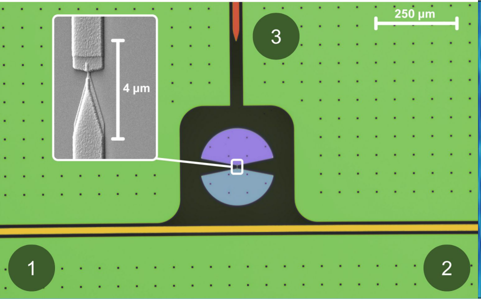
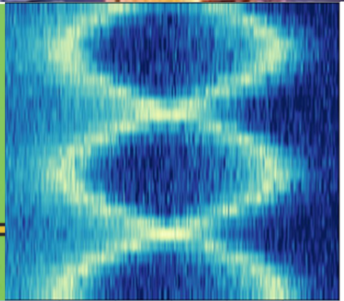
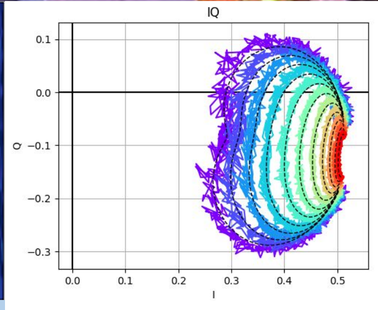
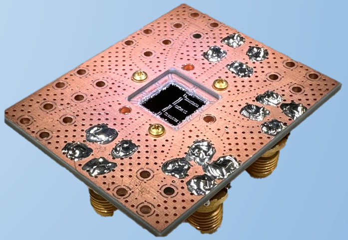
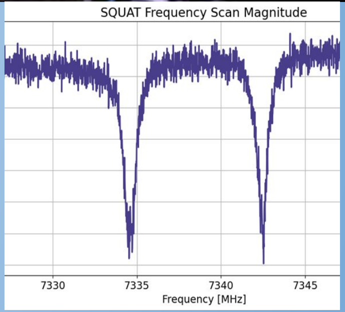
SQUATs Characterization





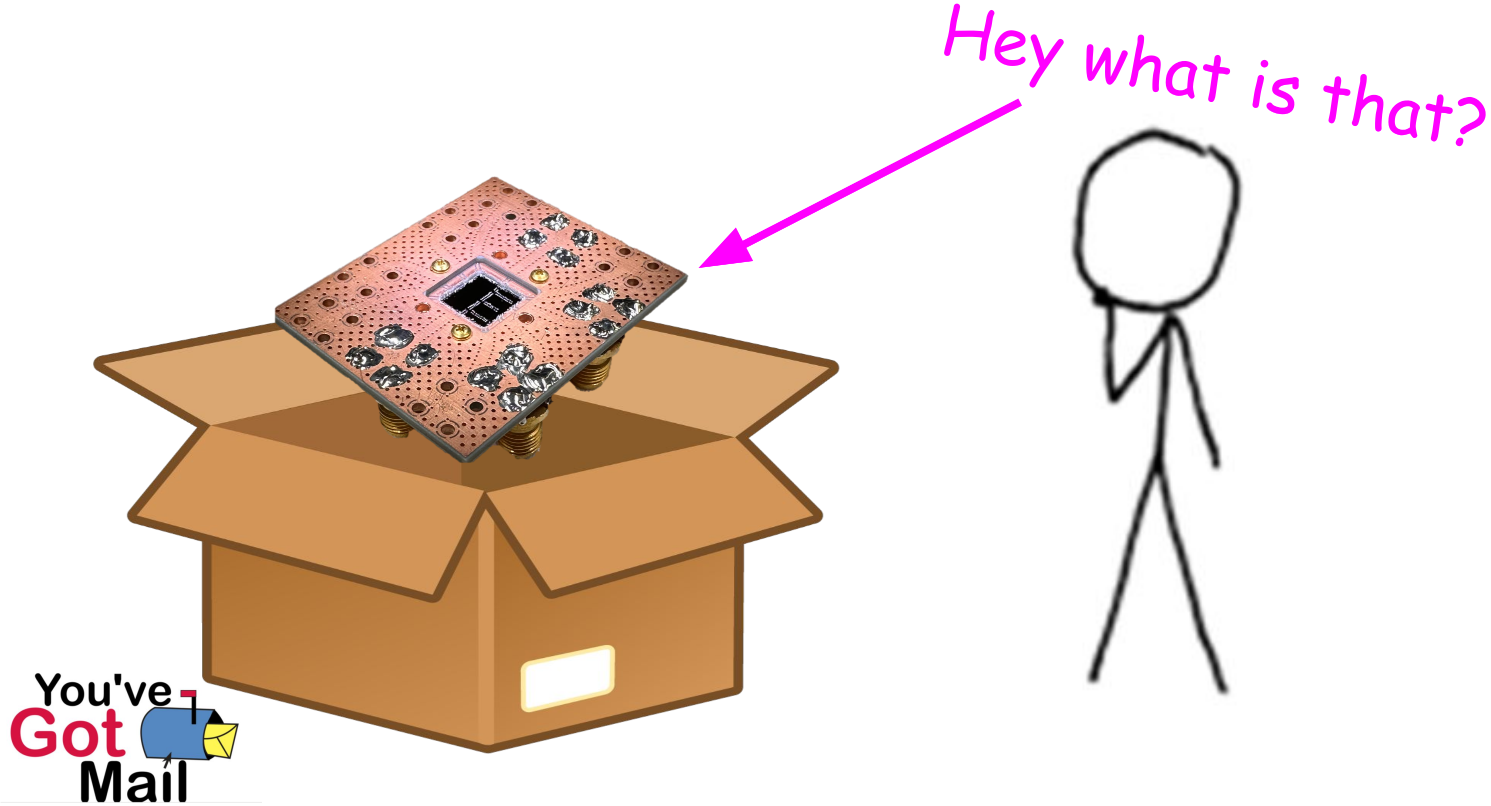






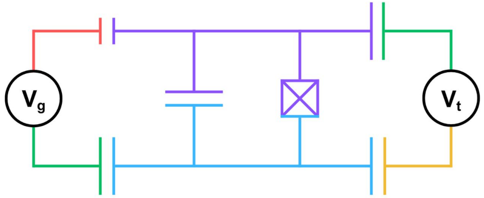
SQUAT workshop, SLAC
10/28/25

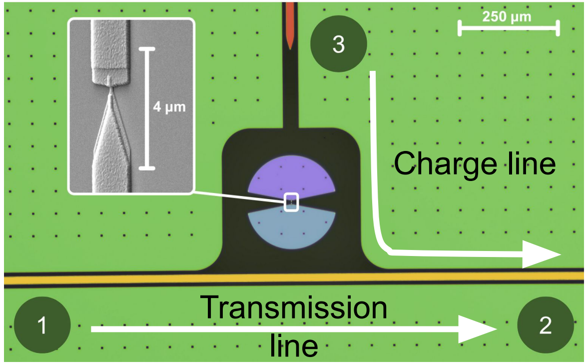
Alex Droster
Postdoc, Stanford/SLAC

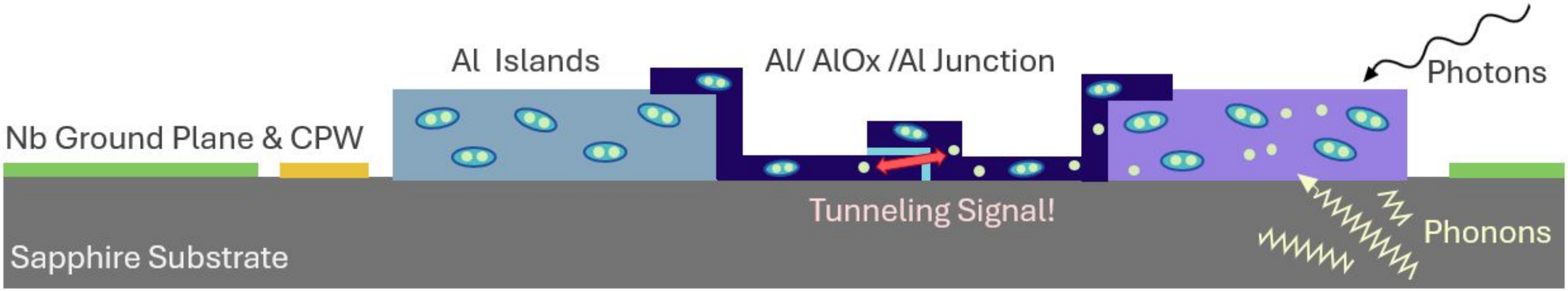

Hey what is that?
You've Got Mail

SQUAT overview

- Event detection manifests as an increase qubit parity switching rate
- We have characterized important SQUAT parameters: T_1, T_2, power dependence, dispersion.
- We have observed the first parity switching events in SQUATs!







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

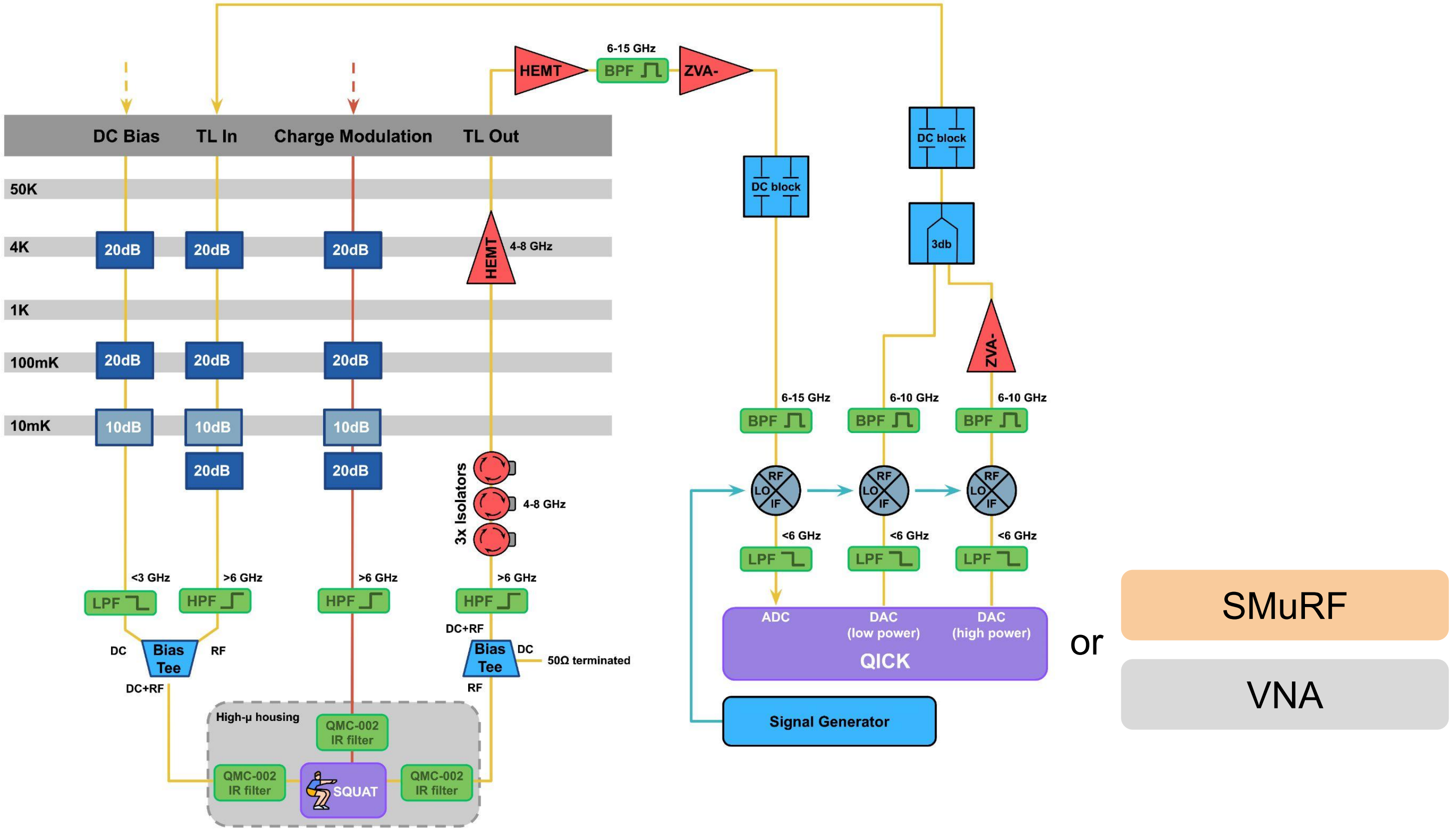
H. Magoon,[1,2,3,*] T. Aralis,[1,2] T. Dyson,[1,2,3] G. Bratrud,[4,5] S. Condon,[1,2,3] J. Anczarski,[1,2,3] C.W. Fink,[6] S. Harvey,[1] A. Simchony,[1,2,3] Z.J. Smith,[1,2,7] N. Tabassum,[1,2] B.A. Young,[8] C.P. Salemi,[1,2,9,10] D.I. Schuster,[7] and N.A. Kurinsky[1,2,†]

[1]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[2]*Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94035, USA*
[3]*Department of Physics, Stanford University, Stanford, CA 94035, USA*
[4]*Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA*
[5]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[6]*Materials Physics and Applications – Quantum, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[7]*Department of Applied Physics, Stanford University, Stanford, CA 94035, USA*
[8]*Santa Clara University, Santa Clara, CA 95053, USA*
[9]*University of California Berkeley, Berkeley, CA 94720, USA*
[10]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: October 27, 2025)

The Superconducting Quasiparticle-Amplifying Transmon (SQUAT) is a new architecture for THz (meV) sensing based on a weakly charge-sensitive transmon directly coupled to a transmission line. Energy depositions break Cooper pairs in the qubit islands, generating quasiparticles; the quasiparticles can tunnel across the Josephson junction, changing the qubit parity and thus generating a measurable signal. This paper presents the first measurements of SQUATs. We describe the design, fabrication, and testing of the sensors and characterize their qubit properties and background switching rate. We also show first evidence for a detection event.

Measurement setup

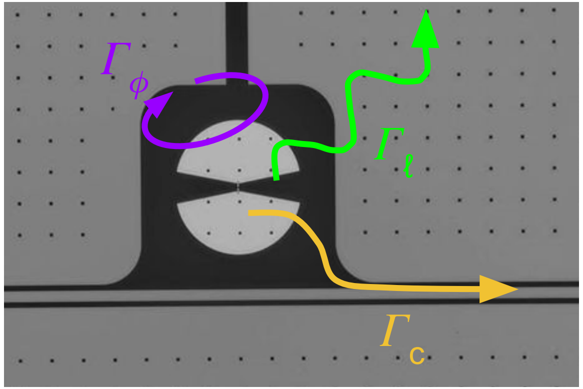


Master Equation, Gammas

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

- 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:

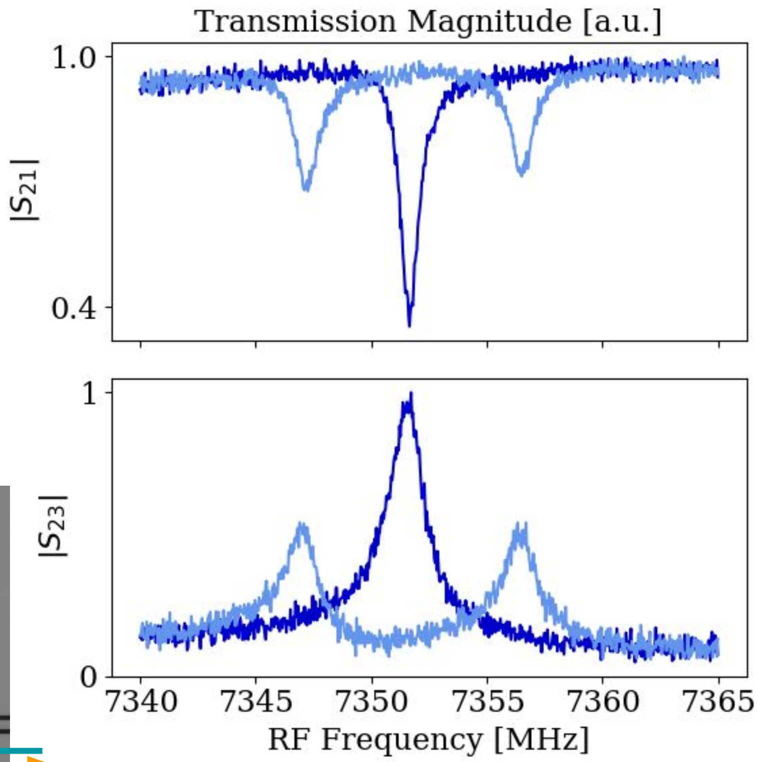
$$\gamma \equiv \frac{\Gamma_r}{2} + \Gamma_\phi = \frac{1}{2}(\Gamma_c + \Gamma_l) + \Gamma_\phi$$



†Upcoming SQUAT design paper, Eq. E5

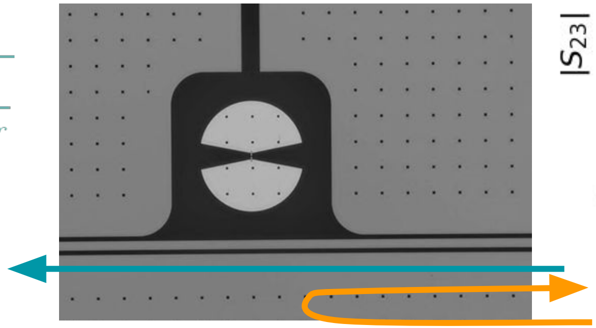
Fit the resonance, get the gammas

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



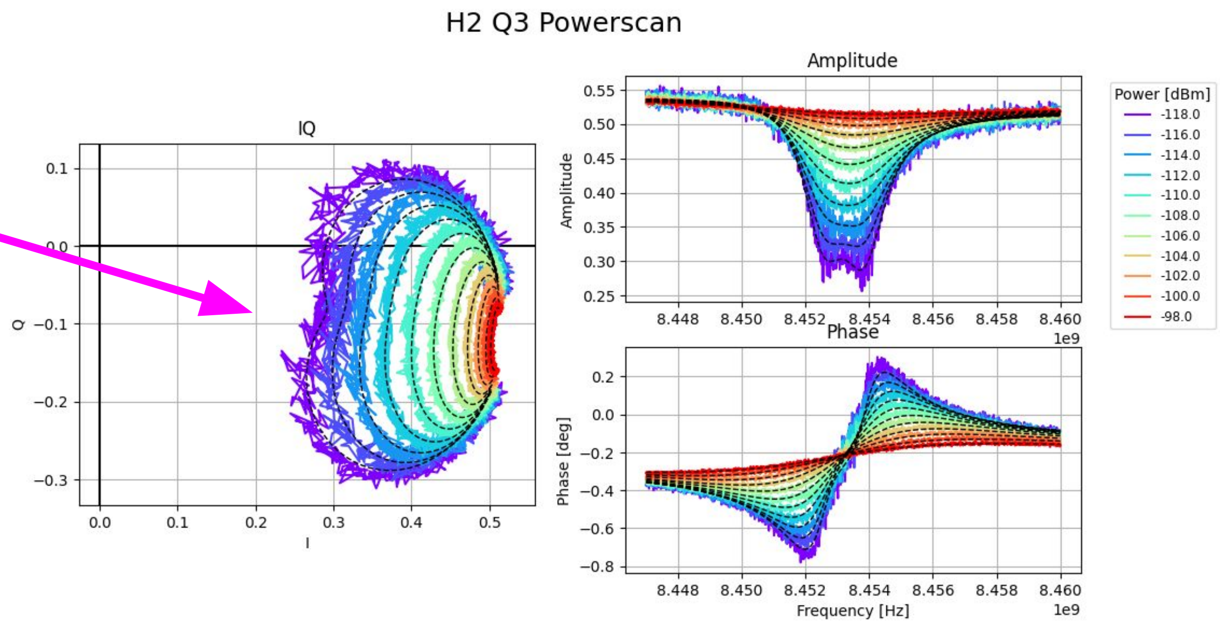
$$t = 1 - \frac{\Gamma_c}{2\gamma} \frac{1 - i\frac{\Delta}{\gamma}}{1 + \left(\frac{\Delta}{\gamma}\right)^2 + \frac{\Omega^2}{\gamma \Gamma_r}}$$

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



Frequency Scans

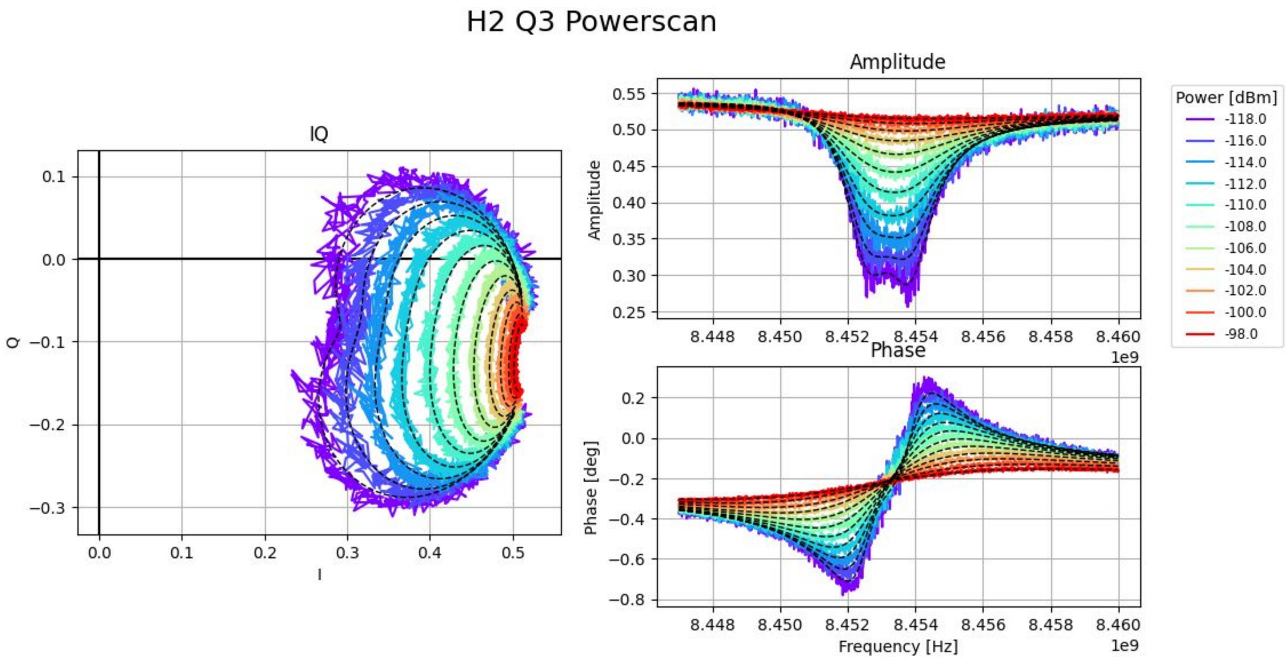
Hey why does it squish
at high powers?



Fit the resonance, get the gammas

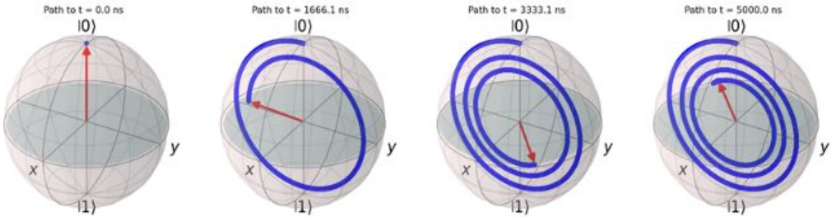
$$t = 1 - \frac{\Gamma_c}{2\gamma} \frac{1 - i\frac{\Delta}{\gamma}}{1 + \left(\frac{\Delta}{\gamma}\right)^2 + \frac{\Omega^2}{\gamma\Gamma_r}}$$

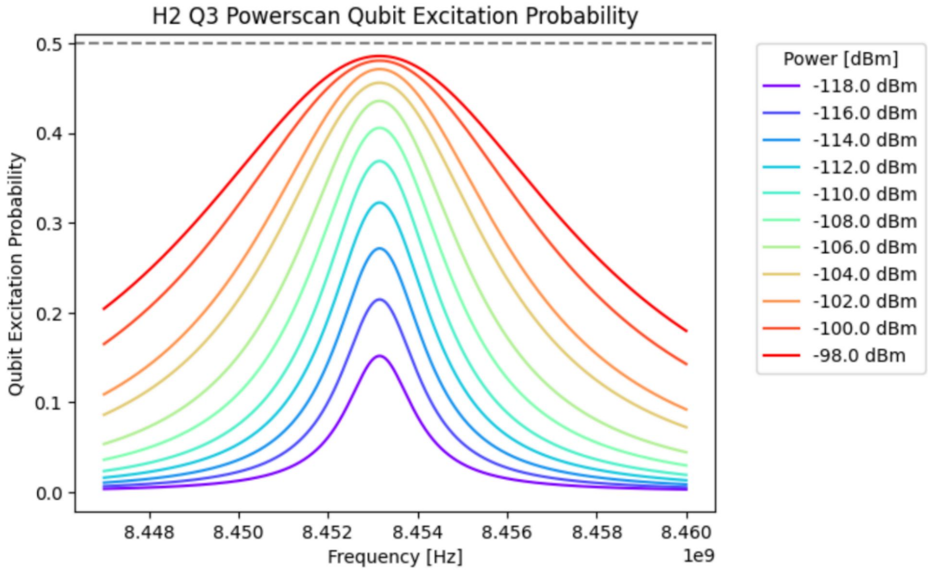
Transmission has a power dependence



Fit the resonance, get the gammas

- As power increases, transition probability saturates at 50%
- Faster Rabi oscillations → greater probability of transition for a wider frequency BW
- **Probability bandwidth broadens**

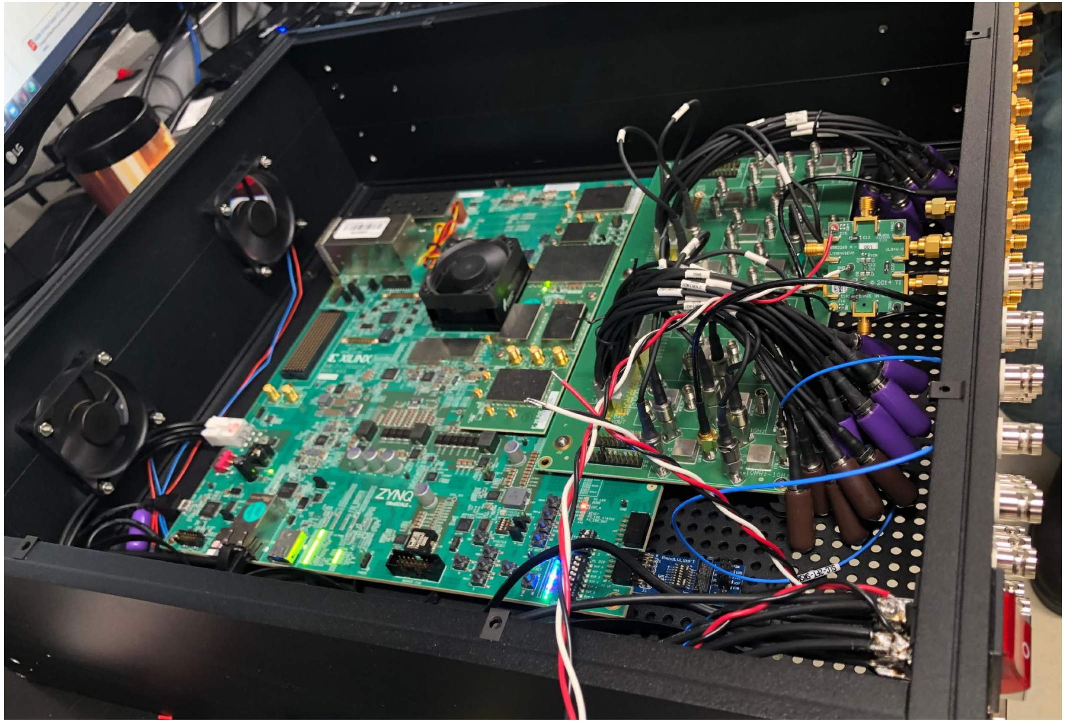




Pulsed Measurements with QICK

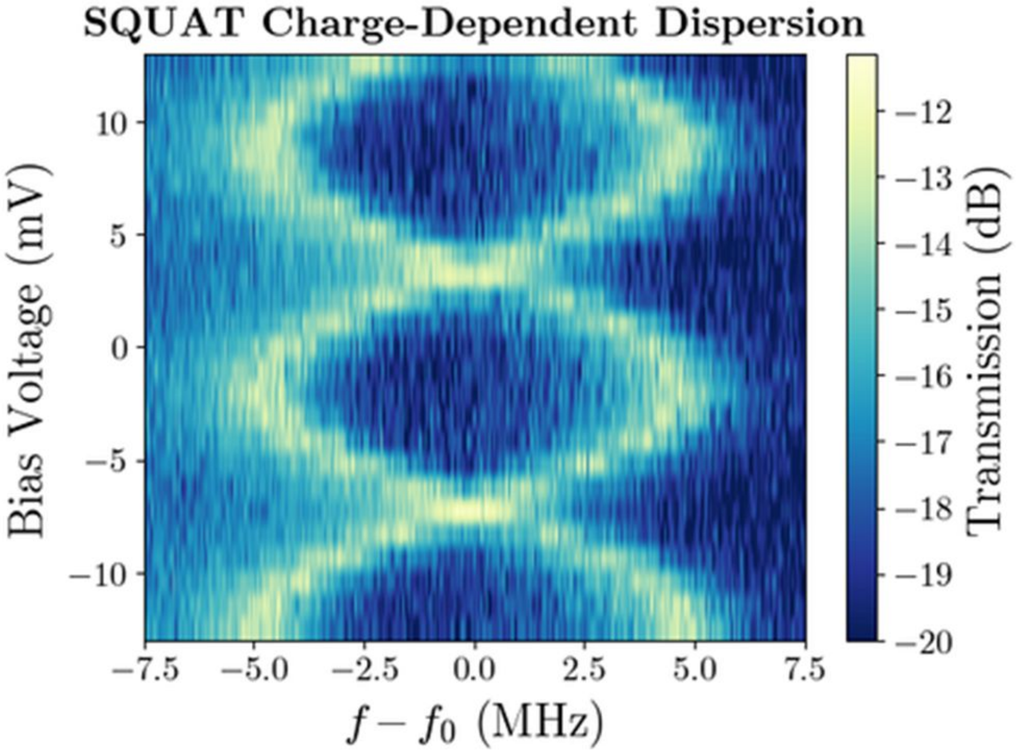
RFSoC board (ZCU 216) running QICK

- When qubit is biased in the degenerate state, well-described as a two-level system
- Short pulses set qubit's state
- Longer pulses drive qubit to intermediate state
- Extract Rabi rate Ω, T_1, T_2



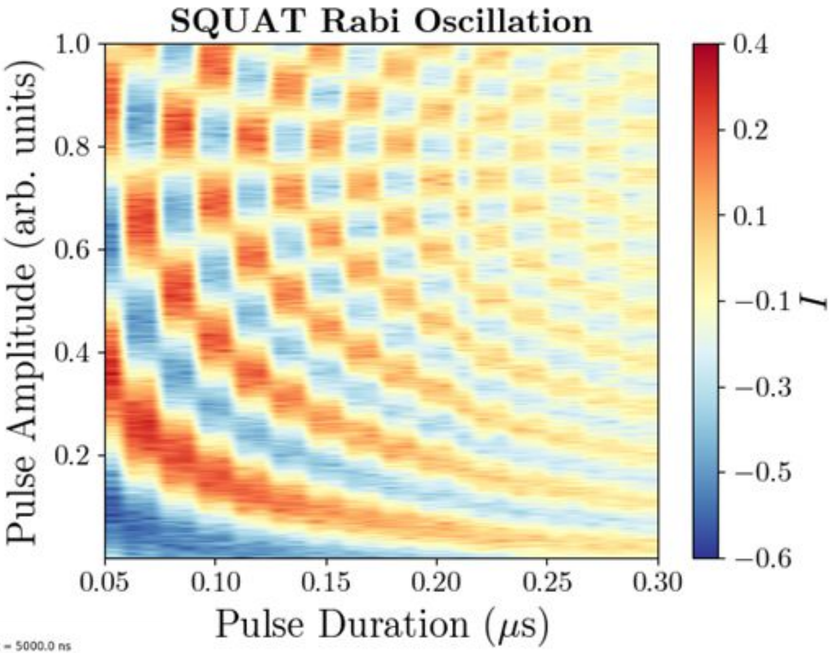
Dispersion

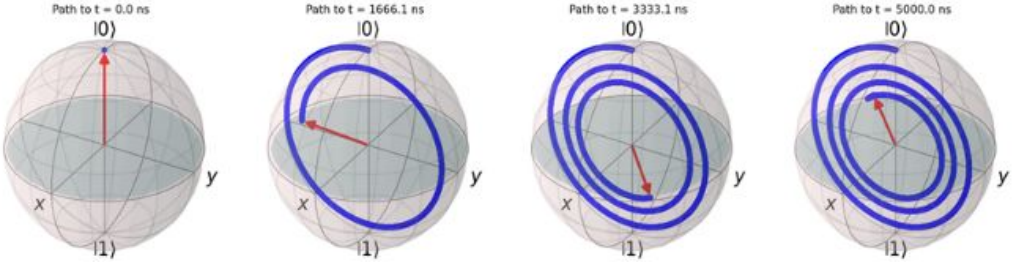
- Tune dispersion by dc biasing SQUAT
- Dispersion $\chi \approx 10Q_0$
  - χ ~ 10 MHz
  - Q_0 ~ 1 MHz
- Two readout modes: phase or amplitude
  - Phase readout improves SNR and ease of implementation



Rabi oscillation

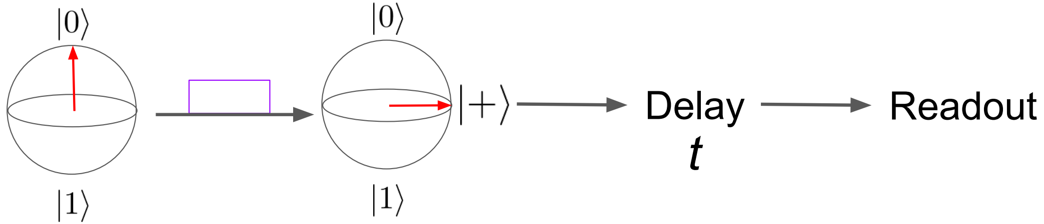
- Apply a pulse at f_0, vary pulse power & duration
- Emitted signal is in XY plane; traces out Rabi oscillations
- Can choose pulse power & duration to prepare qubit in $|+\rangle$ or $|-\rangle$ state

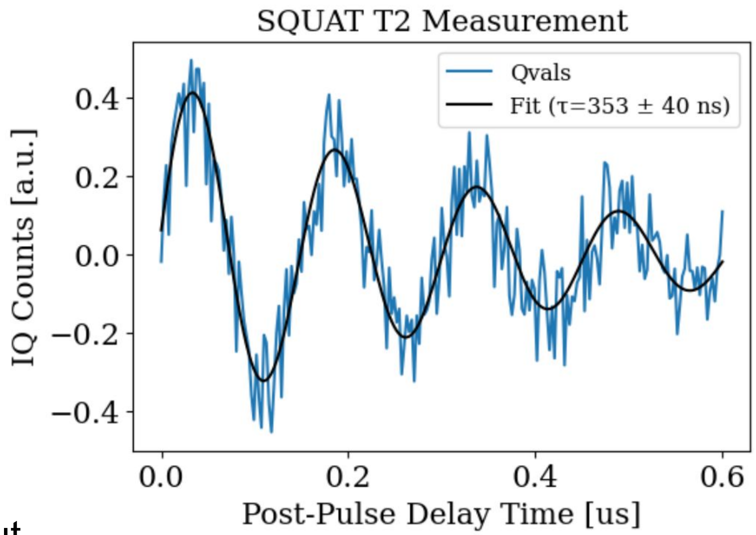




T_2 (dephasing time) measurement

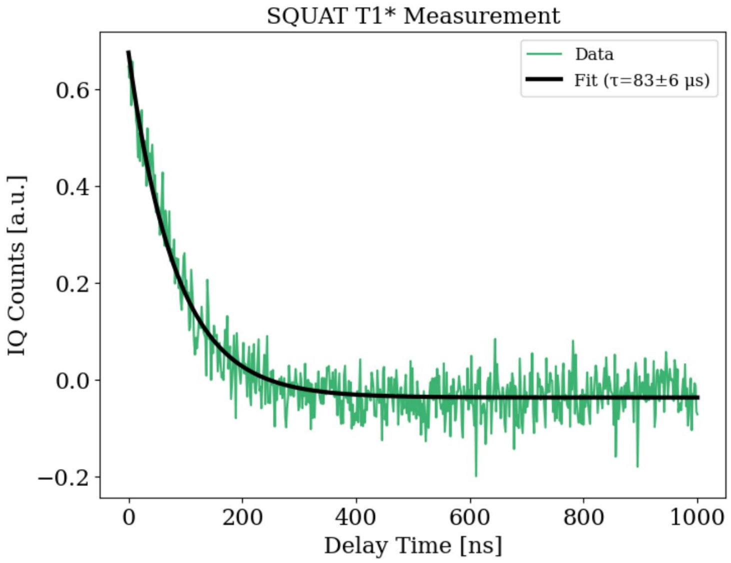
1. With appropriate pulse power & duration, prepare qubit in $|+\rangle$ state
2. Wait variable delay time *t*, measure emission to the feedline
3. Fit to extract T_2

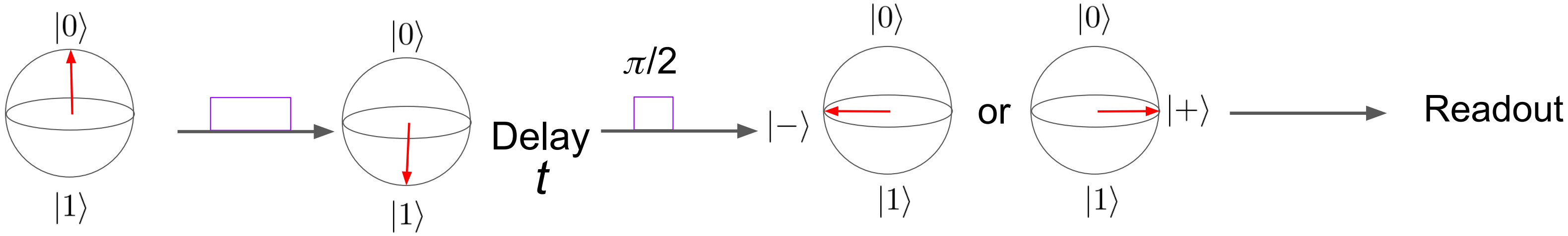




T_1 (energy relaxation time) measurement

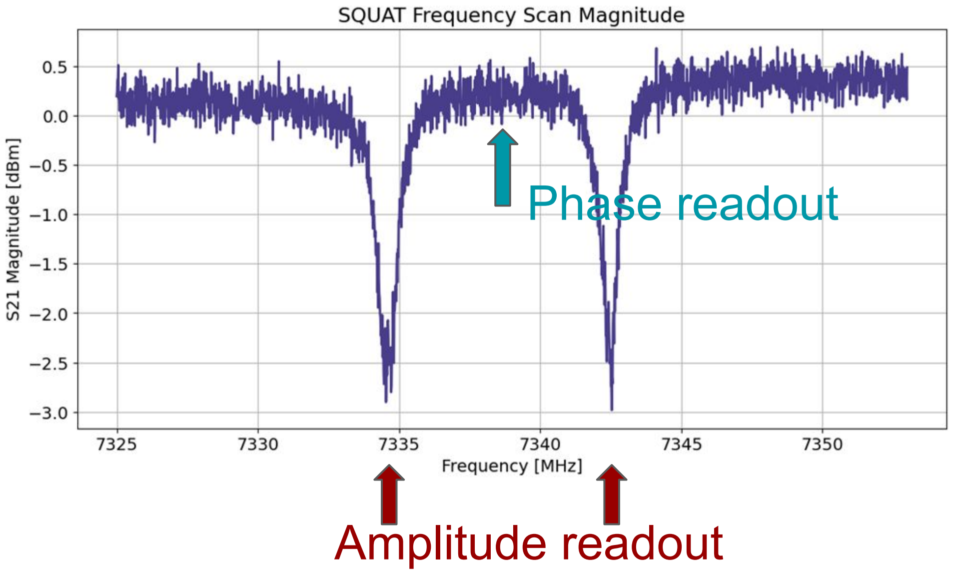
1. Prepare qubit in $|1\rangle$ state
2. Wait variable delay time *t*, apply $\pi/2$ pulse to rotate qubit
3. Measure emission to feedline; result depends on whether qubit decayed to $|0\rangle$ or maintained $|1\rangle$
4. Fit to extract T_1

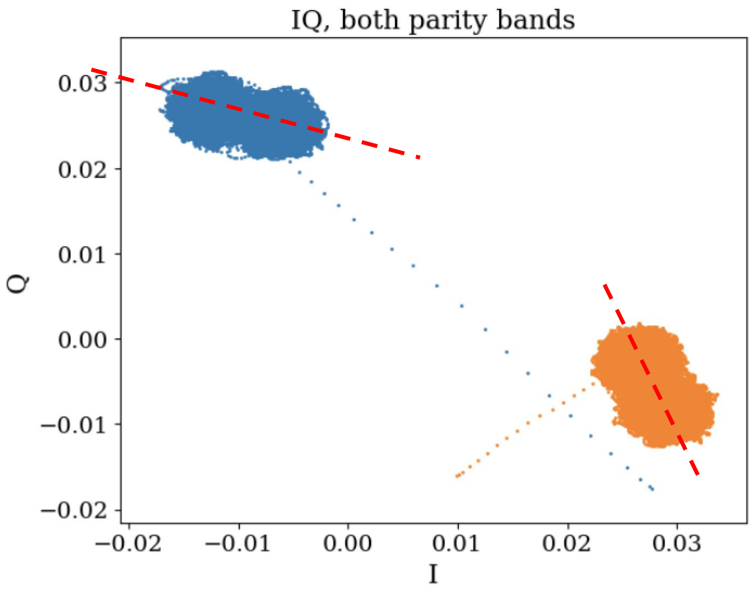




Parity measurements

- Quasiparticle tunneling toggles parity of qubit
- Two possible readout modes: amplitude and phase





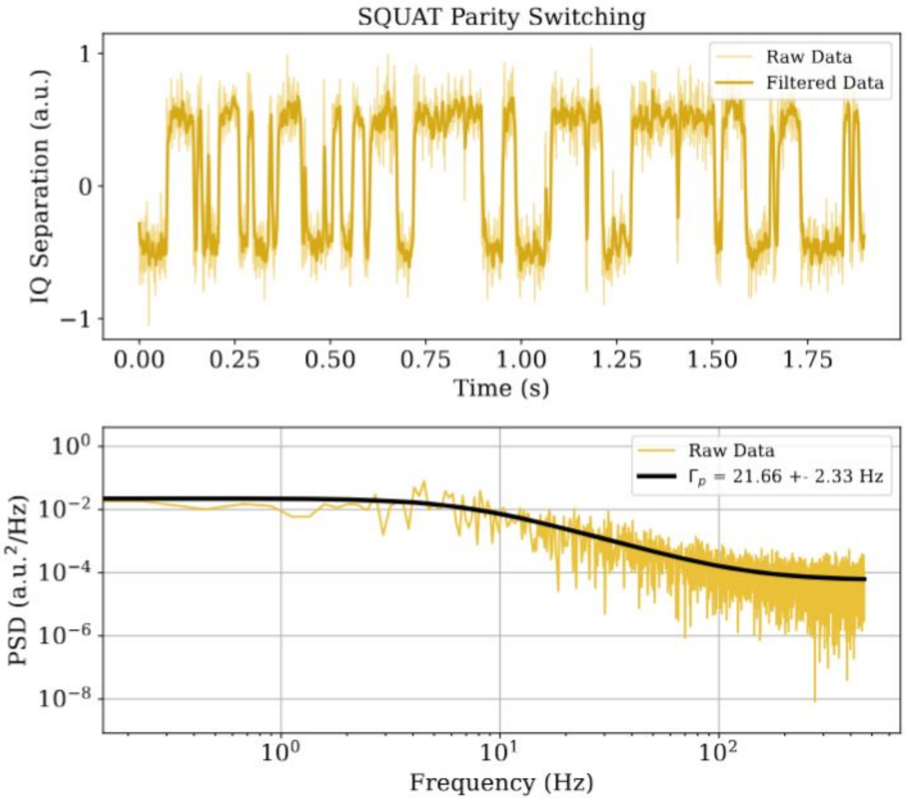
Parity Timestream

- Can be difficult to read out switching rate with time stream data
- Extract switching rate with 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:

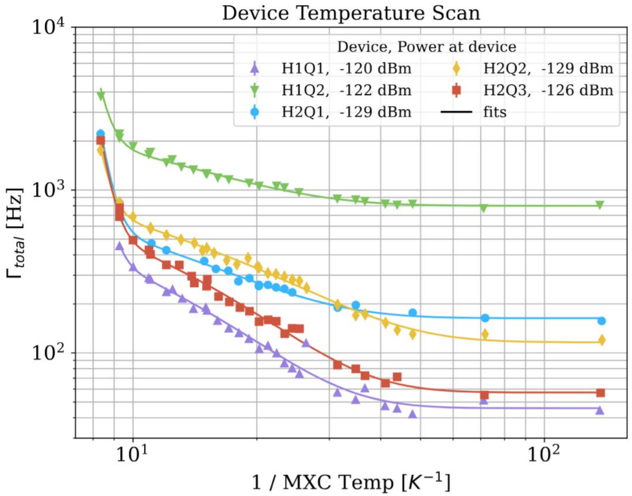
$\Gamma_{qp} \approx 20$ Hz



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

Parity Timestream Tempscan

- From these fits, we also extract:
  - x_{qp}, Quasiparticle density in the film
  - $\delta\Delta$, difference in SC gap energy on either side of the junction
  - arXiv:2505.08104



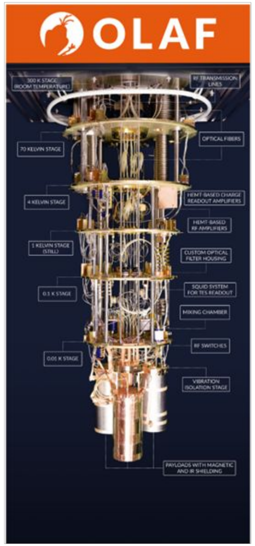
Hey why baselines different for different qubits?

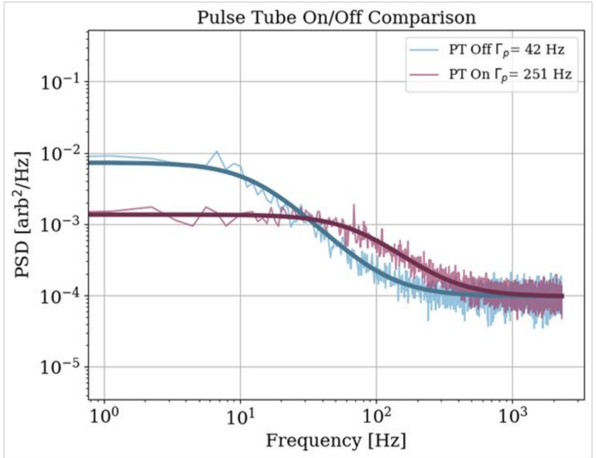
Let's make up a variable and blame him!

Device	x_{qp}^{ne} ($\times10^{-8}$)	$\delta\Delta$ (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

Parity Timestream Tempscan

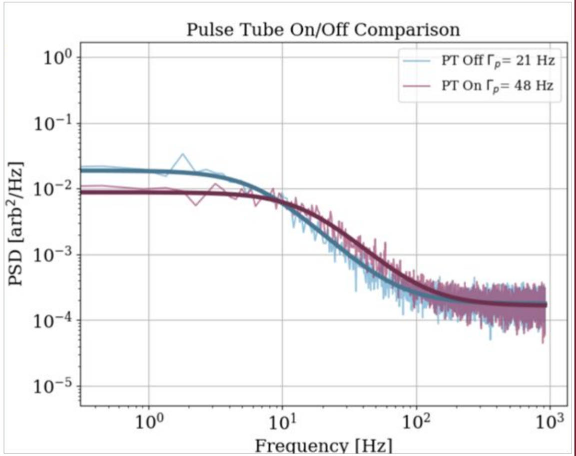
Oxford Proteox





~6x higher tunneling rate with PT on

Bluefors XLD



~2x higher tunneling rate with PT on

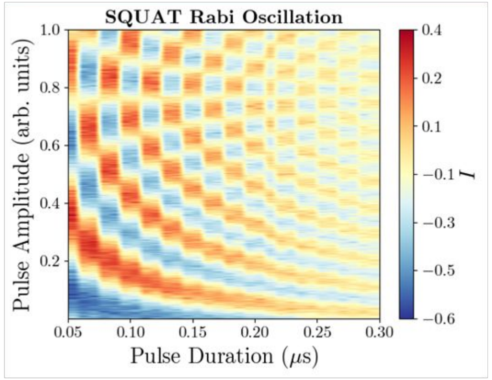
Summary

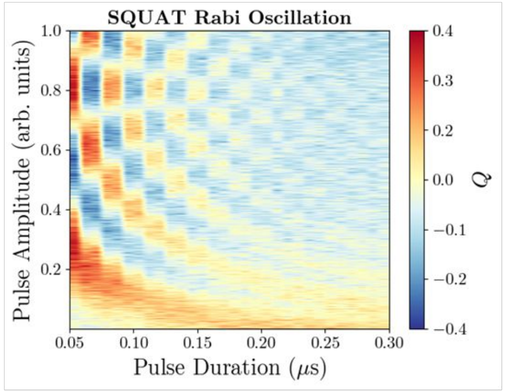
- 5 SQUAT devices are well-characterized with understood dynamics
  - Power scans, frequency scans, time domain and pulsed measurements
- First measurement of parity switching events in SQUATs!
- When you get a SQUAT chip, do these checks
- VNA is a useful tool, but likely moving to SMuRF for long-term readout

Extras

LTD copy paste dump

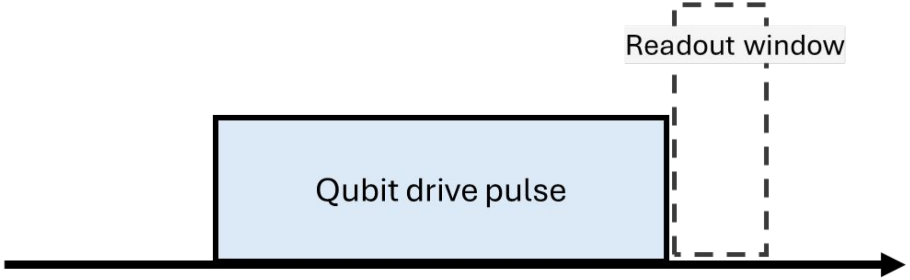
SQUAT Readout Dynamics

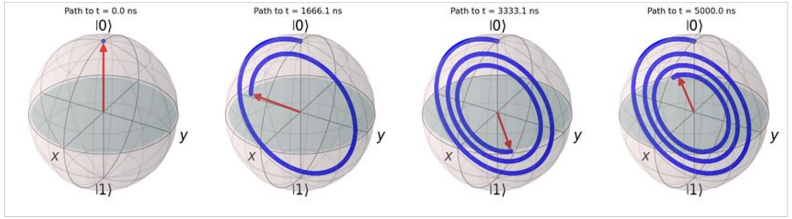




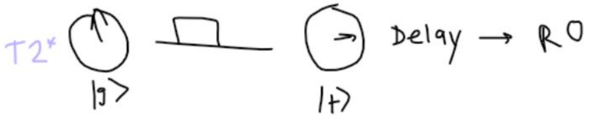
We can use short control pulses to set the qubit's state

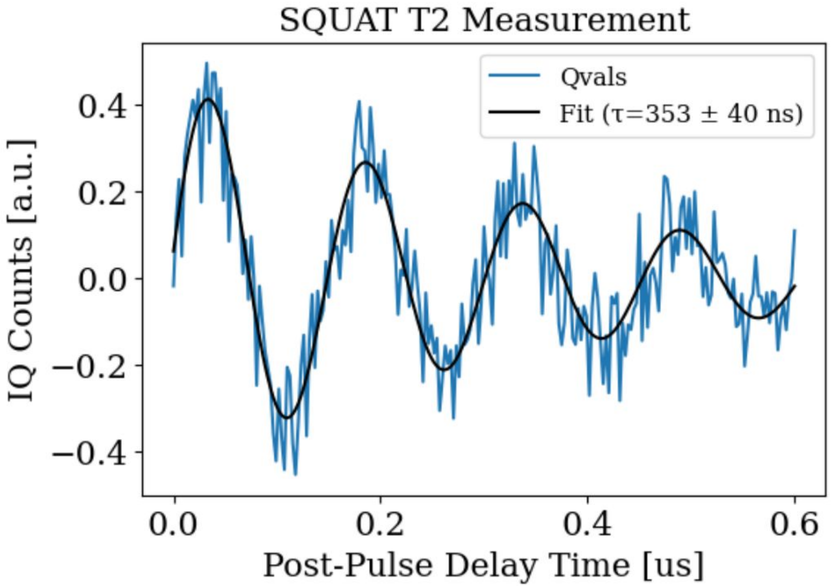
As pulses become longer, we drive the qubit into a mixed state



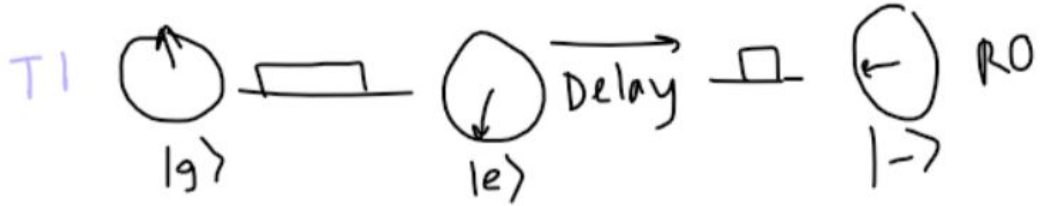


T2

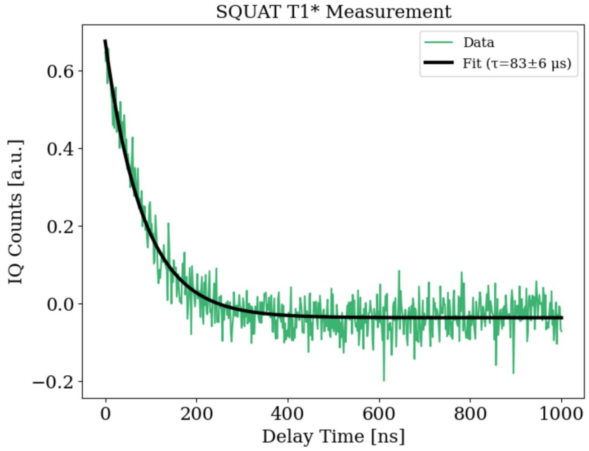

T2*
|g>
|+>
Delay → RO


SQUAT T2 Measurement
Qvals
Fit (τ=353 ± 40 ns)
IQ Counts [a.u.]
0.4
0.2
0.0
−0.2
−0.4
0.0
0.2
0.4
0.6
Post-Pulse Delay Time [us]

T1



T1
|g⟩
|e⟩
Delay
|-⟩
RO



SQUAT T1* Measurement
Data
Fit (τ=83±6 μs)
IQ Counts [a.u.]
Delay Time [ns]
0.6
0.4
0.2
0.0
−0.2
0
200
400
600
800
1000

Master Equation, extract gammas

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

Explain master equation, define gammas

Let’s fit the gammas from the frequency scans

Hannah can make a cartoon to show different decoherence pathways

Fit the resonance, get the gammas

Use the master equation to write EoM for each operator

$$\alpha_{out}^{L,R}(t) = \alpha_{in}^{R,L}(t) - i\frac{\Gamma_c}{2g}\sigma_-$$

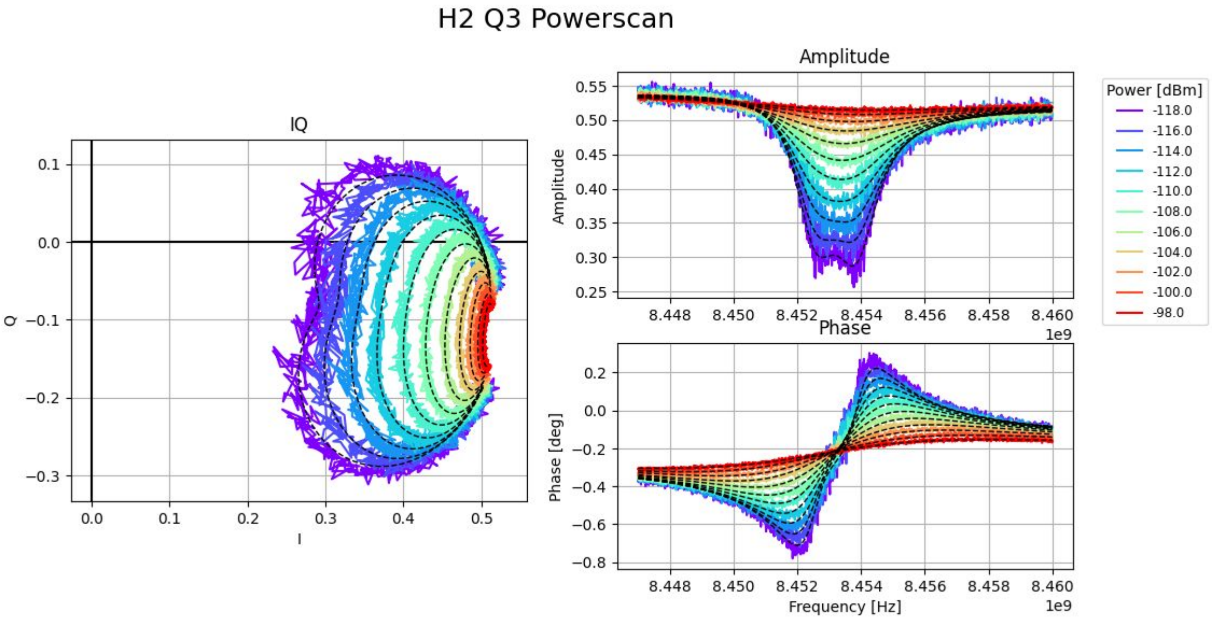
Find steady state solution by setting operator time derivative = 0

Look at expectation value of operators, plug into IO theory equation, find ratio of scattering matrix terms to get transmission and reflection!

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

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

Fit the resonance, get the gammas



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