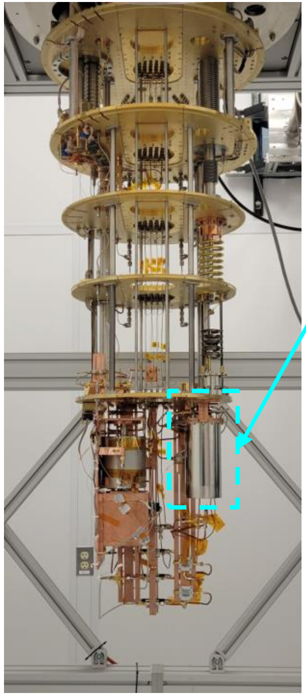
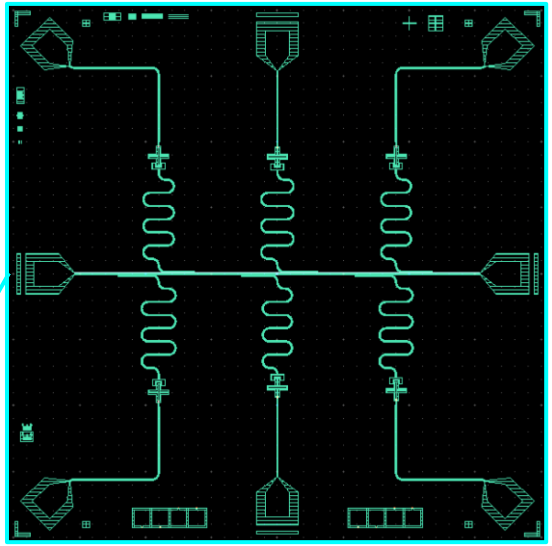
Leveraging Quantum Sensors for Dark Matter Detection

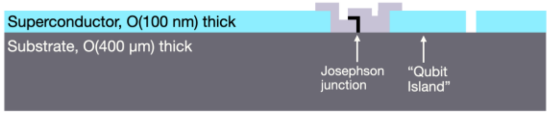
Daniel Baxter
Identification of Dark Matter (IDM 2026)
2 June 2026

Superconducting Qubits – Basics

Let’s start with a “boilerplate” quantum device: a superconducting quantum bit (qubit) chip.







- Microwave circuit pattern etched into thin superconducting film on thicker substrate
- Operated within dilution refrigerators at cryogenic temperatures: 10 mK

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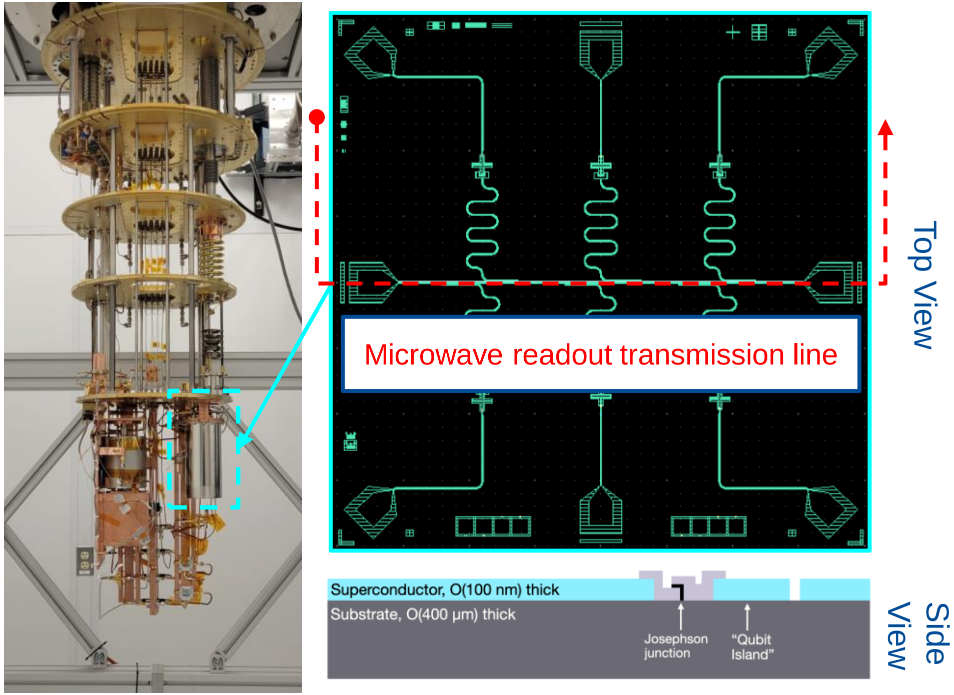
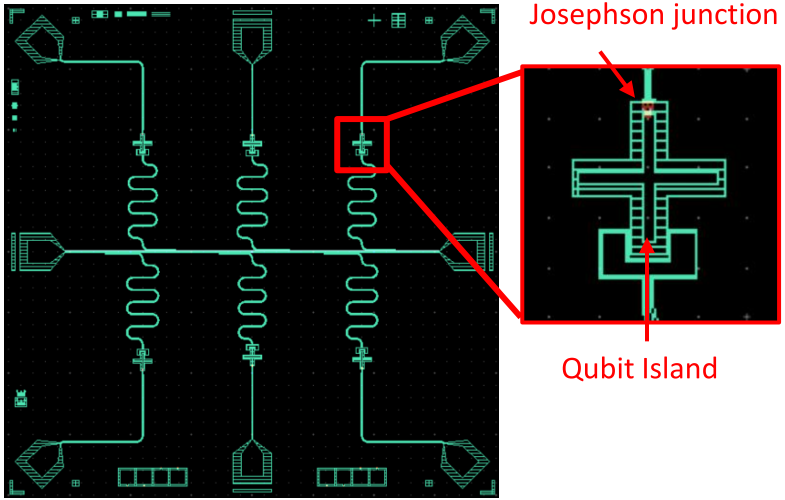


- Microwave circuit pattern etched into thin superconducting film on thicker substrate
- Operated within dilution refrigerators at cryogenic temperatures: 10 mK
- Controlled/read out by microwave pulses

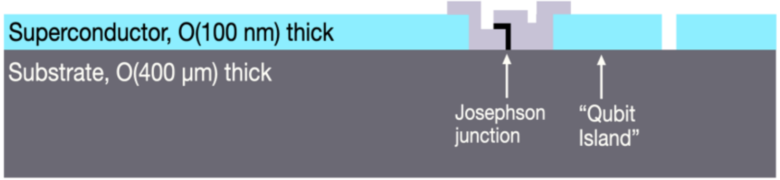
Superconducting Qubits – Basics

Superconducting quantum bits (qubits) are near-dissipationless cryogenic LC circuits which can hold **individual microwave quanta** (photons) for computation.

Top View



Side View



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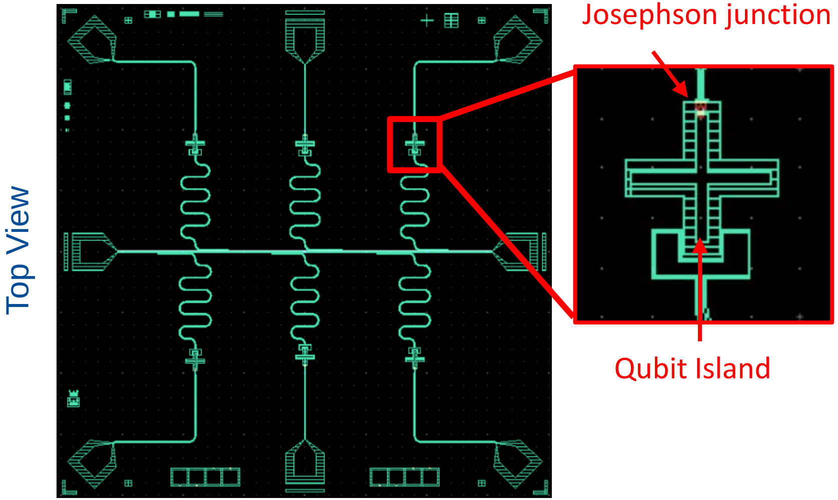
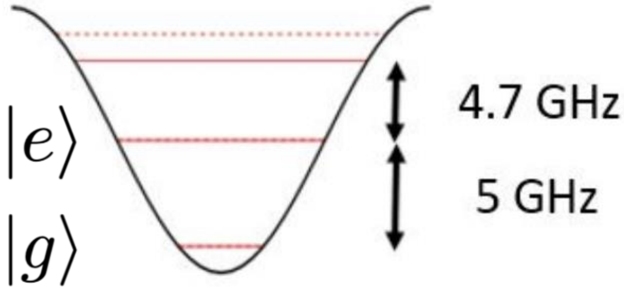


Anharmonic quantum LC oscillator, with…

- "C" → provided by qubit island
- "L" → provided by josephson junction
- Excitation = single microwave photon

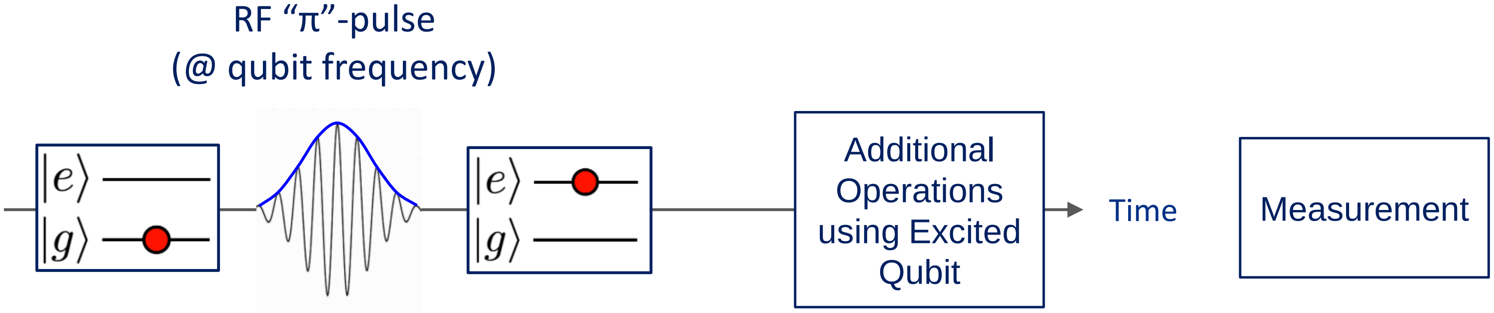


Anharmonicity is key to addressing single energy transition!

Superconducting Qubits – Control

For useful operation of superconducting qubits, we need good **control over qubit frequencies** and good **retention of excitations**.

Example: exciting a qubit (for either QIS or sensing)



Possible failure modes:

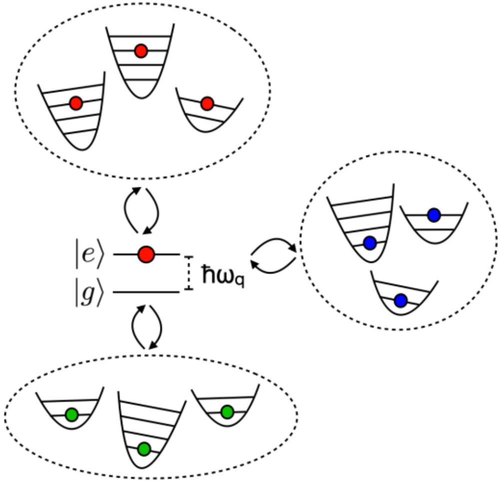
- If π-pulse is not resonant with ω_q, then you may not excite.
- If qubit is excited but you wait too long, excitation decays away.

Superconducting Qubits – Control

Superconducting qubits lose information via environmental effects in two broad ways: **relaxation** and **dephasing**.

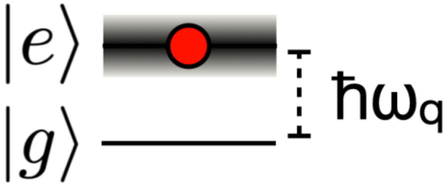
Relaxation: excitations lost from the qubit to environmental systems/baths.

- Characteristic time T_1



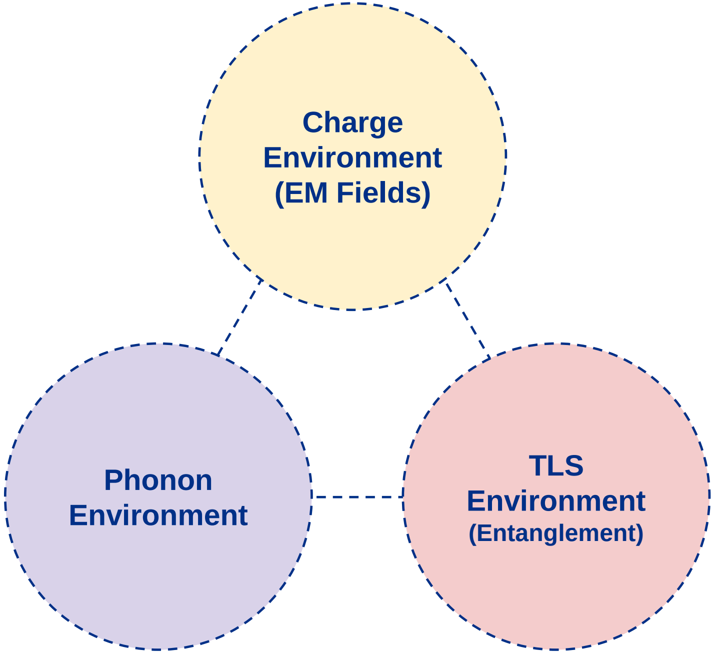
Dephasing: time variation/jitter in the qubit frequency

- Characteristic time T_2



Superconducting Qubits – Control

Particle impacts create transient bursts of activity in multiple different microphysics channels, enhancing qubit information loss to the environment.



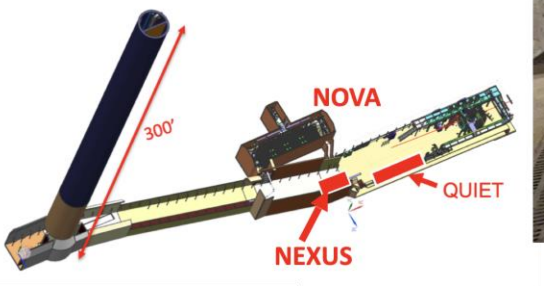
Charge Environment (EM Fields)

Phonon Environment

TLS Environment (Entanglement)

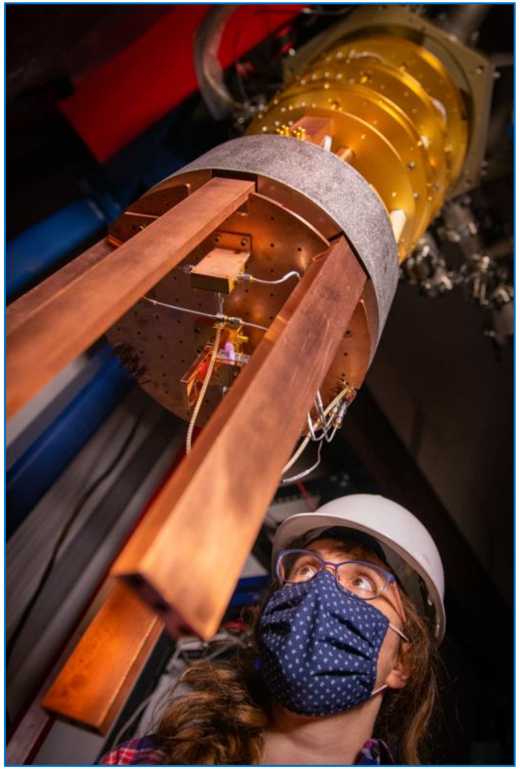
Test Facilities – MINOS Underground Near Detector Hall

- Located in the MINOS hall at Fermilab
  - 100 m (225 mwe) underground for cosmic radiation shielding
  - Easy access
  - Internal lead shield + movable external lead castle



Test Facilities – NEXUS @ FNAL

Northwestern EXperimental Underground Site



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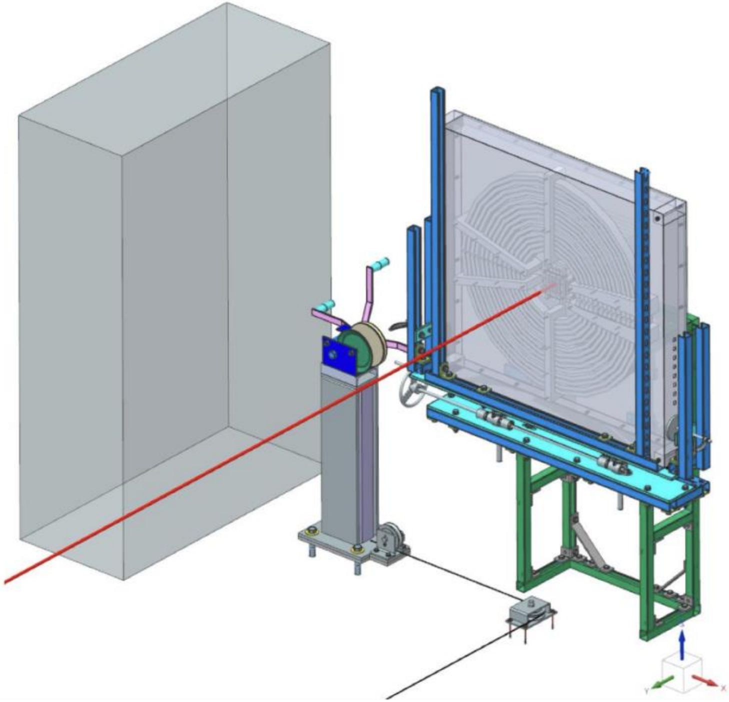
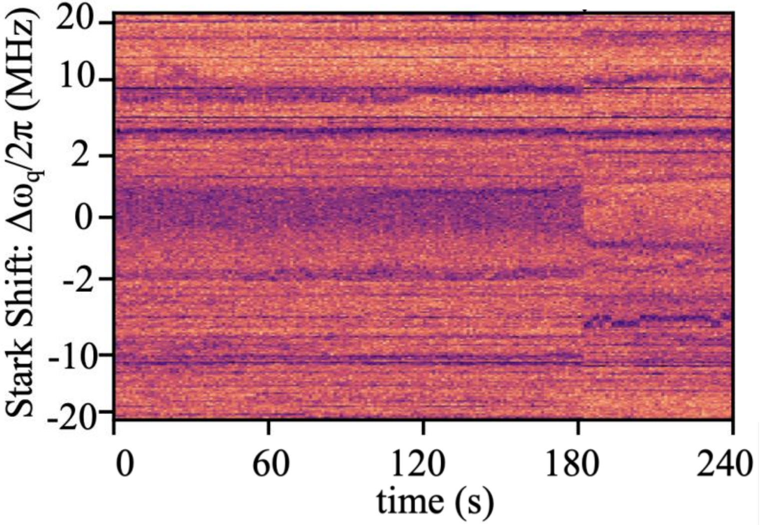


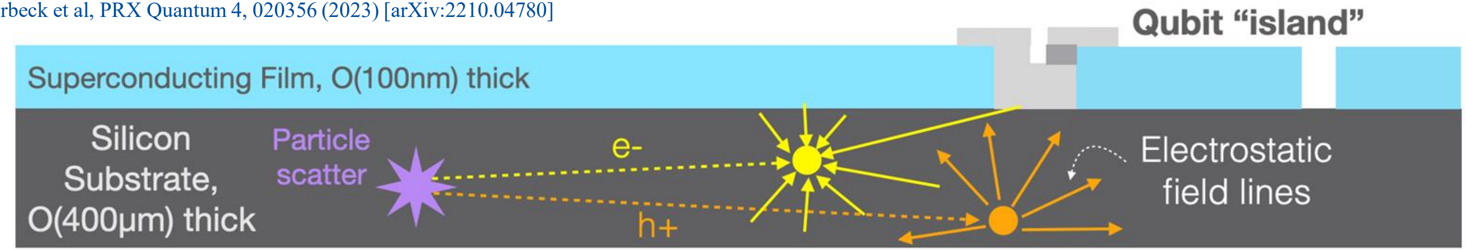
Charge Detection with Qubits



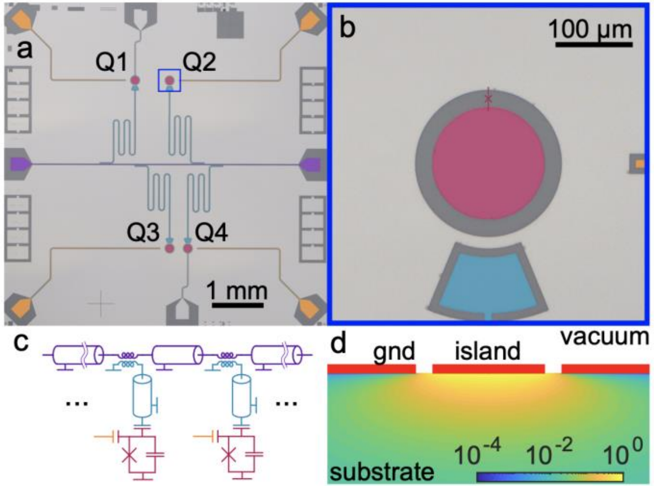
Thorbeck et al, PRX Quantum 4, 020356 (2023) [arXiv:2210.04780]

Charge Burst

- Energy deposits create electrons and holes in the substrate
- Trapped charges induce an electric field near the qubit
- Changes in the electric field are seen as “**charge jumps**” in charge-sensitive qubits
- ‘locks in’ effect of burst for significantly longer timescales: hours-to-days (in the absence of external E-field)



Charge Detection with Qubits



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

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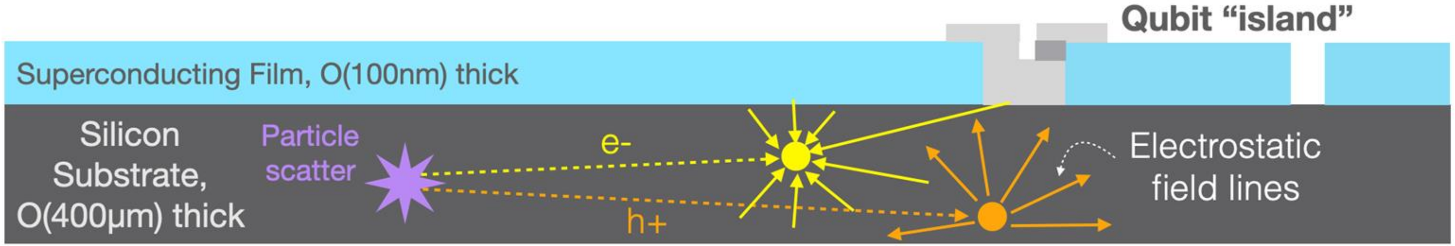
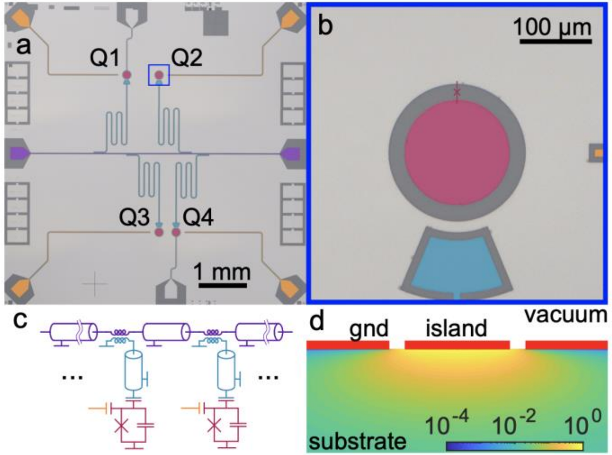


Charge Detection with Qubits



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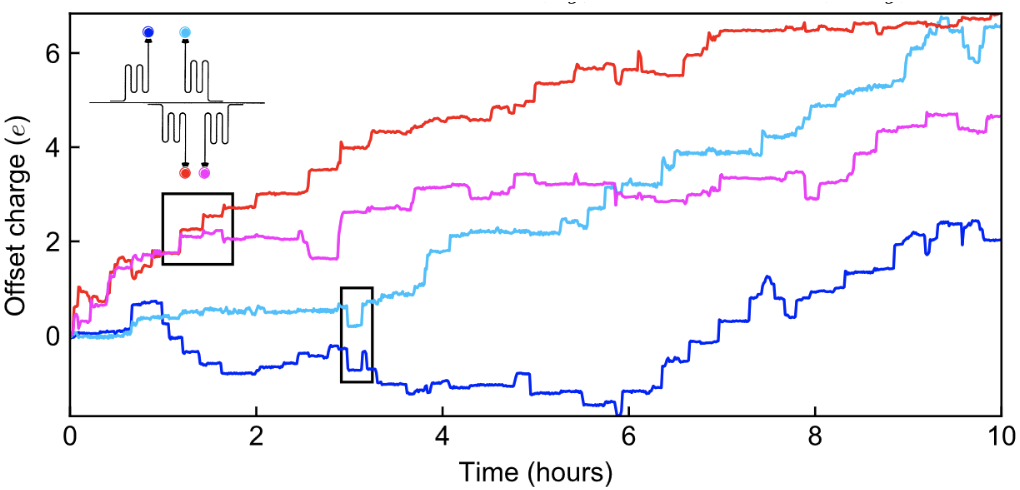


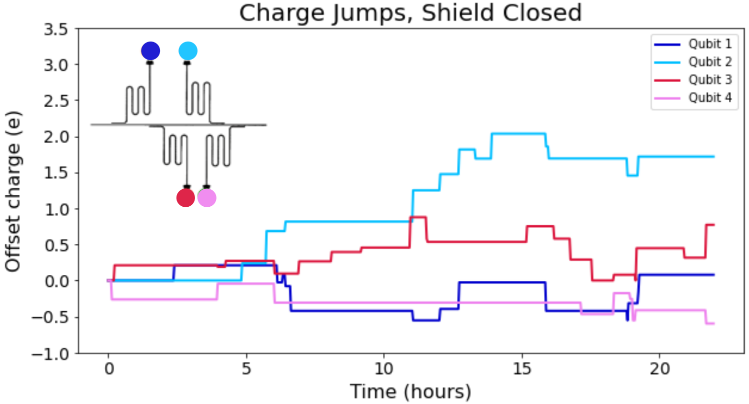
Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear **correlated** offset charge jumps over long times

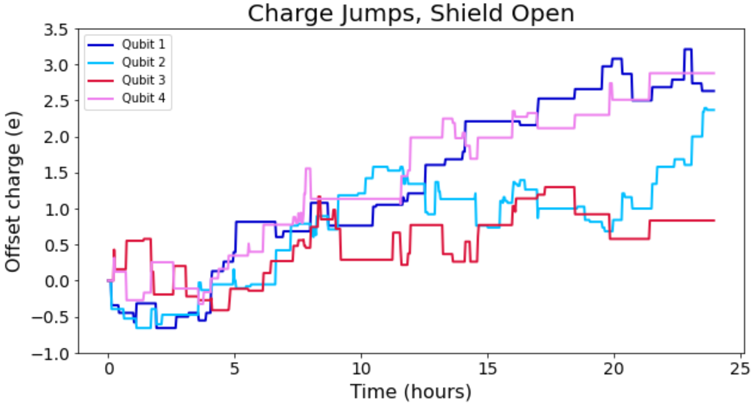
- Correlated jumps → simultaneous errors

Charge Detection with Qubits

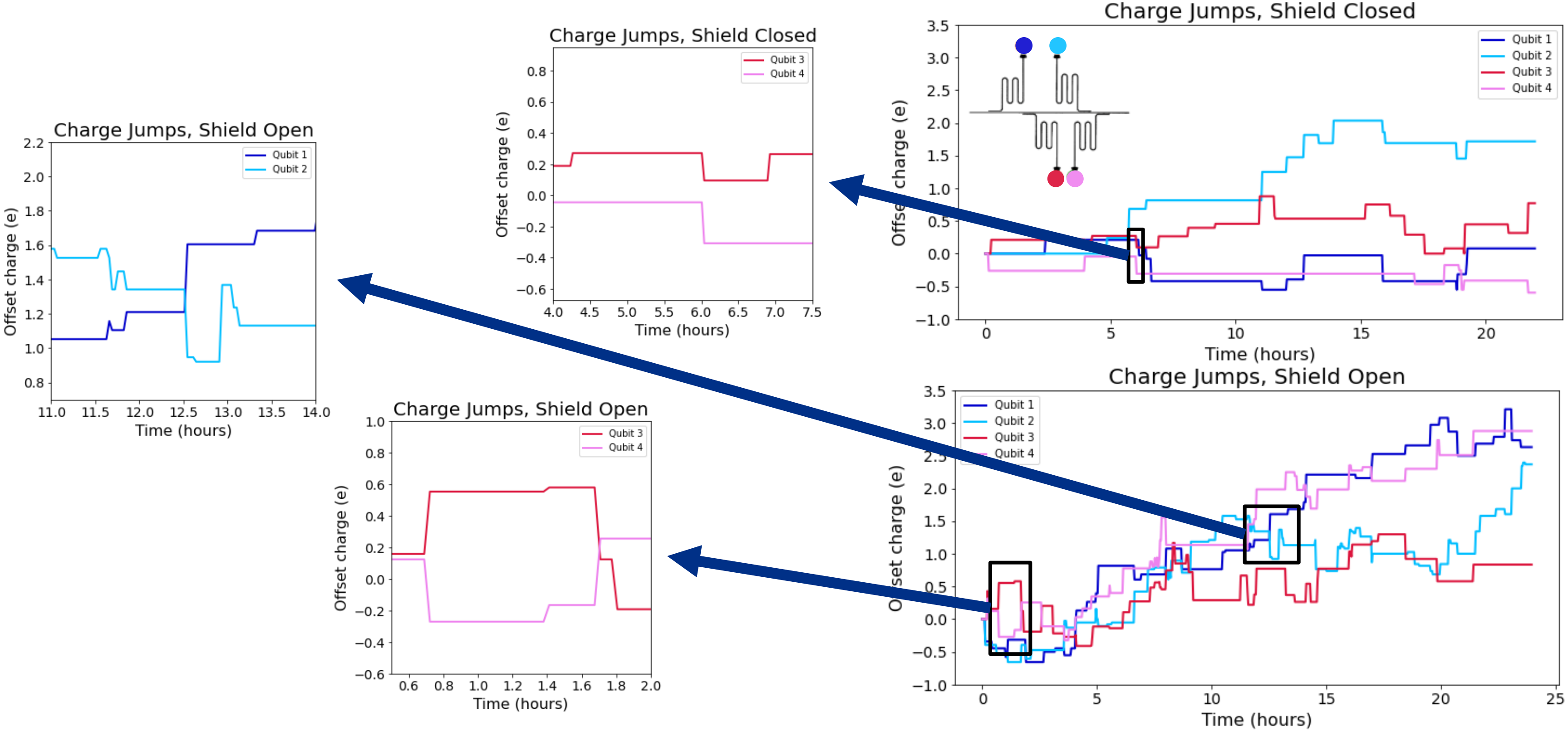
- Repeated long time charge jump measurements with 4 different shielding configurations (2 shown here)
- Change in charge jump rate based on configuration visible!
- Running underground → muon rate reduced by over 2 orders of magnitude compared to at Madison
  - Negligible compared to gamma flux

Bratrud et al, Nature Comm. 16, 9906 (2025) [arXiv:2405.04642]





Charge Detection with Qubits

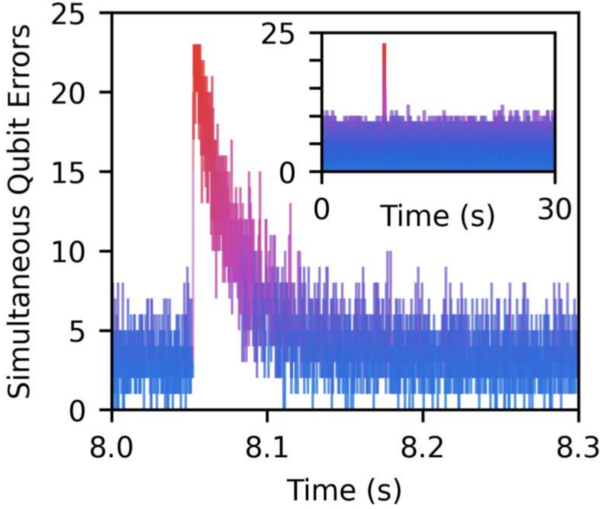


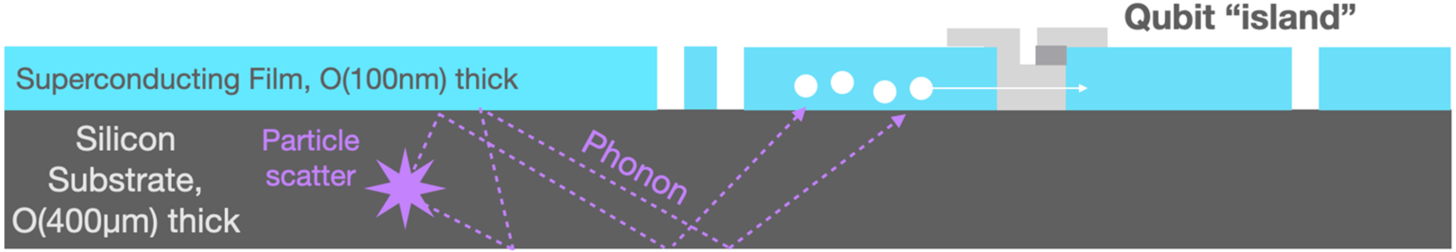
Indirect Phonon Detection with Qubits

T1 Decoherence

- Energy deposits create phonons which break Cooper pairs, leading quasiparticles to tunnel across the junction resulting in qubit decoherence
- Decoherence can be measured as a decrease in T1 (increase in error rate)
- Timescale for disruption: 10's of μs to 100's of ms (depending on thermalization method)

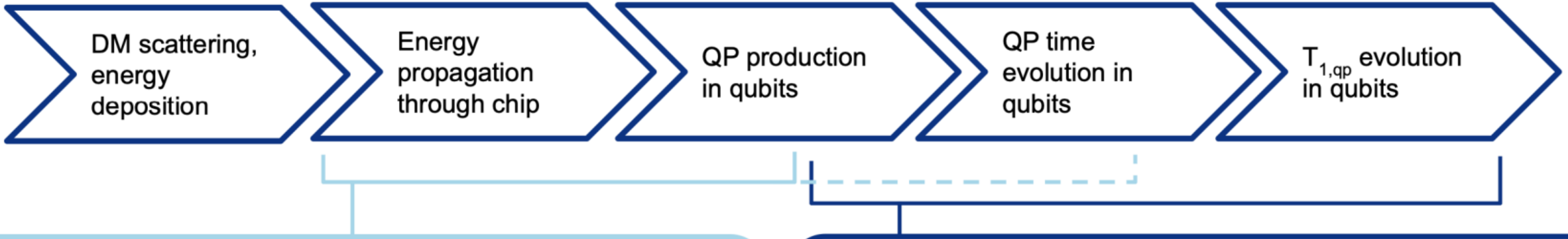
McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]





Indirect Phonon Detection with Qubits

To get a mature estimate of reach, we need to simulate how energy deposits propagate through a detector to impact T1 decoherence times.



DM scattering, energy deposition

Energy propagation through chip

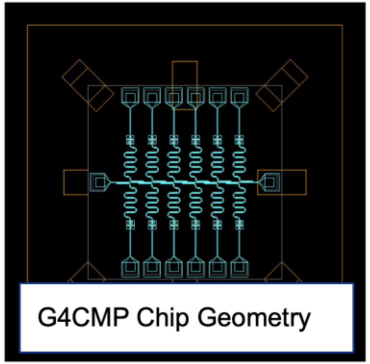
QP production in qubits

QP time evolution in qubits

$T_{1,qp}$ evolution in qubits

G4CMP simulation

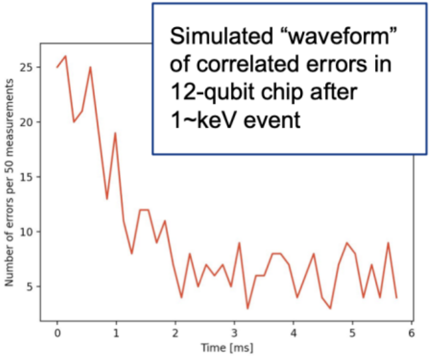
- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



G4CMP Chip Geometry

Quantum Device Response (QDR)

- Folds in detection scheme, critical readout parameters
- Flexible: models multiple sensor types (MKIDs, Transmons), even on same chip!



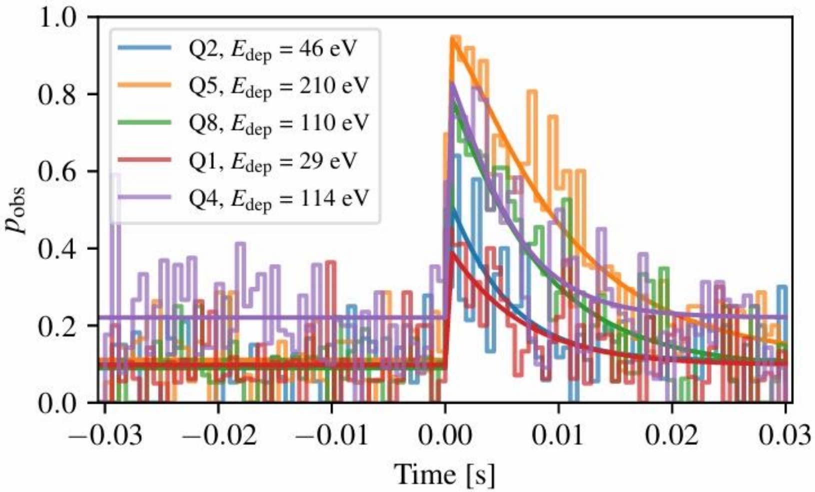
Simulated "waveform" of correlated errors in 12-qubit chip after 1~keV event

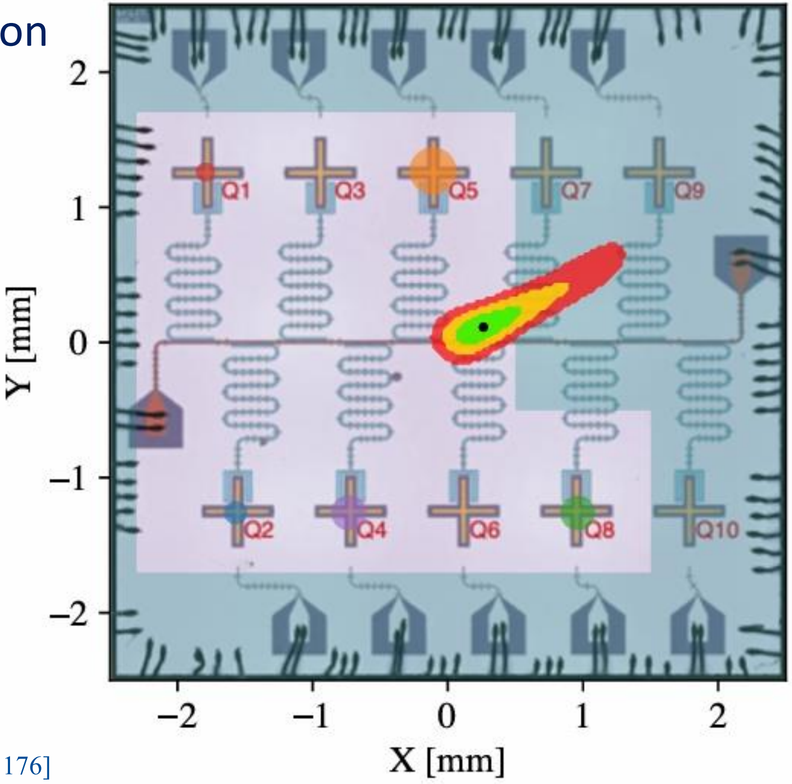
Linehan et al, PRD 111, 063047 (2025) [arXiv:2404.04423]

Indirect Phonon Detection with Qubits

This enables full position and energy reconstruction of particle scattering in qubit chips

- *see Emanuela Celi's talk earlier this session*





Celi et al, (2026) [arXiv:2604.13176]

Resonant Energy Exchange in Qubits

Useful tool for QIS devices: resonant energy exchange (Rabi Oscillations) between coupled oscillators.

Hamiltonian of two quantum oscillators “a” and “b” coupled with strength g:

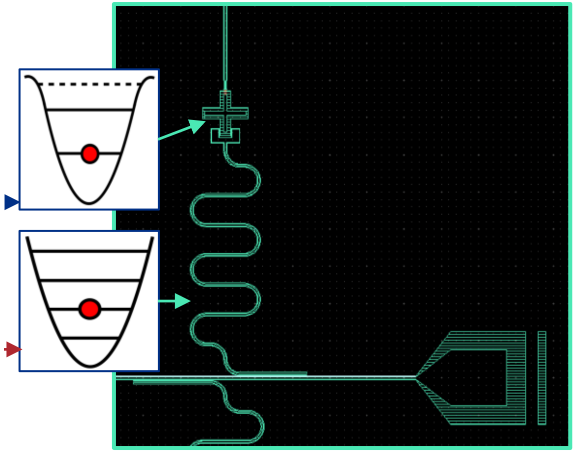
$$H = \boxed{\omega_{\mathrm{q}}\, a^\dagger a} + \boxed{\omega_n\, b^\dagger b} + g\left(\boxed{a^\dagger b} + \boxed{a b^\dagger}\right)$$

Oscillator “a” energy

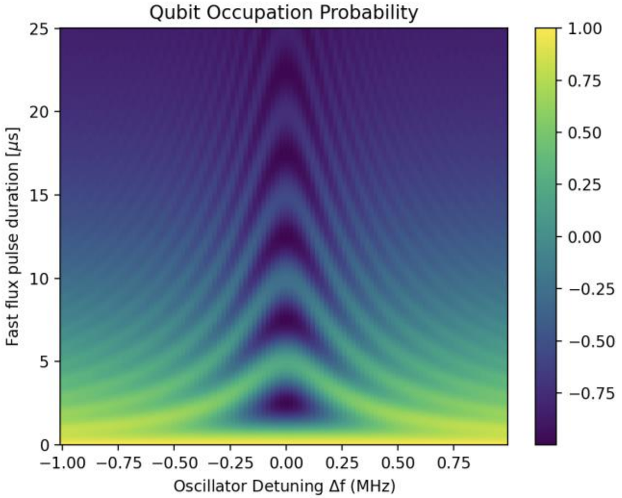
Oscillator “b” energy

Transfer excitation: b→a

Transfer excitation: a→b



When the oscillators’ frequencies are brought on resonance, the total system evolves by swapping an excitation from one oscillator to the other.



Quantum Acoustics

As long as you can physically achieve the coupling g, can generalize resonant exchange to other systems.

Quantum acoustics: piezoelectric coupling between high-overtone bulk acoustic resonator (hBAR) and superconducting qubits.

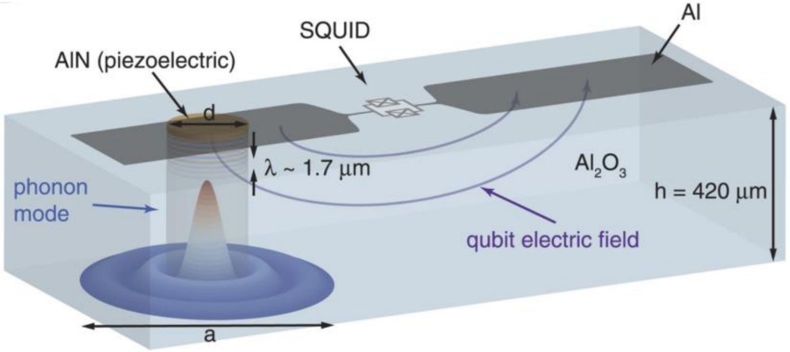
$$H = \boxed{\omega_q \, a^\dagger a} + \boxed{\omega_n \, b^\dagger b} + \boxed{g\left(a^\dagger b + a b^\dagger\right)}$$

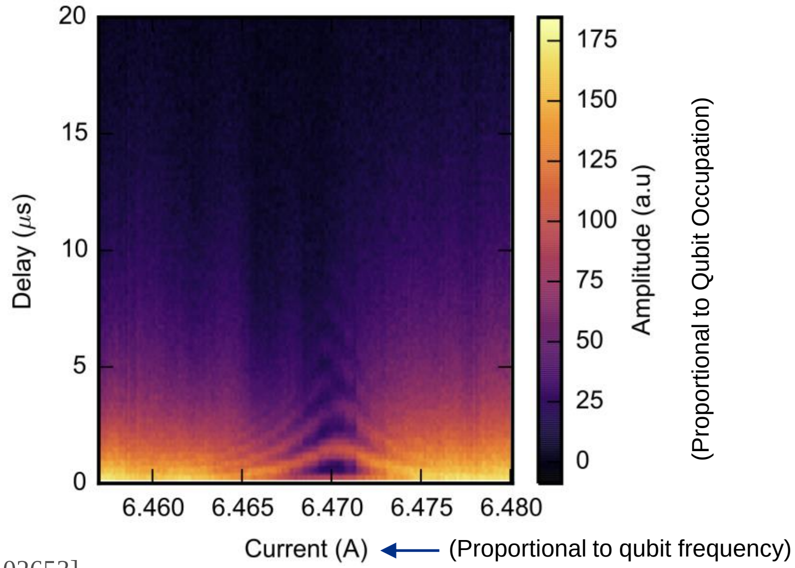
SC Qubit

Acoustic cavity (hBAR)

Piezoelectric coupling term

Single-quanta energy exchange has been achieved between a qubit mode and an acoustic standing wave at few-GHz frequencies (~10μeV)

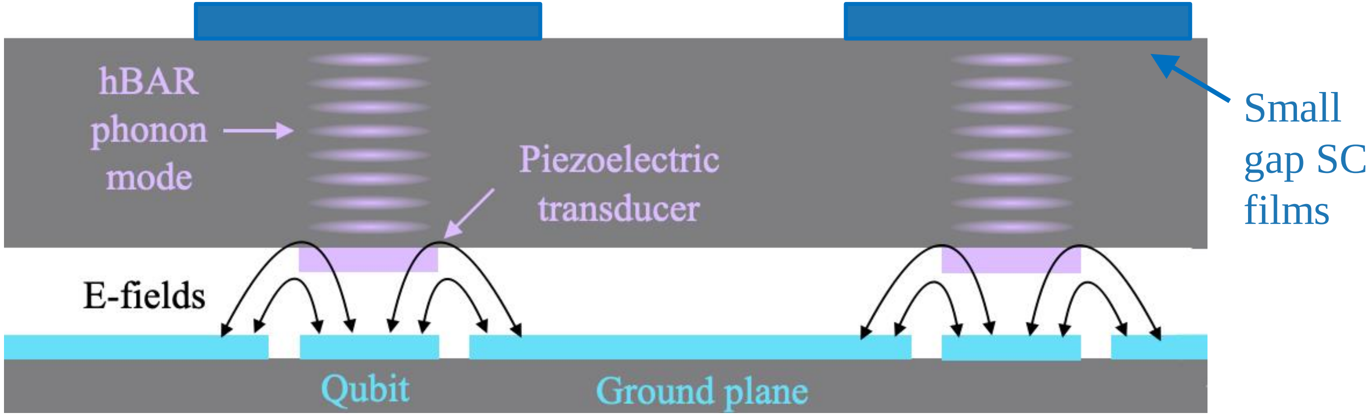




Chu et al, Science 358, 199 (2017)
Omahen et al, preprint [arXiv:2507.02653]

Direct (Quantized) Phonon Detection with Qubits

If we can *control* single phonons at the 10μeV scale, we should be able to *sense* environmental phonons at the same energy scale with similar technology.



Linehan et al, PRD 112, 115005 (2025) [arXiv:2410.17308]

Our Team

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Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

This facility is the deepest low-background underground cryostat dedicated to superconducting qubit operation in the USA

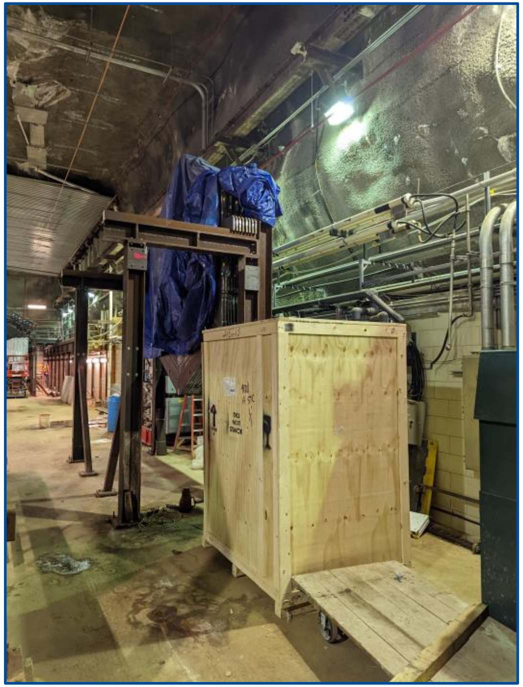
- Oxford Proteox w/ up to 16(48) NbTi(SS) RF lines
- 250 ft^2 Class 10,000 clean room
- 50 ft^2 antechamber for gowning and material cleaning
- >99% reduced cosmic ray muon background
- Design of passive radiation shield is underway

First papers based on qubit data ***soon***!

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

Dec. 9, 2022



Sept. 29, 2023

May 24, 2024

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

Photo credit: Dan Savoboda, Fermilab

Radiation Impact on Superconducting Qubits (RISQ)

Scientific Organizing Committee:
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Travis Humble, ORNL/UTK (director, **QSC**)
Farah Fahim, FNAL (**QSC**)
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Andrew Kubik, SNOLAB

QUANTUM SCIENCE CENTER

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

C^2QA
Co-design Center for Quantum Advantage

2nd iteration on June 15, 2026!
https://indico.slac.stanford.edu/event/10219/

Photo credit: Dan Savoboda, Fermilab

https://indico.fnal.gov/event/63132/

Acknowledgements – CosmiQuantum@FNAL

Intro slides shamelessly stolen from Ryan Linehan

FNAL Group
- Daniel Baxter
- Daniel Bowring
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- Ryan Linehan
- Dylan Temples
- Sami Lewis*
- Kelly Stifter*
- Sara Sussman
- Sho Uemura
- Chris James
- Joyce Christiansen-Salameh*
- Olivia Seidel
- Muntu Munaf
- Tilly Schaaf
- Selby Dang*
- Hannah Magoon*
- Grace Wagner*

NU Group
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- Pratyush Patel
- Firas Abouzahr
- Grace Bratrud
- Arianna Colón Cesaní
- Kyle Kennard
- Alejandro Rodriguez
- Deeksha Sabhari*
- Xavier Dabrowiecki*

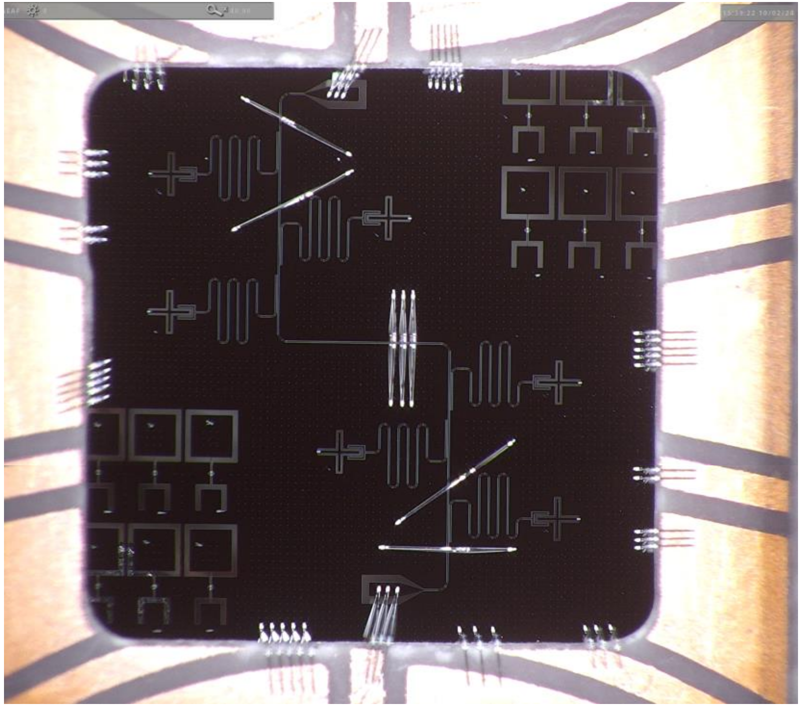
IIT Group
- Rakshya Khatiwada
- Kester Anyang
- Ziyu Cai
- Israel Hernandez
- Daniel Molenaar

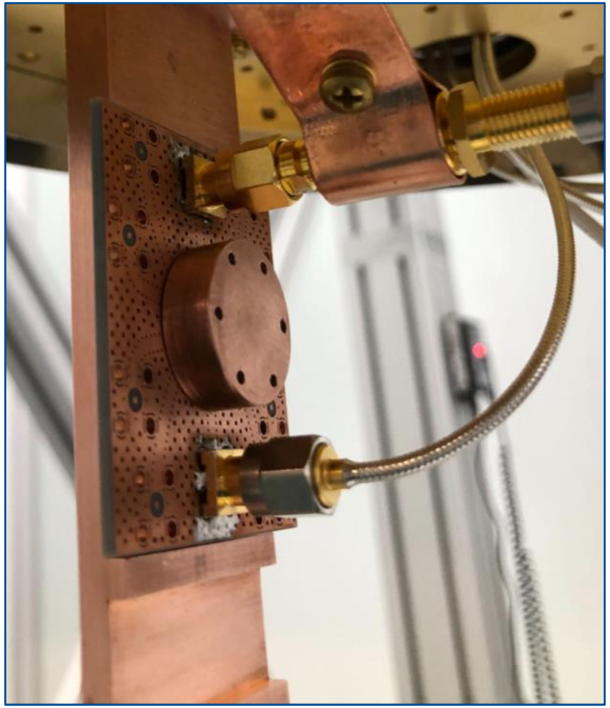
*group alumni

Back-up Slides

Fabrication of Devices

Devices made in-house taking data!

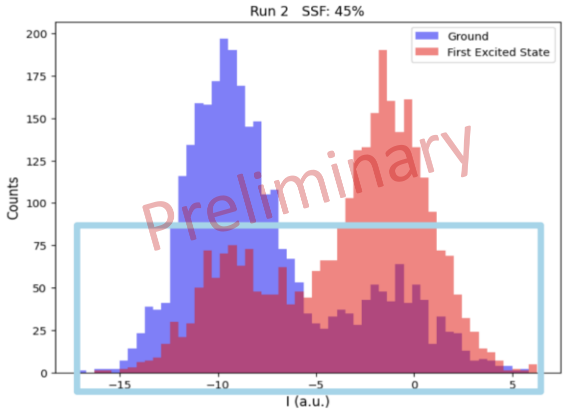


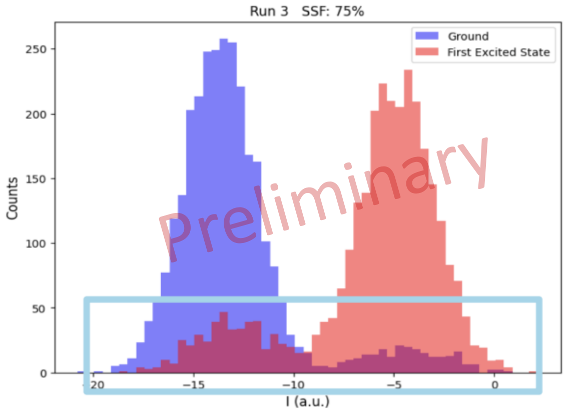


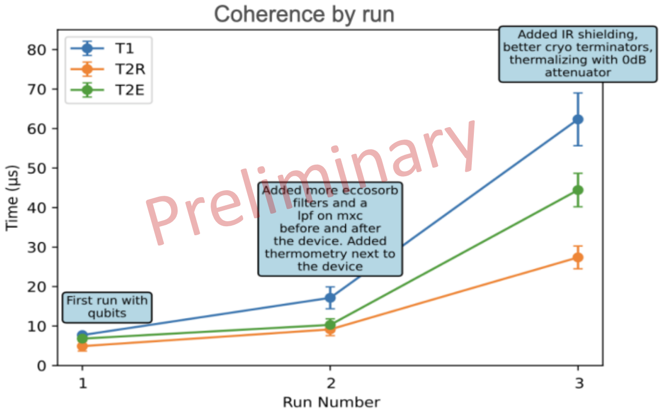
Chip design credit to Ziqian Li of SchusterLab

Optimization of qubits in QUIET

- Significant improvement over IR shielding of our qubits has improved qubit performance enough to begin external radiation studies
- Very interested in studying the dynamics of qubit performance with and without radiation present.





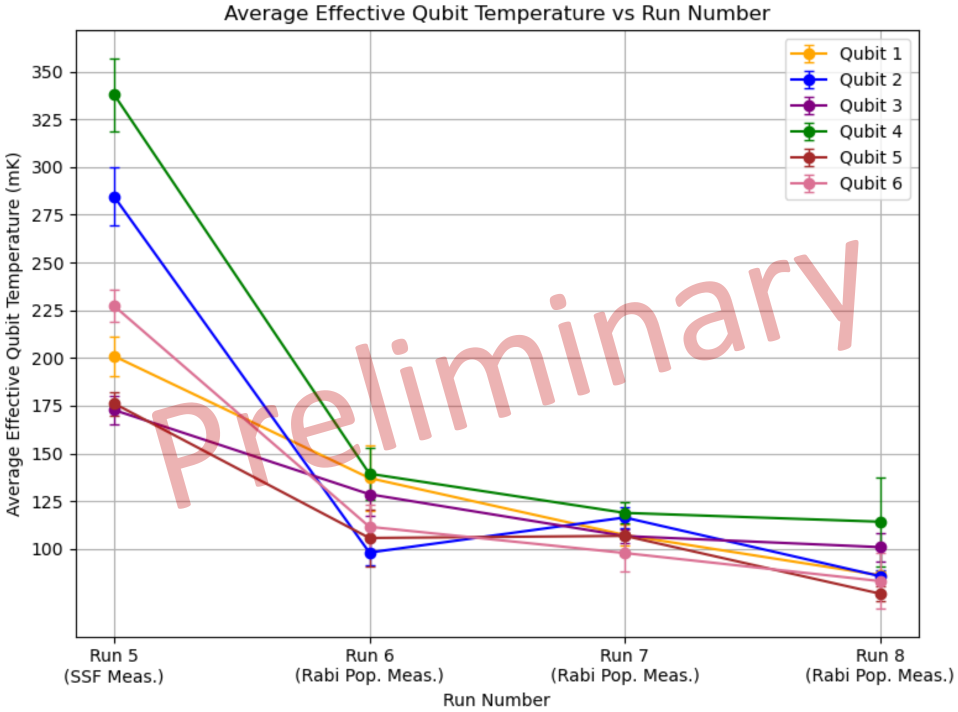


First run with qubits

Added more eccosorb filters and a lpf on mxc before and after the device. Added thermometry next to the device

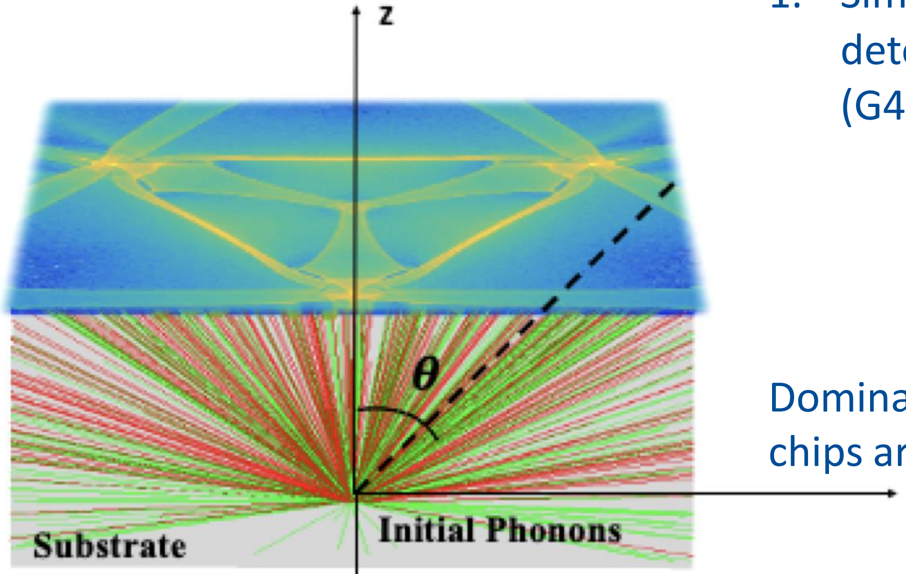
Added IR shielding, better cryo terminators, thermalizing with 0dB attenuator

Optimization of qubits in QUIET



Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate



Phonon trajectories along caustics in sapphire

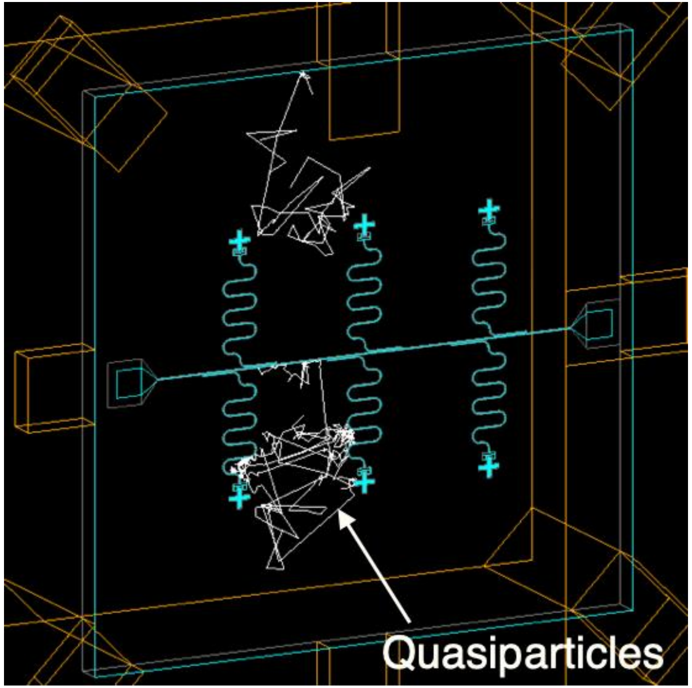
1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
    - w/ ground plane: $\eta_{ph} \approx 0.1\%$
    - w/out ground plane: $\eta_{ph} \approx 2\%$
    - w/ collection fins: $\eta_{ph} \approx 15\%$*

Dominant substrates for superconducting qubit chips are silicon and **sapphire**

Hernandez et al, NIM A 1073, 170172 (2025) [arXiv:2408.04732]

Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate

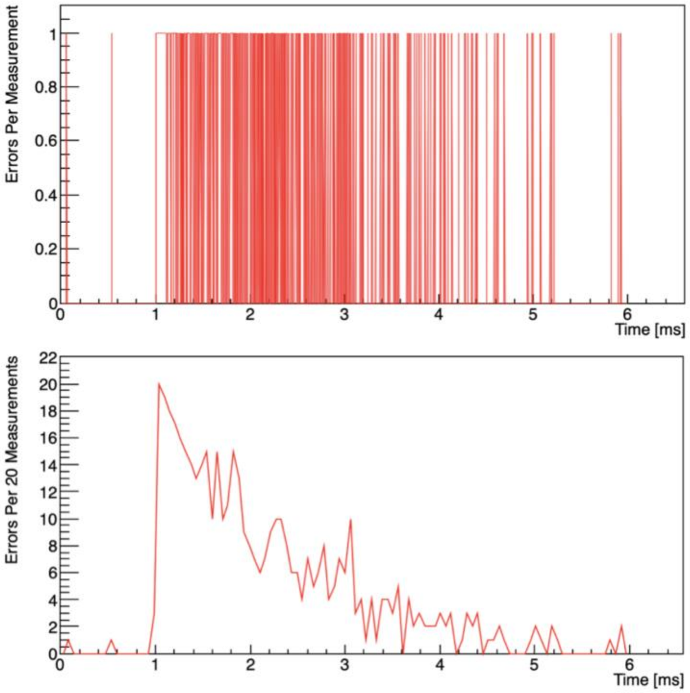


1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor

Linehan et al, *paper in preparation*

Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate

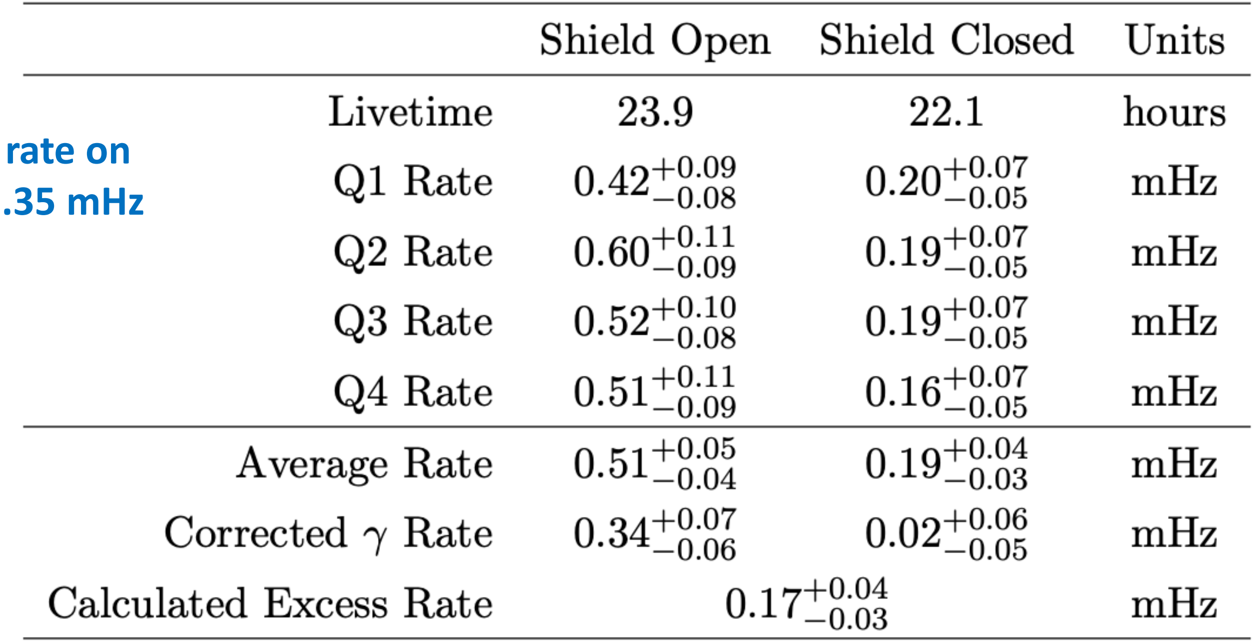


1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme

Linehan et al, PRD 111, 063047 (2025) [arXiv:2404.04423]

Studying Qubit Correlations in NEXUS

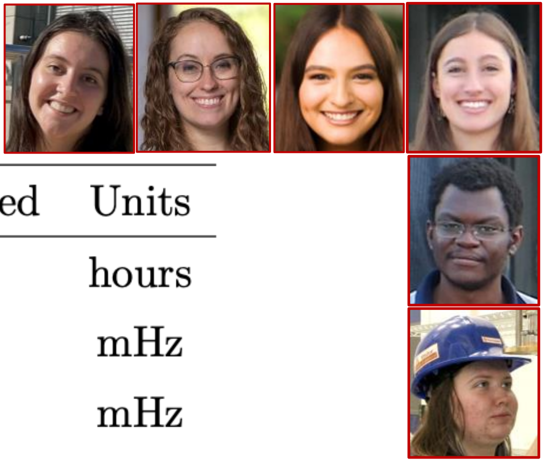
Wilen et al **rate on surface is 1.35 mHz**



	Shield Open	Shield Closed	Units
Livetime	23.9	22.1	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

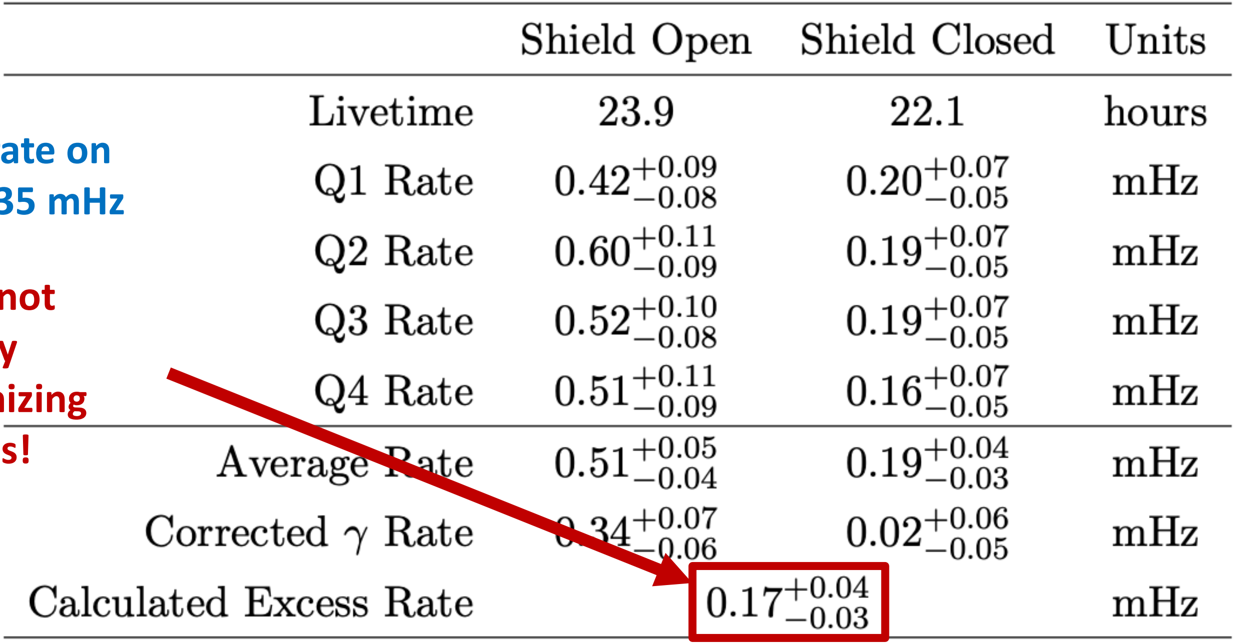
Bratrud et al, accepted for publication in Nature Comm. (2025) [arXiv:2405.04642]

Studying Qubit Correlations in NEXUS



Wilen et al rate on surface is 1.35 mHz

Excess rate not explained by ambient ionizing backgrounds!



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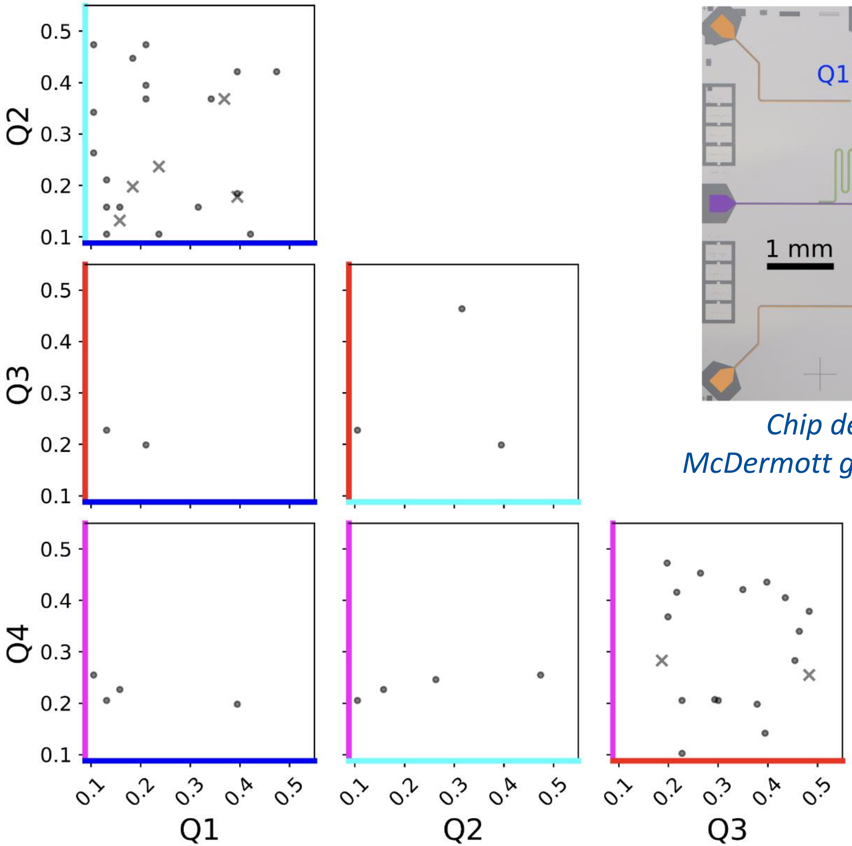
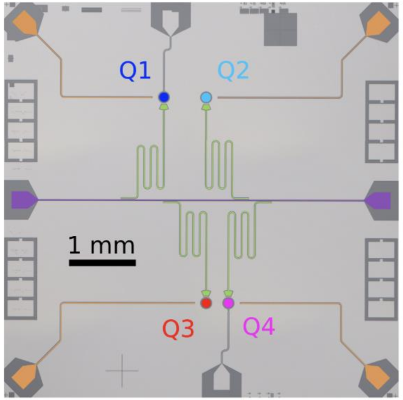
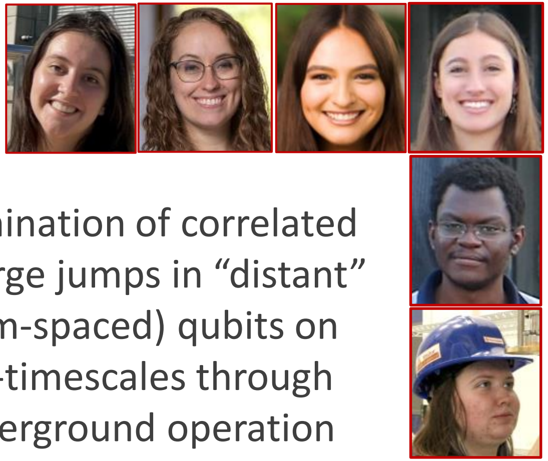




Chip design credit to
McDermott group (UW-Madison)

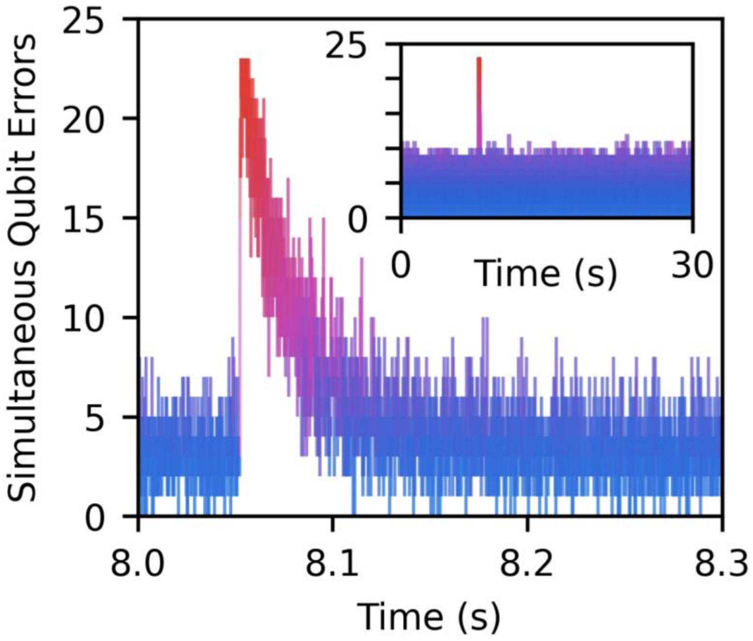


Elimination of correlated charge jumps in “distant” (>3m-spaced) qubits on day-timescales through underground operation and gamma shielding

Bratrud et al, accepted for publication in Nature Comm. (2025) [arXiv:2405.04642]

Radiation-Induced Decoherence

- Google ran a multiplexed (Sycamore) qubit chip and found similar behavior!
- **Correlated relaxation errors across the device due to energy depositions in common substrate (information destroyed every 10s!)**



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

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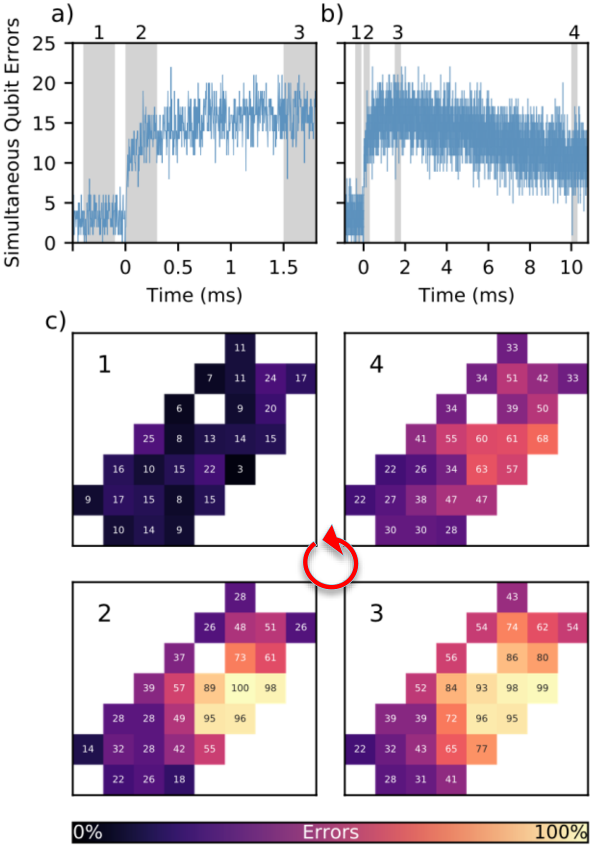

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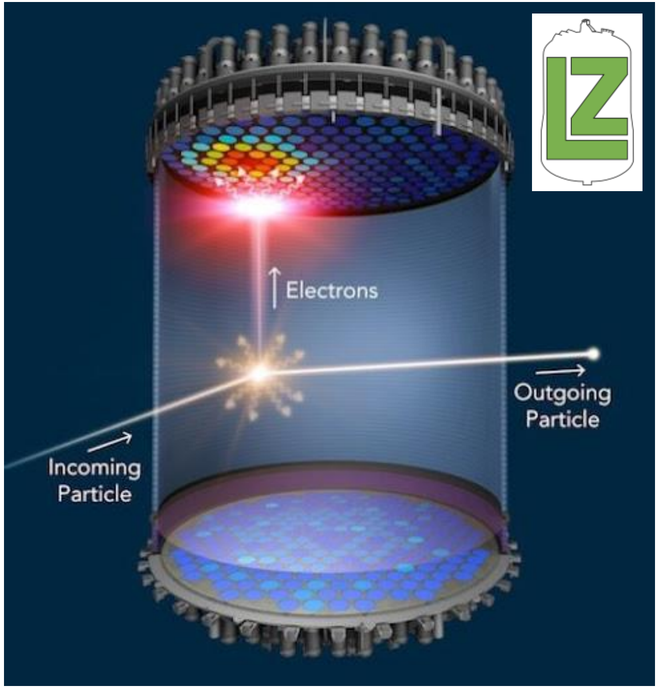

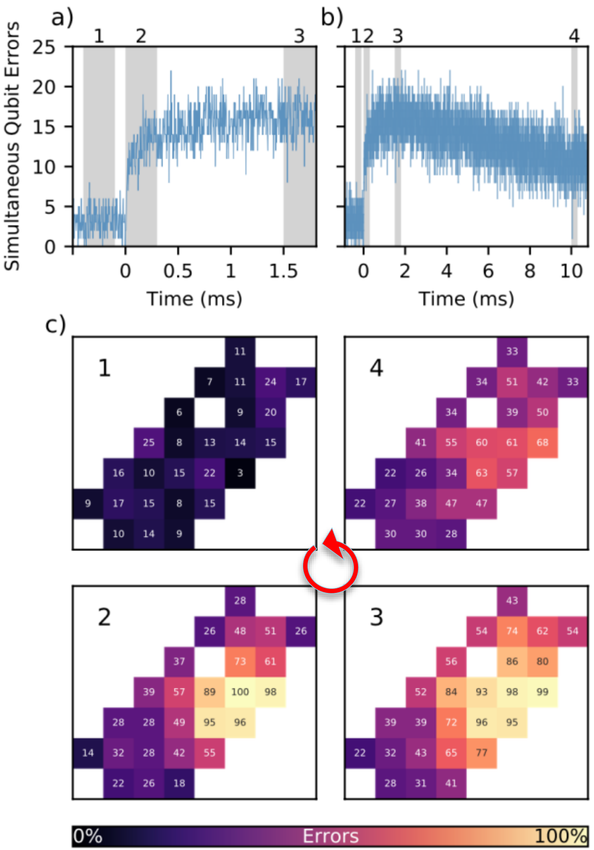

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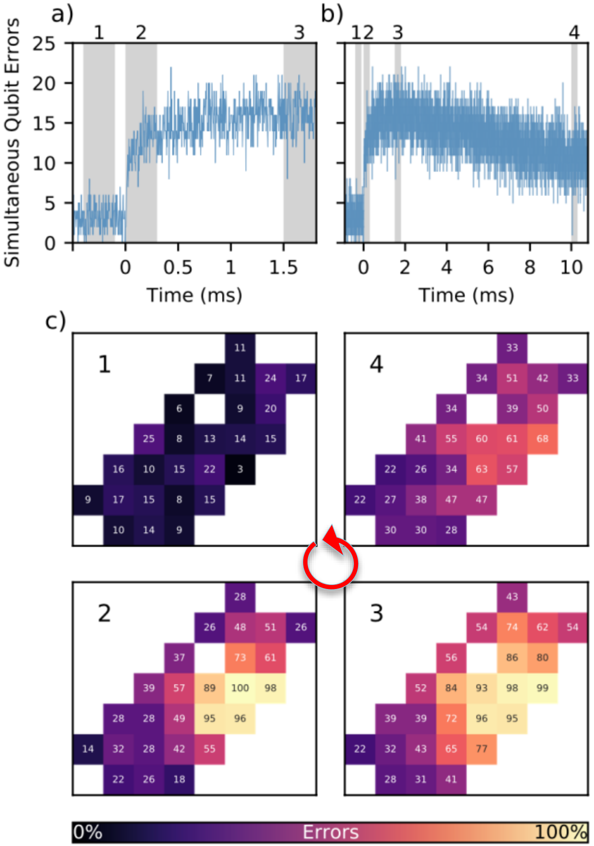
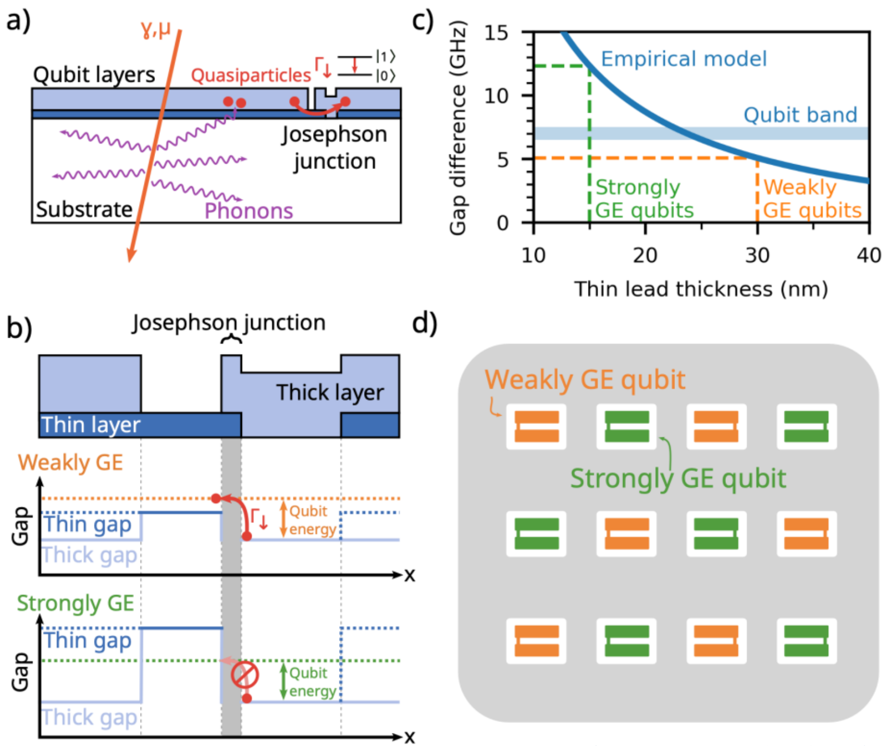
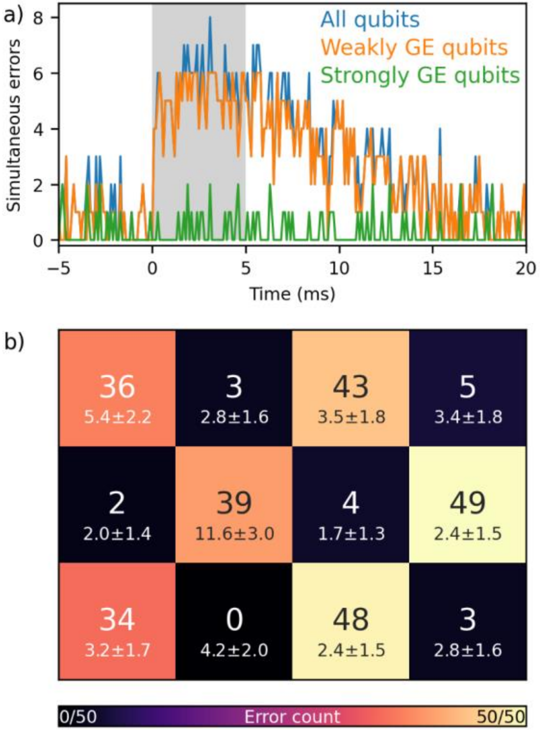
- Caveat: These events have keV-MeV energy depositions



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

Gap-Engineering



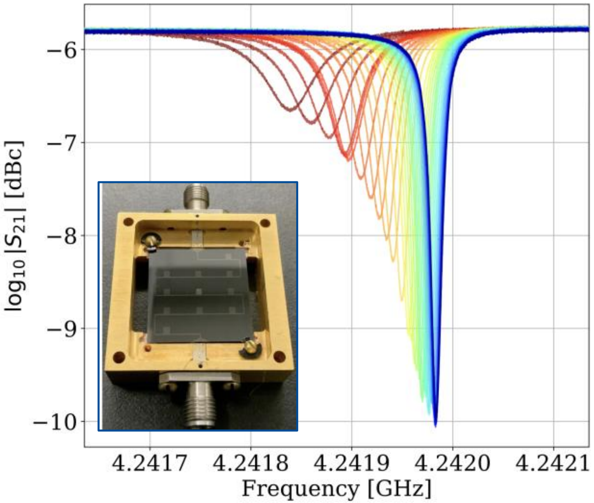


36 5.4±2.2	3 2.8±1.6	43 3.5±1.8	5 3.4±1.8
2 2.0±1.4	39 11.6±3.0	4 1.7±1.3	49 2.4±1.5
34 3.2±1.7	0 4.2±2.0	48 2.4±1.5	3 2.8±1.6

McEwen et al, PRL 133, 240601(2024) [arXiv:2402.15644]

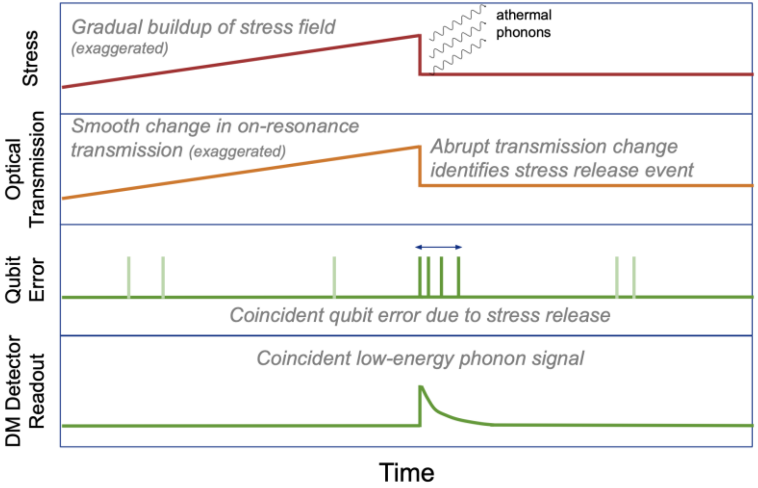
Witness Detector Development

Cross-calibration devices can be patterned alongside qubits



Microwave Kinetic Inductance Detectors

Temples et al, Phys. Rev. Applied 22, 044045 (2024) [arXiv:2402.04473]

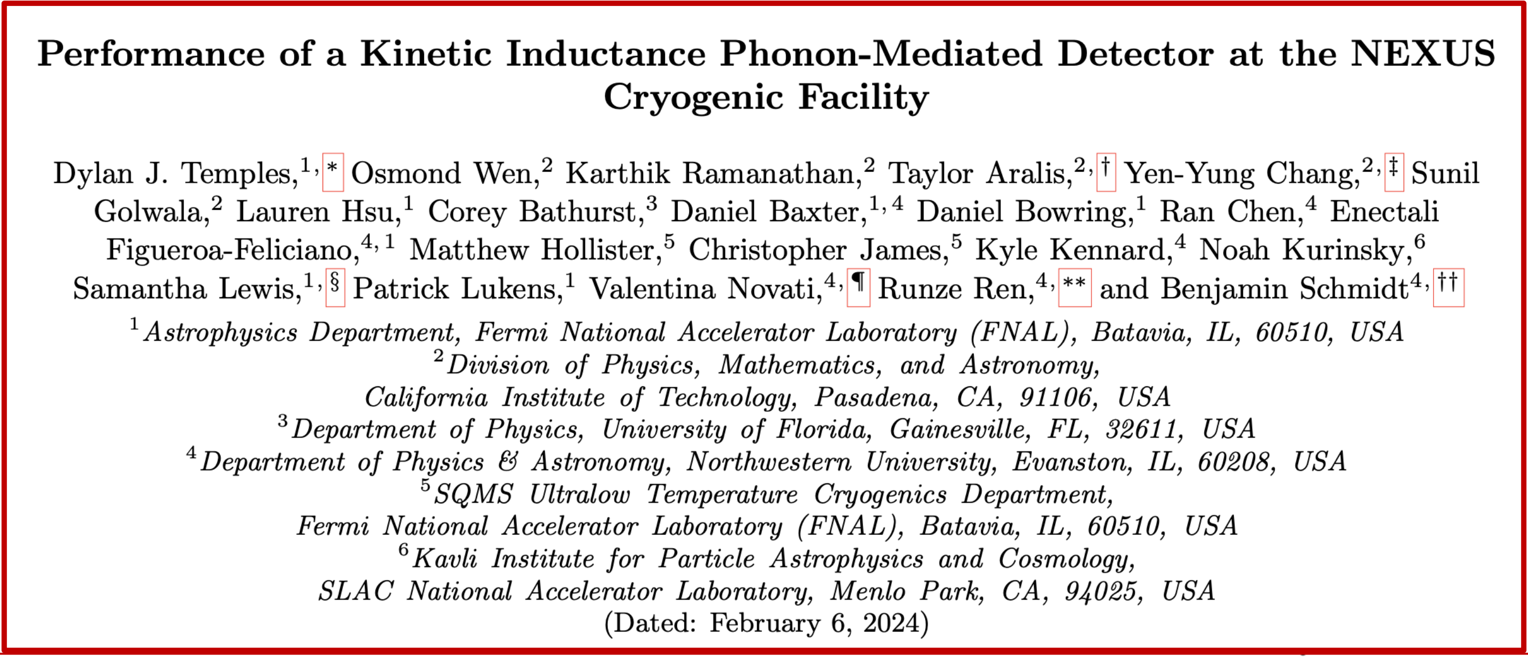


Optomechanical Ring Resonators

Strain sensors embedded under the qubit architecture

Witness Detector Development

Cross-calibration devices can be patterned alongside qubits

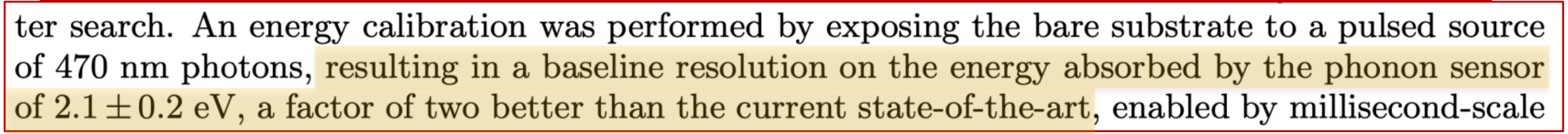


Performance of a Kinetic Inductance Phonon-Mediated Detector at the NEXUS Cryogenic Facility

Dylan J. Temples,[1,*] Osmond Wen,[2] Karthik Ramanathan,[2] Taylor Aralis,[2,†] Yen-Yung Chang,[2,‡] Sunil Golwala,[2] Lauren Hsu,[1] Corey Bathurst,[3] Daniel Baxter,[1,4] Daniel Bowring,[1] Ran Chen,[4] Enectali Figueroa-Feliciano,[4,1] Matthew Hollister,[5] Christopher James,[5] Kyle Kennard,[4] Noah Kurinsky,[6] Samantha Lewis,[1,§] Patrick Lukens,[1] Valentina Novati,[4,¶] Runze Ren,[4,**] and Benjamin Schmidt[4,††]

[1] *Astrophysics Department, Fermi National Accelerator Laboratory (FNAL), Batavia, IL, 60510, USA*
[2] *Division of Physics, Mathematics, and Astronomy,*
California Institute of Technology, Pasadena, CA, 91106, USA
[3] *Department of Physics, University of Florida, Gainesville, FL, 32611, USA*
[4] *Department of Physics & Astronomy, Northwestern University, Evanston, IL, 60208, USA*
[5] *SQMS Ultralow Temperature Cryogenics Department,*
Fermi National Accelerator Laboratory (FNAL), Batavia, IL, 60510, USA
[6] *Kavli Institute for Particle Astrophysics and Cosmology,*
SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA

(Dated: February 6, 2024)

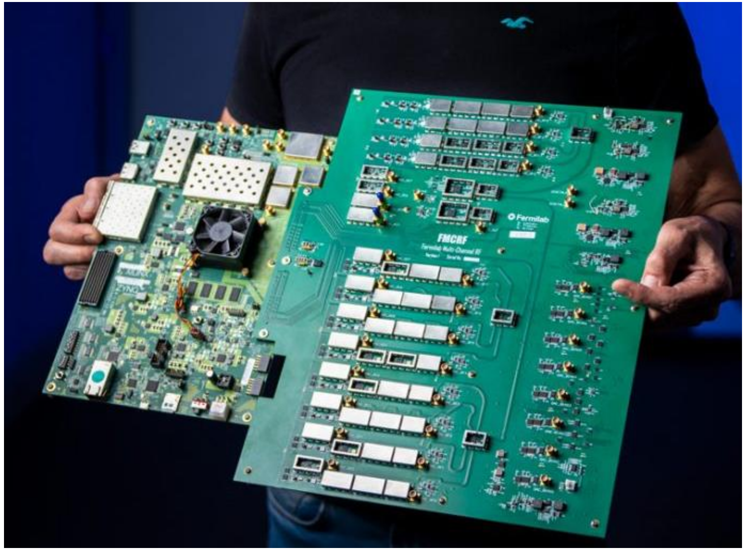


ter search. An energy calibration was performed by exposing the bare substrate to a pulsed source of 470 nm photons, resulting in a baseline resolution on the energy absorbed by the phonon sensor of 2.1 ± 0.2 eV, a factor of two better than the current state-of-the-art, enabled by millisecond-scale

Control & Readout

FNAL group has progress on many fronts towards this goal!

QICK = "Quantum Instrumentation Control Kit"



- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting last year (not including the 2 from FNAL)
- A factor of ~20 cheaper compared to off-the-shelf equipment
- Plans for frequency-multiplexed readout and control of multiple qubits soon!

Stefanazzi et al, Rev. Sci. Instrum. 93, 044709 (2022) [arXiv:2110.00557]

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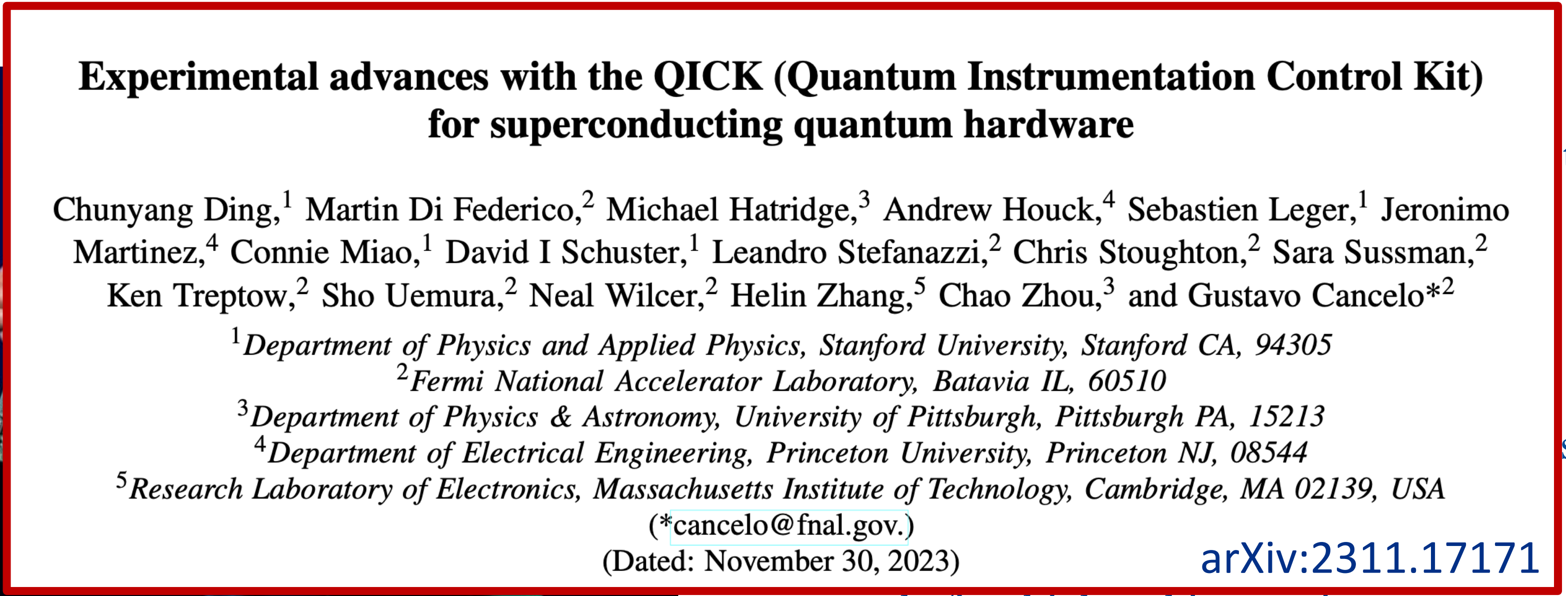

Experimental advances with the QICK (Quantum Instrumentation Control Kit) for superconducting quantum hardware

Chunyang Ding,[1] Martin Di Federico,[2] Michael Hatridge,[3] Andrew Houck,[4] Sebastien Leger,[1] Jeronimo Martinez,[4] Connie Miao,[1] David I Schuster,[1] Leandro Stefanazzi,[2] Chris Stoughton,[2] Sara Sussman,[2] Ken Treptow,[2] Sho Uemura,[2] Neal Wilcer,[2] Helin Zhang,[5] Chao Zhou,[3] and Gustavo Cancelo*[2]

[1] *Department of Physics and Applied Physics, Stanford University, Stanford CA, 94305*
[2] *Fermi National Accelerator Laboratory, Batavia IL, 60510*
[3] *Department of Physics & Astronomy, University of Pittsburgh, Pittsburgh PA, 15213*
[4] *Department of Electrical Engineering, Princeton University, Princeton NJ, 08544*
[5] *Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
(*cancelo@fnal.gov.)

(Dated: November 30, 2023)

arXiv:2311.17171

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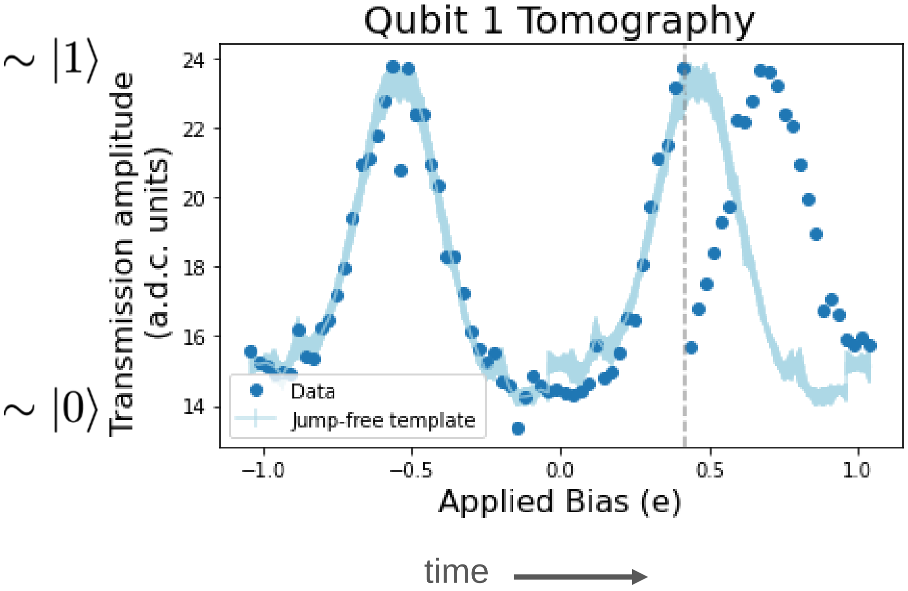
Studying Qubit Correlations in NEXUS



- Ran chip underground at NEXUS, shielded from cosmic rays and gammas
- Ramsey tomography maps offset charge onto the excited state probability of the qubit
  - Qubit state is periodic in applied bias
  - State changes with electric field induced by environmental charges → charge jumps seen as a shift in the phase
  - Timescale to re-equilibrate is much longer than time per scan
- Scans are taken consecutively over O(10) hours

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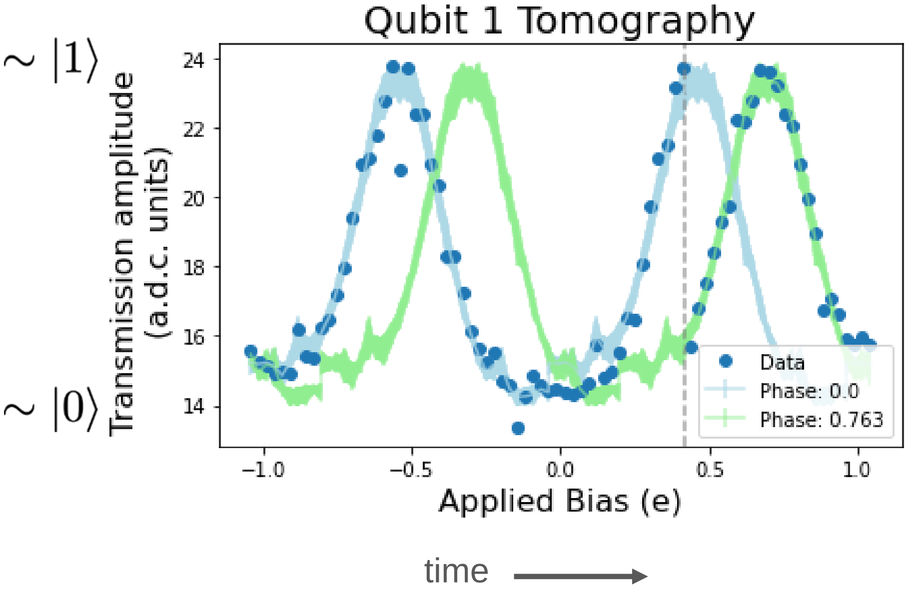

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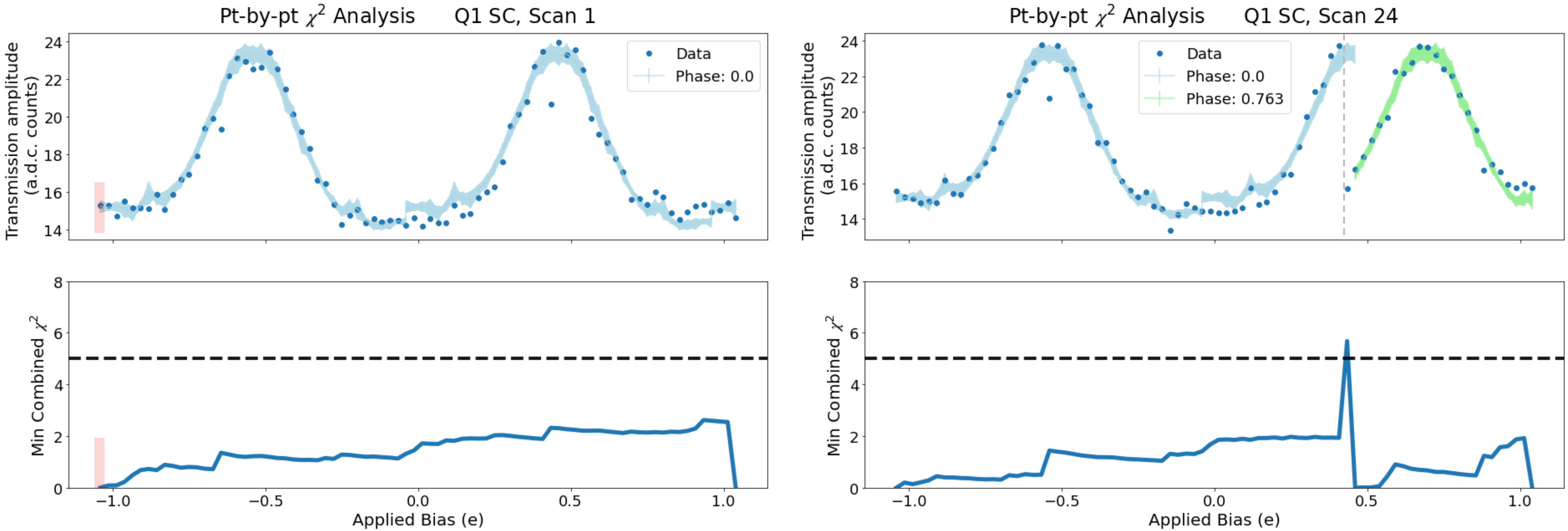
Jump Finding Algorithm: Point-by-point χ^2 Method



$$\chi^2 = \left(\frac{x_{\text{data}} - x_{\text{template}}}{\sigma_{\text{template}}}\right)^2 \qquad \chi^2_{\text{combo}}[n,] = \frac{1}{n+1}\sum_{i=0}^{n} \chi^2[i,]$$

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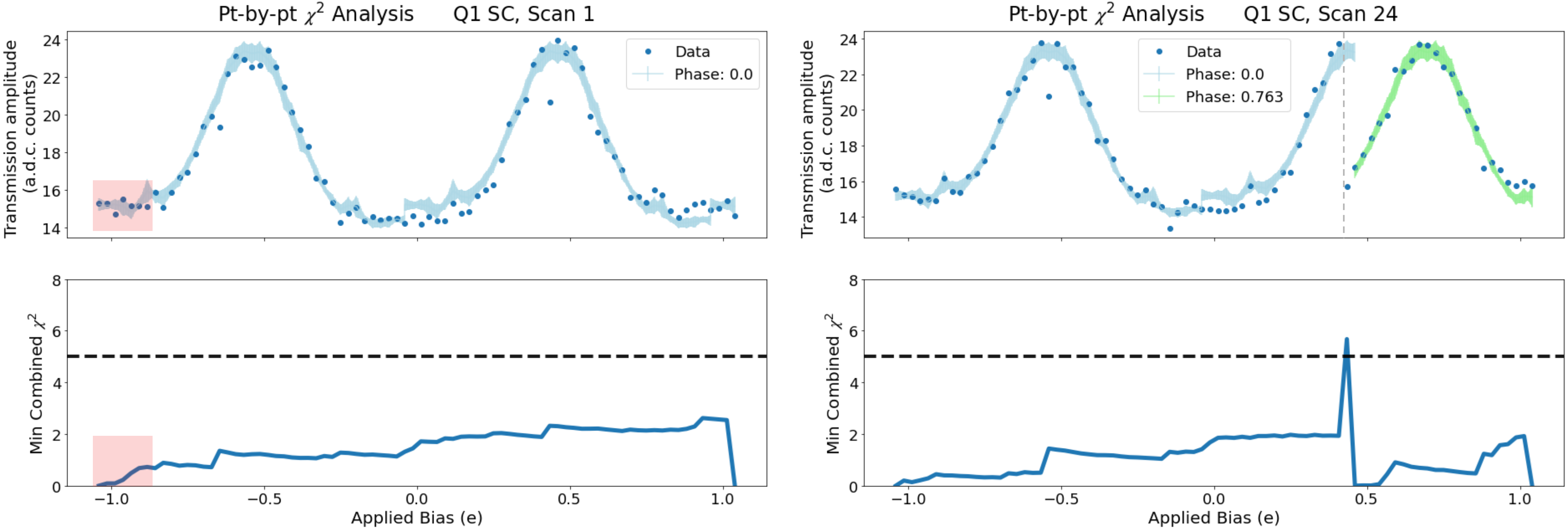

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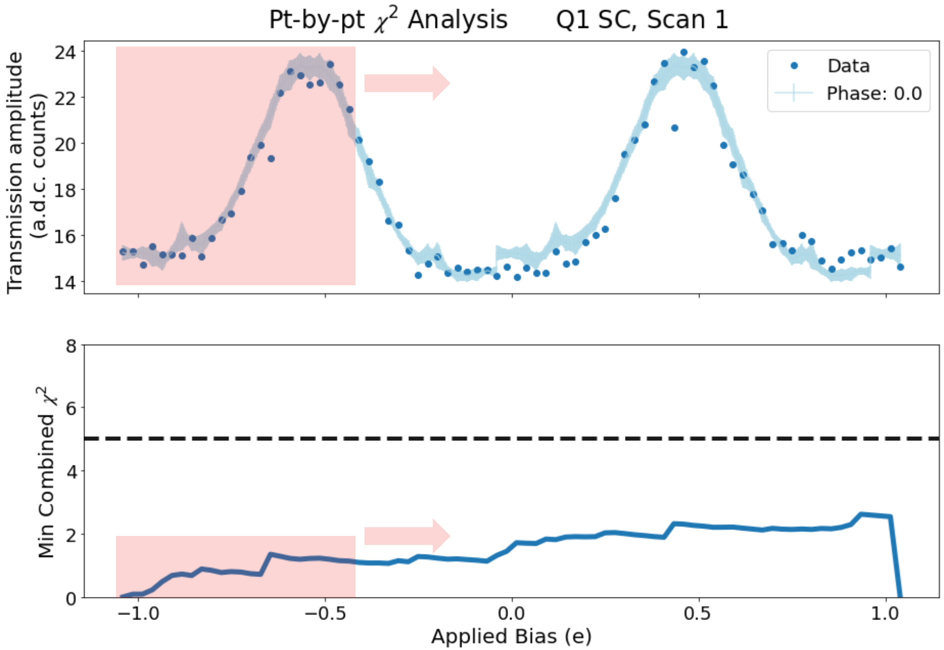
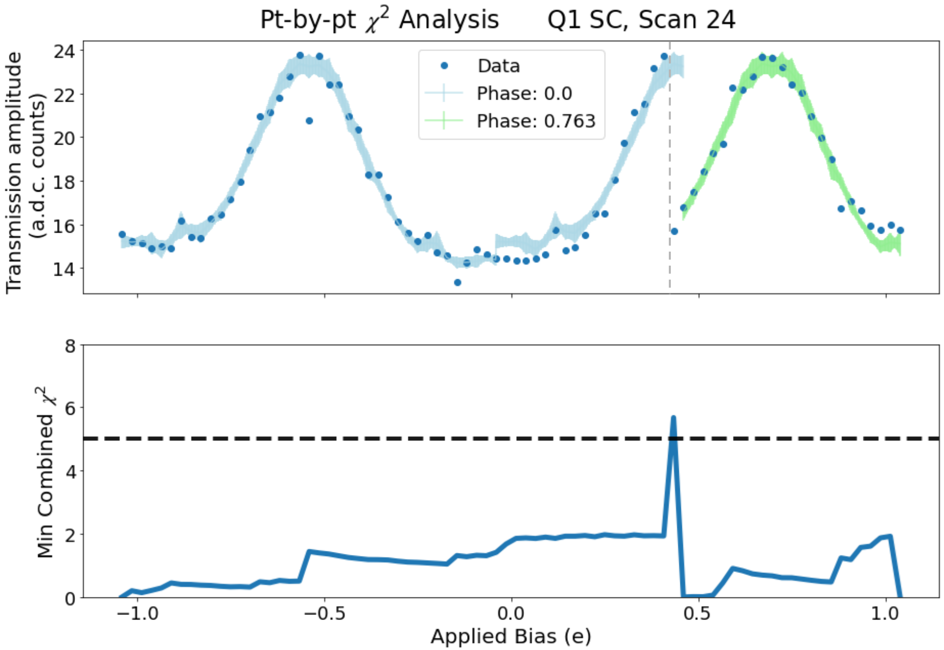


Pt-by-pt χ^2 Analysis Q1 SC, Scan 1



Pt-by-pt χ^2 Analysis Q1 SC, Scan 24

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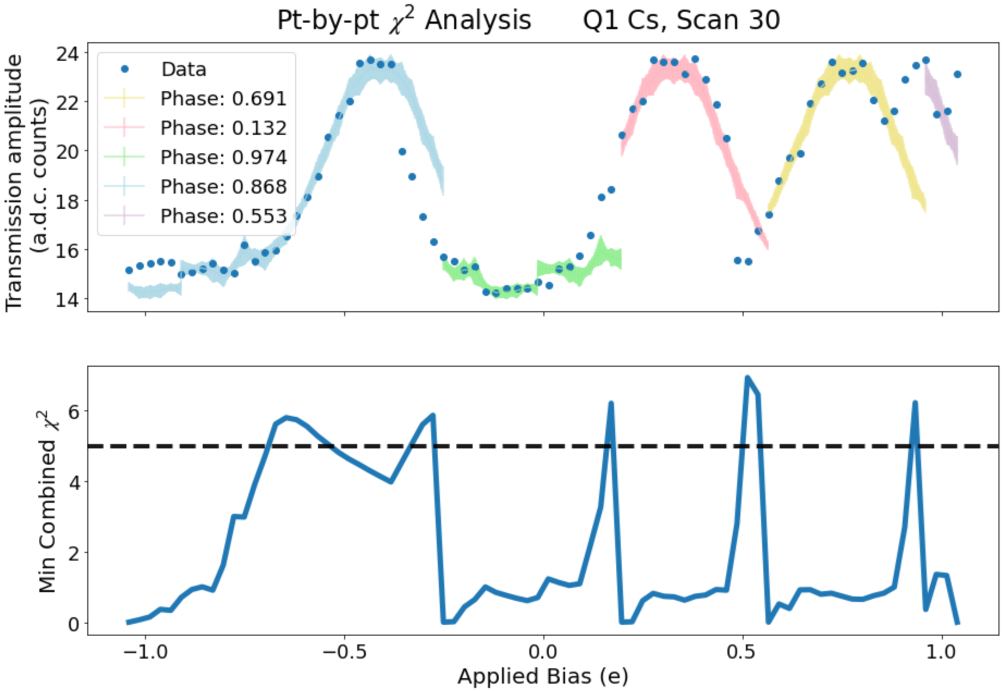

Method handles data with higher rates of jumps → 4 jumps identified in one scan