Northwestern

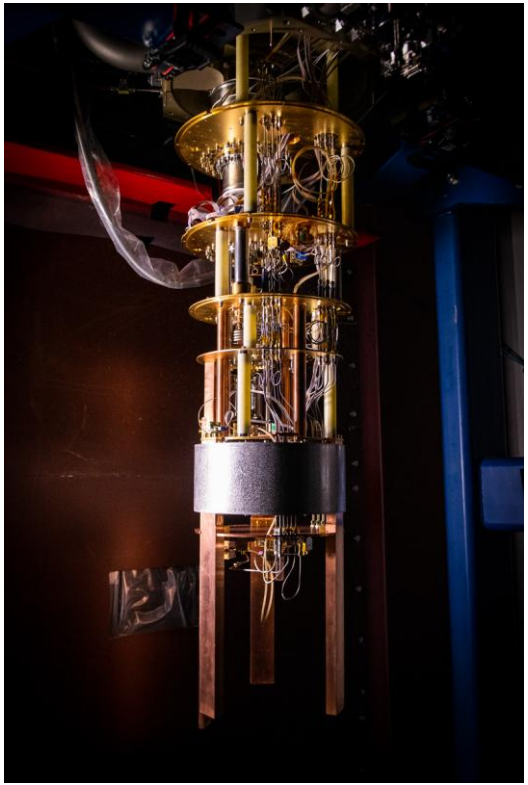
SQUATs Underground + Radiation Sources

Grace Bratrud
Ph.D. Student, Northwestern University
SQUAT Workshop
29 October 2025

Fermilab

Overview

- NEXUS charge qubit measurements
  - Excess low background charge jumps
- Charge and parity measurements with SQUAT device
- Plan for SQUATs underground at Fermilab



Cryostat at NEXUS

Measurement Channels

Quasiparticles Tunneling at Junction

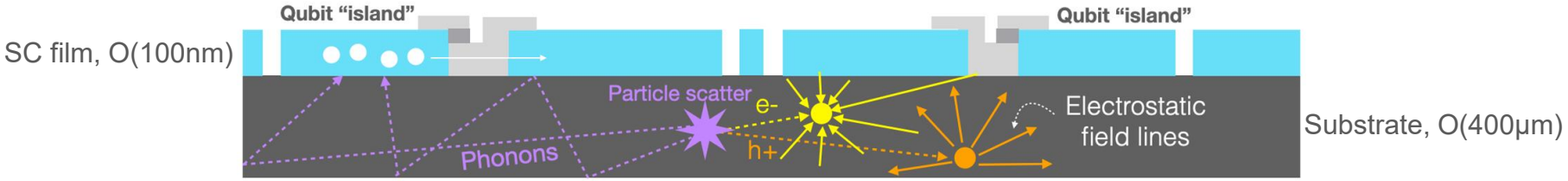
Charge-Parity Switching

- Quasiparticles tunnel across JJ and change the charge parity state of the qubit between even/odd
- Changes frequency of qubit
- Energy deposition causes increased rate of tunneling, timescale: ~ms

Trapped Charges

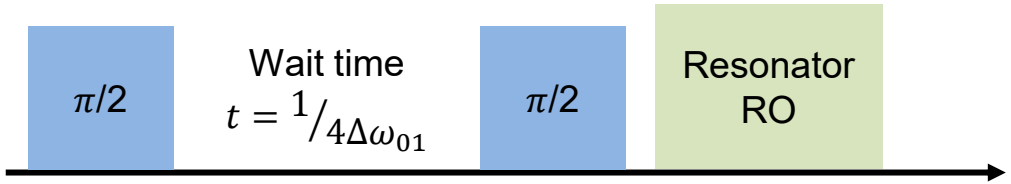
Charge Burst

- Trapped charges induce electric field near the qubit
- Changes in electric field are seen as charge jumps in charge-sensitive qubits
- Effects of charge bursts persist for longer timescales; O(hours) without external E-field.

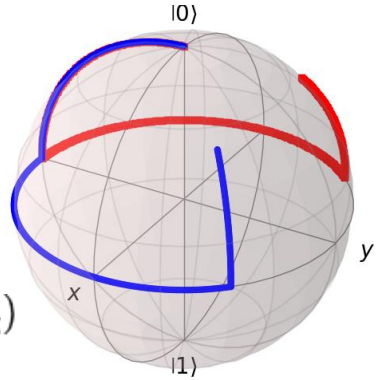


Charge Tomography Measurement

- Maps offset charge to z-axis (readout basis) in charge sensitive transmon qubits with readout resonators
- Pulse sequence is repeated at different charge bias values

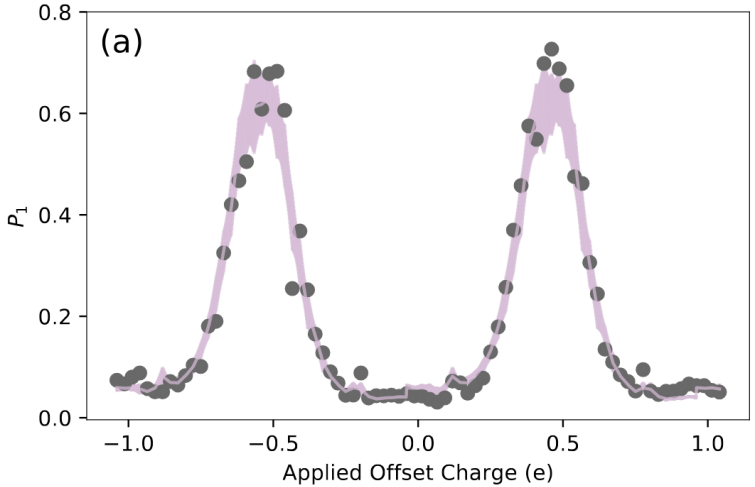


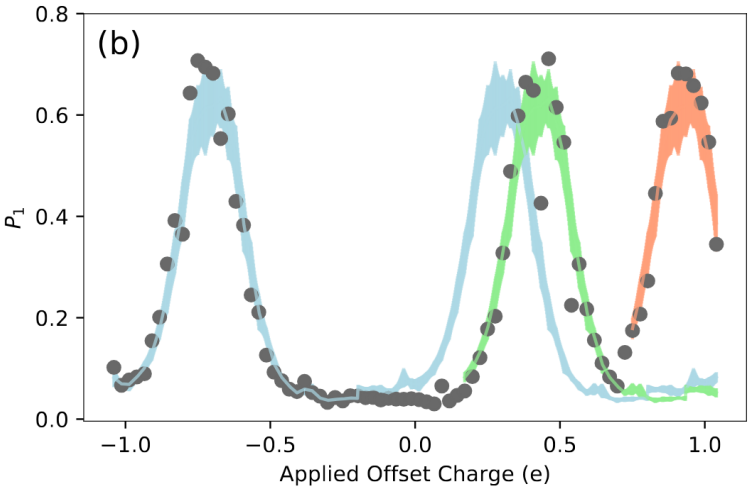
$$\phi(n_g) = \Delta\omega_{01} t_{\text{idle}} \cos(2\pi n_g)$$



Charge Tomography

- If there are no charge jumps, we see uninterrupted periodic behavior with a period of 1e
- If there are charge jumps this will result in a discontinuity and phase change. Below we see two jumps in one scan

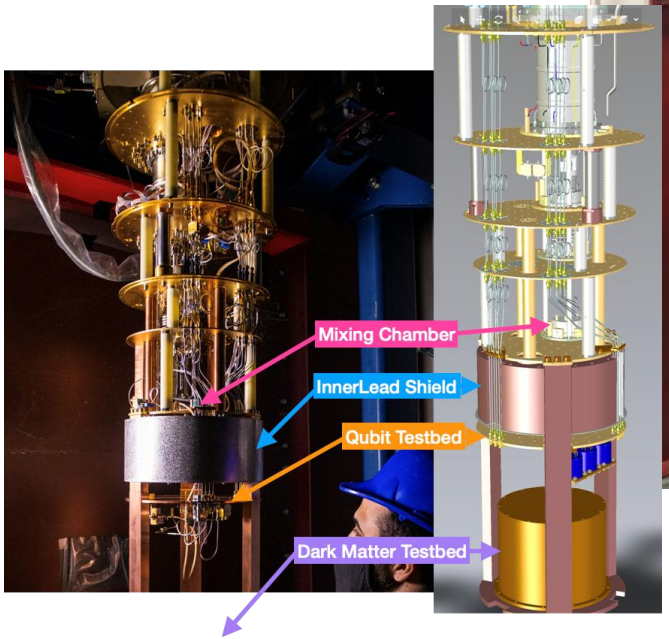




GB et al, (2024) [arXiv:2405.04642]

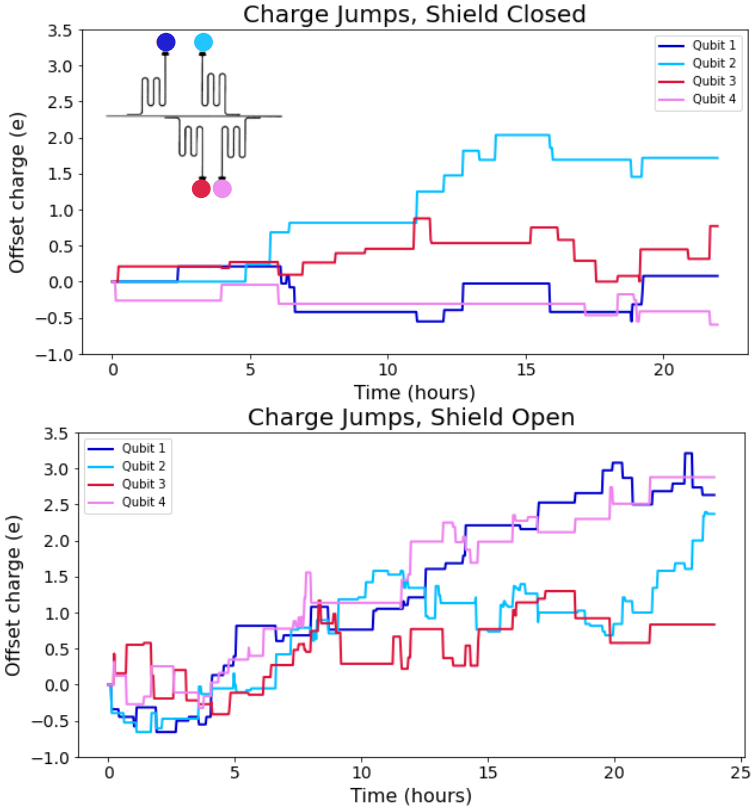
NEXUS Facility

- NEXUS at Fermilab, in MINOS tunnel
- 107 m rock overburden, 225 mwe
- 4π coverage with movable Pb shield castle and internal Pb shield



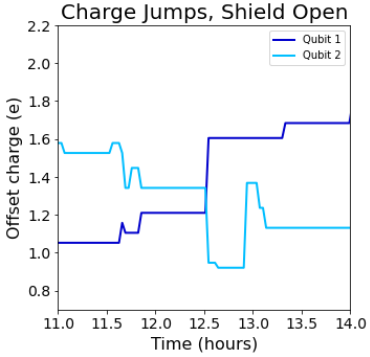
Charge Jump Study Results

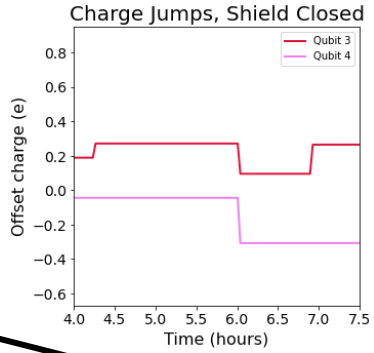
- Took repeated tomography measurements with and without the Pb shield enclosed around the cryostat
  - Saw change in charge jump rate
- Also saw correlated errors

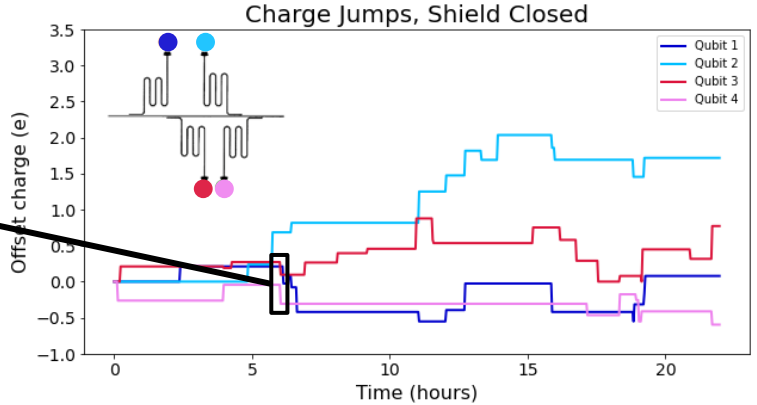


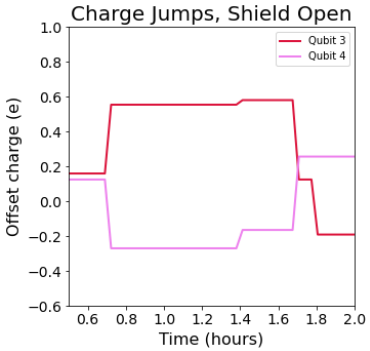
GB et al, (2024) [arXiv:2405.04642]

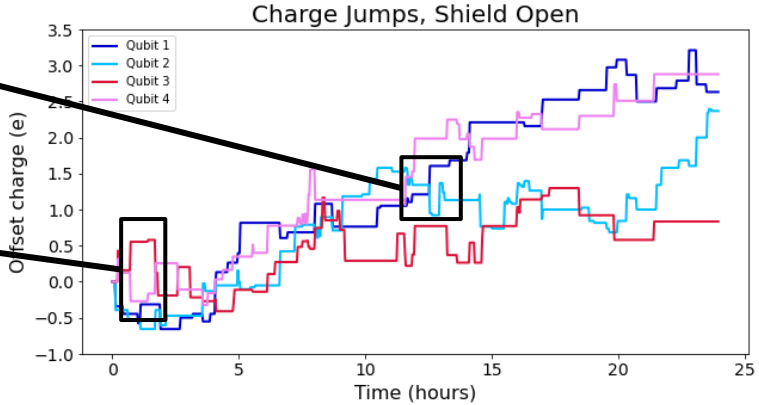
Charge Jump Study Results











GB et al, (2024) [arXiv:2405.04642]

Charge Jump Study Results

- Saw the expected reduction between aboveground rate (1.35 mHz) and the shield open rate
- Gamma flux near the qubit is **20x lower** in the shield closed vs shield open datasets
  - However we saw only a **2.7 reduction** in jump rate → **excess source of charge jumps** in our lowest background dataset

Not explained by ionizing (gamma) backgrounds

	Shield Open	Shield Closed	Units
Average Rate	$0.51^{+0.05}_{-0.04}$	$0.19^{+0.04}_{-0.03}$	mHz
Corrected γ Rate	$0.34^{+0.07}_{-0.06}$	$0.02^{+0.06}_{-0.05}$	mHz
Calculated Excess Rate		$0.17^{+0.04}_{-0.03}$	mHz

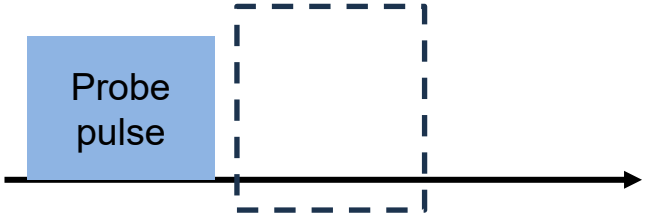
GB et al, (2024) [arXiv:2405.04642]

Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

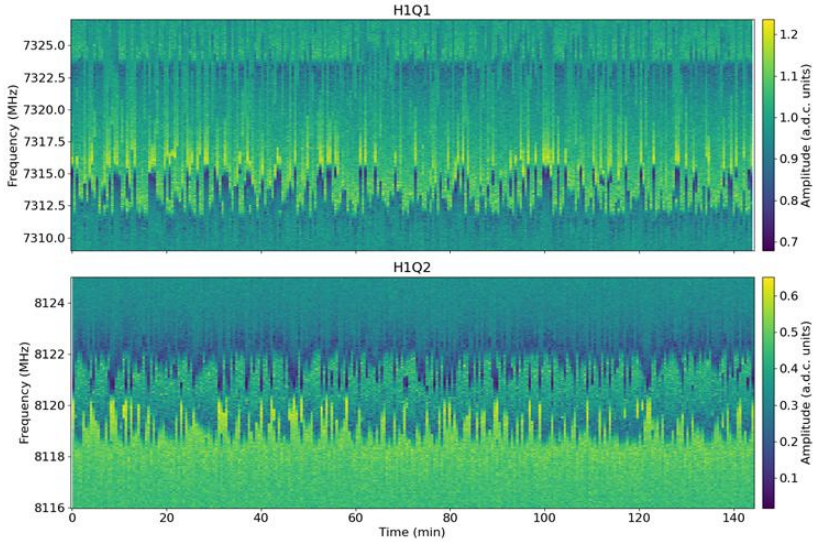
SQUAT Measurements: Charge

Since SQUATs are charge sensitive we can detect charge jumps

- Repeated qubit spectroscopy (S12 measurement)
  - Charge jumps are seen as a change in the frequency of the 2 parity bands
  - Can be done on VNA or QICK



Magoon et al, in prep



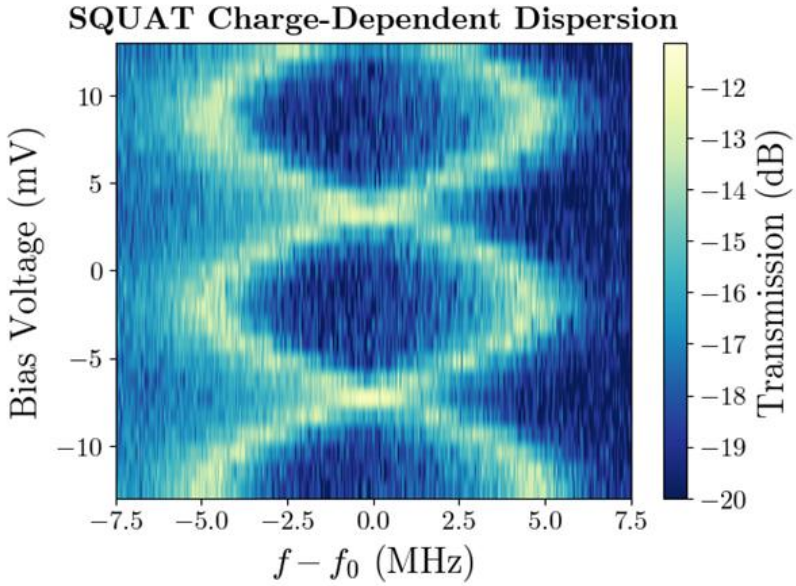
*High charge jump rate due to grounding noise issues in the fridge

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

SQUAT Measurements: Charge

Since SQUATs are charge sensitive we can detect charge jumps

- Repeated bias qubit spectroscopy (S12 measurement)
  - Charge jumps seen as a break in the helix pattern in bias spectroscopy (change in parity band dispersion)
  - Can be done on VNA or QICK



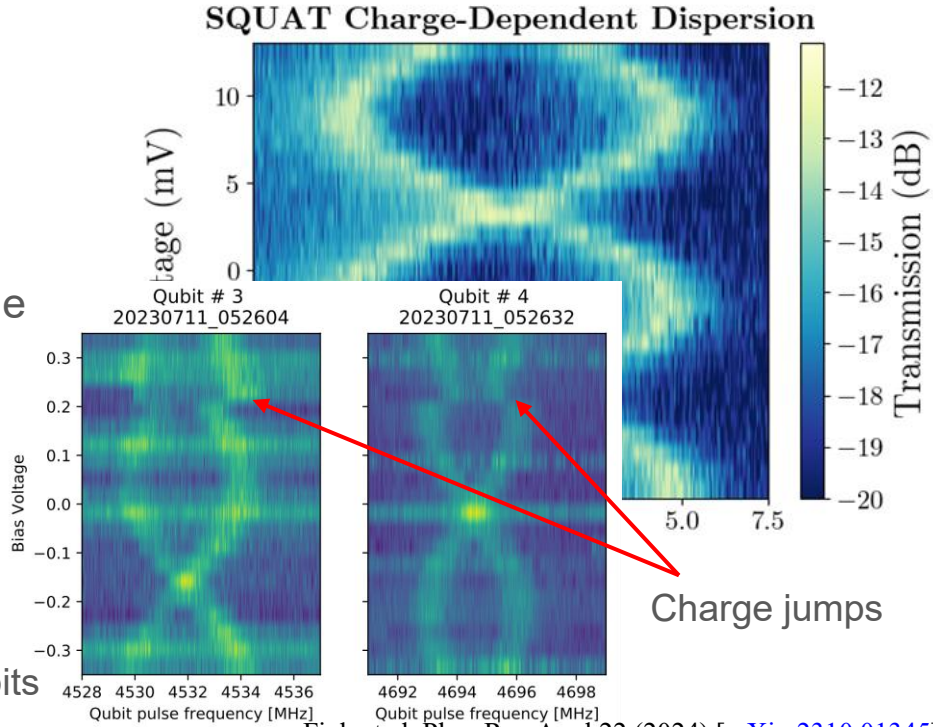
Magoon et al, in prep

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

SQUAT Measurements: Charge

Since SQUATs are charge sensitive we can detect charge jumps

- Repeated bias qubit spectroscopy (S12 measurement)
  - Charge jumps seen as a break in the helix pattern in bias spectroscopy (change in parity band dispersion)
  - Can be done on VNA or QICK



*NEXUS charge qubits

Magoon et al, in prep

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

SQUAT Measurements: Charge

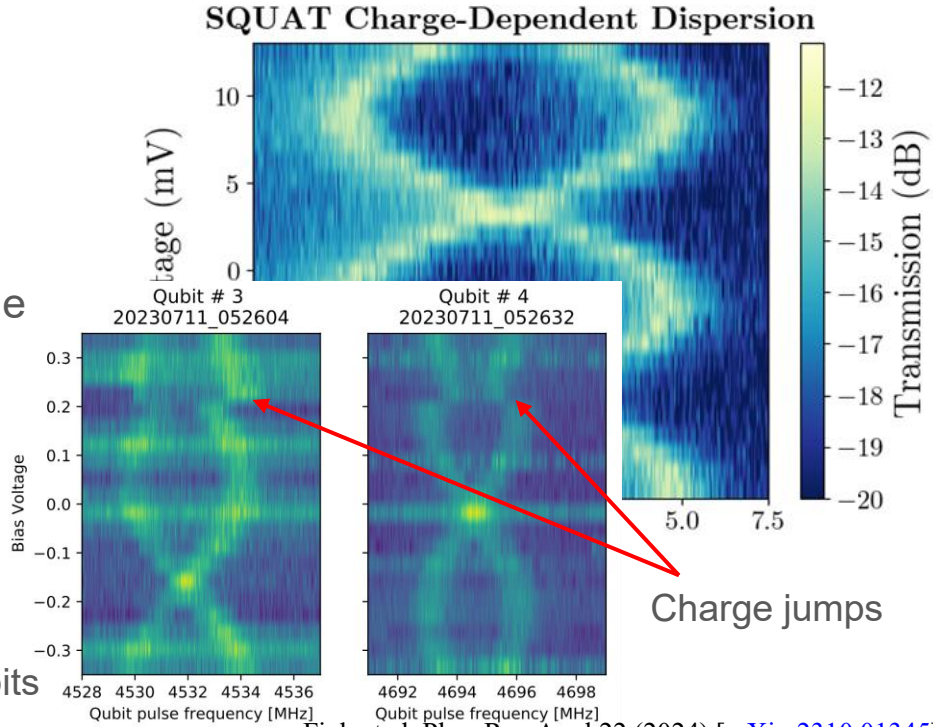
Since SQUATs are charge sensitive we can detect charge jumps

- Repeated bias qubit spectroscopy (S12 measurement)
  - Charge jumps seen as a break in the helix pattern in bias spectroscopy (change in parity band dispersion)
  - Can be done on VNA or QICK

Thoughts on other ways to measure charge jumps in SQUATs?

- Charge tomography doesn't work due to the different readout basis

*NEXUS charge qubits

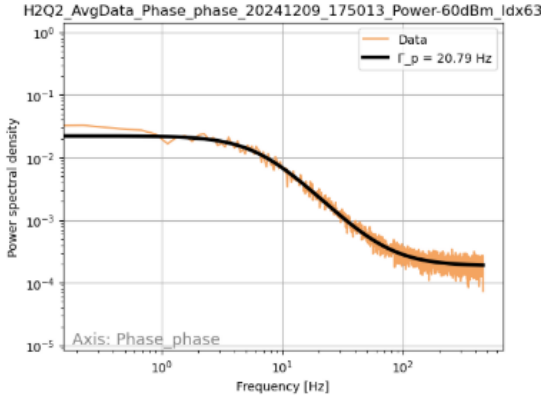


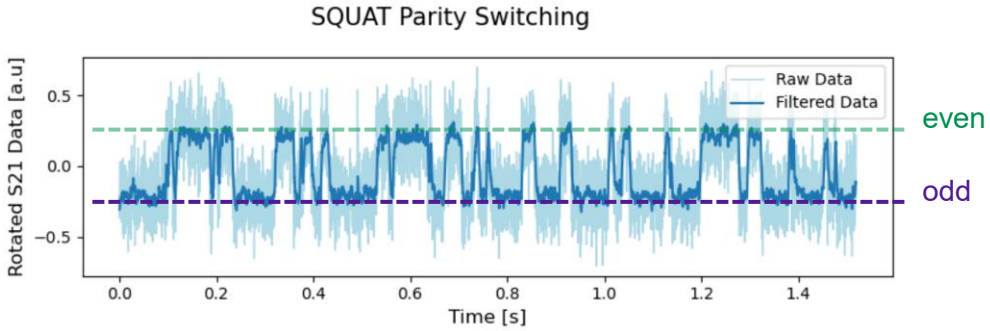
Magoon et al, in prep

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

SQUAT Measurements: Parity

- Parity switching timestream measurements – can be done on VNA or SMuRF RFSoC
  - Get parity switching rate over time (through filter function or PSD)



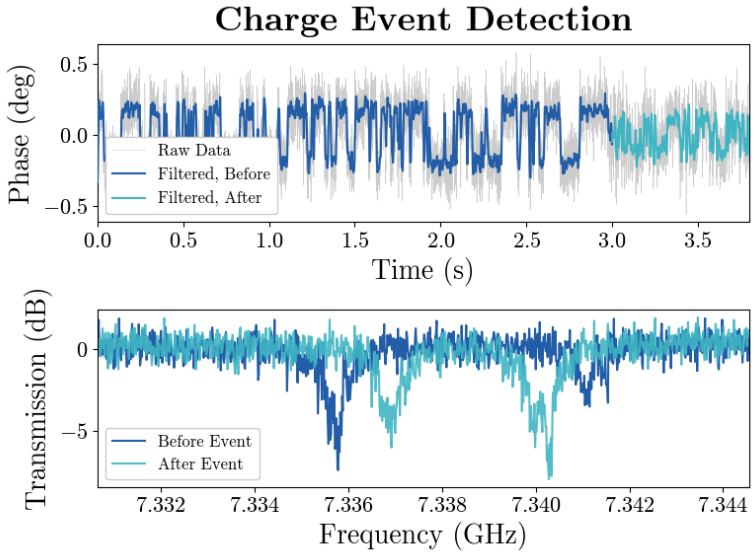


Magoon et al, in prep

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

SQUAT Measurements: Parity

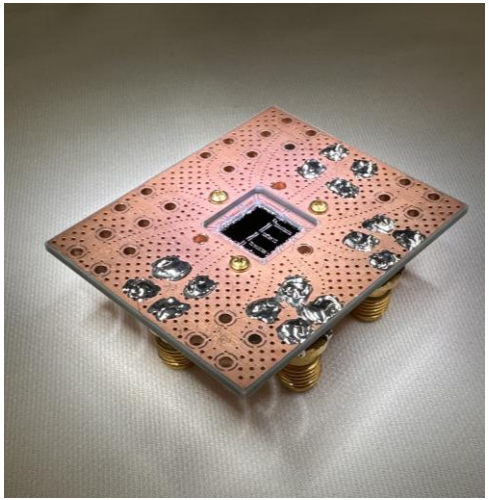
- Parity switching timestream measurements – can be done on VNA or SMuRF RFSoC
  - Get parity switching rate over time (through filter function or PSD)
- We can also see charge jumps in parity timestreams
  - Need low enough charge jump rate so parity switching detection is not impacted



Magoon et al, in prep

Fink et al, Phys Rev Appl 22 (2024) [arXiv:2310.01345]

Measurement Plans @ Fermilab

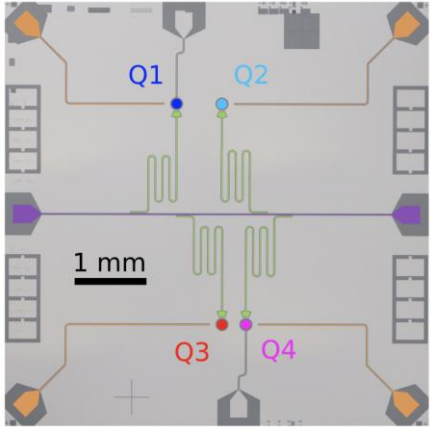


- Measure SQUAT chip underground in NEXUS (and/or QUIET)
- Take charge and parity measurements in different configurations and extract rates
  - Pb shield open and closed
  - Radiation sources near the fridge: Cs-137, Ba-133, Am-241
  - Alpha-emitting housing (Po210 decay)
- Do we see the excess low background events in either charge or parity rates in the SQUATs, as in the charge qubits?
- Can also use the sources to look at energy sensitivity of the SQUATs
  - Parity switching events as a waveform

Backup Slides

Correlated Errors Study @ NEXUS

	Shield Open	Shield Closed	Units
Livetime	23.949	22.075	hours
Q1 Rate	$0.42^{+0.09}_{-0.08}$	$0.20^{+0.07}_{-0.05}$	mHz
Q2 Rate	$0.60^{+0.11}_{-0.09}$	$0.19^{+0.07}_{-0.05}$	mHz
Q3 Rate	$0.52^{+0.10}_{-0.08}$	$0.19^{+0.07}_{-0.05}$	mHz
Q4 Rate	$0.51^{+0.11}_{-0.09}$	$0.16^{+0.07}_{-0.05}$	mHz
Average Rate	$0.51^{+0.05}_{-0.04}$	$0.19^{+0.04}_{-0.03}$	mHz
Corrected γ Rate	$0.34^{+0.07}_{-0.06}$	$0.02^{+0.06}_{-0.05}$	mHz
Calculated Excess Rate	$0.17^{+0.04}_{-0.03}$		mHz

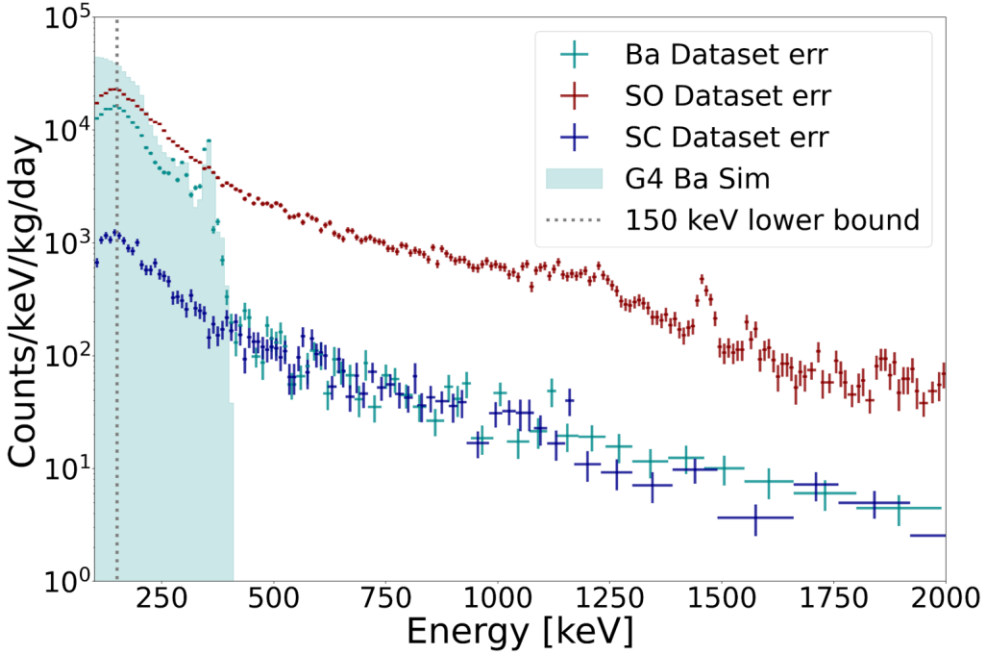


	Q1-Q2	Q3-Q4	Q1-Q3	Q1-Q4	Q2-Q3	Q2-Q4	Units
Separation	640	340	3195	3330	3180	3240	μm
Shield Open	$0.27^{+0.09}_{-0.07}$	$0.29^{+0.09}_{-0.07}$	$0.03^{+0.04}_{-0.02}$	$0.08^{+0.06}_{-0.04}$	$0.05^{+0.05}_{-0.03}$	$0.08^{+0.06}_{-0.04}$	mHz
Shield Closed	$0.10^{+0.07}_{-0.04}$	$0.04^{+0.05}_{-0.03}$	< 0.03	< 0.04	< 0.03	< 0.04	mHz

GB et al, (2024) [arXiv:2405.04642]

Radiation Background Characterization

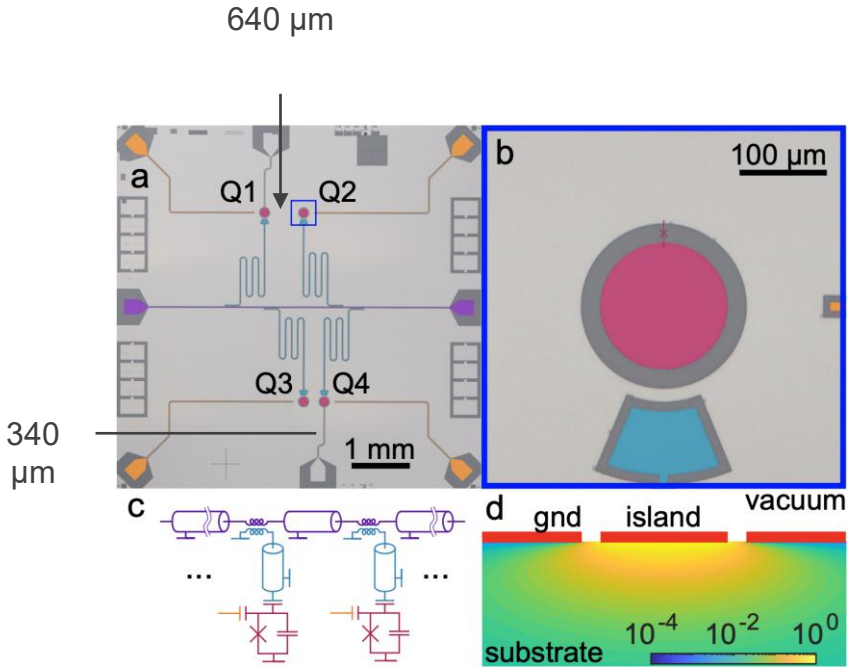
- Cryogenic calorimeter detector (LMO crystal read out by TES) also in NEXUS fridge.
- Spectra from this device shows a 20x reduction in gamma rate between SO and SC configurations



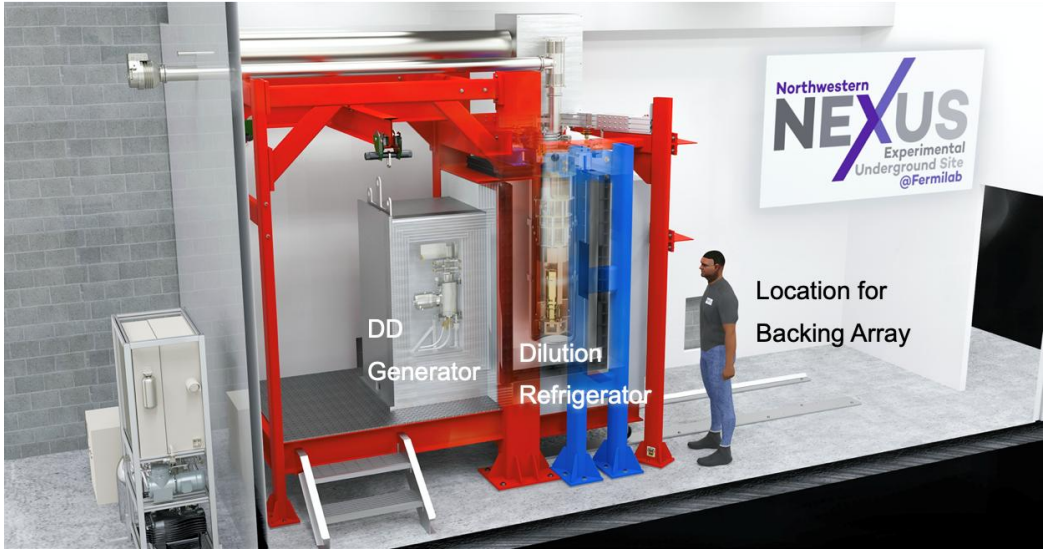
Bratrud et al, (2024) [arXiv:2405.04642]

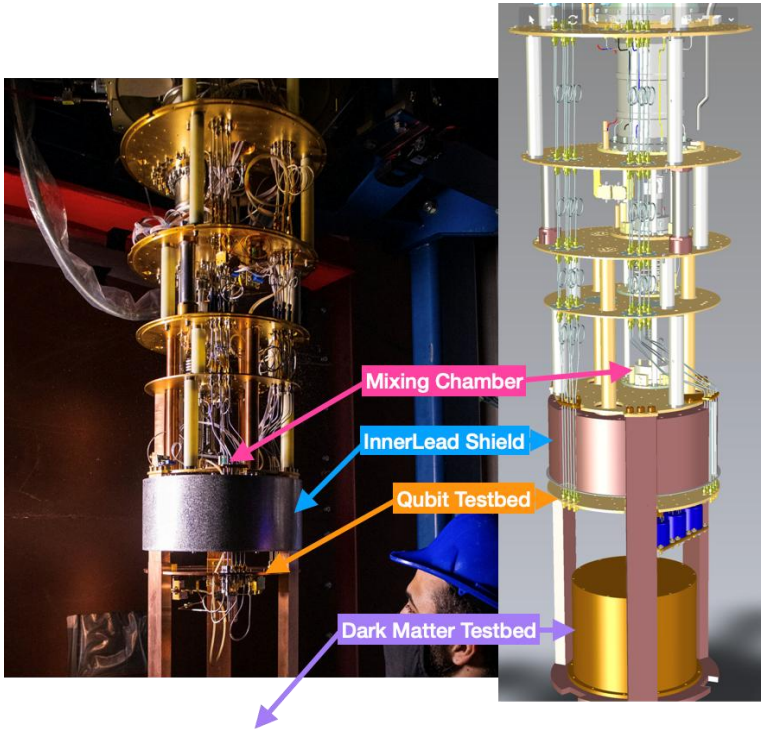
NEXUS Charge Qubits

- Nb groundplane, Nb islands, Al-AlOx-Al junctions



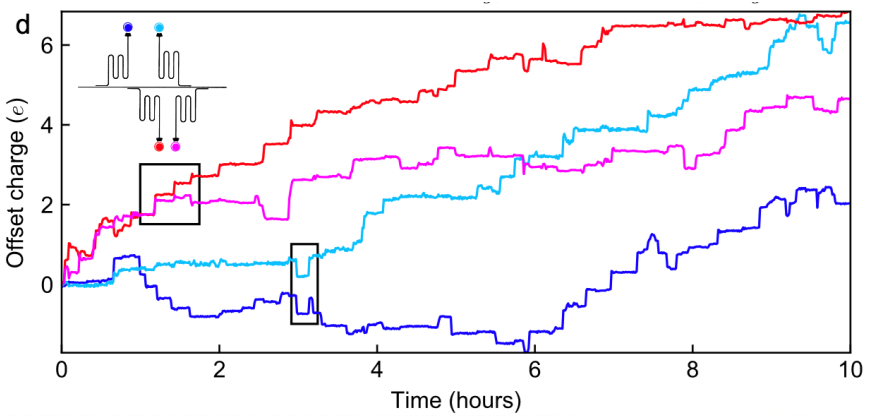
NEXUS Facility

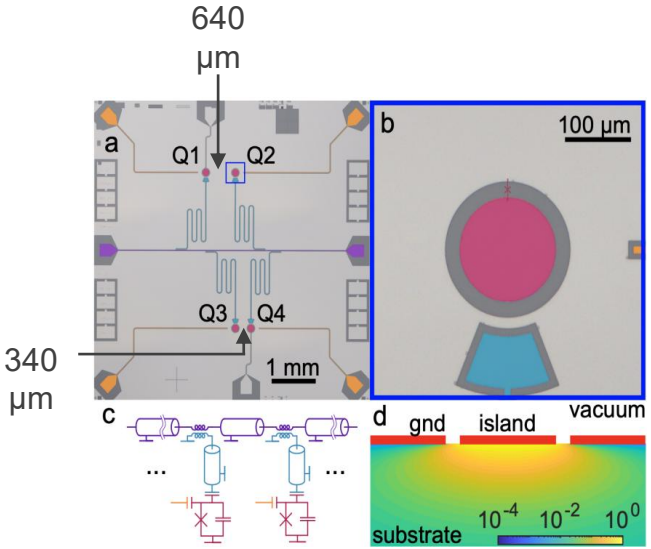




Correlated Charge Errors in SC Qubits

- *Wilen et al* ran a charge sensitive qubit chip in an above-ground fridge
- Found correlated charge jumps between nearby qubits, caused by ionizing radiation





Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]