Leveraging Quantum Sensors for Dark Matter Detection

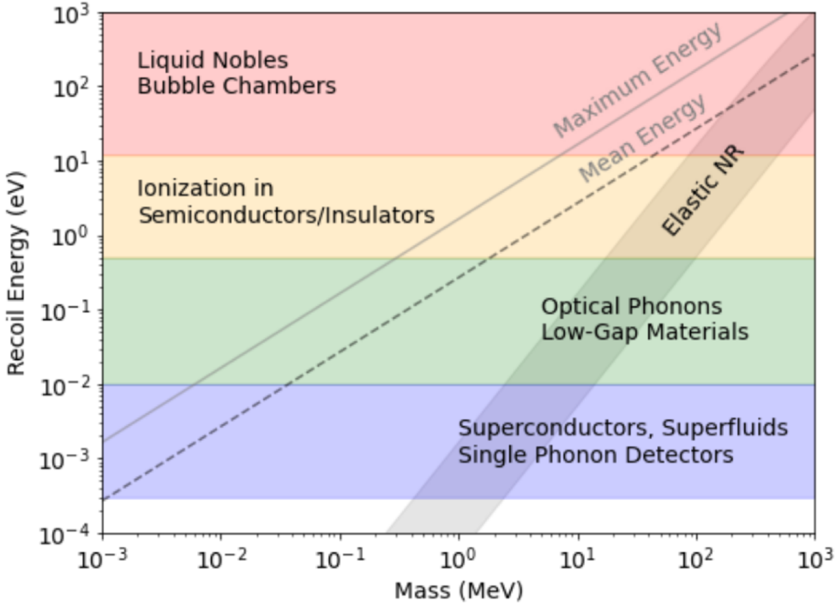
Daniel Baxter

The 14th Conference on the Identification of Dark Matter (IDM 2022)

21 July 2022

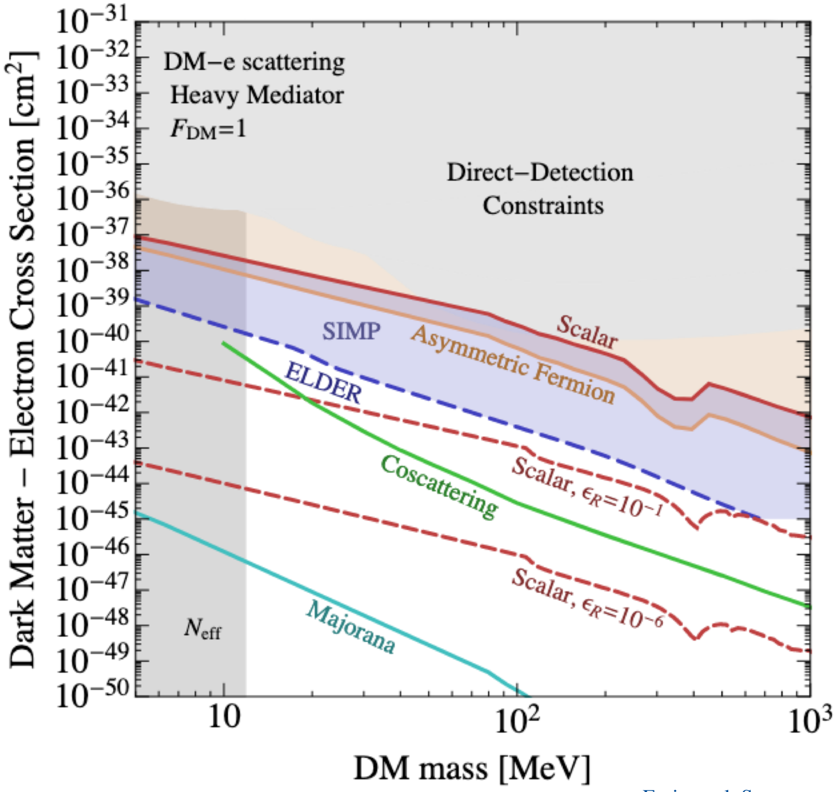
Dark Matter – Lower Thresholds

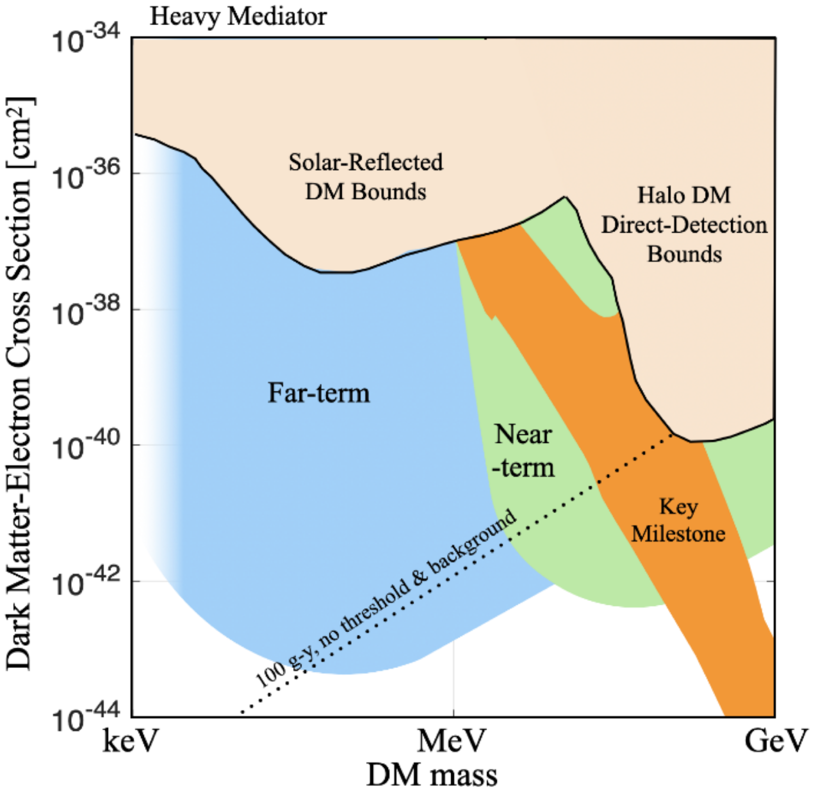
- For DM-nuclear scattering with masses >10 GeV, the LXe TPC's have dominated the last decade and are now mostly just scaling up
- For DM-nuclear scattering <10 GeV, the situation remains a tight, interesting race (targeted parameter space by SuperCDMS)
- For DM-electron scattering with masses >1-10 MeV, a combination of Skipper CCDs and LXe TPCs are providing good coverage, but both are mostly just scaling up
- For DM scattering below 1 MeV, lower thresholds than offered by ionization detectors are required → **new developments**



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

Dark Matter – Electron, Heavy Mediator





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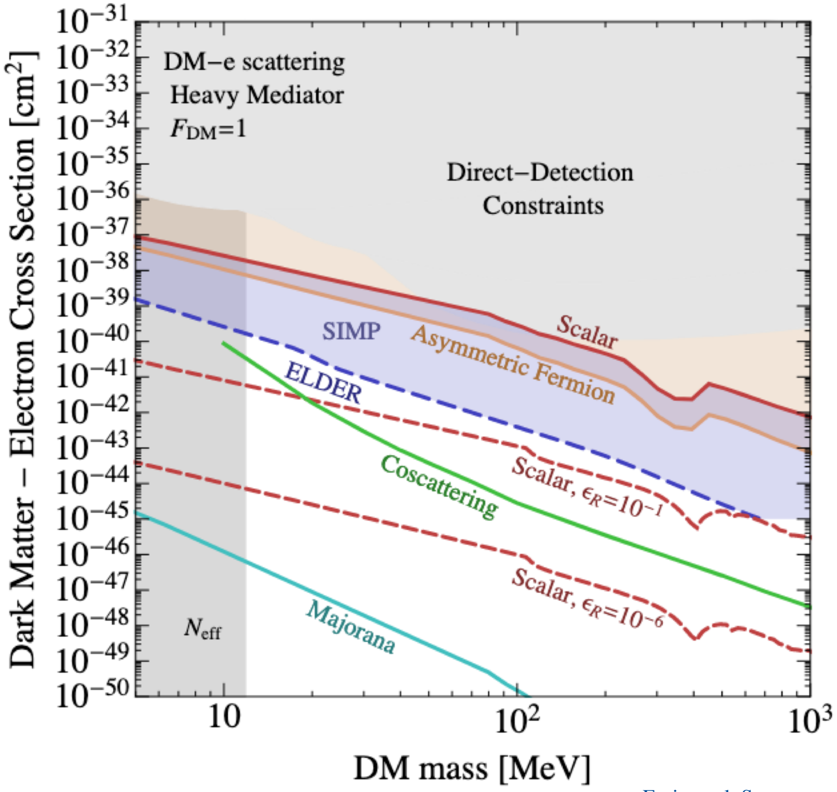
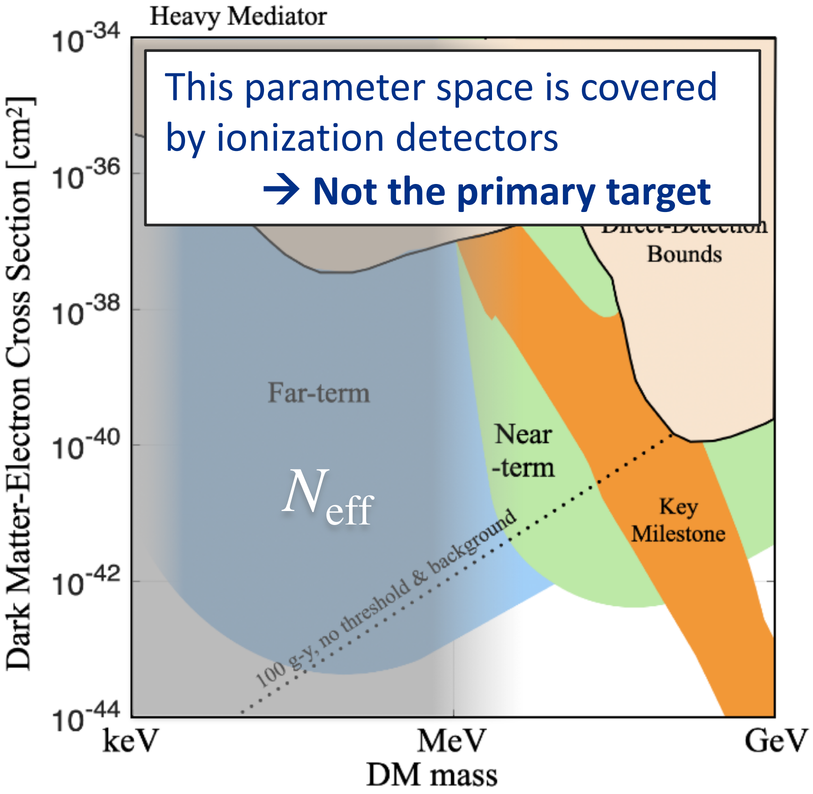


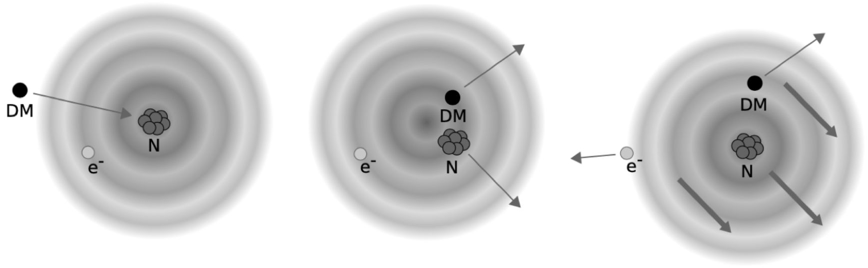


This parameter space is covered by ionization detectors
→ **Not the primary target**

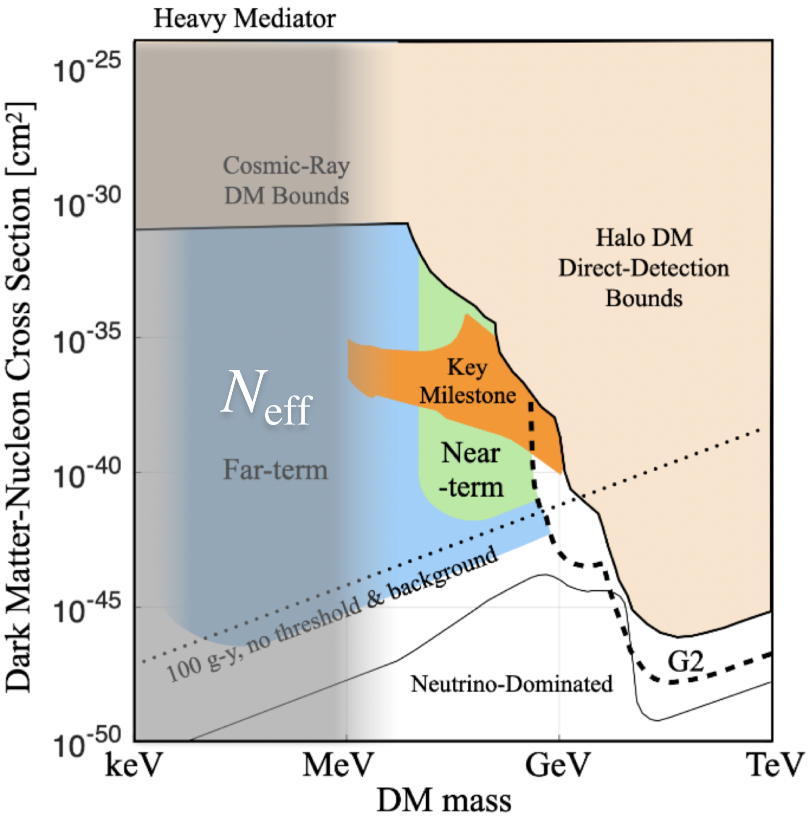
Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Nucleon, Heavy Mediator

- Lower-threshold detectors can still provide complimentary reach against freeze-out targets (orange)
- In particular, ionization detectors can be very powerful here due to the Migdal effect



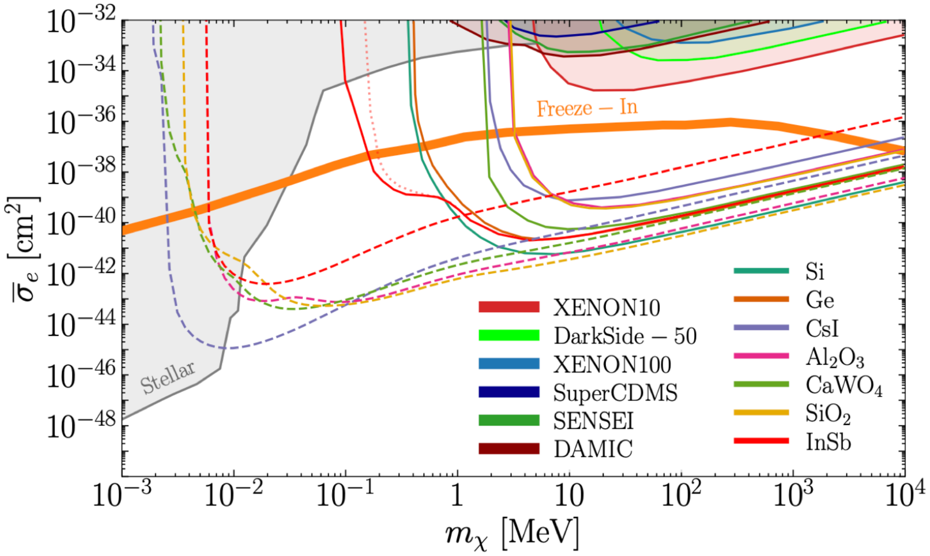
Dolan et al, PRL 121, 101801 (2018) [arXiv:1711.09906]



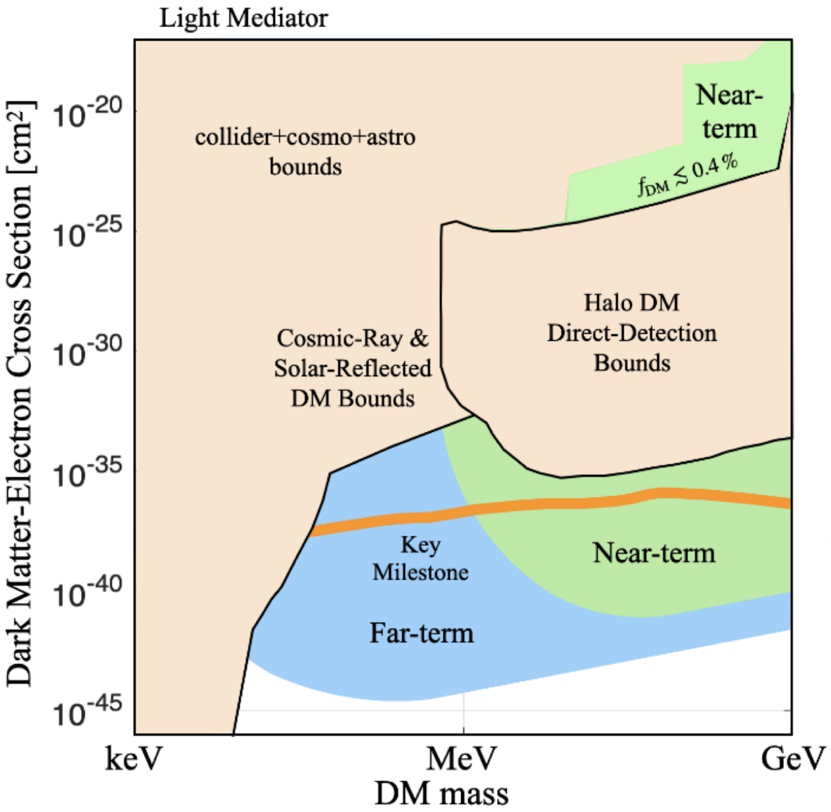
Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Electron, Light Mediator

- Lower-threshold detectors are **essential** to probing the rest of freeze-in target parameter space (orange)



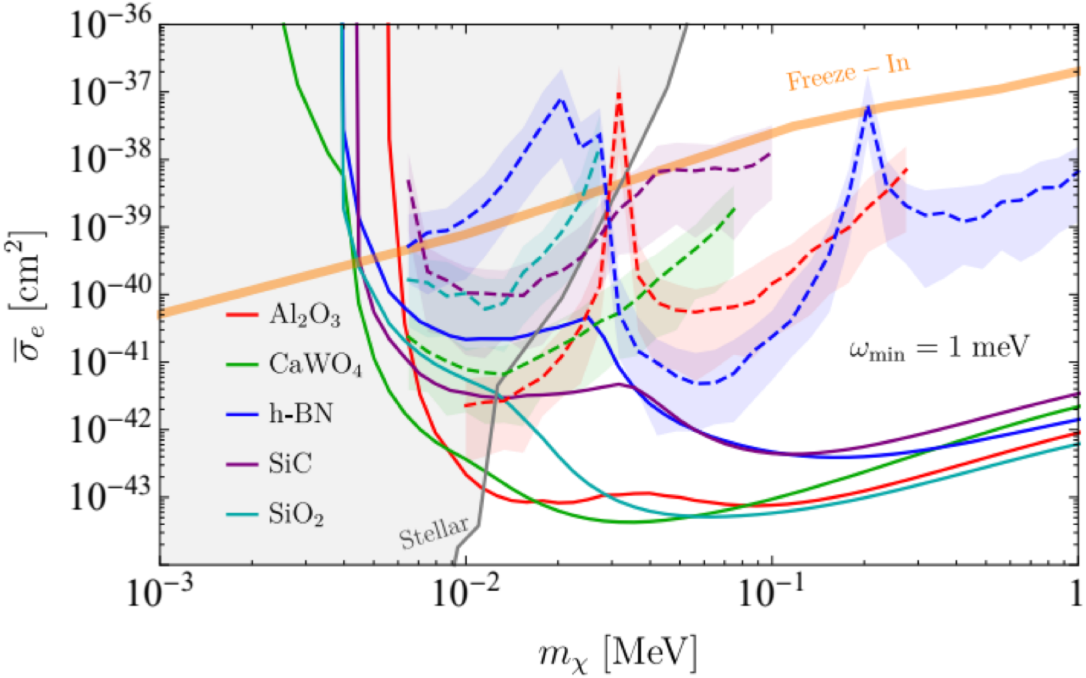
Griffin et al, PRD 101, 055004 (2020) [arXiv:1910.10716]



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

Dark Matter – Electron, Light Mediator

- 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

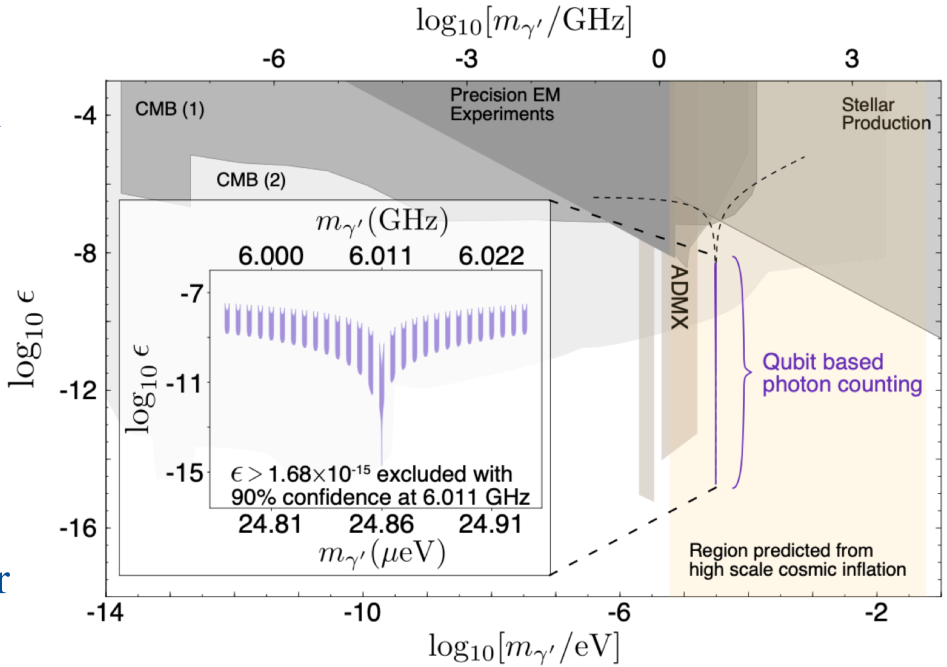


Mitridate et al, (2022) [arXiv:2203.07492]

Defining some terminology

Quantum sensors have been demonstrated for axion/dark photon searches

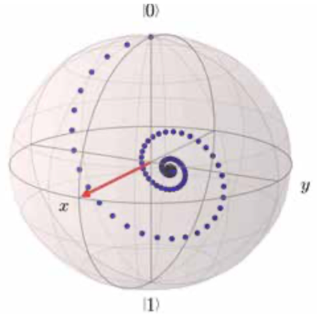
- Quantum Sensors – devices which **require** quantum mechanical description of their behavior
- Qubit – any two-level quantum mechanical system
- Cooper-Pair Box (charge qubit) – qubit whose state is determined by Cooper pairs tunneling across Josephson Junction
- Quasiparticle Poisoning – broken Cooper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

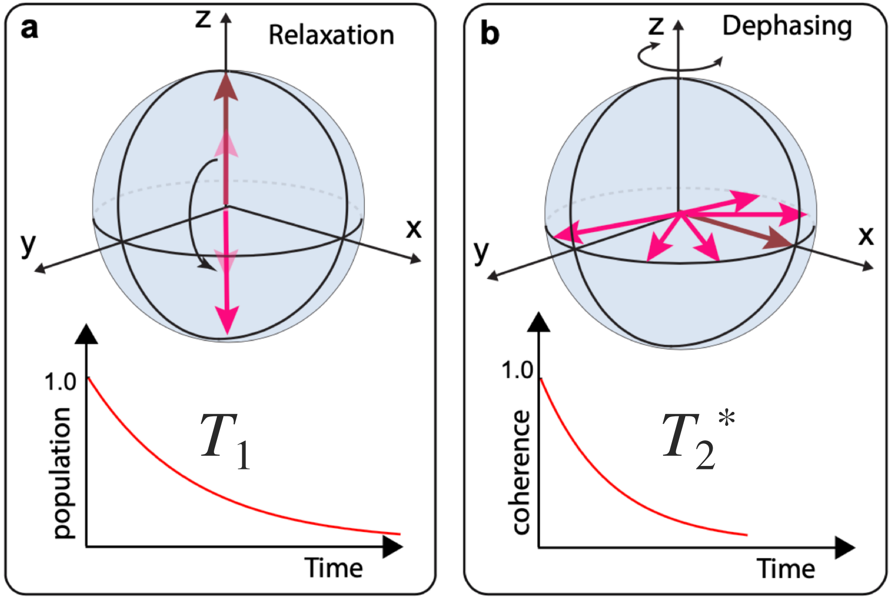


Dixit et al, PRL 126, 141302 (2021) [arXiv:2008.12231]

Superconducting Qubits

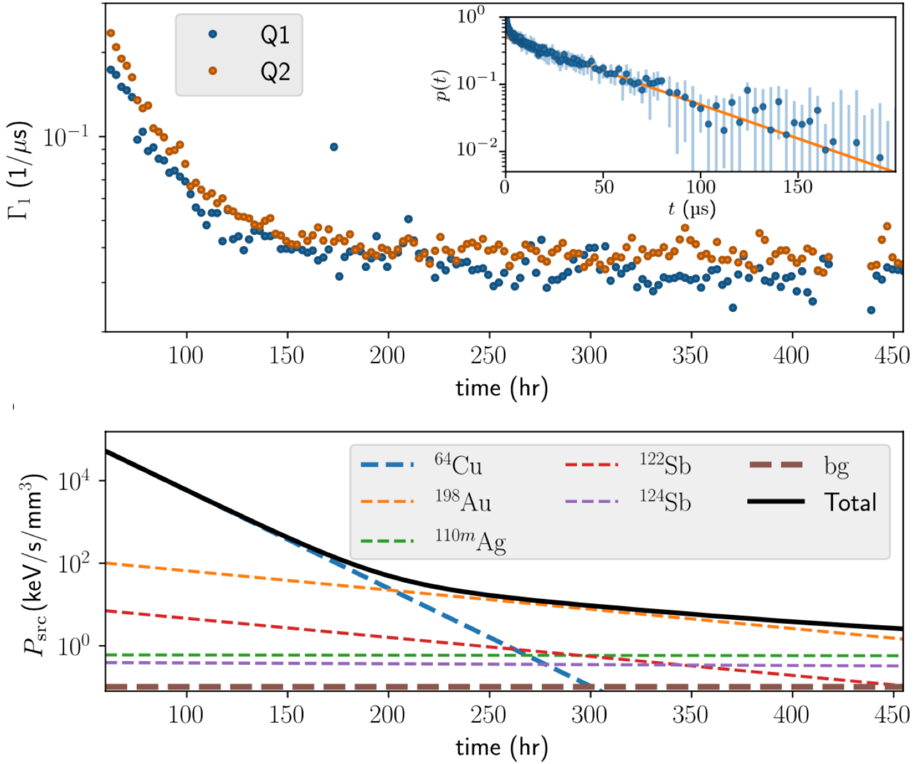
- Decoherence – loss of the qubit state due to relaxation or dephasing
    - **Bad for QIS**
    - **Good for DM detection?**
- T_1 = Relaxation Time – timescale for loss of the energy of the qubit state (ie, 1 → 0)
- T_2^* = Dephasing Time – timescale for loss of the coherence of the qubit state





Mahdi Naghiloo, (2019) [arXiv:1904.09291]

Superconducting Qubits

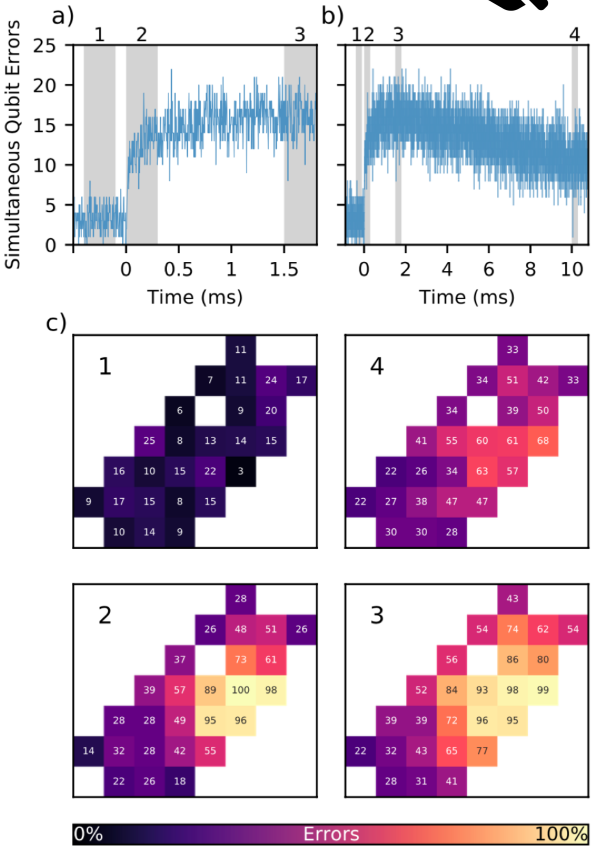


Vepsäläinen et al, Nature 584, 551 (2020) [arXiv:2001.09190]

- 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

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**

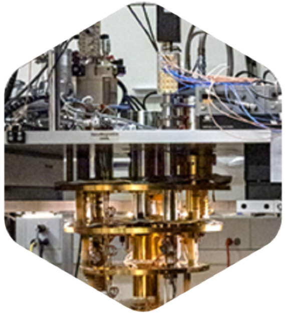


McEwen et al, Nature 18, 107 (2022) [arXiv:2104.05219]

Quantum Science Center

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)



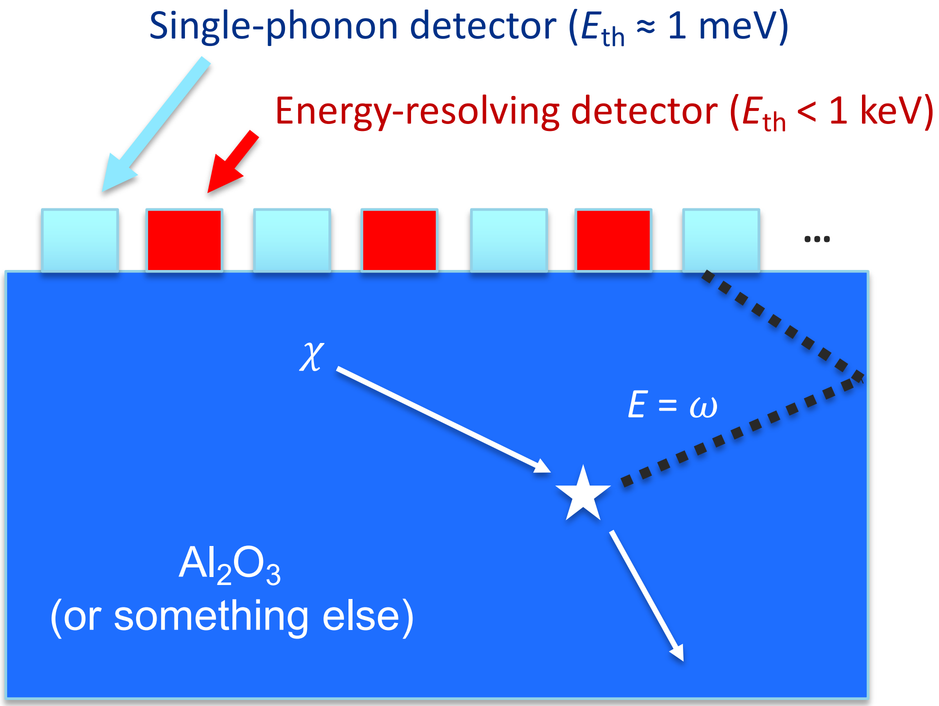
Thrust 3: Quantum Devices and Sensors for Discovery Science

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

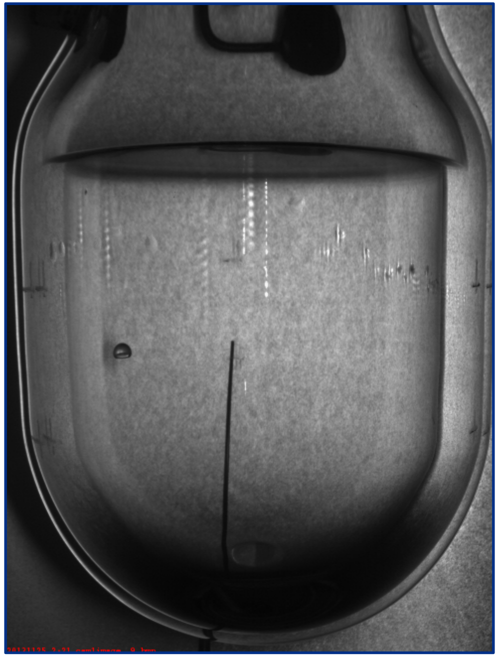
From the perspective of experimental design, this is very similar to a (tiny) bubble chamber!

- Nuclear recoil produces heat, which nucleates a bubble (observed in cameras)

  → **analogous to introducing qubit errors in qubit state**
- Beta/gamma radiation does not produce heat and is rejected

  → **likely to show up in higher-threshold phonon detector (background veto)**
- Signal is a single bubble with small acoustic signal

  → **correlated qubit decoherence without an above-threshold hit in the phonon sensor**

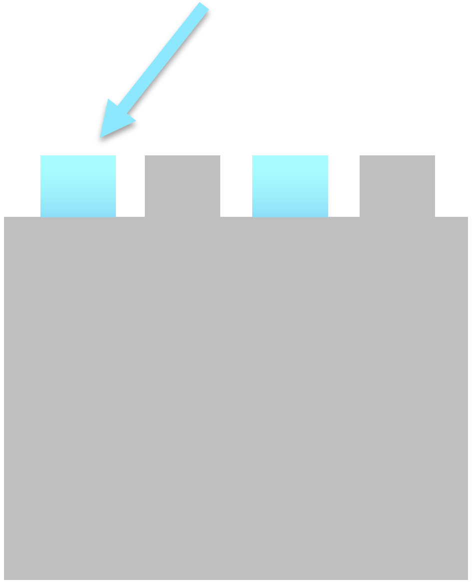


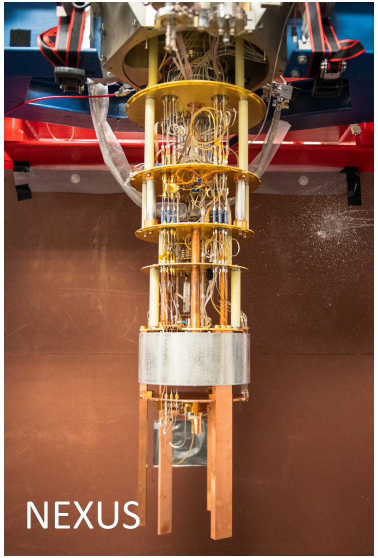
See talks from Tuesday 7/19, parallel 2A on SBC and PICO

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

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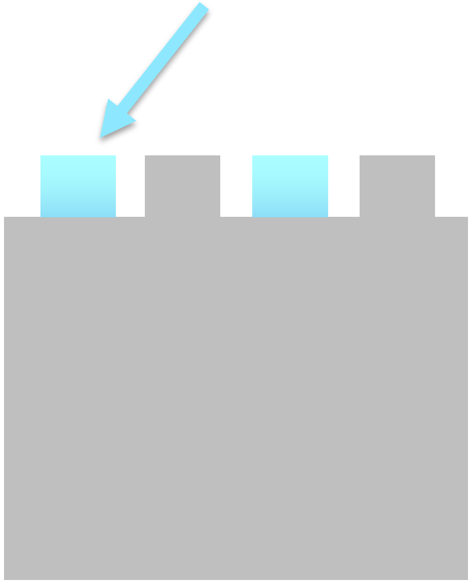
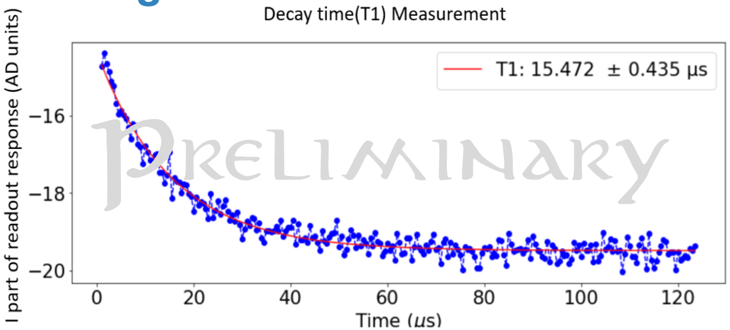
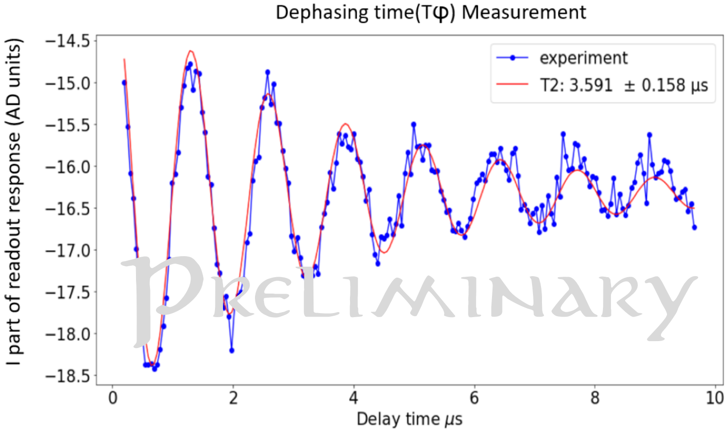


- Qubit device installed in surface setup for frequency multiplexed readout and control of qubits
- T_1 and T_2 measurements made to characterize device performance
- Measurement utilizes new readout (see QICK slide)

Work by Kester Anyang





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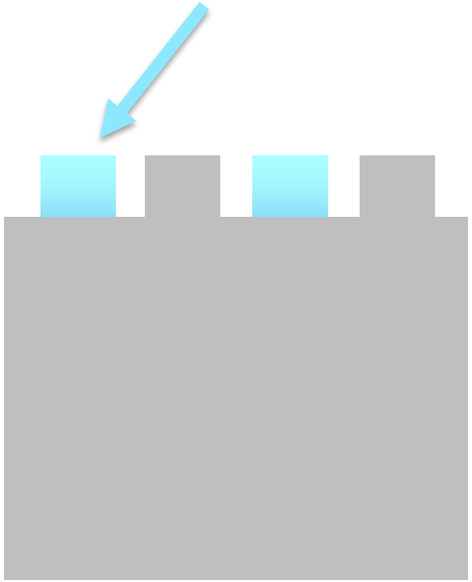
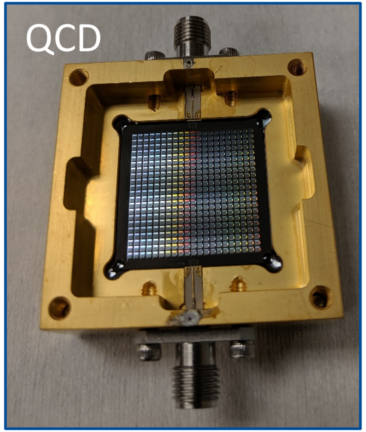




Work by Jialin Yu

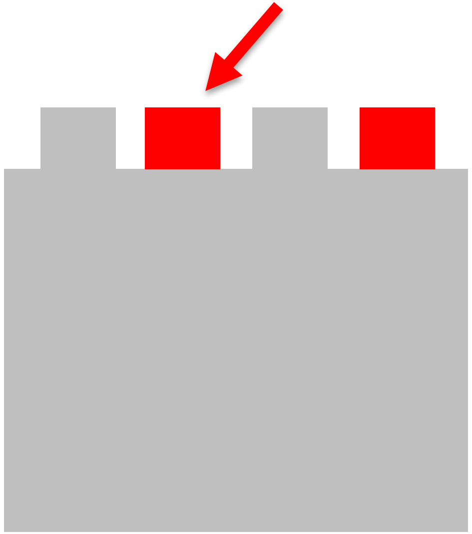
- Quantum Capacitance Detector (QCD) – Based on cooper pair box (charge qubit)
- FNAL/IIT integrating QCD with a Josephson Junction -based weak photon source to characterize a 25 qubit array for DM detector development
- Photon hits the superconducting absorber, resulting in broken Cooper pairs which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

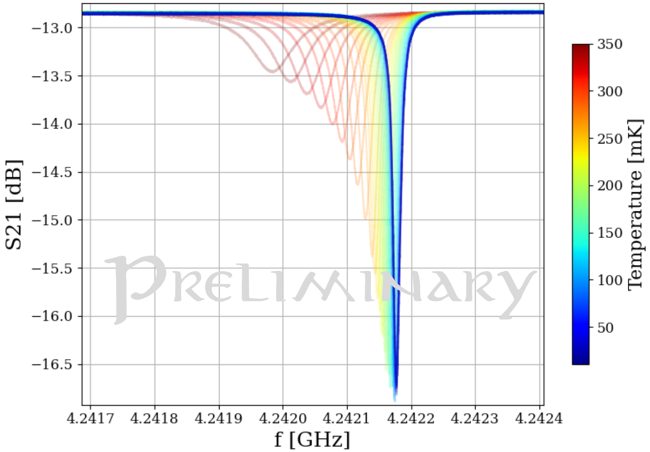
Designing an Experiment

FNAL group has progress on many fronts towards this goal!

<u>KID = "Kinetic Inductance Detector"</u>

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





Work by Dylan Temples & Hannah Magoon

- <u>KID</u> – 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**

See Karthik Ramanathan talk earlier in this session

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

MEMS = "Micro-Electro-Mechanical System"

Calibration

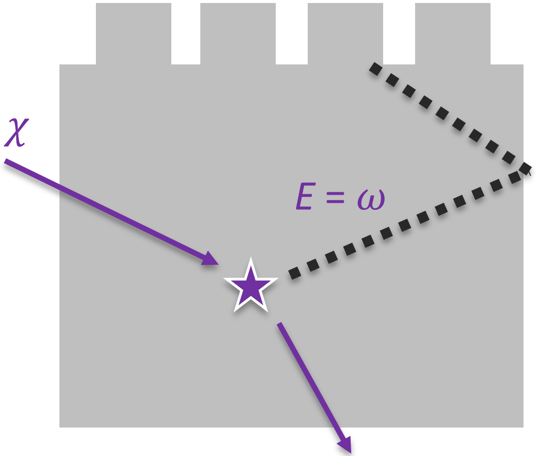


Photo: Hannah Magoon

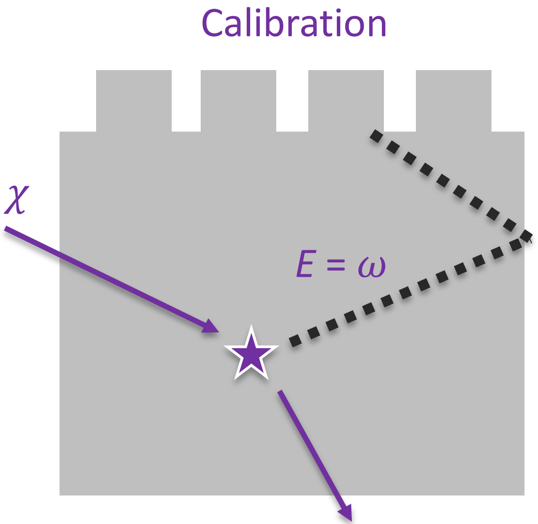
- Laser Calibration – scan over device w/ UV-optical-IR photons to determine phonon response as a function of ***position***
- MEMS Mirror – outputs up to mW at full scanning speed and range, none while stationary
- **Cold tests w/ KIDs to begin next week (after IDM)**

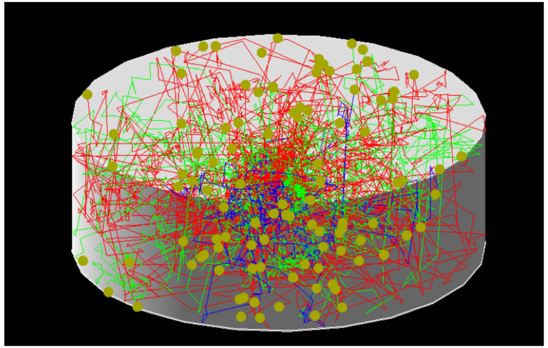
See Kelly Stifter talk earlier today in Parallel 3A

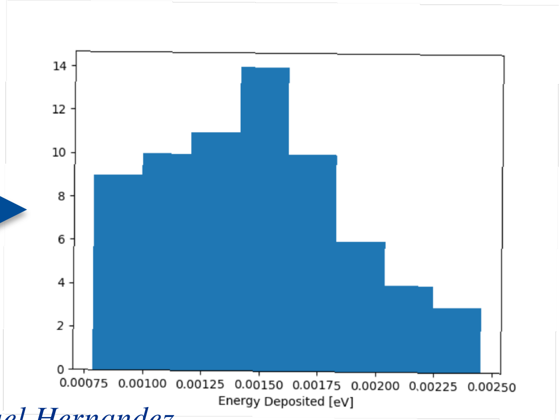
Designing an Experiment

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

Designing an Experiment

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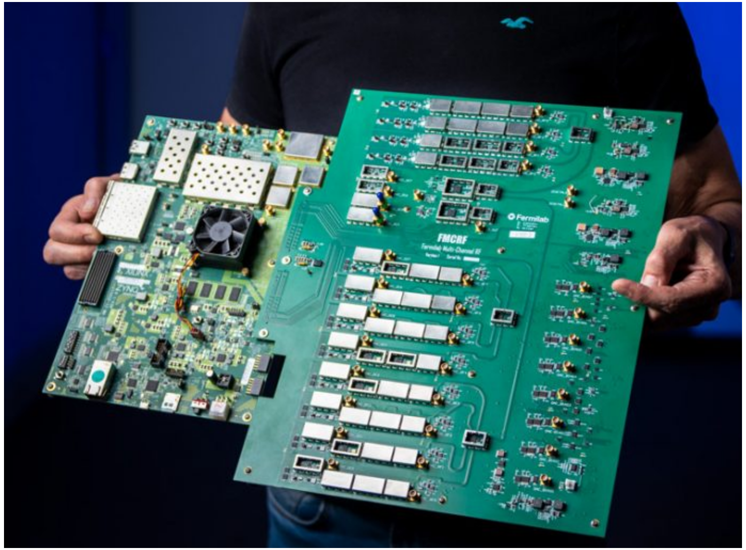
FNAL group has progress on many fronts towards this goal!

QICK = “Quantum Instrumentation Control Kit”



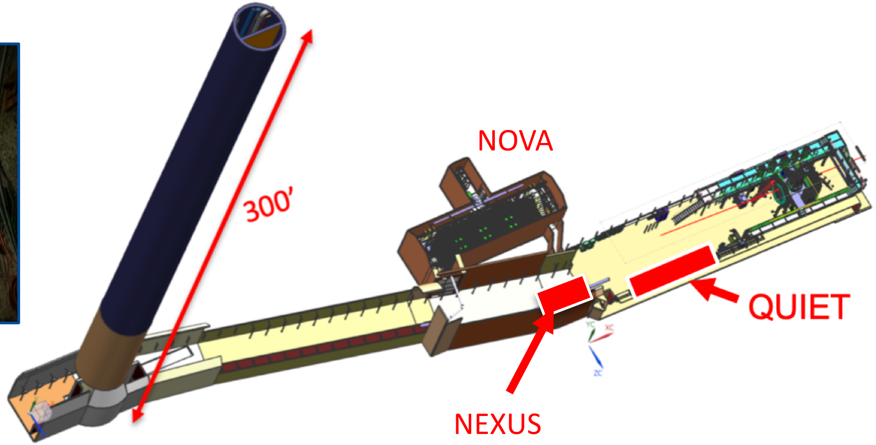
- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting (not including the 2 from FNAL)
- A factor of ~20 cheaper compared to off-the-shelf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

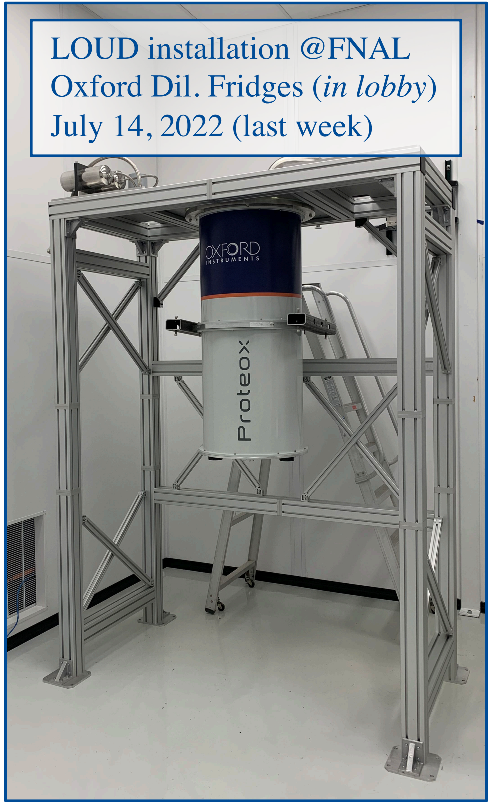
Stefanazzi et al, Rev. Sci. Instrum. 93, 044709 (2022) [arXiv:2110.00557]

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)





Quantum Science Center – Acknowledgements

QSC Thrust 3 Members:

- **FNAL**: Aaron Chou, Daniel Bowring, Gustavo Cancelo, Lauren Hsu, Adam Anderson, Daniel Baxter, Sami Lewis, 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

Postdocs/Students

QSC Thrust 3 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)

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 (see Wednesday plenary talk by Belina von Krosigk and Margarita Kaznacheeva plenary on EXCESS Workshop series)

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