Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Experimental dark matter searches at masses below the GeV mass scale

Daniel Baxter

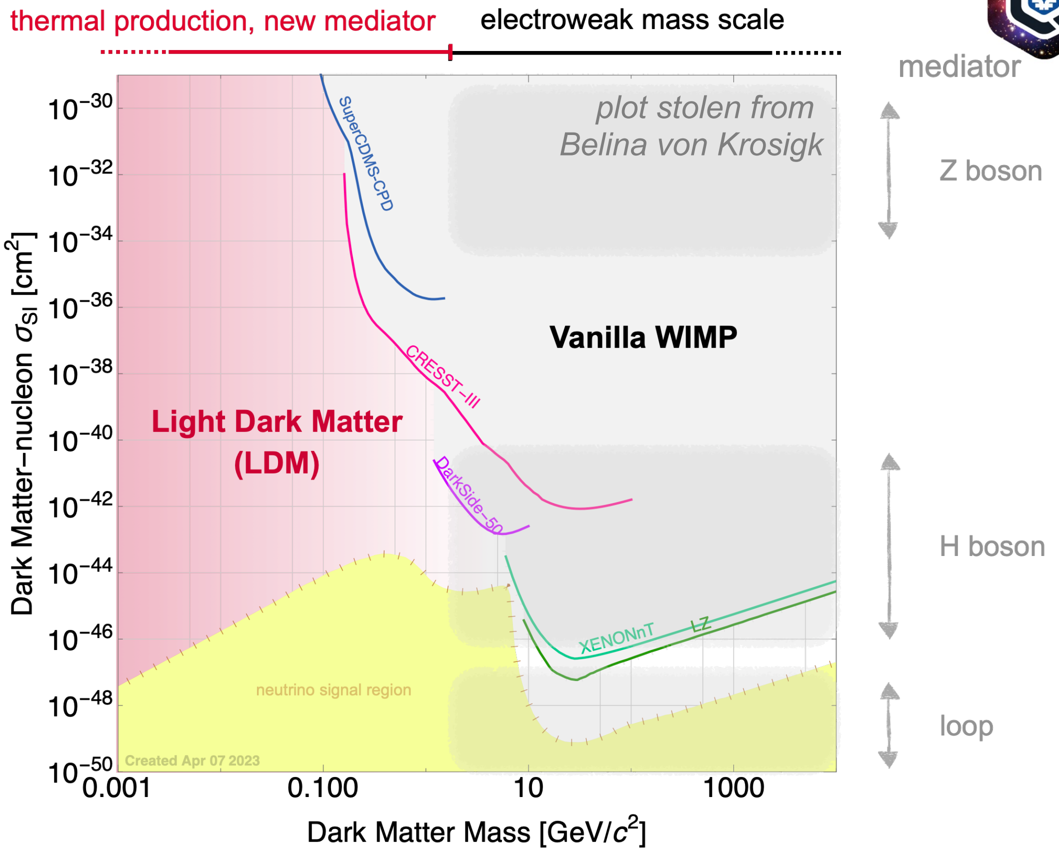
Identification of Dark Matter (IDM 2024)

10 July 2024

Northwestern University

Motivation

- Maria Elena and Lucia very nicely covered the more “traditional” searches **at** and **above** GeV mass
- Those searches mostly rely on elastic scattering of DM off of detector nuclei
- Below the proton mass are very well-motivated models of dark matter (see Kathryn’s talk from this morning)



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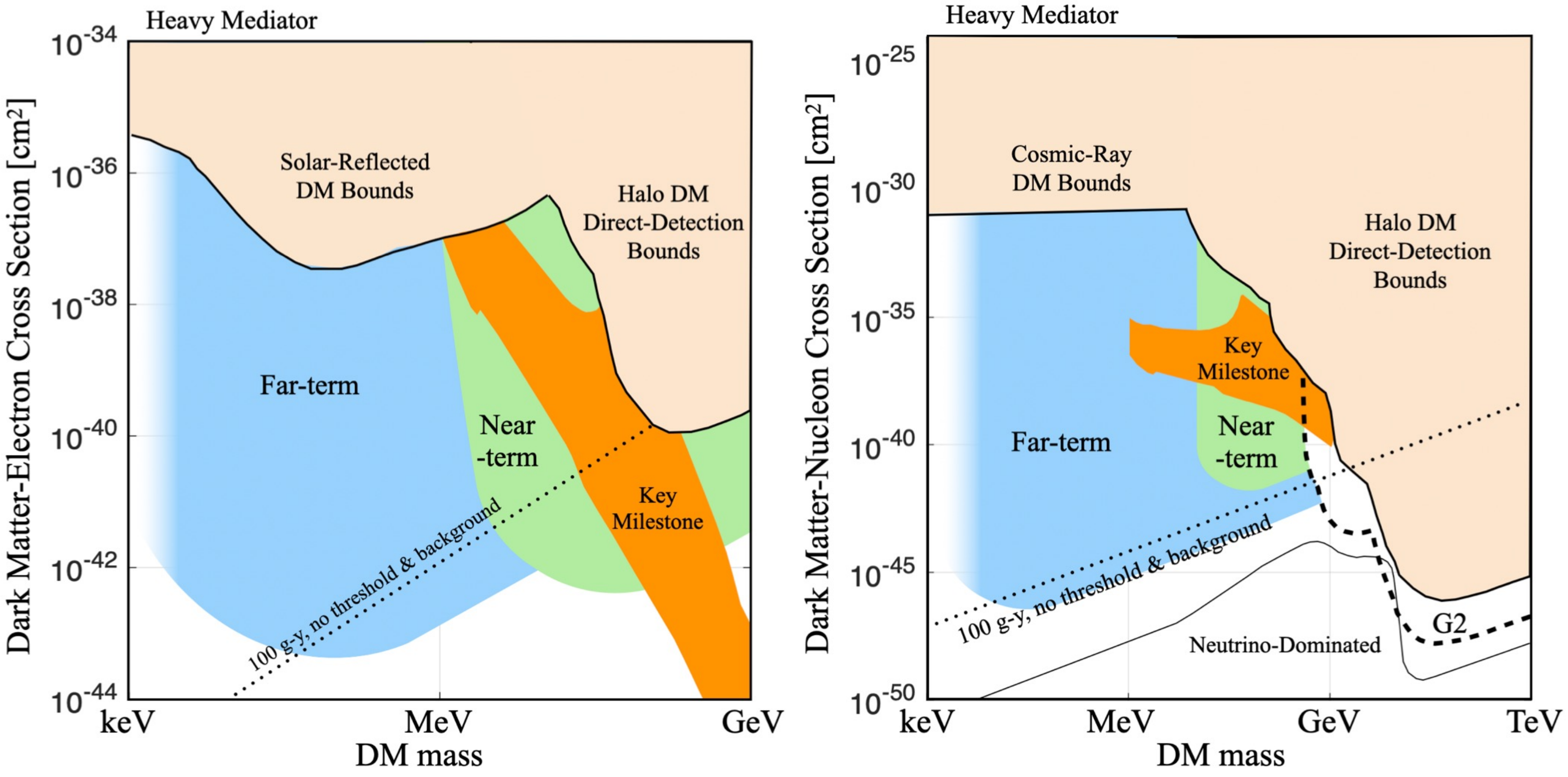
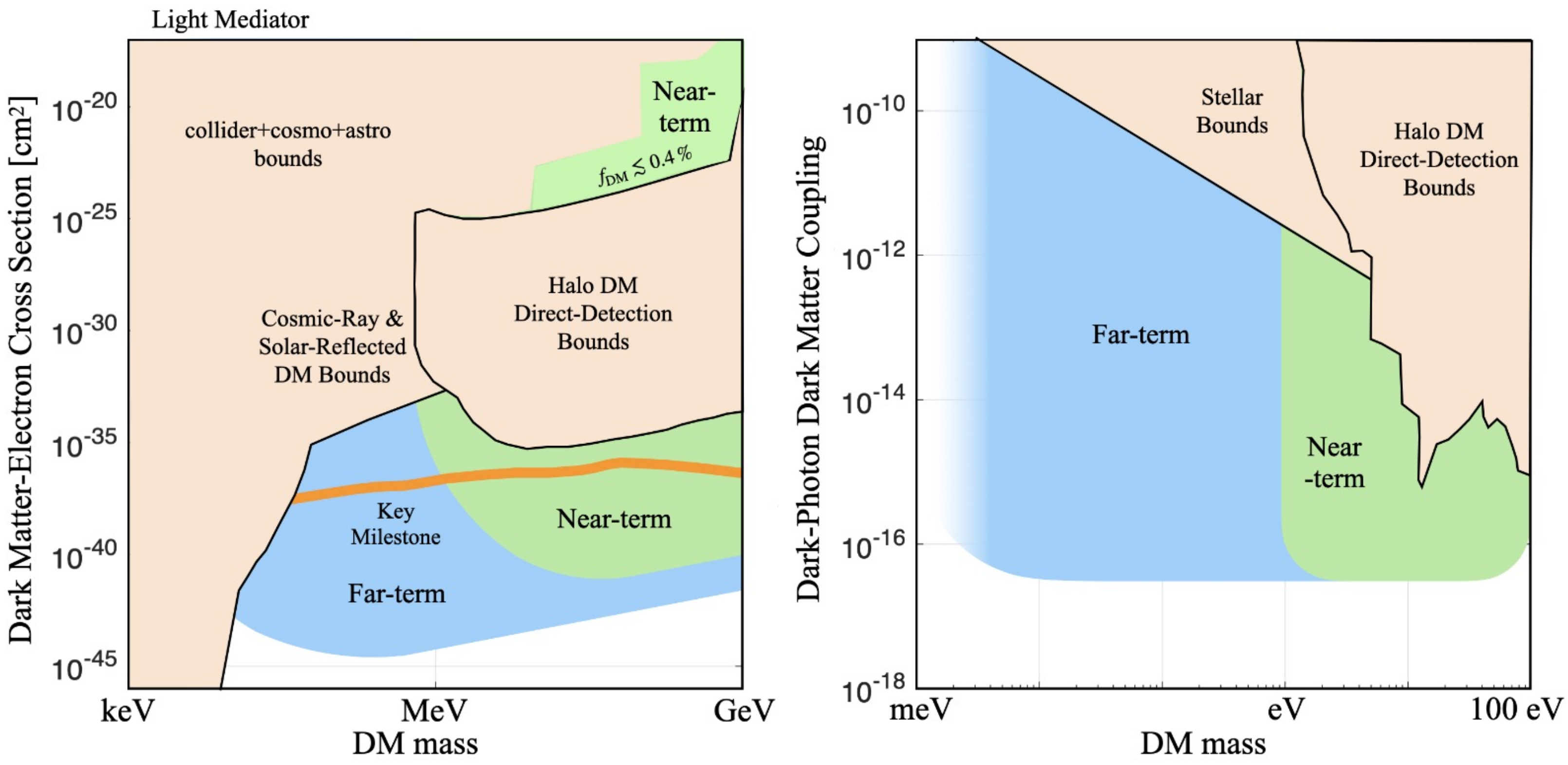
Low-Mass Dark Matter Detection



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

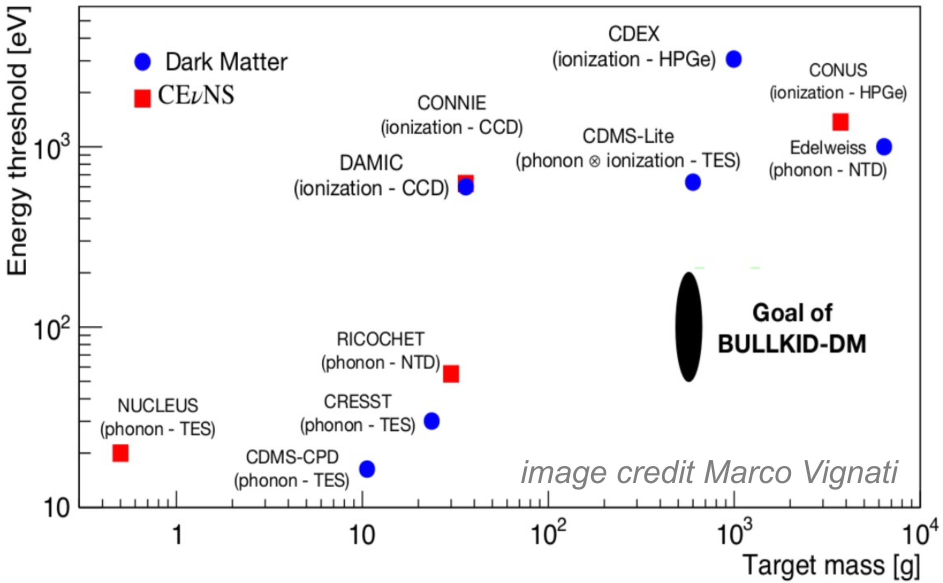
Low-Mass Dark Matter Detection



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

Low-Mass Dark Matter Detection

1. **Energy Threshold**
   - At a minimum, need eV-scale thresholds to be competitive
   - R&D is pushing towards meV-scale energy thresholds
2. **Exposure**
   - Not as important as for WIMP searches
   - Current best limits have kg-days
3. **Backgrounds**
   - Complicated, non-radiogenic excess backgrounds plague lower energies



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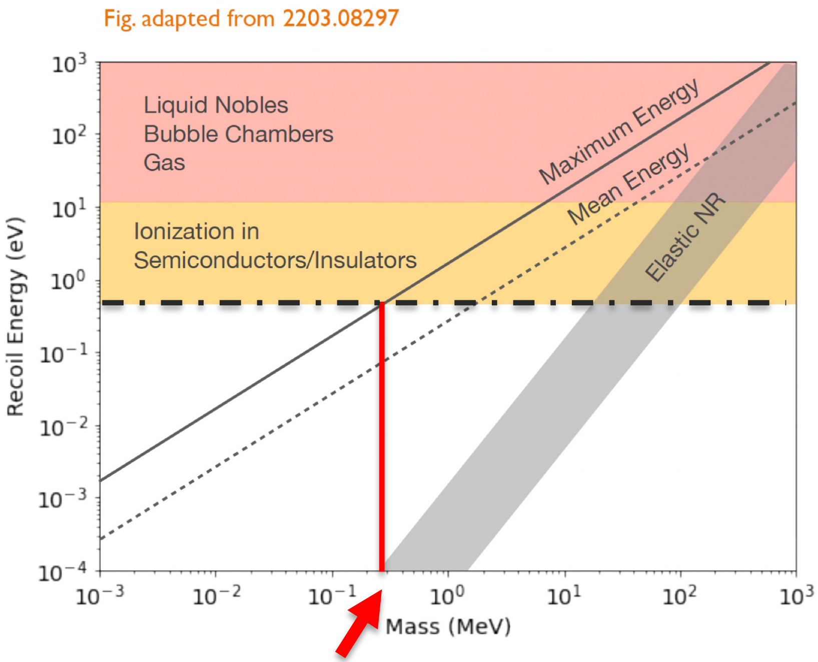
Detectors Searching for Ionization



fundamental lower limit

$\Delta E \sim 1$ eV

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

LZ

XENON

DAMIC-M

SUPER CDMS Cryogenic Dark Matter Search

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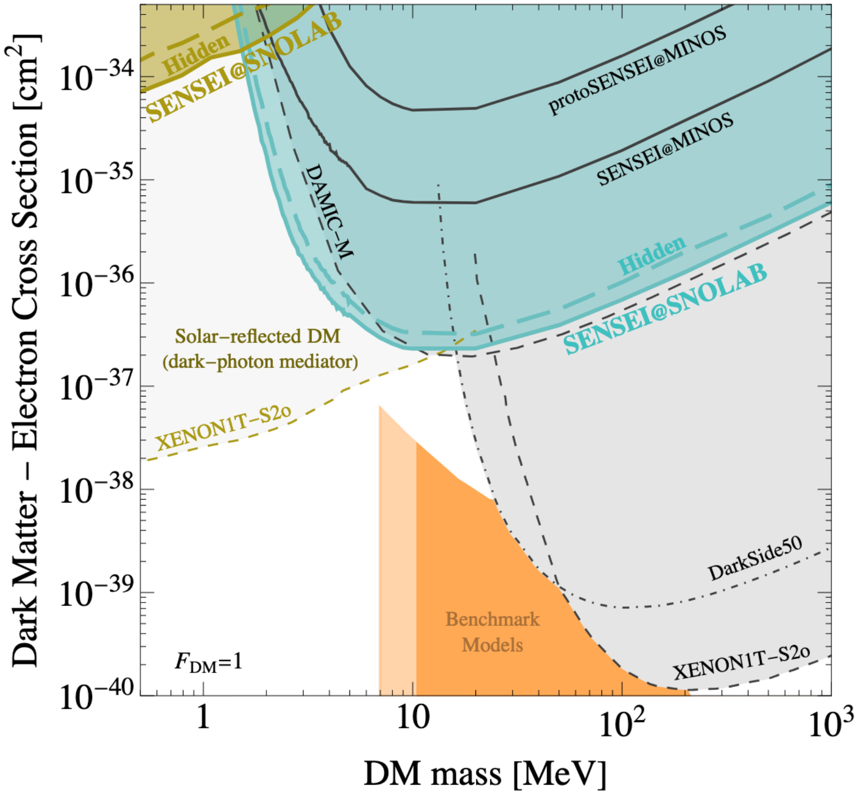
Detectors Searching for Ionization

1. **S2-only Searches in TPCs**
   - XENON
   - DarkSide50
2. **CCD Program**
   - DAMIC at SNOLAB
   - SENSEI at SNOLAB
   - DAMIC at Modane (DAMIC-M)
   - OSCURA
3. **NTL-Amplification**
   - SuperCDMS HVeV
   - EDELWEISS HV
4. **Novel (low bandgap) Materials**
   - SPLENDOR

Adari et al, (2023) [arXiv:2312.13342]



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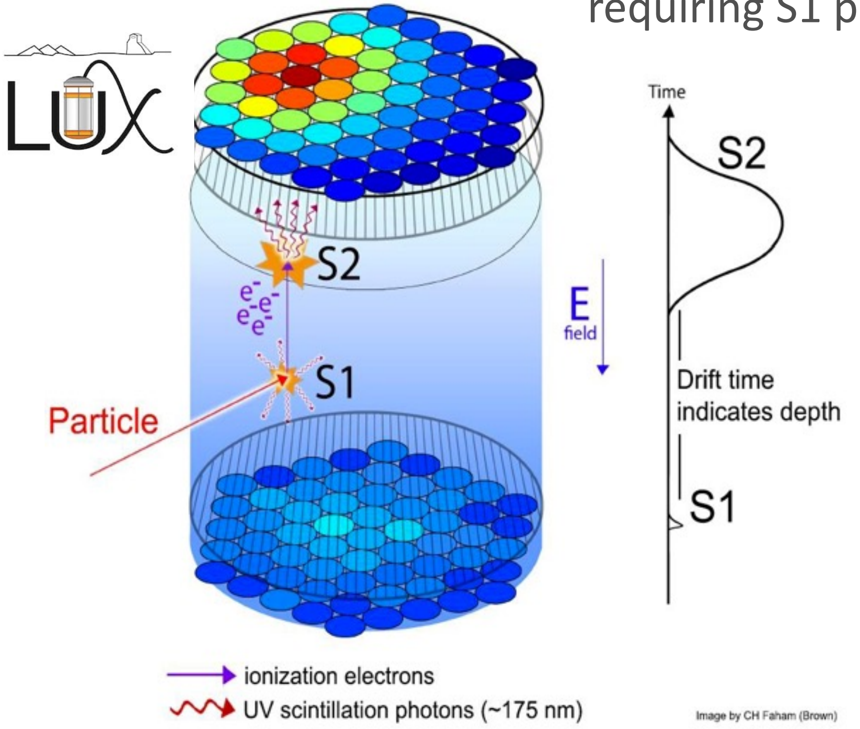
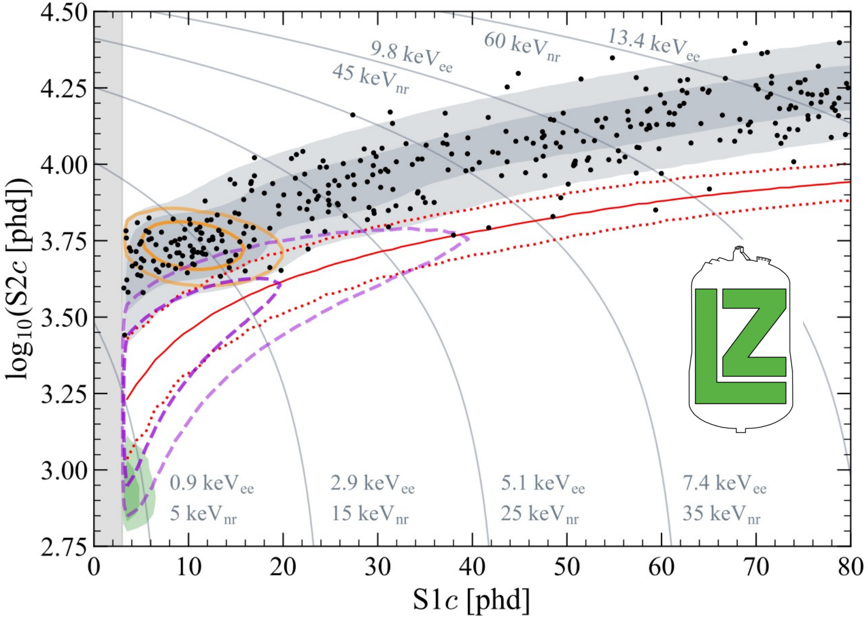
S2-only searches

Can sacrifice discrimination for lower threshold by not requiring S1 photon(s)

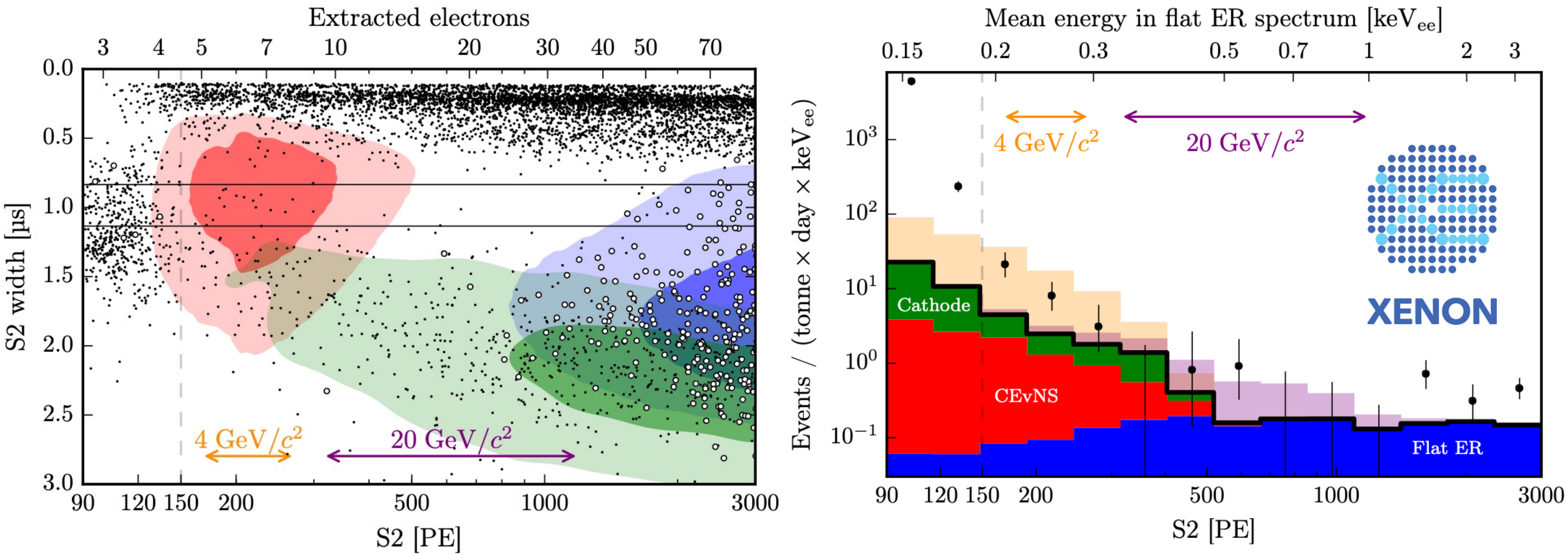




Aalbers et al, PRL 131, 041002 (2023) [arXiv:2207.03764]

S2-only searches – XENON1T

Aprile et al, PRL 123, 251801 (2019) [arXiv:1907.11485]



Pros: massive exposures, 1-10 mdru modeled backgrounds, XY position resolution, timing

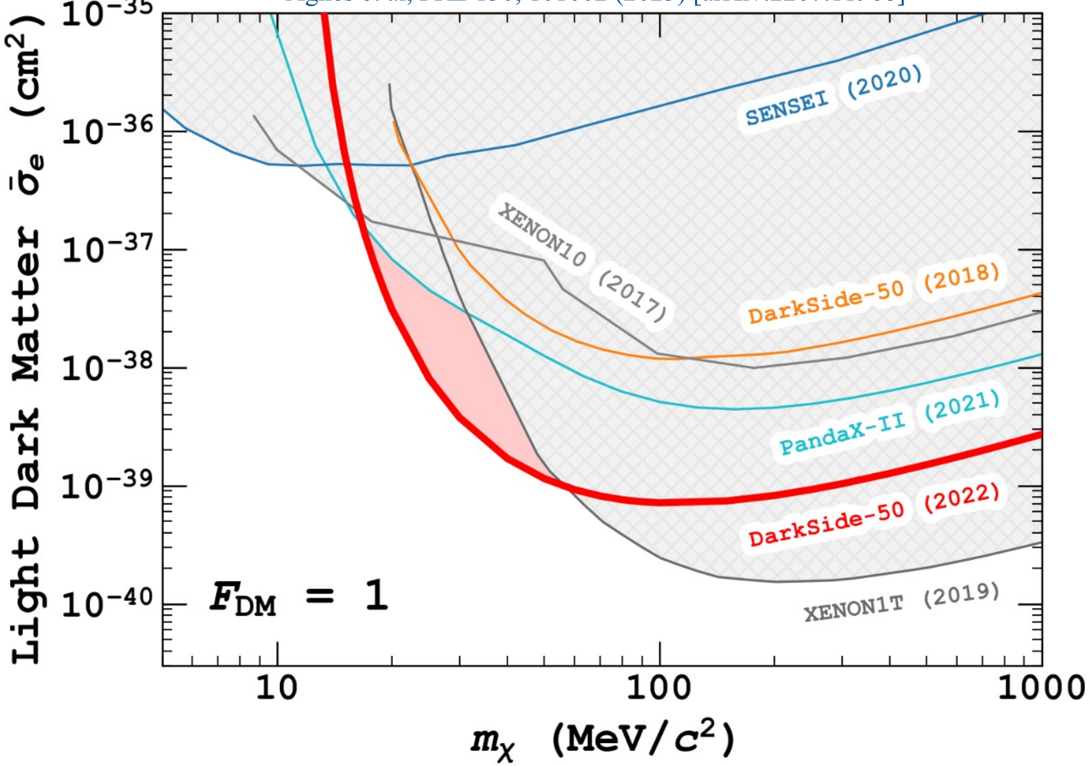
Cons: large unmodeled* dark rate → "high" analysis threshold (100+ eV), no discrimination

**see Wed. talk from Peter Sorensen*

see also Wed. talk from Shuaijie Li on PandaX

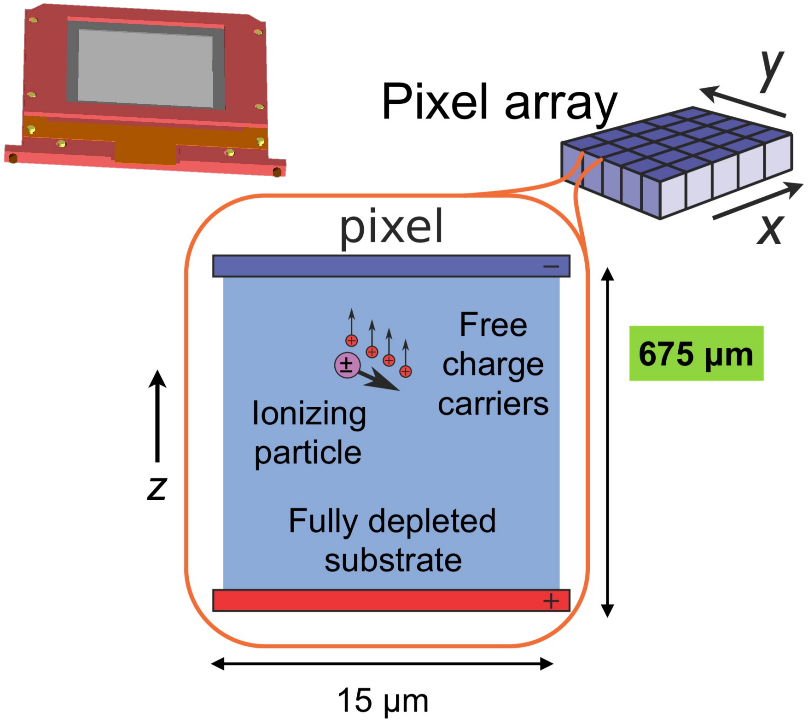
S2-only searches – DarkSide-50

Agnes et al, PRL 130, 101002 (2023) [arXiv:2207.11968]



see Thurs. talk from Marie van Uffelen

The CCD Program

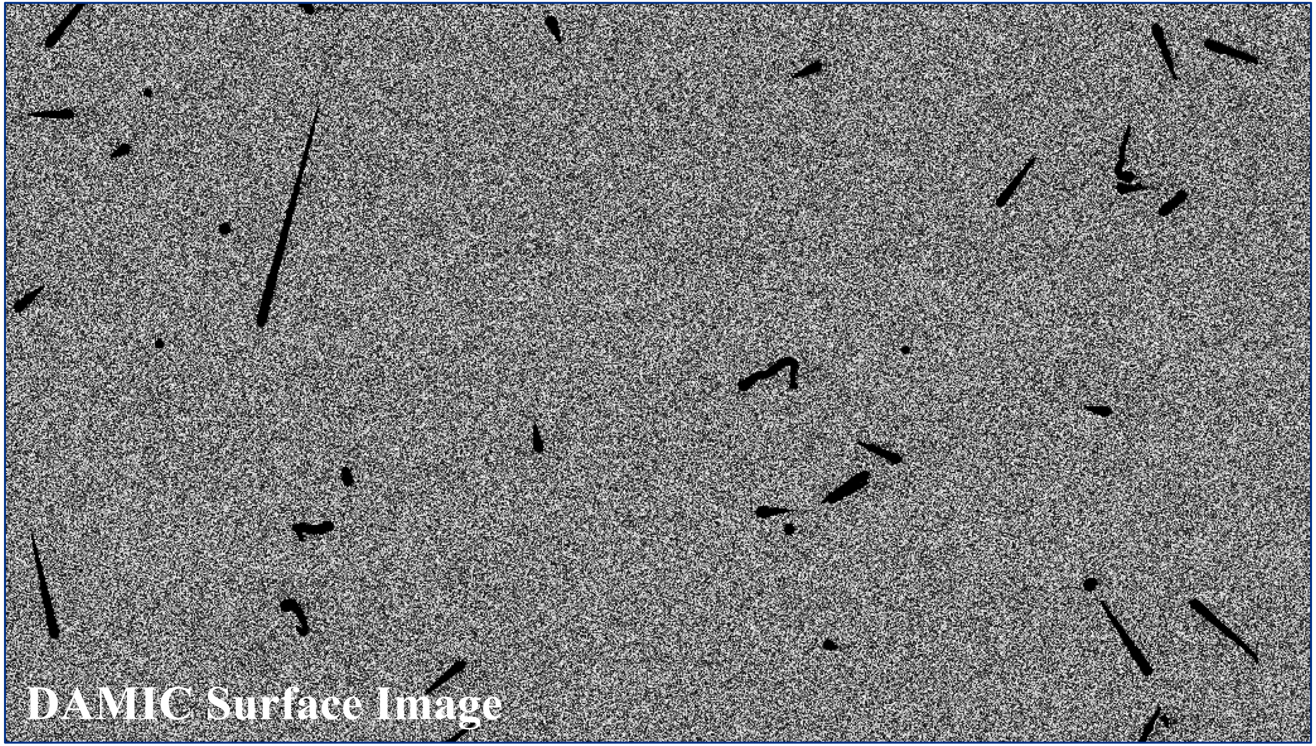


Interaction with silicon produces free charge carriers…

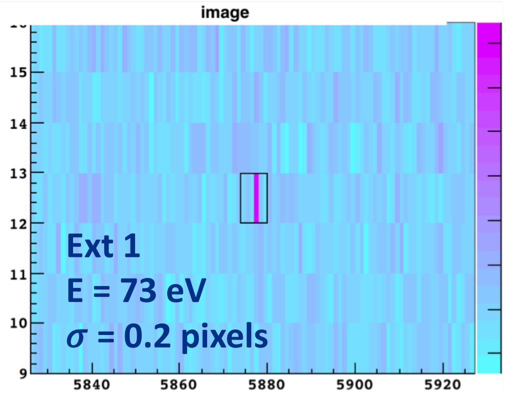
- …which are drifted across fully-depleted region…
  - *no loss of charge*
- …and collected in 15 micron square pixels…
  - *exceptional position resolution*
- …to be stored until a user-defined readout time after many hours.
  - *large exposures*

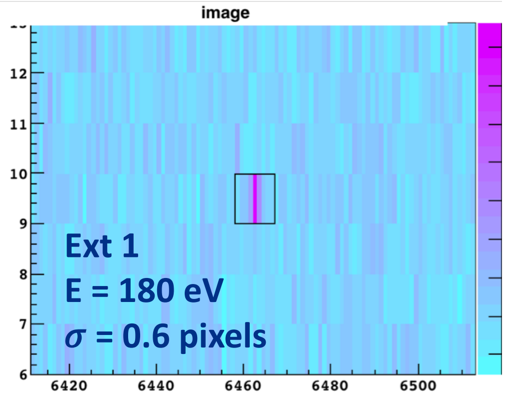
Pros: low dark rates, few eV threshold, 10 micron position resolution, 1-10 dru backgrounds
Cons: silicon target only, lack of timing, no discrimination below 10 keV

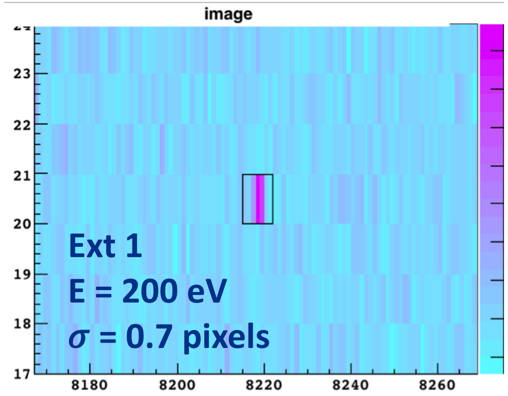
The CCD Program – DAMIC

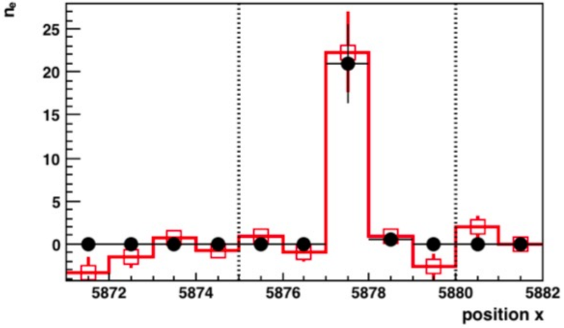


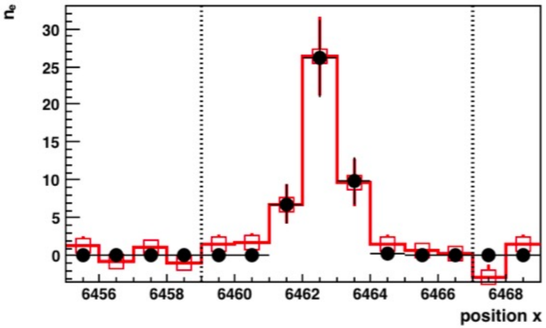
The CCD Program – DAMIC

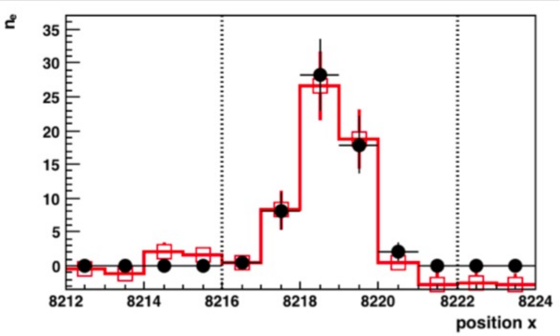












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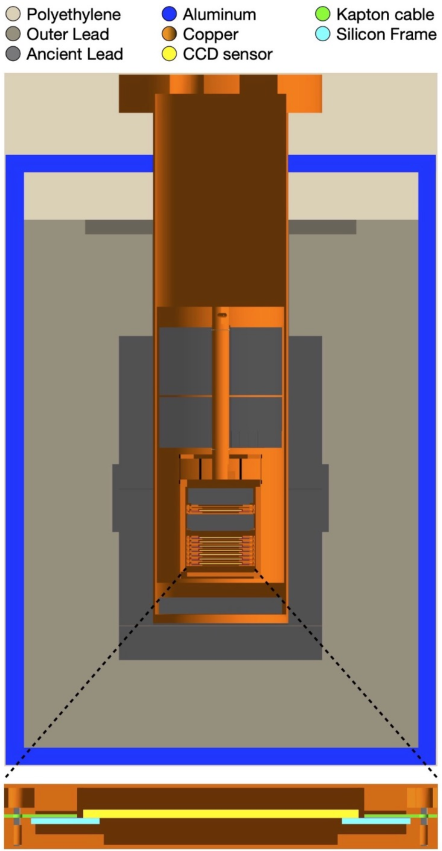
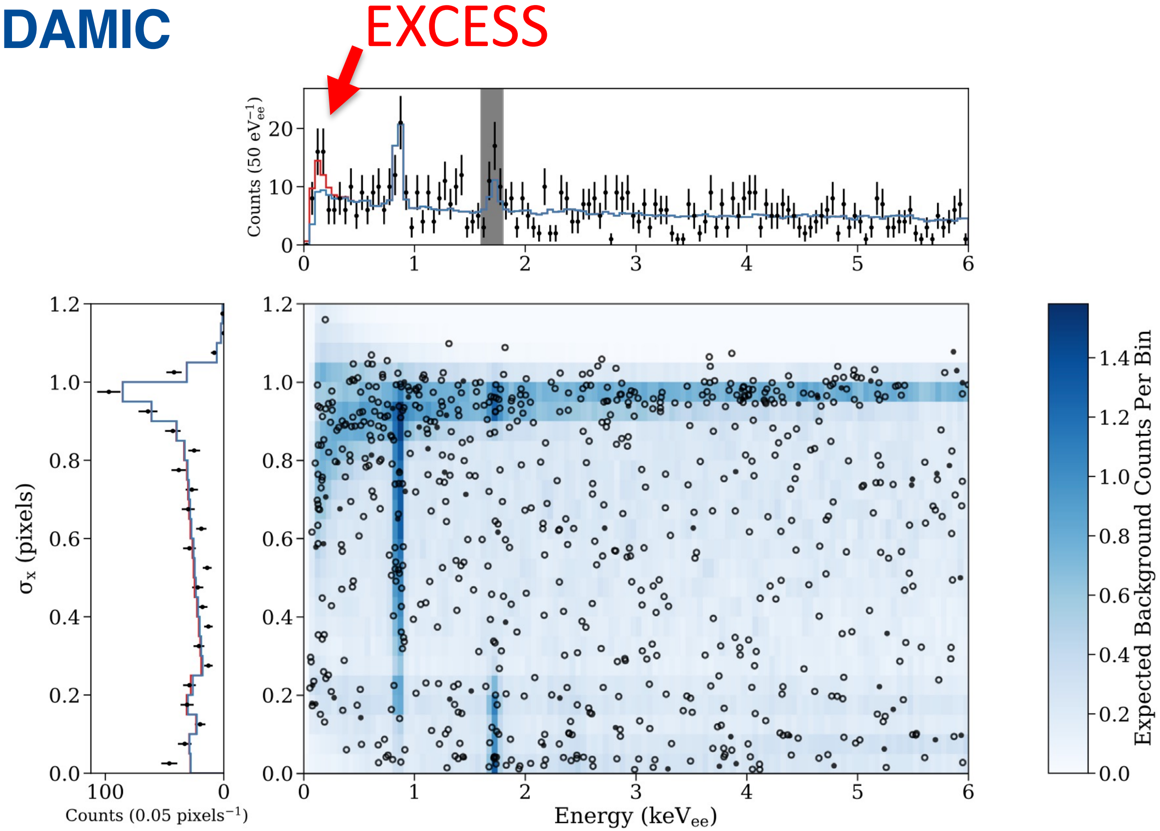
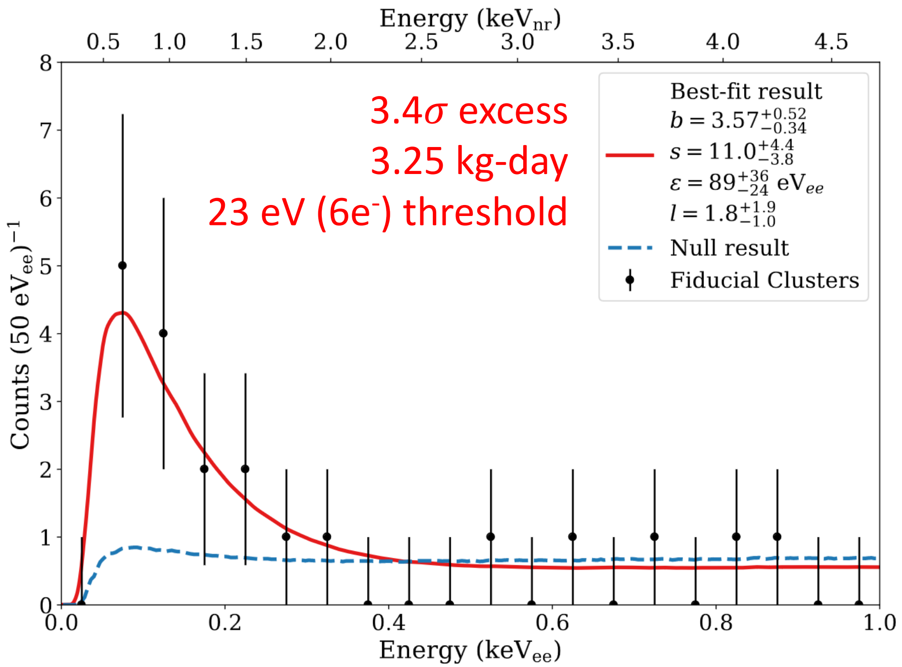
The CCD Program – DAMIC



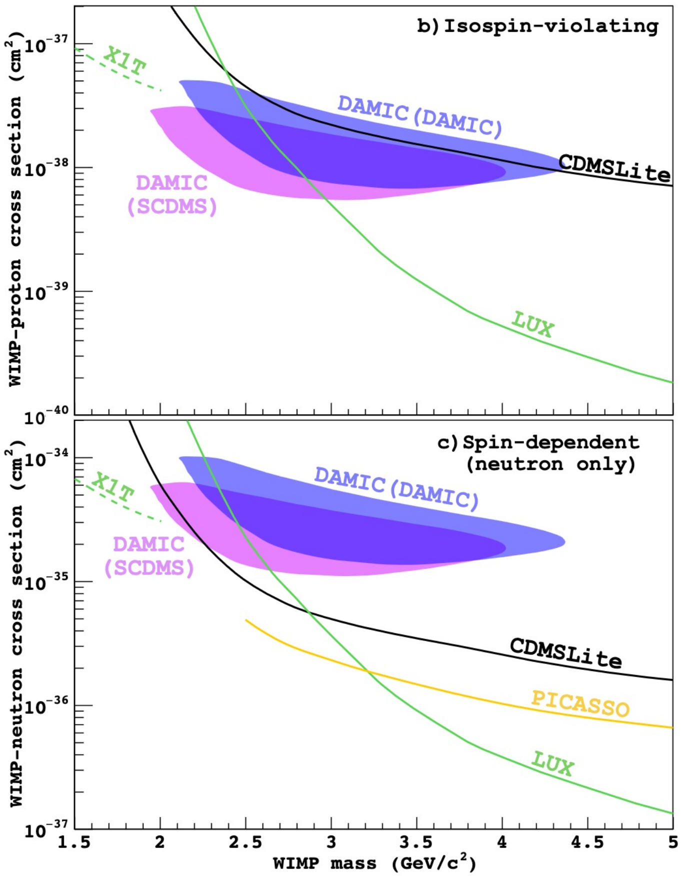


A. Aguilar-Arevalo et al. PRD 105, 062003 (2022) [arXiv:2110.13133]

The CCD Program – DAMIC



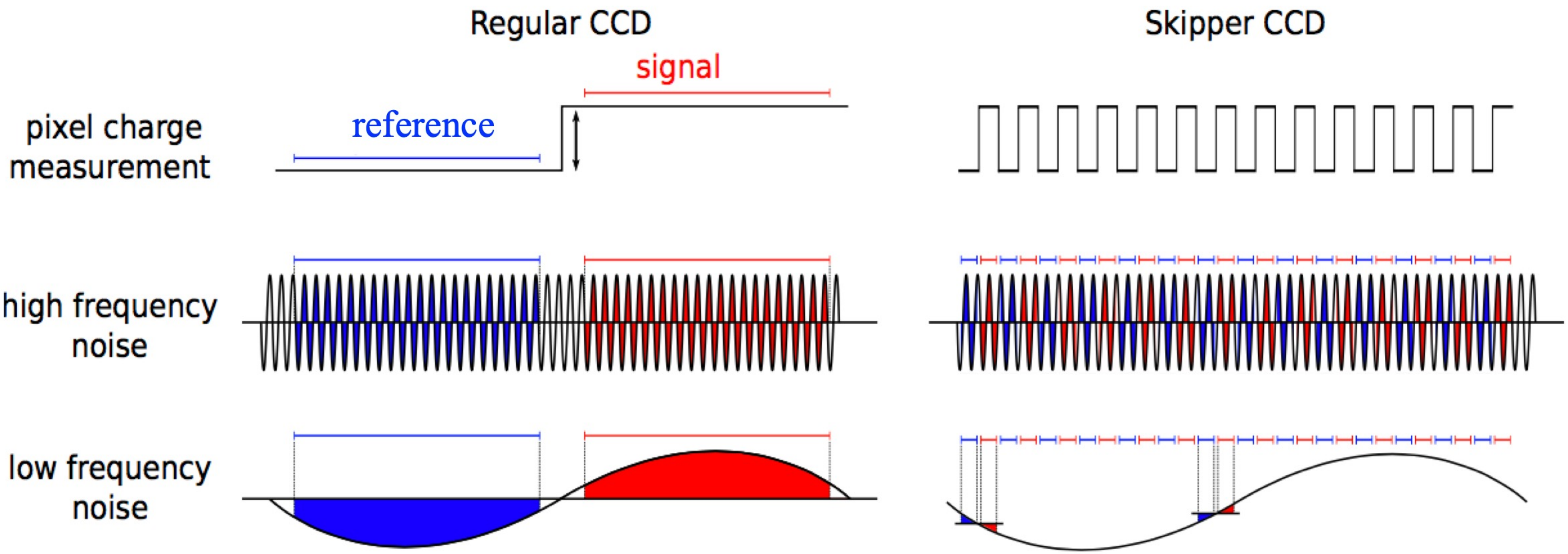
Aguilar-Arevalo et al, PRD 109, 062007 (2024) [arXiv:2306.01717]



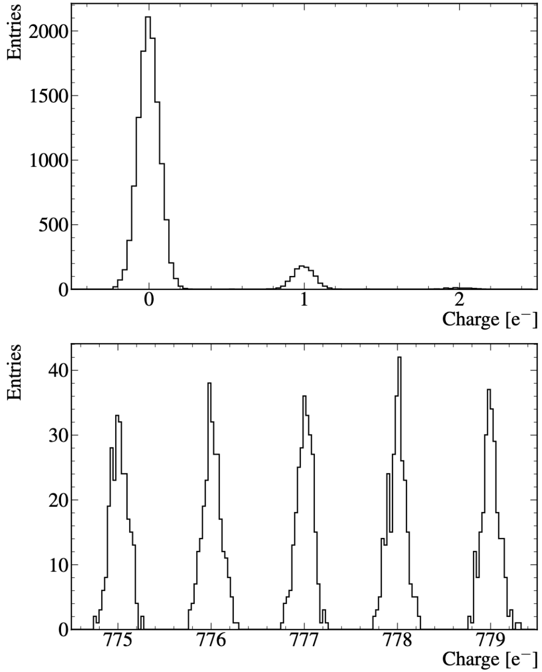
Chavarria et al, (2023) [arXiv:2308.12176]

The CCD Program – Skipper Amplifiers

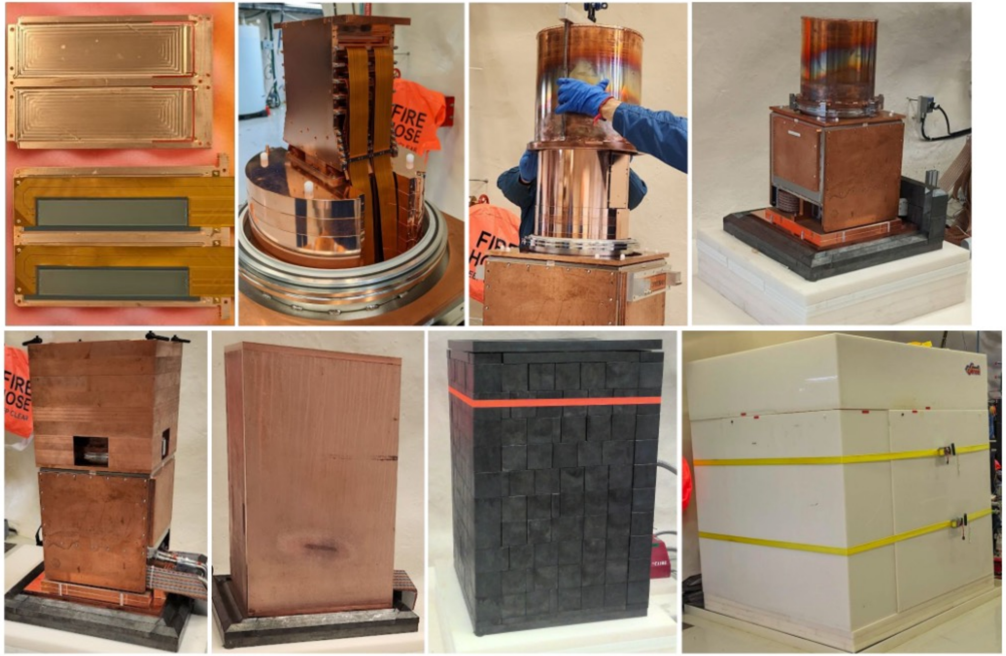
Skipper Amplifiers: allow repeated, non-destructive readout



The CCD Program – SENSEI



- Record silicon dark rates of 1.4 x 10^{-5} e^-/pix/day
- New limits on MeV-scale DM scattering (see Ana's talk)



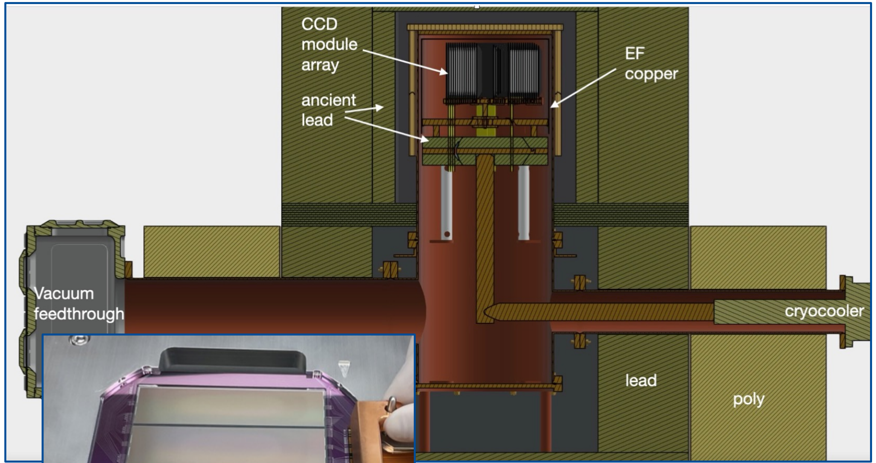
Tiffenberg et al, PRL 119, 131802 (2017) [arXiv:1706.00028] and Adari et al, (2023) [arXiv:2312.13342]

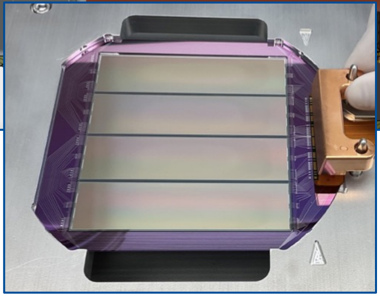
see Wed. talk from Ana Maria Botti

The CCD Program – DAMIC-M

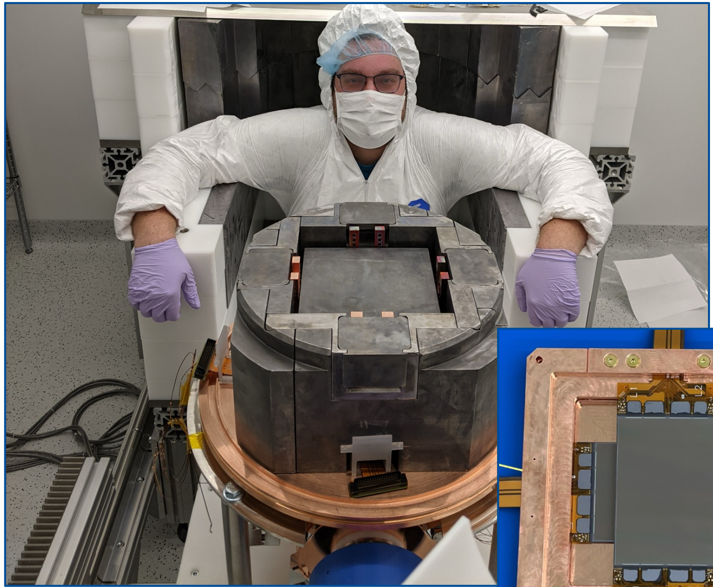
images borrowed from Danielle Norcini's talk at IDM2024 today

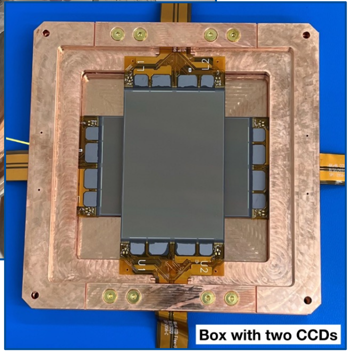
Full Detector (Online in 2025!)





LBC Demonstrator (taking data since 2022)





see Arnquist et al, PRL 130, 171003 (2023) [arXiv:2302.02372]

see Wed. talk from Danielle Norcini

The CCD Program – OSCURA

images borrowed from Brenda Cervantes Vergara's talk at IDM2024 tomorrow

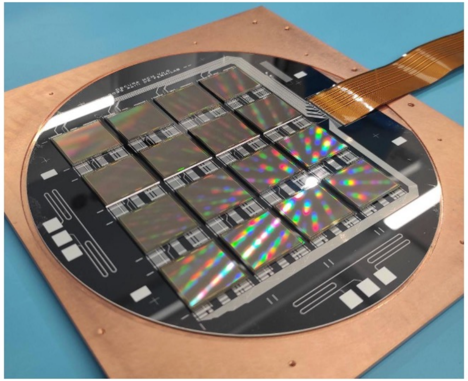
25,600 CCDs → 1,600 MCMs → 100 SMs → 10 kg!

Skipper-CCD

p-channel sensors designed at LBNL
Fabricated at new commercial foundry
1.35 MPix each - 725 μm thick

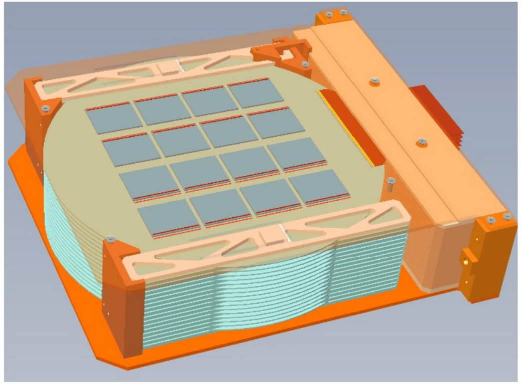
MCM

16 Skipper-CCDs
Intrinsic Si substrate with 1-layer Al traces
Low-background flex cable



SM

16 MCMs
Radiopure materials (Si, PTFE, EF-Cu)



see Thurs. talk from Brenda Cervantes Vergara

The CCD Program – OSCURA

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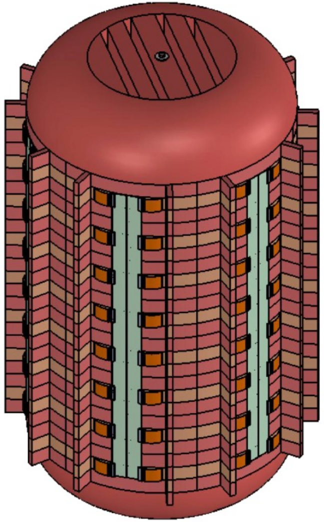
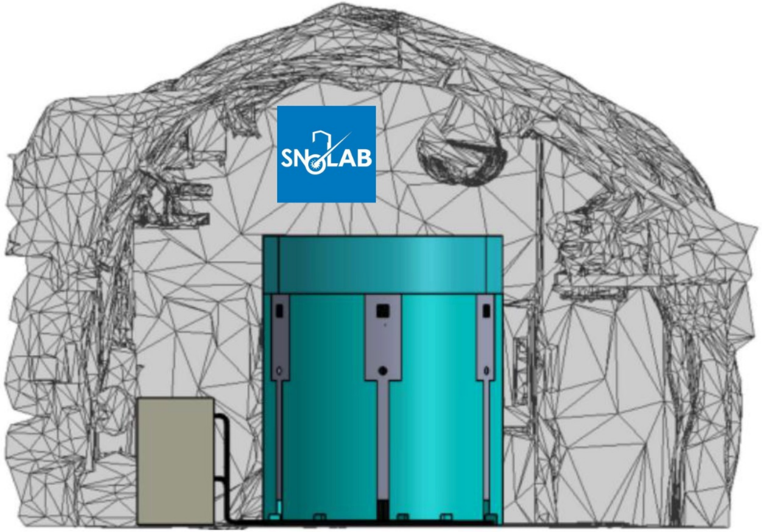
25,600 CCDs → 1,600 MCMs → 100 SMs → 10 kg!

Cylinder-like array
~12.5 kg total (10 kg effective) mass



Construction planned starting late 2025



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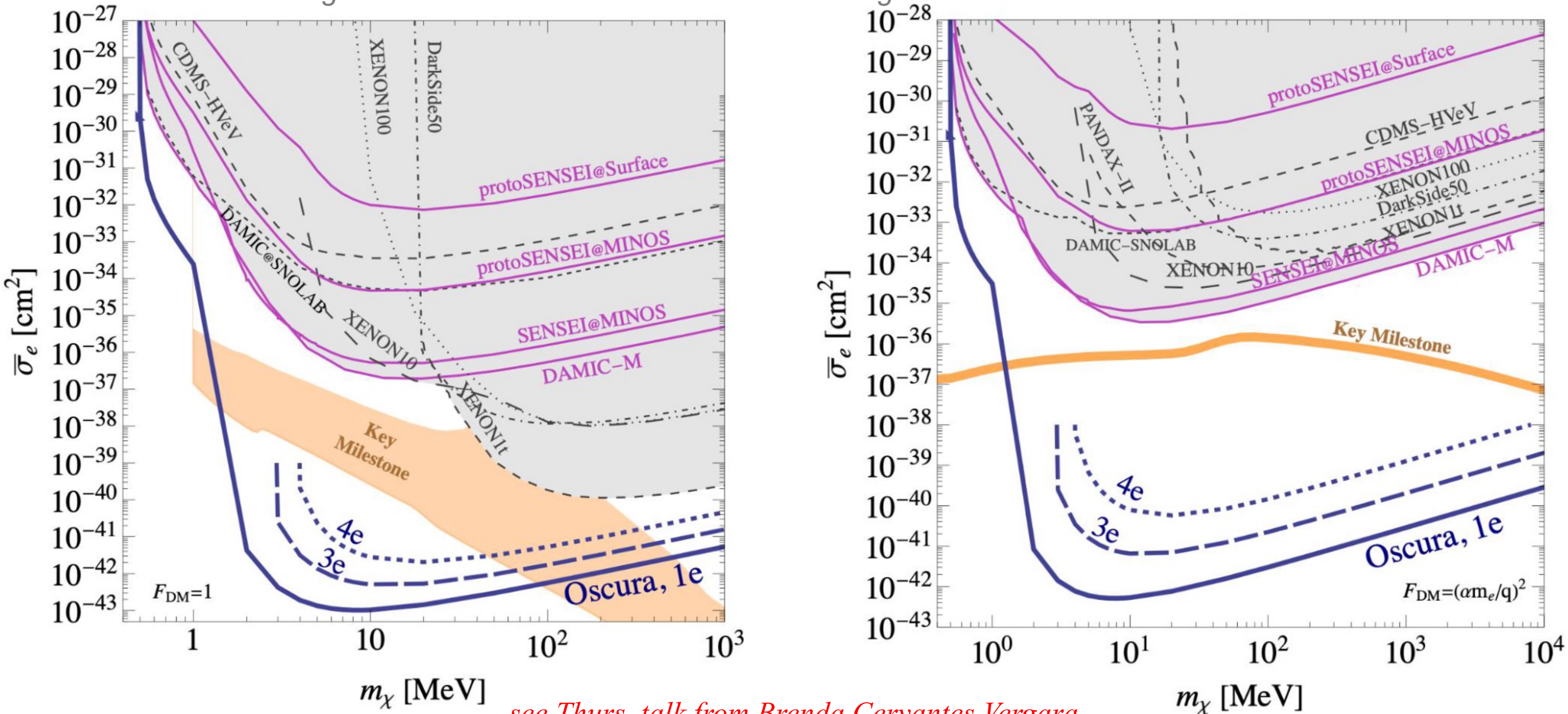


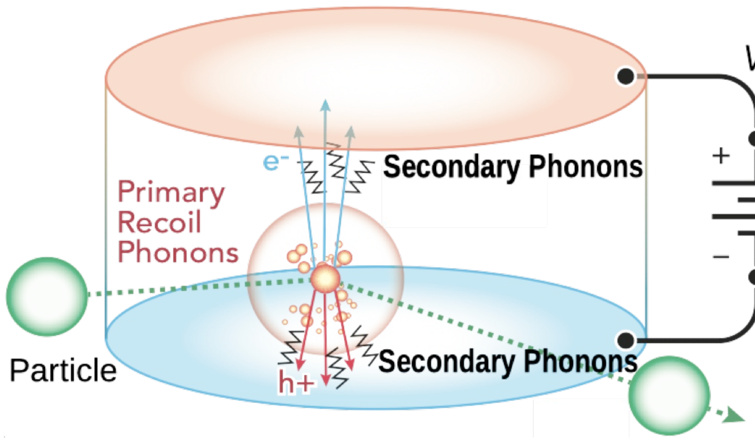
see Thurs. talk from Brenda Cervantes Vergara

Aguilar-Arevalo et al, (OSCURA Collaboration) [arXiv:2202.10518]

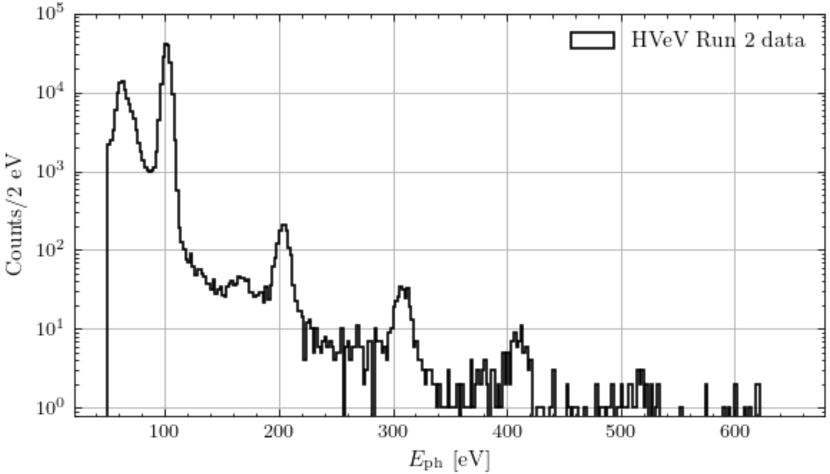
NTL-Amplification – Neganov-Trofimov-Luke Effect

images borrowed from Belina von Krosigk's talk at Invisibles24 Workshop

Clever way to search for individual e-h pair creation with a phonon sensor!



$$E_{ph} = E_r + n_{eh} \cdot e \cdot V_{\text{bias}}$$



Amaral et al, PRD 102, 091101 (2020) [arXiv:2005.14067]

Pros: in-situ aggregate discrimination, target-agnostic*, timing, 1-10 dru backgrounds

Cons: large dark rates, limited position information, no event-by-event discrimination

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NTL-Amplification – Neganov-Trofimov-Luke Effect

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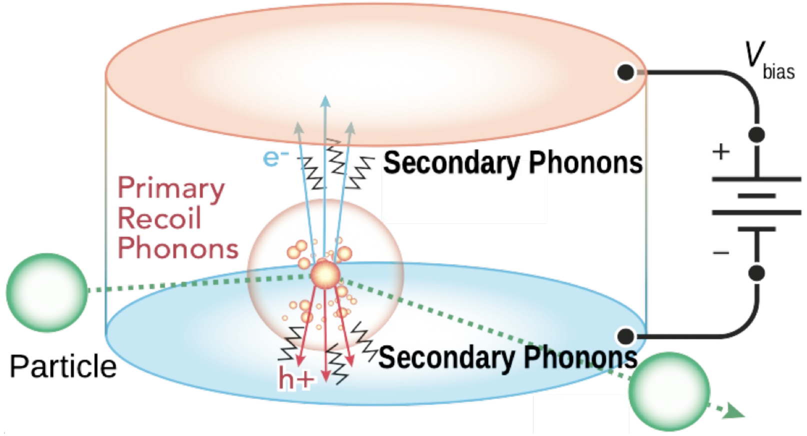

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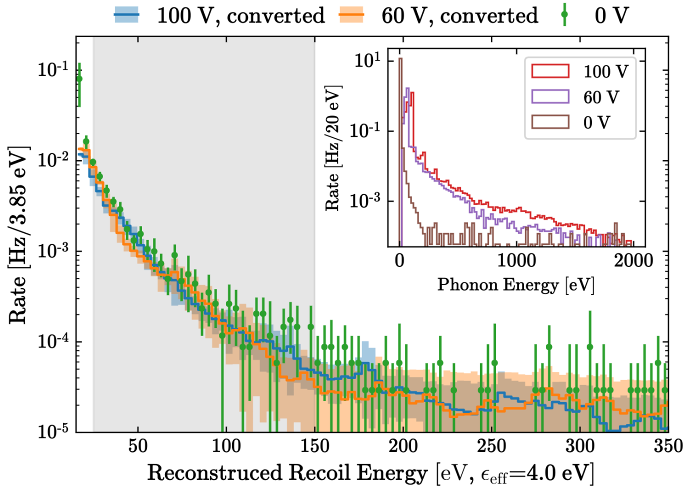


Albakry et al, PRD 105, 112006 (2022) [arXiv:2003.01046]

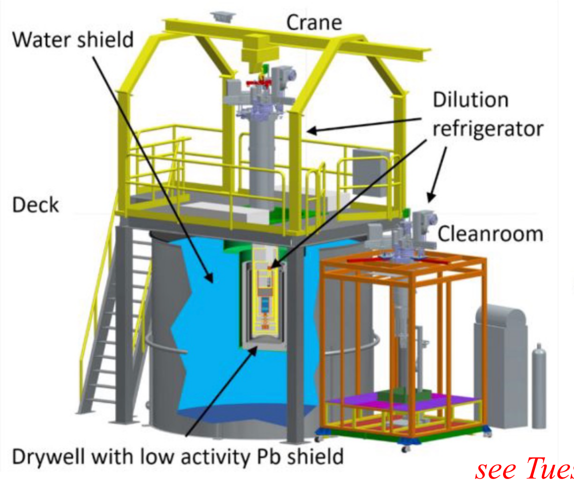
Pros: in-situ aggregate discrimination, target-agnostic*, timing, 1-10 dru backgrounds

Cons: large dark rates, limited position information, no event-by-event discrimination

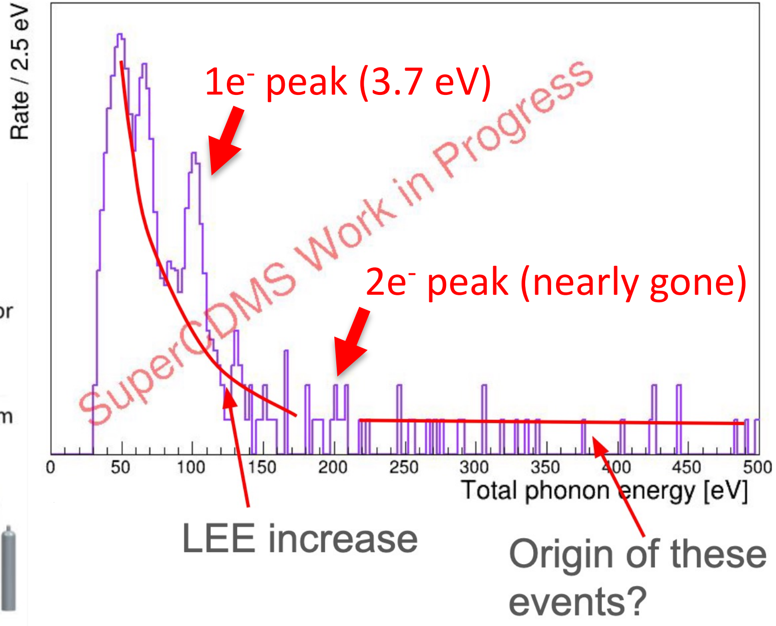
NTL-Amplification – SuperCDMS HVeV / LEGENDRE

images borrowed from Emanuele Michielin's talk at EXCESS24

see also Amaral et al, PRD 102, 091101 (2020) [arXiv:2005.14067]



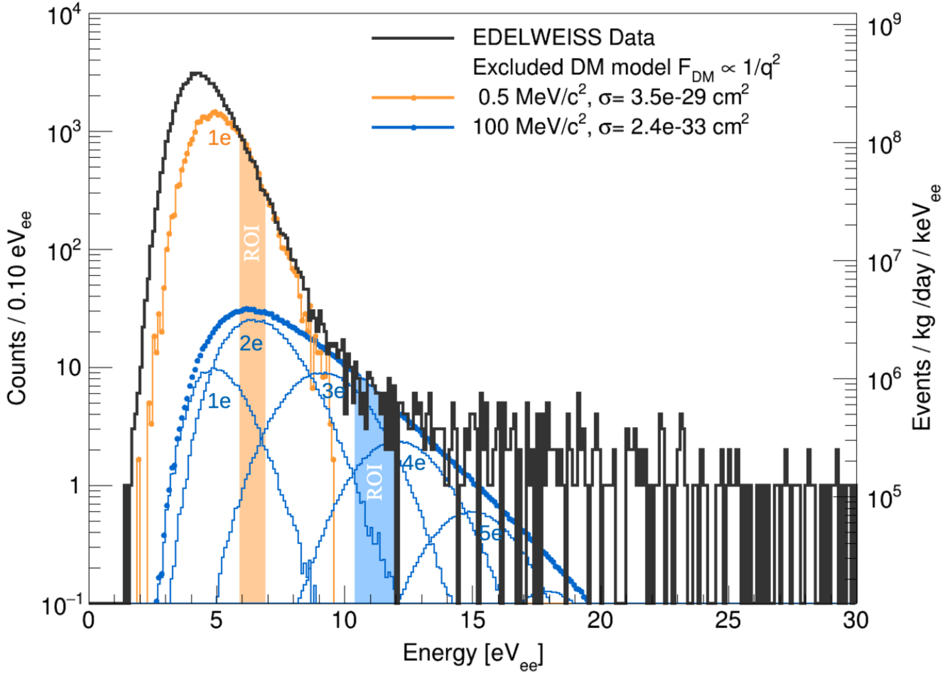
CDMS HVeV Run 4 at NEXUS



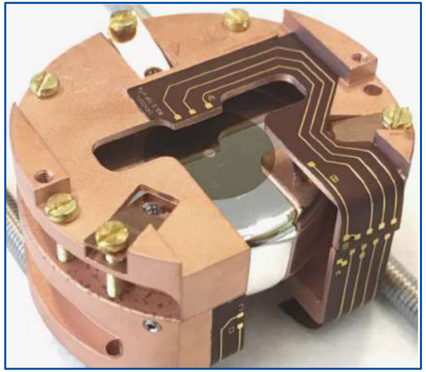
Detectors installed at CUTE

see Tues. talk from Matthew Wilson and Wed. talk from Sukeerthi Dharani

NTL-Amplification – EDELWEISS HV



Arnaud et al, PRL 125, 141301 (2020) [arXiv:2003.01046]



- Sub-e resolution has been achieved (0.5e$^-$)
- First demonstration of sub-electron resolution in a solid-state material other than silicon
- Lays groundwork for other materials…

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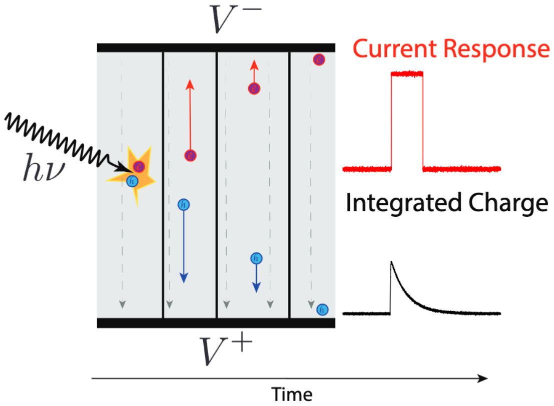
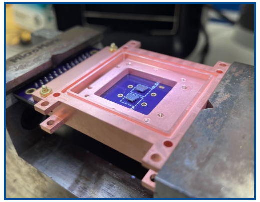
Novel Material Development – SPLENDOR

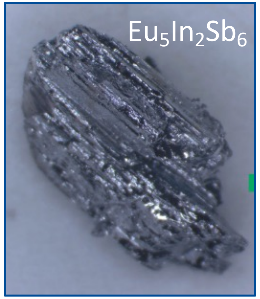
images borrowed from Sam Watkins (as Caleb Fink)'s IDM2024 talk yesterday

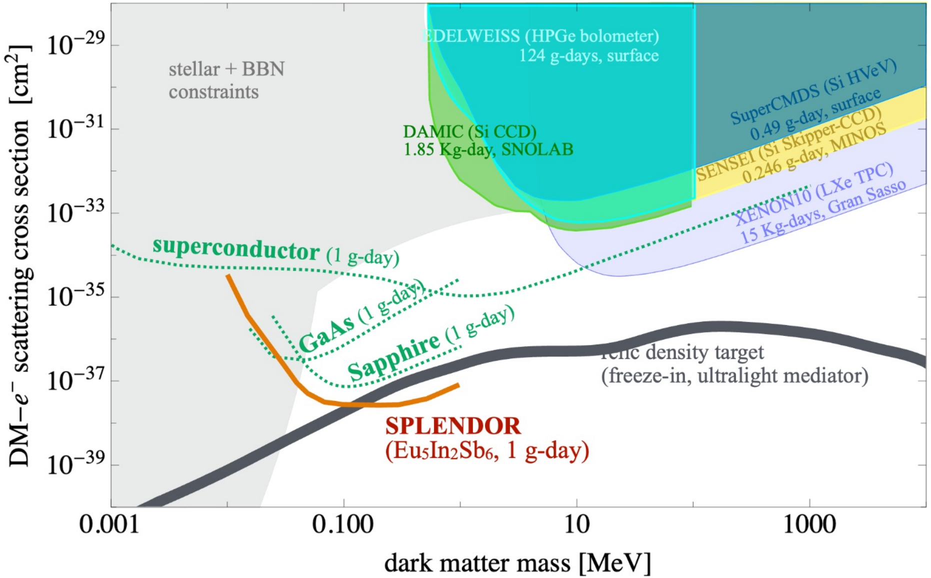
- **Novel narrow-gap semiconductor materials engineered for sub-eV e-h pair collection**

First device tests underway!









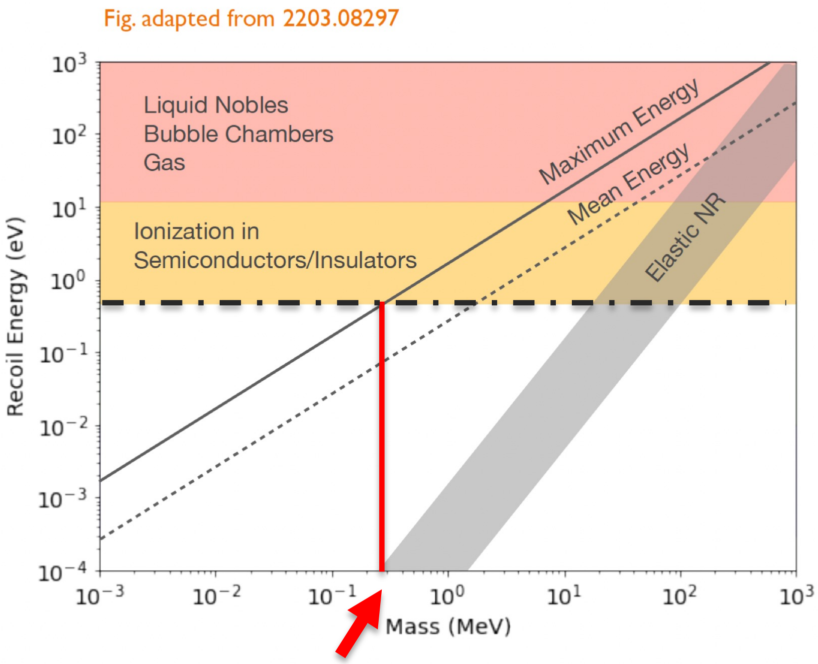
Pros: sub-eV charge threshold, timing

Cons: R&D required, unknown dark rates, no position information

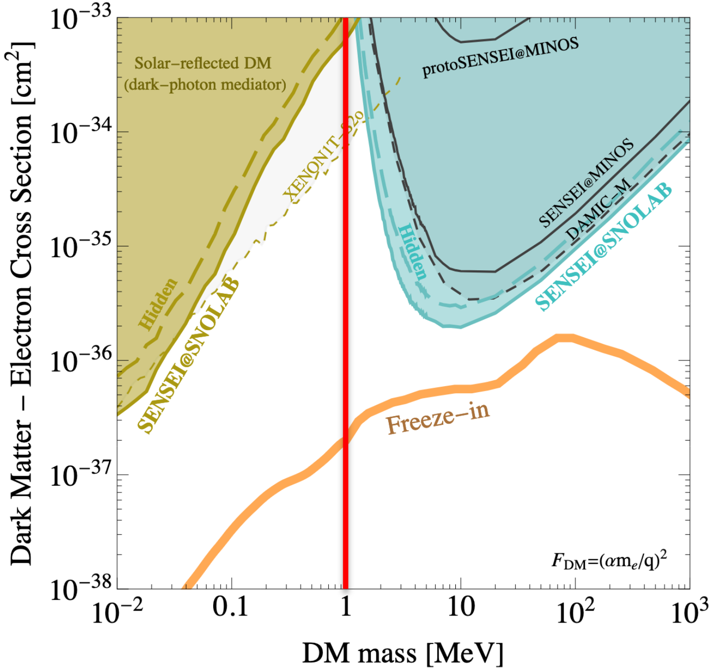
see Tues. talk from Sam Watkins (as Caleb Fink)

Low-Mass Dark Matter Detection

- Charge-hole pair detection is fundamentally limited by material band gaps



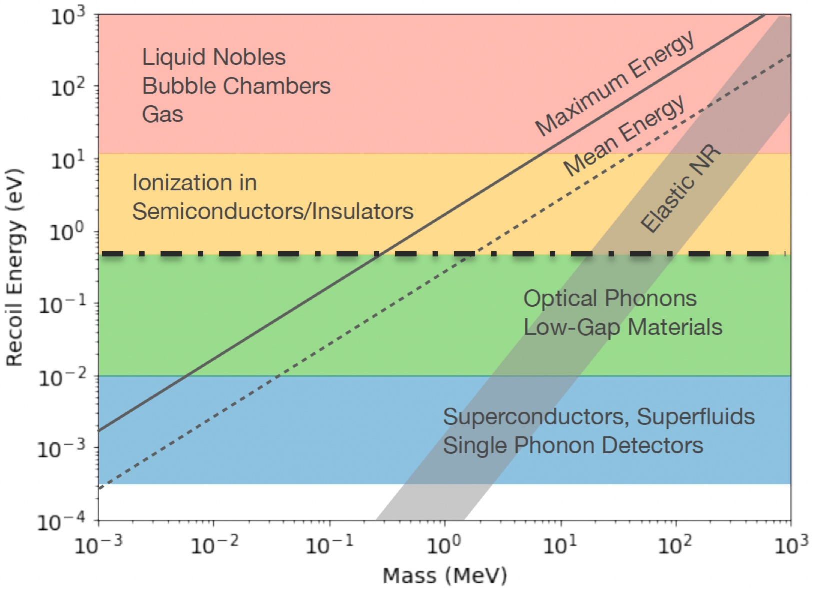
fundamental lower limit



Adari et al, (2023) [arXiv:2312.13342]

Low-Mass Dark Matter Detection

- Pushing to lower masses requires novel detector R&D in phonon detection



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

$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

$\Delta E \sim 1$ meV
e.g. superfluids, superconductors

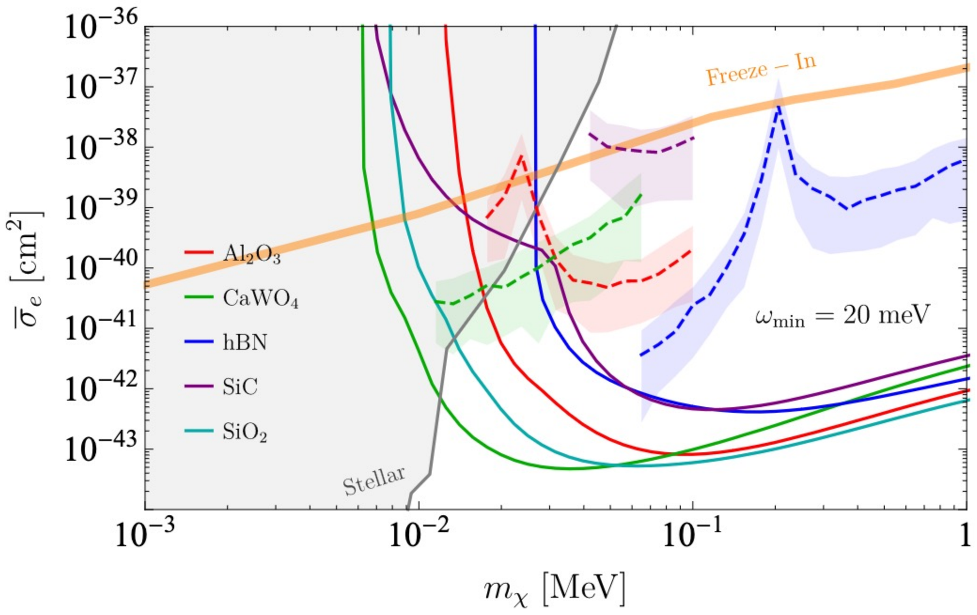
TESSERACT

DELight

Fermilab

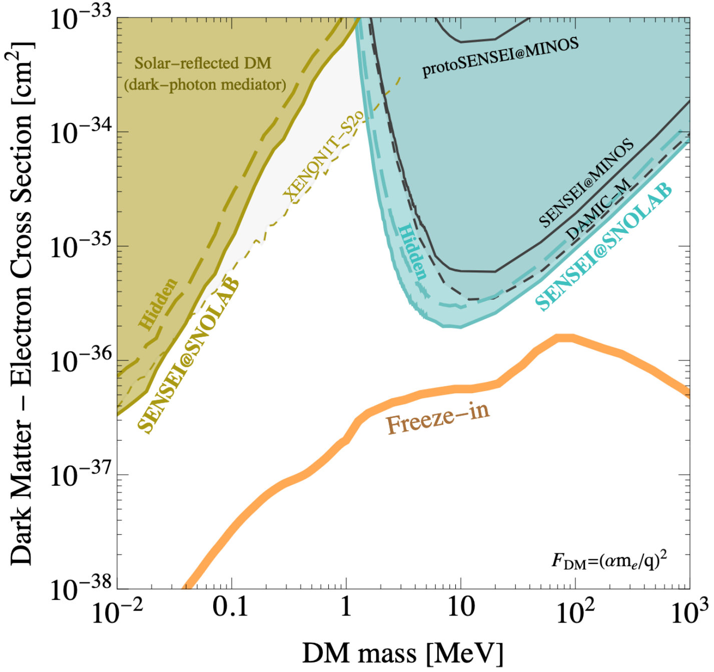
Low-Mass Dark Matter Detection

< MeV (phonons)



Coskuner et al, PRD 105, 015010 (2022) [arXiv:2102.09567]

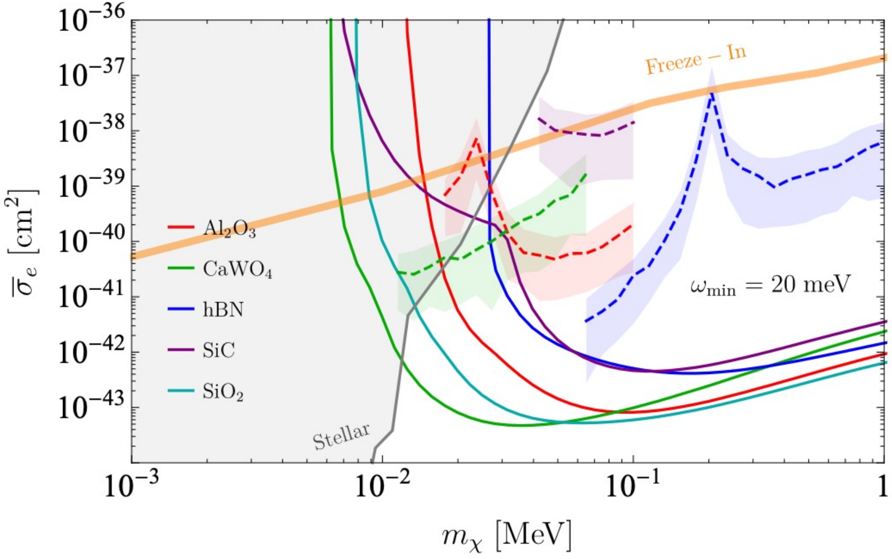
> MeV (charge)



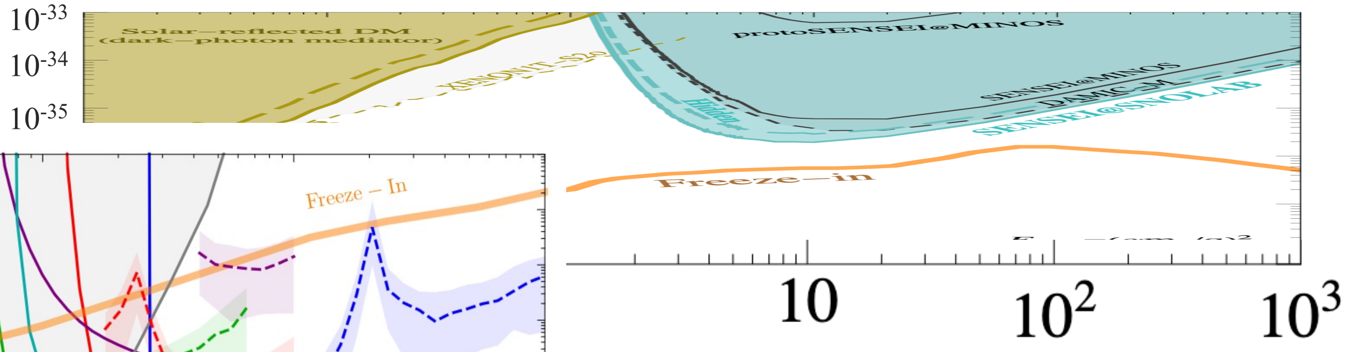
Adari et al, (2023) [arXiv:2312.13342]

Low-Mass Dark Matter Detection

< MeV (phonons) > MeV (charge)



Coskuner et al, PRD 105, 015010 (2022) [arXiv:2102.09567]



- People rarely stitch these regions together, since the types of detectors needed are very different
- Crime against aspect ratios

Adari et al, (2023) [arXiv:2312.13342]

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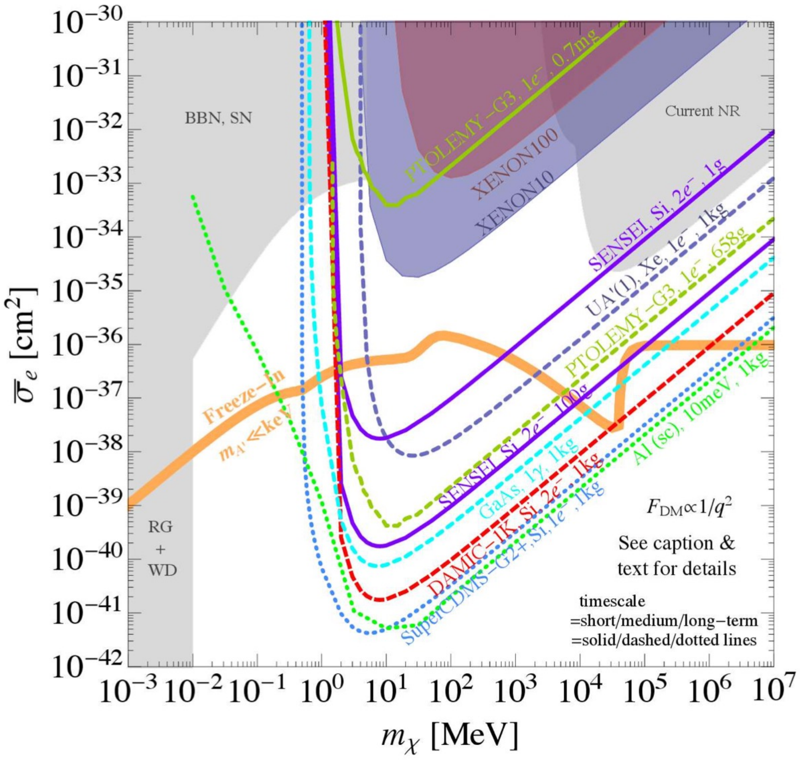
Detectors Searching for Phonons

Battaglieri et al, Cosmic Visions Report (2017) [arXiv:1707.04591]

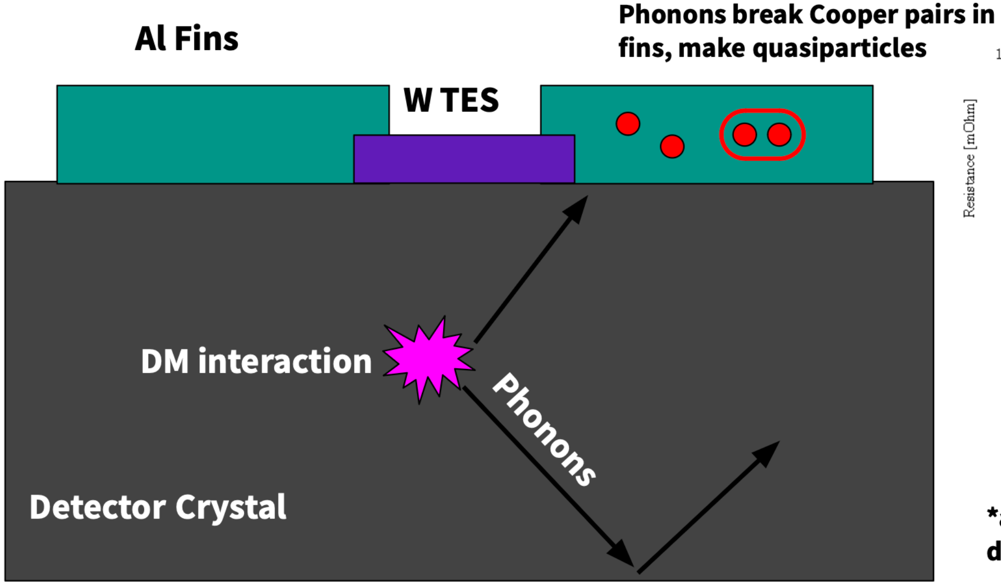
1. **TES-based Crystal Detectors**
   – TESSERACT (SPICE)
2. **Superfluid Helium Detectors**
   – TESSERACT (HeRALD)
   – DELight
3. **MKID-based Detectors**
   – BULLKID
4. **Superconducting Qubit Sensors**
   – Cosmic Quantum (CosmiQ) at FNAL
   – SQUATs

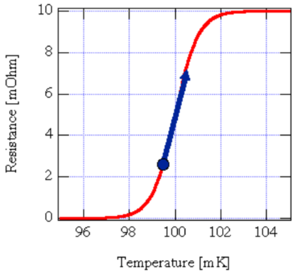


Fermilab

Quasiparticle Detection – Transition Edge Sensors

slide borrowed from Roger Romani's IDM2024 talk tomorrow





***all at ~10 mK in dilution refrigerator**

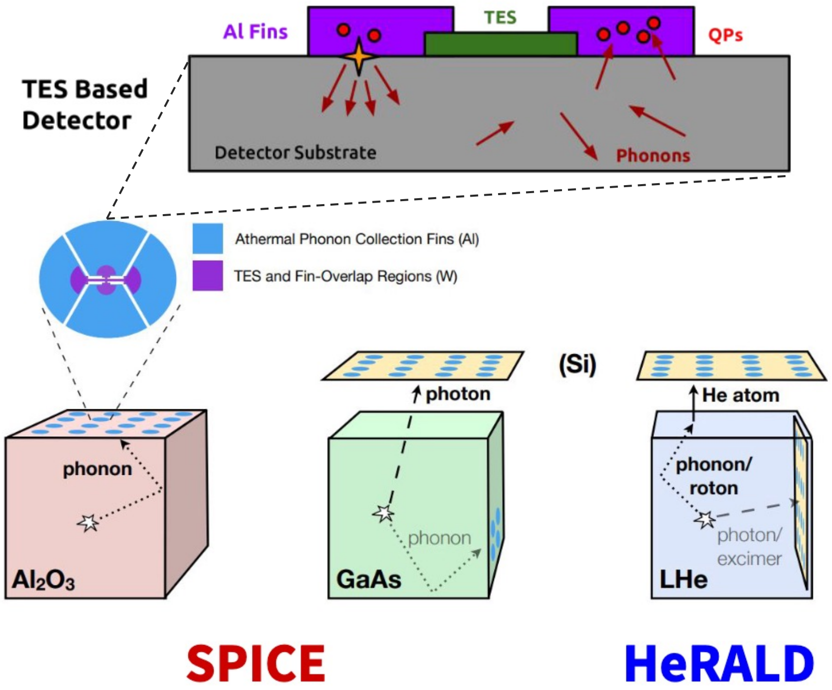
Pros: <u>sub-eV phonon thresholds</u>, timing

Cons: limited position information, no event-by-event discrimination

see Tues. talk from Christina Schwemmbauer

Quasiparticle Detection – TESSERACT

images borrowed from Roger Romani's talk at EXCESS24



- **Sapphire (Al_2O_3)** – optical phonon modes kinematically-matched to sub-MeV DM (need 10 meV energy thresholds)
- **Gallium arsenide (GaAs)** – scintillation light can be collected in addition to phonon signals, potentially enables discrimination
- **Superfluid He (LHe)** – scintillation, triplet excimer signals, *and* phonon/rotons provide many signals for strong discriminatory power

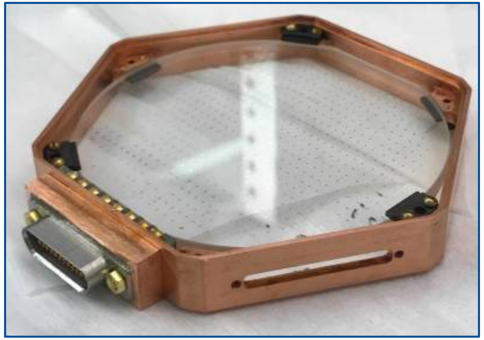
Fermilab

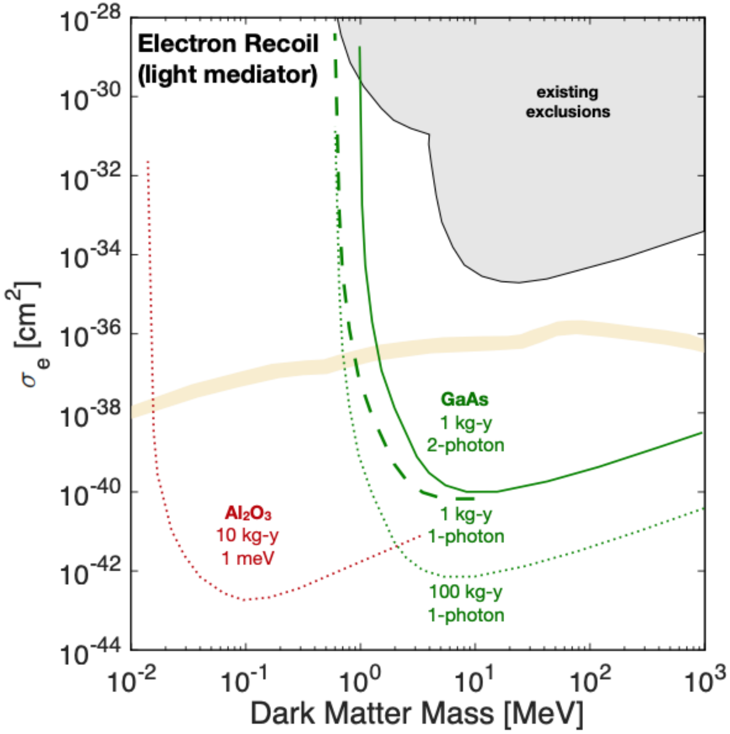
Quasiparticle Detection – SPICE

images borrowed from Roger Romani's IDM2024 talk tomorrow

Sapphire

10-100 meV optical phonon modes make for great DM target

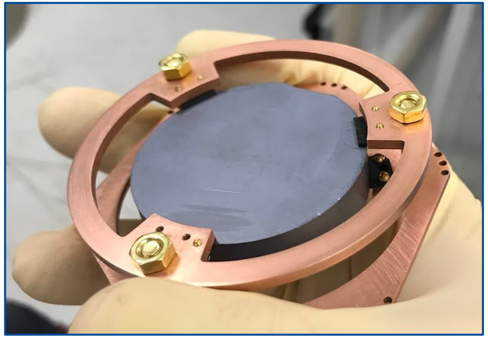




see Thurs. talk from Roger Romani

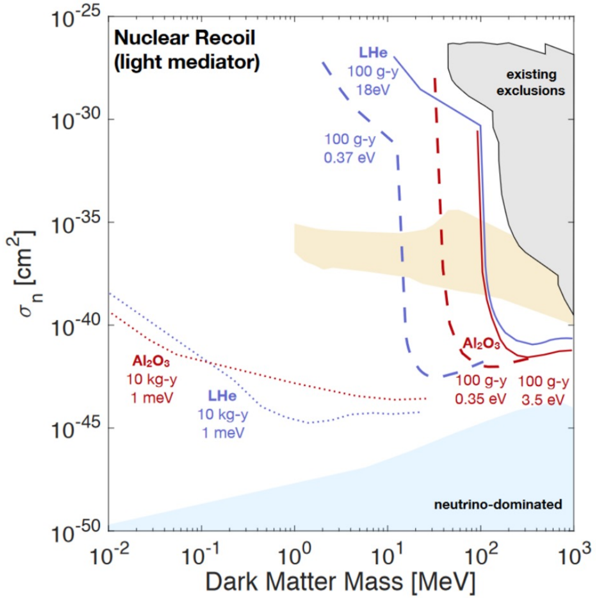
GaAs

Multiple detection channels (light+phonons) allows for event-by-event discrimination



Quasiparticle Detection – Superfluid Helium

image courtesy of Scott Haselschwardt



Three signal channels at different times!

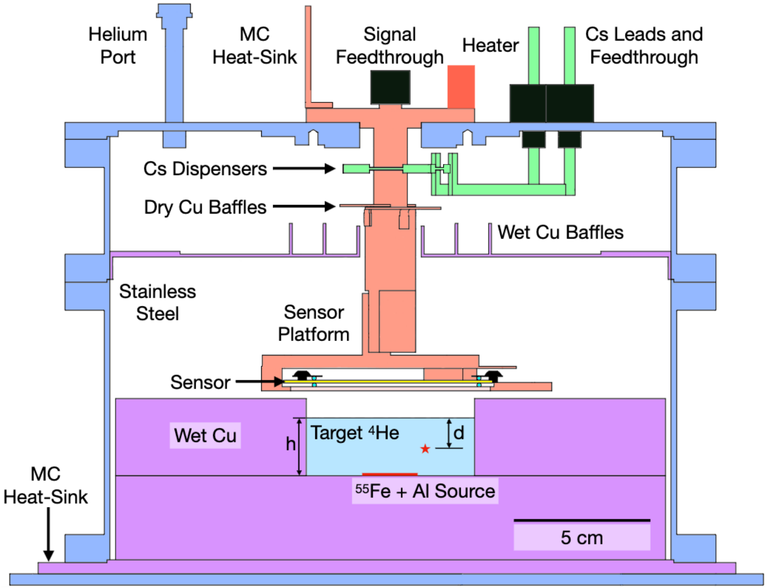
1. Prompt scintillation (dimer state)
2. Quantum evaporation (phonon/rotons)
3. Slow scintillation (trimer state)

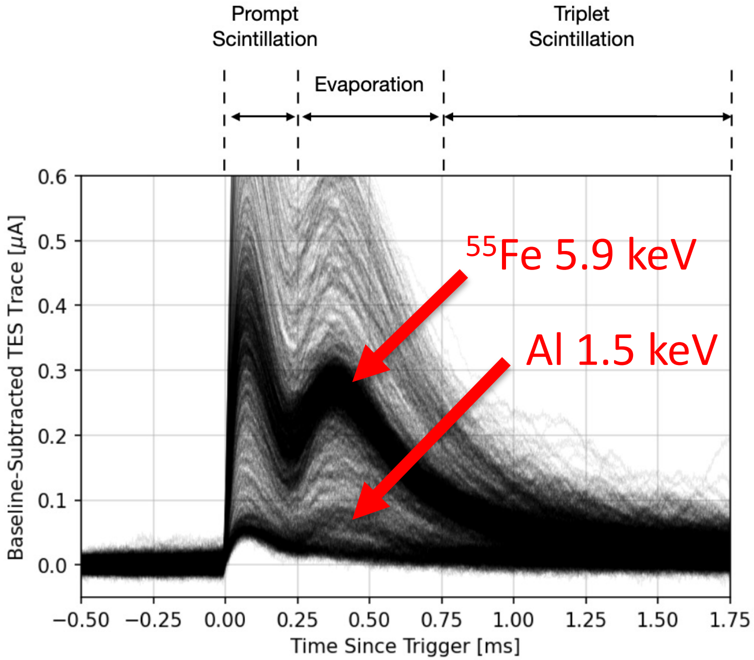
Non-helium impurities freeze out → self-shielding!

Pros: sub-eV thresholds, event-by-event discrimination(!), scalable(!), radiopure(!), timing, …
Cons: R&D required

Quasiparticle Detection – HeRALD

- Currently constructing and optimizing prototype detector at LBNL





Anthony-Petersen et al (2023) [arXiv:2307.11877]

see Thurs. talk from Scott Haselschwardt

Quasiparticle Detection – DELight

images borrowed from Belina von Krosigk's talk at Invisibles24 Workshop

DELight

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

KIT Karlsruhe Institute of Technology

universität freiburg

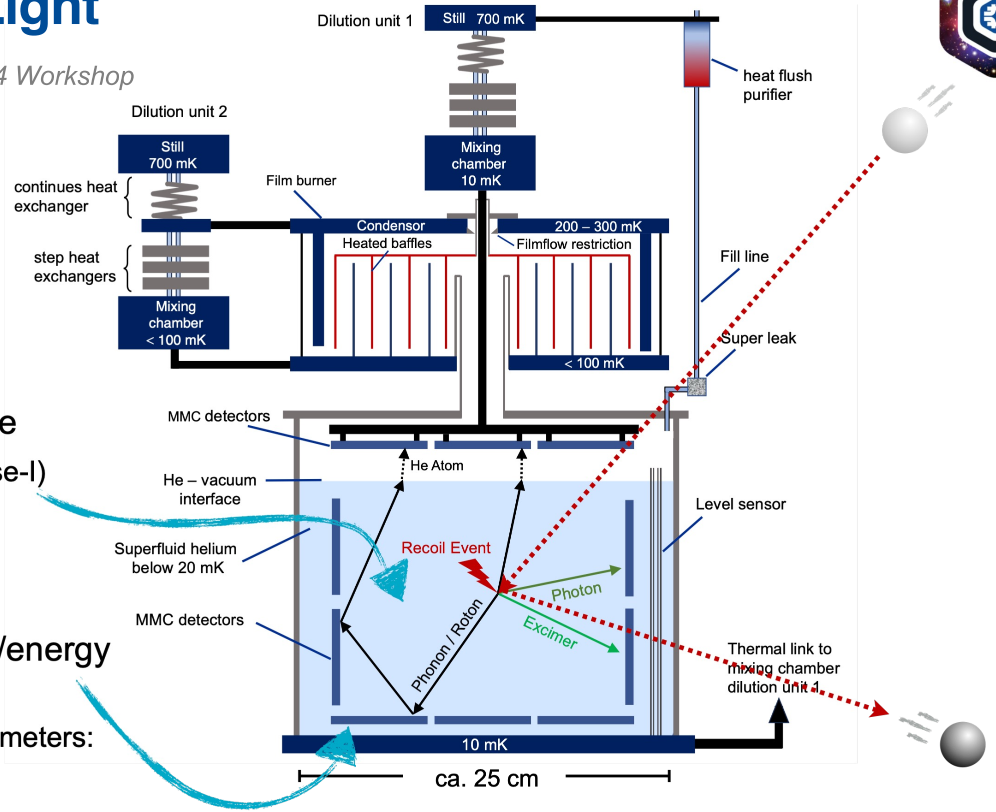
MMCs instead of TESs

Superfluid ^{4}He

(~ 10 liters in phase-I)

Ultra-sensitive heat/energy sensors

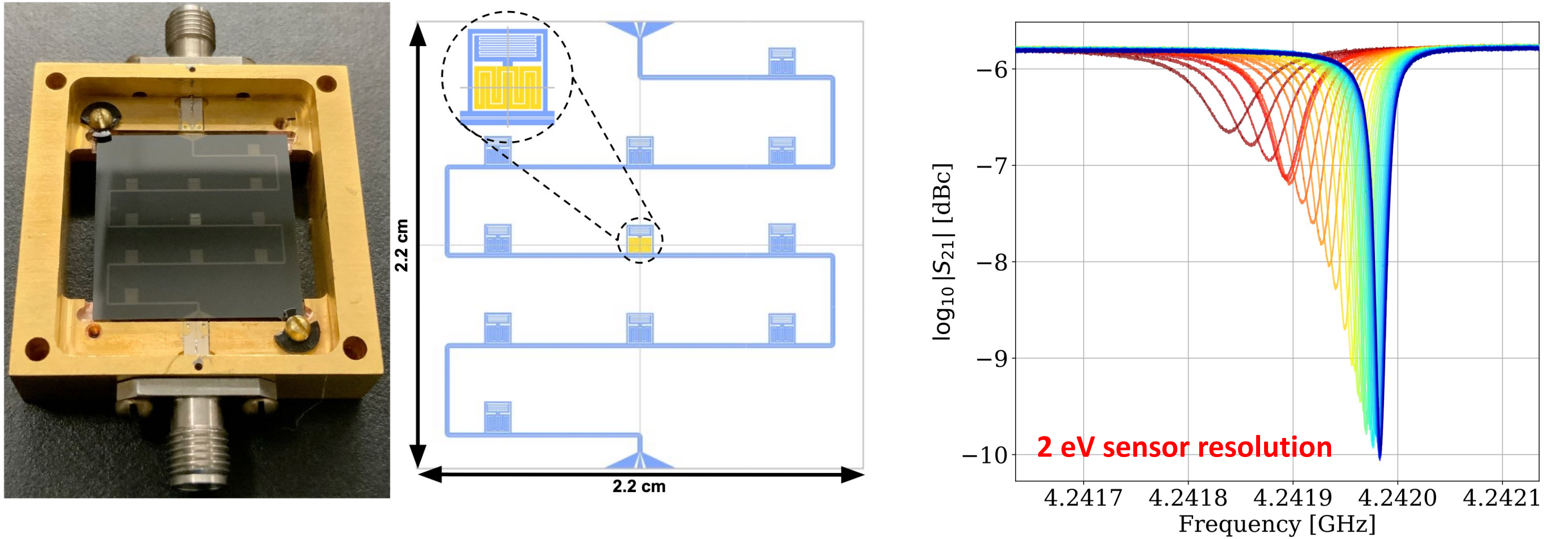
(Magnetic MicroCalorimeters: MMCs)



von Krosigk et al, SciPost Phys. Proc. 12, 016 (2023) [arXiv:2209.10950]

Quasiparticle Detection – MKIDs

- Potentially a nice (RF) alternative to (DC) TES-based sensors



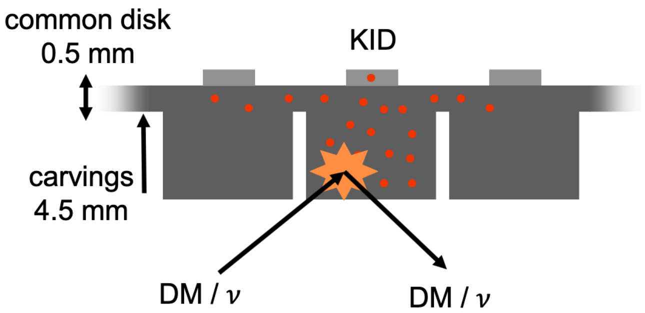
Temples et al (2024) [arXiv:2402.04473]

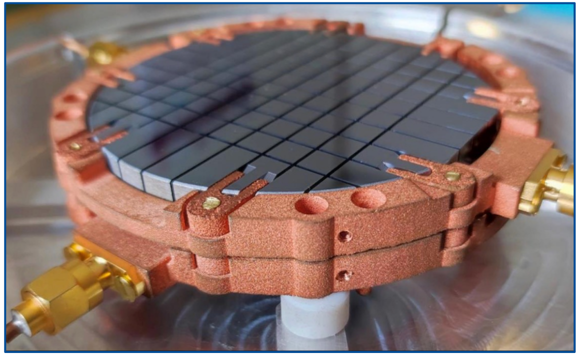
Pros: highly multiplexable → position resolution, eV phonon thresholds, timing, compatible with qubits
Cons: R&D required to improve thresholds, no event-by-event discrimination

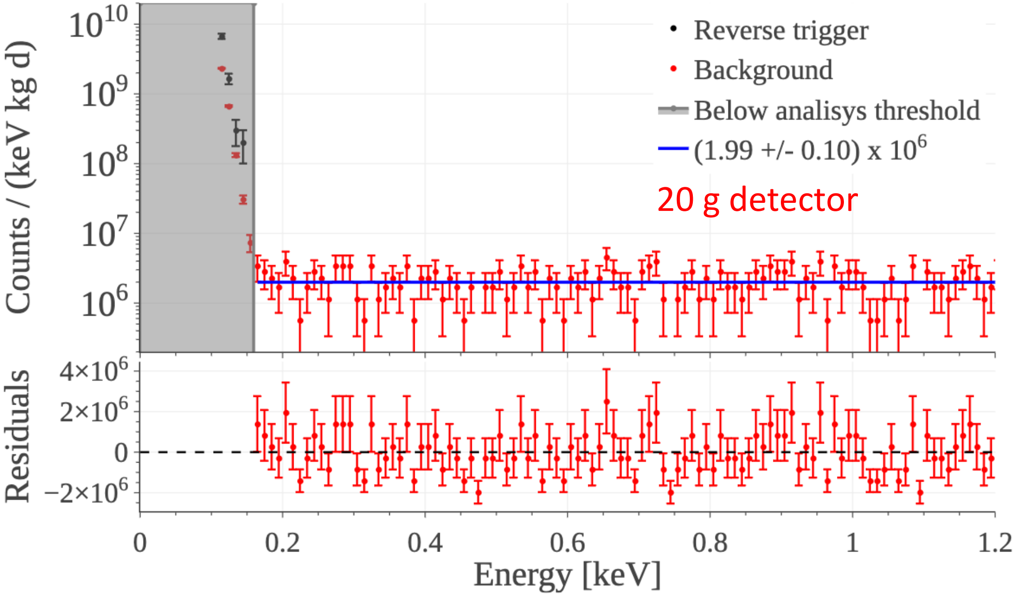
see Tues. talk from Karthik Ramanathan

Quasiparticle Detection – BULLKID

images stolen from Matteo Folcarelli's talk at EXCESS24







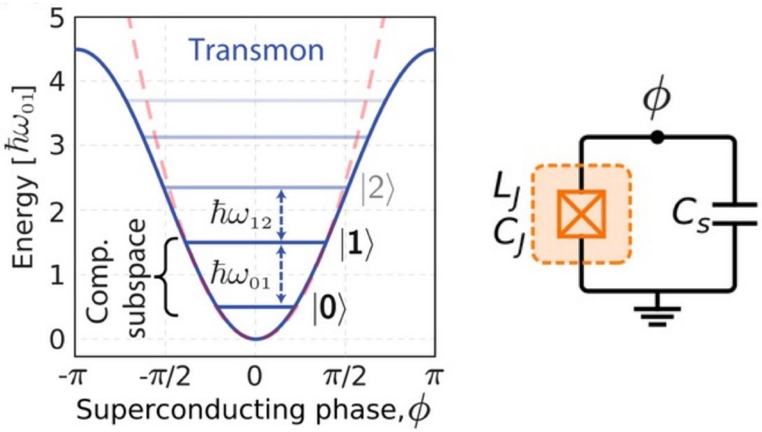
Delicato et al, Eur. Phys. J. C 84, 353 (2024) [arXiv:2308.14399]

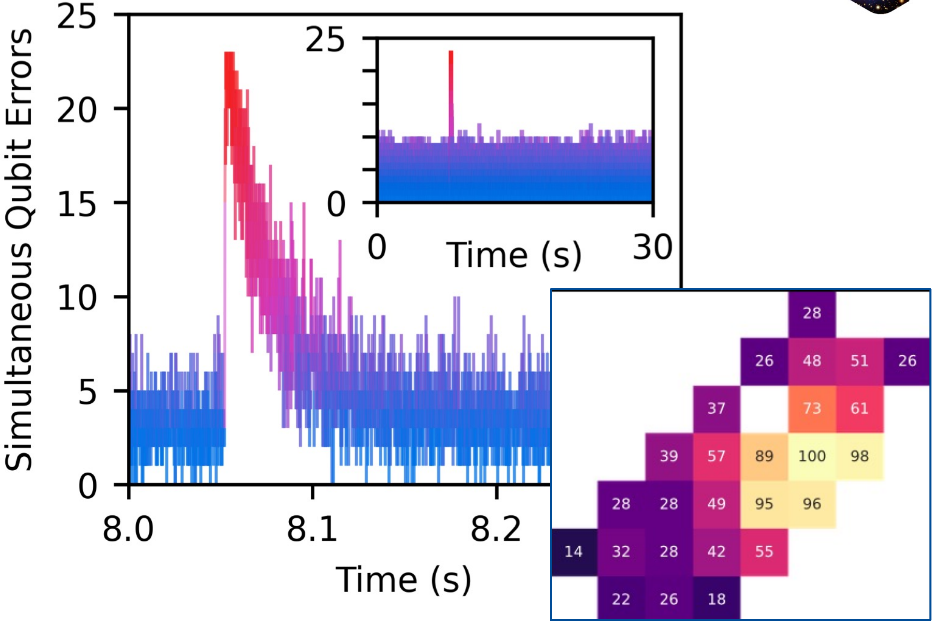
see Tues. talk from Marco Vignati

Quasiparticle Detection (+?) – Superconducting Qubits

- Extremely sensitive to all types of environmental noise at the ueV-level

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





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

Pros: <u>sensitive to ueV-scale single-quanta</u>, timing, position sensitivity, synergistic with QIS

Cons: substantial R&D required

see Tues. talks from Karthik Ramanathan and Anirban Das for more ways to use qubits as sensors

Quasiparticle Detection (+?) – Superconducting Qubits

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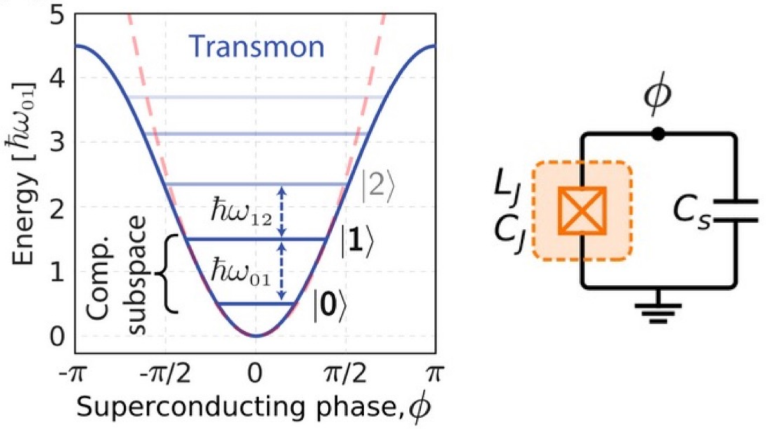

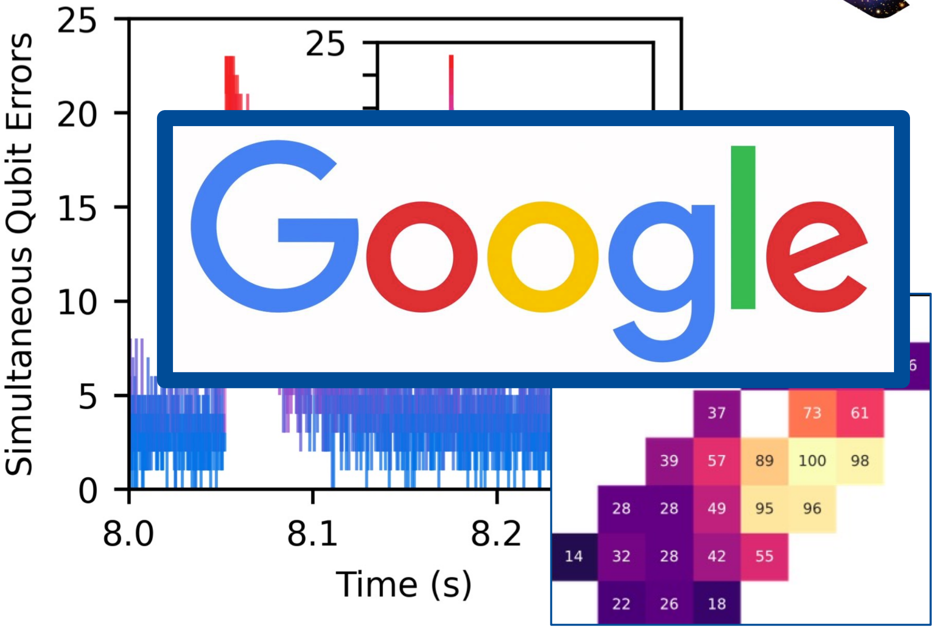

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Radiation Impact on Superconducting Qubits (RISQ) Workshop

Scientific Organizing Committee:
Daniel Baxter, FNAL/NU (SOC chair, **QSC**)
Travis Humble, ORNL/UTK (director, **QSC**)
Farah Fahim, FNAL (**QSC**)
Enectali Figueroa-Feliciano, NU/FNAL (**QSC**)
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Jon Cripe, LPS
Jonathan DuBois, LPS
Andrew Kubik, SNOLAB

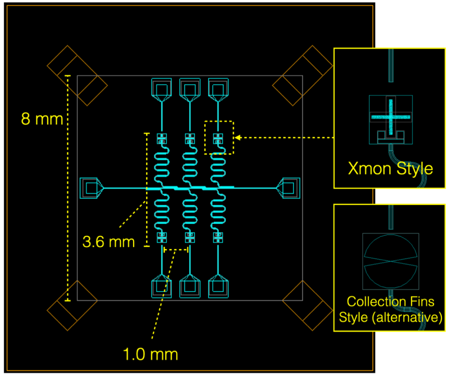
Photo credit: Dan Savoboda, Fermilab

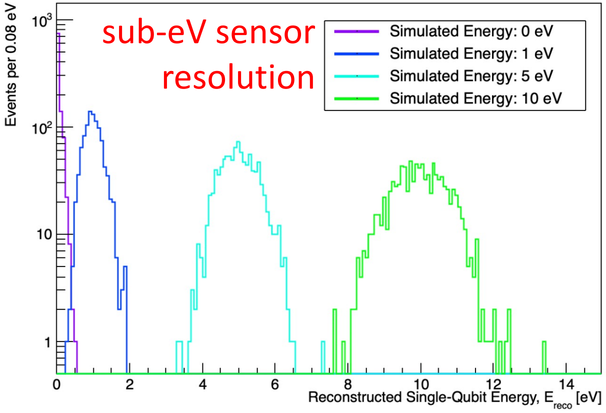
QUIET Underground Facility
Quantum Underground Instrumentation Experimental Testbed

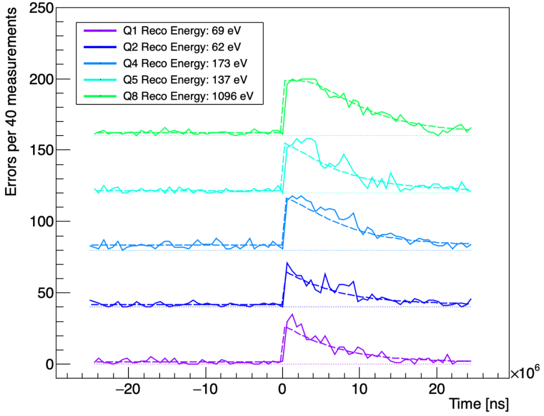
Photo credit: Dan Savoboda, Fermilab

Quasiparticle Detection (+?) – Superconducting Qubits

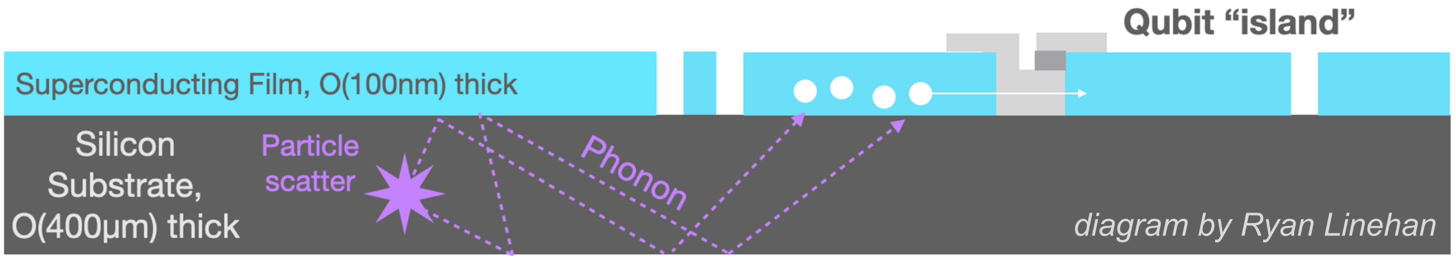
G4CMP Sim → **Sensor Response** → **Compare with data**





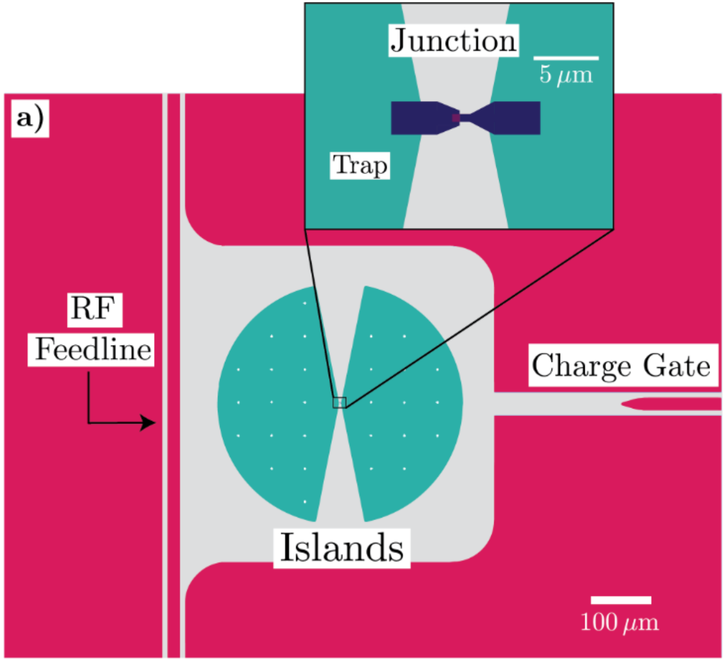


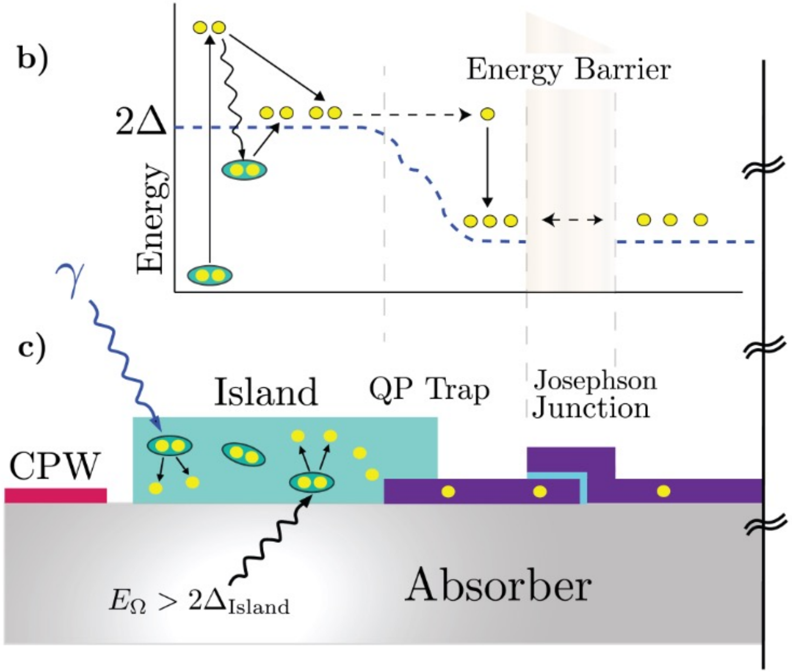
Linehan et al (2024) [arXiv:2404.04423], fit to data from Harrington et al, (2024) [arXiv:2402.03208]



Quasiparticle Detection (+?) – SQUATs

- Combine this with collection fins to improve phonon collection efficiency



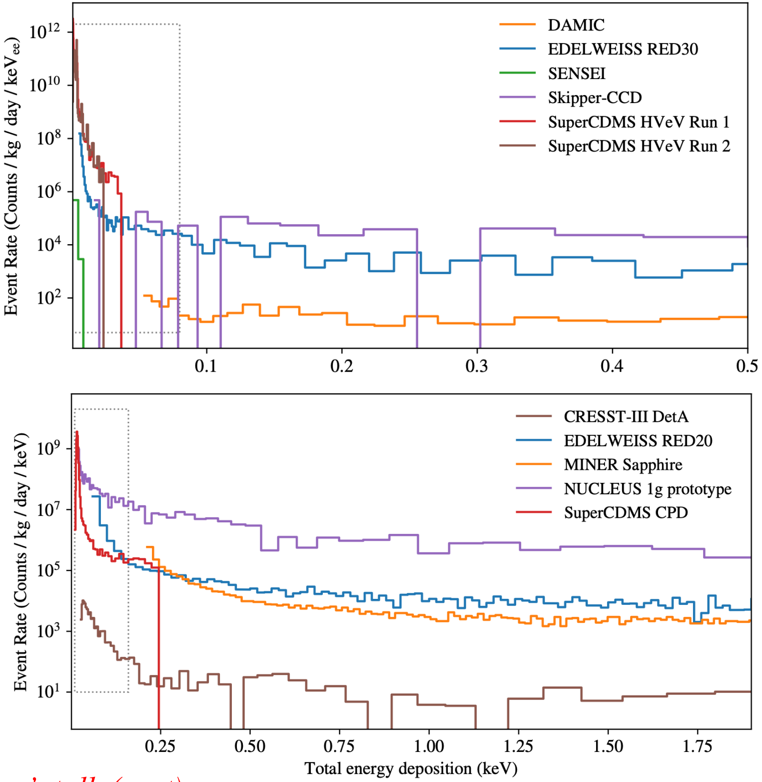


Fink et al (2023) [arXiv:2310.01345]

That's a lot of detectors…

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

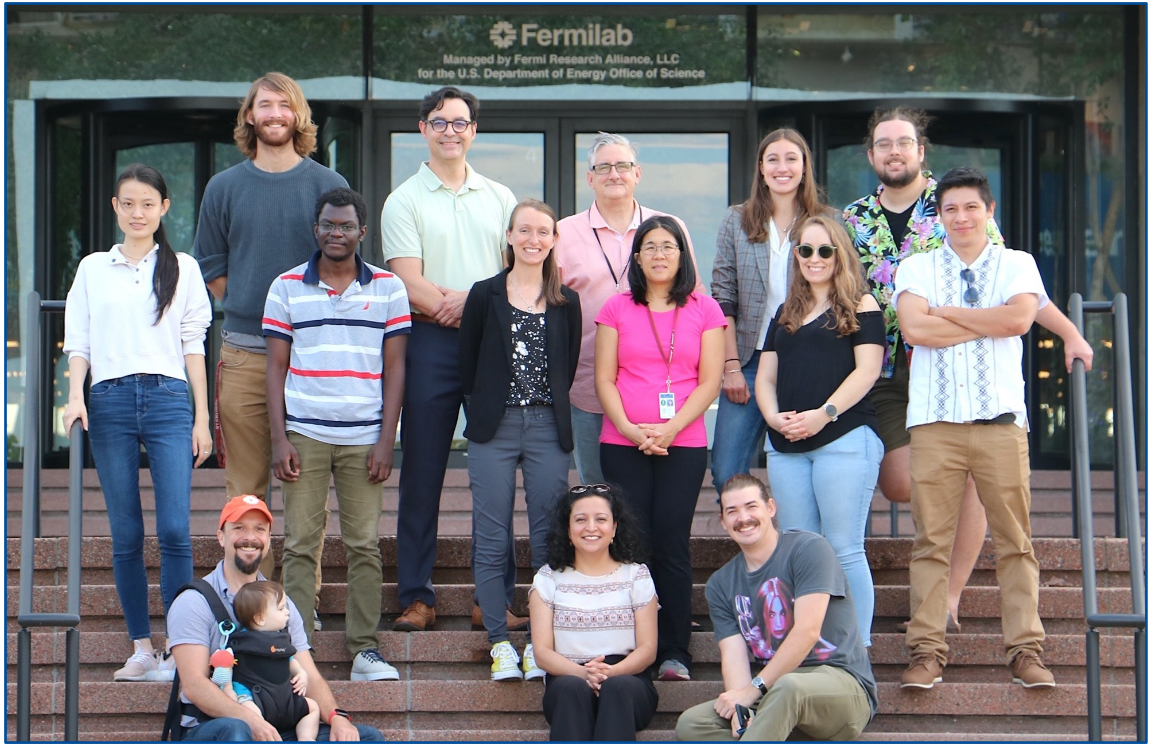
1. **Energy Threshold**
   - At a minimum, need eV-scale thresholds to be competitive
   - R&D is pushing towards meV-scale energy thresholds
2. **Exposure**
   - Not as important as for WIMP searches
   - Current best limits have kg-days
3. **Backgrounds**
   - Complicated, non-radiogenic excess backgrounds plague lower energies
   - (here there be dragons)



see Christian Strandhagen's talk (next)

Back-up Slides

Acknowledgements – CosmiQ@FNAL



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Jialin Yu

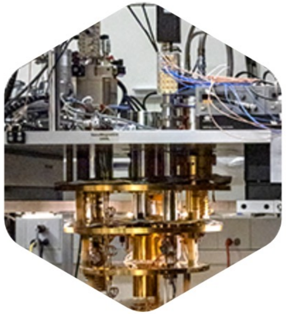
QUANTUM SCIENCE CENTER

*group alumni

Fermilab

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)



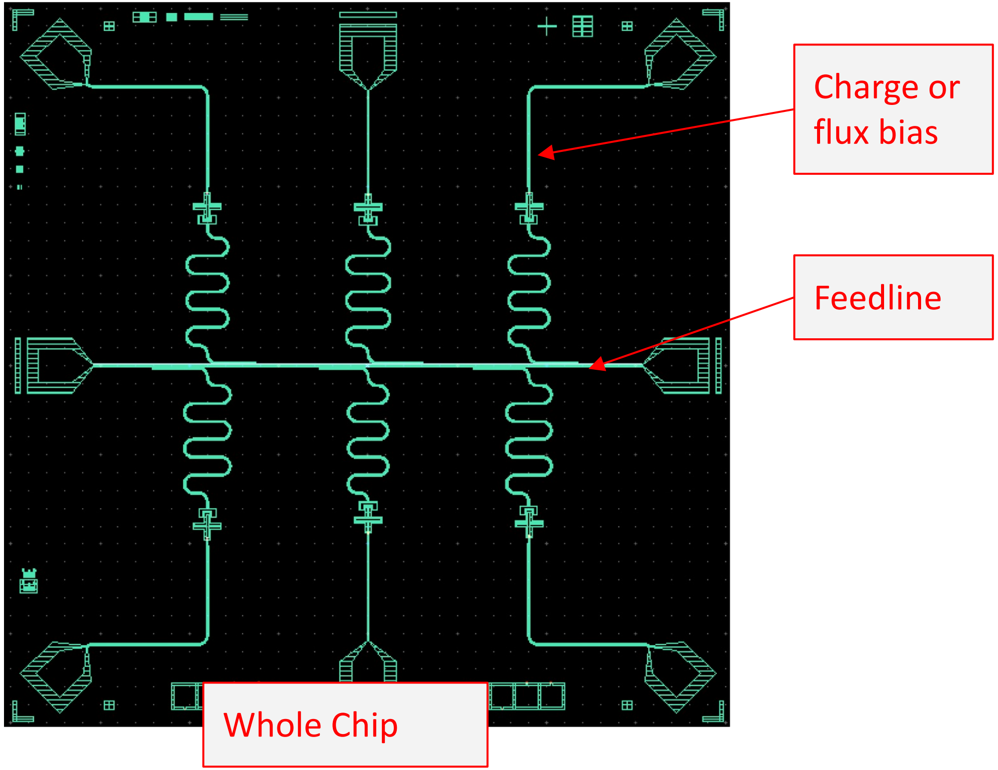
Thrust 3: Quantum Devices and Sensors for Discovery Science

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

Superconducting Qubits

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



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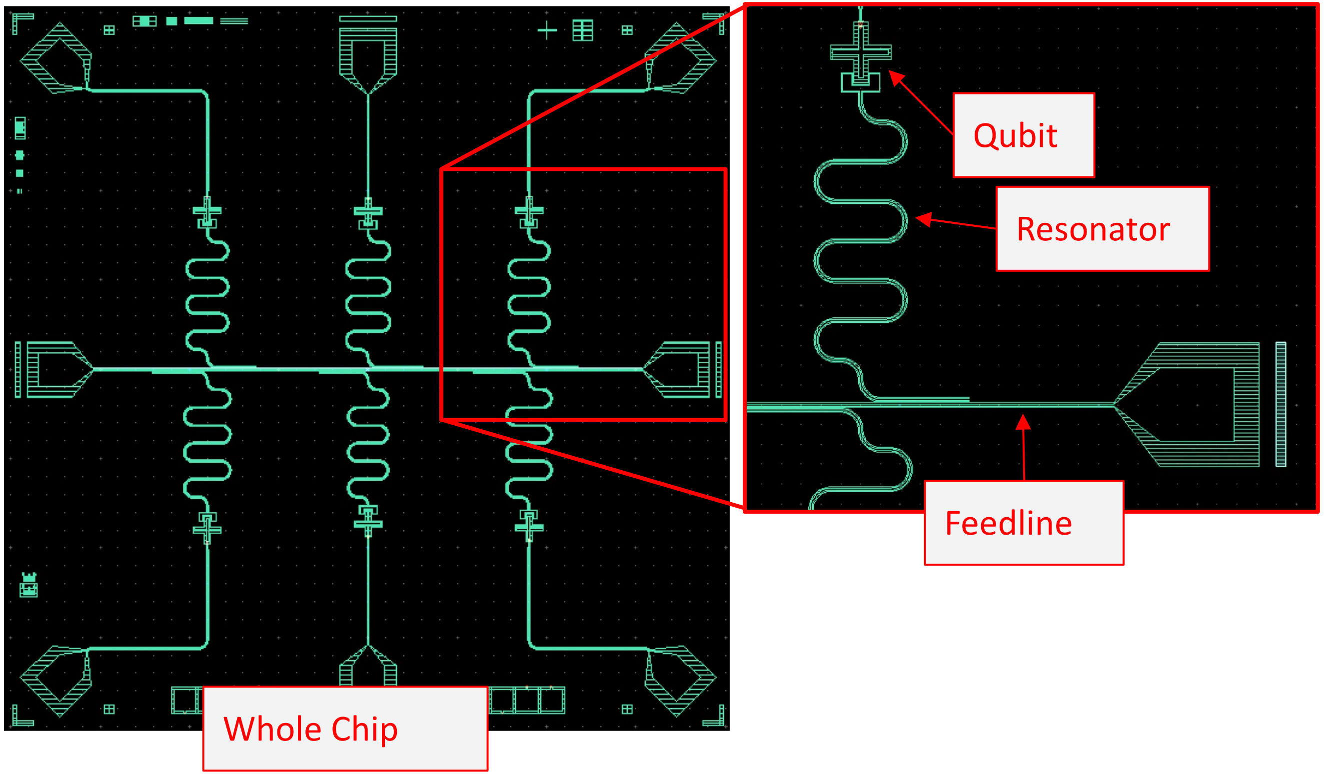

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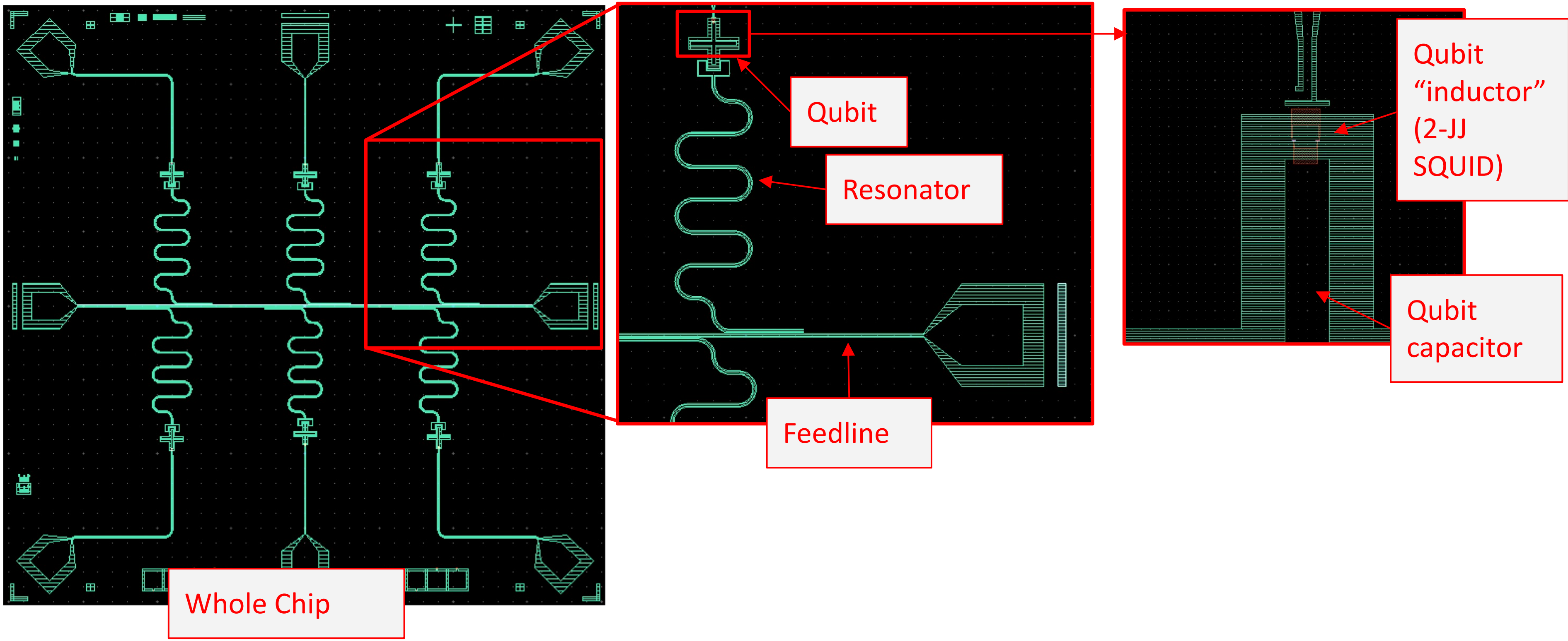

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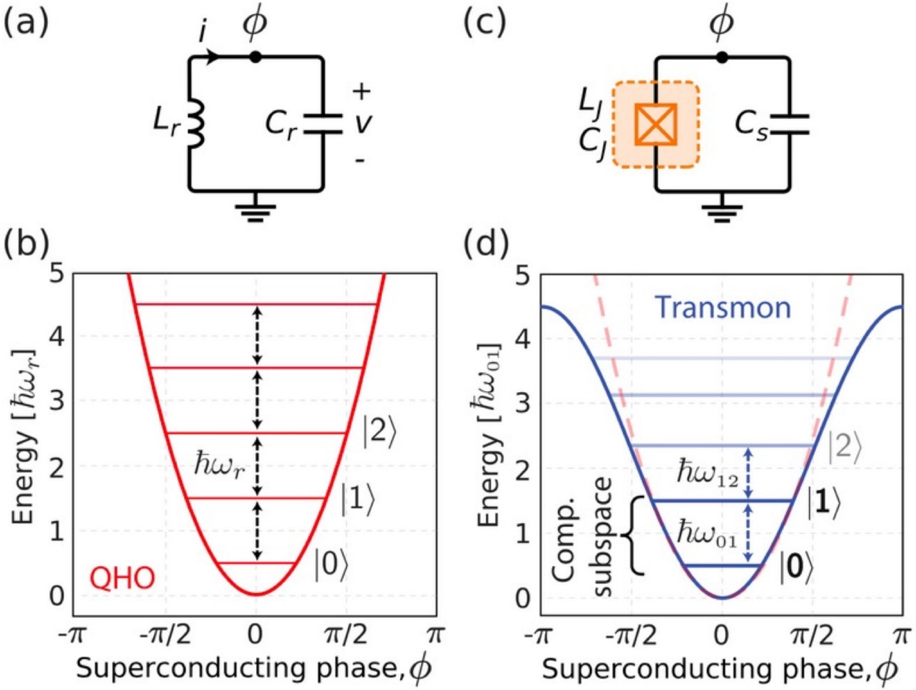

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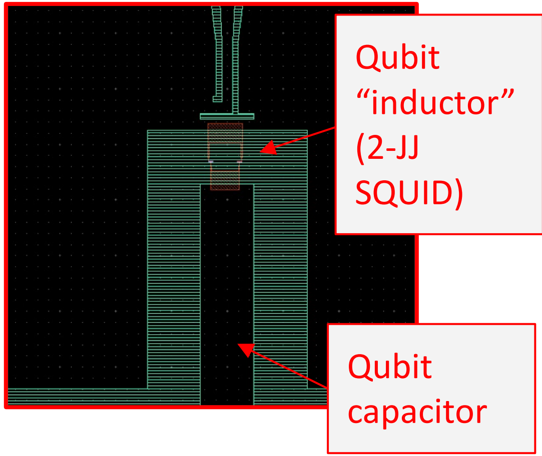
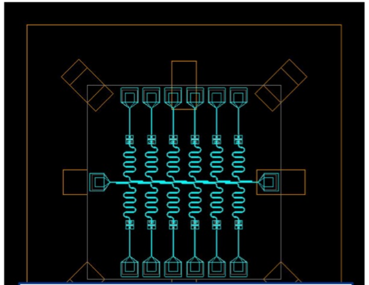


Modeling decoherence from scattering

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

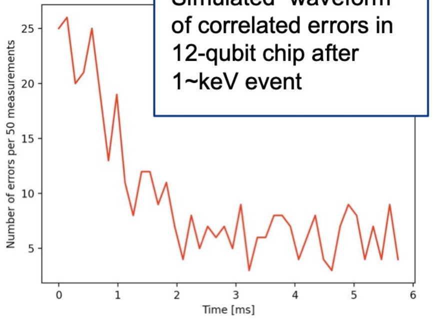
DM scattering, energy deposition → Energy propagation through chip → QP production in qubits → QP time evolution in qubits → $T_{1,qp}$ evolution in qubits

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!

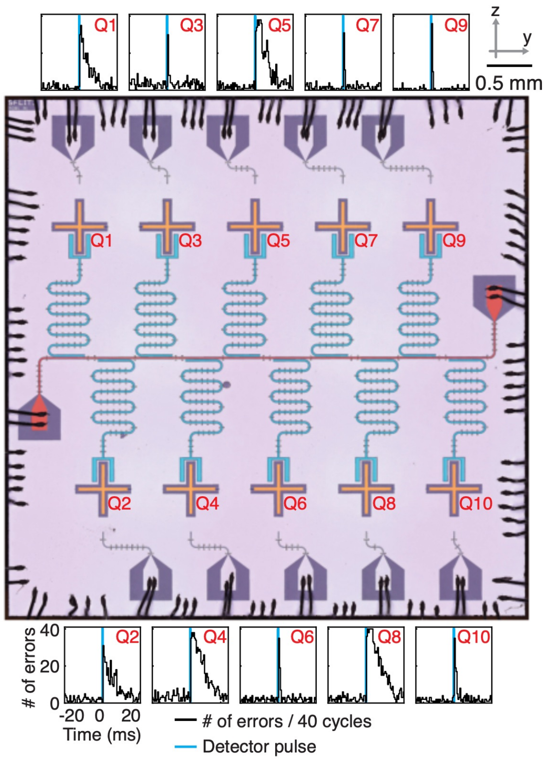


Simulated "waveform" of correlated errors in 12-qubit chip after 1~keV event

Modeling decoherence from scattering

QUANTUM SCIENCE CENTER

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate



Harrington et al, (2024) [arXiv:2402.03208]

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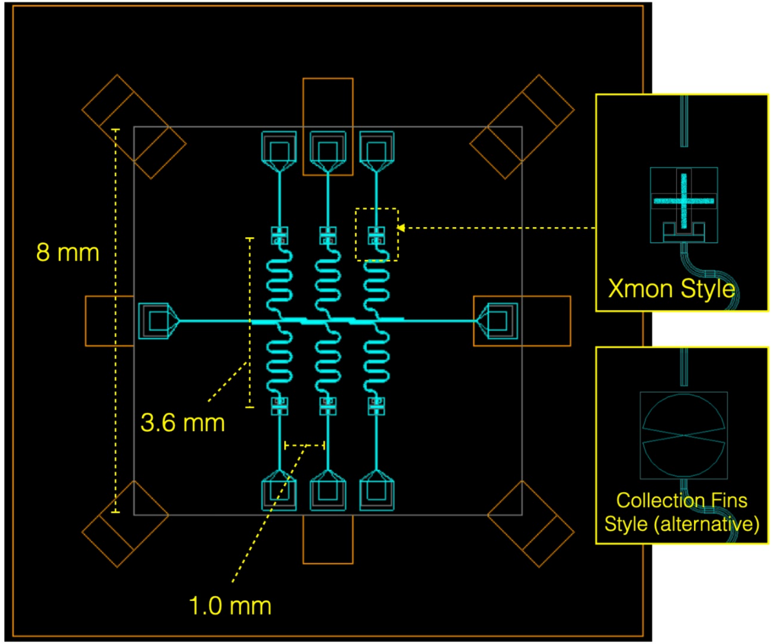

1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
   - w/ ground plane: $\eta_{ph} \approx 0.1\%$
   - w/out ground plane: $\eta_{ph} \approx 2\%$
   - w/ collection fins: $\eta_{ph} \approx 15\%$*

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Modeling decoherence from scattering

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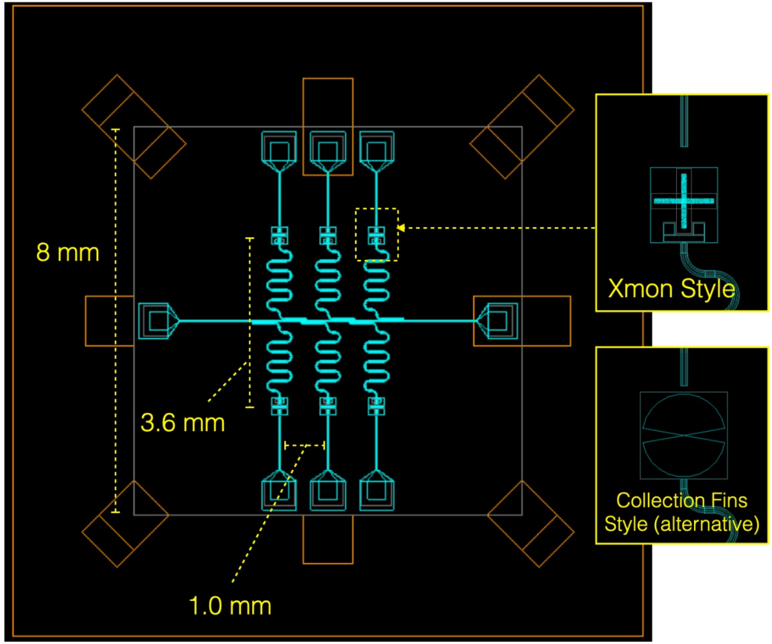

1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Modeling decoherence from scattering

QUANTUM SCIENCE CENTER

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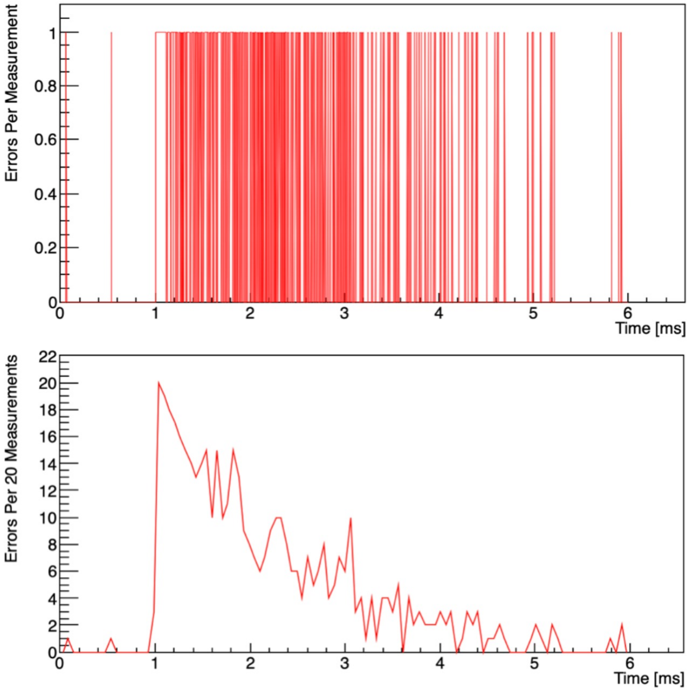
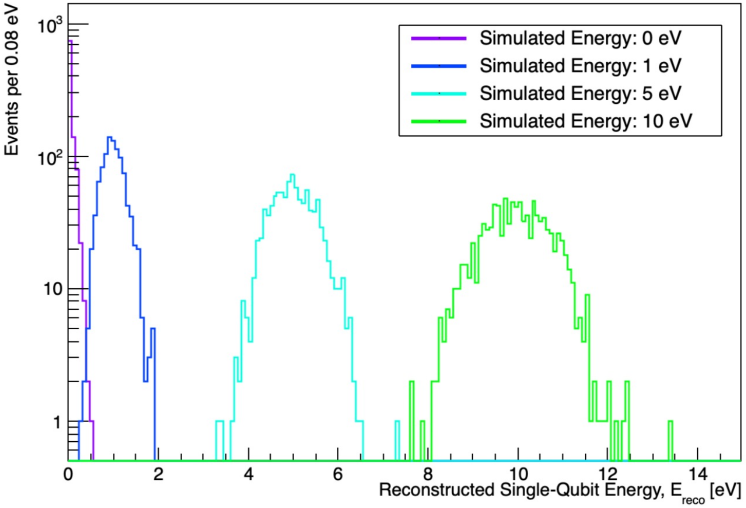


1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate

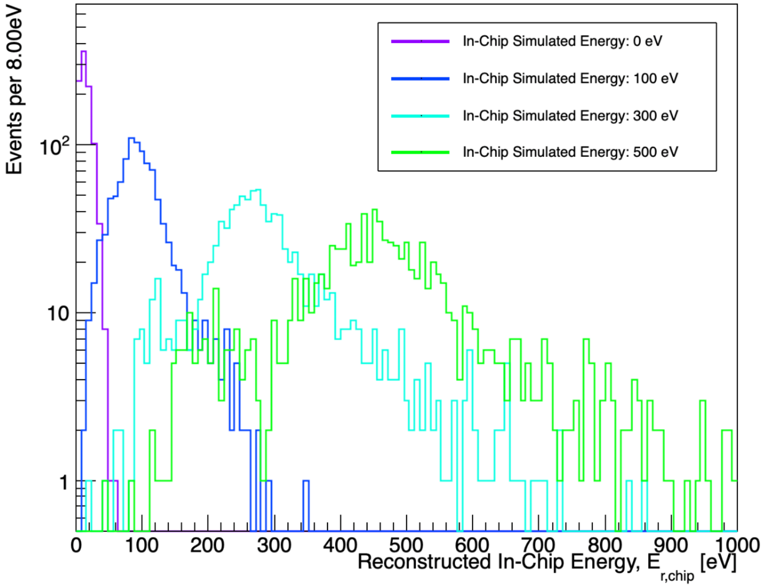


1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme
4. Determine the sensitivity of a single qubit

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate



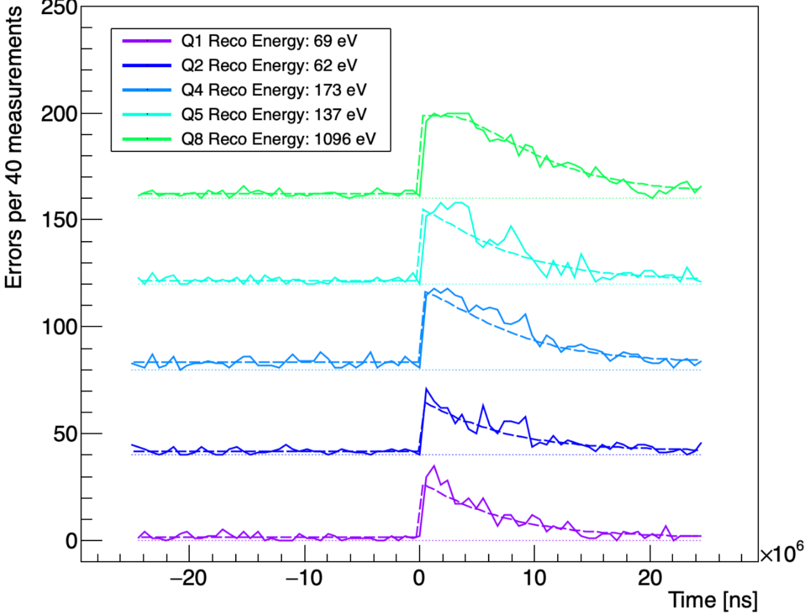
1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme
4. Determine the sensitivity of a single qubit
5. Determine the sensitivity of the whole chip

Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Modeling decoherence from scattering

Creating a full simulation chain to model the decoherence response of a qubit to energy-deposition in the substrate

Fit to data from Harrington et al, (2024) [arXiv:2402.03208]



1. Simulate phonon propagation in the chip, and determine phonon collection probability η_{ph} (G4CMP)
2. Model the quasiparticle population dynamics in the superconductor
3. Model the quantum state evolution and readout scheme
4. Determine the sensitivity of a single qubit
5. Determine the sensitivity of the chip
6. Test it with data (Harrington et al)

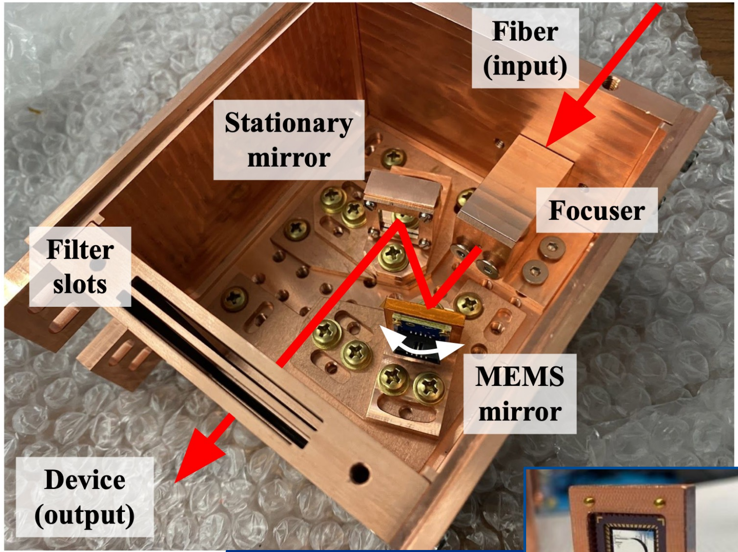
Linehan et al, "Estimating the Energy Threshold of Phonon-mediated Superconducting Qubit Detectors Operated in an Energy-Relaxation Sensing Scheme " (2024) [arXiv:2404.04423]

Cryogenic Optical Calibration

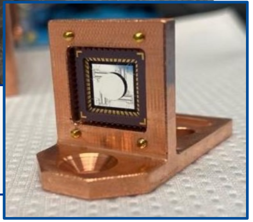
<u>Goal</u>: Design a modular calibration system that can thermalize to the MCP and steer a beam of single-photons repeatably and precisely over the surface of a device for characterization

MEMS mirror used to steer laser beam

- Capacitively controlled by DC bias lines
- No power dissipation while stationary
- Modified control lines to function at cryogenic temperatures (10mK)
- Large deflection angles (< ±5° = cm²)
- High deflection resolution (0.001°)
- High broadband reflectance



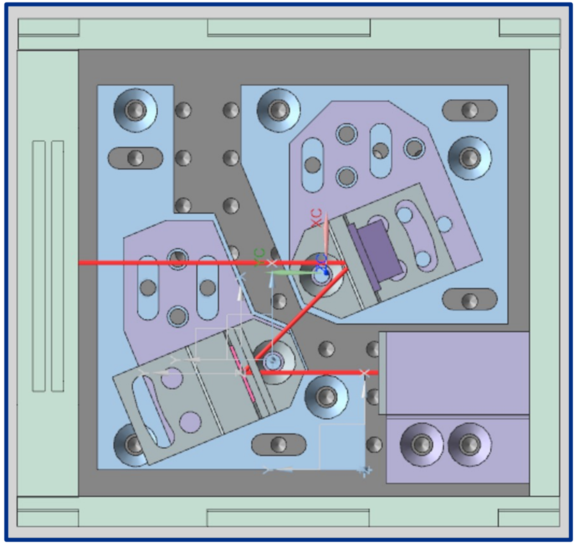
mirrorcle TECHNOLOGIES, INC.



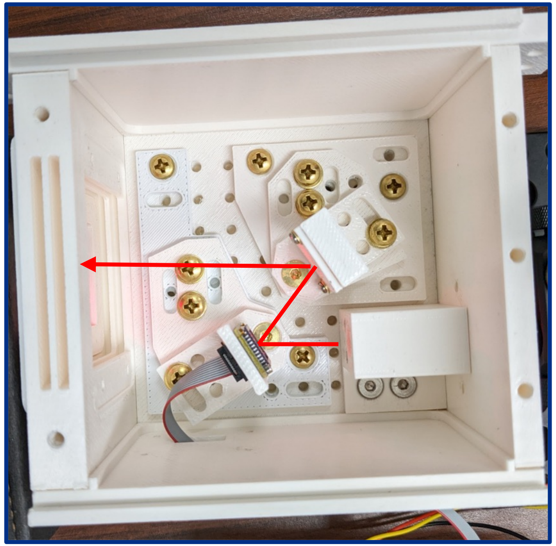
Stifter et al, "Cryogenic optical beam steering for superconducting device calibration" (2024) [arXiv:2405.02258]

Fermilab

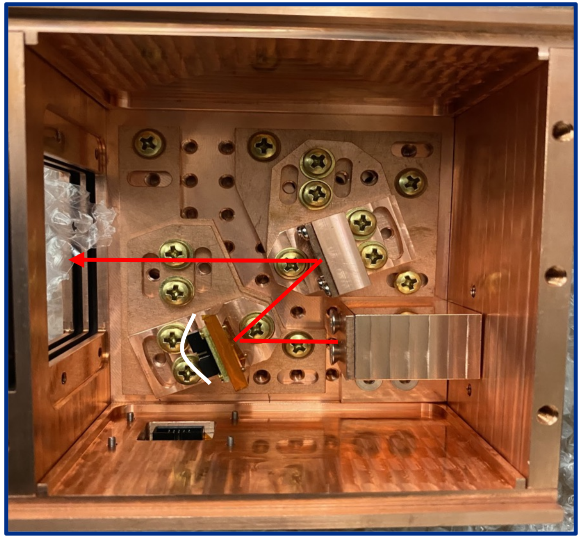
Cryogenic Optical Calibration



CAD model of enclosure
(March 2022)



3D print prototype
(April 2022)

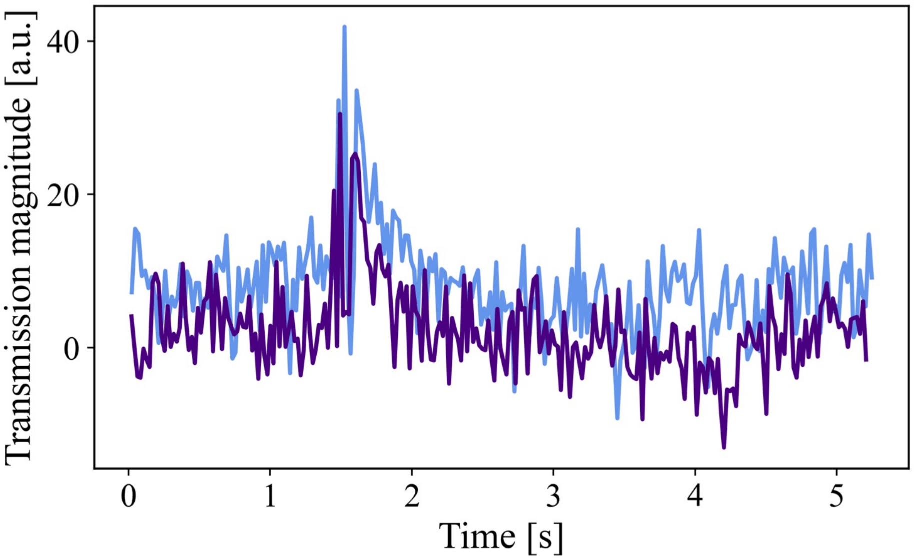


Copper enclosure
(June 2022)

Stifter et al, "Cryogenic optical beam steering for superconducting device calibration" (2024) [arXiv:2405.02258]

Fermilab

Cryogenic Optical Calibration



- Initial tests with MKID are successful!
- Scanning system does not significantly add power to the fridge
- Photon position is reproducible and precise (~100 microns)
- **Testing with transmon qubits is underway**

Stifter et al, "Cryogenic optical beam steering for superconducting device calibration" (2024) [arXiv:2405.02258]