Development of new techniques for low-mass dark matter detection

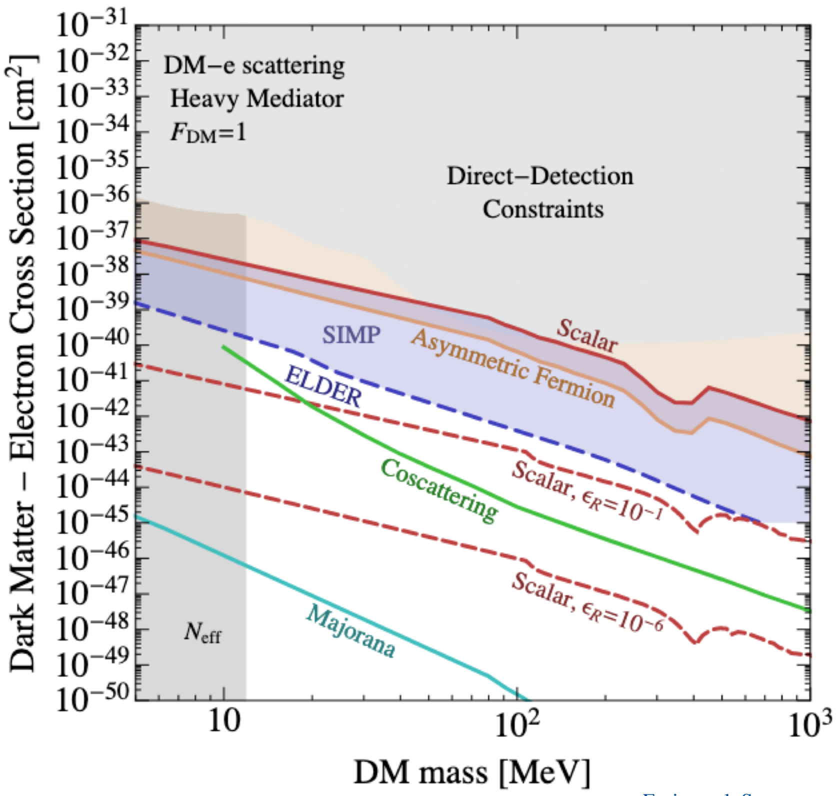
Daniel Baxter
GUINEAPIG Workshop on Light Dark Matter
10 September 2022

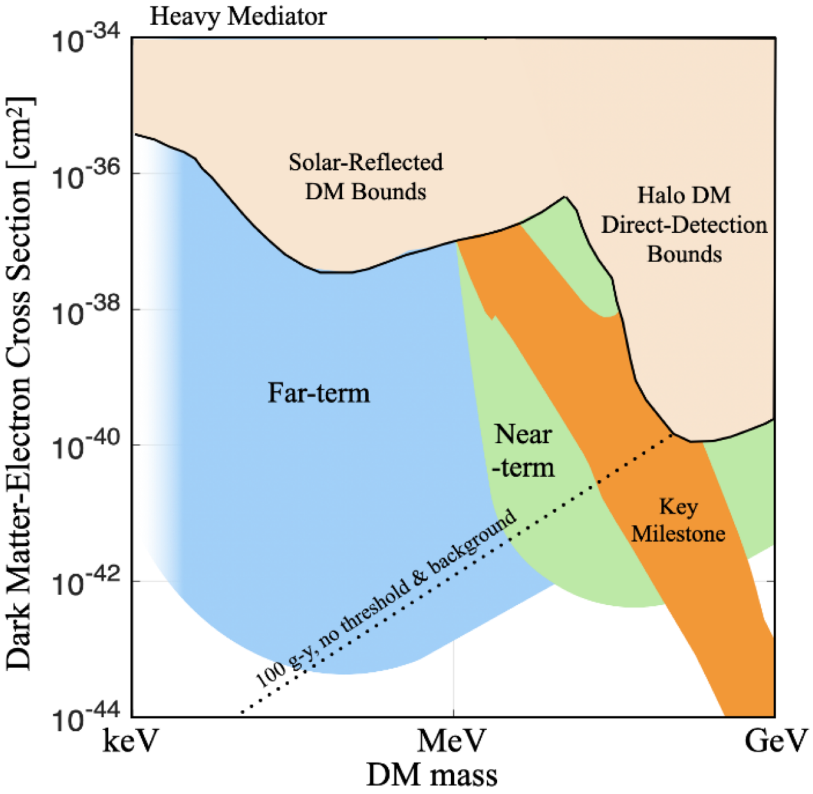
Dark Matter – Direct Detection Overview

- *Particle* dark matter direct detection can be easily sub-divided into six experimental regimes:
    1. NR w/ mass above ^{8}B neutrino (> 10 GeV)
    2. **NR w/ mass below ^{8}B neutrino (< 10 GeV) – ionization detectors (Migdal)**
    3. ER w/ mass above electron BE (> 1 MeV)
    4. **Electric coupling below electron BE (< 1 MeV) – single-phonon detectors**
    5. Stable dark photon (< 2 m_e = 1 MeV)
    6. *Nightmare scenario* (gravity only)

- Notably, individual detector technologies have simultaneous, independent, and inherent sensitivity to these different regimes

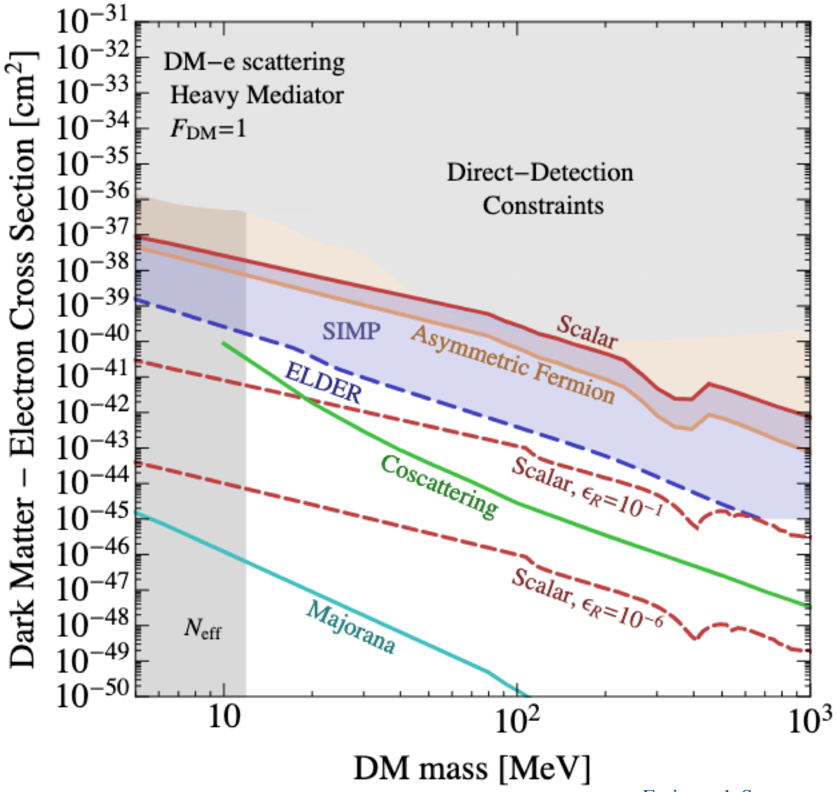
Dark Matter – Electron, Heavy Mediator

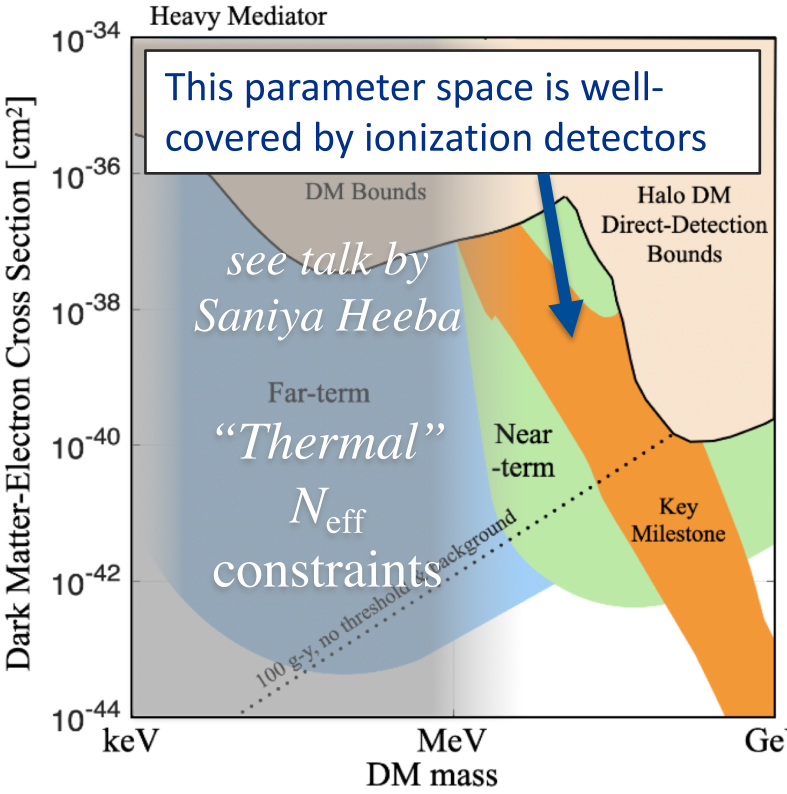




Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Electron, Heavy Mediator

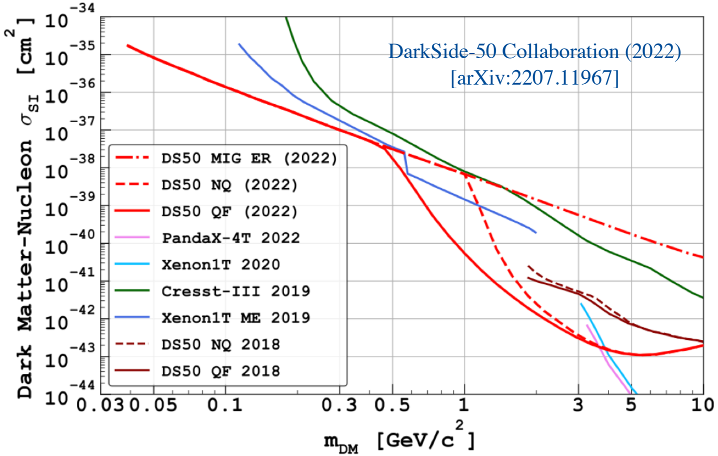


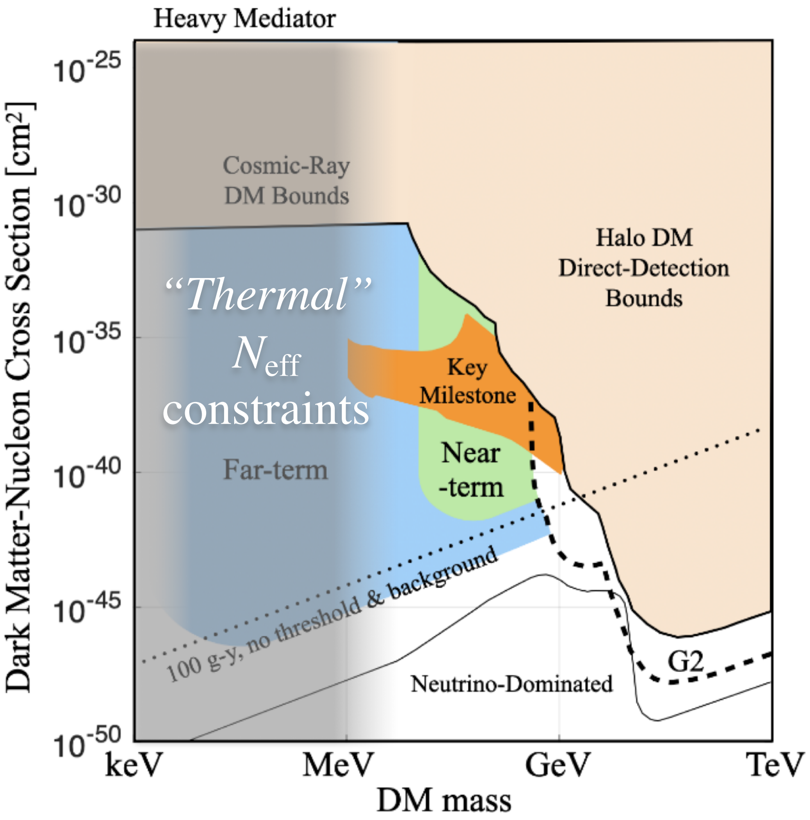


Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Nucleon, Heavy Mediator

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

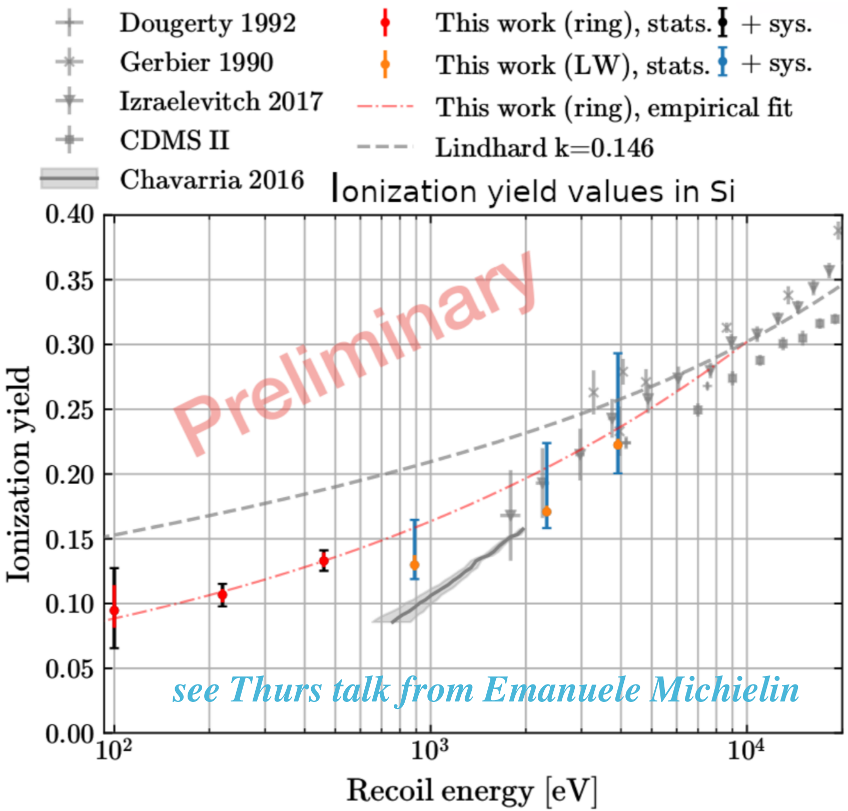




Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

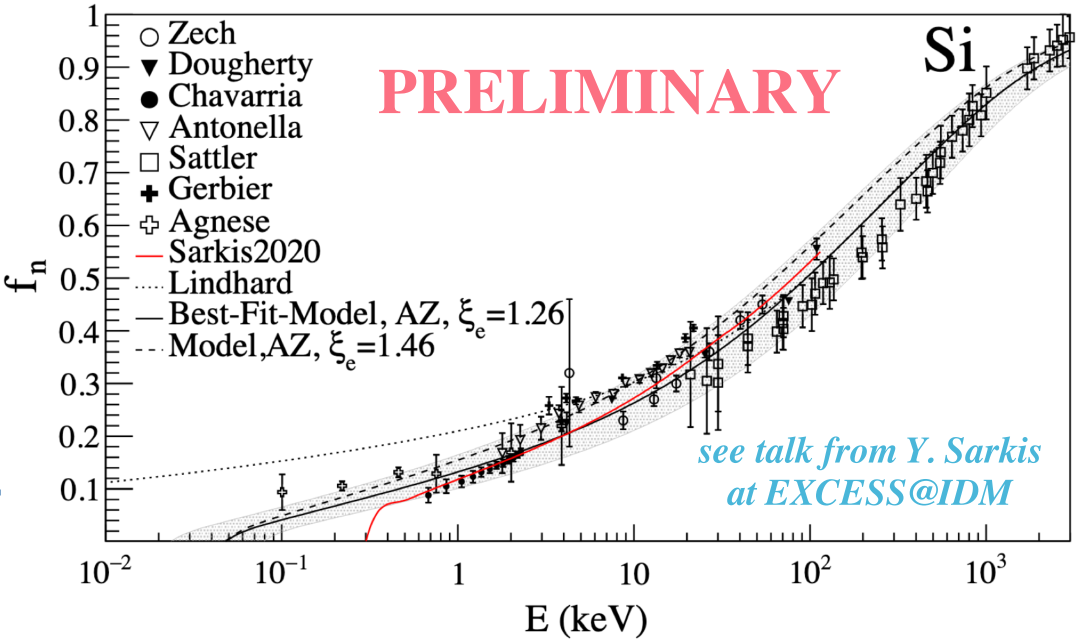
Ionization Yield for Low-Energy Nuclear Recoils

- Many of the limits on DM-NR coupling for mass < 10 GeV depend on assumptions about ***ionization yield***
- For some elastic NR energy deposit, how much of that energy ends up as detectable charge
- **(RIGHT) Best [unpublished] measurements of ionization yield in silicon come from IMPACT measurement by SuperCDMS at TUNL**



Ionization Yield for Low-Energy Nuclear Recoils

- Many of the limits on DM-NR coupling for mass < 10 GeV depend on assumptions about ***ionization yield***
- For some elastic NR energy deposit, how much of that energy ends up as detectable charge
- **(RIGHT) Data agrees shockingly well with state-of-the art theoretical models**



previous work: Y. Sarkis et al Phys. Rev. D 101, 102001 (2020) [arXiv:2001.06503]

Ionization Yield for Low-Energy Nuclear Recoils

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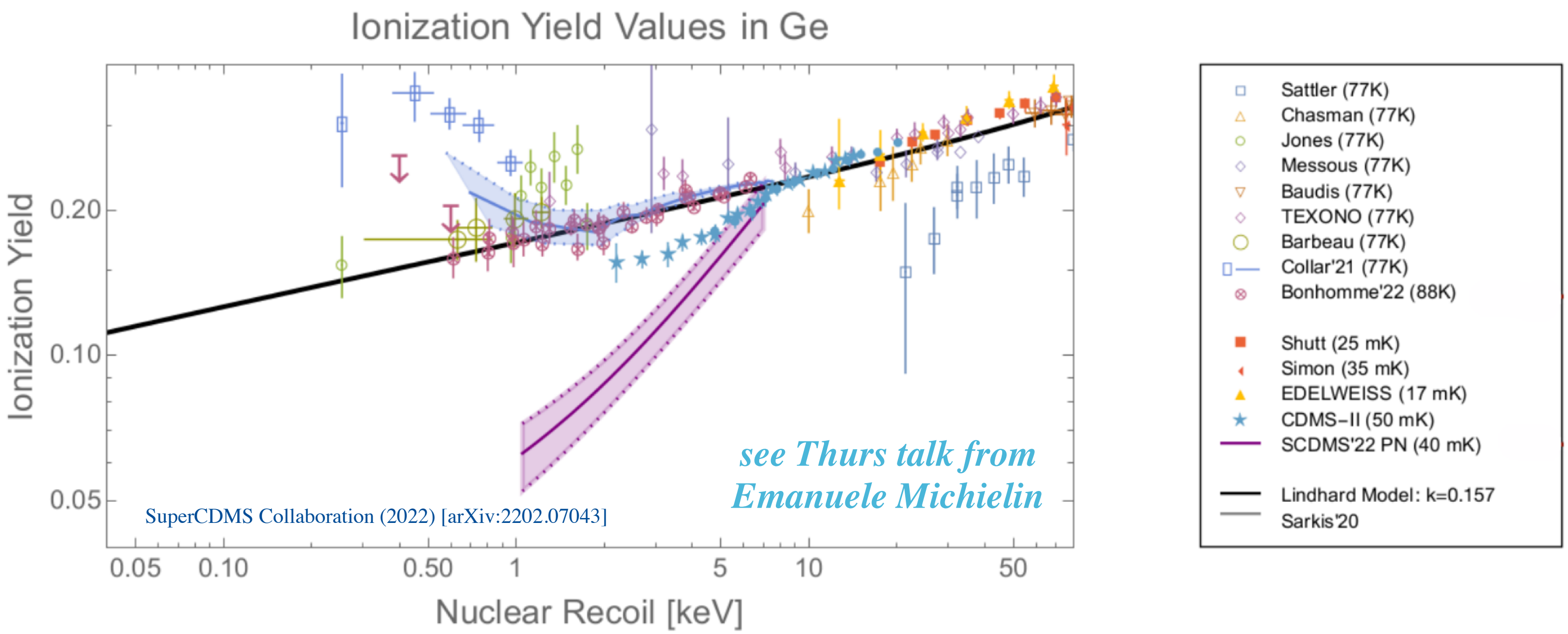
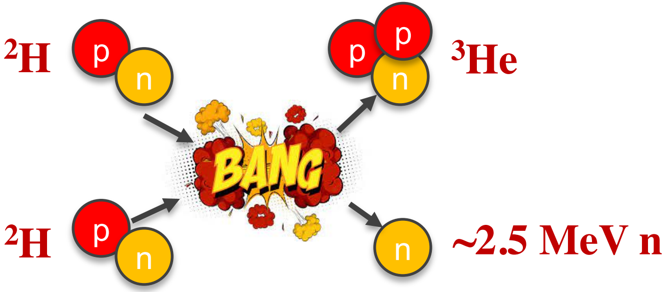
The situation in silicon is relatively consistent compared to germanium…

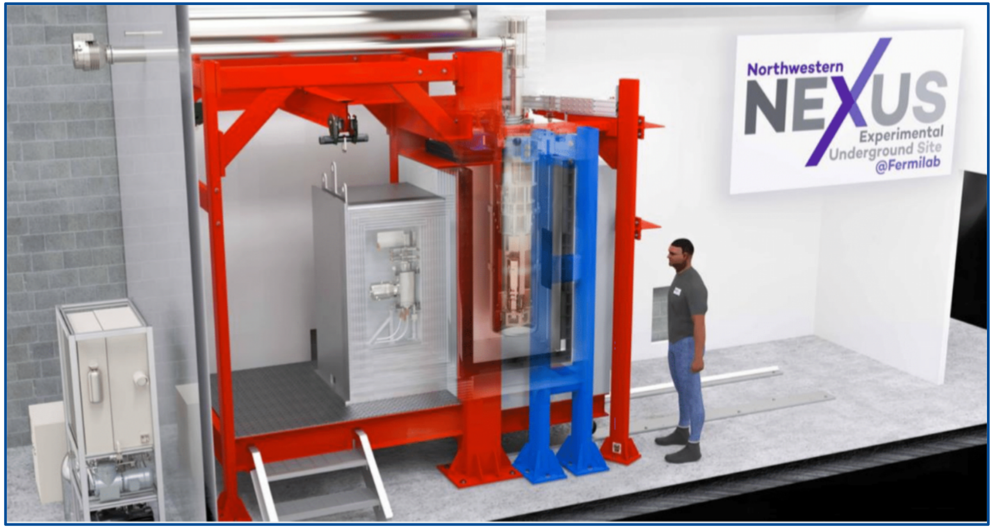


NEXUS Introduction

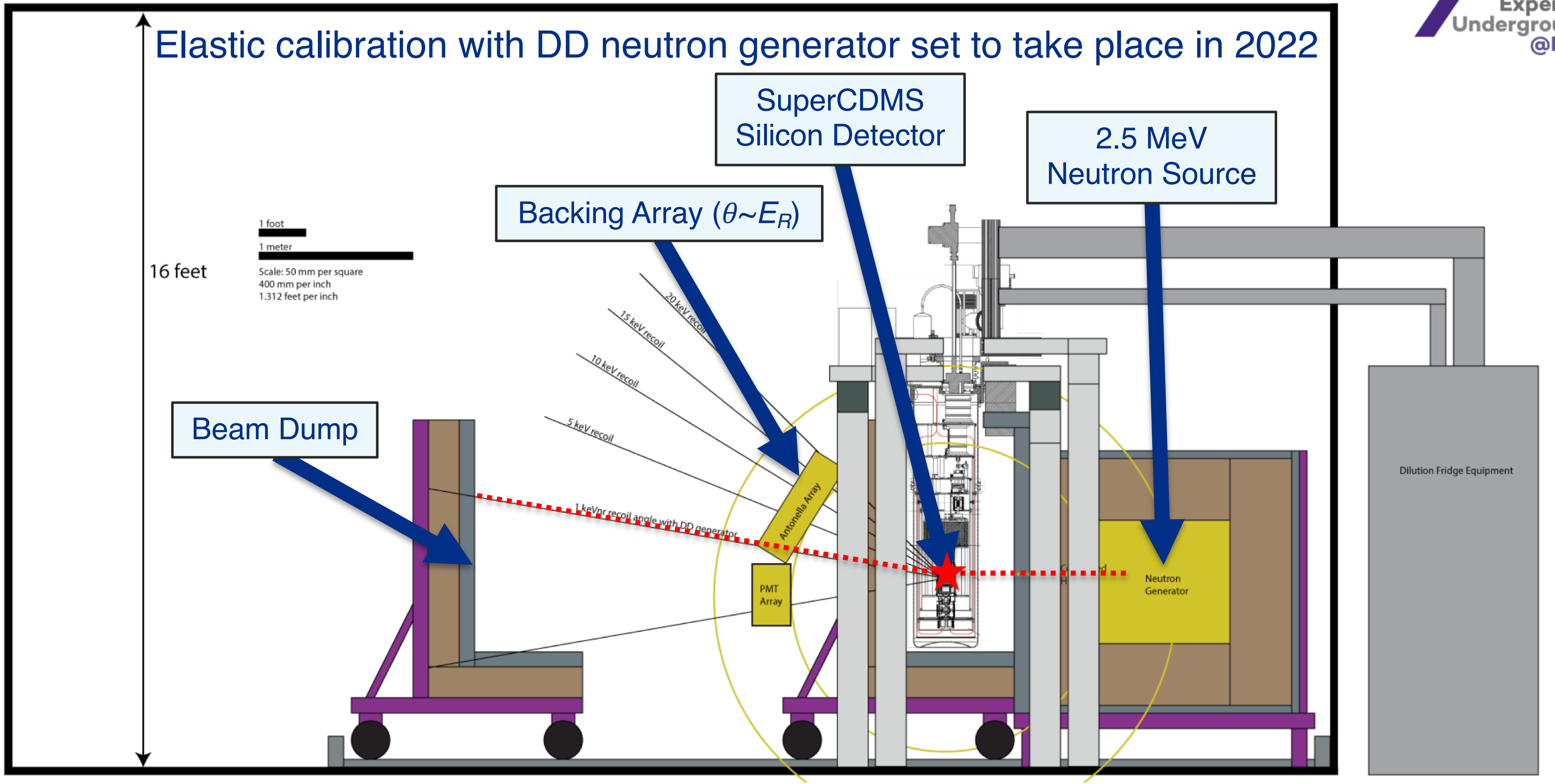
- Low-energy ionization yield measurements are **REALLY** hard
- They require high signal-to-background and very long exposures
- <u>Our approach</u>: *Use a shielded DD generator incident on a 200 dru cryostat underground*



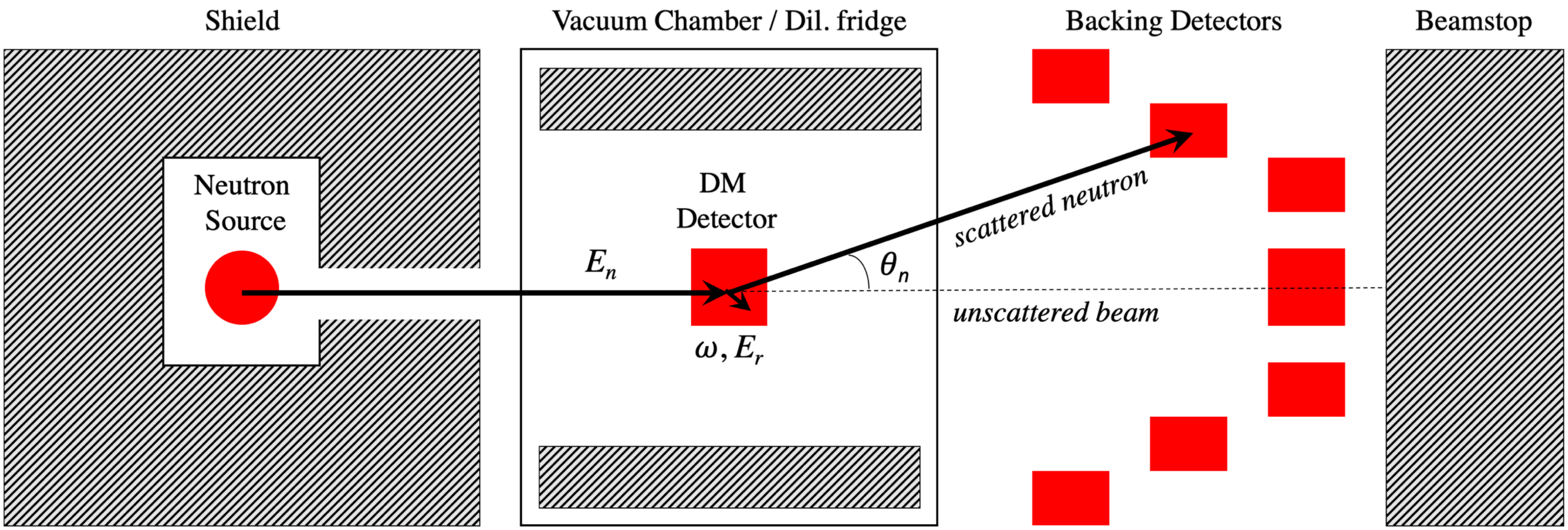
<u>Main advantage</u>: Mono-energetic source with no primary beam-related backgrounds (secondaries expected from interactions in shielding)



NEXUS Introduction



NEXUS Introduction

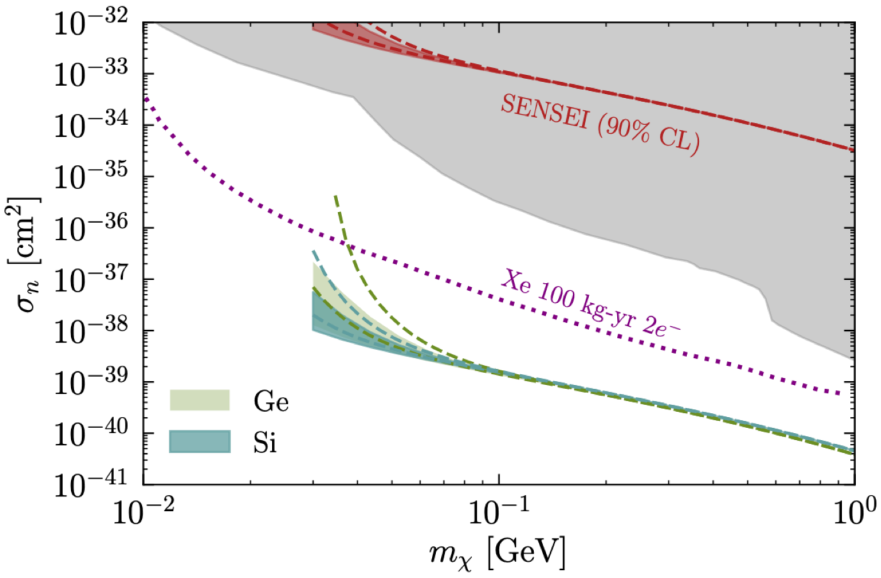


Same diagram (flipped), but now we allow for inelasticity ω to the electronic system…

Duncan Adams, **DB**, Hannah Day, Rouven Essig, Yoni Kahn, [arXiv:2209.xxxxx]

The Migdal Effect Introduction

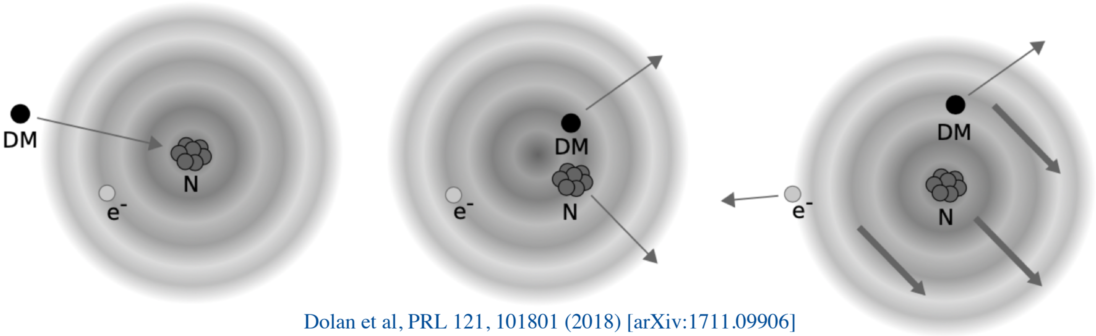
- Goes back to the work of **Arkady Migdal** in the 1940's
- These exists a small probability that a sub-threshold nuclear recoil will ***ionize*** the recoiling atom (**basic QM**)
- For dark matter masses where the ***nuclear recoil*** energy is always below threshold ($\lesssim$ keV), this signal could dominate other channels
- This should result in a small number of individual charges, similar to an ***electron recoil*** signal, but spectrally distinct



Knapen et al, PRL 127, 081805 (2021) [arXiv:2011.09496]

The Migdal Effect Introduction

$$\Psi_{E_A}(\mathbf{x}_N, \{\mathbf{x}\}) \simeq e^{i\mathbf{p}_N \cdot \mathbf{x}_N} e^{i\sum_{i=1}^{N_e} \mathbf{q}_e \cdot \mathbf{x}_i} \Psi_{E_A}^{(\mathrm{rest})}(\mathbf{x}_N, \{\mathbf{x}\})$$



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

$$|\Phi_{ec}\rangle \rightarrow |\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle \rightarrow \mathcal{P} = |\langle\Phi^*_{ec}|\Phi'_{ec}\rangle|^2$$

- The interaction is coherent with the **nucleus**, but the full **atomic** wave-function is used to represent the system.

Northwestern NEXUS Experimental Underground Site @Fermilab

The ME probes the *exact* same matrix element as DM-electron scattering (in atoms), at a different momentum transfer scale

Migdal

$$|\langle\Psi_{\mathbf{v}_A}|\Psi_i\rangle|^2 \sim |\langle\psi_f|e^{i\mathbf{q}_e\cdot\mathbf{x}}|\psi_i\rangle|^2$$

Electron

$$|\langle\Psi_f|H_{\mathrm{int}}|\Psi_i\rangle|^2 \sim |\langle\psi_f|e^{i\mathbf{q}\cdot\mathbf{x}}|\psi_i\rangle|^2$$

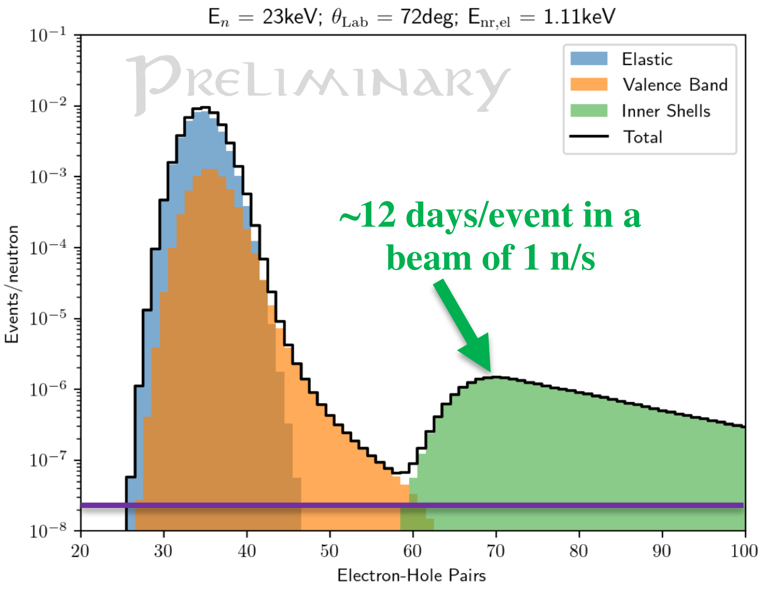
DB, Kahn, Krnjaic, PRD 101, 076014 (2020) [arXiv:1908.00012],
Essig, Pradler, Sholapurkar, Yu, PRL 124, 021801 (2020) [arXiv:1908.10881]

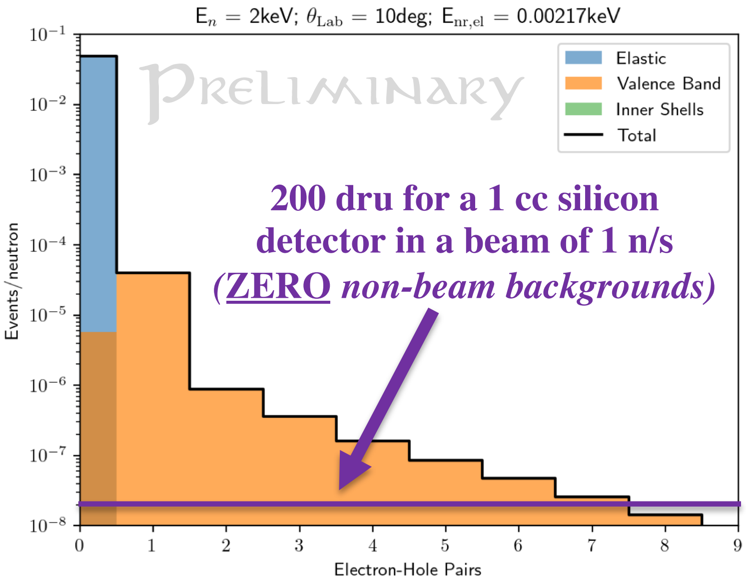
Angular Migdal Spectra for Neutron Scattering

This lays out an experimental roadmap for how to separately calibrate:

(1) Sarkis Model: elastic ionization yield w/ high-energy neutrons
(2) Ibe ME: inner shell ME w/ medium—high energy wide-angle scatters (*left*)
(3) DarkELF ME: valence shell ME w/ low-energy wide-angle scatters (*right*)

see talk from D. McKinsey later today…





Duncan Adams, **DB**, Hannah Day, Rouven Essig, Yoni Kahn, [arXiv:2209.xxxxx]

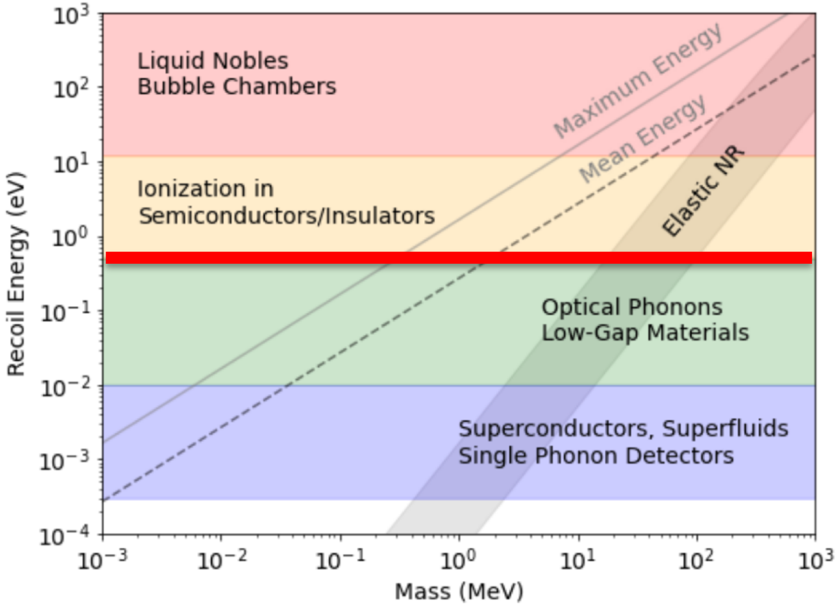
Dark Matter – Direct Detection Overview

- For DM-electron scattering with masses >1-100 MeV and DM-nuclear scattering with masses <10 GeV, ionization detectors are providing good coverage
- For DM scattering below 1 MeV, lower thresholds than offered by ionization detectors are required

→ **new device development!**

- *Noah gave a fantastic talk about this yesterday, with a focus on device development*

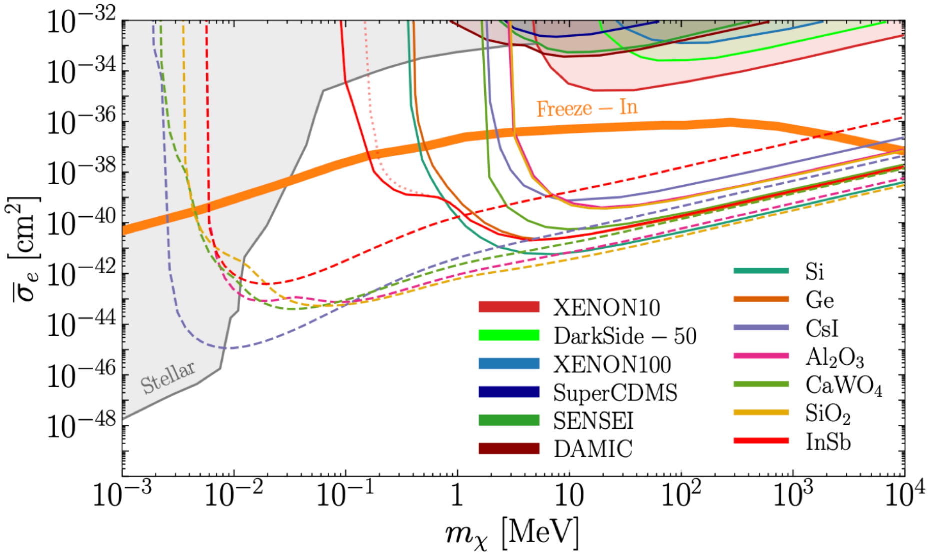
→ **let's talk testing!**



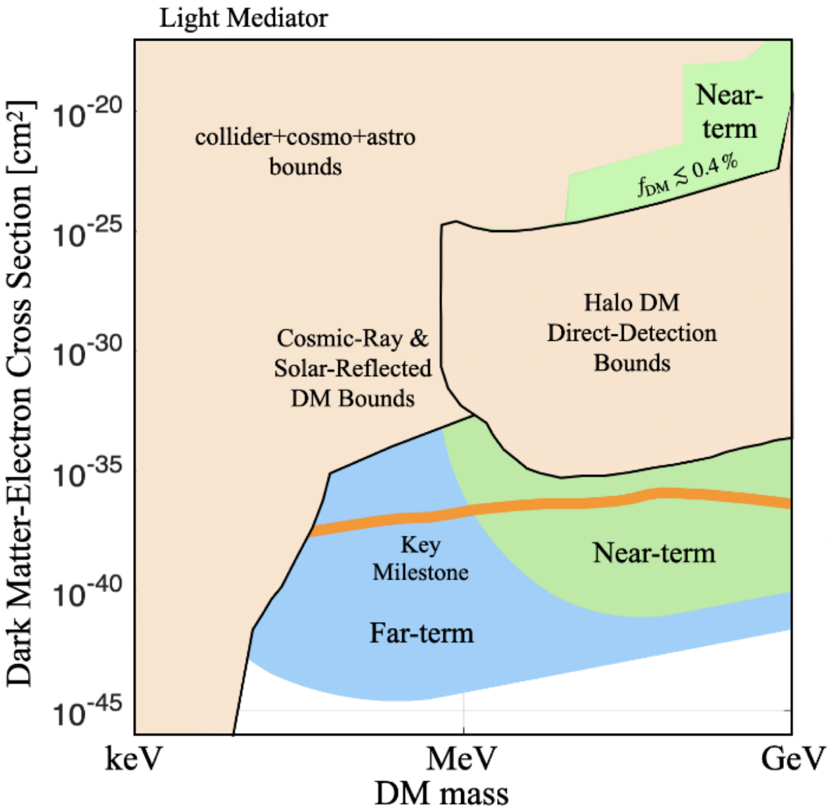
Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Dark Matter – Electric Coupling, Light Mediator

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



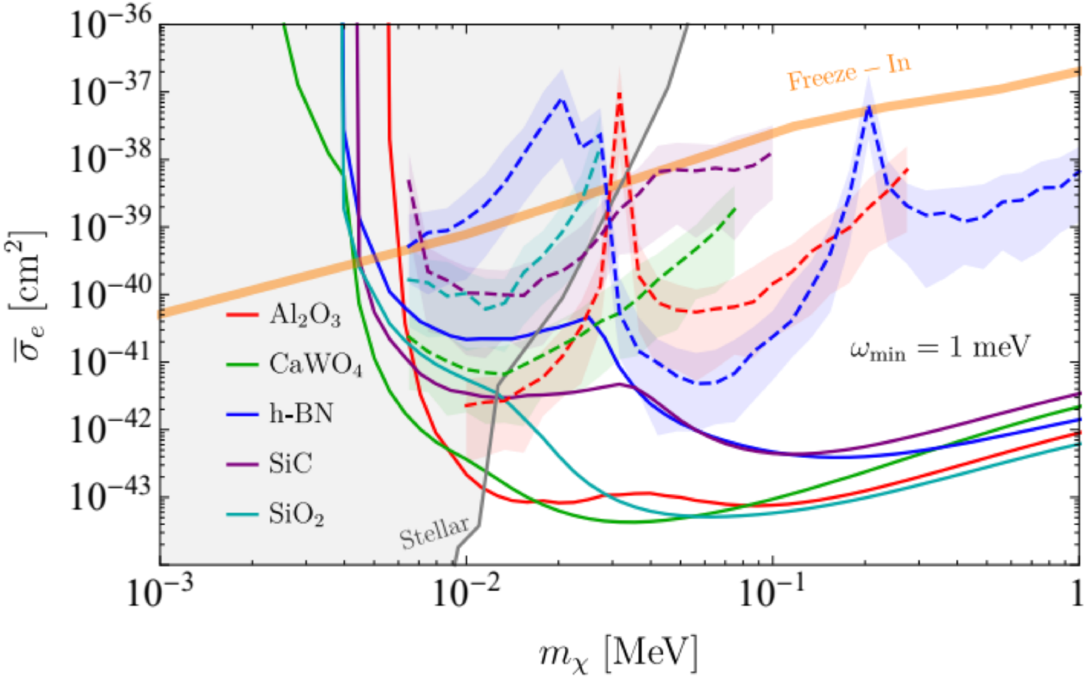
Griffin et al, PRD 101, 055004 (2020) [arXiv:1910.10716]



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

Dark Matter – Electric Coupling, 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

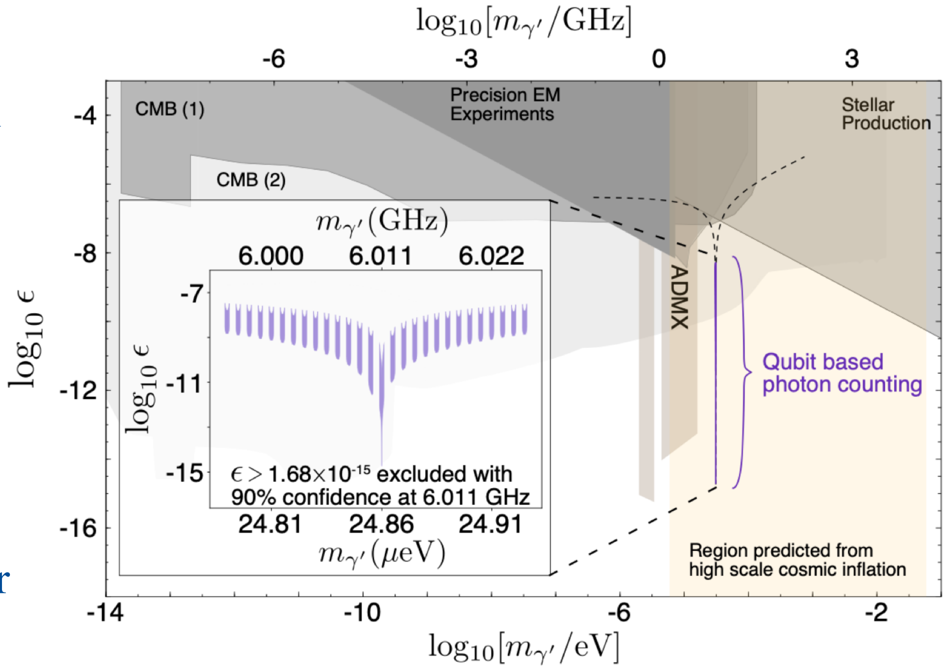


Mitridate et al, (2022) [arXiv:2203.07492]

Defining some terminology

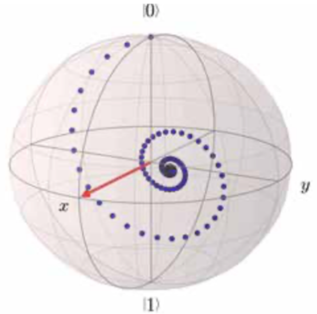
Quantum sensors have been demonstrated for axion/dark photon searches

- 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]

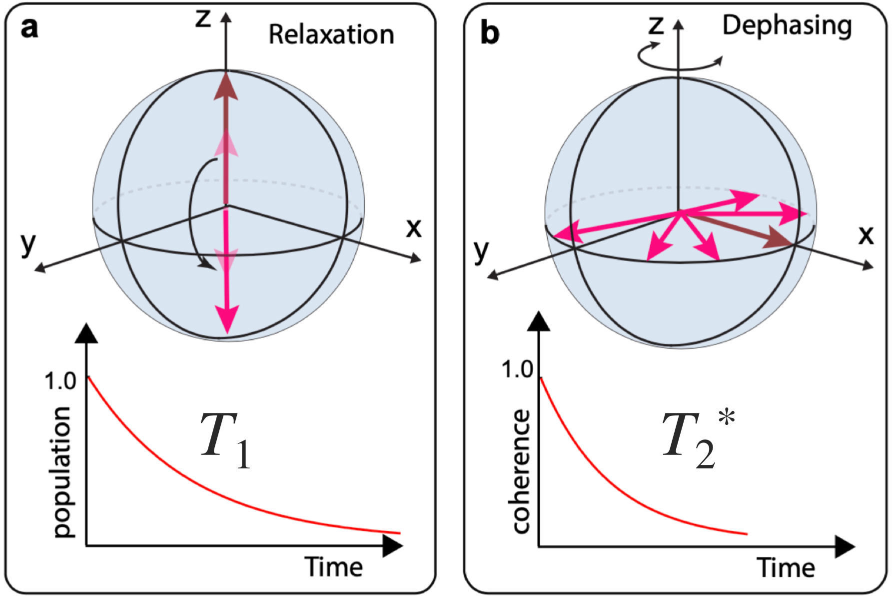
Superconducting Qubits



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

see talk from Jeter Hall Friday

- 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]

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Fermilab

Superconducting Qubits

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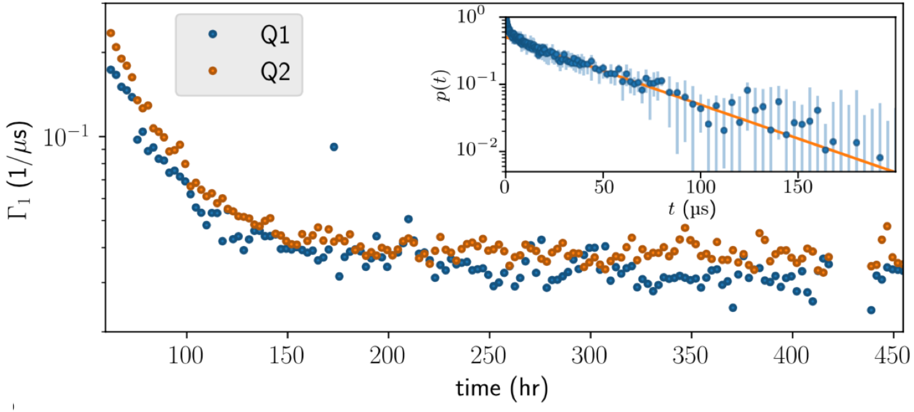
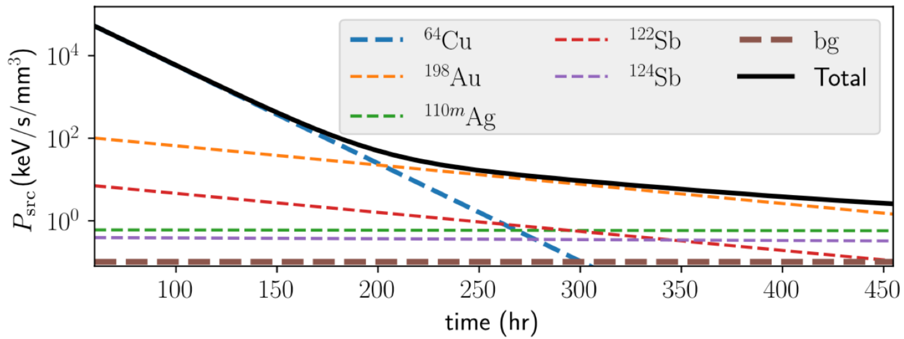




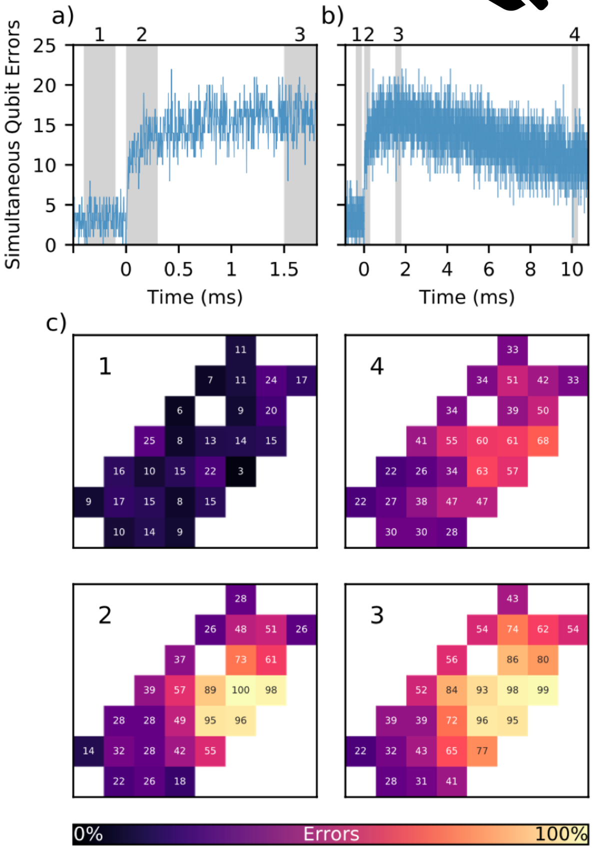
- Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source
- Clear correlation between T_1 and decay of ^{64}Cu source in two separate qubit sensors!
- Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs is a limiting factor in superconducting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

see talk from John Orrell later today…

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

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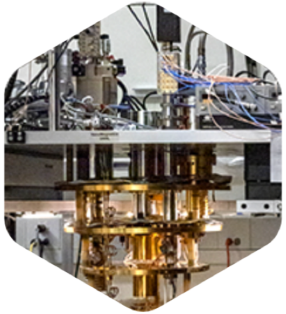
- US Department of Energy recently funded five National Quantum Information (NQI) Science Research Centers to advance QIS technologies in the US
- ORNL hosts the **Quantum Science Center** (QSC) which includes as one of its three thrusts the goal of ensuring some of this investment goes back into discovery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



Thrust 3: Quantum Devices and Sensors for Discovery Science

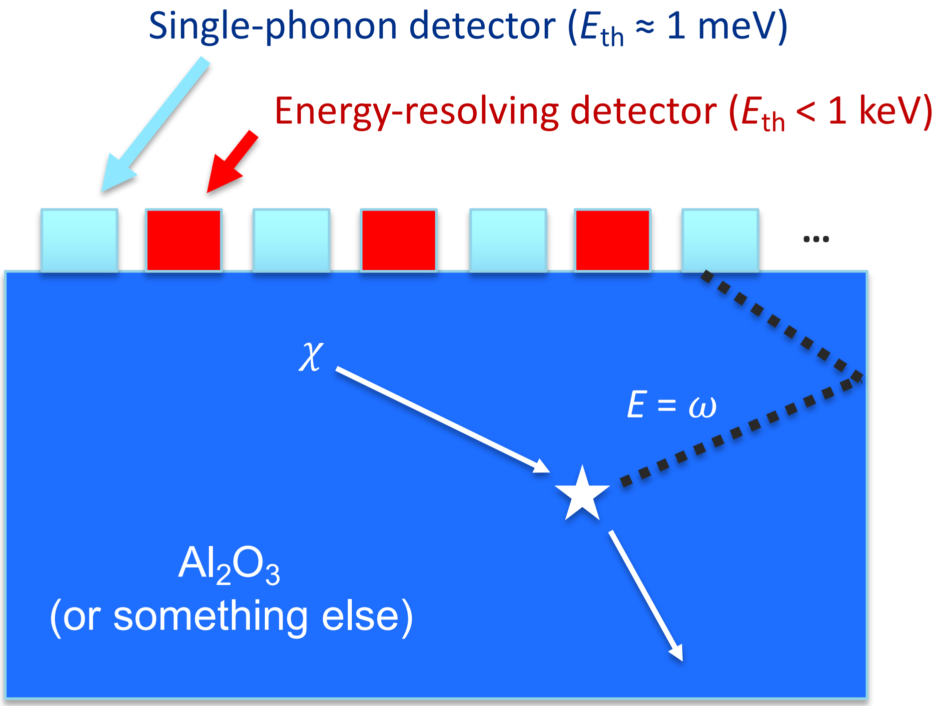
Thrust 3 develops an understanding of fundamental sensing mechanisms in high-performance quantum devices and sensors. This understanding allows QSC researchers, working across the Center, to co-design new quantum devices and sensors with improved energy resolution, lower energy detection thresholds, 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

Fermilab

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

QUANTUM SCIENCE CENTER

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)

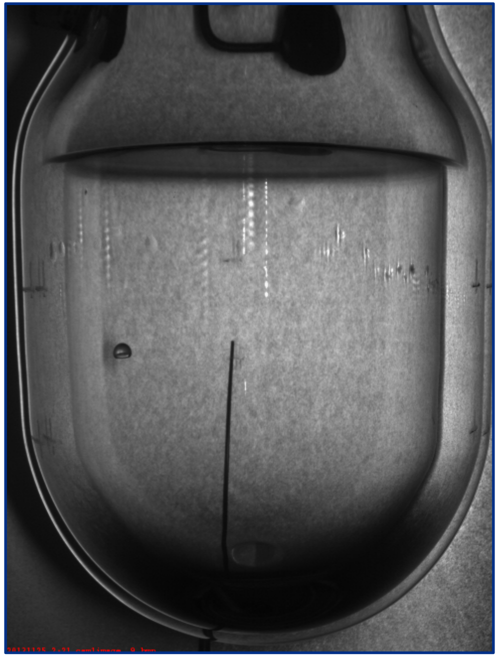
  → **analogous to introducing qubit errors in qubit state**

- Beta/gamma radiation does not produce heat and is rejected (or produces scintillation light)

  → **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**



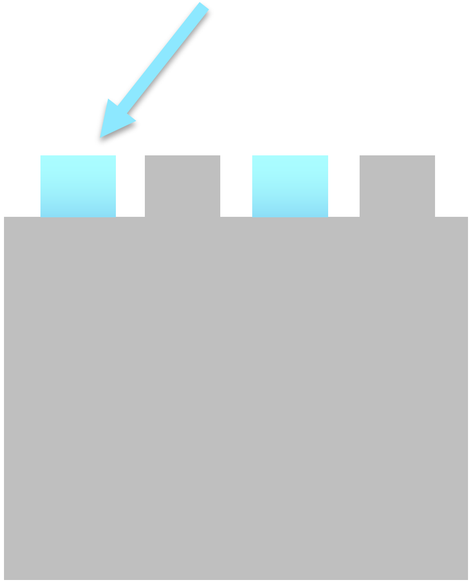
see talk from Ken Clark on Thursday

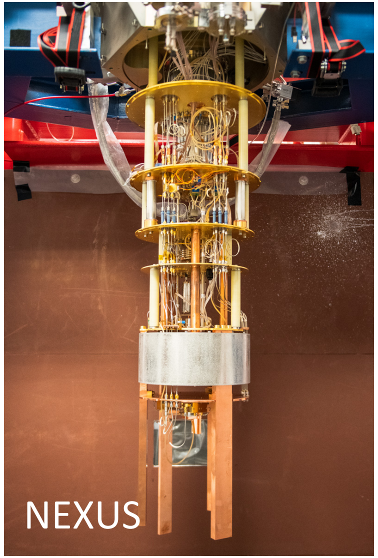
Fermilab

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

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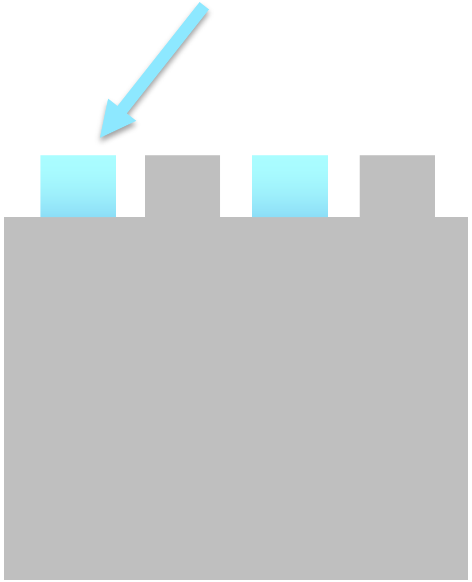
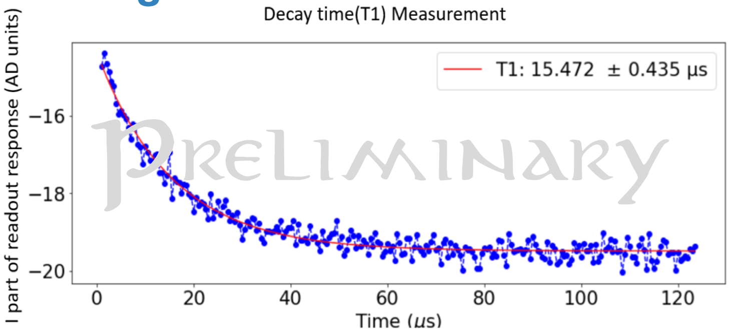
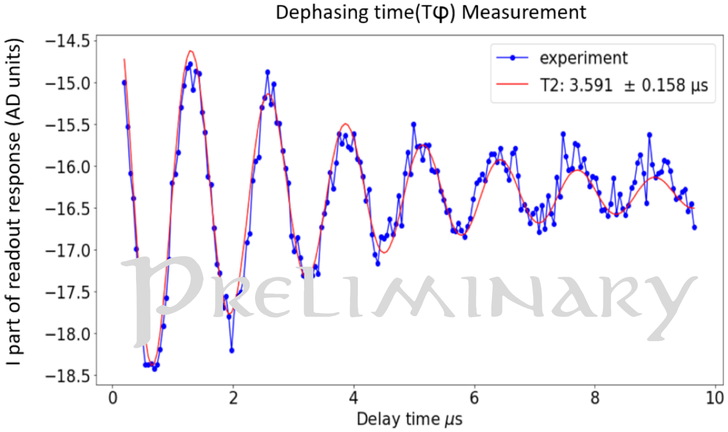
Single-phonon detector ($E_{th} \approx 1$ meV)



- 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

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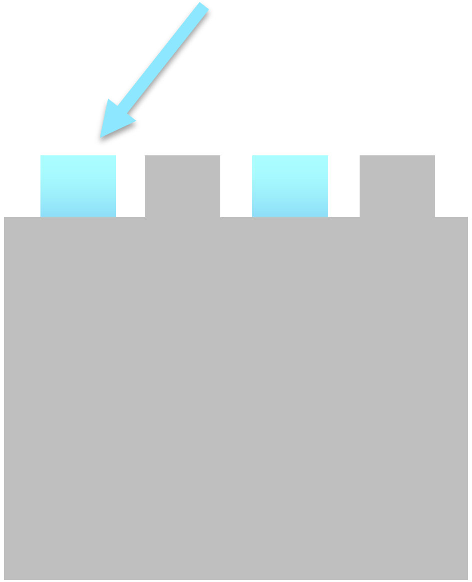
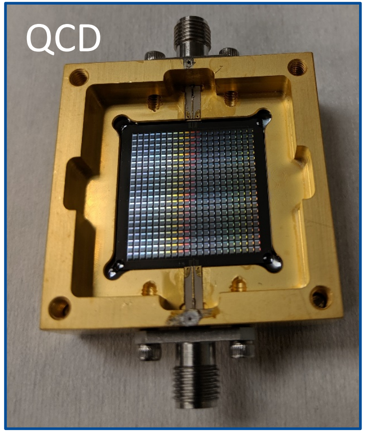




Work by Jialin Yu

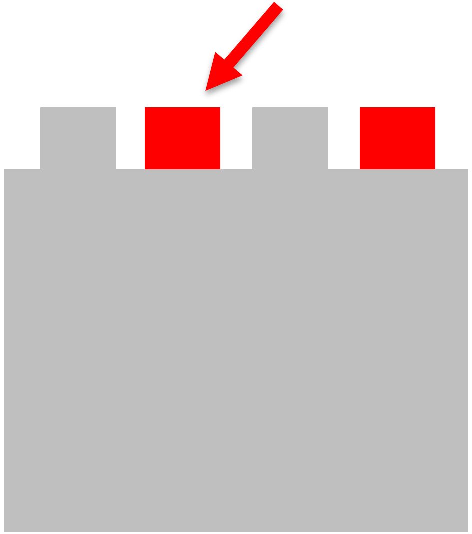
- Quantum Capacitance Detector (QCD) – Based on cooper pair box (charge qubit)
- FNAL/IIT integrating QCD with a Josephson Junction -based weak photon source to characterize a 25 qubit array for DM detector development
- Photon hits the superconducting absorber, resulting in broken Cooper pairs which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

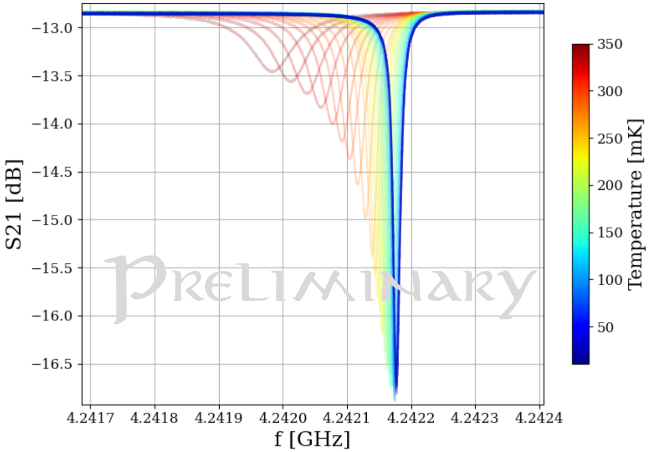
Designing an Experiment

FNAL group has progress on many fronts towards this goal!

KID = "Kinetic Inductance Detector"

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





Work by Dylan Temples

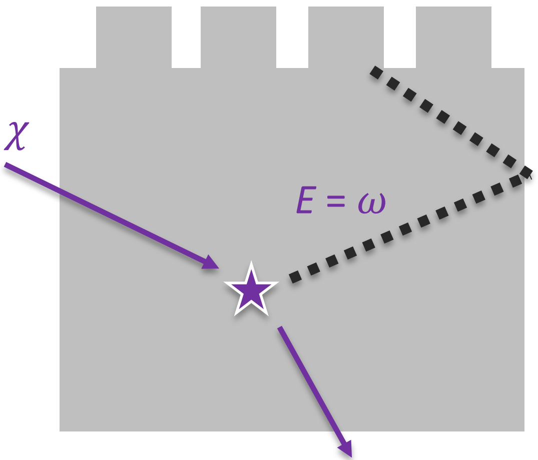
- KID – N. Kurinsky LDRD at NEXUS in collaboration w/ Caltech & SLAC
- Able to be highly multiplexed (1000's of sensors on a single RF line)
- Identical readout and fabrication to qubits naturally enables production of KID/Qubit devices
- **single-device KID resolution is ~20 eV but we expect to achieve 1 eV by the end of the LDRD program**

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

MEMS = "Micro-Electro-Mechanical System"

Calibration



Work by Kelly Stifter & Hannah Magoon

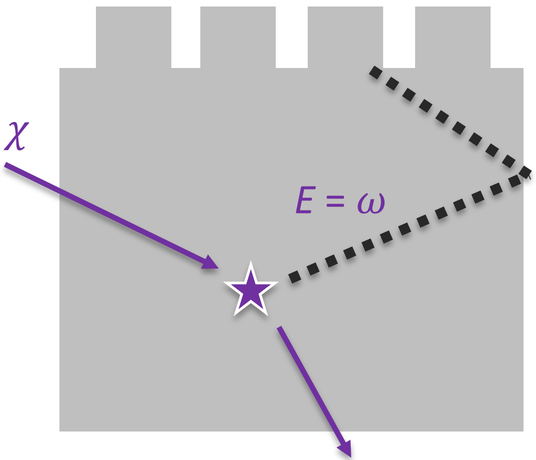
- Laser Calibration – scan over device w/ UV-optical-IR photons to determine phonon response as a function of ***position***
- MEMS Mirror – outputs up to mW at full scanning speed and range, "none" while stationary
- **Initial cold tests w/ KIDs are successful!**

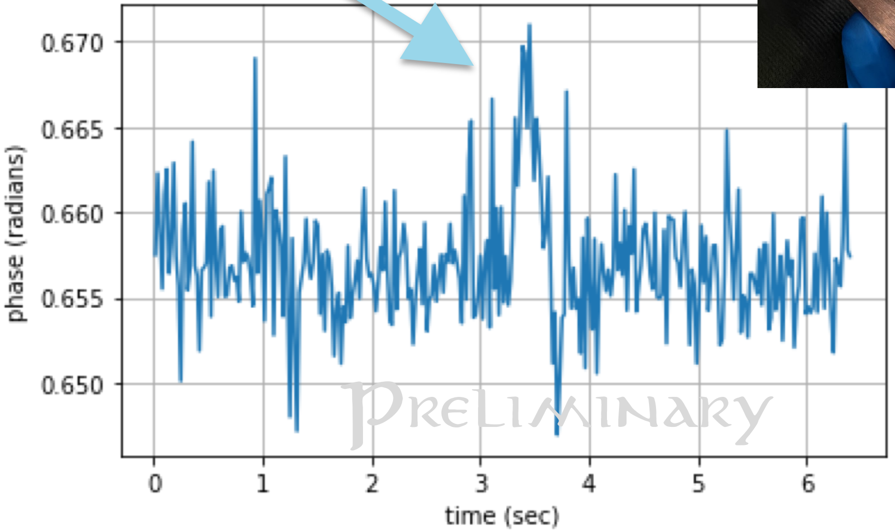
Designing an Experiment

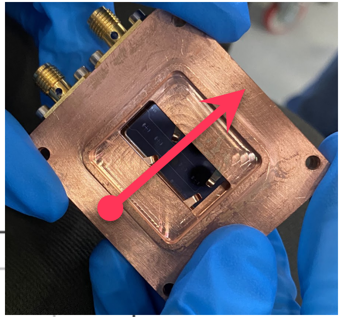
FNAL group has progress on many fronts towards this goal!

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

Calibration







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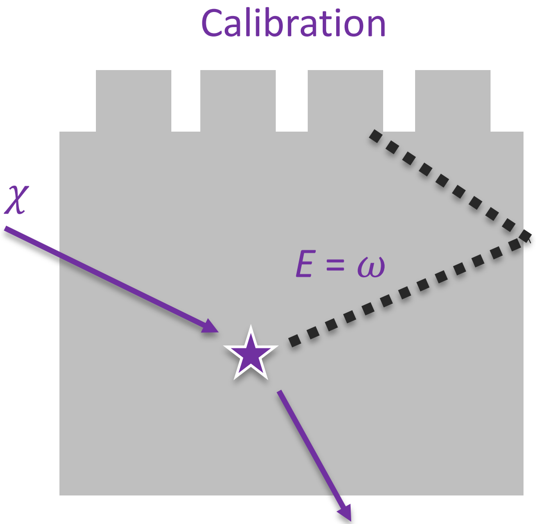
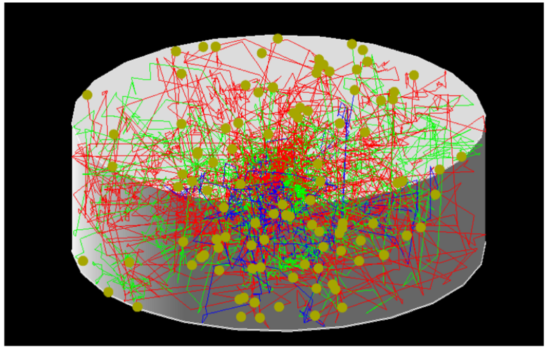
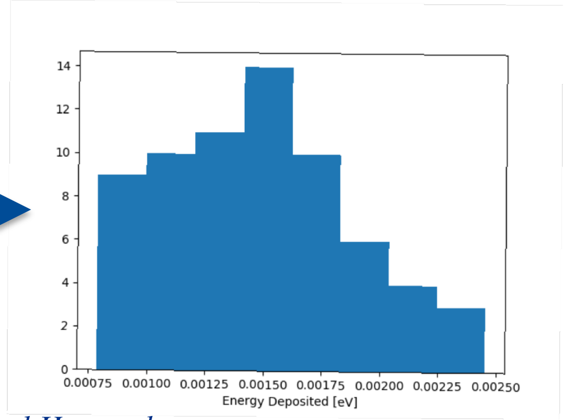
FNAL group has progress on many fronts towards this goal!



- 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



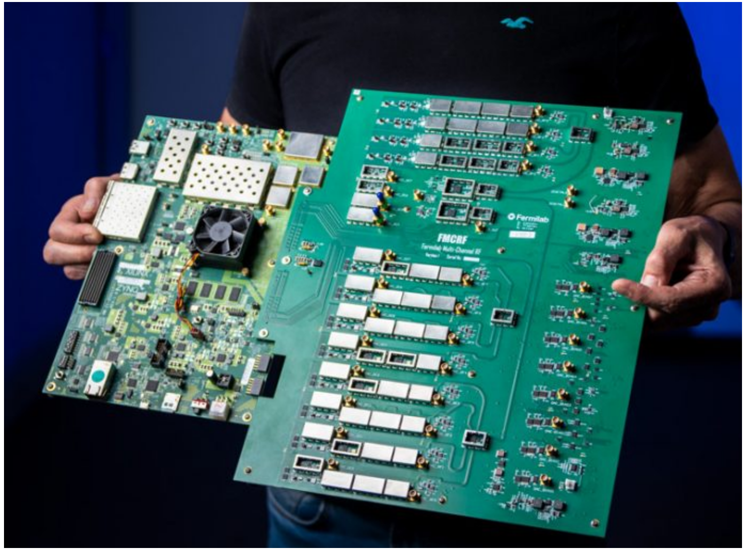


Work by Israel Hernandez

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

QICK = "Quantum Instrumentation Control Kit"



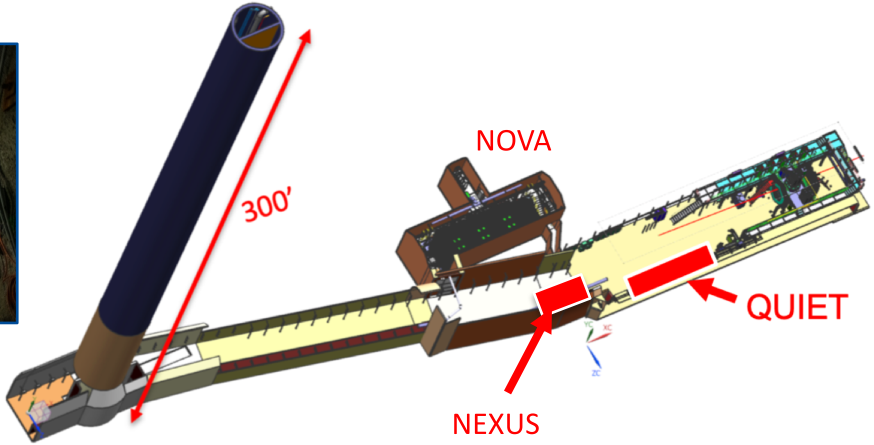
- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting (not including the 2 from FNAL)
- A factor of ~20 cheaper compared to off-the-shelf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

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Fermilab

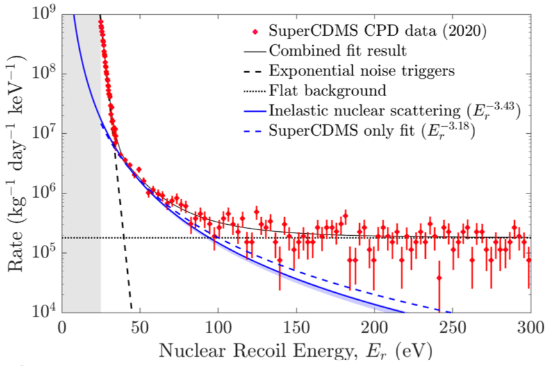
First Big Concern – the phonon "EXCESS"

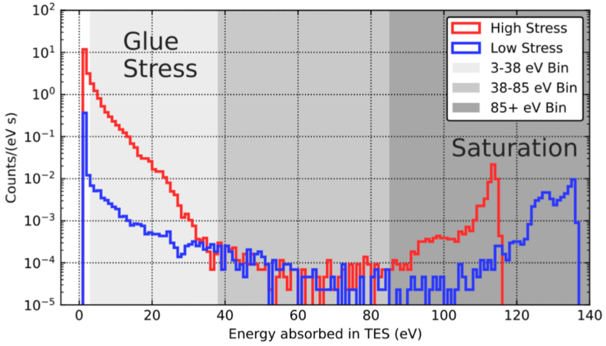
Existing detectors measure a large "EXCESS" background which limits sensitivity

Summary as of EXCESS@IDM:

1. **Non-ionizing**: *see talk from Emanuele Michielin on Thurs.*
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!

Abbamonte et al, PRD 105, 123002 (2022) [arXiv:2202.03436]





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

Conclusions

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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

Upcoming "Teased" Results

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<u>Many</u> exciting results just on the horizon:

✓ Calculations for neutron ME angular spectrum are complete:
  - Duncan Adams, **DB**, Hannah Day, Rouven Essig, Yoni Kahn; paper in ~weeks

✓ DD Generator "first light" expected in next run of NEXUS (cooldown this month)
  - Planned calibrations for SuperCDMS HVeV, Ricochet, KID, qubits, and more…

✓ First QSC fridge "LOUD" successfully tested at FNAL w/ first science run in October

✓ Cold MEMS system has been tested with KID successfully!
  - Next steps: probe individual device structures and write device paper…

✓ Two separate qubit systems operational at FNAL studying decoherence, with two more being commissioned now

Quantum Science Center – Acknowledgements

QSC Thrust 3 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

Postdocs/Students

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- **SLAC**: Noah Kurinsky, Taj Dyson, Sadaf Kadir
- **Caltech**: Sunil Golwala, Karthik Ramanathan, Taylor Aralis, Osmond Wen
- **Tufts**: Hannah Magoon (co-op w/ FNAL)