Fermilab's Underground Facilities for Quantum Sensing

Daniel Baxter
Joint Experimental-Theoretical Physics (Wine and Cheese) Seminar
19 January 2024

Outline

QUANTUM SCIENCE CENTER

- Direct Detection of Particle Dark Matter
- *Brief* detour into quantum computing
- Radiation dependence of superconducting qubits
- Superconducting qubits for particle detection
- Underground Facilities within the Cosmic Quantum (**CosmiQ**) group at FNAL

Snowmass 2021

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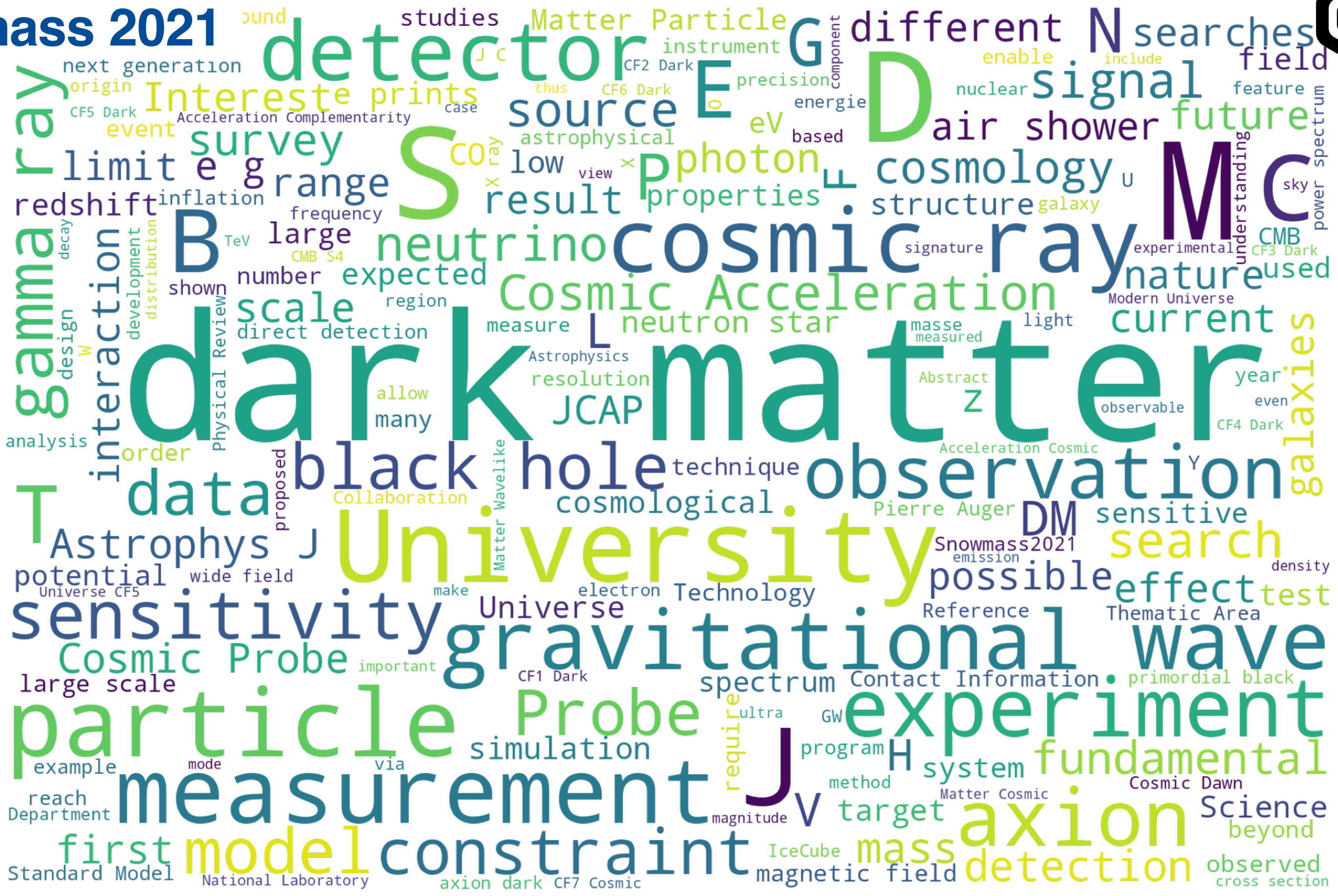

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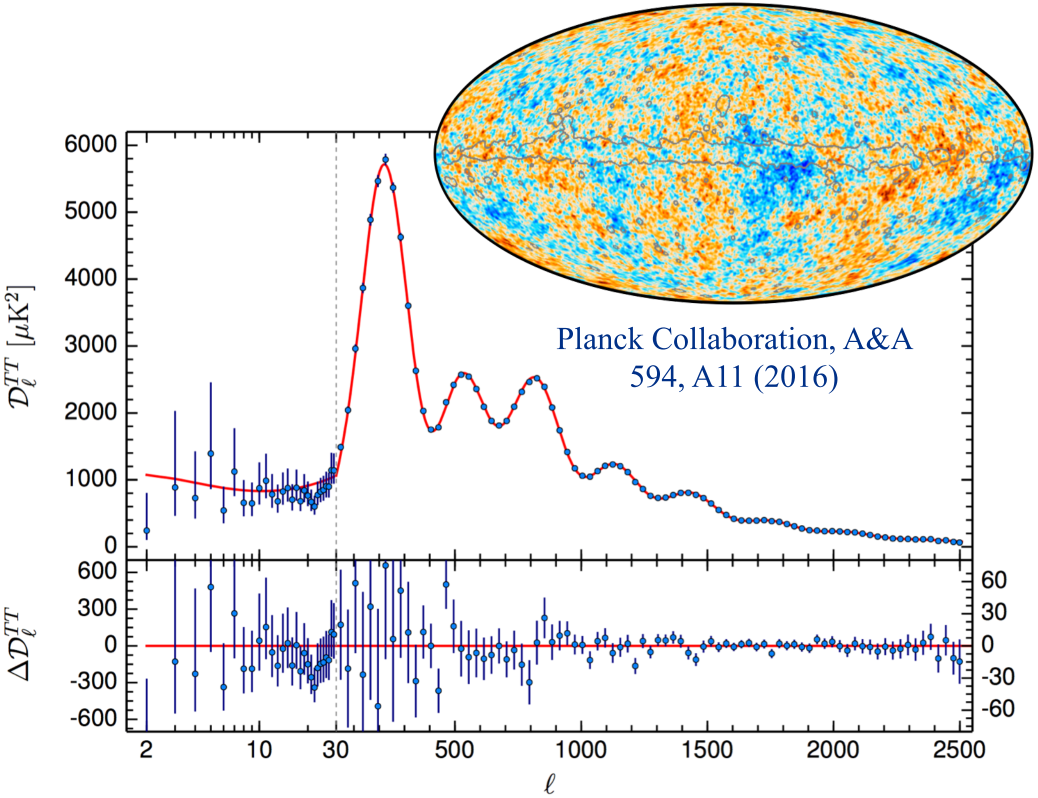
Dark Matter

Modern measurements of the CMB (in combination with other observations) overwhelmingly support the hypothesis of:

- **Cold** = non-relativistic; specifically, the galactic velocity of DM is roughly 10^{-3} *c*
- **Non-baryonic** = DM is *not* made up of protons/neutrons
- **Particle** = evidence points to a new particle, rather than modifications to our understanding of gravity
- **Dark** = net-*charge* of 0*; DM does not interact directly via the electromagnetic force
- **Matter** = DM has *mass*

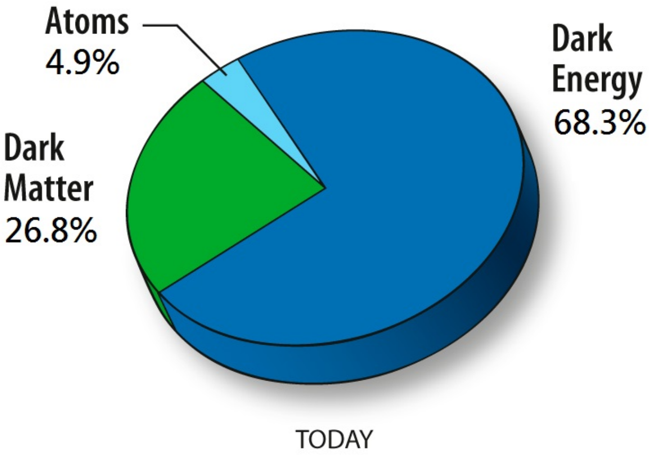


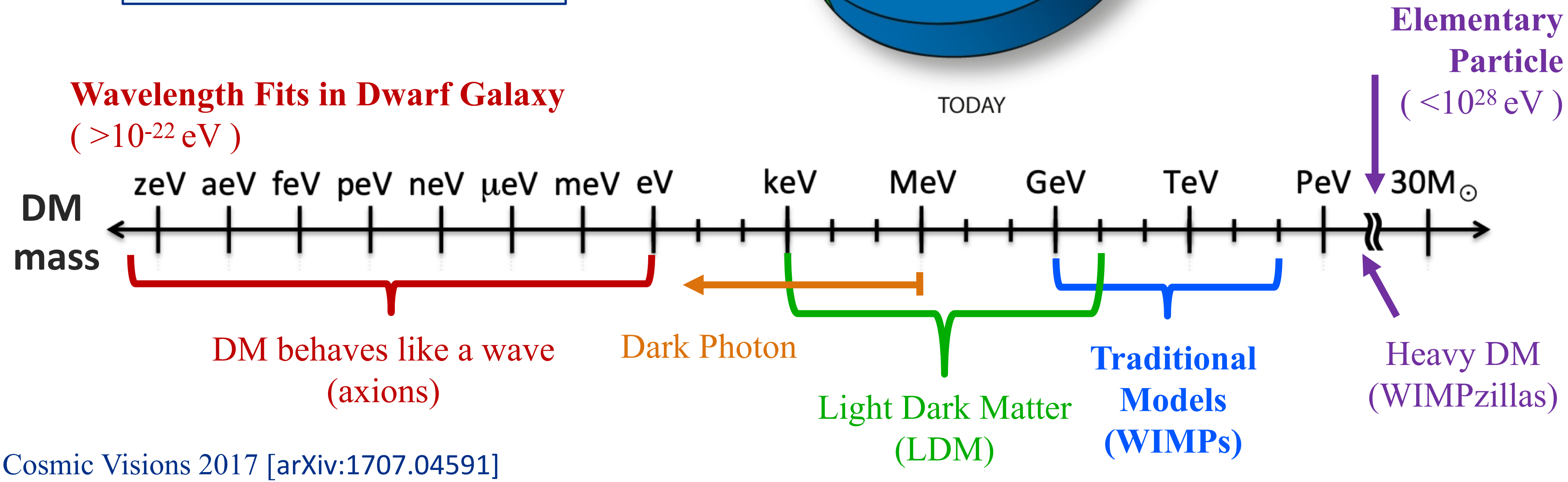
Dark Matter

Gravity – YES (*matter*)

EM – No* (*dark*)

weak? – Not* the $W^{\pm}/Z$





Cosmic Visions 2017 [arXiv:1707.04591]

Dark Matter – Particle Direct Detection

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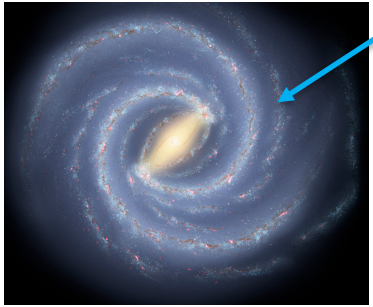
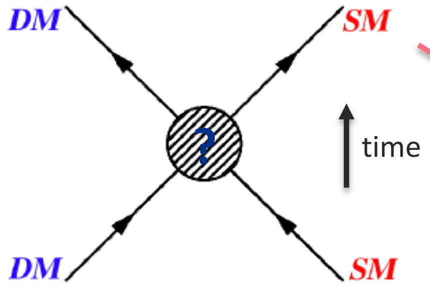
A priori, there is no reason DM has to have a non-gravitation interaction with normal matter. However, adding one can solve a variety of theoretical problems.

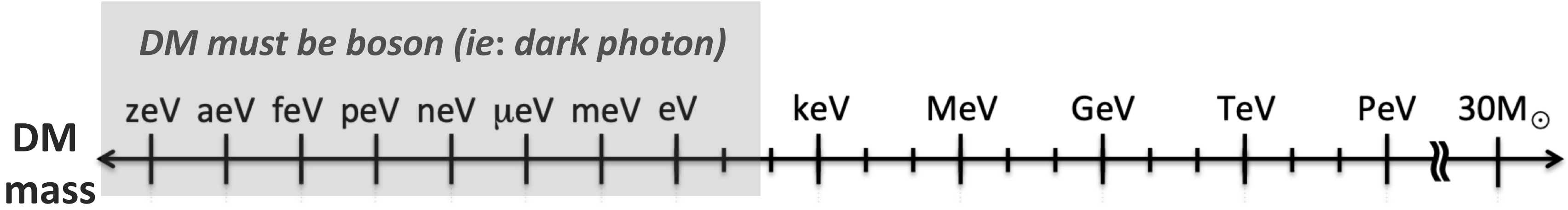
Milky Way





Detector

Direct Detection:
from bottom-to-top, you have *galactic* DM scattering off of normal matter



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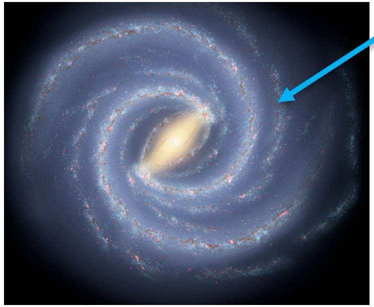

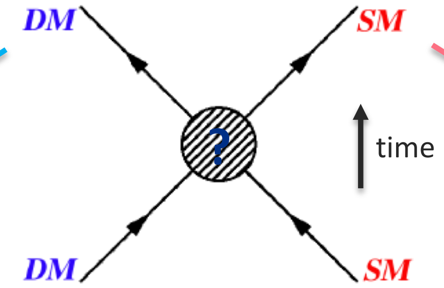

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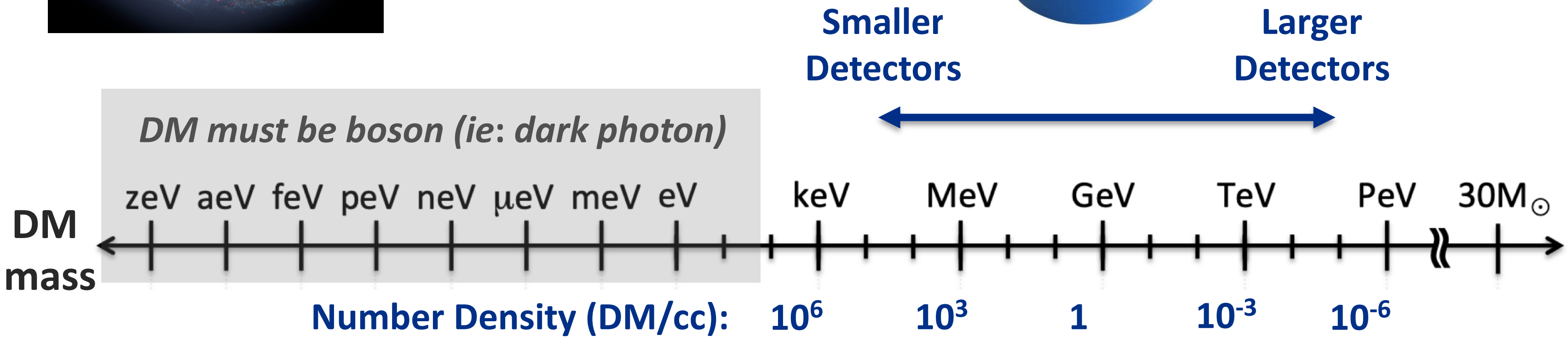

Snowmass 2021 – Dark Matter Direct Detection

Decadal Overview of Future Large-Scale Projects		
Frontier/Decade	2025 - 2035	2035 -2045
Energy Frontier	U.S. Initiative for the Targeted Development of Future Colliders and their Detectors	
		Higgs Factory
Neutrino Frontier	LBNF/DUNE Phase I & PIP- II	DUNE Phase II (incl. proton injector)
Cosmic Frontier	Cosmic Microwave Background - S4	Next Gen. Grav. Wave Observatory*
	Spectroscopic Survey - S5*	Line Intensity Mapping*
	Multi-Scale Dark Matter Program (incl. Gen-3 WIMP searches)	
Rare Process Frontier		Advanced Muon Facility

Table 1-1. *An overview, binned by decade, of future large-scale projects or programs (total projected costs of $500M or larger) endorsed by one or more of the Snowmass Frontiers to address the essential scientific goals of the next two decades. This table is not a timeline, rather large projects are listed by the decade in which the preponderance of their activity is projected to occur. Projects may start sooner than indicated or may take longer to complete, as described in the frontier reports. Projects were not prioritized, nor examined in the context of budgetary scenarios. In the observational Cosmic program, project funding may come from sources other than HEP, as denoted by an asterisk.*

Butler et al, Snowmass Report (2023) [arXiv:2301.06581]

Snowmass 2021 – Dark Matter Direct Detection

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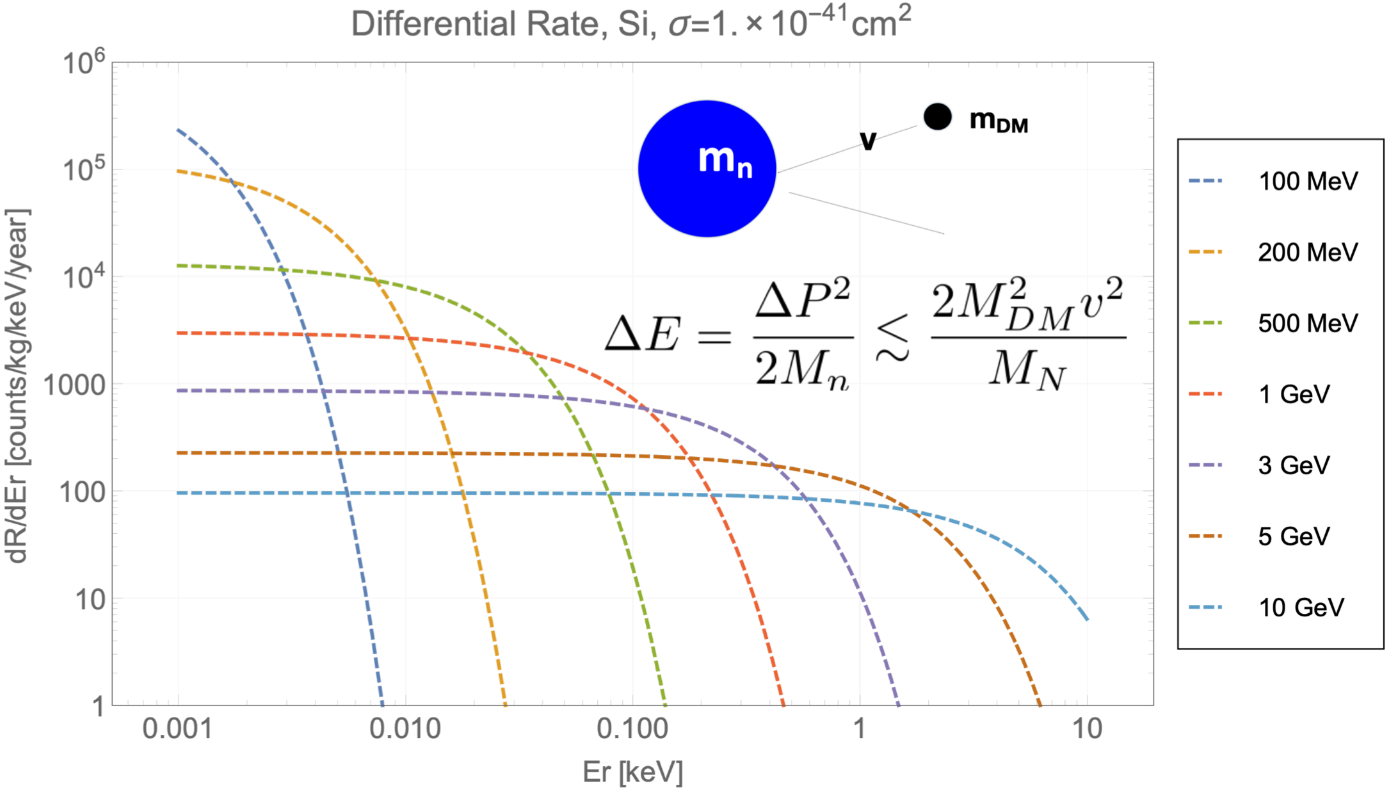
Determine the Nature of Dark Matter. The gravitational evidence for dark matter is overwhelming. We have many ideas for what dark matter could be, with a handful of particularly compelling candidates with viable cosmological histories. The number of strong candidates inspires a multifaceted campaign to determine the nature of dark matter, leveraging underground facilities, quantum sensors, telescopes, and accelerator-based probes.

excerpt from P5

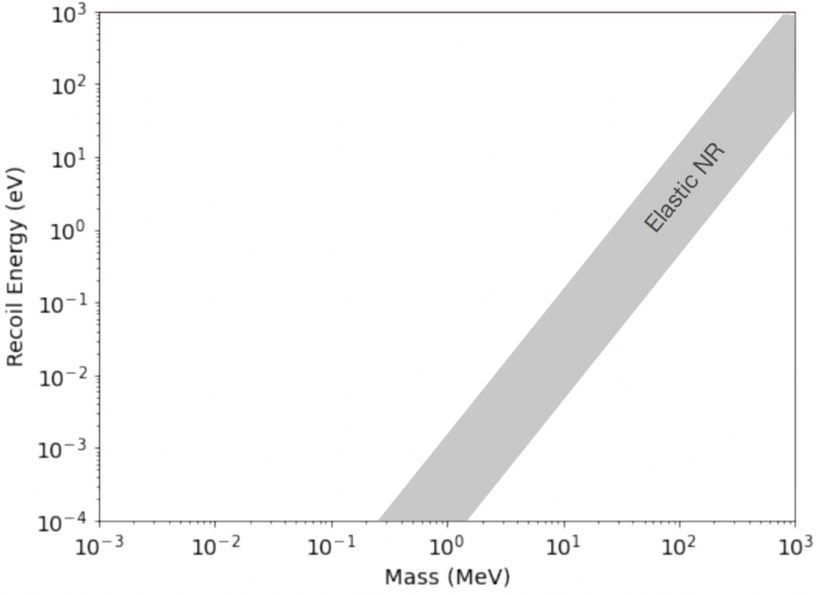
Direct Detection of Particle Dark Matter



$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

Direct Detection of Particle Dark Matter

Fig. adapted from 2203.08297

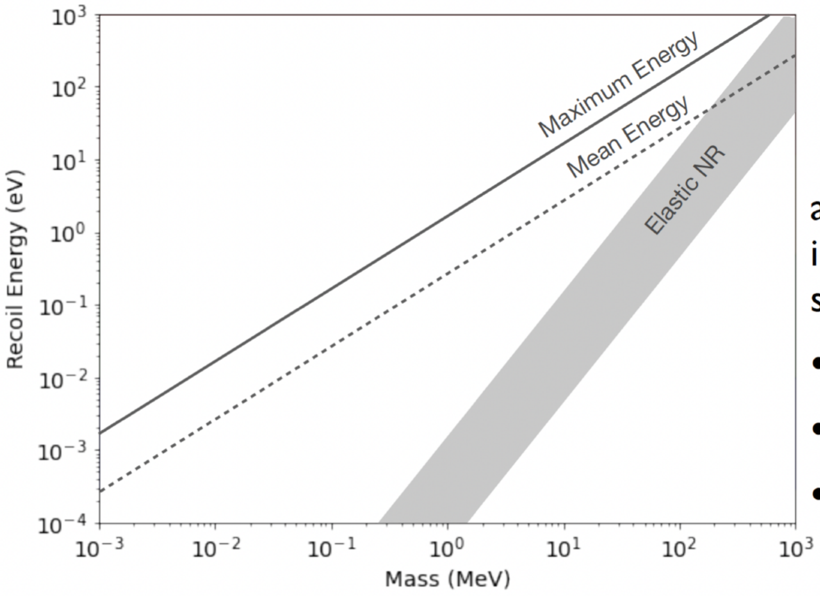


elastic DM-nucleus scattering:

$$E_{\mathrm{NR}} = \frac{q^2}{2m_N} \sim 1\ \mathrm{eV} \left(\frac{m_{\mathrm{DM}}}{100\ \mathrm{MeV}}\right)^2 \left(\frac{28\ \mathrm{GeV}}{m_N}\right)$$

Direct Detection of Particle Dark Matter

Fig. adapted from 2203.08297

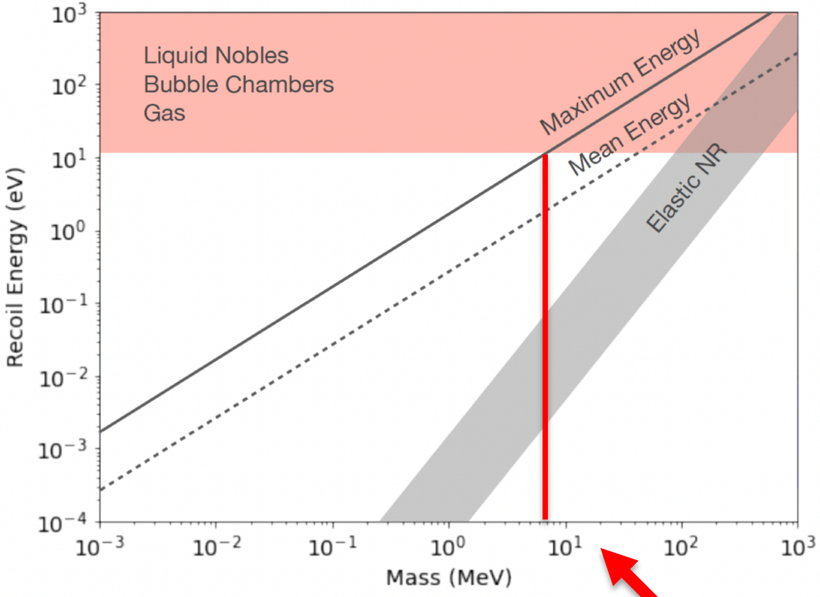


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal
- DM scattering w/ collective modes (e.g. phonons, magnons)

Direct Detection of Particle Dark Matter

Fig. adapted from 2203.08297



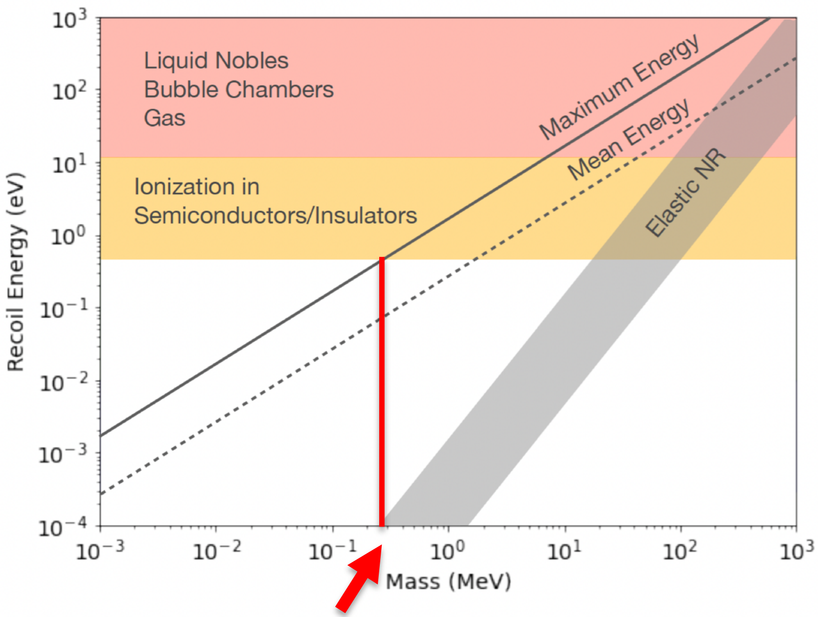
$\Delta E \sim 10$ eV

e.g. Xe, Ar, He

fundamental lower limit

Direct Detection of Particle Dark Matter

Fig. adapted from 2203.08297



fundamental lower limit

$\Delta E \sim 1$ eV

e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

OSCURA

Direct Detection of Particle Dark Matter

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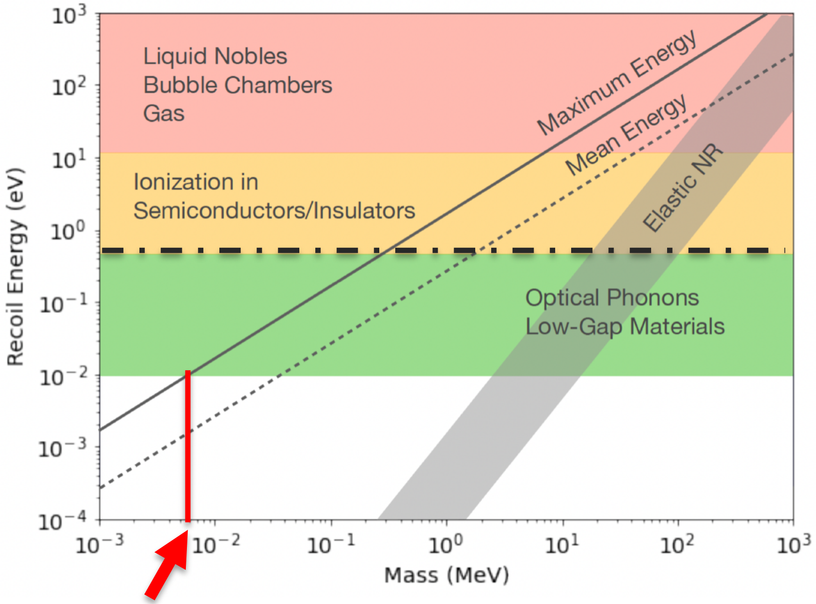
Fig. adapted from 2203.08297



fundamental lower limit

Anything beyond this point is novel detector R&D

$\Delta E \sim 10 - 100$ meV

e.g. GaAs, sapphire, Dirac materials, doped s/c, …

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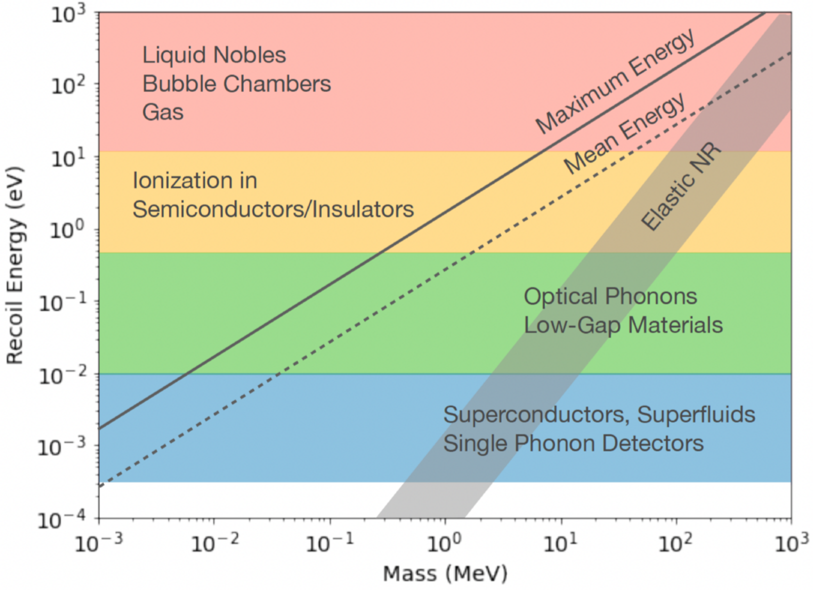
Direct Detection of Particle Dark Matter

Fig. adapted from 2203.08297



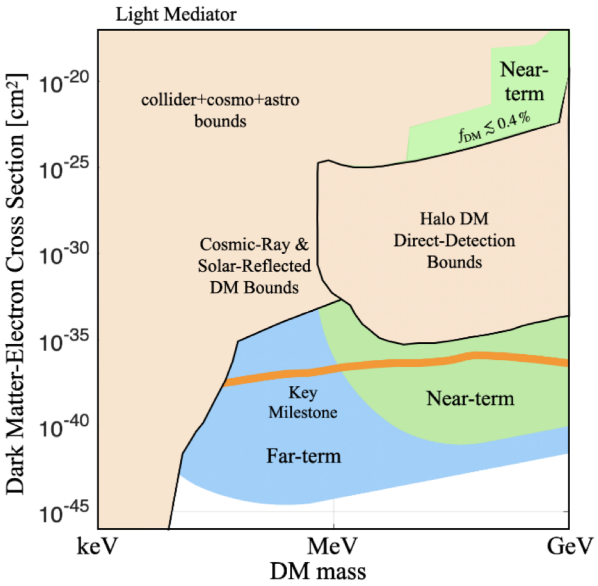
$\Delta E \sim 1\ \mathrm{meV}$

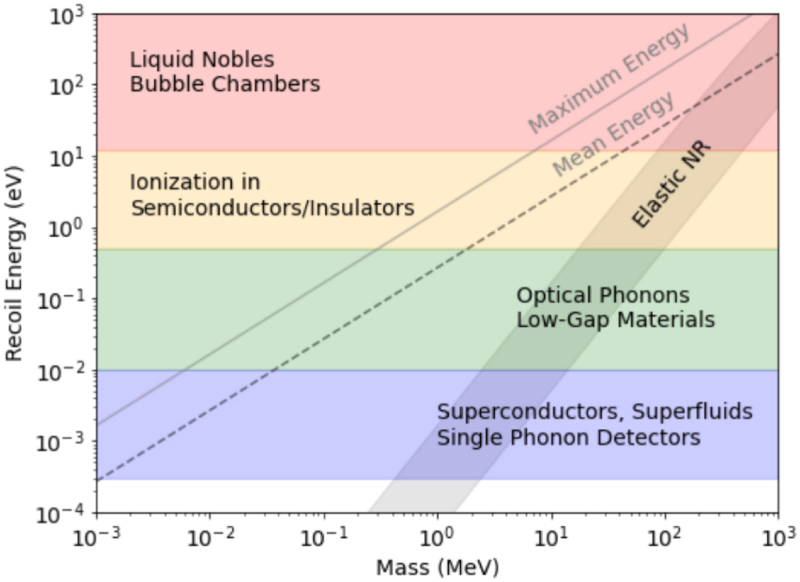
e.g. superfluids, superconductors

Direct Detection of Particle Dark Matter

Development of lower-threshold detectors is a huge focus of Snowmass and P5 report

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

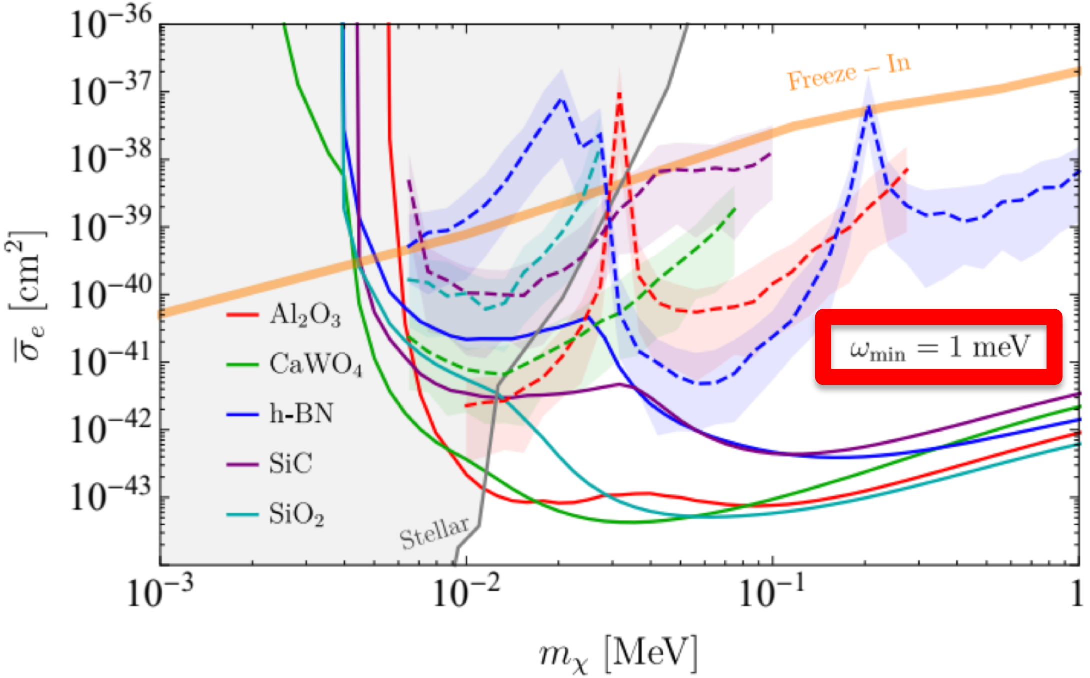




Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Direct Detection of Particle Dark Matter

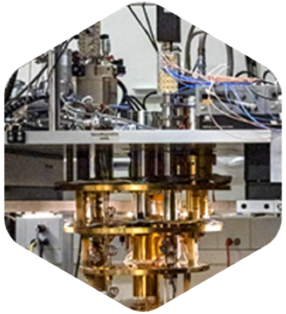
- Solid projections indicate 95% CL with single-phonon excitations in various materials for 1 kg-yr
- Dashed lines indicate where daily modulations become statistically significant
- For a sapphire target, 30 g-days with no background already probes **ALL** of freeze-in



Mitridate et al, (2022) [arXiv:2203.07492]

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

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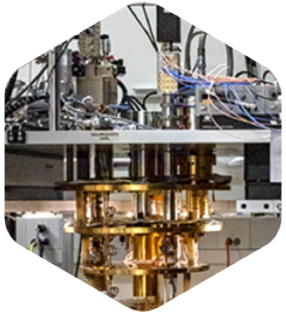

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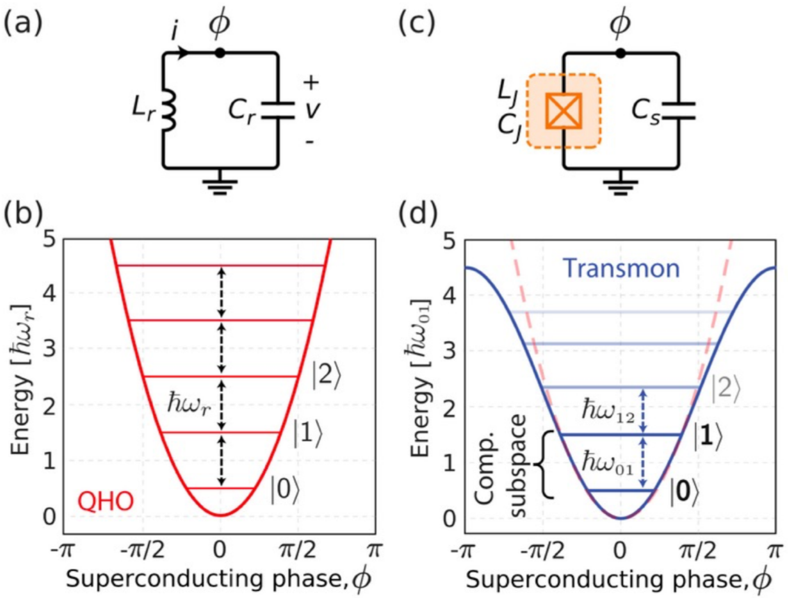
Defining some terminology

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



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

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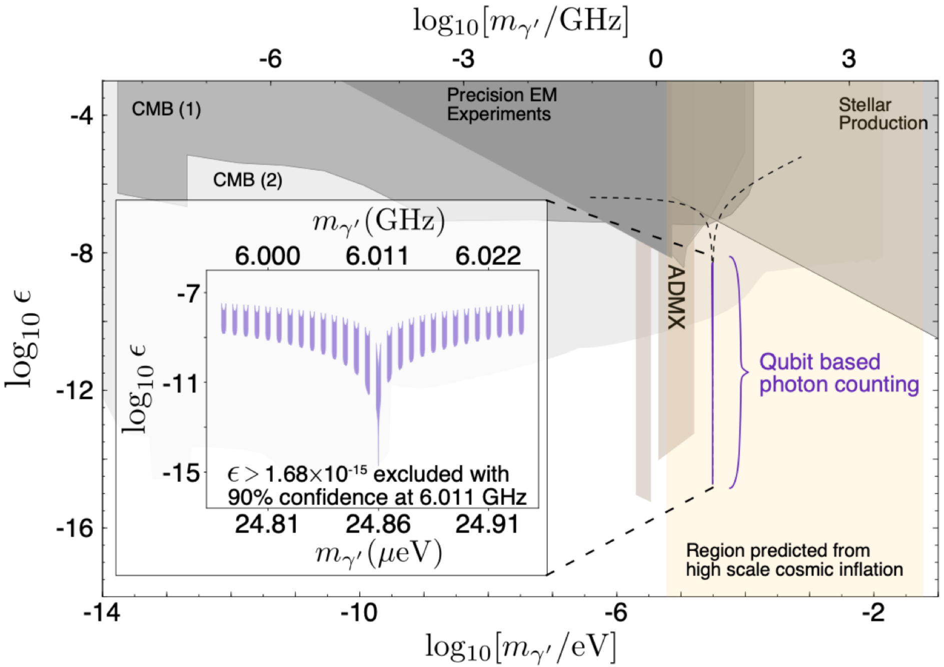

Dixit et al, PRL 126, 141302 (2021) [arXiv:2008.12231]

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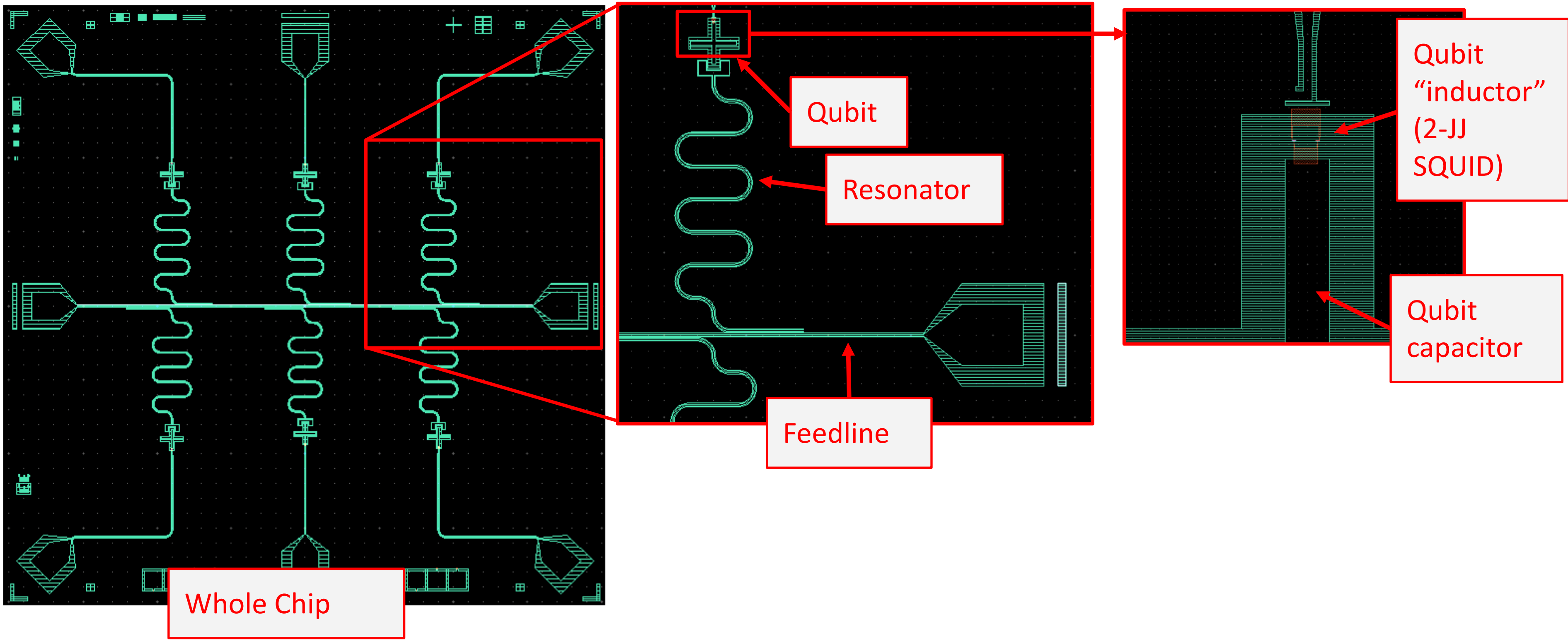
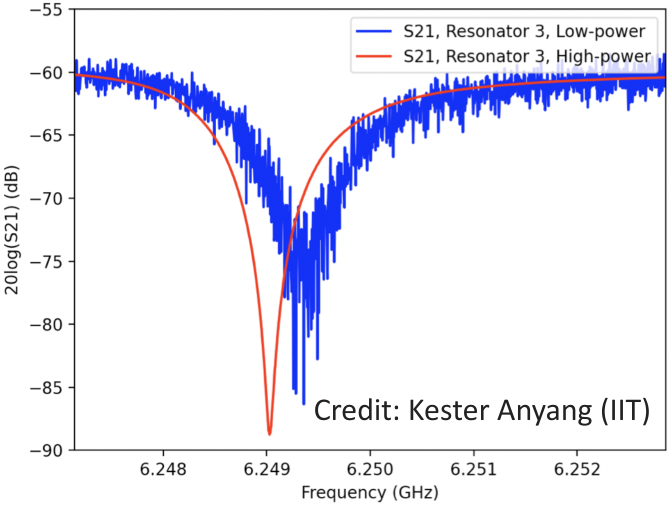
Defining some terminology

Qubits read out using coplanar waveguide resonators coupled to a shared RF feedline.



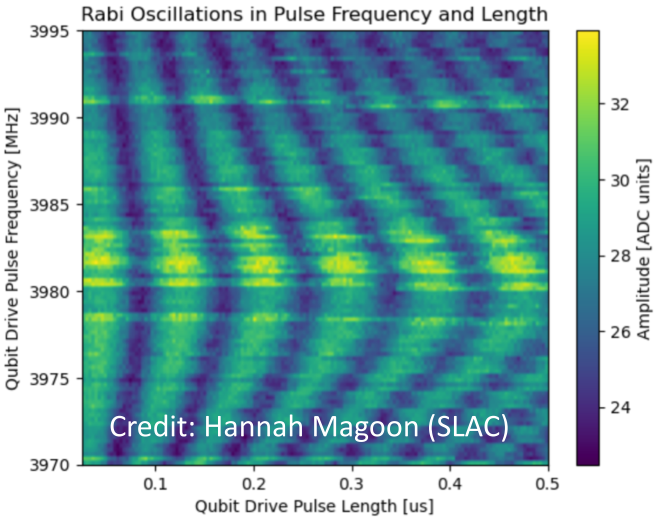
Defining some terminology

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



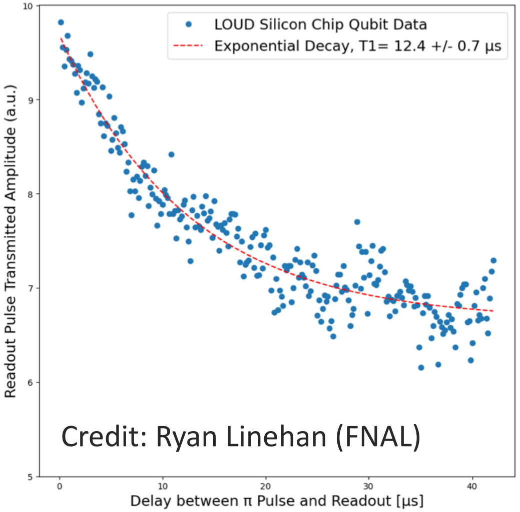
Purpose: determine that the qubit (i.e. the Josephson Junction) is "alive", i.e. not burned out

Qubit spectroscopy + Rabi Oscillations



Purpose: find the qubit excitation frequency and calibrate a $|0\rangle \rightarrow |1\rangle$ pulse

T1 Relaxation Time

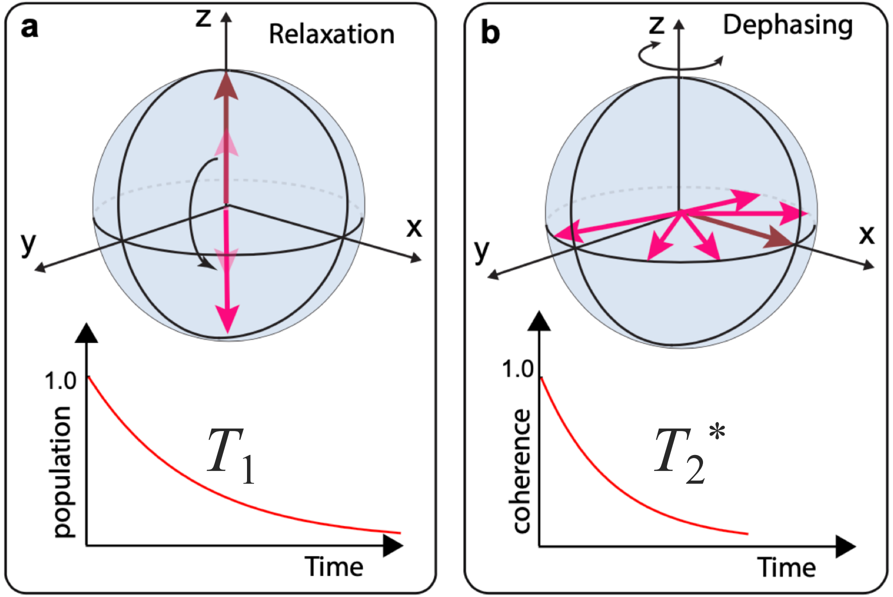


Purpose: Probe qubit decoherence times

Defining some terminology

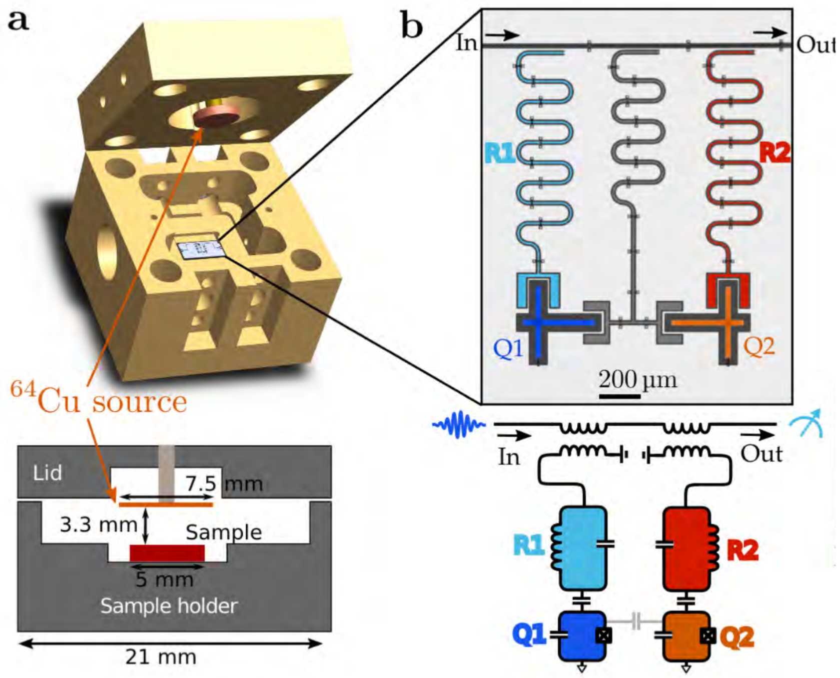
Could they be useful for particle dark matter detection?
(Spoiler: yes!)

- Decoherence – loss of the qubit state due to relaxation or dephasing
    - **Bad for QIS**
    - **Good for DM**
- 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]

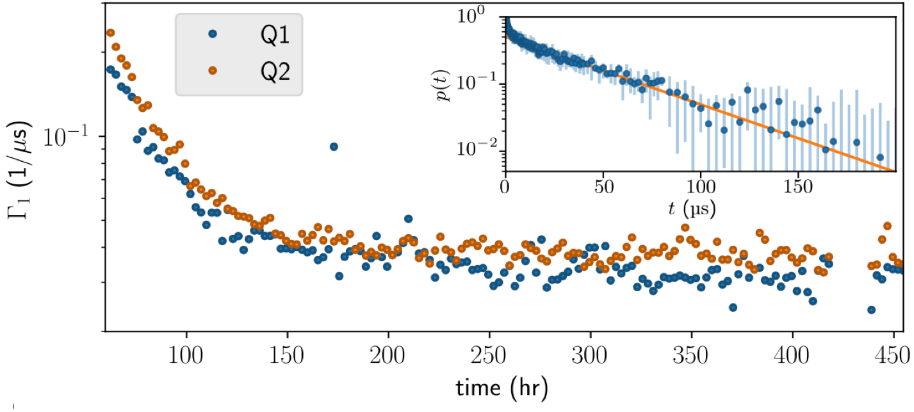
Radiation-Induced Decoherence

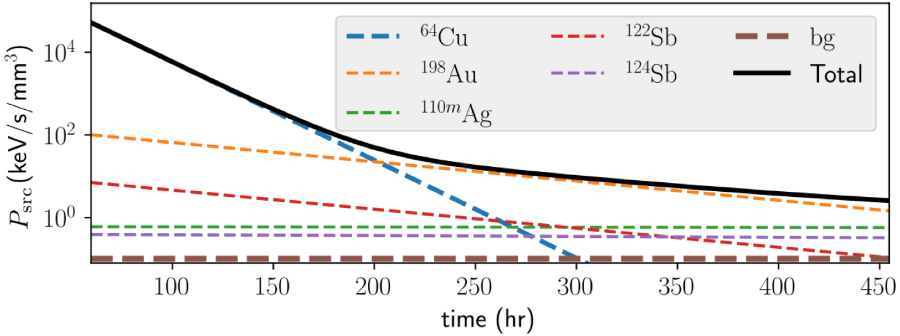


- Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source

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

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!

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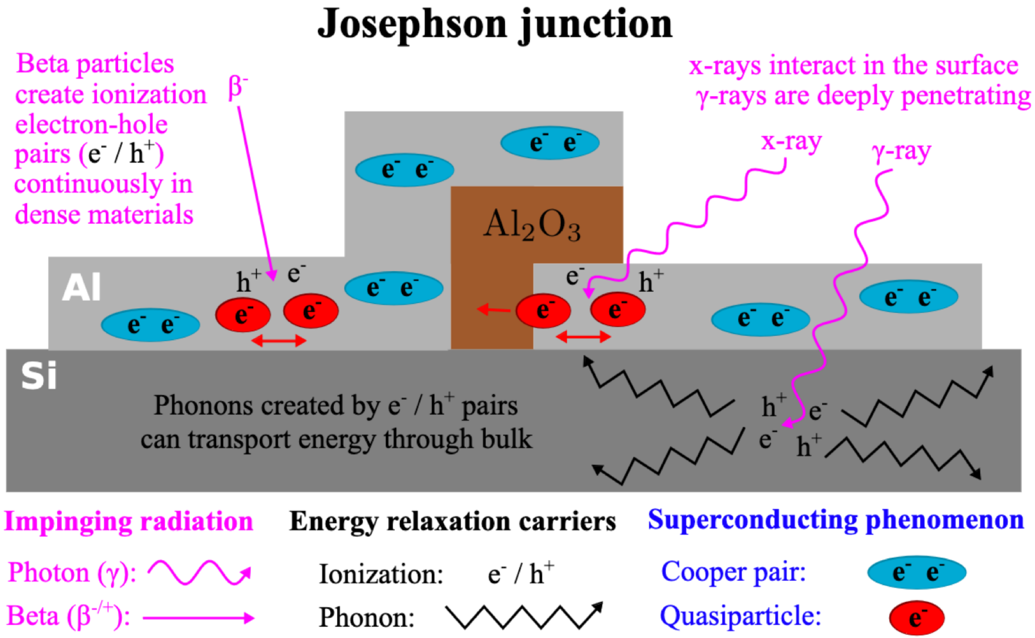
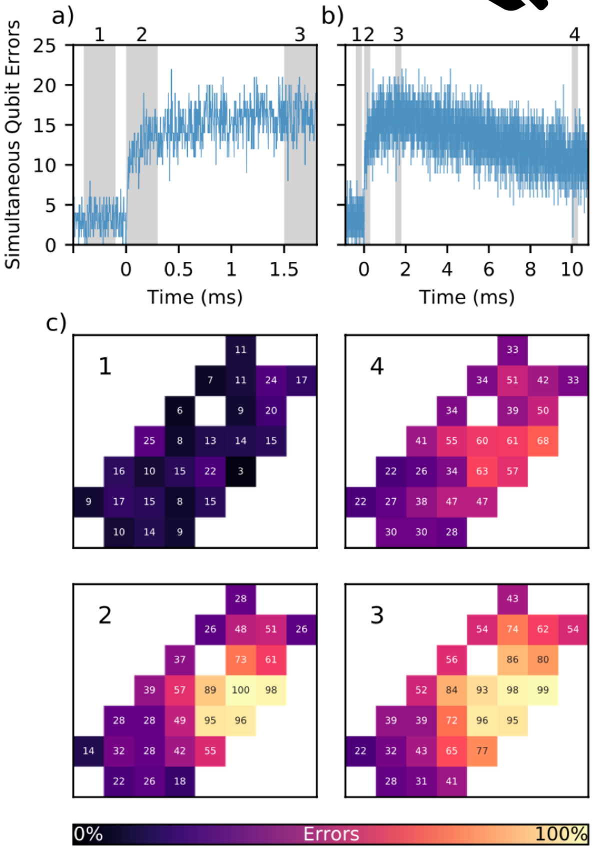


- Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source
- Clear correlation between T_1 and decay of ^{64}Cu source in two separate qubit sensors!
- Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs *can be* a limiting factor in superconducting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

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

Radiation-Induced Decoherence

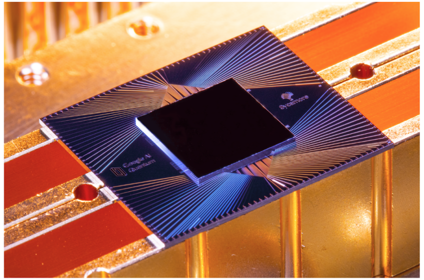
- Google ran a multiplexed (Sycamore) qubit chip and found similar behavior!
- **Correlated relaxation errors across the device due to energy depositions in common substrate (information destroyed every 10s!)**
- **Hypothesis: energy depositions in a substrate cause *correlated* decoherence across qubits due to quasiparticle poisoning**
- Caveat: These events have keV-MeV energy depositions

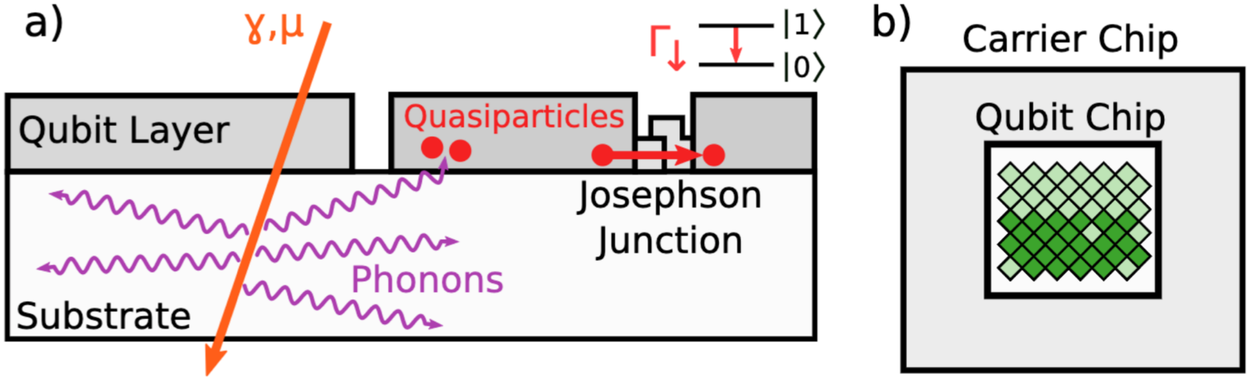


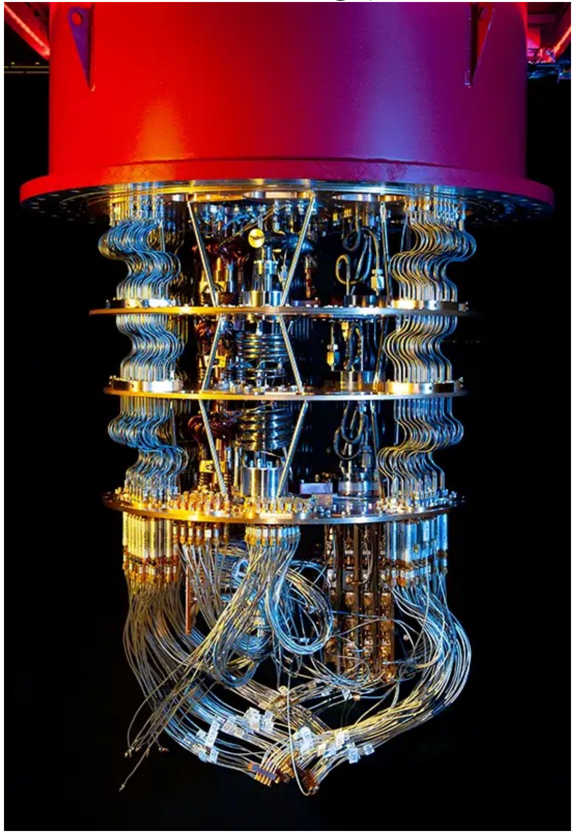
McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

Quantum Computing and Background Radiation

Hypothesis: Energy depositions in a substrate cause correlated decoherence across qubits due to quasiparticle poisoning **that can be exploited as a means of particle (dark matter) detection**







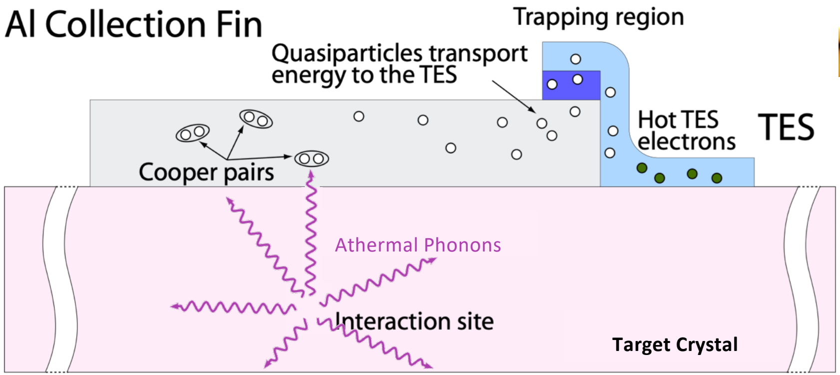
Google Sycamore team: arXiv:2104.05219

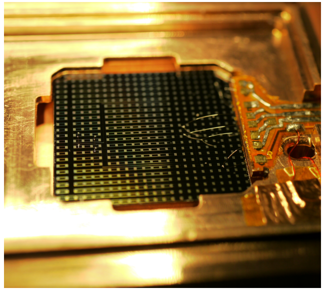
Quantum Computing and Background Radiation

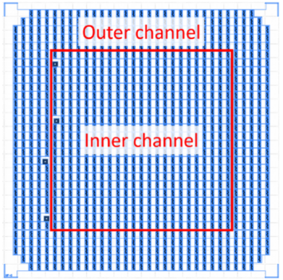
We have all the tools to work on this problem!

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

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

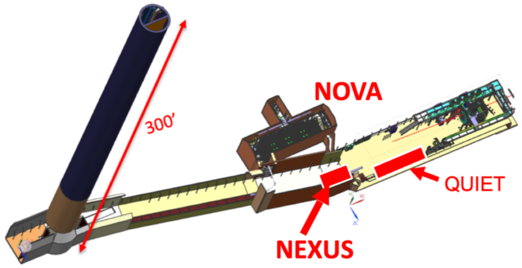




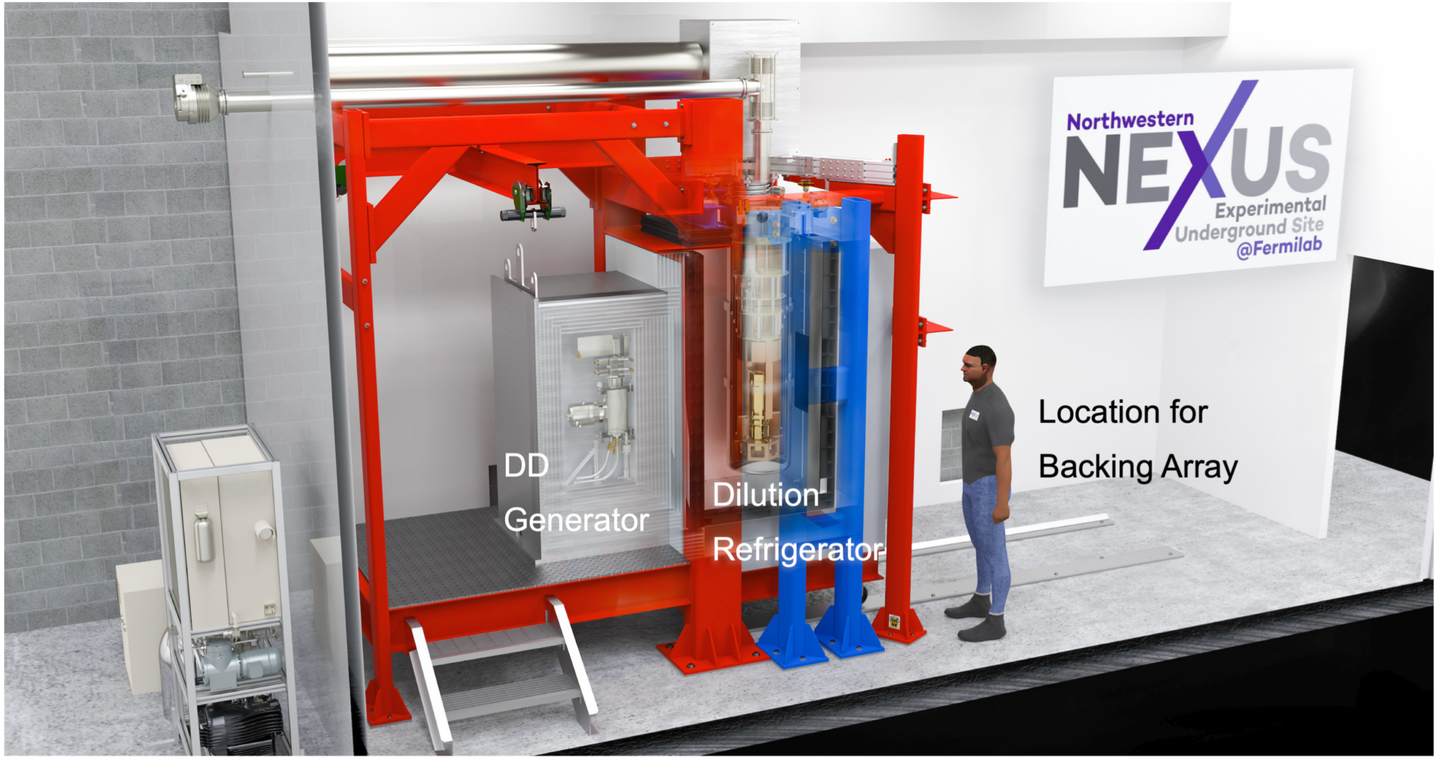


Test Facilities – MINOS Near Detector Hall

- 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



Test Facilities – NEXUS @ FNAL

Test Facilities – NEXUS @ FNAL

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

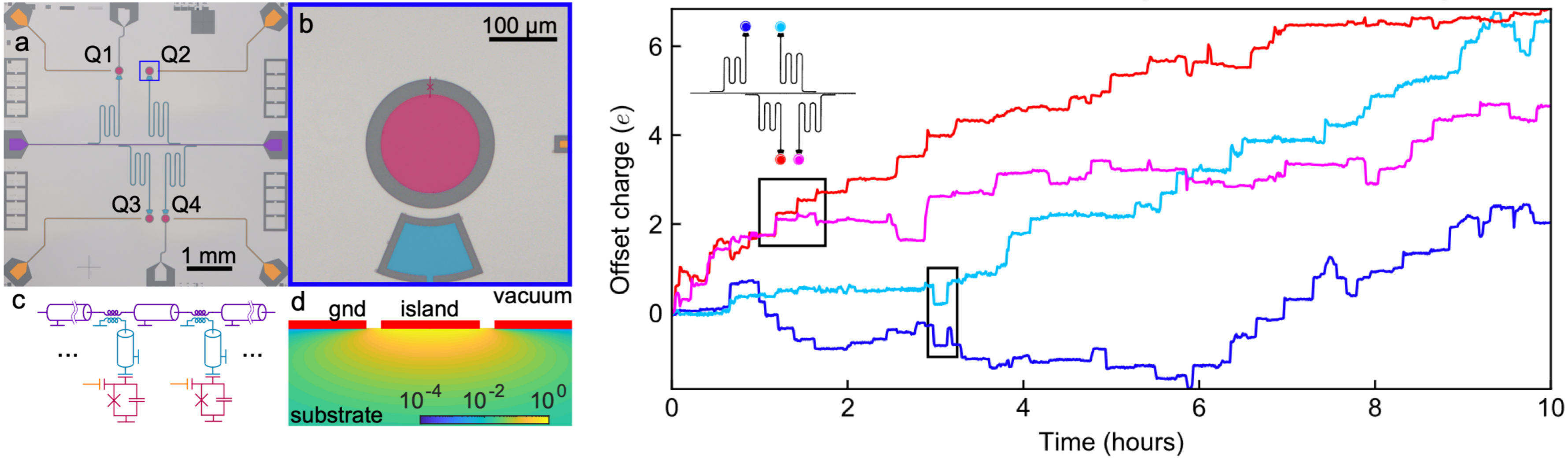
- Developed new modular architecture for neutrino physics detectors
- Deploying at ILL nuclear reactor next year
- R&D for future CUPID upgrades

Low-background Quantum Computing

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

Radiation-Induced Decoherence

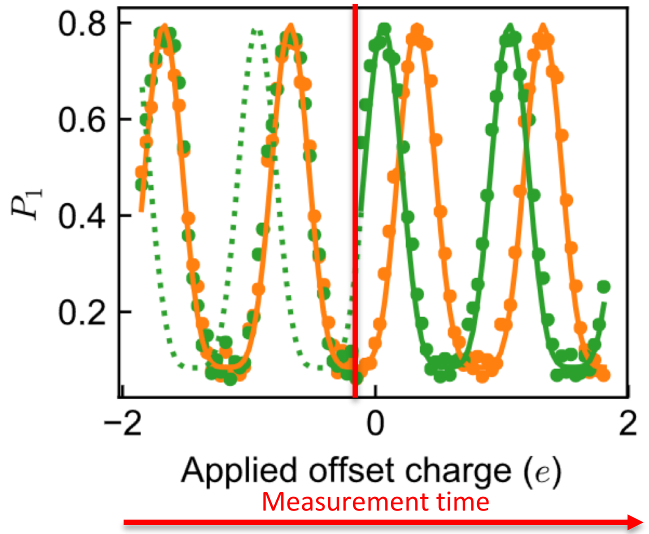
Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]



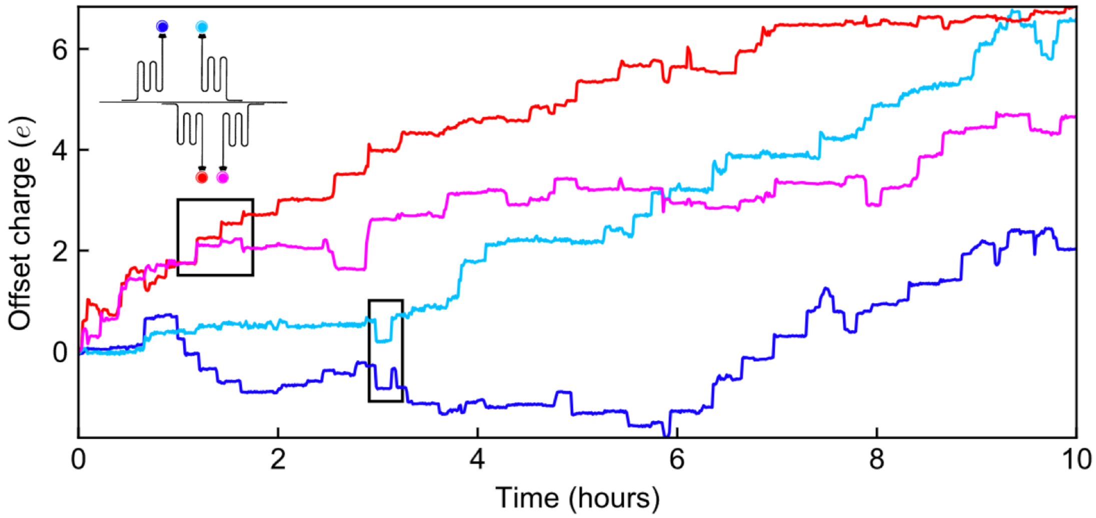
- Chip w/ four weakly charge-sensitive transmon qubits demonstrates clear **correlated** offset charge jumps over long times
- Correlated jumps → simultaneous quasiparticle poisoning

Radiation-Induced Decoherence

Ramsey amplitude vs. offset charge

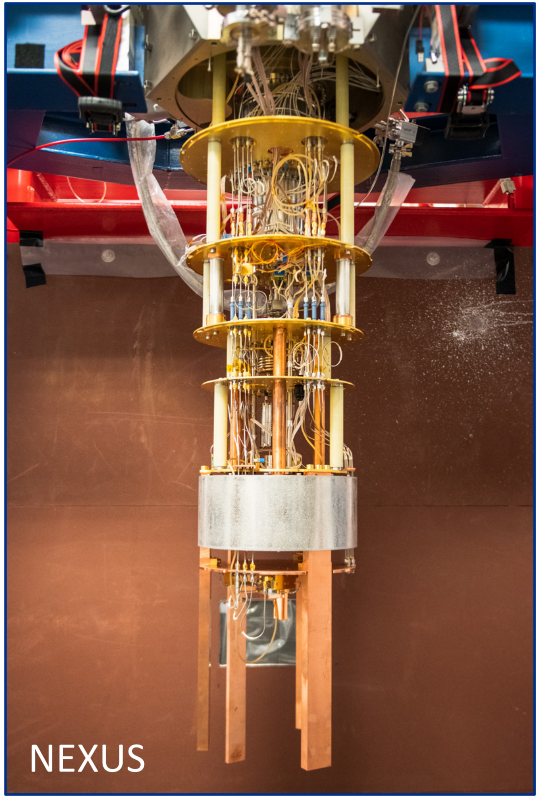


Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]



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

Studying Qubit Correlations in NEXUS



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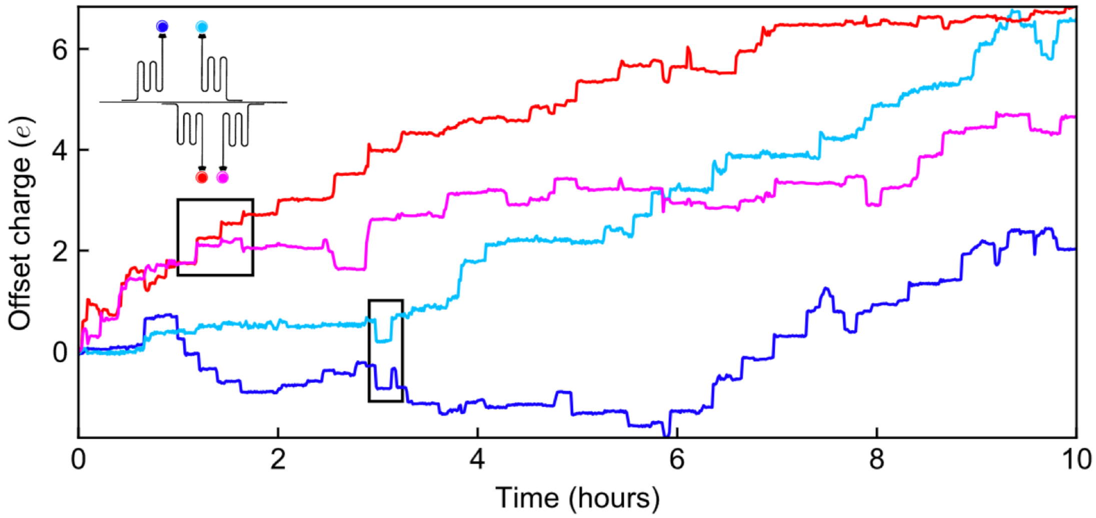


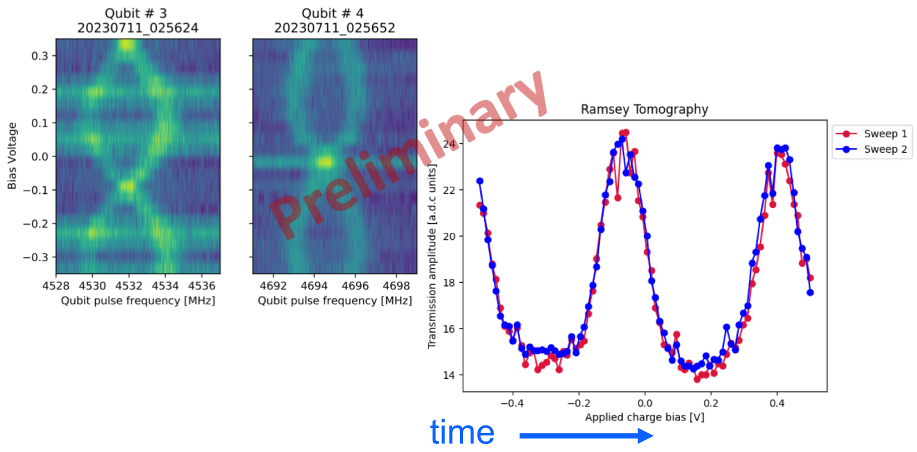
- Repeat this measurement in NEXUS w/ x100 muon flux reduction and varying shielding configurations

*Work by Kester Anyang, **DB**, Daniel Bowring, Grace Bratrud, Arianna Colon Cesani, Tali Figueroa-Feliciano, Riccardo Gualtieri, Sami Lewis, Ryan Linehan, Hannah Magoon, Dylan Temples, Grace Wagner, Jialin Yu*

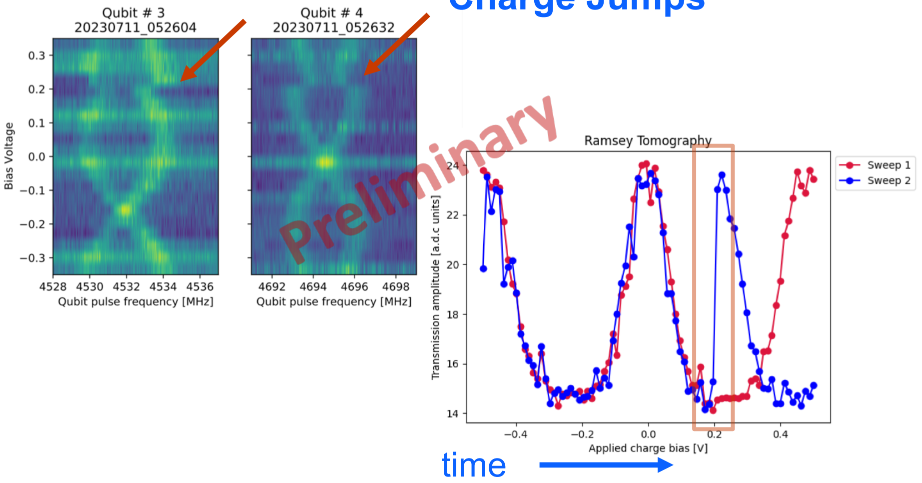
Studying Qubit Correlations in NEXUS

QUANTUM SCIENCE CENTER

No Charge Jumps



Charge Jumps



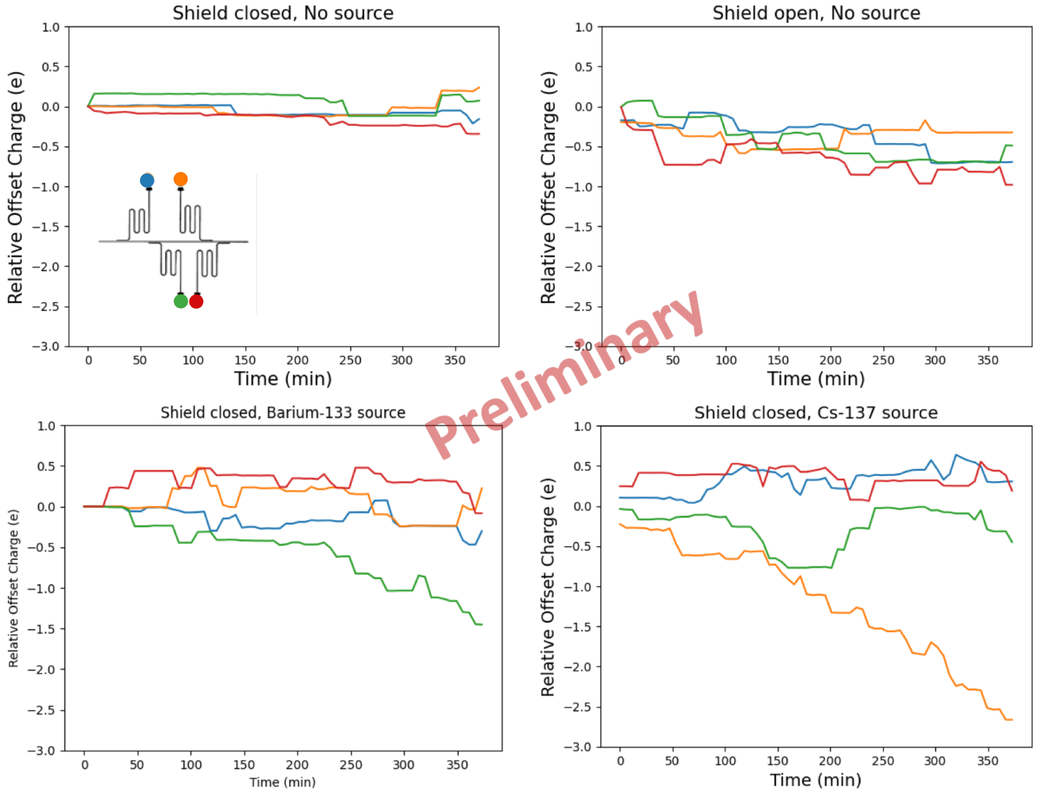
- Ran UW chip underground at NEXUS
- Read out qubits consecutively while sweeping applied charge bias for 5-10 hours
- Identify and measure charge jumps using analysis and fitting techniques
  - Charge jumps are seen as disruptions in the periodic behavior of amplitude

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

Studying Qubit Correlations in NEXUS

QUANTUM SCIENCE CENTER

- 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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Studying Qubit Correlations in NEXUS

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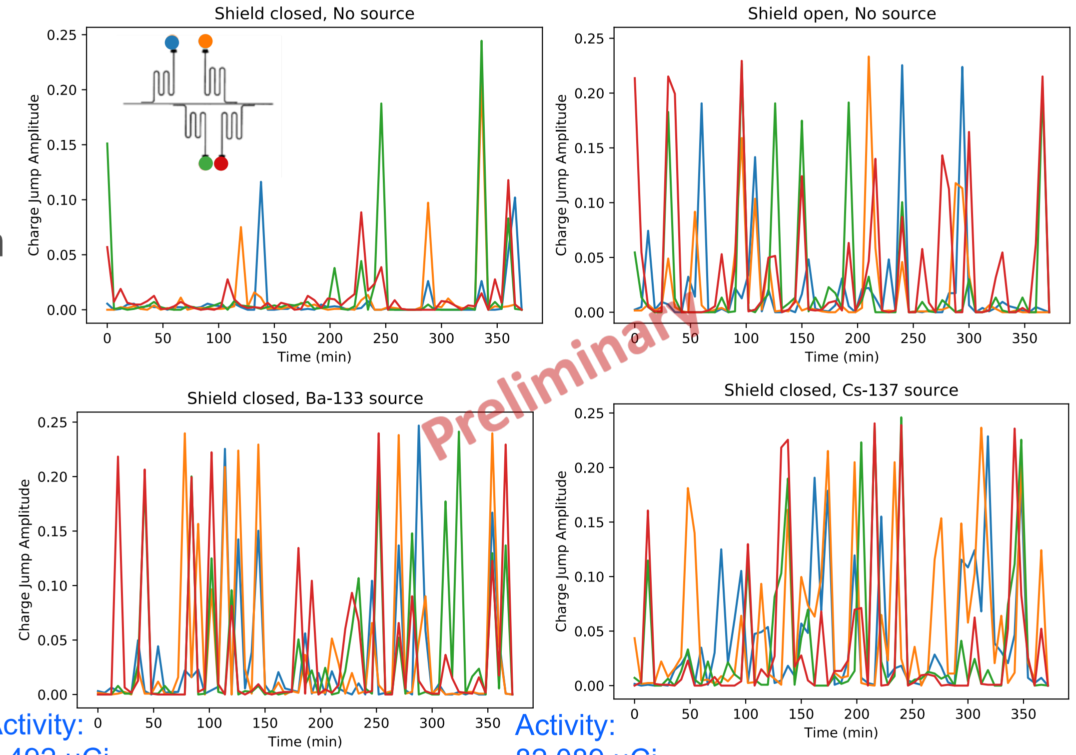
GEANT4 Monte Carlo model under development



Activity: 0.492 μCi

Activity: 82.089 μCi

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

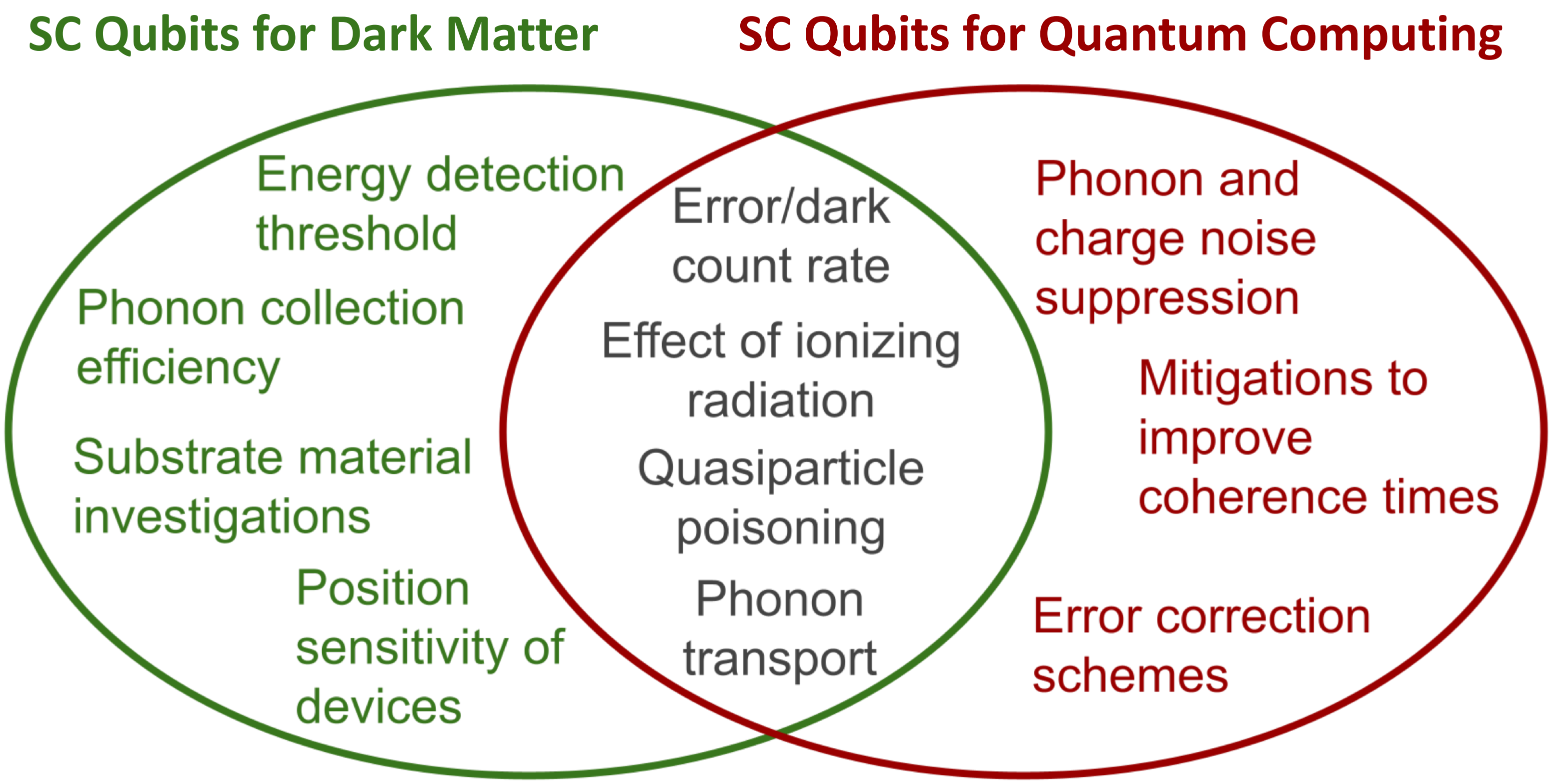
Looking Forward – Underground studies in QUIET
Quantum Underground Instrumentation Experimental Testbed

QUANTUM SCIENCE CENTER

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

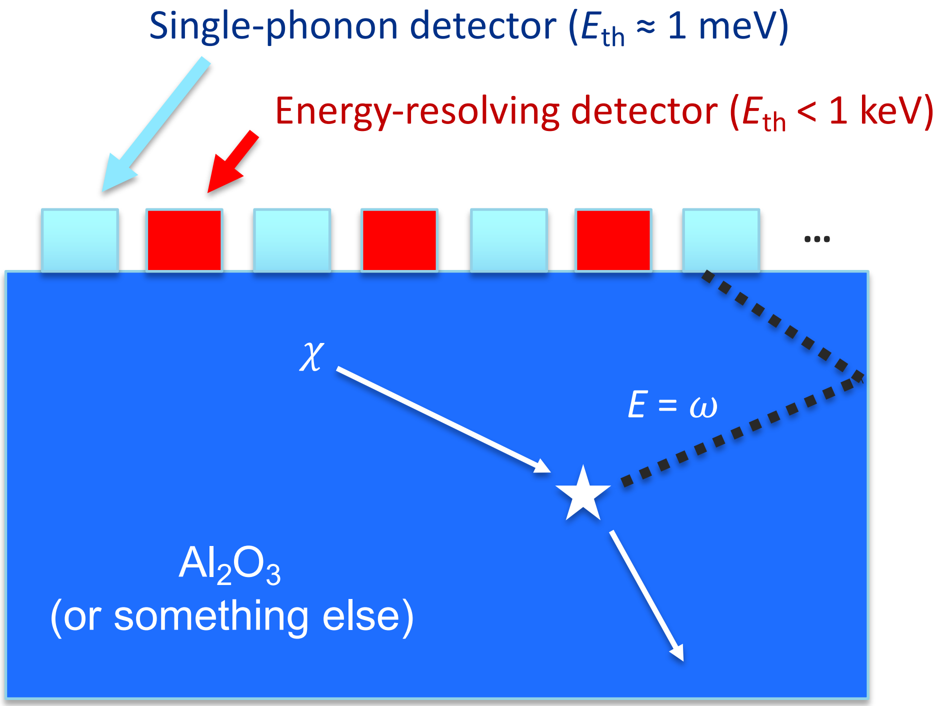
- Oxford Proteox w/ up to 16(48) NbTi(SS) RF lines
- 250 ft^2 Class 10,000 clean room
- 50 ft^2 antechamber for gowning and material cleaning
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Facility is complete! including electrical power, chilled water, network, and fire suppression systems
- Initial fridge test reached 8.9mK w/ no issues

How does this impact QIS technology development?



Designing an Experiment – Big Picture

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

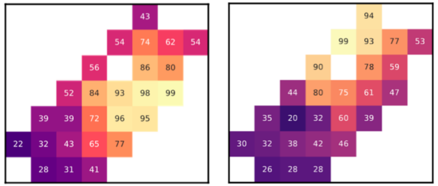
Designing an Experiment – Big Picture

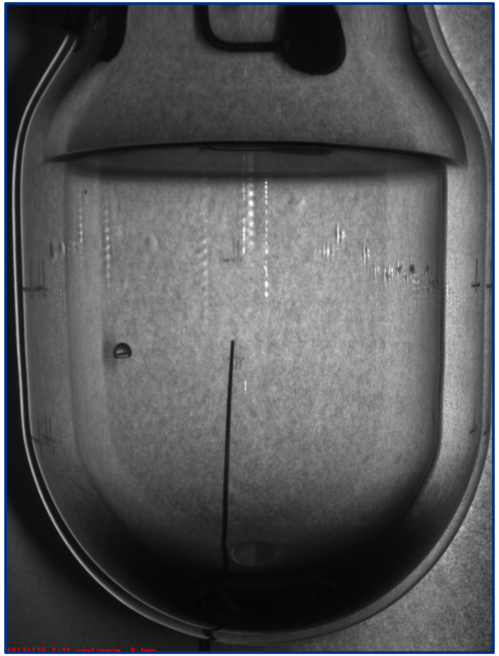
QUANTUM SCIENCE CENTER

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 $|1\rangle \rightarrow |0\rangle$)

- 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, limited energy information (at low energies)
  - → **but yes to position information!**



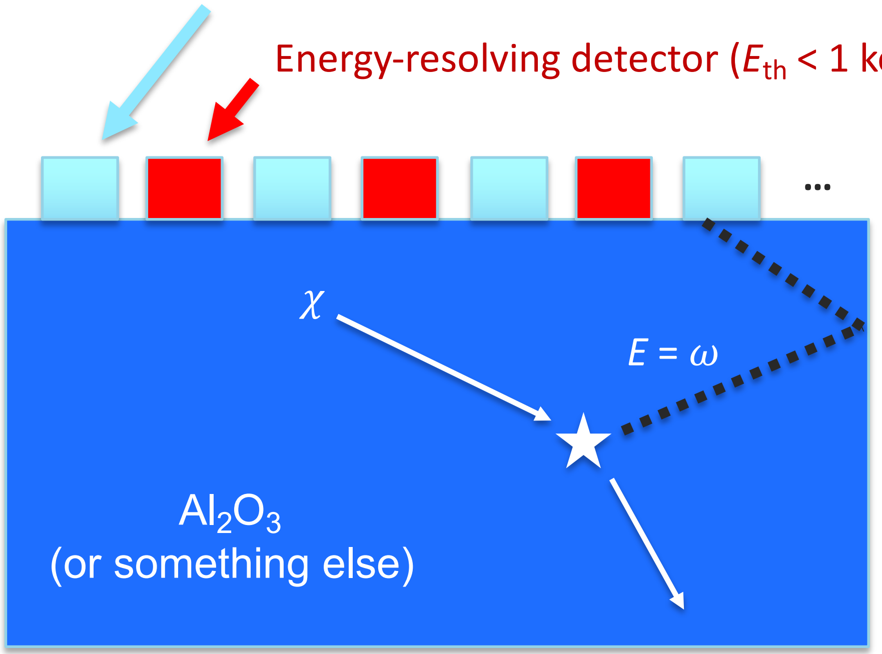


McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

Designing an Experiment – Big Picture

QUANTUM SCIENCE CENTER

Proposing a novel, multiplexed quantum device for particle physics detection



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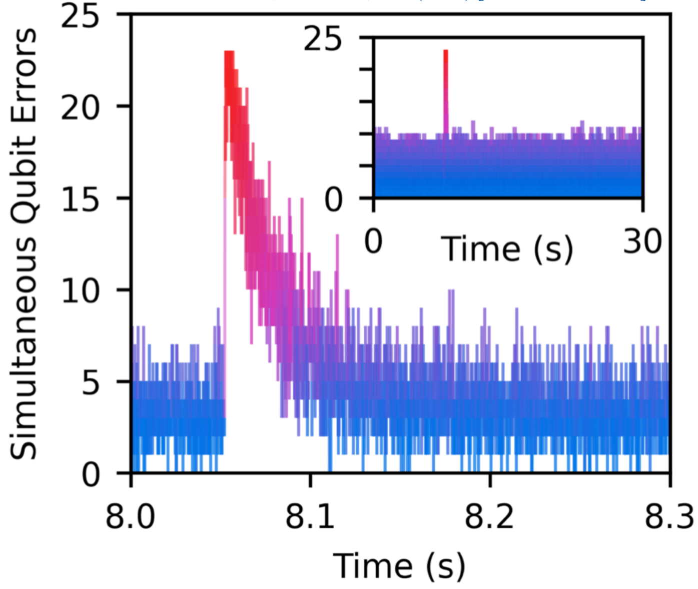
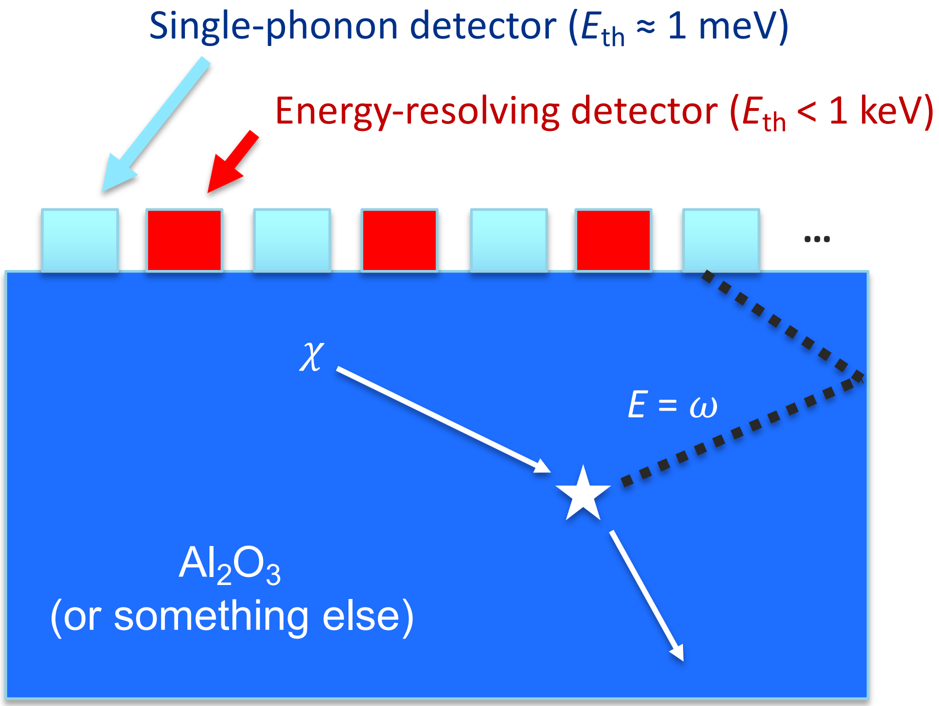


Fermilab

Designing an Experiment – Big Picture

Proposing a novel, multiplexed quantum device for particle physics detection



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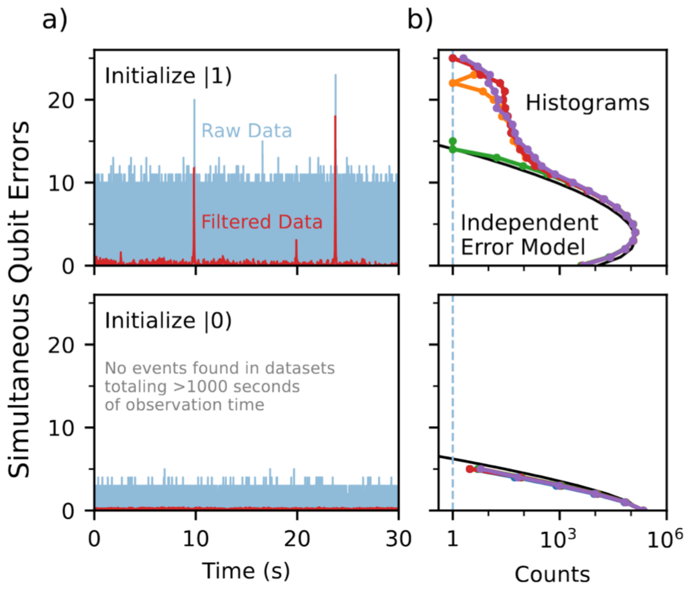
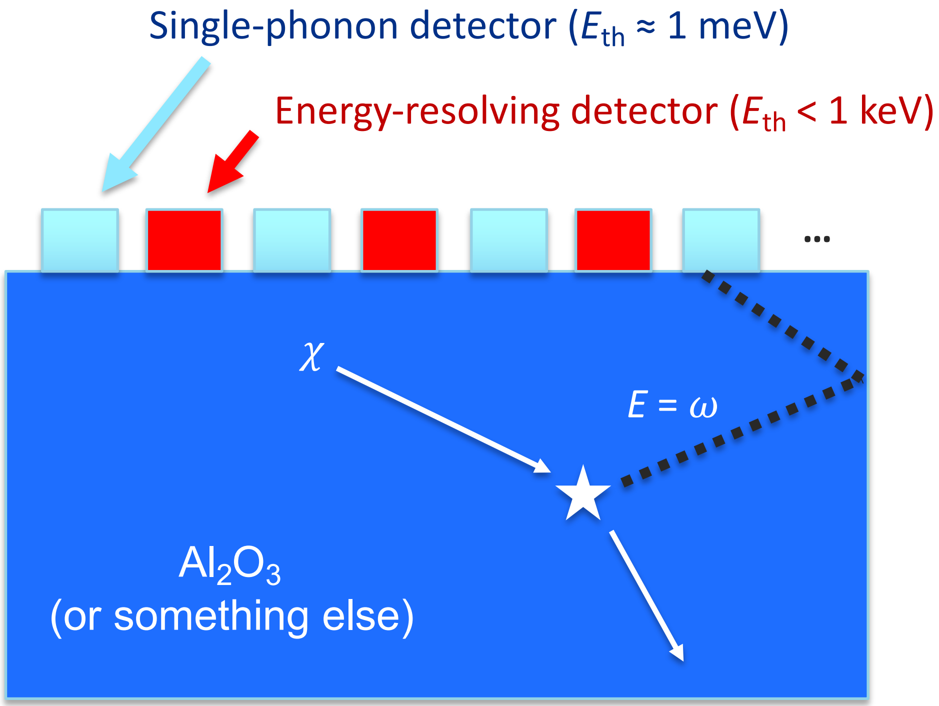


Designing an Experiment – Big Picture

Proposing a novel, multiplexed quantum device for particle physics detection



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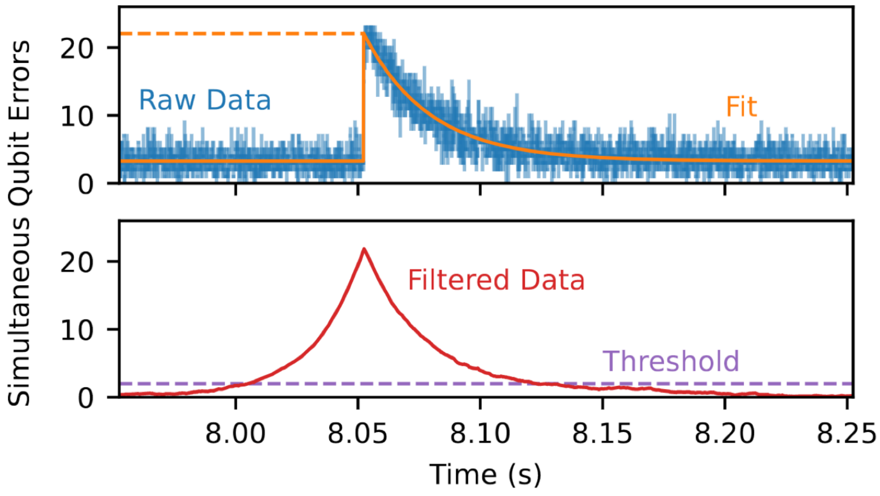

Designing an Experiment – Big Picture

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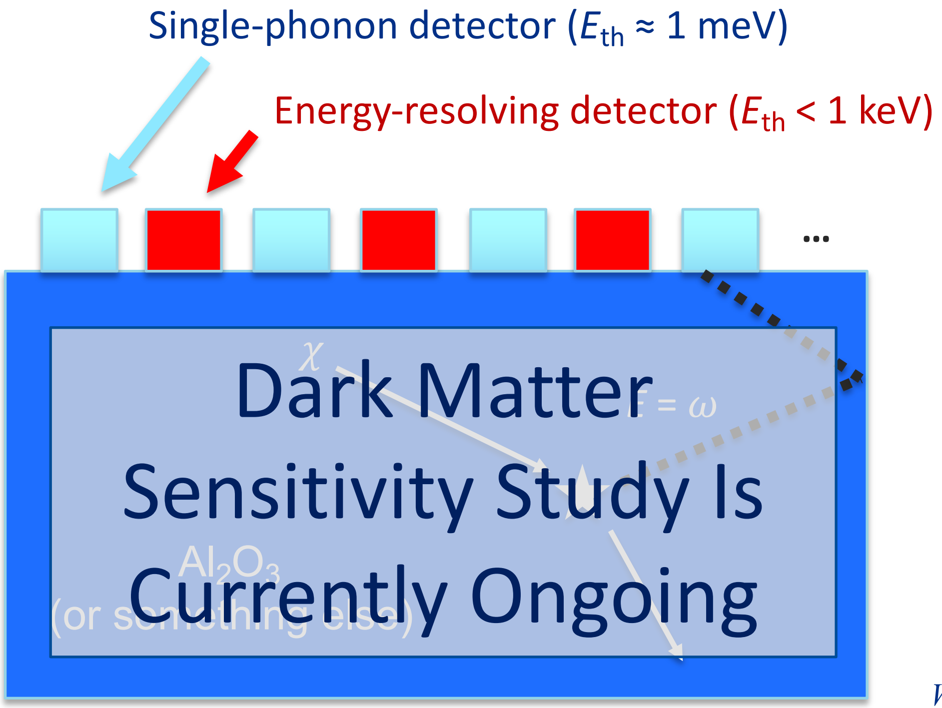
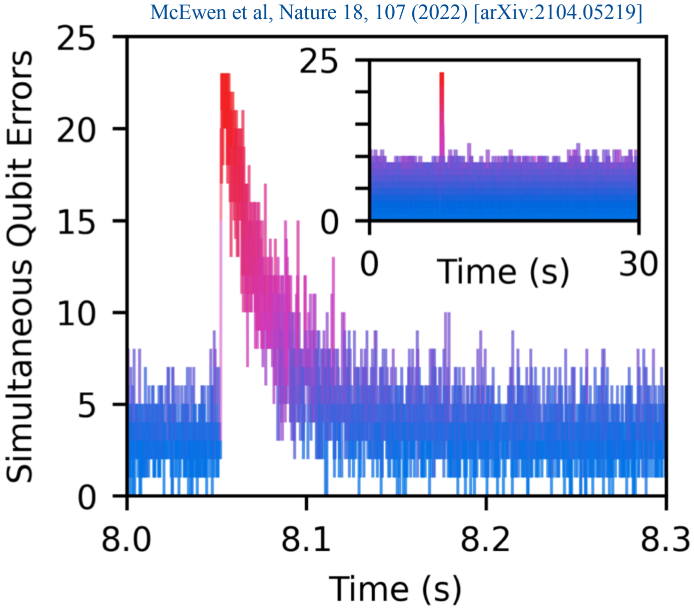




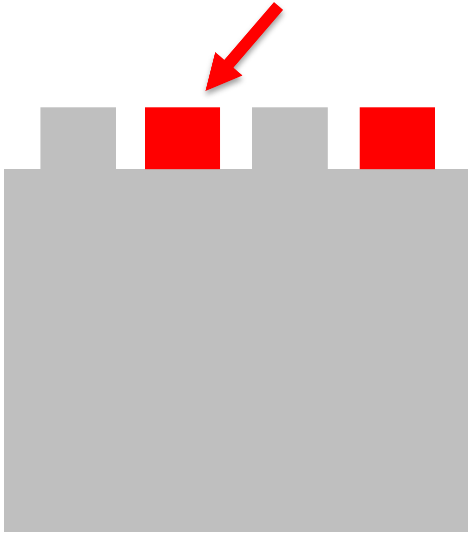
Work by Ryan Linehan

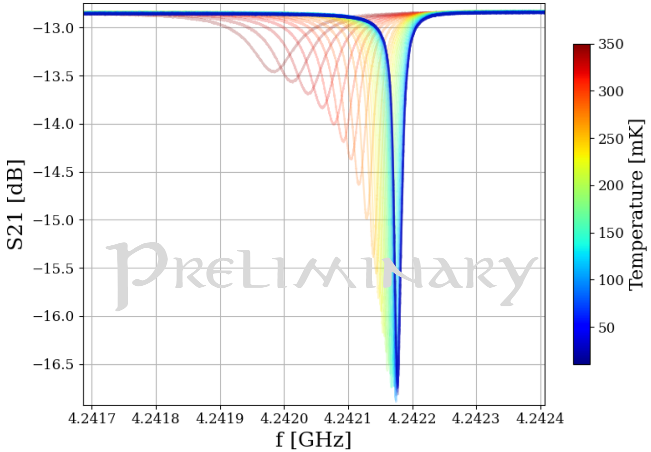
Designing an Experiment – "Classical" Detector

FNAL group has progress on many fronts towards this goal!

KID = "Kinetic Inductance Detector"

Energy-resolving detector ($E_{th} \approx 1$ eV)





Work by Dylan Temples

- N. Kurinsky LDRD at NEXUS in collaboration w/ Caltech & SLAC
- Able to be highly multiplexed (1000's of sensors on a single RF line)
- Identical readout and fabrication to qubits naturally enables production of KID+Qubit devices
- **Demonstrated single-device KID resolution is 2.6 eV**

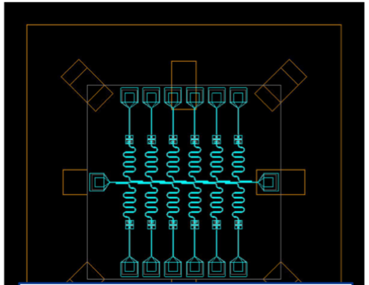
Designing an Experiment – Simulation Chain

QUANTUM SCIENCE CENTER

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

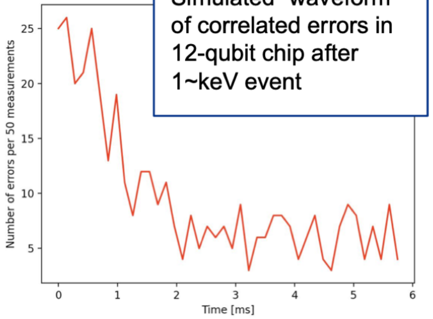
DM scattering, energy deposition → Energy propagation through chip → QP production in qubits → QP time evolution in qubits → $T_{1,qp}$ evolution in qubits

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!

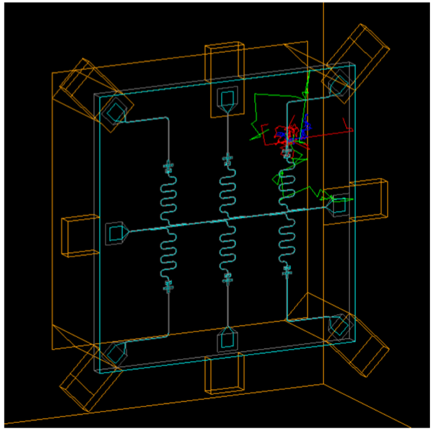


Simulated “waveform” of correlated errors in 12-qubit chip after 1~keV event

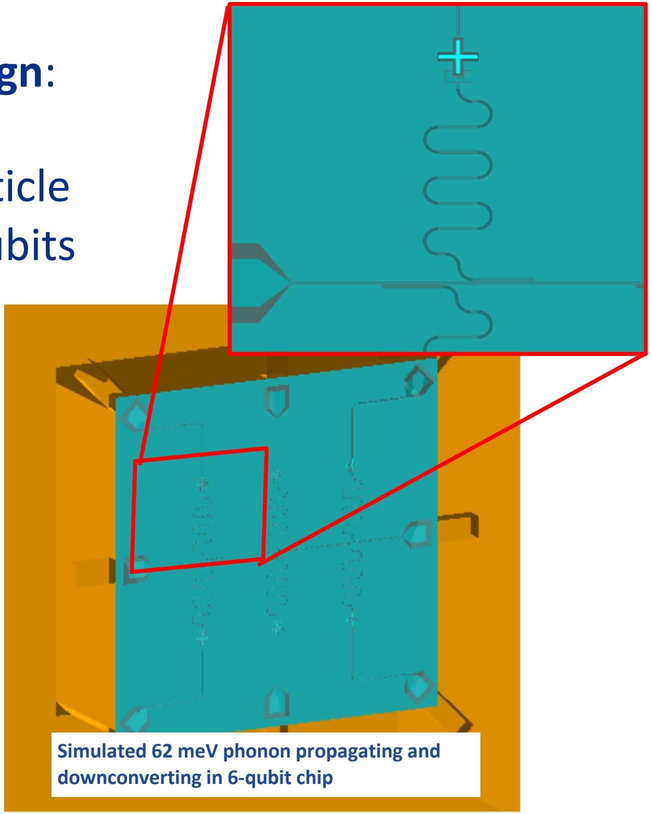
Work by Ryan Linehan & Israel Hernandez

Designing an Experiment – Simulation Chain

Current G4CMP campaign: map in-chip energy depositions to quasiparticle populations affecting qubits

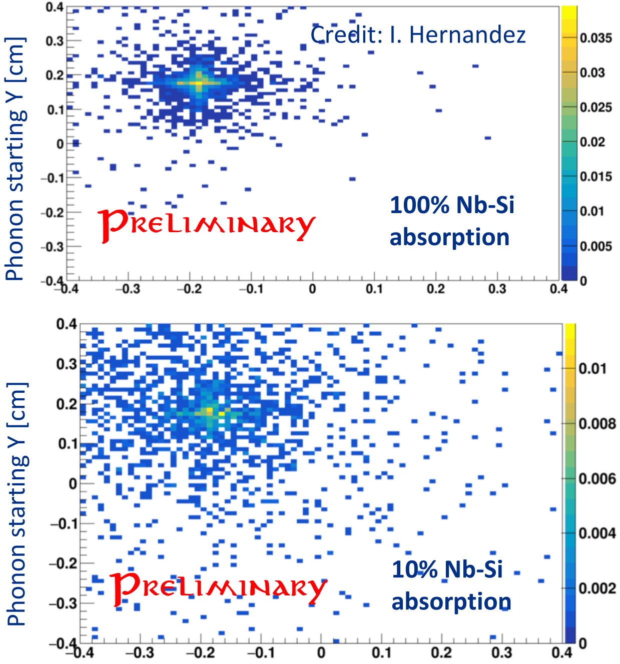


Work by Israel Hernandez & Ryan Linehan



Simulated 62 meV phonon propagating and downconverting in 6-qubit chip

Phonon collection efficiencies in transmon shunt capacitor (G4CMP)



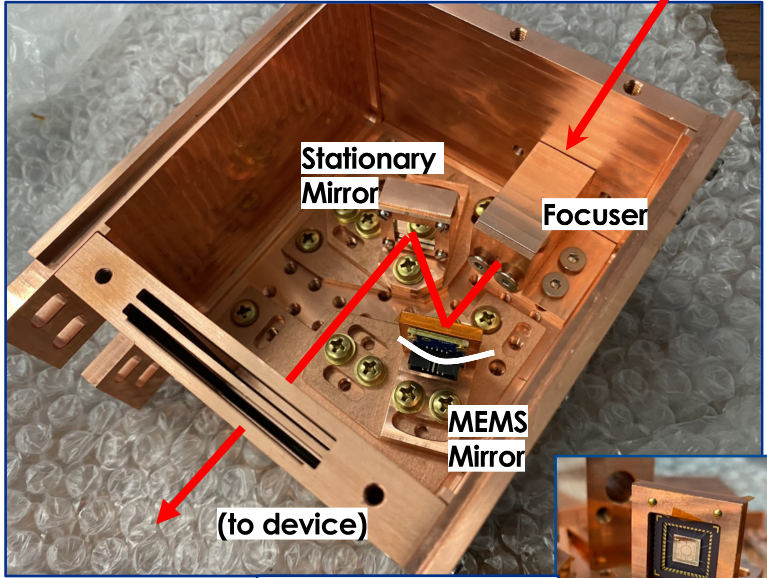
Designing an Experiment – Calibration Development

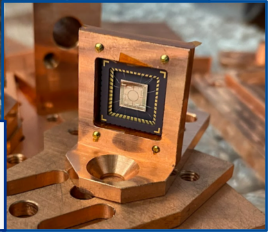
QUANTUM SCIENCE CENTER

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

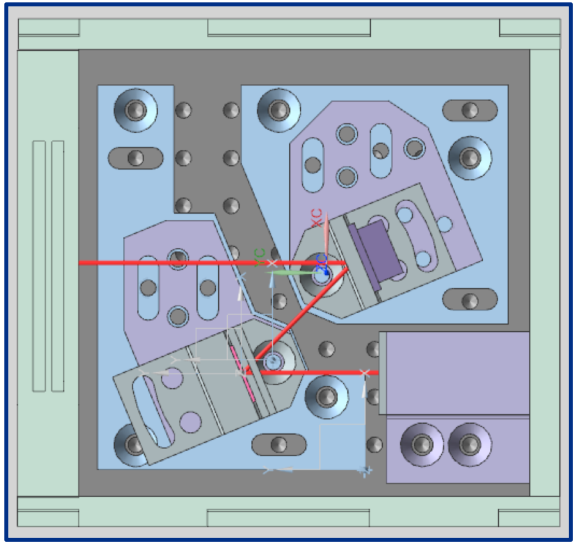
Work by Kelly Stifter & Hannah Magoon



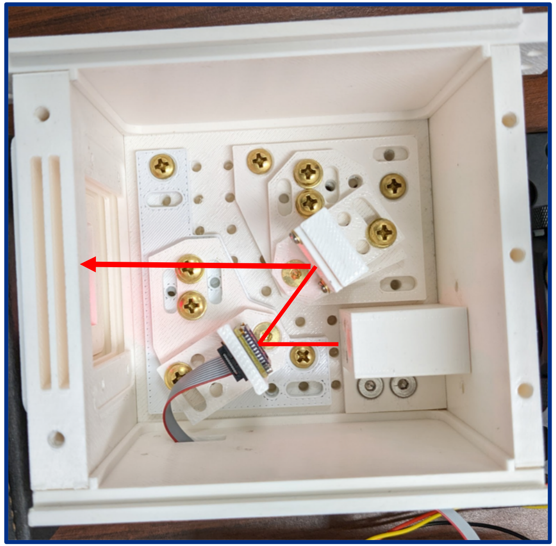


mirrorcle TECHNOLOGIES, INC.

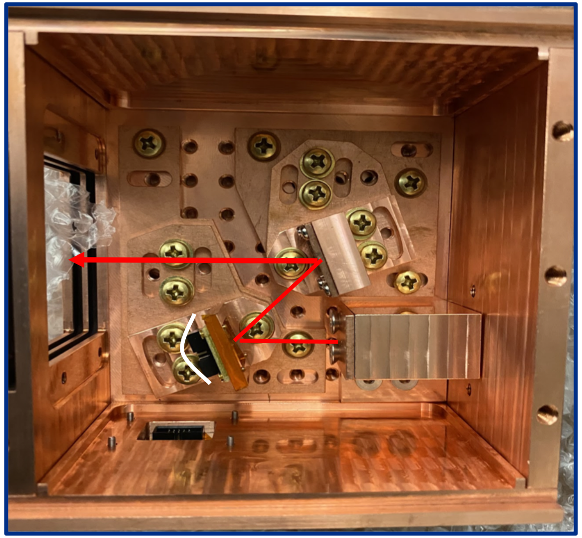
Designing an Experiment – Calibration Development



CAD model of enclosure
(March 2022)



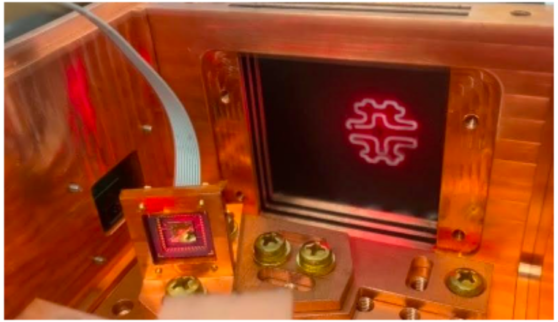
3D print prototype
(April 2022)

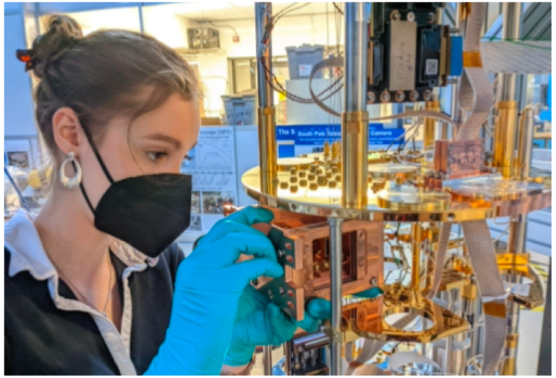


Copper enclosure
(June 2022)

Work by Kelly Stifter & Hannah Magoon

Designing an Experiment – Calibration Development

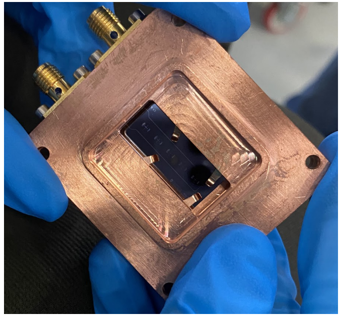


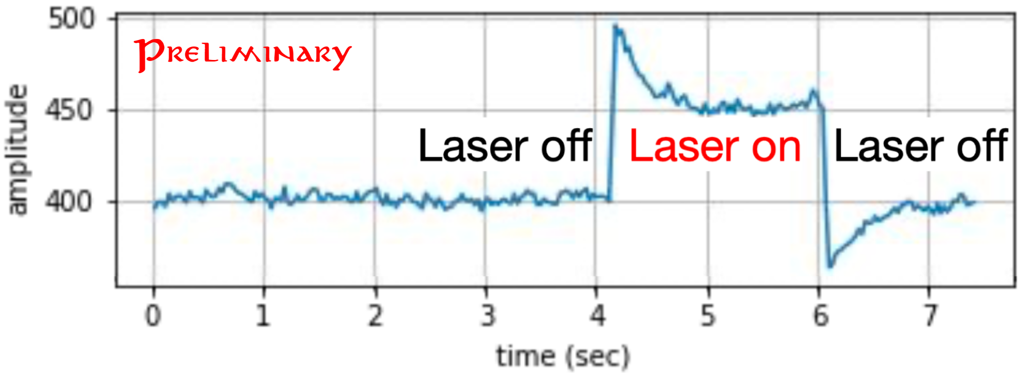


Work by Kelly Stifter
& Hannah Magoon

Anticipated Functionality

- <100μm spot size
- ~10μm position resolution
- O(100)Hz scanning speed
- O(μs) pulse width
- O(10mK) operating temperature
- Single wavelength within 0.6-6.9eV
- Up to 1”x1” scanning range





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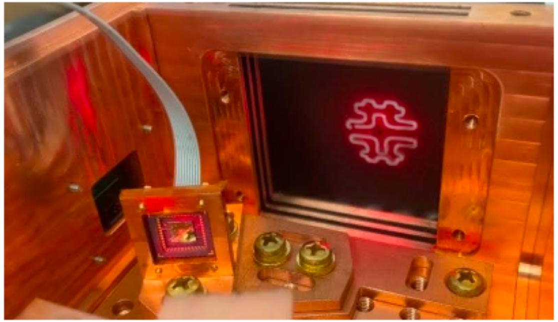

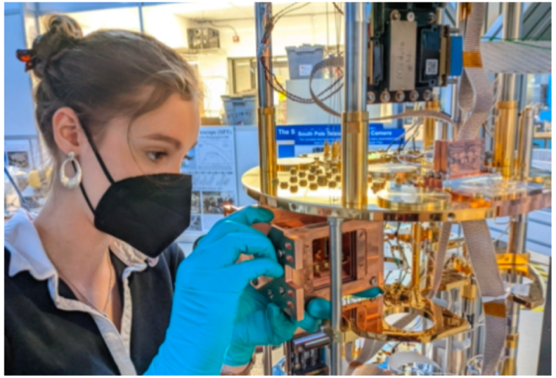

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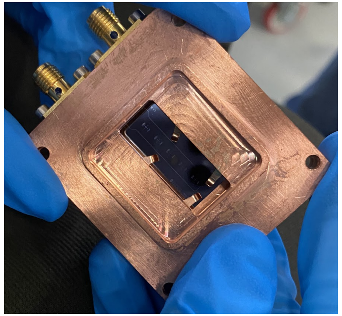
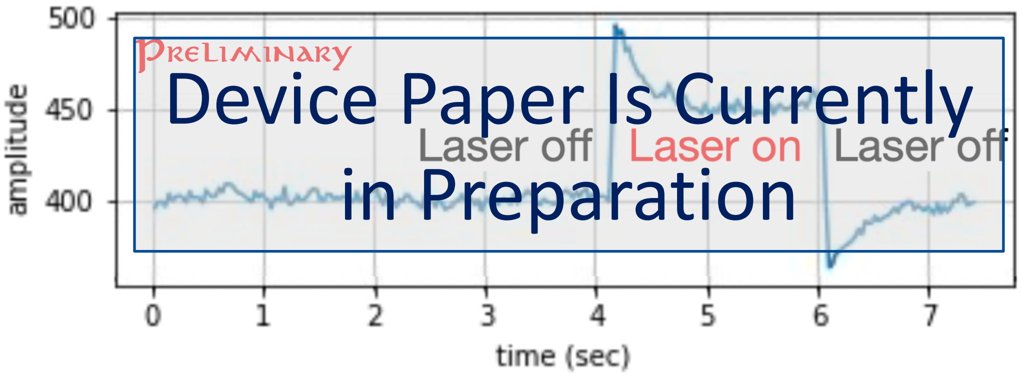


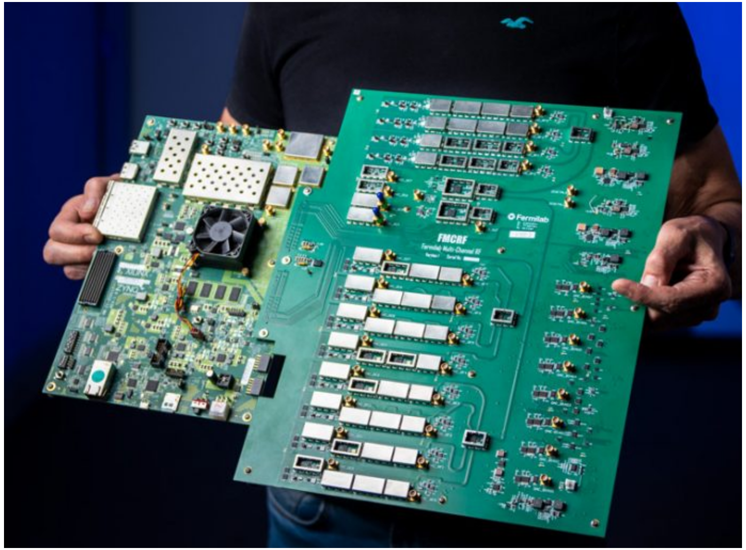


Designing an Experiment – Control & Readout

QUANTUM SCIENCE CENTER

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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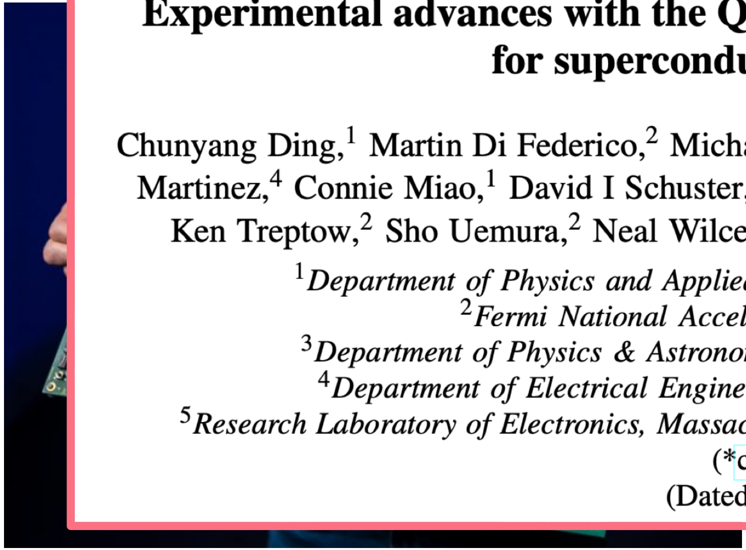

Experimental advances with the QICK (Quantum Instrumentation Control Kit) for superconducting quantum hardware

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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shelf

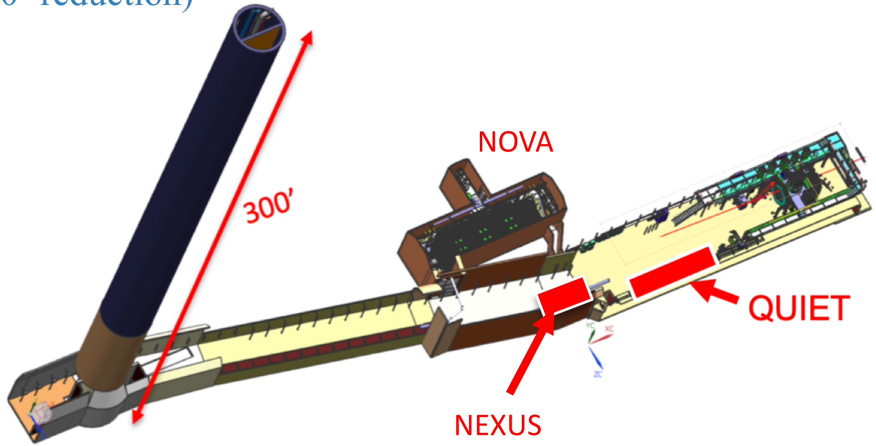
control of multiple qubits soon!

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

Designing an Experiment – Test 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 clean facility (next to NEXUS; 225 mwe) to operate characterized devices in low-background (target 100 dru) environment (x10^3 reduction)



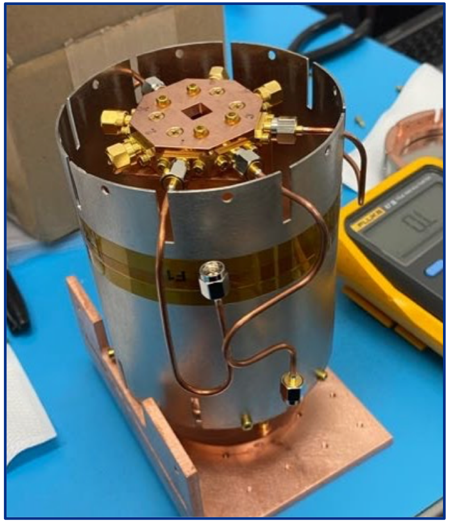
LOUD Run Coordinator: Ryan Linehan

Test Facilities – LOUD

New DR installed at FNAL

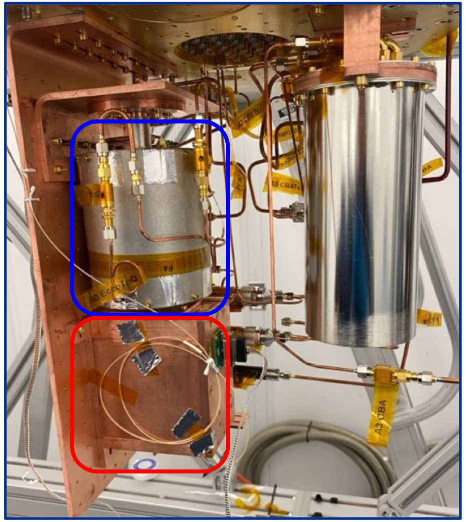
(August 2022)

6-qubit array borrowed from McDermott group



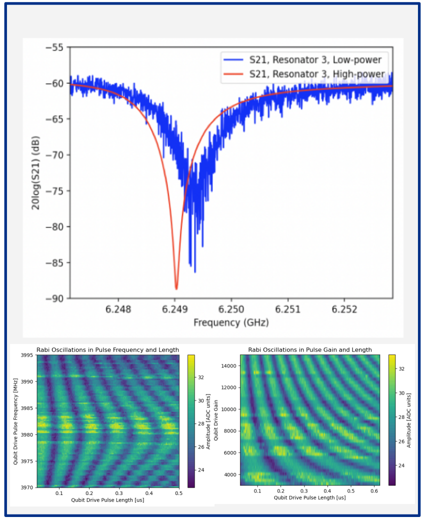
(October 2022)

Magnetic shielding coupled to scanning unit and installed in DR



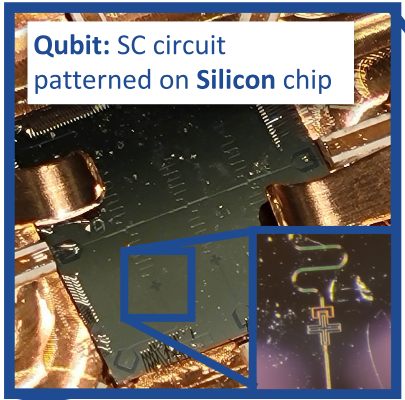
(November 2022)

Run 1: First demonstration of live qubits



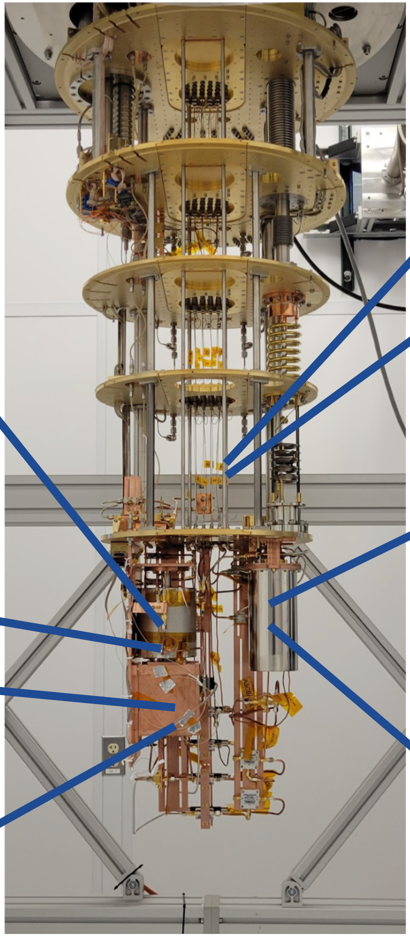
(February 24th 2023) - March 14th 2023

Test Facilities – LOUD

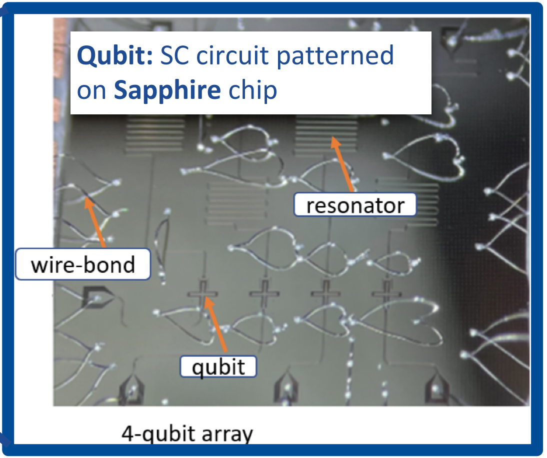


chip from R. McDermott group at UWMadison

MEMS: steerable cryogenic optical laser calibration



(*not shown*) KID payload and JPA



4-qubit array

chip from A. Ma group at Purdue

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

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
– Facility is complete! including electrical power, chilled water, network, and fire suppression systems
– Initial fridge test reached 8.9mK w/ no issues

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

Dec. 9, 2022

Sept. 29, 2023

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

QUANTUM SCIENCE CENTER

2020 2021 2022 2023 2024 2025

Fridge PO'ed
Oxford Proteox

Project Manager
hired D. Baxter

UG Chiller PO'ed
Haskris

UG Clean Room PO'ed
Thornel

Nov. 2022: Cleared internal (FNAL) approval to build UG facility

Dec. '22: Cleared space of "debris" for use

Jan. '23: Dilution refrigerator arrives

Feb. '23: Clean room constructed

June. '23: UG chilled water infrastructure complete

Aug. '23: UG electrical infrastructure complete

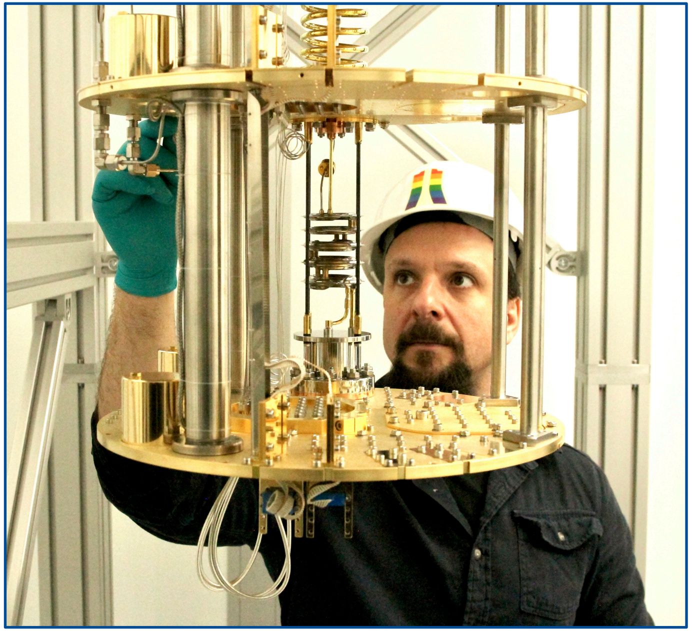
Oct. 5 '23: Fridge hits base temp of 8.9 mK

Fermilab

Test Facilities – QUIET

Quantum Underground Instrumentation Experimental Testbed

Our group is working hard to commission the RF systems for first qubit devices in March 2024!



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

This intersection of the DM and QIS fields is brand new, making this an interesting time on the cusp of a lot of new, exciting science

Conclusions

Benchmarks for advancing superconducting qubits for QIS:

- Determine, quantitatively, the effects of radiation on detector performance (qubit decoherence) in collaboration with DM community
- Develop calibration sources to study the loss of information in a controlled experiment
- Understand background contributions down to and below a few eV

This intersection of the DM and QIS fields is brand new, making this an interesting time on the cusp of a lot of new, exciting science

Acknowledgements

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CosmiQ "Local" Group Members:

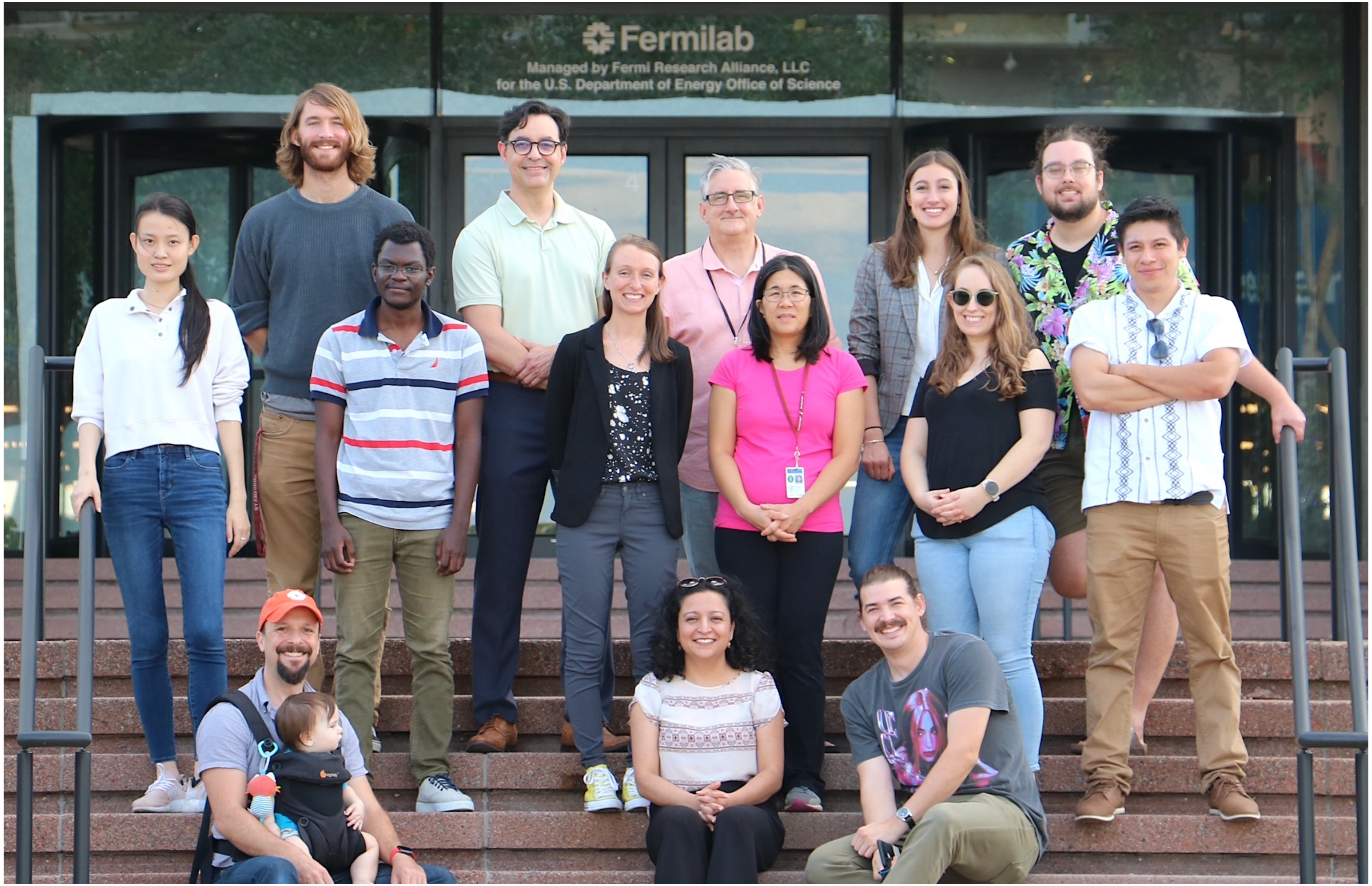
- **FNAL**: Aaron Chou, Daniel Bowring, Gustavo Cancelo, Lauren Hsu, Adam Anderson, Daniel Baxter, Ryan Linehan, Sara Sussman, Dylan Temples, Grace Wagner
- **IIT**: Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Jialin Yu
- **Northwestern University**: Enectali Figueroa-Feliciano (joint w/ FNAL), Riccardo Gualtieri, Grace Bratrud, Arianna Colon Cesani

Postdocs/Students

External Collaborators:

- **UW Madison**: Robert McDermott, Sohair Abdullah, Gabe Spahn
- **SLAC**: Noah Kurinsky, Kelly Stifter, Hannah Magoon
- **Caltech**: Sunil Golwala, Karthik Ramanathan, Osmond Wen

Work presented is supported by QSC, LDRD, KA-25, and Daniel Bowring's ECA



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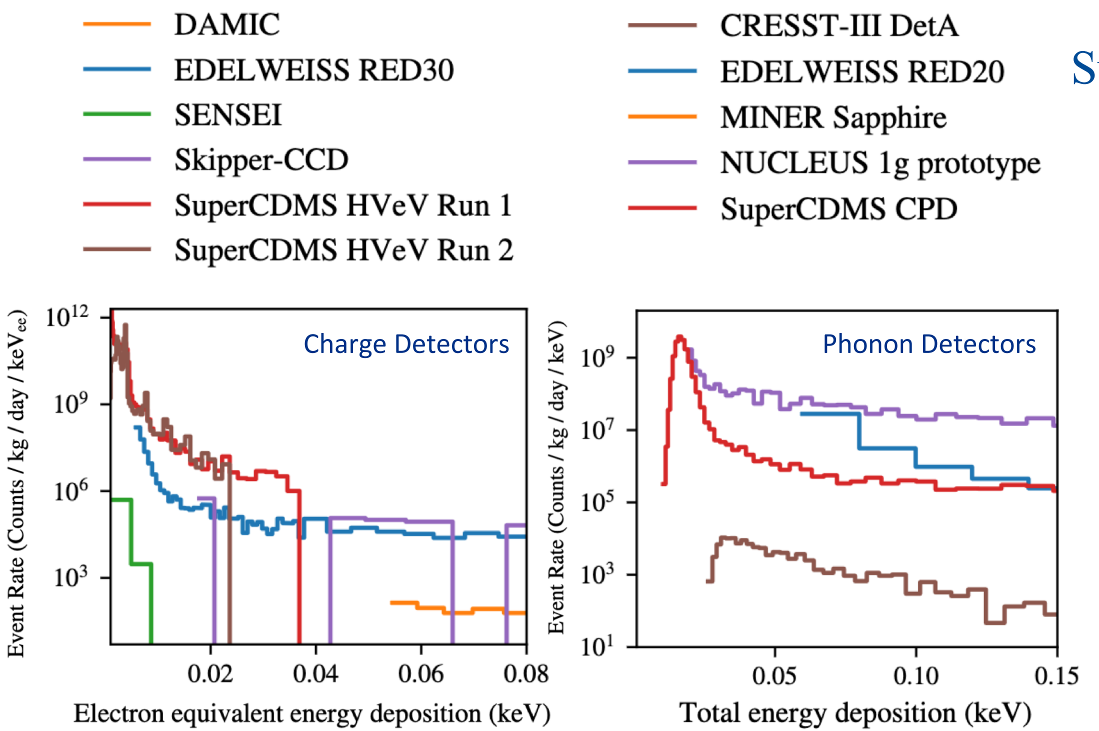
Not pictured:
Aaron Chou (FNAL)
Gustavo Cancelo (FNAL)
Adam Anderson (FNAL)
Sara Sussman (FNAL)
Grace Wagner (FNAL)
Riccardo Gualtieri (NU)
Grace Bratrud (NU)
Arianna Colon Cesani (NU)

Back-up Slides

Detector Backgrounds – The Phonon Excess

Problem! All low-threshold phonon detectors have large, unmodeled, uncalibrated backgrounds



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

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

Detector Backgrounds – The Phonon Excess

- June 15-16, 2021: **EXCESS workshop,** community-wide gathering of [solid-state] experiments to discuss unmodeled low-threshold detector rates
- February 10, 2022: A white paper summarizing the discussion and results of this workshop posted to arXiv:2202.05097 [SciPost Phys. Proc. 9, 001 (2022)]
- February 15-17, 2022: **EXCESS 2022**, follow-up [virtual] workshop focused on phenomenology, calibration, and future detector ideas **(with the final day dedicated to quantum detectors)**
- July 16, 2022: **EXCESS@IDM**, first in person meeting of the community to discuss this problem
- August 26, 2023: **EXCESS@TAUP**
- July 6, 2024: **EXCESS 2024 at IDM**

Starts 15 Feb 2022, 16:00
Ends 17 Feb 2022, 21:00
Europe/Berlin

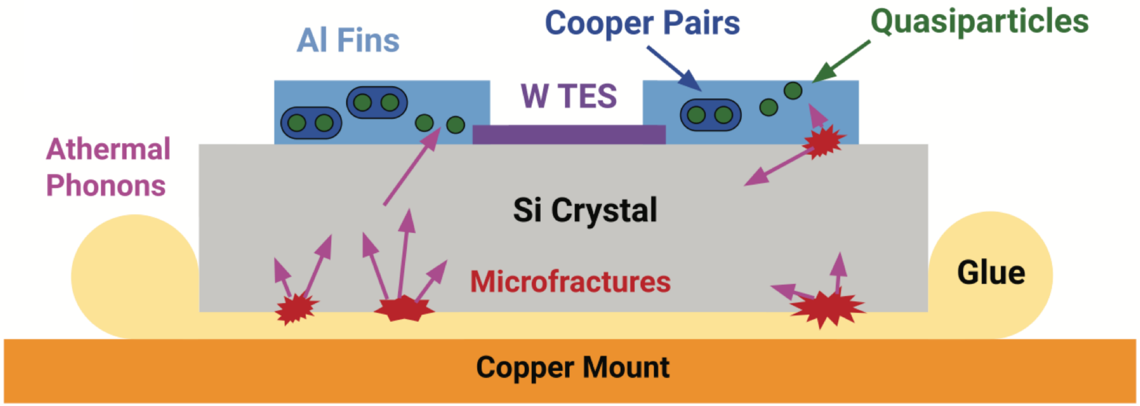
Belina von Krosigk
Daniel Baxter
Marie-Cécile Piro
Rouven Essig
Yonit Hochberg

Detector Backgrounds – The Phonon Excess

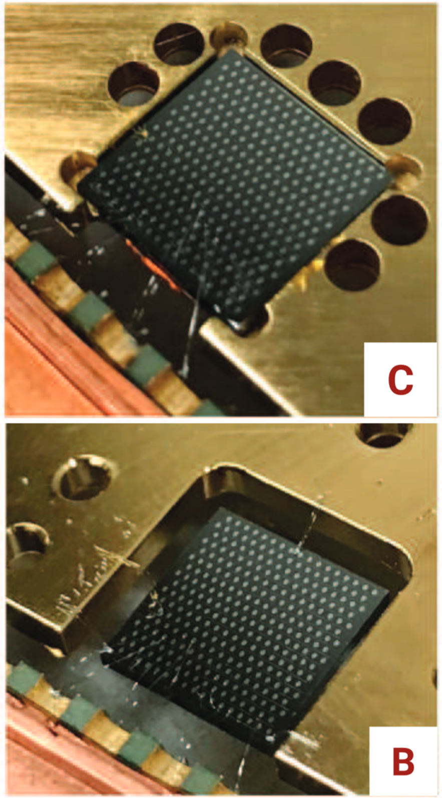
A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

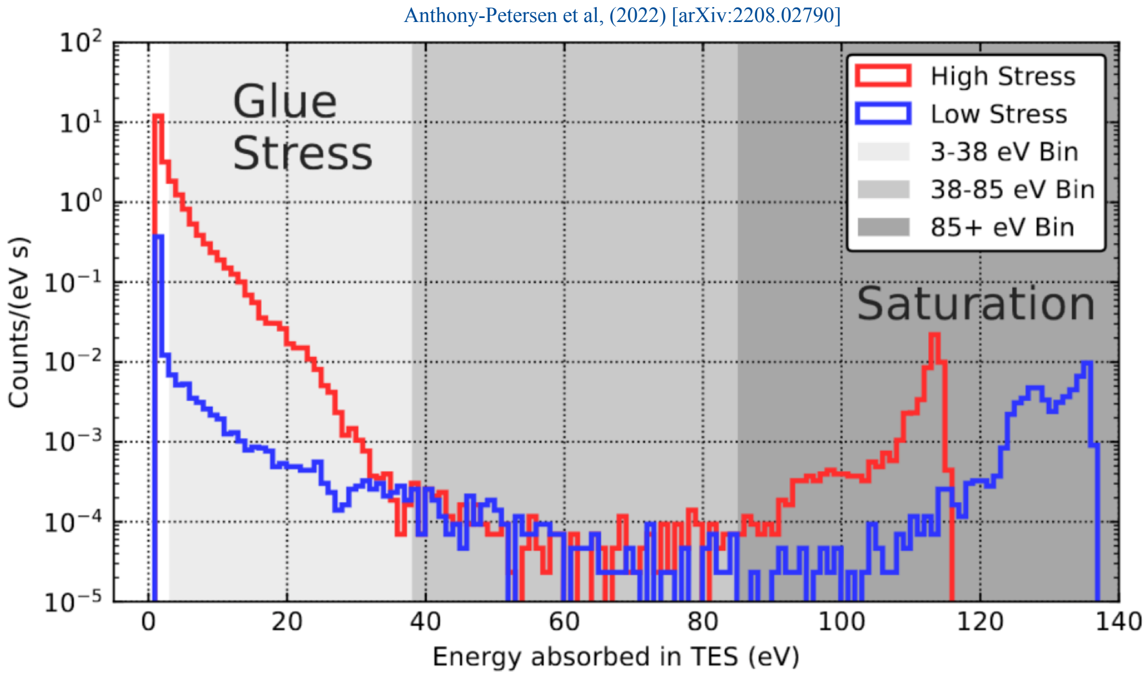
R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7] E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7] Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9] D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7] B. Penning,[16] H.D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1] B. Sadoulet,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8] V. Velan,[1,2] G. Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

arXiv:2208.02790



Detector Backgrounds – The Phonon Excess





Detector Backgrounds – The Phonon Excess

In two of the *foundational* studies of superconducting qubit decoherence, this is found to be a *dominant* source of quasiparticle poisoning over high-energy contributions!!!

Impact of ionizing radiation on superconducting qubit coherence

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

Nature **584**, 551–556 (2020) | Cite this article

A superconductor free of quasiparticles for seconds

E. T. Mannila, P. Samuelsson, S. Simbierowicz, J. T. Peltonen, V. Vesterinen, L. Grönberg, J. Hassel, V. F. Maisi & J. P. Pekola

Nature Physics **18**, 145–148 (2022) | Cite this article

Anthony-Petersen et al, (2022) [arXiv:2208.02790]

In the case of the qubit, we find that our stress-induced background would produce a reduced quasiparticle density of $x_{qp} \approx 5.0 \times 10^{-8}$, while high-energy backgrounds should induce $x_{qp} \approx 1.5 \times 10^{-8}$. The latter is in general agreement with the lower bound of $x_{qp} \geq 7 \times 10^{-9}$ estimated in Ref. [11] for high-energy backgrounds. For the system in Ref. [15], we find that our stress events induce $x_{qp} \approx 2.8 \times 10^{-11}$, while high-energy backgrounds induce $x_{qp} \approx 3.3 \times 10^{-10}$.

Detector Backgrounds – The Phonon Excess

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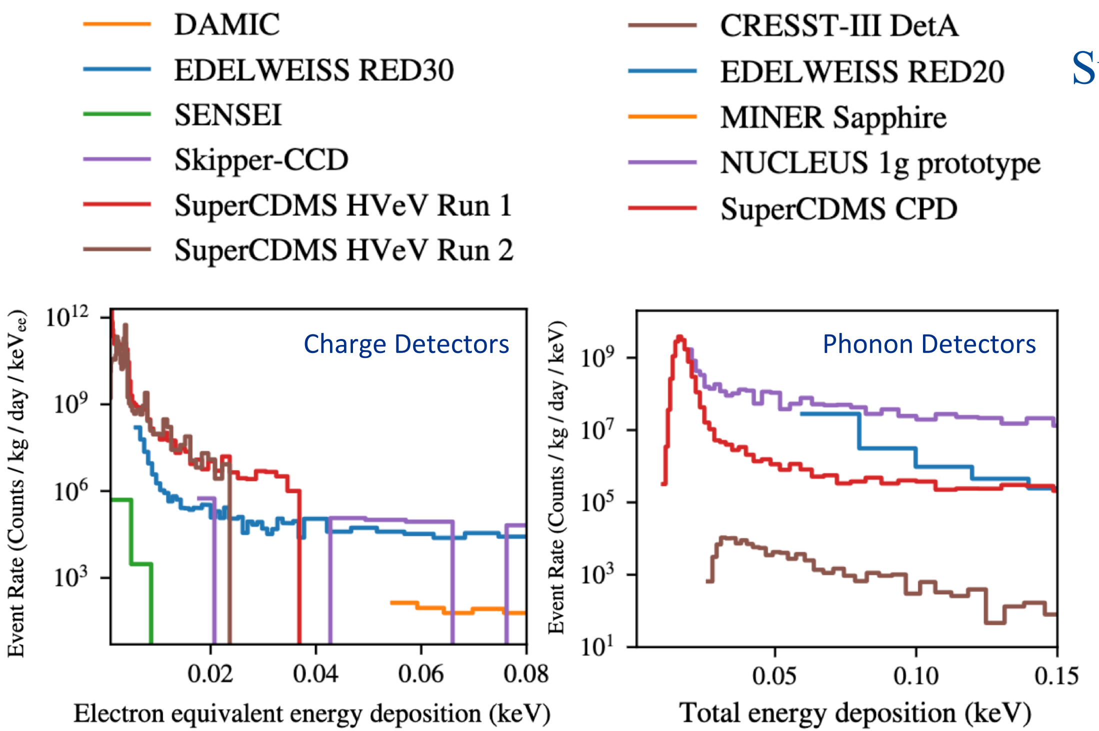

Summary of what we know:

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]