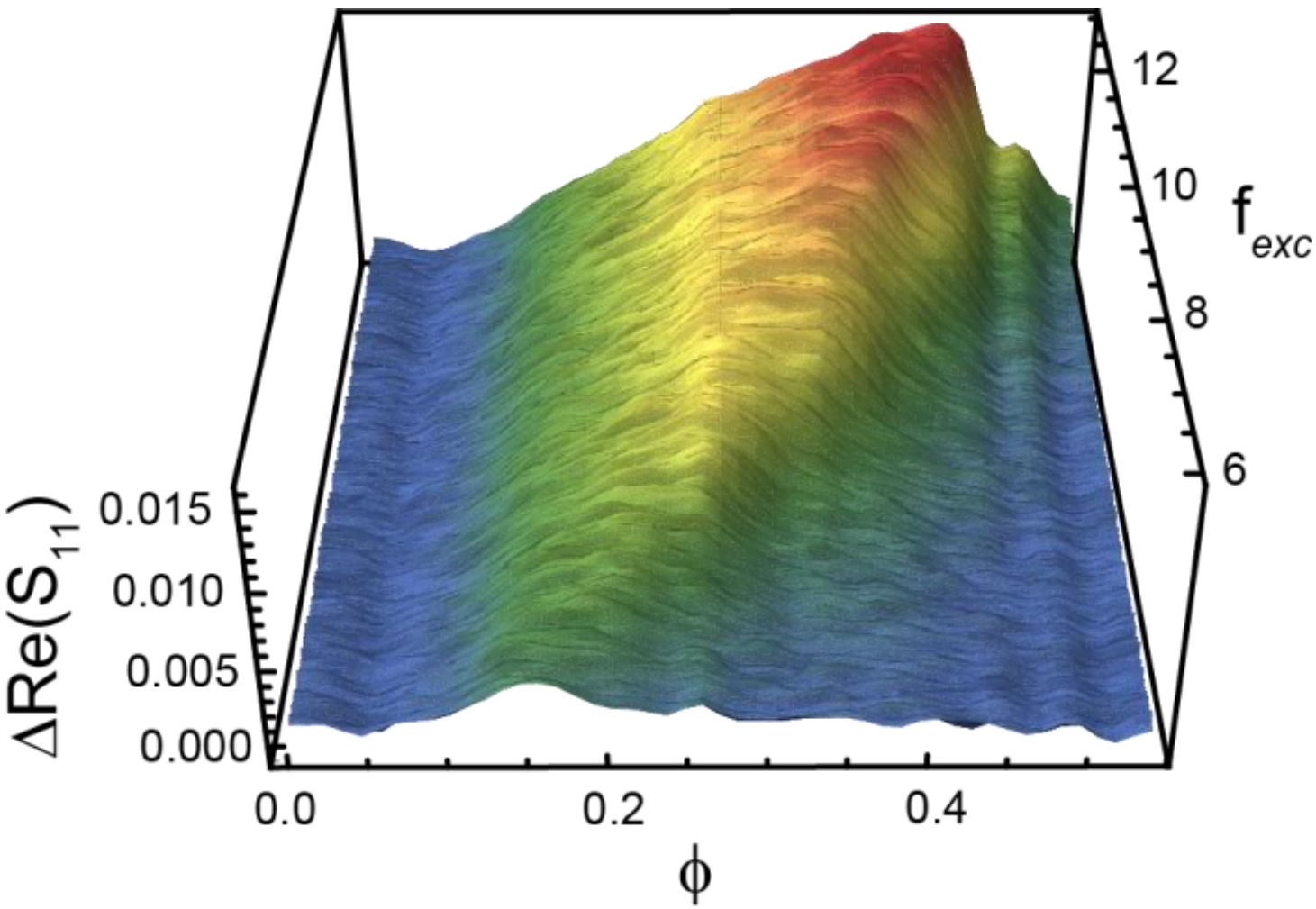
Clearing Traps



Levenson-Falk 2014

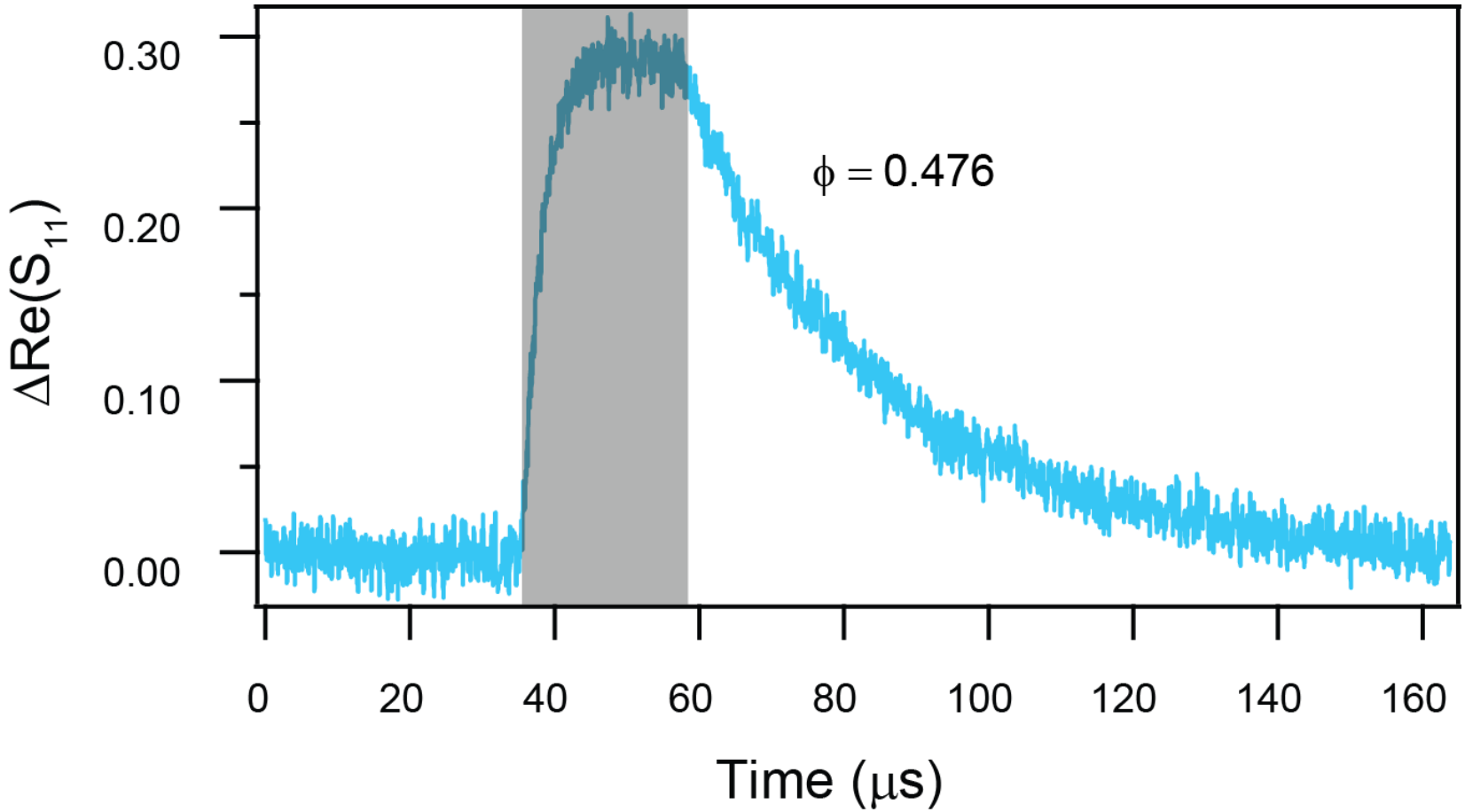
Bias Tone Spectroscopy

Probing "Andreev gap" $\Delta_A \equiv \Delta - E_A = \Delta - \Delta\sqrt{1 - \tau \sin^2 \frac{\delta}{2}}$



Consistent with theory

Untrapping and Retrapping

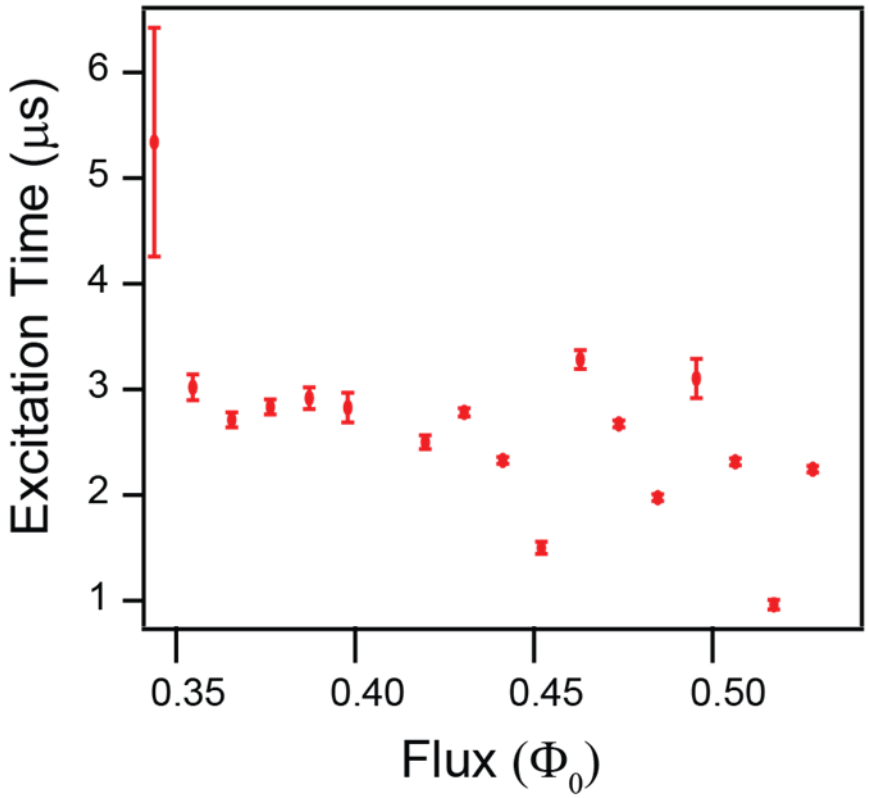


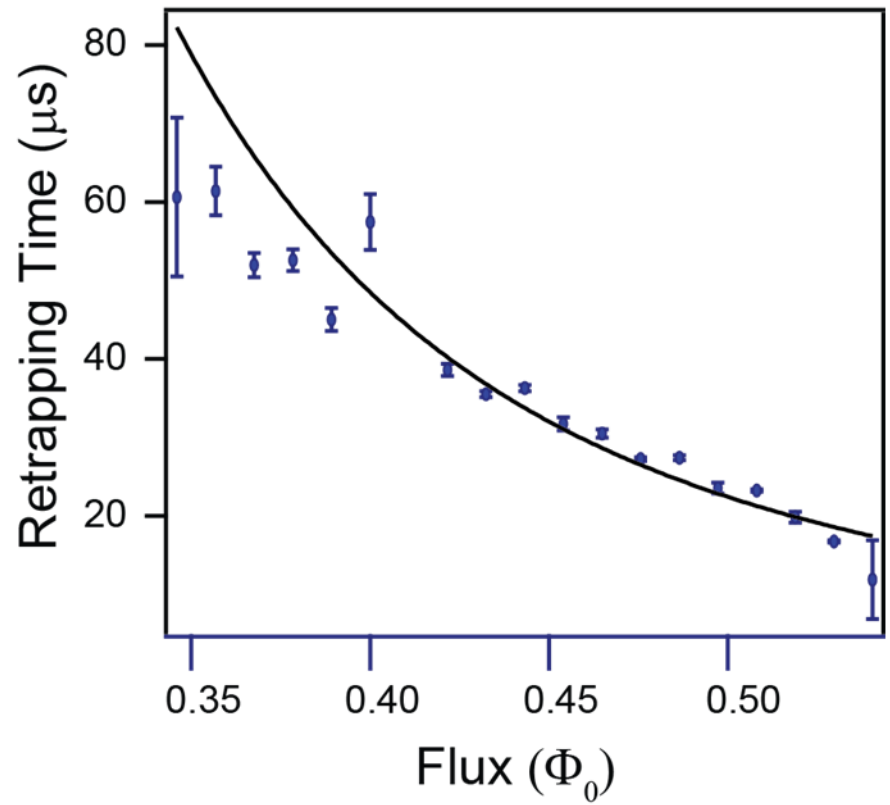
Electron-phonon relaxation:

$$H_{e-ph} = \frac{1}{\sqrt{N}} \sum_{\boldsymbol{k},\boldsymbol{q},\sigma} \alpha\sqrt{q}\,(a^*_{\boldsymbol{k}+\boldsymbol{q},\sigma} a_{\boldsymbol{k},\sigma} b_{\boldsymbol{q}} + a^*_{\boldsymbol{k},\sigma} a_{\boldsymbol{k}+\boldsymbol{q},\sigma} b^*_{\boldsymbol{q}})$$

Levenson-Falk 2014

Time Constants





Retrapping time: $\tau_T = \left(\frac{2\Delta}{\Delta - E_A}\right)^2 \tau_R$

Levenson-Falk 2014

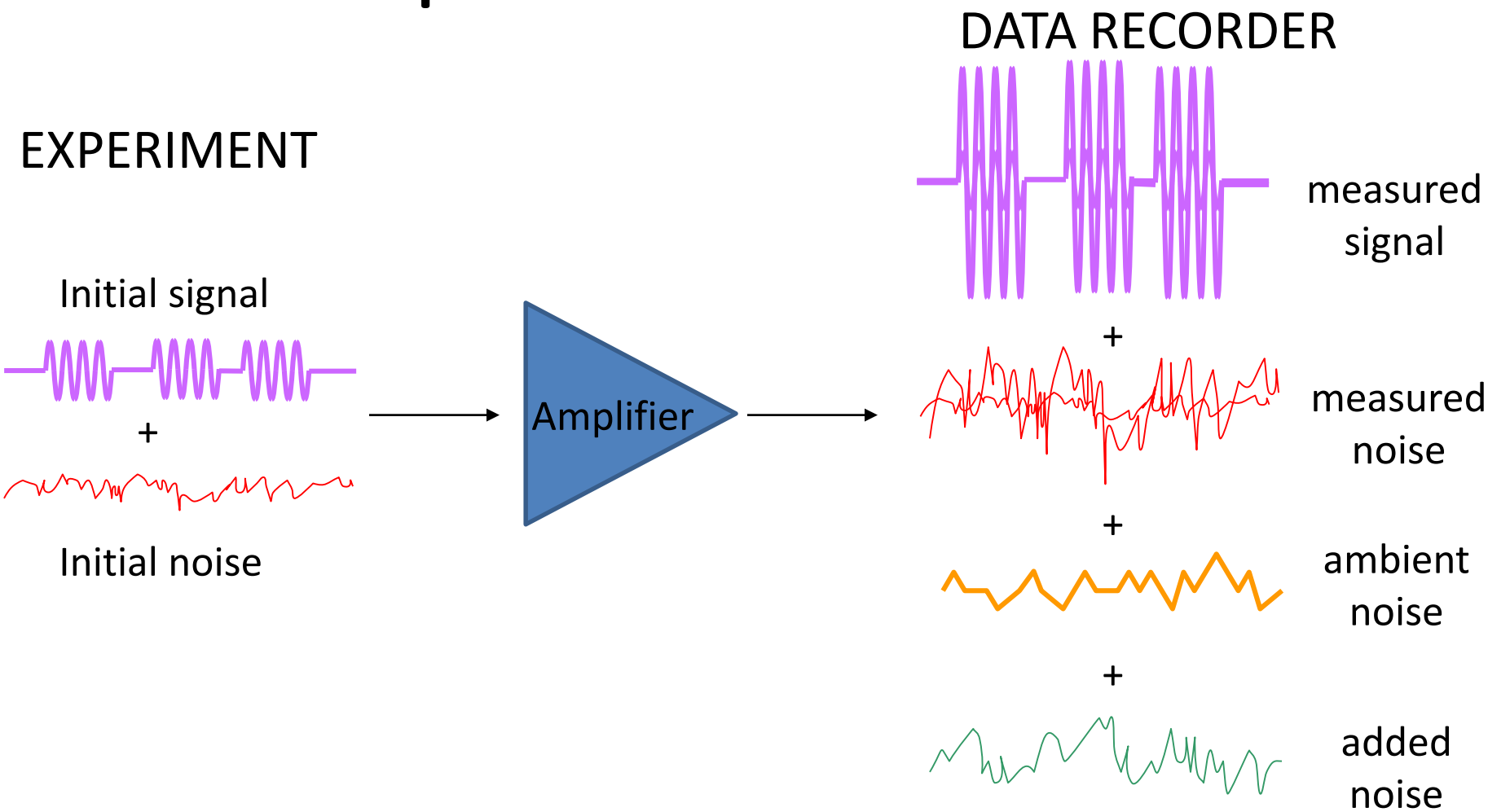
Next Steps

- Observe real time trapping / untrapping
- Statistics of QPs—correlation?
- Measure non-thermal distribution
- Explore use as detector
- Mitigation strategies—what limits annihilation rate?

Want to see things in real time, single-shot

Need more SNR!

Amplification and Noise

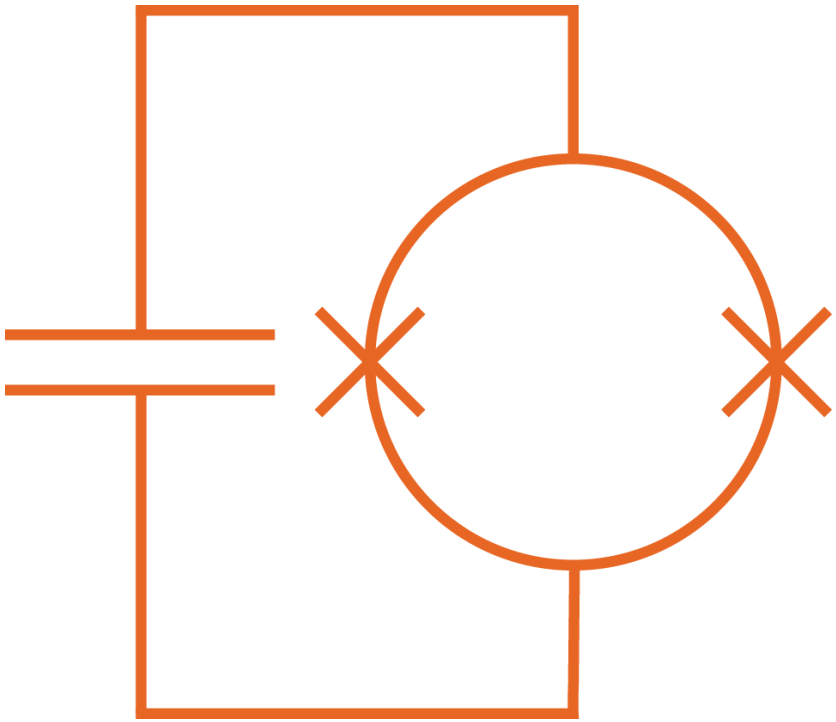


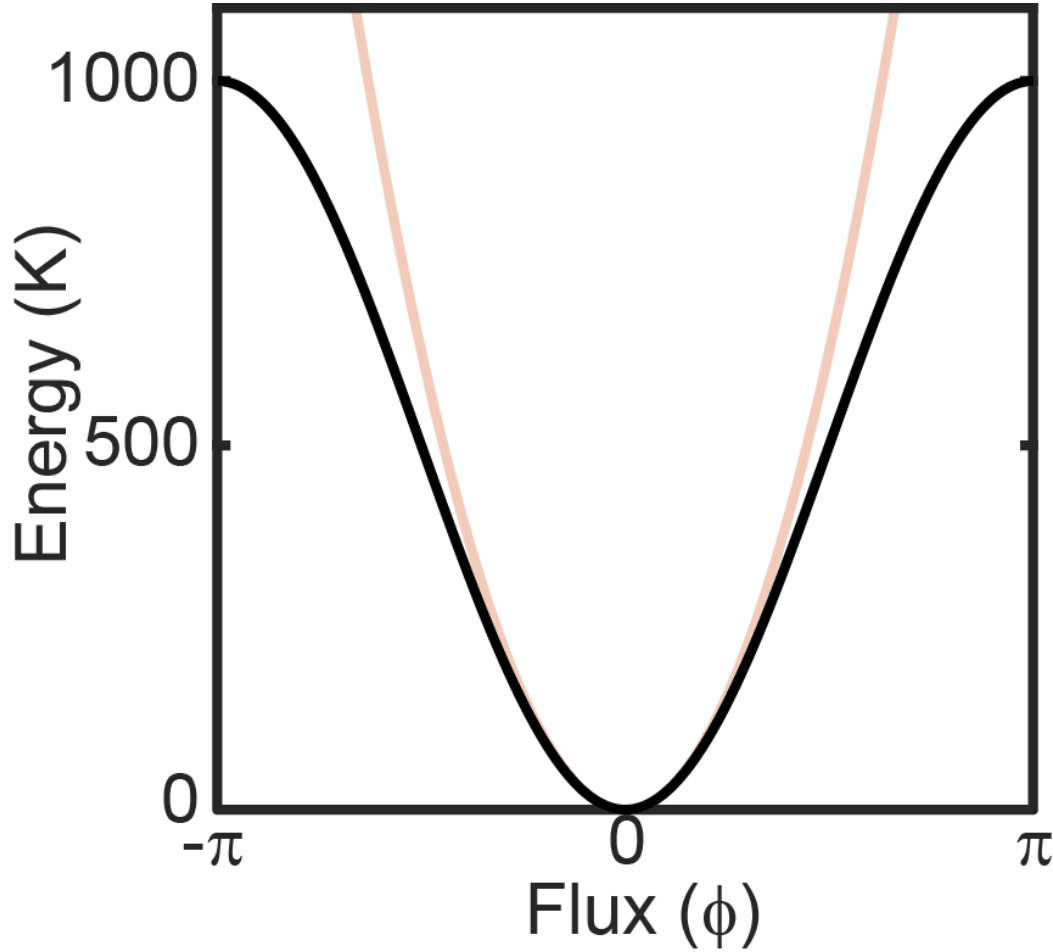
AMPLIFIER MAKES AMBIENT NOISE INCONSEQUENTIAL!

Amplifiers, in general, degrade signal to noise ratio

Usual amplifier (HEMT) limits SNR

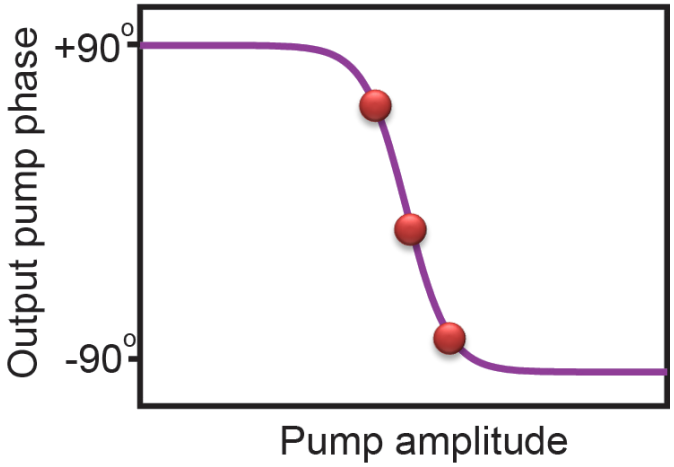
Nonlinear Resonator

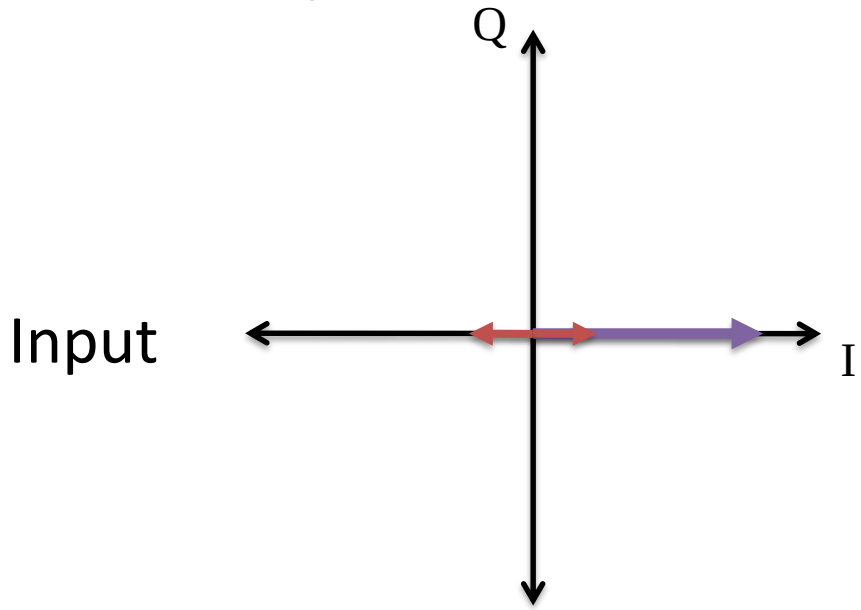


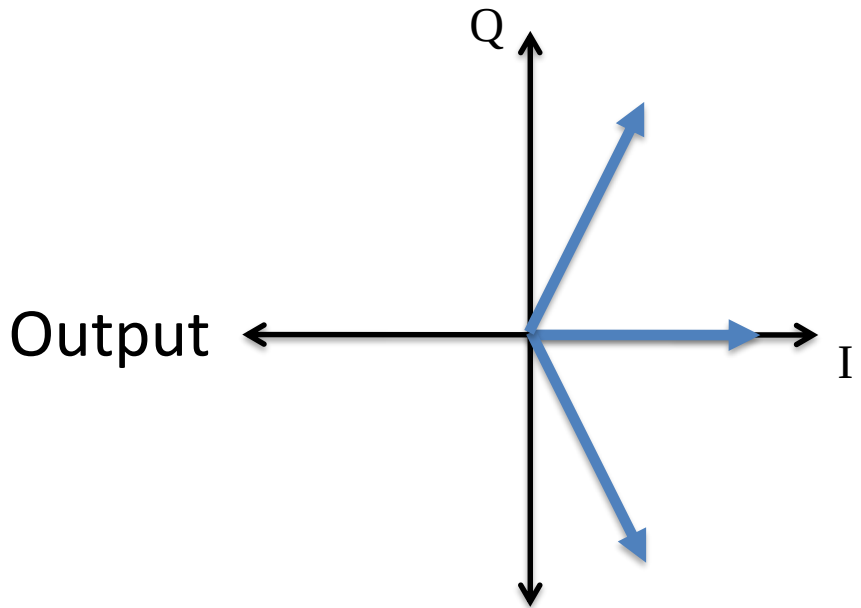


Many levels, can treat classically

Phase-sensitive amplification

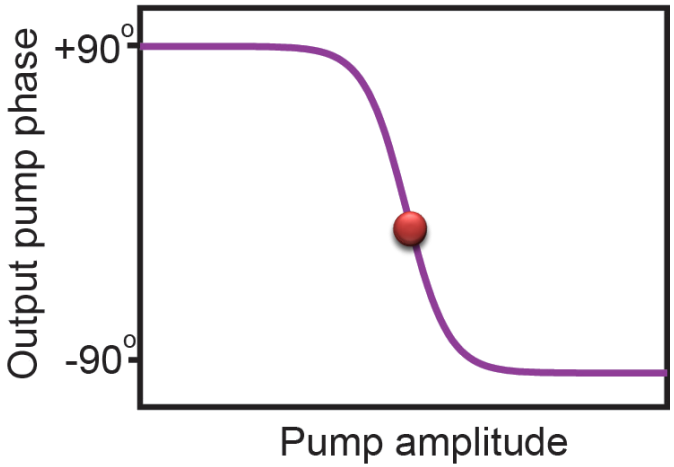


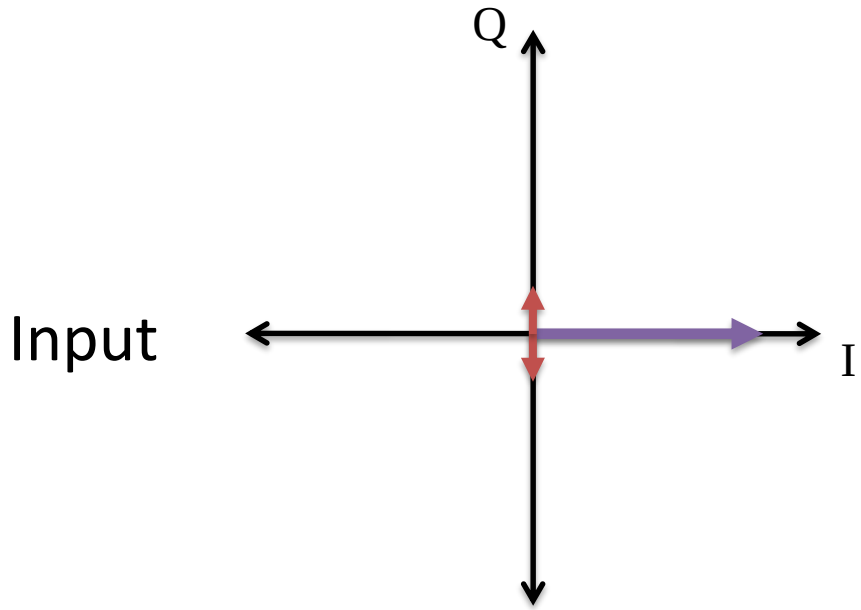


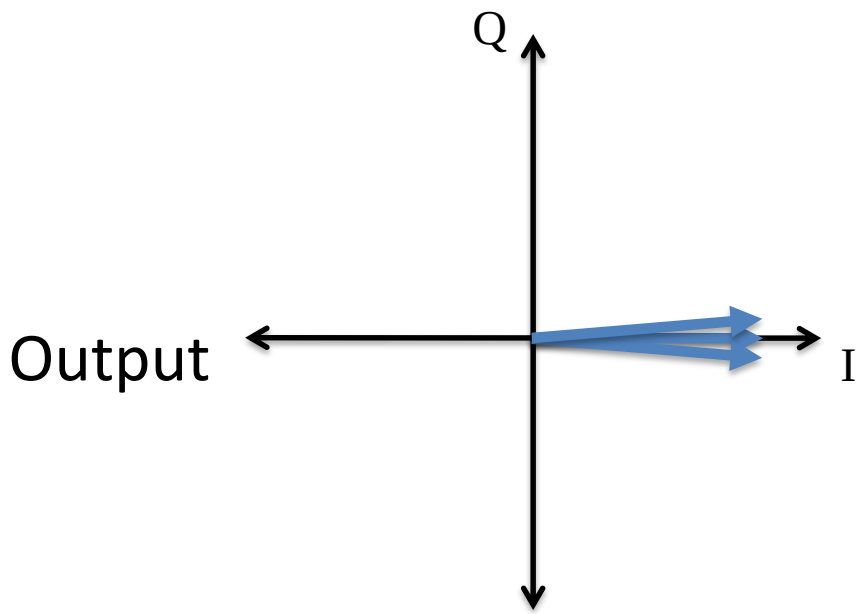


Signals in phase with the pump are amplified

Phase-sensitive amplification

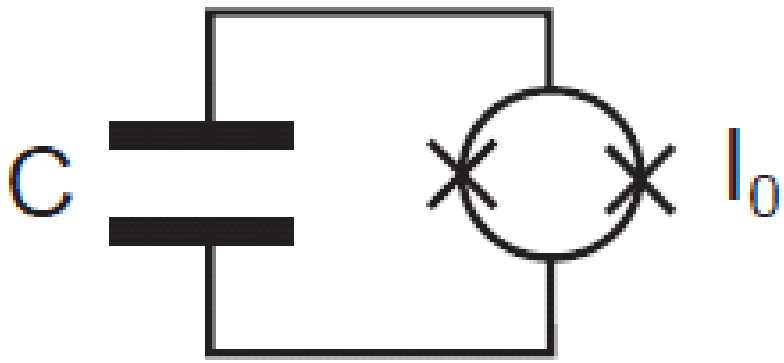


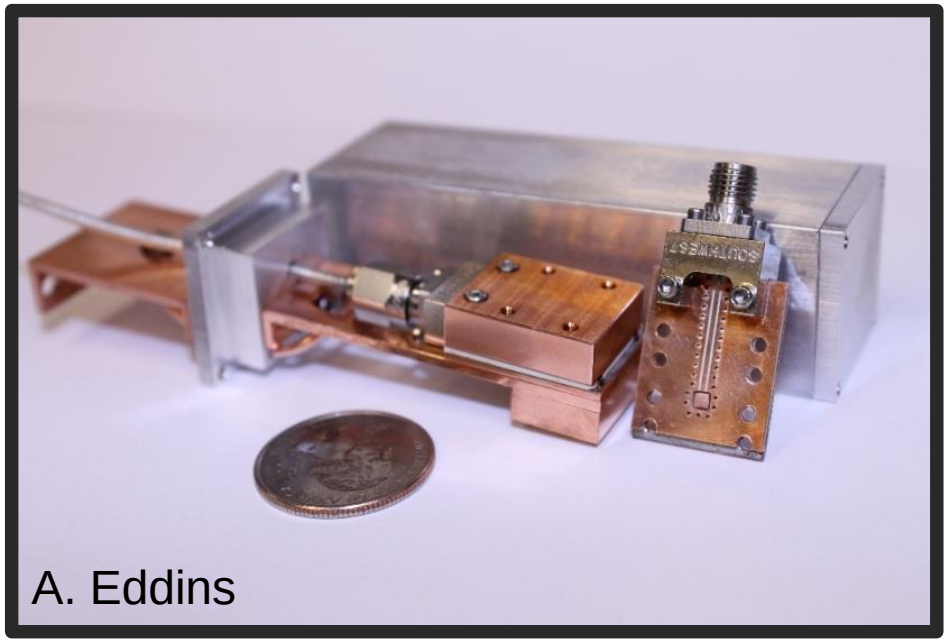




Signals in quadrature phase with the pump are de-amplified

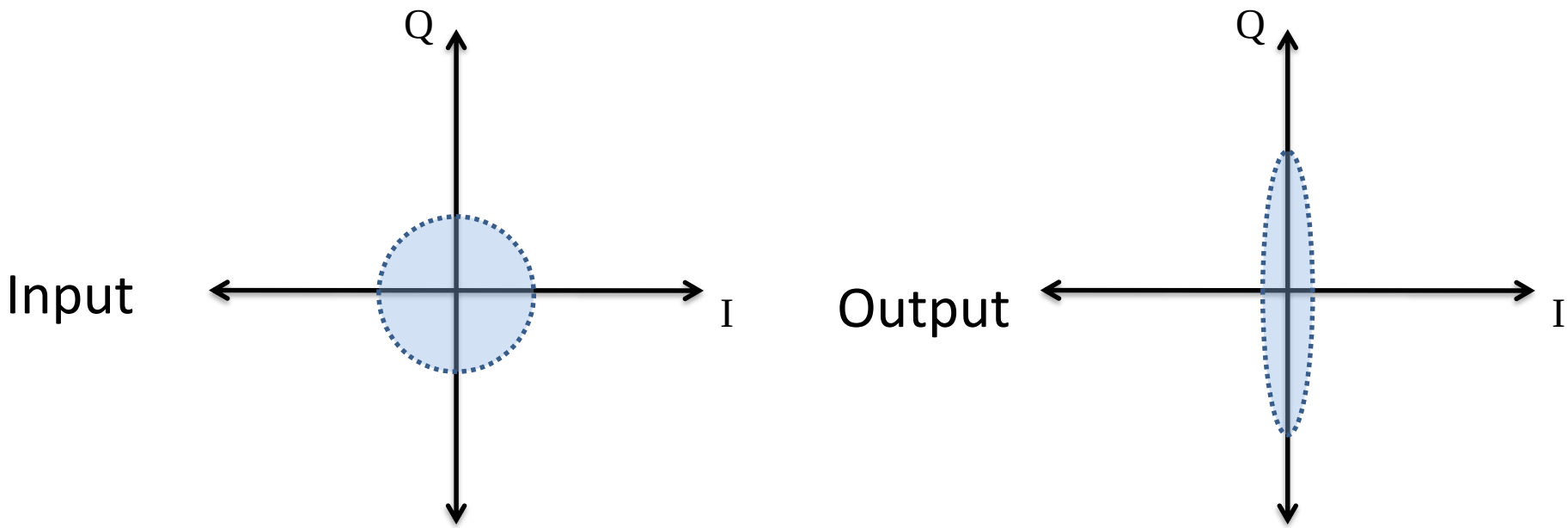
Lumped-element Josephson Parametric Amplifier (LJPA)





- 20-30 dB gain, 5-50 MHz BW
- Quantum limited noise: $k_B T_N = \frac{\hbar\omega}{2} \approx 150$ mK
- Can be used as squeezer for signals and vacuum

Squeezing



- Light-matter interactions, quantum measurement
- Lower noise “beyond quantum limit” for detectors
- Plug-n-play resource for quantum optics!

Murch 2013, Shokair 2014

THANK YOU!