Review of Low-Mass “WIMP” Direct Detection with Ionization Detectors

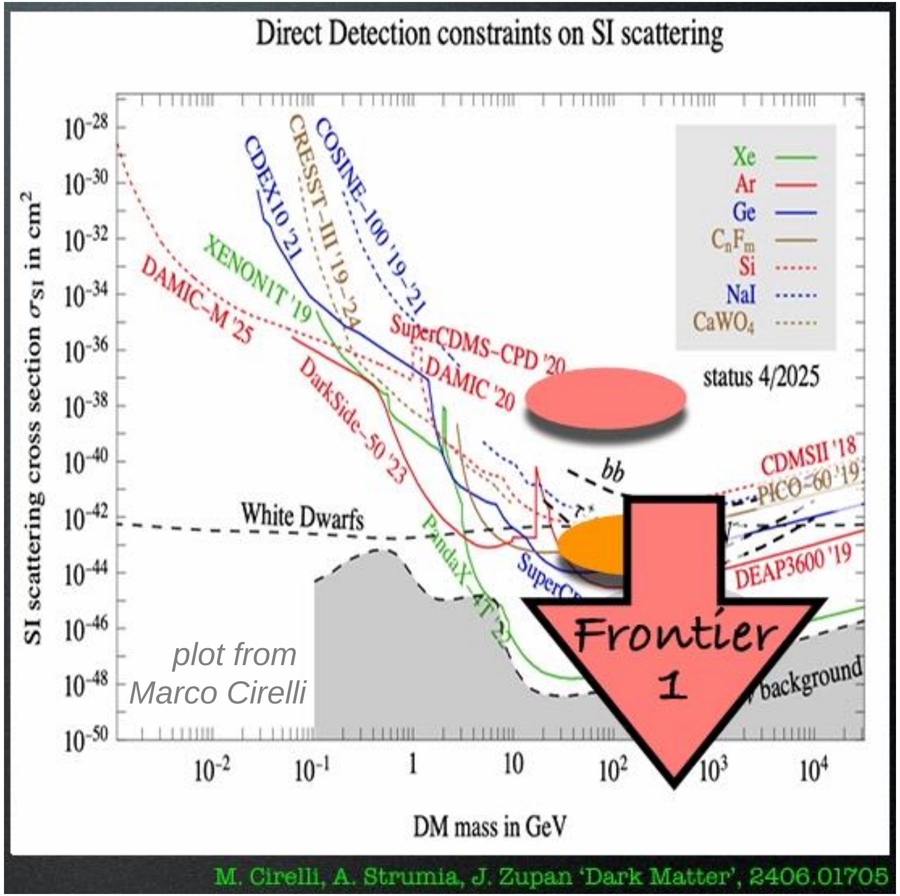
Daniel Baxter

Identification of Dark Matter (IDM 2026)

4 June 2024

Motivation

- Yesterday, multiple plenary speakers covered the more “traditional” searches **at** and **above** GeV mass
  - Marco called “Frontier 1”
- Those searches mostly rely on elastic scattering of DM off detector nuclei
  - Bigger = better!



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  - Marco called “Frontier 1”
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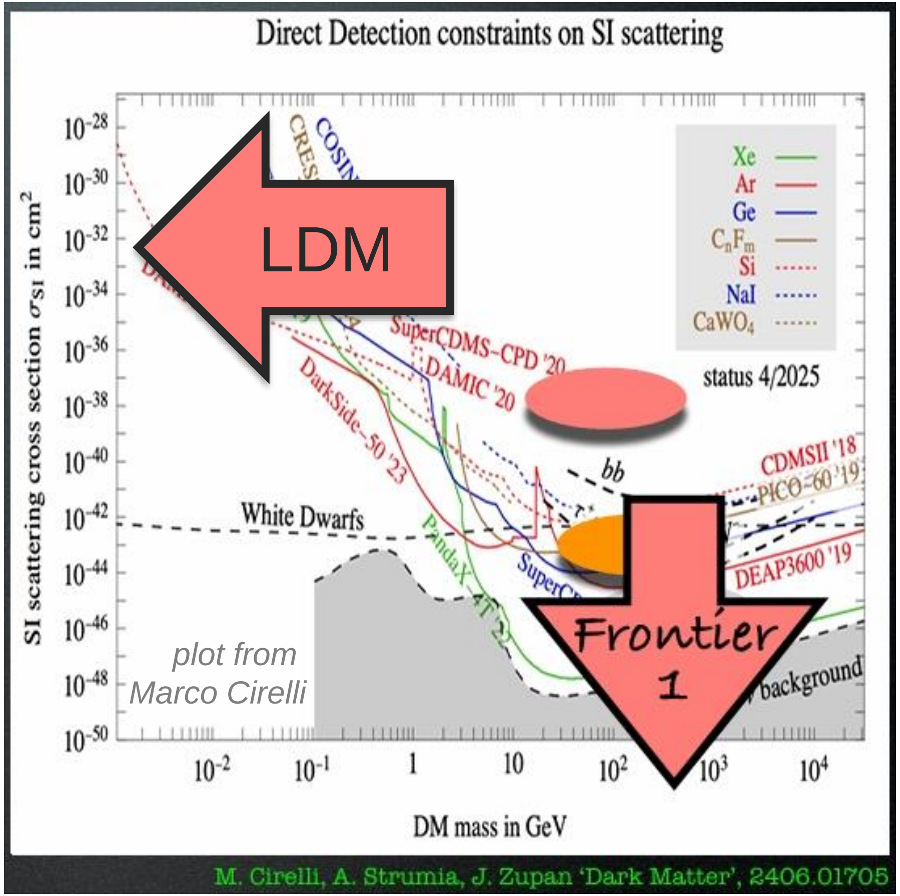
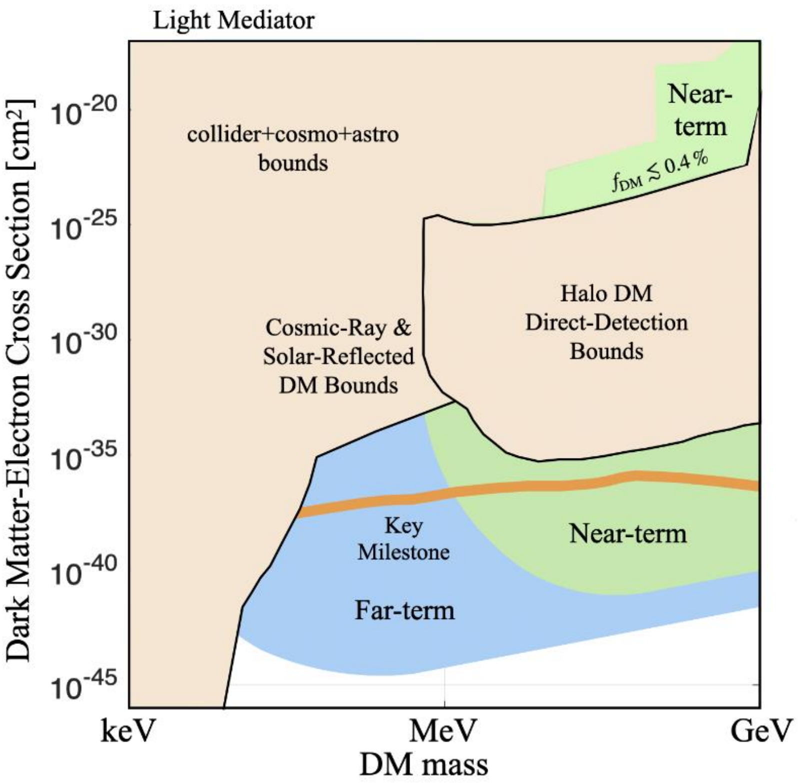
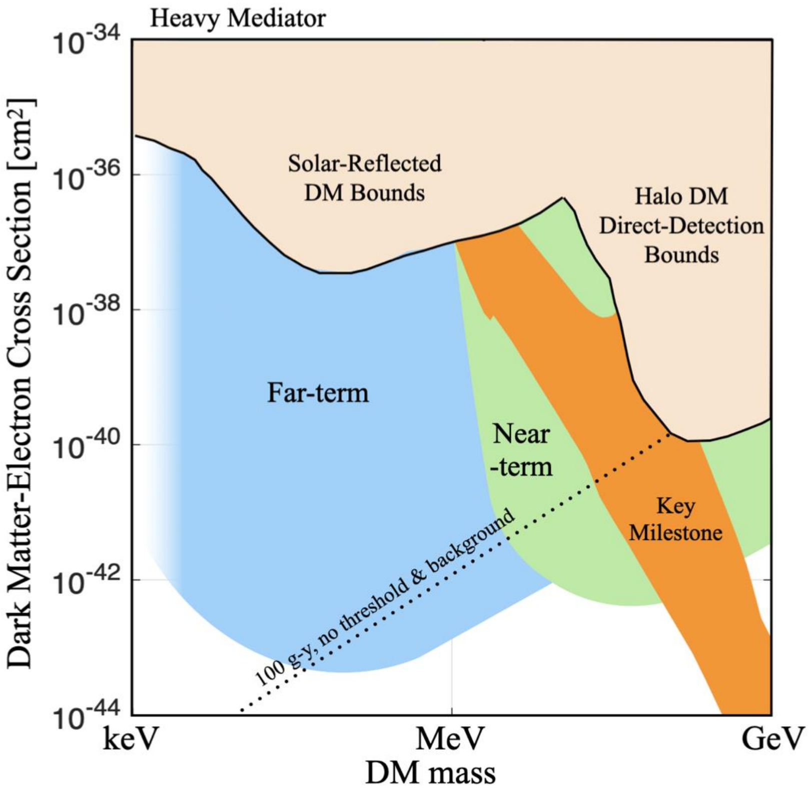
  - Bigger = better!
- Below the proton mass are very well-motivated models of dark matter



Low-Mass Dark Matter Detection

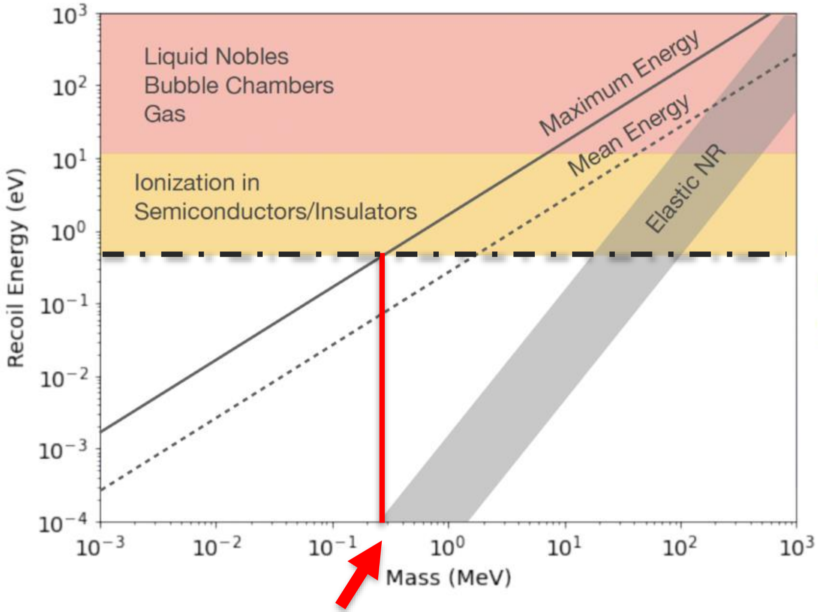




Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

Low-Mass Dark Matter Detection

Fig. adapted from 2203.08297



fundamental lower limit

$\Delta E \sim 1$ eV

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

Low-Mass Dark Matter Detection

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

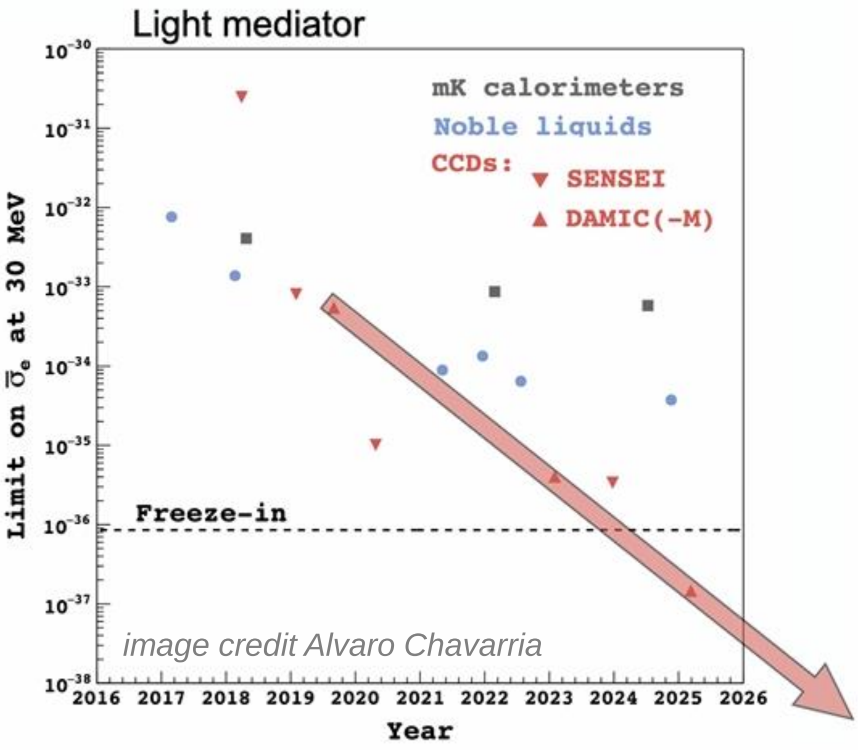


image credit Alvaro Chavarria

Fermilab

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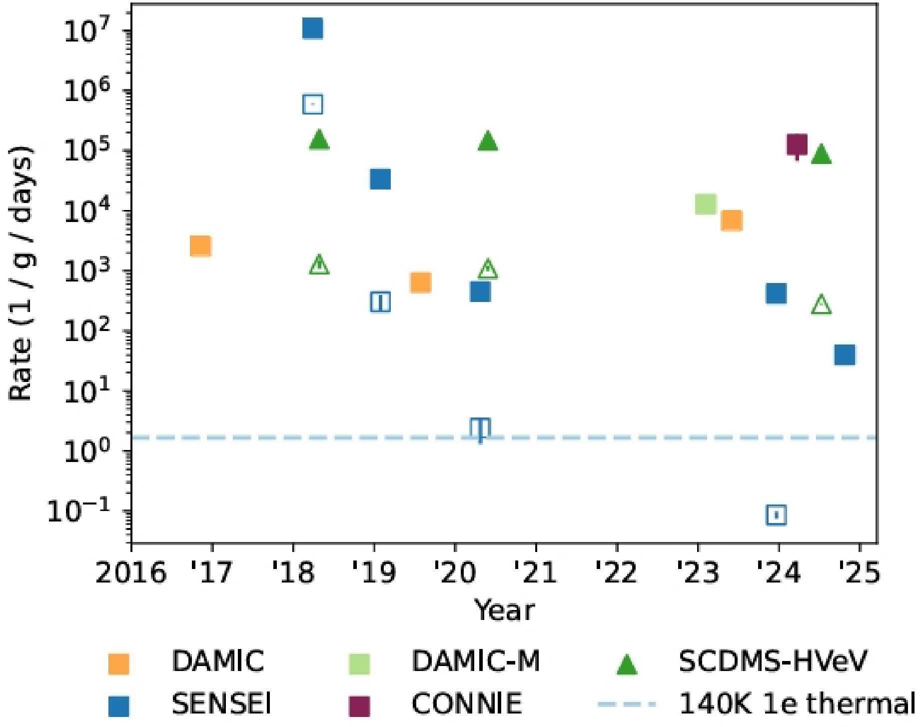
Single electron dark rates



Baxter et al, Ann. Rev. Nucl. Part. Sci. 75, 301 (2025) [arXiv:2503.08859]

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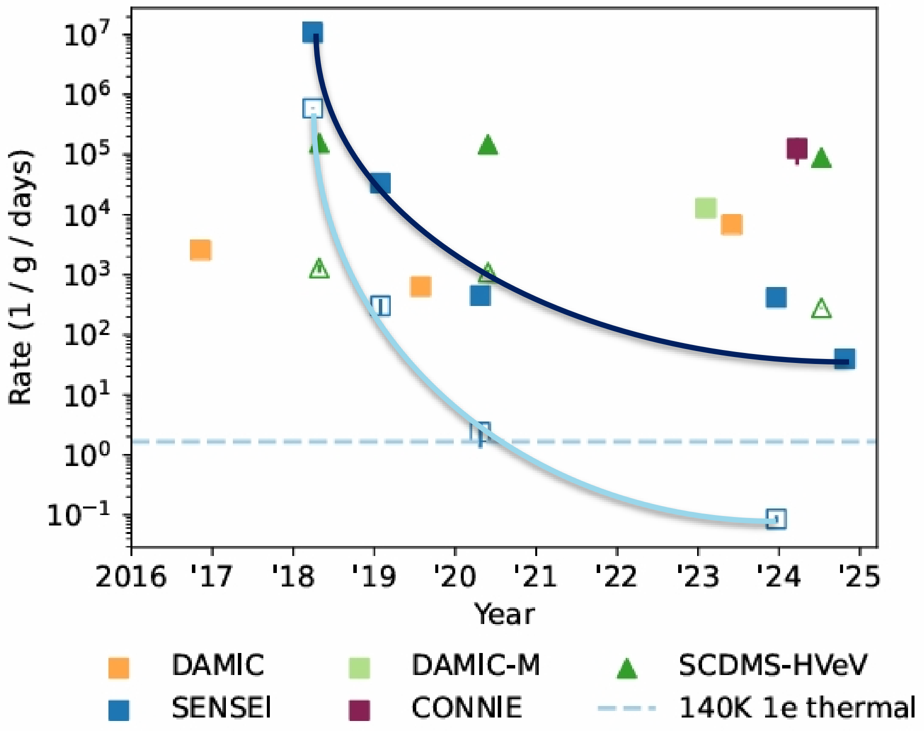

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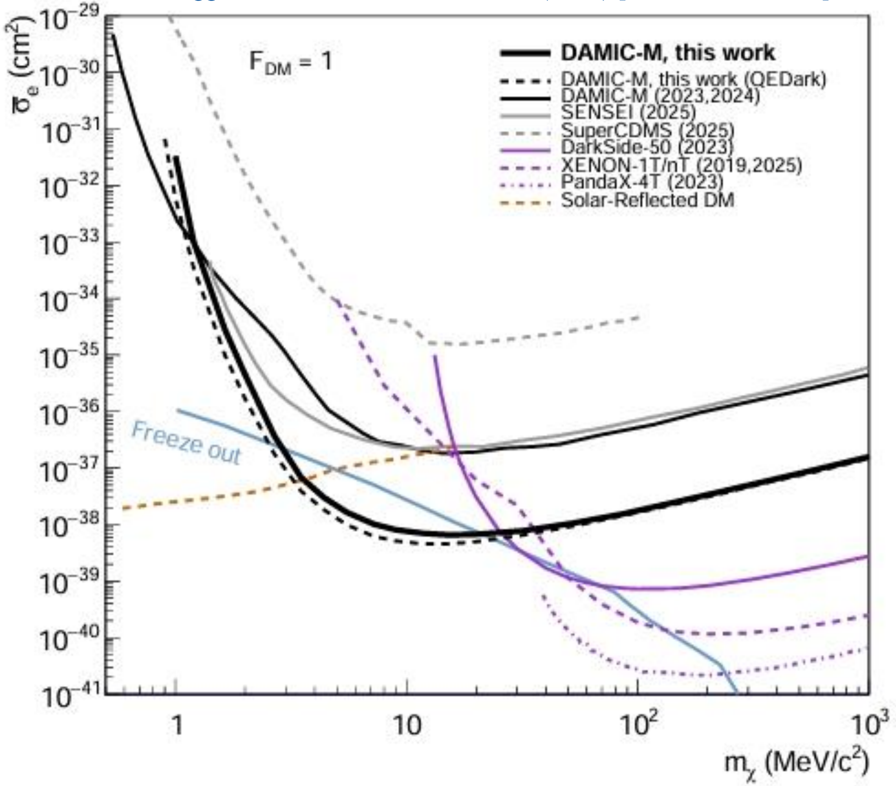
Detectors Searching for Ionization

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

Aggarwal et al, PRL 135, 071002 (2025) [arXiv:2503.14617]



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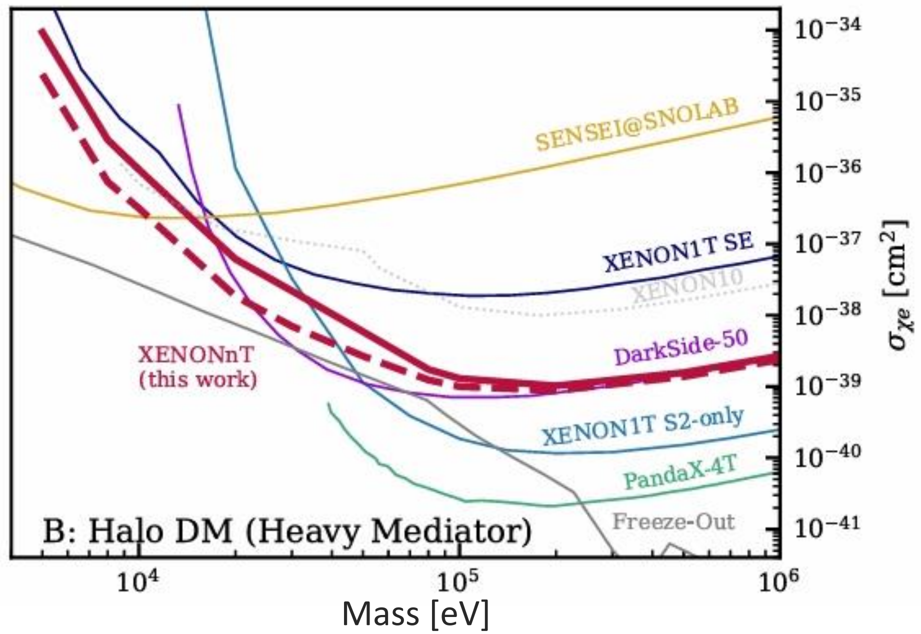
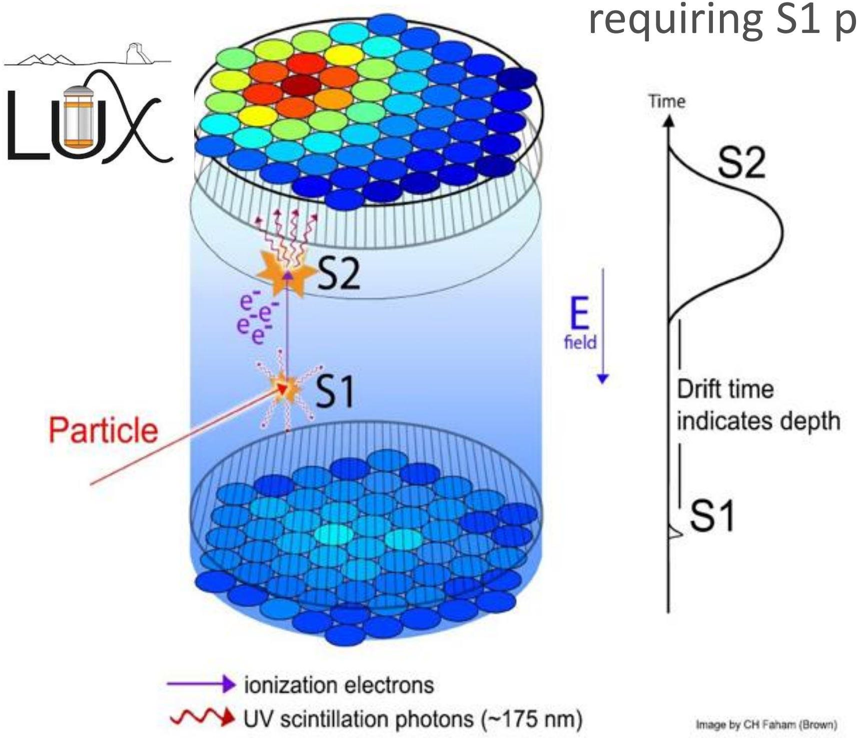
Aprile et al, PRL 134, 161004 (2025) [arXiv:2411.15289]

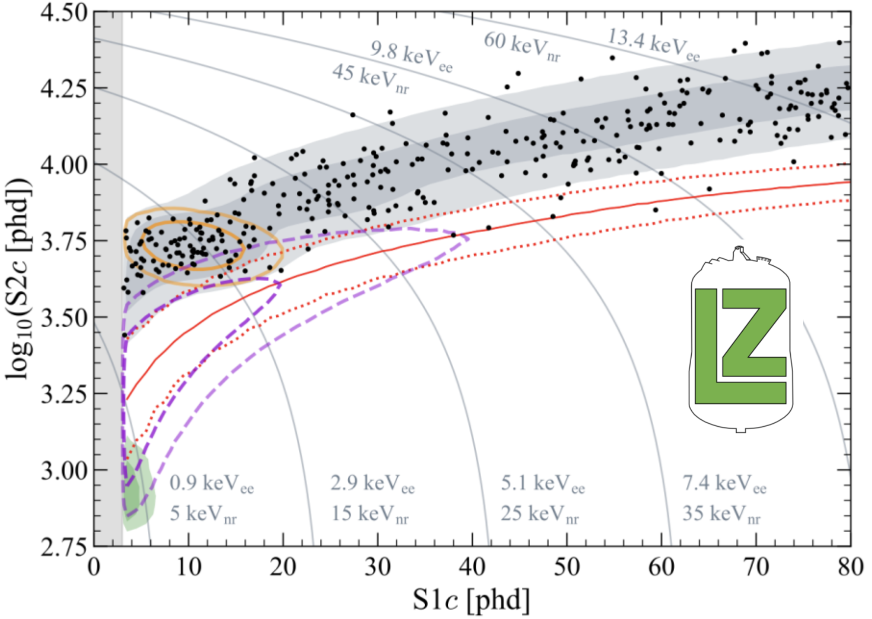


S2-only searches

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



see Wed. plenary from Rick Gaitskell on LXeTPCs



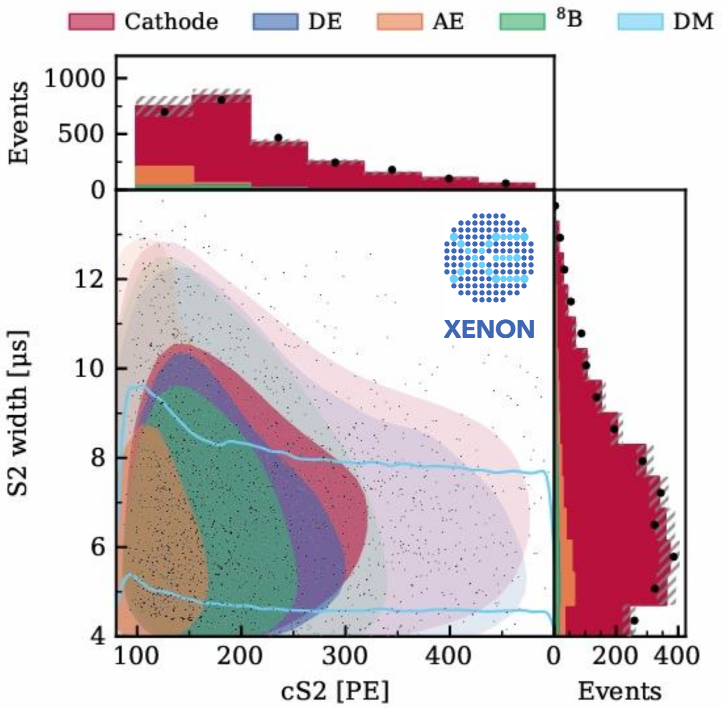
Aalbers et al, PRL 131, 041002 (2023) [arXiv:2207.03764]

S2-only searches

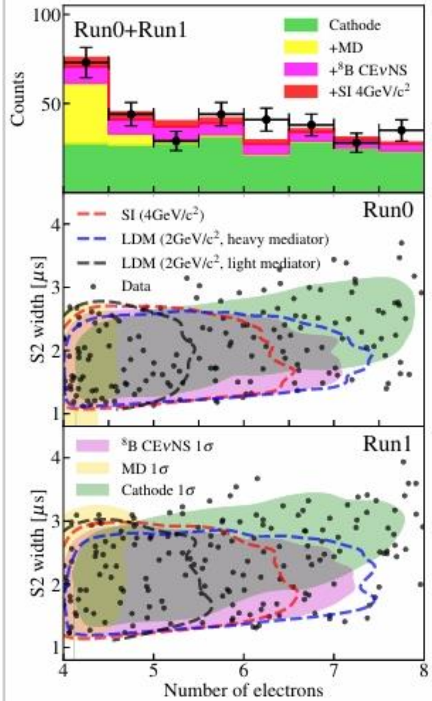
Pros:
[massive exposures](), [1-10 mdru modeled backgrounds](), XY position resolution, timing

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

Aprile et al, (2026) [arXiv:2601.11296]



PandaX-4T



see Tues. talks from Maxime Pierre and Xiaopeng Zhou, and Wed. talk from Ying-Ting Lin

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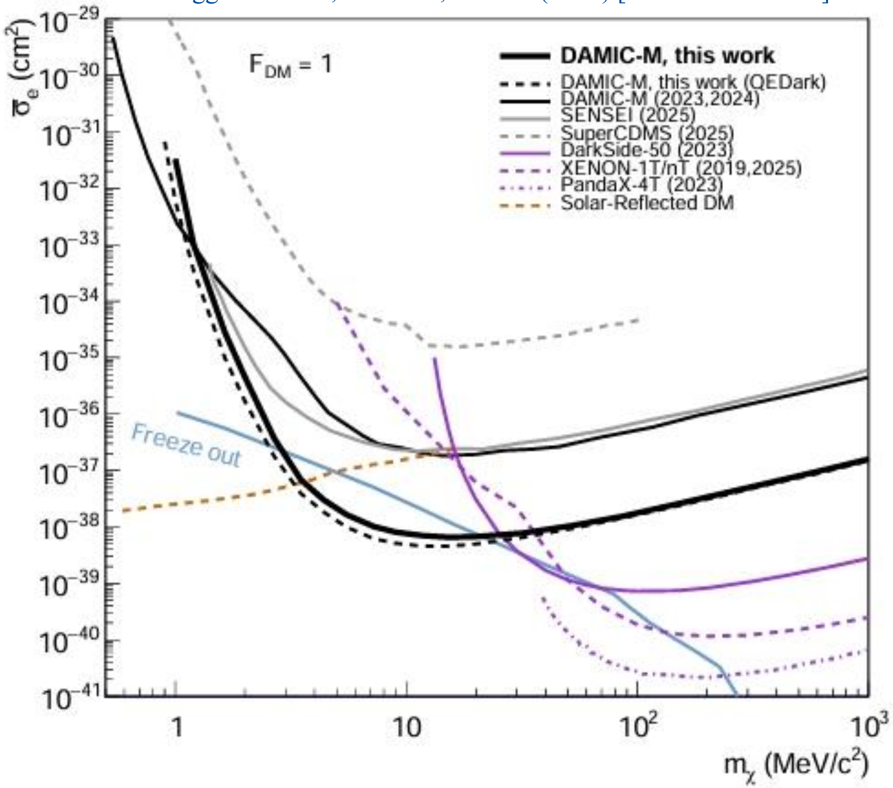
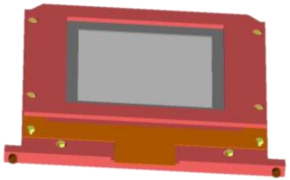
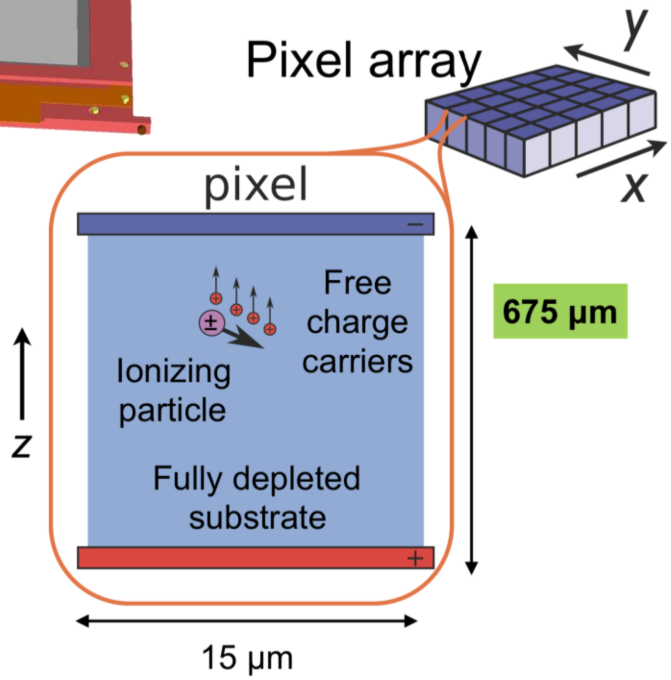


The CCD Program





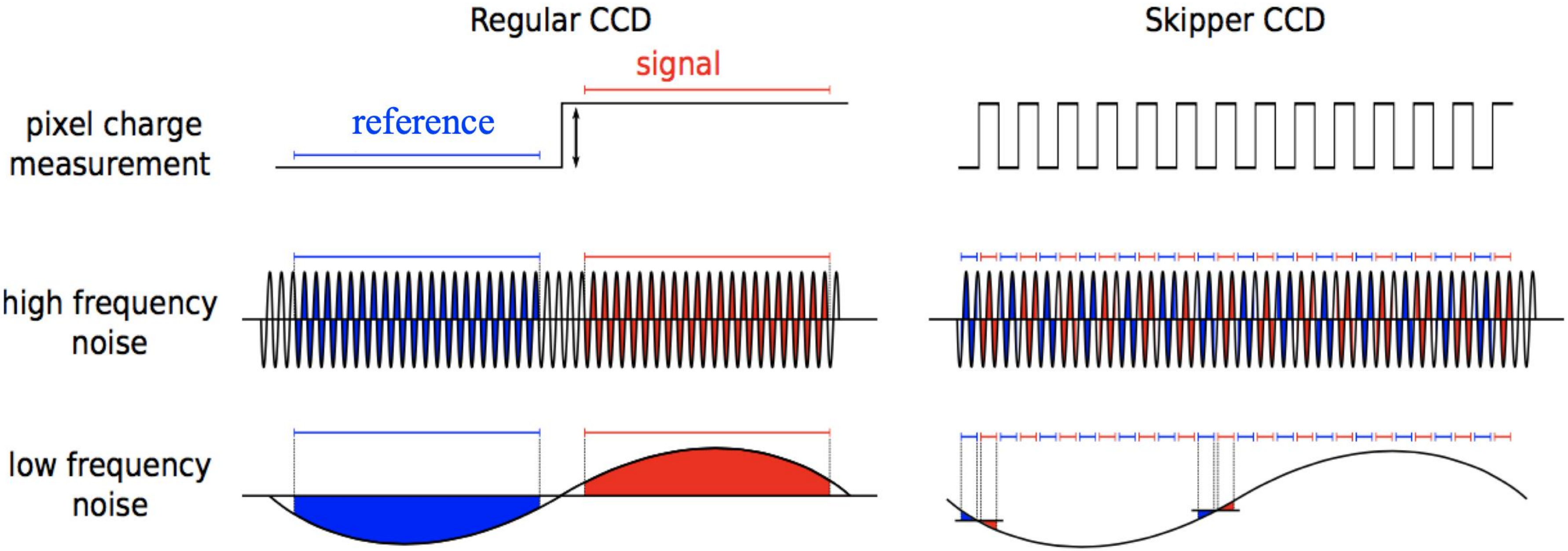
Interaction with silicon produces free charge carriers…

- …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

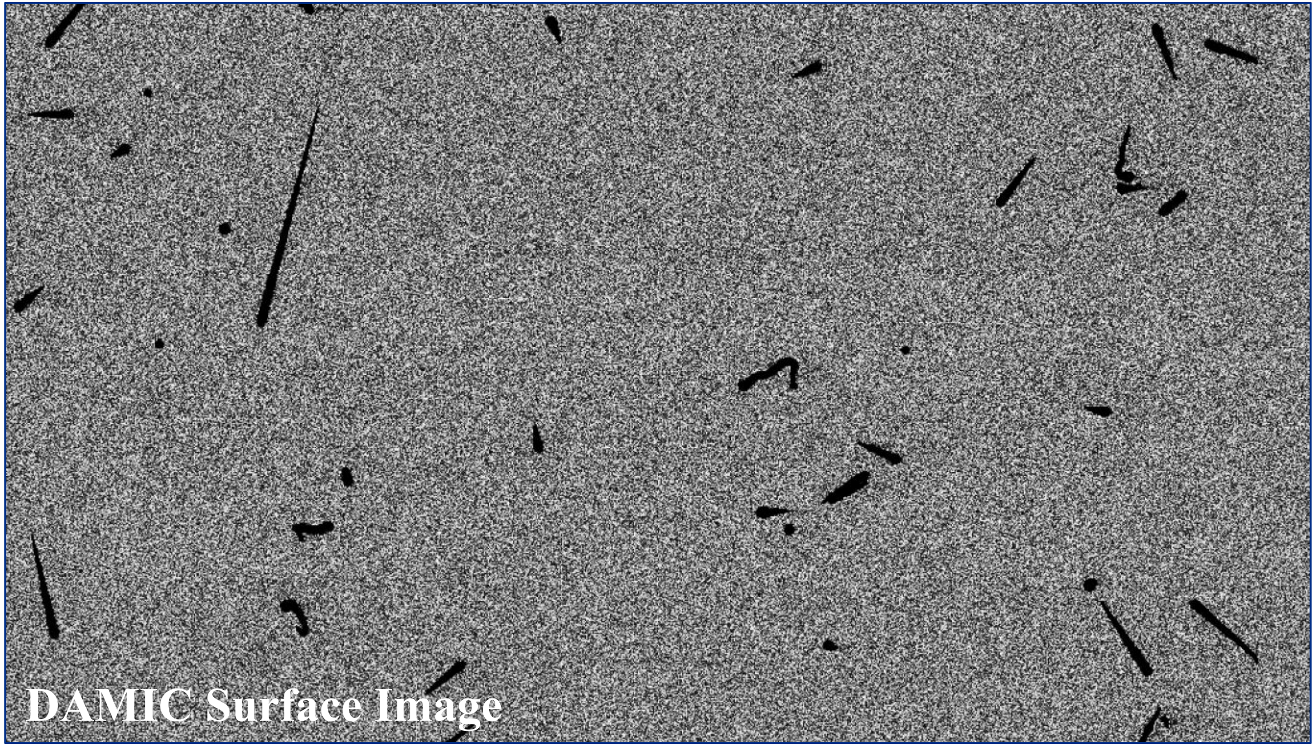
The CCD Program – Skipper Amplifiers

Skipper Amplifiers: allow repeated, non-destructive readout



Tiffenberg et al, PRL 119, 131802 (2017) [arXiv:1706.00028]

The CCD Program – DAMIC



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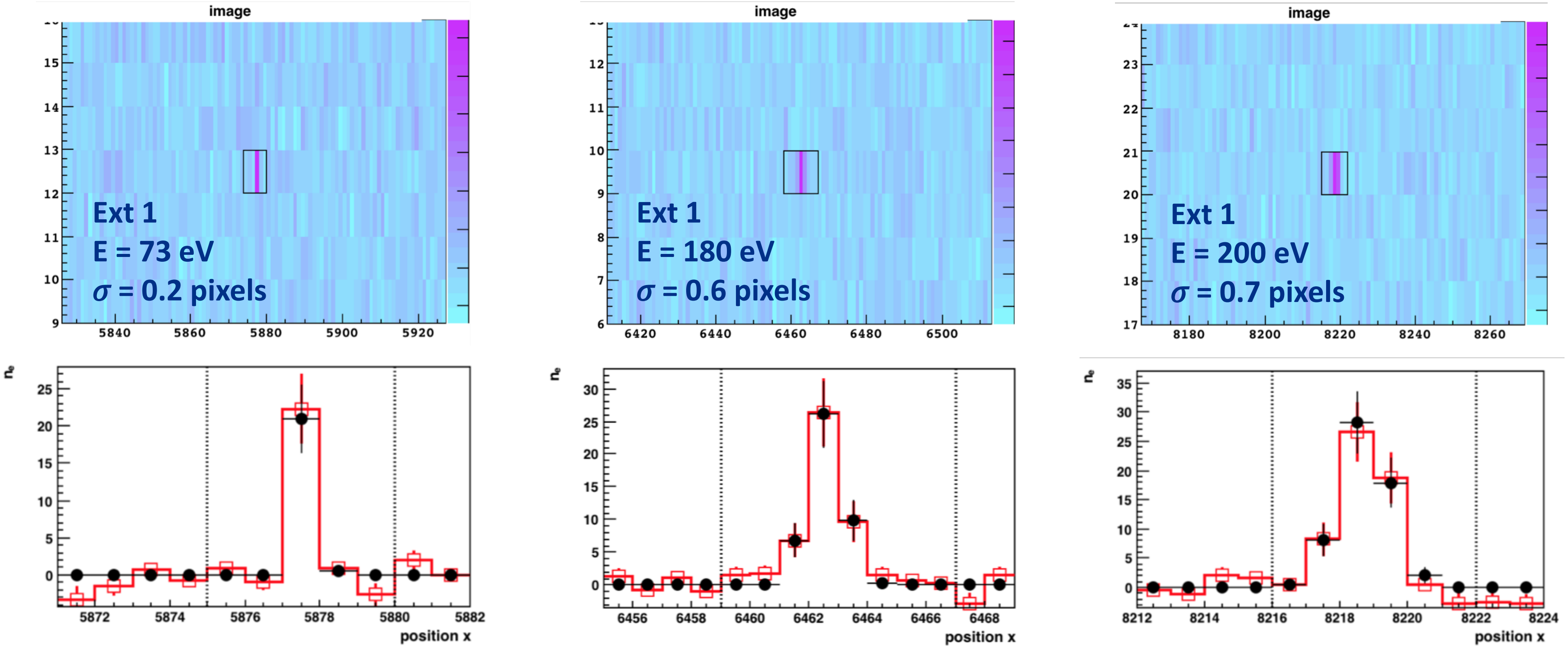

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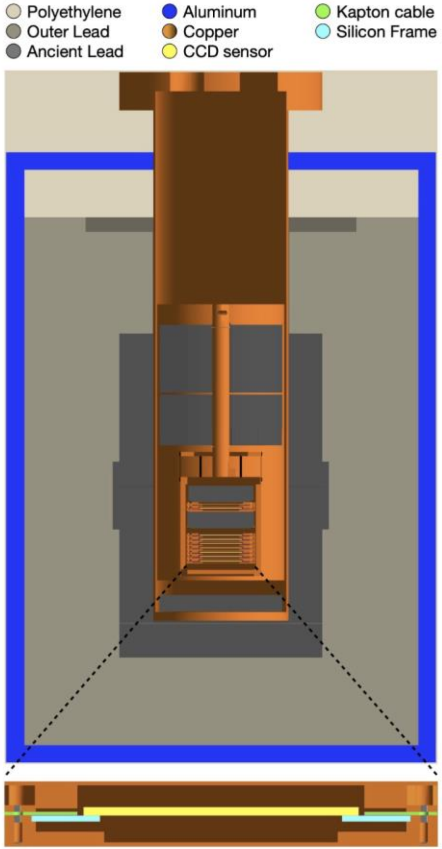
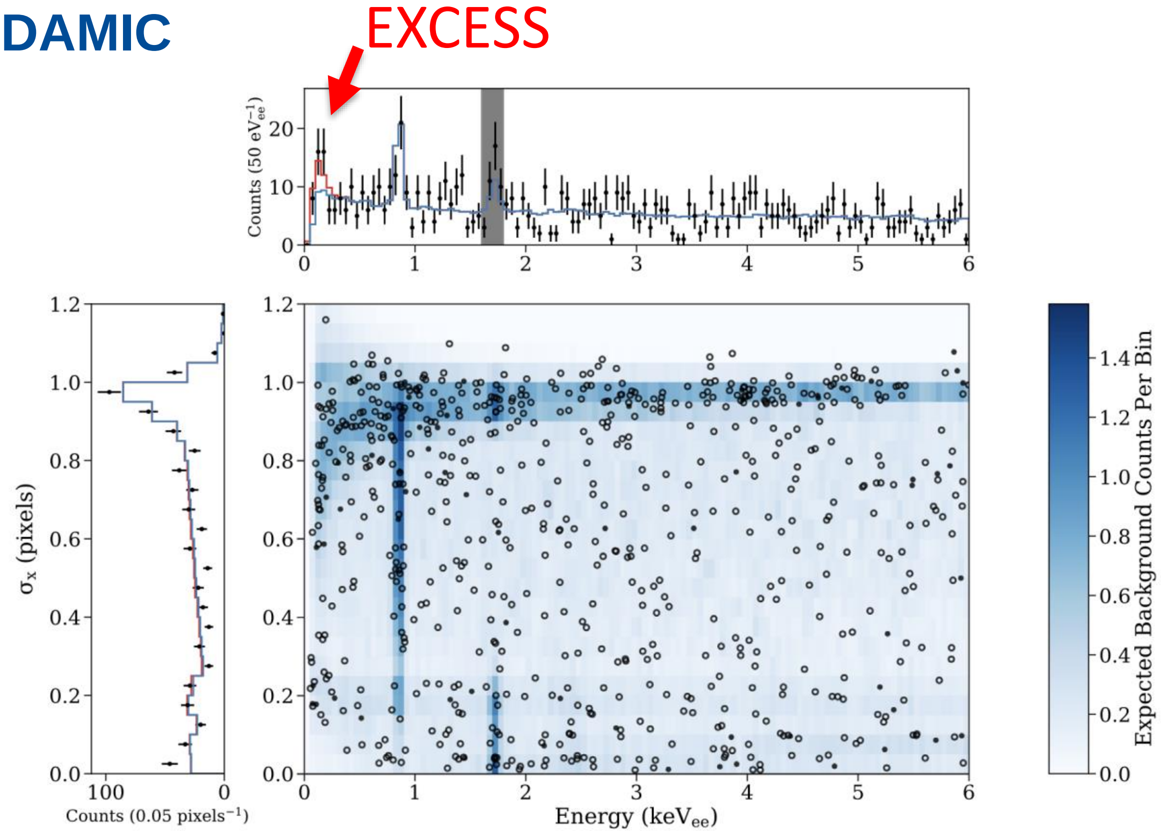
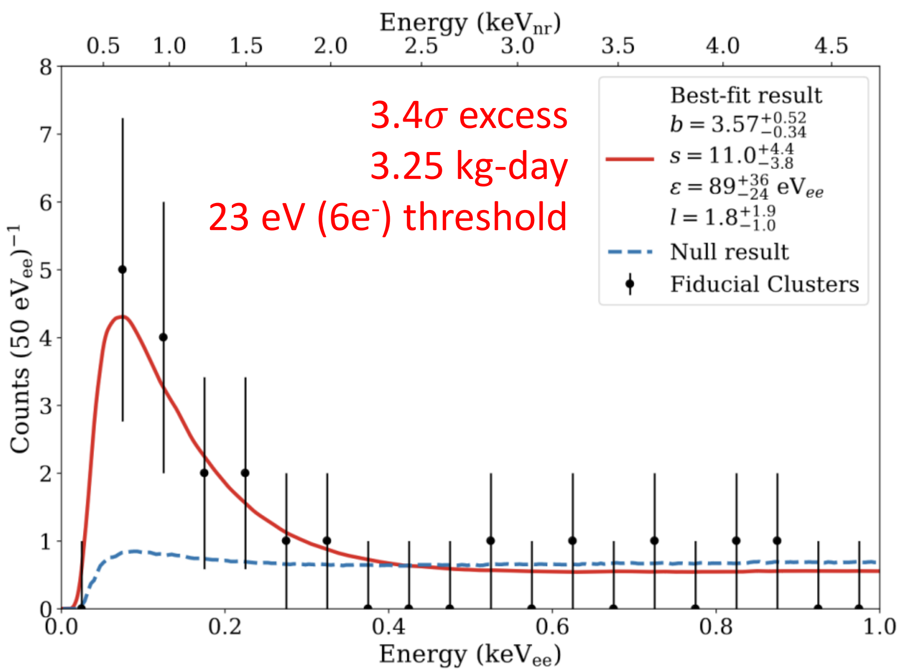


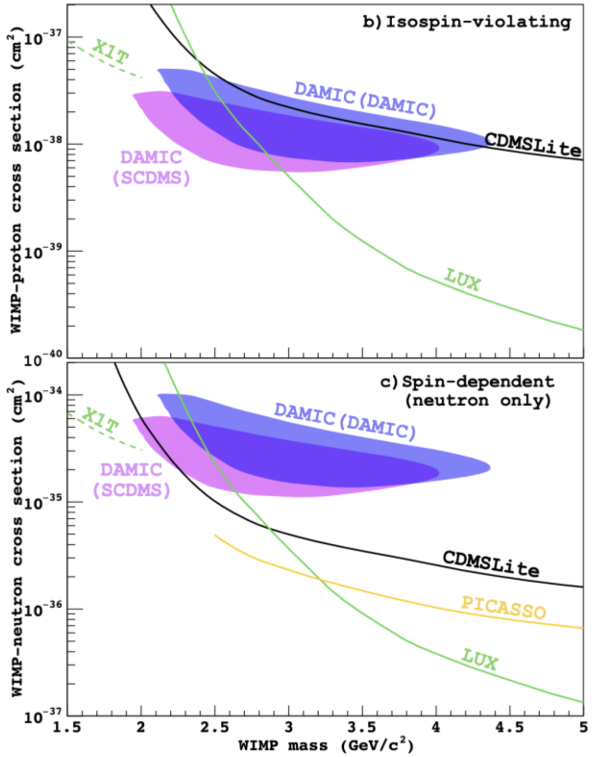


A. Aguilar-Arevalo et al. PRD 105, 062003 (2022) [arXiv:2110.13133]

The CCD Program – DAMIC (20g; 6e threshold)

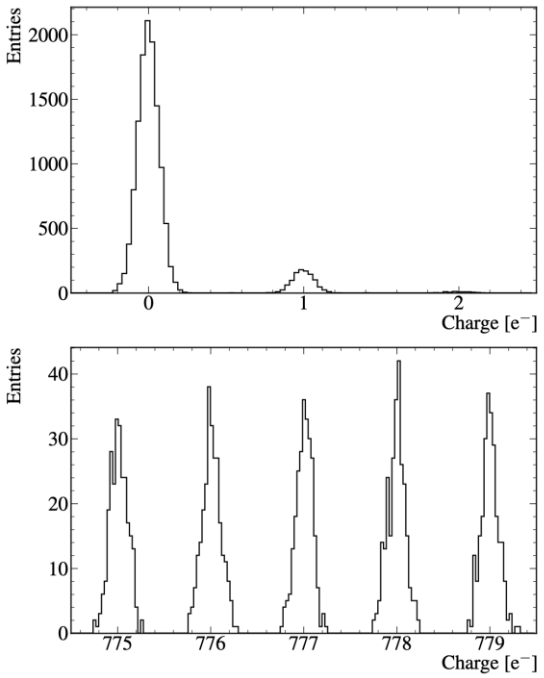


Aguilar-Arevalo et al, PRD 109, 062007 (2024) [arXiv:2306.01717]



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

The CCD Program – SENSEI (40g; 1-2e threshold)



Tiffenberg et al, PRL 119, 131802 (2017) [arXiv:1706.00028]
and Adari et al, PRL 134, 011804 (2025) [arXiv:2312.13342]

see Tues. talk from Ansh Desai

- Record silicon dark rates of 1.4 x 10^{-5} e^-/pix/day
- New limits on MeV-scale DM scattering

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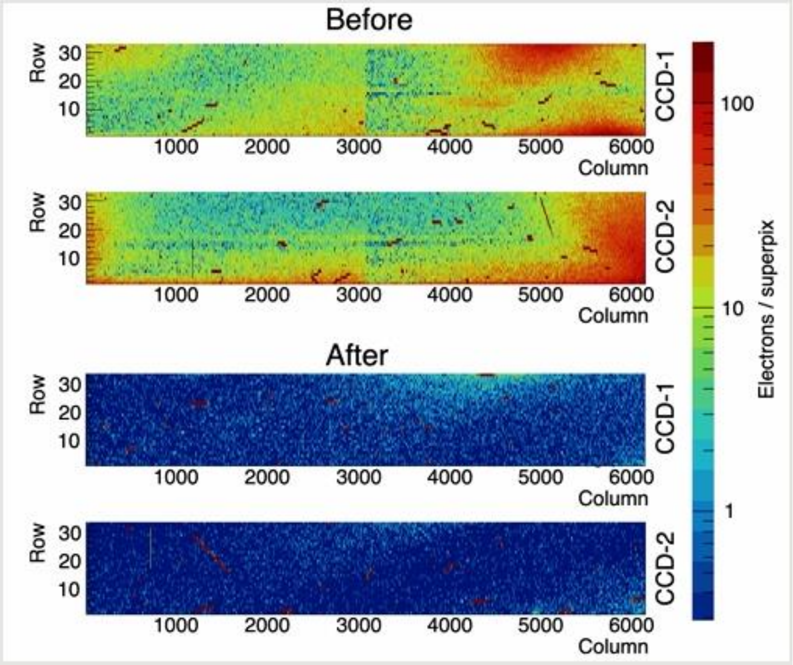

Bloch et al, PRL 134, 161002 (2025) [arXiv:2410.18716]

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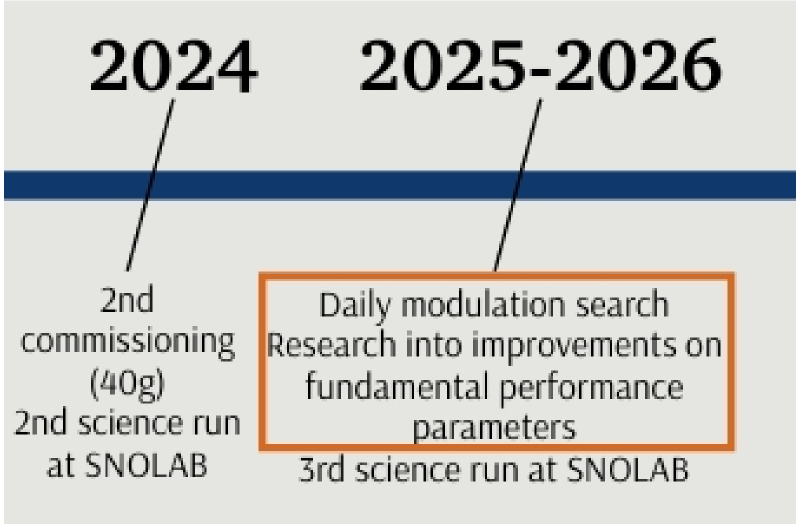
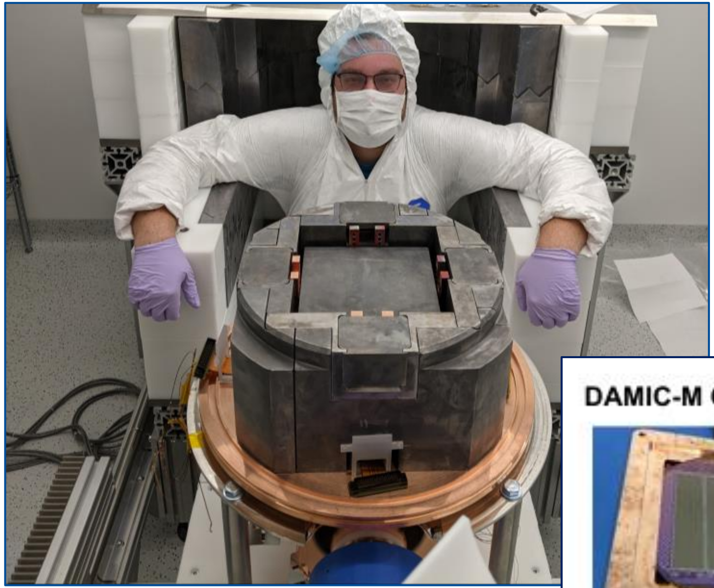


see Tues. talk from Ansh Desai

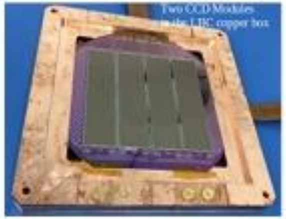
Fermilab

The CCD Program – DAMIC-M LBC (26g; 1-3e threshold)

LBC Demonstrator (taking data since 2022)



DAMIC-M CCD module



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

see Tues. talk from Nuria Castello-Mor

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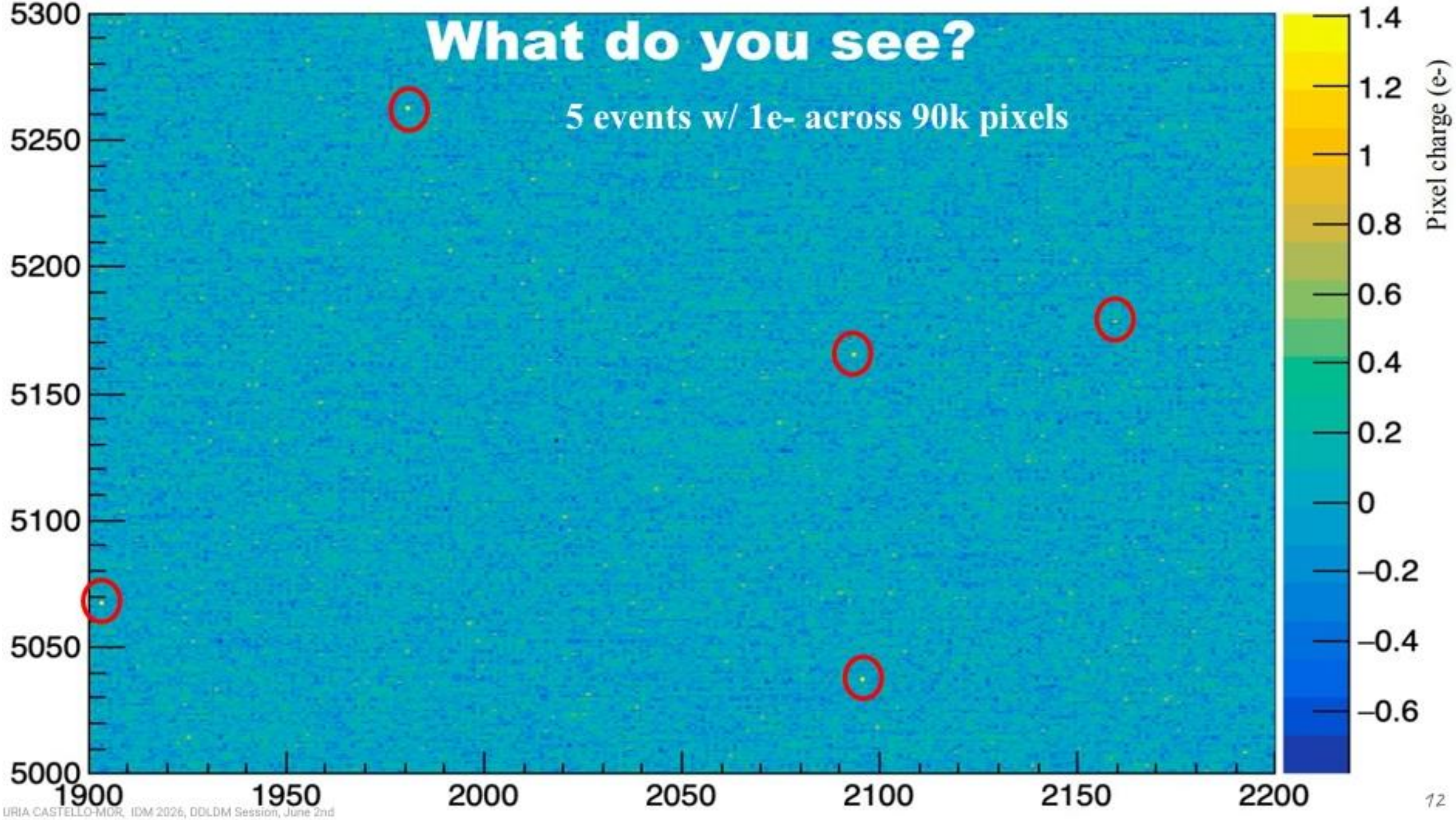
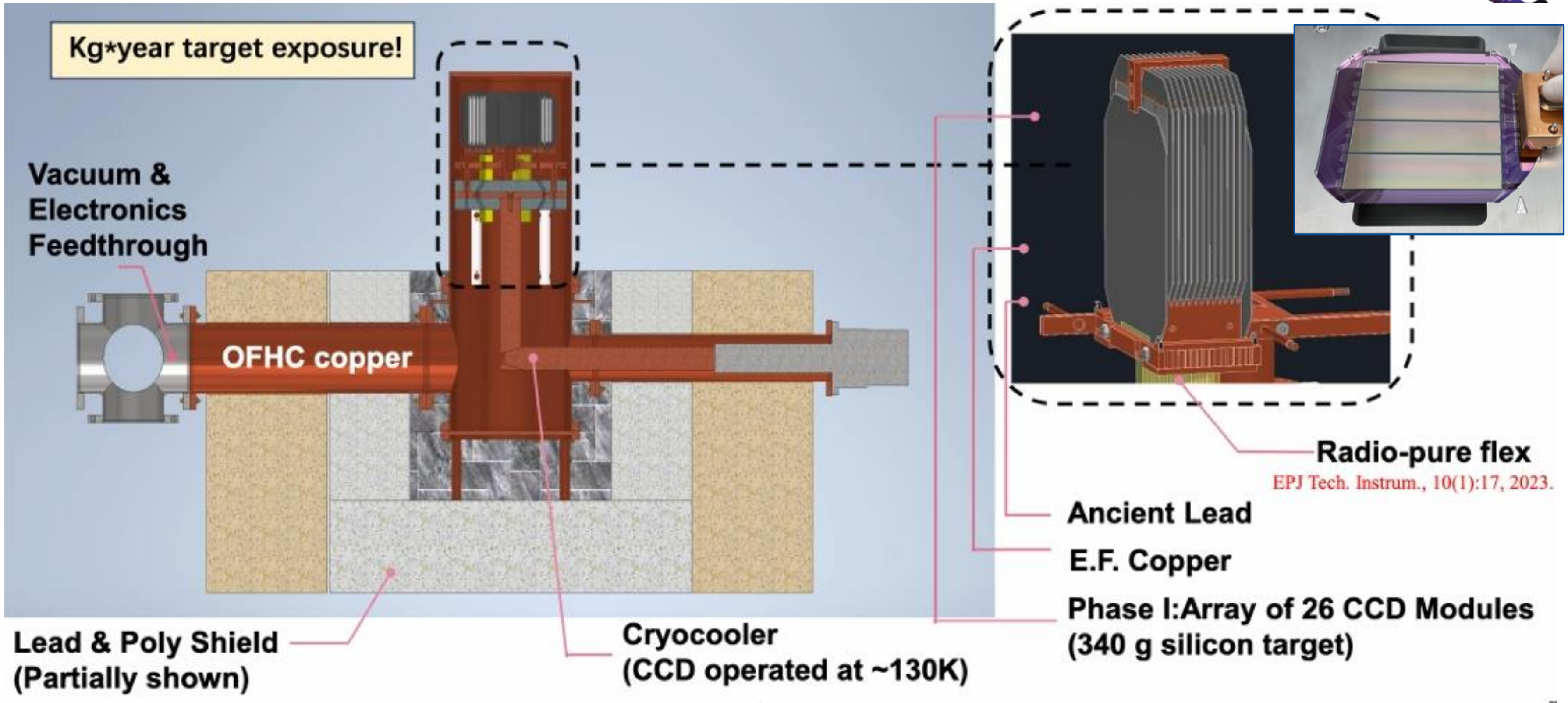


see Tues. talk from Nuria Castello-Mor

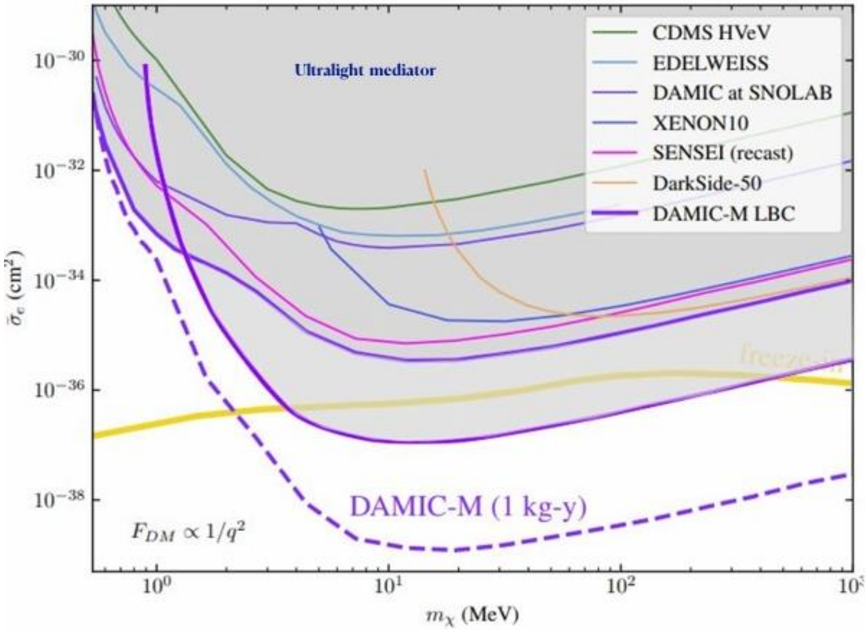
The CCD Program – DAMIC-M (~250g; 1e threshold)



see Tues. talk from Rocio Vilar

The CCD Program – DAMIC-M (~250g; 1e threshold)

- Installation happening this summer, with commissioning first data by end of 2026.



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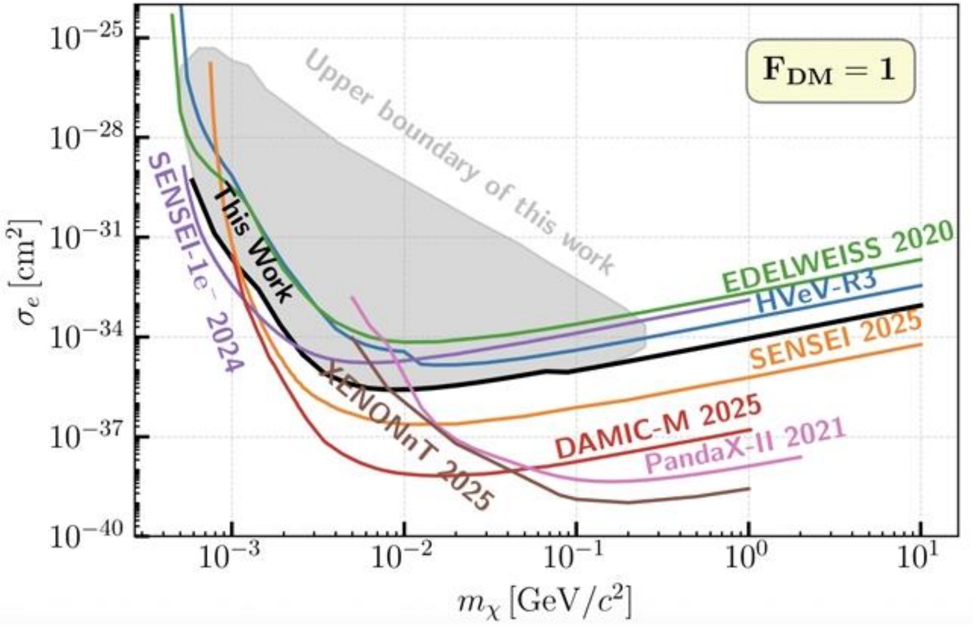
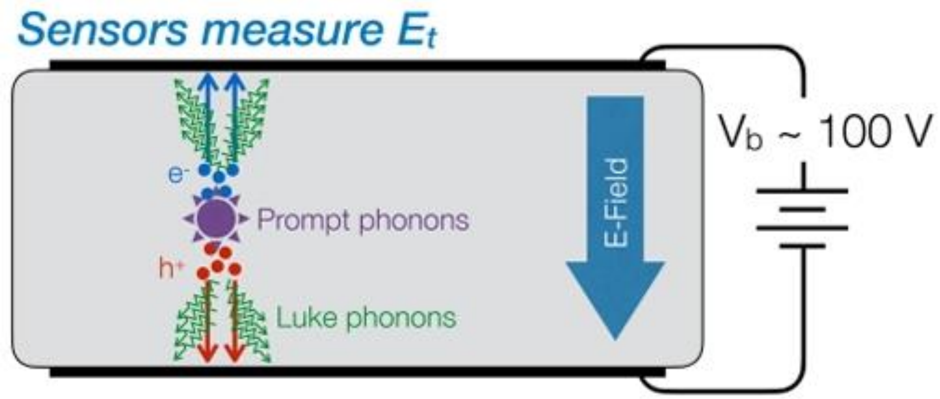
Albakry et al, PRD 113, 032001 (2026) [arXiv:2509.03608]

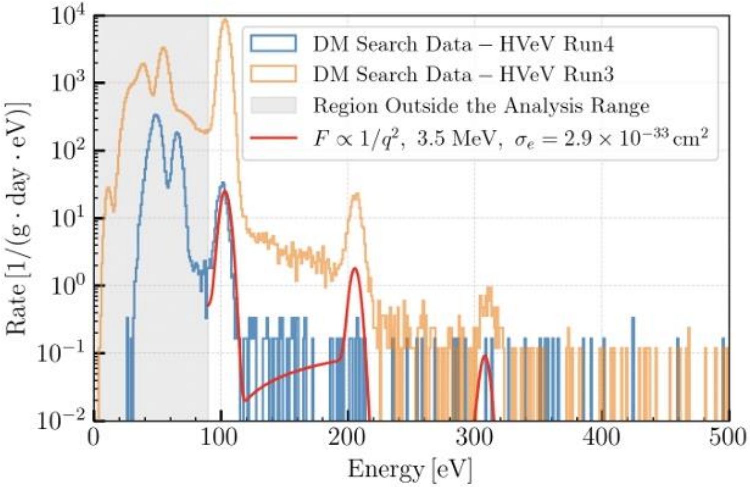


NTL-Amplification – Neganov-Trofimov-Luke Effect

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



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



Albakry et al, PRD 113, 032001 (2026) [arXiv:2509.03608]

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

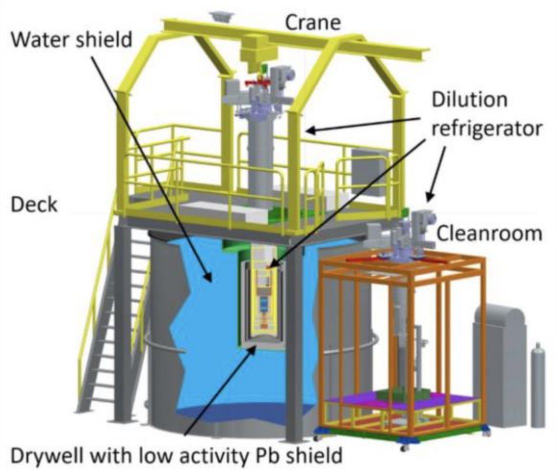
Cons: large dark rates, limited position information, no event-by-event discrimination

see Mon. talk from Aditi Pradeep, Wed. talk from Aviv Simchony, and see Wed. plenary from Belina von Krosigk for more information on SuperCDMS

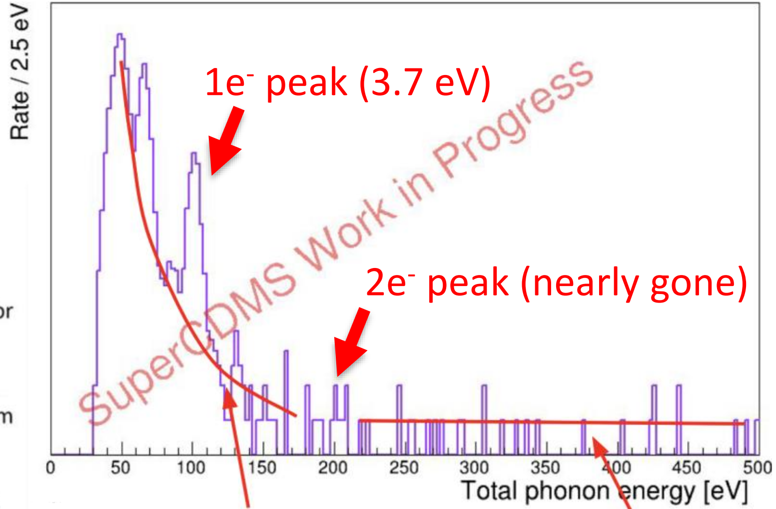
NTL-Amplification – SuperCDMS HVeV

images borrowed from Emanuele Michielin's talk at EXCESS24

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



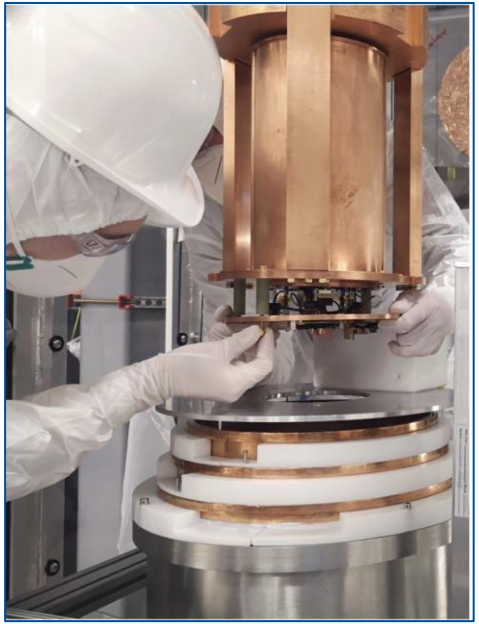
CDMS HVeV Run 4 at NEXUS



LEE increase

Origin of these events?

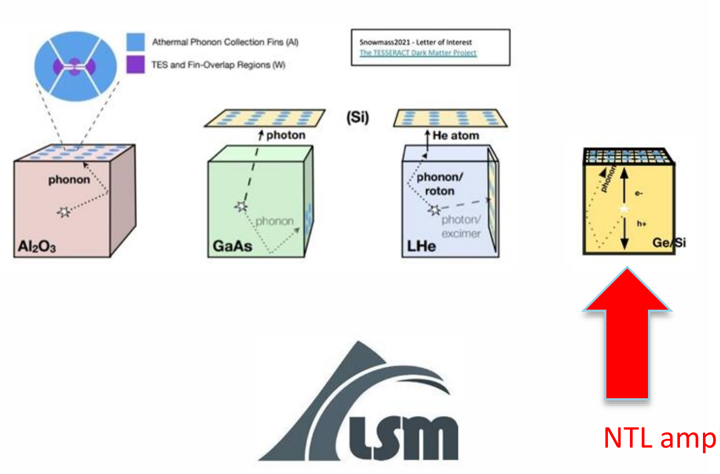
Detectors installed at CUTE



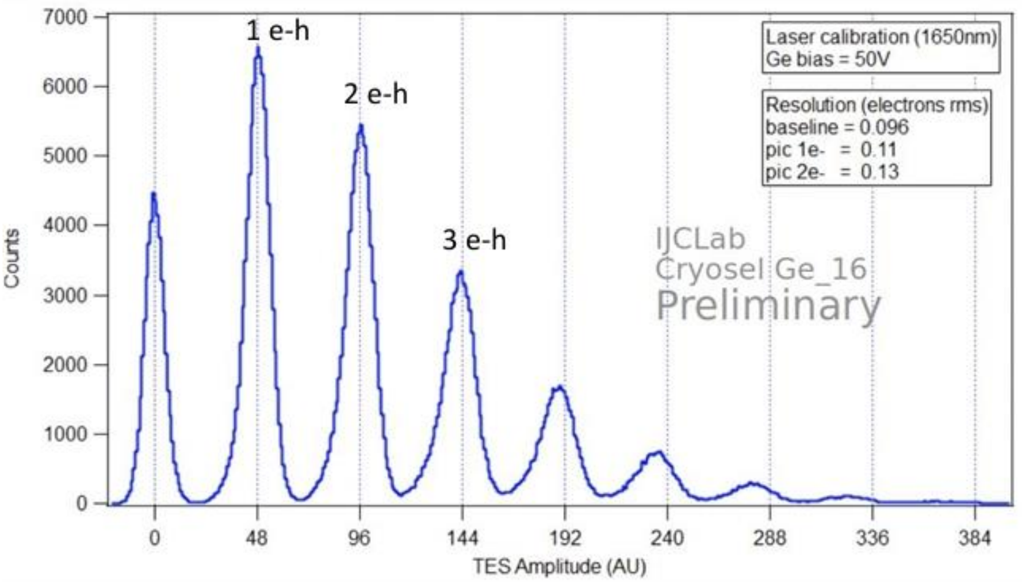
see Thurs. talk from Kyle Kennard for update!

NTL-Amplification – TESSERACT

- First demonstration of single-electron resolution with NTL in a massive (40g) Ge crystal!



NTL amplification



see Wed. talk from Juliette Blé and Thurs. talk from Dan McKinsey

Fermilab

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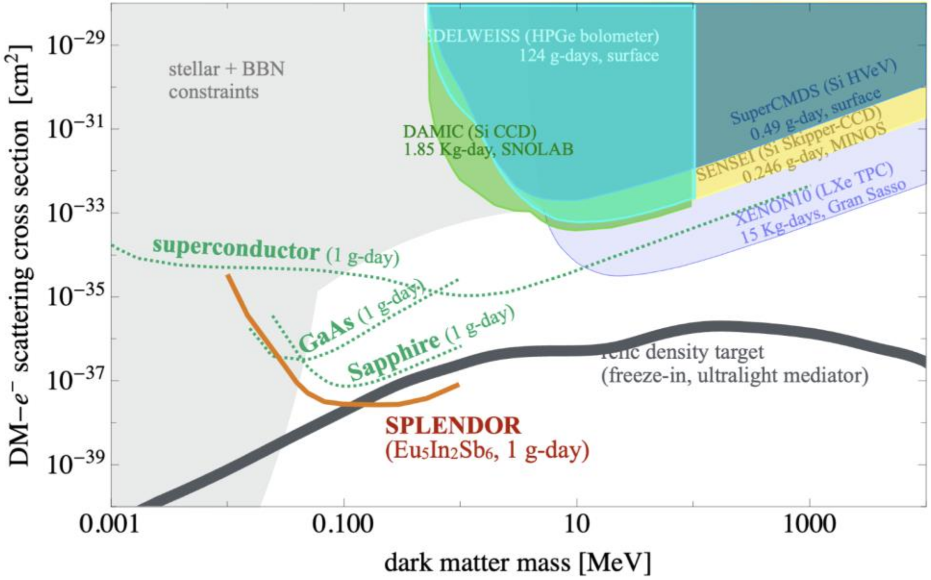
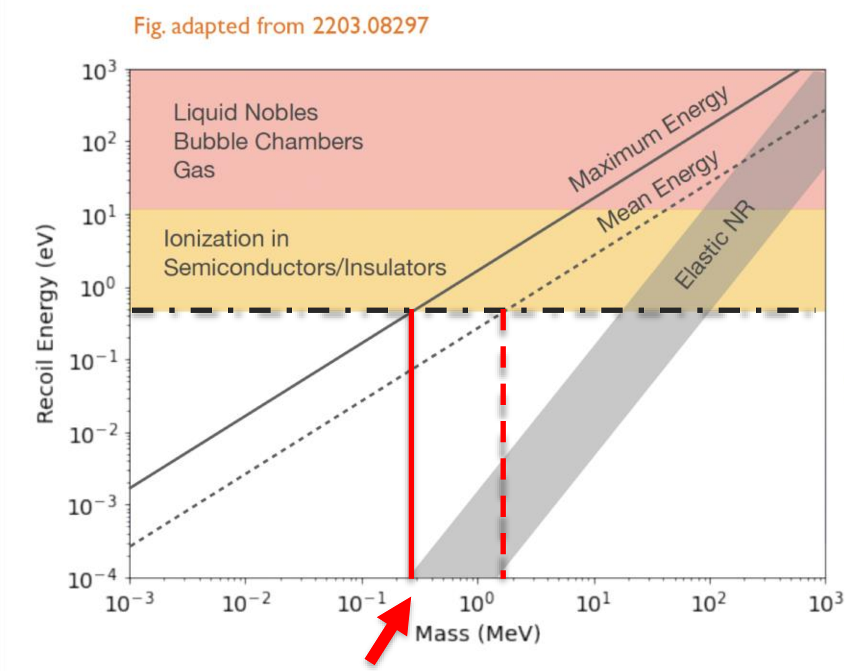
image borrowed from Sam Watkins (as Caleb Fink)'s IDM2024 talk

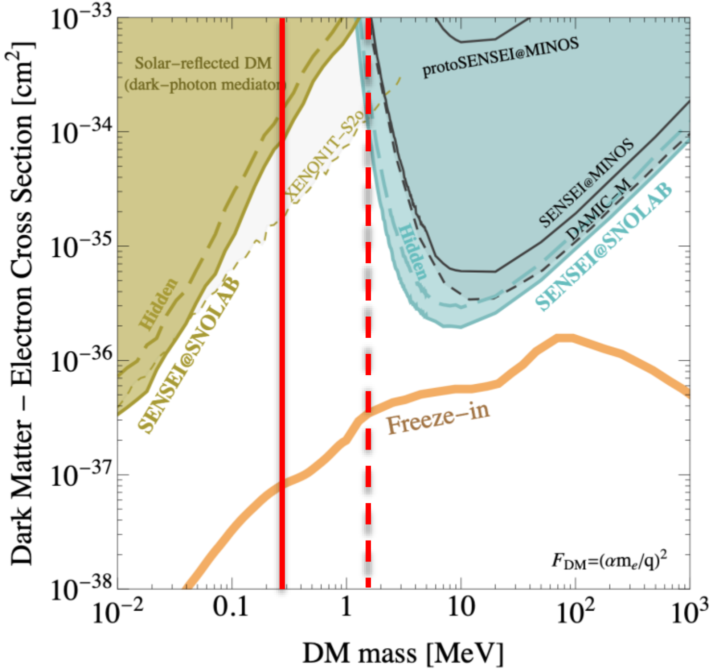


Low-Mass Dark Matter Detection

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



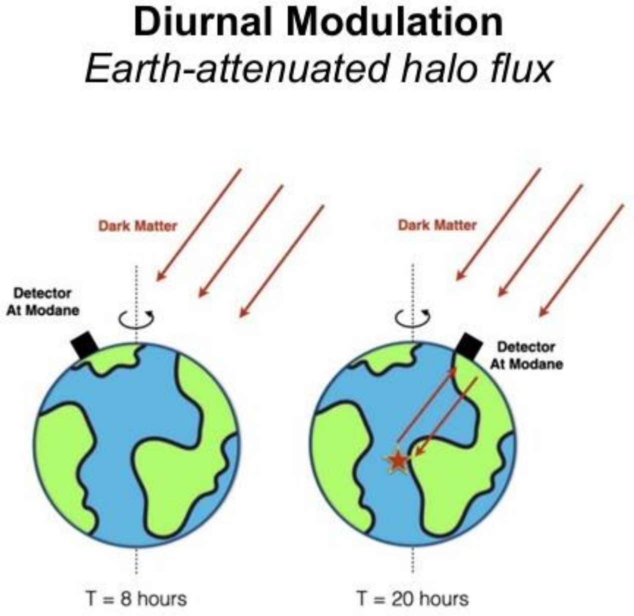
fundamental lower limit



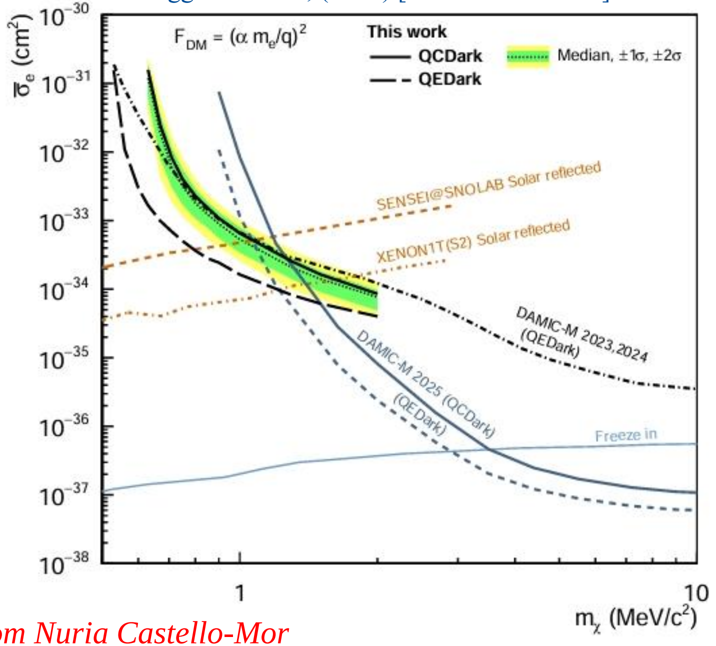
Adari et al, (2023) [arXiv:2312.13342]

Backgrounds and Daily Modulation

- For sufficiently large cross sections, the rotation of overburden relative to Cygnus results in a non-negligible change in flux underground!



Aggarwal et al, (2025) [arXiv:2511.13962]



see Tues. talk from Nuria Castello-Mor

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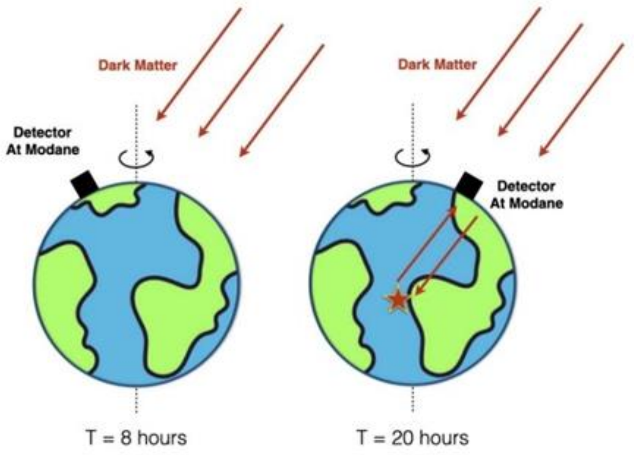
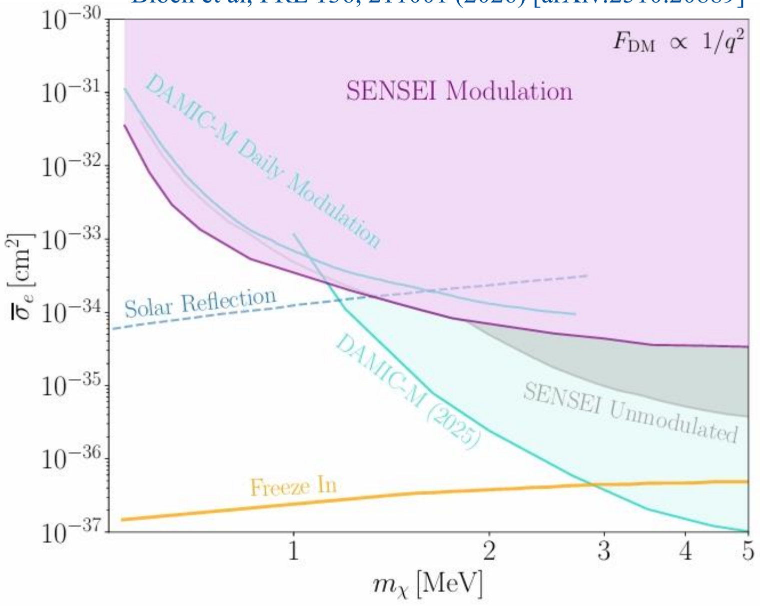
Diurnal Modulation

Earth-attenuated halo flux



Bloch et al, PRL 136, 211001 (2026) [arXiv:2510.20889]



see Tues. talk from Ansh Desai

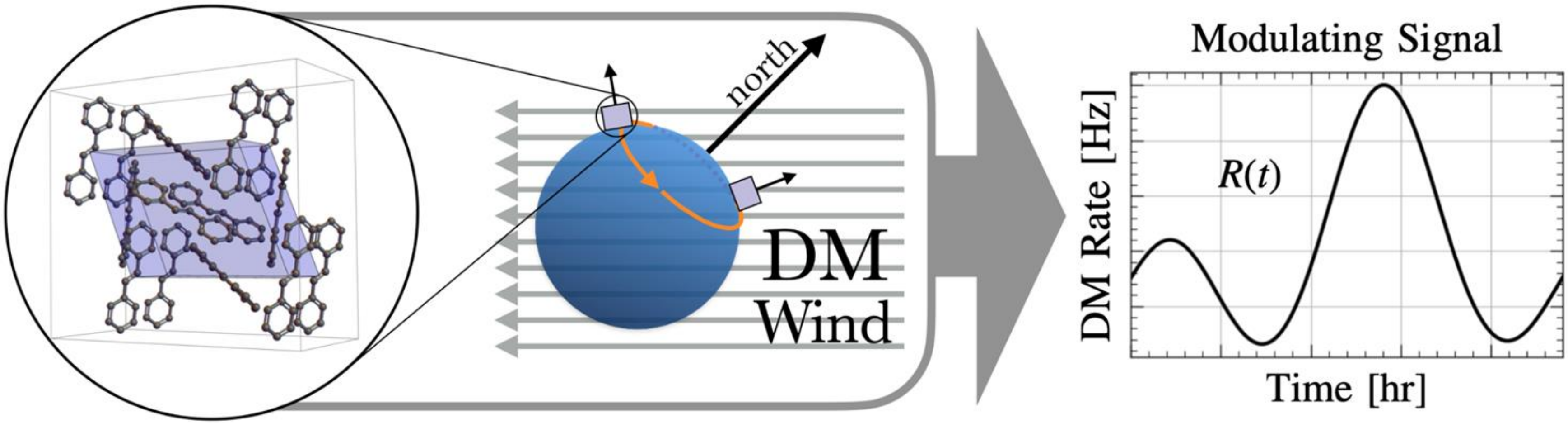
Directional Sub-GeV Dark Matter

- What if the anisotropy came from the detector, and not the overburden?

Bloch et al, PRL 136, 211001 (2026) [arXiv:2510.20889]

Directional Sub-GeV Dark Matter – Organic Scintillators

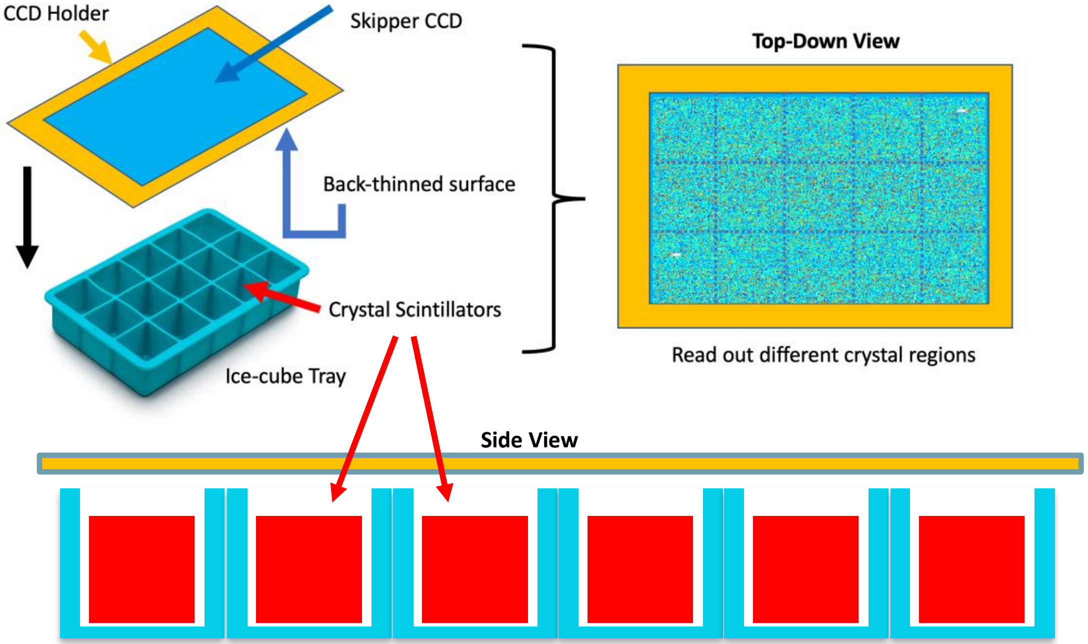
- Directionality remains the only definitive way to maintain discovery power in the face of the (still-unmodeled) low-energy excess and the neutrino fog
- We've demonstrated single-electron (eV-threshold) charge detectors with unprecedentedly-low dark rates (10-100 e- per g-day)

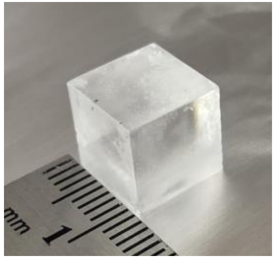


Blanco et al, PRD 104, 036011 (2021) [arXiv:2103.08601]

Directional Sub-GeV Dark Matter – Organic Scintillators

- 10g trans-Stilbene prototype read out by Skipper CCD deployed in MINOS this year





2025
1g cubes

20XX
100g+ "cubes"

Sample/photo from LLNL

Fermilab

Directional Sub-GeV Dark Matter – Organic Scintillators

FNAL/NU Team – D. Baxter

FNAL/UofC Team – A. Drlica-Wagner, B. Roach, E. Marrufo (GIRA), A. Williams

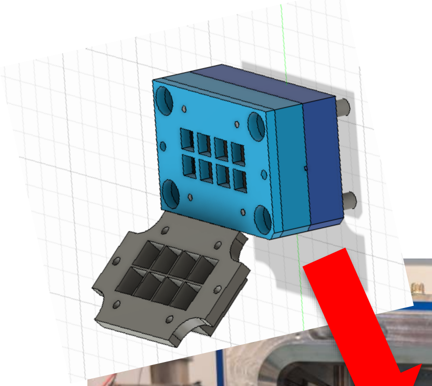
MIT Physics Team – L. Winslow, **N. Hoch (GIRA)**

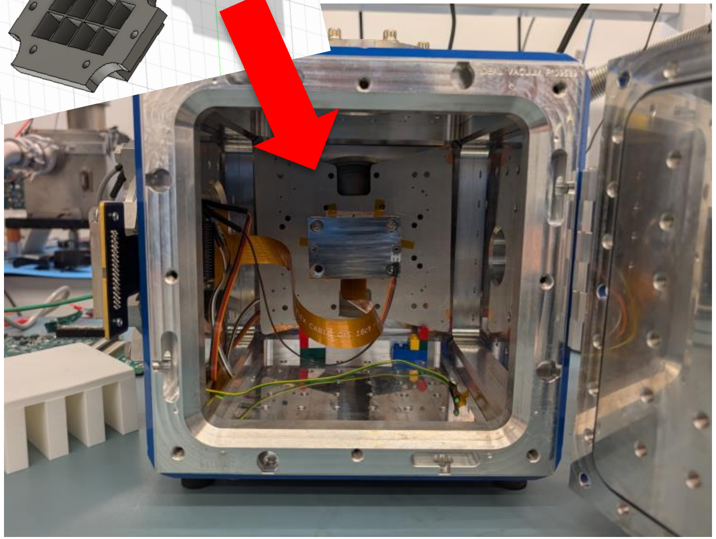
MIT Chemistry Team – D. Freedman, D. Johnson

UIUC Team – P. Abbamonte, D. Balut, L. Haske, L. Thompson, J. Oh

Penn State – C. Wagner, B. Lillard

Toronto – M. Diamond, Y. Kahn

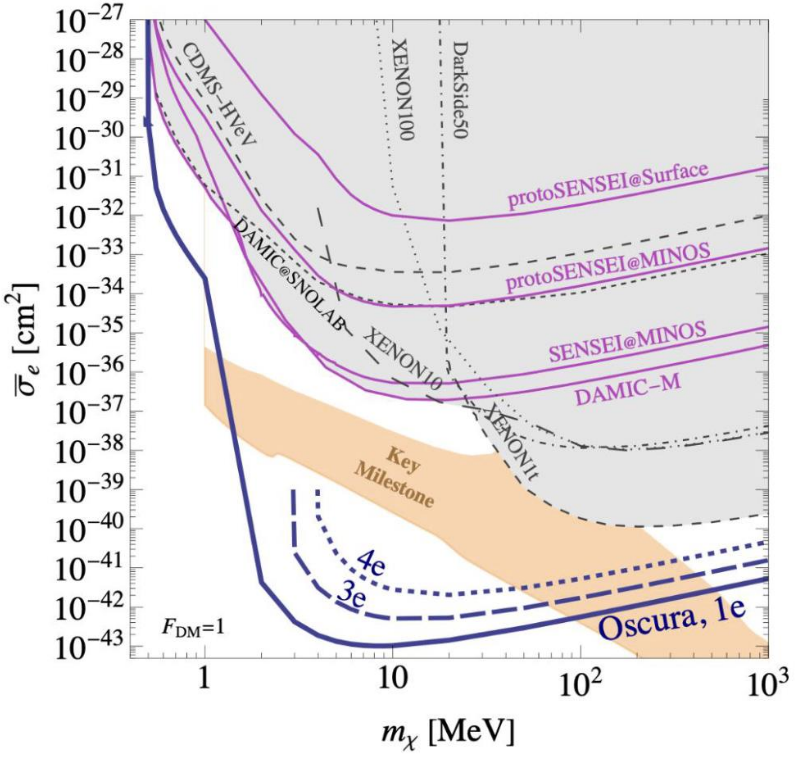


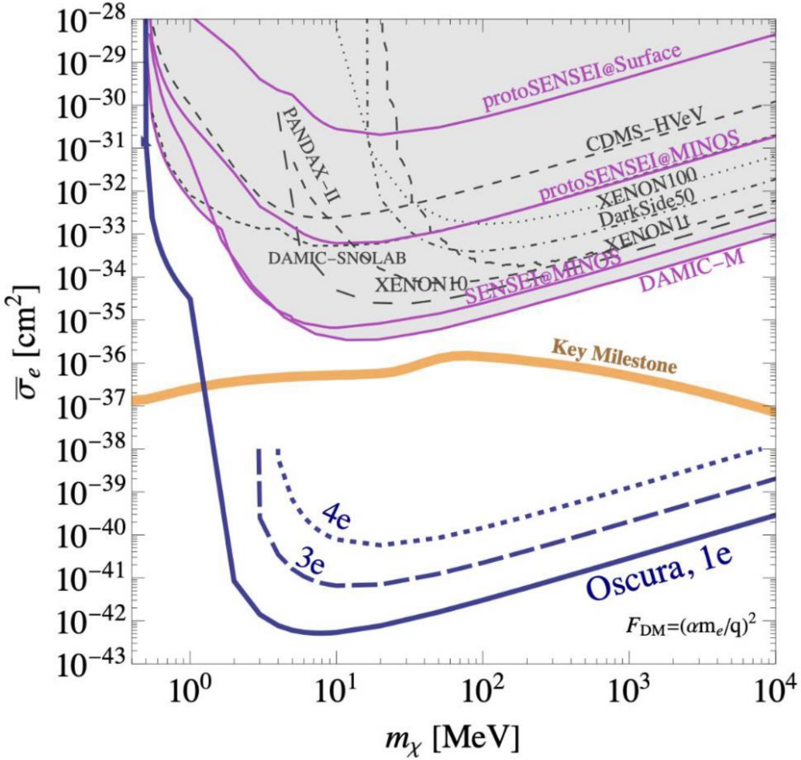


Special Thanks – J. Estrada, J. Tiffenberg

Back-up Slides

The CCD Program – OSCURA





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