Quantum Science Center Summary of Efforts

Daniel Baxter
On behalf of the QSC
May 30, 2024

Goals of the QSC

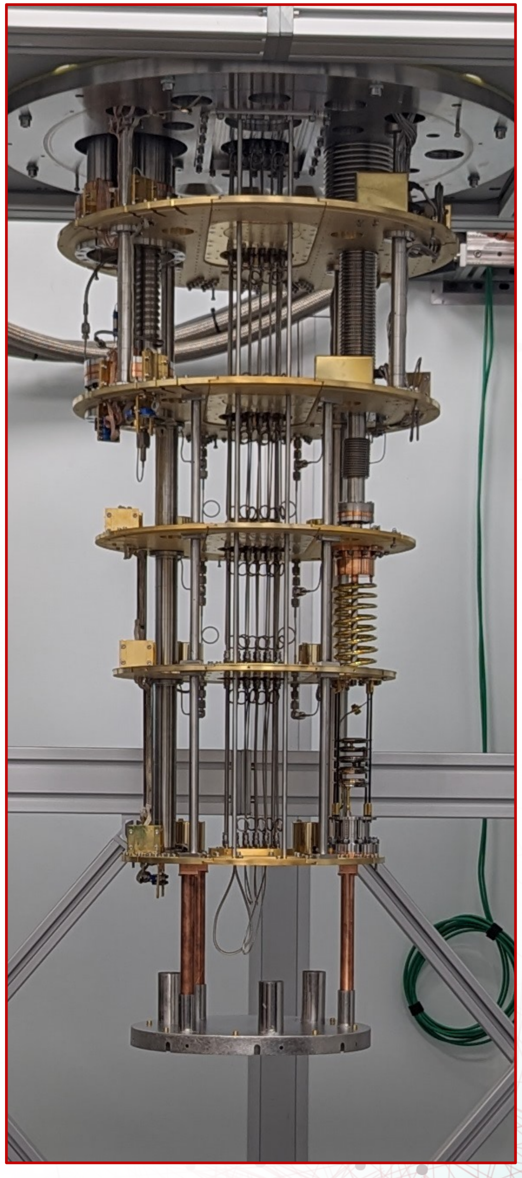
QSC uses QIS concepts for characterizing and mitigating noise in quantum materials and quantum devices by integrating…

1. **Materials**: The development of topological materials to overcome the fragility of the quantum state.
2. **Algorithms**: The creation and implementation of algorithms that exploit topological systems.
3. **Sensing**: The development, optimization, and demonstration of new quantum systems and supporting algorithms to measure exceptionally weak signals.

Understanding, controlling, and eliminating sources of errors in qubits for advancement in both computing and sensing applications.

Overview

- **FNAL Cosmic Quantum (CosmiQ) group**
  Why a HEP group doing quantum?
- **FNAL Facilities for Radiation Studies**
- **Calibration, Simulation, and Material Characterization**
- **Systems Engineering**
  - How to design, integrate, and manage complex systems



Excess backgrounds in qubits (2018-20)

Hot nonequilibrium quasiparticles in transmon qubits

K. Serniak,[1,*] M. Hays,[1] G. de Lange,[1,2] S. Diamond,[1] S. Shankar,[1] L. D. Burkhart,[1] L. Frunzio,[1] M. Houzet,[3] and M. H. Devoret[1,†]

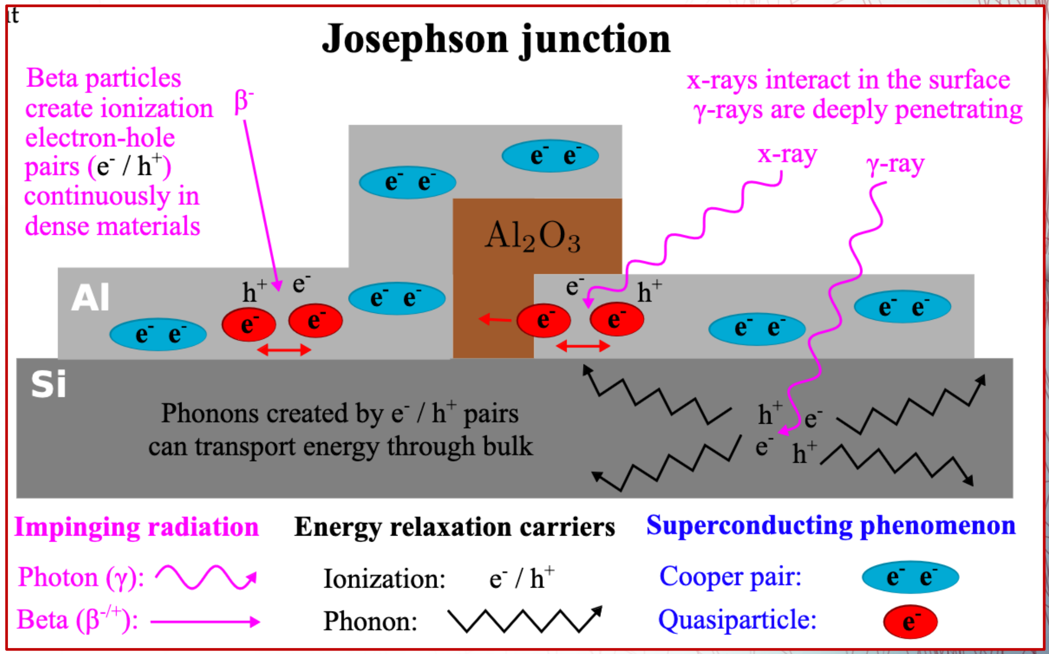
[1]*Department of Applied Physics, Yale University, New Haven, CT 06520, USA*
[2]*QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands*
[3]*Univ. Grenoble Alpes, CEA, INAC-Pheliqs, F-38000 Grenoble, France*
(Dated: October 16, 2018)

Impact of ionizing radiation on superconducting qubit coherence

Antti P. Vepsäläinen[1,*], Amir H. Karamlou[1], John L. Orrell[2,], Akshunna S. Dogra[1,4], Ben Loer[2], Francisca Vasconcelos[1], David K. Kim[3], Alexander J. Melville[3], Bethany M. Niedzielski[3], Jonilyn L. Yoder[3], Simon Gustavsson[1], Joseph A. Formaggio[1], Brent A. VanDevender[2], and William D. Oliver[1,3]**

[1]Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[2]Pacific Northwest National Laboratory, Richland, WA 99352, USA
[3]MIT Lincoln Laboratory, Lexington, MA 02421, USA
[4]Harvard University, Cambridge, MA 02138, USA
[*]Corresponding author for qubit operations: avepsala@mit.edu
[**]Corresponding author for radiation exposure: john.orrell@pnnl.gov

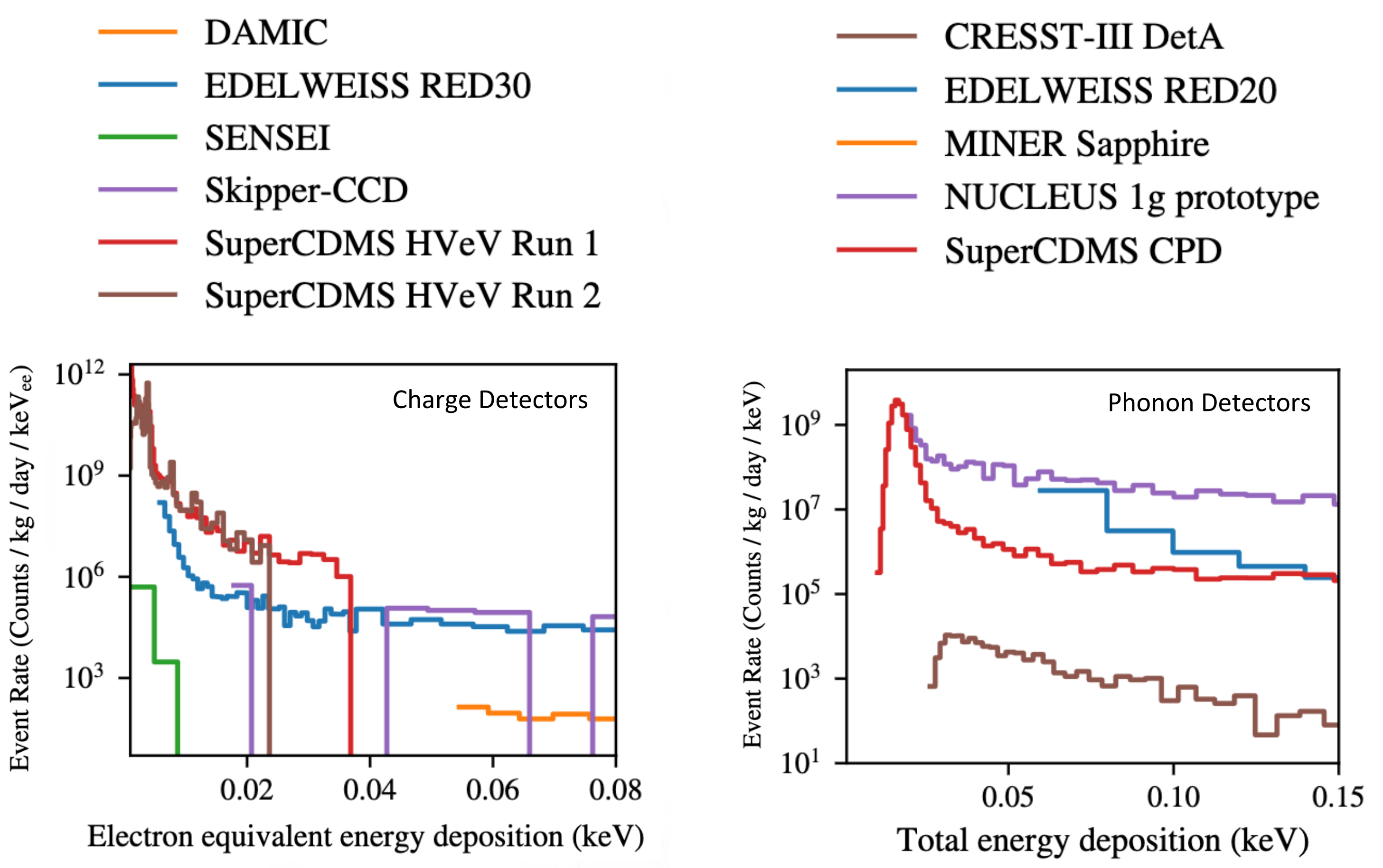
Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]



…and in dark matter detectors (2018-22)

Summary of what we know:

1. **Non-ionizing**: produces a phonon signal, not charge
2. **Power Law**: spectral shape follows a power law out to high energies
3. **Time-since-cooldown**: background seems to decay with a long time constant since reaching mK temperatures
4. **Stress-dependent**: reducing stress from mounting reduces background!



Adari et al, SciPost Phys. Proc. 9, 001 (2022) [arXiv:2202.05097]

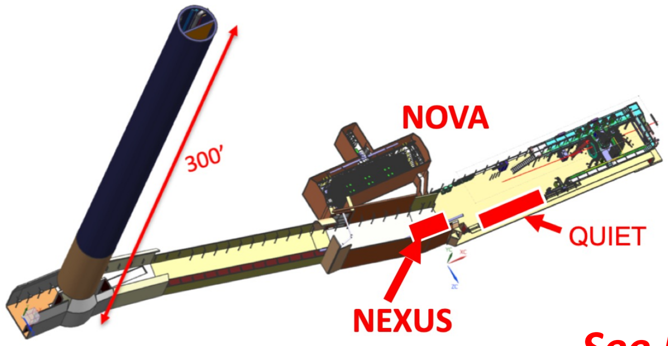
EXCESS Workshop Series

1. June 15-16, 2021: **EXCESS workshop,** community-wide gathering of solid-state experiments to discuss unmodeled low-energy detector rates
2. February 15-17, 2022: **EXCESS 2022**, follow-up workshop focused on phenomenology, calibration, and future detector ideas **(with a focus on quantum detectors)**
3. July 16, 2022: **EXCESS@IDM**, first in-person meeting of the community to discuss this problem
4. August 26, 2023: **EXCESS@TAUP**
5. July 6, 2024: **EXCESS24 at IDM**

Adari et al, SciPost Phys. Proc. 9, 001 (2022) [arXiv:2202.05097]

NEXUS
Northwestern EXperimental Underground Site

- 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



See Enectalí Figueroa-Feliciano's talk tomorrow for more details

QUANTUM SCIENCE CENTER

NEXUS

Northwestern **EX**perimental **U**nderground **S**ite

See Enectalí Figueroa-Feliciano's talk tomorrow for more details

NEXUS

Northwestern EXperimental Underground Site

Dark Matter Searches with SuperCDMS, KIDs, and QSC

- 2 eV energy resolution TES-based 2cm x 2cm x 4mm athermal phonon detectors
- KID LDRD wrapping up now

Neutrino Physics with Ricochet and CUPID

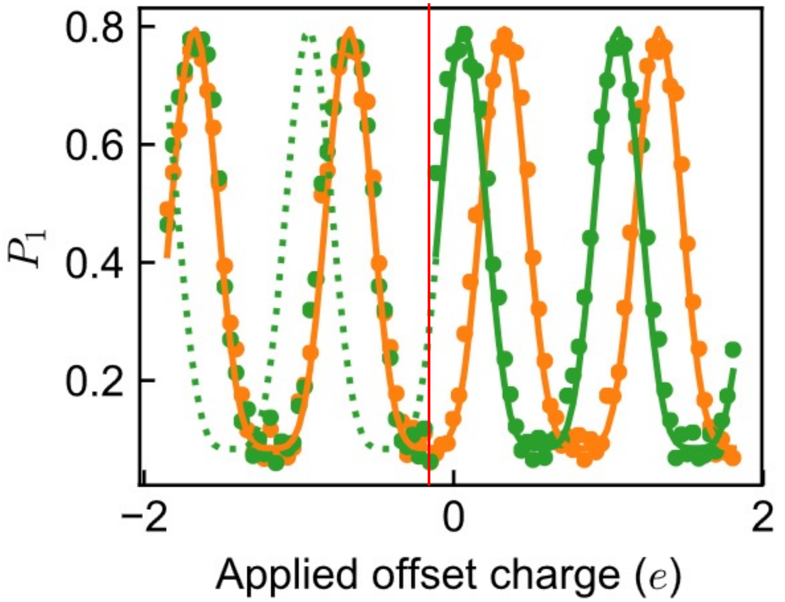
- Developed new modular architecture for neutrino physics detectors
- Deploying at ILL nuclear reactor next year
- R&D for future CUPID upgrades

Low-background Quantum Computing

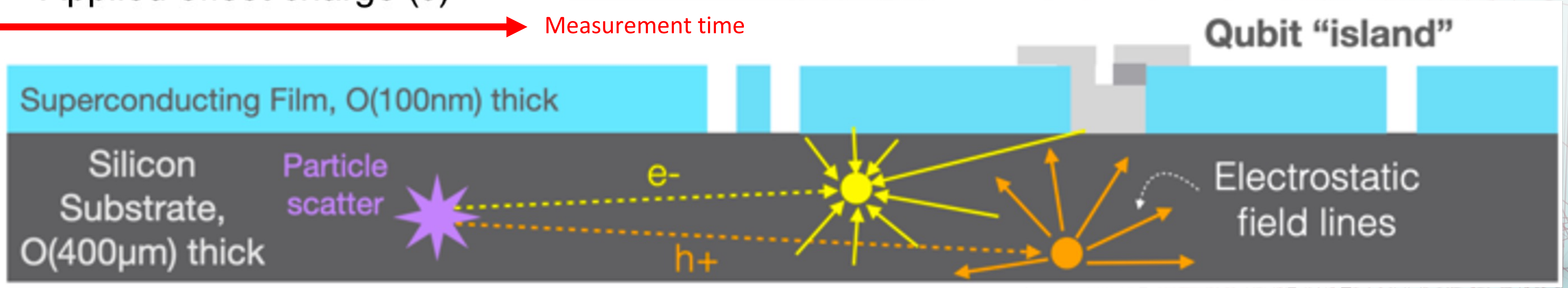
- Qubit testing underway underground at NEXUS
- Developing R&D program for low-background quantum architectures

NEXUS
Northwestern **EX**perimental **U**nderground **S**ite

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



Measurement time



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)

NEXUS

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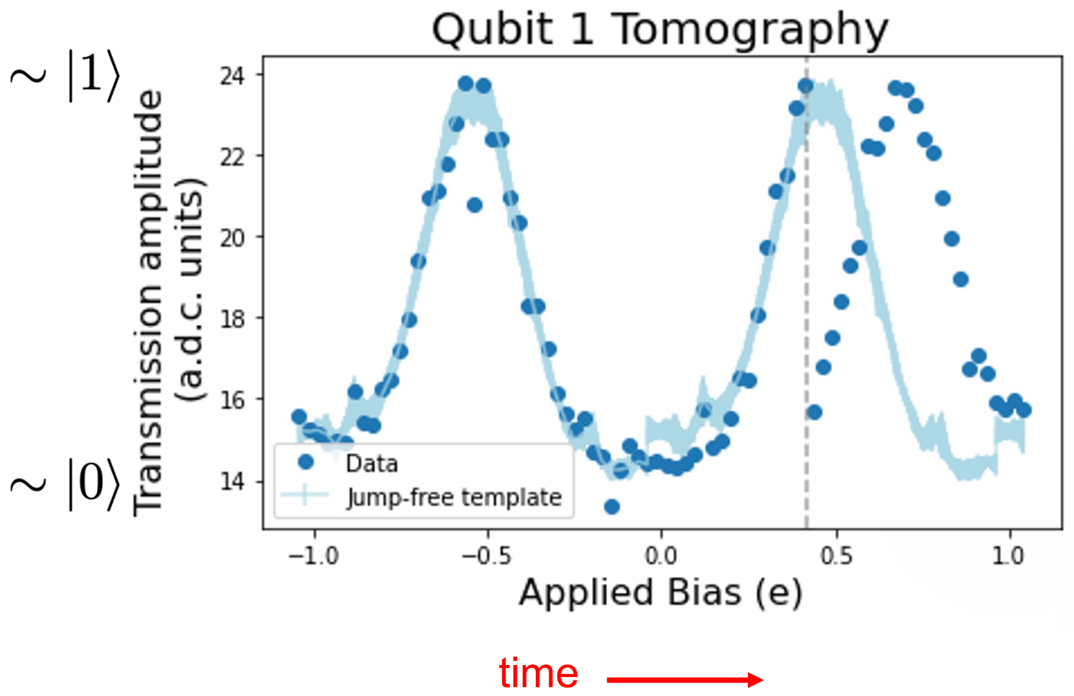


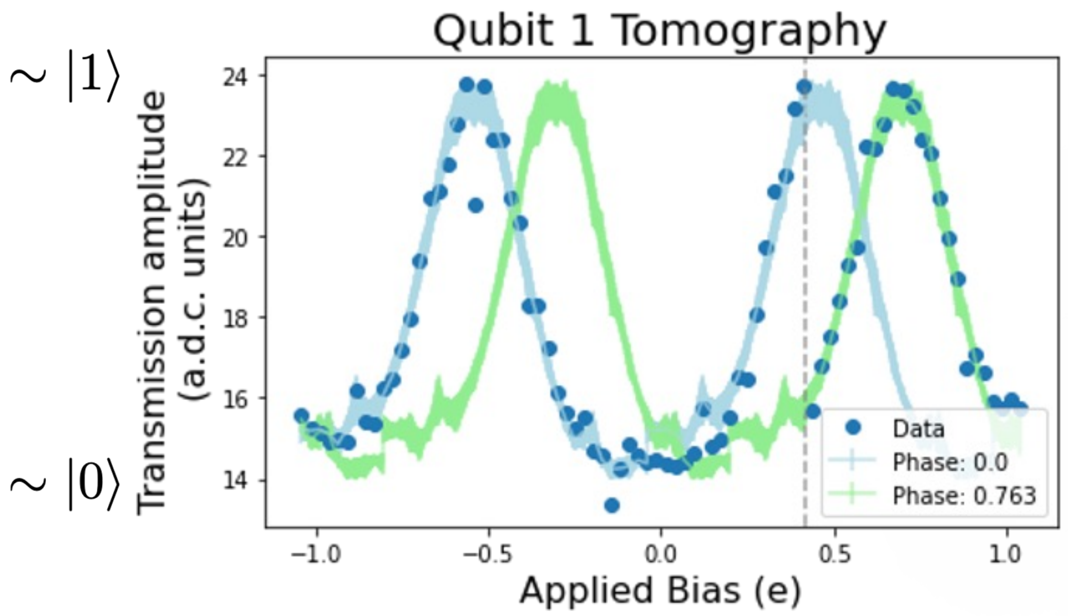
Bratrud et al, "First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility" (2024) [arXiv:2405.04642]

- 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 (hours)
- Scans are taken consecutively over over 20 hours

Work in collaboration with Daniel Bowring ECA

NEXUS

Northwestern **EX**perimental **U**nderground **S**ite



time →

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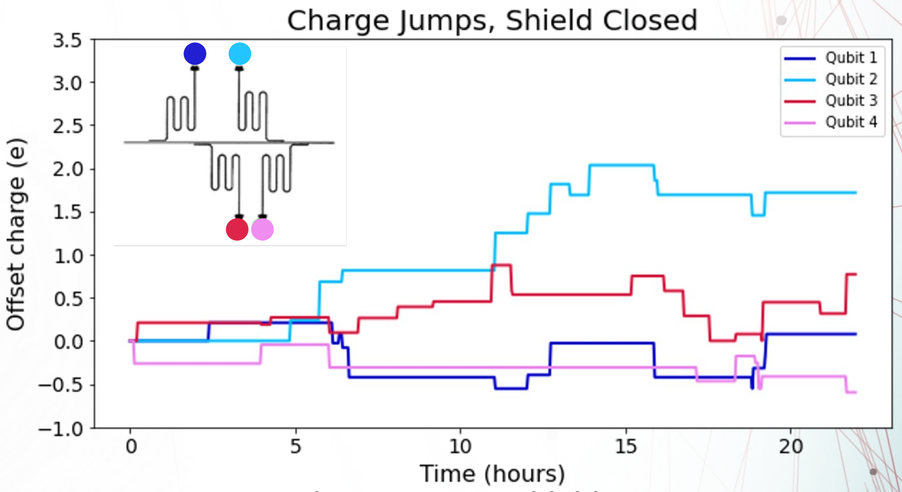
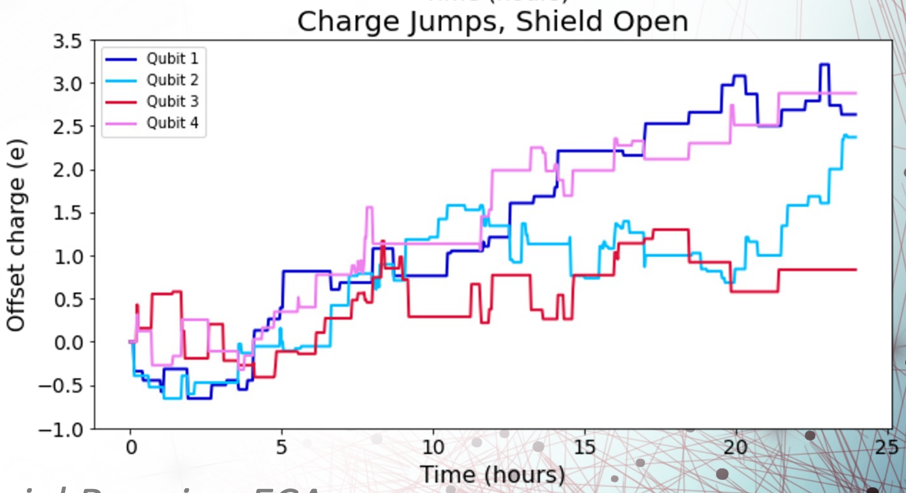
NEXUS

Northwestern **EX**perimental **U**nderground **S**ite

- 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
- GEANT4 Monte Carlo model under development





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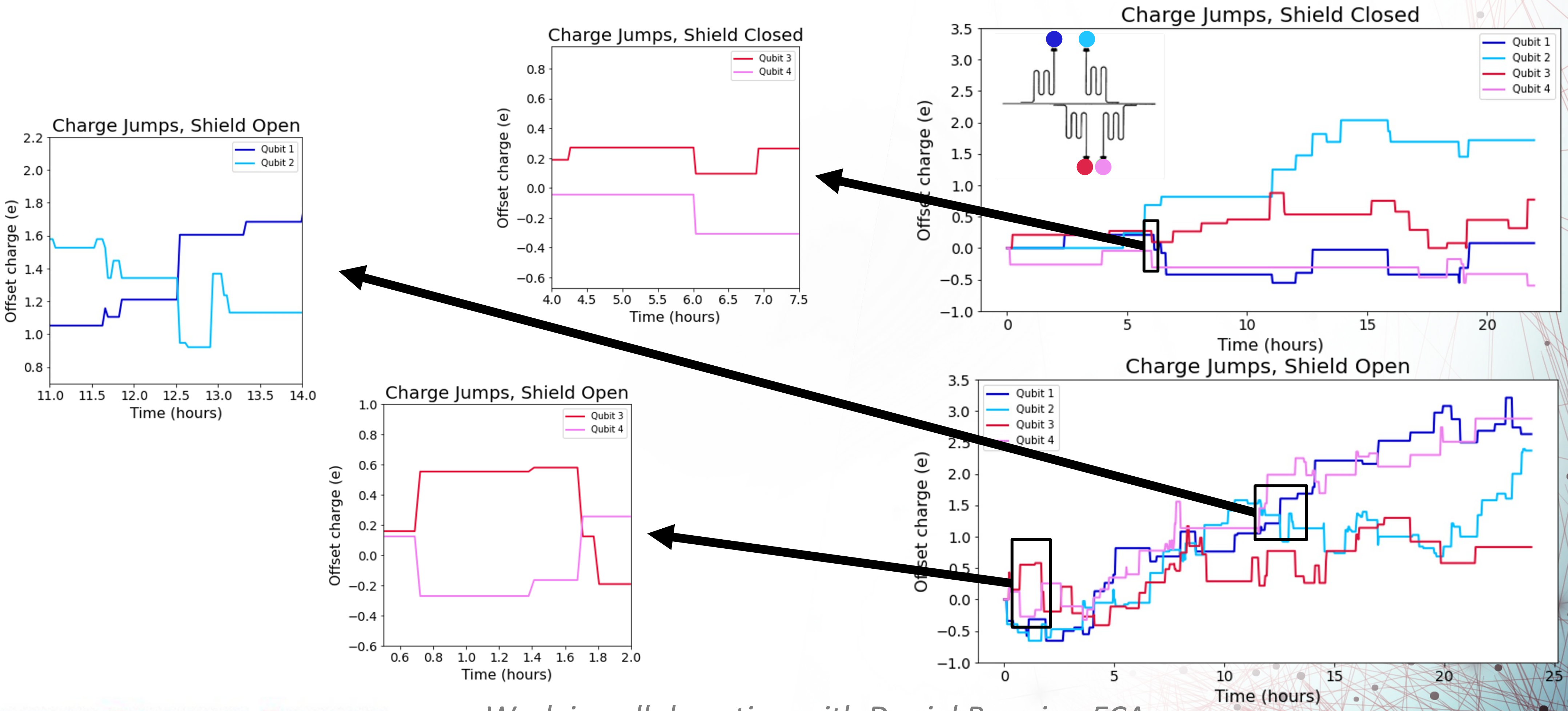

Work in collaboration with Daniel Bowring ECA

NEXUS

Northwestern **EX**perimental **U**nderground **S**ite

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	$0.35^{+0.07}_{-0.06}$	$0.03^{+0.06}_{-0.05}$	mHz
Calculated Excess Rate	$0.16^{+0.05}_{-0.04}$		mHz

Bratrud et al, "First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility" (2024) [arXiv:2405.04642]

Work in collaboration with Daniel Bowring ECA

NEXUS

Northwestern **EX**perimental **U**nderground **S**ite

Wilen et al rate on surface is 1.35 mHz

Excess rate not explained by ambient ionizing backgrounds!

	Shield Open	Shield Closed	Units
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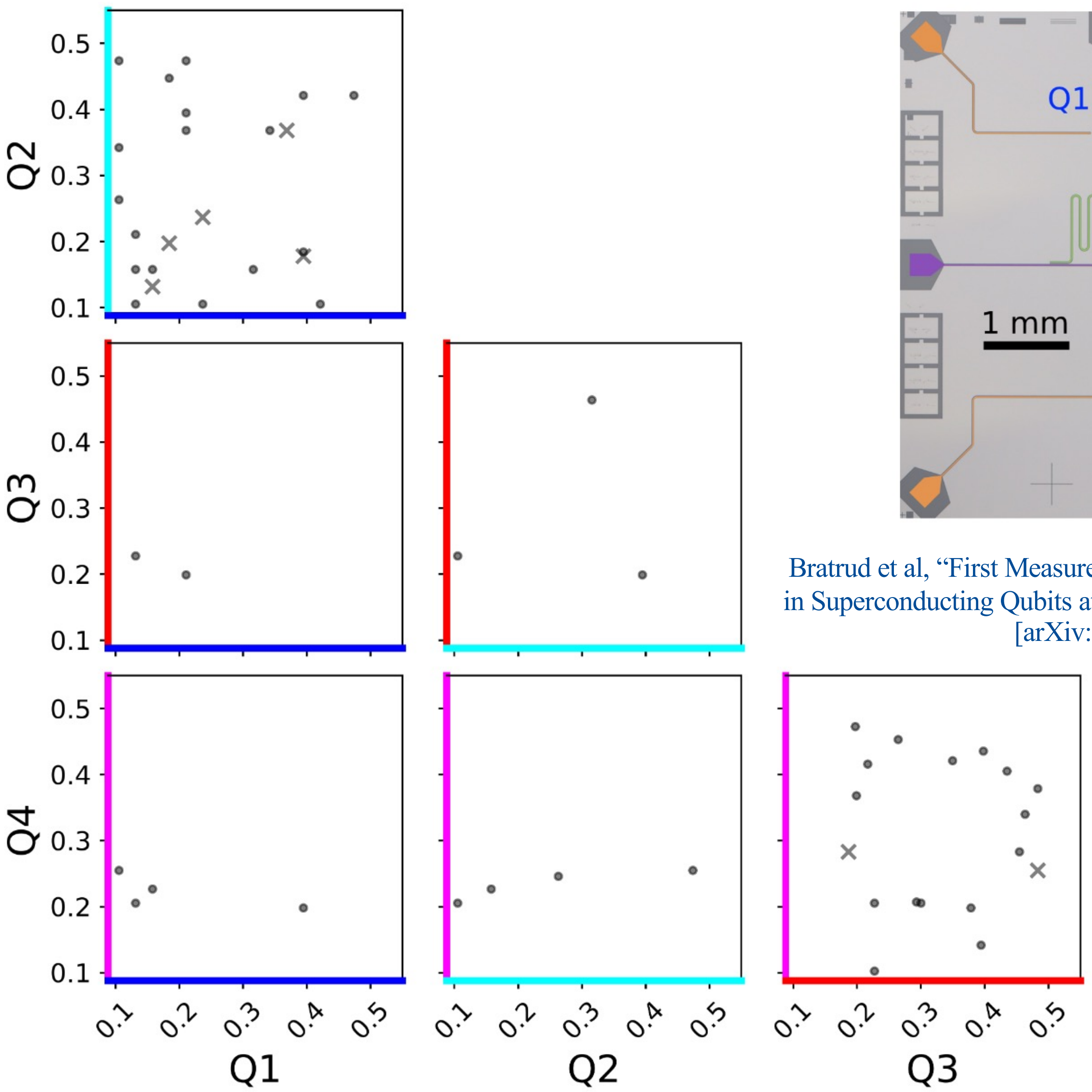
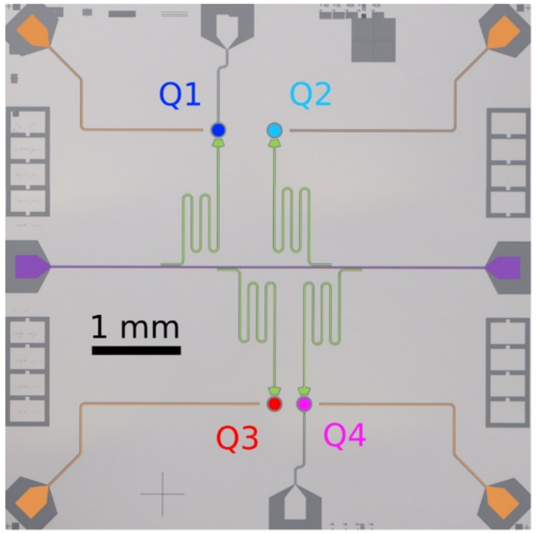
Work in collaboration with Daniel Bowring ECA

NEXUS

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





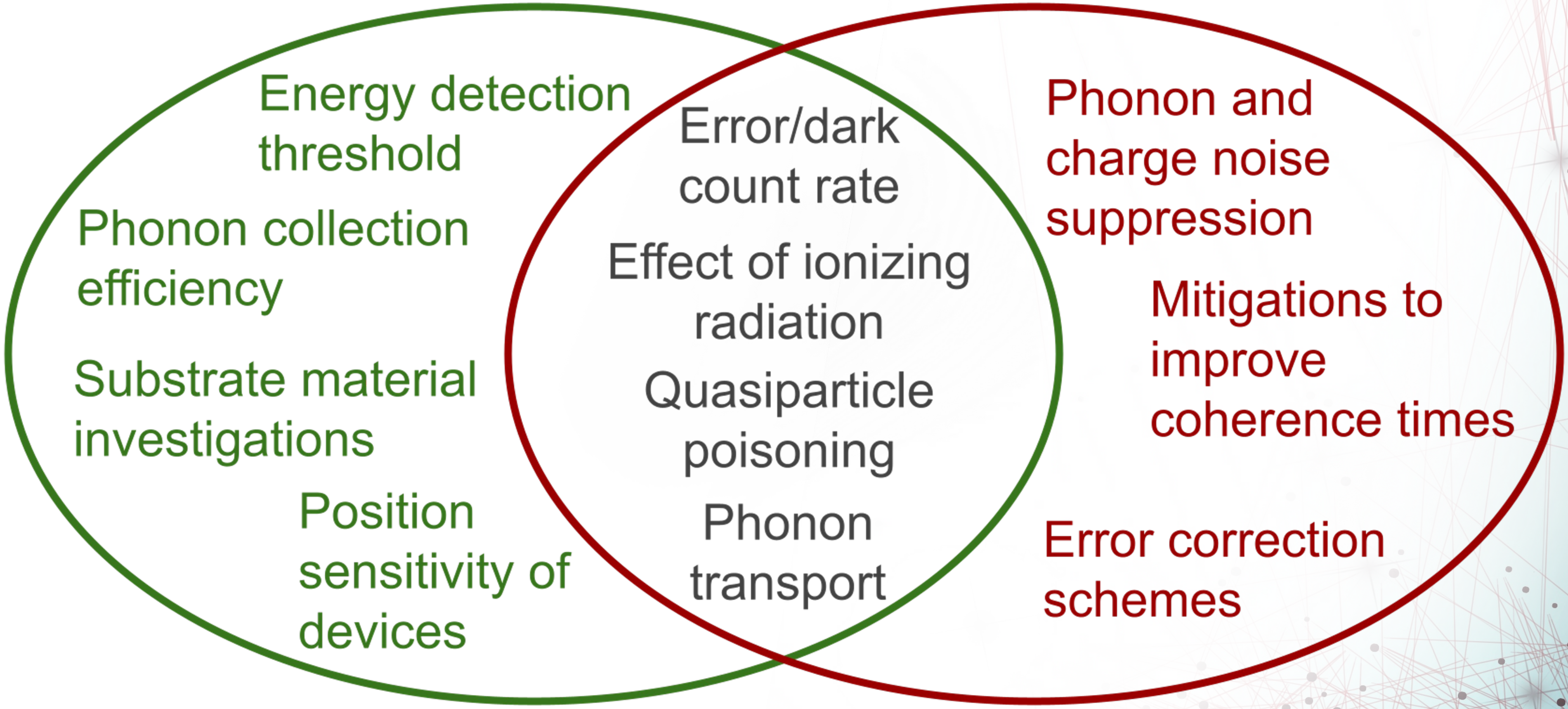
Bratrud et al, “First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility” (2024) [arXiv:2405.04642]

For more information, see poster by students who led the analysis

Synergy in underground science!

NEXUS

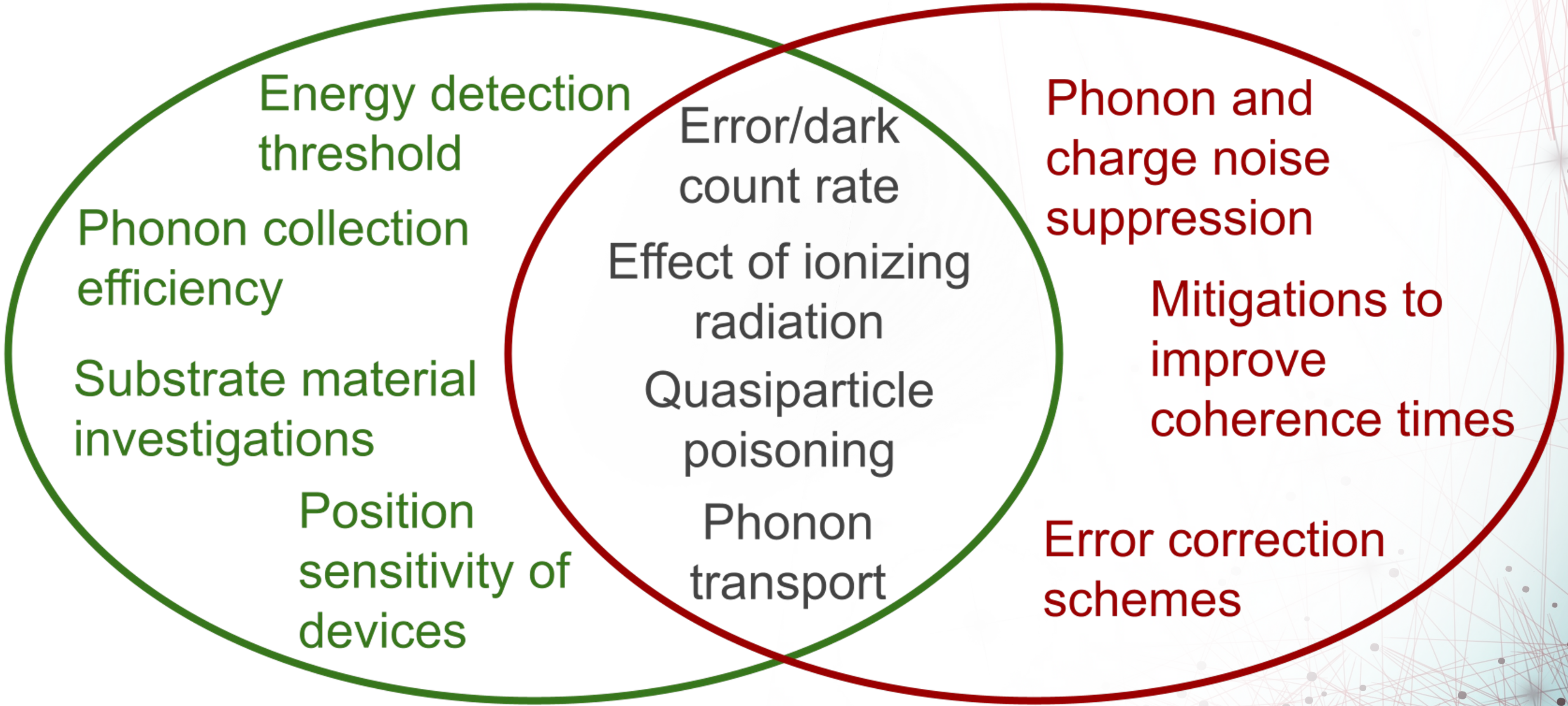
Dark matter sensors **Superconducting qubits**



Synergy in underground science!

NEXUS — **Dark matter sensors**

QUIET — **Superconducting qubits**



QUIET
Quantum **U**nderground **I**nstrumentation **E**xperimental **T**estbed

This QSC facility is the first 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
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Initial fridge test reached 8.9mK w/ no issues

See Enectalí Figueroa-Feliciano's talk tomorrow for more details

QUIET

Quantum **U**nderground **I**nstrumentation **E**xperimental **T**estbed

Dec. 9, 2022

Sept. 29, 2023

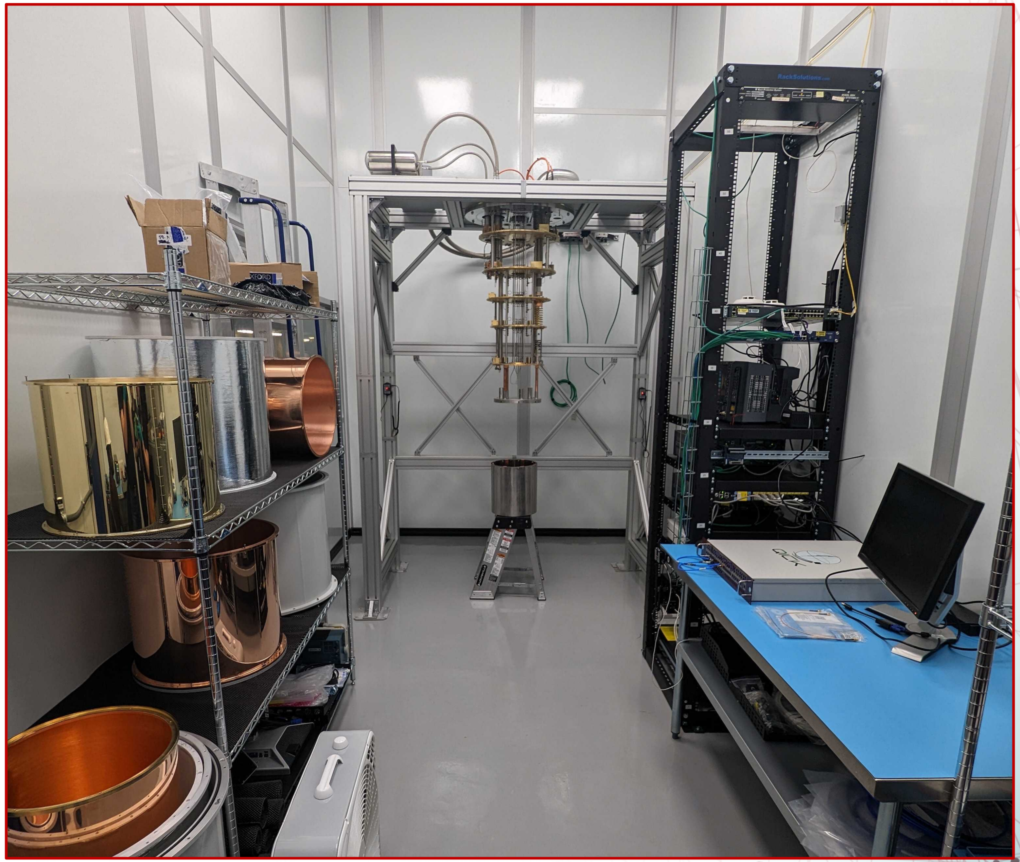
May 24, 2024

See Enectalí Figueroa-Feliciano's talk tomorrow for more details

QUIET

Quantum **U**nderground **I**nstrumentation **E**xperimental **T**estbed

VIP Ribbon Cutting will take place at 5pm today starting off the poster reception, including remarks by Dr. Lia Merminga, Director of FNAL



See Enectalí Figueroa-Feliciano's talk tomorrow for more details *see Kester's poster for more details*

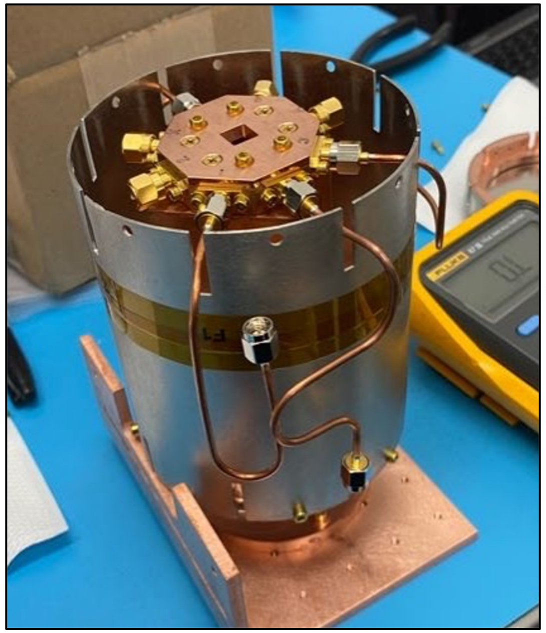
LOUD

High-throughput Surface Sister Facility to QUIET

New DR installed at FNAL

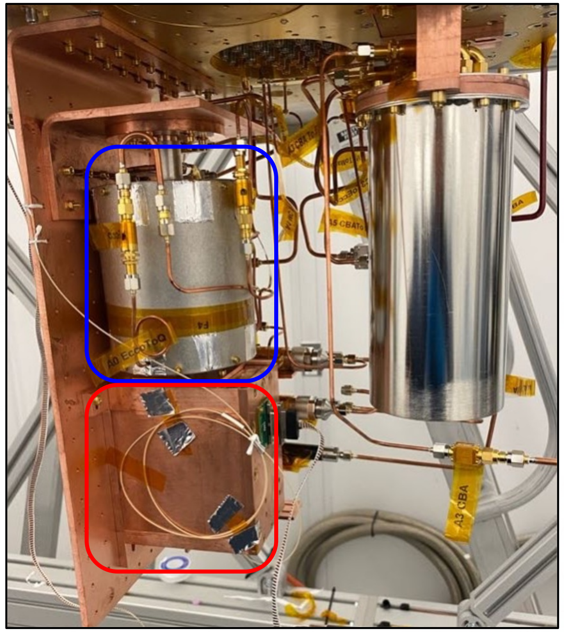
(August 2022)

6-qubit array borrowed from McDermott group



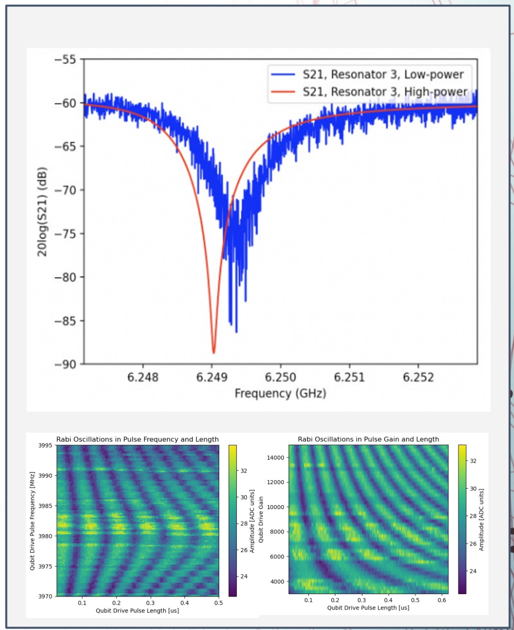
(October 2022)

Magnetic shielding coupled to scanning unit and installed in DR



(November 2022)

Run 1: First demonstration of live qubits



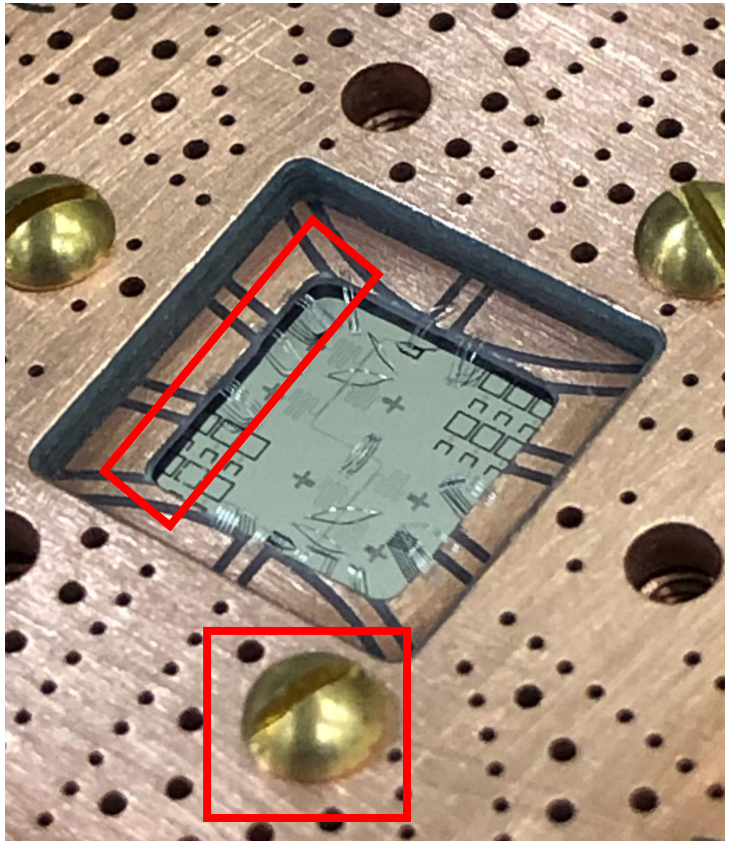
(February 24th 2023)

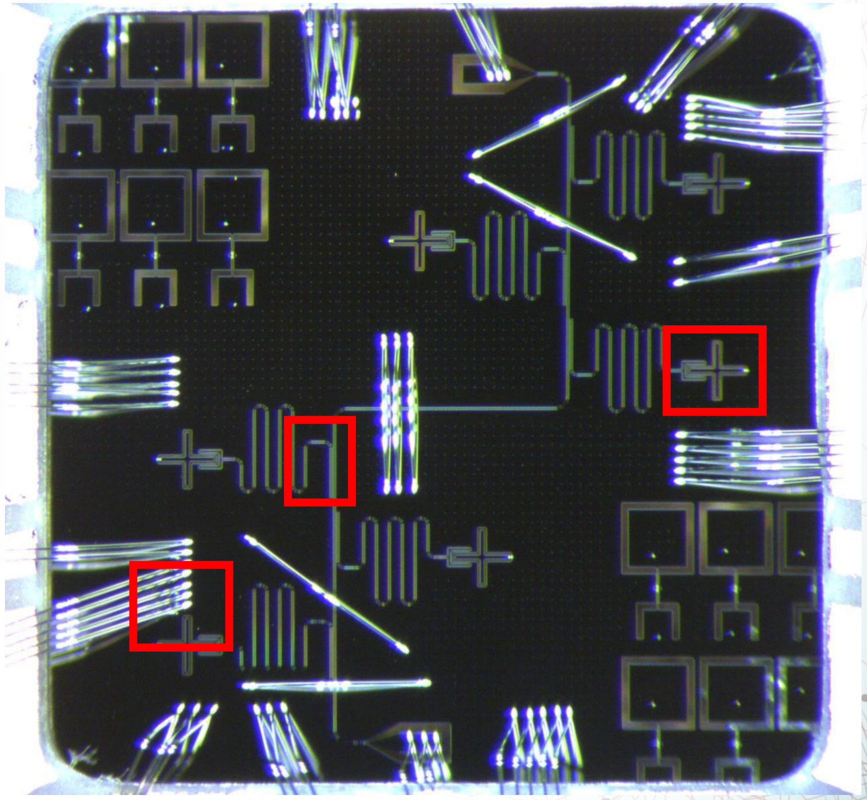
Talk to Rakshya Khatiwada (facility lead) for collaboration opportunities

In-House Qubit Design & Fabrication

So many aspects that limit performance right now!

CosmiQ qubit design class every other Friday on Zoom: theory + open source tools, Qiskit Metal



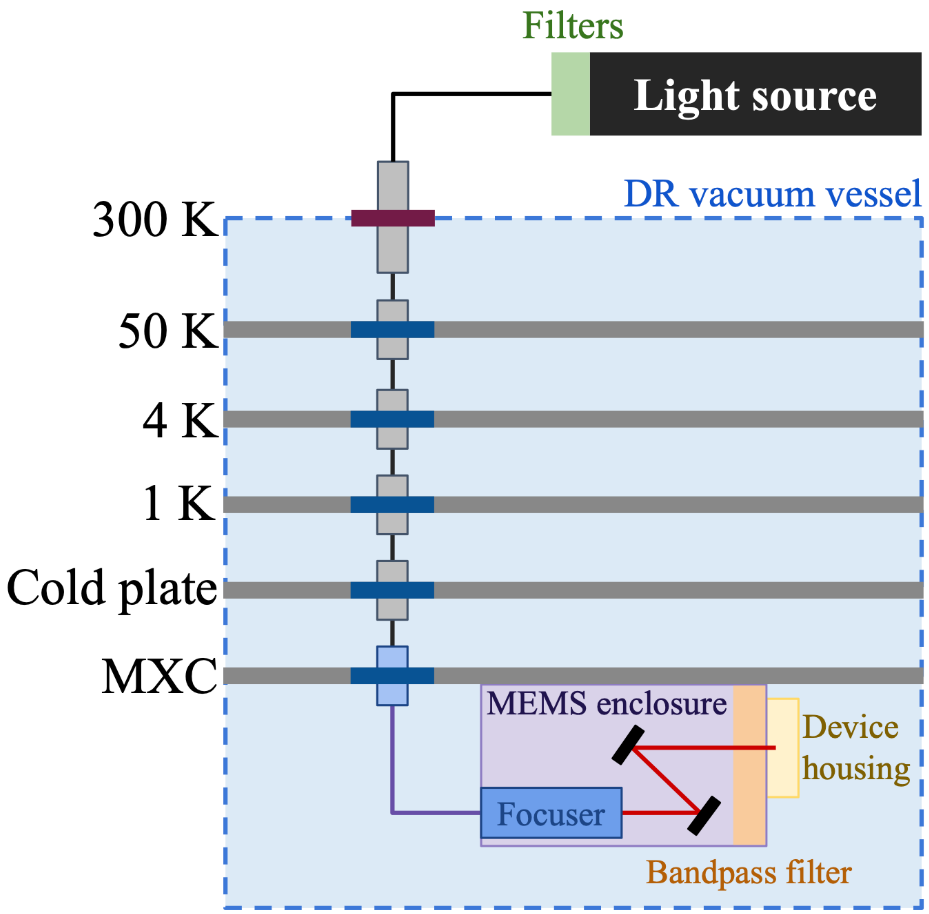


Talk to Sara Sussman to join the mailing list!

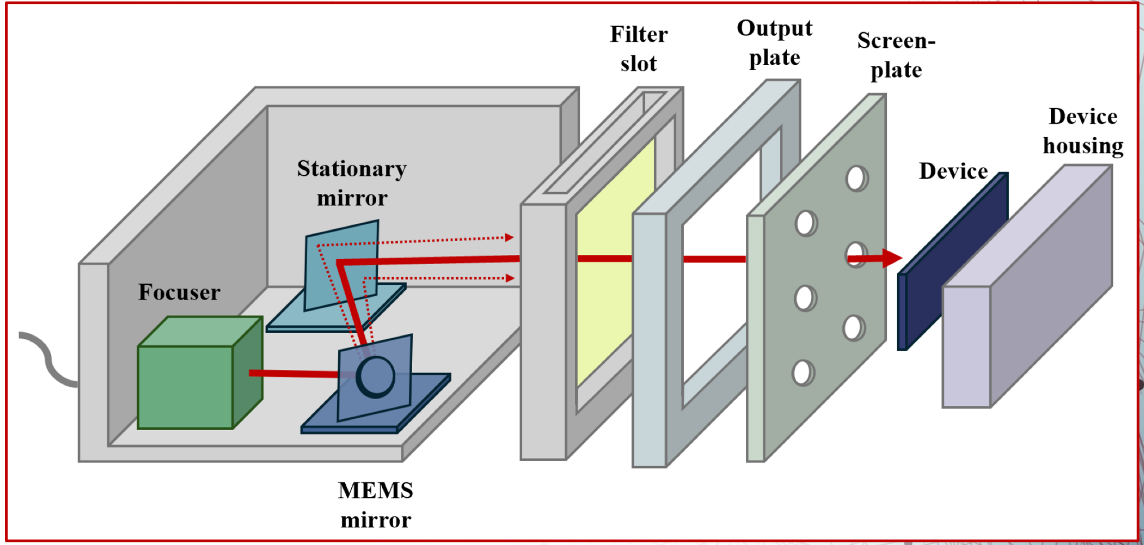
Calibration Tools

Cryogenic optical beam steering

Idea by postdoc Noah Kurinsky (now at SLAC) and funded as part of QSC QRPA program



<u>Goal</u>: Design a modular calibration system that can thermalize to the MCP and steer a beam of single-photons repeatably and precisely over the surface of a device for characterization



Stifter et al, "Cryogenic optical beam steering for superconducting device calibration" (2024) [arXiv:2405.02258]

Calibration Tools

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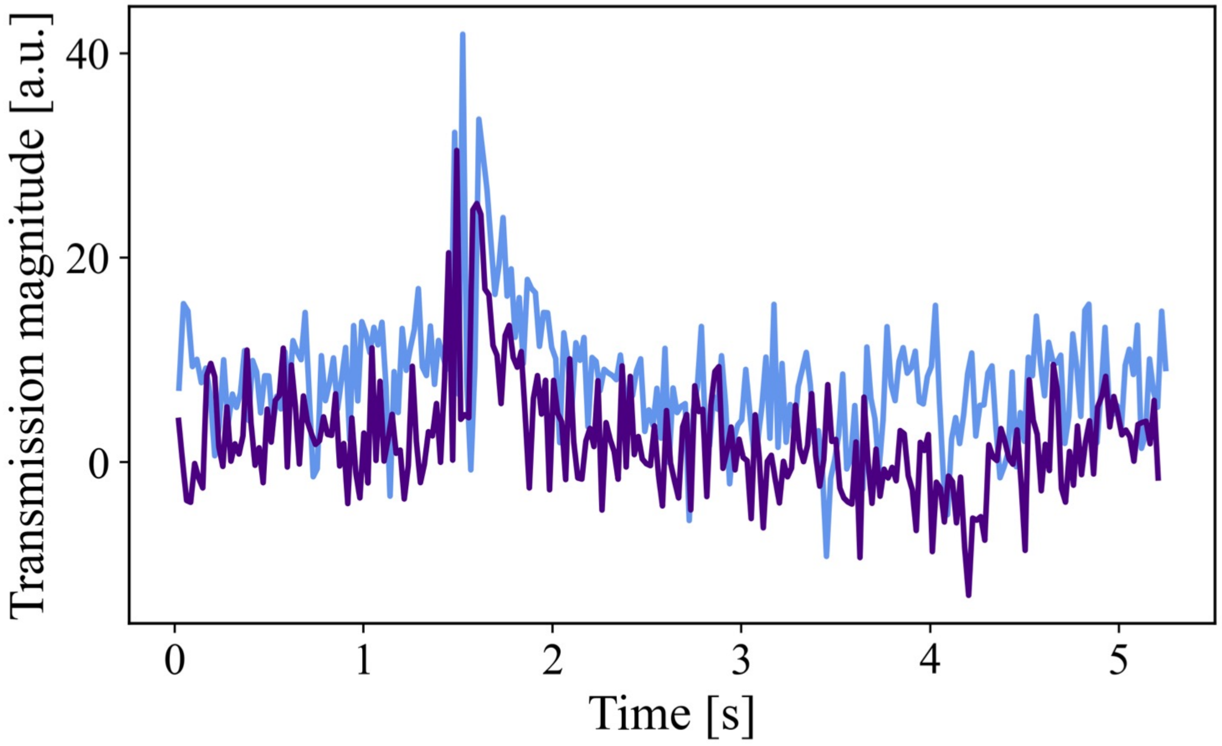


- Initial tests with MKID are successful!
- Scanning system does not significantly add power to the fridge
- Photon position is reproducible and precise (~100 micons)
- **Testing with transmon qubits is underway**

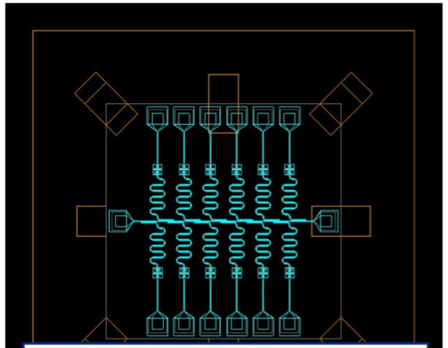
Stifter et al, "Cryogenic optical beam steering for superconducting device calibration" (2024) [arXiv:2405.02258]

Simulation Tools
G4CMP and Quantum Device Response (QDR)

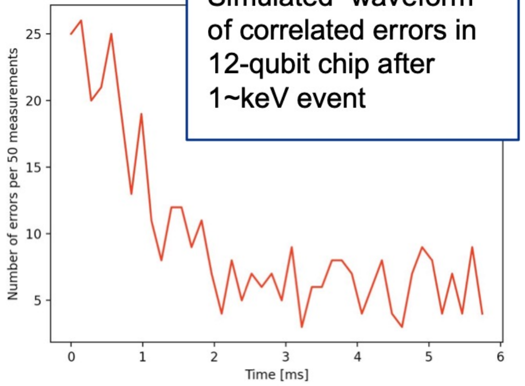
To understand our qubit response, we need to simulate how energy deposits in the chip propagate to impact qubit performance, for example T1 decoherence times

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!



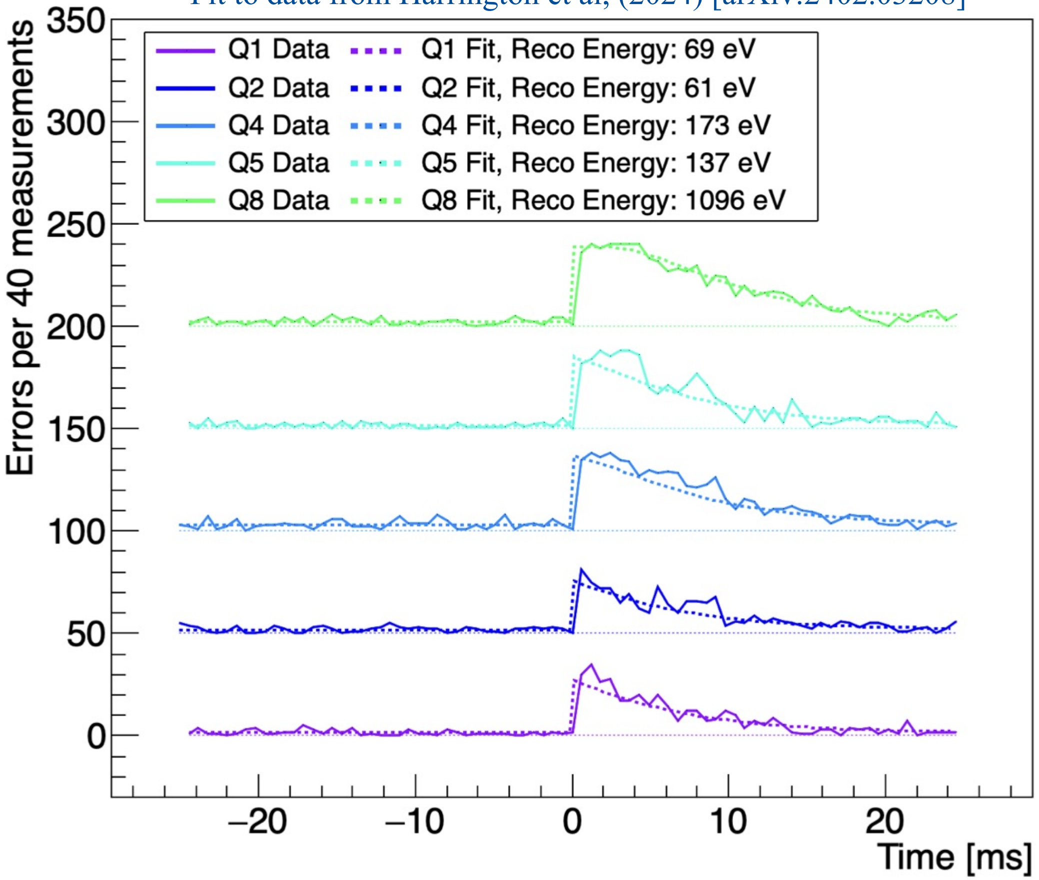
Simulated "waveform" of correlated errors in 12-qubit chip after 1~keV event

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Simulation Tools

G4CMP and Quantum Device Response (QDR)

Fit to data from Harrington et al, (2024) [arXiv:2402.03208]



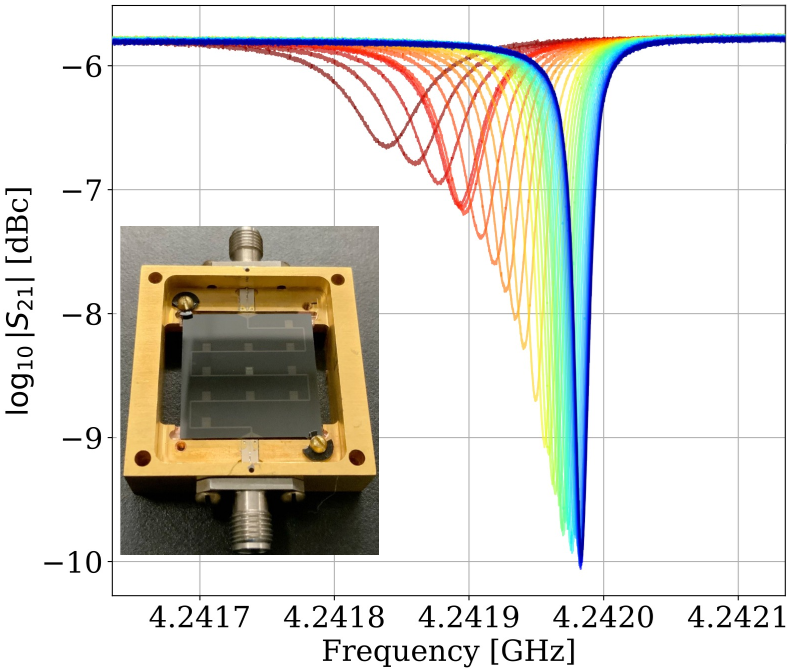
1. Simulate phonon propagation in the chip, and determine phonon collection probability (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme
4. Determine the sensitivity of a single qubit
5. Determine the sensitivity of the chip
6. Test it with data (Harrington et al)

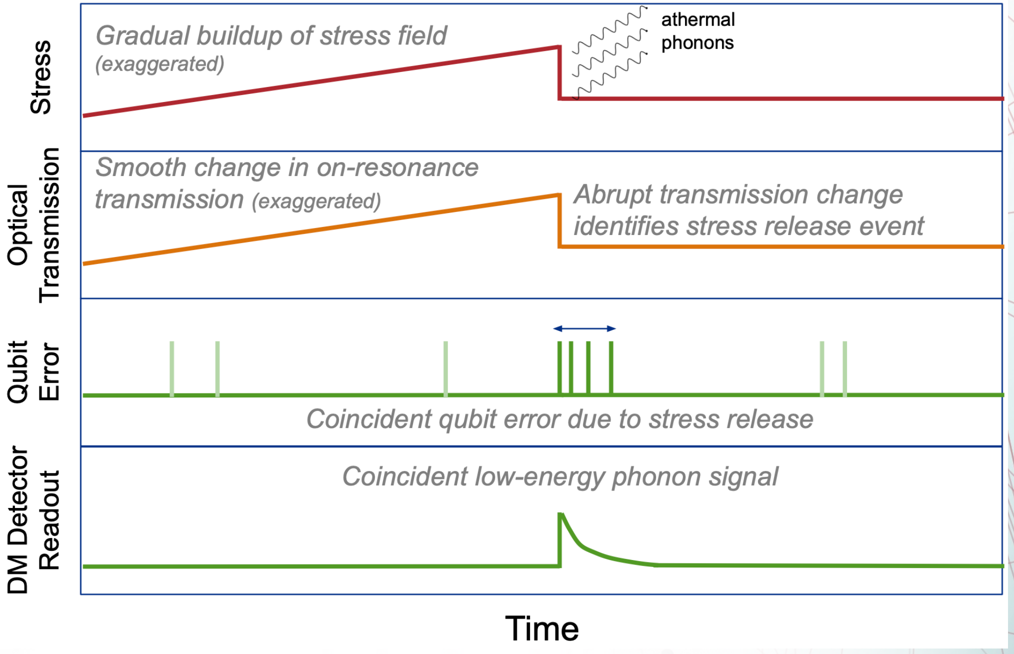
see Israel & Ryan's posters for more details

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Witness Detector Development

Calibrated sensors that can be patterned on-chip with qubits





Microwave Kinetic Inductance Detectors

Temples et al, "Performance of a Kinetic Inductance Phonon-Mediated Detector at the NEXUS Cryogenic Facility" (2024) [arXiv:2402.04473]

Optomechanical Ring Resonators

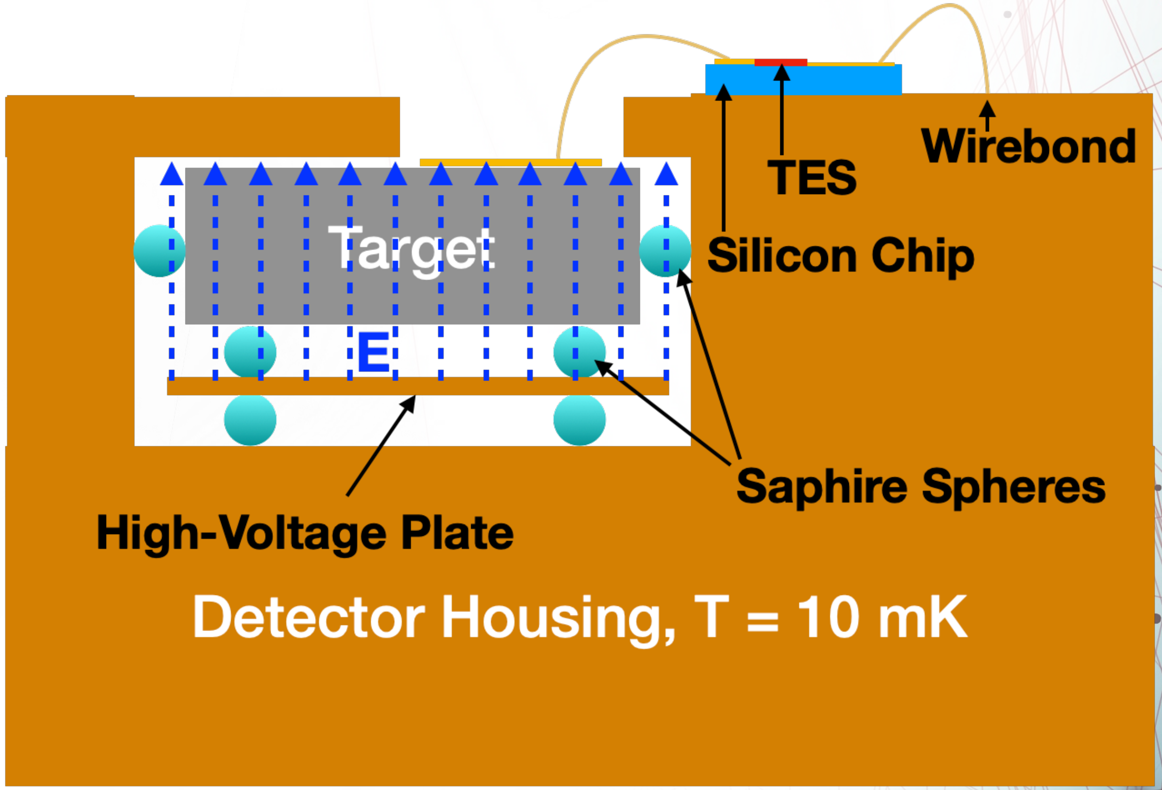
Collaboration with QSC Bhave group funded through Dylan Temples QRPA

(***see Dylan's poster for more details***)

Witness Detector Development

Can also be used for novel material characterization!

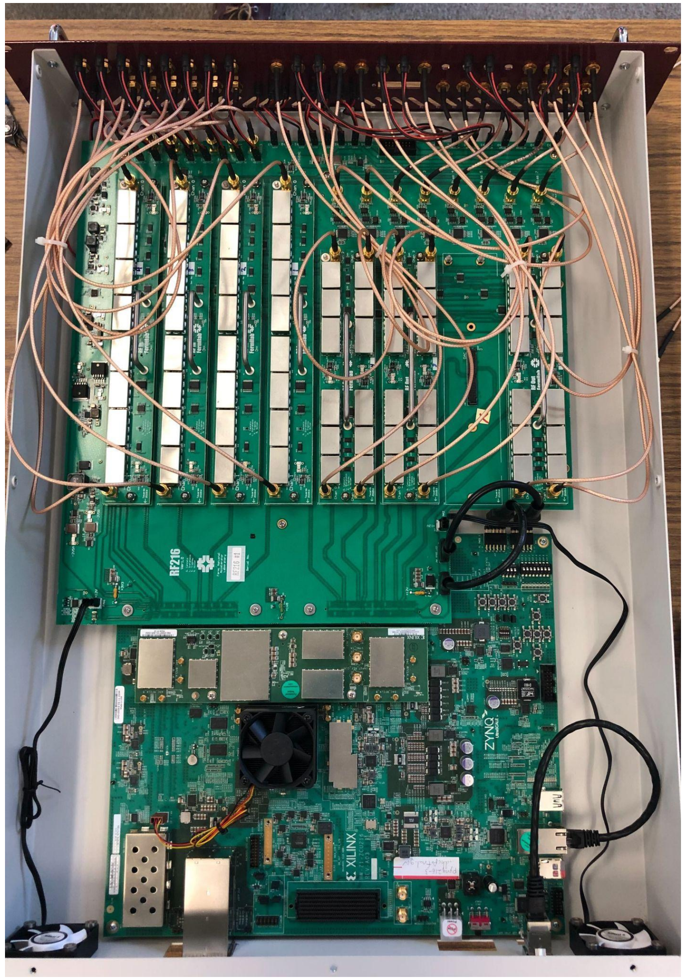
- Luke-Neganov voltage amplification technique uses phonon amplification to measure charge with single-electron resolution
- Technology developed for the Ricochet neutrino experiment uses TESs to measure heat deposited on sample
- Technique is agnostic to target material, can be used as a novel quantum material characterization system!



Chen et al "Modeling and characterization of TES-based detectors for the Ricochet experiment" (2023) [arXiv:2311.13007]

QICK

Quantum **I**nstrumentation **C**ontrol **K**it



- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed!
  - Has already been adopted by QIS groups around the world (including many of you)
- A factor of ~20 cheaper compared to off-the-shelf equipment
- QICK team ongoing work includes paper on quantum measurement & readout fidelity, and major firmware upgrade

See demo in QUIET Lab Tour

QICK

Quantum **I**nstrumentation **C**ontrol **K**it

Ding et al, “Experimental advances with the QICK (Quantum Instrumentation Control Kit) for superconducting quantum hardware” Phys.Rev.Res. 6 (2024) 1, 013305

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)

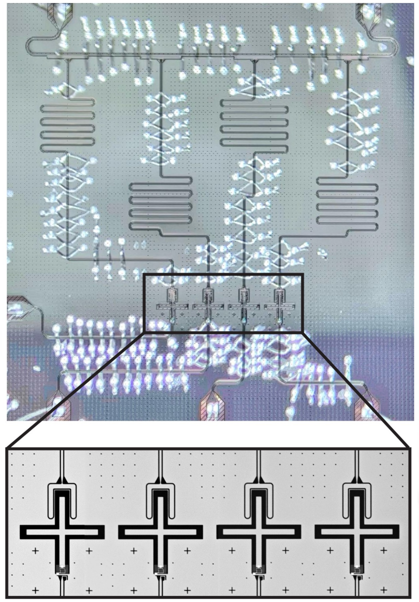
arXiv:2311.17171

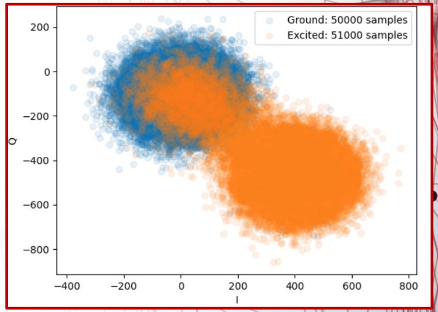
See demo in QUIET Lab Tour

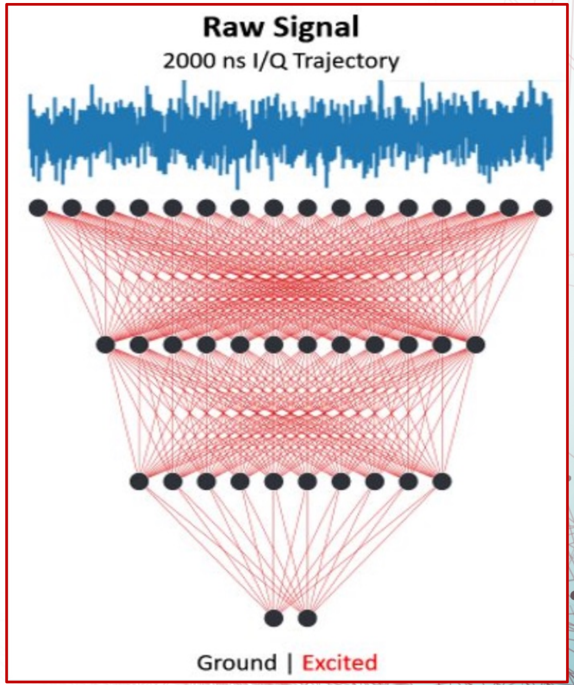
QICK

Can be integrated with classical NN

- As the number of qubits in a system grows, **how do we scale efficiently?**
- QICK's FPGA can host a neural network. How can we use NNs to optimize resource requirements (power into the fridge, total measurement time, etc.) in a many-qubit system?
- The "hello world" for such work: Load a simple state classifier NN onto QICK (via hls4ml) use it to read out qubits.
- 96% NN classification accuracy, on par with time-averaged thresholding.
- Publication pending!



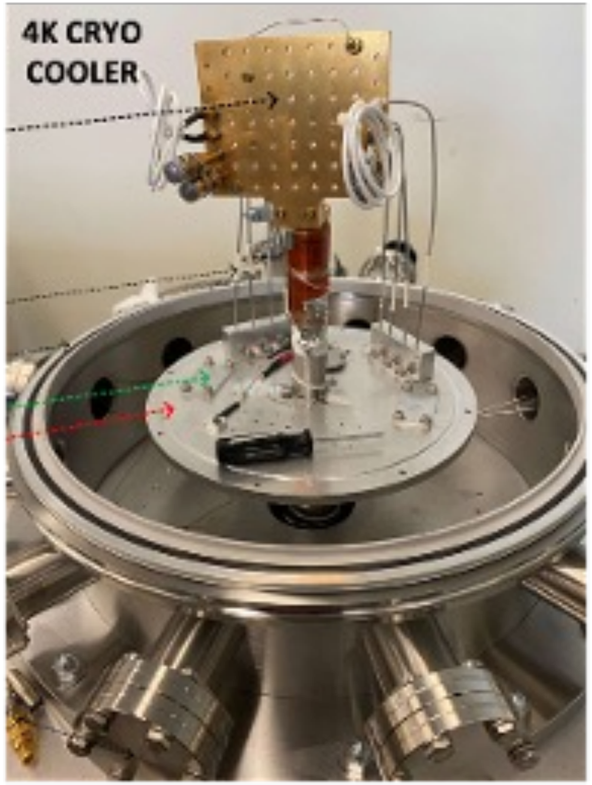


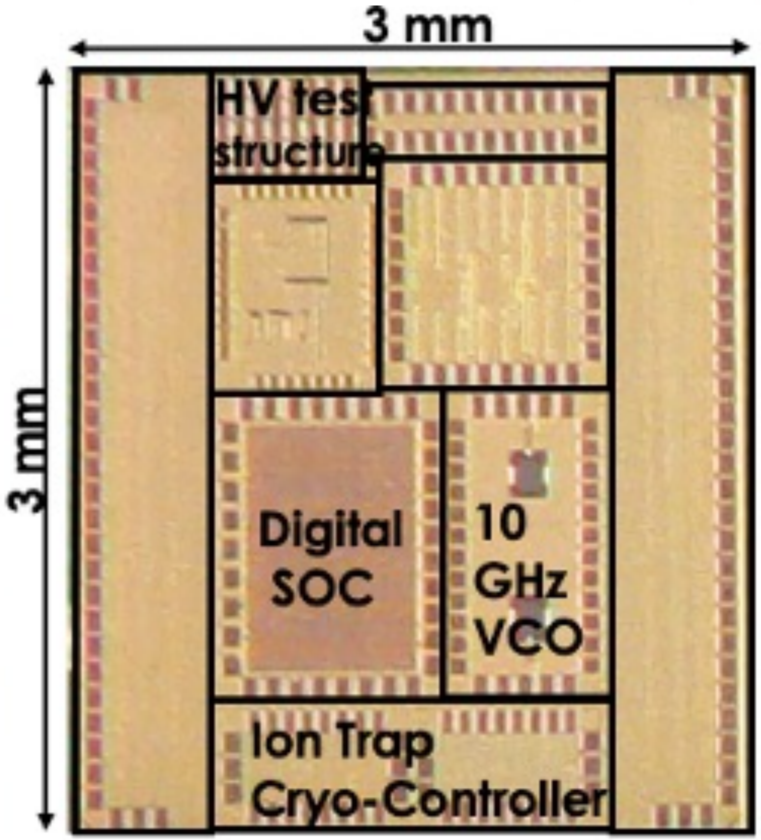


Talk to Daniel Bowring for more details

ASIC Controls

Can we do the same thing cryogenically?



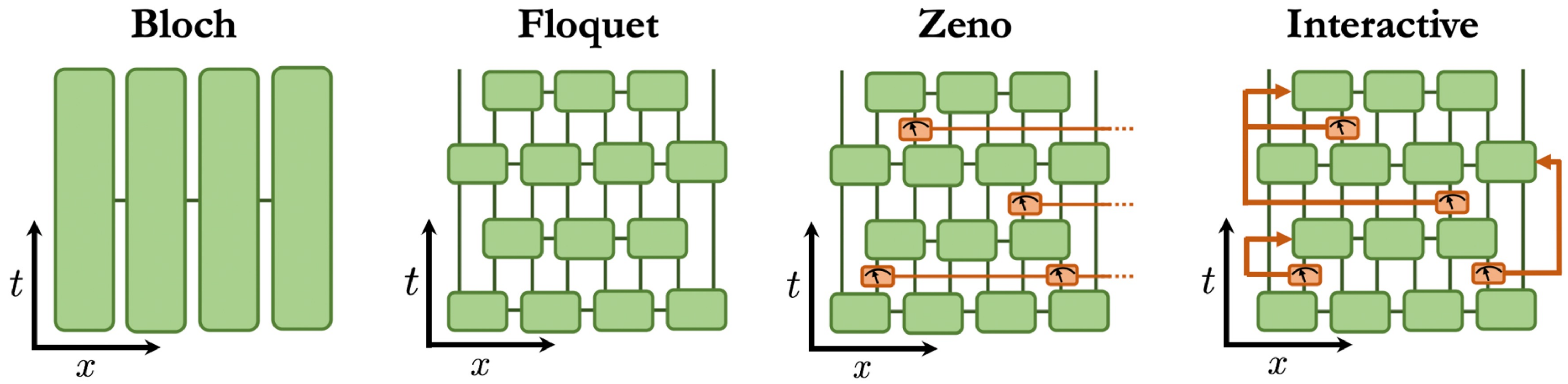


Talk to Farah Fahim for more details

- Following from the previous slide: what additional resource optimization is possible if the NN lives at 4 K, instead of at room temperature?
- We are developing NN methods for cryogenic ASIC-based qubit readout as well.

Interactive Quantum Matter

- By having these control systems, we can start to ask questions about how we interact with these quantum systems, opening up new sensing paradigms
- Including an observer and classical feedback as essential elements of the quantum system defines new field of *quantum interactive matter*



Conclusions

- DOE labs are the ideal place to **host qubit systems** and **perform materials research** in collaboration with academia and industry
- QSC's focus on **systems engineering** and **codesign** will enable advances in quantum sensing and quantum computing

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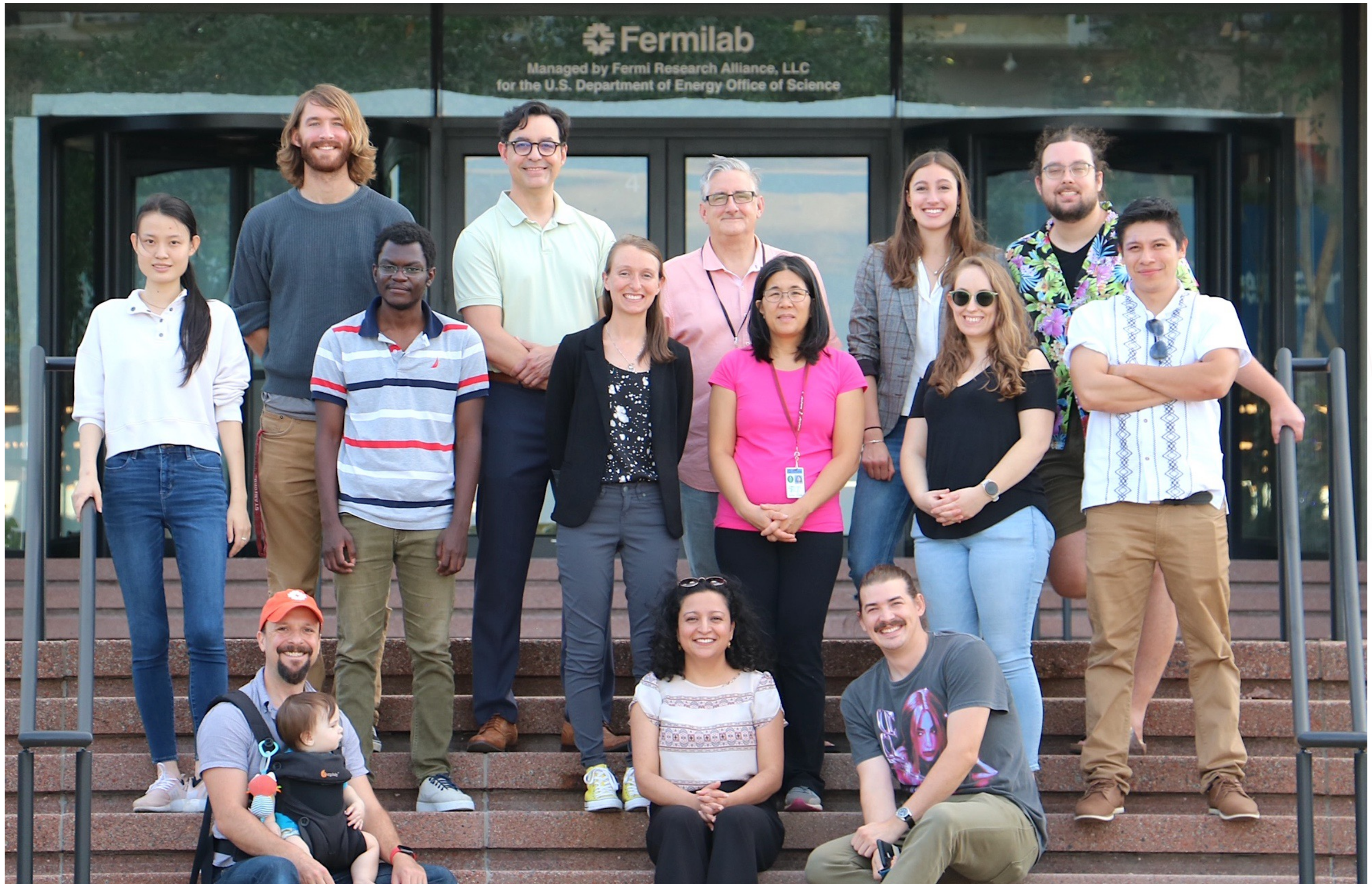

FNAL Group
Daniel Baxter
Daniel Bowring
Gustavo Cancelo
Aaron Chou
Lauren Hsu
Sami Lewis*
Ryan Linehan
Kelly Stifter*
Sara Sussman
Dylan Temples
Sho Uemura
Matthew Hollister
Chris James
Hannah Magoon*
Grace Wagner
Stella Dang

NU Group
Enectalí Figueroa-Feliciano
Riccardo Gualtieri
Grace Bratrud
Arianna Colón Cesaní
Deeksha Sabhari
Shilin Ray

IIT Group
Rakshya Khatiwada
Kester Anyang
Israel Hernandez
Jialin Yu

*group alumni