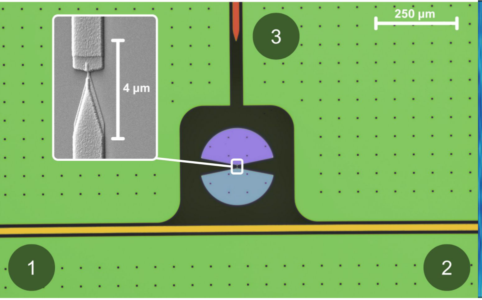
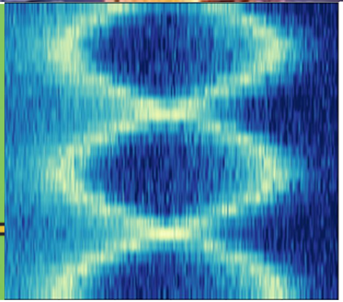
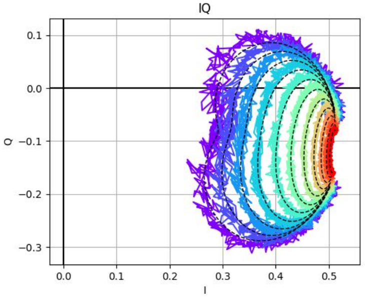
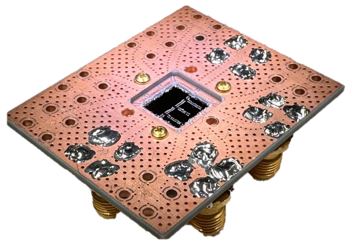
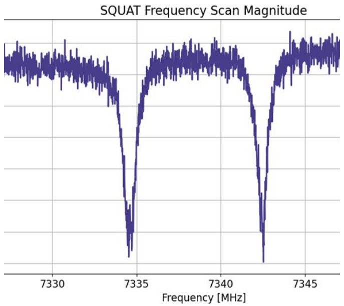
First demonstration of the Superconducting Quasiparticle Amplifying Transmon (SQUATs)









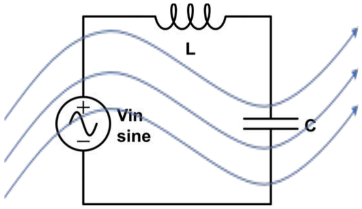


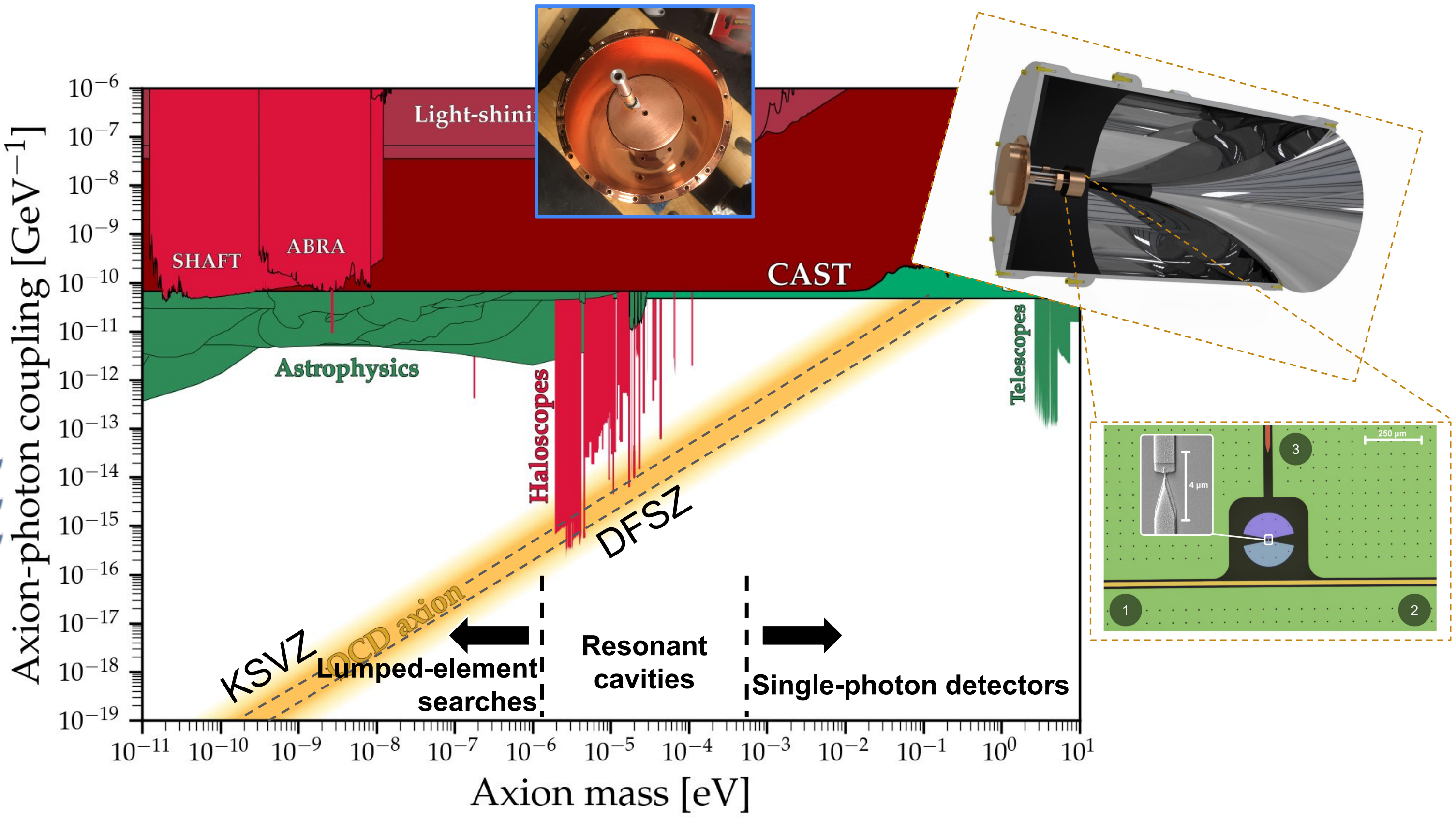
Alex Droster, postdoc at Stanford/SLAC
BREAD collaboration meeting, Harvard University
01/15/26

Outline

1. Single photon detectors for axion experiments
2. The quantum capacitance detector (QCD)
3. SQUATs
    a. Design, operating principle, readout
    b. Frequency-domain measurements
    c. Pulsed measurements
    d. Parity measurements
    e. Antenna modes
    f. Temperature dependence

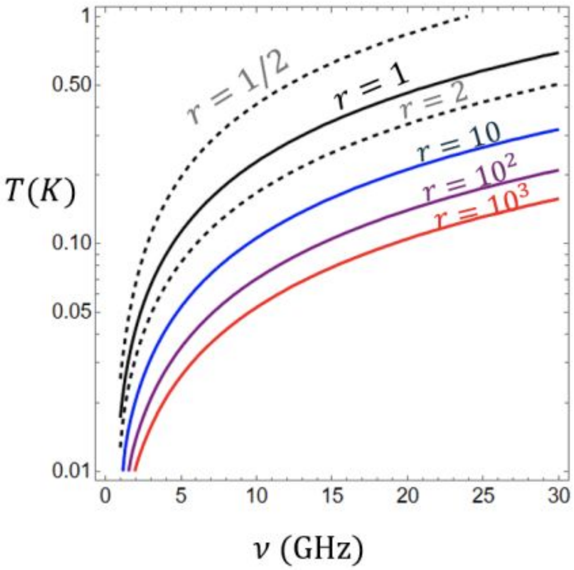
SQUATs as THz axion detectors





Searching for high-mass axions requires new detector technology

SQL amplifier vs 100s^{-1} dark count rate SPD

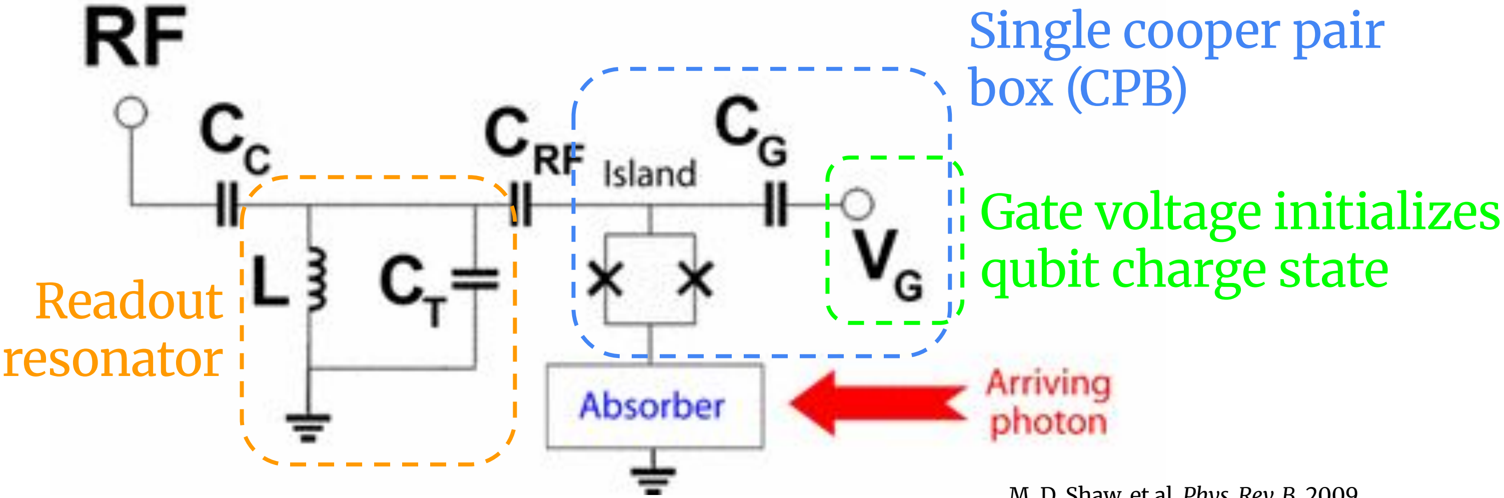


$$r = \frac{\text{Scan rate}_{SPD}}{\text{Scan rate}_{amp}}$$

Maximizing Quantum Enhancement in Axion Dark Matter Experiments, *Phys. Rev. D.*, 2025

Quantum capacitance detectors (QCD)

- Quantum capacitance detectors are proven sensors of THz photons†
- Photon event changes charge state of qubit, changes capacitance of Cooper pair box (CPB)
- Signal is read out with an RF probe tone: photon event changes resonant frequency



†P. M. Enternach, et al., *Nature Astronomy*, 2017

M. D. Shaw, et al. *Phys. Rev. B*, 2009

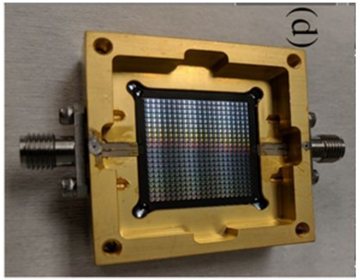
We know qubits can detect THz radiation… so what good are SQUATs?

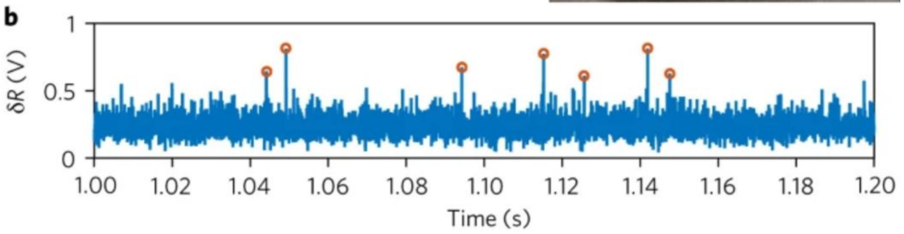
Article | Published: 06 November 2017

Single photon detection of 1.5 THz radiation with the quantum capacitance detector

P. M. Echternach, B. J. Pepper, T. Reck & C. M. Bradford

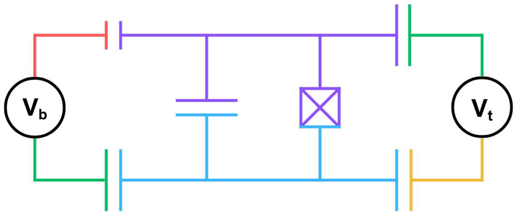
Nature Astronomy **2**, 90–97 (2018) | Cite this article

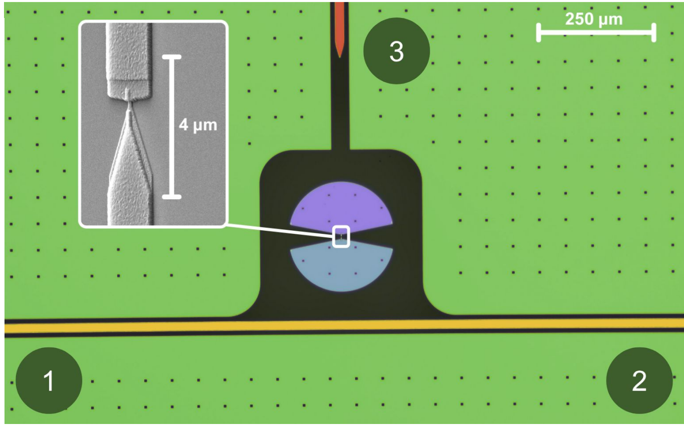


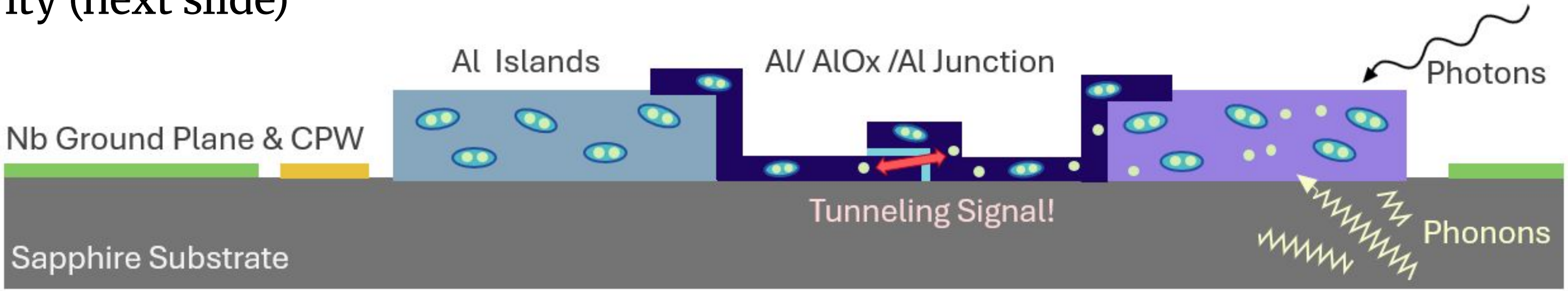


SQUATs are optimized for *low-threshold* particle detection

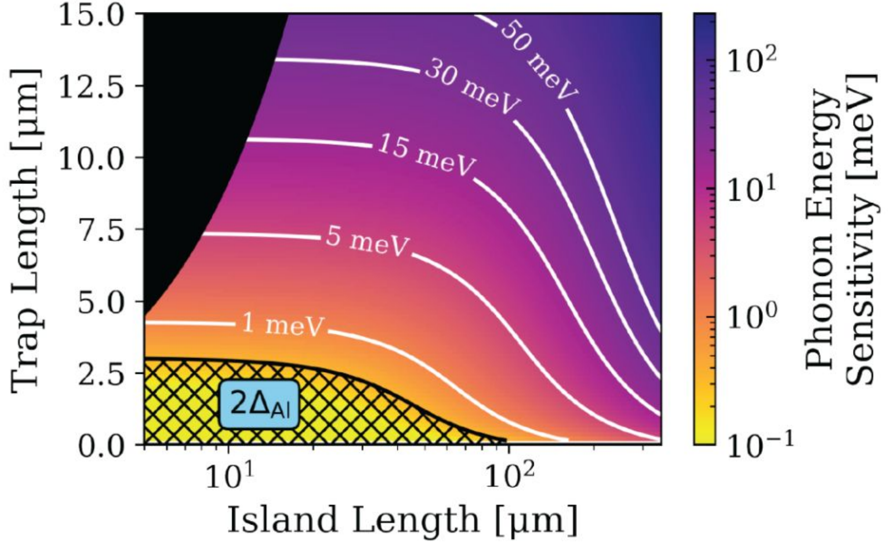
- Unlike the QCD, the SQUAT is not coupled to a resonator.
  - Smaller footprint on chip
- Sensitive to qubit's inductance (not quantum capacitance)
- Improved energy sensitivity (next slide)

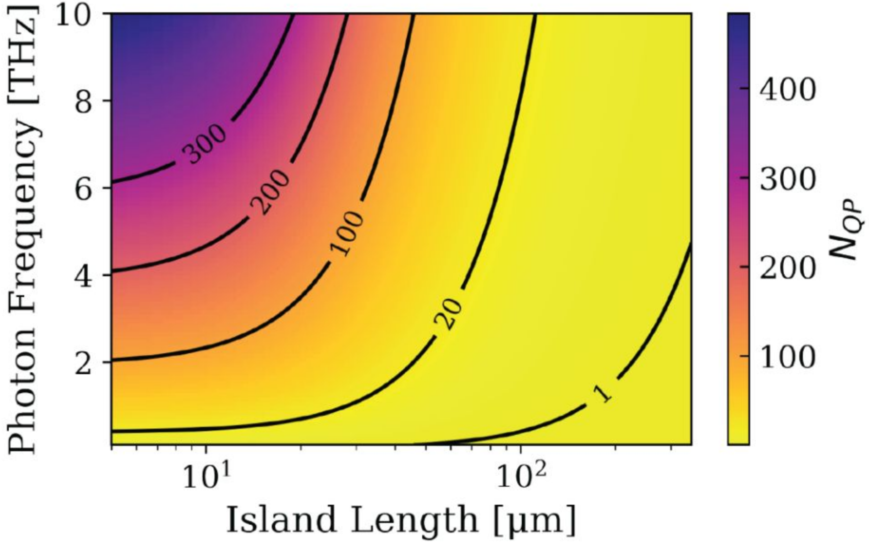






SQUATs will be made with *novel materials* to reach ~10-100 meV sensitivity to phonons, THz photons





Making the junction of the qubit out of a **low-T_c material** (e.g. hafnium) **traps** and **multiples** quasiparticles

SQUAT design paper: C. Fink, et al. *Phys. Rev. Appl.*, 2024

A First Demonstration of the SQUAT Detector Architecture: Direct Measurement of Resonator-Free Charge-Sensitive Transmons

H. Magoon,[1,2,3,*] T. Aralis,[1,2,†] T. Dyson,[1,2,3] J. Anczarski,[1,2,3] D. Baxter,[4,5] G. Bratrud,[5,4] R. Carpenter,[1,2,6] S. Condon,[1,2,3] A. Droster,[1,2] E. Figueroa-Feliciano,[5,4] C.W. Fink,[7,8] S. Harvey,[1] A. Simchony,[1,2,3] Z.J. Smith,[1,2,6] N. Tabassum,[1,2] B.A. Young,[9] C.P. Salemi,[1,2,10,11] K. Stifter,[1,2] D.I. Schuster,[6] and N.A. Kurinsky[1,2]

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[10] *University of California Berkeley, Berkeley, CA 94720, USA*
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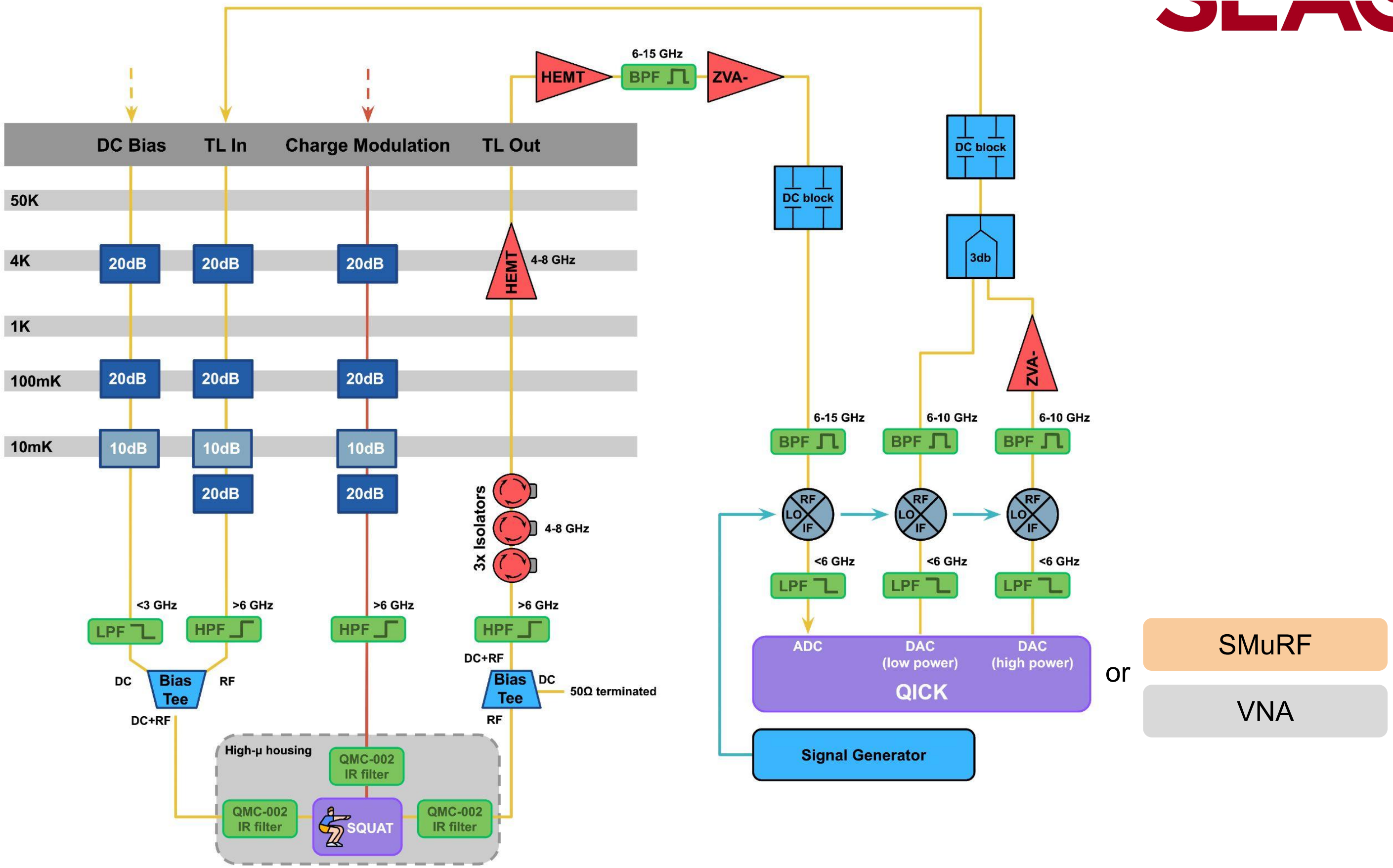
(Dated: January 8, 2026)

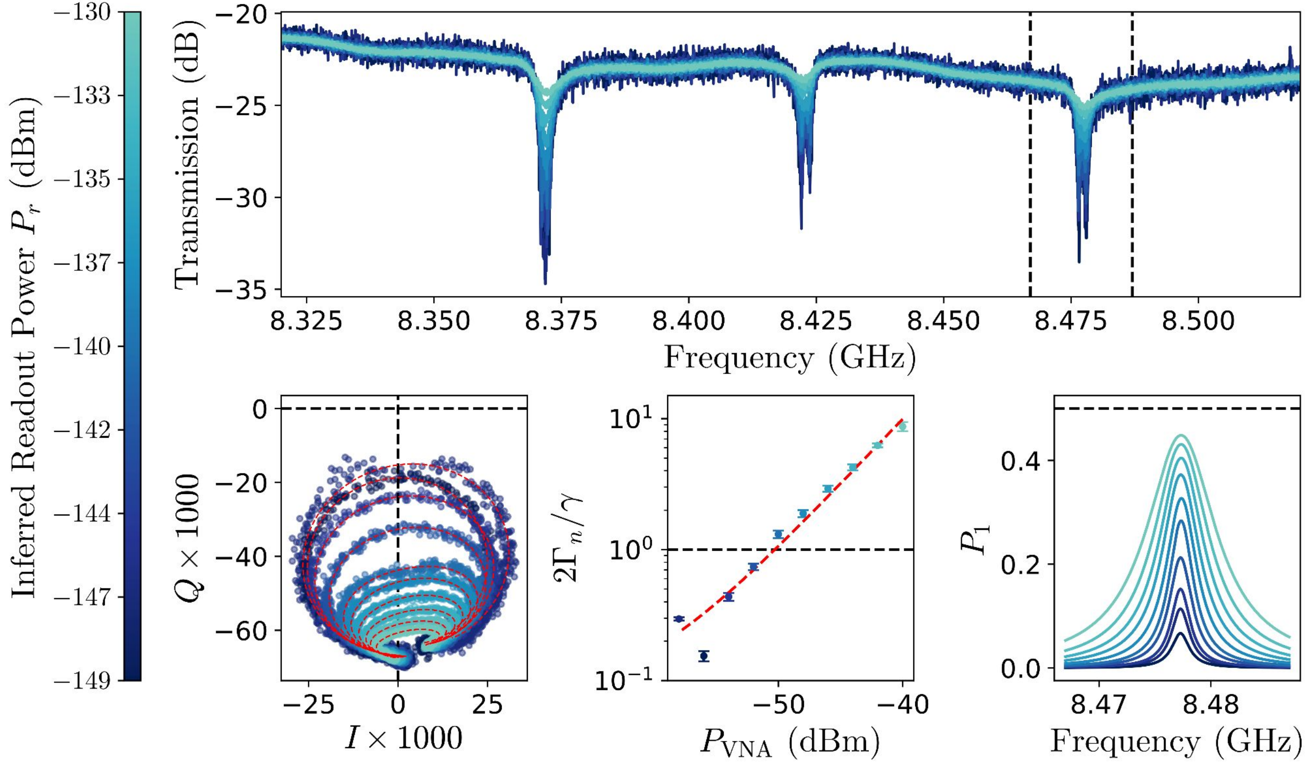
The Superconducting Quasiparticle-Amplifying Transmon (SQUAT) is a new detector architecture for THz (meV) sensing based on a weakly charge-sensitive transmon directly coupled to a transmission line. In such devices, energy depositions break Cooper pairs in the qubit capacitor islands, generating quasiparticles. Quasiparticles that tunnel across the Josephson junction change the transmon qubit parity, generating a measurable signal. In this paper, we present the design of first-generation SQUATs and demonstrate an architecture validation. We summarize initial characterization measurements made with prototype devices, comment on background sources that influence the observed parity-switching rate, and present experimental results showing simultaneous detection of charge and quasiparticle signals using aluminum-based SQUATs.

On the arXiv next week!

Measurement setup



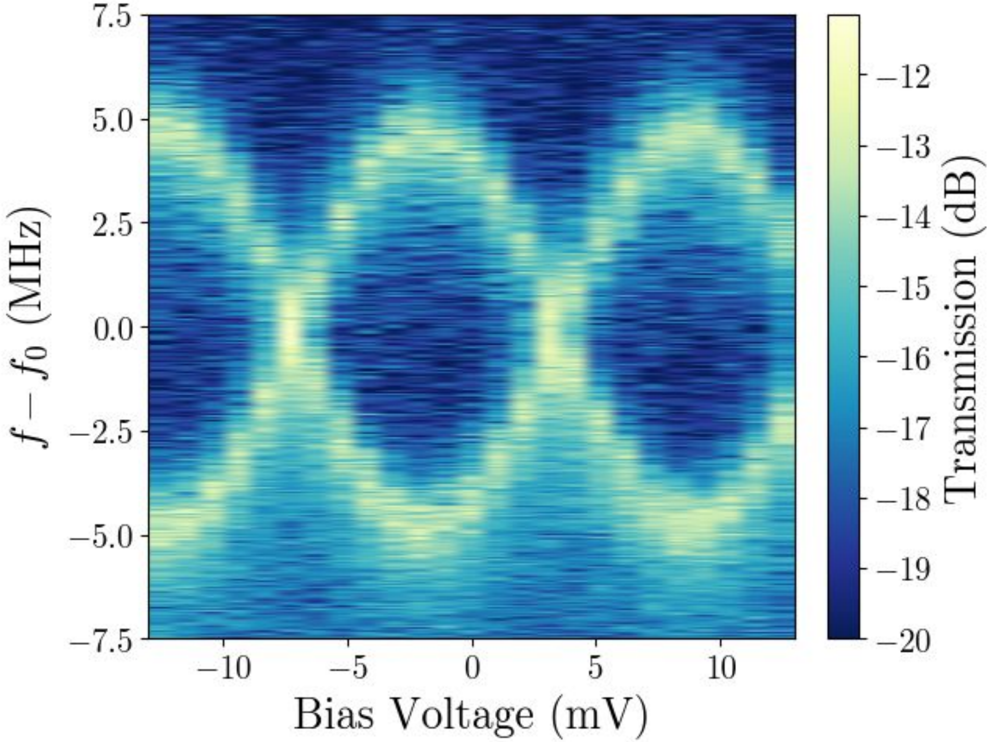
SQUAT properties vary with readout power



- As probe power increases, transition probability saturates at 50%
- Faster Rabi oscillations
- Probability bandwidth broadens

SQUAT dispersion changes as function of island charge

- Tune dispersion of qubit states by dc biasing SQUAT
- Dispersion $\chi \approx 10Q_0$
  - χ ~ 10 MHz
  - Q_0 ~ 1 MHz
- In this way, we can bias qubit into the degenerate state or maximum dispersion state



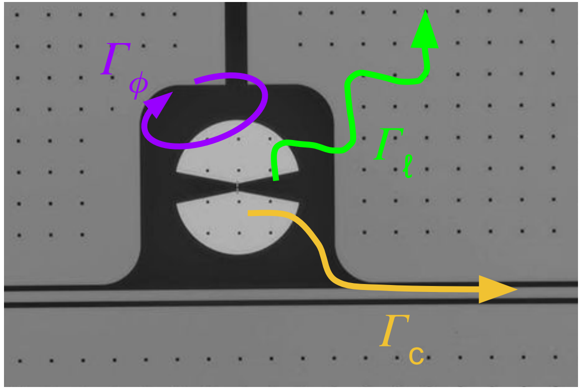
Pulsed measurements with QICK

$$H_{\text{system}} = H_{\text{qubit}} + H_{TL} + H_{int}$$

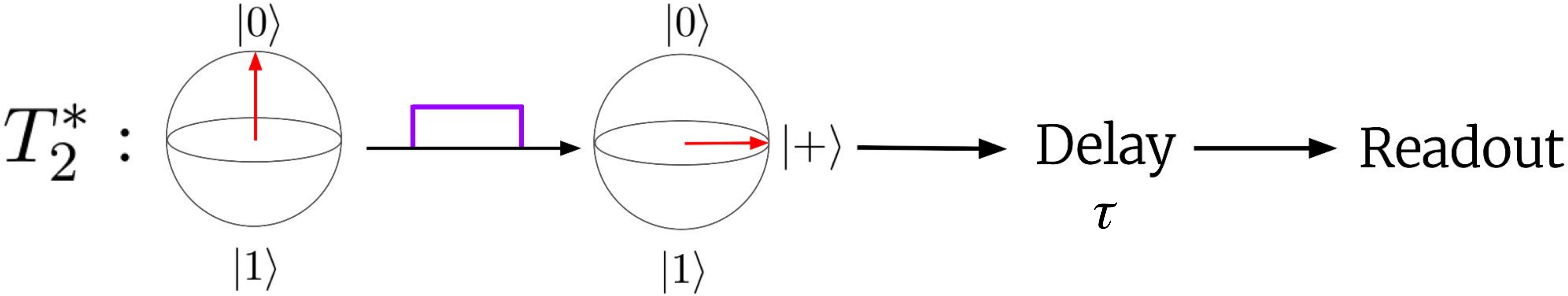
Contains three loss mechanisms:

- Γ_r: radiative decay rate, $\Gamma_r = 1/T_1$
  - $\Gamma_r = \Gamma_c + \Gamma_\ell$, where Γ_c is coupling to feedline, Γ_ℓ is loss rate
- Γ_ϕ: dephasing rate, $\Gamma_\phi = 1/T_2$
- Total decay rate:

$$\gamma \equiv \frac{\Gamma_r}{2} + \Gamma_\phi = \frac{1}{2}(\Gamma_c + \Gamma_l) + \Gamma_\phi$$



T_2^* (dephasing time) measurement

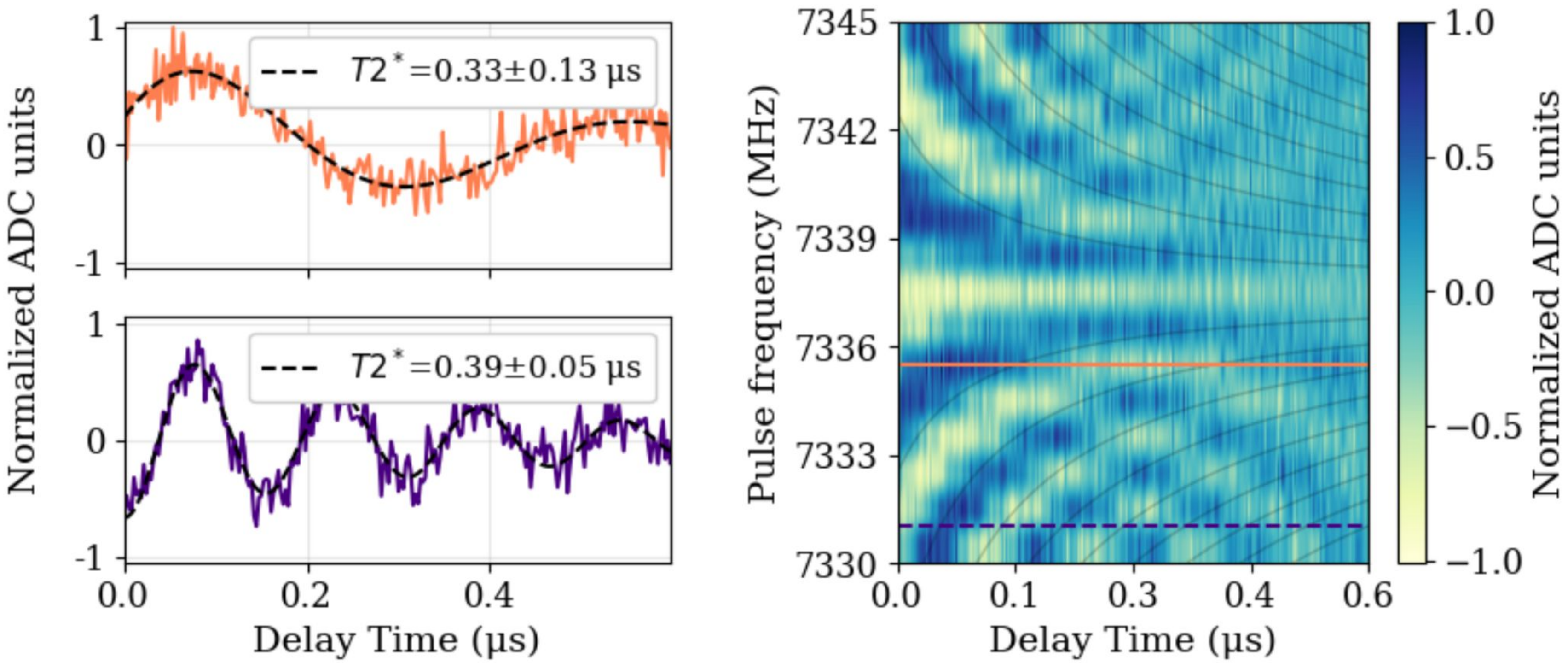


1. Prepare qubit in the ground state, apply $\pi/2$ pulse to rotate to the $|+\rangle$ state
2. The qubit precesses (not shown) about the Z axis at rate set by detuning, δf
3. Emitted field goes as

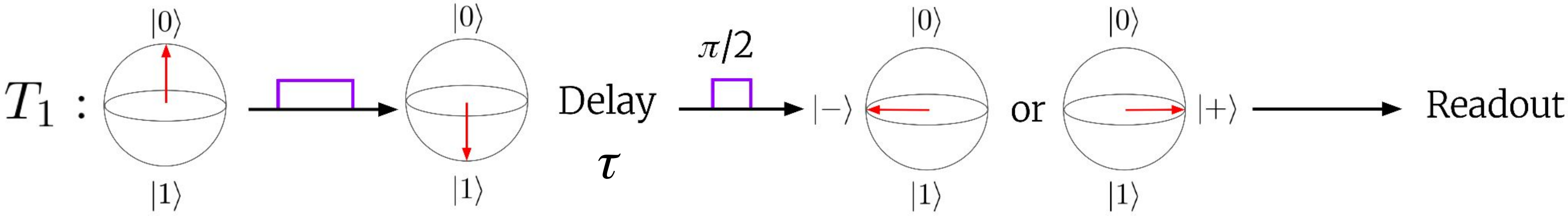
$$\propto e^{-\tau/T_2^*} \cos\left(2\pi\delta f\tau + \phi_0\right)$$

4. Vary τ, fit to extract T_2^*

T_2^* (dephasing time) measurement



T_1 (energy relaxation time) measurement

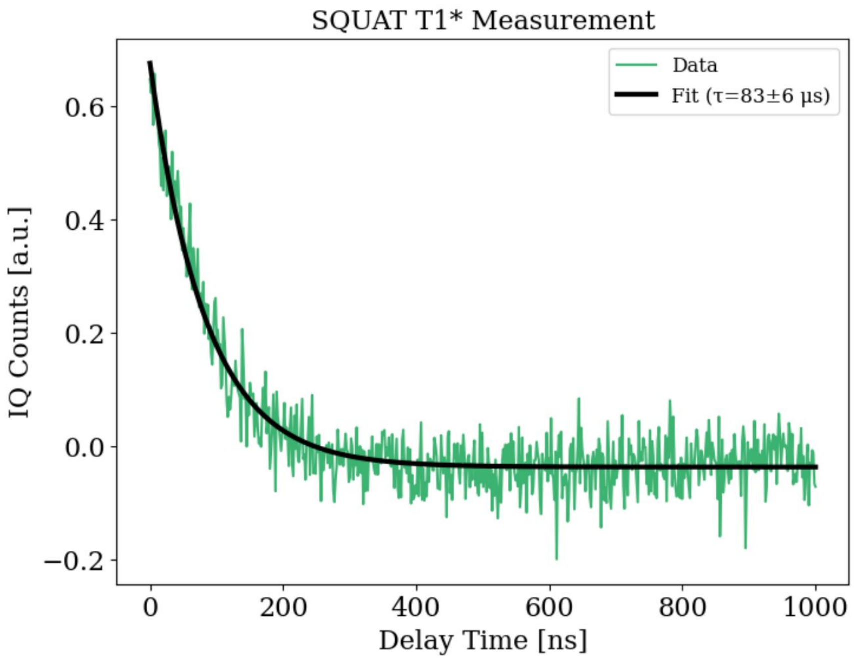


1. Prepare qubit in the excited state
2. The qubit precesses (not shown) about the Z axis at rate set by detuning, δf
3. Wait variable delay time τ, apply $\pi/2$ pulse to rotate qubit into the XY plane
4. Emitted field depends on whether the qubit decayed or not:

$$\propto \begin{cases} +1 & \text{if qubit decayed to } |0\rangle \\ -1 & \text{if qubit remained in } |1\rangle \end{cases}$$

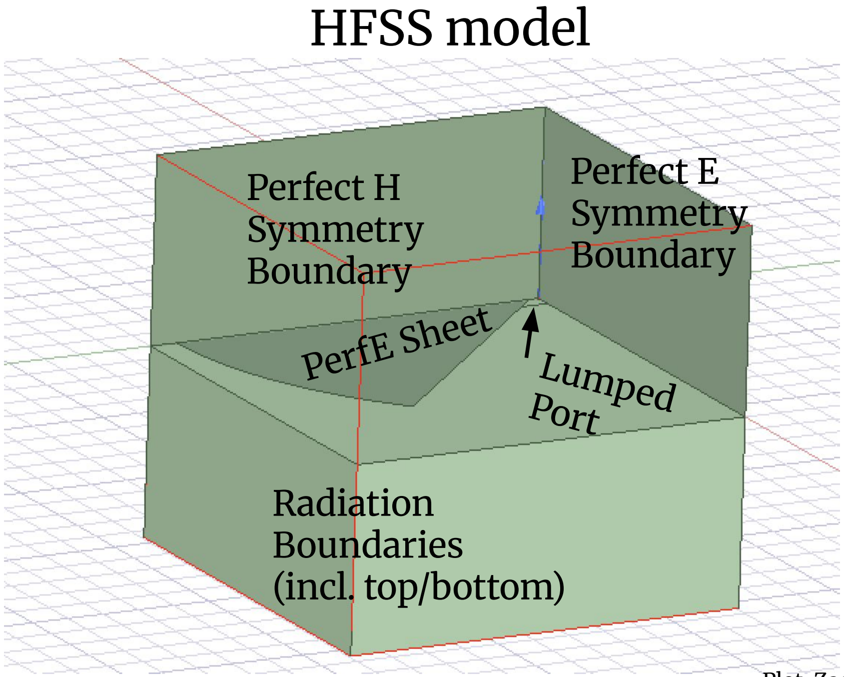
5. Measure emission to the feedline, fit to extract T_1

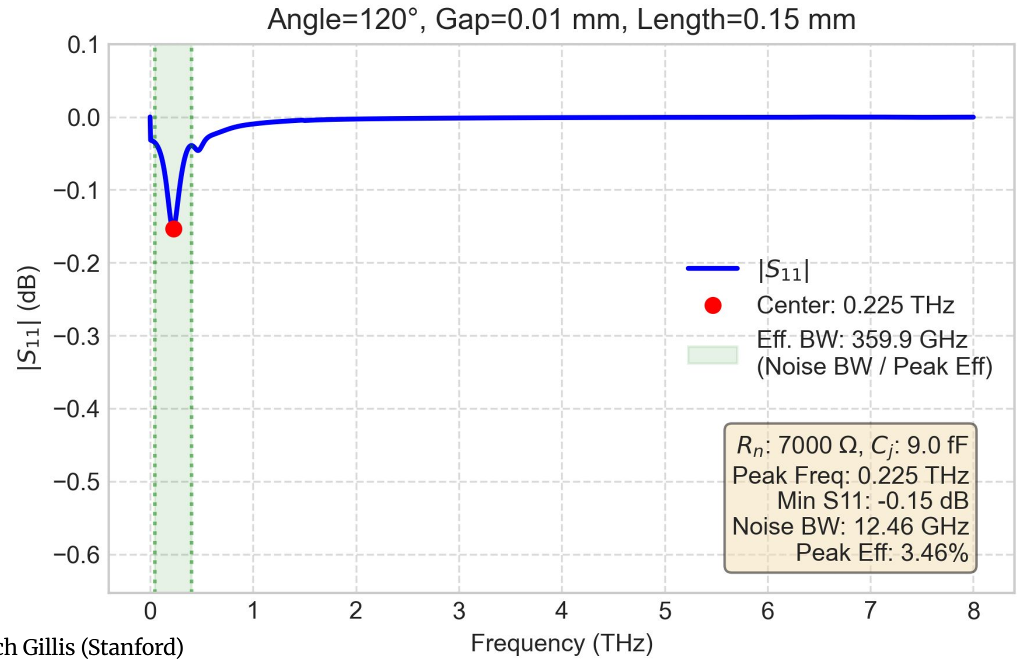
T_1 (energy relaxation time) measurement



- Typical T_1 times are ~100 ns
- Significantly shorter than typical transmon qubits due to the fact that we desire quasiparticle tunneling

SQUATs have well-understood coupling to THz radiation

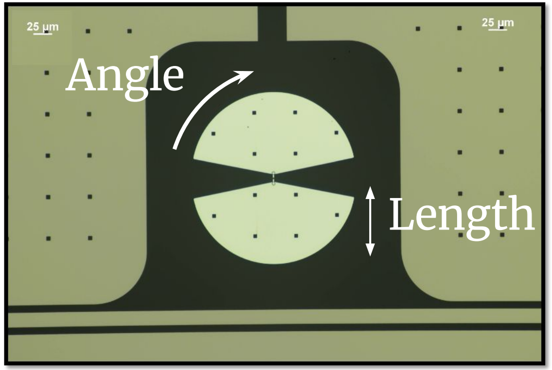




Plot: Zach Gillis (Stanford)

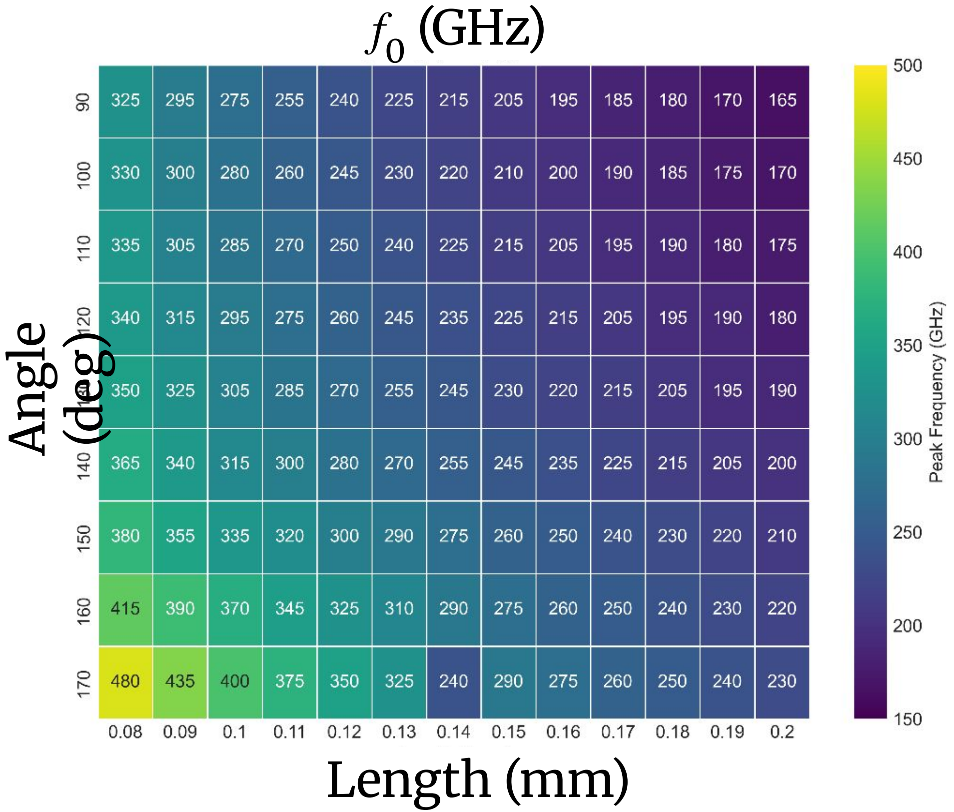
Method follows Rafferty, et al. arXiv:2103.06803

Defining central bands for an array of SQUATs



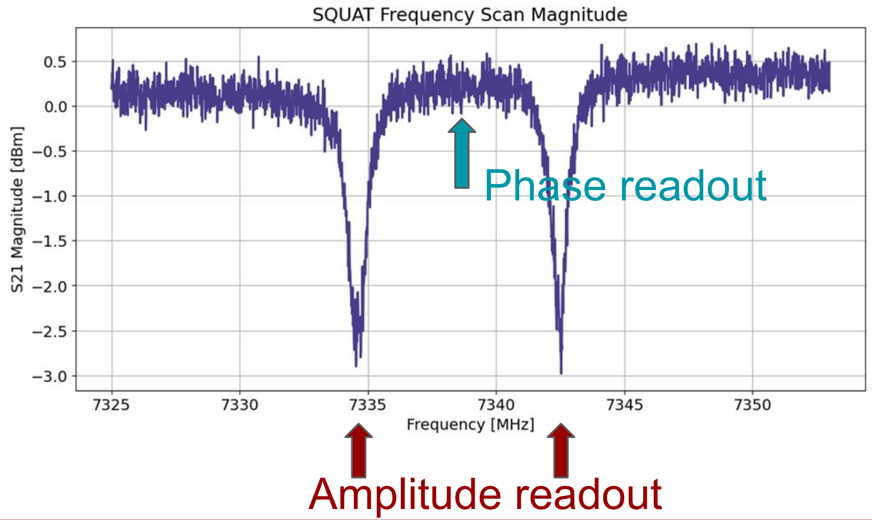
Not shown here, but also well-characterized:

- Bandwidth
- Coupling efficiency
- Parity switching rate dependence on temperature



Parity measurements

1. Quasiparticle tunneling toggles the parity state of the SQUAT
2. By directly coupling the SQUAT to the feedline, the parity state can be monitored with a continuous microwave tone
3. Two possible readout modes: amplitude and phase



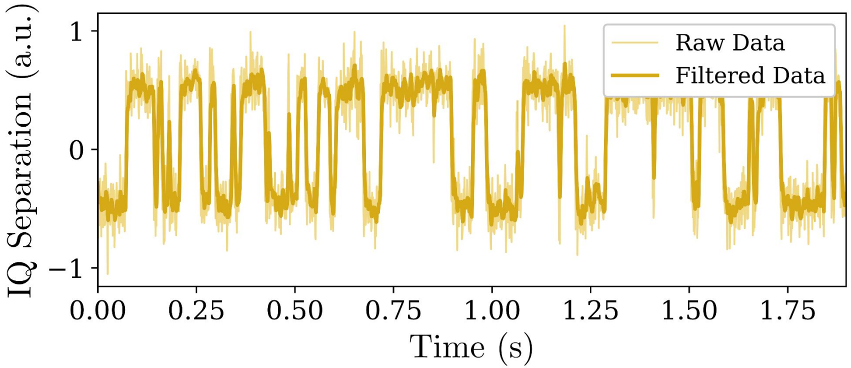
Parity measurements: extracting Γ_{qp}

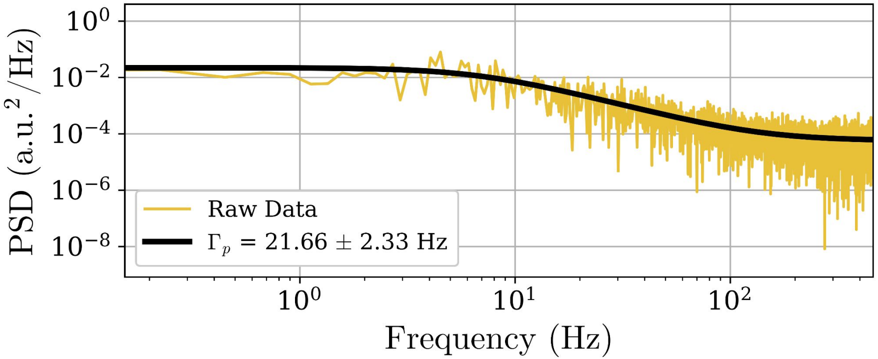
Extract switching rate by fitting† to the FFT via:

$$S(f) = F^2 \frac{4\Gamma_{qp}}{(2\Gamma_{qp})^2 + (2\pi f)^2} + (1 - F^2) f_{bw}^{-1}$$

Parity switching rate:

$\Gamma_{qp} \approx 20$ Hz

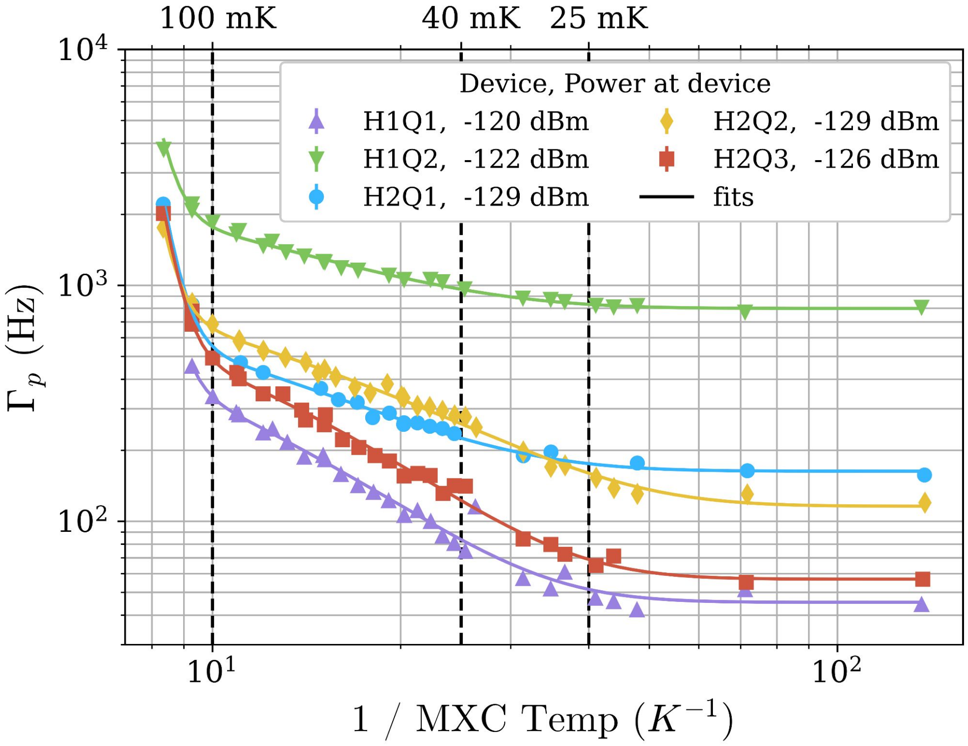




†Riste, D, et al. *Nature Communications, 2013*

Parity switching rate temperature dependence

- †By measuring Γ_p as function of temperature, we can extract non-equilibrium quasiparticle density, x_{qp}, and SC gap difference, $\delta\Delta$
- 3 regimes:
  - Low temp: non-thermal processes dominate (i.e. photon events)
  - Intermediate temps: thermal activation of quasiparticles increases rate
  - High temp: x_{qp} increases, leading to exponential increase in rate



†Nho, et al., arXiv:2505.08104

Parity switching rate temperature dependence

Why different baselines for different qubits?

Device	x_{qp}^{ne} ($\times 10^{-8}$)	$\delta\Delta$ (GHz)	T_c (K)	Γ_{other} (Hz)
H1Q1	1.99 ± 0.06	2.59 ± 0.06	1.114 ± 0.008	45.8 ± 0.8
H1Q2	4.8 ± 0.3	2.2 ± 0.1	1.076 ± 0.005	800 ± 8
H2Q1	1.7 ± 0.1	2.2 ± 0.1	1.098 ± 0.004	163 ± 2
H2Q2	2.14 ± 0.04	1.59 ± 0.03	1.141 ± 0.003	116 ± 2
H2Q3	1.93 ± 0.04	2.32 ± 0.04	1.103 ± 0.002	57.2 ± 1.0

Make up a nuisance variable and blame him!

[†]Fit function:

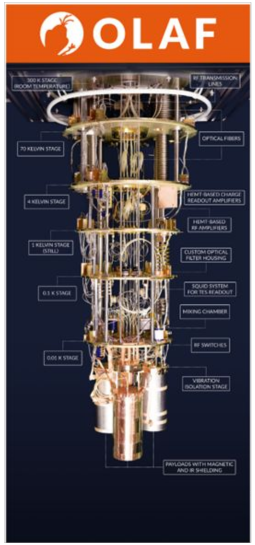
$$\Gamma_p(1/T) = (1 - P_1)\Gamma_0 + P_1\Gamma_1 + \Gamma_{other}$$

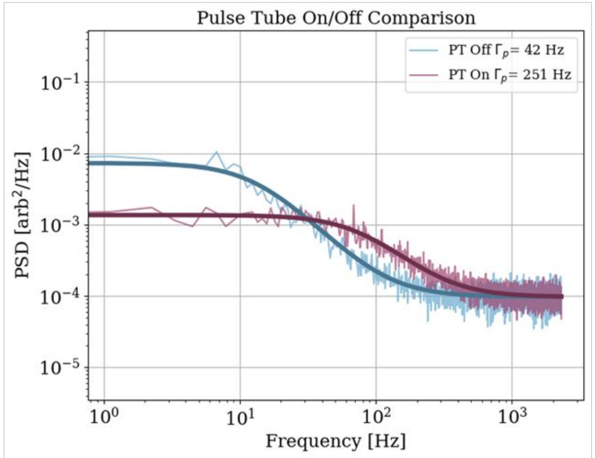
Contains x_{qp}, $\delta\Delta$ dependence

[†]Nho, et al., arXiv:2505.08104

Pulse tube vibrations contribute to background rates

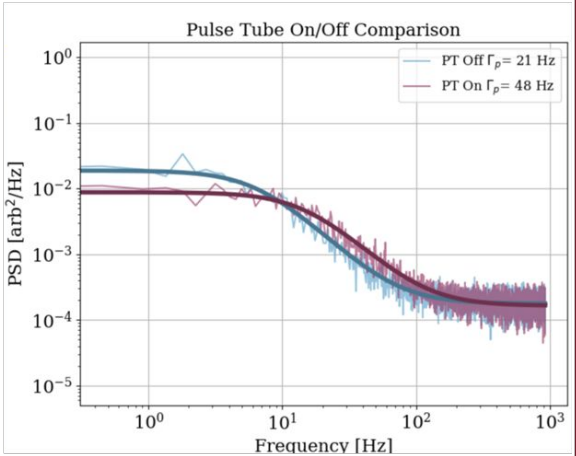
Oxford Proteox





~6x higher tunneling rate with PT on

Bluefors XLD



~2x higher tunneling rate with PT on

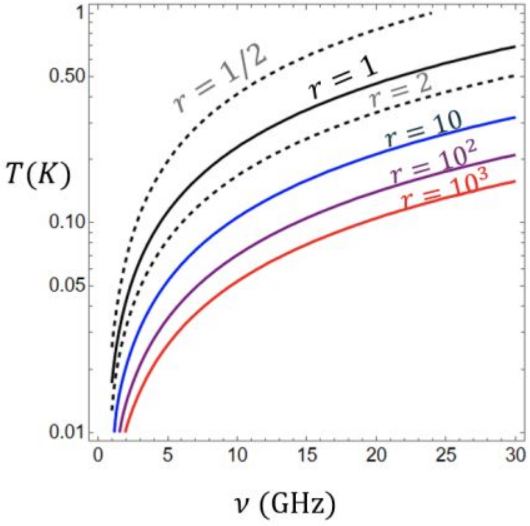
Summary

- 5 SQUAT devices are well-characterized with understood dynamics
  - Power scans, frequency scans, pulsed measurements, time domain measurements
- First measurement of parity switching events in SQUATs!
- Future work will focus on understanding backgrounds, antenna modes
- Next-gen detectors are being fabricated with gap engineering
- BREAD-compatible focal plane of SQUATs is realistic and on the horizon

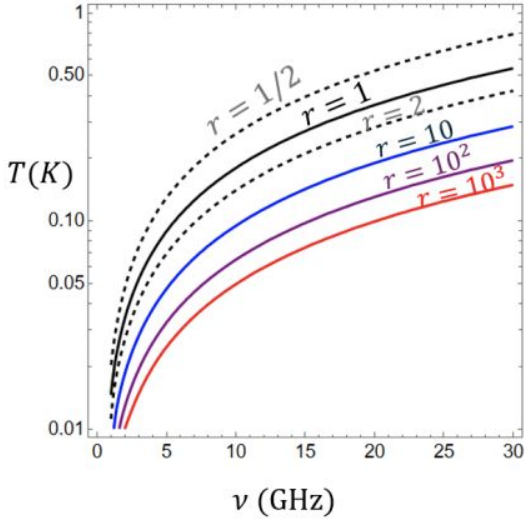
Extras

Searching for high-mass axions requires new detector technology

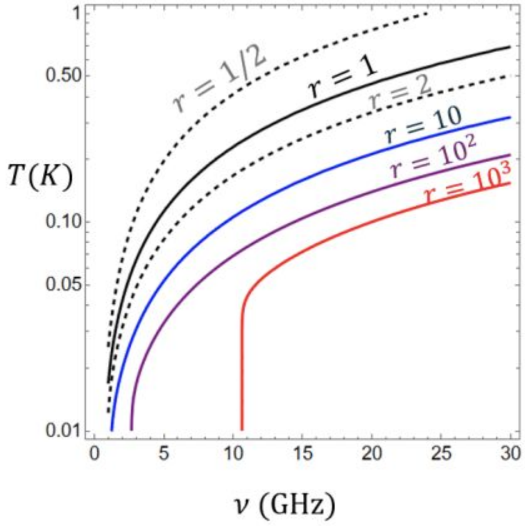
SQL amplifier vs 100s^{-1} dark count rate SPD



Squeezed amplifier vs 100s^{-1} dark count rate SPD



SQL amplifier vs 10^{3}s^{-1} dark count rate SPD



Maximizing Quantum Enhancement in Axion Dark Matter Experiments: arXiv:2411.13776

SQUATs vs QCDs

- Unlike the QCD, the SQUAT is not coupled to a readout resonator
  - No longer sensitive to quantum capacitance, but rather the qubit's inductance
- Significant reduction in footprint
  - Improved pixel density, photon sensing efficiency
- Multiplexing is straightforward
- Reduced TLS noise
- Improved energy sensitivity

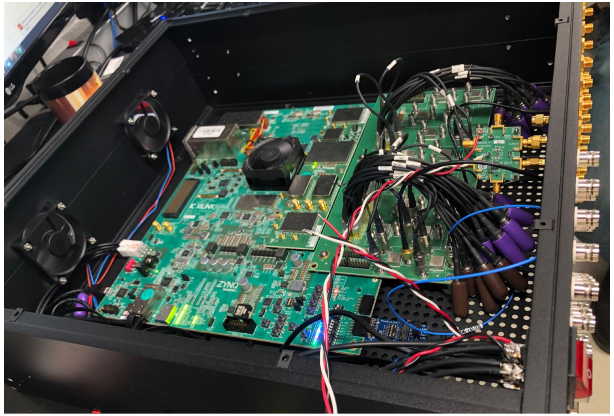
SQUAT fabrication

1. Anneal 430 um thick C-plane sapphire wafer at 1200 C for 2 hours
2. Deposit 100 nm Nb ground plane using Plassys MEB550S at 2.5e-8 Torr, with Ti getter before every deposition
   a. Pattern ground plane feature with optical lithography
3. Deposit layer of 200 nm Al using Plassys
4. Dolan junctions were patterned with a Raith EBPG 5200+ Electron Beam Lithography System on a bi-layer of 895 MMA EL 13 and PMMA 950 A4.
   a. The first layer is composed of 45 nm aluminum deposited at -23°.
   b. The chamber was filled with an 897 O2/Ar mix and static oxidation was run at 30 Torr
   c. A second layer of aluminum was deposited with 115nm thickness 898 at angle +23°.

Readout

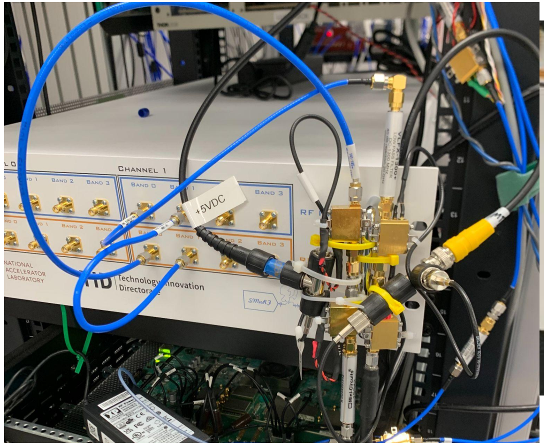
Pulsed measurements with QICK

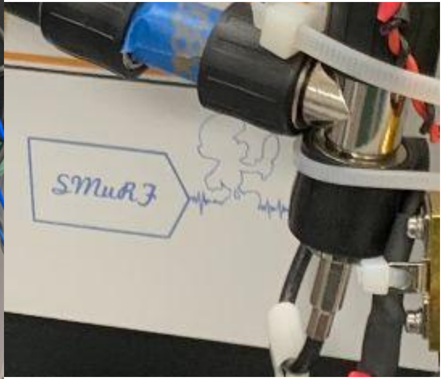
- RFSoC board (ZCU 216) running QICK
- Short pulses set qubit's state
- Extract Rabi rate Ω, T_1, T_2



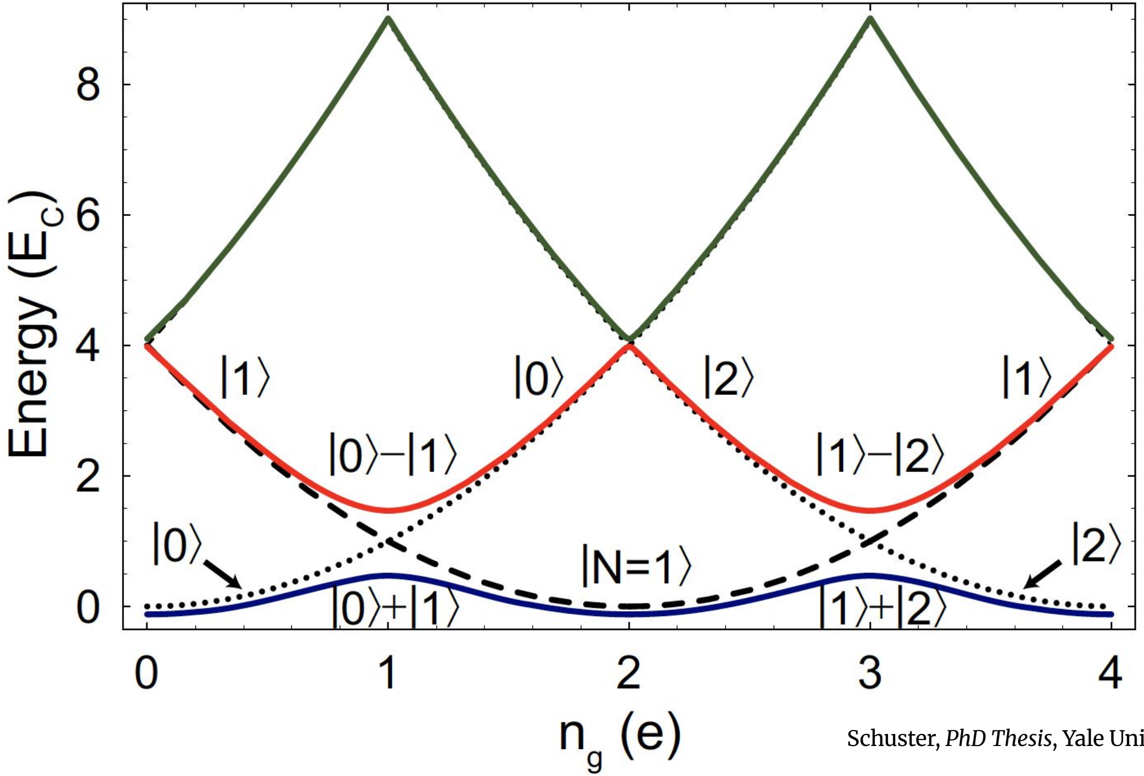
Steady-state measurements with SMuRF

- RFSoC board running SMuRF software
- Developed for readout of CMB experiments



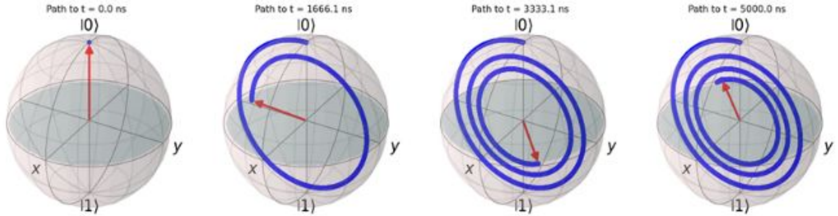


Cooper pair box qubit energy levels

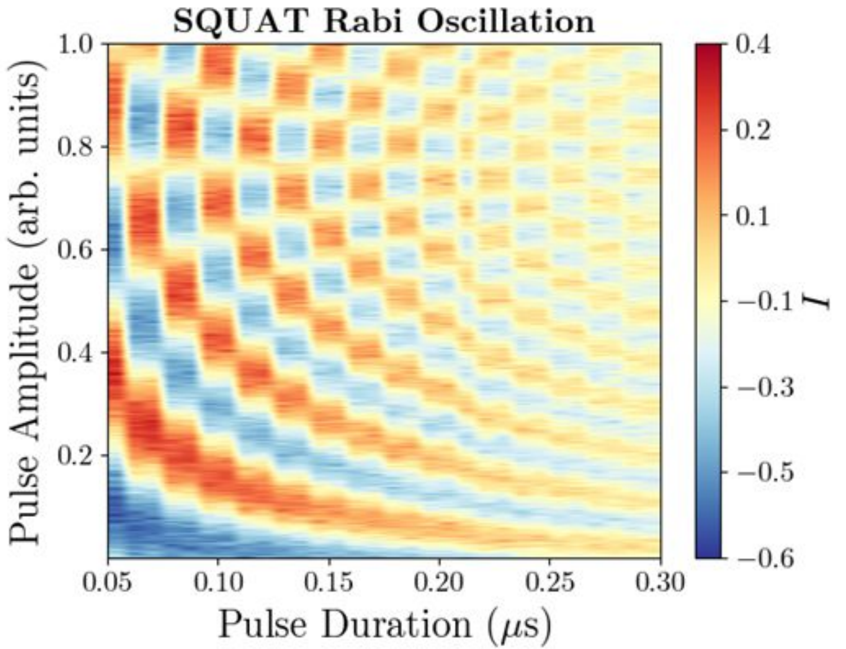


Schuster, *PhD Thesis*, Yale University, 2007

Measuring Rabi oscillations allow us to prepare qubit in $|+\rangle$ or $|-\rangle$ state



1. Apply a pulse at f_0, vary power & duration
2. Qubit precesses in Bloch sphere
3. Measure the emitted field, sensitive to $\langle \sigma_- \rangle$

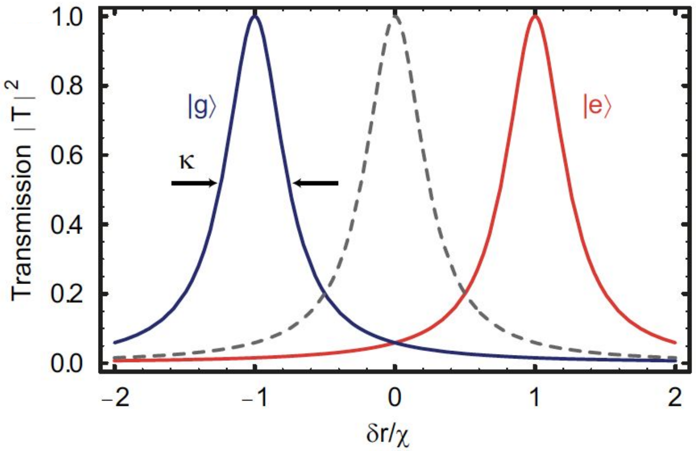


SQUAT properties

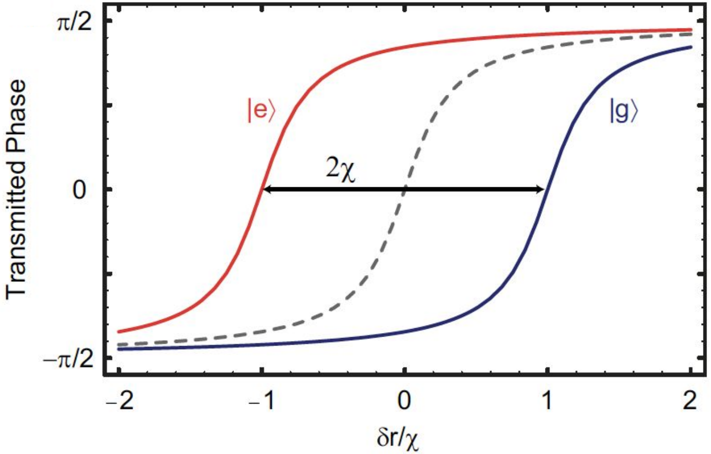
Device	f_0 (GHz)	$2\chi_0$ (MHz)	E_J/h (GHz)	E_C/h (MHz)	γ (MHz) $\to T_2$ (ns)	Γ_r (MHz) $\to T_1$ (ns)	Γ_c (MHz)	T_2^* (ns)	T_1 (ns)
H1Q1	7.35	9.46	12.8	626	3.670 ± 0.003 $\to$ *266.5 ± 0.2*	6.35 ± 0.06 $\to$ *156 ± 1*	6.301 ± 0.004	291 ± 18	210 ± 8
H1Q2	8.18	3.10	15.7	622	5.564 ± 0.002 $\to$ *179.54 ± 0.08*	11.106 ± 0.005 $\to$ *90.00 ± 0.04*	11.140 ± 0.004	143 ± 5	98 ± 3
H2Q1	8.37	1.92	16.6	615	10.01 ± 0.09 $\to$ *98.8 ± 0.9*	19.3 ± 0.1 $\to$ *51 ± 3*	18.8 ± 0.1	116 ± 2	81 ± 2
H2Q2	8.42	2.11	16.7	618	4.80 ± 0.03 $\to$ *207 ± 1*	9.60 ± 0.06 $\to$ *103.7 ± 0.7*	9.61 ± 0.06	106 ± 5	103 ± 9
H2Q3	8.47	1.57	17.2	606	5.6 ± 0.1 $\to$ *174 ± 4*	10.7 ± 0.7 $\to$ *93 ± 6*	10.4 ± 0.2	85 ± 3	104 ± 4

Parity measurements

Amplitude readout



Phase readout



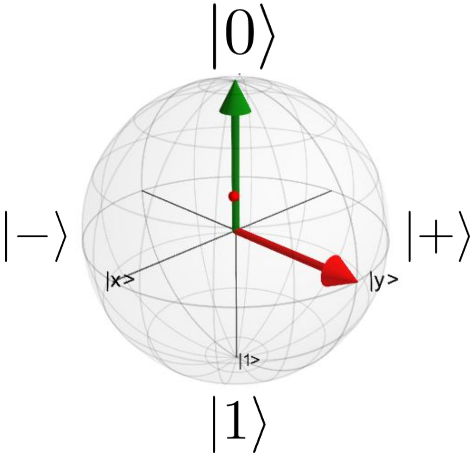
Phase readout is more advantageous than amplitude readout for a few reasons:

1. Amplitude readout requires 2 tones, or tone tracking due to variable n_g. Phase readout requires 1 tone and no tone tracking.
2. Phase readout measures charge and parity events simultaneously.
3. When optimized, phase readout has twice the SNR of amplitude readout.

Pulsed measurements

We measures the phase of the emitted field, which is sensitive to $\langle \sigma_- \rangle$

$$H_{\text{system}} = H_{\text{qubit}} + H_{TL} + H_{int}$$

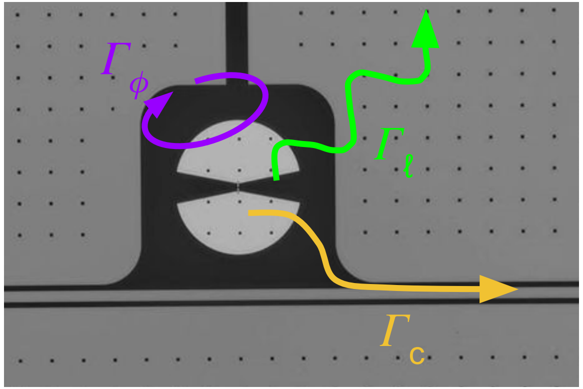


Master Equation, Gammas

$$\frac{d}{dt}\rho(t) = -i\left[H_{\text{eff}}, \rho\right] + \Gamma_r \mathcal{D}[\sigma_-]\rho + \frac{\Gamma_\phi}{2}\mathcal{D}[\sigma_z]\rho$$ †

- Γ_r: radiative decay rate, $\Gamma_r = 1/T_1$
  - $\Gamma_r = \Gamma_c + \Gamma_\ell$, where Γ_c is coupling to feedline, Γ_ℓ is loss rate
- Γ_ϕ: dephasing rate, $\Gamma_\phi = 1/T_2$
- Total decay rate:

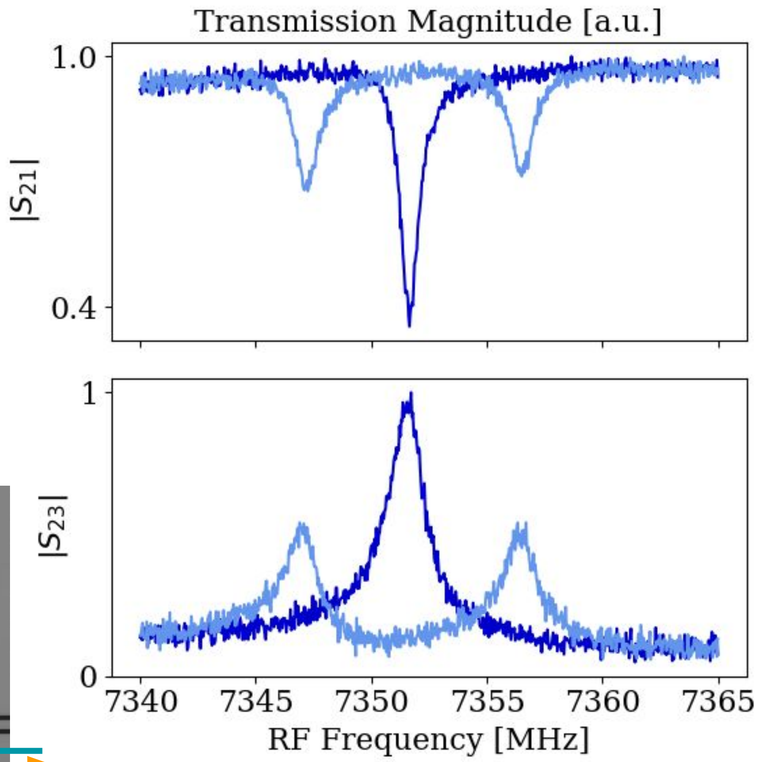
$$\gamma \equiv \frac{\Gamma_r}{2} + \Gamma_\phi = \frac{1}{2}(\Gamma_c + \Gamma_l) + \Gamma_\phi$$



†Upcoming SQUAT design paper, Eq. E5

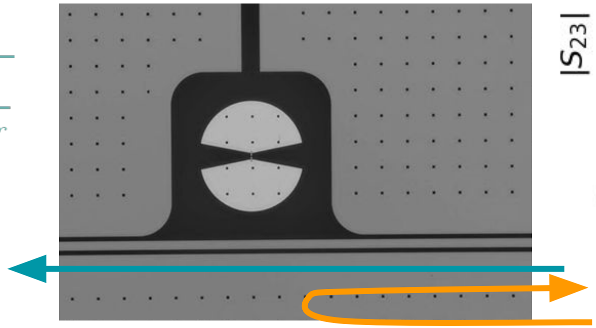
Fit the resonance, get the gammas

1. Use the master equation to write EoM for each operator
2. Find steady state solution by setting $\langle \dot{\sigma_-} \rangle = \langle \dot{\sigma_z} \rangle = 0$
3. Plug solution into IO theory to get transmission, reflection
4. Fit to extract Gammas

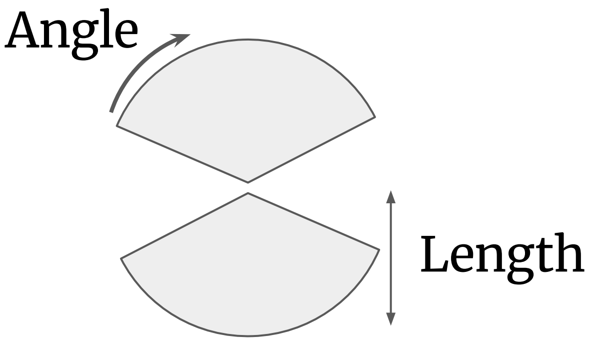


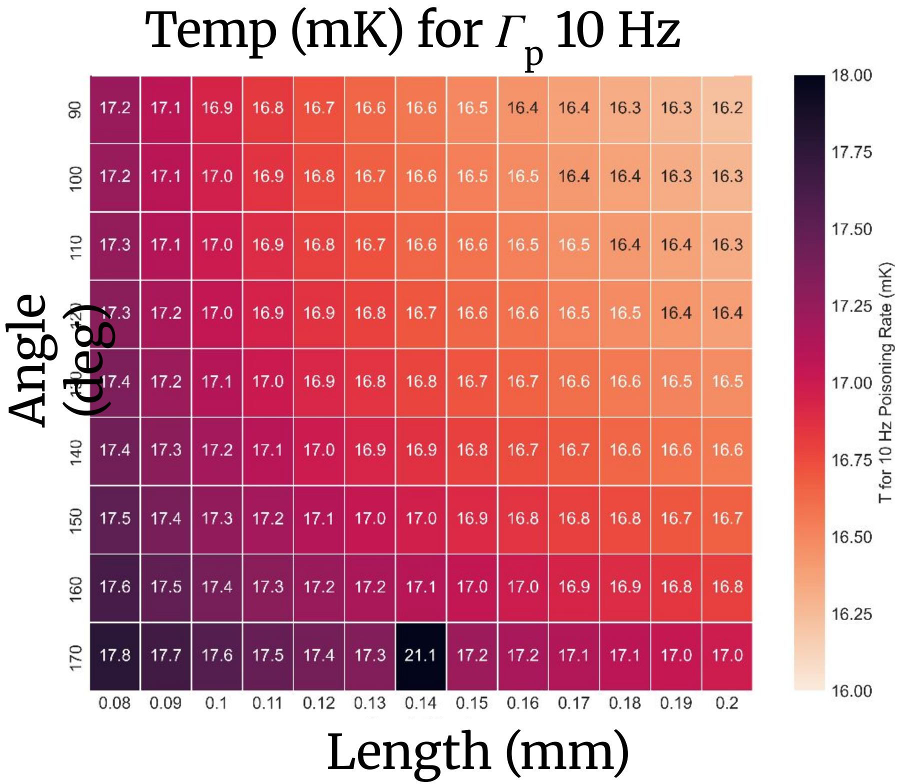
$$t = 1 - \frac{\Gamma_c}{2\gamma} \frac{1 - i\frac{\Delta}{\gamma}}{1 + \left(\frac{\Delta}{\gamma}\right)^2 + \frac{\Omega^2}{\gamma\Gamma_r}}$$

$$r = -\frac{\Gamma_c}{2\gamma} \frac{1 - i\frac{\Delta}{\gamma}}{1 + \left(\frac{\Delta}{\gamma}\right)^2 + \frac{\Omega^2}{\gamma\Gamma_r}}$$



SQUATs have well-understood coupling to THz radiation

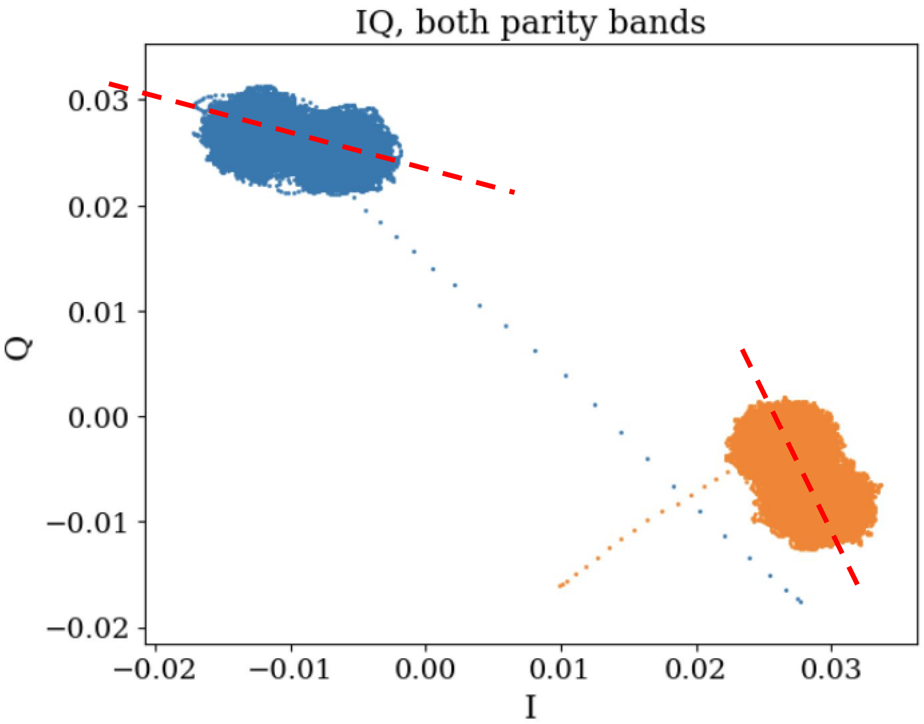




Rafferty, et al. arXiv:2103.06803

Parity measurements

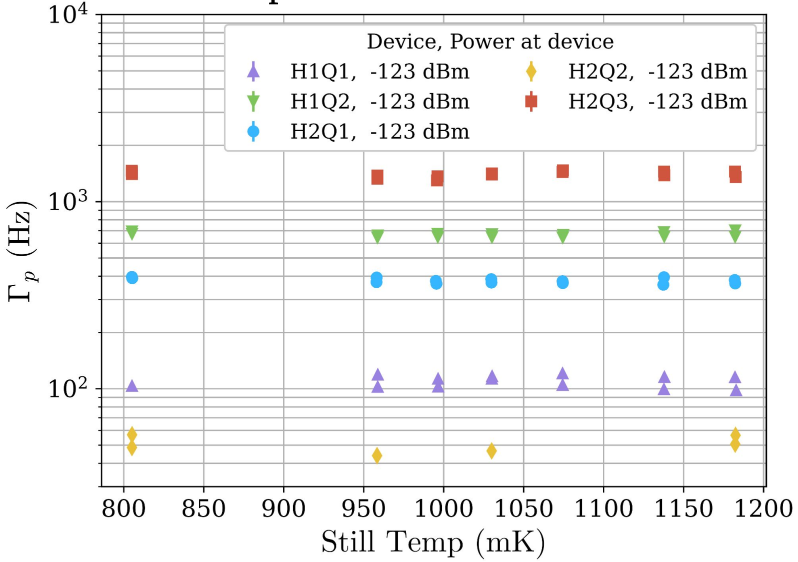
- Parity states appear as separate blobs in IQ space
- Readout occurs on the axis of maximum separation
- We optimizing readout power to give maximum phase space separation between the two parity states



What drives background rates?

1. IR environment is sub-dominant contribution
2. Increasing readout power increases Γ_p. 3 likely mechanisms:
   a. Increases qubit transition probability
   b. Adds energy to quasiparticles
   c. Increased dissipation in attenuators changes blackbody environment
3. Pulse tube vibrations

Γ_p as vs still power



Monte Carlo