Studying Correlated Charge Fluctuations of Superconducting Qubits in a Low-Background Underground Facility

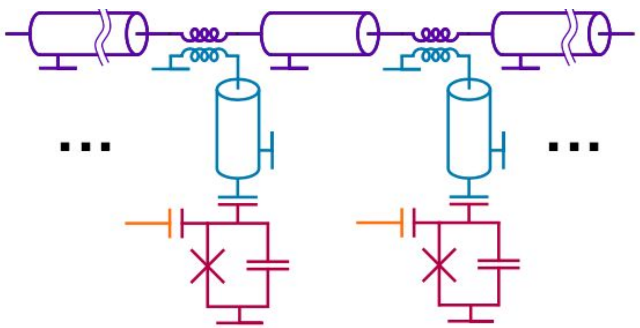
Hannah Magoon

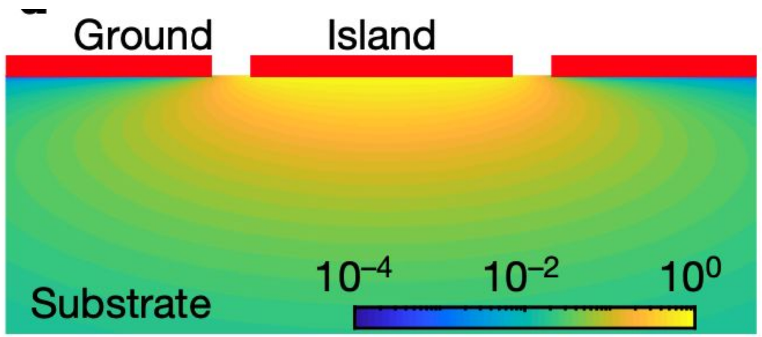
CPAD, 11/8/2023

Superconducting Qubits

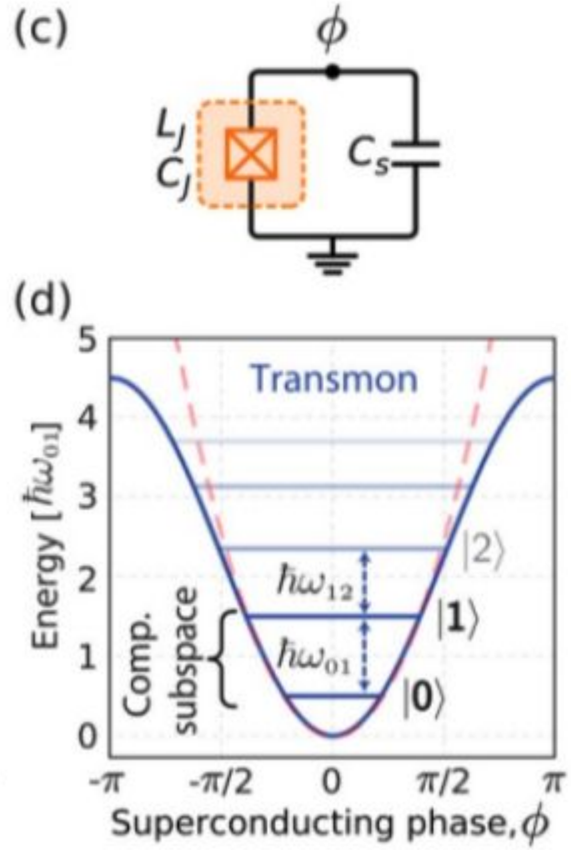
What are superconducting qubits?

- Two level systems in the form of anharmonic oscillator, coupled to a harmonic readout resonator
- The qubit state can be modulated with gate pulses applied through a transmission line
- Qubits have demonstrated sensitivity to ionizing radiation, as measured in both charge and logic state





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



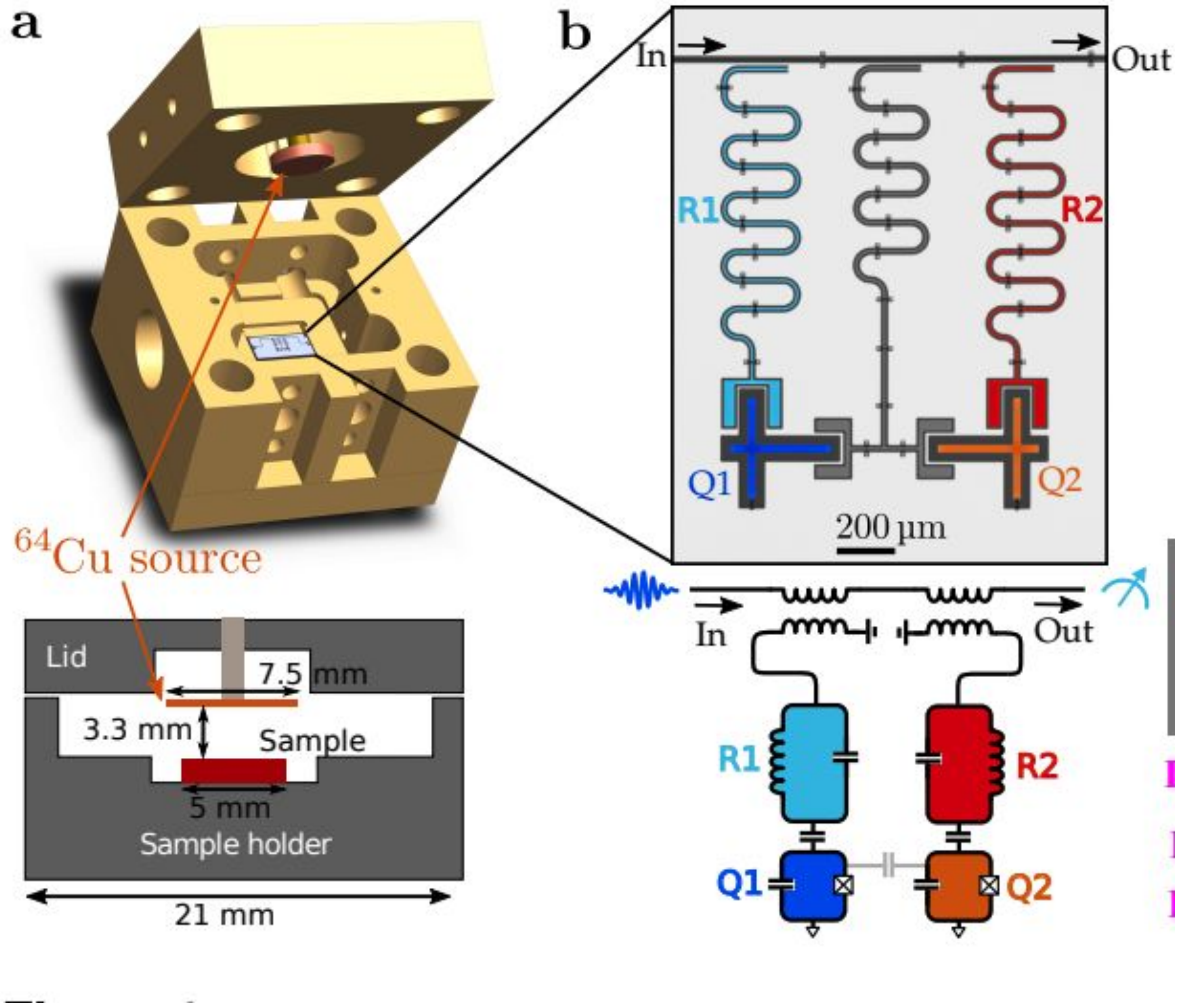
Krantz et al, Applied Physics Reviews 6, (2019) [arXiv:1904.06560]

Motivating Study #1: Radiation induced decoherence

Measured T1 decoherence rates in the presence of a ^{64}Cu source

Demonstrated reduced coherence times in the presence of the source for two separate qubits

Mitigated these effects by installing a lead shield and observing coherence times improved by 0.2% in the presence of the shielding



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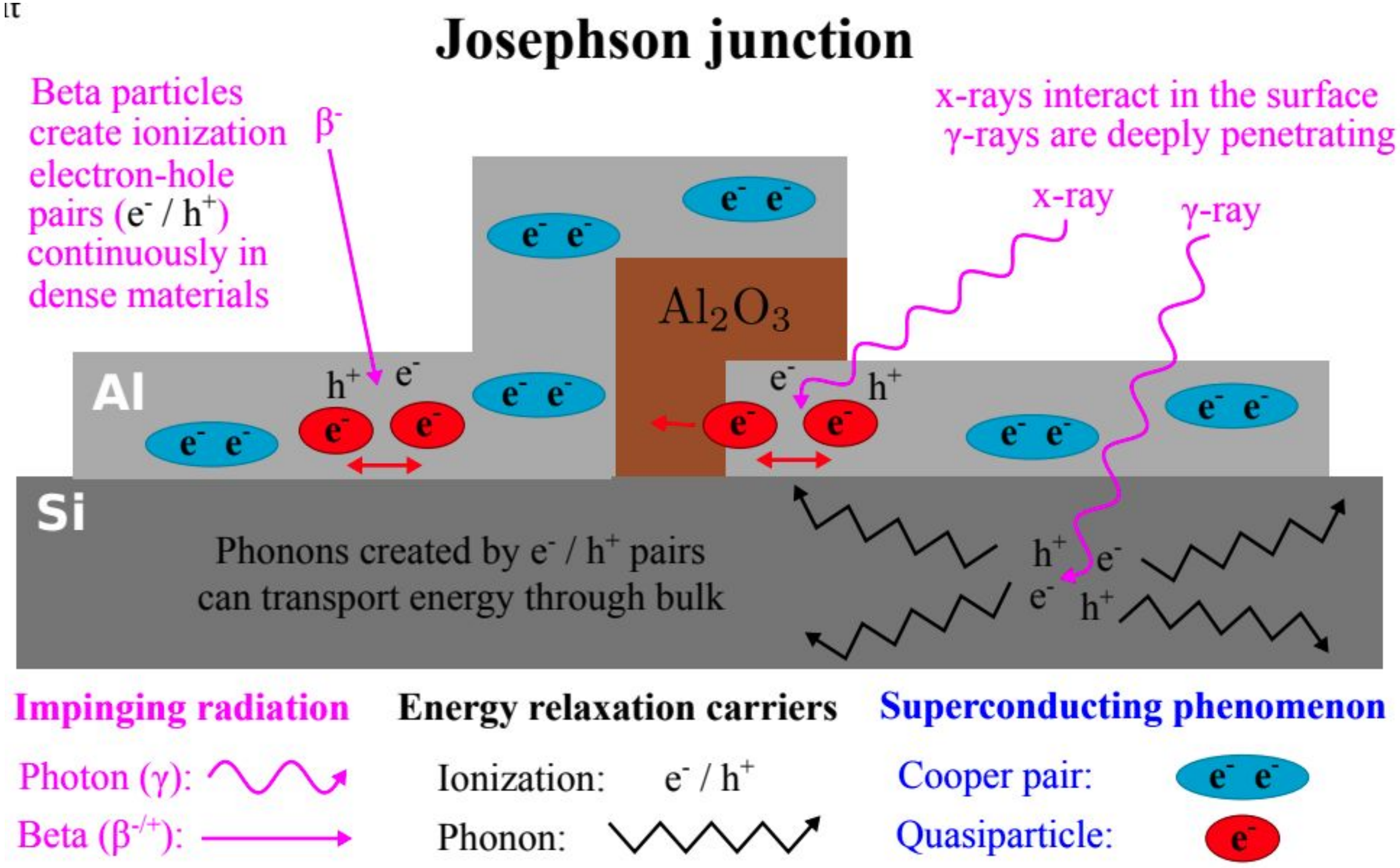

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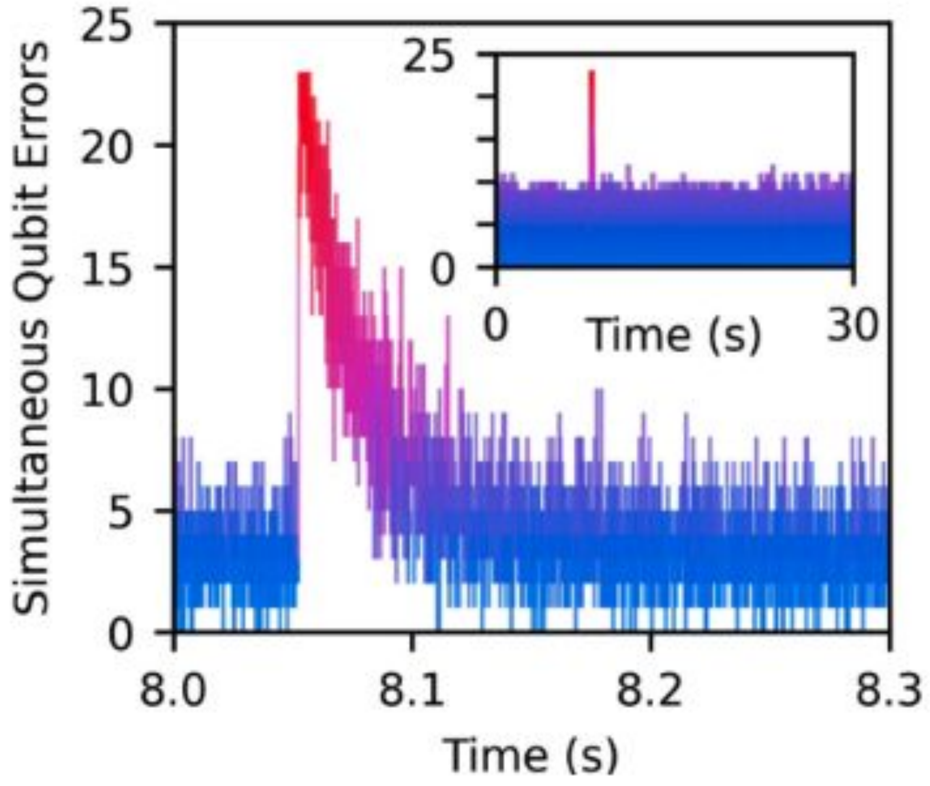
Motivating Study #2: Cosmic ray induced error "bursts"

Cosmic ray interactions in substrate induce high energy phonons, which propagate and generate quasiparticles.

These quasiparticle bursts can cause correlated errors across multiple qubits, as seen on the 26-qubit Google Sycamore chip.

Burst events were found to be long-lived, falling off with a exponential time constant of 25 ms.



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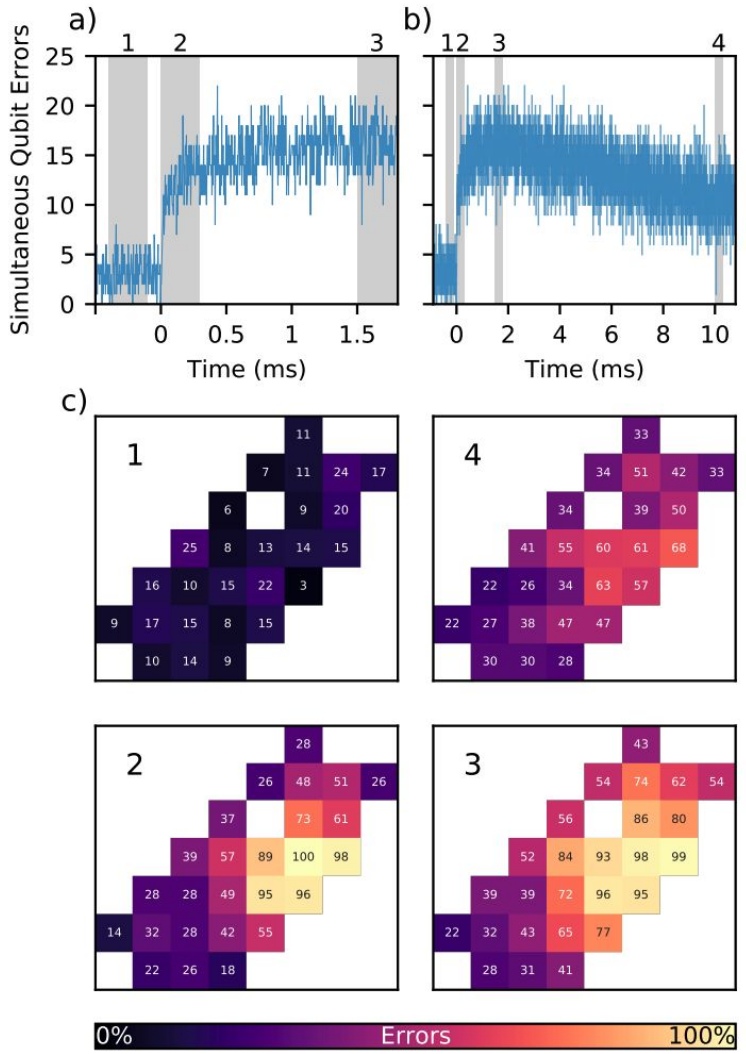

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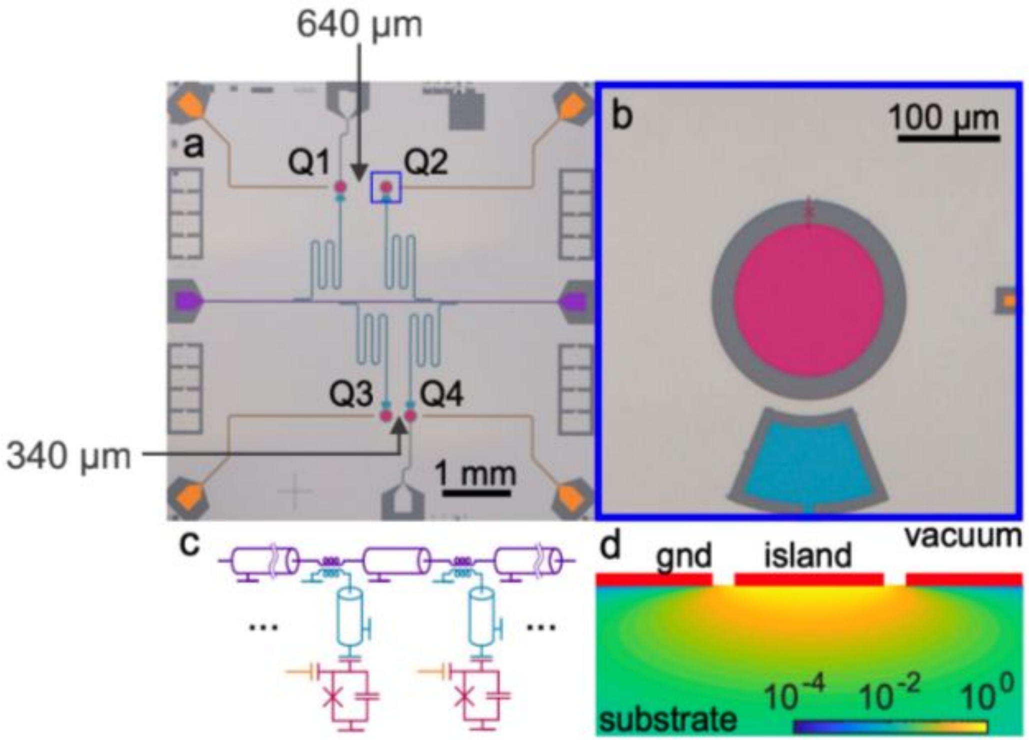
The McDermott group at UW Madison fabricated an array of 4 weakly charge-sensitive qubits.

The qubits were found to exhibit spatially correlated jumps in offset charge due to ambient ionizing radiation.



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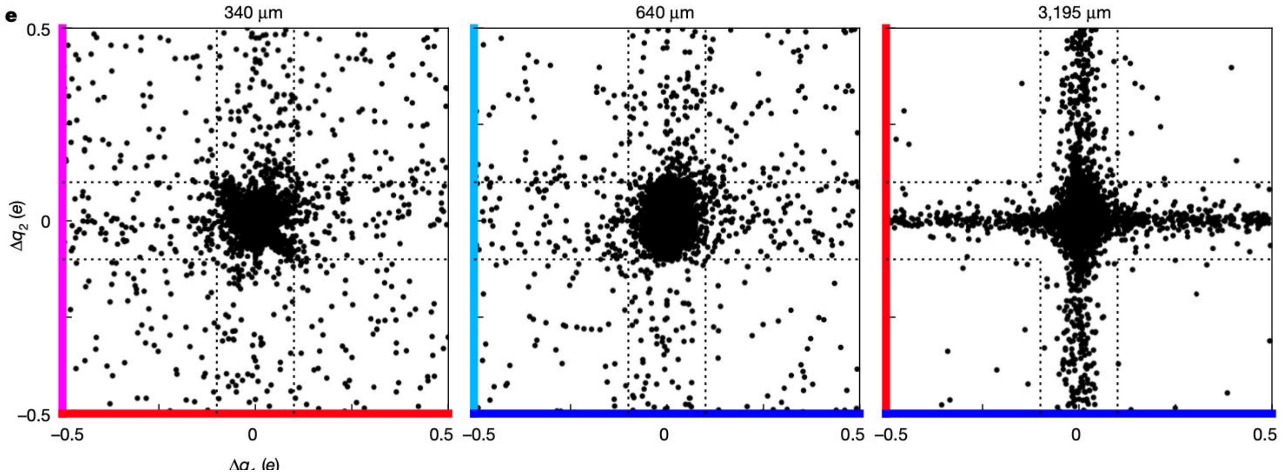

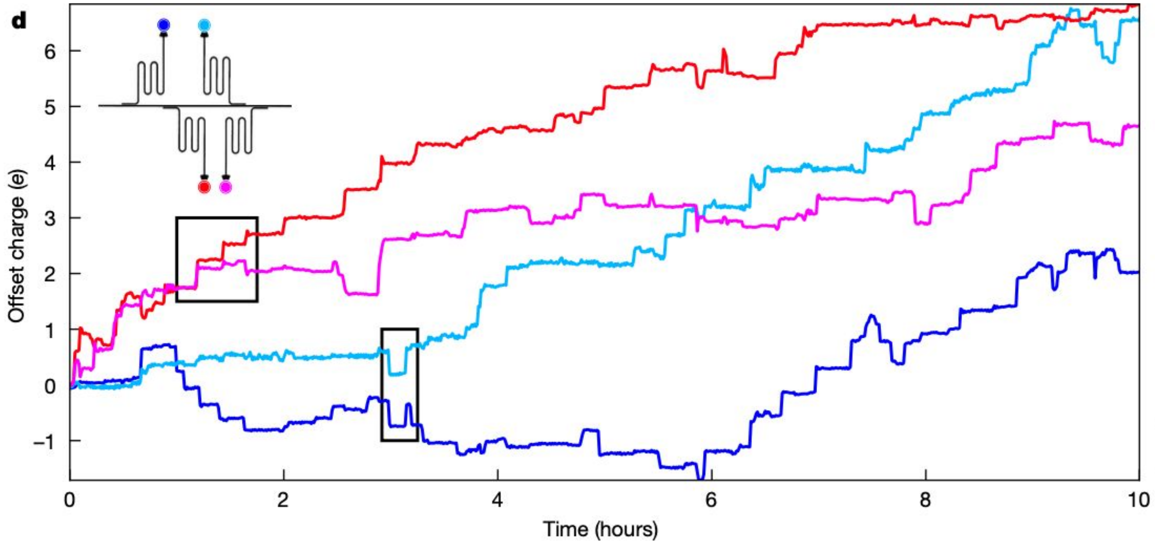

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NEXUS Facility

NEXUS: A low background underground test facility for superconducting detectors

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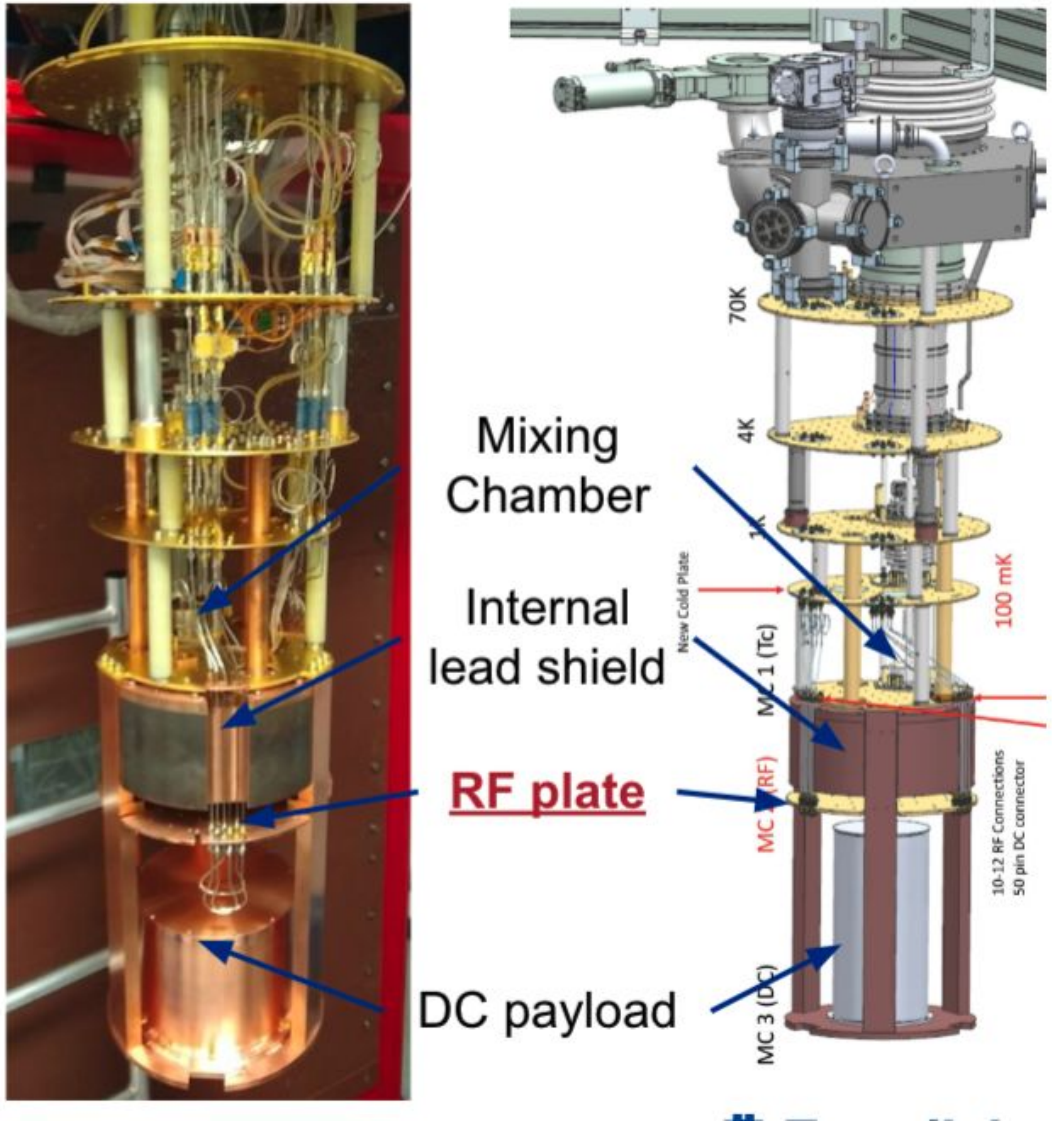
Facility:

- located 107m (300 mwe) underground
- muon rate: 3.4/cm^2/day *(compared to surface rate of 1440/cm^2/day)*
- 10mK dilution fridge inside of a class 10,000 clean room

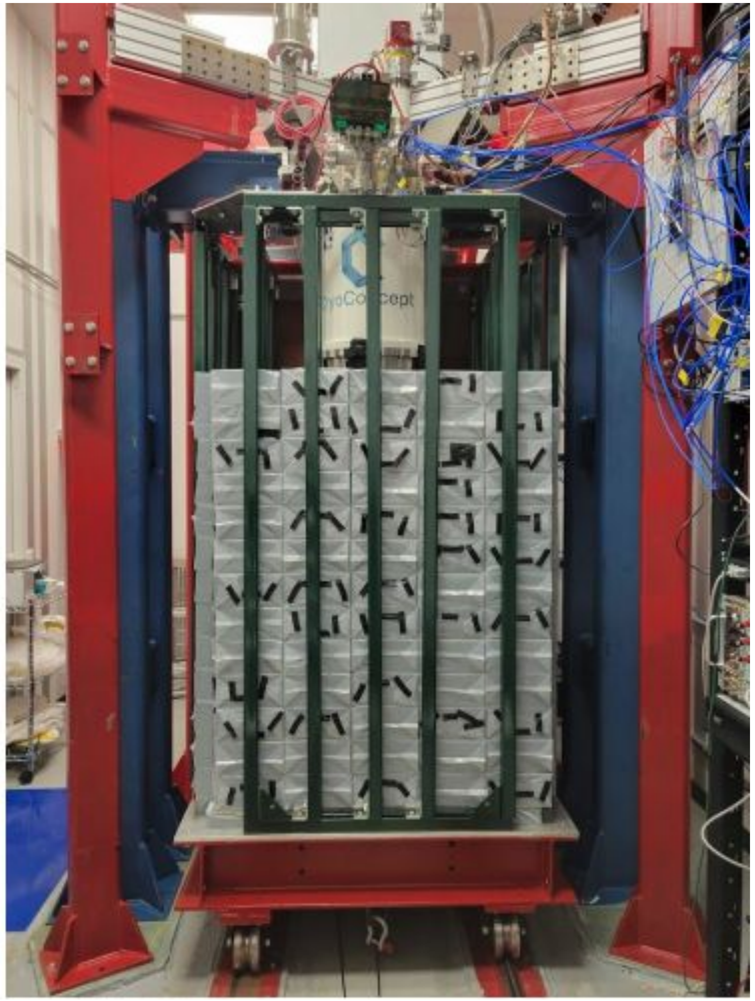


NEXUS Facility

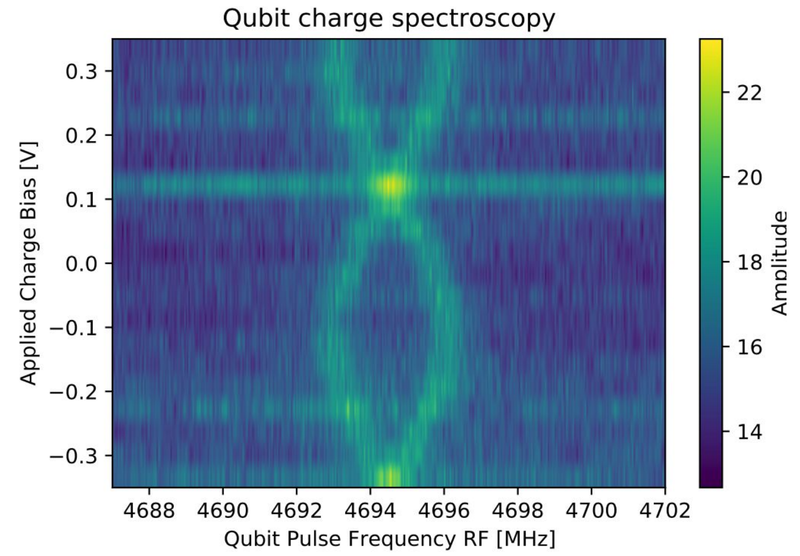
Shielding:

~4π coverage with lead shielding (movable external lead castle + fixed shielding internal to cryostat) ⇒ this gives us 2 orders of magnitude reduction in backgrounds!

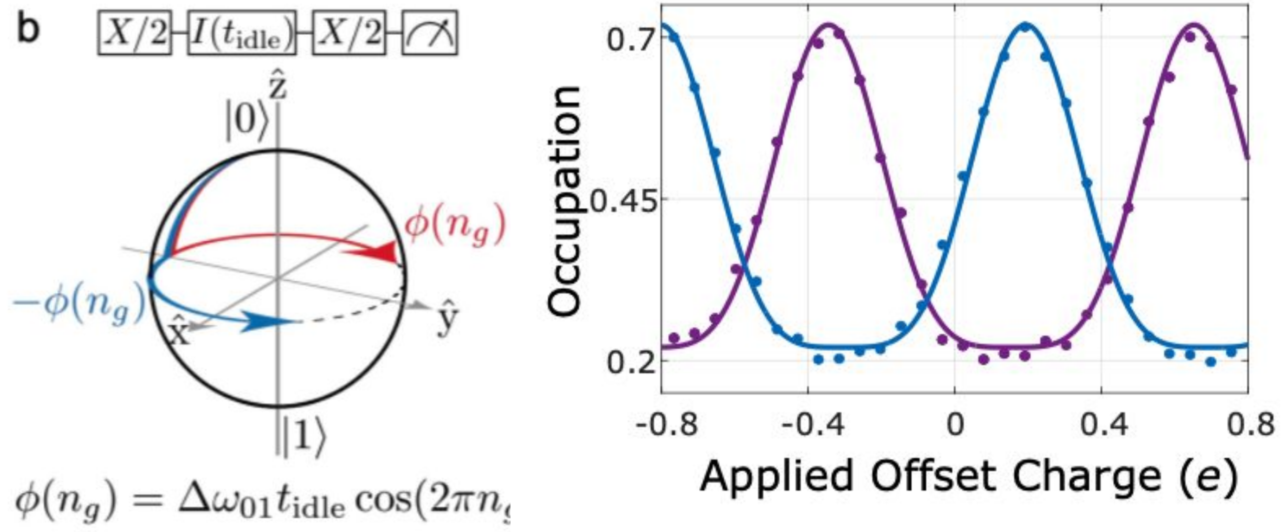
Cryostat surrounded in external mu-metal magnetic shield



Qubit Charge Offset Mapping



We can tune qubit frequency by sweeping charge bias. As we do so, we observe two QP parity bads. Both bands are present in this plot due to high QP tunneling rates compared to measurement duration.



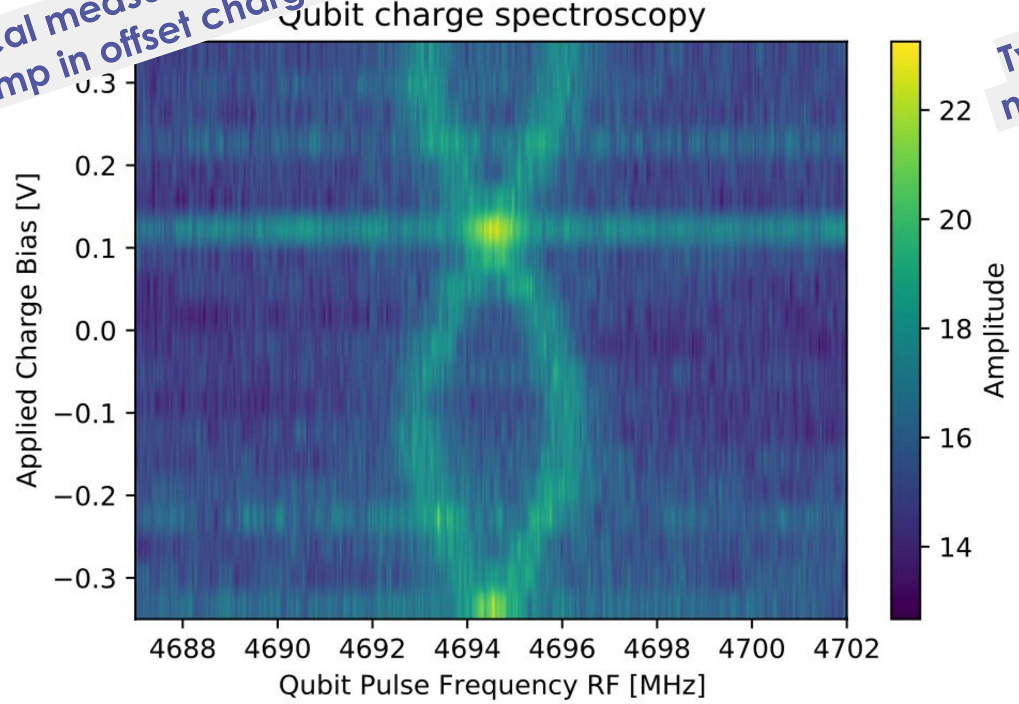
We use a Ramsey tomography procedure to make a parity-insensitive measurement of qubit offset charge

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

Qubit Charge

When charge is deposited on the gate, it appears as a phase shift in the tomography data. By monitoring the tomography phase over time, we can measure these shifts and correlate them across all 4 qubits on the chip.

Typical measurement, no jump in offset charge



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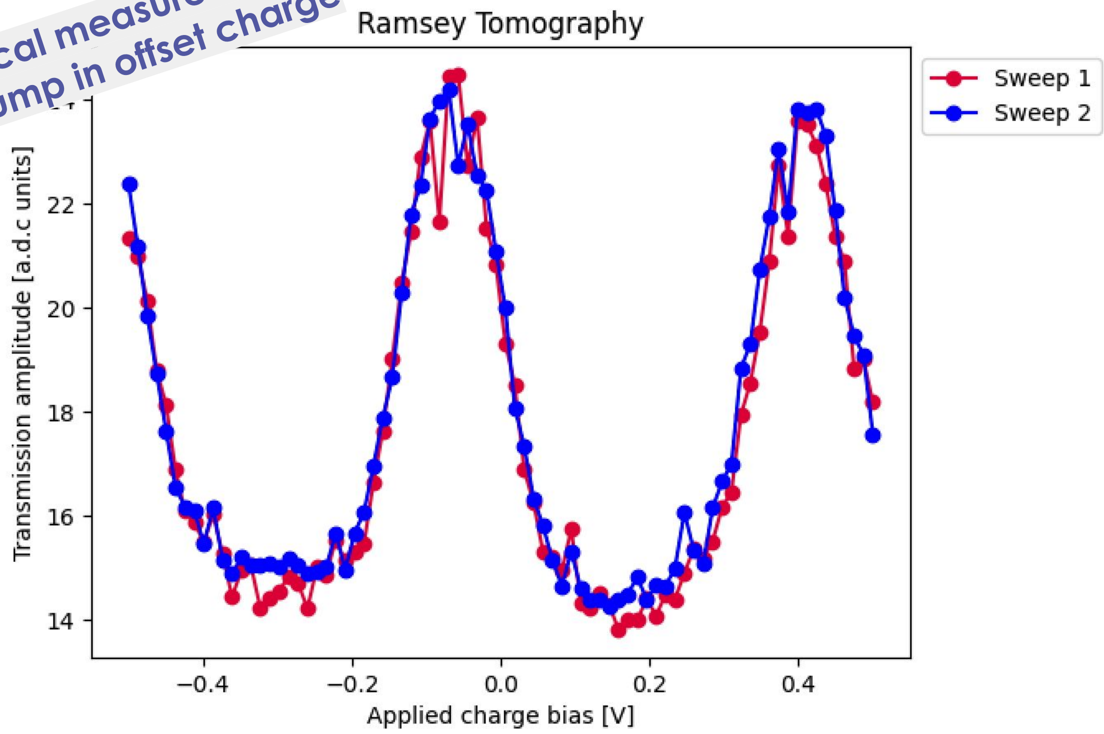

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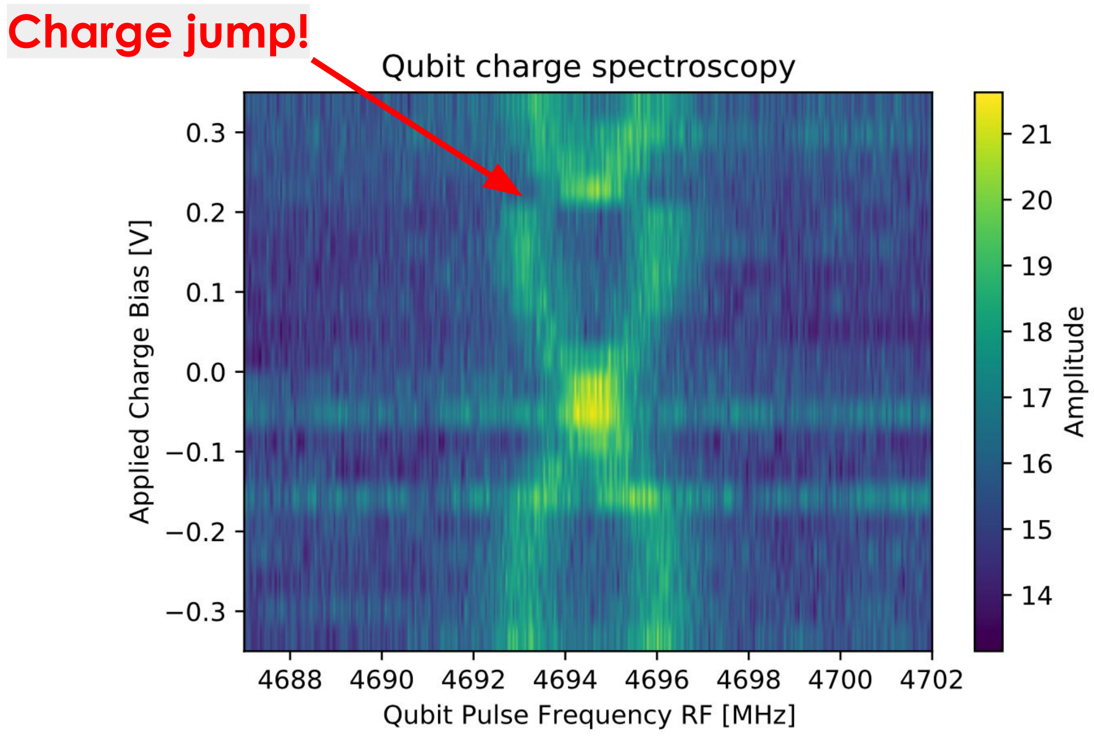

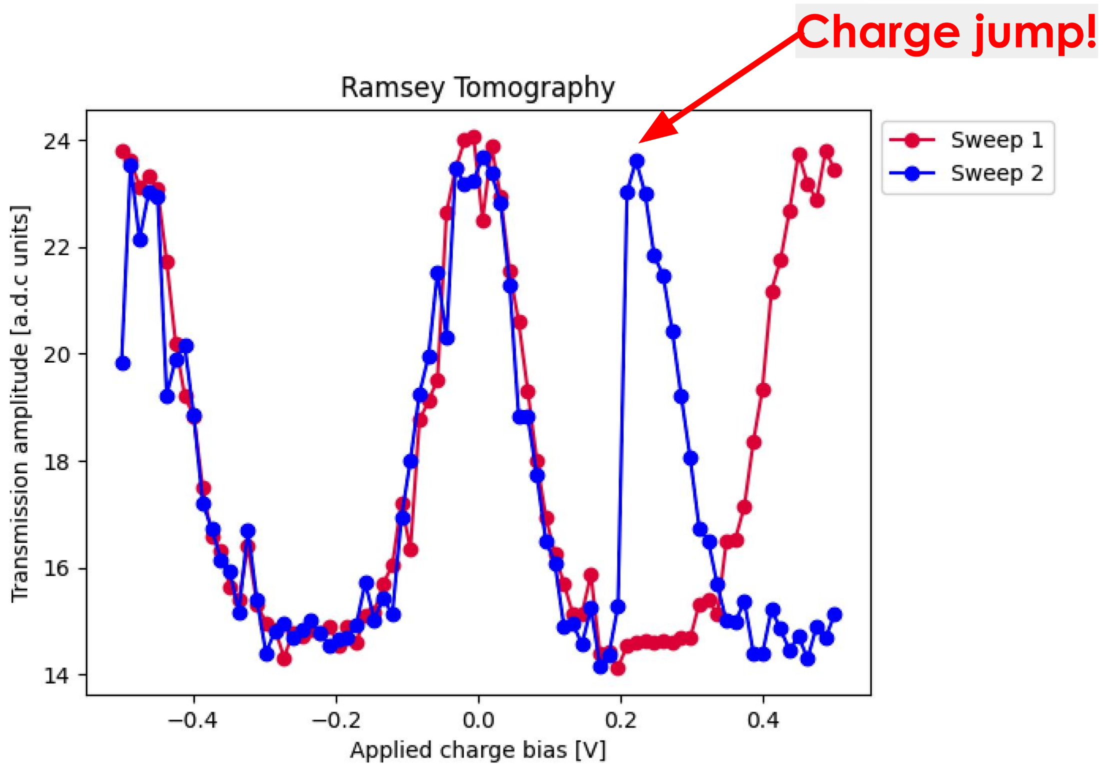

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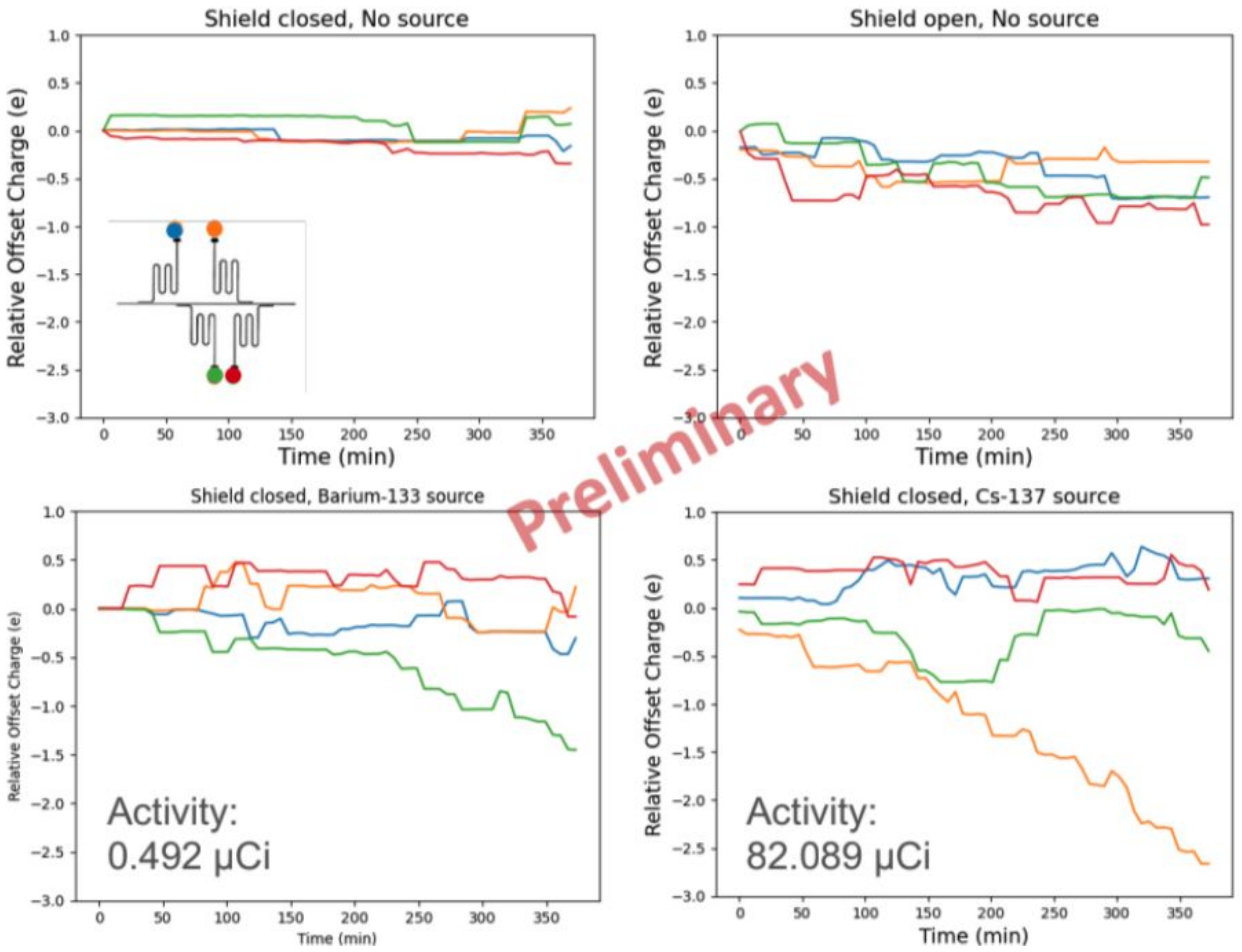
Qubit Charge Offset Mapping Over Time

We repeated this procedure for extended intervals of time, and fit to locate charge jumps of varying magnitudes

We ran this measurement across various shielding and source configurations.

Running underground in NEXUS will enable us to isolate the effects of gamma flux on charge error rate.



Correlated Charge Errors at NEXUS

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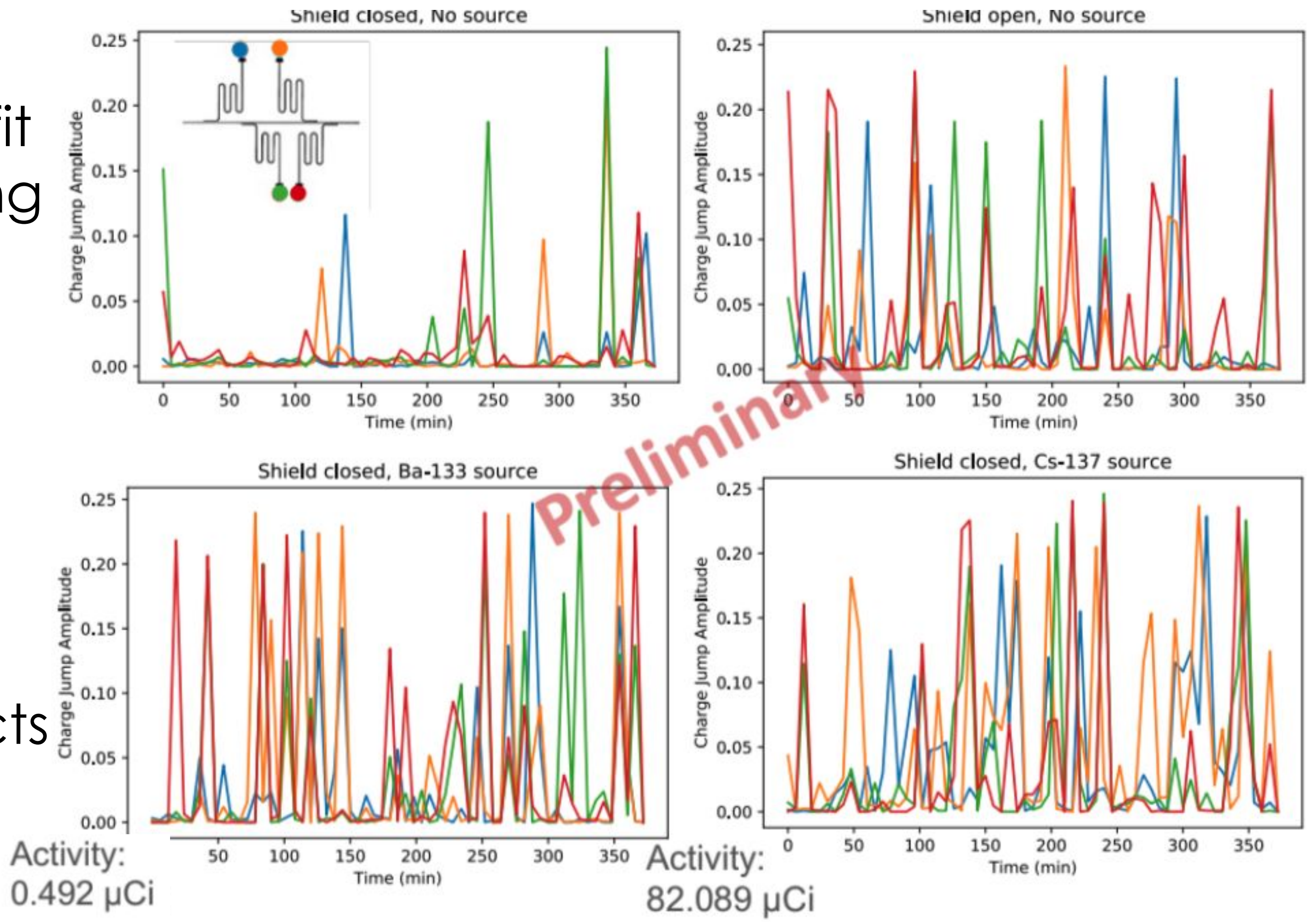

Moving Forward

R&D for Use of Superconducting Qubits as Dark Matter Detectors

Nov 9, 2023, 2:00 PM
15m
51/1-102 - Kavli Auditorium (SLAC)
Oral | RDC8: Quantum and... | RDC8

Ryan Linehan

Sapphire substrate qubit-based detector for light dark matter search

Nov 9, 2023, 1:30 PM
15m
51/1-102 - Kavli Auditorium (SLAC)
Oral | RDC8: Quantum and... | RDC8

Kester Anyang

Energy dissipation and phonon kinematics simulation in qubits with G4CMP

Israel Hernandez

Nov 8, 2023, 4:30 PM
15m
48/1-112C/D - Redwood C/D (SLAC)
Oral | RDC7: Low-Backgro... | RDC7

New Facility: QUIET

- "Quantum Underground Instrumentation Experimental Testbed"
- Located underground in MINOS hall, next to NEXUS
- Sister facility above ground ("LOUD")
- One of the only dedicated underground facilities for superconducting qubit operations

QUIET Facility at Fermilab

Fermilab QSC group:

Aaron Chou (FNAL)
Gustavo Cancelo (FNAL)
Dan Baxter (FNAL)
Daniel Bowring (FNAL)
Lauren Hsu (FNAL)
Rakshya Khatiwada (FNAL / IIT)
Adam Anderson (FNAL)
Enectalí Figueroa-Feliciano (FNAL / NU)
Sami Lewis (Wellesley College)
Kelly Stifter (SLAC)
Sara Sussman (Fermilab)
Dylan Temples (FNAL Lederman Fellow)
Ryan Linehan (FNAL Postdoc)
Grace Bratrud (NU grad)
Grace Wagner (FNAL)
Alejandro Rodriguez (NU grad)
Israel Hernandez (IIT grad)
Kester Anyang (IIT grad)
Jialin Yu (IIT grad)
Hannah Magoon (Stanford grad)
Shilin Ray (NU undergrad)

External Collaborators

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Sohair Abdullah (UW Madison)
Gabe Spahn (UW Madison)
Noah Kurinsky (SLAC)

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