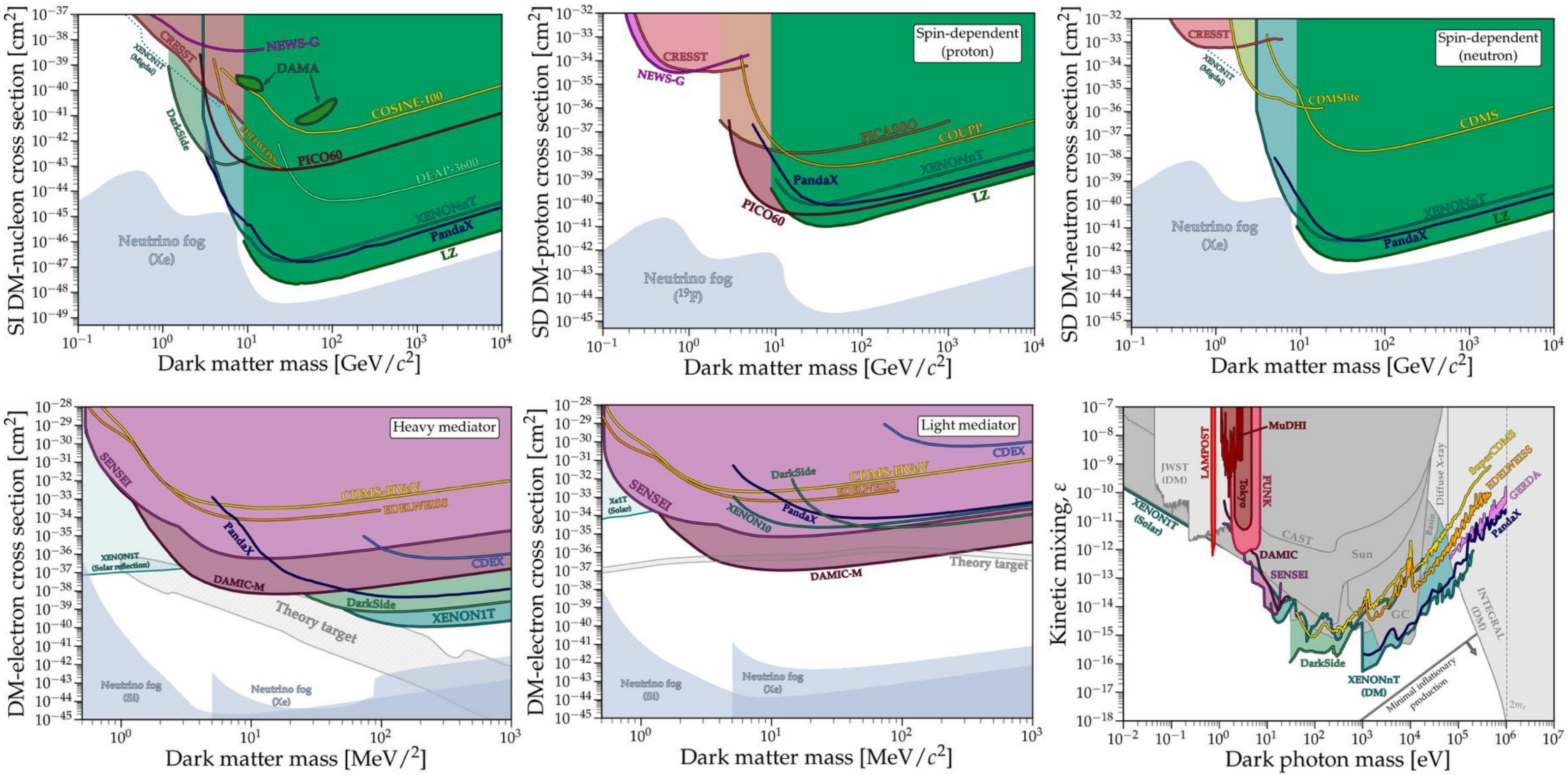
Experimental Landscape for Particle-like Dark Matter

Daniel Baxter

SLAC Summer Institute 2026

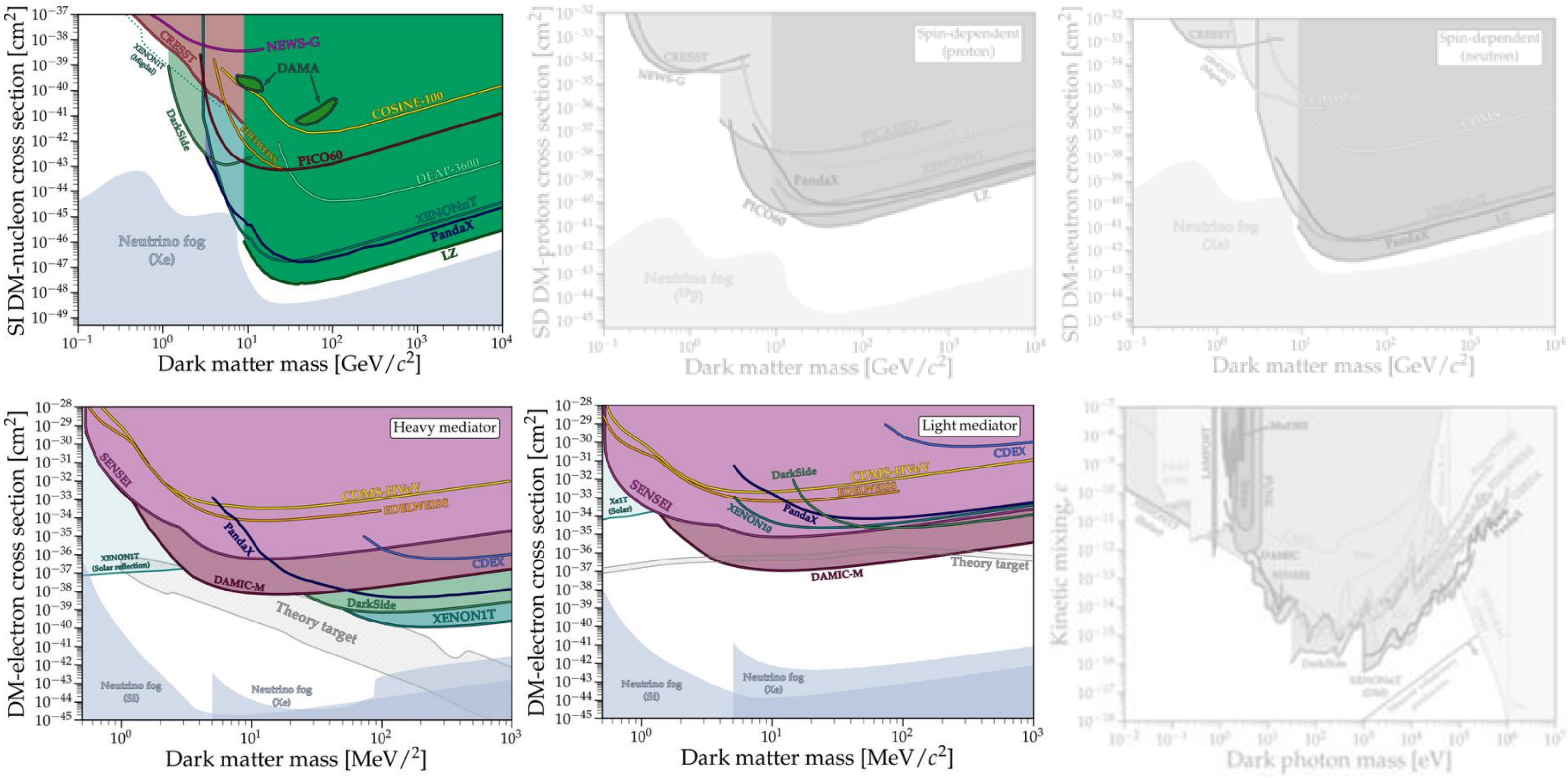
12 August 2026

What does the experimental landscape look like?



Plots from Ciaran O'Hare [https://github.com/cajohare/DirectDetectionPlots]

What does the experimental landscape look like?



Plots from Ciaran O'Hare [https://github.com/cajohare/DirectDetectionPlots]

Where does the idea for particle direct detection begin?

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky

Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Where does the idea for particle direct detection begin?

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Where does the idea for particle direct detection begin?

PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

Detecting cold dark-matter candidates

Andrzej K. Drukier
Max-Planck-Institut für Physik und Astrophysik, 8046 Garching, West Germany
and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, Massachusetts 02138

Katherine Freese and David N. Spergel
Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, Massachusetts 02138
(Received 2 August 1985)

We consider the use of superheated superconducting colloids as detectors of weakly interacting galactic-halo candidate particles (e.g., photinos, massive neutrinos, and scalar neutrinos). We discuss realistic models for the detector and for the galactic halo. We show that the expected count rate ($\approx 10^3$ count/day for scalar and massive neutrinos) exceeds the expected background by several orders of magnitude. For photinos, we expect ≈ 1 count/day, more than 100 times the predicted background rate. We find that if the detector temperature is maintained at 50 mK and using SQUID electronic read out with the system, noise is reduced below 5×10^{-4} flux quanta, particles with mass as low as 2 GeV can be detected. Any particle capable of resolving the solar-neutrino problem by altering energy transport in the Sun can be detected. We show that Earth's motion around the Sun can produce a significant annual modulation in the signal.

Where does the idea for particle direct detection begin?

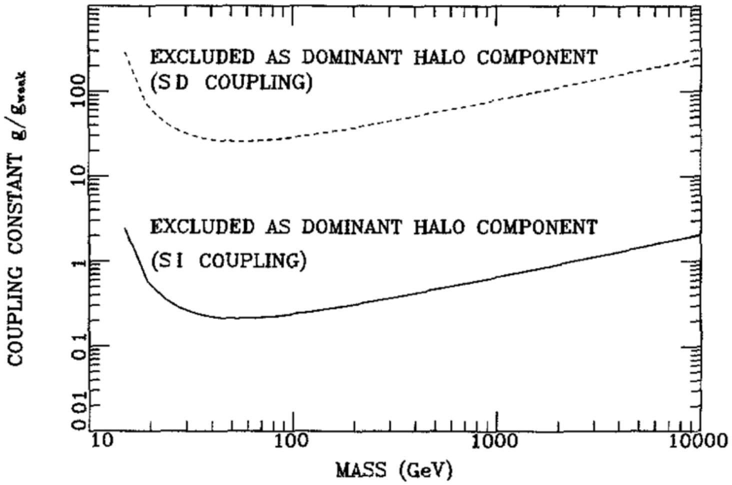
Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr , Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987



Setting some historical context

- The first "modern" detector was theorized for neutrino detection by *Blas Cabrera et al*
- A decade of R&D established foundations of this technology
- With the major "breakthrough" being the invention of the QET here in 1995!

VOLUME 55, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1985

Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41MeV) *pp* ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of *pp*, ^{7}Be, and ^{8}B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).

A quasiparticle-trap-assisted transition-edge sensor for phonon-mediated particle detection

K. D. Irwin,[a] S. W. Nam, B. Cabrera, and B. Chugg
Department of Physics, Stanford University, Stanford, California 94305-4060

B. A. Young
Department of Physics, Santa Clara University, Santa Clara, California 95053

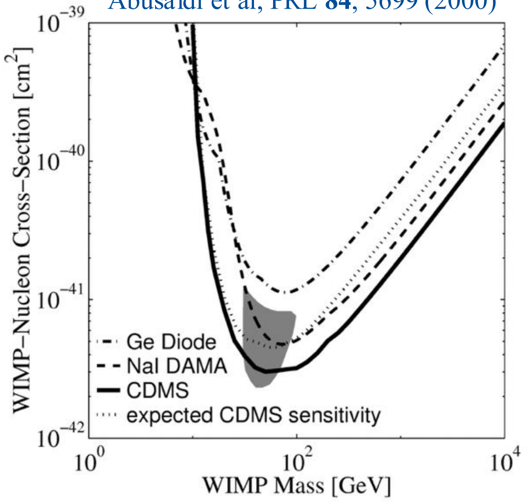
(Received 20 April 1995; accepted for publication 19 June 1995)

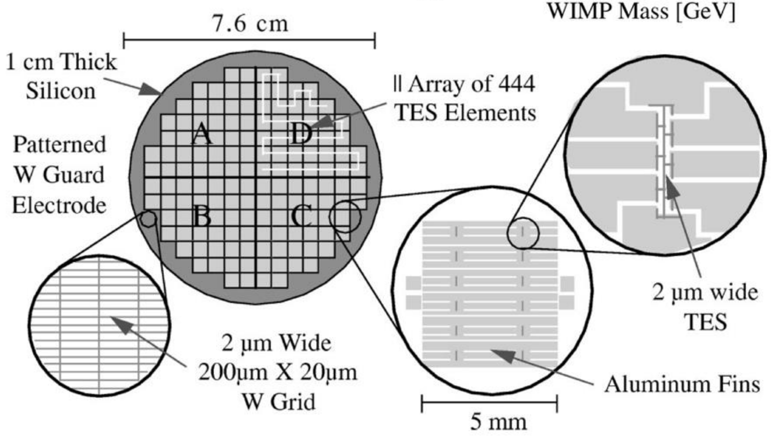
***QET** = **Q**uasiparticle-trap-assisted **E**lectrothermal-feedback **T**ransition-edge sensor*

Setting some historical context

- There are three main detector properties that set the sensitivity to dark matter
  - **Exposure (mass x time)**
  - **Energy Threshold**
  - **Backgrounds**
- Between 1985-2015, experiments made enormous progress advancing each of these, but ESPECIALLY on increasing mass.

Abusaidi et al, PRL **84**, 5699 (2000)





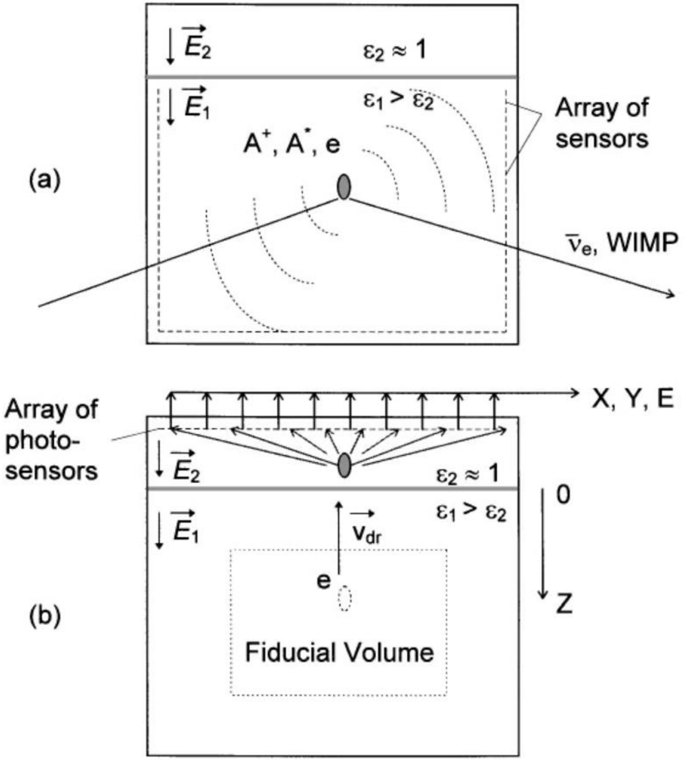
Abrams et al, PRD **66**, 122003 (2002)

Setting some historical context – TPCs

- The great leap in sensitivity came with the use of dual-phase liquid noble **time-projection chambers (TPCs)**
- Particle scatters on liquid noble target (Ar, Xe) produce prompt charge & light
  - Light can be collected immediately (**S1**)
  - Charge can be drifted to a delayed collection signal (**S2**)

Charge accelerated through gas produces light!

Bolozdynya, NIM A **422**, 314 (1999)

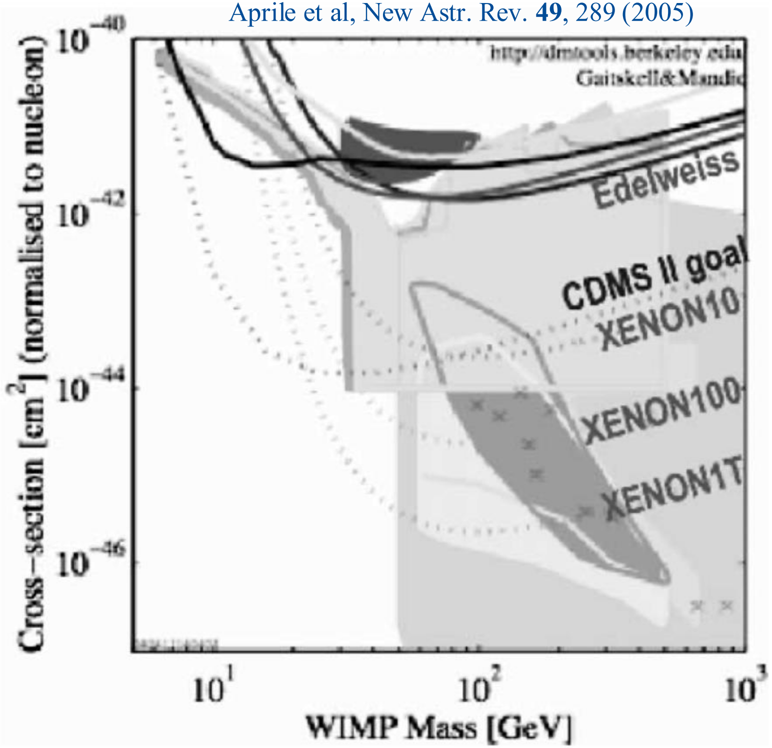


Setting some historical context – TPCs

Features:

- ***Scalability***: if your detector is liquid, you just need a bigger vat
- ***Self-Shielding***: most backgrounds have a pathlength in the target shorter than the detector diameter
- ***Backgrounds***: The separation of **S1** and **S2** allows for considerable rejection of ionizing backgrounds, which produce a higher charge-to-light ratio than a **nuclear recoil (NR)**

Aprile et al, New Astr. Rev. **49**, 289 (2005)



Fermilab

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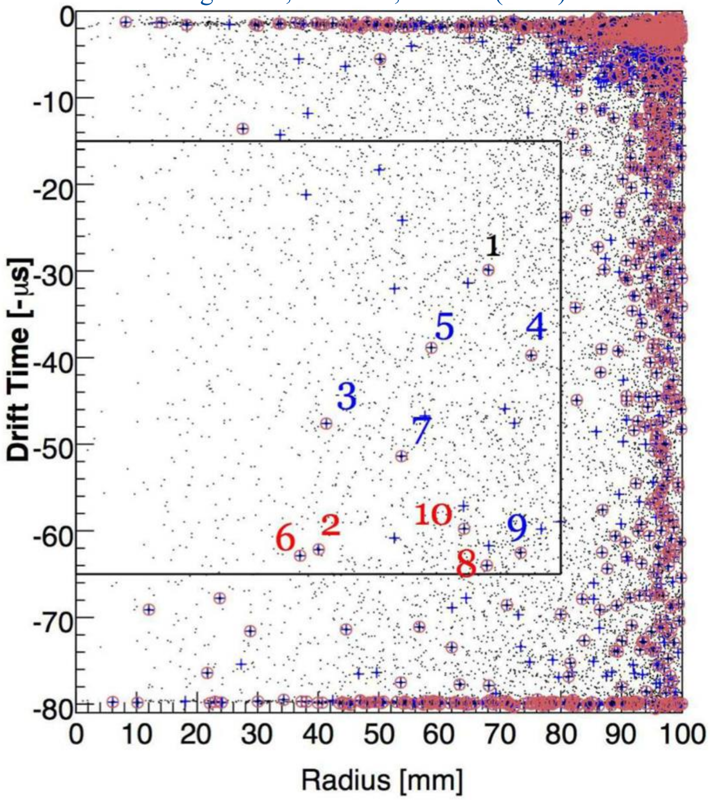
Angle et al, PRL **100**, 021303 (2008)



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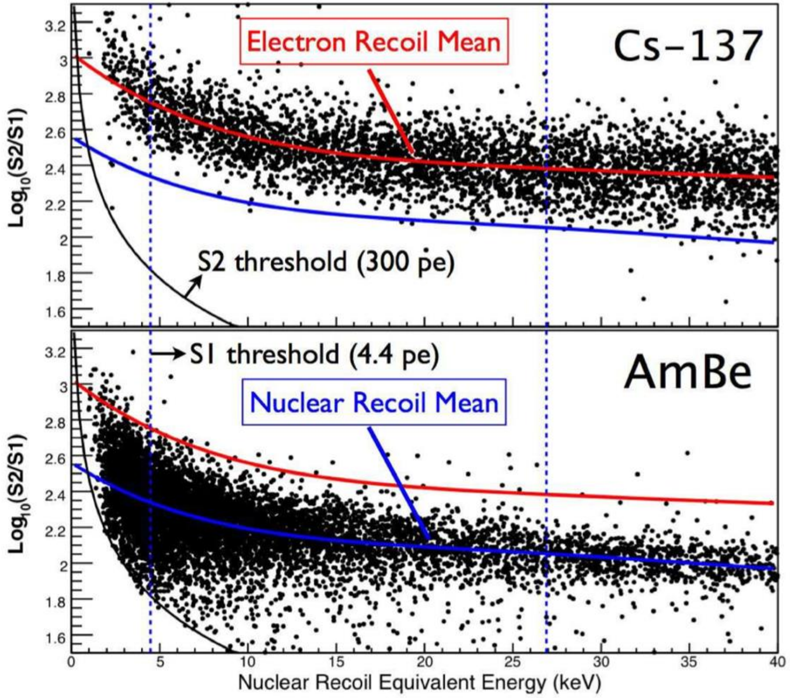

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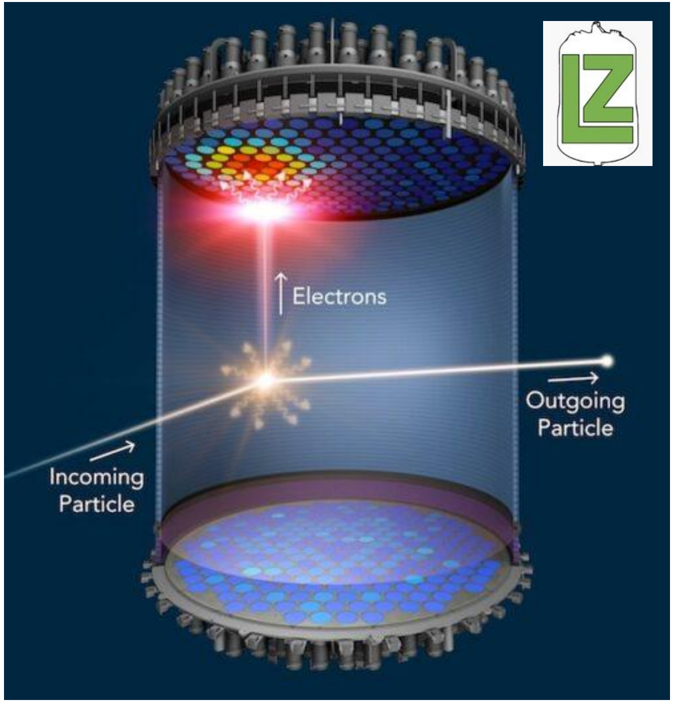

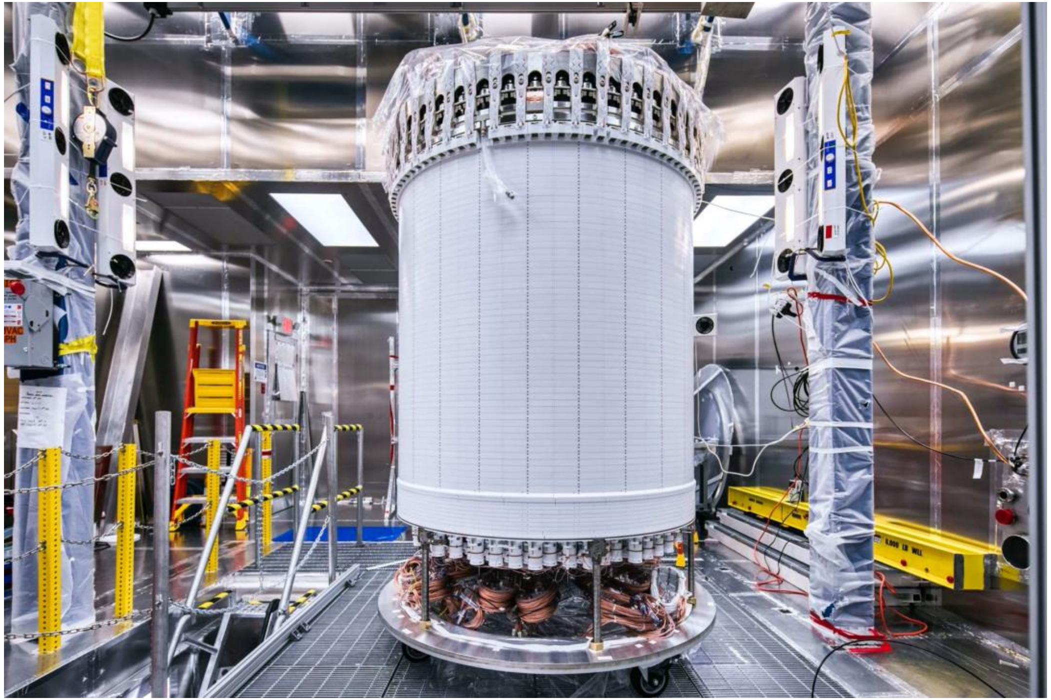

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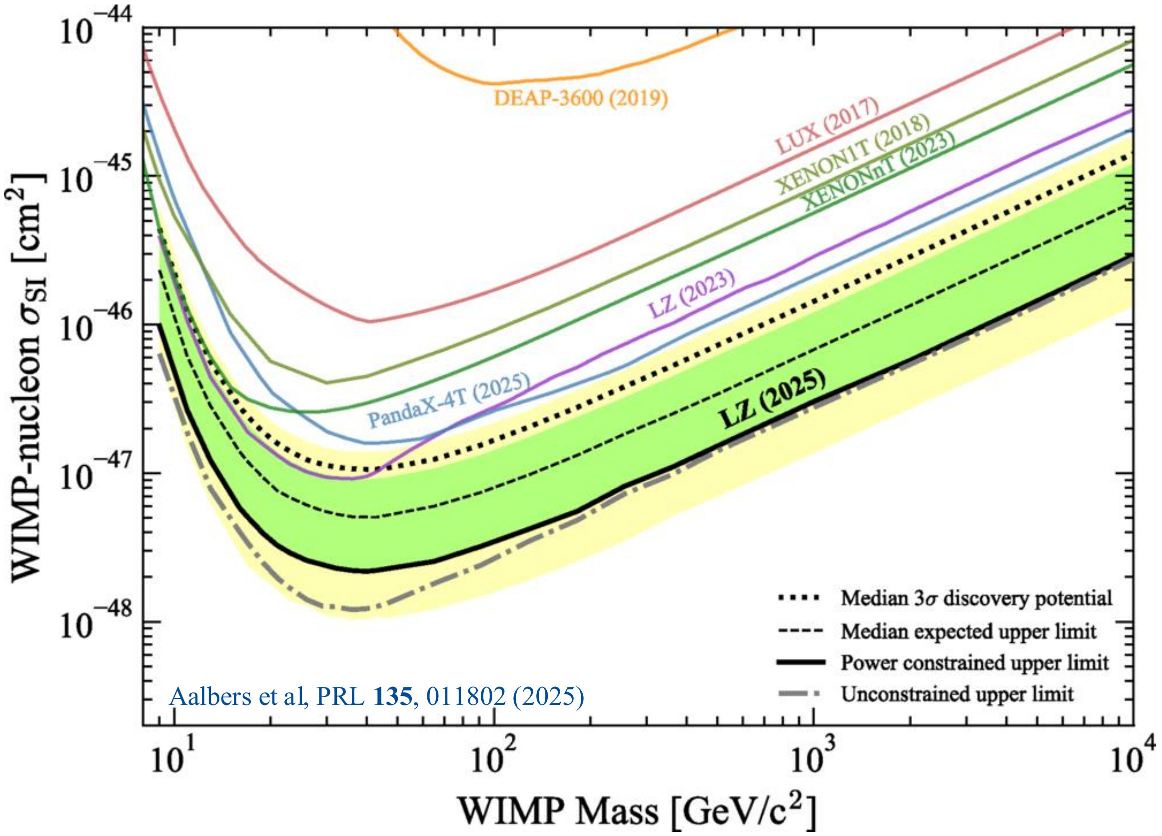
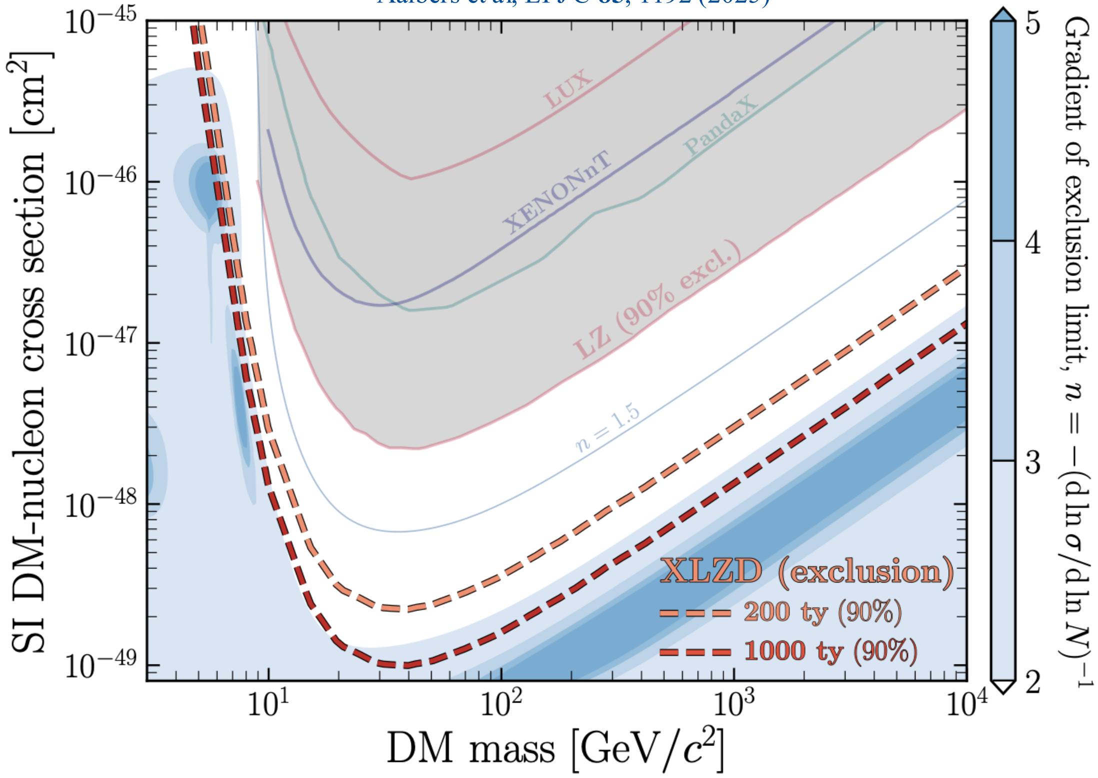


Setting some historical context – TPCs

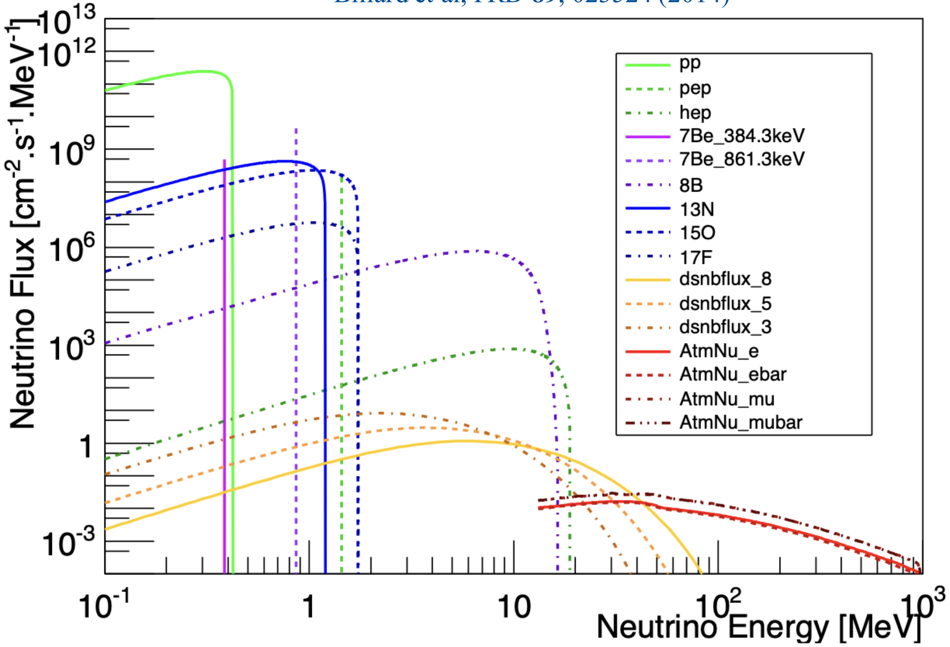
Aalbers et al, EPJ C **85**, 1192 (2025)



Setting some historical context – the neutrino "floor"

- As you get big enough, you start to reach an "irreducible" background from **coherent elastic neutrino-nucleus scatters (CEvNS)** from:
  - Solar Neutrinos (< 8 GeV)
  - ^{8}B Solar Neutrinos (= 8 GeV)
  - Atmospheric Neutrinos (> 8 GeV)
- The community has recently recast this problem as the **neutrino "fog"**, because spectral information can be used to distinguish between DM and CEvNS

Billard et al, PRD **89**, 023524 (2014)



Fermilab

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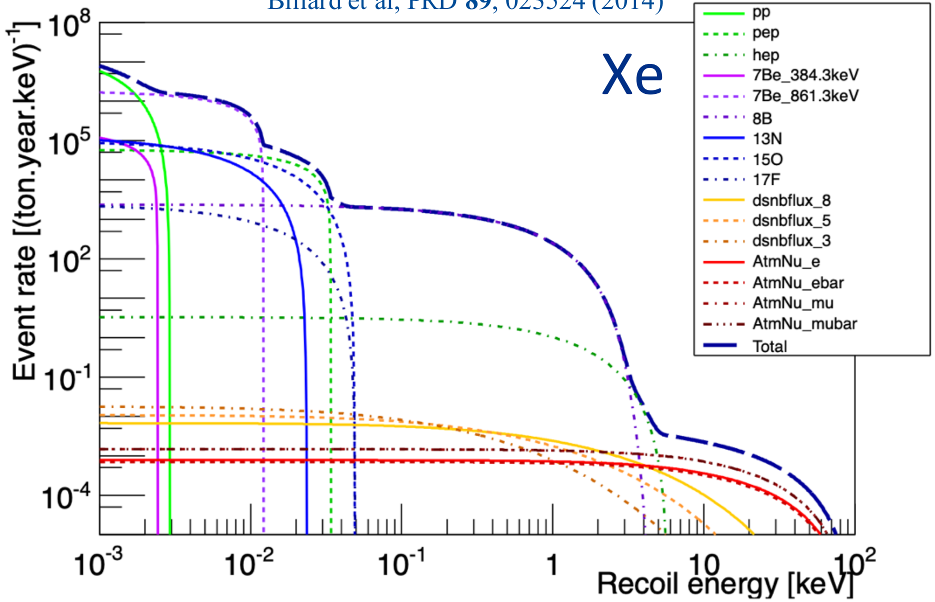

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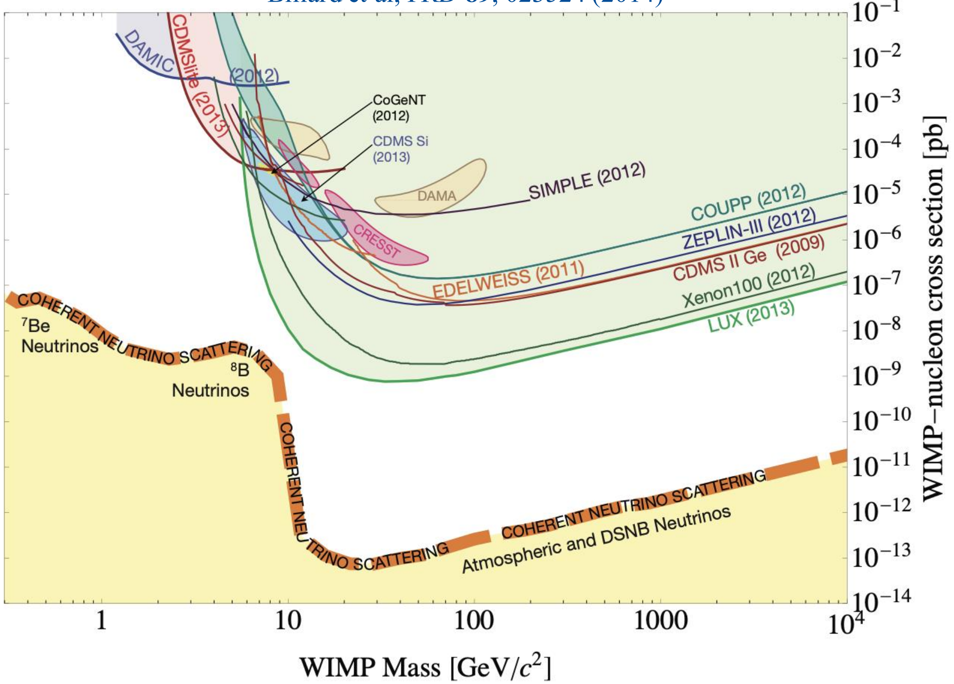

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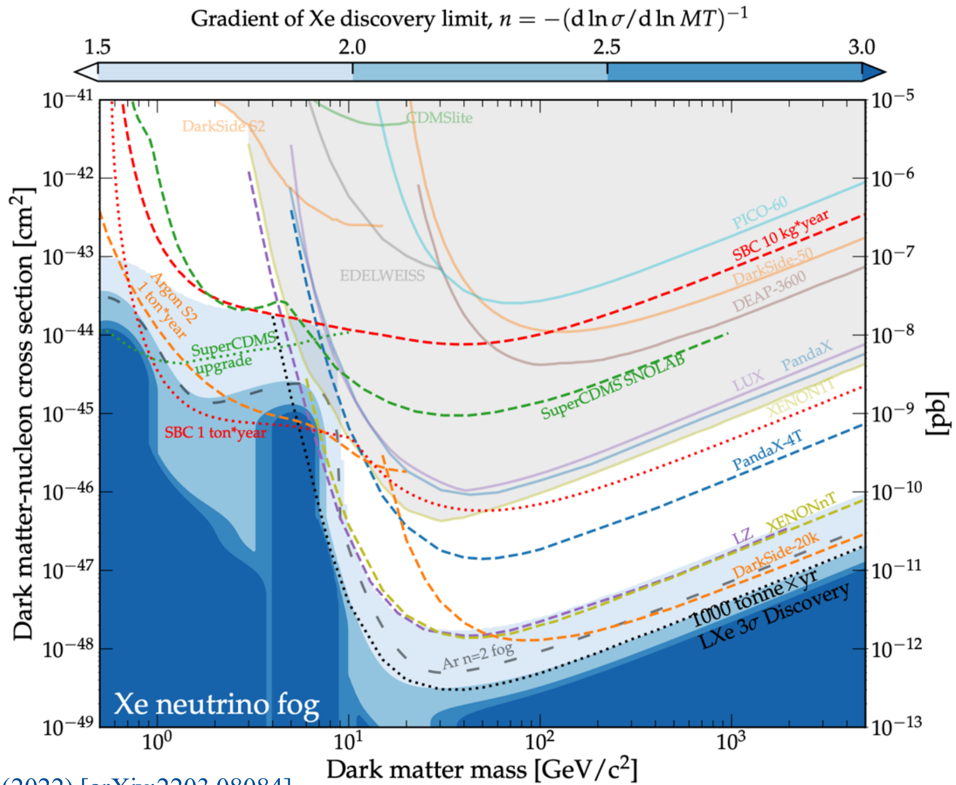


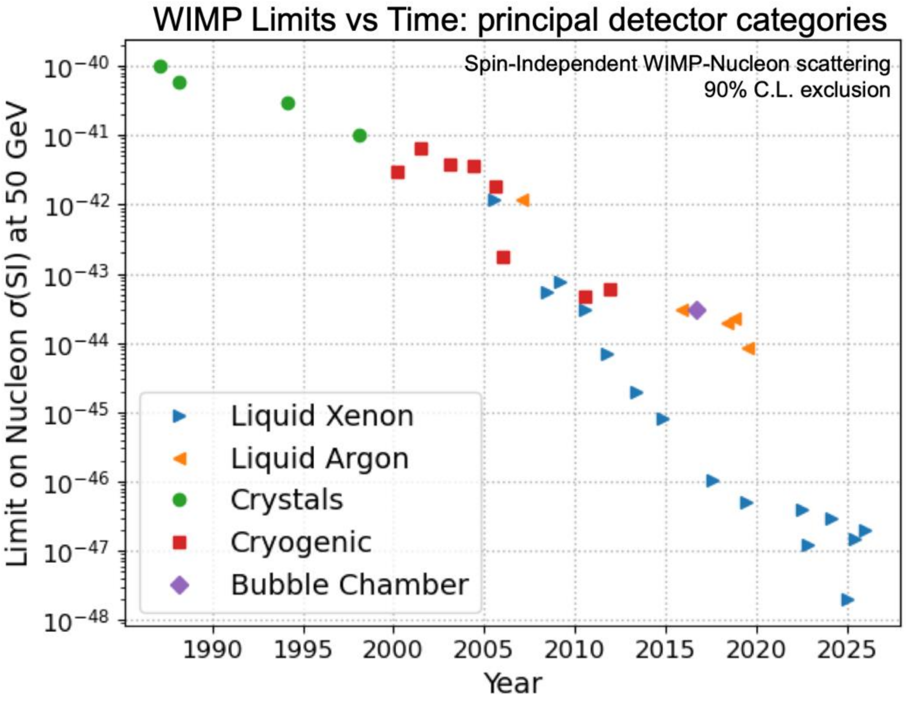
Akerib et al, Snowmass21 (2022) [arXiv:2203.08084]

Setting some historical context – the neutrino “floor”

XLZD would be the conclusion of a thirty-year program to build a neutrino observatory

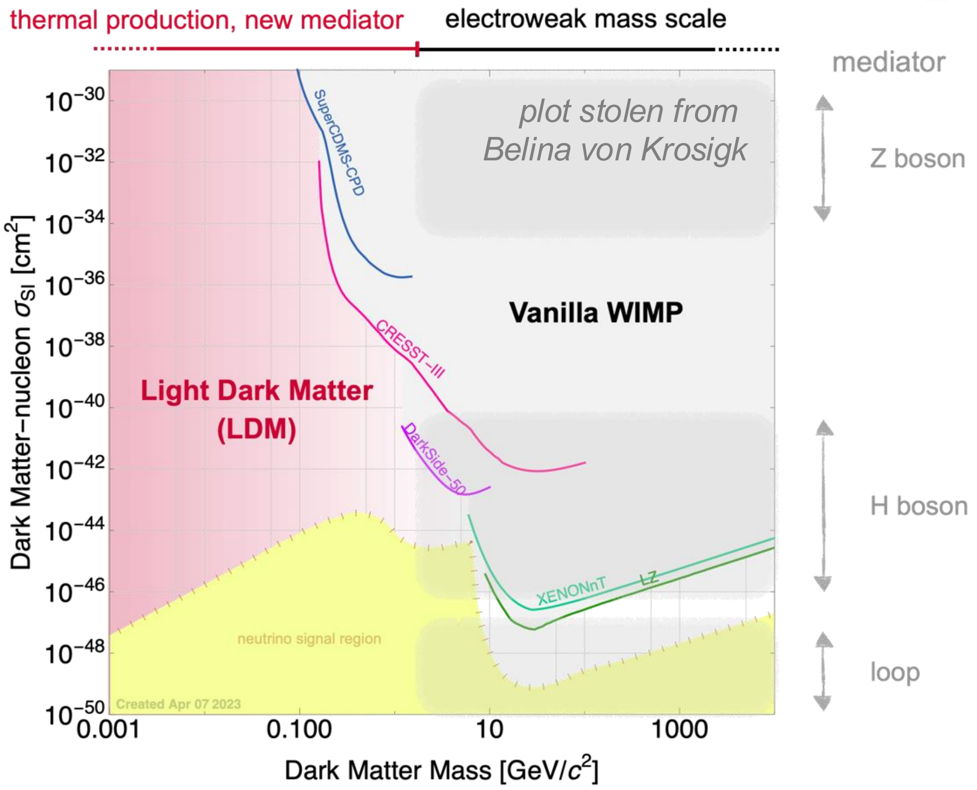
- 2007: ZEPLIN-II
- 2008: XENON10
- 2009: ZEPLIN-III
- 2010: XENON100
- 2014: LUX
- 2017: XENON1T
- 2023: LUX-ZEPLIN (LZ)
- 2023: XENONnT
- **2025: LZ Full Result**
- 20XX: XENON-LUX-ZEPLIN-DARWIN (XLZD)

- 2014: PandaX-I
- 2016: PandaX-II
- 2021: PandaX-4T



Setting some historical context – light dark matter (LDM)

- There are three main detector properties that set the sensitivity to dark matter
  - ~~Exposure (mass x time)~~ *TPC wins*
  - **Energy Threshold** *Let's focus on this*
  - Backgrounds



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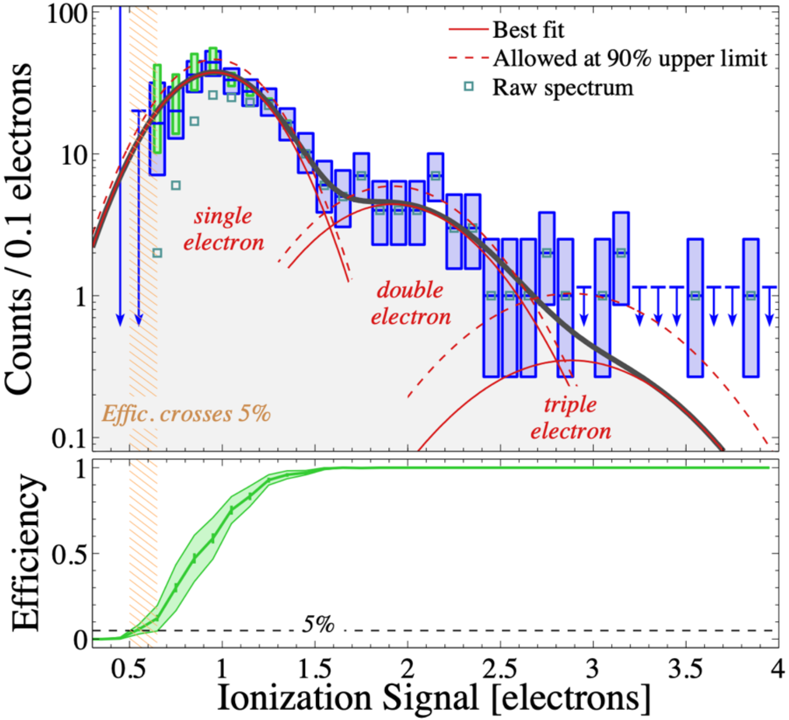
Essig et al, PRL **109**, 021301 (2012)



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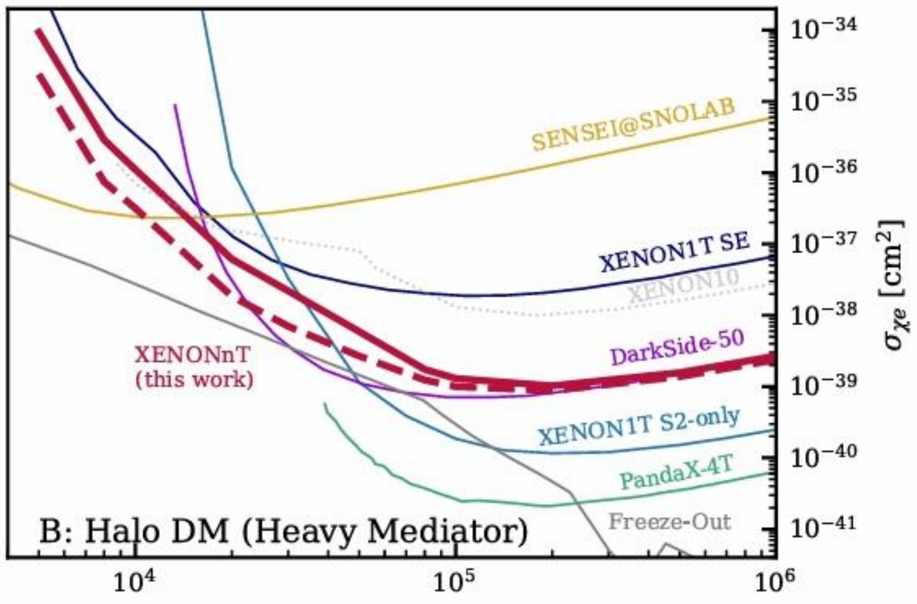
Aprile et al, PRL **134**, 161004 (2025)



Fermilab

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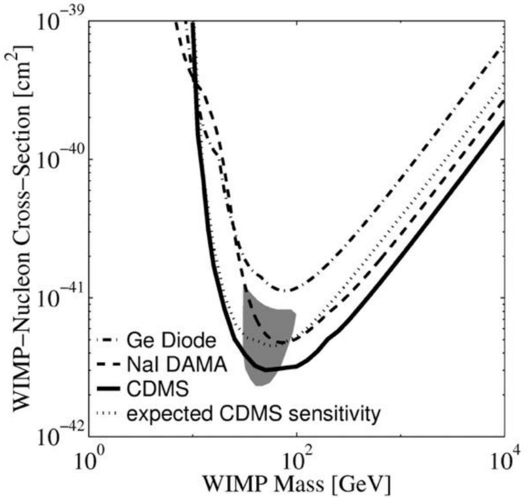
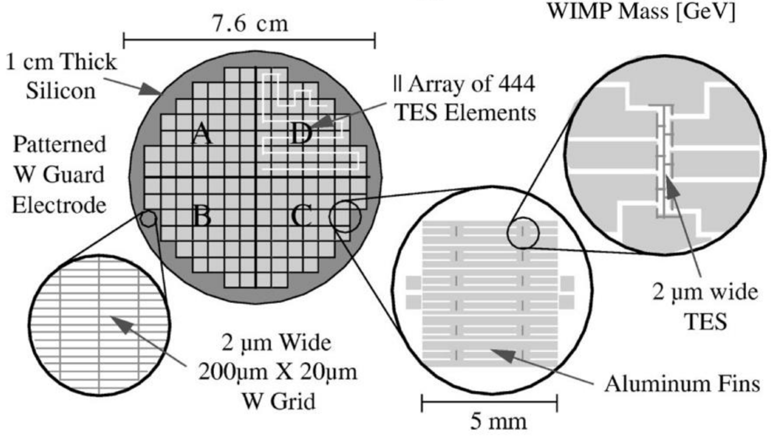


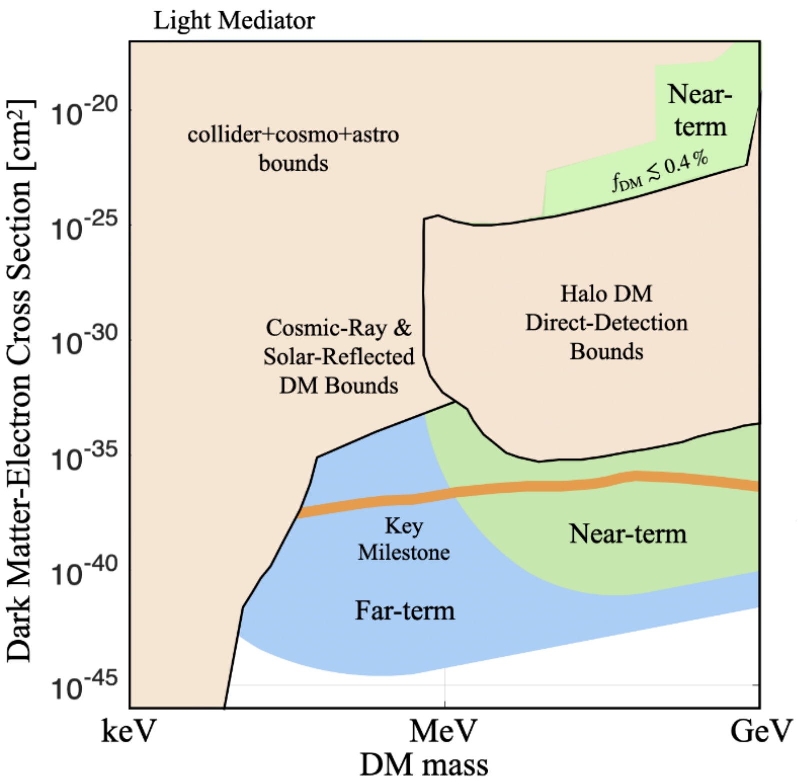
- **Cryogenic detectors are GREAT at low-threshold measurement**
  - Xe charge threshold = ~9eV
  - Si bandgap = ~1eV

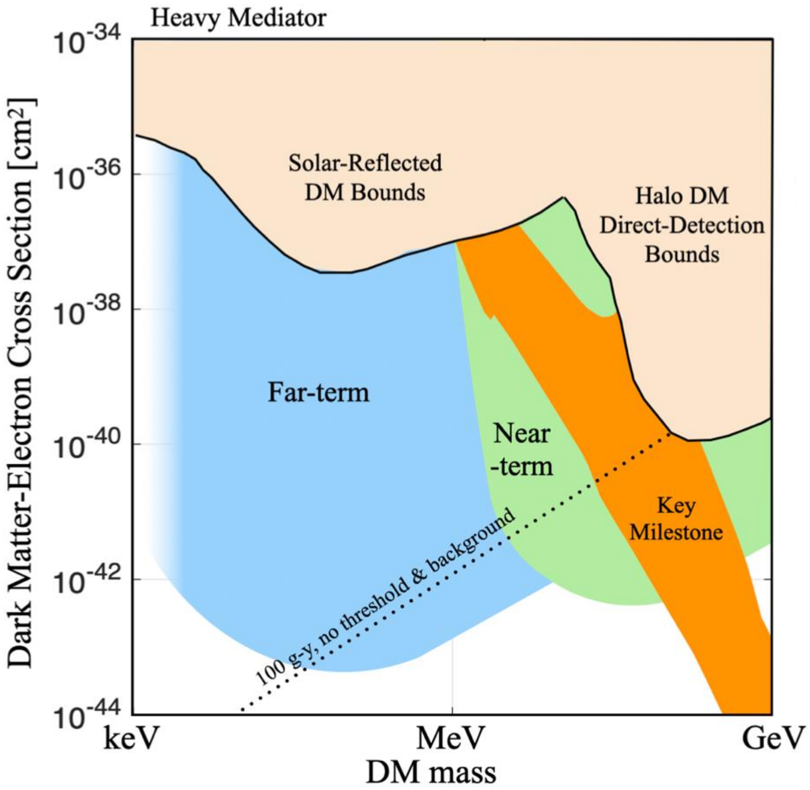


Abrams et al, PRD **66**, 122003 (2002)

Fermilab

Light (Low-Mass) Dark Matter Detection Landscape





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

Summary so far – Xe TPCs

- Dual-Phase Xe time-projection chambers (TPCs) are exceptional measures of **single-charge production in xenon** ($E_{th} > 9\,eV$), as expected for DM-electron scattering
- Dual-Phase Xe TPCs are exceptional measures of **high-energy (>keV) nuclear recoils (NRs)** due to **scalability**, **self-shielding**, and **electron recoil (ER) background discrimination**

- Dual-Phase Xe TPCs searching for **DM-nucleon** scattering lose background rejection capabilities below ~keV energies
- Dual-Phase Xe TPCs searching for **DM-electron** remain **background-limited**, and therefore struggle to improve limits in terms of either cross section (down) or threshold (left)

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Quantum 0-1.0 Detectors

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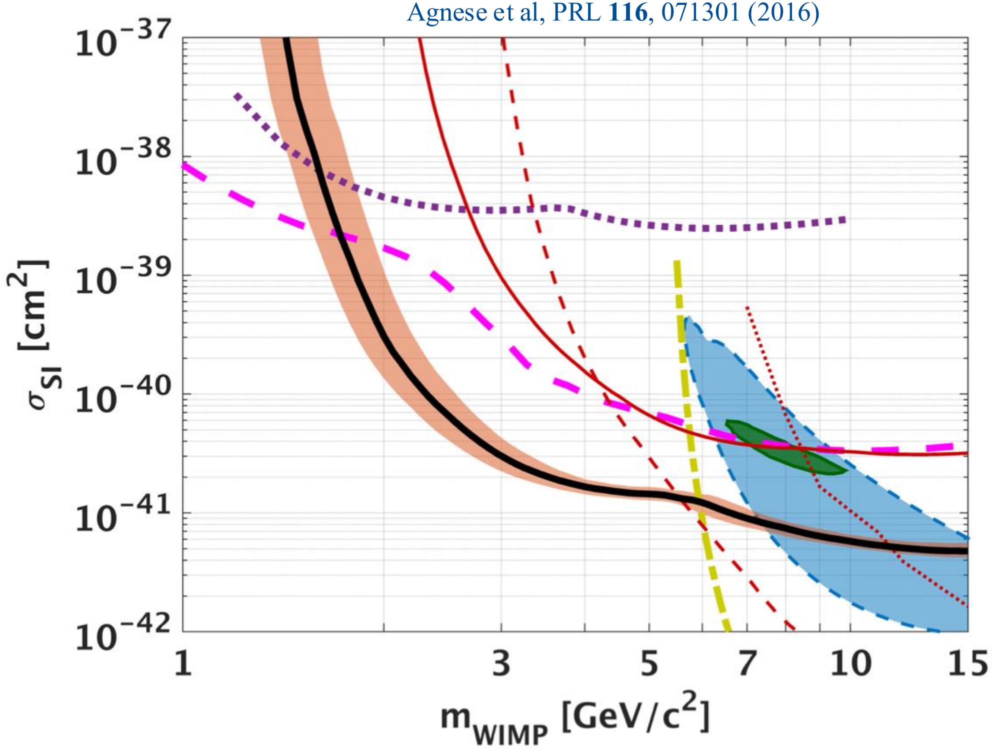
Quantum 2.0+ Detectors

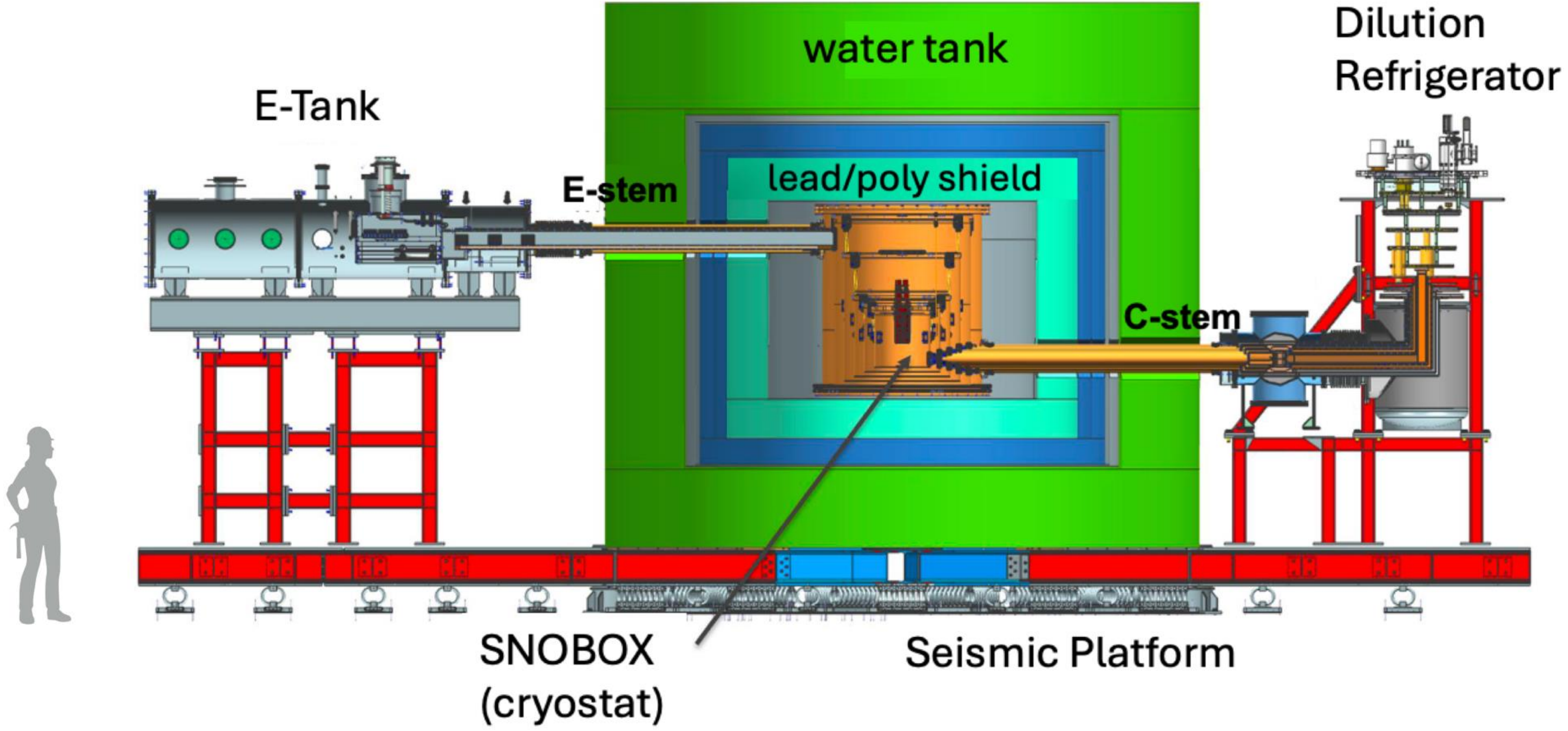
Cryogenic Bolometers – CDMS

- As dual-phase Xe TPCs took off in searches for heavy WIMPs, the **Cryogenic Dark Matter Search (CDMS)**, turned its sites to lower masses
- This involved sacrificing background discrimination for lower thresholds

Agnese et al, PRL **116**, 071301 (2016)

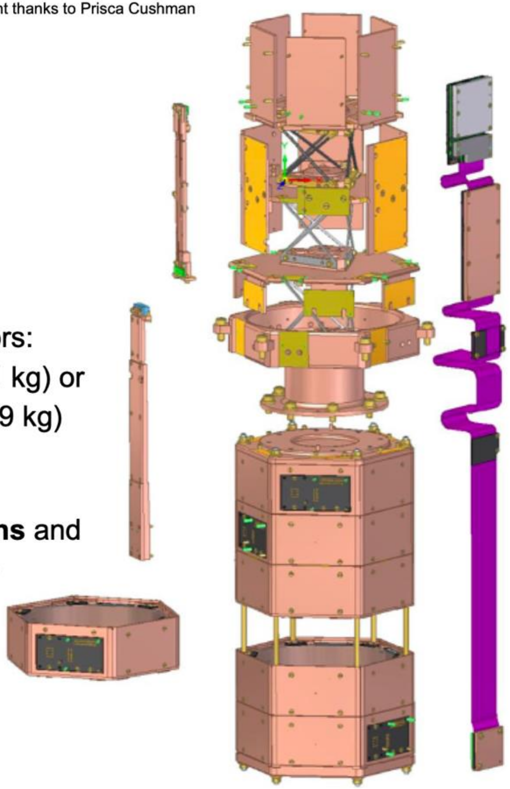


Cryogenic Bolometers – SuperCDMS at SNOLAB



Cryogenic Bolometers – SuperCDMS at SNOLAB

Slide content thanks to Prisca Cushman



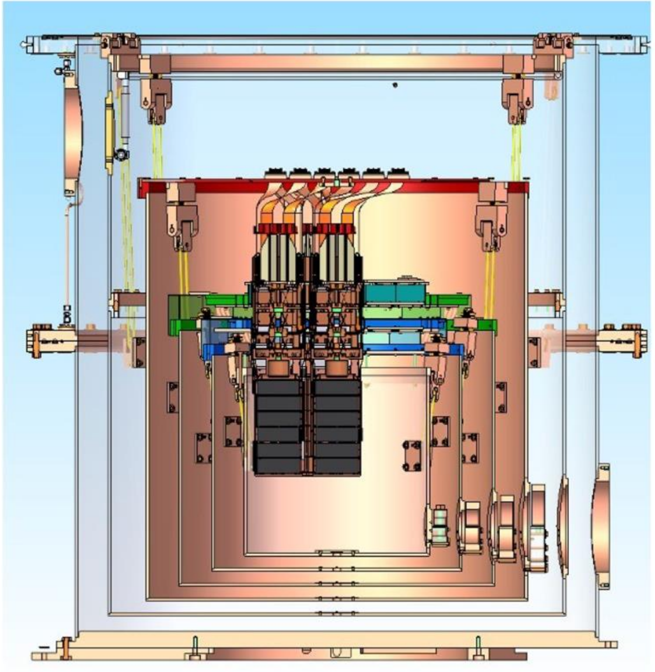
Detectors:
Si (0.61 kg) or
Ge (1.39 kg)

Signal:
phonons and
charge

HEMT: amplifier for iZIP charge channels (4K stage)

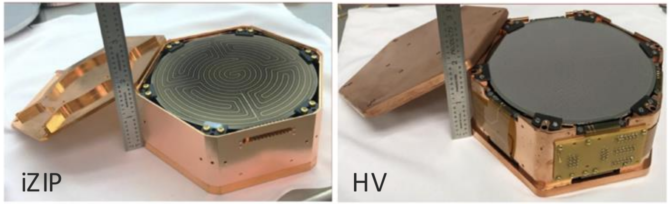
SQUID: **TES**-based (Transition Edge Sensor) readout (1K stage)

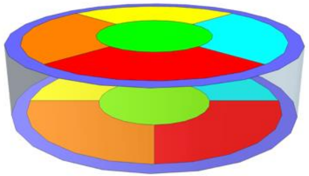
Detectors are kept at the MC stage (base temperature **~15 mK**)

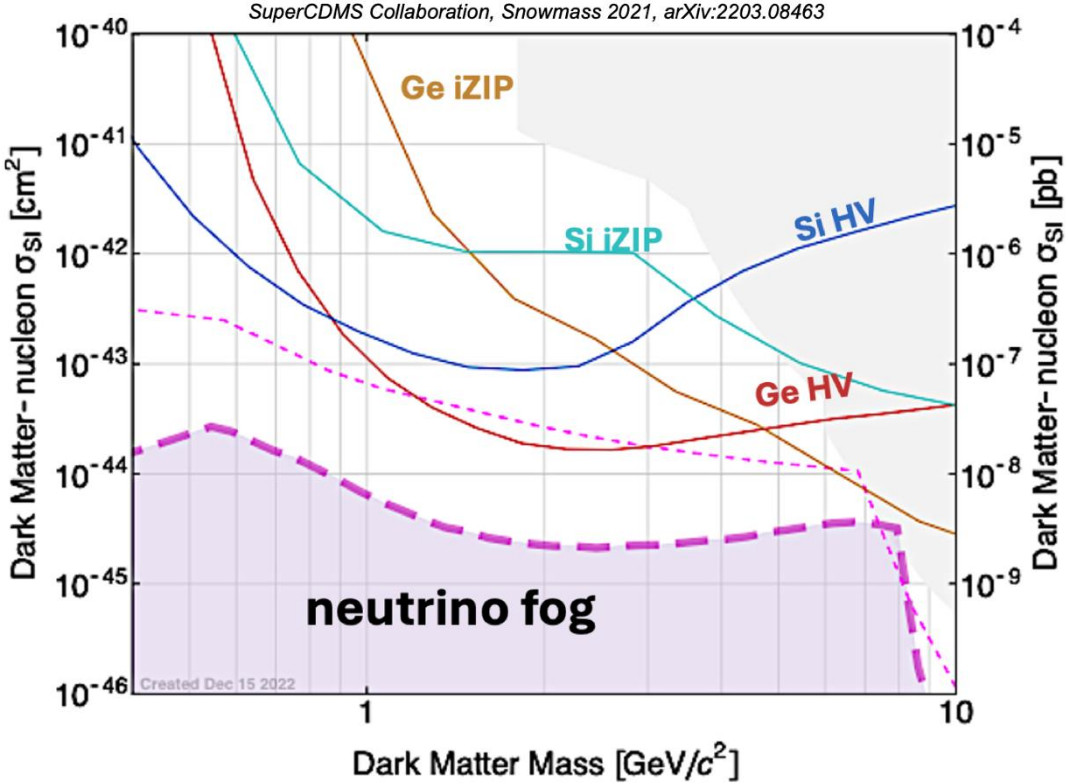


Cryogenic Bolometers – SuperCDMS at SNOLAB

- SuperCDMS at SNOLAB will be a huge step towards reaching the ***solar*** neutrino fog for DM masses below 10 GeV



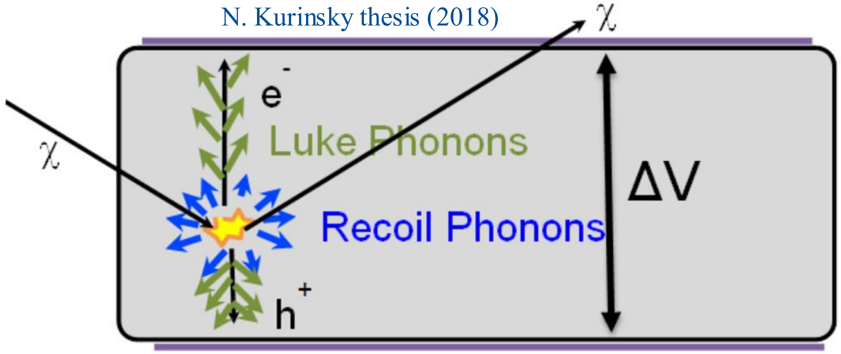




NTL-Amplification – Neganov-Trofimov-Luke Effect

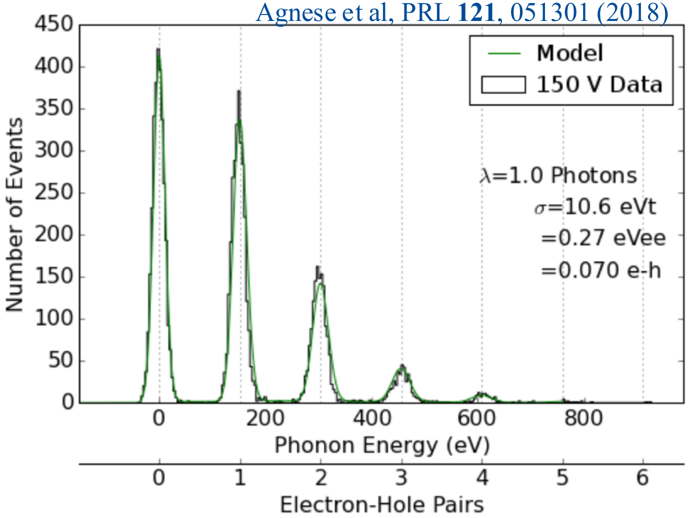
Clever way to search for individual e-h pair creation with a phonon sensor!

N. Kurinsky thesis (2018)



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

Agnese et al, PRL **121**, 051301 (2018)

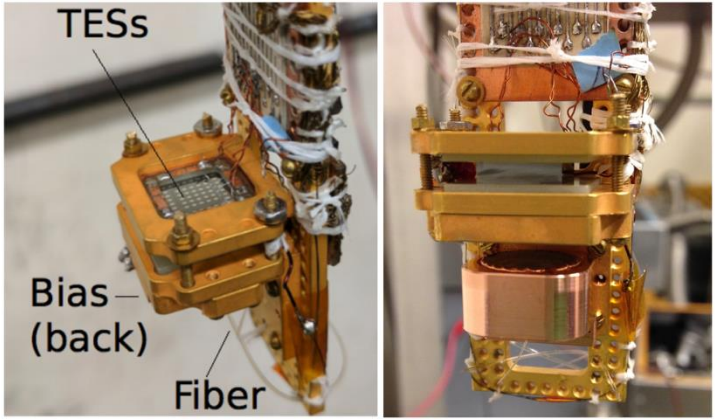


Pros: in-situ aggregate discrimination, target-agnostic*, timing, 1-10 dru backgrounds
Cons: large dark rates, limited position information, no event-by-event discrimination

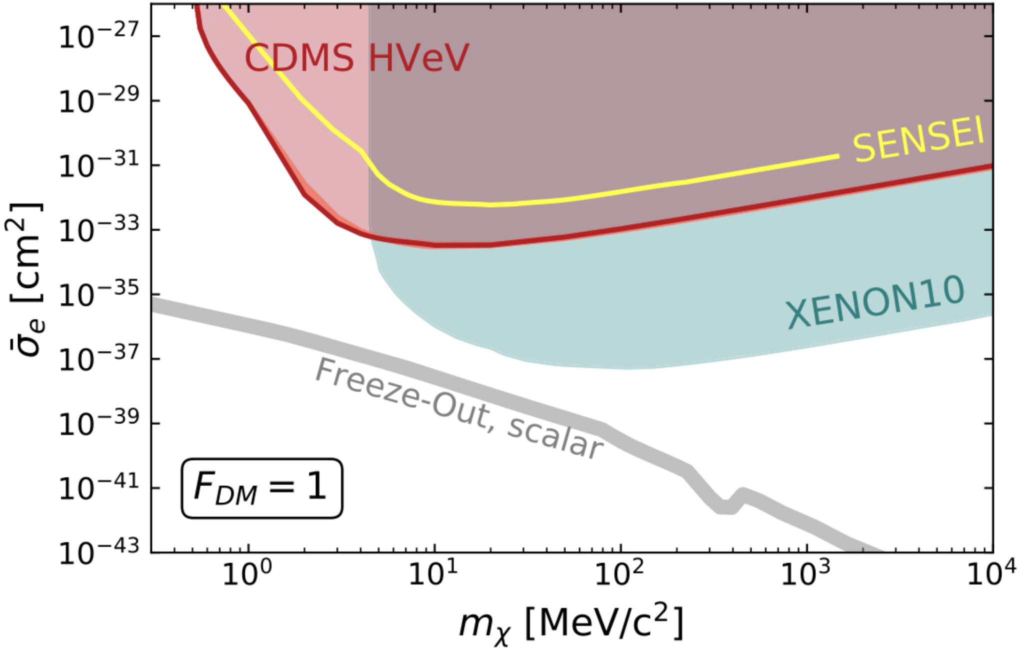
Fermilab

Cryogenic Bolometers – CDMS-HVeV

- This effect was used to place bounds on DM-electron scattering below what could be done with XENON



Agnese et al, PRL **121**, 051301 (2018)

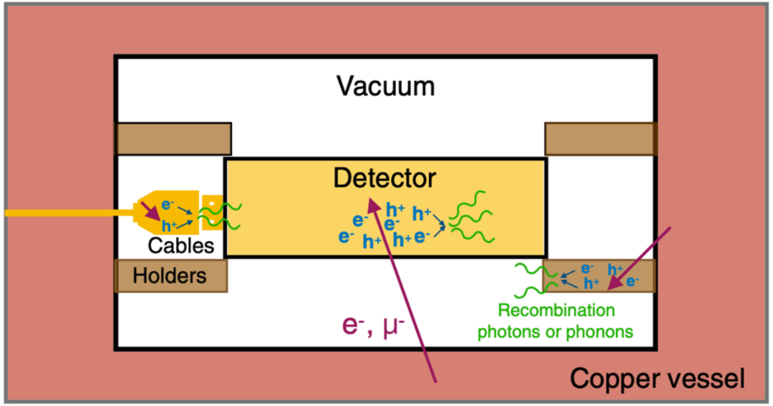


Fermilab

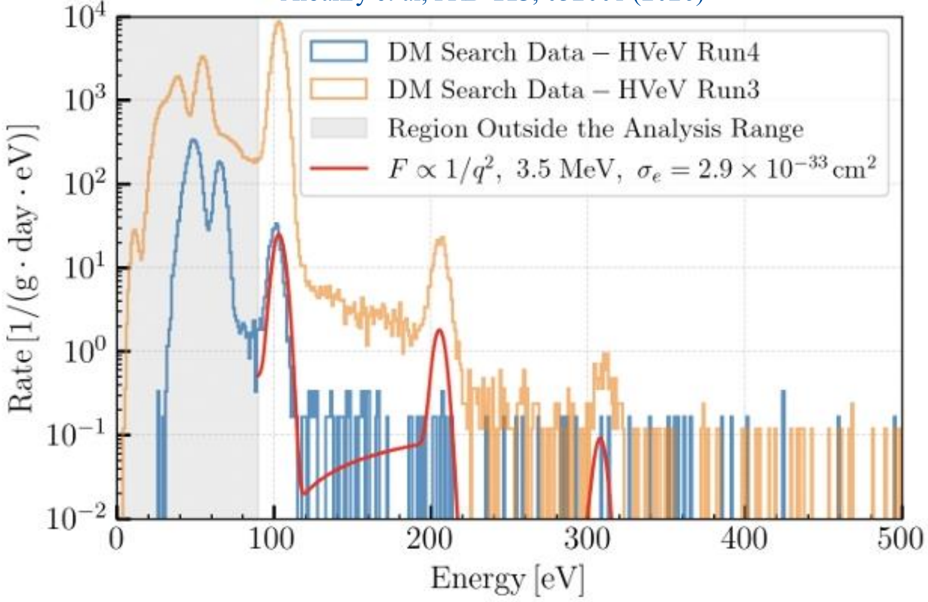
Cryogenic Bolometers – CDMS-HVeV

- Initial dark rates were improved by moving underground (Run 3) and removing luminescent materials (Run 4)

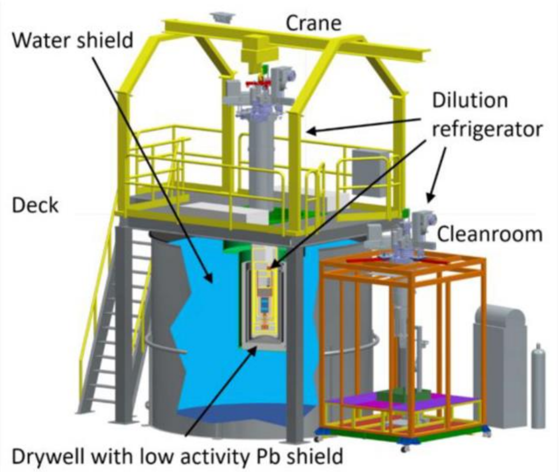
Du et al, PRX **12**, 011009 (2022)



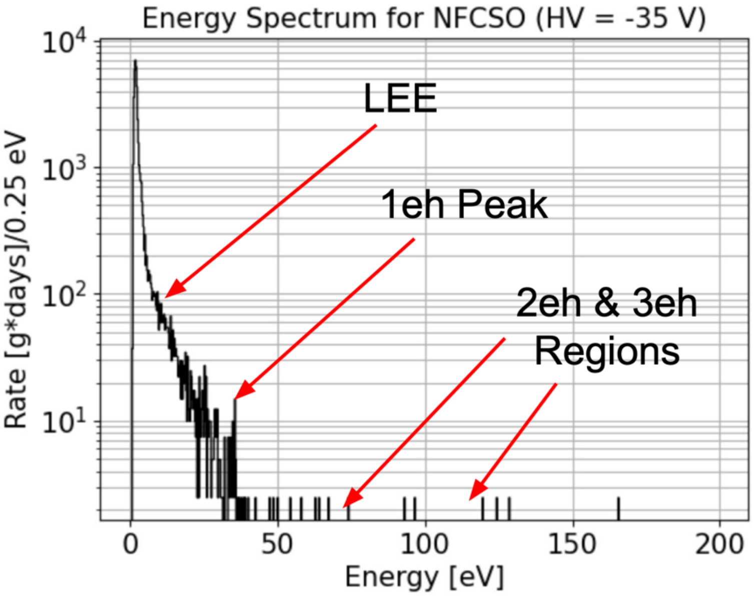
Albakry et al, PRD **113**, 032001 (2026)



Cryogenic Bolometers – CDMS-HVeV



- Run 5 dark rates dramatically reduced in SNOLAB data!



see talk from Kyle Kennard at IDM 2026

Detectors installed at CUTE

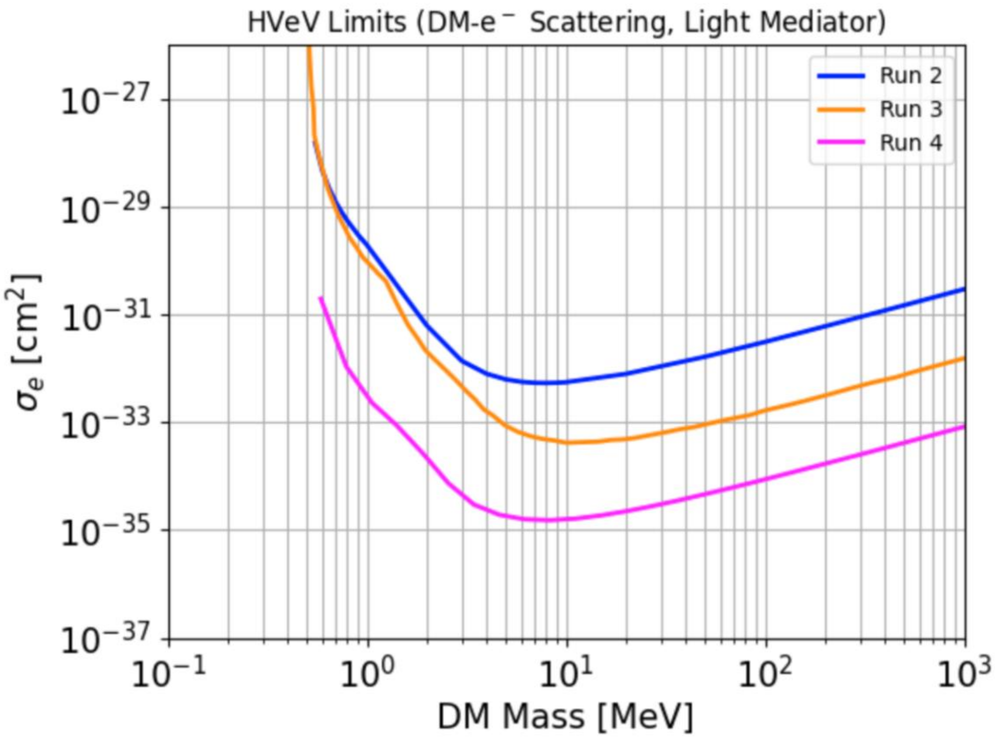
Fermilab

Cryogenic Bolometers – CDMS-HVeV

- The CDMS HVeV program has overcome its dark rate background problem
- Now a **leading technology** for single-charge detection in silicon

  (we'll talk about another later)
- General technique expandable to other target materials! (e.g., Ge)

K. Kennard thesis (2026)

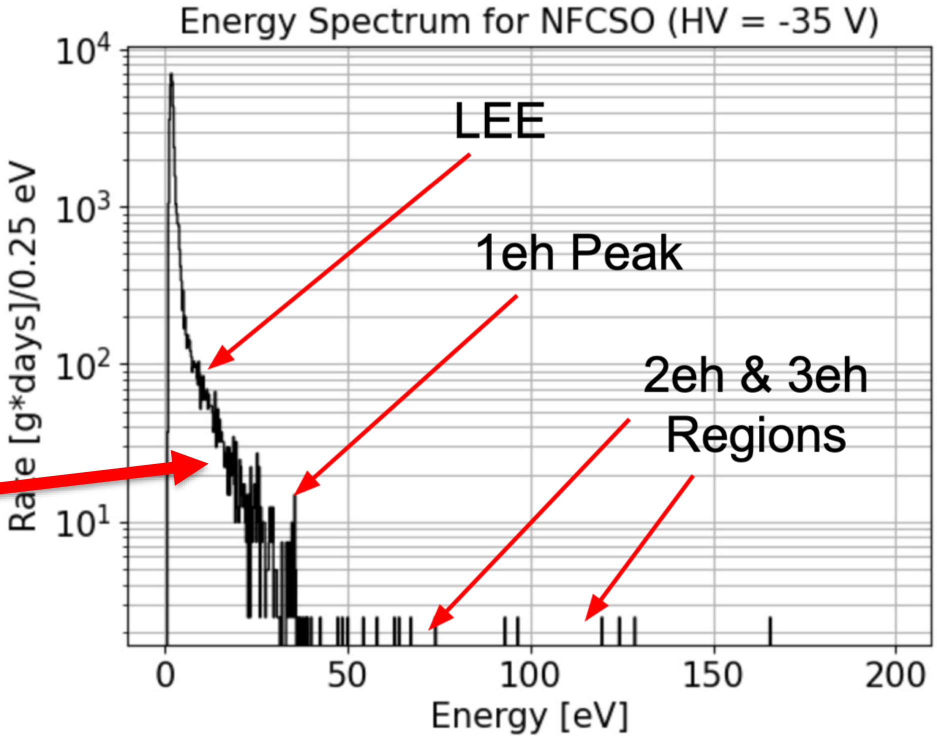


Fermilab

Cryogenic Bolometers – CDMS-HVeV

- The CDMS HVeV program has overcome its dark rate background problem
- Now a **leading technology** for single-charge detection in silicon

  (we'll talk about another later)
- General technique expandable to other target materials! (e.g., Ge)
- **BUT WHAT IS THIS**



see talk from Kyle Kennard at IDM 2026

Cryogenic Bolometers – CRESST

- The ***CRESST*** project proceeded in parallel to ***CDMS*** in Europe alongside ***EDELWEISS***
- Each of these is a cryogenic dark matter search looking for athermal phonons

Astroparticle Physics

Astroparticle Physics 12 (1999) 107–114

www.elsevier.nl/locate/astropart

The CRESST dark matter search

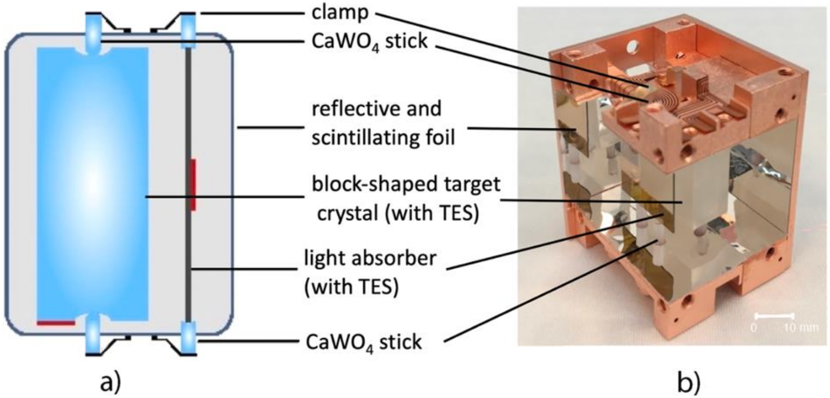
M. Bravin [a], M. Bruckmayer [b], C. Bucci [c], S. Cooper [b], S. Giordano [a], F. von Feilitzsch [d], J. Höhne [d], J. Jochum [d], V. Jörgens [c], R. Keeling [b], H. Kraus [b], M. Loidl [a], J. Lush [a], J. Macallister [b], J. Marchese [b], O. Meier [a], P. Meunier [a], U. Nagel [d], T. Nüssle [d], F. Pröbst [a], Y. Ramachers [b], M. Sarsa [d], J. Schnagl [d], W. Seidel [a], I. Sergeyev [a,1], M. Sisti [a], L. Stodolsky [a], S. Uchaikin [a,1], L. Zerle [a]

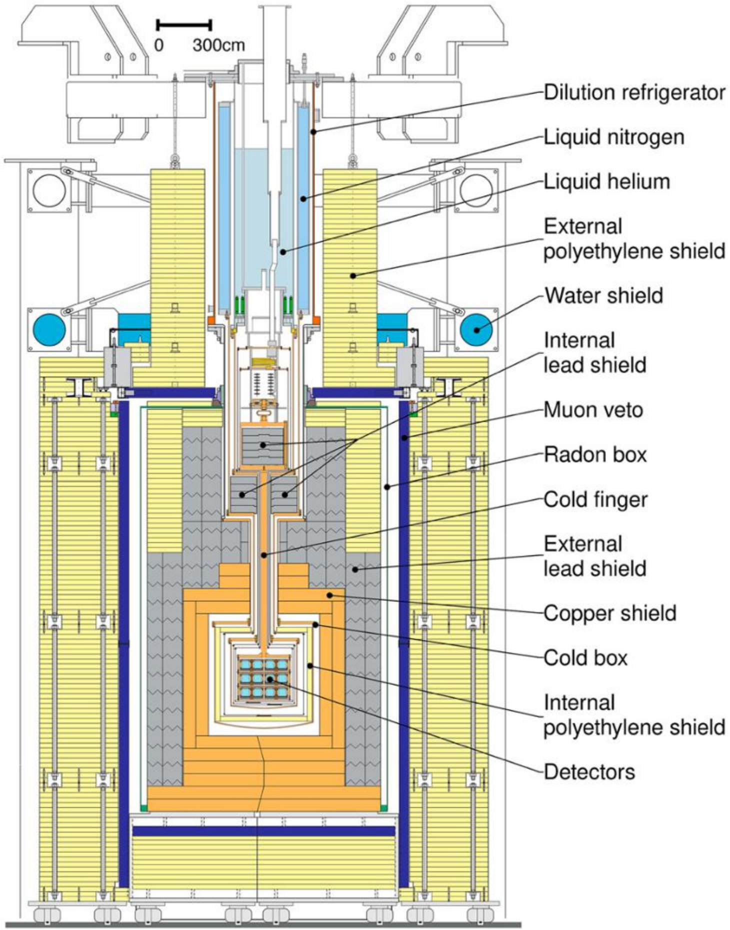
[a] *Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 Munich, Germany*
[b] *Univeristy of Oxford, Physics Department, Oxford OX1 3RH, UK*
[c] *Laboratori Nazionali del Gran Sasso, I-67010 Assergi, Italy*
[d] *Technische Universität München, Physik Department, D-85747 Munich, Germany*

Received 8 February 1999; accepted 1 April 1999

Cryogenic Bolometers – CRESST

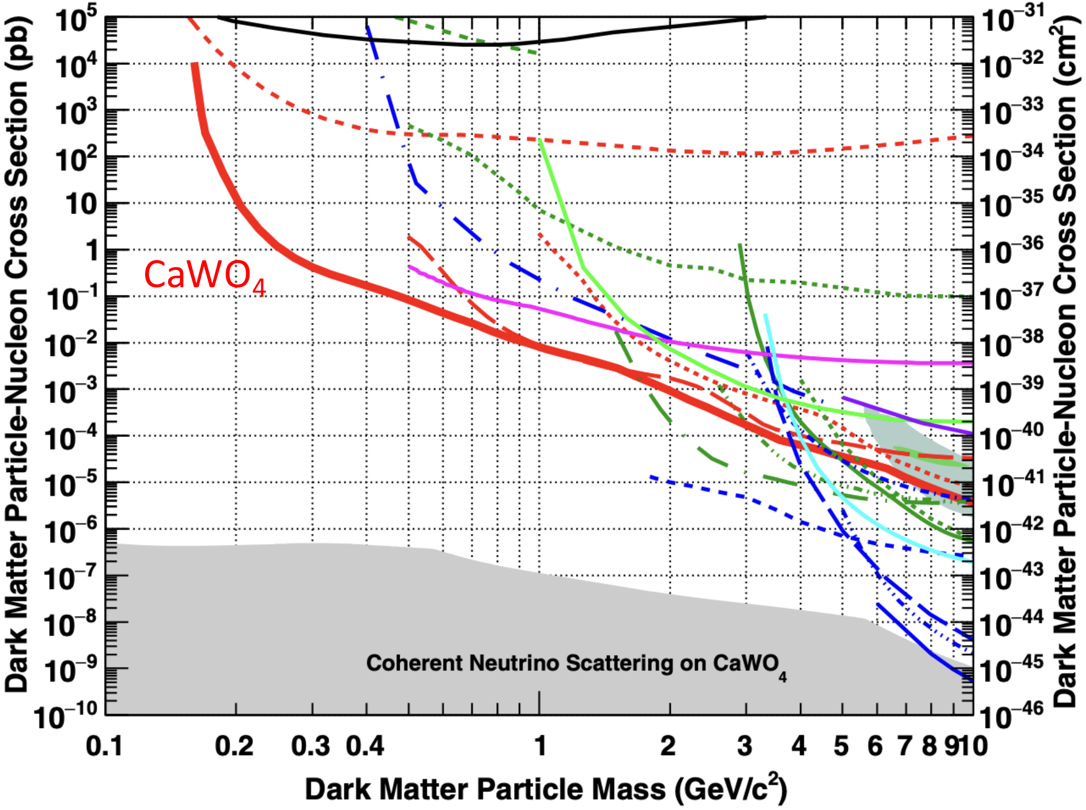
- The ***CRESST*** project proceeded in parallel to ***CDMS*** in Europe alongside ***EDELWEISS***
- Each of these is a cryogenic dark matter search looking for athermal phonons





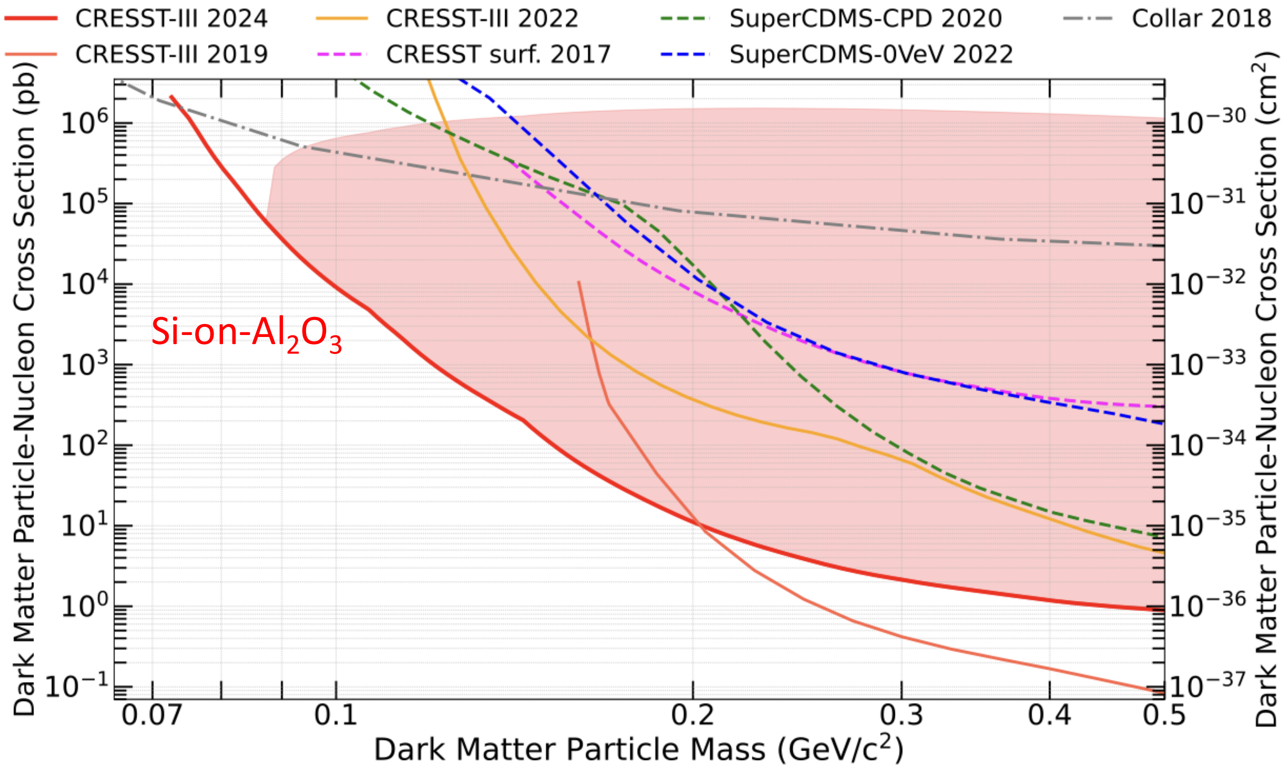
Angloher et al, Comms. Phys. **9**, 163 (2026)

Cryogenic Bolometers – CRESST



Abdelhameed et al, PRD **100**, 102002 (2019)

Cryogenic Bolometers – CRESST

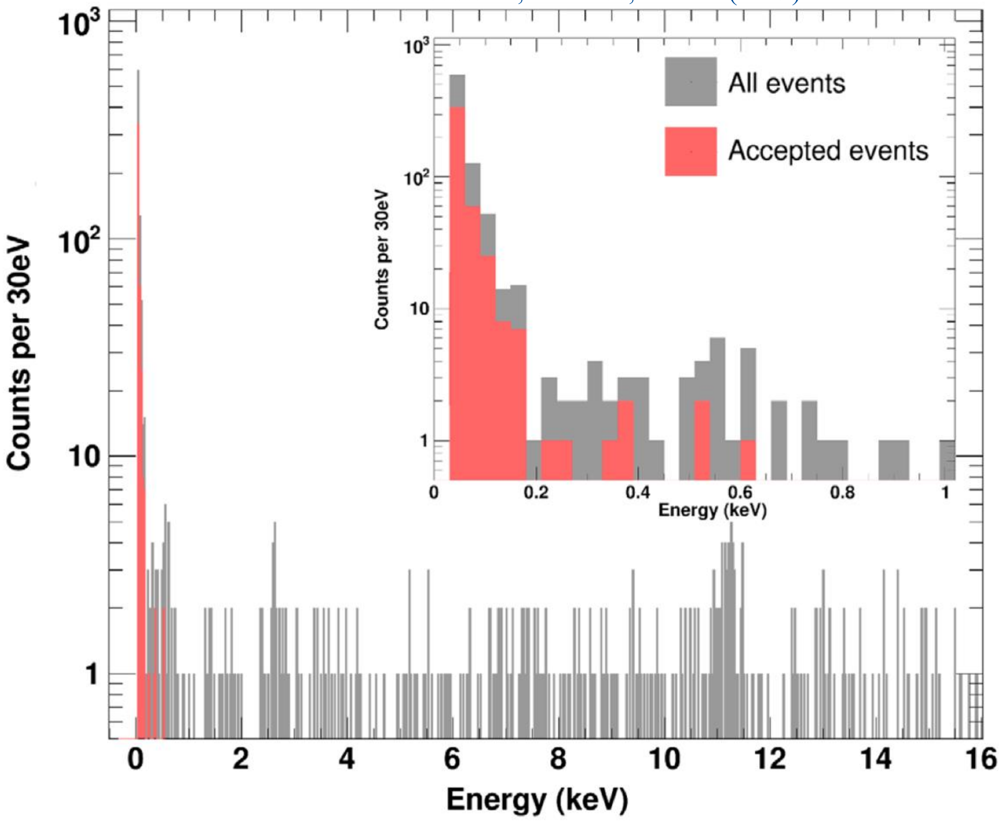


Angloher et al, PRD **110**, 083038 (2024)

Cryogenic Bolometers – CRESST Backgrounds

- But CRESST also is limited by a large event excess at the lowest energies…

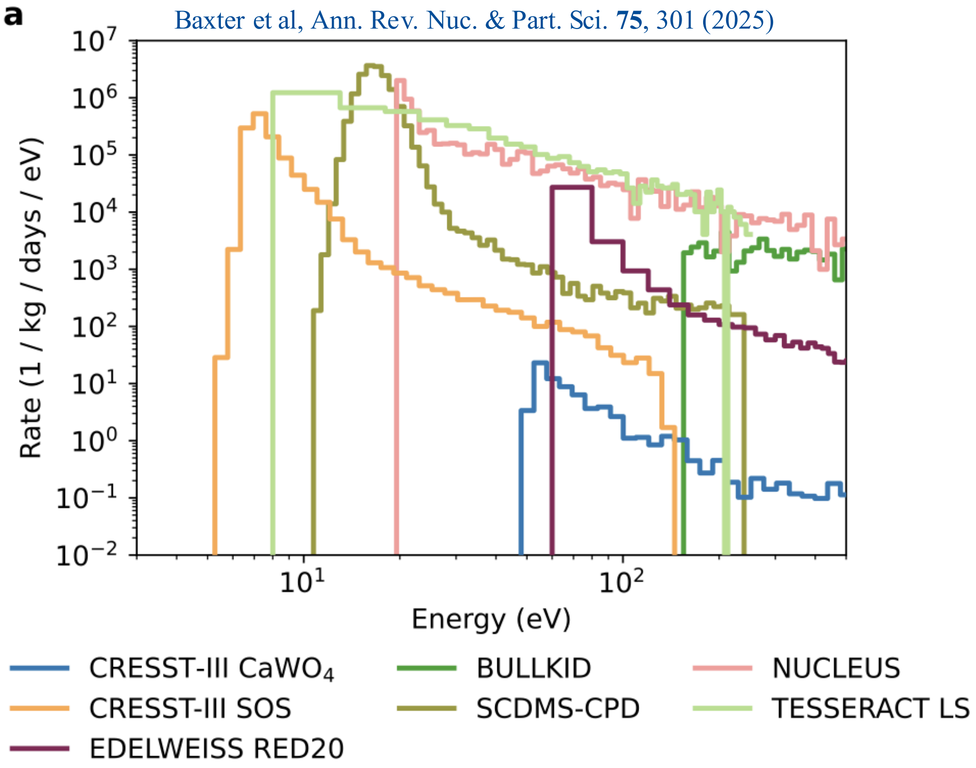
Abdelhameed et al, PRD **100**, 102002 (2019)



Fermilab

Cryogenic Bolometers – the Low-Energy Excess

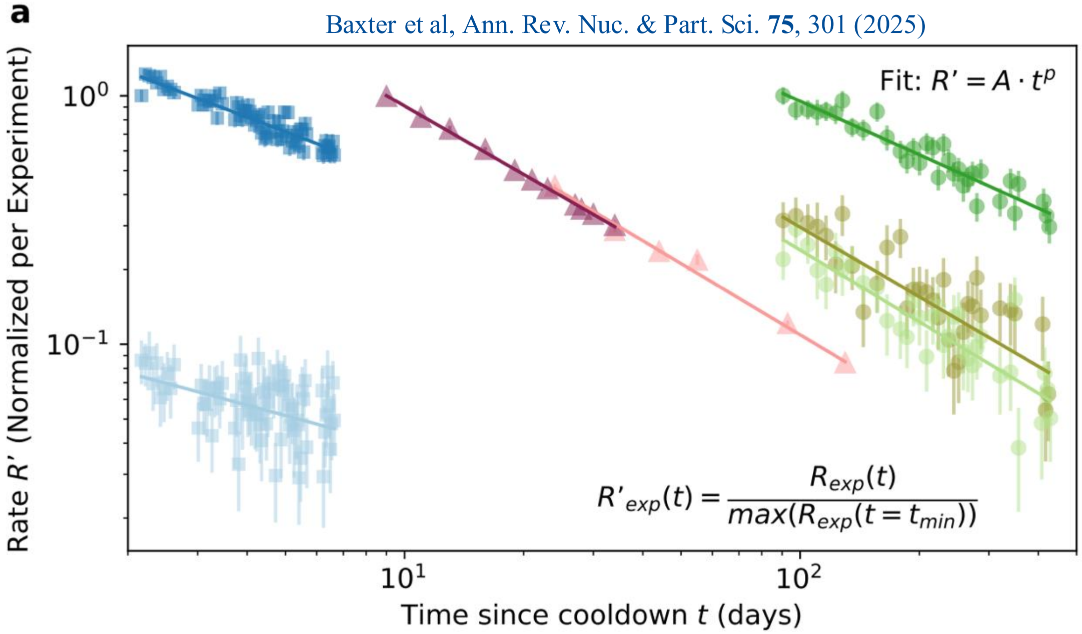
- Unfortunately, everyone sees it…
- But is has some common features:
  - **Exponentially-rising rates at low energies**



Cryogenic Bolometers – the Low-Energy Excess

- Unfortunately, everyone sees it…
- But is has some common features:
  - Exponentially-rising rates at low energies
  - Decays since cooldown

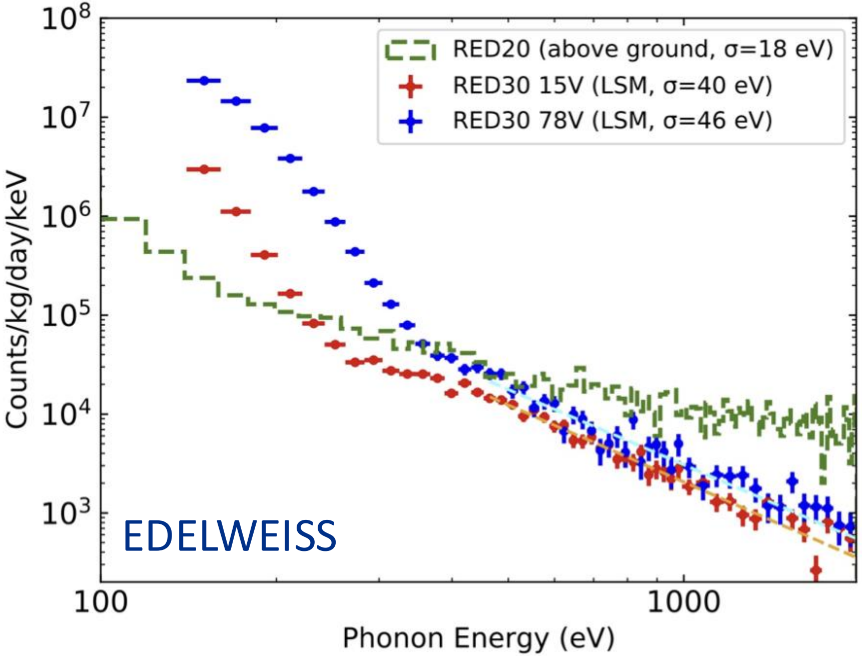
Baxter et al, Ann. Rev. Nuc. & Part. Sci. **75**, 301 (2025)



Cryogenic Bolometers – the Low-Energy Excess

- Unfortunately, everyone sees it…
- But is has some common features:
  - Exponentially-rising rates at low energies
  - Decays since cooldown
  - **Non-ionizing**

Adari et al, SciPost Phys. Proc. 9, 001 (2022)



Cryogenic Bolometers – the EXCESS Workshop

EXCESS 2021

EXCESS 2022

EXCESS22@IDM

EXCESS23@TAUP

EXCESS24@IDM

EXCESS25@LTD

EXCESS26@IDM

Next Workshop: EXCESS27@TAUP

EXCESS

Technical University of Munich

TUM

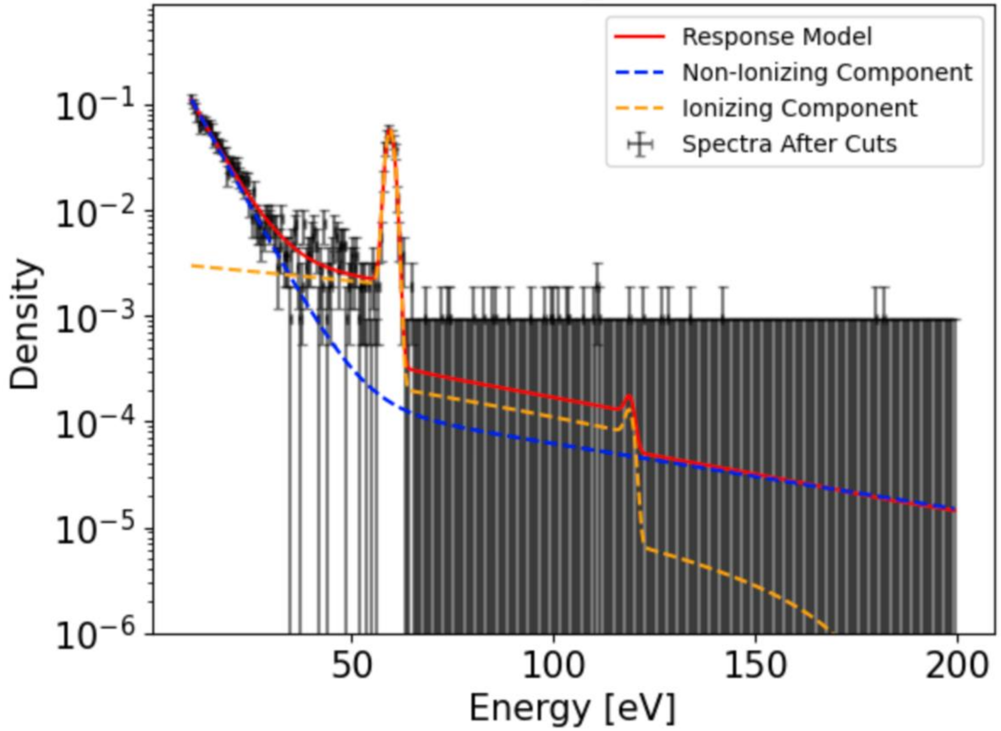
Fermilab

Cryogenic Bolometers – CDMS-HVeV Backgrounds

Different strategies have been tried to handle this

- CDMS HVeV use the 0V data to ***subtract*** the LEE from HV

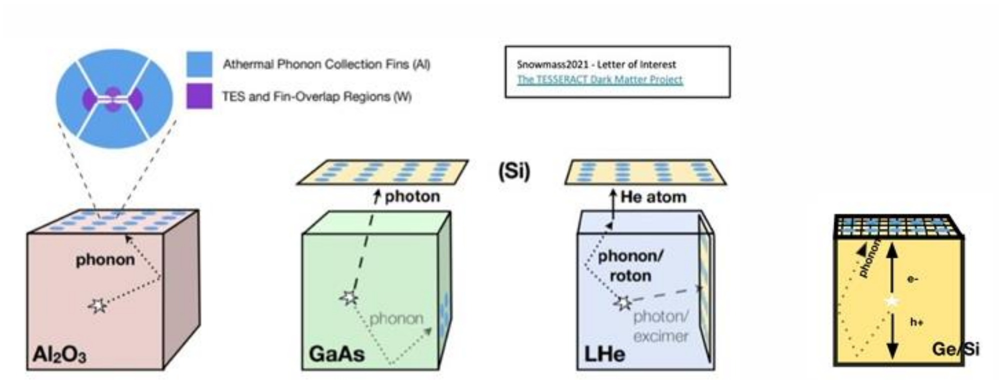
K. Kennard thesis (2026)



Cryogenic Bolometers – TESSERACT

Different strategies have been tried to handle this

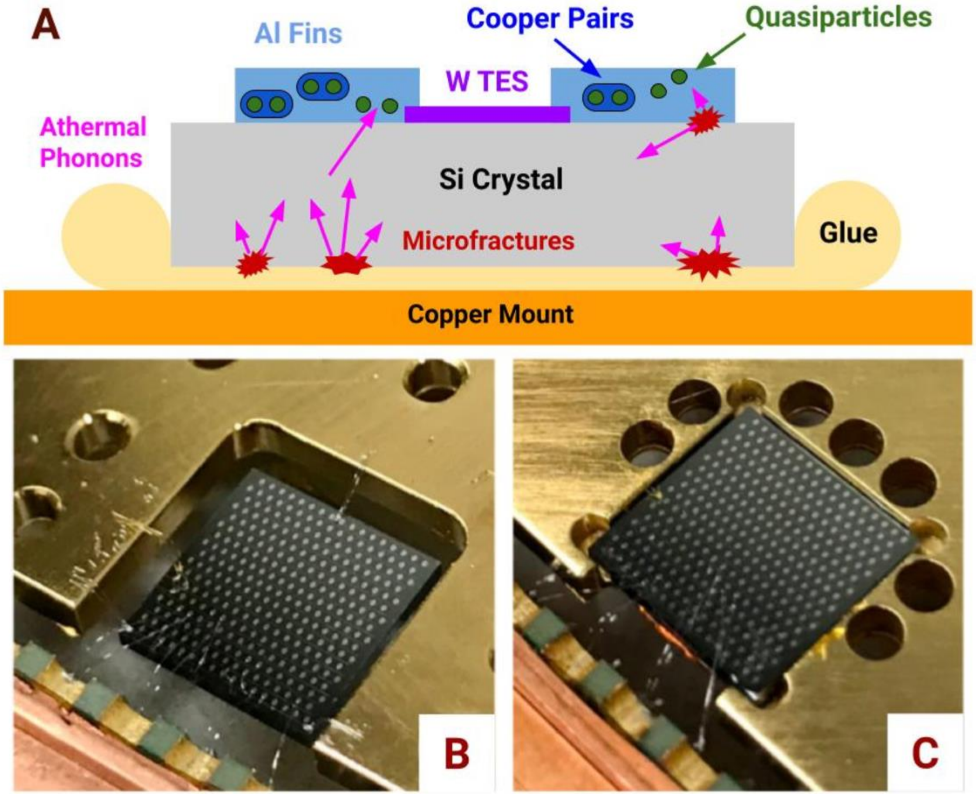
- CDMS HVeV use the 0V data to ***subtract*** the LEE from HV
- TESSERACT is trying different methods in different **targets**



Cryogenic Bolometers – TESSERACT LEE Studies (Berkeley)

Different strategies have been tried to handle this

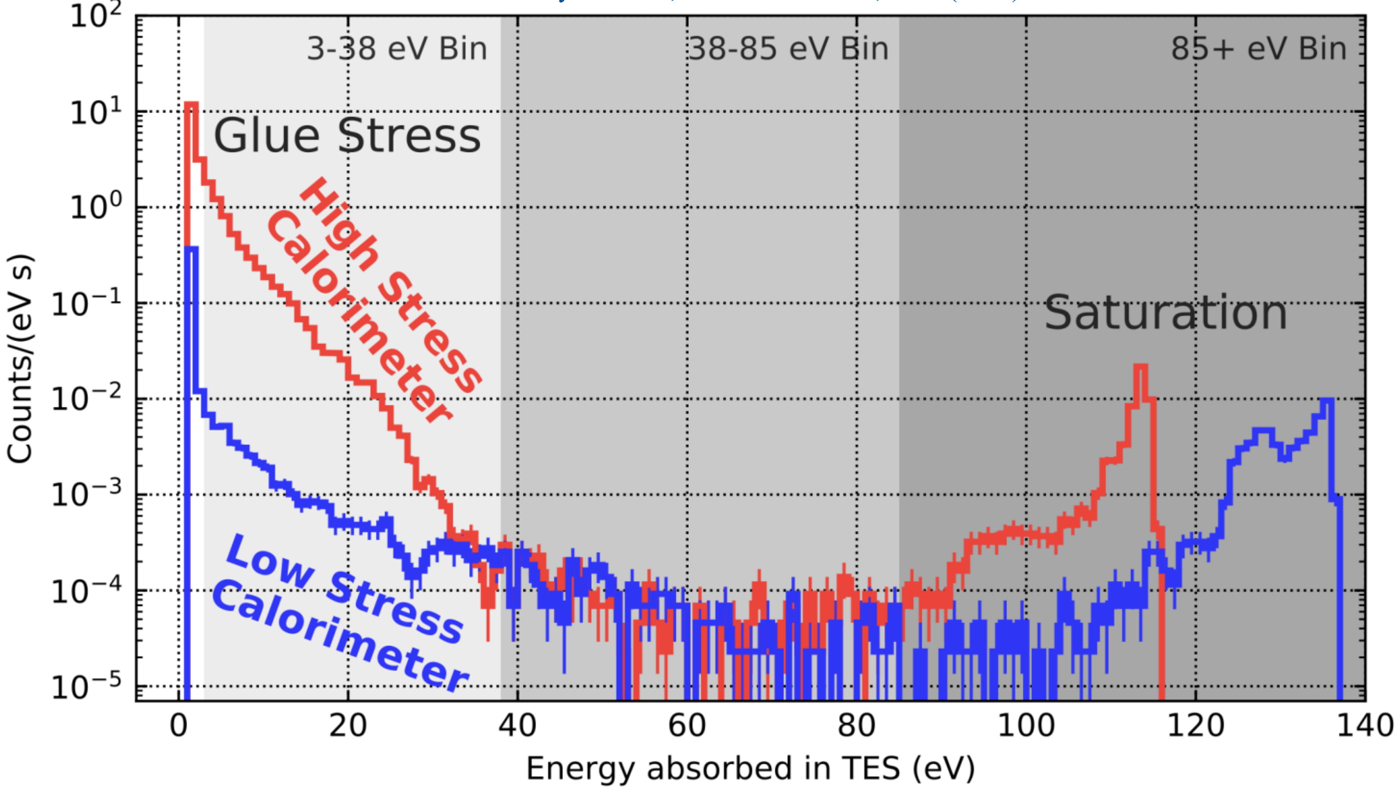
- CDMS HVeV use the 0V data to ***subtract*** the LEE from HV
- TESSERACT is trying different methods in different **targets**
- Berkeley group (Matt Pyle) focused on removing **mounting stress**



Anthony-Petersen, Nat. Commun. **15**, 6444 (2024)

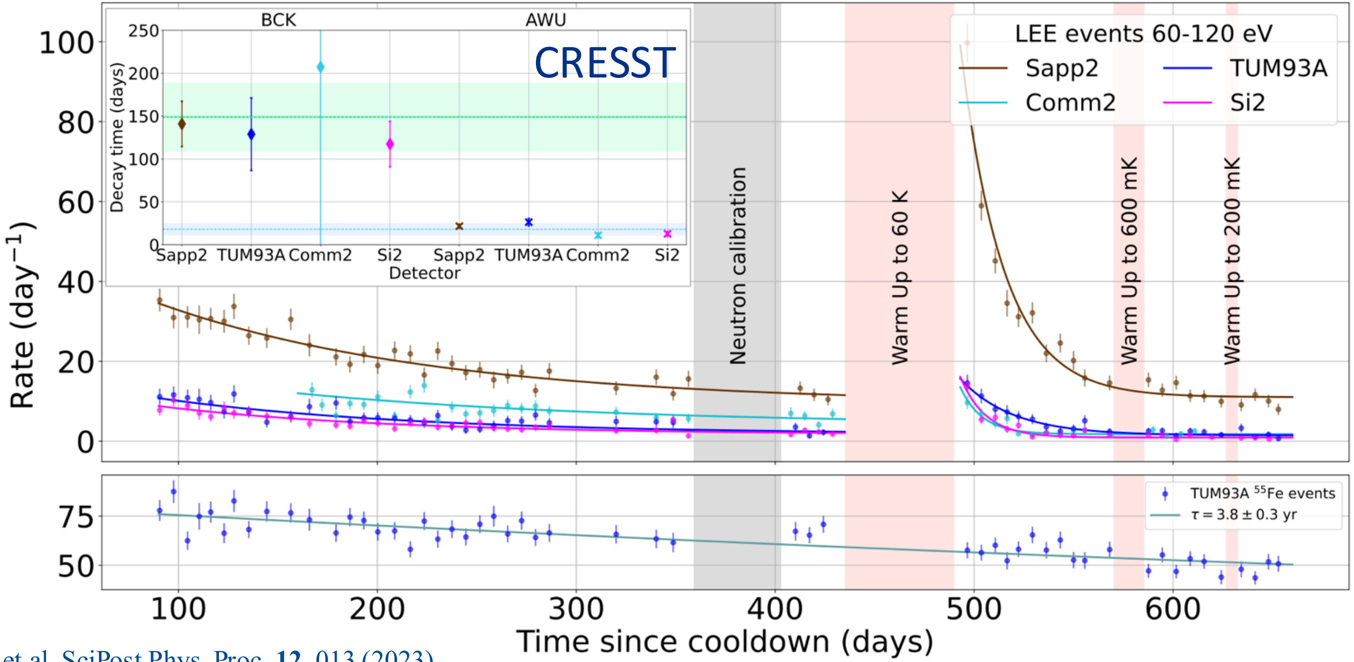
Cryogenic Bolometers – TESSERACT LEE Studies (Berkeley)

Anthony-Petersen, Nat. Commun. **15**, 6444 (2024)



Cryogenic Bolometers – the Low-Energy Excess

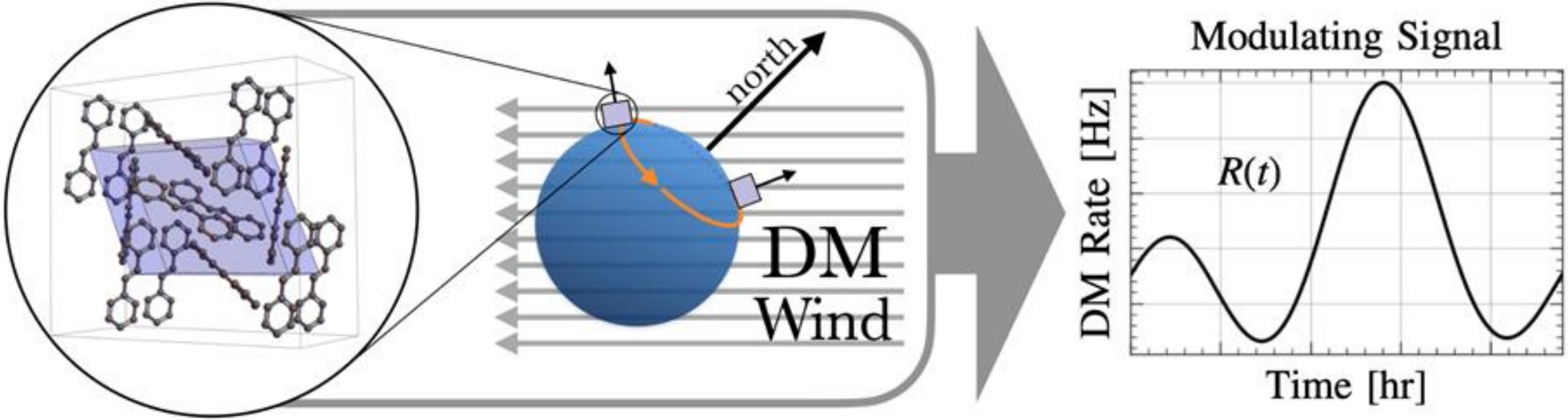
- Leading theory: **stress** is frozen into **metastable states** upon cooldown, either in the bulk or at interfaces, and gradually **releases over long time scales** in **avalanche cascades** that can release large total amounts of energy in the form **phonons**.



Angloher et al, SciPost Phys. Proc. **12**, 013 (2023)

Directional Sub-GeV Dark Matter

- 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)

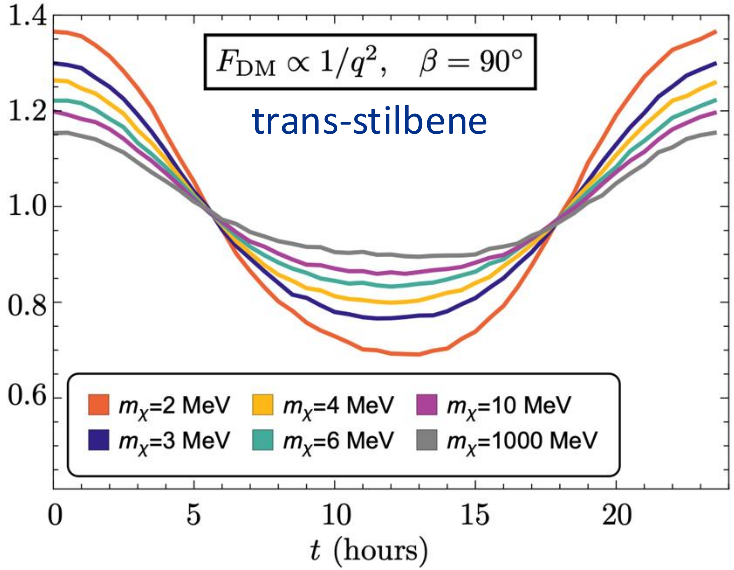


Blanco et al, PRD **104**, 036011 (2021) [arXiv:2103.08601]

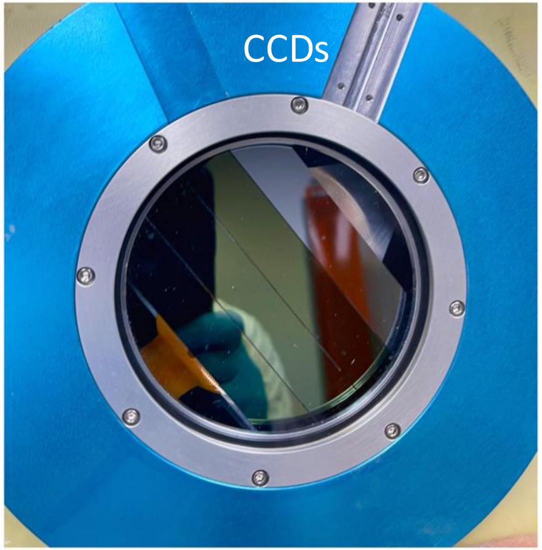
Directional Sub-GeV Dark Matter – A *daily* modulation

1. Need a scalable(=affordable), scintillating solid crystal material that exhibits a strongly-anisotropic wavefunction

2. Need a single-photon counter capable of measuring crystal scintillation light signal



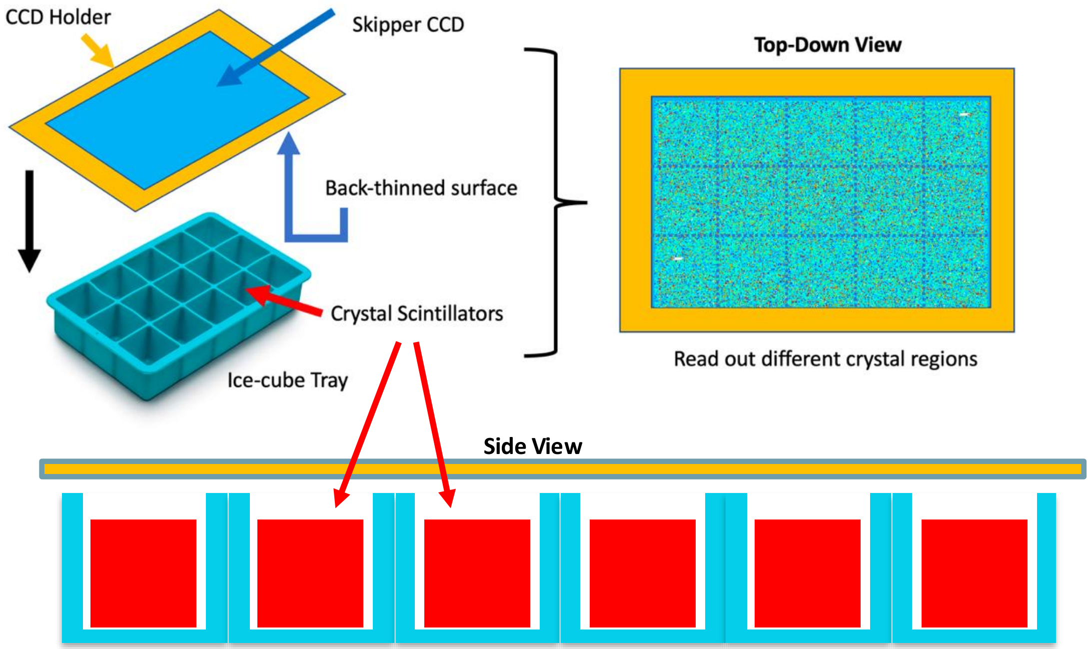
Blanco et al, PRD **104**, 036011 (2021)

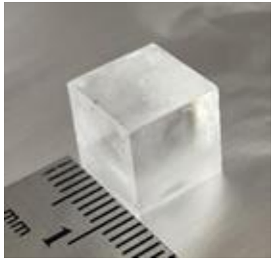


Marrufo Villalpando et al, Proc. SPIE Int. Soc. Opt. Eng. **13103**, 131030F (2024)

Directional Sub-GeV Dark Matter – Organic Scintillators

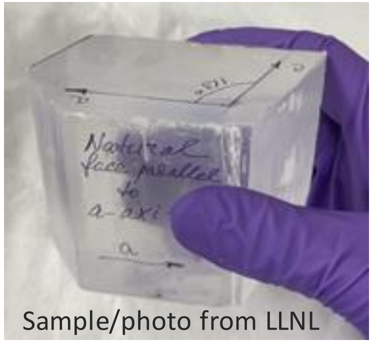
- 10g trans-Stilbene prototype read out by Skipper CCD deployed in MINOS this year





2025
1g cubes

20XX
100g+ “cubes”



Sample/photo from LLNL

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

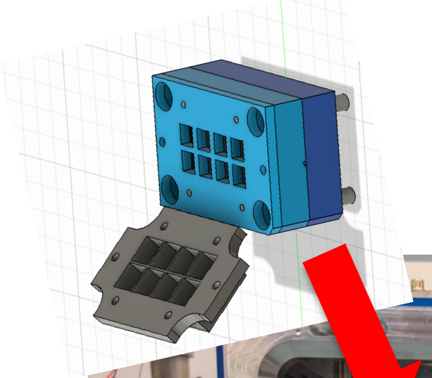
MIT Physics Team – L. Winslow, **N. Hoch (GIRA)**

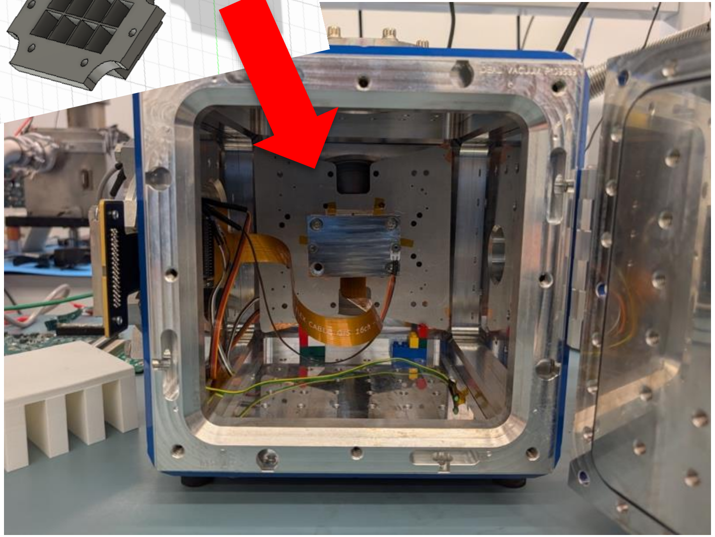
MIT Chemistry Team – D. Freedman, D. Johnson

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

Penn State – C. Wagner, B. Lillard

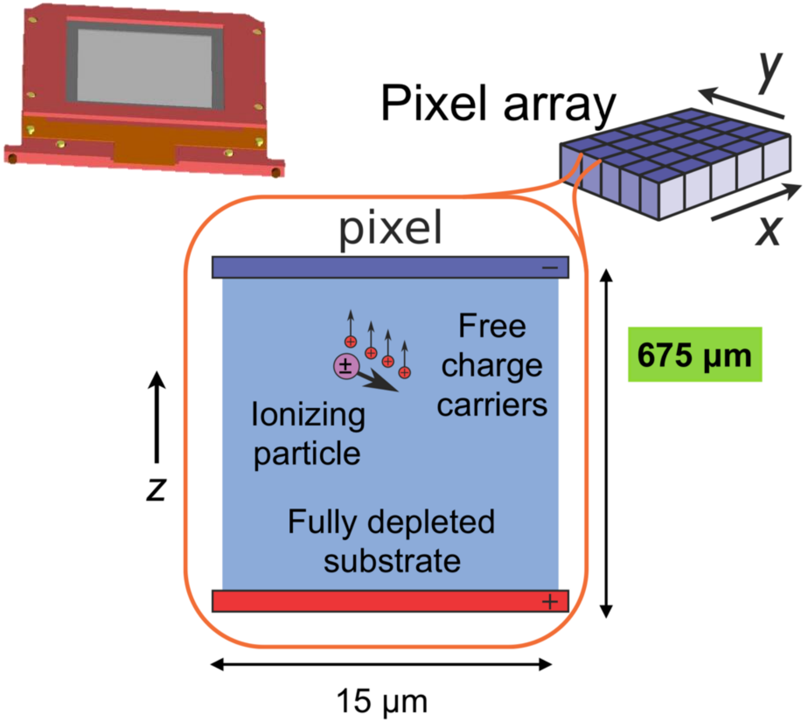
Toronto – M. Diamond, Y. Kahn





Special Thanks – J. Estrada, J. Tiffenberg

The CCD Program

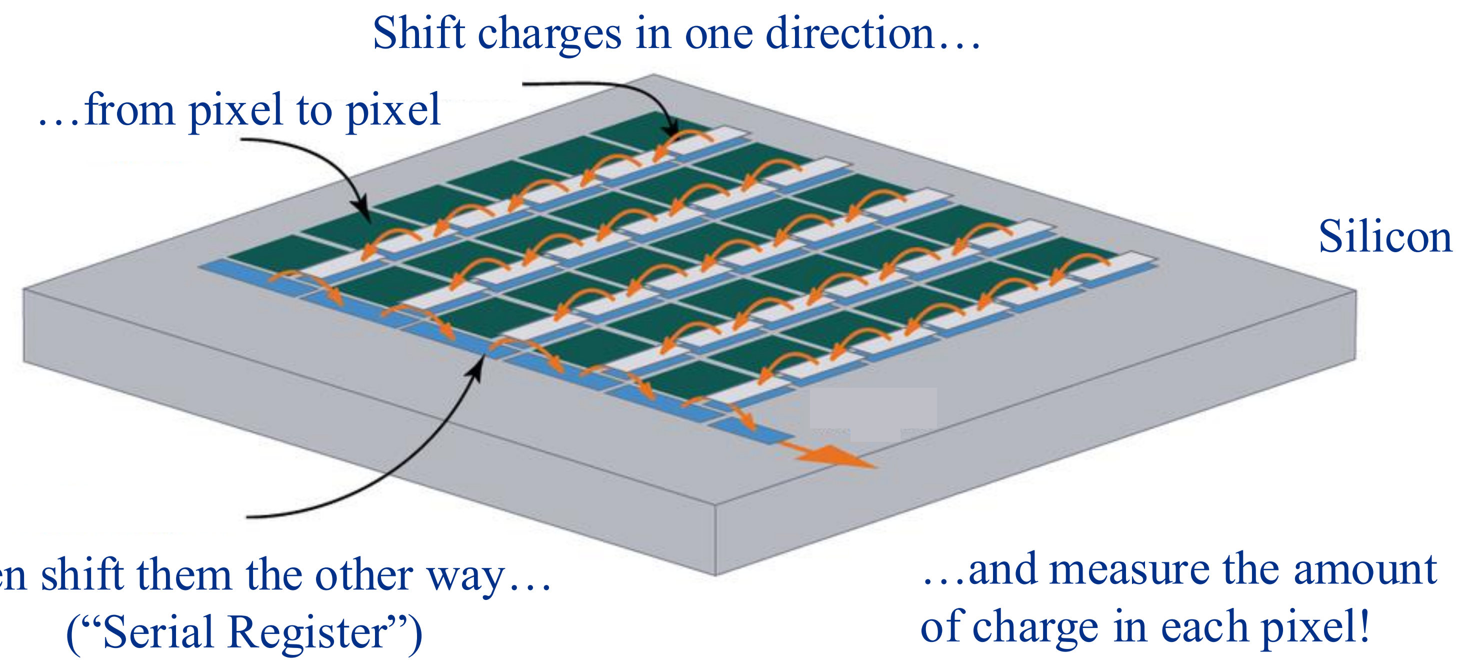


Interaction with silicon produces free charge carriers…

- …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

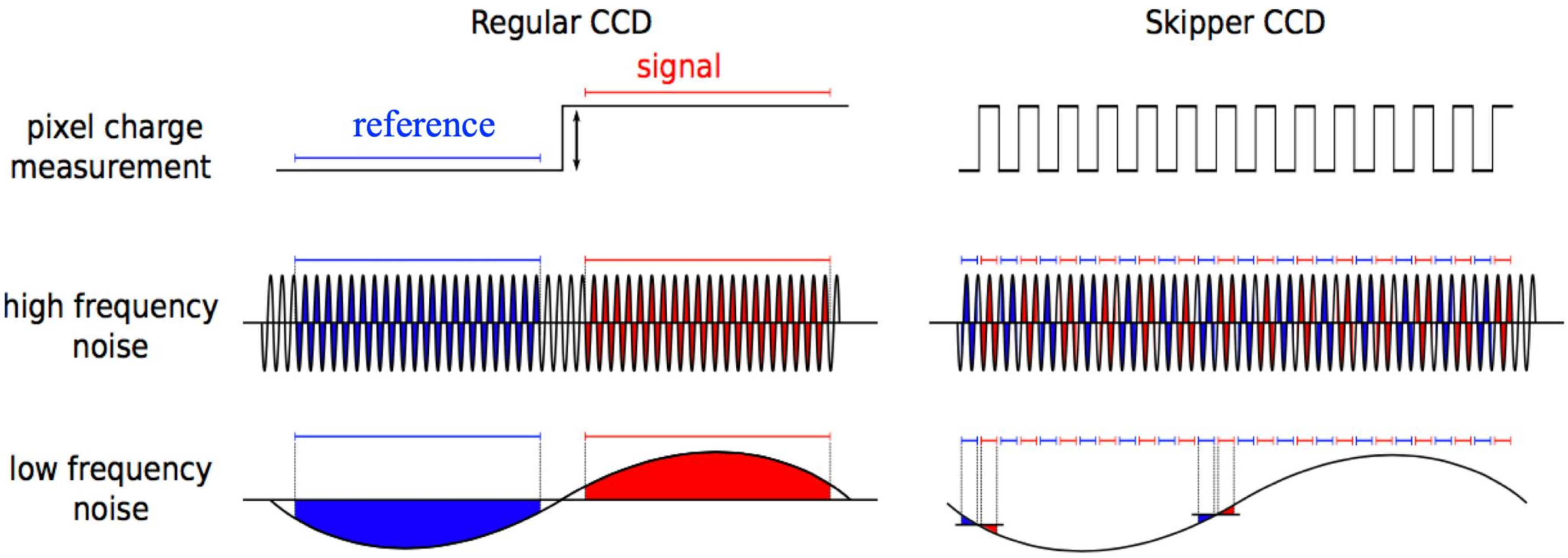
Charge Coupled Devices



Graphic by Stemmer Imaging

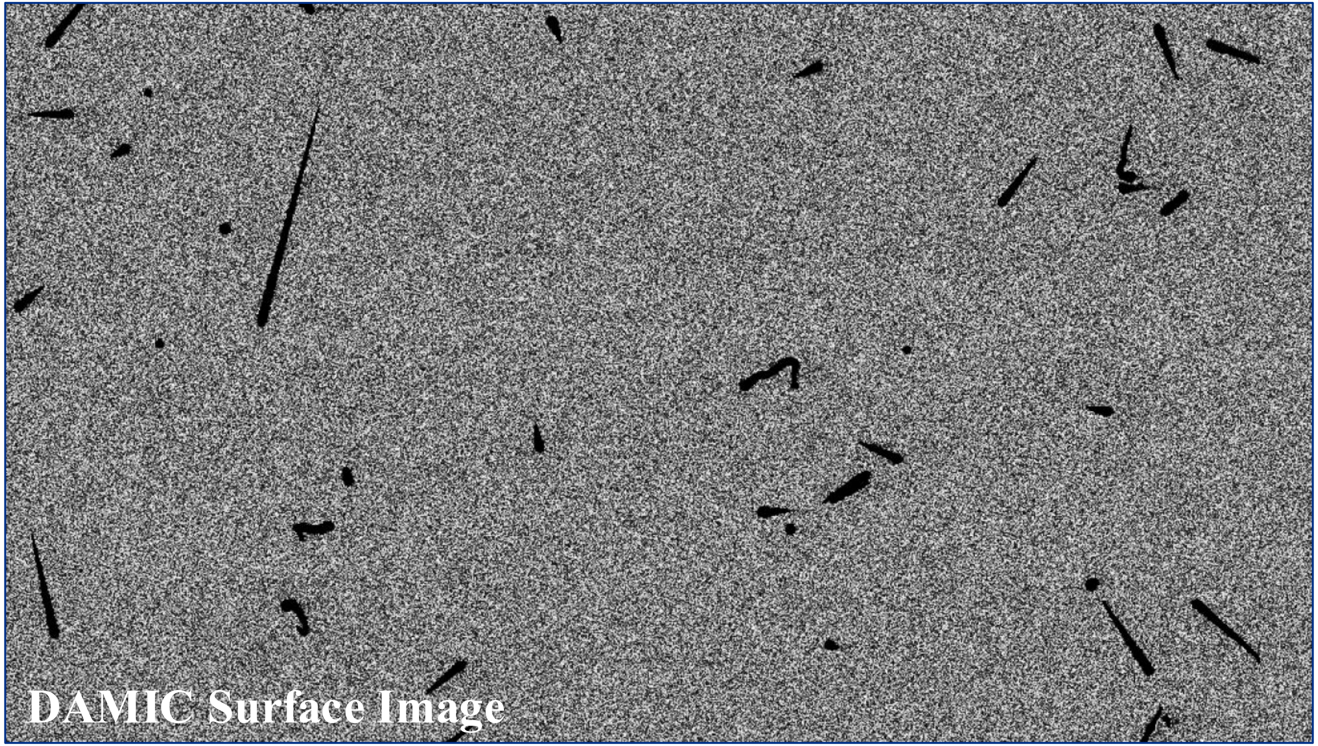
The CCD Program – Skipper Amplifiers

Skipper Amplifiers: allow repeated, non-destructive readout

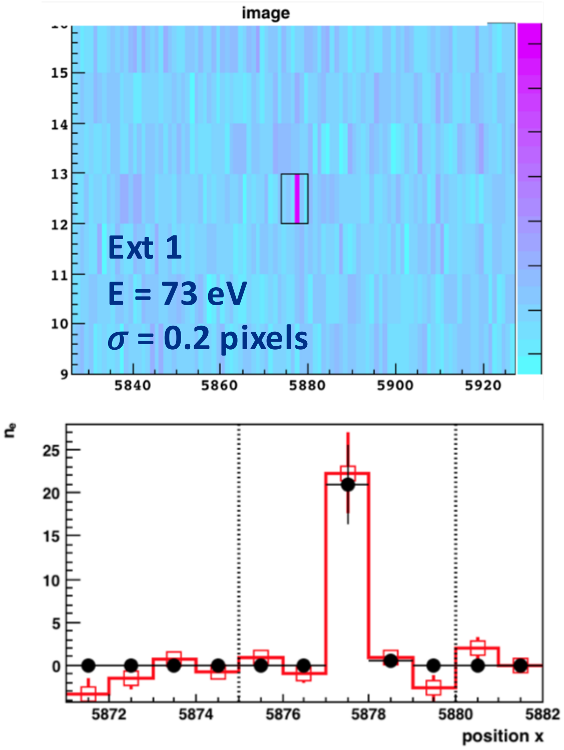


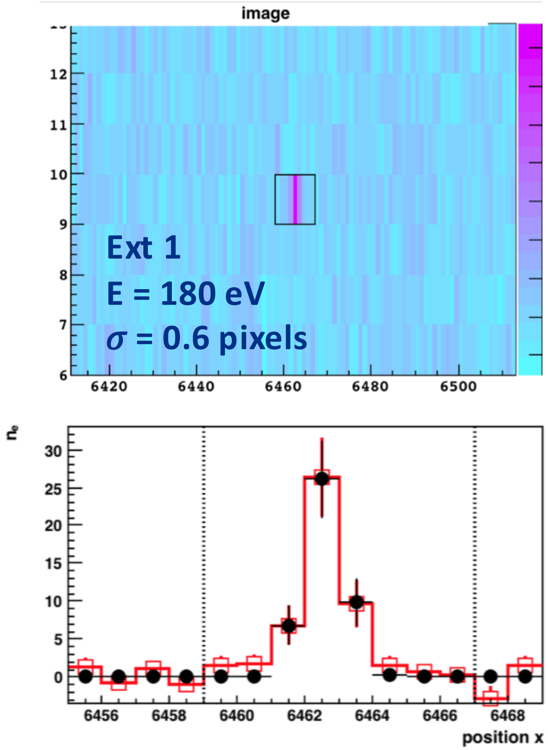
Tiffenberg et al, PRL **119**, 131802 (2017) [arXiv:1706.00028]

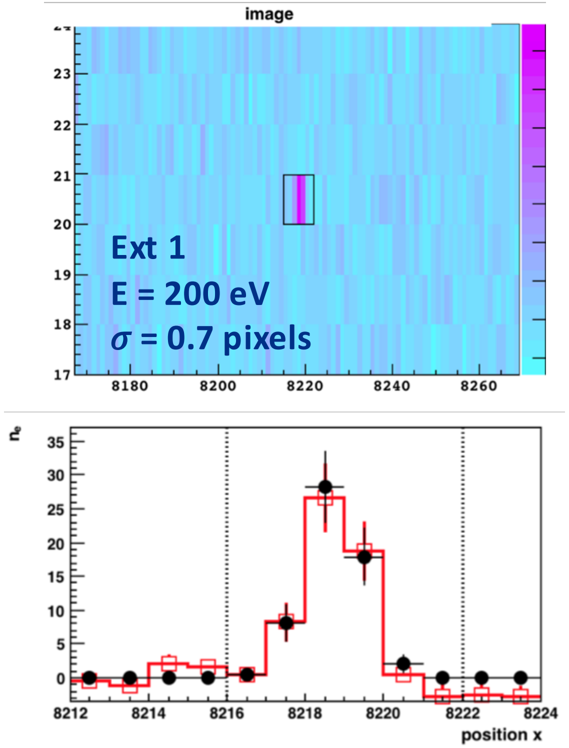
The CCD Program – DAMIC



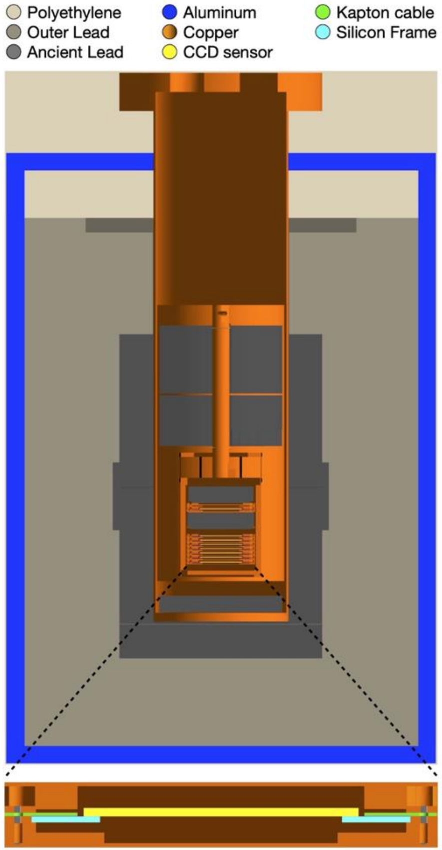
The CCD Program – DAMIC

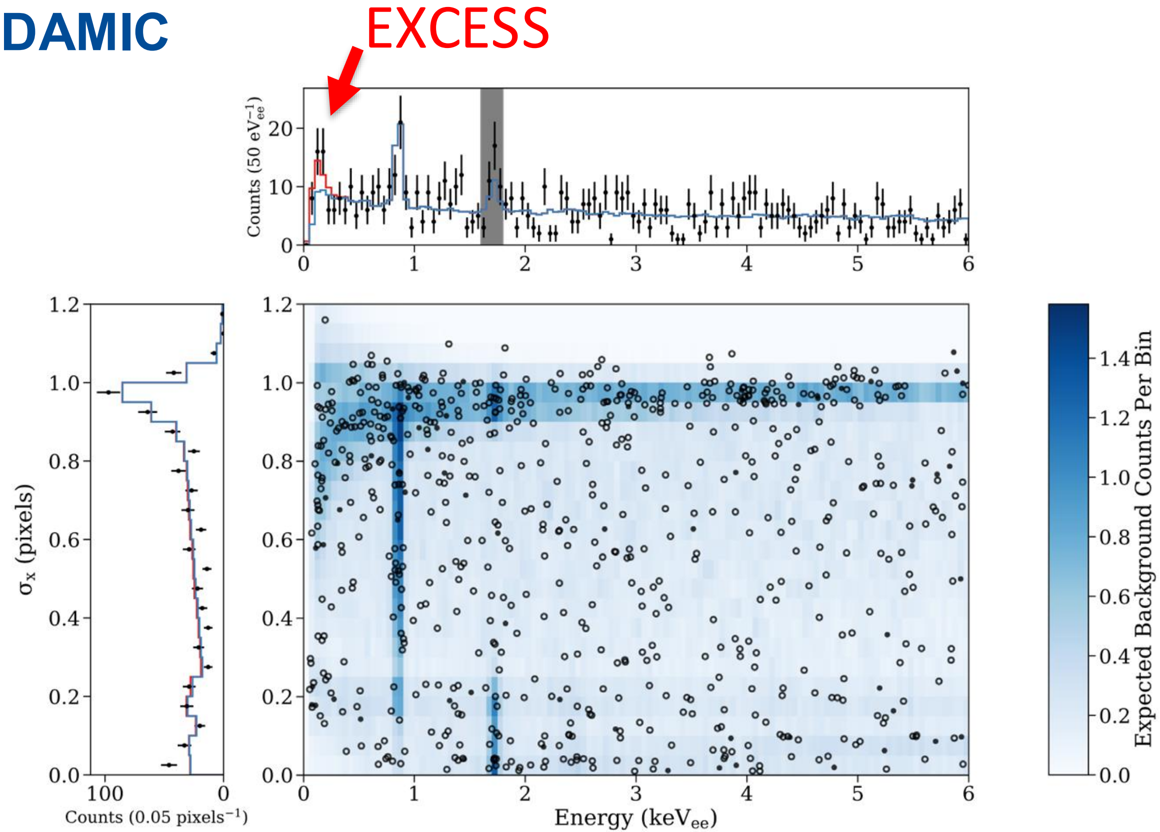






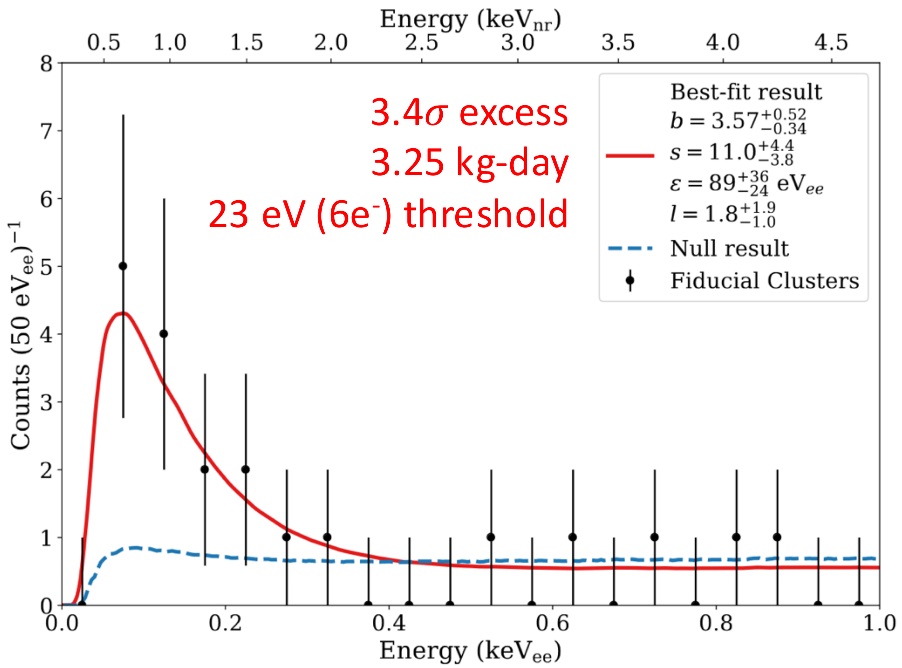
The CCD Program – DAMIC



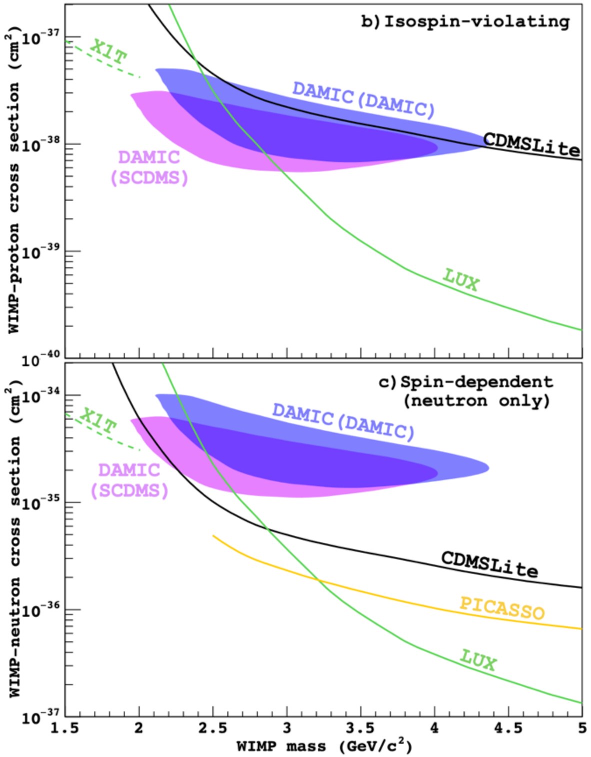


A. Aguilar-Arevalo et al. PRD **105**, 062003 (2022) [arXiv:2110.13133]

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

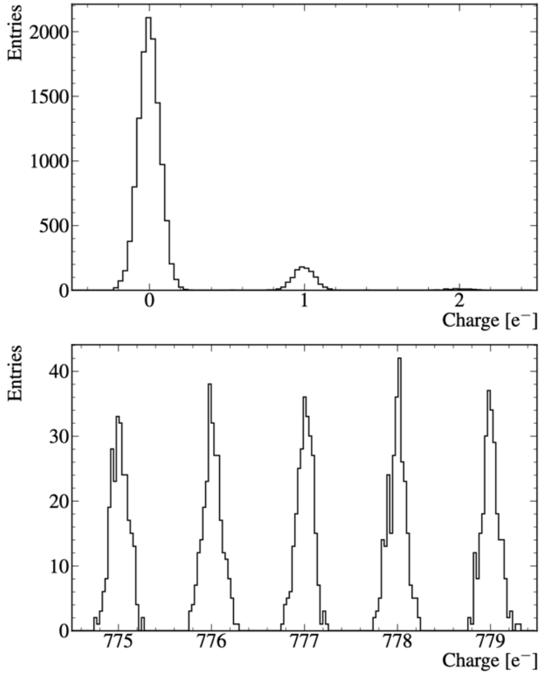


Aguilar-Arevalo et al, PRD **109**, 062007 (2024) [arXiv:2306.01717]



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

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

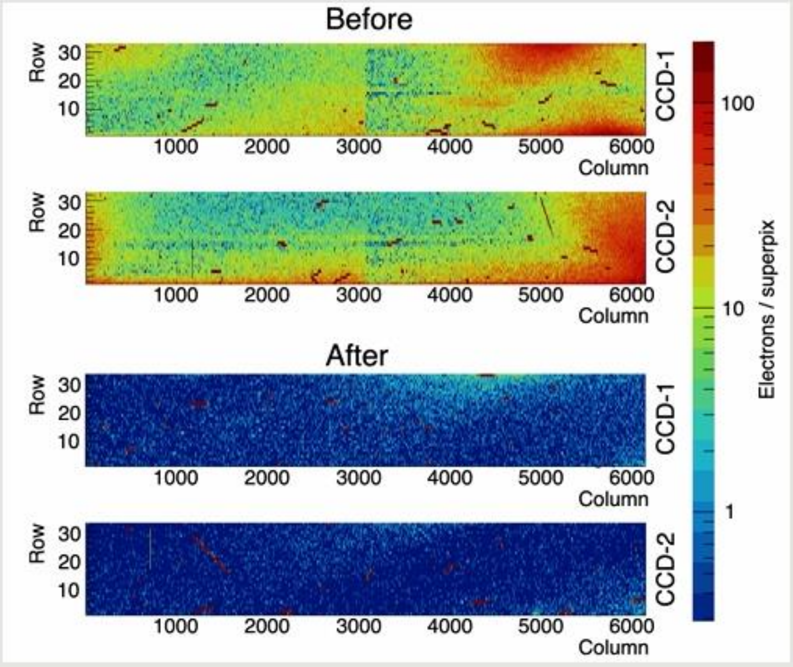


- Record silicon dark rates of 1.4 x 10^{-5} e^-/pix/day
- New limits on MeV-scale DM scattering

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

see talk from Ansh Desai at IDM 2026

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



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

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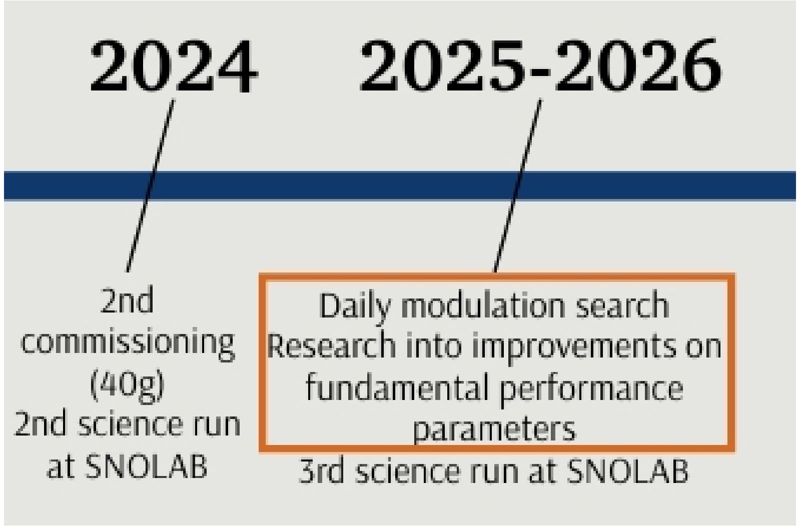
- New limits on MeV-scale DM scattering

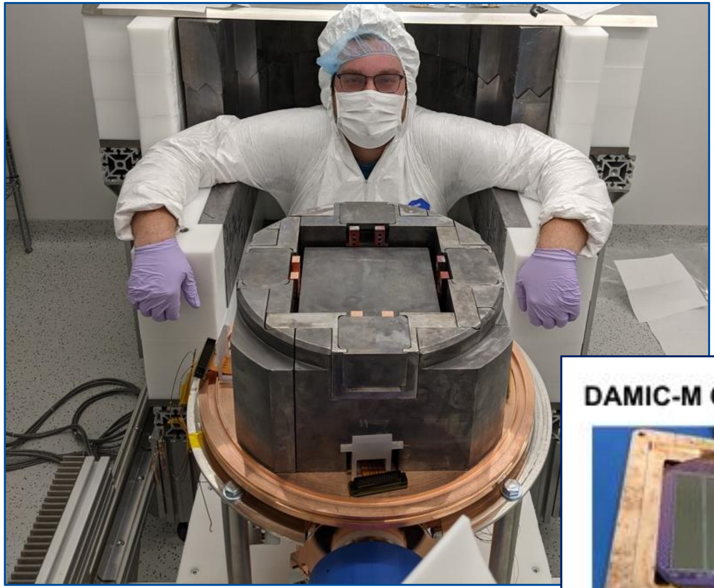


see talk from Ansh Desai at IDM 2026

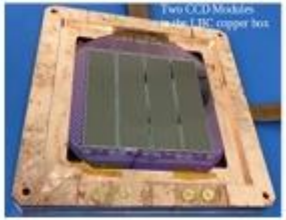
Fermilab

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

LBC Demonstrator (taking data since 2022)

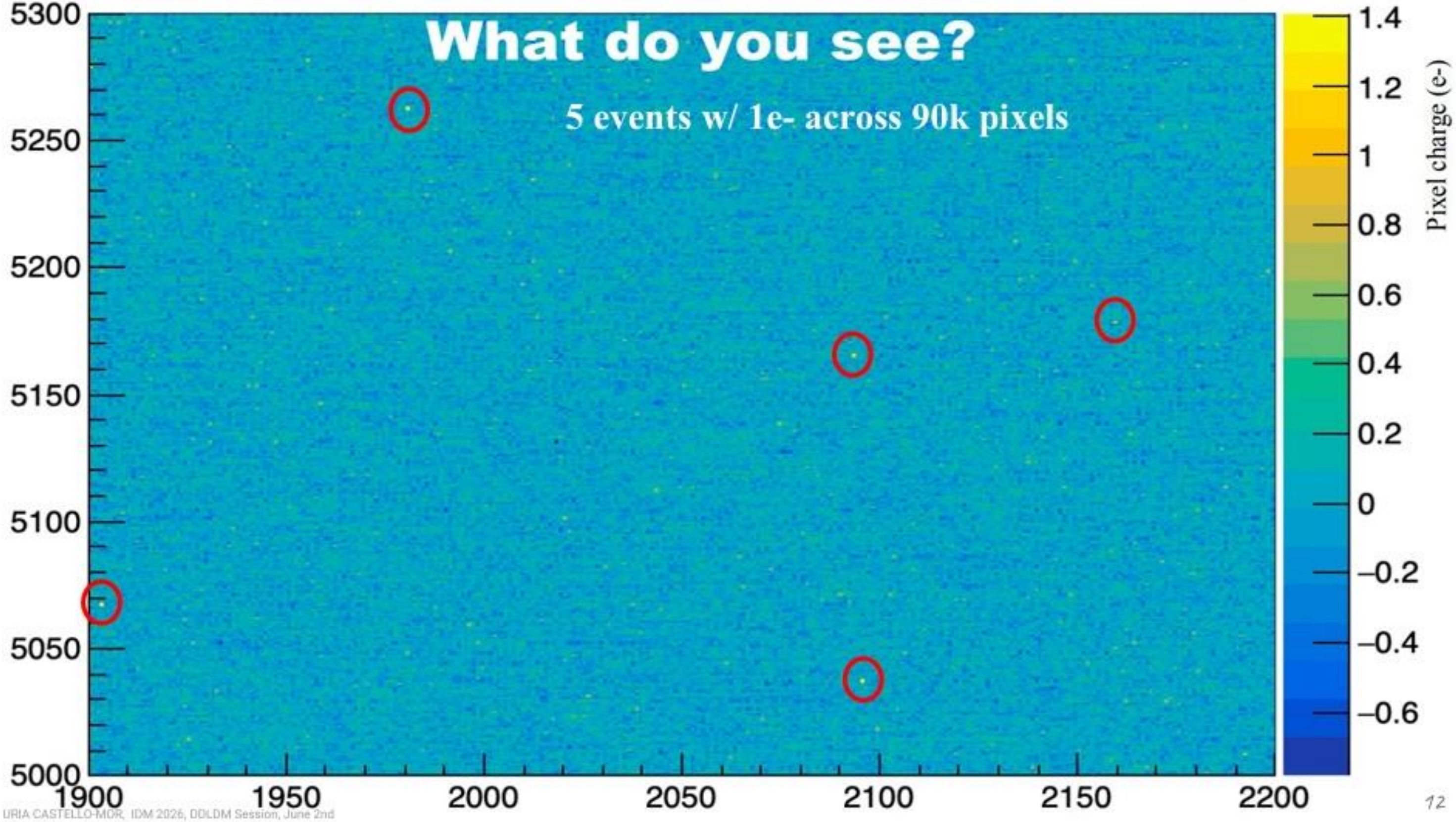


DAMIC-M CCD module



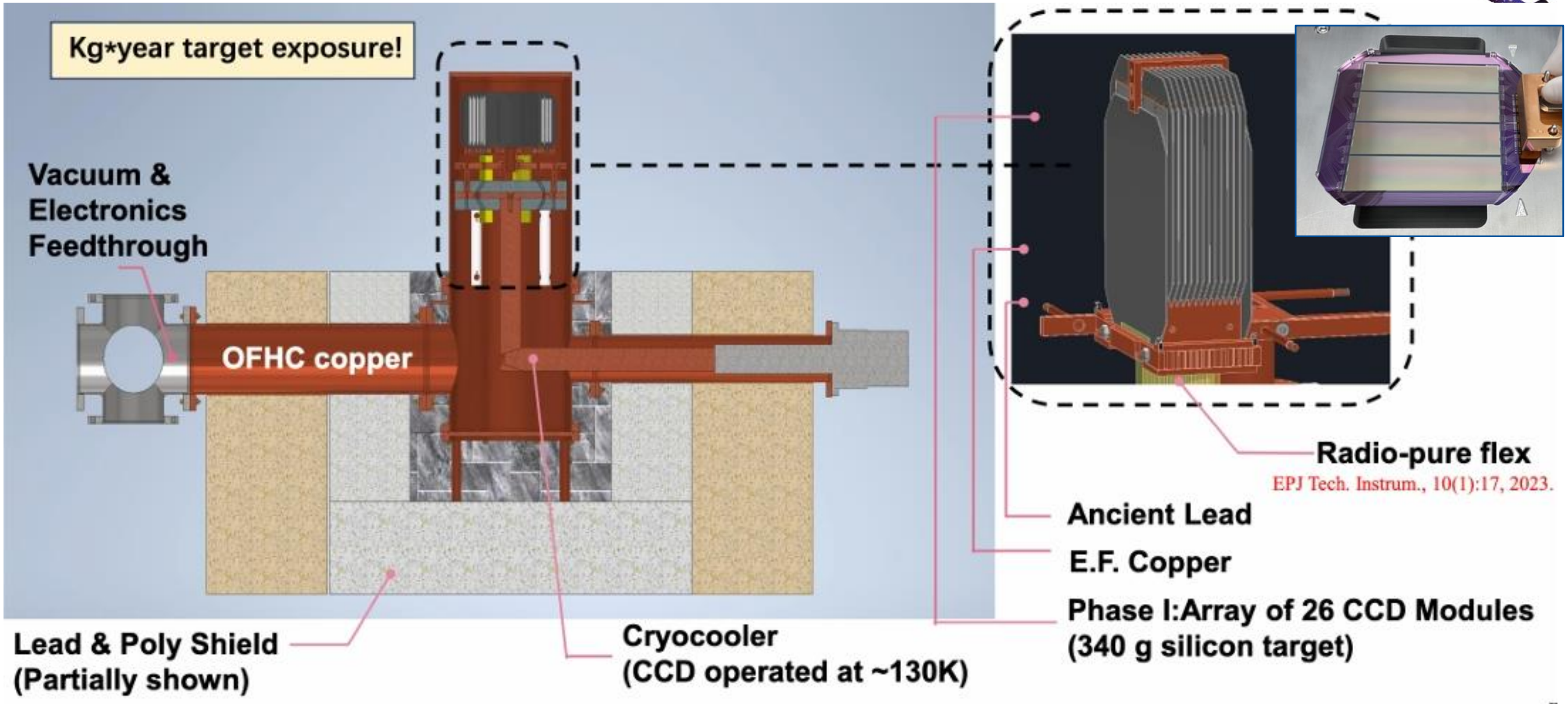
see Arnquist et al, PRL **130**, 171003 (2023) [arXiv:2302.02372]

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



see talk from Nuria Castello-Mor at IDM 2026

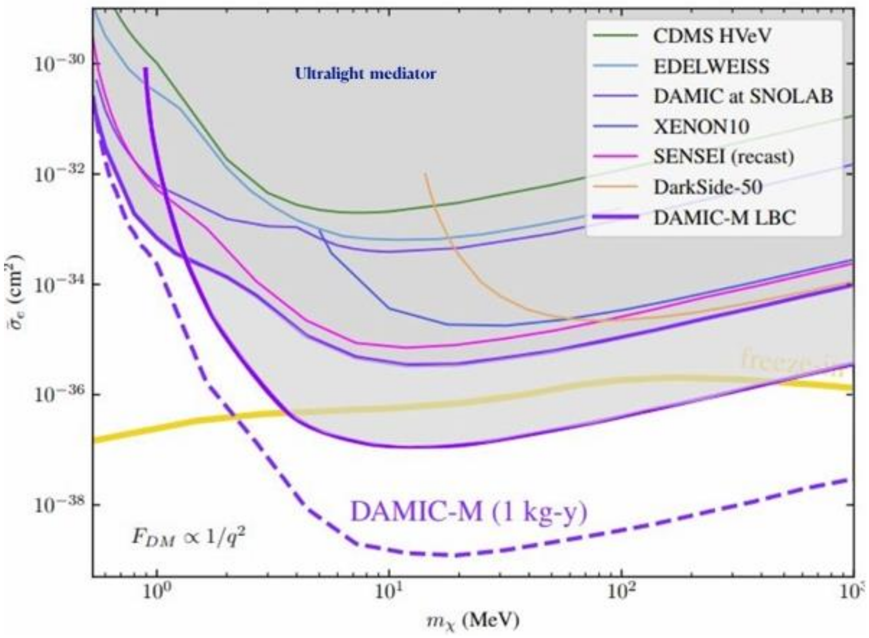
The CCD Program – DAMIC-M (~250g; 1e threshold)



see talk from Rocio Vilar at IDM 2026

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

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



see talk from Rocio Vilar at IDM 2026

What have I covered?

- The **history** of particle DM direct detection since the mid-90's
- The **Xe TPC program**, its limitations, and the physics motivation for *precision*, low-energy threshold detectors
- **Single-charge detectors**, such as Skipper CCDs, cryogenic NTL phonon sensors, (and TPCs)
- **Quantum 1.0 phonon detectors** – like **SuperCDMS**, **CRESST**, and **TESSERACT** – measuring spikes in the QP volume density of a superconductor
- **Cryogenic phonon backgrounds**, classified as the low-energy excess (LEE) and some strategies to overcome or avoid it

What didn't I cover?

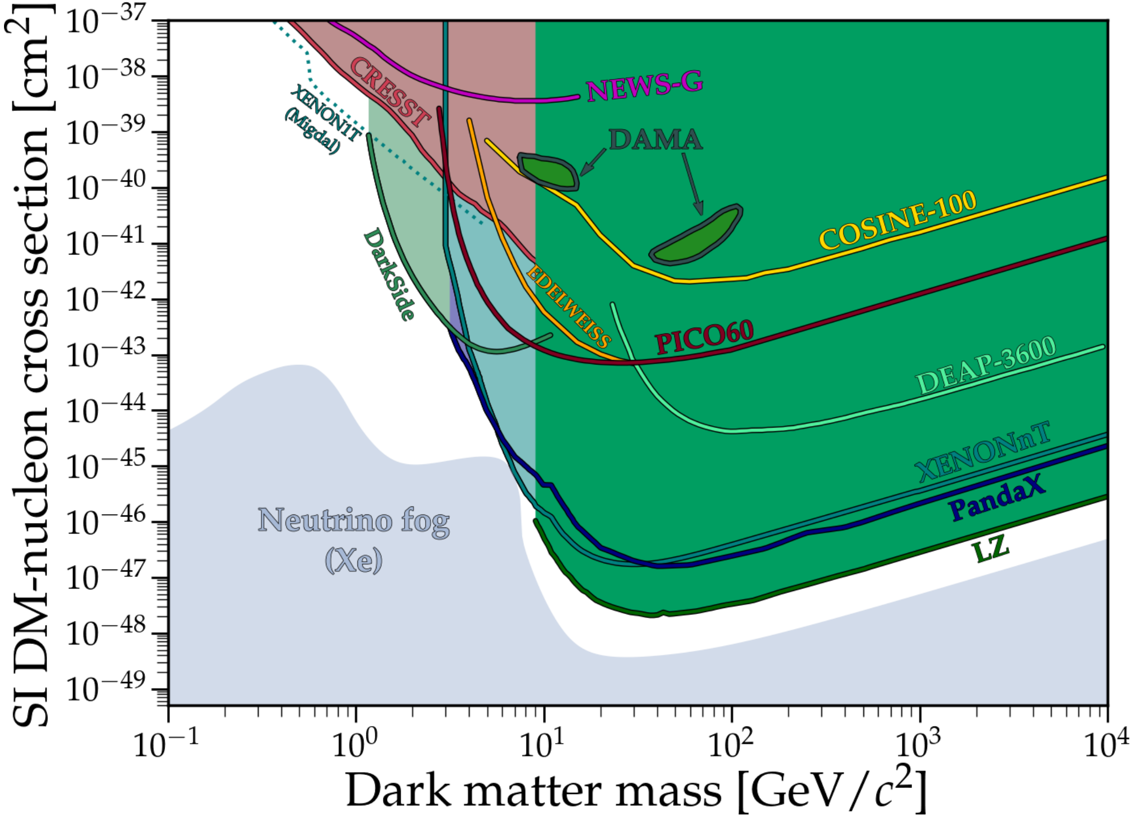
- Annual Modulation & the **DAMA** Excess
  - its impact on the growth of the field
  - its possible explanations
  - the myriad of experiments attempting to verify its signal
- Argon experiments (**Darkside**, **DEAP**)
  - Very similar to the Xe TPC program I described, but not as competitive*
  - Pulse shape discrimination mechanisms!
- Bubble Chambers & Spin-Dependent Detection (**PICO/SBC**) – my own thesis!
  - Up to 10^9 background rejection, easy scalability, target flexibility
- Future Novel Detectors (**RES-NOVA**, **SPLENDOR**, **HONEYCOMB**, **HERALD, DELight**)
  - These almost all use a combination of the discussed technologies, but with novel targets or integration

What didn't I cover?

- Annual Modulation & the **DAMA** Excess
  - its impact on the growth of the field
  - its possible explanations
  - the myriad of experiments attempting to verify its signal
- Argon experiments (**Darkside**, **DEAP**)
  - Very similar to the Xe TPC program I described, but not as competitive*
  - Pulse shape discrimination mechanisms!
- Bubble Chambers & Spin-Dependent Detection (**PICO/SBC**) – my own thesis!
  - Up to 10^9 background rejection, easy scalability, target flexibility
- Future Novel Detectors (**RES-NOVA**, **SPLENDOR**, **HONEYCOMB**, **HERALD, DELight**)
  - These almost all use a combination of the discussed technologies, but with novel targets or integration
- **Quantum 2.0 Sensors… (anything based on qubits & utilizing entanglement)**

Landscape for Particle-like DM – Nucleon

- DM-nucleon coupling has been heavily probed by xenon & argon experiments



Plots from Ciaran O'Hare [https://github.com/cajohare/DirectDetectionPlots]

Landscape for Particle-like DM – Nucleon

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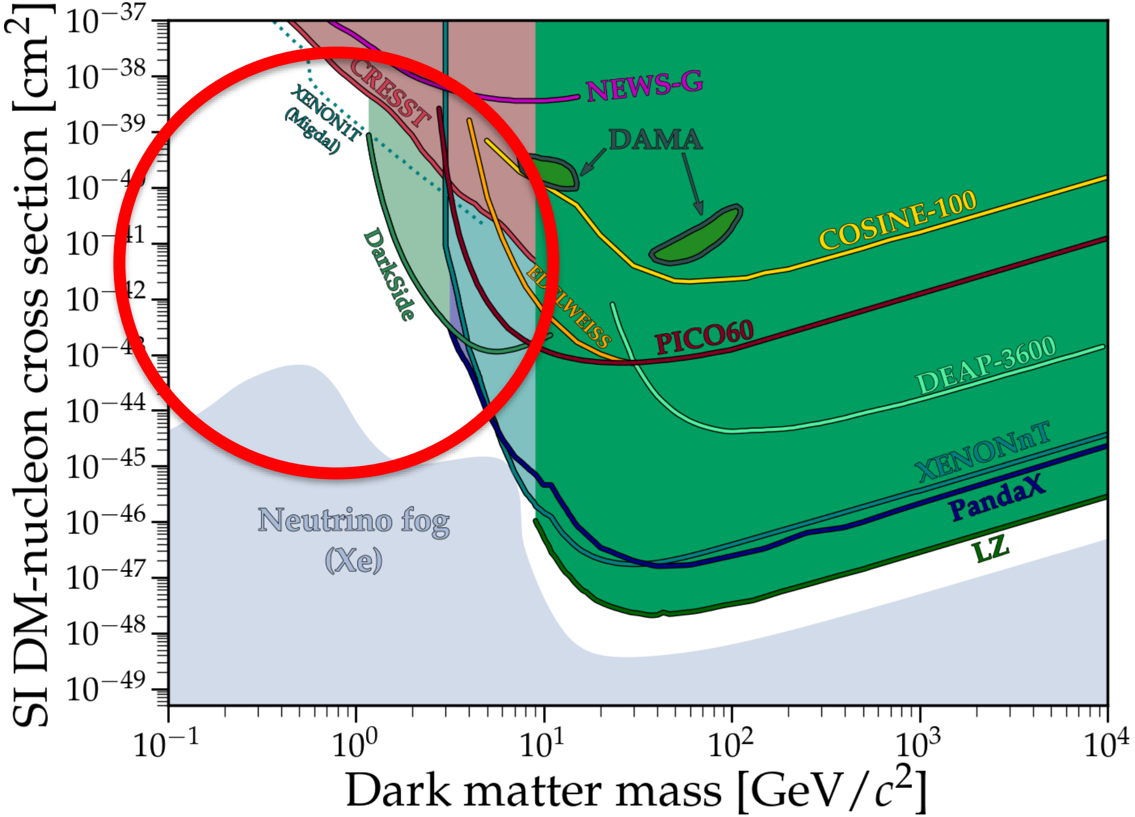

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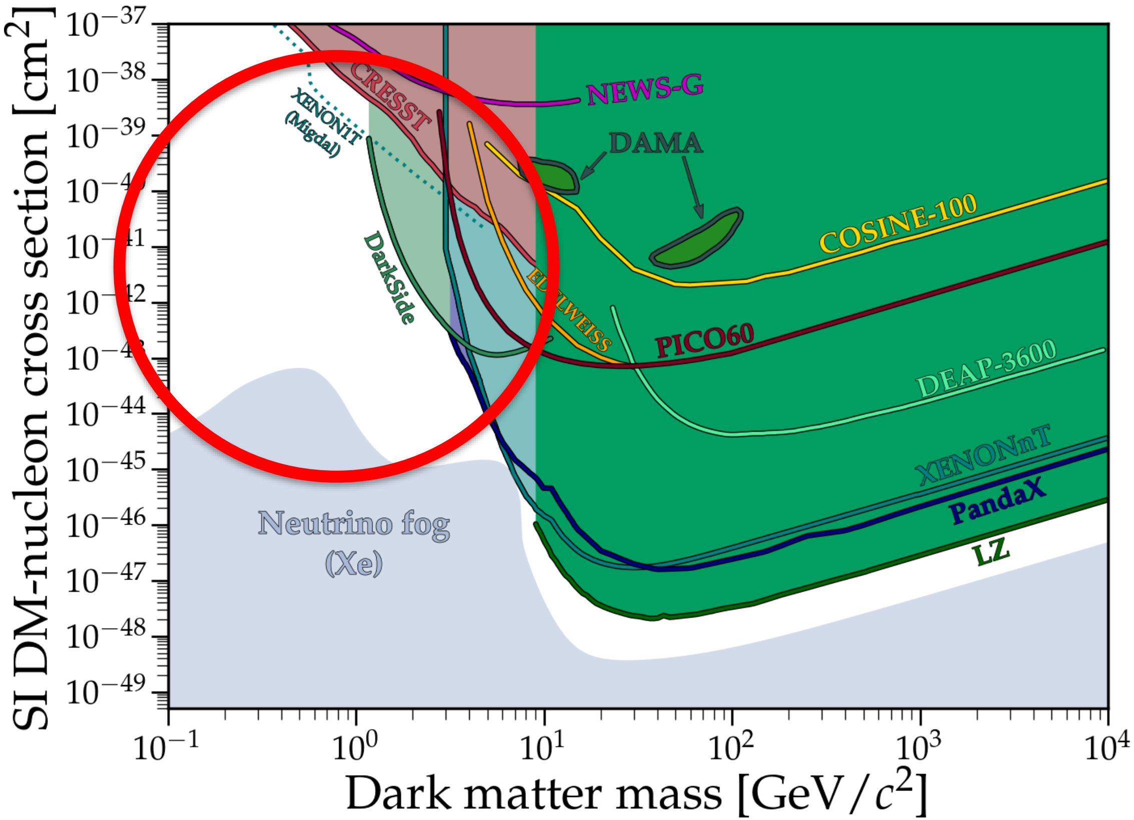
Fermilab

Landscape for Particle-like DM – Nucleon

- DM-nucleon coupling has been heavily probed by xenon & argon experiments
- **Lots of room for novel low-threshold detectors that can scale to neutrino fog**

- **SuperCDMS at SNOLAB is going to cover some of this w/ TES-based detectors**



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Landscape for Particle-like DM – Electron (heavy mediator)

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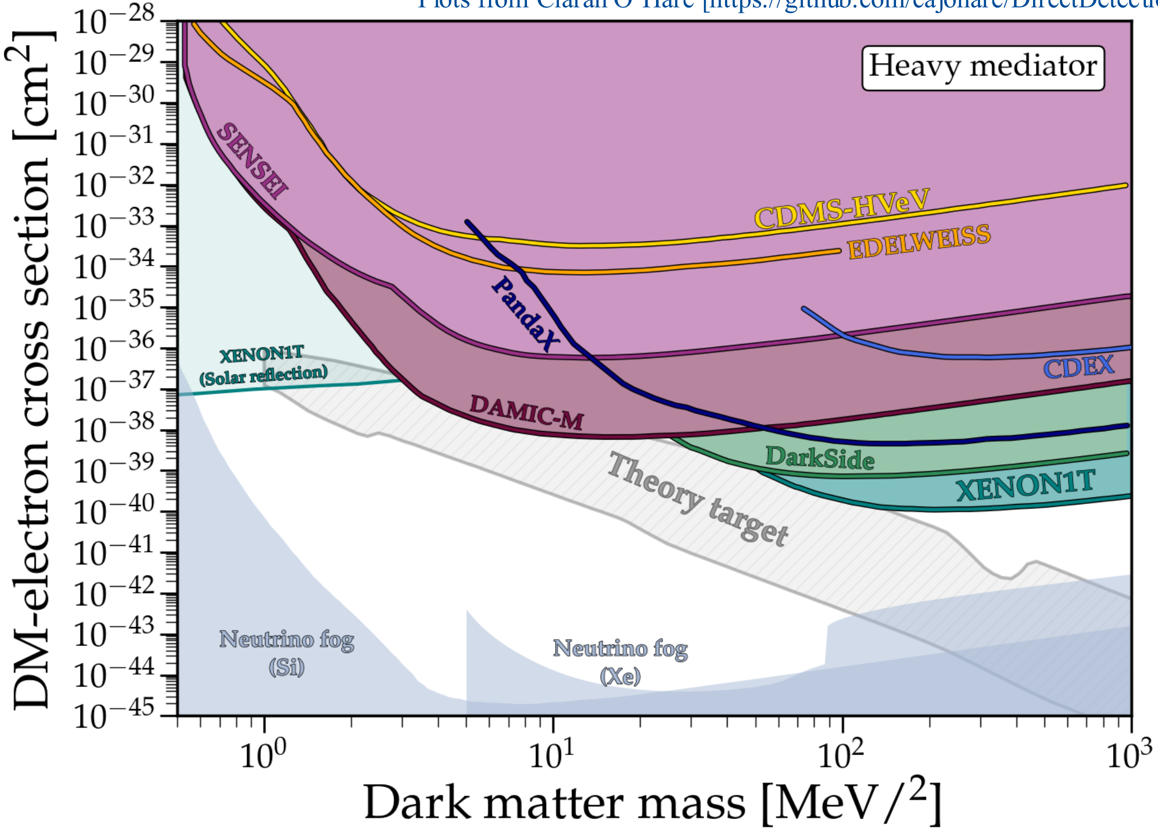

- Meanwhile, DM-e searches are almost entirely dominated by LEE backgrounds and dark rates

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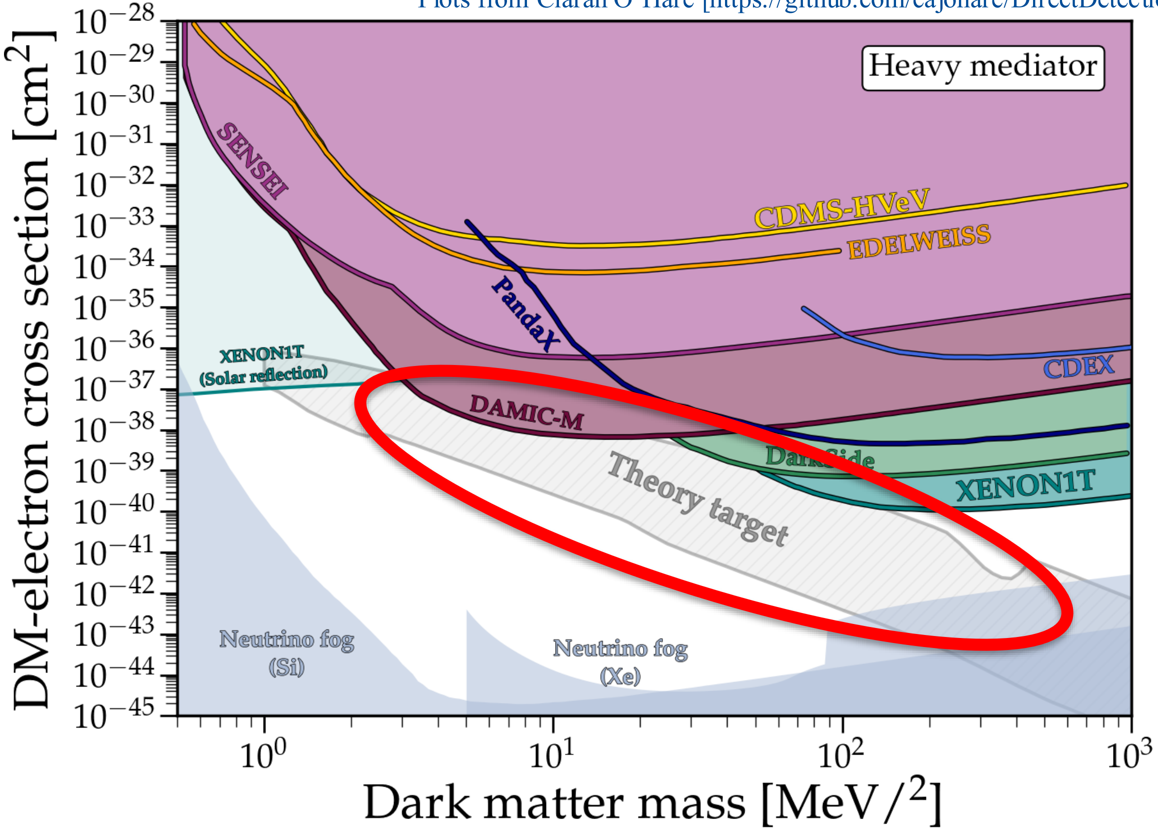

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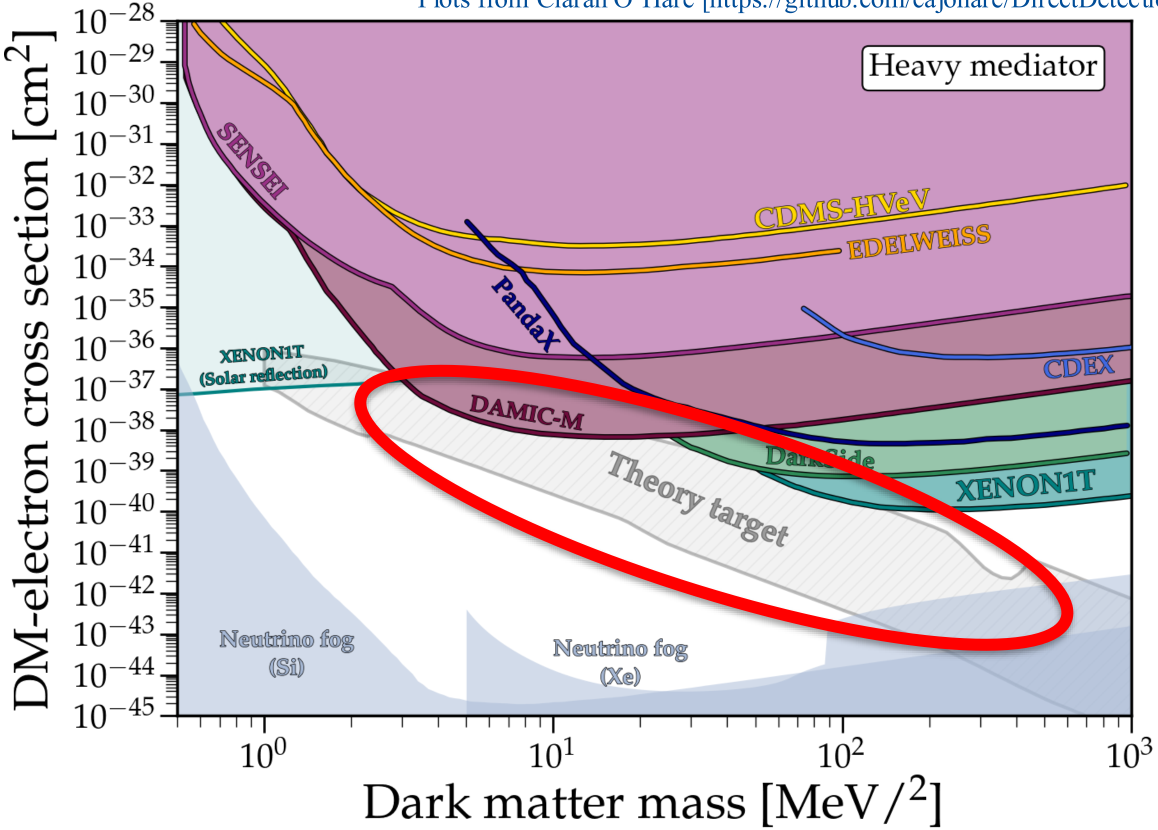

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- **Novel techniques needed to break through to neutrino fog**
- **DAMIC-M will cover some of this w/ CCDs**

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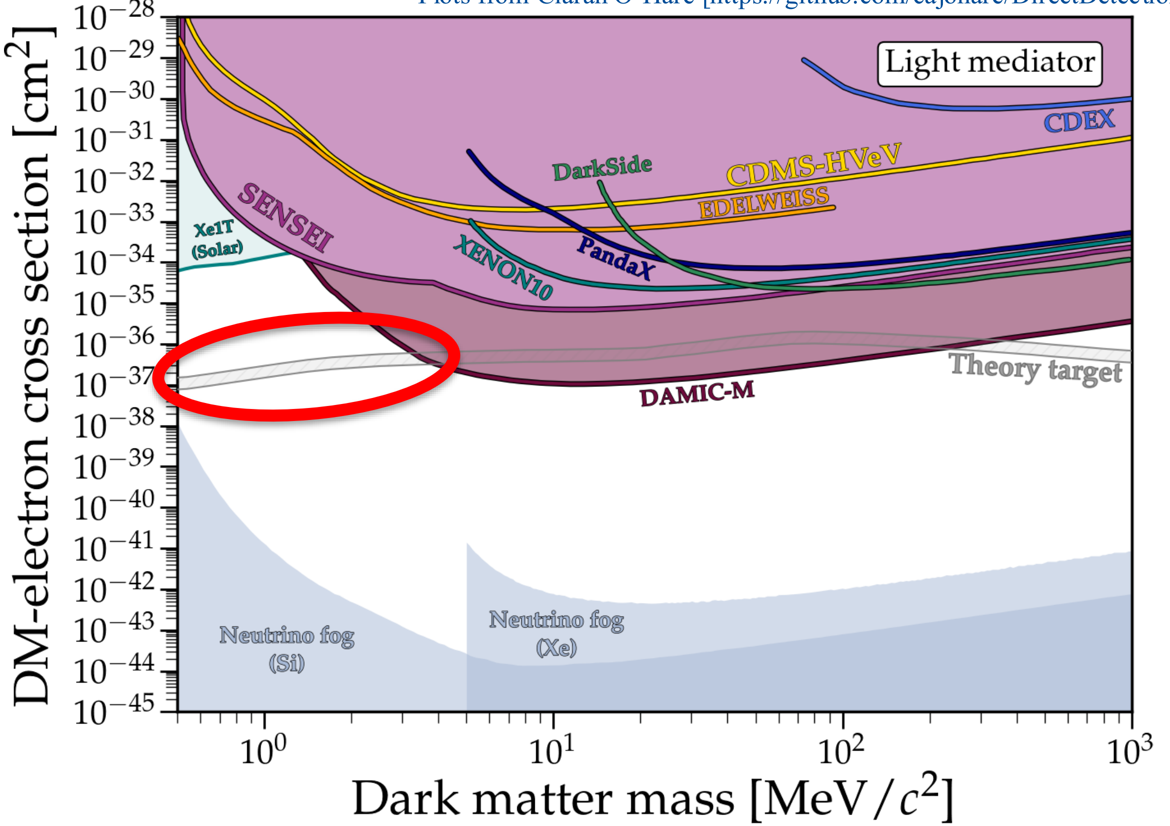

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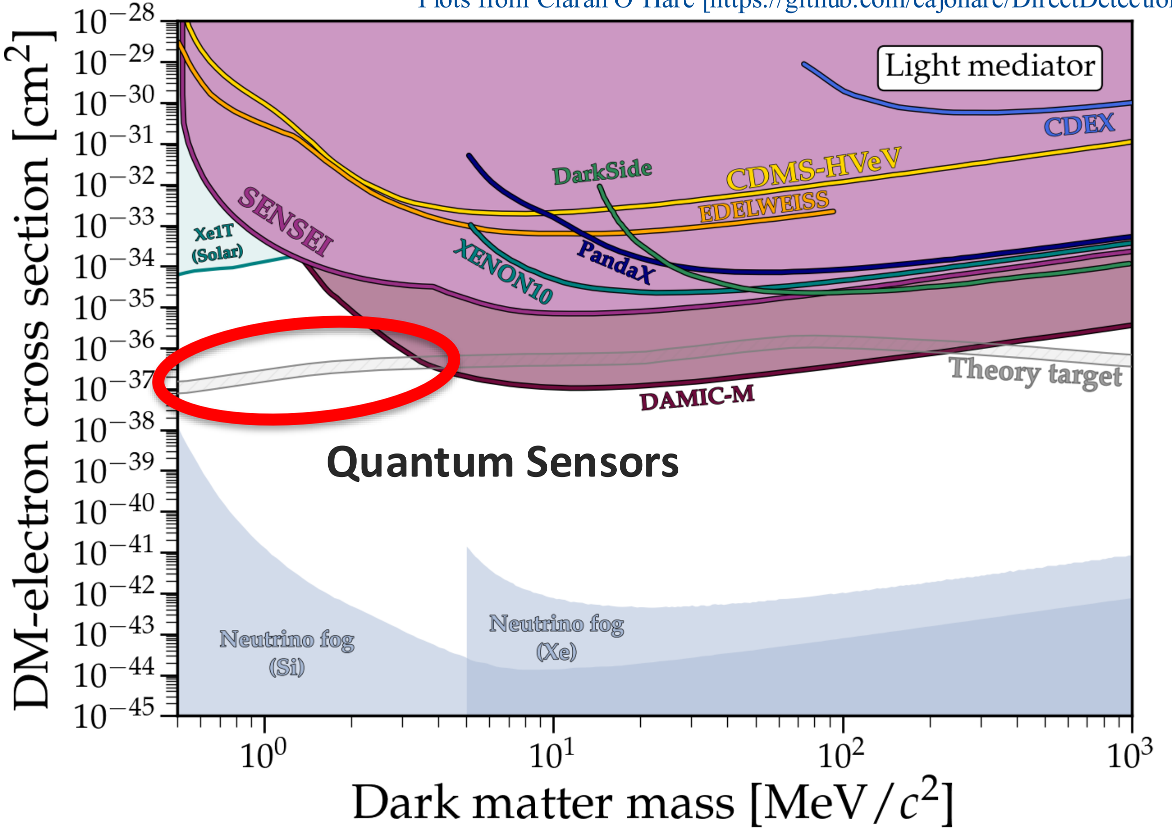

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Fermilab

Acknowledgements – CosmiQuantum@FNAL

FNAL Group

Daniel Baxter
Daniel Bowring
Gustavo Cancelo
Lauren Hsu
Ryan Linehan
Dylan Temples
Sara Sussman
Sho Uemura
Chris James
Olivia Seidel
Muntu Munaf
Tilly Schaaf

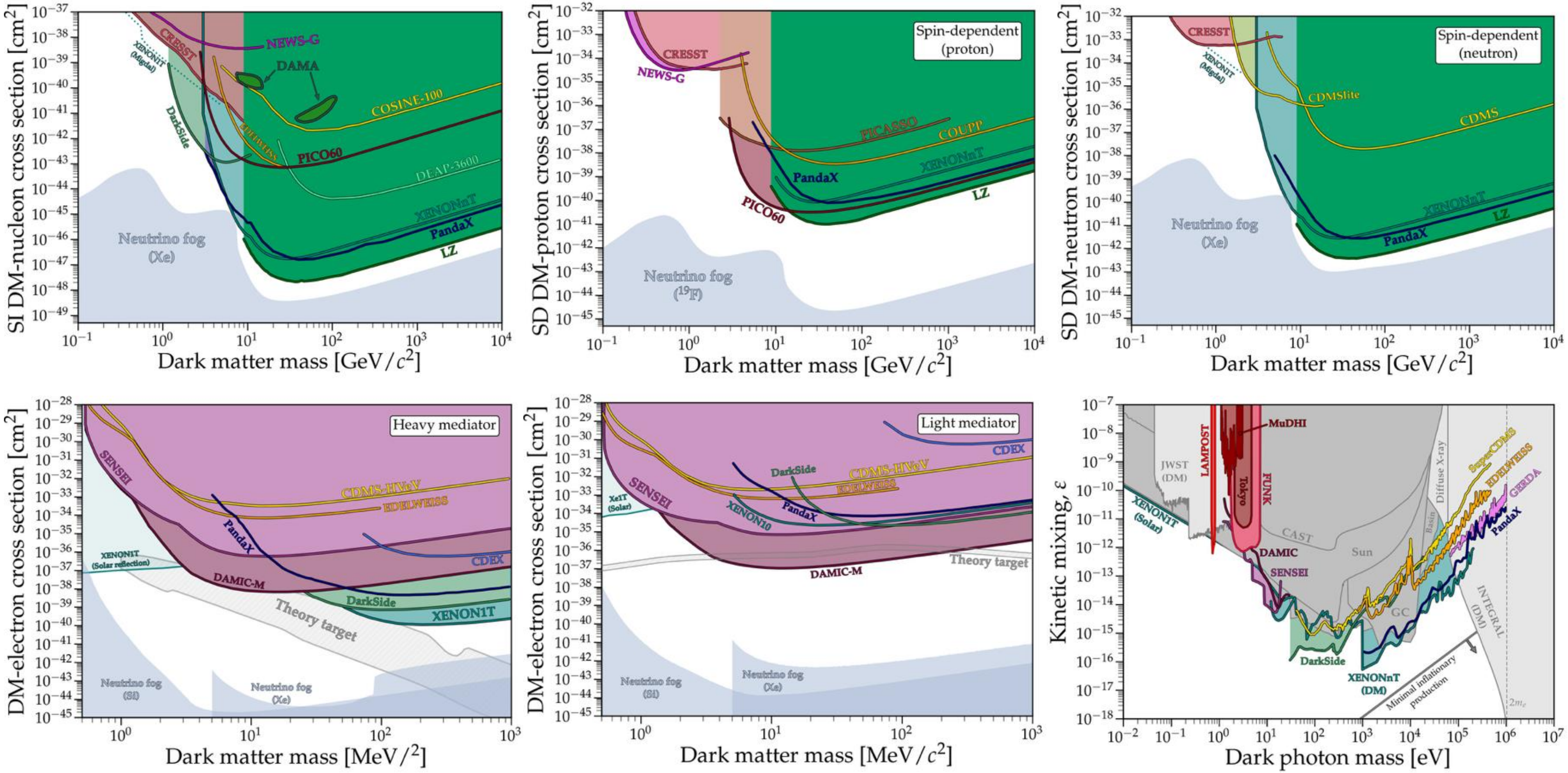
NU Group

Enectalí Figueroa-Feliciano (PI)
Emanuela Celi
Pratyush Patel
Firas Abouzahr
Grace Bratrud
Arianna Colón Cesaní
Lily Johnson
Giana Perez
Alejandro Rodriguez

IIT Group

Rakshya Khatiwada (PI)
Kester Anyang
Ziyu Cai
Israel Hernandez
Daniel Molenaar

What does the experimental landscape look like?



Plots from Ciaran O'Hare [https://github.com/cajohare/DirectDetectionPlots]

Back-up Slides

Landscape for Particle-like DM – DM absorption

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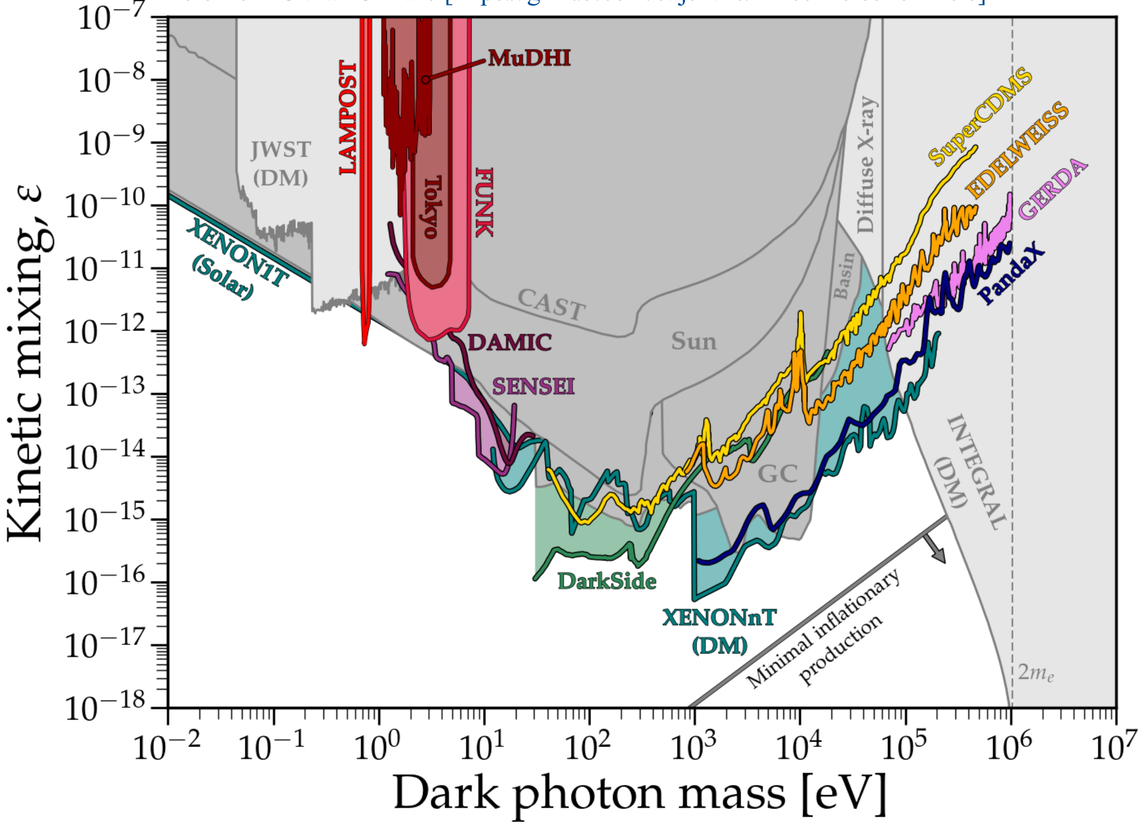
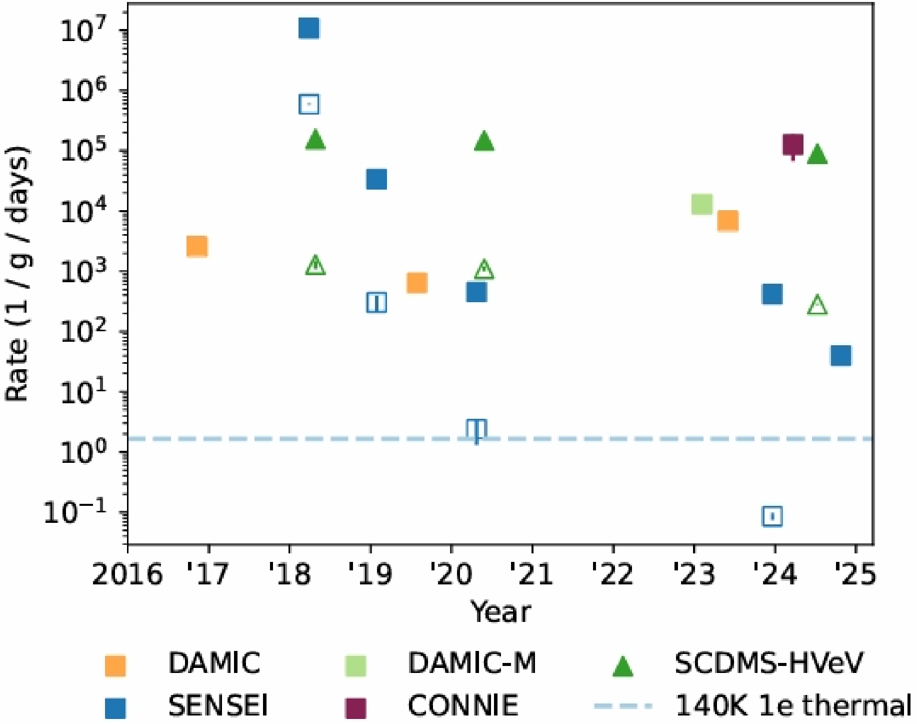


Low-Mass Dark Matter Detection

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

Single electron dark rates



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

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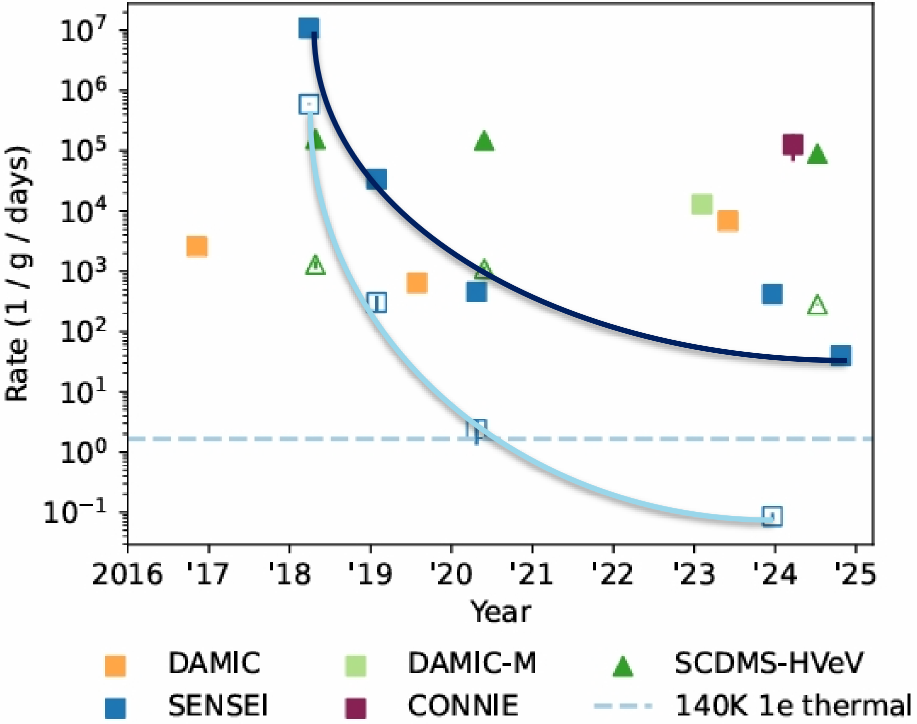

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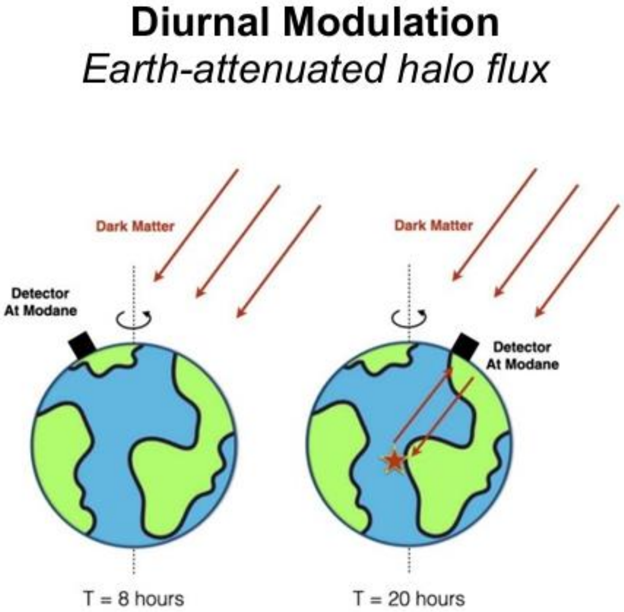
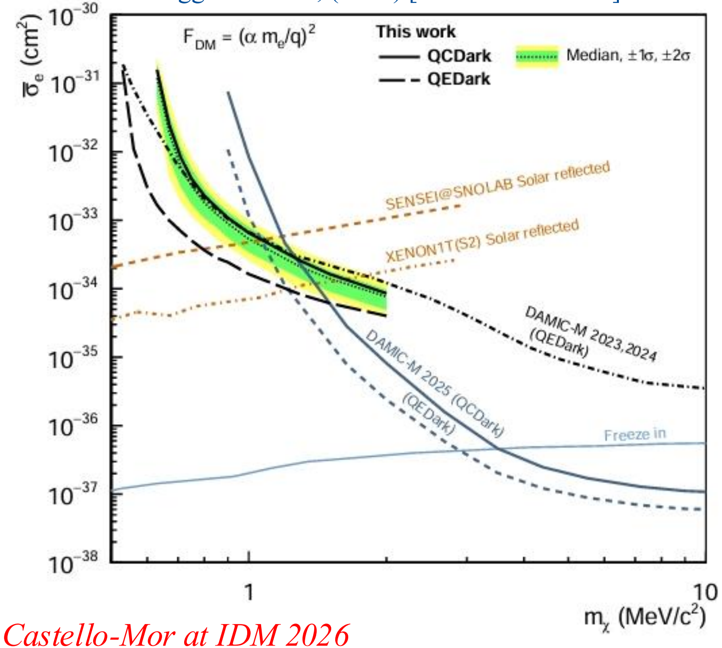
Backgrounds and Daily Modulation

- 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 talk from Nuria Castello-Mor at IDM 2026

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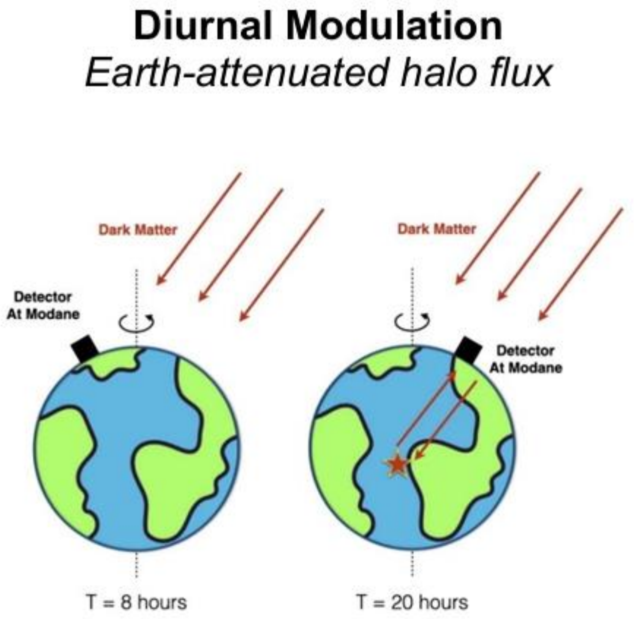
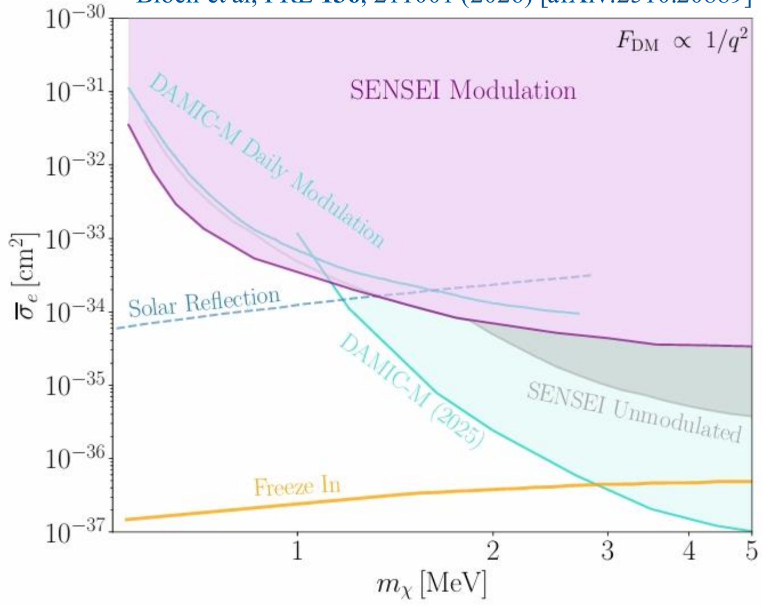


Bloch et al, PRL **136**, 211001 (2026) [arXiv:2510.20889]



see talk from Ansh Desai at IDM 2026