Leveraging Quantum Sensors for Dark Matter Detection

Daniel Baxter

APS DPF Coordinating Panel for Advanced Detectors (CPAD) 2022

30 November 2022

QUANTUM SCIENCE CENTER

Outline

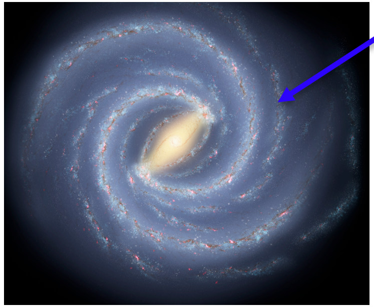
- **<u>Goal of this talk</u>: Contextualize the role of quantum detectors in searching for particle dark matter, highlight the challenges associated with this, and suggest some of the ways we are approaching the problem.**

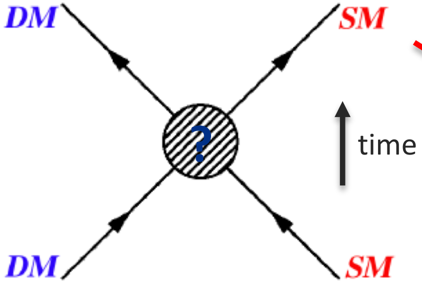
→ Demonstrate how advancing quantum detectors for dark matter detection feeds back into advancing QIS technologies

Dark Matter – Particle Direct Detection

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



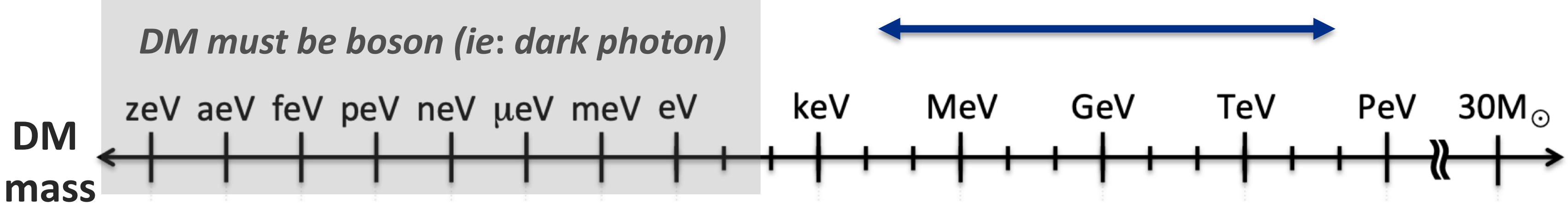


Detector

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

Smaller Detectors

Larger Detectors



Number Density (DM/cc): 10^6 10^3 1 10^{-3} 10^{-6}

QUANTUM SCIENCE CENTER

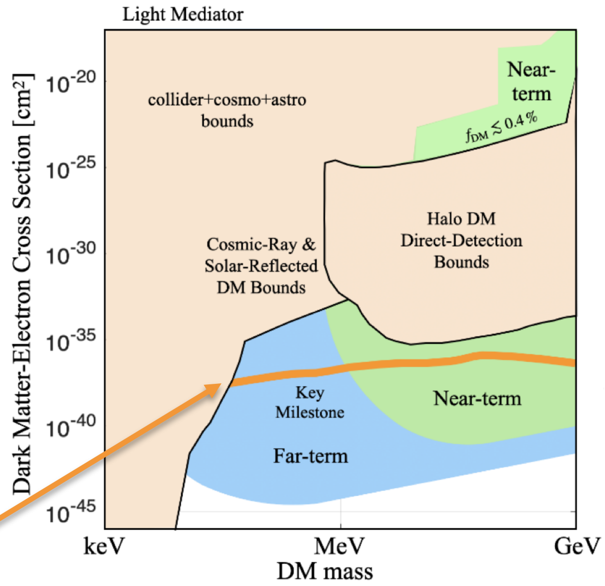
Dark Matter – Particle Direct Detection

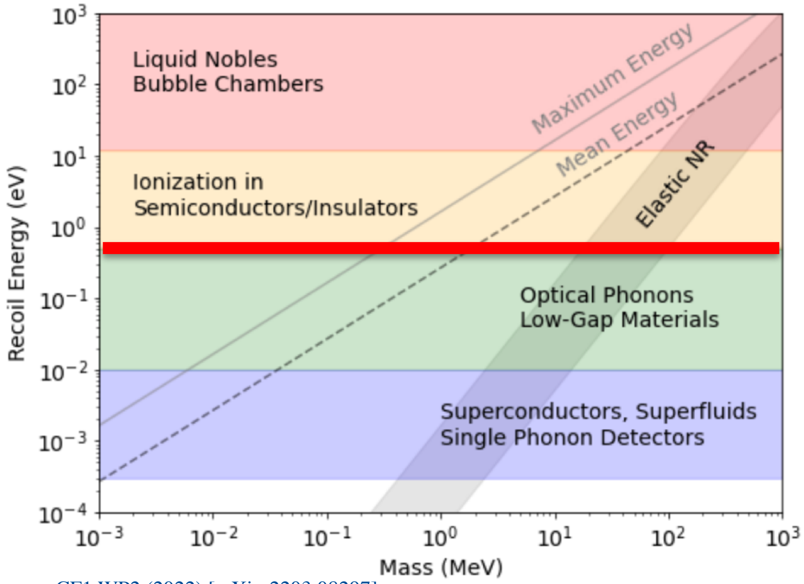
Development of lower-threshold detectors is a huge focus of the recent decadal Snowmass particle physics study

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

→ **new device development!**

thermal freeze-in

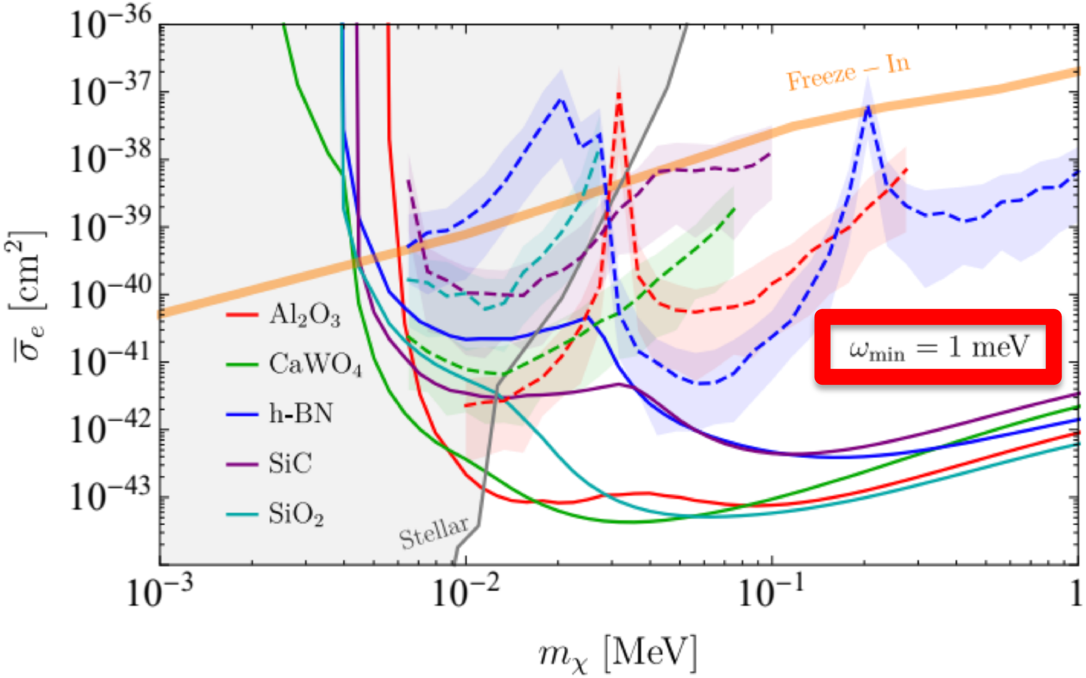




Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Particle Direct Detection

- 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



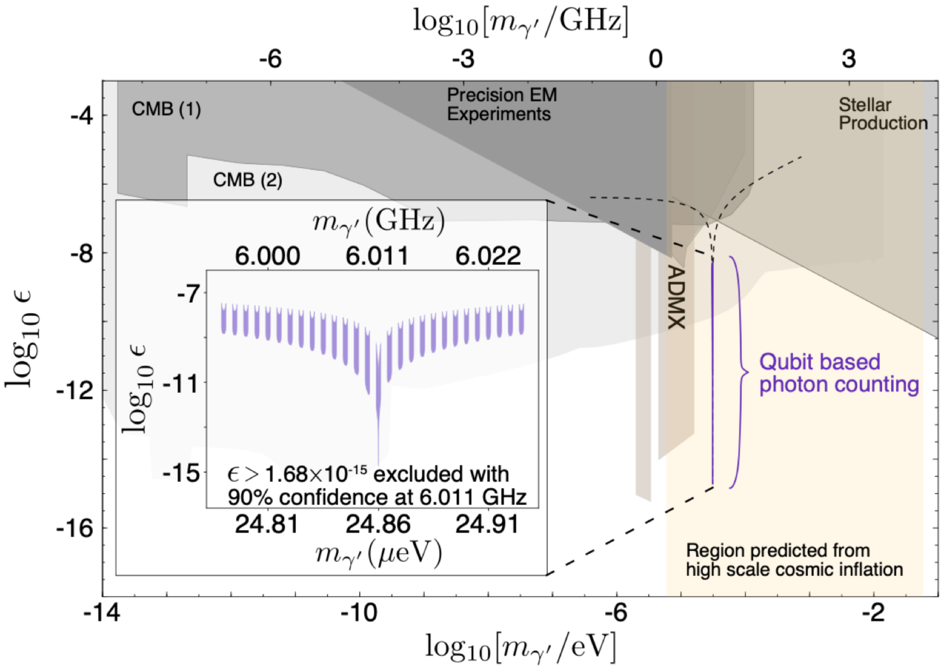
Mitridate et al, (2022) [arXiv:2203.07492]

Defining some terminology

QUANTUM SCIENCE CENTER

Quantum sensors have been demonstrated for axion/dark photon searches

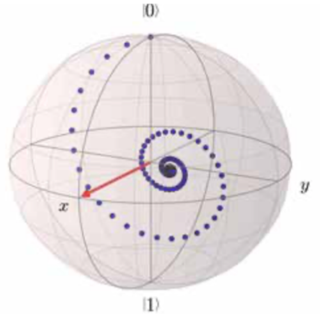
- Quantum Sensors – devices which **require** quantum mechanical description of their behavior
- Qubit – any two-level quantum mechanical system
- Cooper-Pair Box (charge qubit) – qubit whose state is determined by Cooper pairs tunneling across Josephson Junction
- Quasiparticle Poisoning – broken Cooper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



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

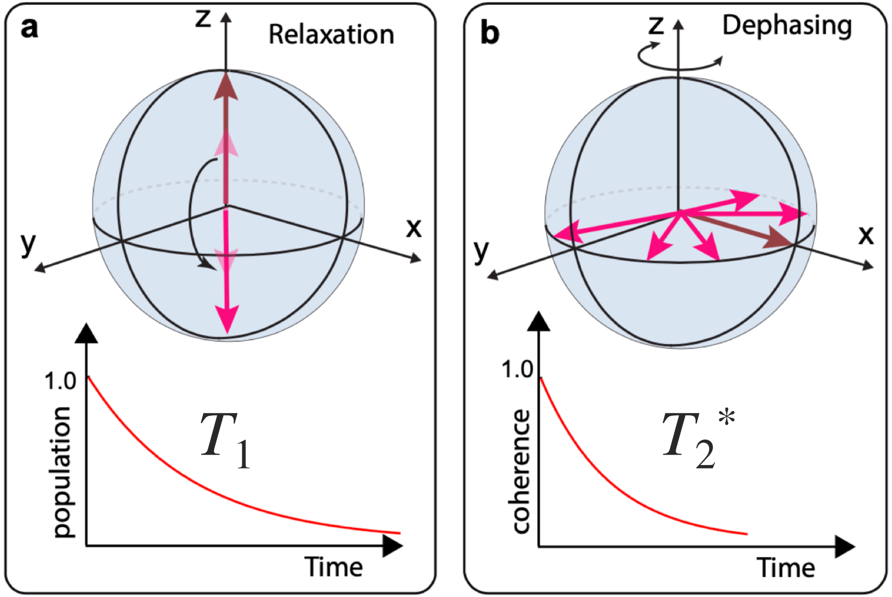
Fermilab

Superconducting Qubits



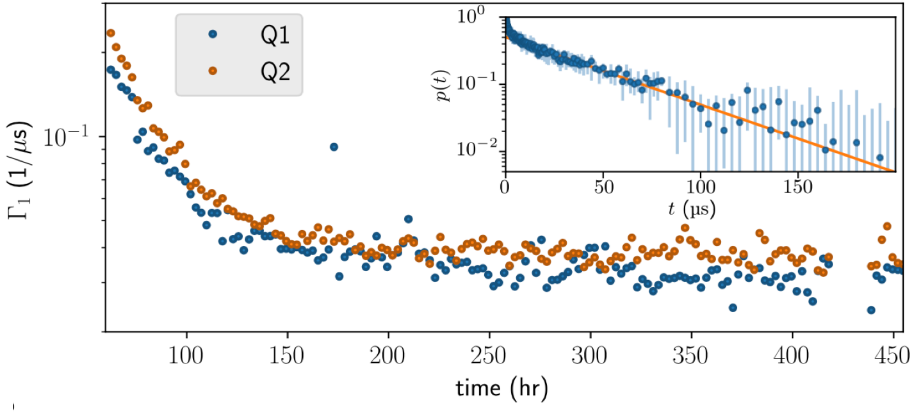
Could they be useful for particle dark matter detection?
(Spoiler: yes!)

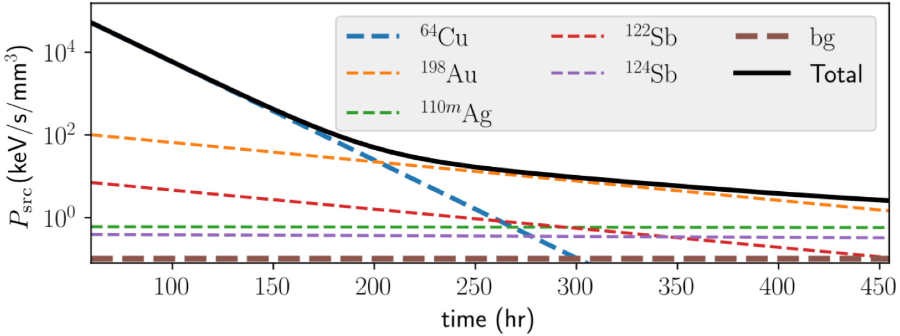
- Decoherence – loss of the qubit state due to relaxation or dephasing
    - **Bad for QIS**
    - **Good for DM detection?**
- T_1 = Relaxation Time – timescale for loss of the energy of the qubit state (ie, 1 → 0)
- T_2^* = Dephasing Time – timescale for loss of the coherence of the qubit state



Mahdi Naghiloo, (2019) [arXiv:1904.09291]

Superconducting Qubits





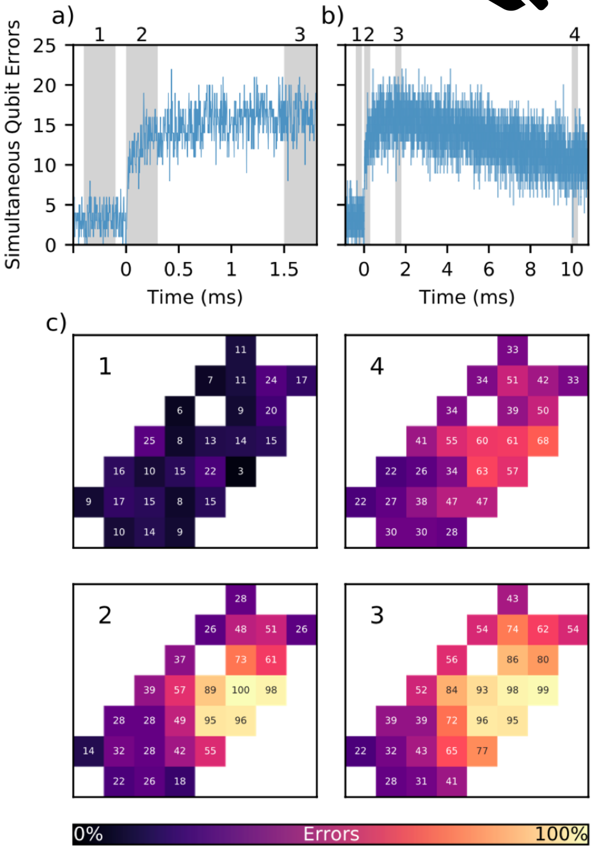
- Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source
- Clear correlation between T_1 and decay of ^{64}Cu source in two separate qubit sensors!
- Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs is a limiting factor in superconducting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

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

Superconducting Qubits

- This alone isn't enough to say that qubits can be useful as meV-scale detectors, since individual superconducting qubit lifetimes are on the order of 1-100 ms
- Further studies of radiation-dependence actually show correlated relaxation errors qubits across the device due to energy depositions in common substrate (information destroyed every 10s!)

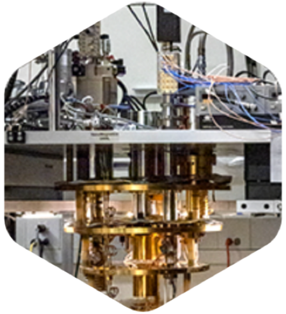
- **<u>Hypothesis</u>: energy depositions in a substrate cause correlated decoherence across qubits due to quasiparticle poisoning**



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

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)



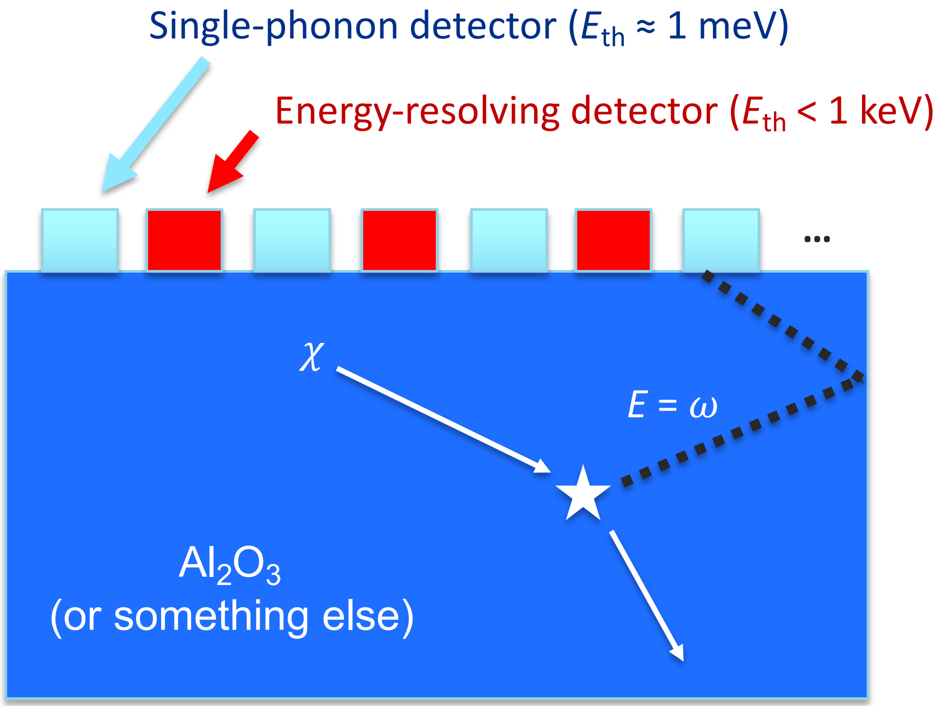
Thrust 3: Quantum Devices and Sensors for Discovery Science

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

Designing an Experiment

Proposing a novel, multiplexed quantum device for particle physics detection



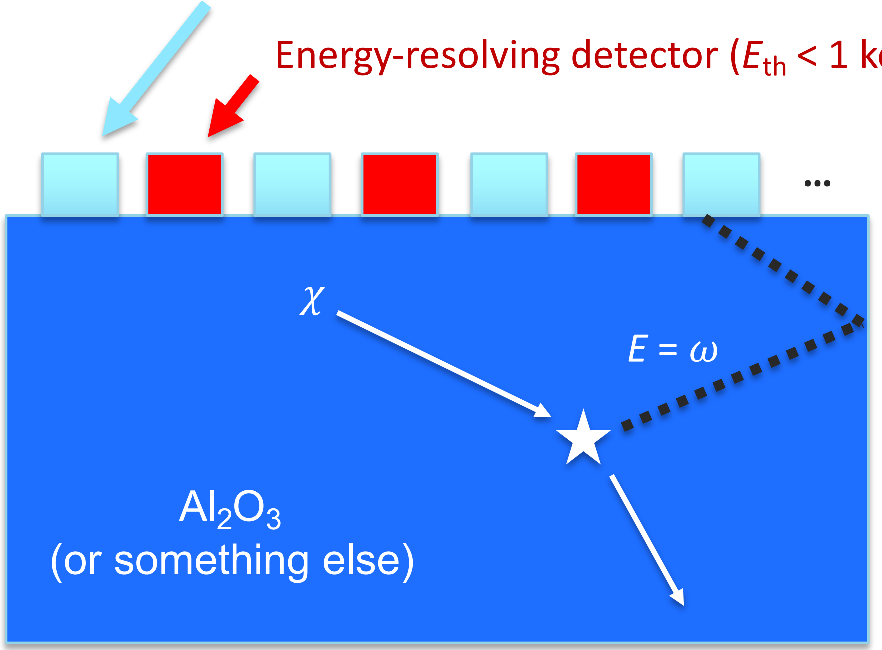
- A low-mass DM recoil will deposit order meV-keV of energy ω in the substrate at location $\boldsymbol{r}$, producing phonons
- These will break Cooper-pairs in single-phonon detectors (qubits) with some efficiency $\varepsilon(\omega, \boldsymbol{r})$
- The energy-resolving detectors (veto), which have much higher thresholds, should see no simultaneous hits, since the energy deposition is below detector threshold

Designing an Experiment

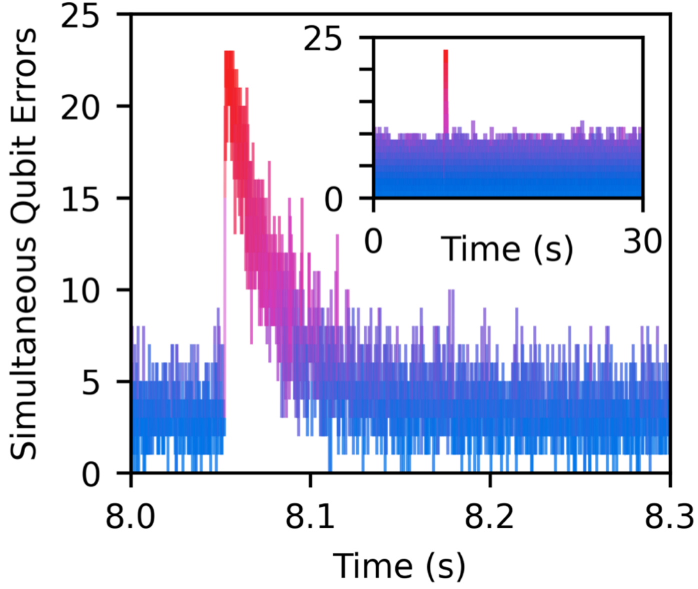
Proposing a novel, multiplexed quantum device for particle physics detection

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

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



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

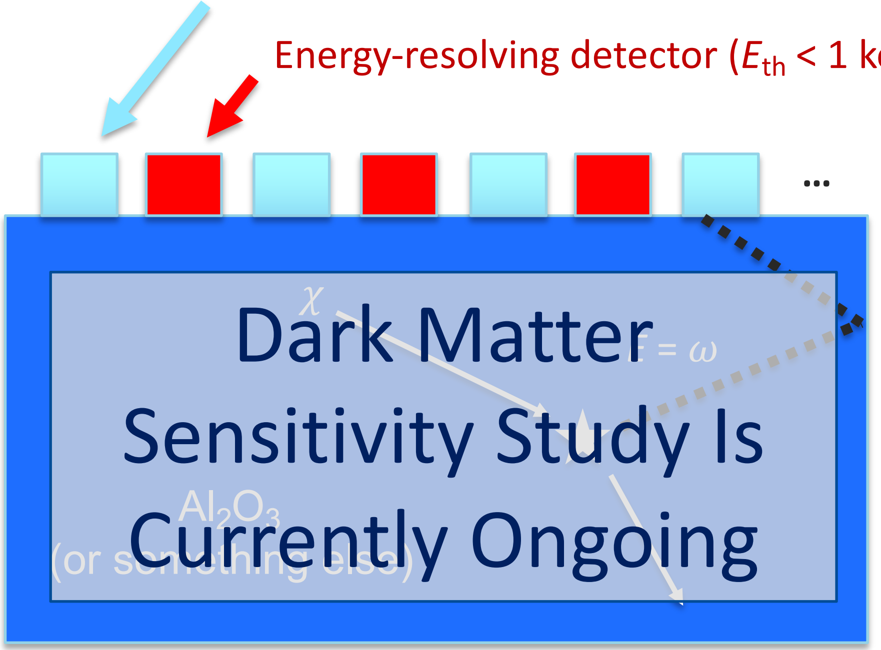


Designing an Experiment

Proposing a novel, multiplexed quantum device for particle physics detection

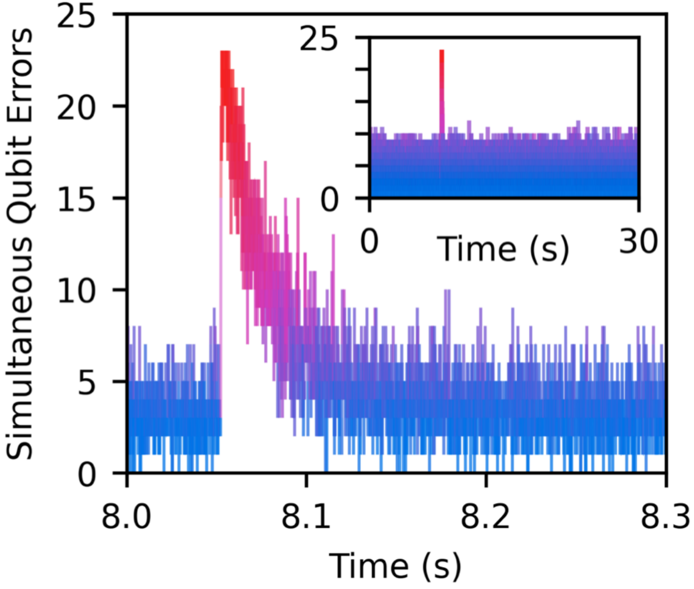
Single-phonon detector ($E_{th} \approx 1$ meV)

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



Dark Matter Sensitivity Study Is Currently Ongoing

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

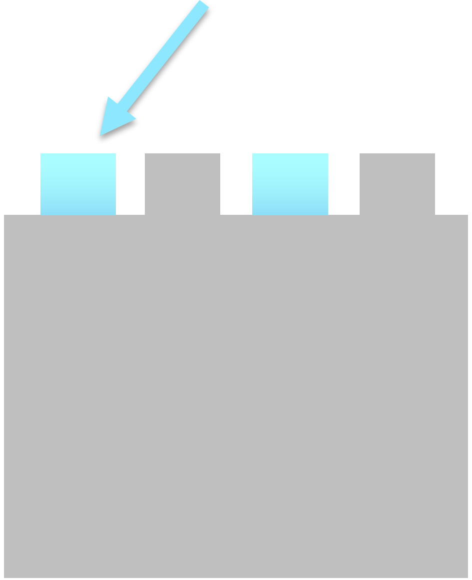


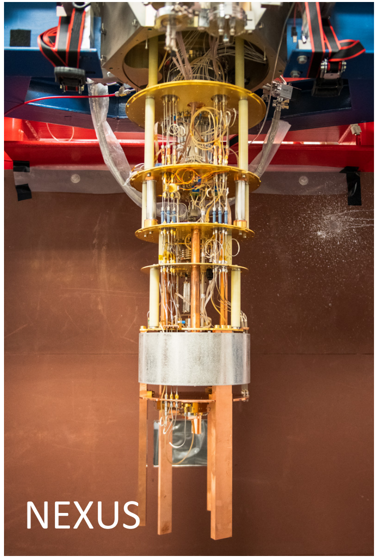
Fermilab

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

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





- Superconducting qubits – building off of Daniel Bowring's ECA collaboration w/ Robert McDermott's group at UW Madison
- Utilizing an RF-retrofit of the NEXUS underground facility at Fermilab
- Charge-sensitive qubit array currently operating in a modular background environment as low as 100 dru
- **Expect results later this year…**

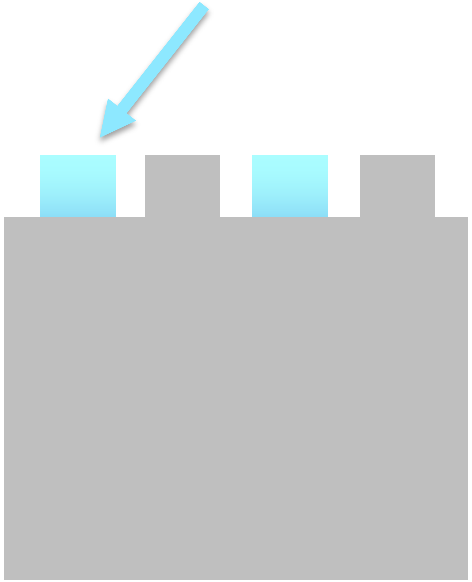
Work by Sami Lewis & Grace Bratrud

see previous work in Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

Designing an Experiment

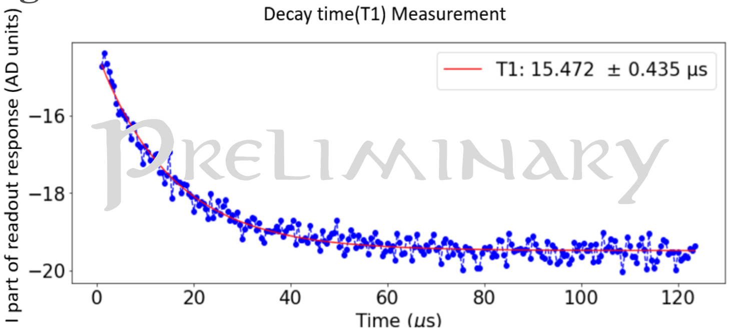
FNAL group has progress on many fronts towards this goal!

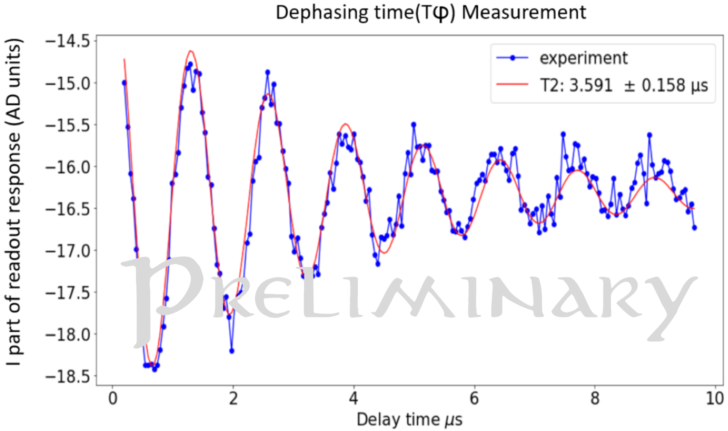
Single-phonon detector ($E_{th} \approx 1$ meV)



- Qubit device installed in surface setup for frequency multiplexed readout and control of qubits
- T_1 and T_2^* measurements made to characterize device performance
- Measurement utilizes new readout (see QICK slide)

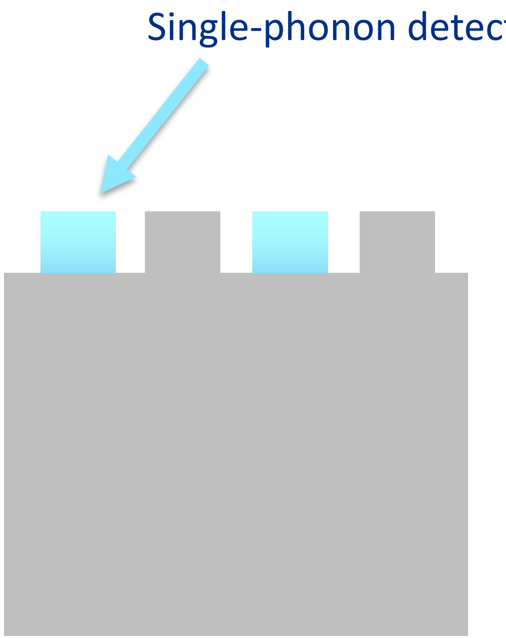
Work by Kester Anyang

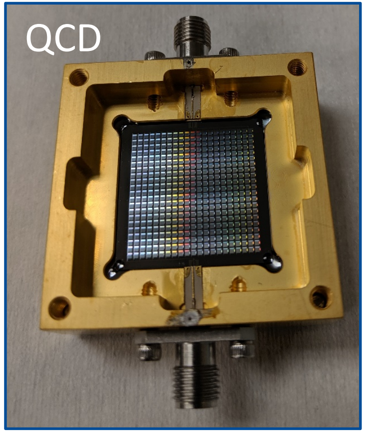




Designing an Experiment

FNAL group has progress on many fronts towards this goal!





Work by Jialin Yu

- Quantum Capacitance Detector (QCD) – Based on cooper pair box (charge qubit)
- FNAL/IIT integrating QCD with a Josephson Junction -based weak photon source to characterize a 25 qubit array for DM detector development
- Photon hits the superconducting absorber, resulting in broken Cooper pairs which tunnel into a small capacitive island and cause the non-equilibrium quasiparticle population to increase

Designing an Experiment

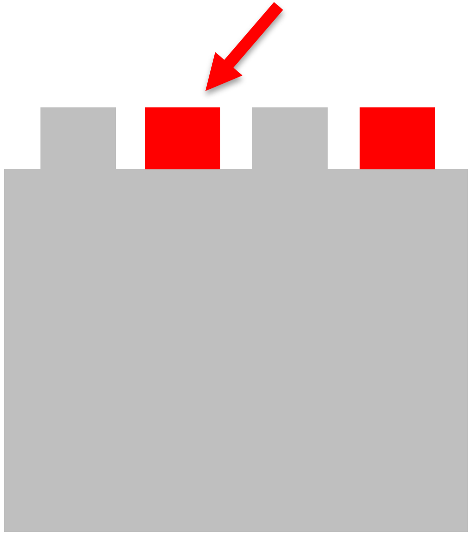
see Thurs WG4 talk by Osmond Wen

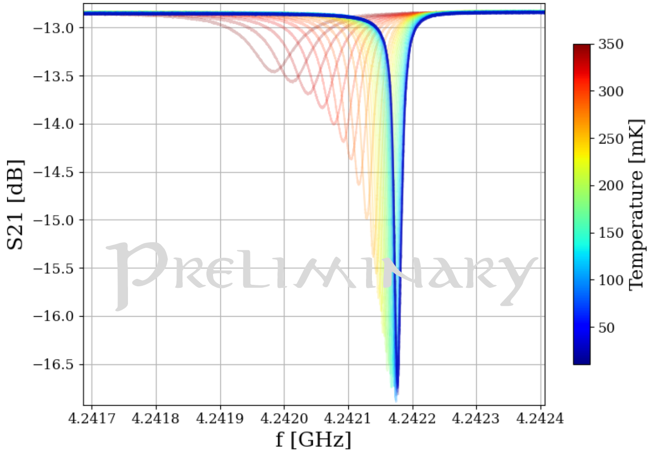
QUANTUM SCIENCE CENTER

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

- KID – 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
- **Single-device KID resolution is ~20 eV but we expect to achieve 1 eV by the end of the LDRD program**

Designing an Experiment

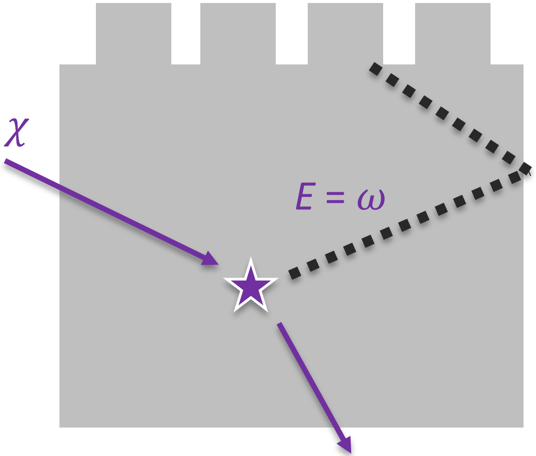
see plenary today by Kelly Stifter

QUANTUM SCIENCE CENTER

FNAL group has progress on many fronts towards this goal!

MEMS = "Micro-Electro-Mechanical System"

Calibration



Work by Kelly Stifter & Hannah Magoon

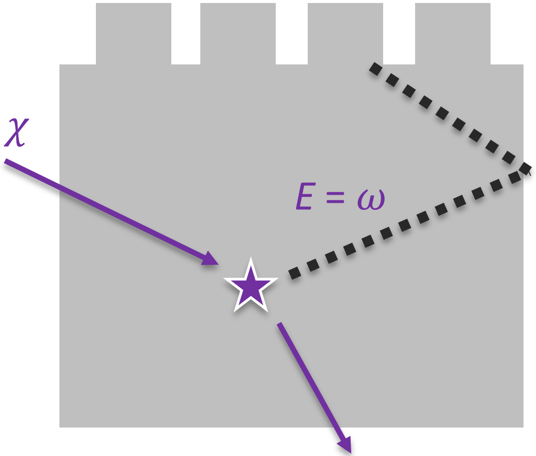
- Laser Calibration – scan over device w/ UV-optical-IR photons to determine phonon response as a function of ***position***
- MEMS Mirror – outputs up to mW at full scanning speed and range, "none" while stationary
- **Initial cold tests w/ KIDs are successful!**

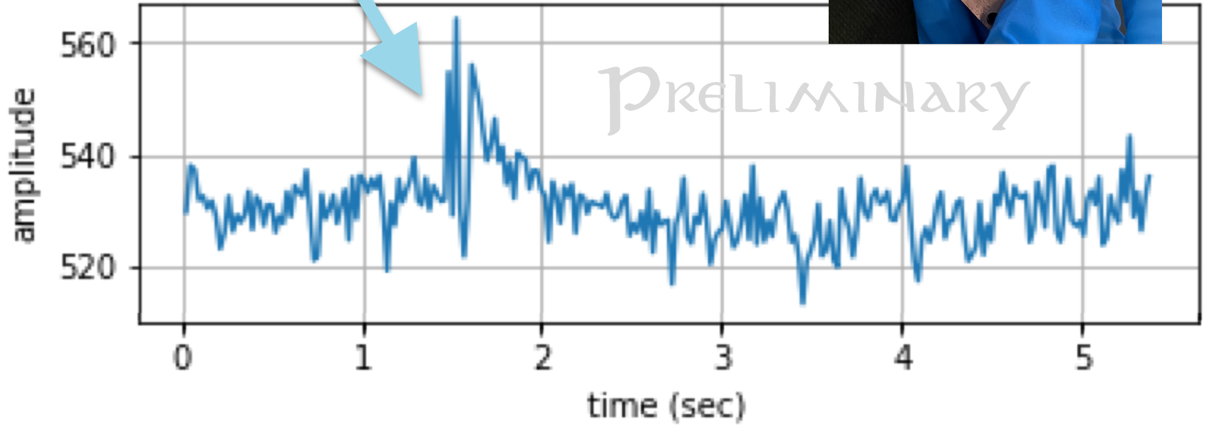
Designing an Experiment

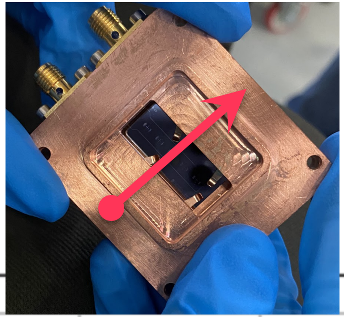
see plenary today by Kelly Stifter

FNAL group has progress on many fronts towards this goal!

- We can clearly when we scan the laser over a chip at very low power!







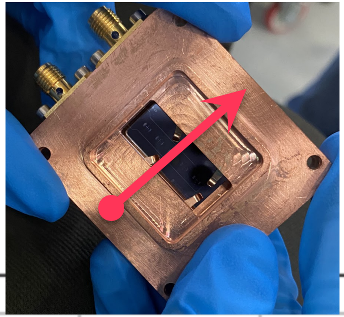
Work by Kelly Stifter & Hannah Magoon

Designing an Experiment

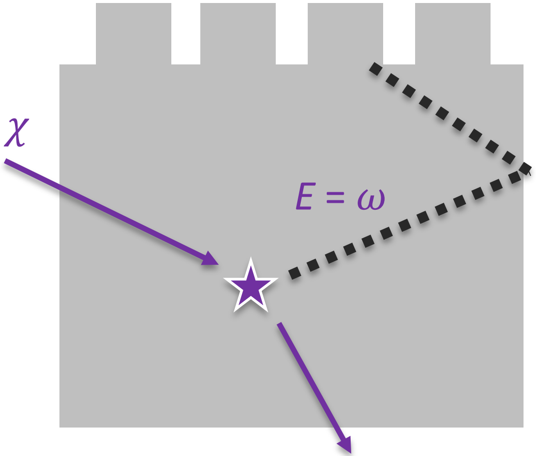
see plenary today by Kelly Stifter

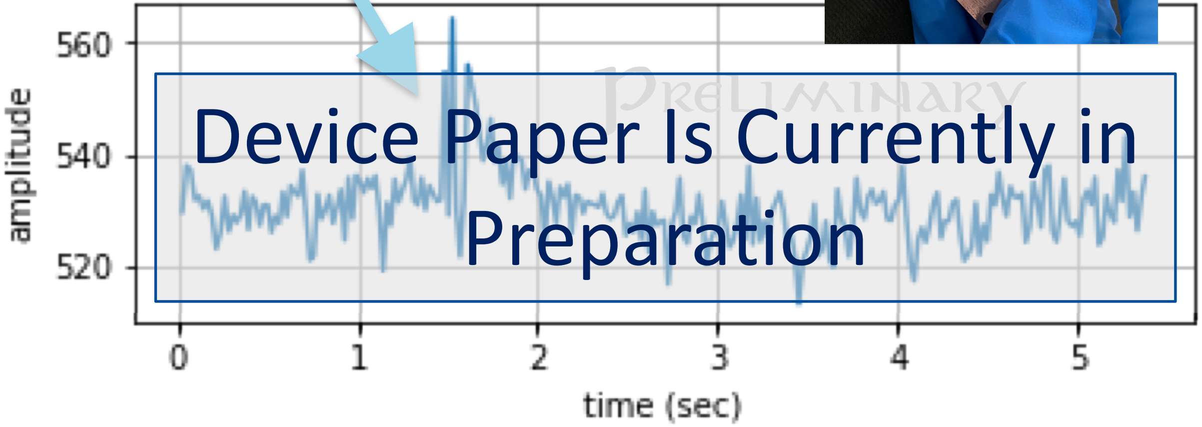
FNAL group has progress on many fronts towards this goal!

- We can clearly when we scan the laser over a chip at very low power!



Calibration



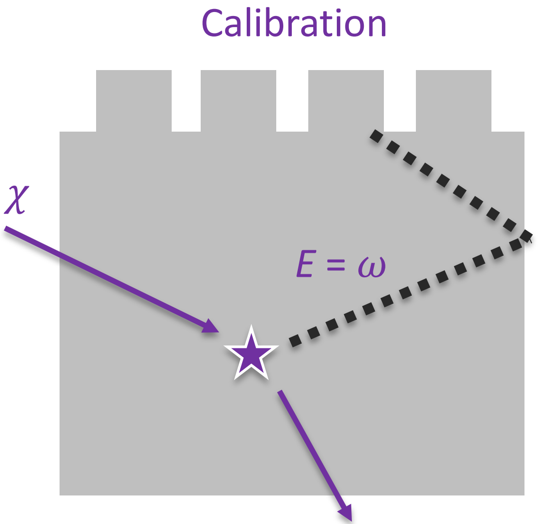


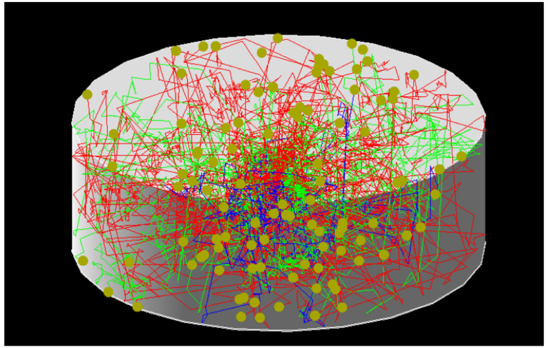
Work by Kelly Stifter & Hannah Magoon

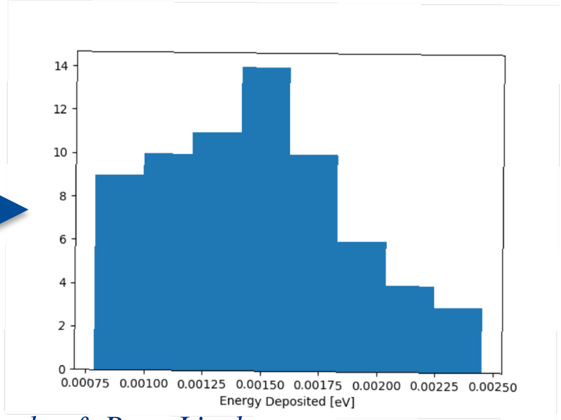
Designing an Experiment

FNAL group has progress on many fronts towards this goal!

- G4CMP – build on efforts within SuperCDMS to simulate phonon propagation/kinematics in devices and compare with laser calibration scan
- Seek better understanding on the impact of radiation on qubits and the propagation of incident energy that results in the broken Cooper pairs in aluminum





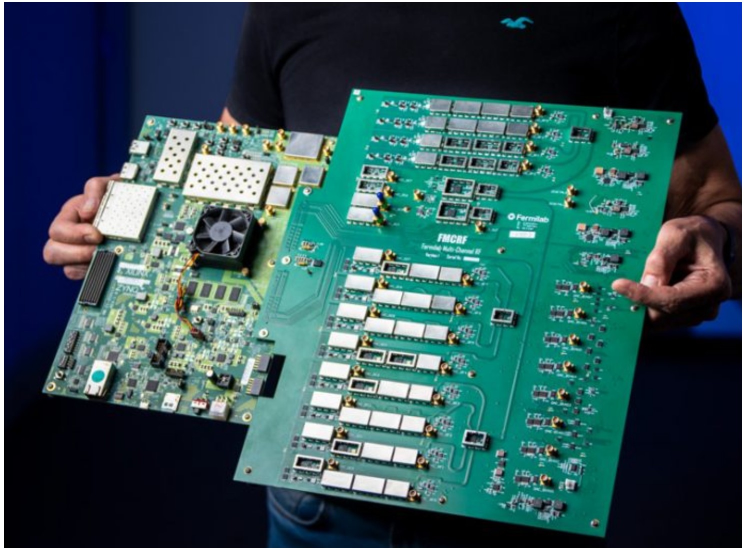


Work by Israel Hernandez & Ryan Linehan

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

QICK = "Quantum Instrumentation Control Kit"



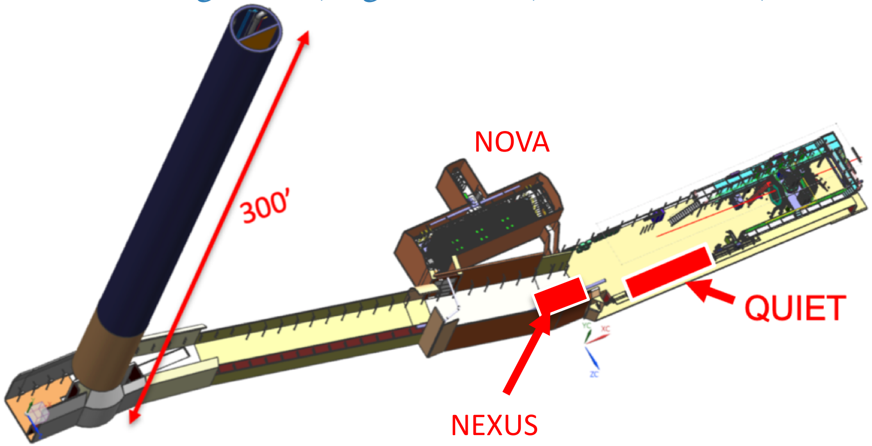
- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting (not including the 2 from FNAL)
- A factor of ~20 cheaper compared to off-the-shelf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

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

- **Two identical new facilities being constructed at FNAL over the next year!**
- 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

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 *includes* better understanding of existing detector excesses that are hard to untangle without lower thresholds, such as the phonon "EXCESS"

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

Acknowledgements

QSC Local Group Members:

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

Postdocs/Students

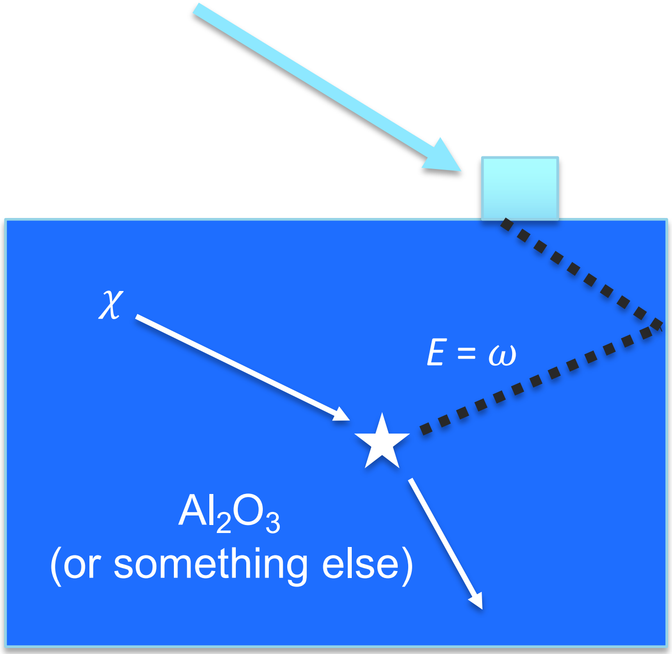
QSC External Collaborators:

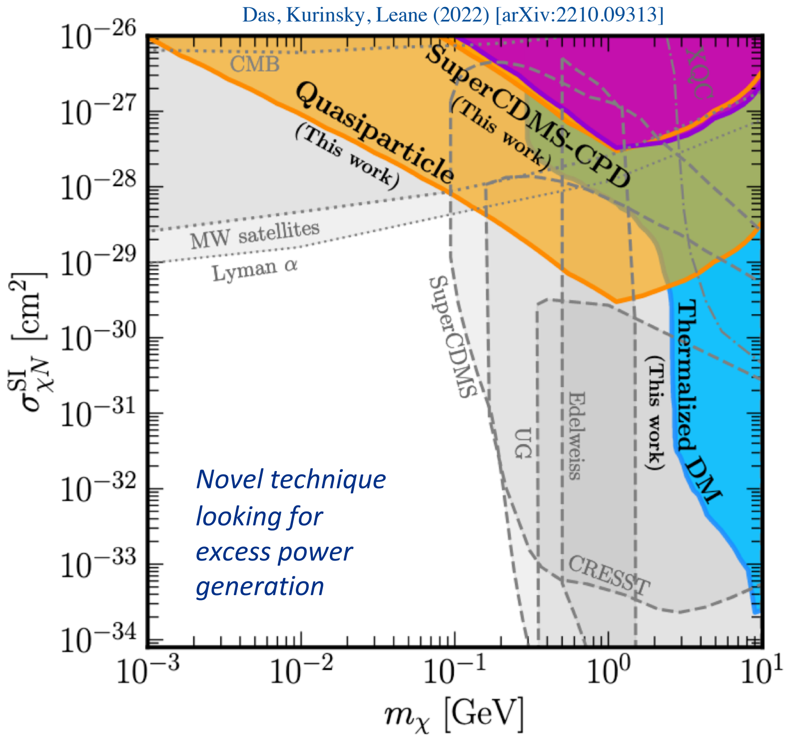
- **UW Madison**: Robert McDermott, Sohair Abdullah, Gabe Spahn
- **SLAC**: Noah Kurinsky, Taj Dyson, Sadaf Kadir
- **Caltech**: Sunil Golwala, Karthik Ramanathan, Taylor Aralis, Osmond Wen
- **Tufts**: Hannah Magoon (co-op w/ FNAL)

Back-up Slides

Designing an Experiment

Proposing a novel, multiplexed quantum device for particle physics detection





How does this impact QIS technology development?

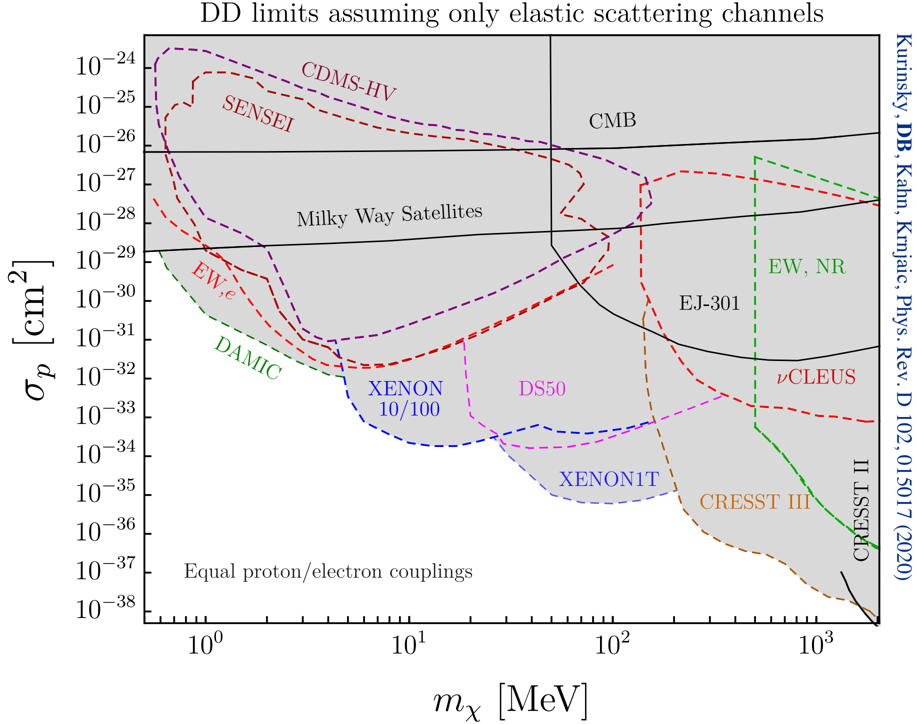
- Goal of this talk: Contextualize the role of quantum detectors in searching for particle dark matter, highlight the challenges associated with this, and suggest some of the ways we are approaching the problem.

→ Demonstrate how advancing quantum detectors for dark matter detection feeds back into advancing QIS technologies

1. **Understanding the relationship between energy deposits in a substrate and qubit decoherence is *critical* to increasing qubit coherence times**
2. **Particle physics perspectives are already revealing new problems (and solutions) that the QIS community has not even considered!**

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
4. **Stress-dependent**: reducing stress from mounting reduces background!

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

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

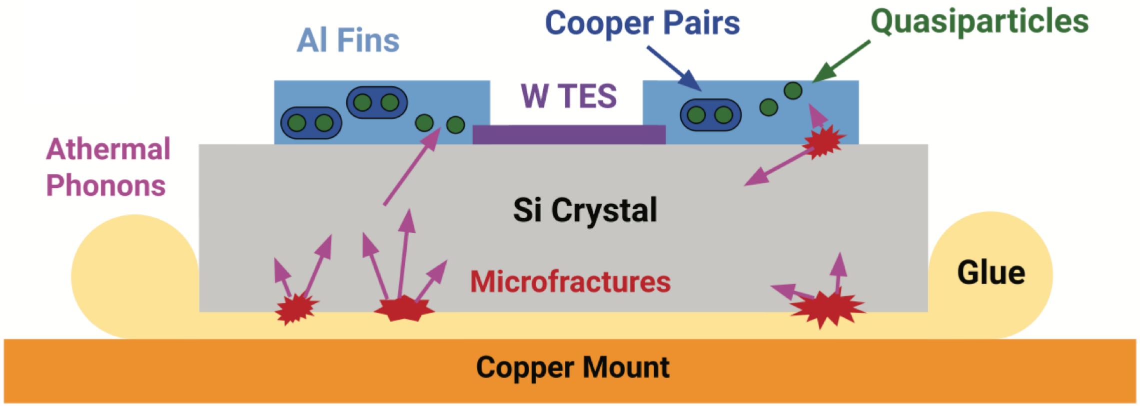
Belina von Krosigk
Daniel Baxter
Marie-Cécile Piro
Rouven Essig
Yonit Hochberg

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

QUANTUM SCIENCE CENTER

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

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 $x_{qp} \approx 3.3 \times 10^{-10}$.

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

Fermilab