Towards the deployment of DAMIC-M: status and latest results

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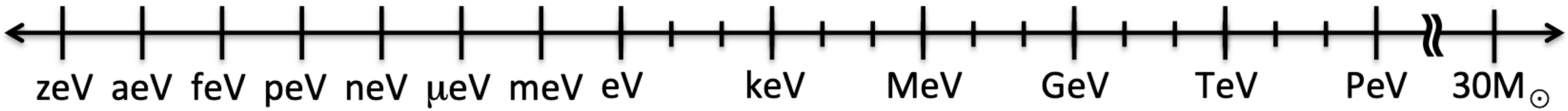
Outline:

1. Dark Matter
2. Scientific CCDs
3. DAMIC-M and LBC
4. Latest Science Results
5. Status and Prospects
6. Conclusions

Dark Matter… and where to find it



“wave-like” dark matter

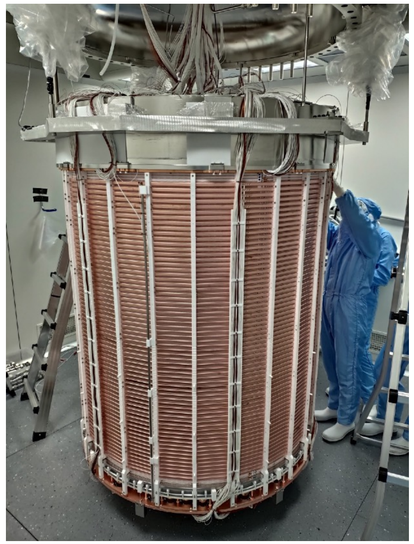
“particle-like” dark matter

black holes

Dark Matter… and how to find it

ADMX

XENON



zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV $30M_{\odot}$

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Dark Matter… and how to find it

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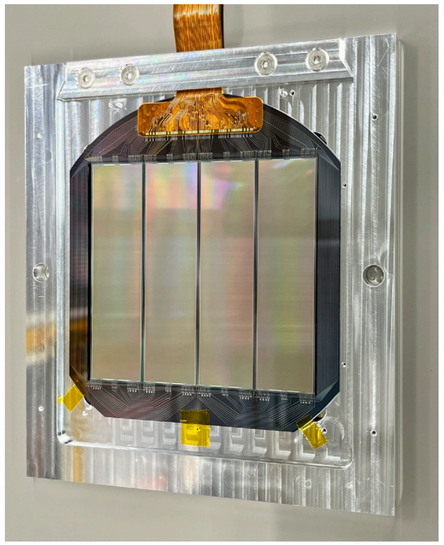
DAMIC-M



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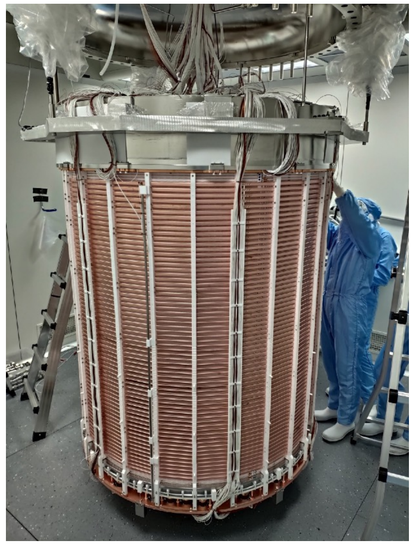

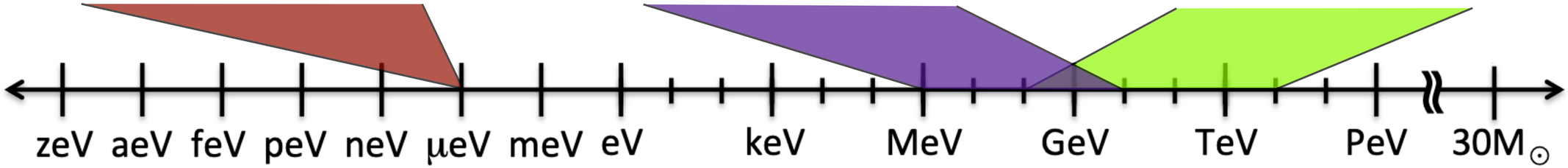

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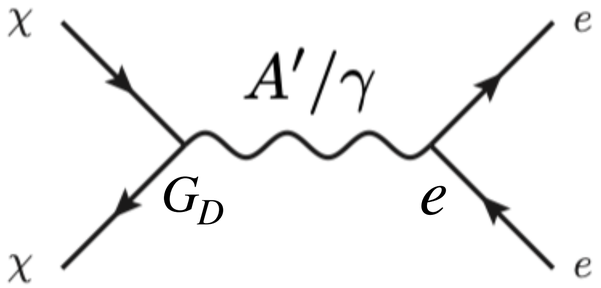
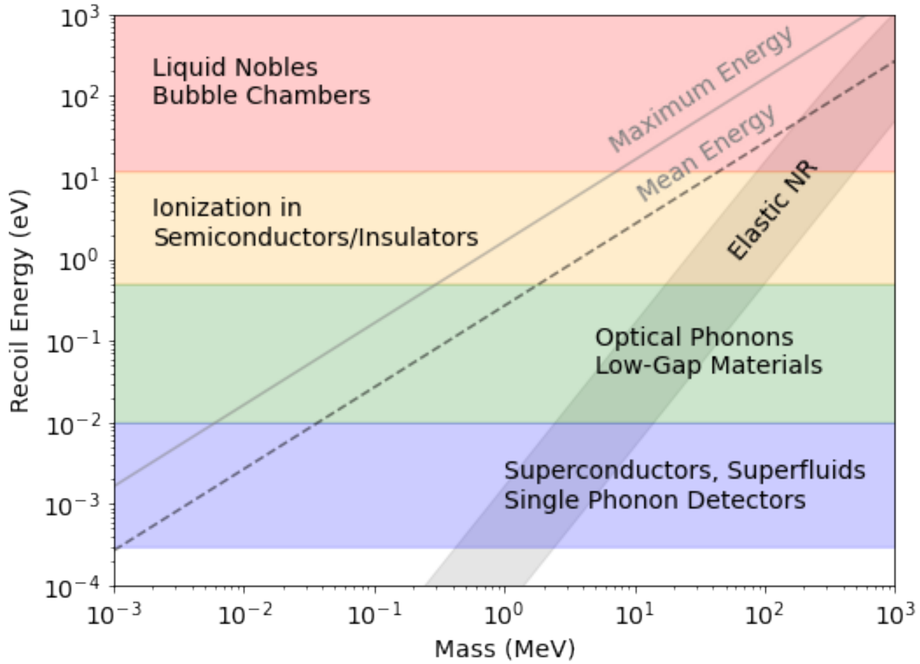
DM-e^- scattering

- WIMP miracle: weak-scale coupling and mass. WIMPs undetected so far.
- WIMPless miracle: new couplings and mass scales in the hidden sector.
  - Simple mechanism: DM-e^- through a massive mediator mixed with the photon.

  ➡ Probe DM via electronic recoil.
- Electrons are a lighter target and offer full ionization yield. However:
  - DM $\vec{Q}$ must overlap with crystal response.
  - No coherent enhancement, unlike DM-n scatter.

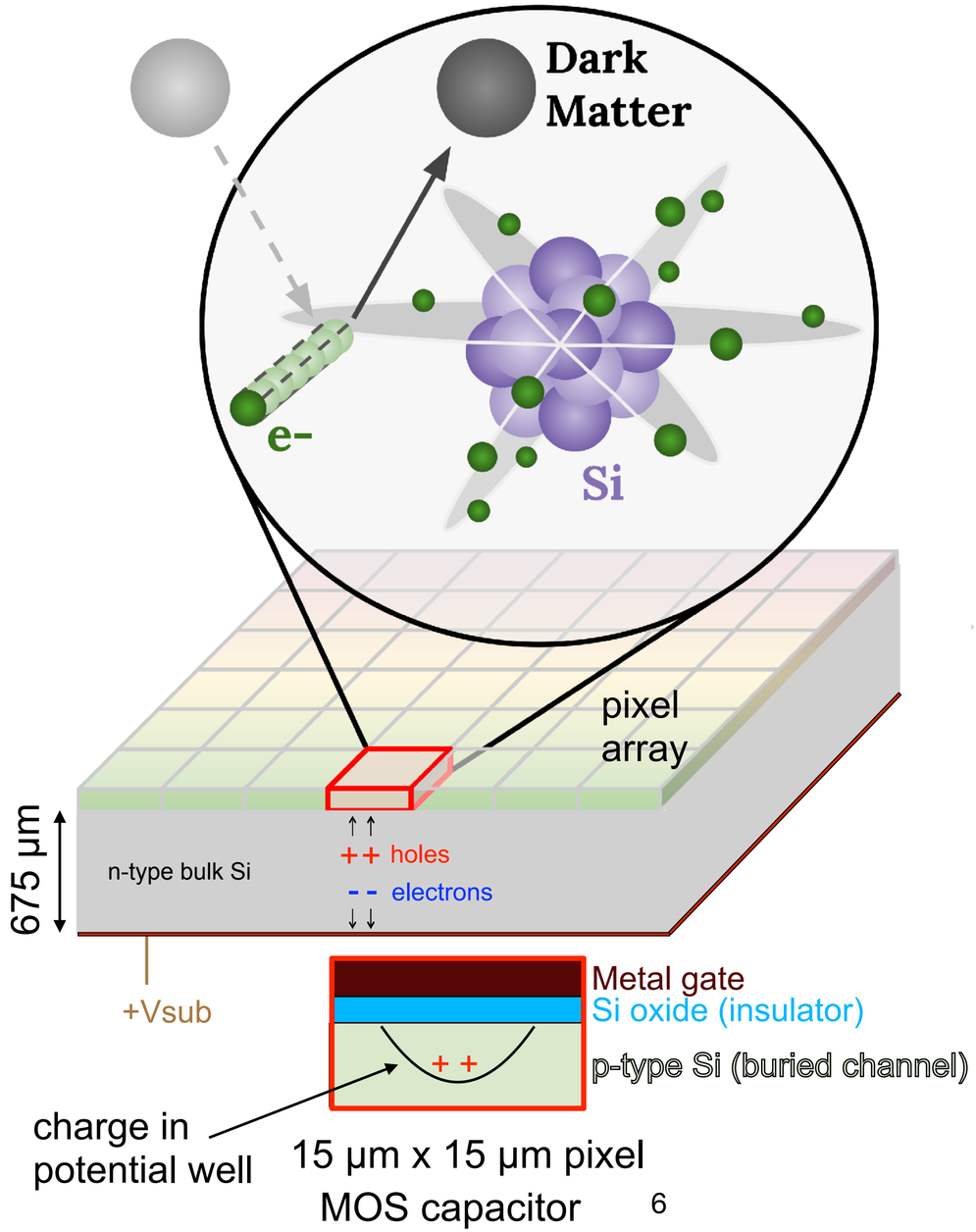
$$\Omega_X \sim \langle \sigma_A v \rangle^{-1} \sim \frac{m_X^2}{g_X^4}$$





Scientific CCDs

- P-type buried channel structure (LBNL).
- Fully depleted at $40\ \mathrm{V}\ (\sim 10\ \mathrm{k\Omega \cdot cm})$.
- 15 μm x 15 μm pixel.



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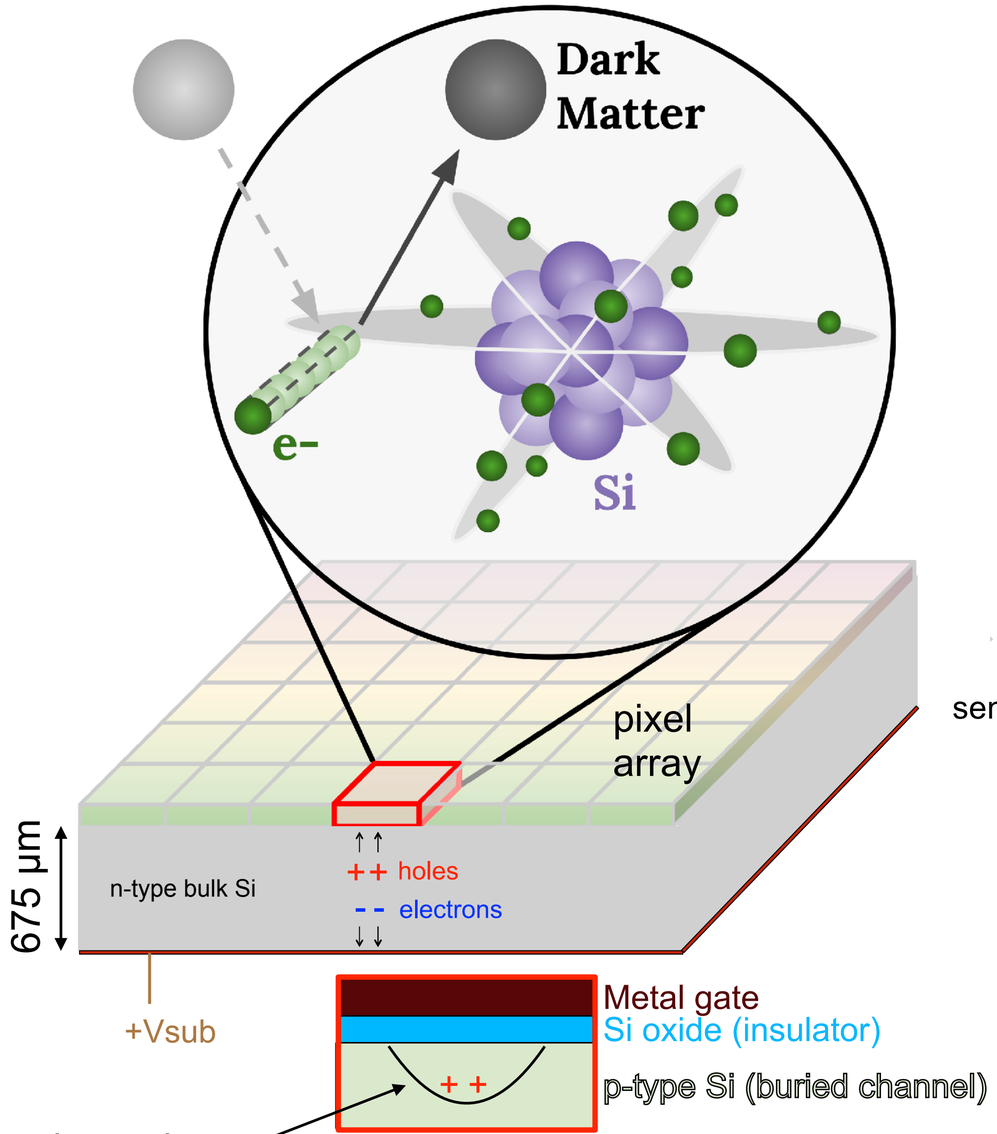
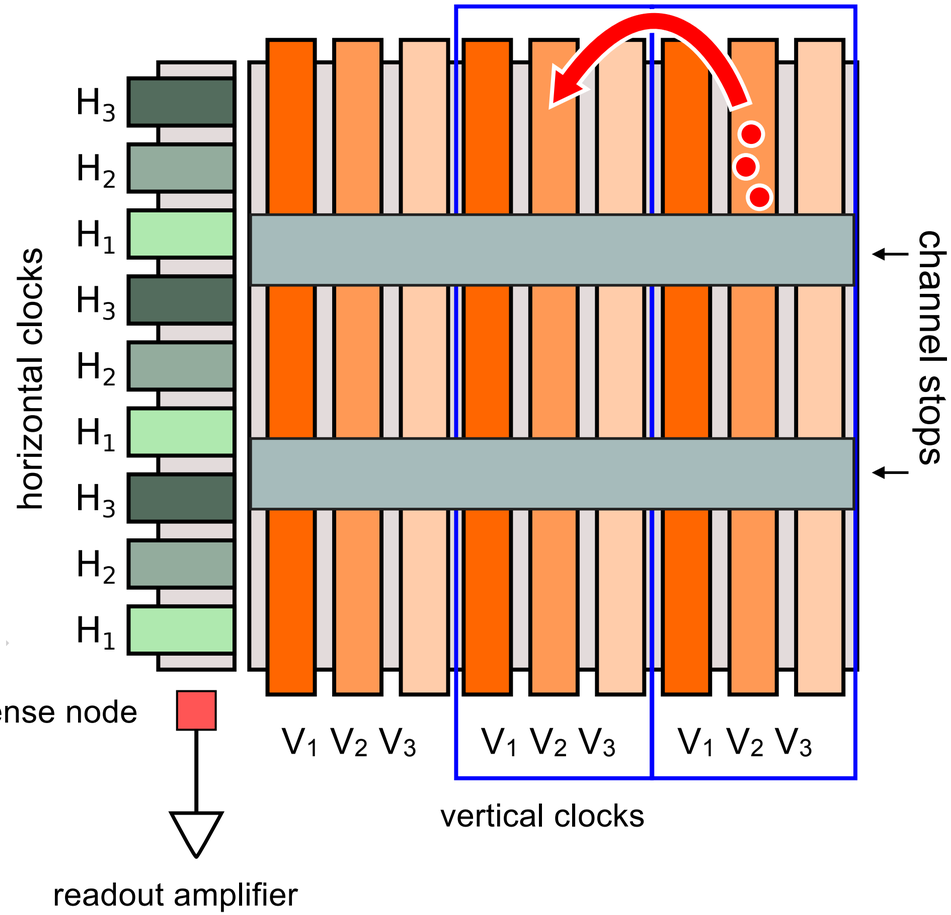


3x3 pixels CCD



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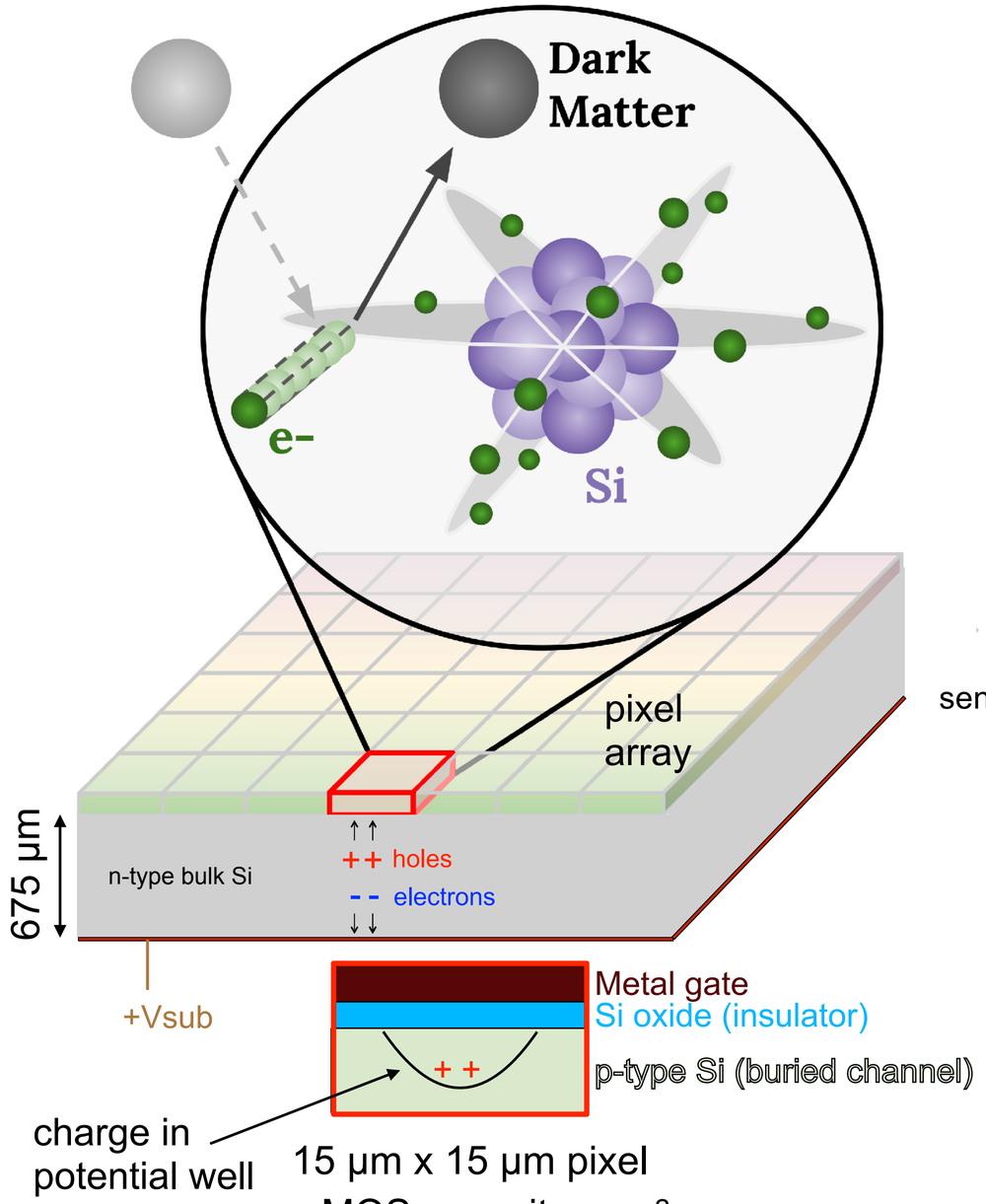
- Depth (z) reconstructed from distribution of charge on pixel array.



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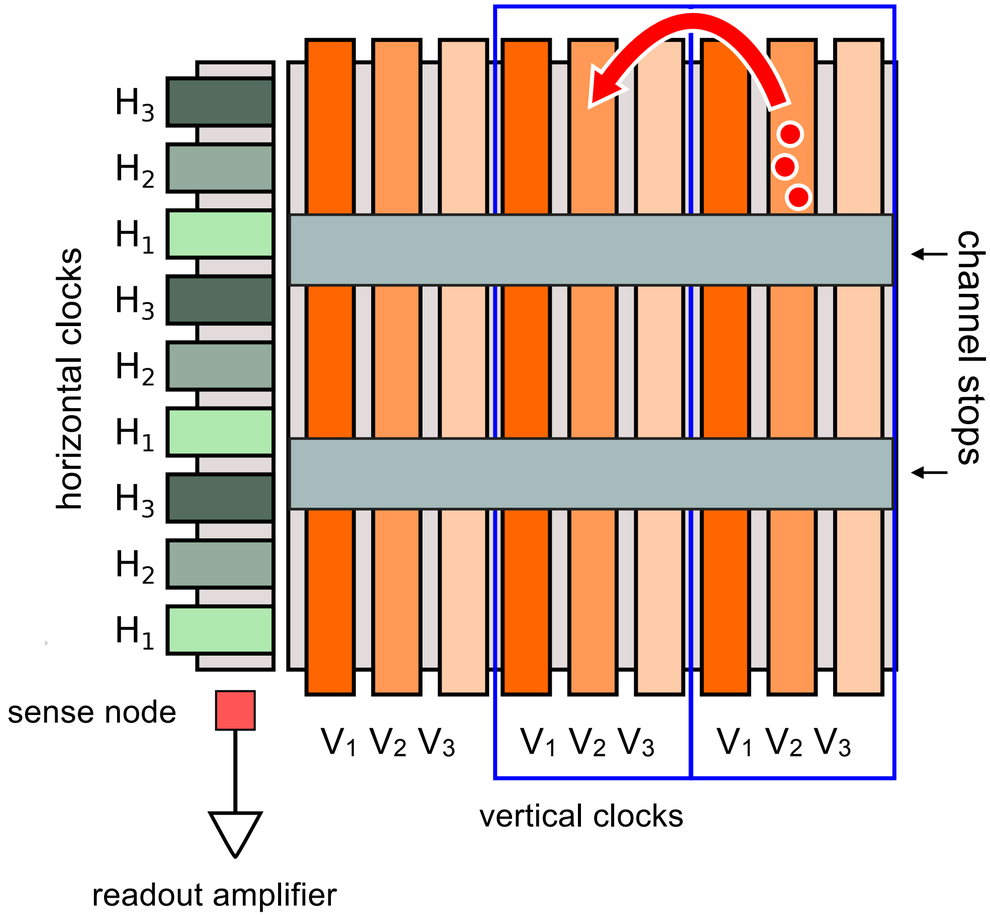
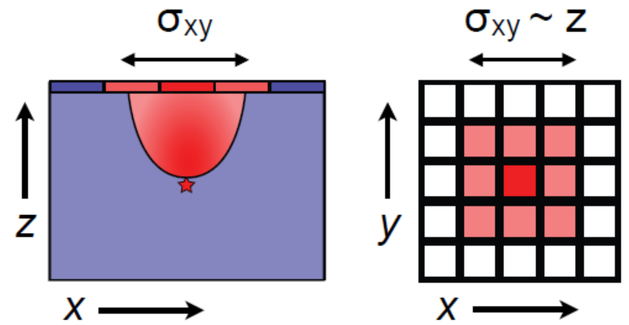
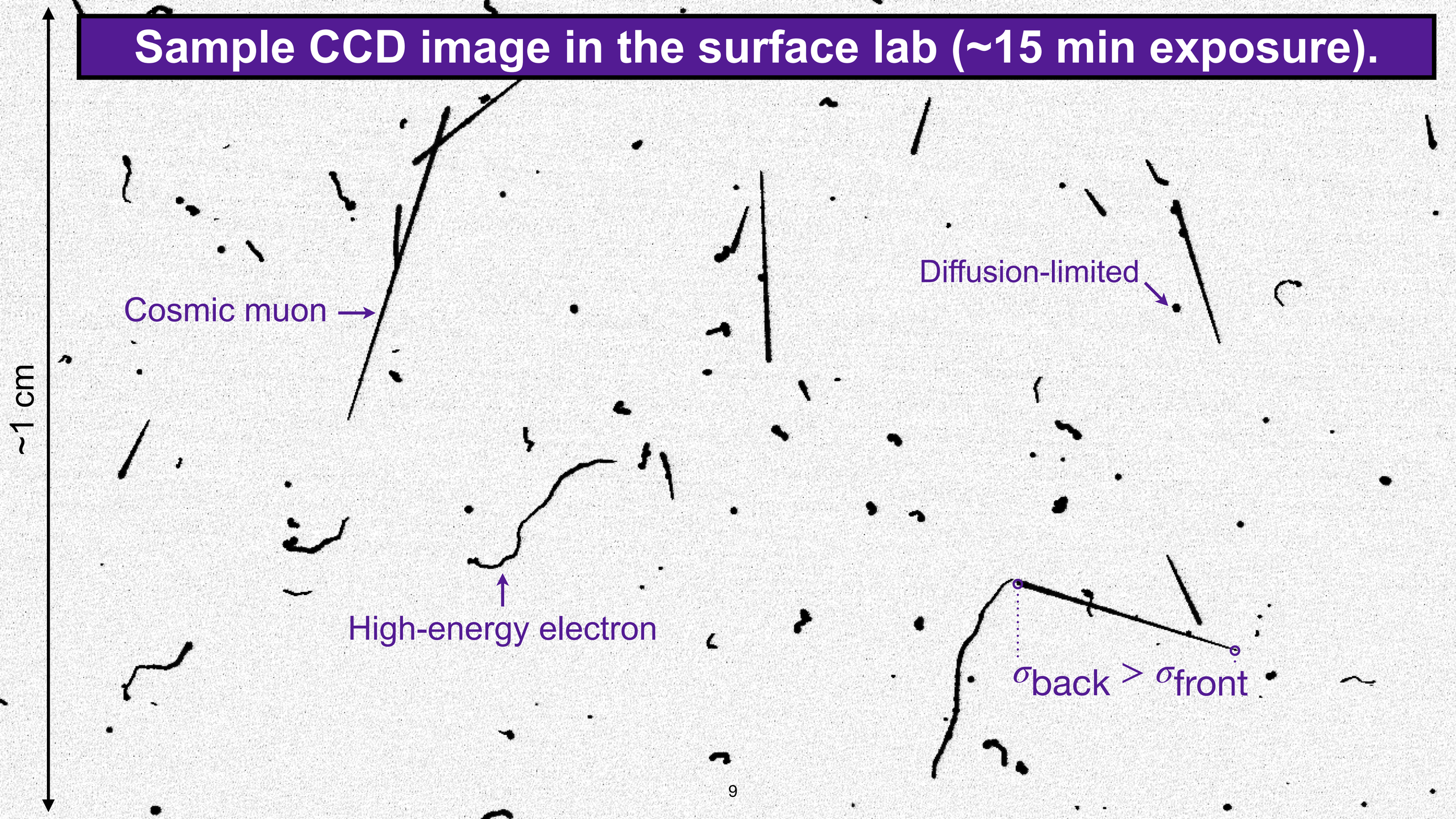


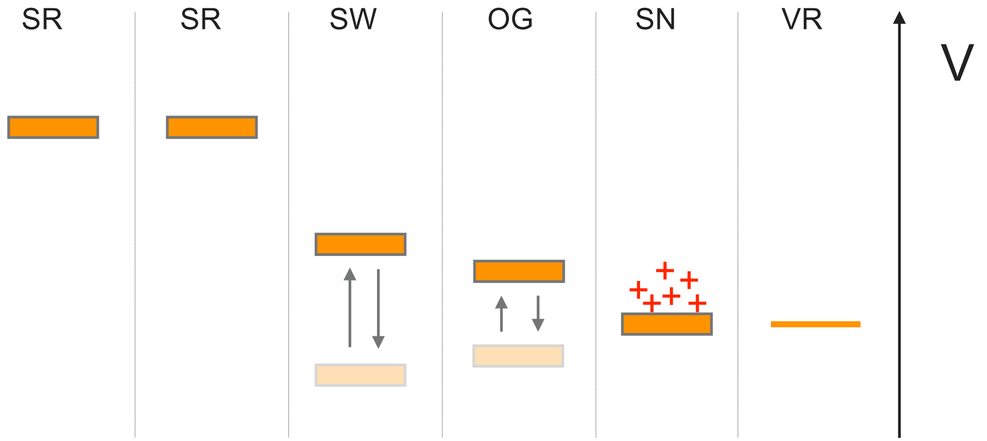


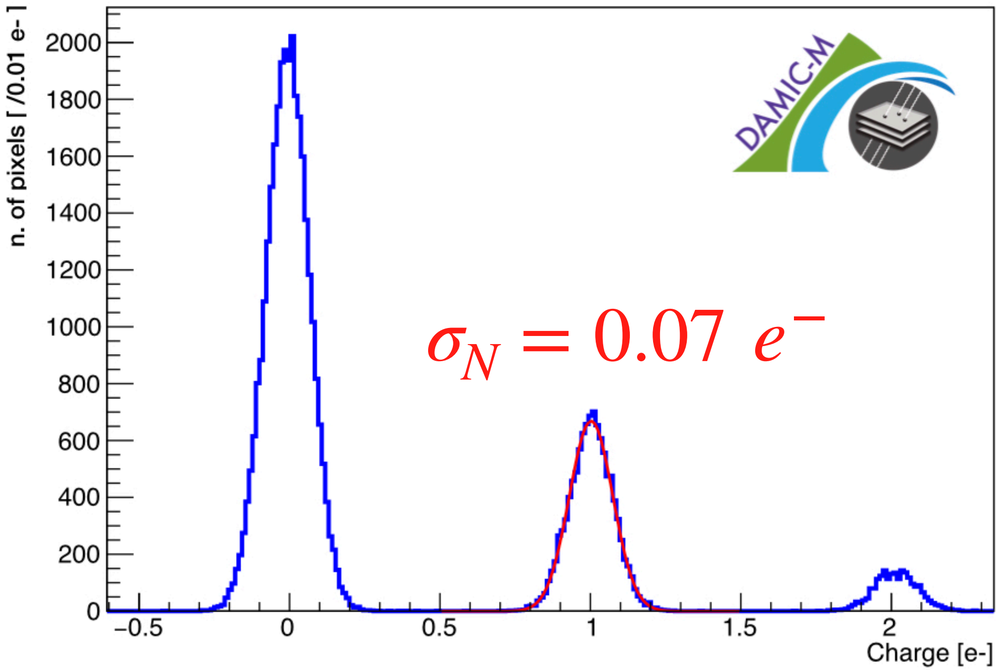
Sample CCD image in the surface lab (~15 min exposure).

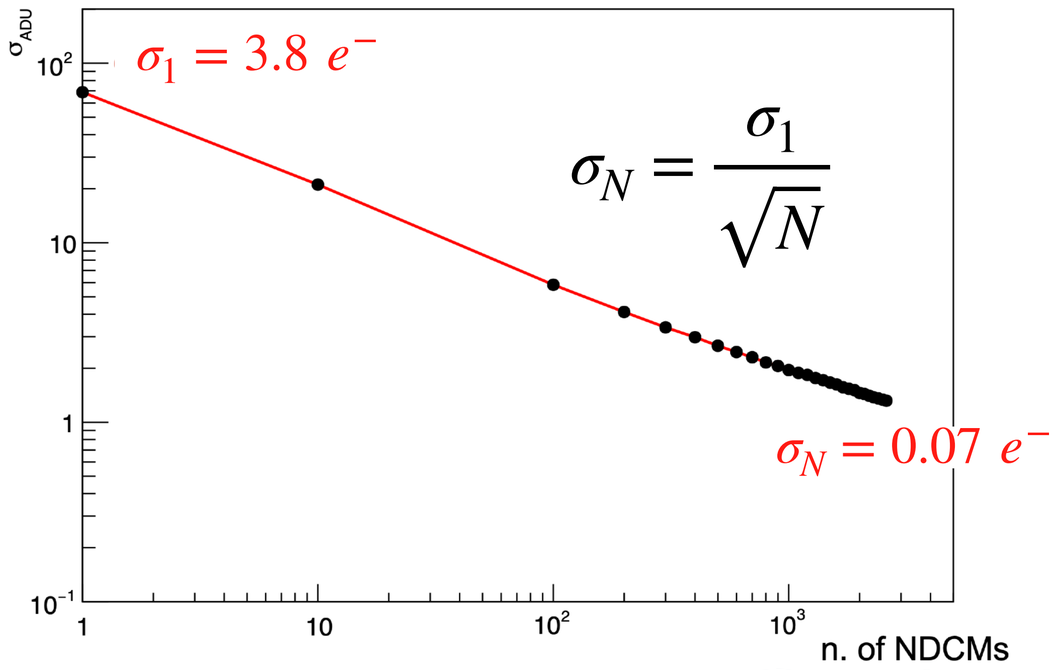


Skipper readout

- Non-destructive charge measurement (Janesick et al. 1990).
- Re-engineered for LBNL CCDs (Tiffenberg et al. 2017).
- Sub-electron resolution via NDCMs.







DArk Matter In CCDs: Timeline

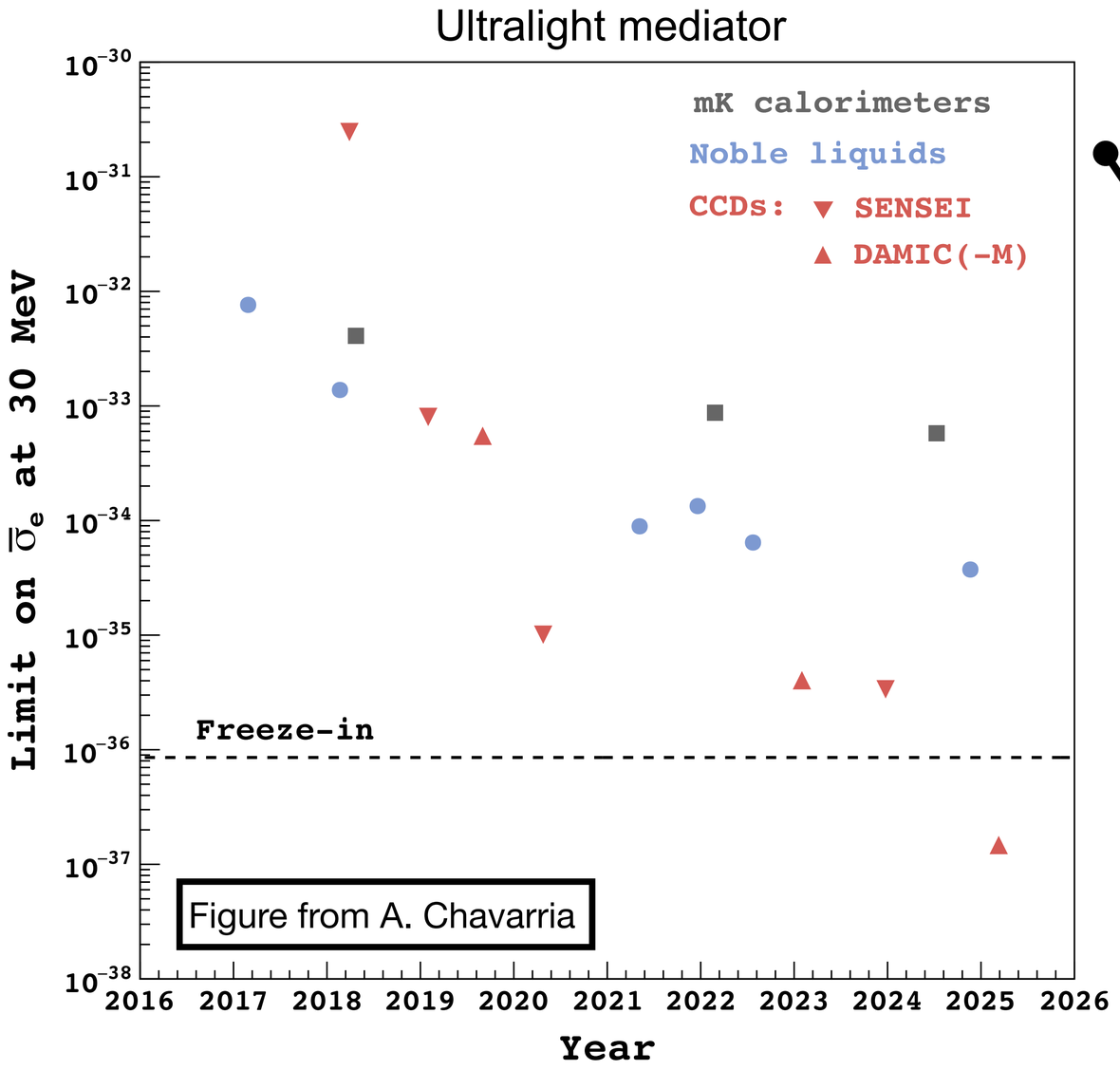


Figure from A. Chavarria

2012: DAMIC at SNOLAB starts: first low-bkg CCD array for DM searches.

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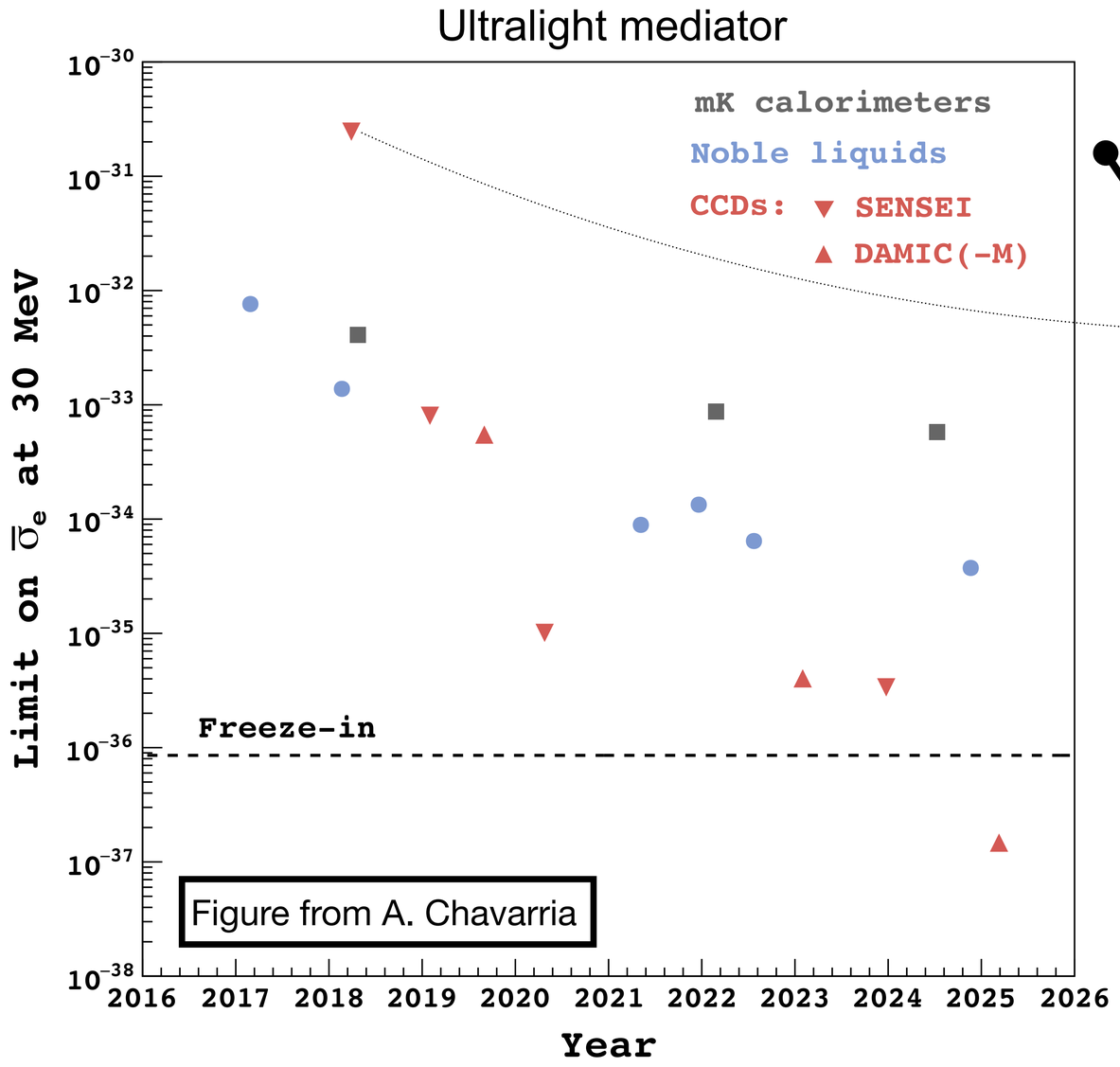

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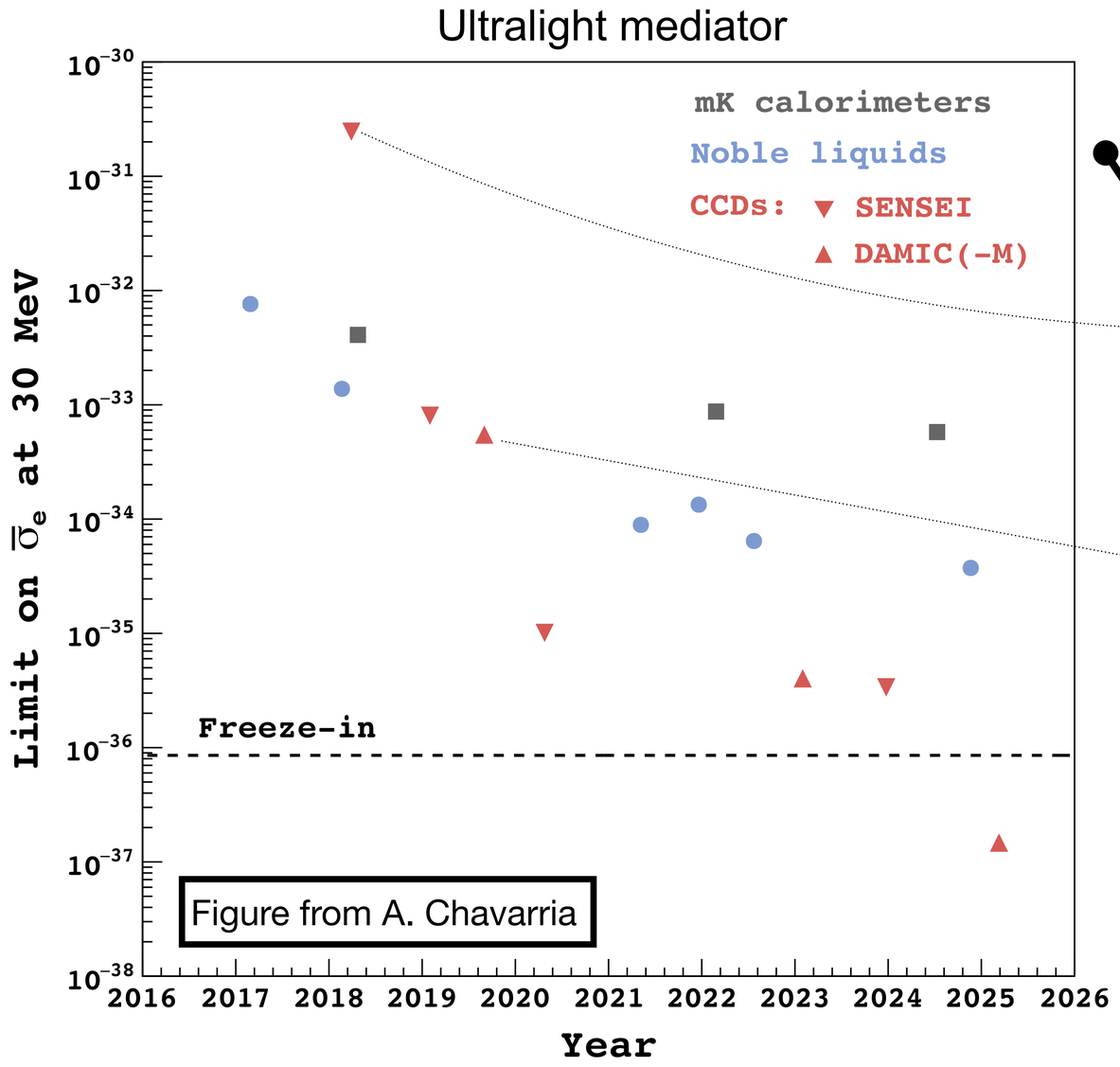

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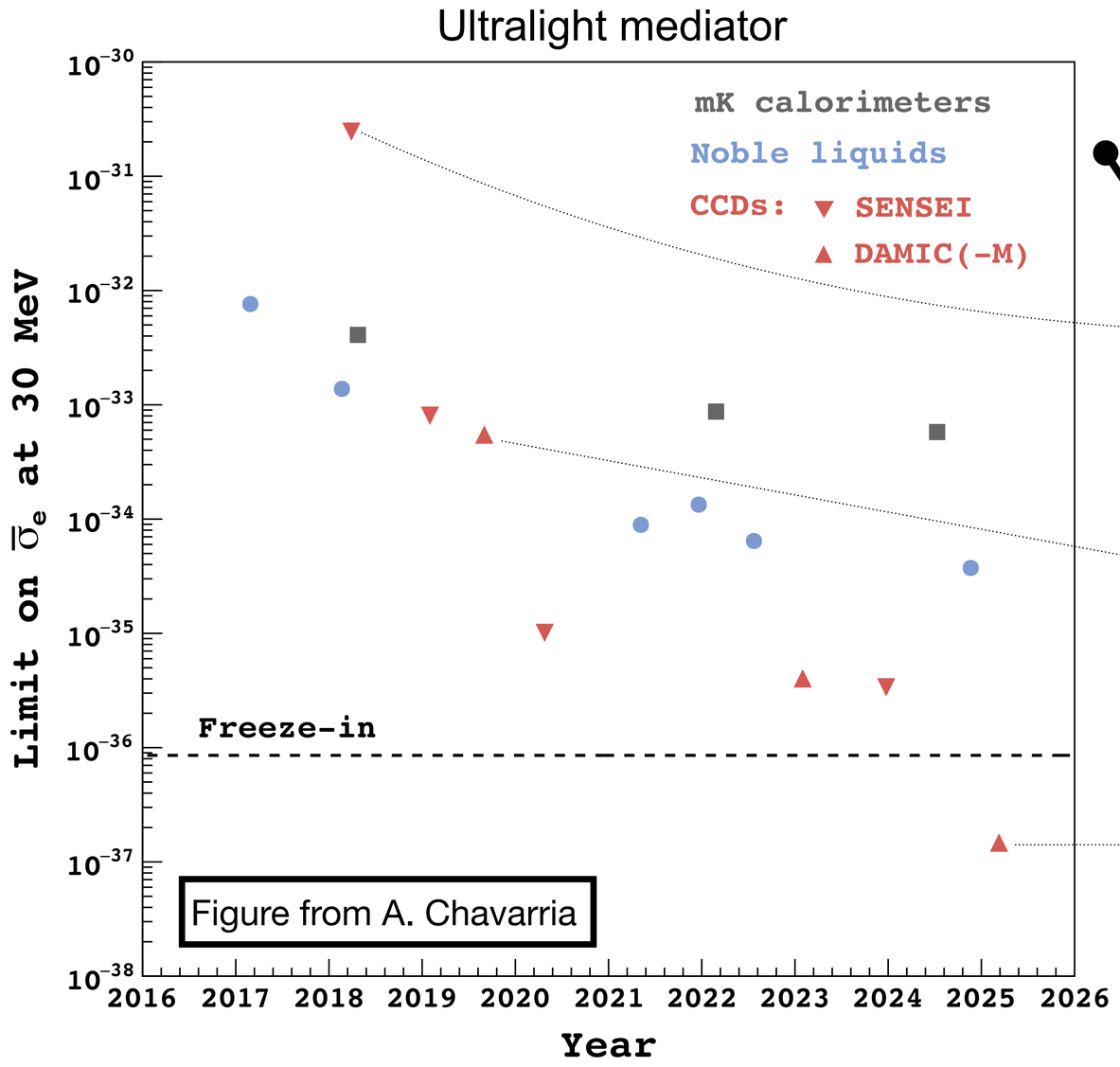

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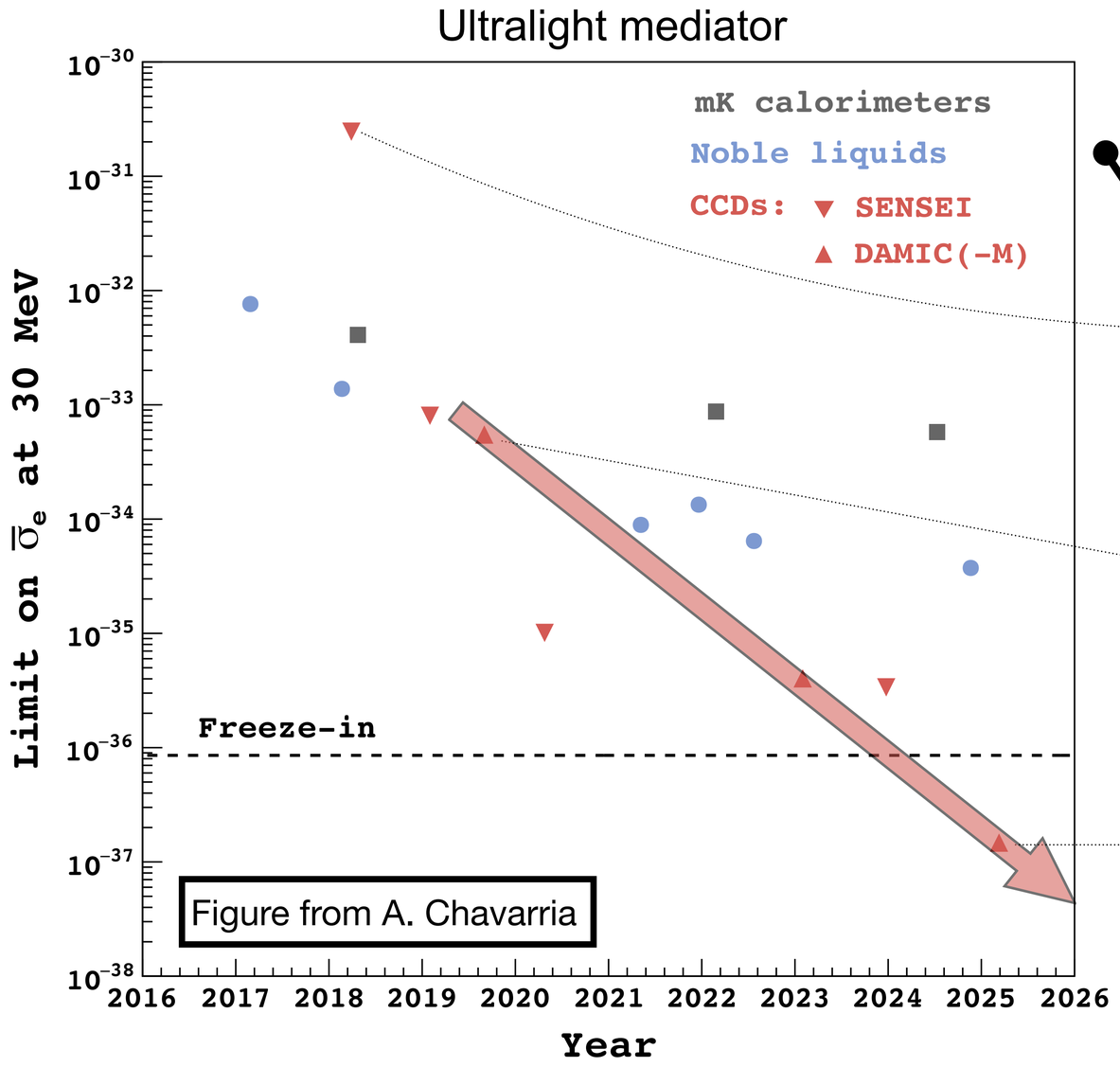

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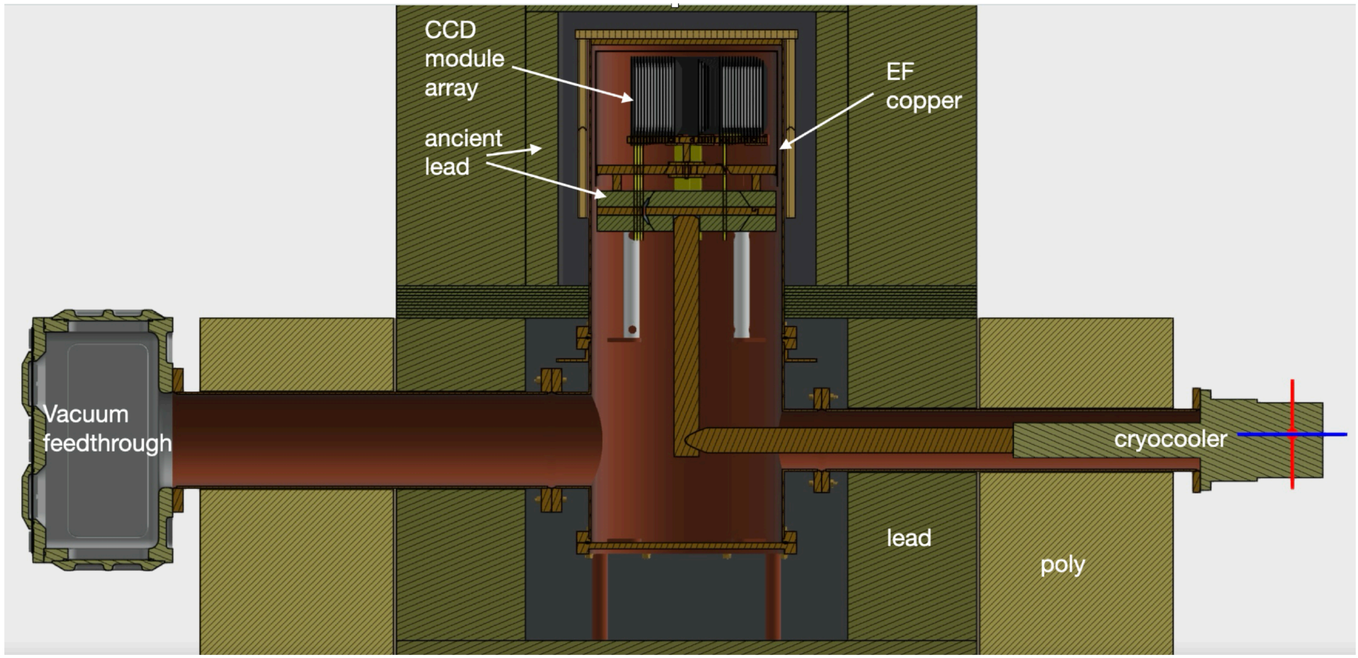
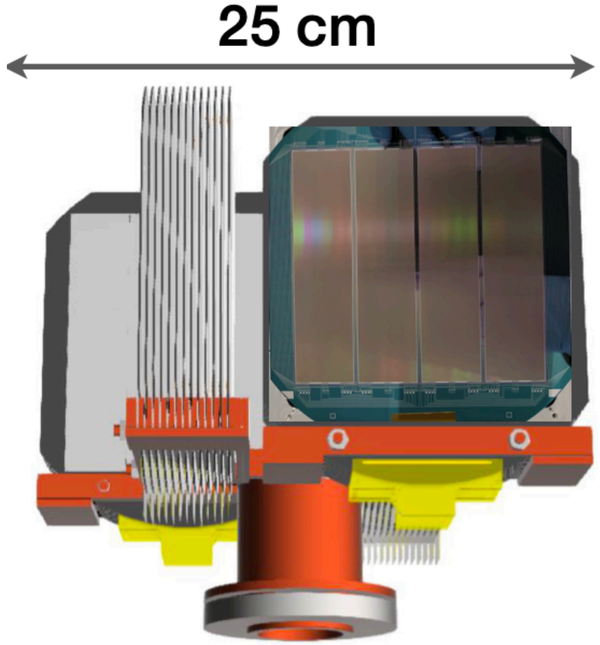
The DAMIC-M Experiment

DAMIC-M: DArk Matter In CCDs at Modane

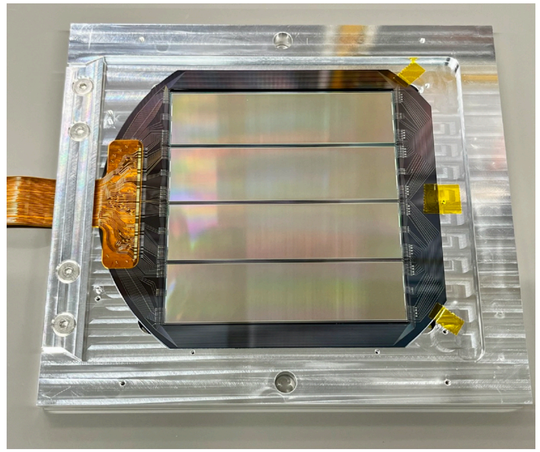
- 52 CCD modules in LSM (France) for kg-year target exposures (~700 g sensitive mass).
- Skipper readout for sensitivity to single charges.
- Background below 1 d.r.u. (events per keV-kg-day).
- Installation early 2026!



Rendering of DAMIC-M final design



Rendering of DAMIC-M CCD array



DAMIC-M CCD module

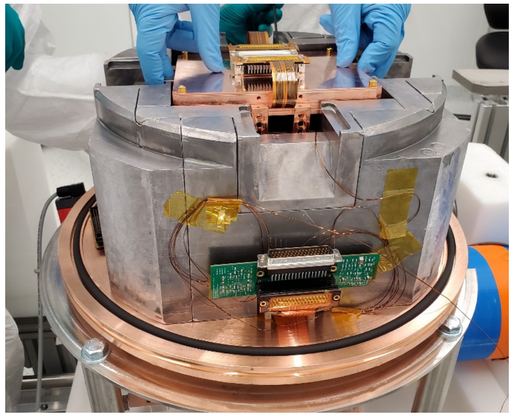
The Low-Background Chamber

- Low-background DAMIC-M prototype (~7 dru). Operational since 2021.

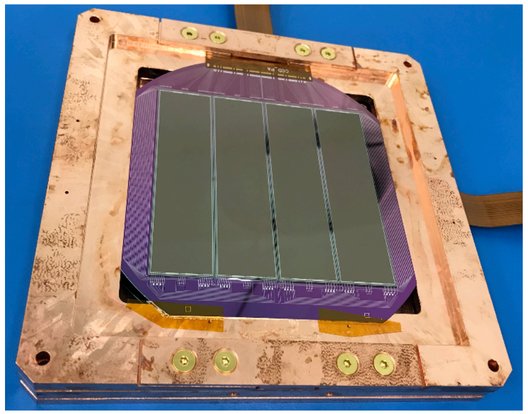
- Objectives: CCD performance, backgrounds, components for DAMIC-M, and first science results with skipper CCDs.

- World-leading results in 2023, 2024 and 2025.

PRL130(2023)171003	PRL132(2024)101006	PRL135(2025)071002
SR1 (science run 1)	SR1	SR2

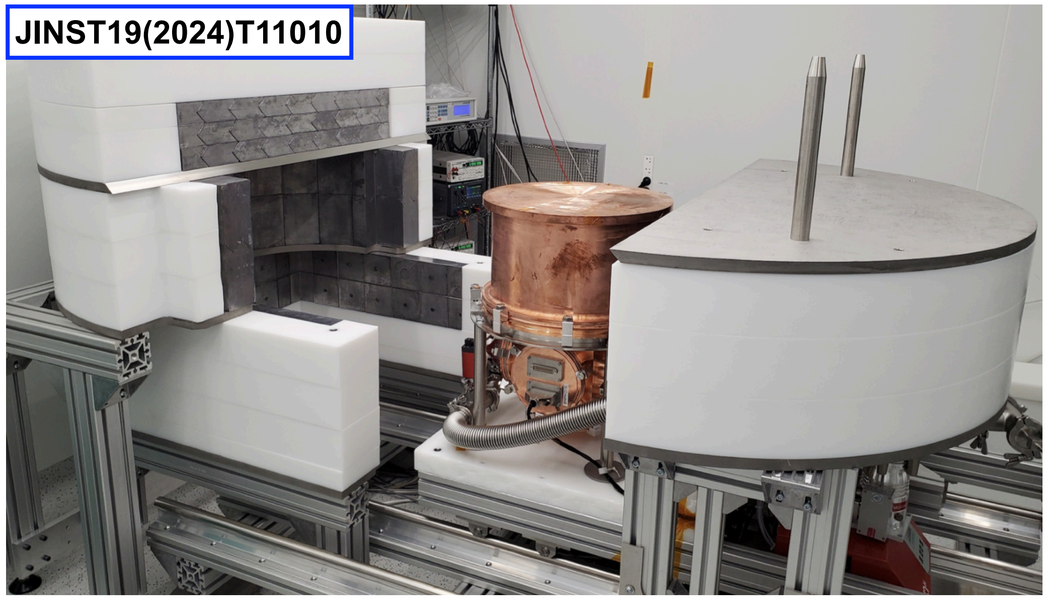


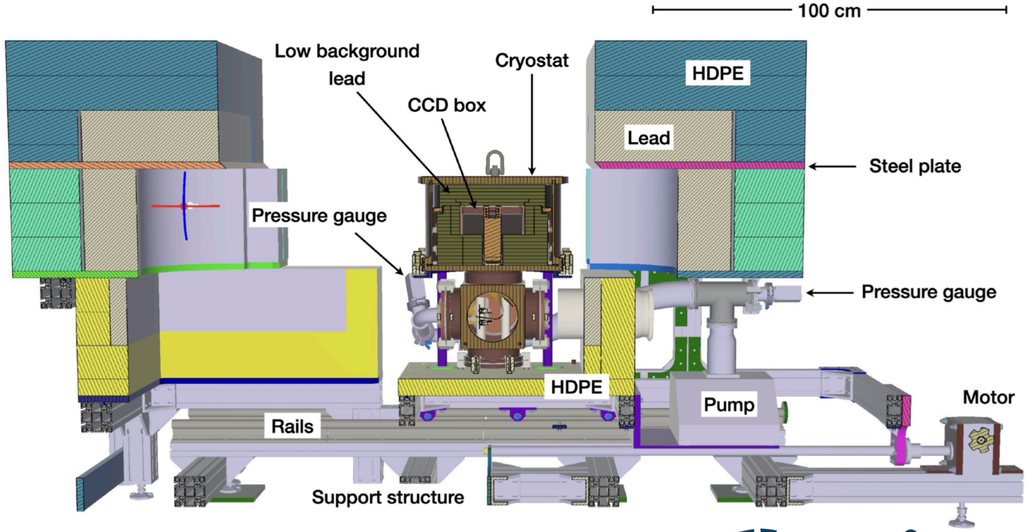
Inner cryostat



CCD module in Cu box

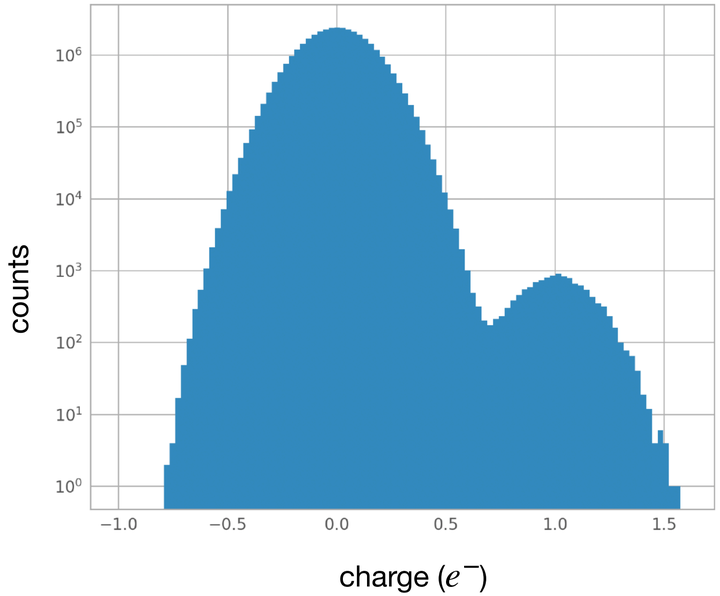
JINST19(2024)T11010

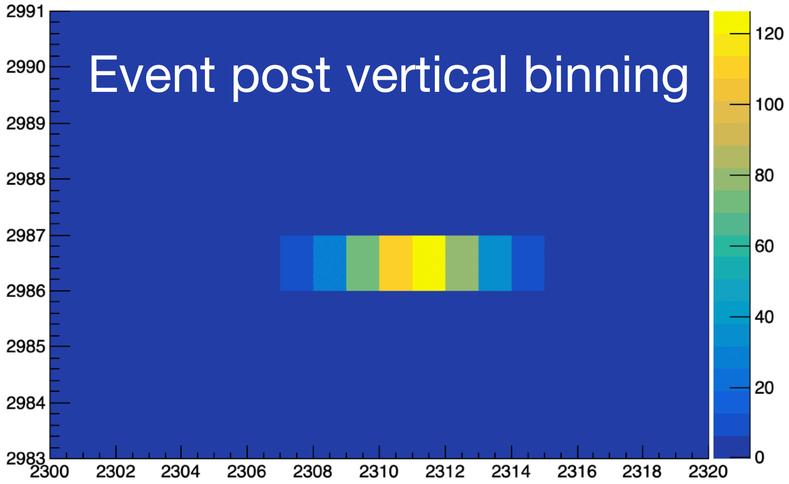




Science run 2

- LBC upgrades post-SR1:
  - 2x CCD modules: 8x 9-Mpixel CCDs, total mass: ~26 g.
  - EFCu lids for copper box. Improved light-tightness.
  - DAMIC-M low-noise electronics.
- SR2 readout parameters:
  - Continuous readout. 1 amplifier per CCD.
  - Pixel binning: 1x100.
- Performance:
  - Readout noise: $0.16e^-$ with 500 NDCM.
  - Reduced dark current: $5 \times 10^{-3} \rightarrow 10^{-4}$ e^-/pix/day.



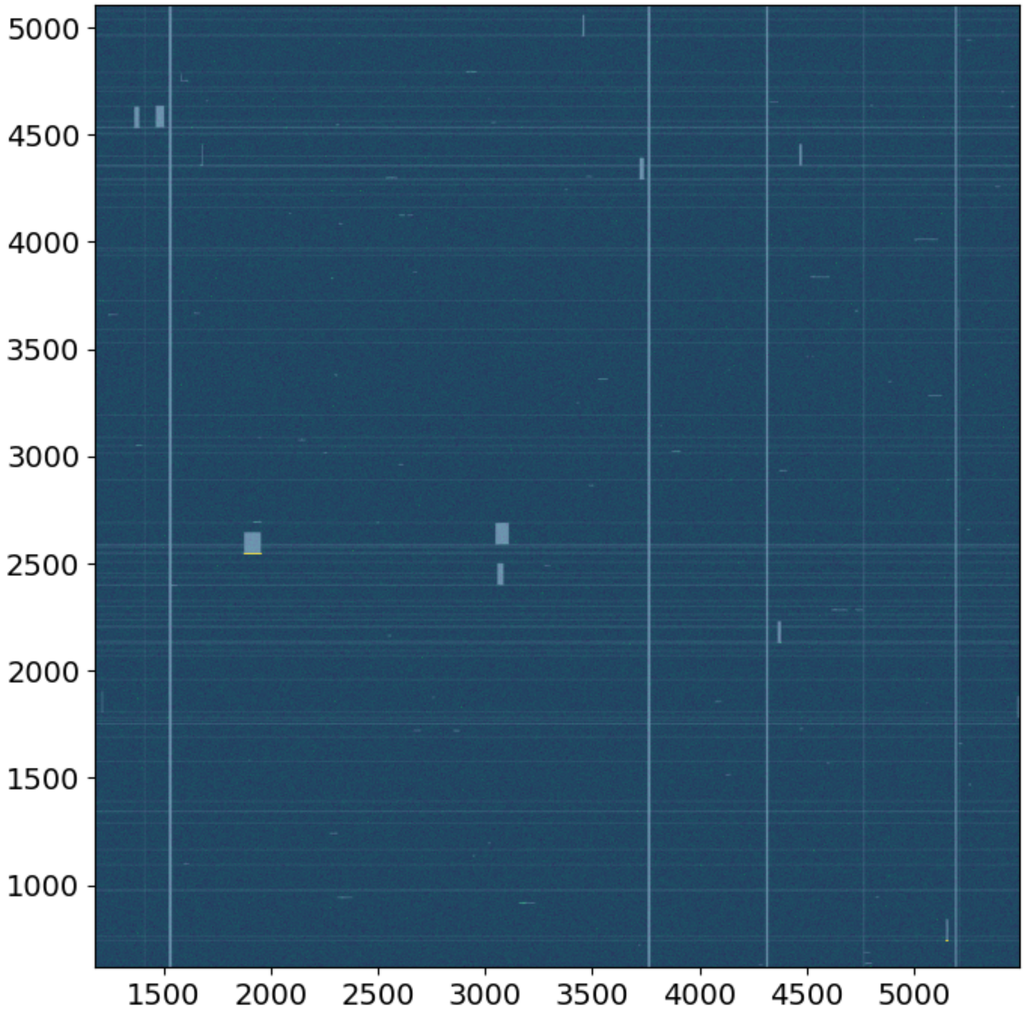


Data selection criteria

- Dataset 1: to establish selections (139 g-day).
- Selected out:
  - Hot columns.
  - Clusters with total charge $\geq 6e^-$.
  - Charge-transfer inefficiency: mask 100 rows above any pixel with $q > 100e^-$ and its row.
  - Cross-talk: pixels in same-module CCDs from high-energy cluster in one CCD.
  - Correlated-noise: pixels in same-module with correlated charge in multiple CCDs.

$$p_{corr} = -\log\left[\prod_L F_{q_{i,j,L}}(0)\right]$$

CCD-1A: ~300 images



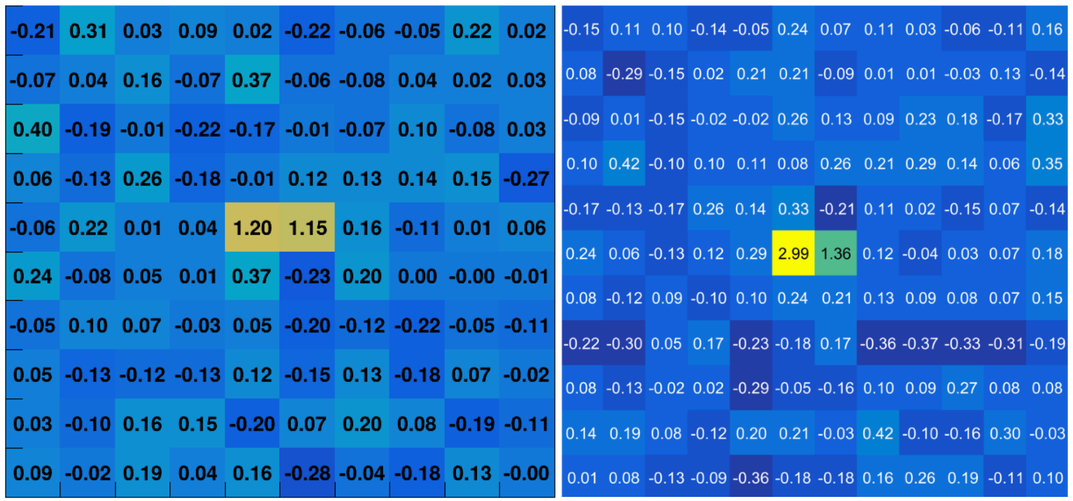
Pattern analysis

- Dataset 2: blinded analysis (1.26 kg-day, ~95% sel. efficiency).
- Candidate selection:
  - Horizontal consecutive pixels with total charge $2,\ 3$ and $4e^-$. $p_{mn} = -\log[F_{q_{i,j}}(m) F_{q_{i+1,j}}(n)]$
  - Efficiency: probability of pattern from ionization event with total charge N_{e^-} . the efficiency for a $(2,\ 3,\ 4,\ 5)\ e^-$ as a pattern is $\sim(38, 65, 79, 86)\%$,
- Backgrounds:
  - Random coincidence of uncorrelated-pixel patterns.
  - Radiogenic, scaled from high energies (2.5 to 7.5 keV).

$$B_p^{\text{rad}} = \tau_p N_{\text{obs}}^{\text{rad}}$$

	Pattern p		
	$\{11\}$	$\{21\}$	$\{111\}$
D_p	144	0	0
B_p^{rc}	141.4	0.111	0.042
B_p^{rad}	0.039	0.039	0.016
	$\{31\}$	$\{22\}$	$\{211\}$
D_p	1	0	0
B_p^{rc}	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.052	0.011	0.035

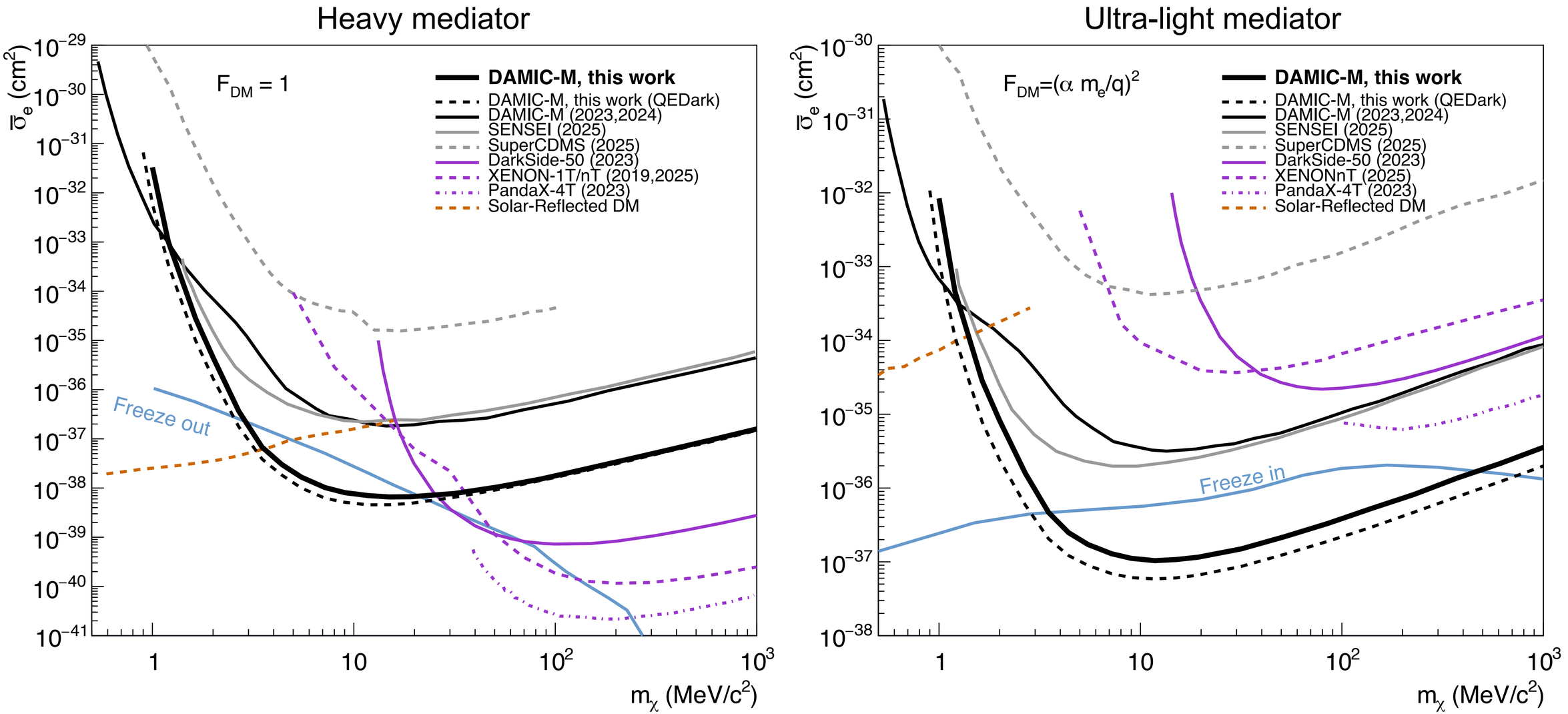
TABLE I. The number of candidates D_p in the D2 data set, and the number expected from backgrounds due to random coincidences, B_p^{rc}, and to radioactive decays, B_p^{rad}.



{1,1} and {3,1} candidates.

DAMIC-M exclusion limits

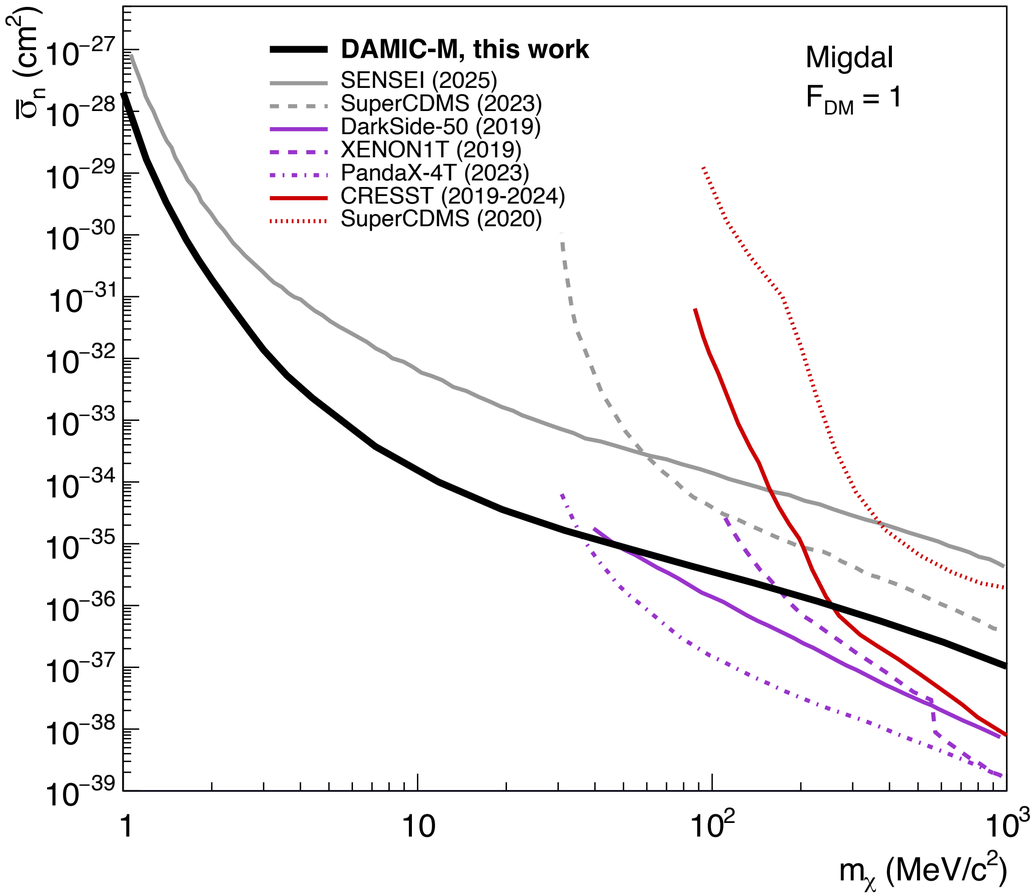
PRL135(2025)071002



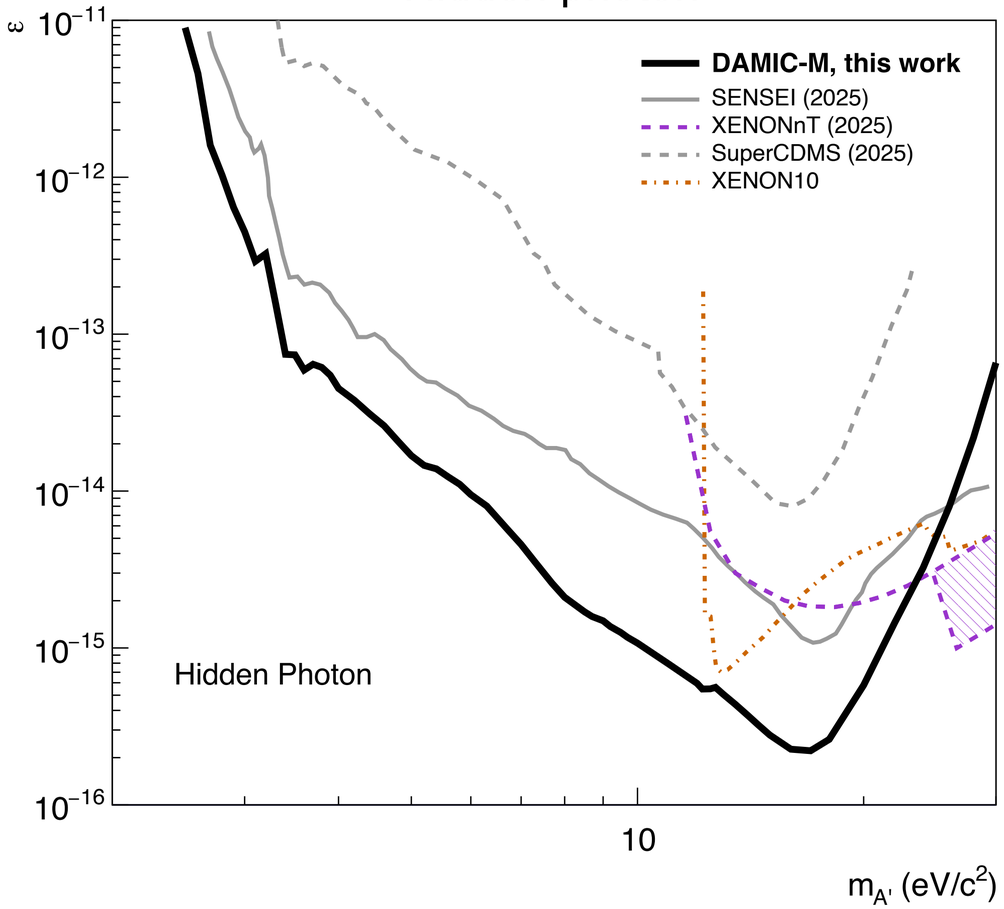
DAMIC-M exclusion limits

PRL135(2025)071002

Migdal via DM-nucleus scattering



Hidden photon



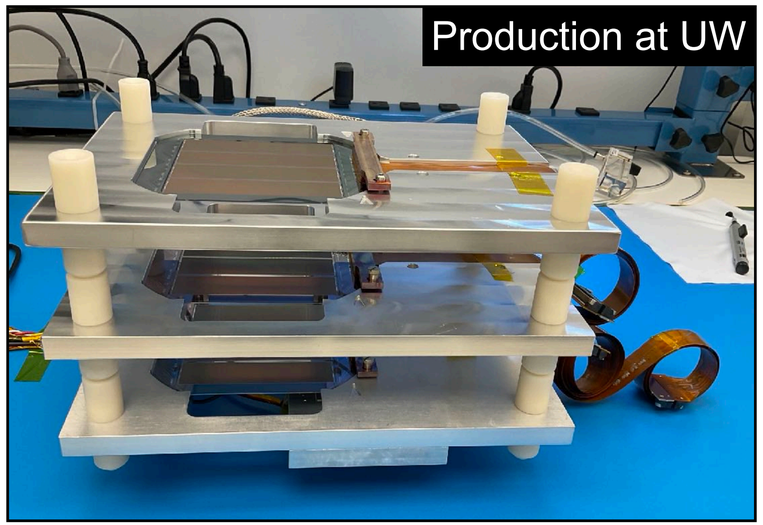
DAMIC-M status

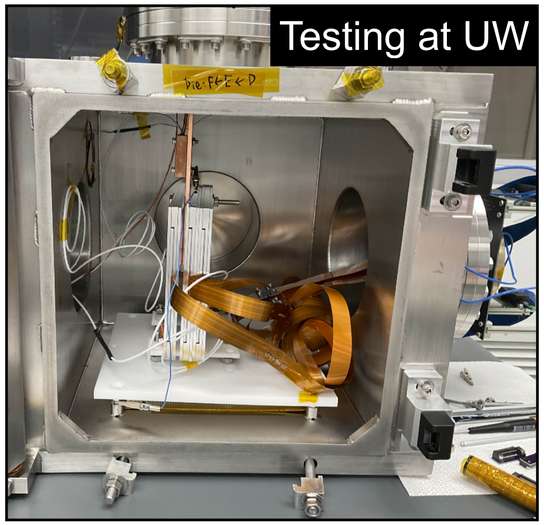
- CCD module production at UW completed (late 2024).

➡ Underground characterization before array assembly (ongoing).

- Copper machining ongoing, lead and poly shield ready.
- Production electronics testing ongoing.
- Detector installation in early 2026!

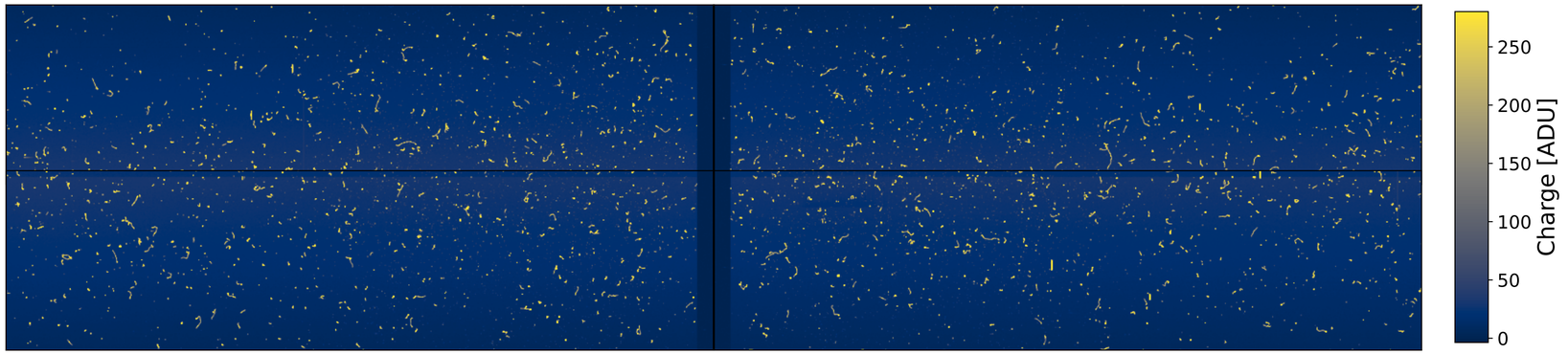
Soon on the arXiv!



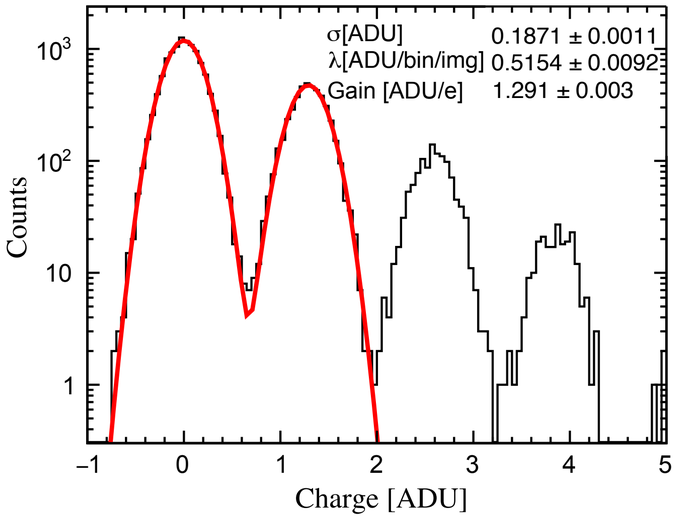


Snapshots from testing at LSM

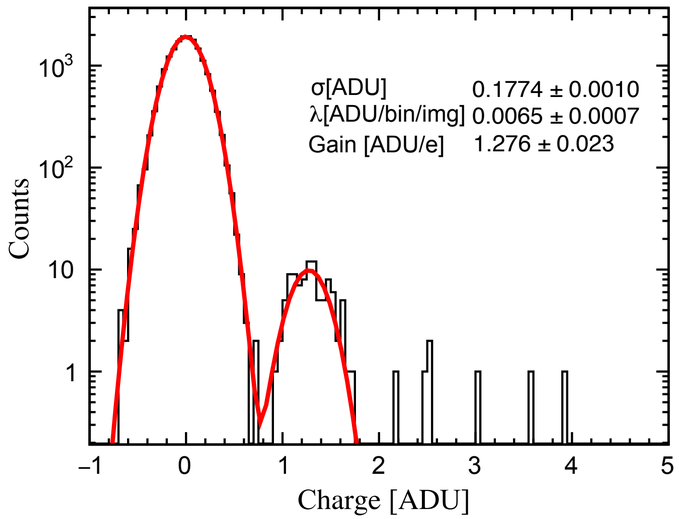
- In-depth characterization of DAMIC-M “DM” modules.
- Testing protocols optimized for underground.



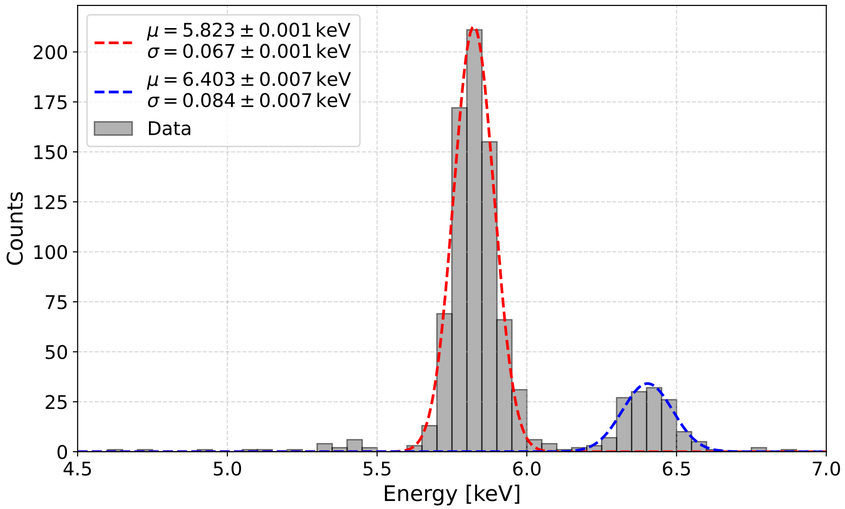
DM-03 image (4 CCDs).



PCD at 185 K



PCD at 135 K



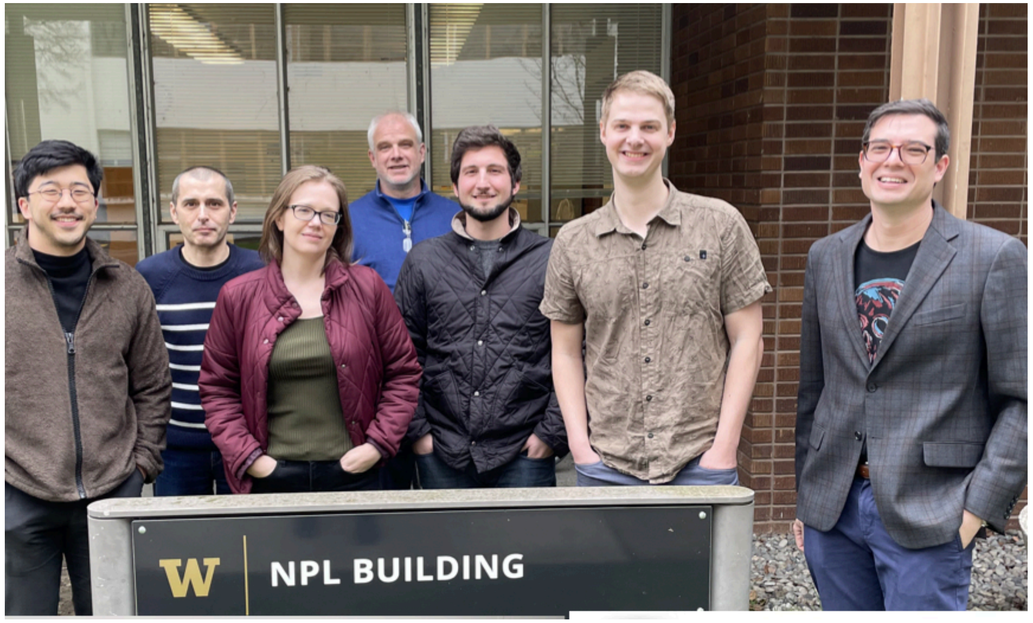
Fe-55 calibration

Conclusions

- With this search, DAMIC-M establishes the most stringent limits to date on DM particles interacting with electrons between 1 and 1000 MeV. PRL135(2025)071002
- First experiment to rule out that relic DM features ultralight-mediator DM (freeze-in) as a dominant component between 3.5 and 490 MeV.
- Also rules out heavy-mediator scalar DM (freeze-out) in any fraction between 2.9 and 21.5 MeV.
- We fabricated and tested 28 low-background CCD modules at the University of Washington. In depth characterization ongoing at LSM.
- DAMIC-M will be deployed in early 2026.


Thanks!
LABORATOIRE SOUTERRAIN de MODANE


DAMIC-M


NPL BUILDING

IFCA

The DAMIC-M Collaboration

Relic abundance from the hidden sector

- Hidden-sector DM models can give rise to the observed relic density.

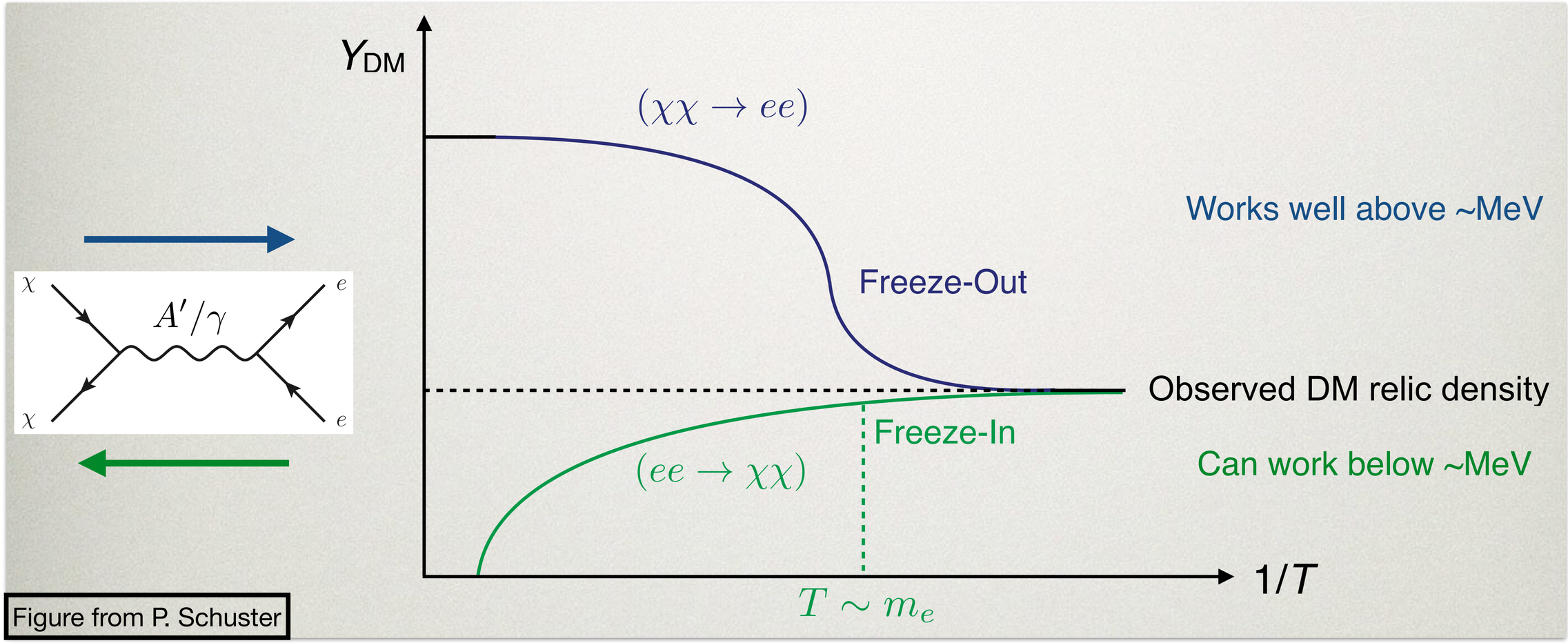


Figure from P. Schuster

Signal model and limit

theory input

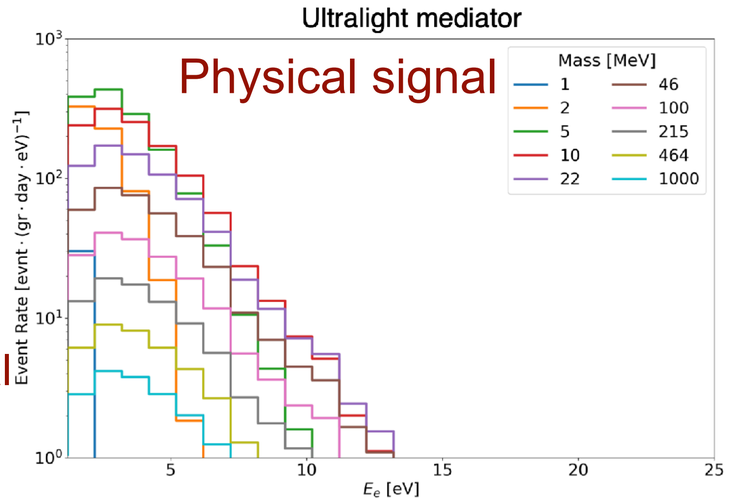
DM galactic halo

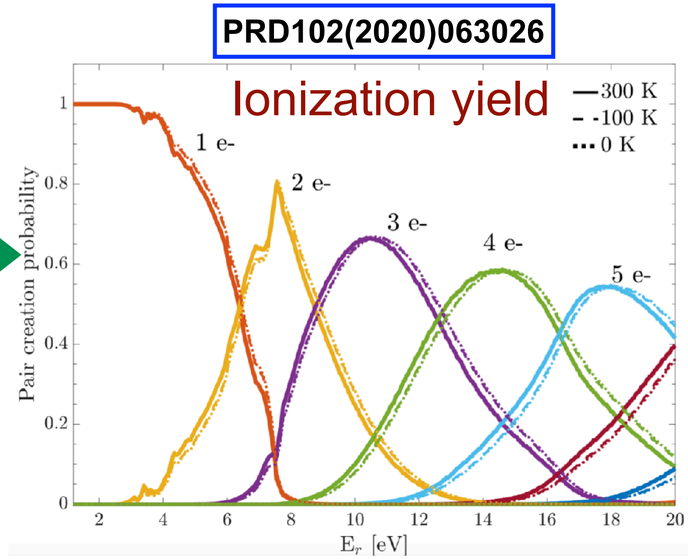
DM-e cross section

DM form factor

crystal

$$\frac{\mathrm{d}R}{\mathrm{d}E_e} \propto \bar{\sigma}_e \int \frac{\mathrm{d}q}{q^2} \left[\int \frac{f(\mathbf{v})}{\mathrm{v}} \mathrm{d}^3\mathrm{v} \right] |F_{\mathrm{DM}}(q)|^2 \, |F_{\mathrm{c}}(q, E_e)|^2$$





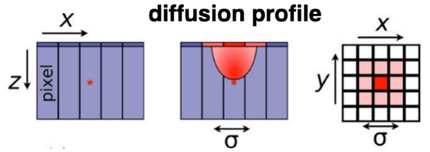
N. of patterns *p*

number of DM interactions resulting in q_e ionization

$$S_p = \sum_{q_e} N_{q_e}(\bar{\sigma}_e, m_\chi) P_{q_e \to p}$$

Probability that q_e charges result in a pattern *p*

from MC simulation, including charge diffusion and pattern selection



$\bar{\sigma}_e$

nuisance

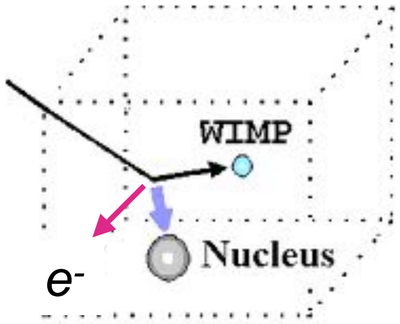
$$\mathcal{L}(\mu, \theta) = \prod_p \frac{(S_p(\mu) + B_p^{rc} + \theta B_p^{rad})^{D_p} e^{-(S_p(\mu) + B_p^{rc} + \theta B_p^{rad})}}{D_p!} \prod_p \frac{(\theta \tau_p B_p^{rad})^{N_{rad}} e^{-(\theta \tau_p B_p^{rad})}}{N_{rad}!}$$

control sample

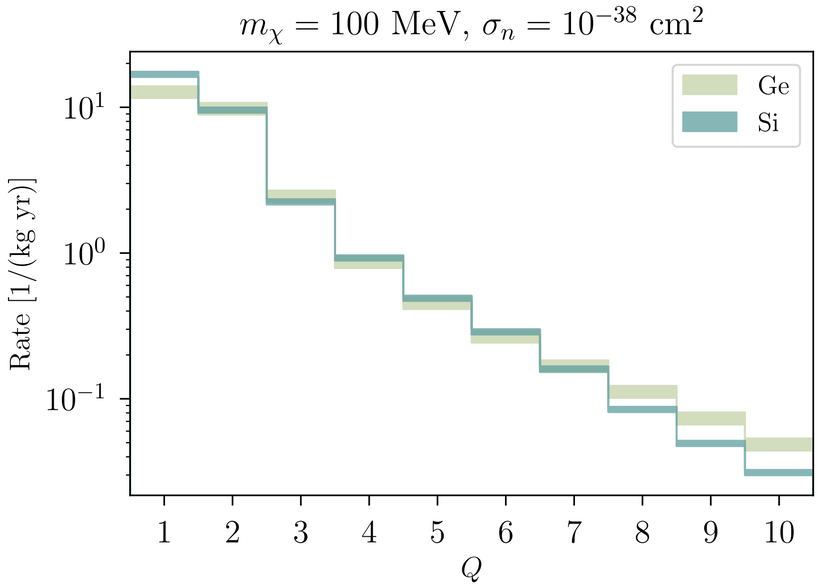
The background-only null hypothesis has $p_0 = 0.24$ (0.10), so we place 90% CL exclusion limits using the profile likelihood ratio test statistics.

Migdal electrons

Three-body final state:



- Migdal effect: an additional (atomic e^-) in the final state.
- *E* and *p* conserved even when e^- takes most of the WIMP kinetic energy.
- Very rare process.
- Not yet observed for keV energies. Uncalibrated. We have plans to do it.

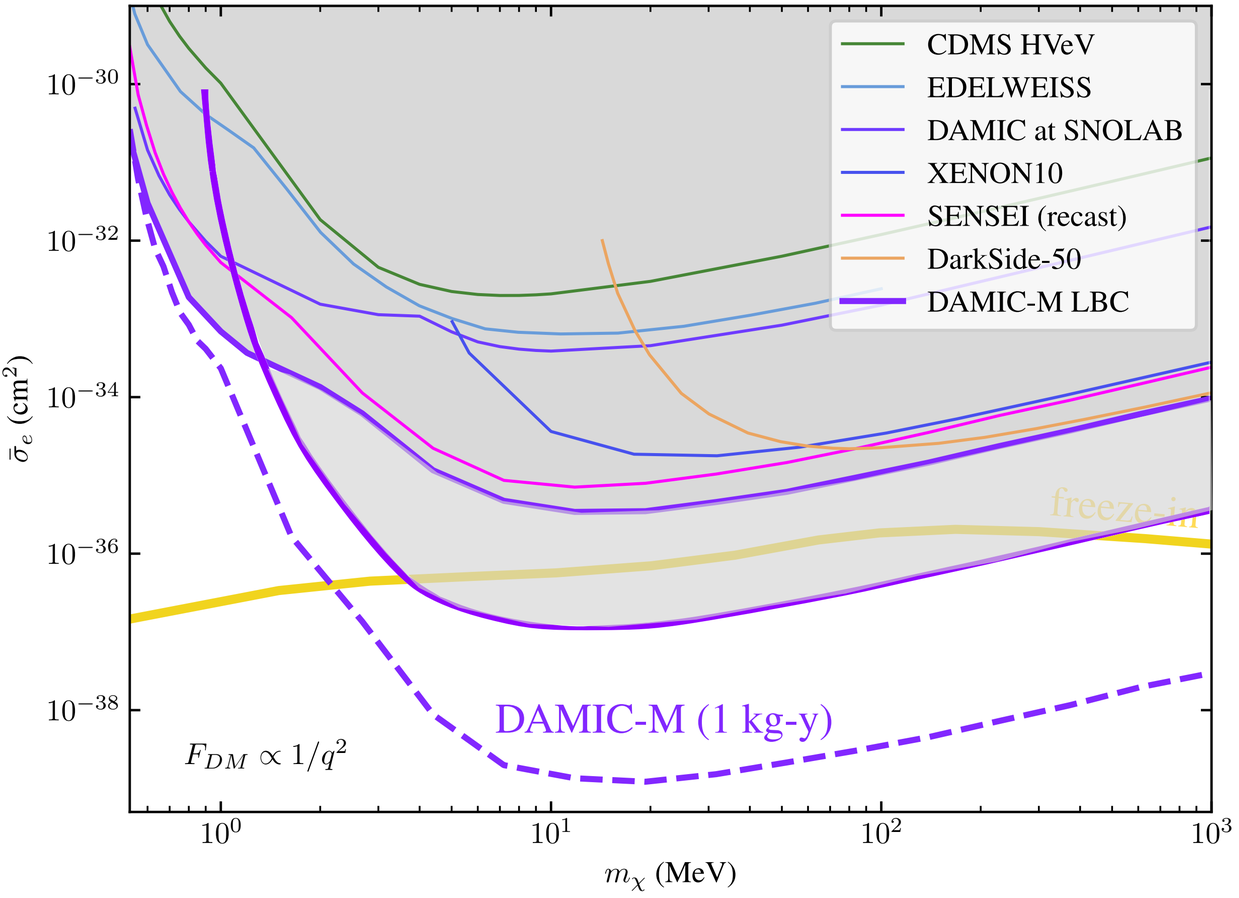


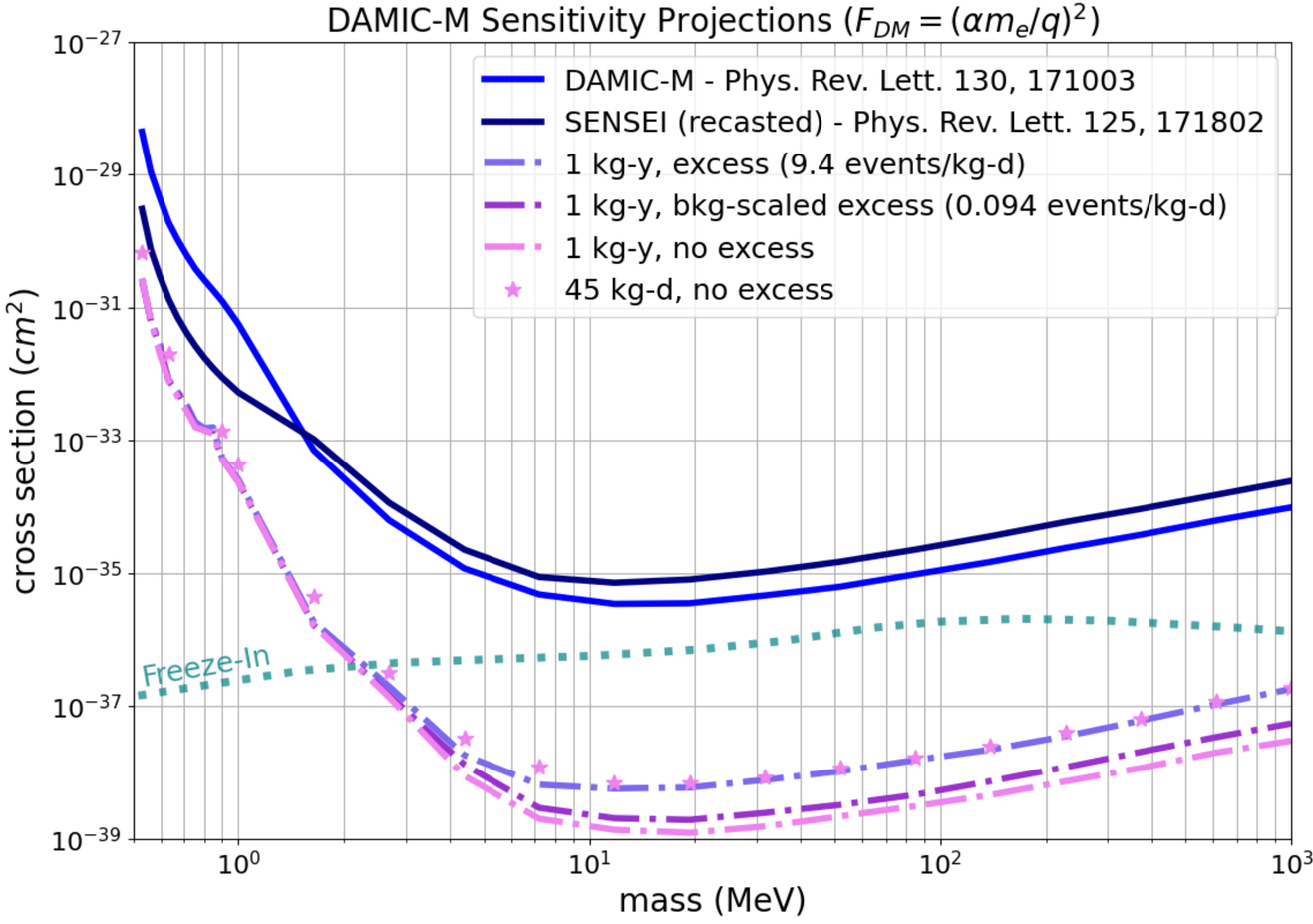
Bosonic DM absorption:

- DM particle is a boson that couples to the electron, e.g., a “dark” or “hidden” photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

Electronic recoil result re-interpreted as limit on DM-N scattering (Migdal) or DM absorption

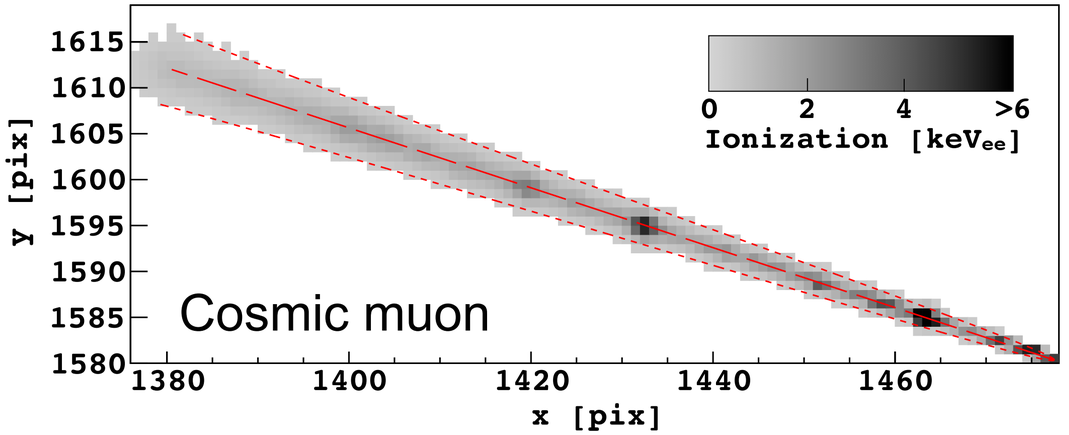
Sensitivity projections

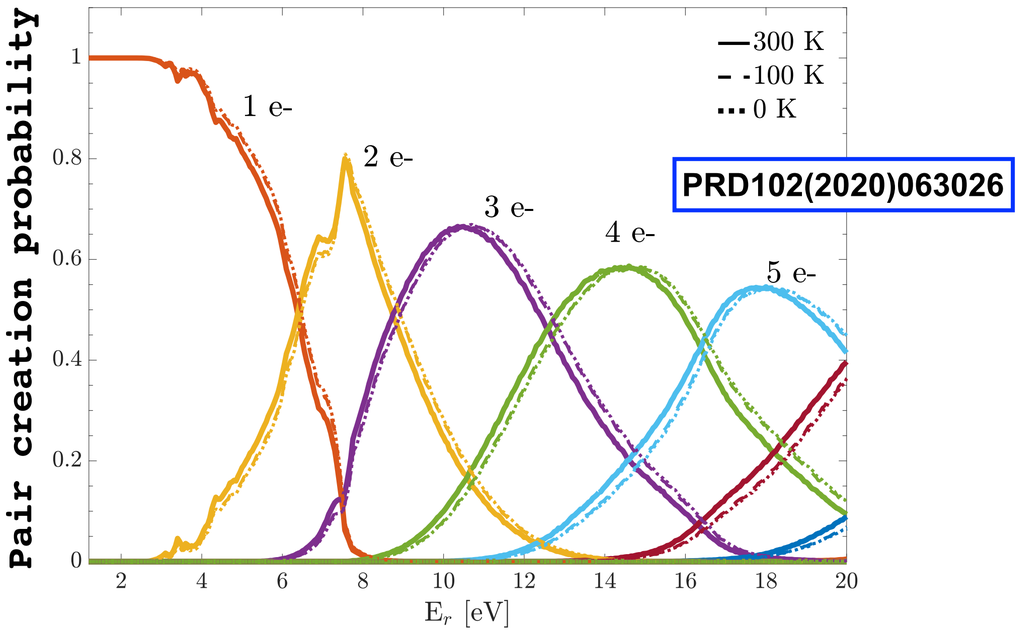


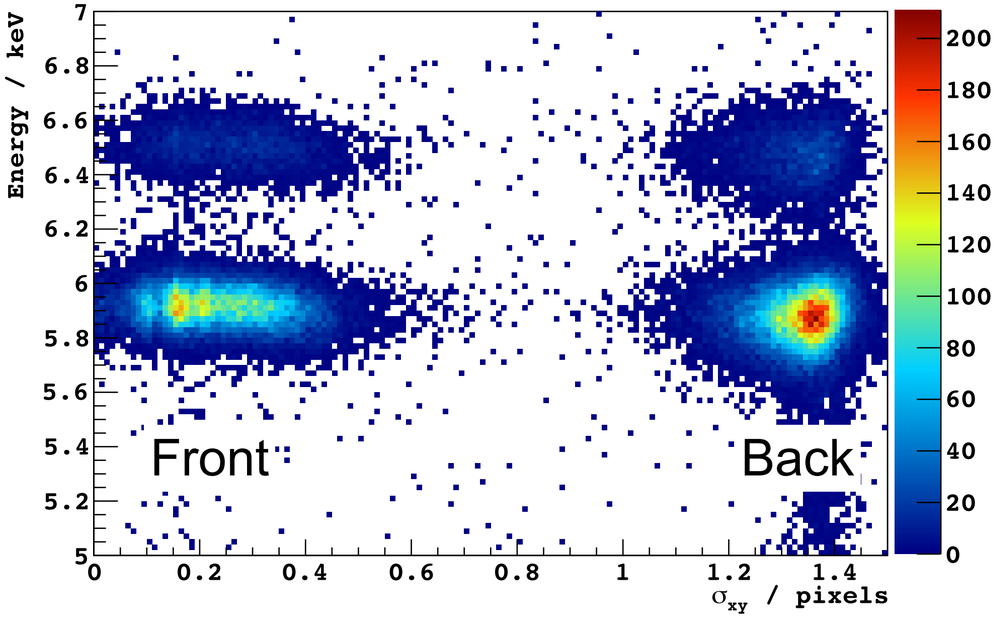


CCD response

- Extensive research program to characterize the response of CCDs: energy / *z* recon.
- Sources: optical photons, X rays, γ rays, neutron sources, etc.
- Detailed models, e.g., charge generation, diffusion and collection.

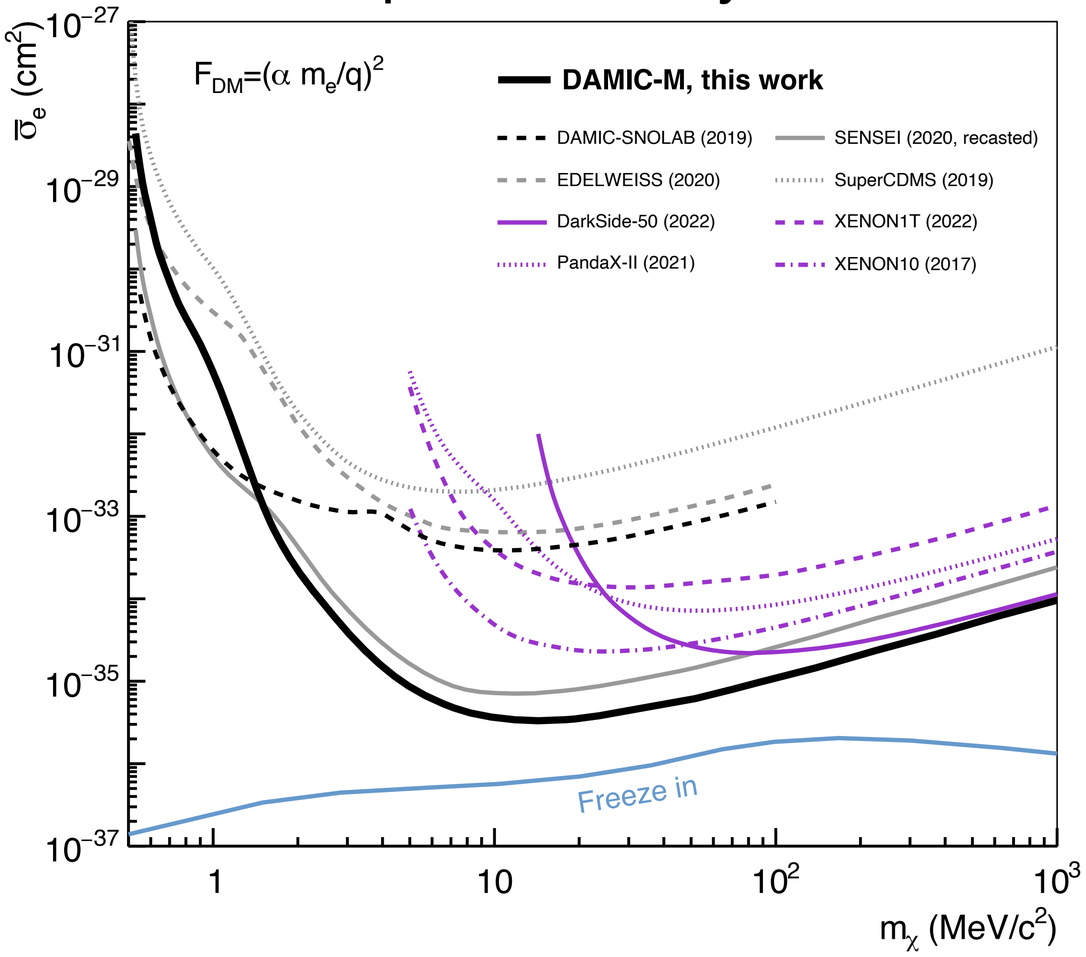




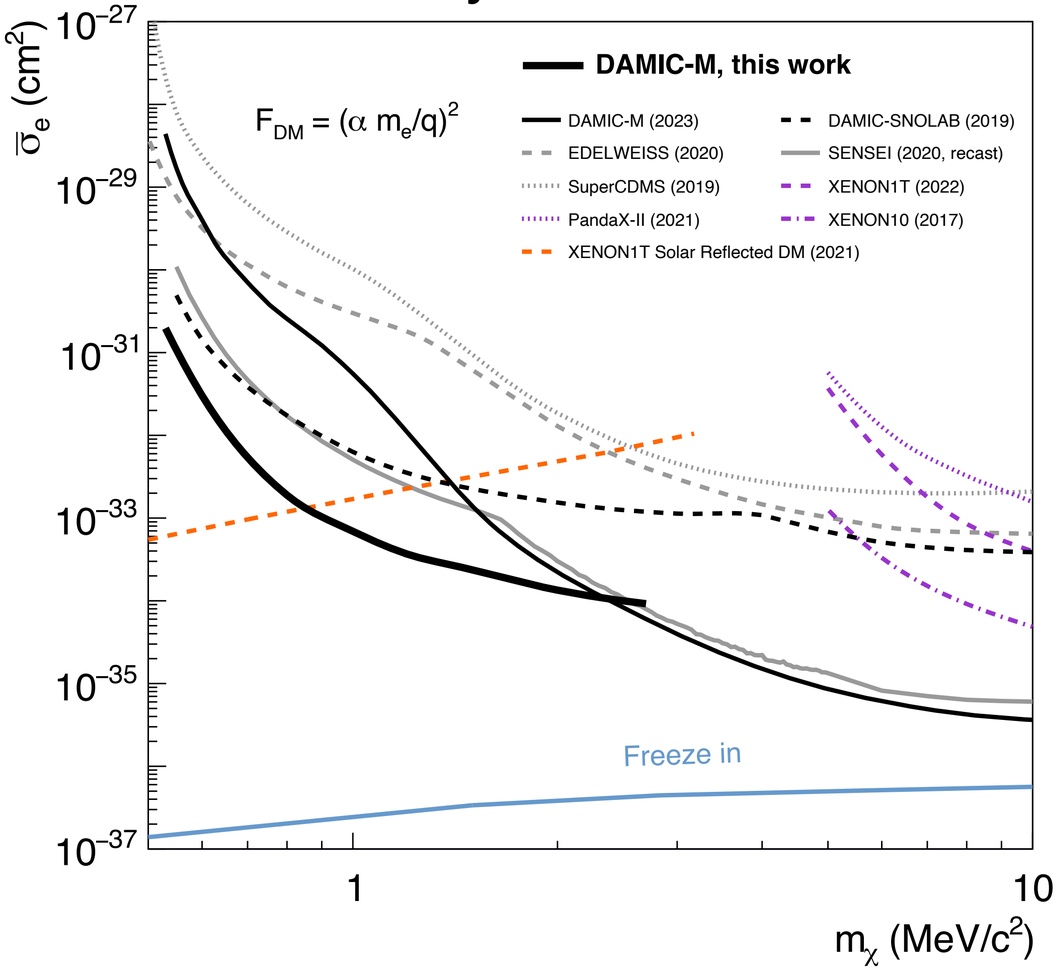


SR1 results

Spectral analysis



Daily modulation



Daily modulation