Quantum Science Center & NEXUS (& SBC)

Daniel Baxter
Astrophysics Department - Cosmic Day
30 October 2023

QUANTUM SCIENCE CENTER

Group Leads

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Person	QSC	NEXUS	SBC
PIs			
Daniel Baxter	UG PM		
Aaron Chou			
Pat Lukens			
Lauren Hsu		CDMS lead	
Daniel Bowring			
Adam Anderson			
Gustavo Cancelo	QICK PM		
Chris Stoughton			
Rakshya Khatiwada (IIT)	Surface PM		
Enectalí Figueroa-Feliciano (NU)		NU lead	
Eric Dahl (NU)			lead
Postdocs			
Kelly Stifter	Accepted Faculty position at SLAC		
Dylan Temples			
Ryan Linehan			
Sara Sussman			
Sohitri Ghosh			

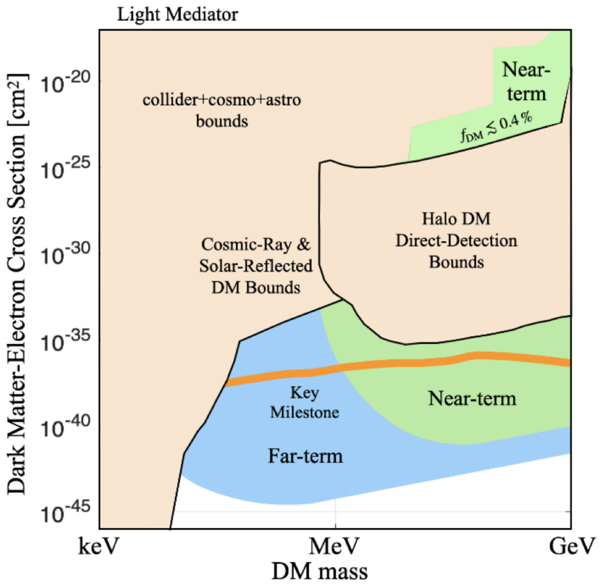
Fermilab

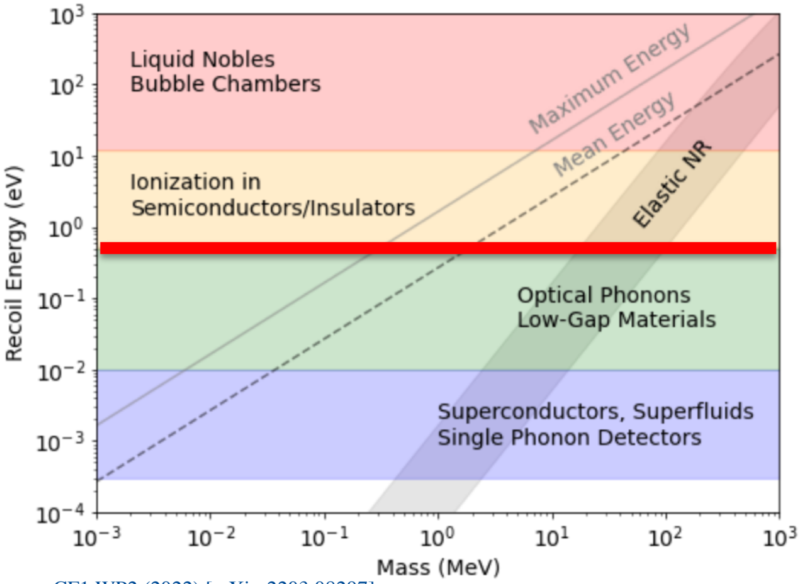
Dark Matter – Particle Direct Detection

Development of lower-threshold detectors is a huge focus of the recent decadal Snowmass particle physics study

For DM scattering below 1 MeV, lower thresholds than offered by ionization detectors are required

→ **new device development!**



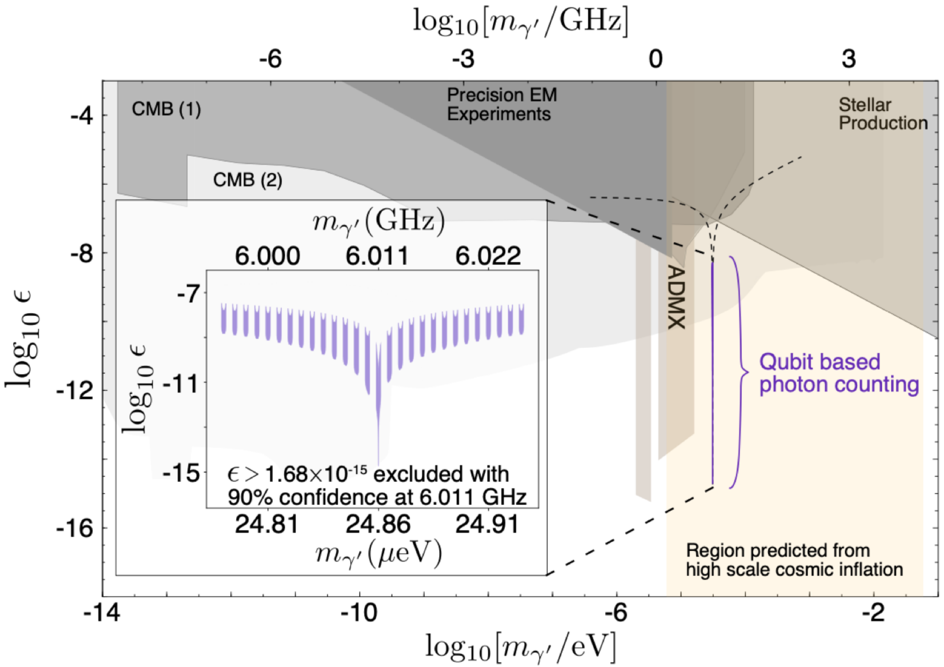


Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Defining some terminology

Quantum sensors have been demonstrated for axion/dark photon searches

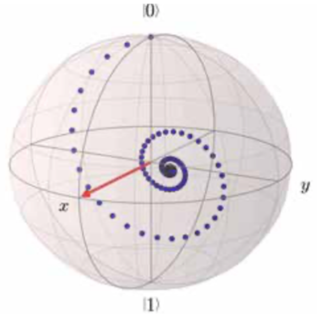
- Quantum Sensors – devices which **require** quantum mechanical description of their behavior
- Qubit – any two-level quantum mechanical system
- Cooper-Pair Box (charge qubit) – qubit whose state is determined by Cooper pairs tunneling across Josephson Junction
- Quasiparticle Poisoning – broken Cooper pairs (as from radiation/phonons) can lead to decoherence of the qubit



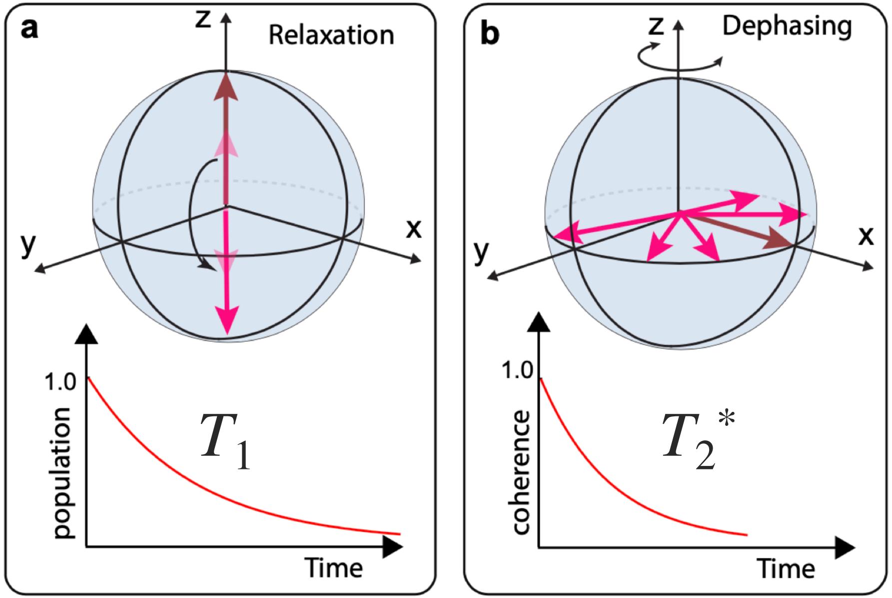
Dixit et al, PRL 126, 141302 (2021) [arXiv:2008.12231]

Defining some terminology

Could they be useful for particle dark matter detection?
(Spoiler: yes!)

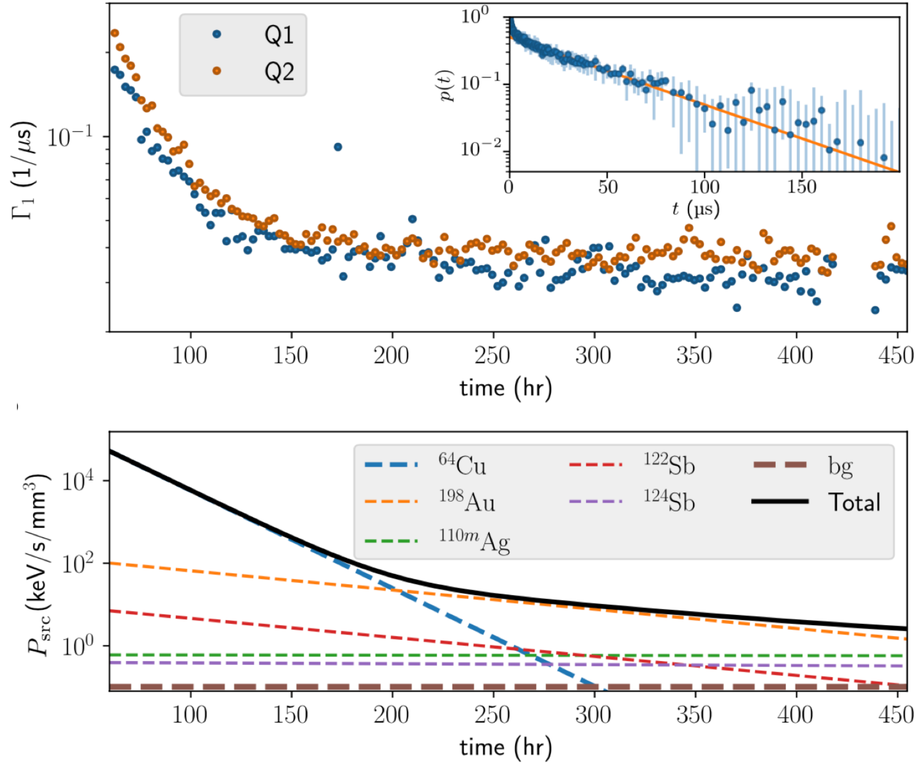


- Decoherence – loss of the qubit state due to relaxation or dephasing
    - **Bad for QIS**
    - **Good for DM detection?**
- T_1 = Relaxation Time – timescale for loss of the energy of the qubit state (ie, 1 → 0)
- T_2^* = Dephasing Time – timescale for loss of the coherence of the qubit state



Mahdi Naghiloo, (2019) [arXiv:1904.09291]

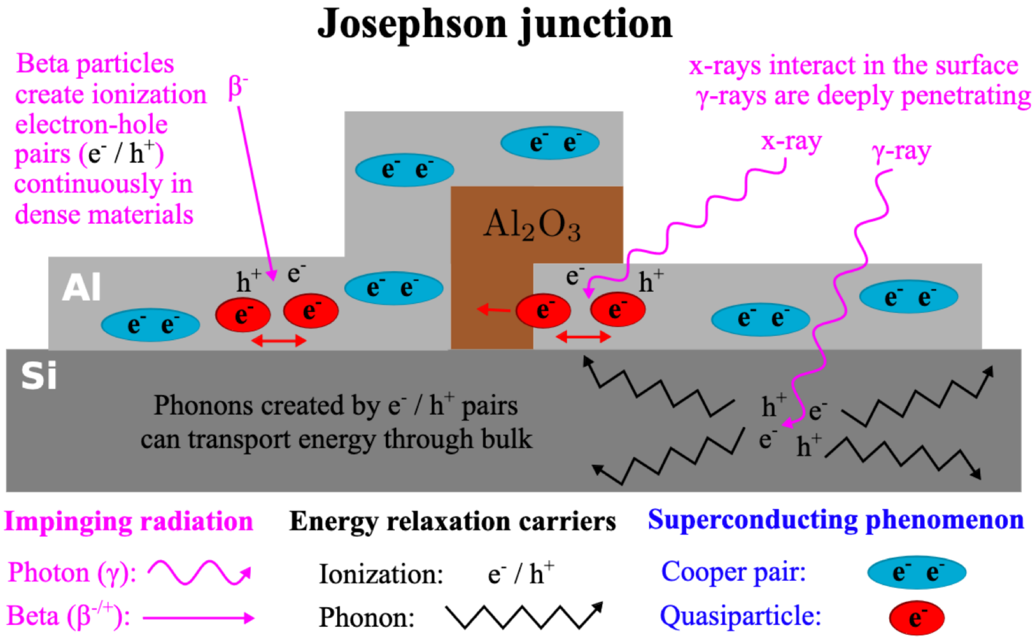
Radiation-Induced Decoherence



- Measurements of decoherence relaxation rates ($1/T_1$) in the 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]

Radiation-Induced Decoherence



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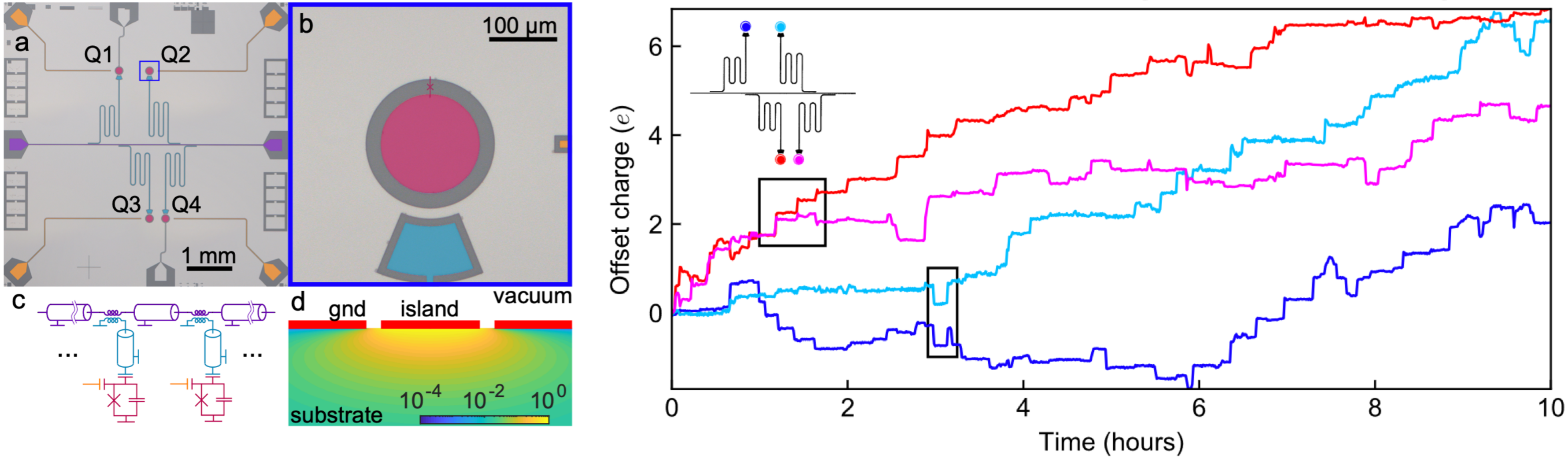
Radiation-Induced Decoherence

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

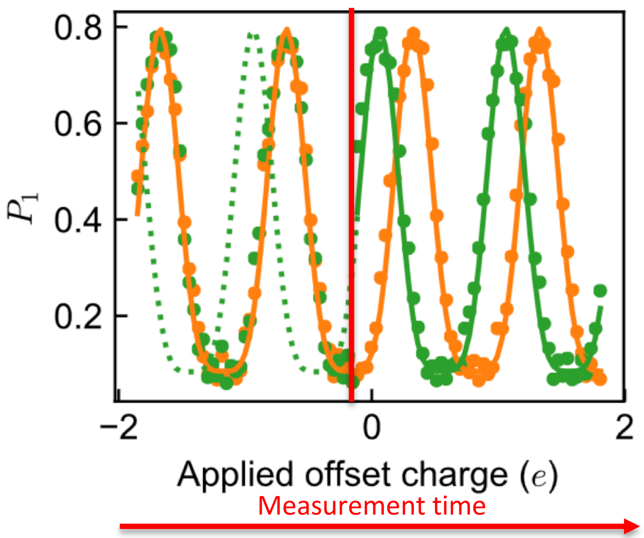


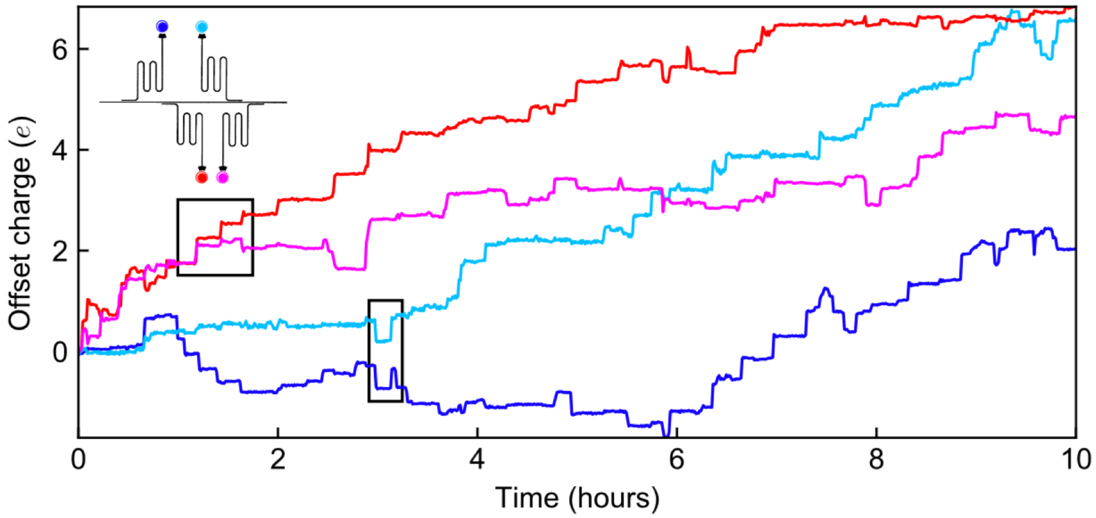
- Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear **correlated** offset charge jumps over long times
- Correlated jumps → simultaneous quasiparticle poisoning

Radiation-Induced Decoherence

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

Ramsay amplitude vs. offset charge

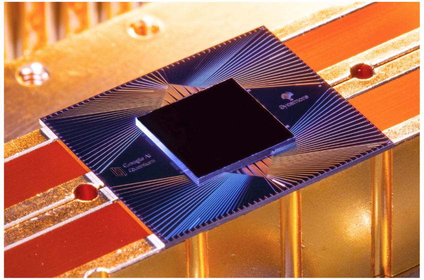


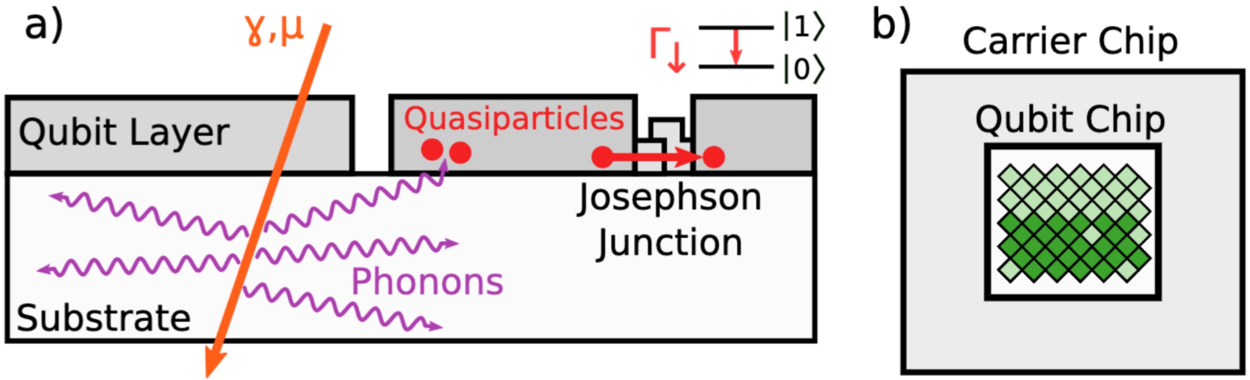


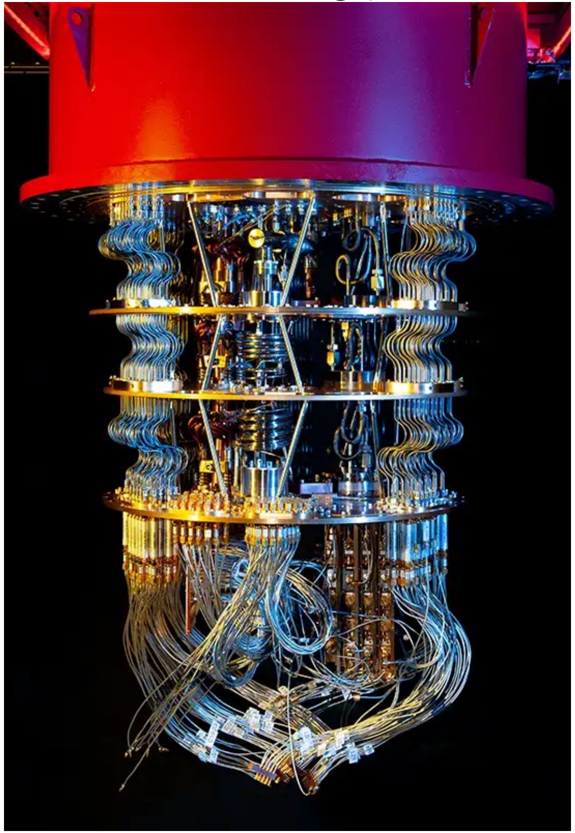
- Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear **correlated** offset charge jumps over long times
- Correlated jumps → simultaneous quasiparticle poisoning

Quantum Computing and Background Radiation

Several studies have shown that background radiation is very disruptive to superconducting qubits (quasiparticle poisoning causing correlated errors)







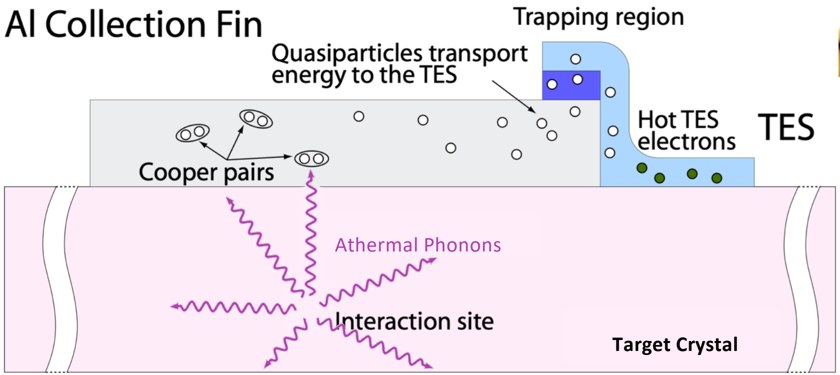
Google Sycamore team: [arXiv:2104.05219](https://arxiv.org/abs/2104.05219)

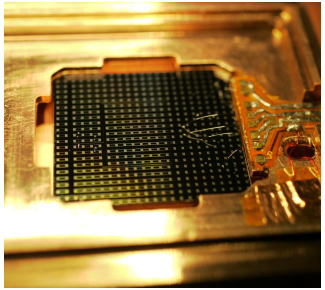
Quantum Computing and Background Radiation

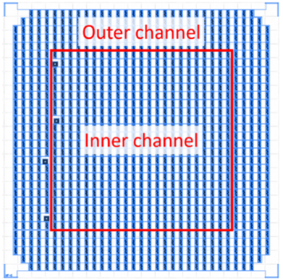
We have all the tools to work on this problem!

Our dark matter detectors work by measuring phonons in silicon through TES detectors and Al superconducting collectors films

We are bringing our knowledge of cryogenics, background reduction, particle detection, phonon and quasiparticle physics, and superconducting readout to Quantum Computing Problems







Studying Qubit Correlations in NEXUS *(collab w/ Bowring ECA)*

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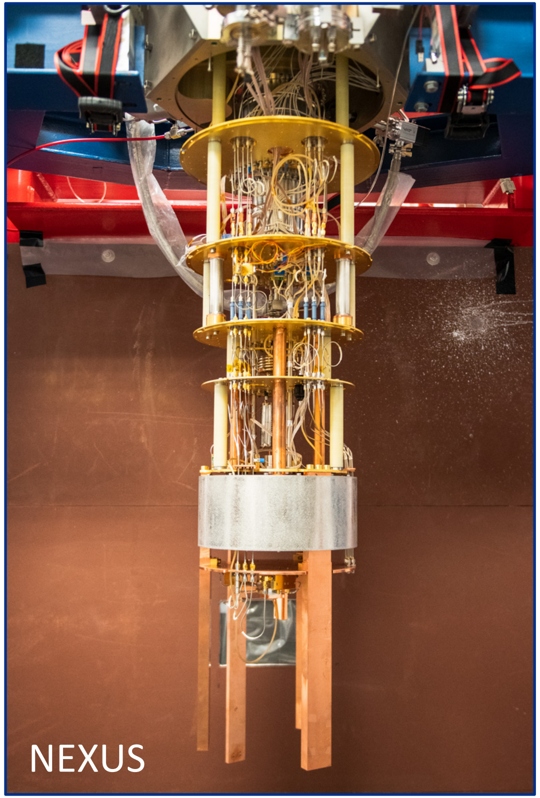

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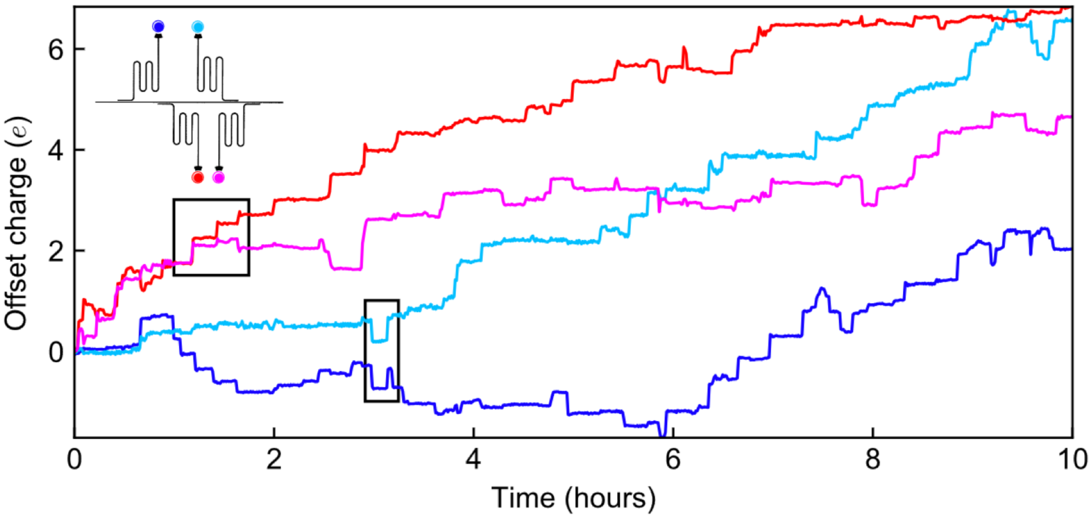

- Repeat this measurement in NEXUS w/ x100 muon flux reduction and varying shielding configurations

*Work by Kester Anyang, **DB**, Daniel Bowring, Grace Bratrud, Enectali Figueroa-Feliciano, Sami Lewis, Ryan Linehan, Hannah Magoon, Dylan Temples, Grace Wagner, Jialin Yu*

Studying Qubit Correlations in NEXUS *(collab w/ Bowring ECA)*

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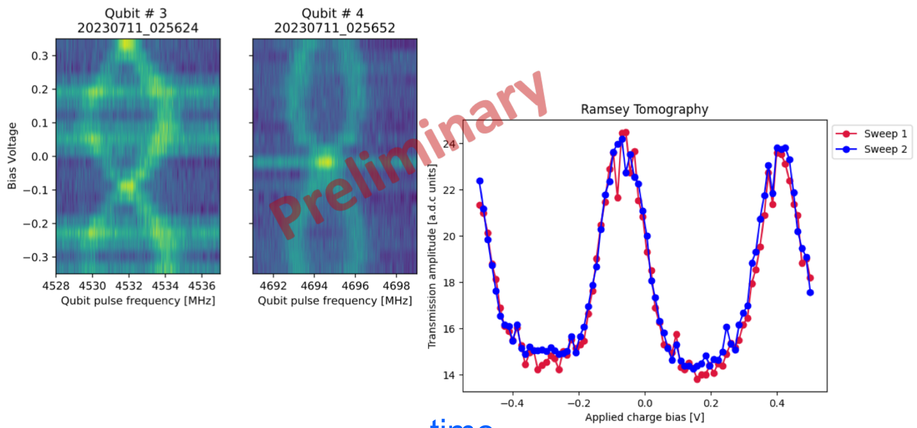
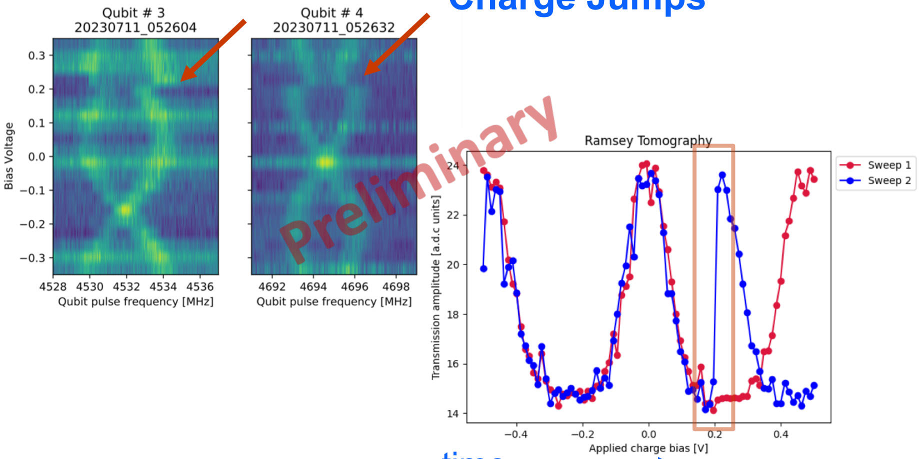
No Charge Jumps



time

Charge Jumps



time

- 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, **DB**, Daniel Bowring, Grace Bratrud, Enectali Figueroa-Feliciano, Sami Lewis, Ryan Linehan, Hannah Magoon, Dylan Temples, Grace Wagner, Jialin Yu*

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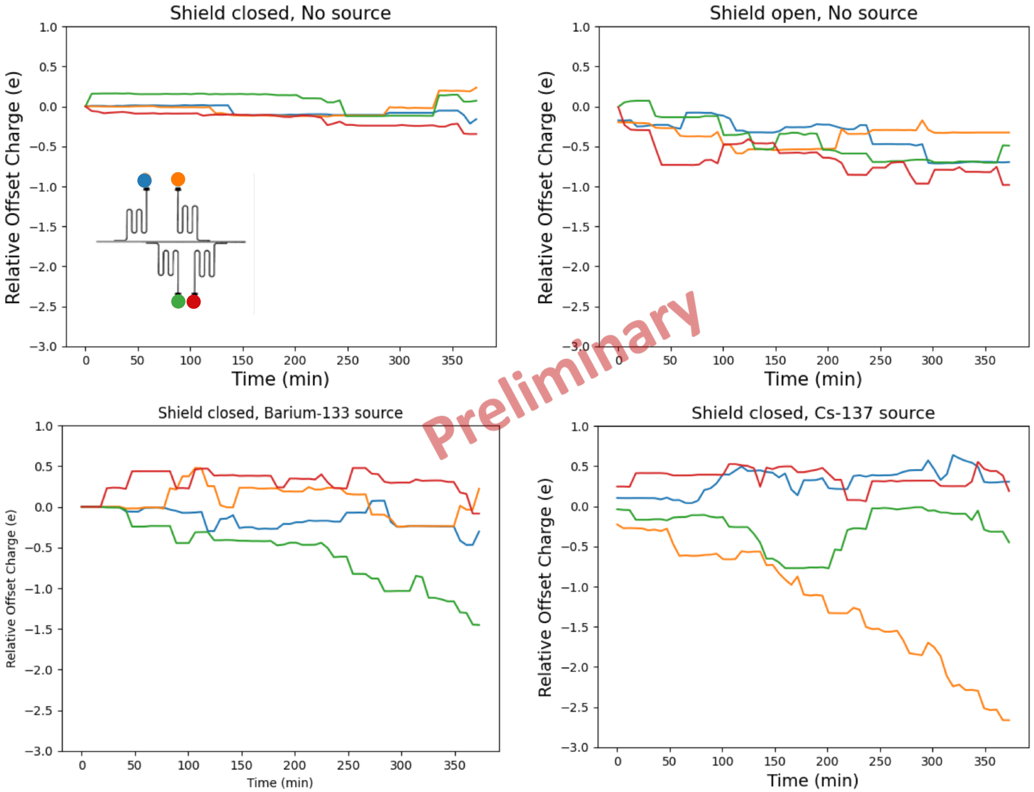
Repeated long time charge jump measurements with 4 different shielding configurations

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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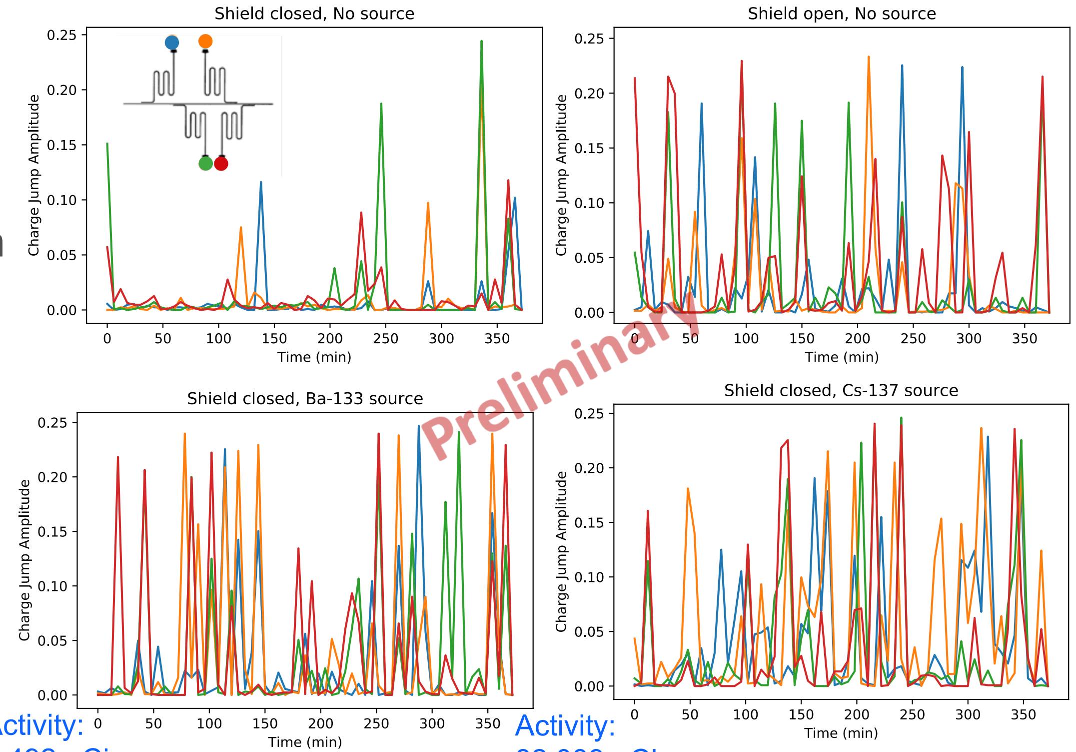


Activity: 0.492 μCi

Activity: 82.089 μCi

*Work by Kester Anyang, **DB**, Daniel Bowring, Grace Bratrud, Enectali Figueroa-Feliciano, Sami Lewis, Ryan Linehan, Hannah Magoon, Dylan Temples, Grace Wagner, Jialin Yu*

Summary of NEXUS work:

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

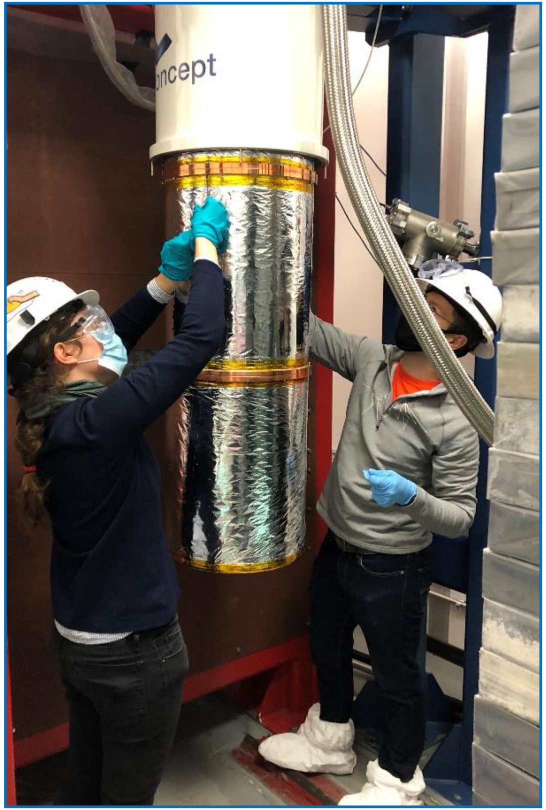
Neutrino Physics with Ricochet and CUPID

- 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

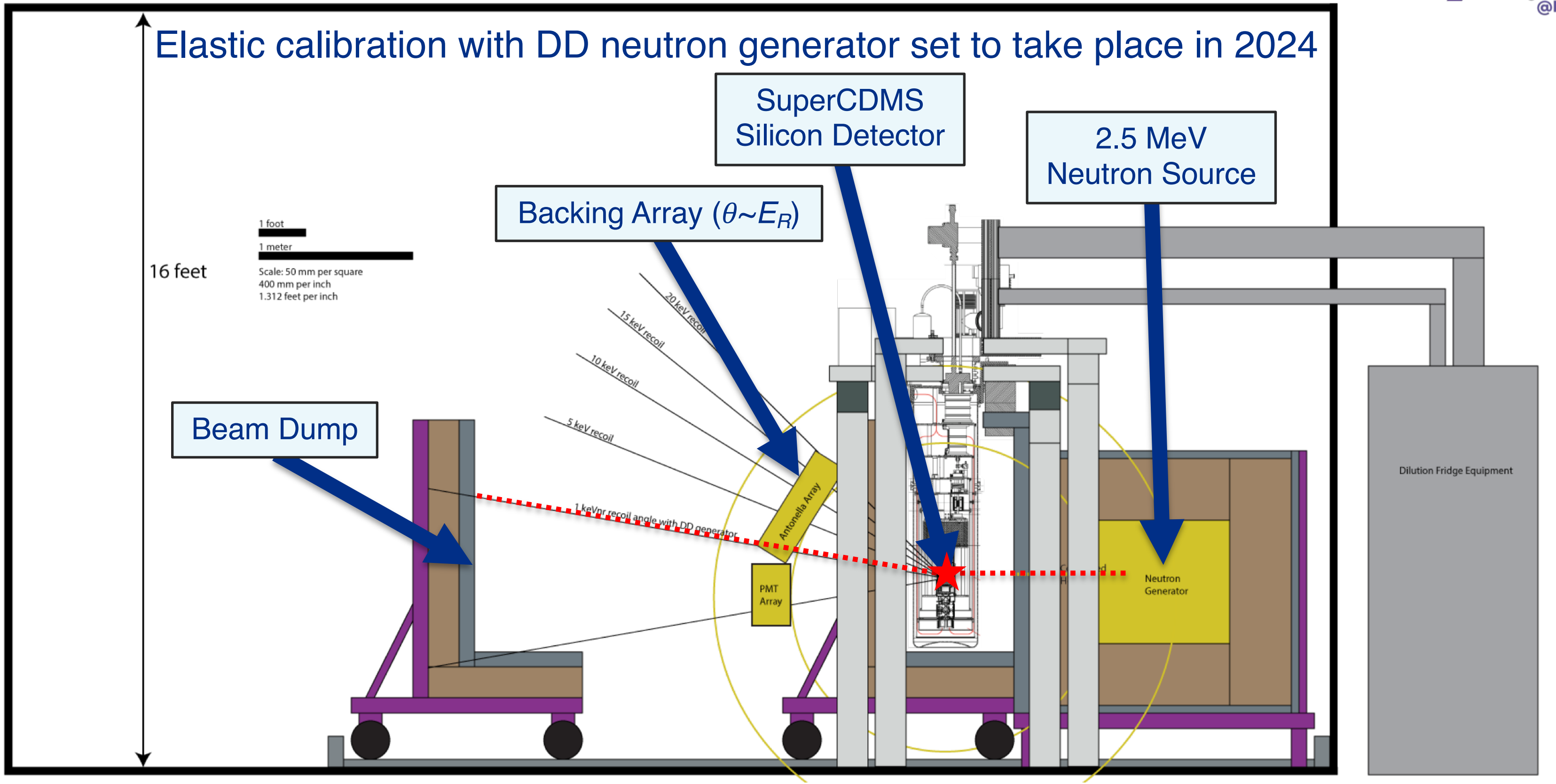
- Qubit testing underway underground at NEXUS
- Developing R&D program for low-background quantum architectures

Summary of NEXUS work:



Summary of NEXUS work:

Elastic calibration with DD neutron generator set to take place in 2024



Looking Forward – Underground studies in QUIET

Quantum Underground Instrumentation Experimental Testbed

This QSC facility, once complete, will house one of the only dedicated, low-background cryostats for superconducting qubit operations

- Class 10,000 clean room
- Oxford Proteox w/ 8.9mK base temperature
- 50 ft^2 antechamber for gowning and material cleaning
- 250 ft^2 main room will contain a shielded Oxford dil. fridge w/ up to 16(48) NbTi(SS) RF lines
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Facility is complete! including electrical power, chilled water, network, and fire suppression systems

Looking Forward – Underground studies in QUIET

Quantum Underground Instrumentation Experimental Testbed

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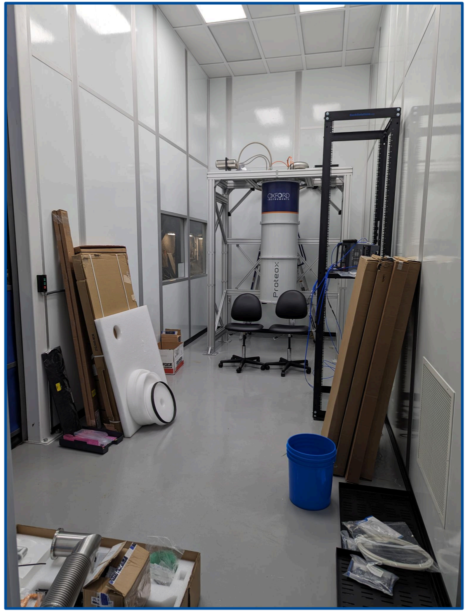
Dec. 9, 2022

Sept. 29, 2023



Looking Forward – Underground studies in QUIET

Quantum Underground Instrumentation Experimental Testbed

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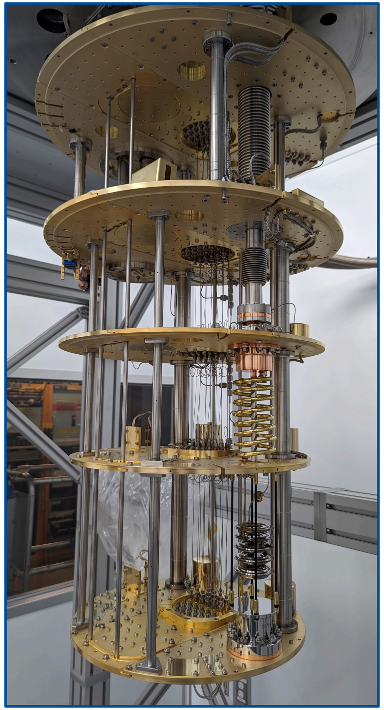
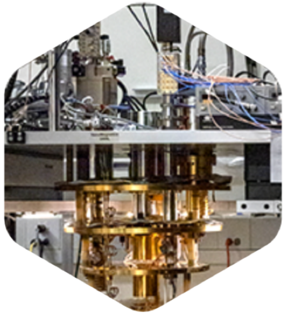
The **only** operational dedicated underground quantum research facility in the world

1. LGNS – not dedicated but operational (3400 mwe)
2. **NEXUS@FNAL – not dedicated but operational (225 mwe)**
3. **QUIET@FNAL (225 mwe)**
4. PNNL – dedicated but not yet operational (<100 mwe)
5. Boulby, UK – dedicated but not yet operational (2800 mwe)
6. CUTE@SNOLAB – operational but devoted to CDMS thru 2024 (6000 mwe)



Quantum Science Center

- US Department of Energy recently funded five National Quantum Information (NQI) Science Research Centers to advance QIS technologies in the US
- ORNL hosts the **Quantum Science Center** (QSC) which includes as one of its three thrusts the goal of ensuring some of this investment goes back into discovery science (led by FNAL)



Thrust 3: Quantum Devices and Sensors for Discovery Science

Thrust 3 develops an understanding of fundamental sensing mechanisms in high-performance quantum devices and sensors. This understanding allows QSC researchers, working across the Center, to co-design new quantum devices and sensors with improved energy resolution, lower energy detection thresholds, better spatial and temporal resolution, lower noise, and lower error rates. Going beyond proof-of-principle demonstrations, the focus is on implementation of this hardware in specific, real-world applications.

Led by Fermilab's Aaron Chou

How does this impact QIS technology development?

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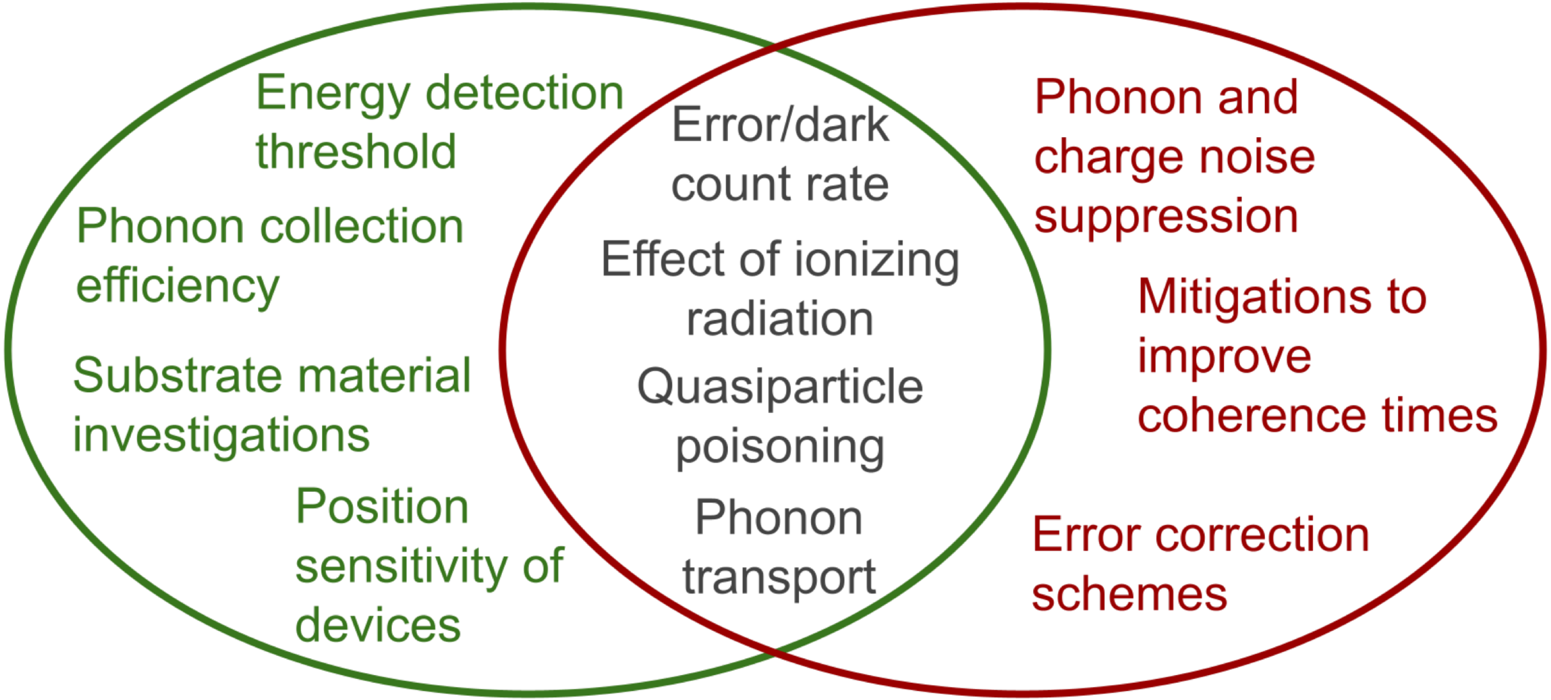
SC Qubits for Dark Matter

SC Qubits for Quantum Computing

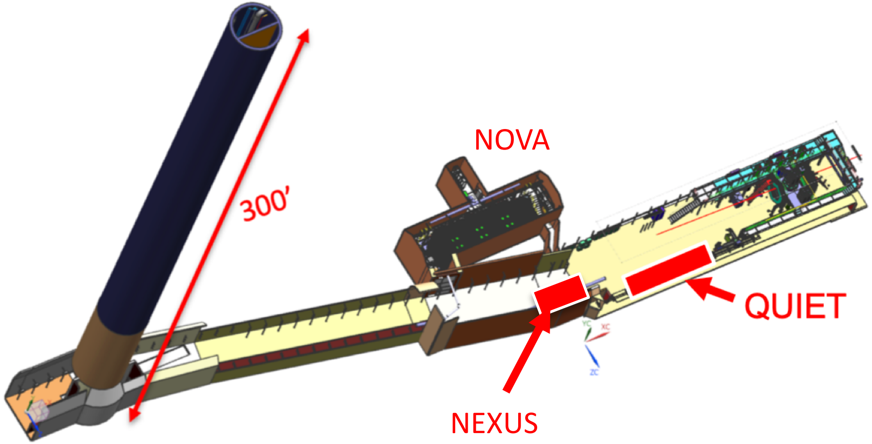


Fermilab

Superconducting Qubits as Detectors – Facilities

FNAL group has progress on many fronts towards this goal!

- **Two identical new facilities at FNAL!**
  - LOUD – high-throughput surface facility to advance qubit-based technology necessary to develop DM & radiation detectors
  - QUIET – underground facility (next to NEXUS; 225 mwe) to operate characterized devices in low-background (target 100 dru) environment ($\times 10^3$ reduction)



LOUD Run Coordinator: Ryan Linehan

Superconducting Qubits as Detectors – LOUD

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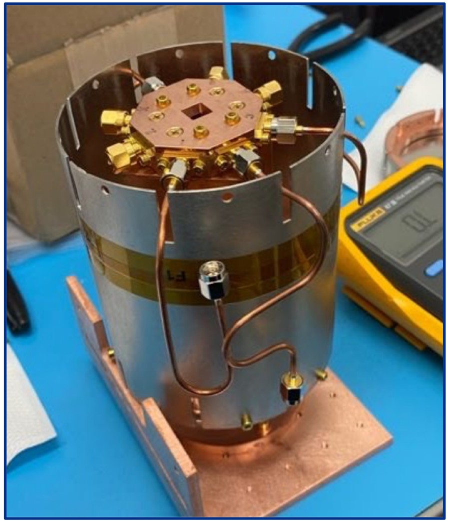
New DR installed at FNAL

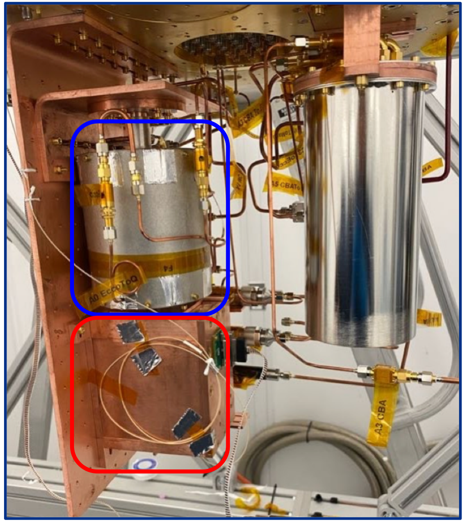
(August 2022)

6-qubit array borrowed from McDermott group



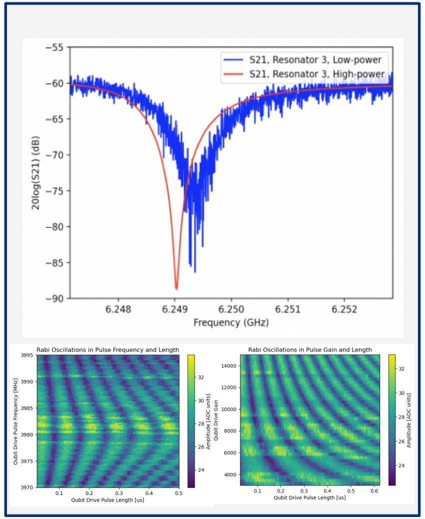
(October 2022)

Magnetic shielding coupled to scanning unit and installed in DR



(November 2022)

Run 1: First demonstration of live qubits



(February 24th 2023) - March 14th 2023

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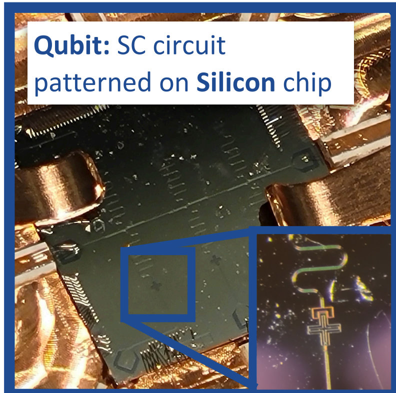
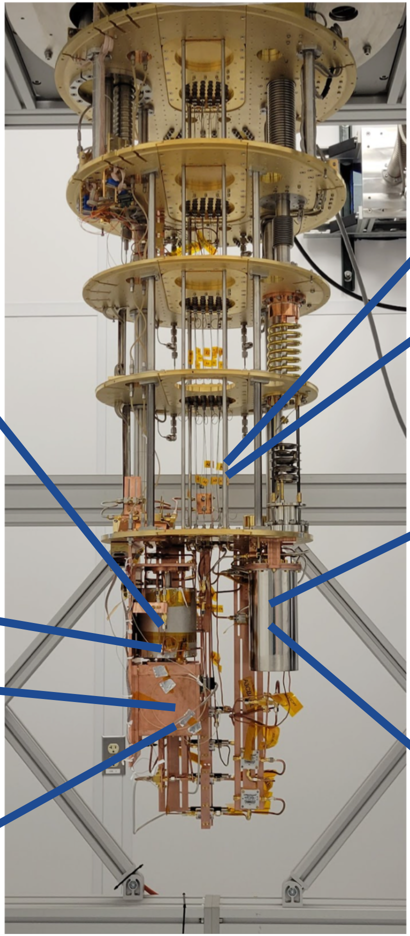
Qubit: SC circuit patterned on **Silicon** chip



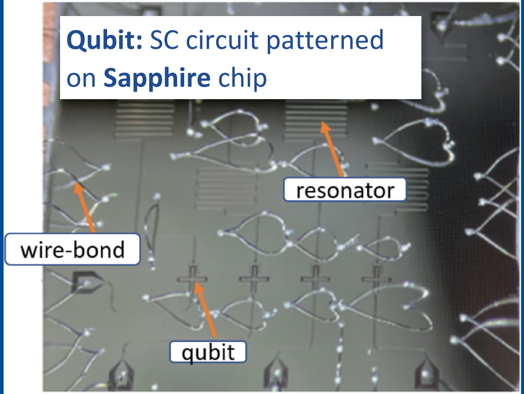
chip from R. McDermott group at UWMadison

MEMS: steerable cryogenic optical laser calibration



(*not shown*) KID payload and JPA focus of Run 2

Qubit: SC circuit patterned on **Sapphire** chip

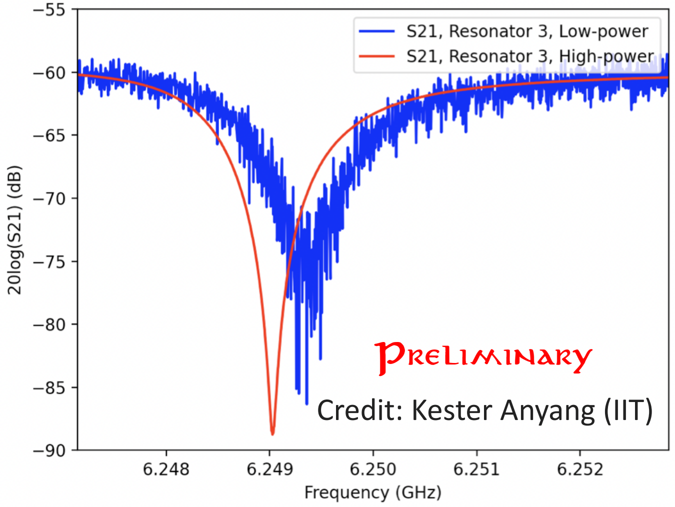


4-qubit array

chip from A. Ma group at Purdue

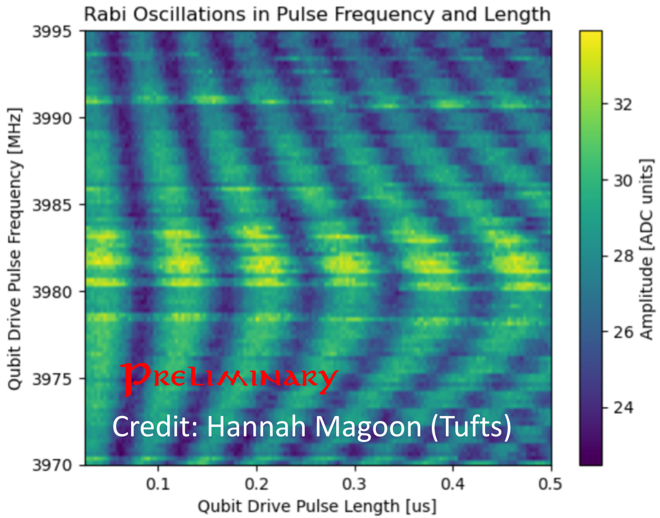
Superconducting Qubits as Detectors – LOUD

One-tone resonator spectroscopy ("punch-out")



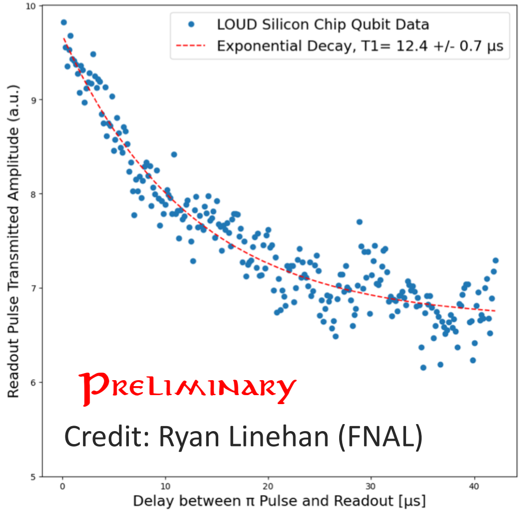
Purpose: determine that the qubit (i.e. the Josephson Junction) is "alive", i.e. not burned out

Qubit spectroscopy + Rabi Oscillations



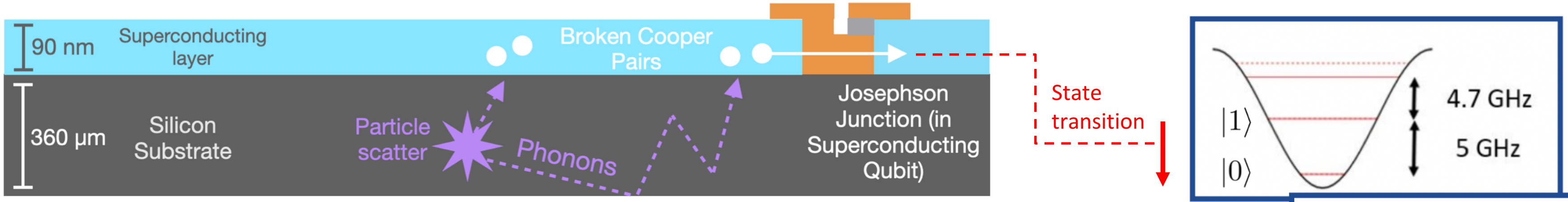
Purpose: find the qubit excitation frequency and calibrate a |0⟩ → |1⟩ pulse

T1 Relaxation Time



Purpose: Probe qubit decoherence times

Superconducting Qubits as Detectors – Simulation



Graphic by Ryan Linehan

Qubit acts as anharmonic LC oscillator[4]

- Need to model phonon creation, propagation, down-conversion, reflection (at surfaces), and transmission into superconducting layer

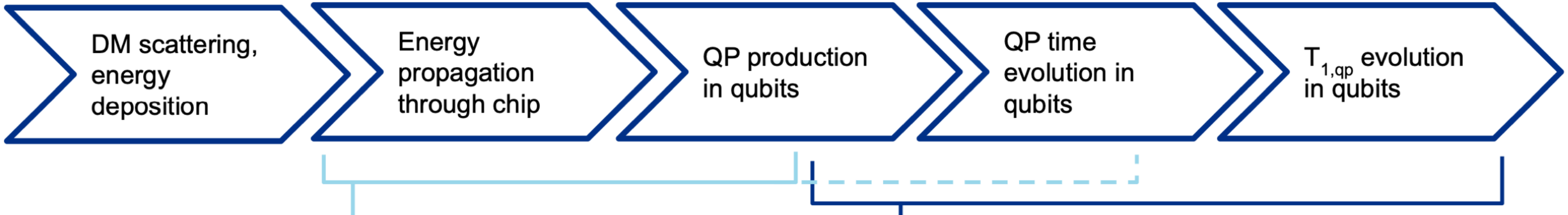
G4CMP: Condensed Matter Physics Simulation Using the GEANT4 Toolkit

M. H. Kelsey[a,*], R. Agnese[b], Y. F. Alam[a], I. Ataee Langroudy[a], E. Azadbakht[a], D. Brandt[c], R. Bunker[d,*], B. Cabrera[e], Y.-Y. Chang[f], H. Coombes[b], R. M. Cormier[g], M. D. Diamond[g], E. R. Edwards[d], E. Figueroa-Feliciano[h], J. Gao[i], P. M. Harrington[j], Z. Hong[g], M. Hui[g], N. A. Kurinsky[c], R. E. Lawrence[a], B. Loer[d], M. G. Masten[k], E. Michaud[l], E. Michielin[m,n], J. Miller[d], V. Novati[h], N. S. Oblath[d], J. L. Orrell[d], W. L. Perry[a], P. Redl[e], T. Reynolds[g], T. Saab[b], B. Sadoulet[o,p], K. Serniak[j,q], J. Singh[e], Z. Speaks[b], C. Stanford[r], J. R. Stevens[i], J. Strube[d,s], D. Toback[a], J. N. Ullom[i,t], B. A. VanDevender[d], M. R. Vissers[t], M. J. Wilson[u], J. S. Wilson[v], B. Zatschler[g], S. Zatschler[g]

Kelsey et al, (2023) [arXiv:2302.05998]

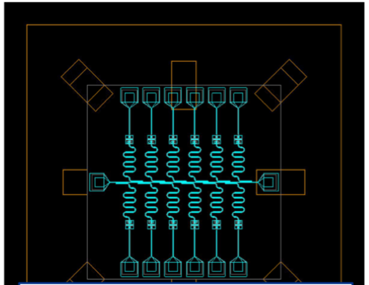
Superconducting Qubits as Detectors – Simulation

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



G4CMP simulation

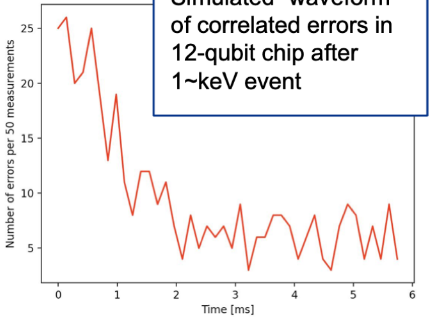
- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



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

Work by Ryan Linehan, Israel Hernandez, and Stella Dang

Superconducting Qubits as Detectors – Calibration

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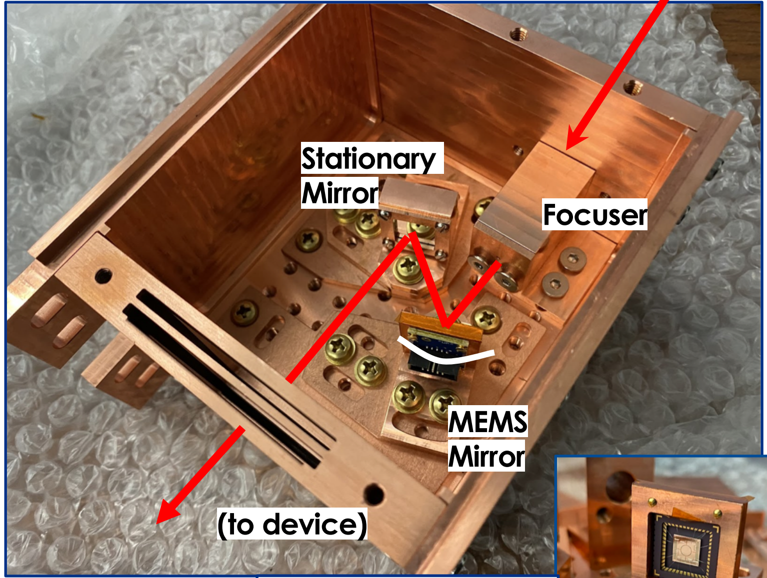
MEMS mirror used to steer laser beam

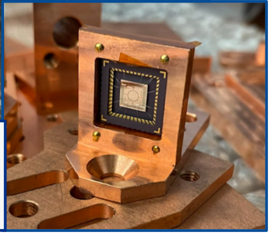
- No power dissipation while stationary
- Modified control lines to function at cryogenic temperatures (>10mK)
- Large deflection angles (< ±5°)
- High deflection resolution (>0.001°)
- High broadband reflectance

Work by Kelly Stifter & Hannah Magoon

Optical Cable
(from laser into dilution fridge)

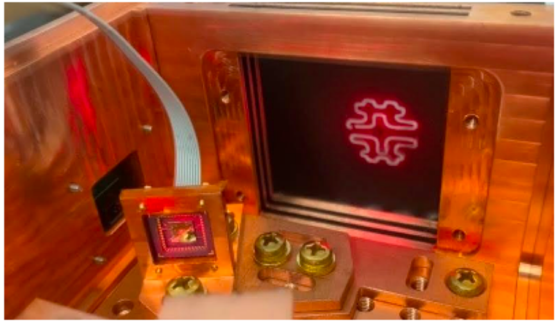


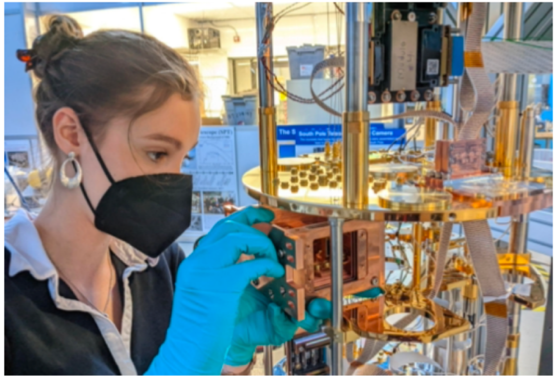
mirrorcle TECHNOLOGIES, INC.



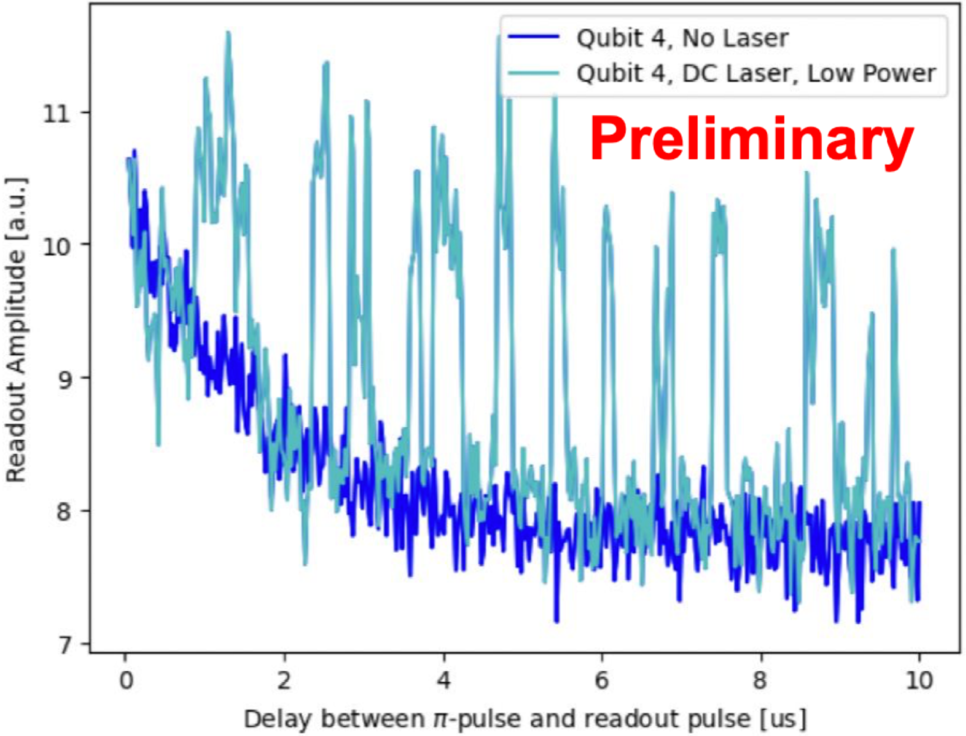
Fermilab

Superconducting Qubits as Detectors – Calibration





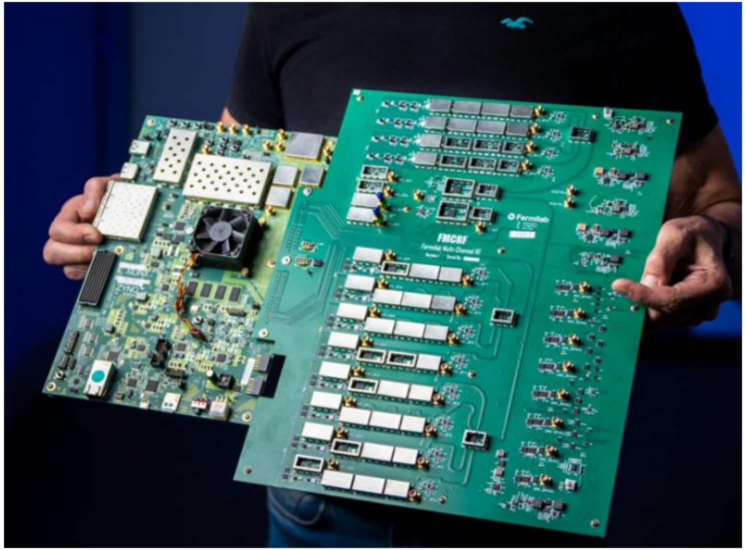
Work by Kelly Stifter & Hannah Magoon



Superconducting Qubits as Detectors – 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 (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 this Fall

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

Conclusions

Benchmarks for applying quantum detectors for dark matter:

- Determine, quantitatively, the effects of radiation on detector performance (qubit decoherence) in collaboration with QIS community
- Develop calibration sources to mimic the scattering of sub-MeV DM
- Understand background contributions down to and below a few eV

We're just starting the process of turning quantum sensors into DM detectors, making this an interesting time on the cusp of a lot of new, exciting science

Liquid Noble Bubble Chambers

Objective:

Quasi-background-free detection of sub-keV Nuclear Recoils

Signal:

Single bubble with little or no coincident scintillation

Backgrounds:

ER's (beta, gamma):

No bubbles

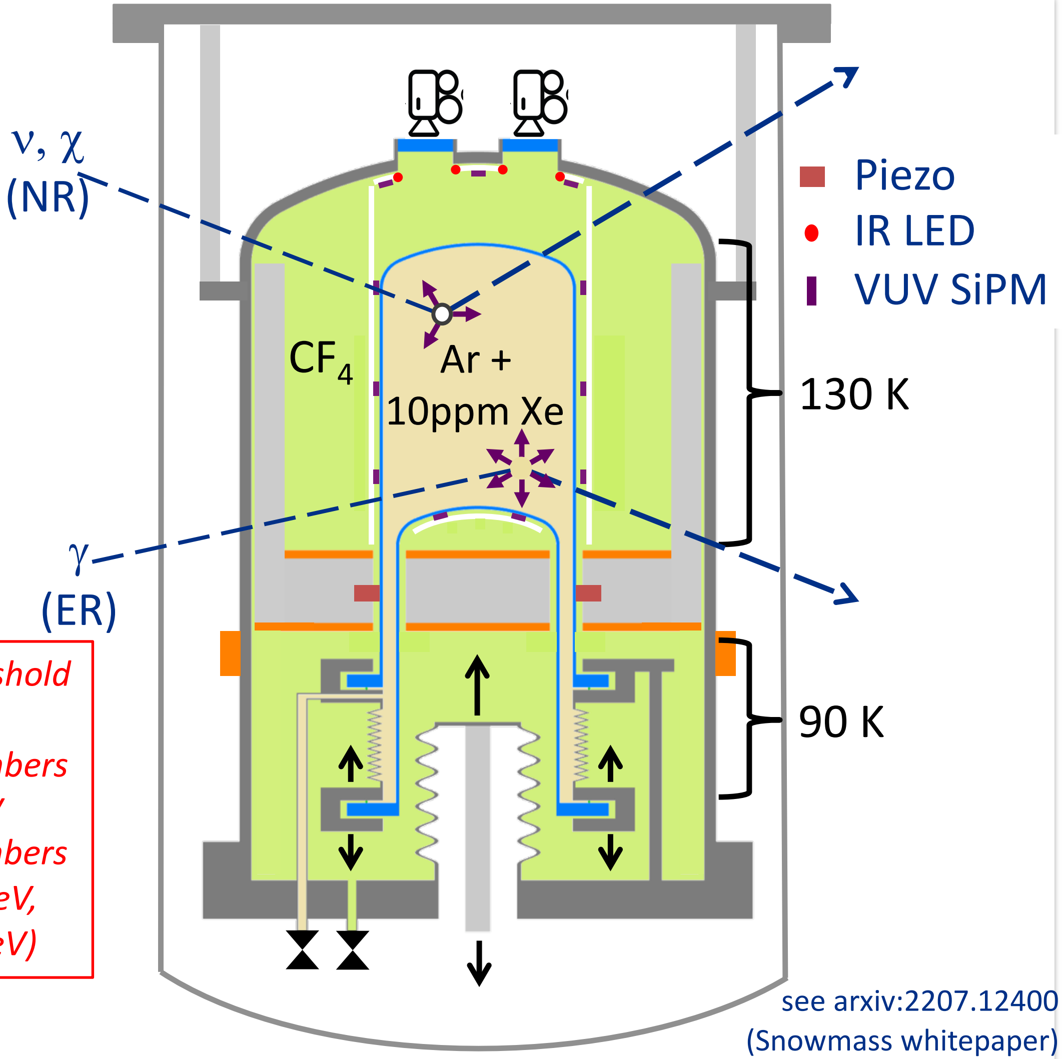
Depends on NR threshold and target fluid:

- *Freon-based chambers ER-blind @ ~3 keV*
- *Liquid-noble chambers ER-blind @ < 500 eV, (target 100 eV)*

NR's (fast neutron):

Multiple bubbles

Strong coincident scintillation



see arxiv:2207.12400 (Snowmass whitepaper)

Liquid Noble Bubble Chambers

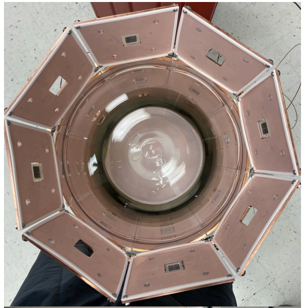
SBC-LAr10
(former LDRD 2018-003)

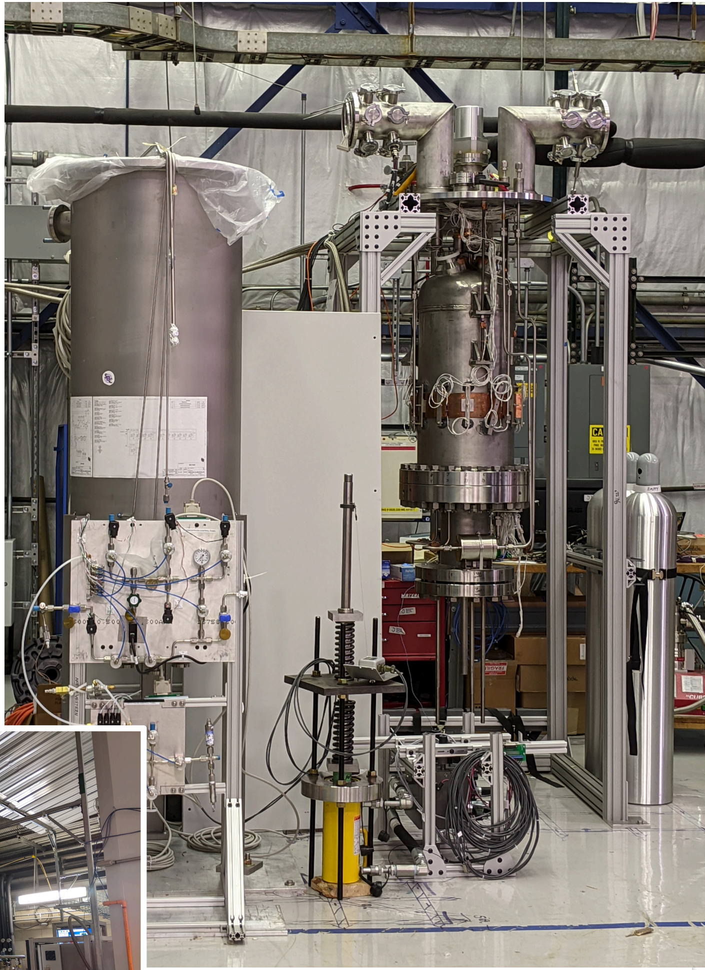
Objectives:

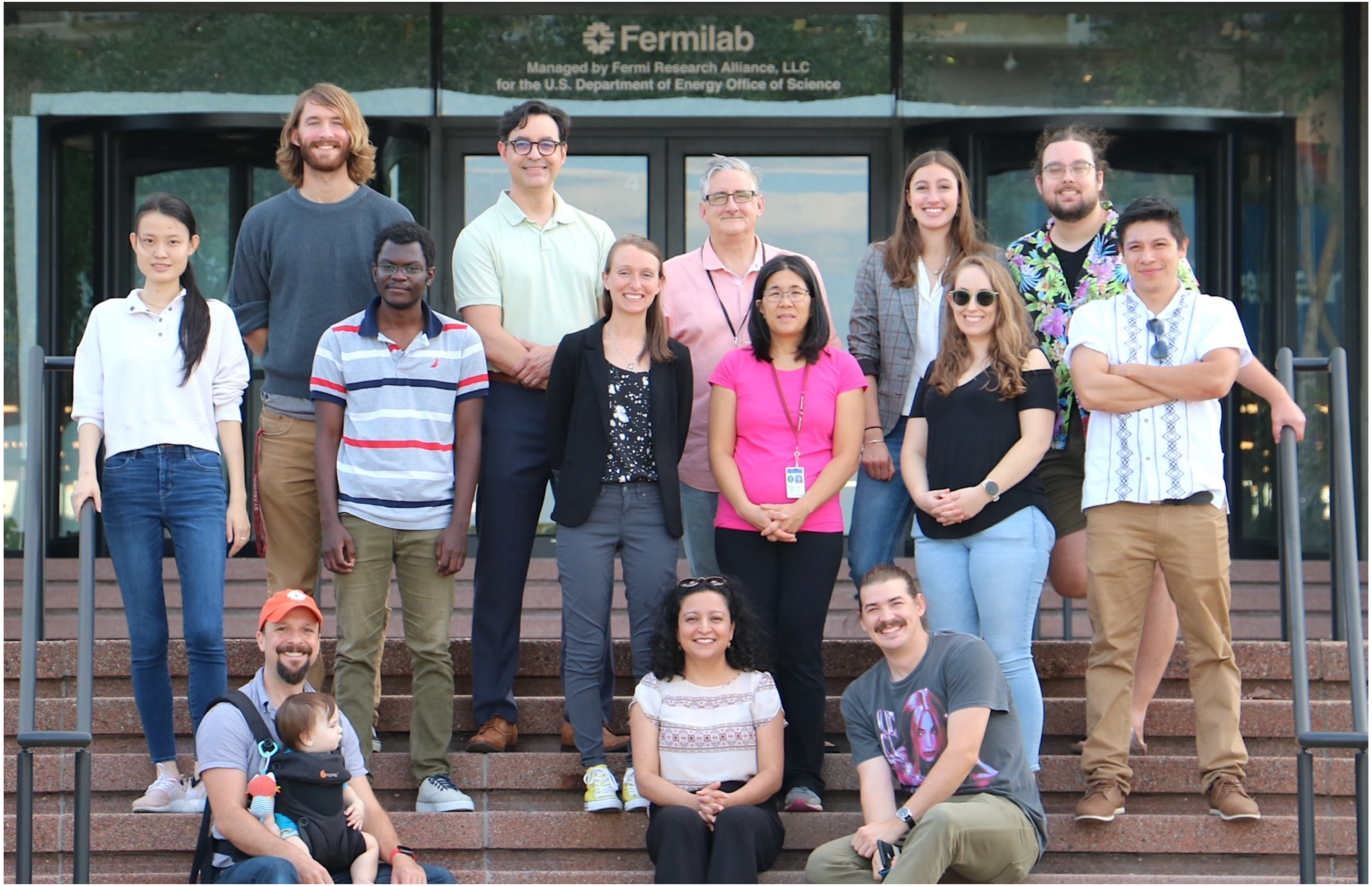
- Demonstrate operation of physics-scale (10-kg) LAr bubble chamber
- Calibrate at low-threshold:
  Measure NR bubble nucleation down to 100-eV with 10-eV resolution

Status:

- Engineering run completed March 2023
- Inner assembly (jars, SiPMs, piezos, etc) installation 95% complete
- MINOS space ready for occupancy in < 1 month
- Expect first bubbles this spring!





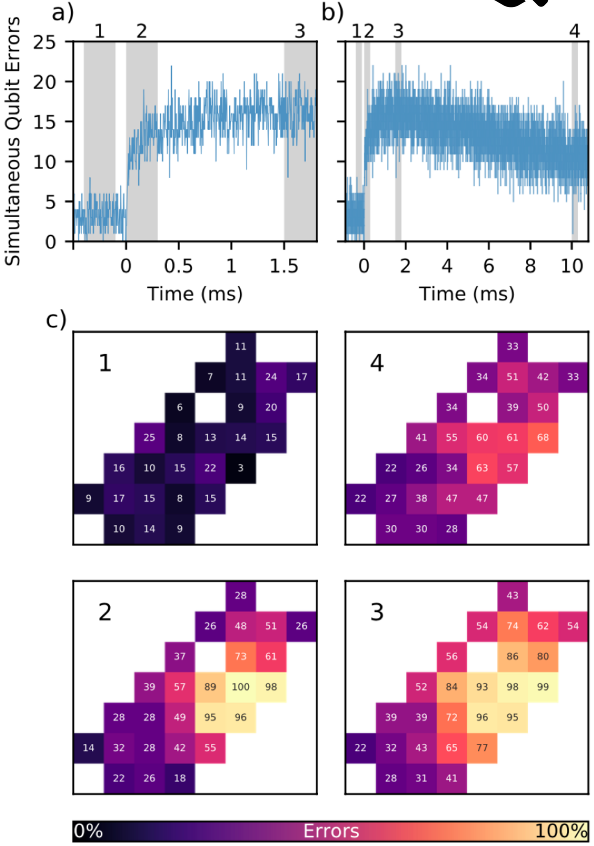


Not pictured:
Aaron Chou (FNAL)
Gustavo Cancelo (FNAL)
Adam Anderson (FNAL)
Valentina Novati (NU)
Grace Bratrud (NU)
Alejandro Rodriguez (NU)

Backup Slides

Superconducting Qubits as Detectors

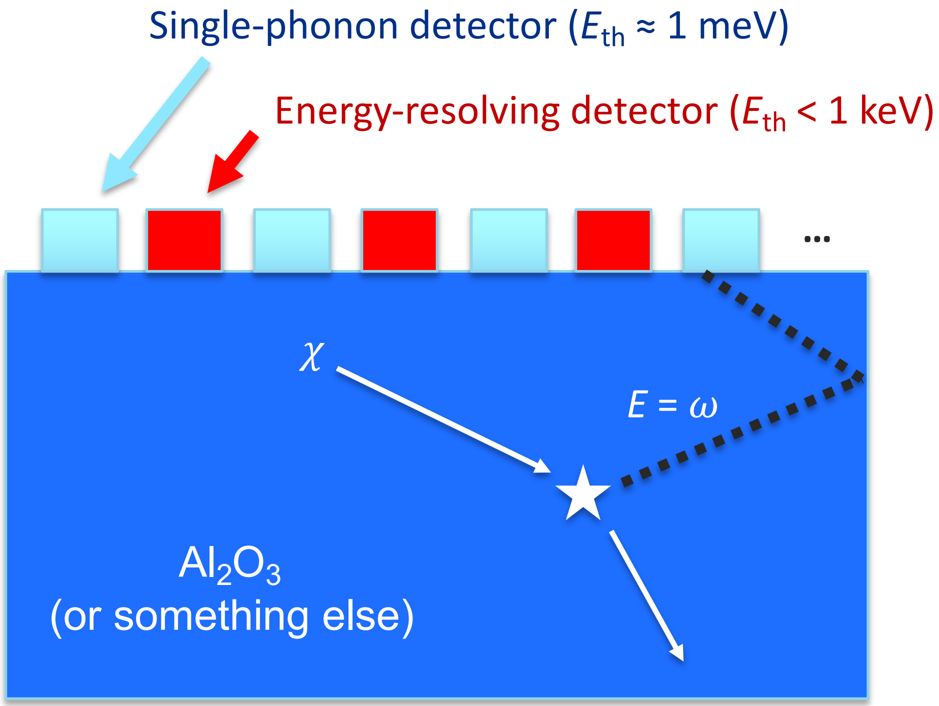
- Individual superconducting qubit lifetimes are on the order of 10-100 μs and we aren't only interested in ionizing events (higher threshold)
- Further studies of radiation-dependence actually show correlated relaxation errors across the device due to energy depositions in common substrate (information destroyed every 10s!)
- **<u>Hypothesis</u>: energy depositions in a substrate cause *correlated* decoherence across qubits due to quasiparticle poisoning**



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

Superconducting Qubits as Detectors

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 $\boldsymbol{r}$, 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

A tangential analogy…

From the perspective of experimental design, this is very similar to a (tiny) bubble chamber!

- A "run" consists of a series of exposures, at the end of each the system is assessed for whether there was a state change (bubble OR |1⟩ → |0⟩)

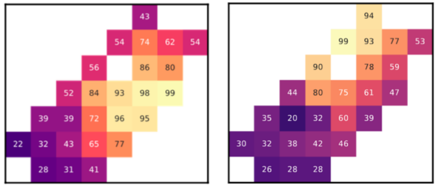
  → **bubble chambers usually detect that bubble immediately, but in principle, they could just wait the pre-determined exposure time and check the state**

- The majority of background events will be higher energy (> eV) at scales we are very good at detecting

  → **this means we can veto them!**

- Similar to a bubble chamber, no primary energy information

  → **but yes position information!**



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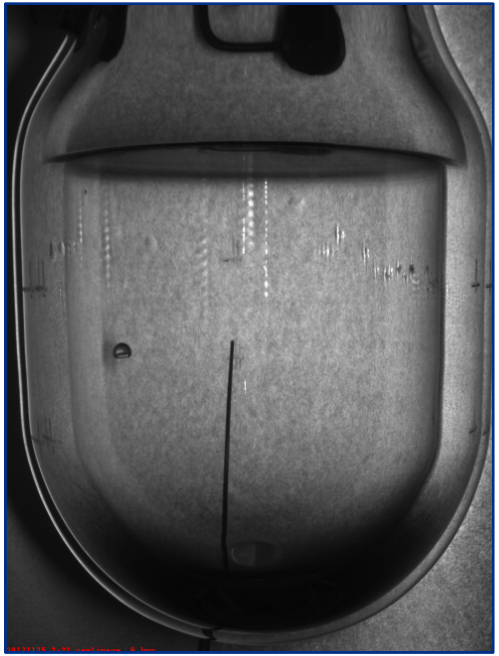
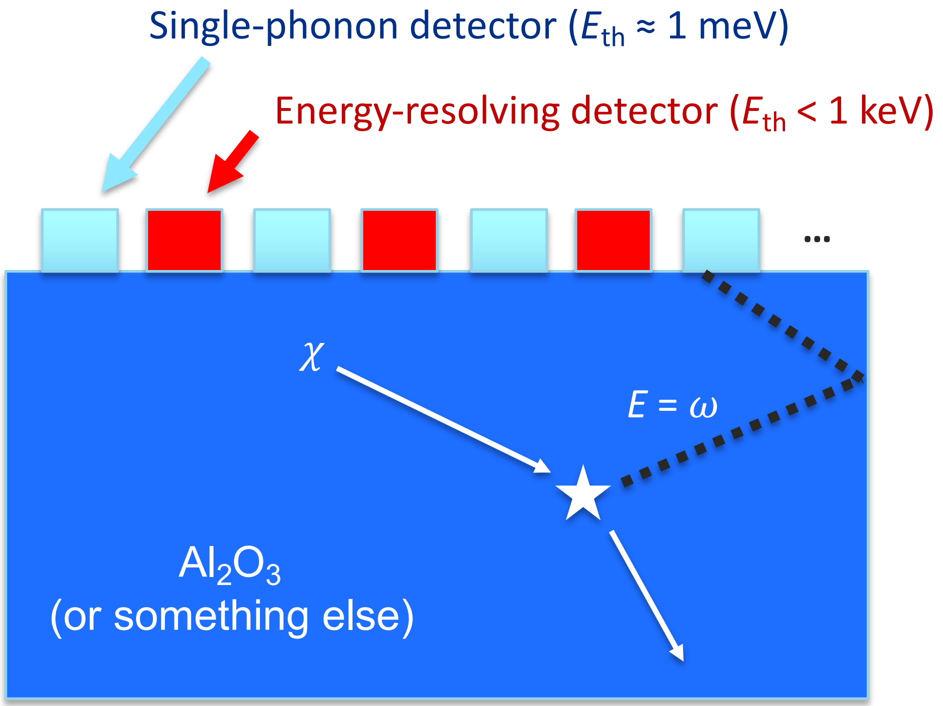
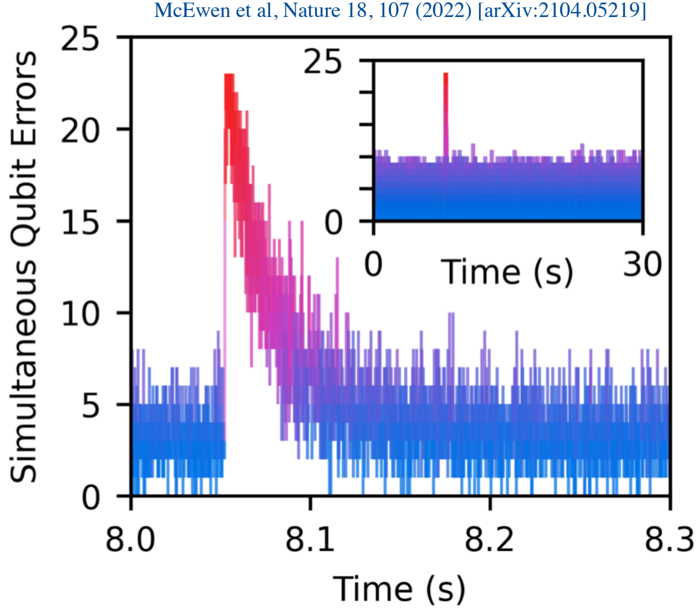


Superconducting Qubits as Detectors

QUANTUM SCIENCE CENTER

Proposing a novel, multiplexed quantum device for particle physics detection





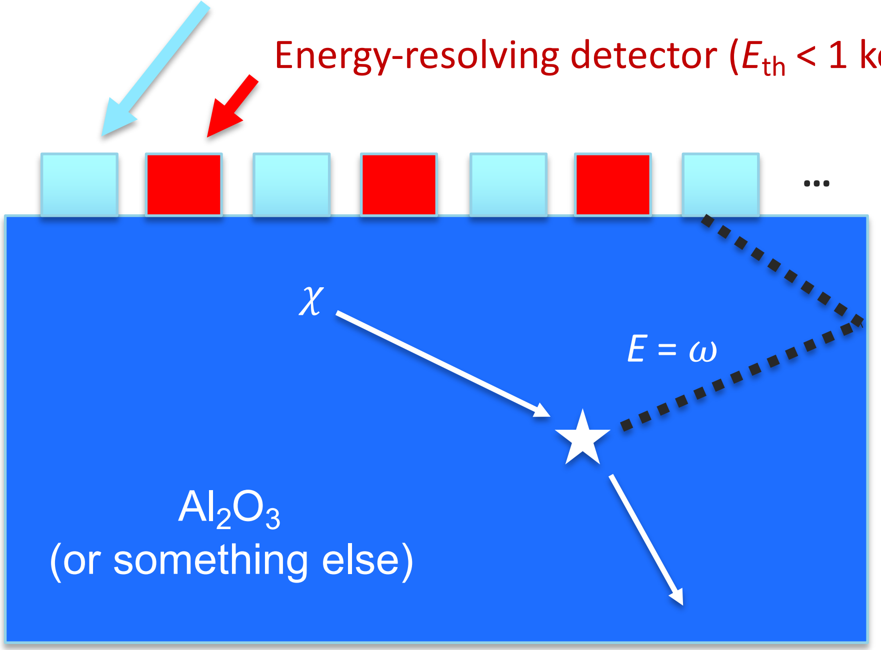
Fermilab

Superconducting Qubits as Detectors

Proposing a novel, multiplexed quantum device for particle physics detection

Single-phonon detector ($E_{th} \approx 1$ meV)

Energy-resolving detector ($E_{th} < 1$ keV)



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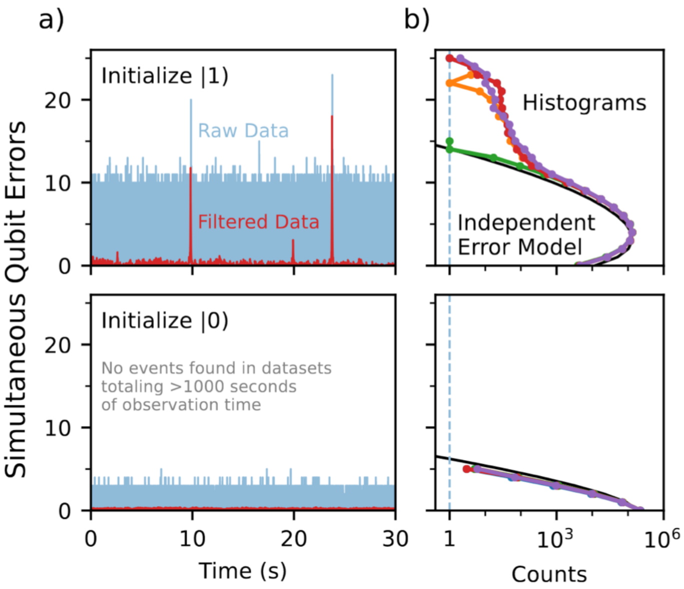
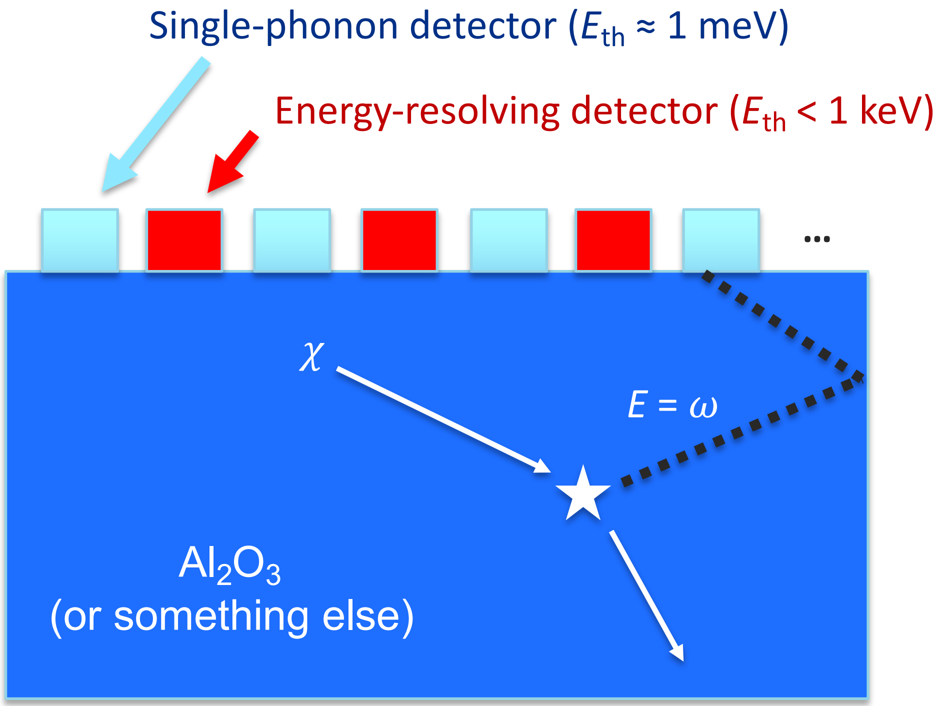


Superconducting Qubits as Detectors

Proposing a novel, multiplexed quantum device for particle physics detection



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