Northwestern

Studying Correlated Errors in Superconducting Qubits Underground in NEXUS

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28 August 2023

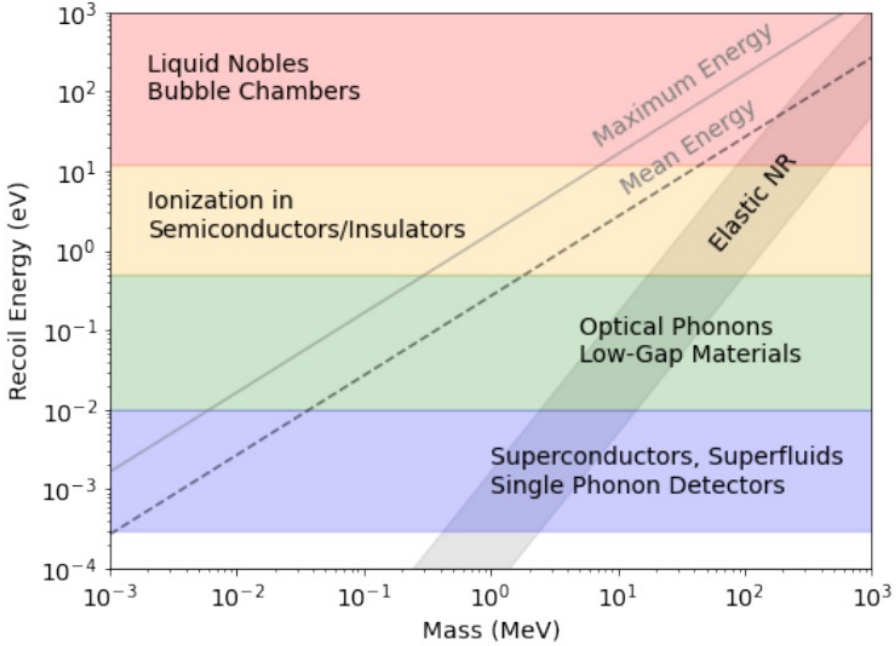
QUANTUM SCIENCE CENTER

Fermilab

Overview

- SC qubit review
- Radiation effects on qubits
- Study of correlated errors in qubits
  - At UW Madison and NEXUS
- Future Work

Goal: Understand and exploit radiation effects on qubits to optimize design for quantum sensing

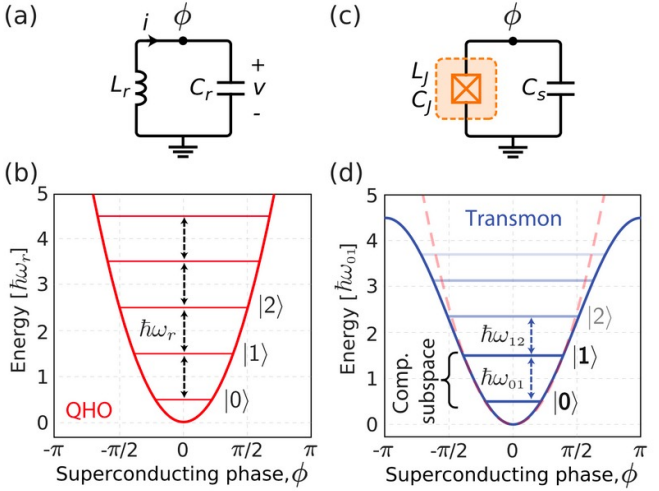


Essig et al, Snowmass CFI WP2 (2022) [arXiv:220308297]

Superconducting Qubits

Qubit: Any two-level quantum system

- Start with quantum harmonic oscillator (LC circuit)
  - Energy levels are equally spaced → Not a Qubit!
- Let's replace the inductor with a Josephson junction (nonlinear inductor)
  - Anharmonic energy levels → A Qubit!

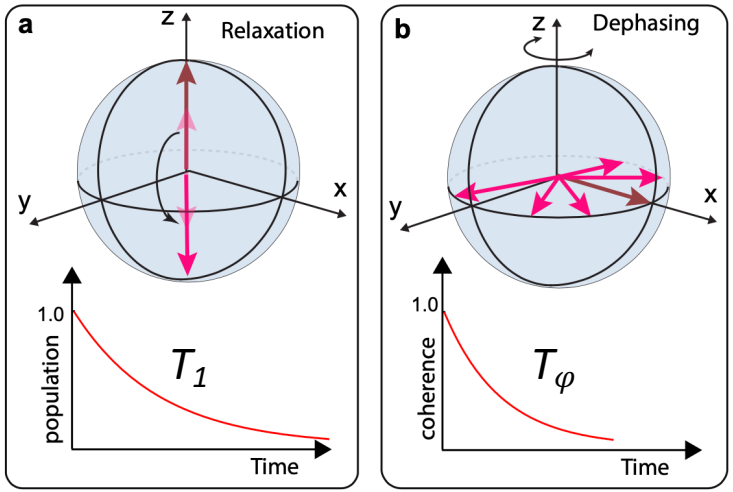


Krantz et al, Applied Physics Reviews 6, (2019) [arXiv:1904.06560]

Superconducting Qubits

- Decoherence: loss of qubit state
  - Problem for QIS
  - Possible opportunity for particle/DM detection

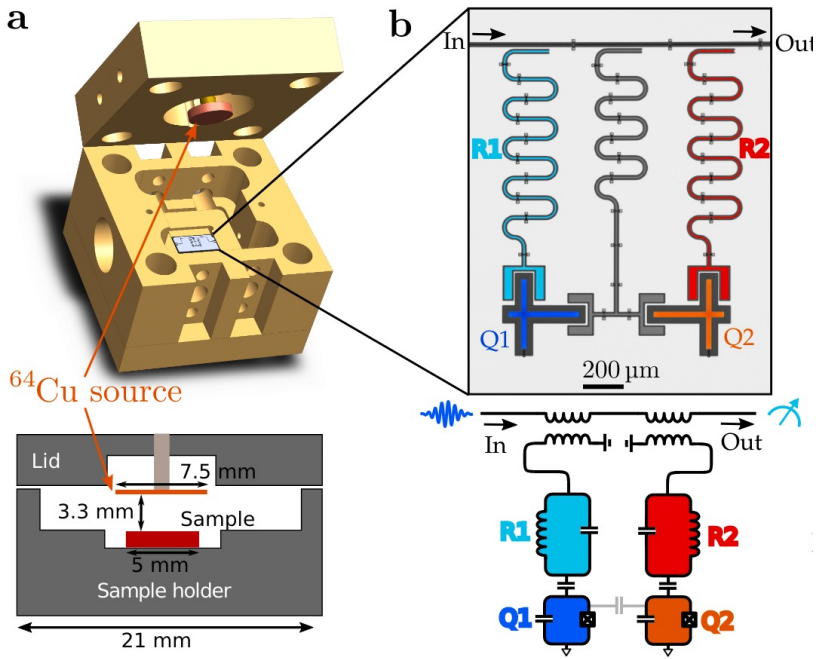
- Relaxation: Loss of qubit state **energy** $|1\rangle \rightarrow |0\rangle$
  - $\mathbf{T_1}$ timescale
- Dephasing: Loss of qubit state **coherence**
  - $\mathbf{T_\varphi}$ timescale



Mahdi Naghiloo, (2019) [arXiv:1904.09291]

3 Papers on How Radiation Effects Qubits

P1: Effects of Radiation on SC Qubits



- Measurements of decoherence relaxation rates ($1/T_1$) in presence of a ^{64}Cu source
- Clear correlation between T_1 and decay of ^{64}Cu source in two separate qubit sensors
- Strong evidence of quasiparticle poisoning due to radiation breaking Cooper pairs

Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]

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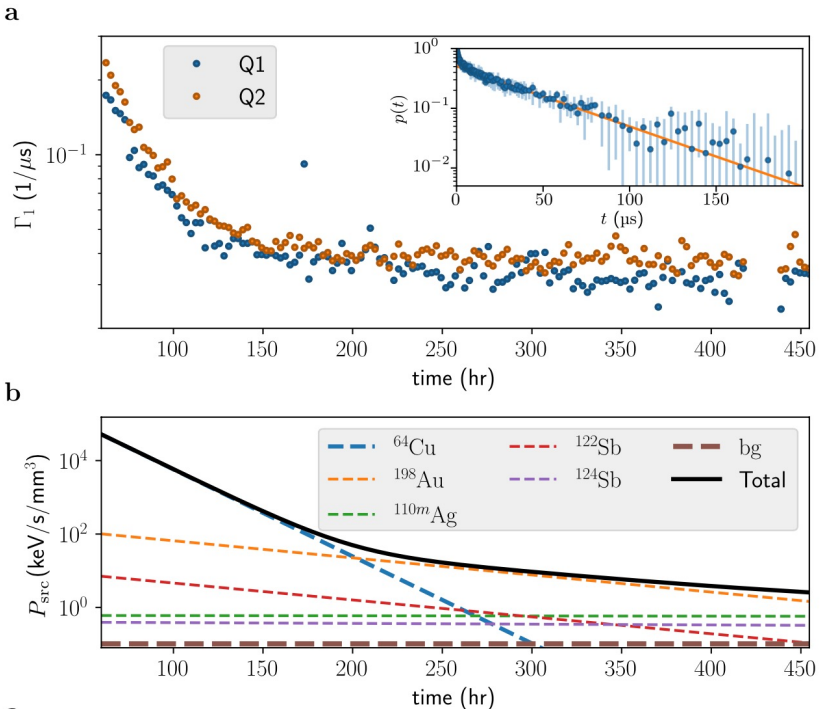

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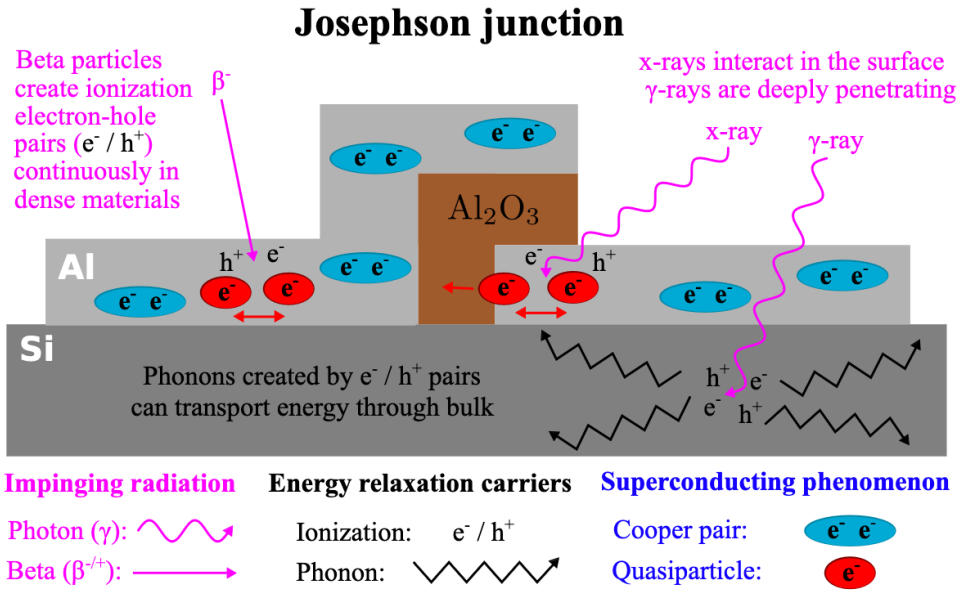

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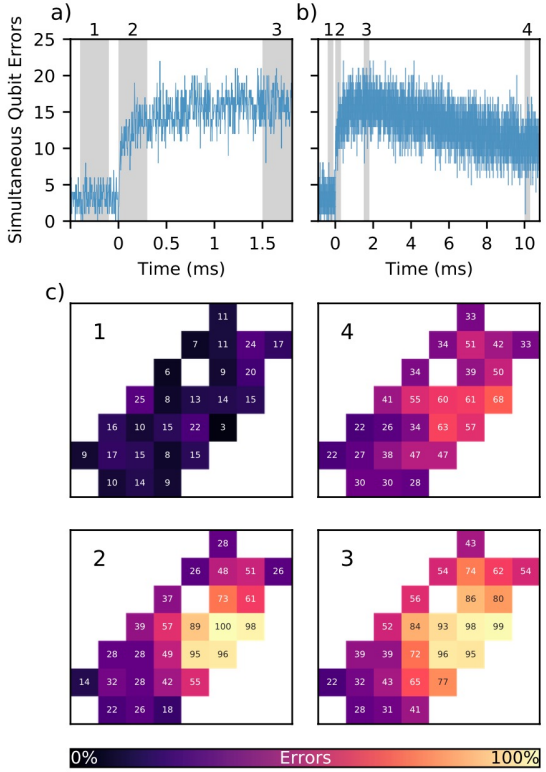
P2: Catastrophic Error Bursts from Cosmic Rays

- This study found *correlated errors* in qubits across the device due to energy depositions in common substrate
  - Information destroyed every ~10 sec!
- These events have keV-MeV energy depositions
  - Current work is focused on understanding qubit response to lower energies



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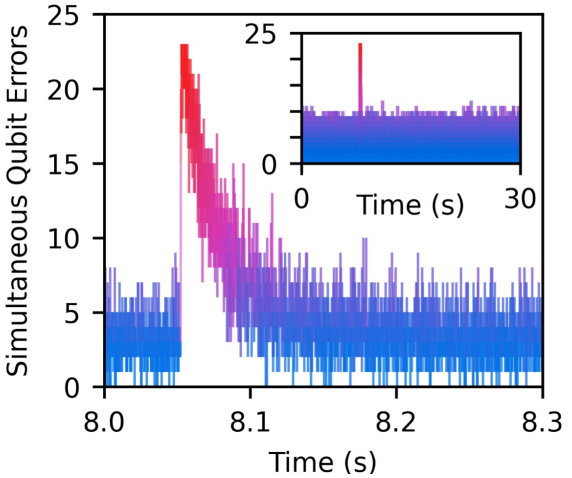

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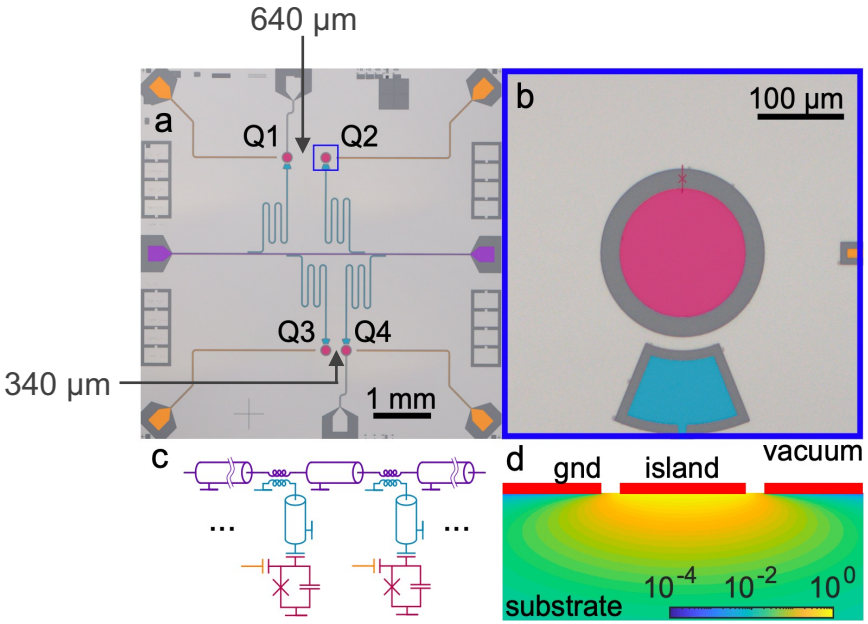
P3: Correlated Charge Errors in SC Qubits

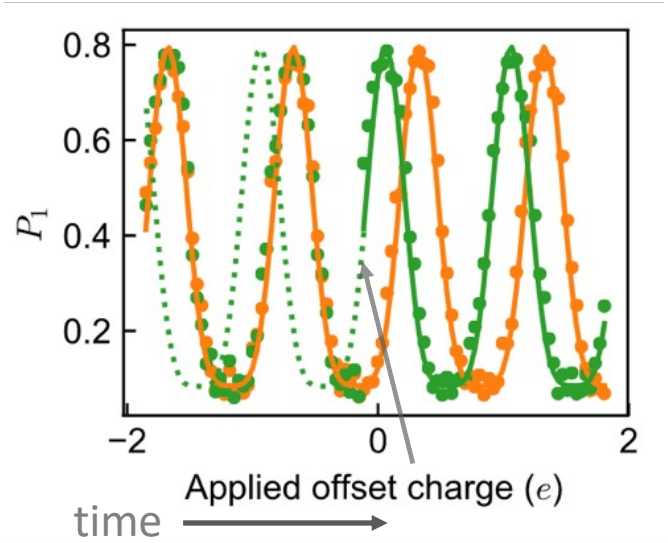
- UW Madison ran a charge sensitive qubit chip in an above-ground fridge
- Found correlated charge jumps between nearby qubits, caused by ionizing radiation

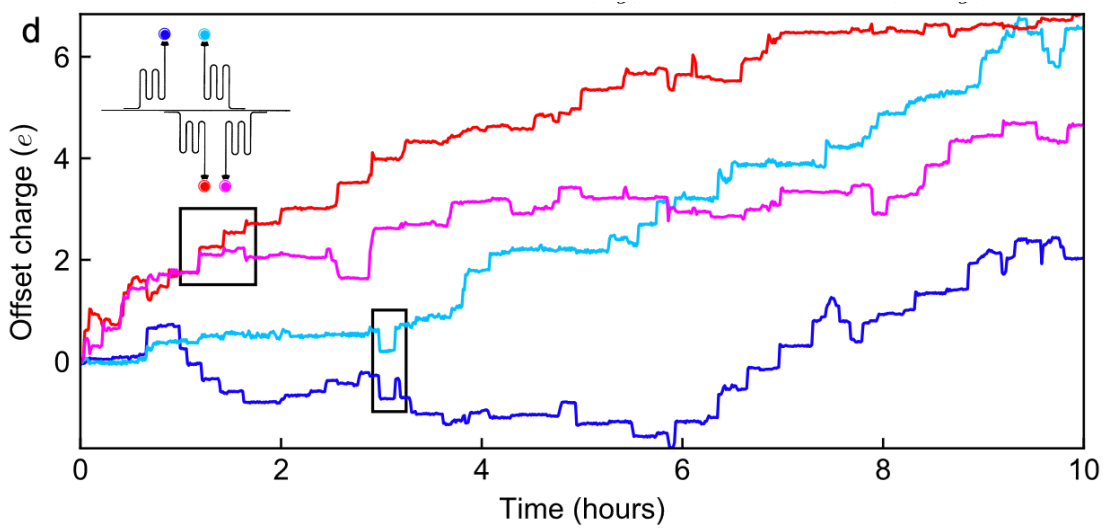


Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

P3: Correlated Charge Errors in SC Qubits

- Ionizing radiation incident on qubit substrate causes charge jumps
- Evidence for *correlated* jumps → simultaneous quasiparticle poisoning





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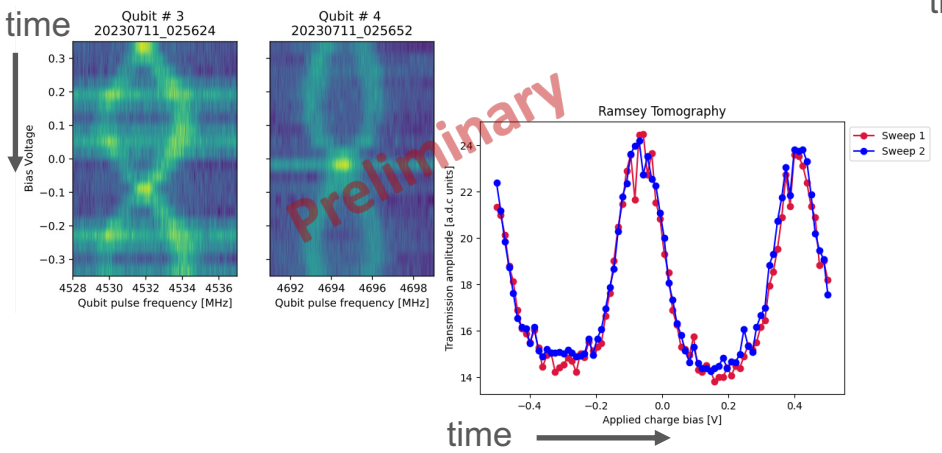
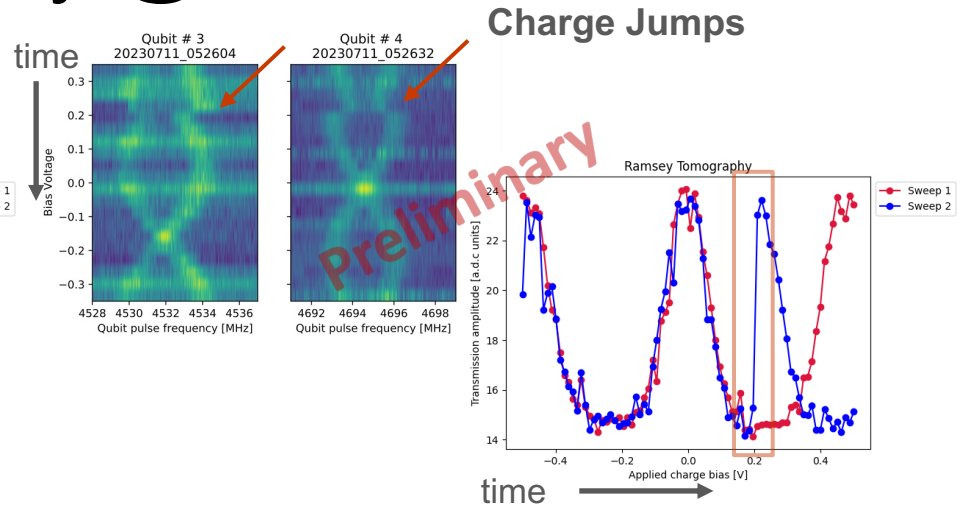
Correlated Errors Study @ NEXUS

No Charge Jumps



Charge Jumps



- Ran UW chip underground at NEXUS
- Read out qubits consecutively while sweeping applied charge bias for 5-10 hours
- Identify and measure charge jumps using analysis and fitting techniques
  - Charge jumps are seen as disruptions in the periodic behavior of amplitude

*Work by Kester Anyang, Dan Baxter, Daniel Bowring, **GB**, Enectali Figueroa-Feliciano, Sami Lewis, Ryan Linehan, Hannah Magoon, Dylan Temples, Jialin Yu*

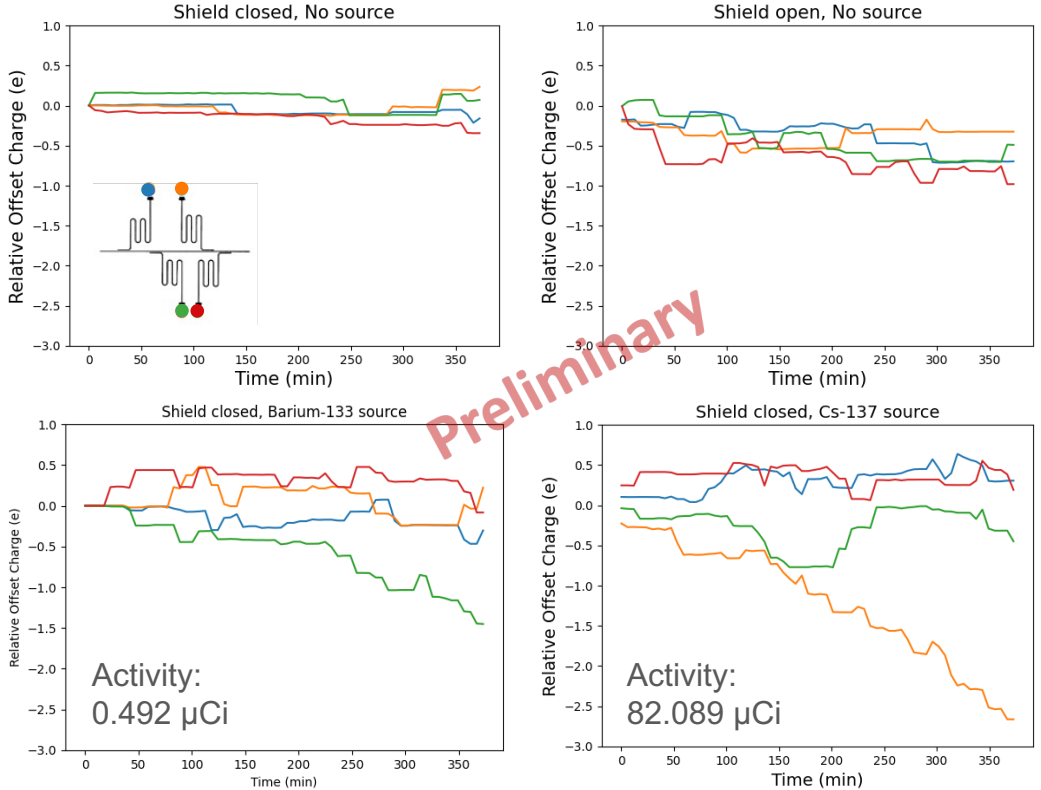
Study Comparison

	Year	# of Qubits	Shielding?	Source?	Result/Goal
P1, Vepsäläinen et al	2020	2	Above-ground, no rad shield [for shown results]	^{64}Cu	Radiation → More relaxation errors
P2, McEwen et al	2022	26	Above-ground, no rad shield	None	Radiation → Errors correlated in *space and time*
P3, Wilen et al	2021	4	Above-ground, no rad shield	None	Radiation → Correlated charge jumps in charge sensitive qubit
Our Work		4	Underground, rad shield [multiple configurations]	^{133}Ba, ^{137}Cs, Neutrons…	**Controlled** radiation → **Controlled** correlated charge jump rate

Hypothesis: energy depositions in substrate cause *correlated* decoherence across qubits due to quasiparticle poisoning that can be exploited as a means of particle detection.

Correlated Errors Study @ NEXUS

- Repeated long time charge jump measurements with 4 different shielding configurations
- Change in charge jump rate based on configuration visible!
- Running underground → muon rate reduced by 2 orders of magnitude compared to Madison measurement
  - Negligible compared to gamma flux
- GEANT4 Monte Carlo model under development



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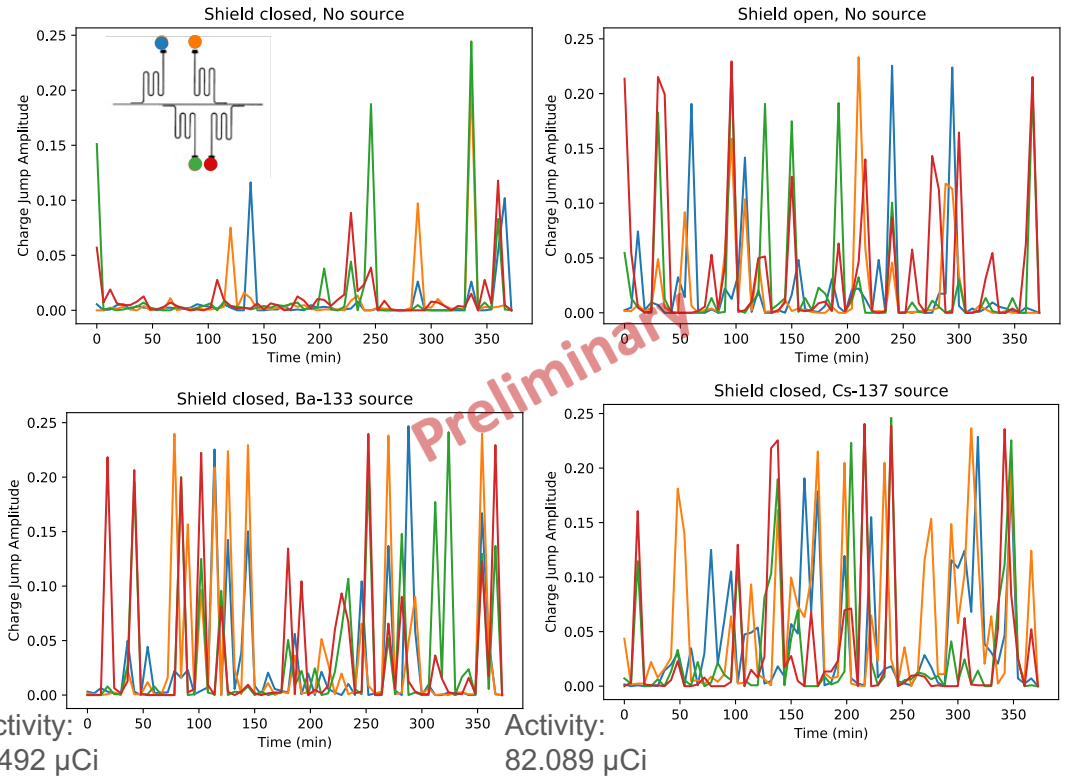

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Looking Forward

- Proposing a novel, multiplexed quantum device for particle physics detection
  - Interested? Attend **Ryan Linehan's** talk "*Developing Qubit-Based Detectors for Low-Threshold Dark Matter Searches at Fermilab*", DM parallel session 8A, Thursday 4:45 PM - 5:00 PM
- Introducing a new QSC test facility @ Fermilab: **QUIET**
  - Quantum Underground Instrumentation Experimental Testbed
  - One of the only dedicated underground facilities for superconducting qubit operations

Acknowledgments

QSC Local Group Members:

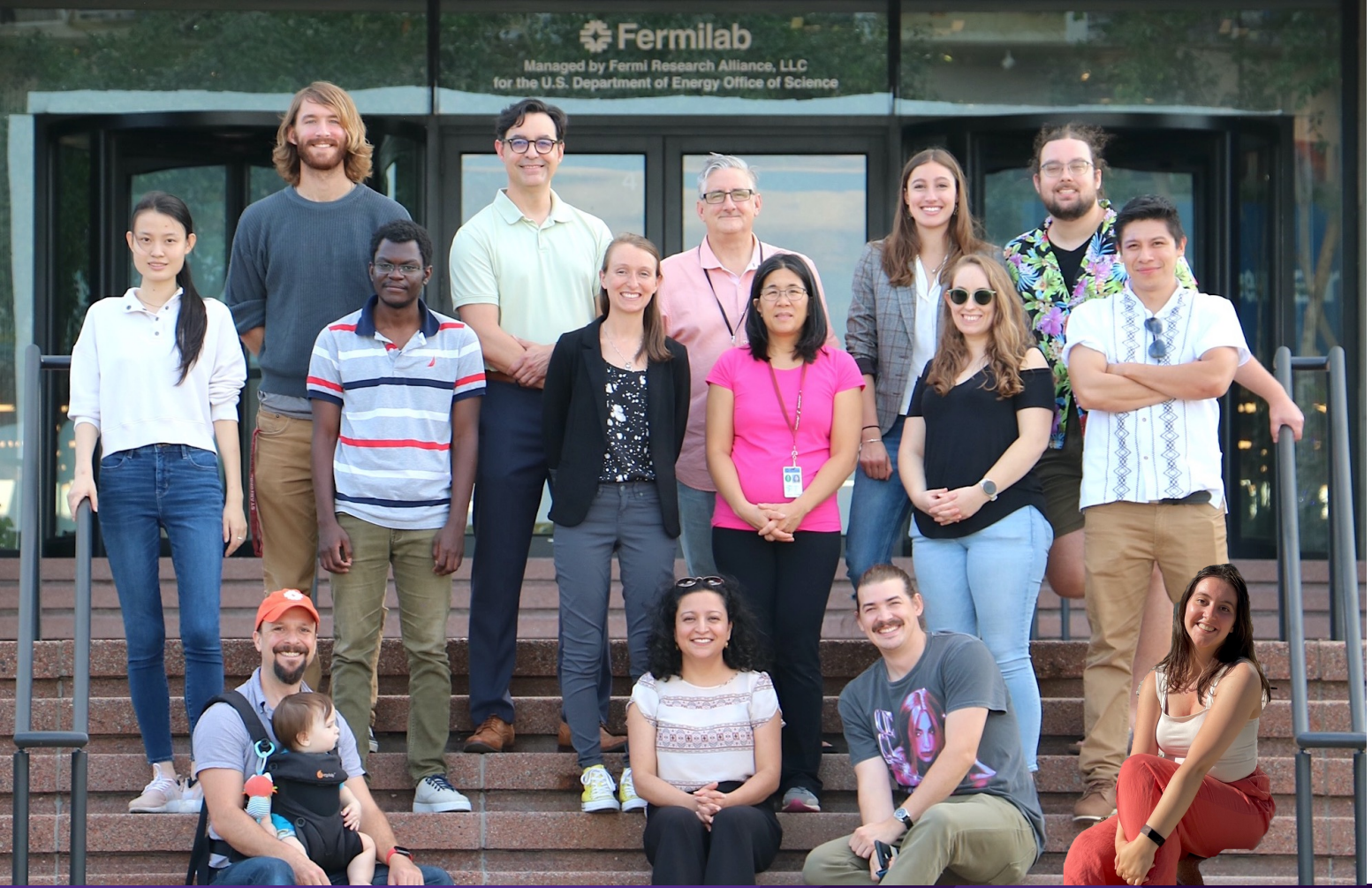
- **FNAL**: Aaron Chou, Daniel Bowring, Gustavo Cancelo, Lauren Hsu, Adam Anderson, Daniel Baxter, Sami Lewis, Ryan Linehan, Kelly Stifter, Dylan Temples
- **IIT**: Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Jialin Yu
- **Northwestern University**: Enectali Figueroa-Feliciano (joint w/ FNAL), Valentina Novati, Grace Bratrud, Alejandro Rodriguez

QSC External Collaborators:

- **UW Madison**: Robert McDermott, Sohair Abdullah, Gabe Spahn
- **SLAC**: Noah Kurinsky, Taj Dyson
- **Tufts**: Hannah Magoon (co-op w/ FNAL)

Postdocs/Students

Work supported by Daniel Bowring's ECA



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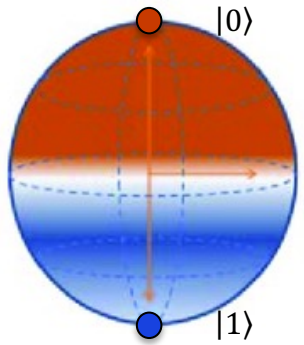
Not pictured:
Aaron Chou (FNAL)
Gustavo Cancelo (FNAL)
Adam Anderson (FNAL)
Valentina Novati (NU)
Alejandro Rodriguez (NU)

Superconducting Qubits

- **Classical Bits**: Only 2 discrete values allowed
  - 0 or 1

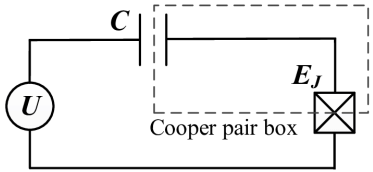
- **Qubits**: Continuum of allowed states as superpositions between 0 and 1
  - $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
  - Described by all points on surface of Bloch sphere

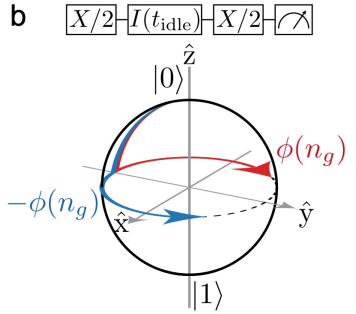


Maheshwari et al, IEEE 10, (2022) [doi: 10.1109/ACCESS.2022.3195044]

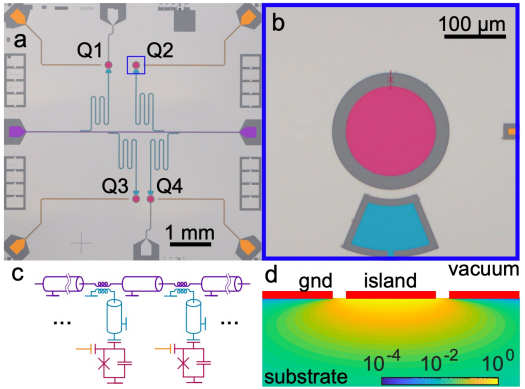
Correlated Errors Study

- Charge sensitive qubit
  - Qubit states are based on the number of quasiparticle that have tunneled across junction and are present/absent on the island
- Island = Cooper pair box
  - Biased by gate voltage
  - $n_g = \frac{C_g V_g}{2e} = \frac{\Delta q}{2e}$
    - Δq is the offset charge





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

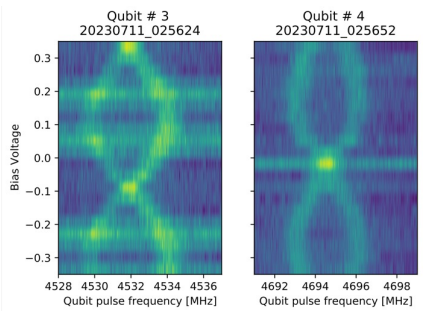


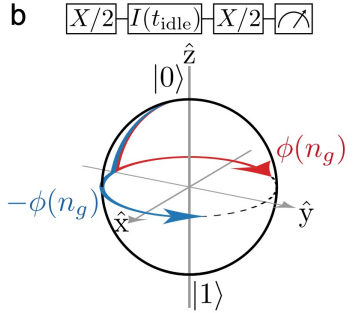
Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

Wu et al, Physical Review A (2012) [arXiv:1211.5186]

Correlated Errors Study

- Quasiparticle Parity bands
  - Both parity bands are visible in charge spectroscopy measurements since the parity switching rate is much faster than measurement rate
  - Charge jumps are the result of parity band dephasing, $\phi(n_g) = \Delta\omega_{01} t_{idle} \cos(2\pi n_g)$
    - $\Delta\omega_{01}$ is the frequency difference between the ground and excited states
- Resonator coupling
  - ~27 MHz for all 4 qubit-resonator pairs
  - Resonator decay rate ~295 1/ns





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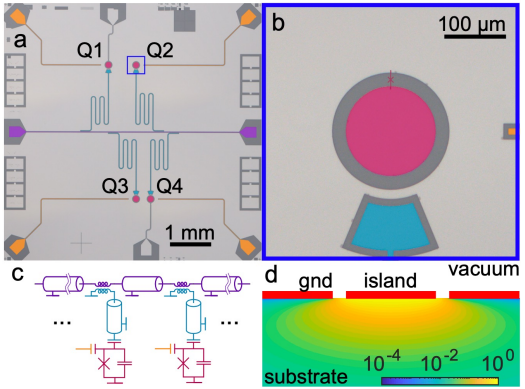

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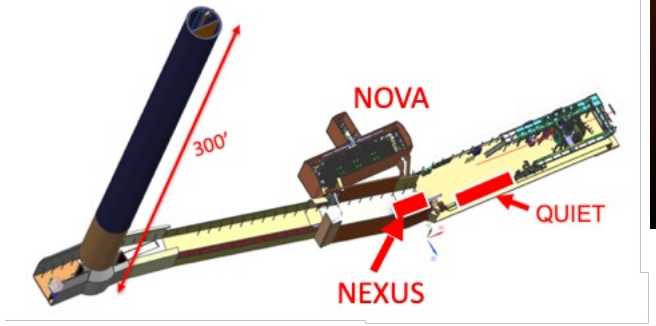
Correlated Errors Study: NEXUS Facility

- NEXUS at Fermilab, in MINOS tunnel
- 107 m rock overburden, 225 mwe



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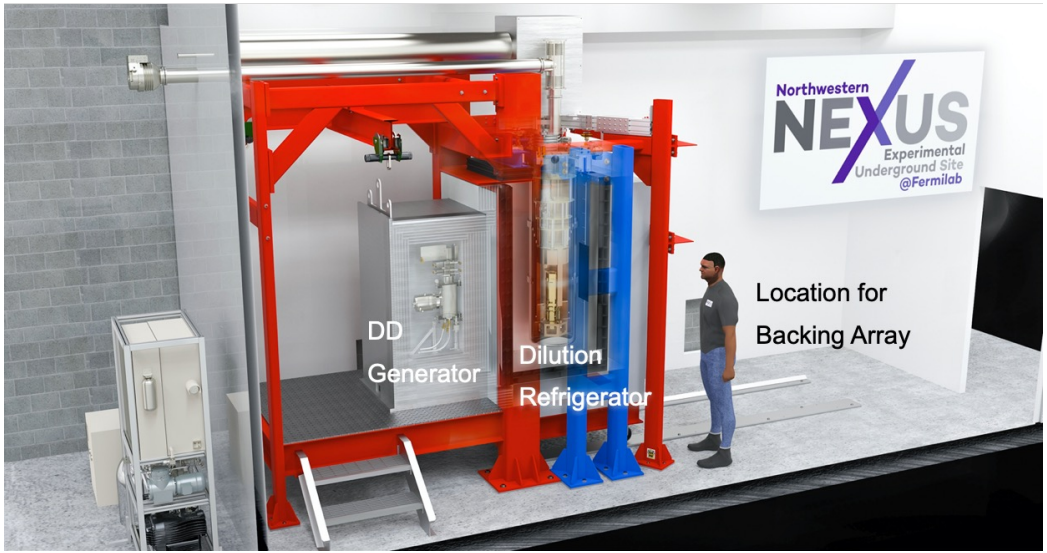
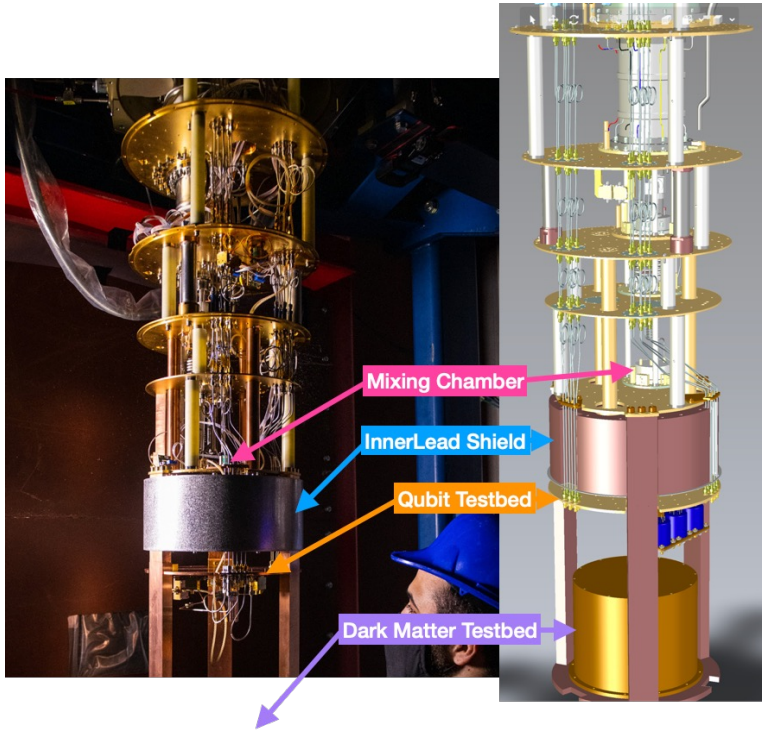
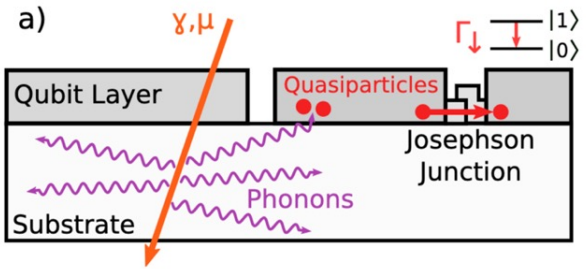
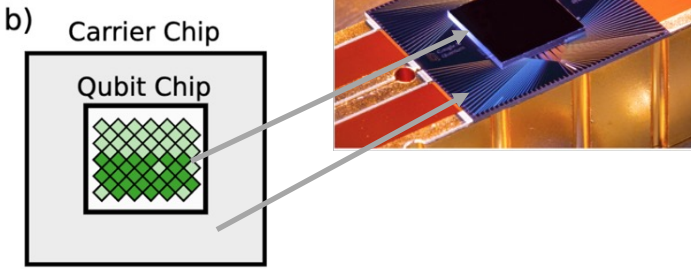


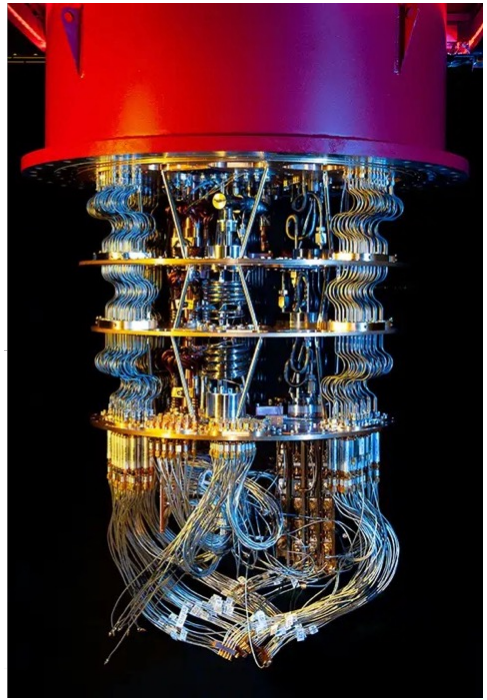


Catastrophic Error Bursts from Cosmic Rays

- **<u>Hypothesis</u>: energy depositions in a substrate cause *correlated* decoherence across qubits due to quasiparticle poisoning that can be exploited as a means of particle (and specifically dark matter) detection.**







McEwen et al (Google Sycamore team), Nature 18, 107 (2022) [arXiv:2104.05219]

Looking Forward

Proposing a novel, multiplexed quantum device for particle physics detection

- A low-mass DM recoil will deposit order meV-keV of energy ω in the substrate at location r, producing phonons
- These will break Cooper-pairs in aluminum which are measured in quasiparticle detectors (qubits)
- The energy-resolving detectors (veto), which have much higher thresholds, should see no simultaneous hits, since the energy deposition is below detector threshold