The search for dark matter with CCDs

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DAMIC-M

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Outline

- Dark matter (DM) direct detection.
- DM-e^- scattering searches.
- Charge-coupled devices (CCDs).
- DAMIC-M at Modane Underground Lab.
- Results from the LBC test stand.
- DAMIC-M status and prospects.

Dark matter particles

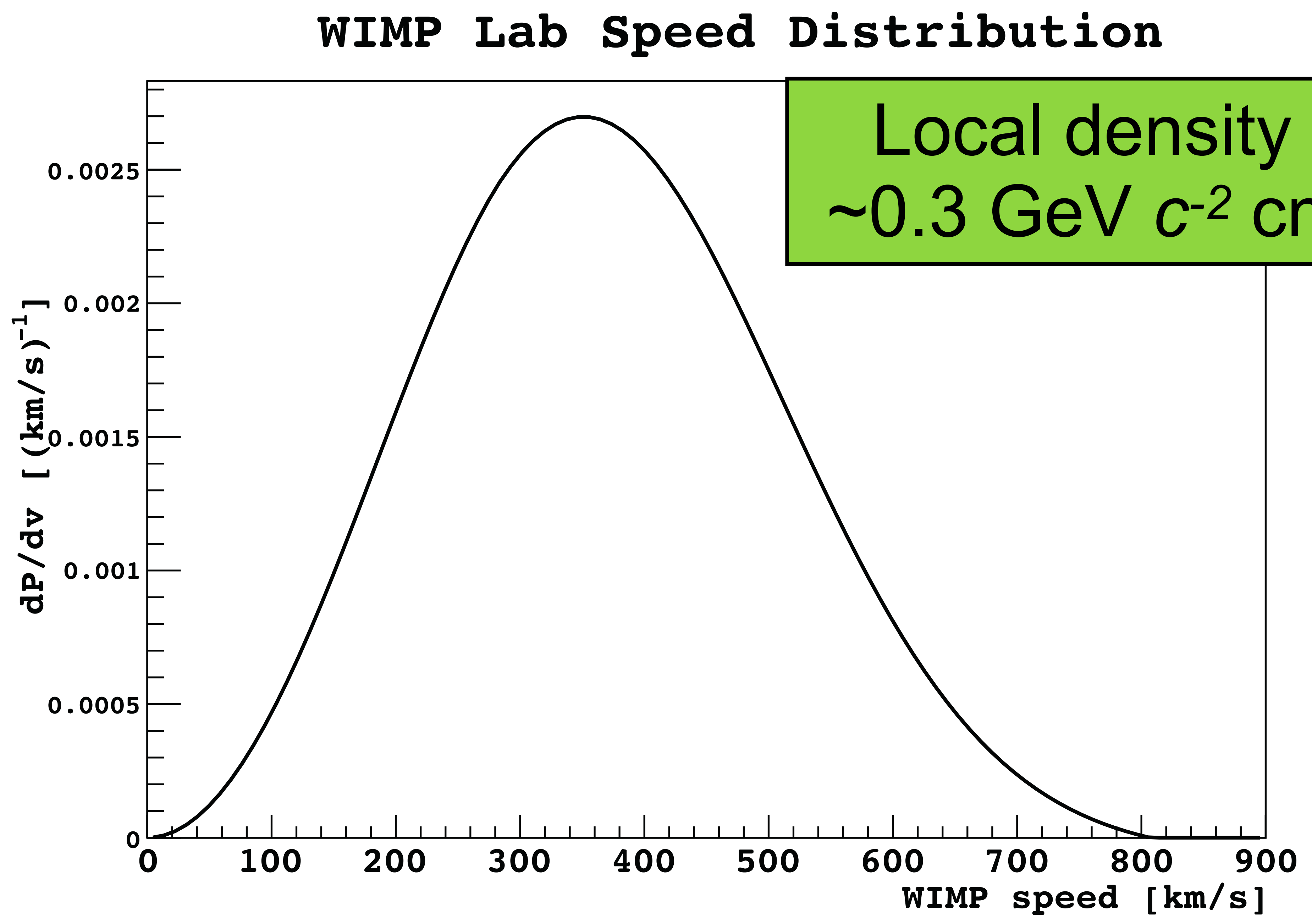
Dark matter is *cold*, i.e., it is bound to the galaxy.

Hence, the dark matter particle speed is ~the same as stars: 100s km/s.

$$E_\chi = \frac{1}{2} M_\chi v^2$$

$$E_\chi = \frac{1}{2} M_\chi c^2 \beta^2 \qquad \beta \approx 10^{-3}$$

$$E_\chi \approx \left(\frac{M_\chi c^2}{\mathrm{GeV}} \right) \mathrm{keV}$$



Local density is ~0.3 GeV c^{-2} cm^{-3}.

We do not know the particle mass (M_χ)

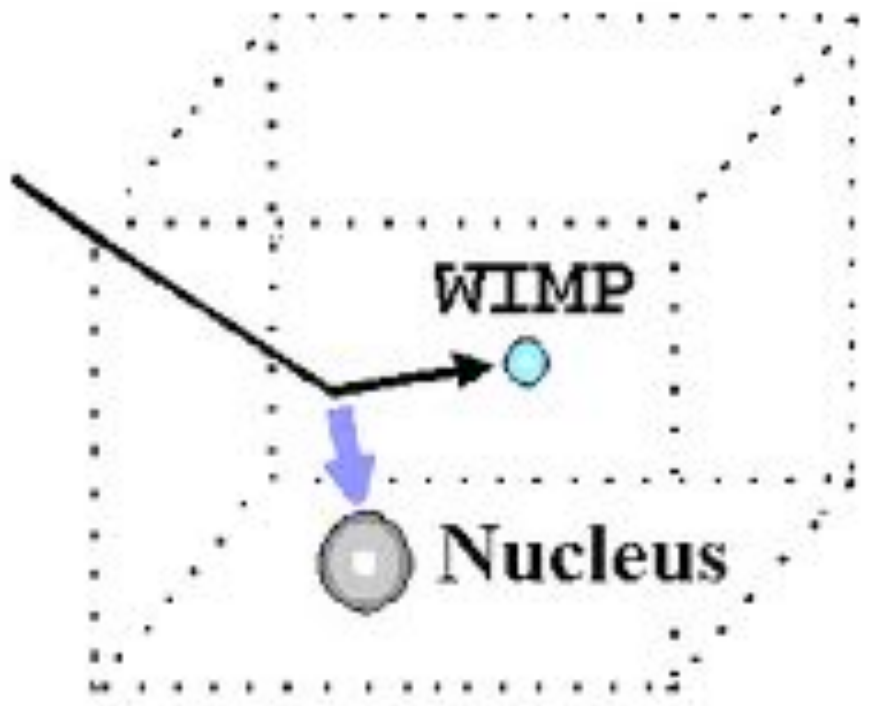
A 1 GeV (proton-mass) particle has 1 keV of kinetic energy (very little).

Dark matter signal

- Small interaction cross-section.
- Need detector with low energy threshold, largest possible exposure and correspondingly low backgrounds.

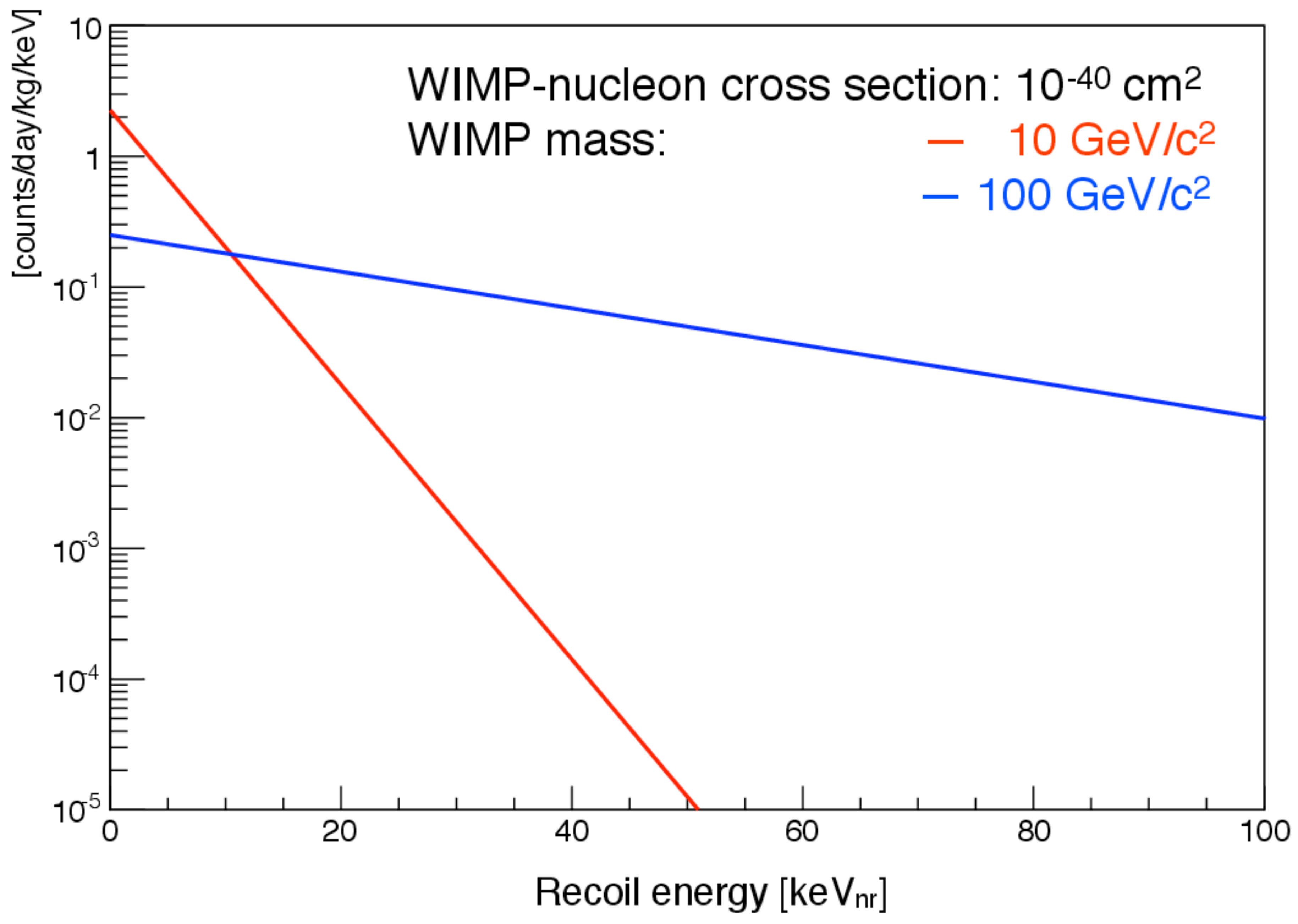
Traditional mechanism for WIMP searches:

Coherent enhancement: $\sigma_N \propto A^2$



Maximum energy transfer when $M \sim A$

Recoil spectrum in Si target

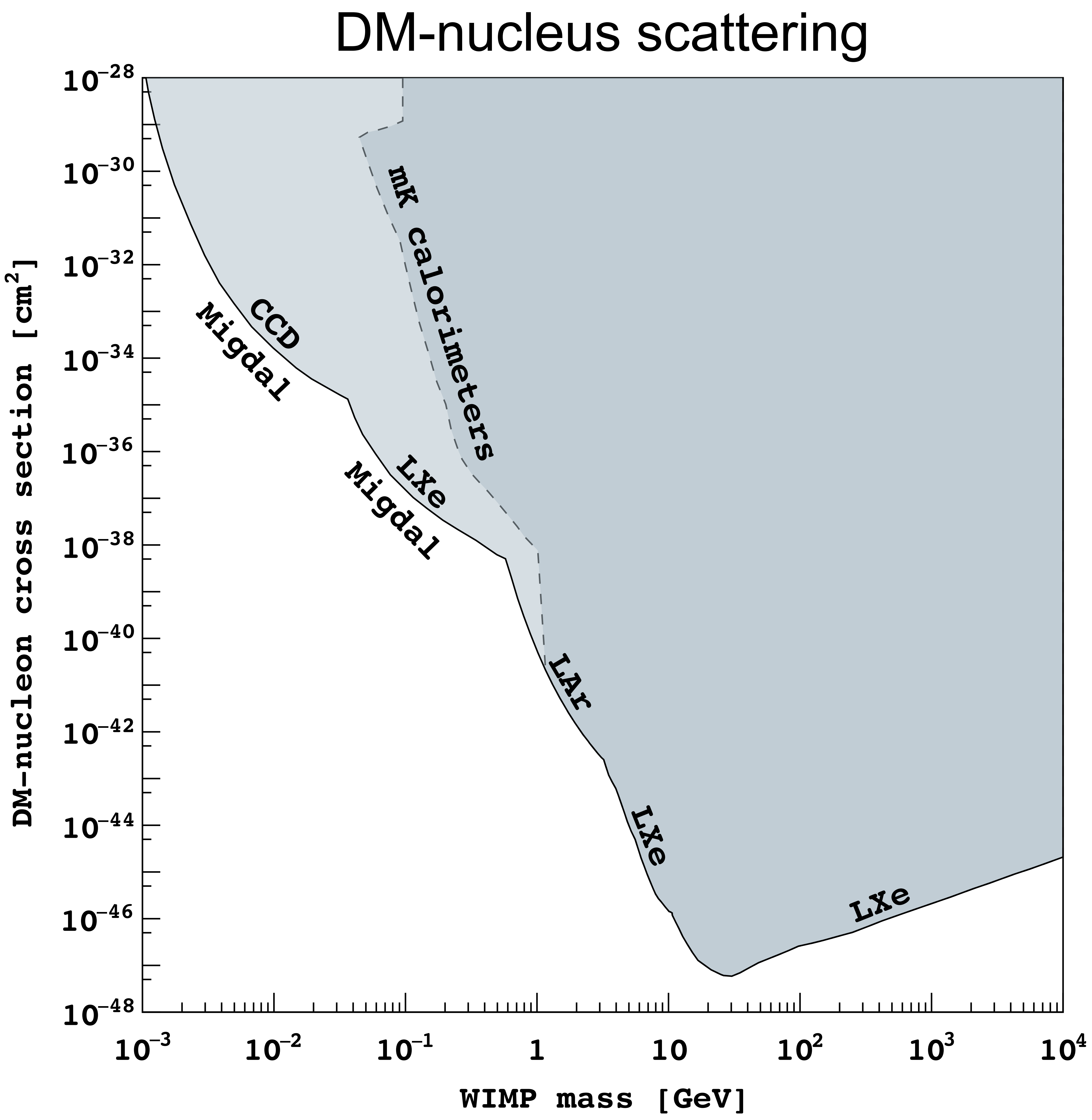


For low-mass WIMP: $M_T \gg M_\chi$

$$E_T < 4\frac{M_\chi}{M_T}E_\chi$$

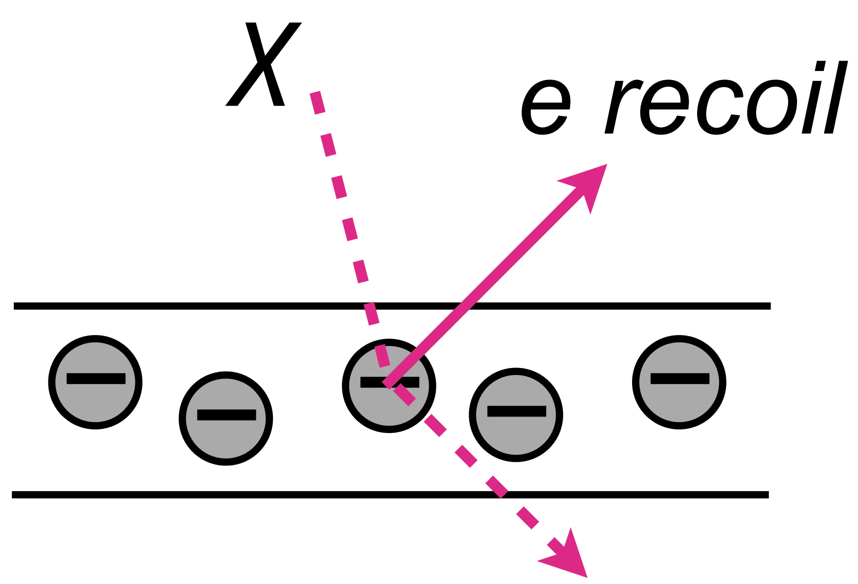
World Status

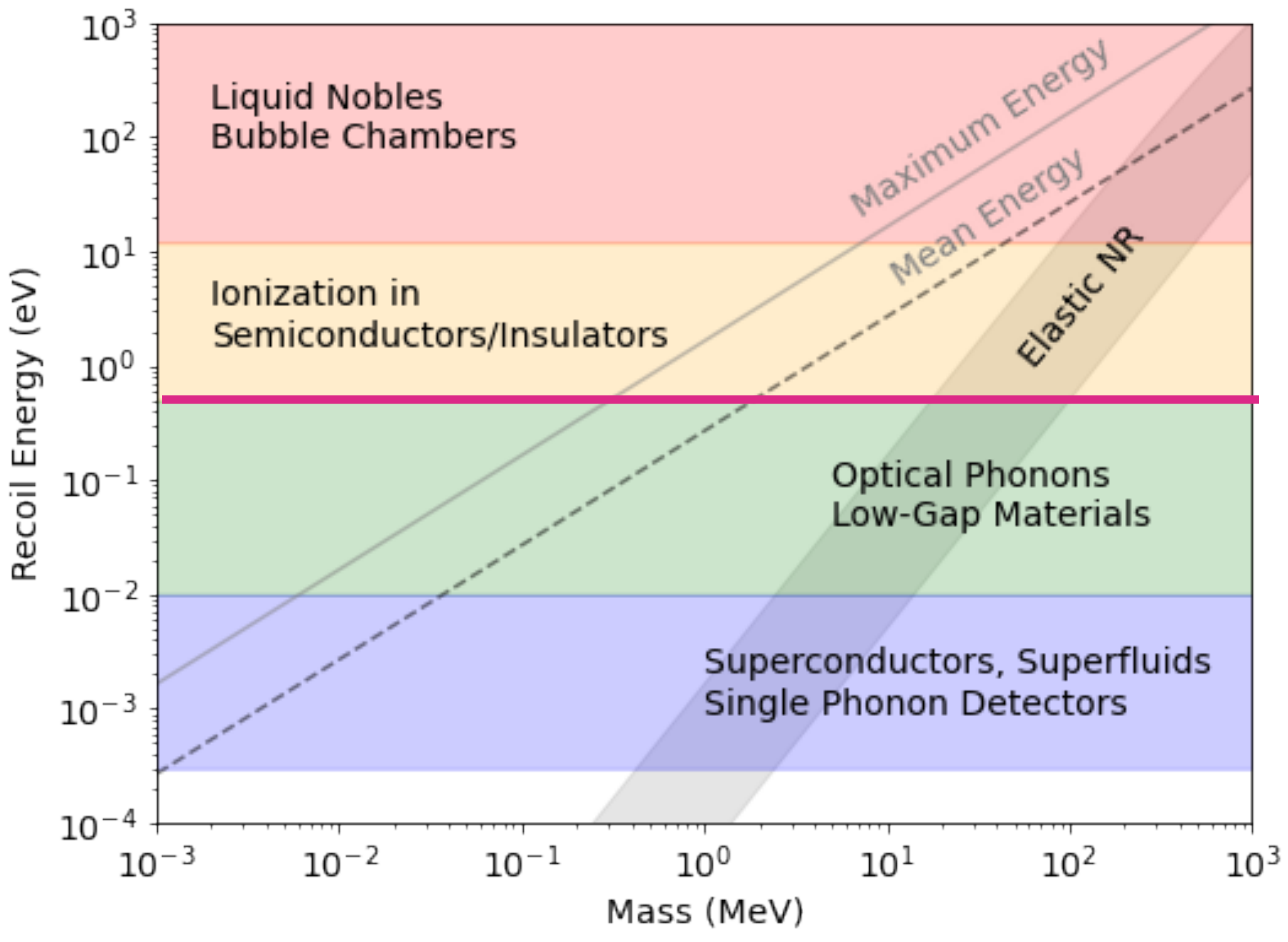
- World-wide effort to directly detect DM signals.
- For "particle" DM the search currently spans from ~1 MeV to the Planck mass.
- Different technologies target different mass ranges.
- CCDs have greatest sensitivity below 35 MeV*
- *Depends on the Migdal effect (10^{-6} probability of ionization, see McCabe's talk)



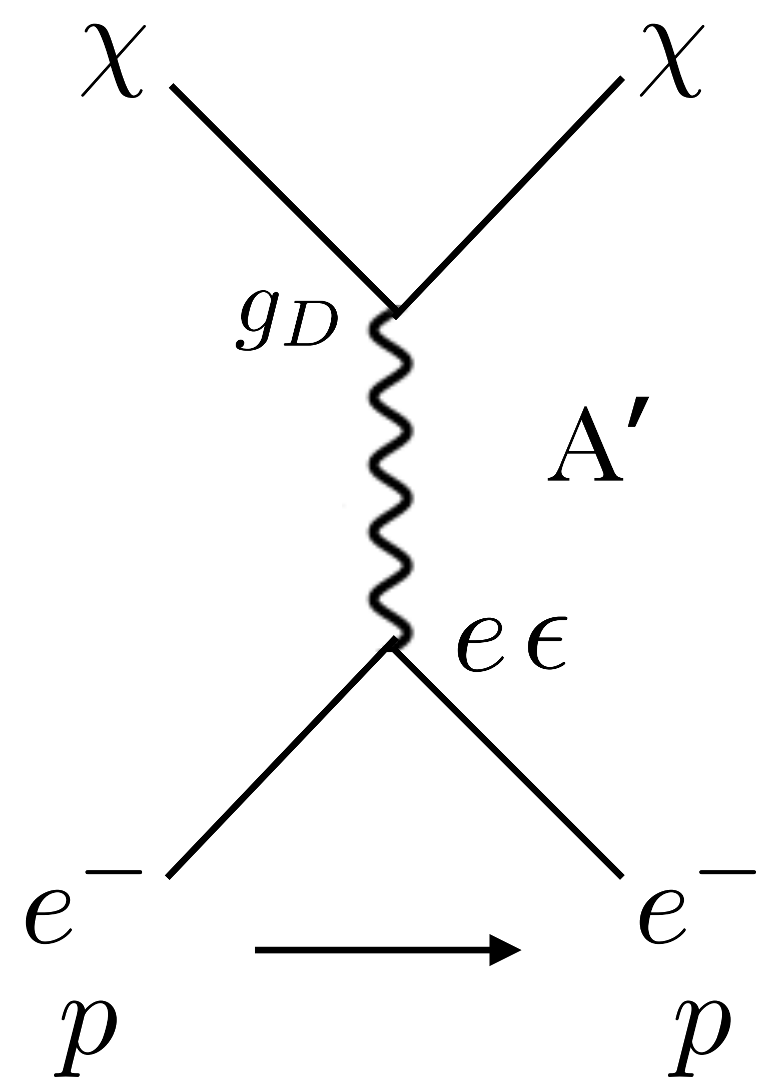
DM-e scattering

- Electrons are a lighter target and *ER visible as ionization*.
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.





- Mediator A' mixes with SM photon.



- Most sensitive direct-detection probe for sub-GeV hidden-sector DM!

- Momentum distributions in some targets better "kinematically matched" to the DM than others.
- Phase-space 'penalty,' no coherent enhancement and probing DM-e interaction cross-section.

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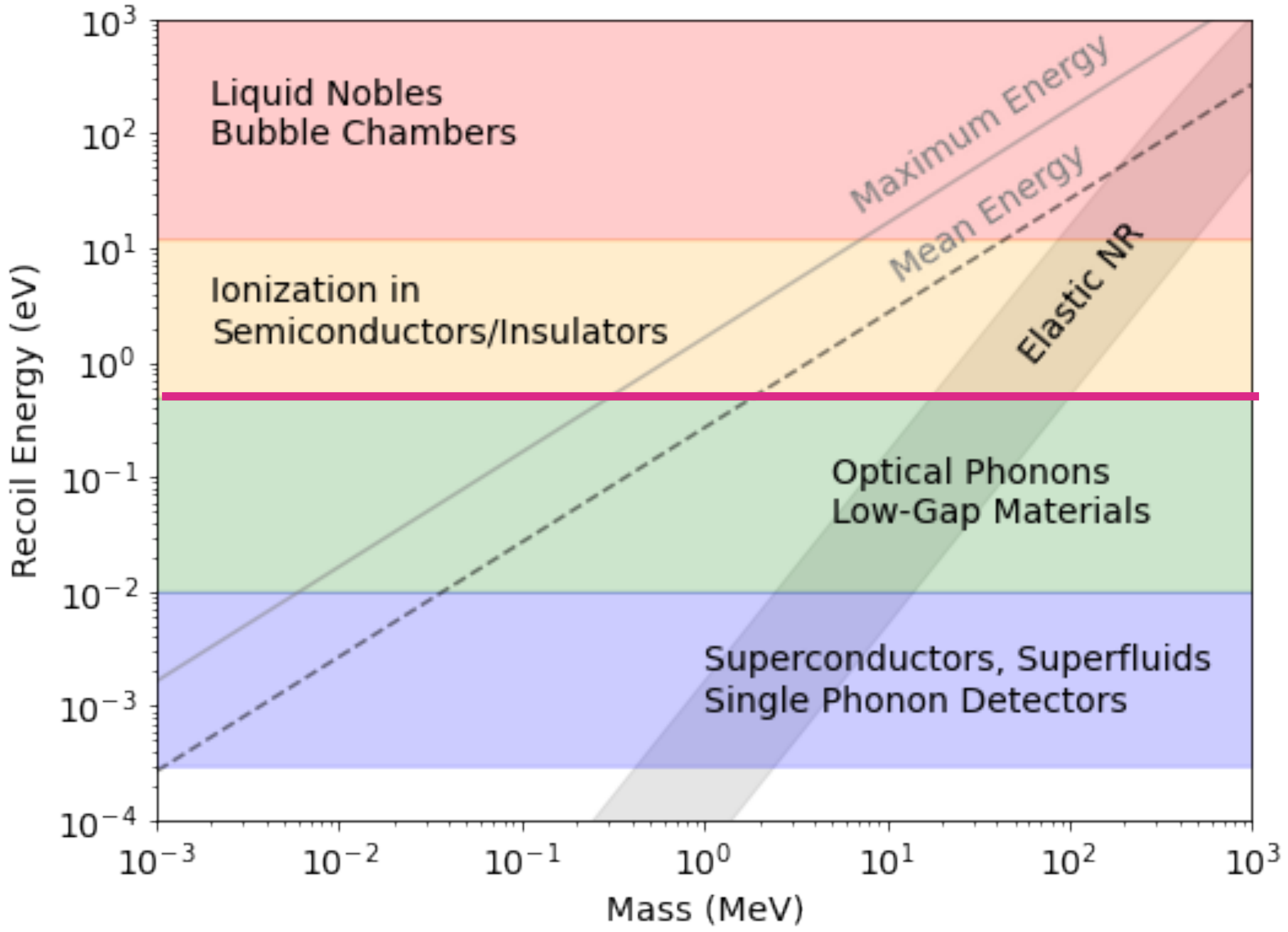

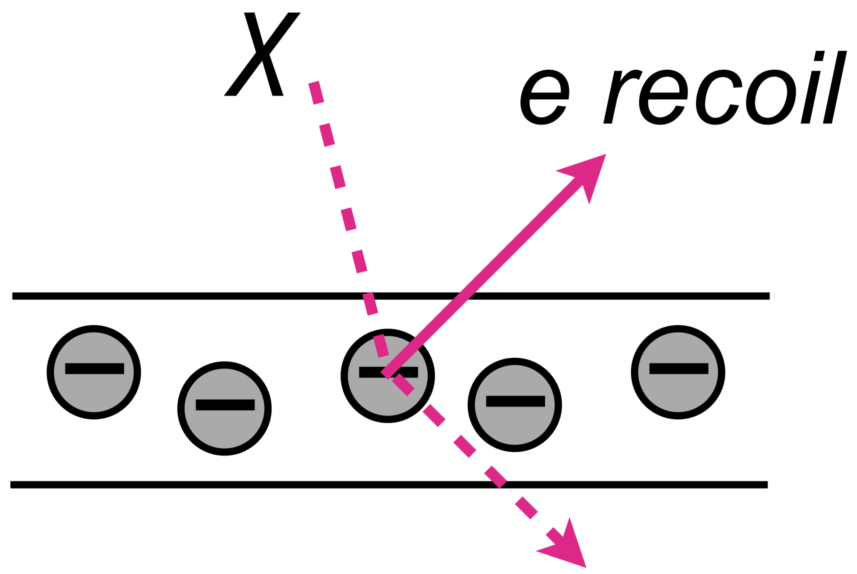

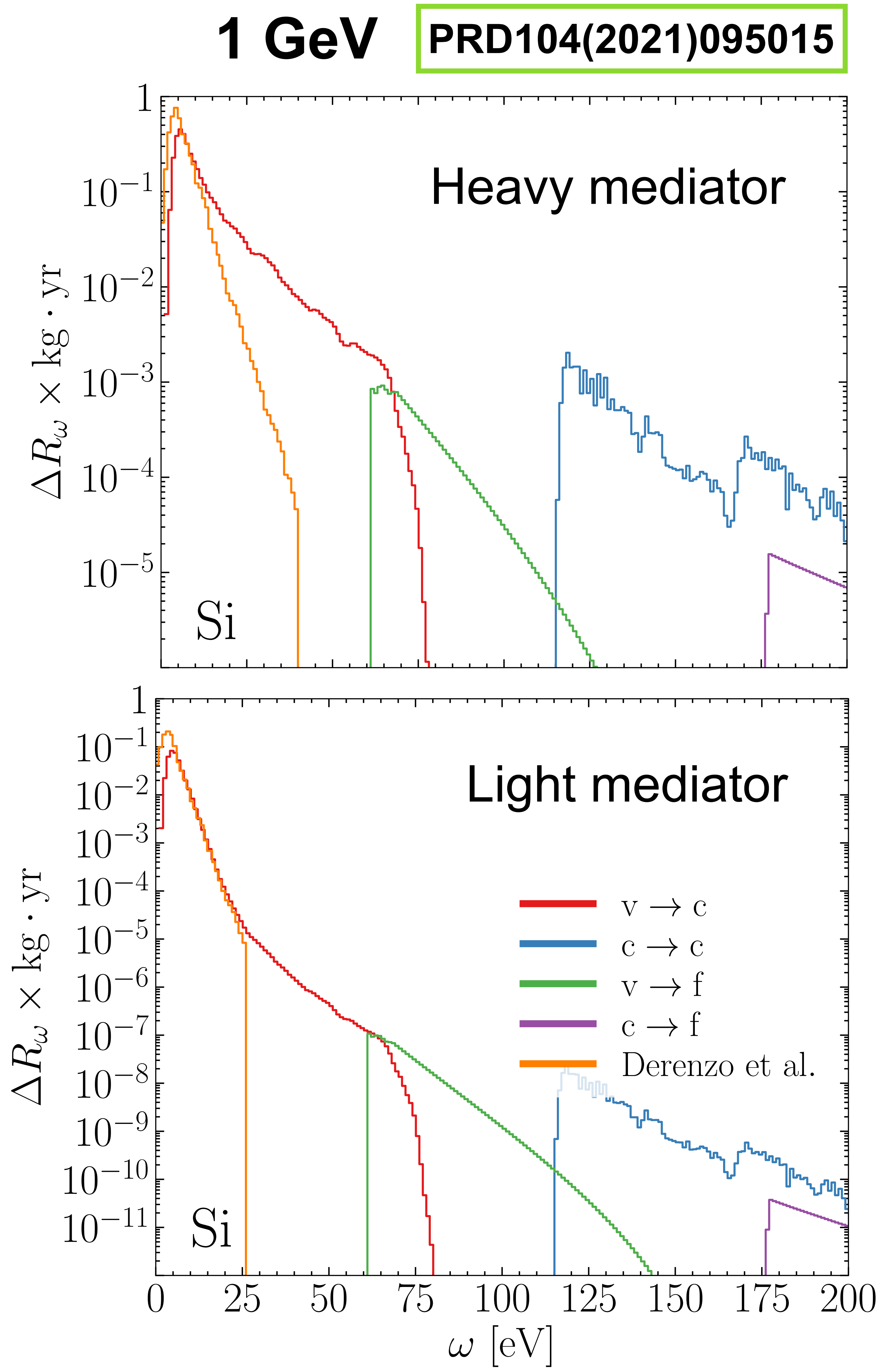

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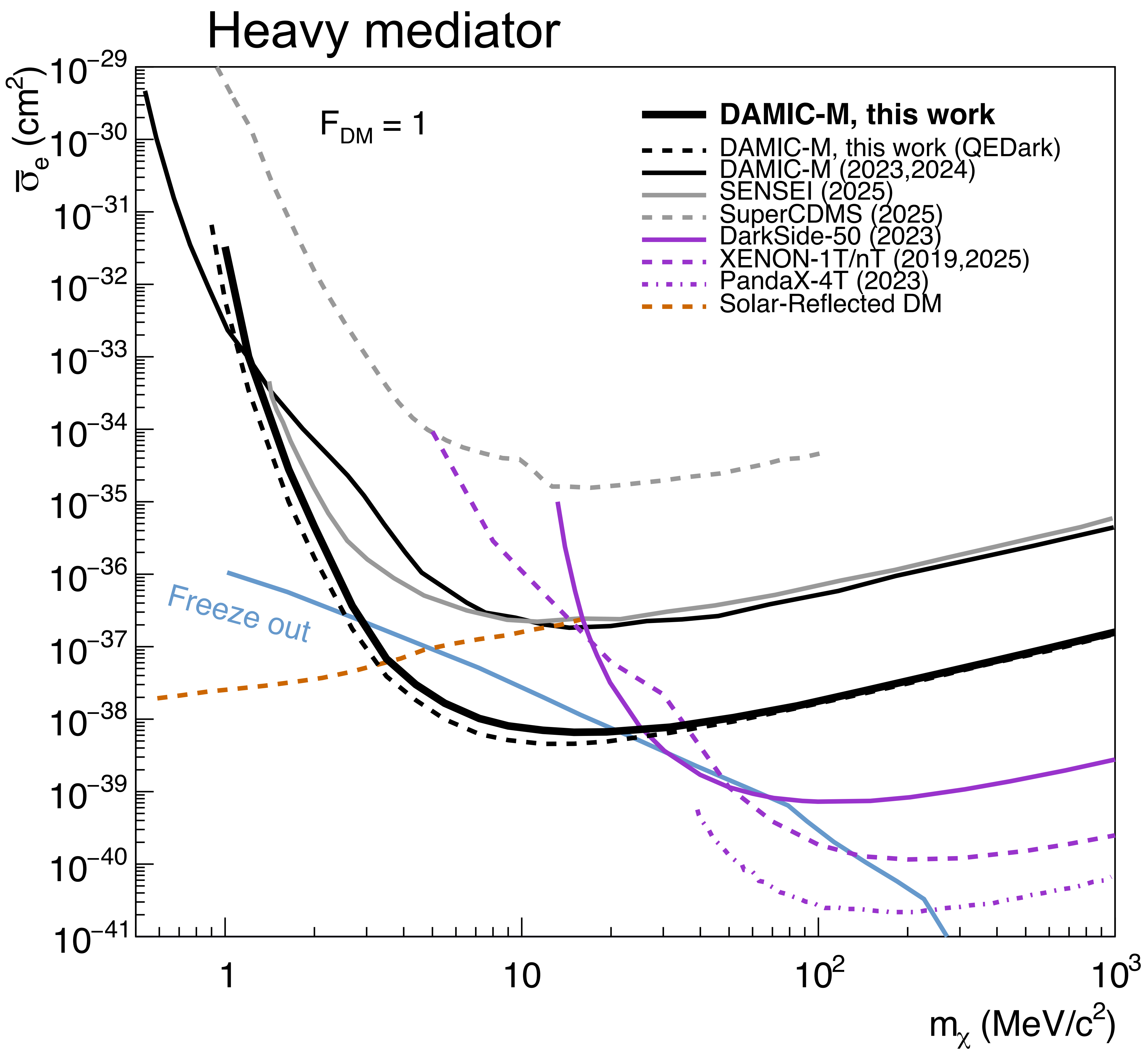
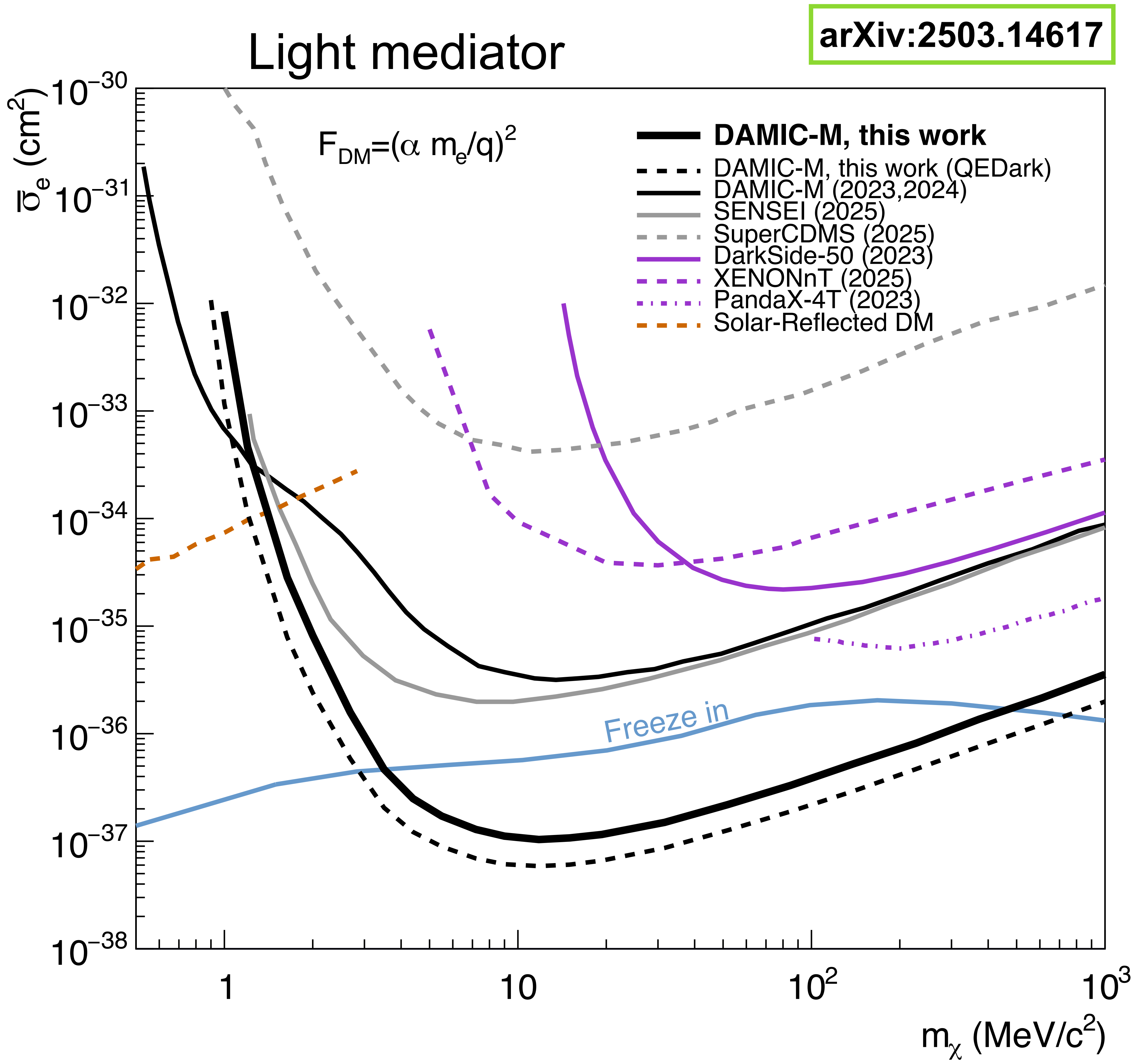
- Phase-space 'penalty,' no coherent enhancement and probing DM-e interaction cross-section.

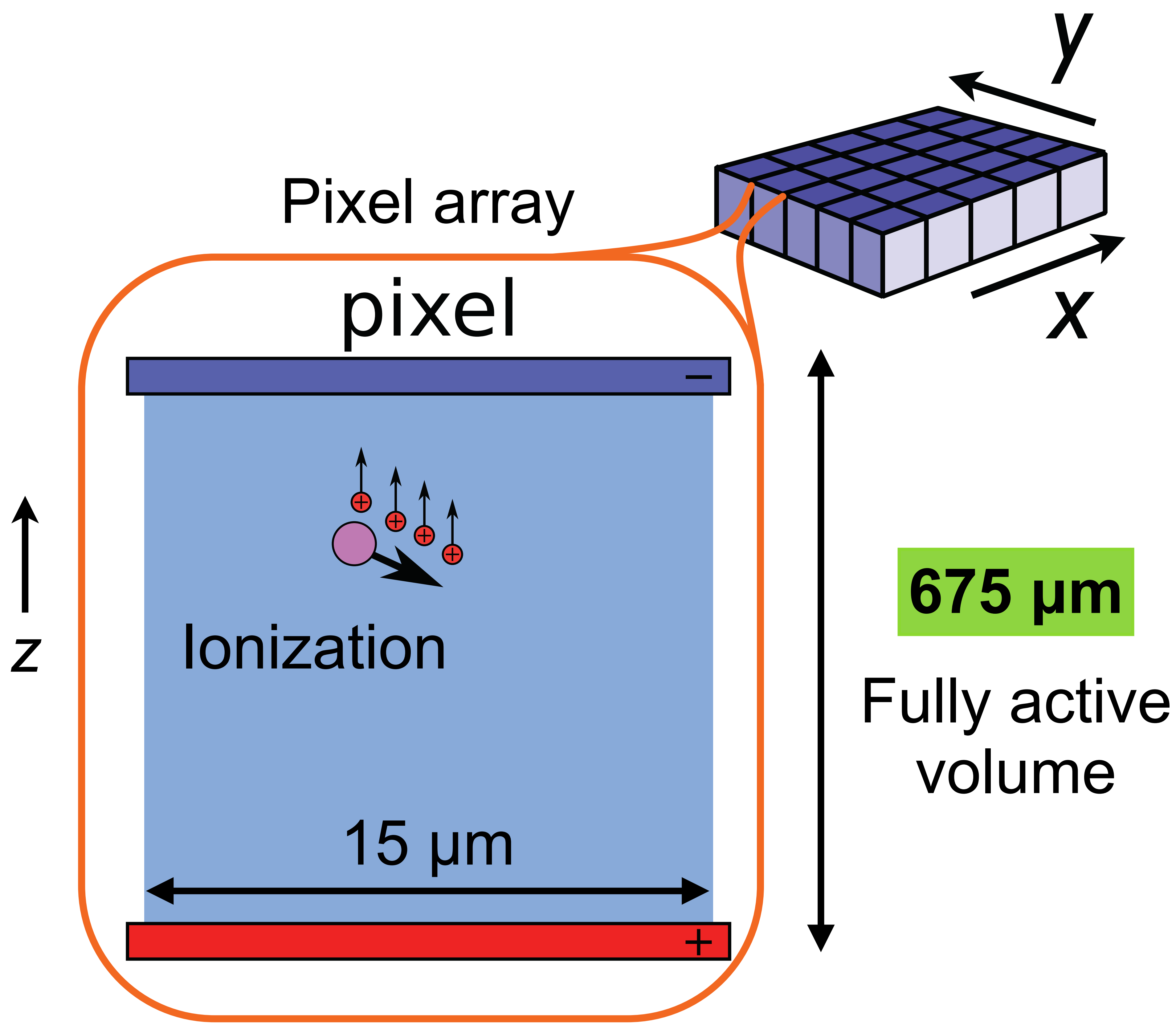
DM-e exclusion limits

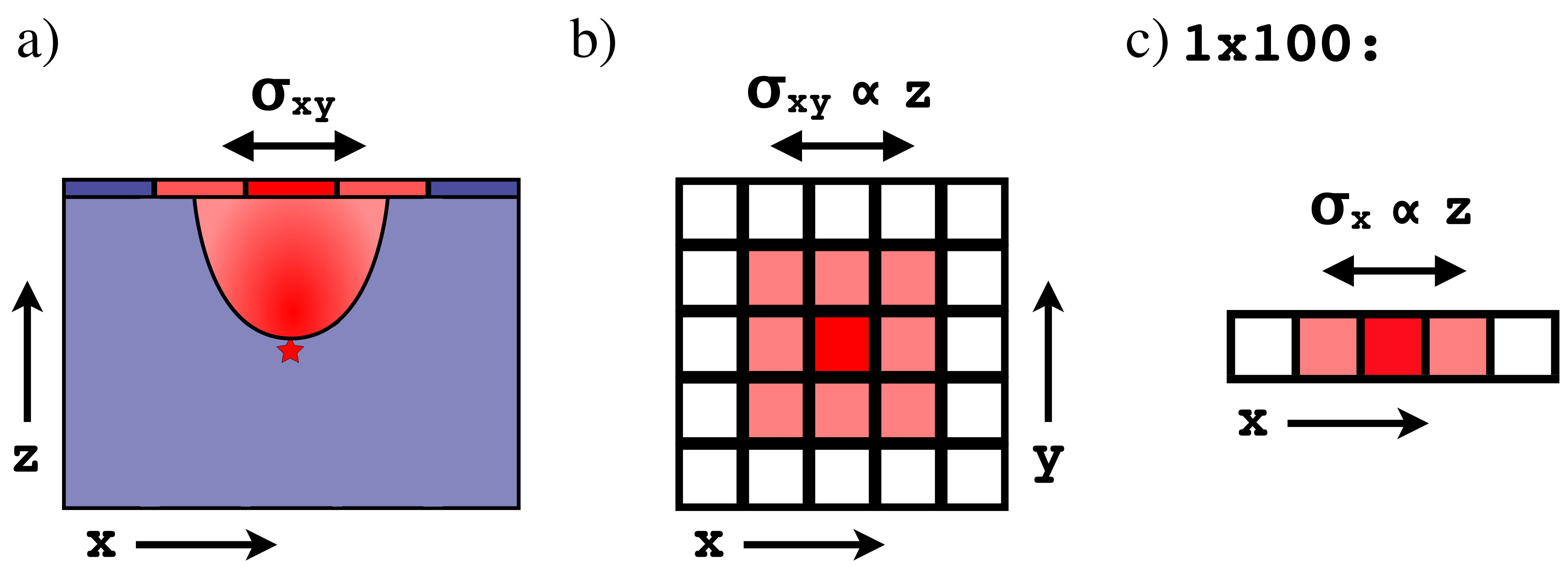




- DAMIC-M has world-leading exclusion limits for sub-GeV hidden-sector DM!

Charge-coupled devices



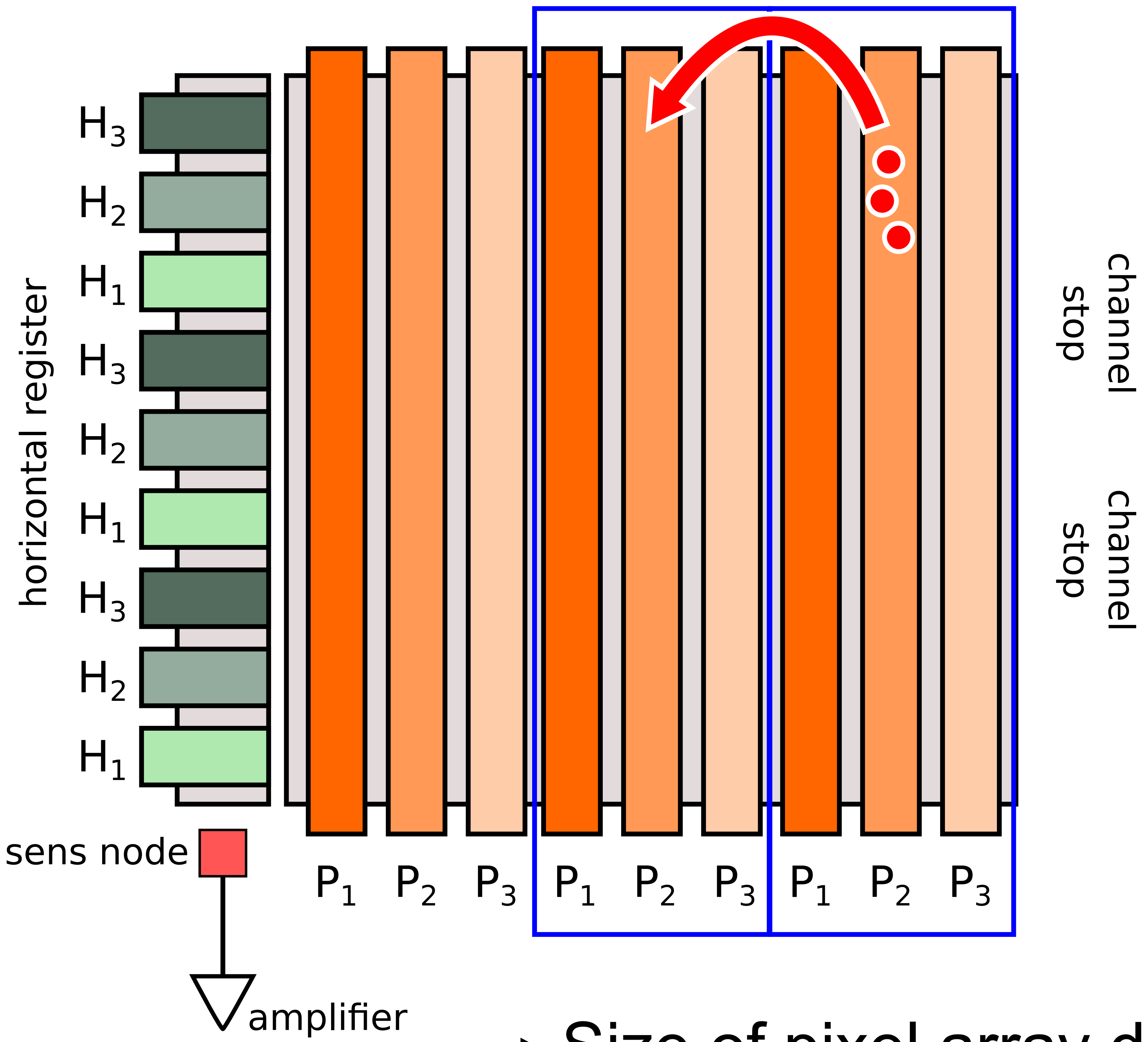


Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is "exposed," collecting charge until user commands readout.
- Readout can be slow: **very low noise.**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

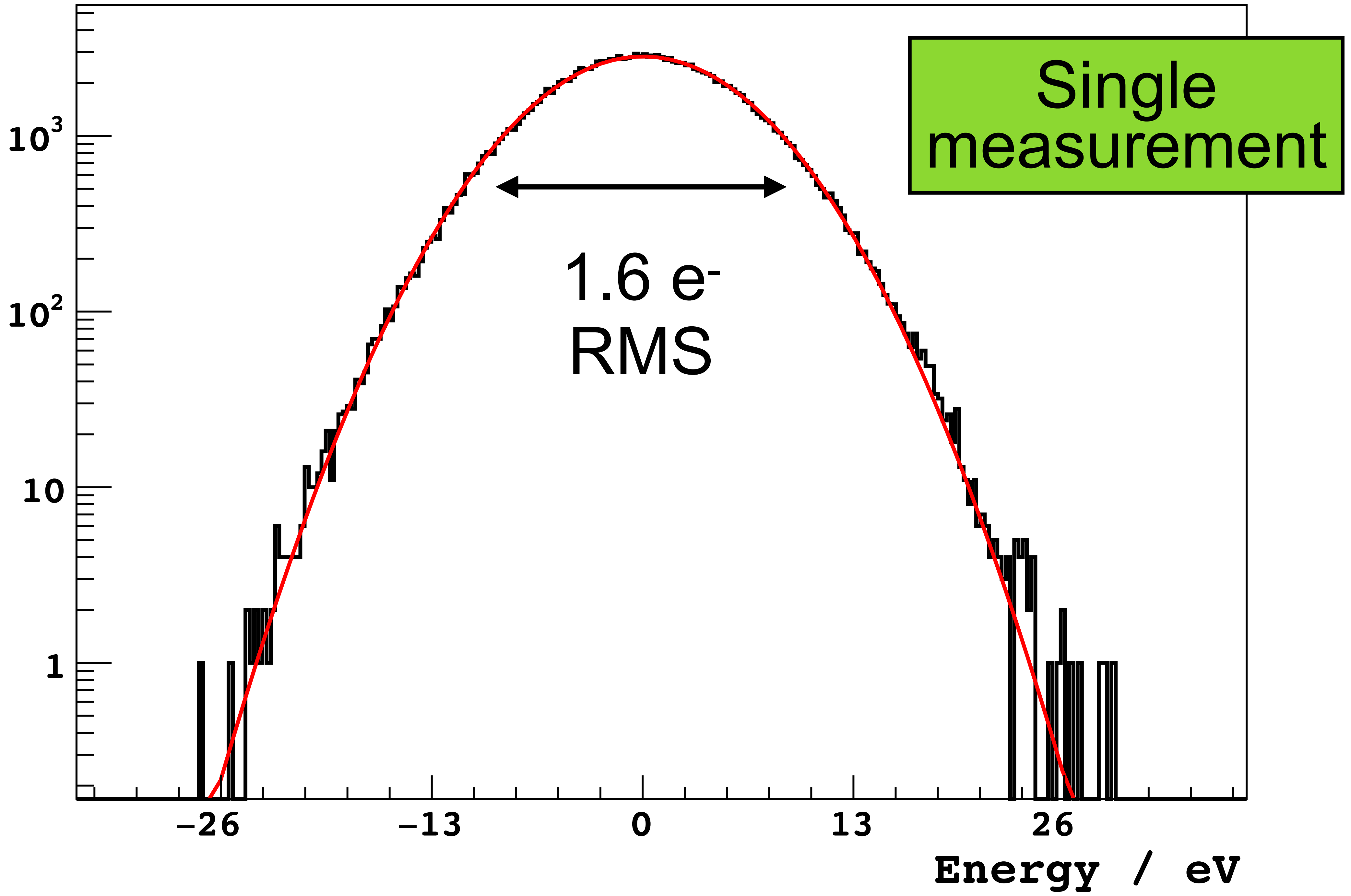
CCD readout

3x3 pixels CCD



***C* ~ 10 fF**

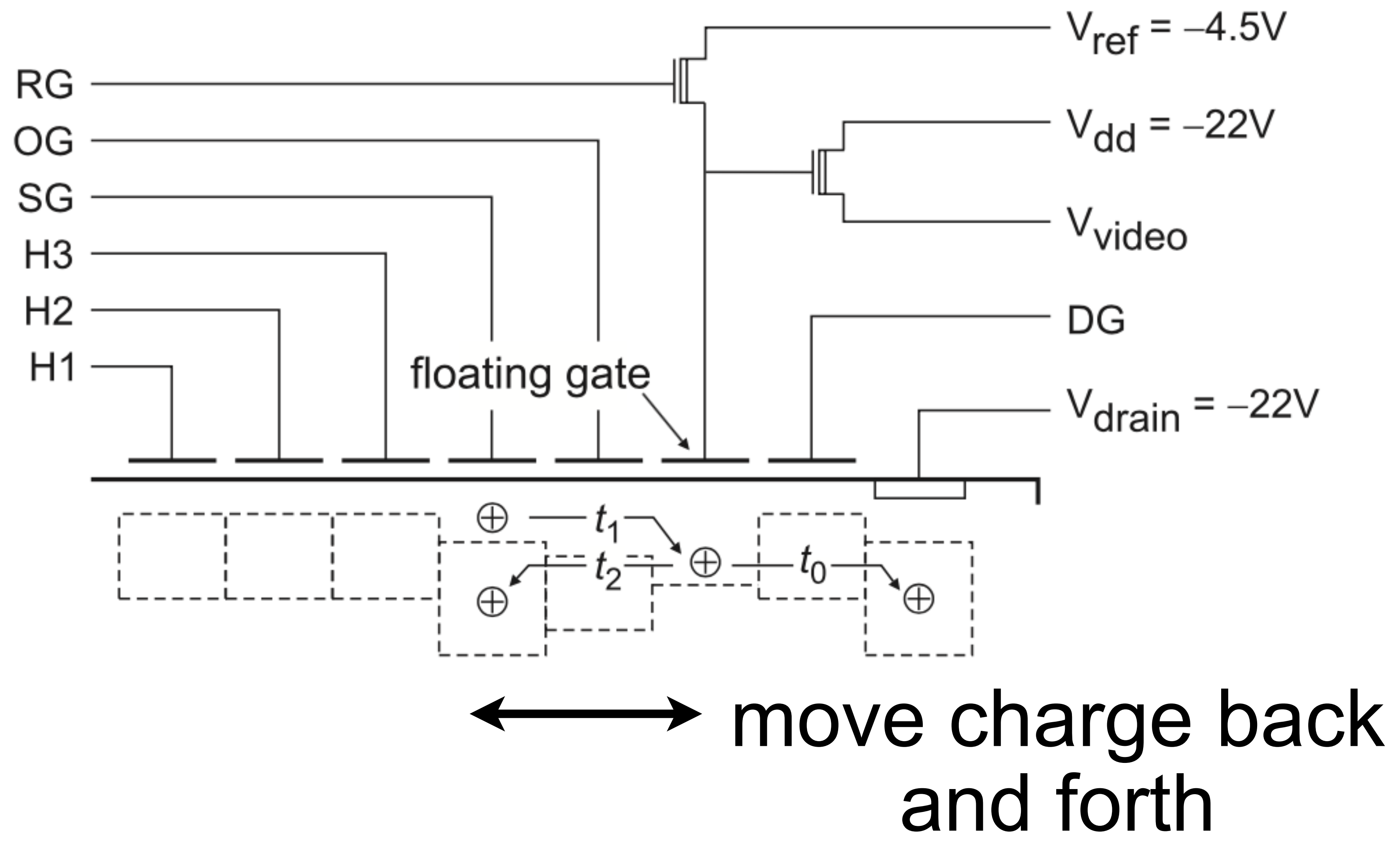
- Size of pixel array decoupled from capacitance of output node (device noise).



- Extremely low ~10^{-6} inefficiency in charge transfer.
- Extremely low leakage current **~7 e^-/cm^2/day**. arXiv:2410.18716

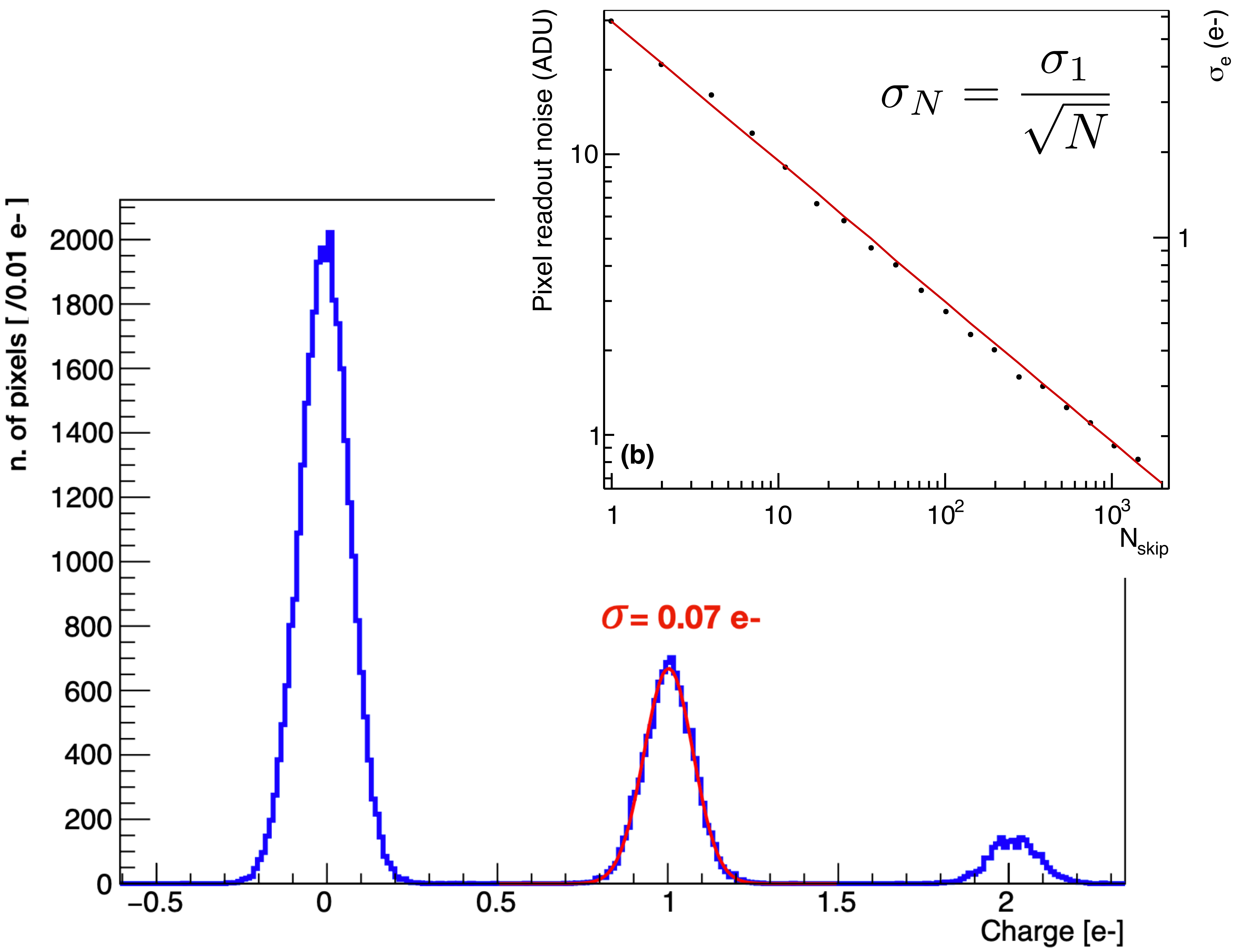
Skipper readout

"Skipper" readout:
Perform *N* uncorrelated measurements of the same pixel.



Introduced to particle physics in 2017

PRL119(2017)131802




Sample CCD image (~15 min exposure)
segment in the surface lab.
~1 cm
Cosmic muon
Point-like
β particle
Zoom
50 pixels
Low-energy
candidates
Electron
α
Muon
15x15 μm²
pixels
5
10
15
20
25
30
Energy measured by pixel [keV]

Spatial resolution

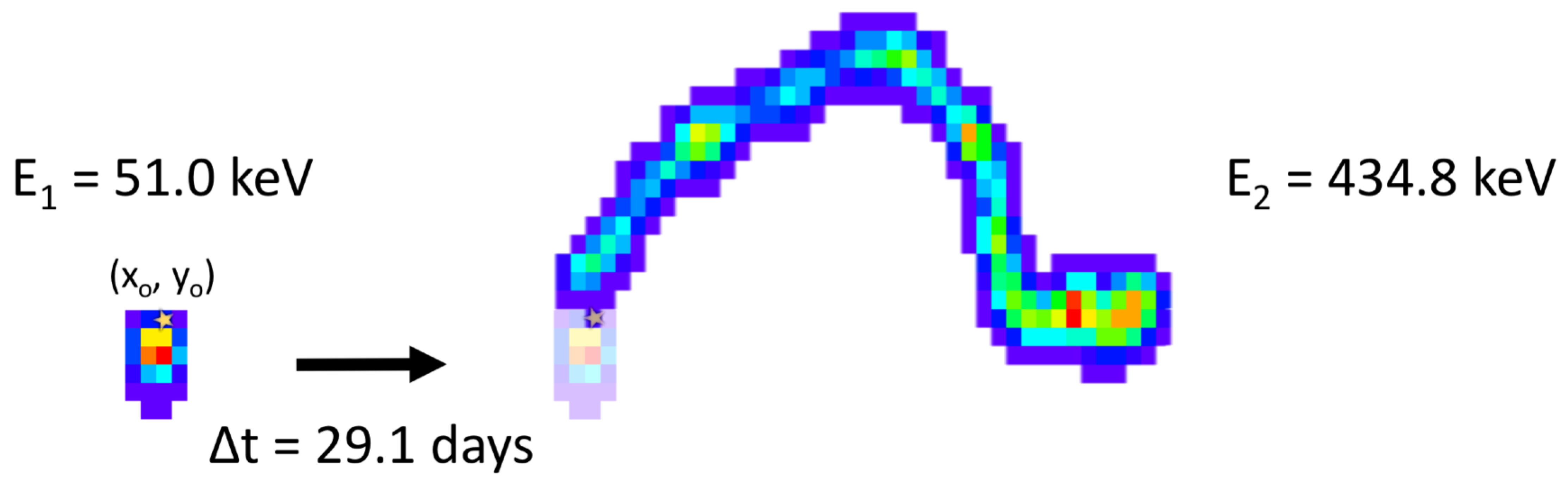
- Surface background rejection by depth (z) reconstruction, and classification (α, β, NR) by track topology (at high E>80 keV_{ee}).

- Spatial coincidence searches to identify decay sequences: JINST16(2021)P06019

- **Cosmogenic ^{32}Si:** ^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)

140 ± 30 μBq / kg

- Also upper limits on every β emitter in the U/Th chain.

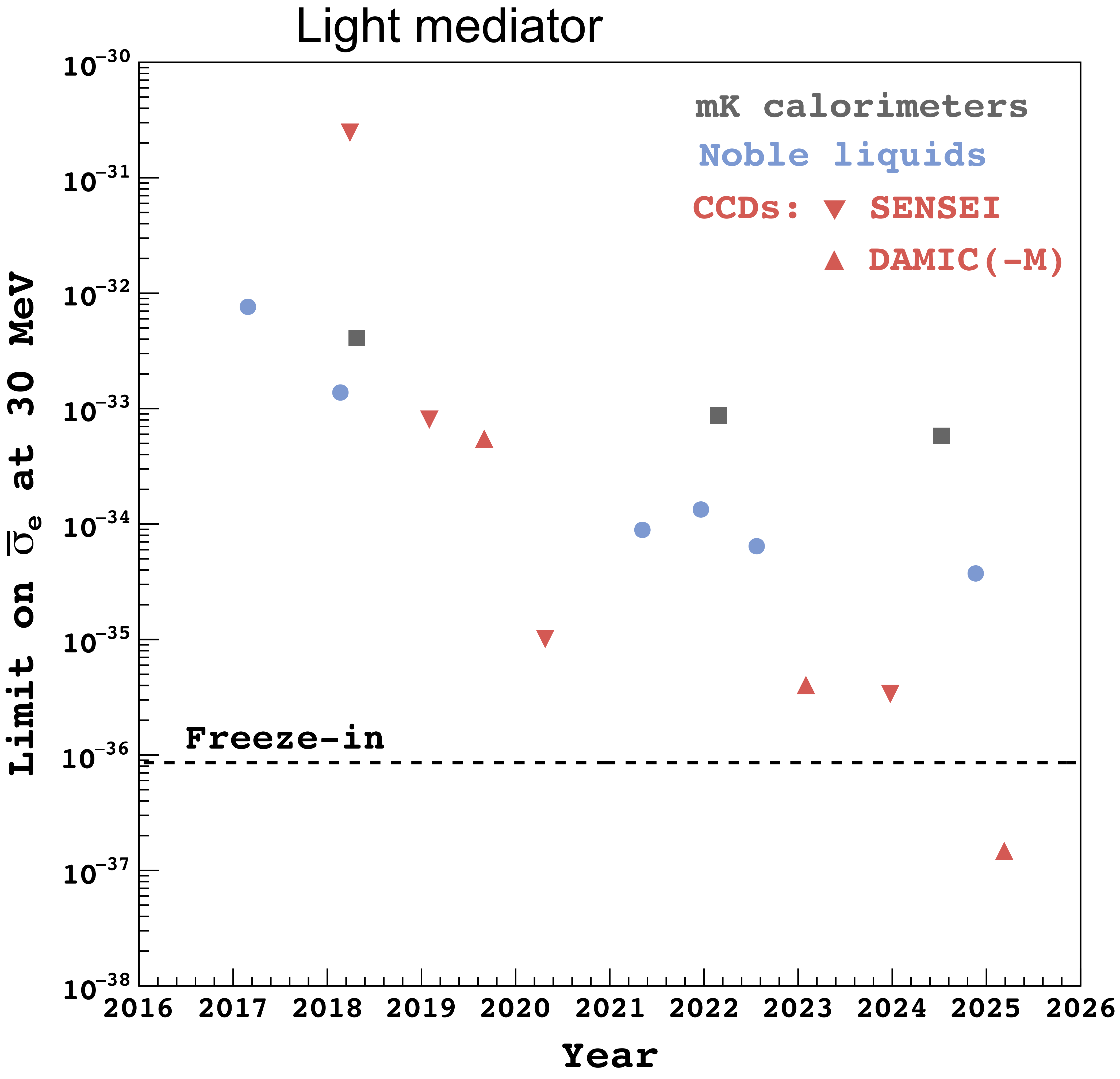


- Reject crystal defects “hot spots” that dominate device leakage current.

- NR identification by spatial correlation between ionization event and defect left behind in the crystal (R&D): PRD110(2024)043008

CCD timeline

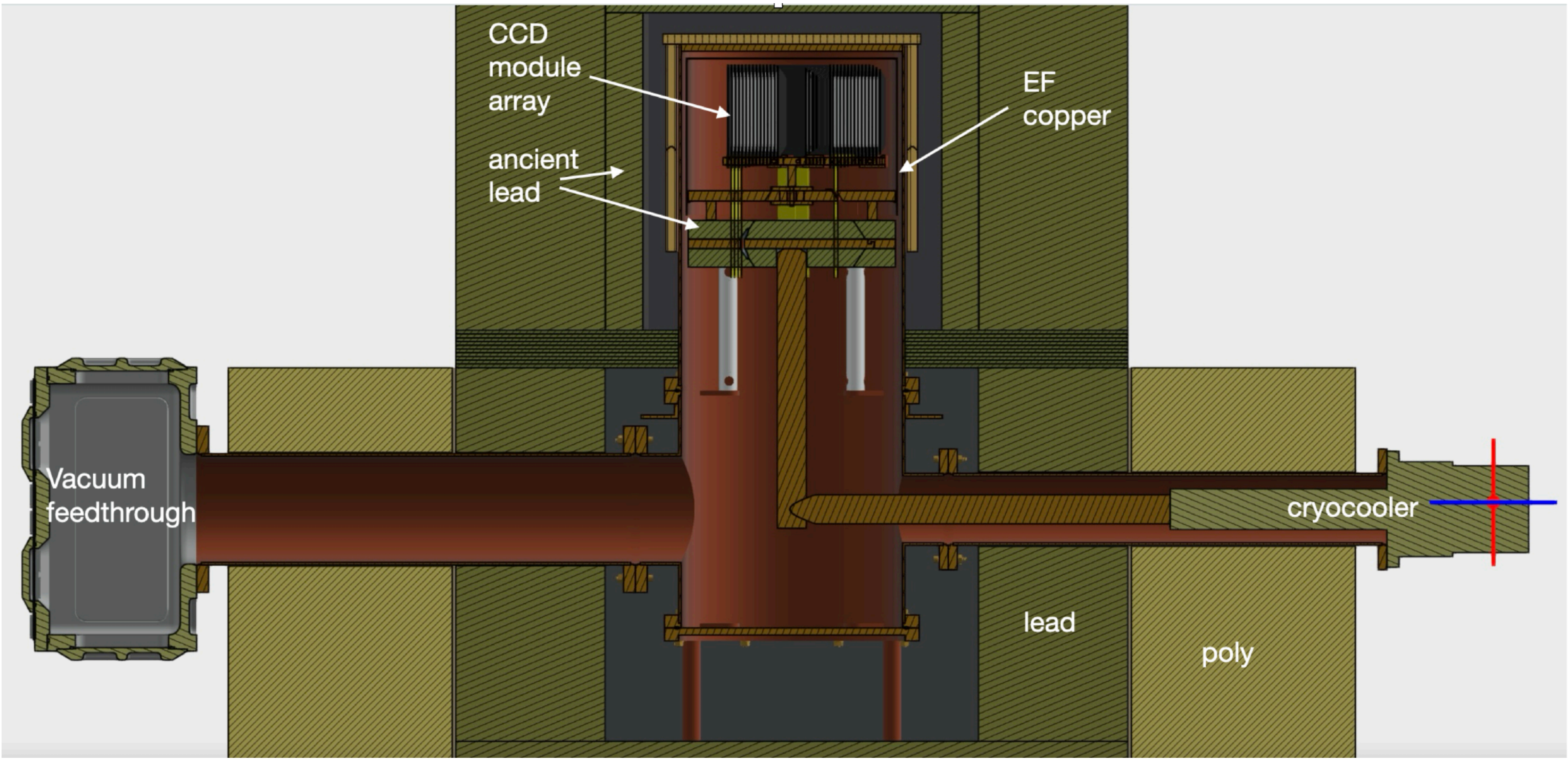
- **2012–2017:** we built DAMIC at SNOLAB, the first low background CCD array for DM searches.
- **2017:** DAMIC releases first DM search results from ~eV ionization signals.
- **2017:** “Skipper” CCDs are introduced for 10x improvement in noise to provide increased sensitivity for DM-e searches.
- Two skipper-CCD experiments started: **SENSEI** and **DAMIC-M**.
- Multiple detector iterations, fast progress from both collaborations until now.
- **2025:** DAMIC-M’s LBC probes benchmark hidden-sector models: Highlight of today
- **2026+:** DAMIC-M coming online with >100 CCDs!

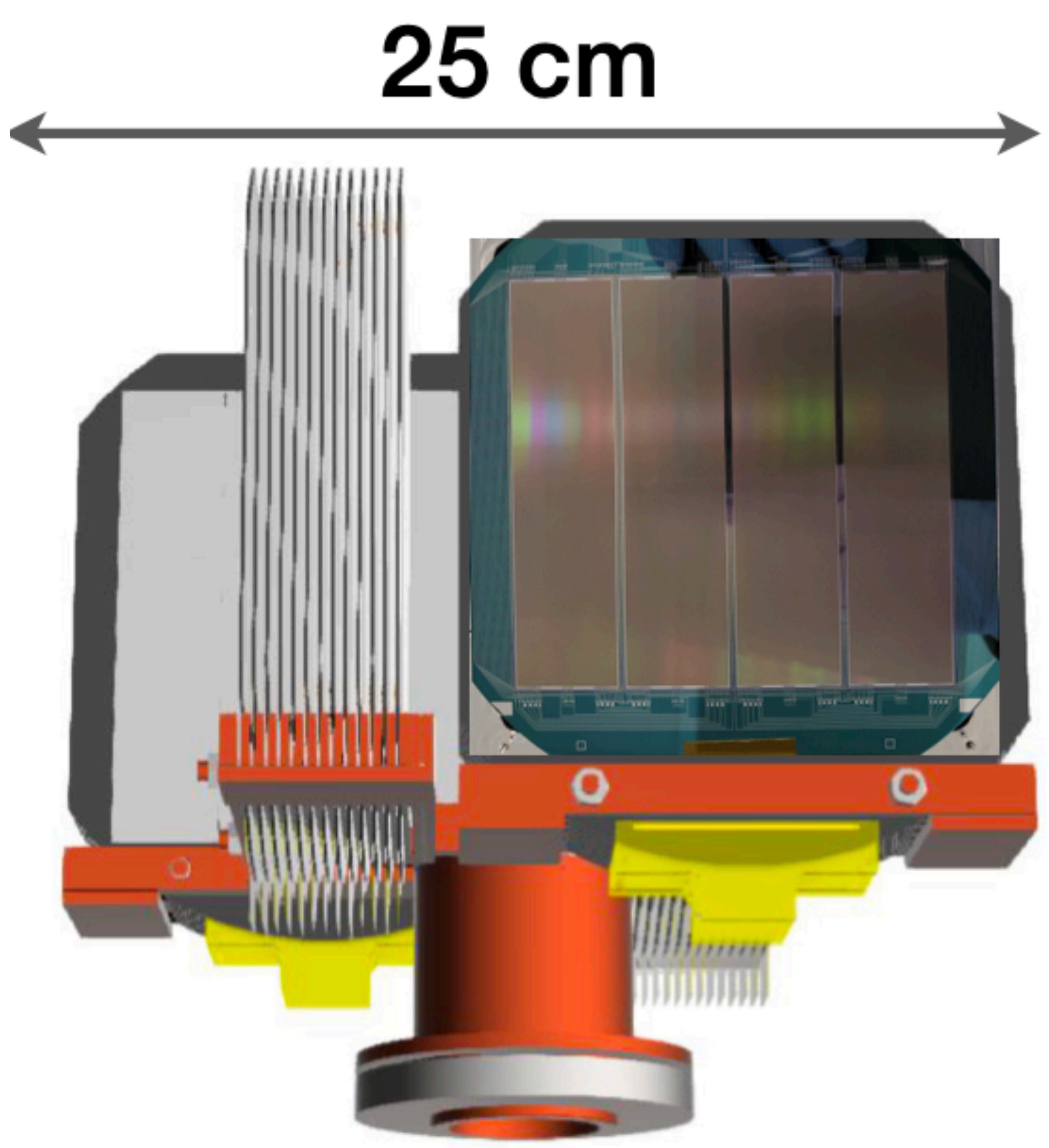


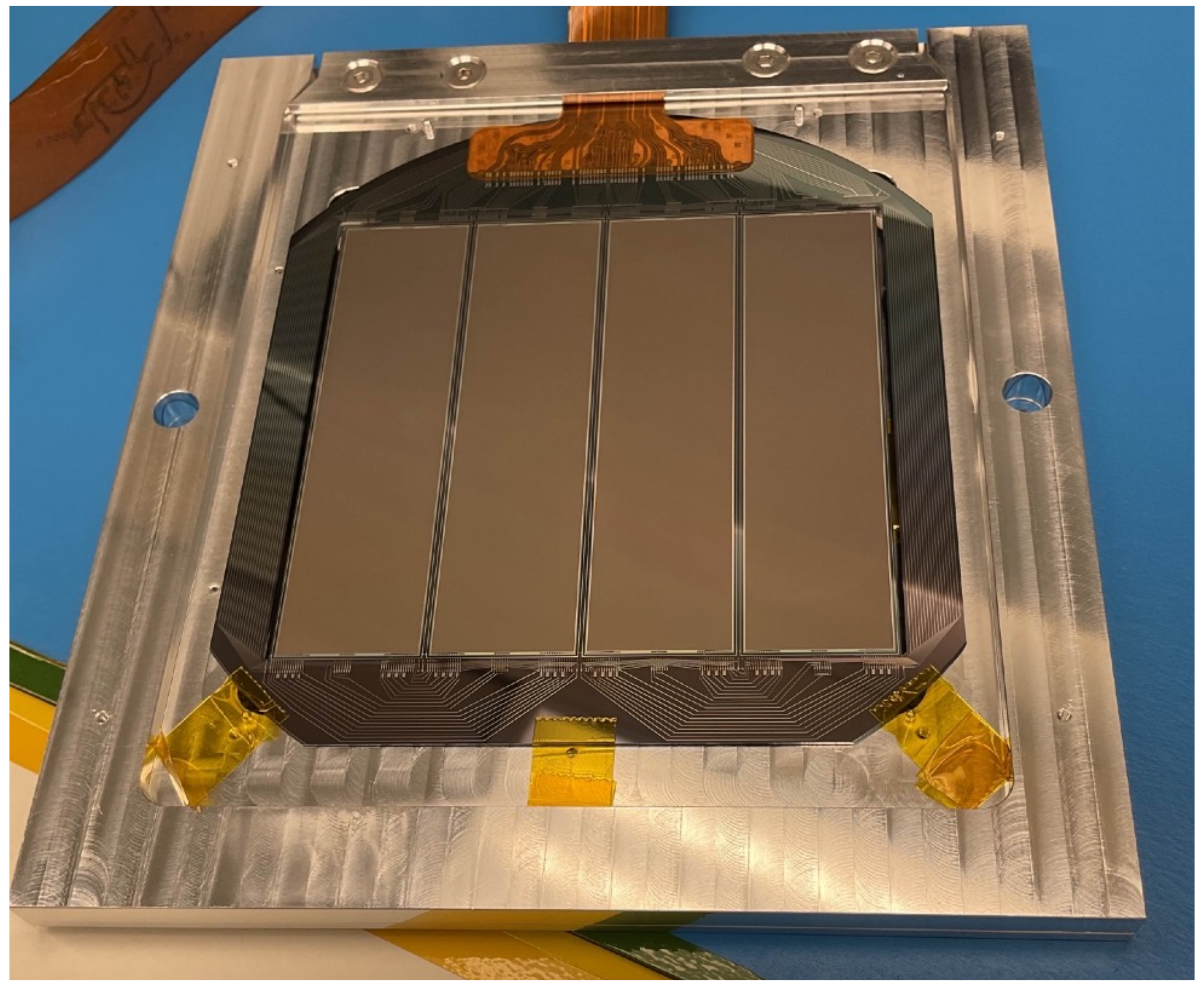
DAMIC-M

DAMIC-M

- 52 CCD modules in LSM (France) for kg-year target exposures.
- Skipper readout for 2 or 3 e- threshold.
- Background reduction to a fraction of d.r.u. (events per kg-day).
- Under construction. Commissioning by end of 2025!

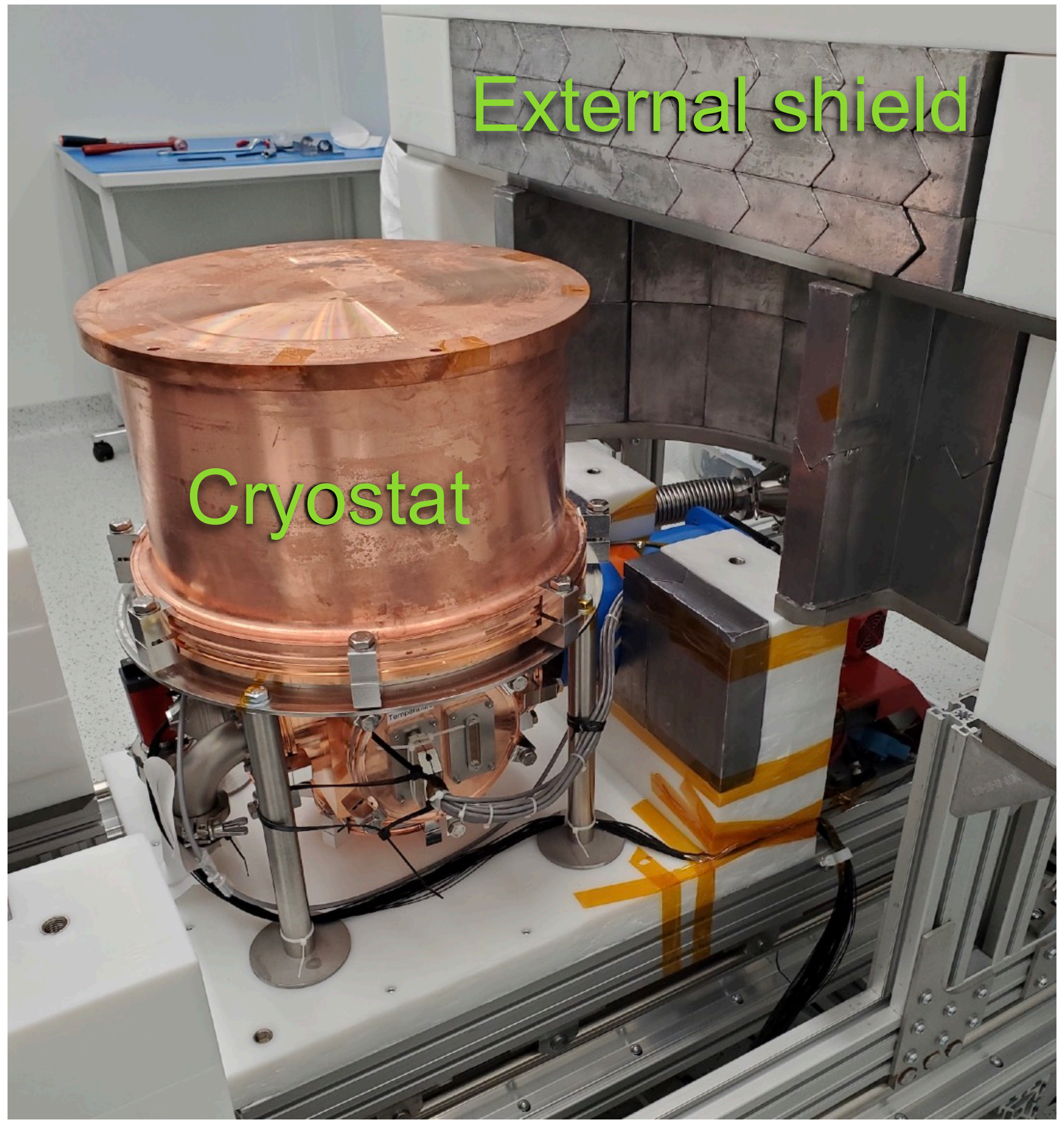


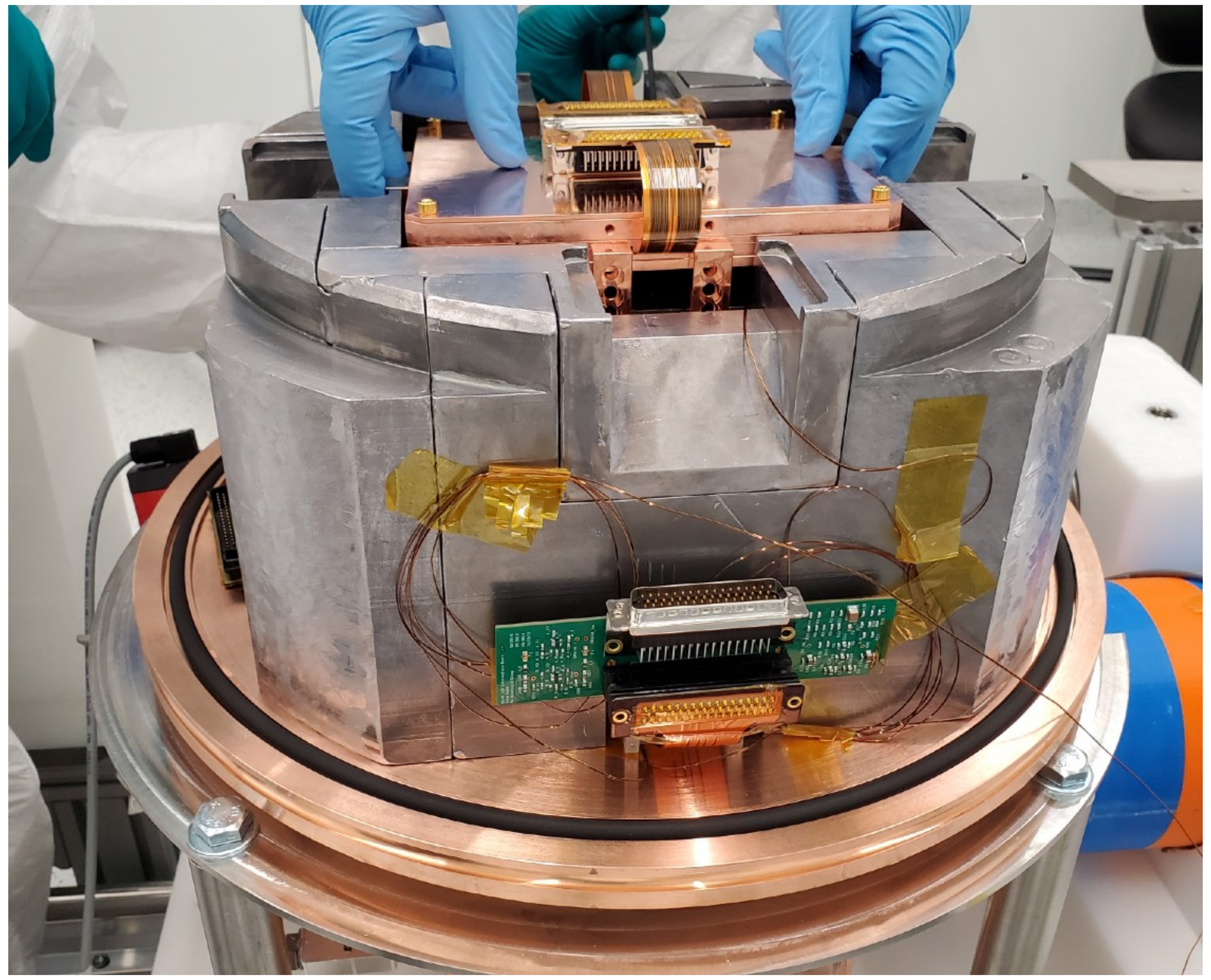


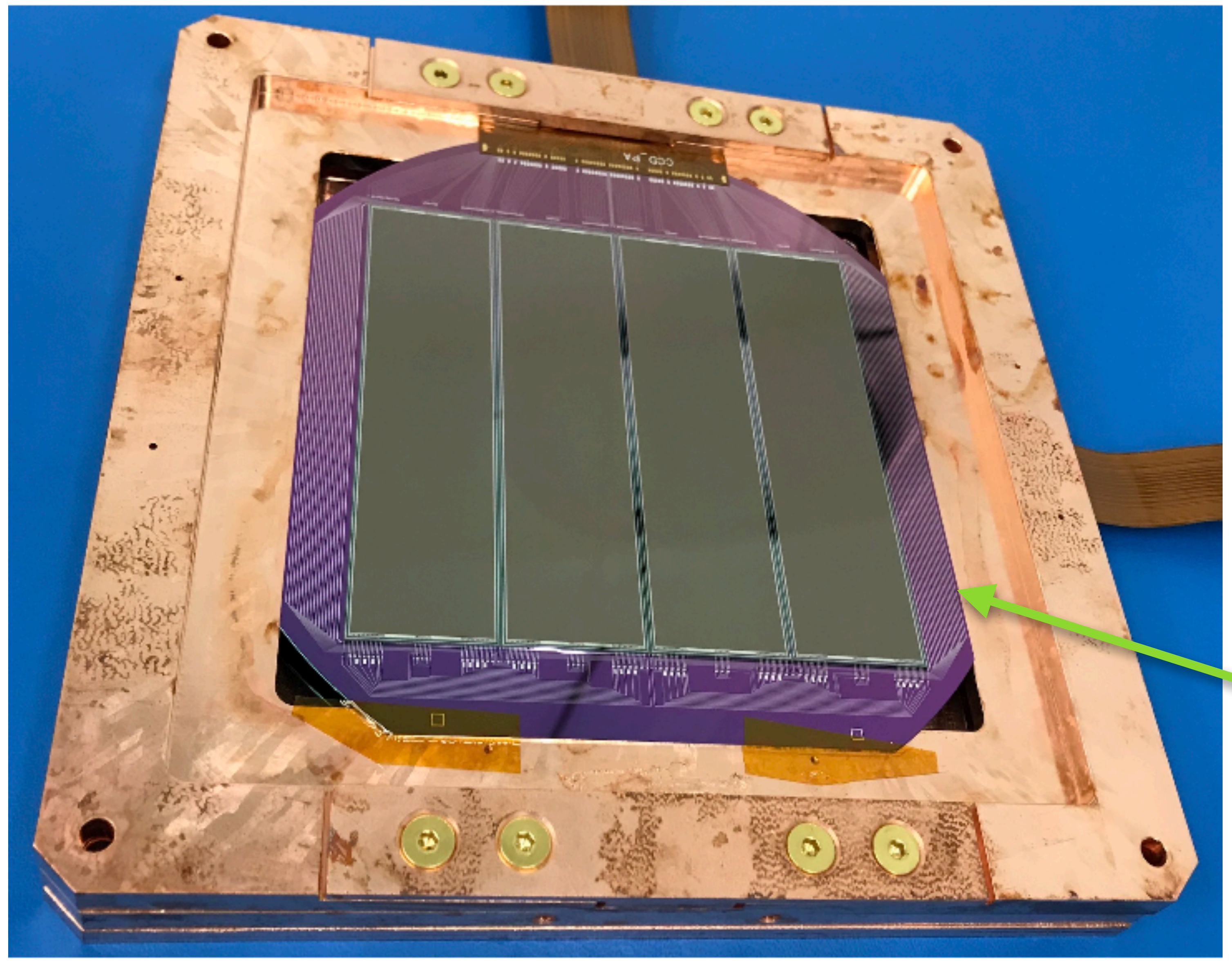


Law Background Chamber

- Low Background Chamber (LBC) test setup for DAMIC-M at LSM for performance and background studies.
- Operating in LSM clean room since 2022.
- Several detector iterations. Details in JINST19(2024)T11010
- First science results. Spectral analysis: PRL130(2023)171003
- Daily modulation: PRL132(2024)101006



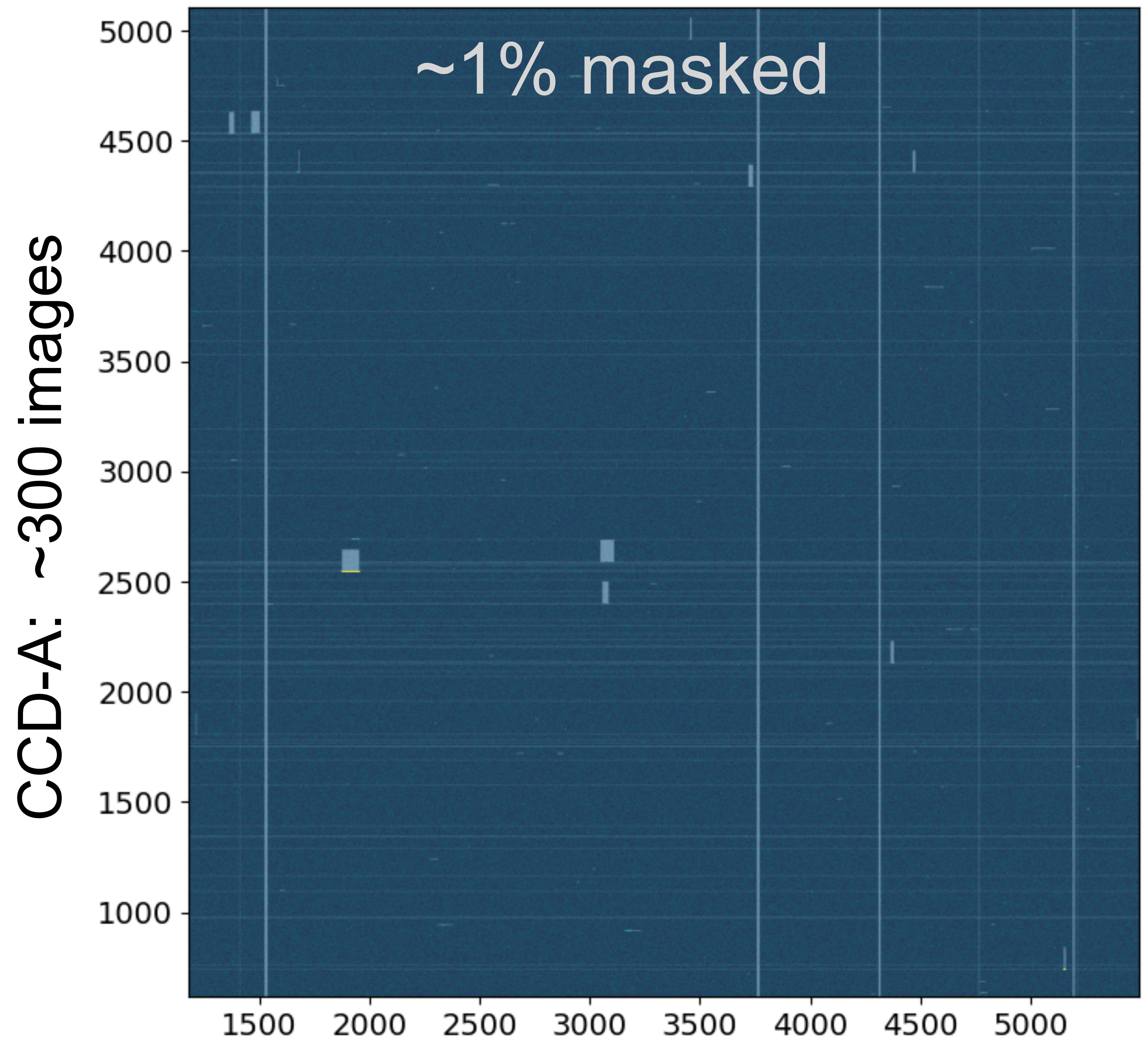




Prototype CCD module packaged and tested at UW

Science Run 2

Detector upgrades
- Two DAMIC-M modules (8 CCDs for 26g)
- electroformed copper box lids
- DAMIC-M low-noise electronics



Parameters
- read out 1 amplifier per CCD
- binning: 1 pixel x 100 pixel (col x row)
- temperature: ~130 K

Performance
- reduced dark current: ~10^{-4} e-/pixel/day (previous 50x)
- background: ~15 dru with shield partly open
- readout noise = 0.16e- with 500 skips
- data set exposure: 1.3 kg-day (previous 85 g-day)

Image masking – 95% of data are kept
- hot regions in CCDs (large 1e- rate)
- clusters of high-charge pixels ($\geq$ 6e-)
- clusters in CCDs of same module (cross-talk)
- charge-correlated pixels in CCDs of same module
- 100 pixels above + row of pixel with >100 e- (charge traps)

Pattern analysis

Blind analysis
- Data set 1 (D1): selection sample (130 g-day)
- Data set 2 (D2): blinded analysis set (1.3 kg-day)

Candidate selection
- look for horizontal for consecutive pixels with 2, 3, or 4 e-: {11}, {21}, {111}, {31}, {22}, {211}
- exclude isolated pixels with $\geq$ 2e$^-$

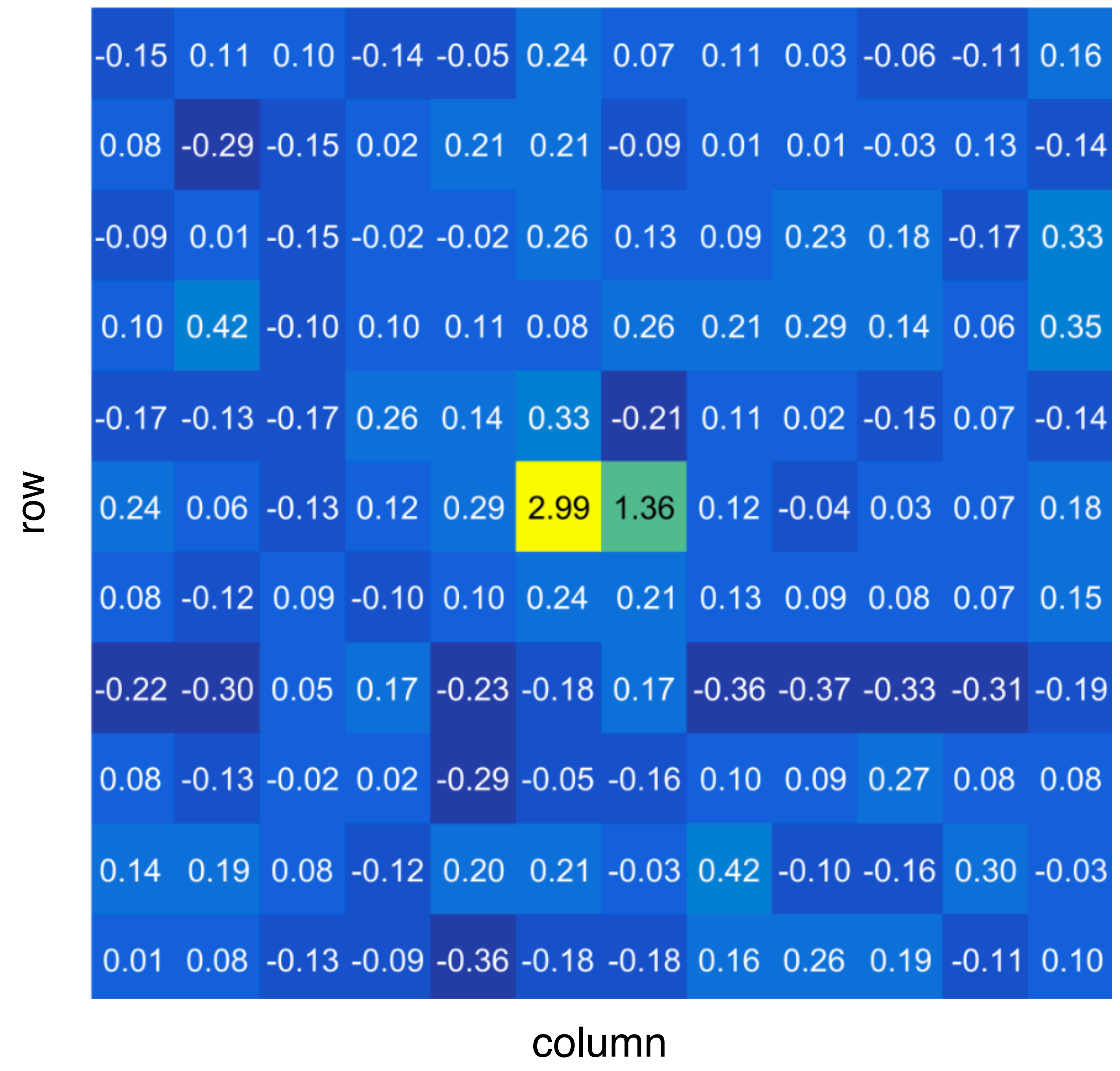
Efficiency
- calculate probability to obtain pattern from ionization events with initial charge N_e (includes charge diffusion and noise)

Backgrounds
- estimate radiogenic background by scaling measured high energy events (2.5 to 7.5 keV) with Geant4
- random coincidences of uncorrelated pixels next to each other evaluated toy MC

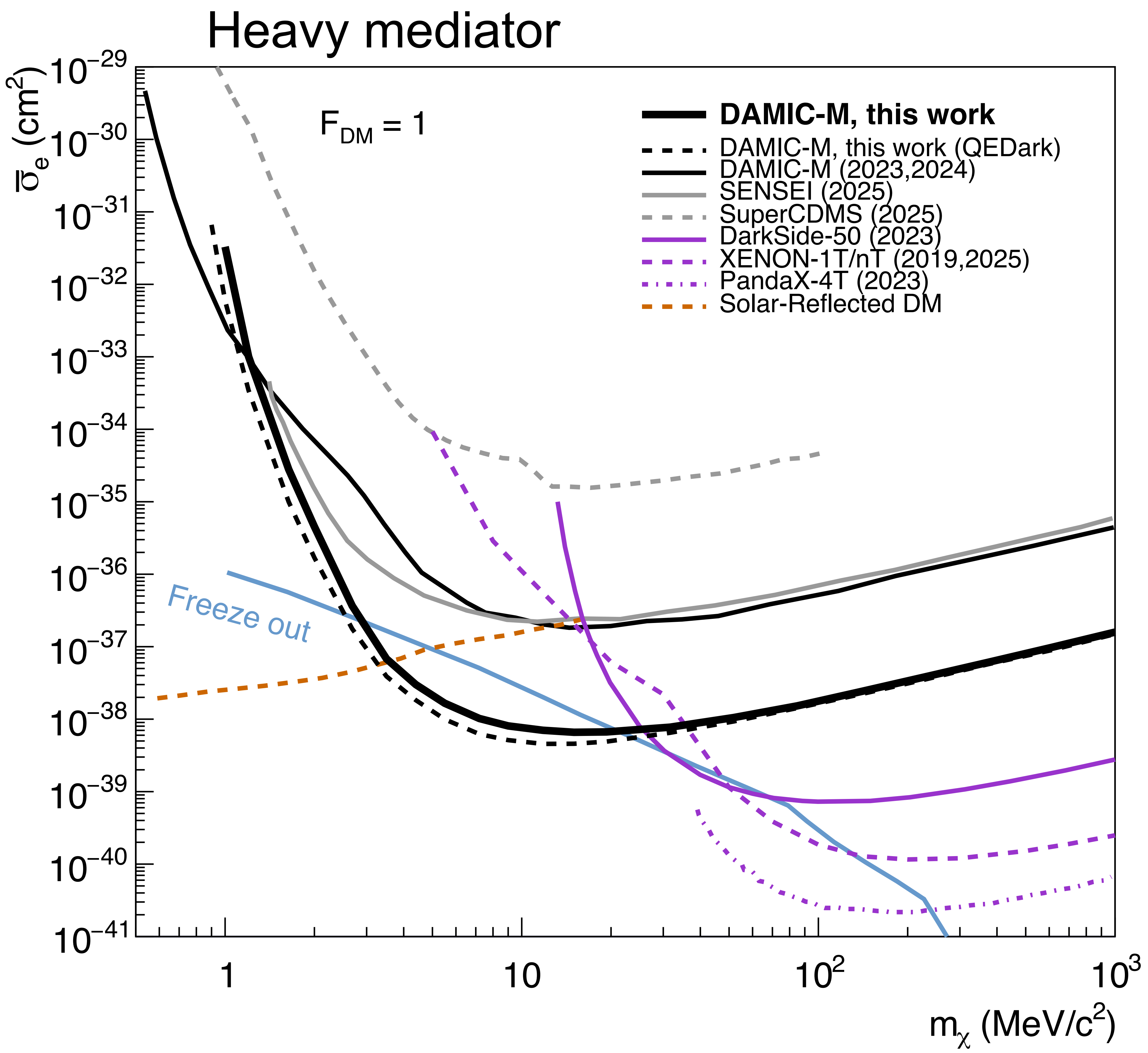
	Pattern p		
	{11}	{21}	{111}
D_p	144	0	0
$B_p^{\rm rc}$	141.4	0.111	0.042
$B_p^{\rm rad}$	0.039	0.039	0.016
	{31}	{22}	{211}
D_p	1	0	0
$B_p^{\rm rc}$	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
$B_p^{\rm rad}$	0.052	0.011	0.035

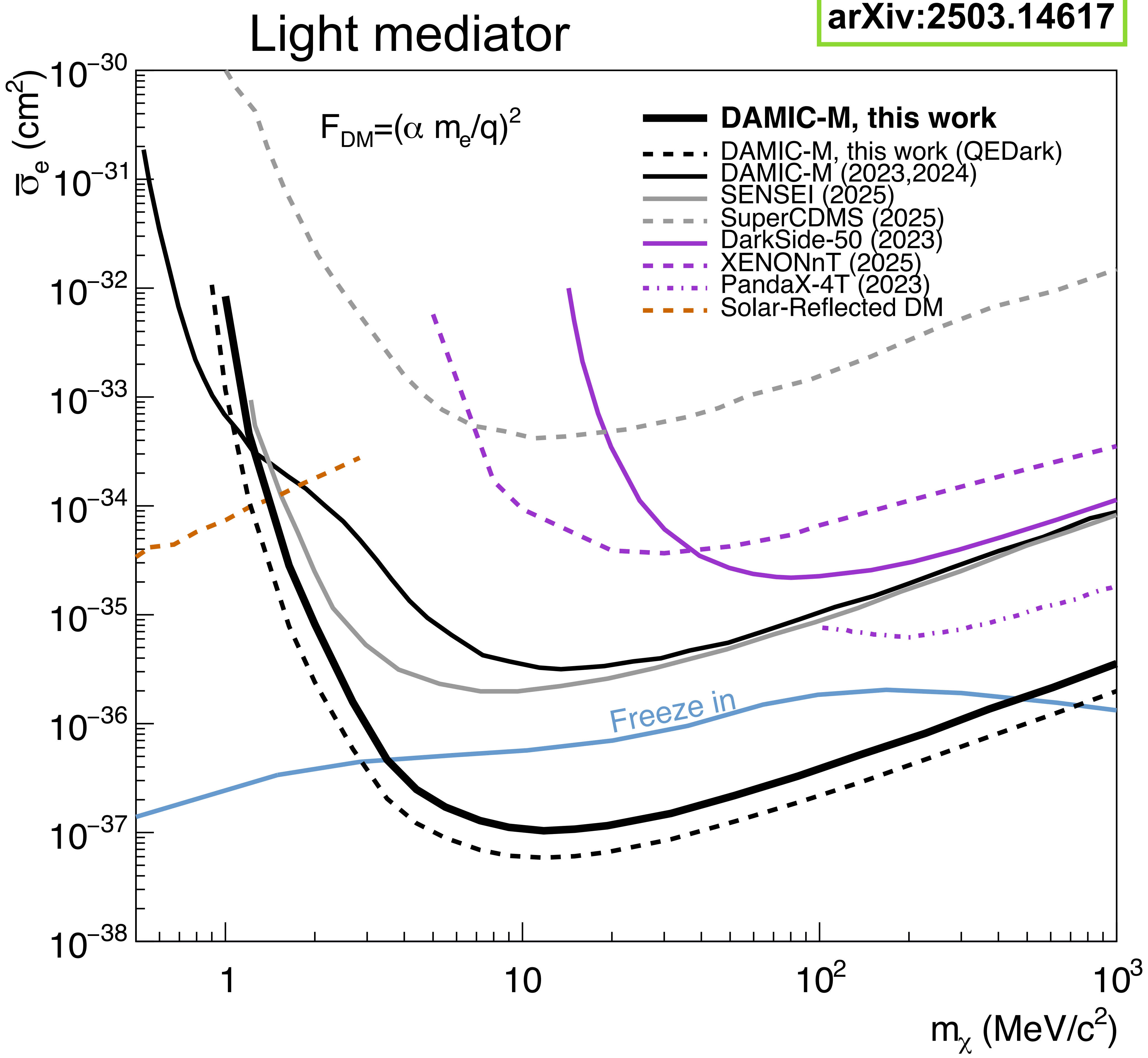
TABLE I. The number of candidates D_p in the D2 data set, and the number expected from backgrounds due to random coincidences, $B_p^{\rm rc}$, and to radioactive decays, $B_p^{\rm rad}$.

{31} candidate



DM-e exclusion limits

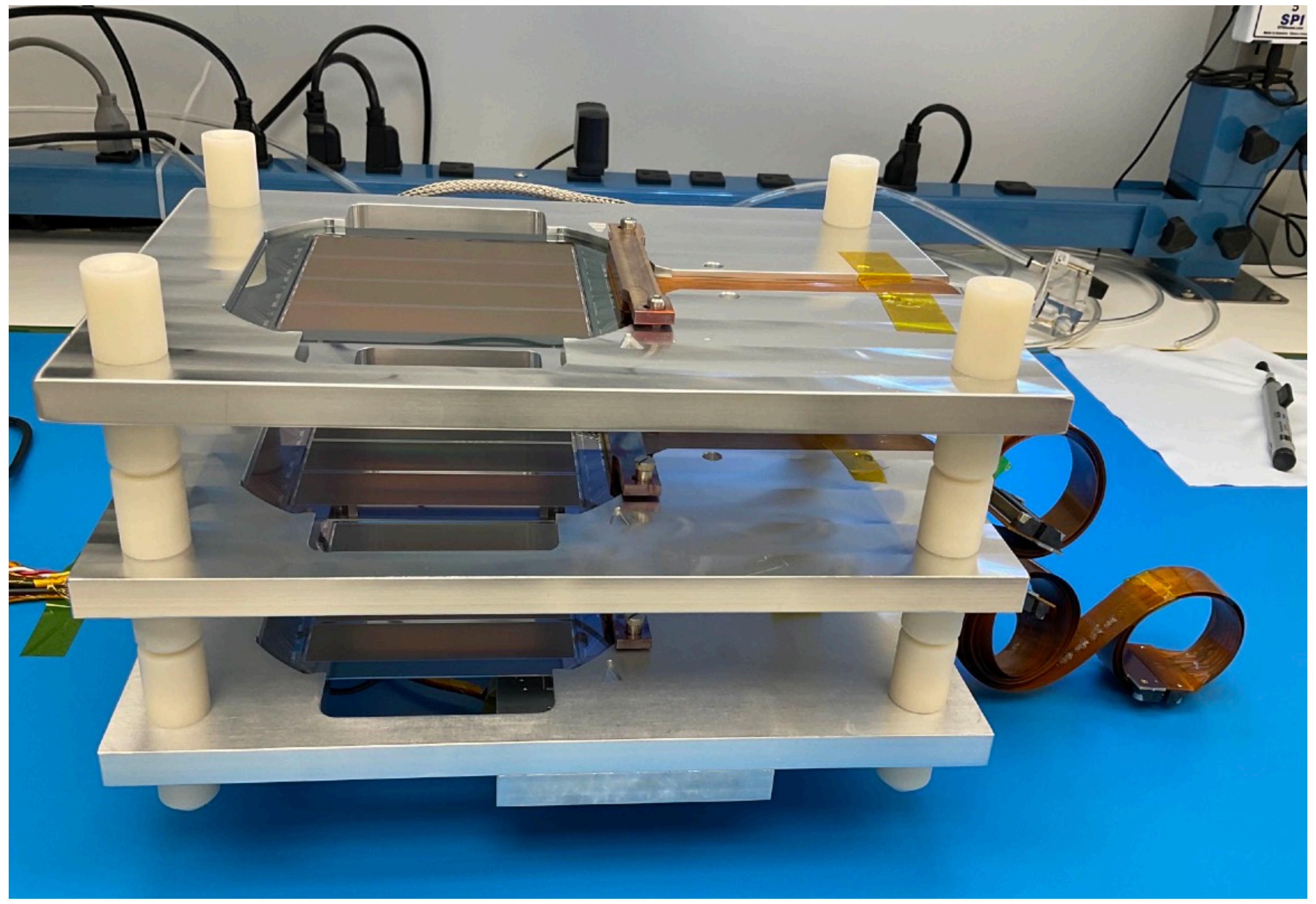


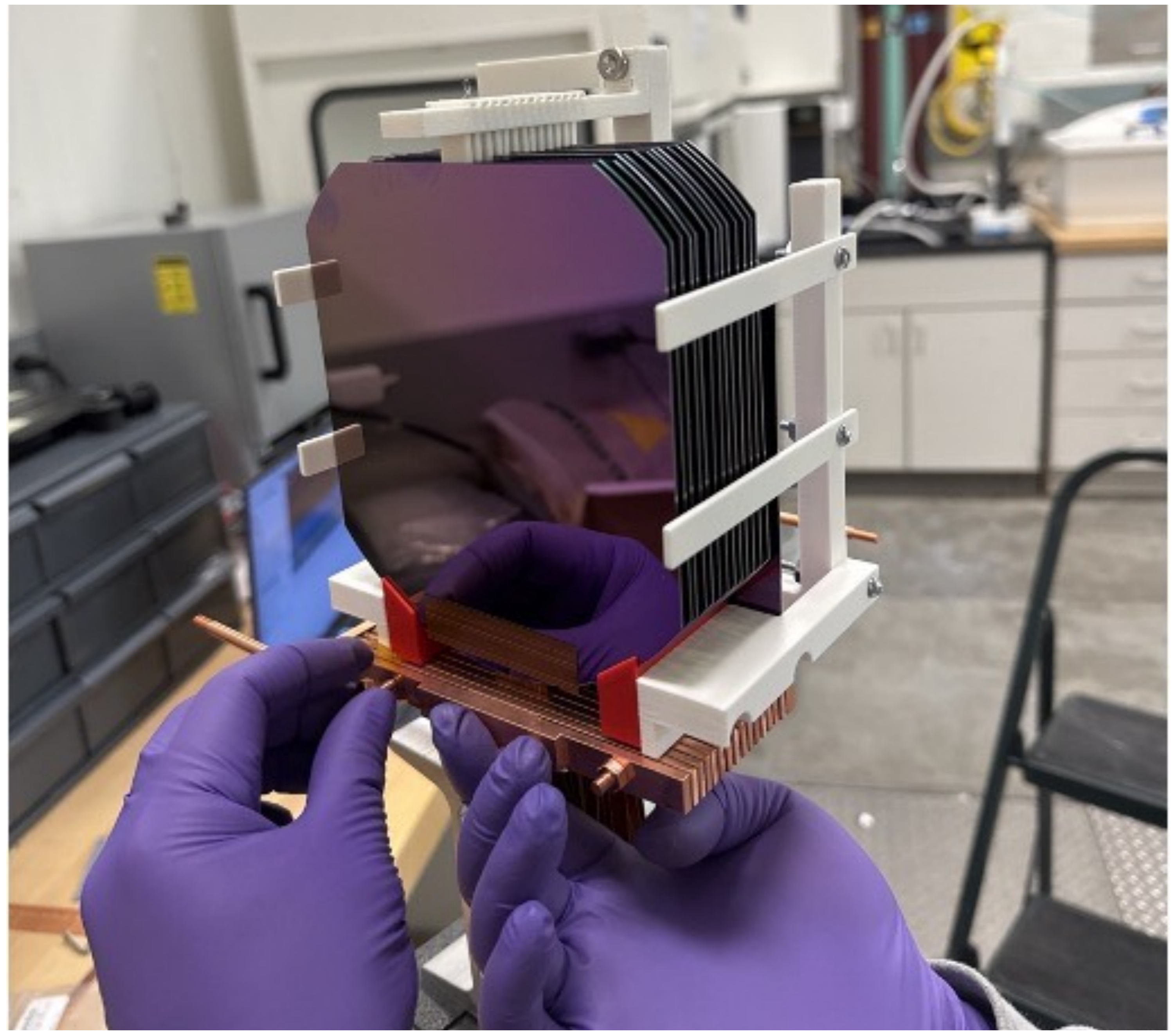


- **DAMIC-M probes benchmark hidden-sector dark-matter models!**

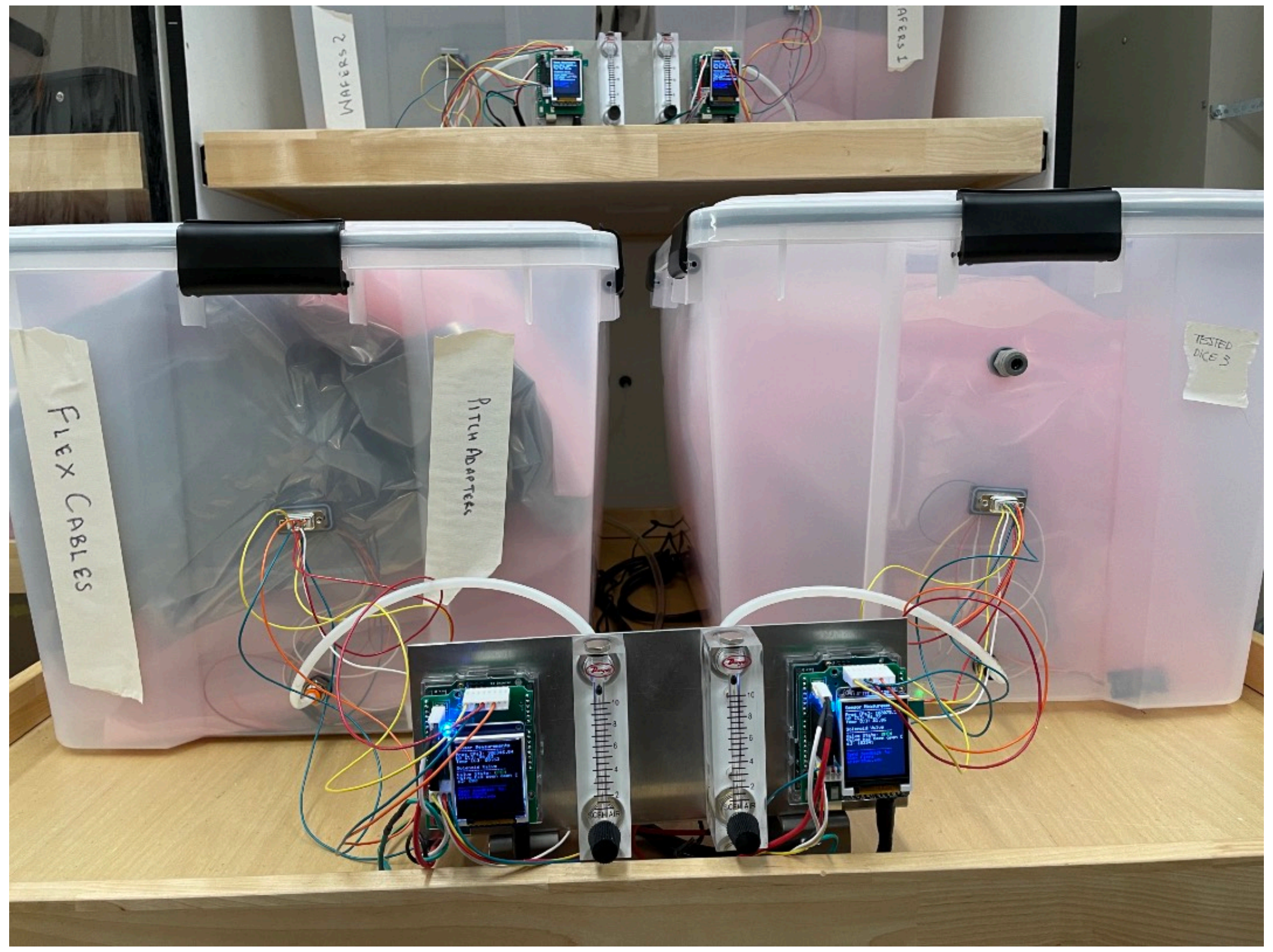
DAMIC-M Status

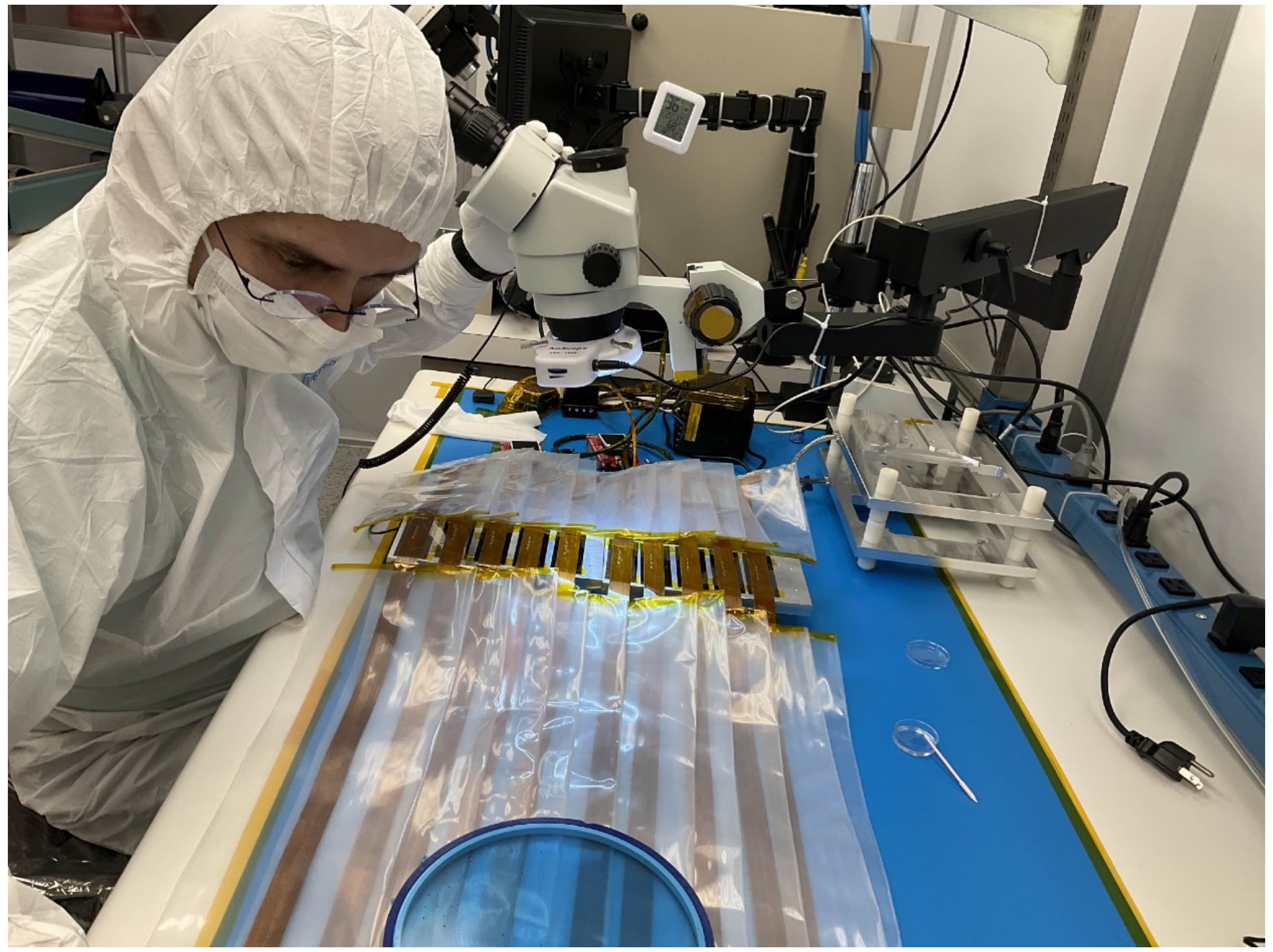
- Tested 188 CCDs at UW in Q3 2024.
- 28 CCD modules fabricated, shipped to LSM in their shielded container.
- LBC relocated to second clean room at LSM.
- Reconditioning clean rooms for CCD array assembly and detector installation.
- Copper machining ongoing, lead and poly being prepared for shipment.
- Custom electronics under procurement and testing.
- Detector installation in second-half 2025, commissioning by end of 2025.



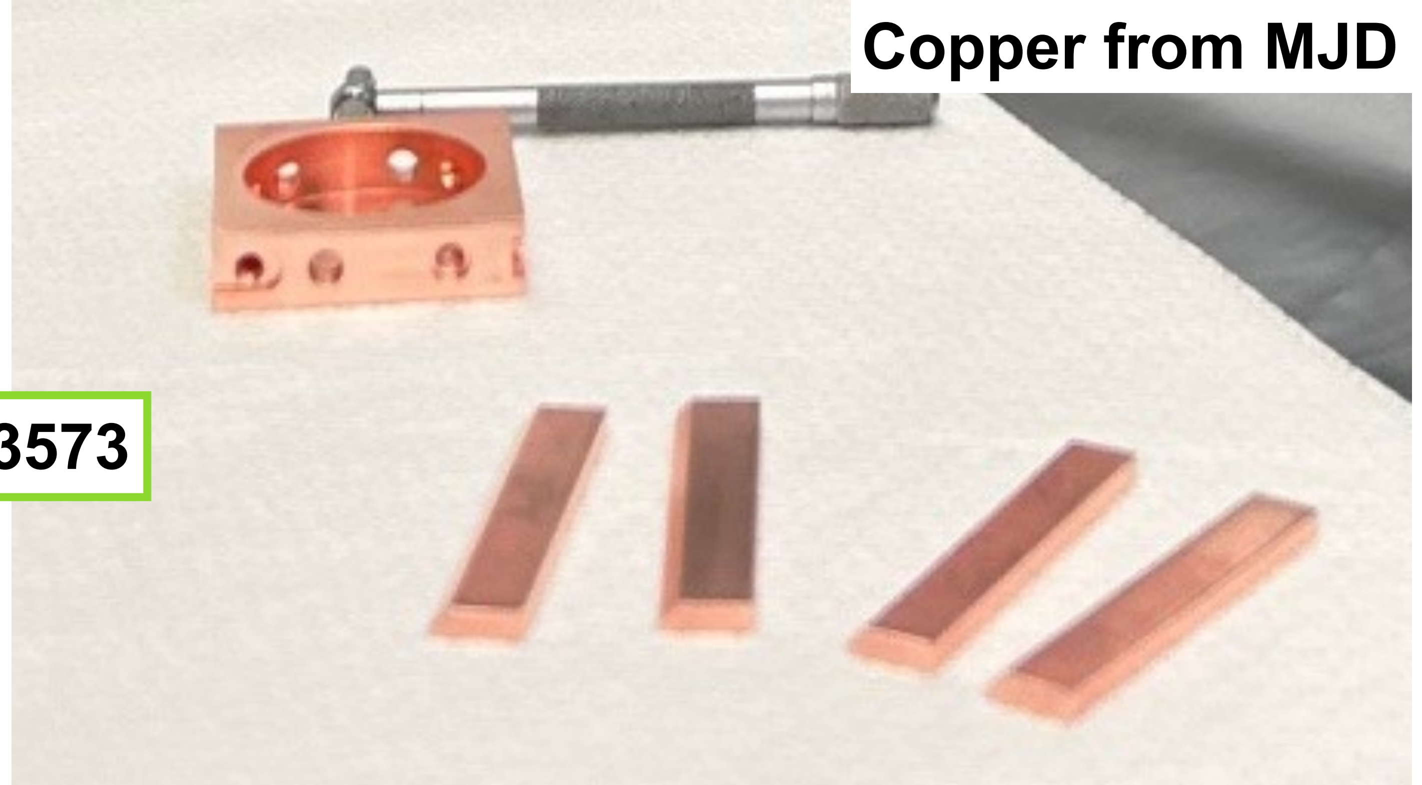


Low-background

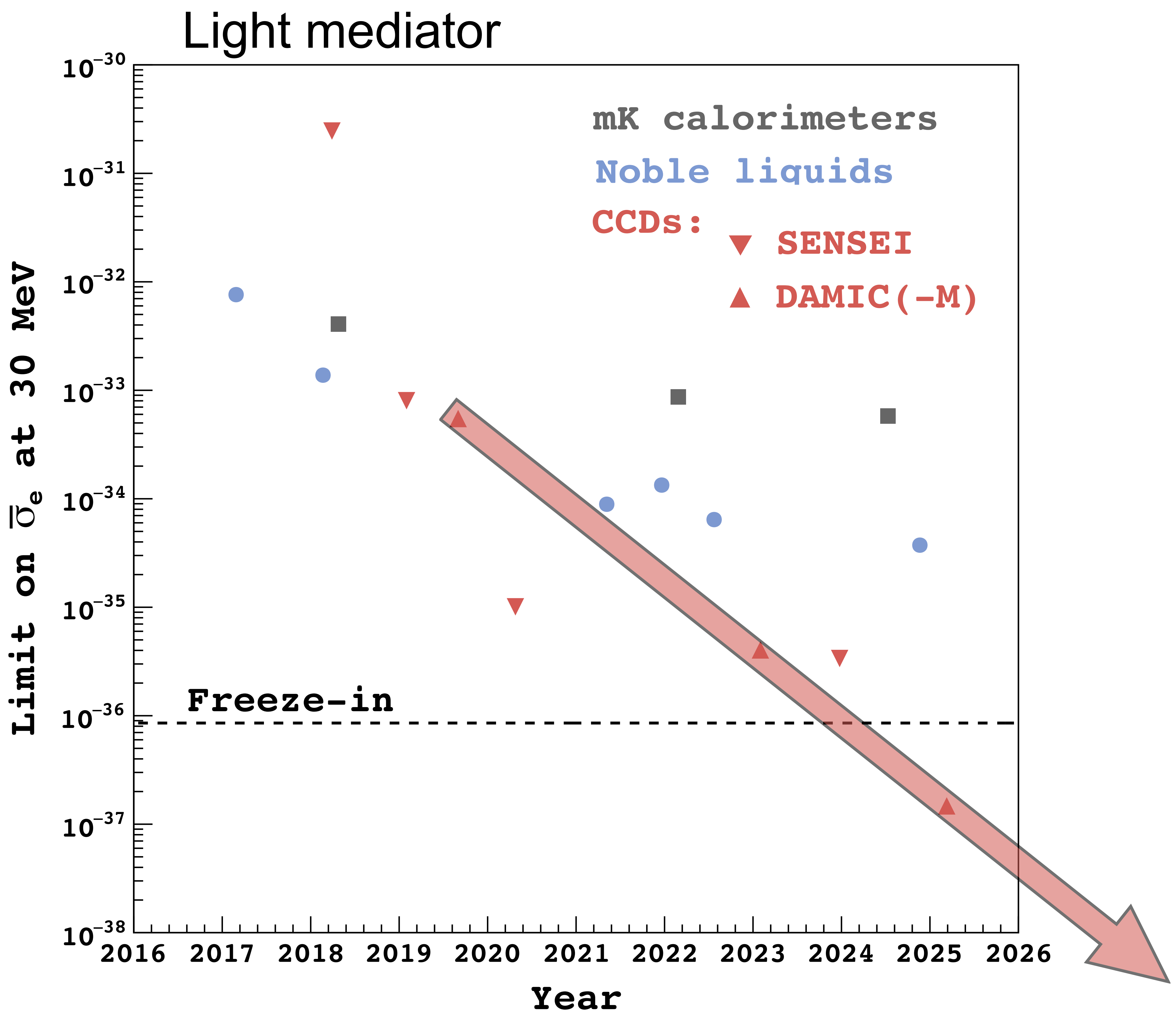


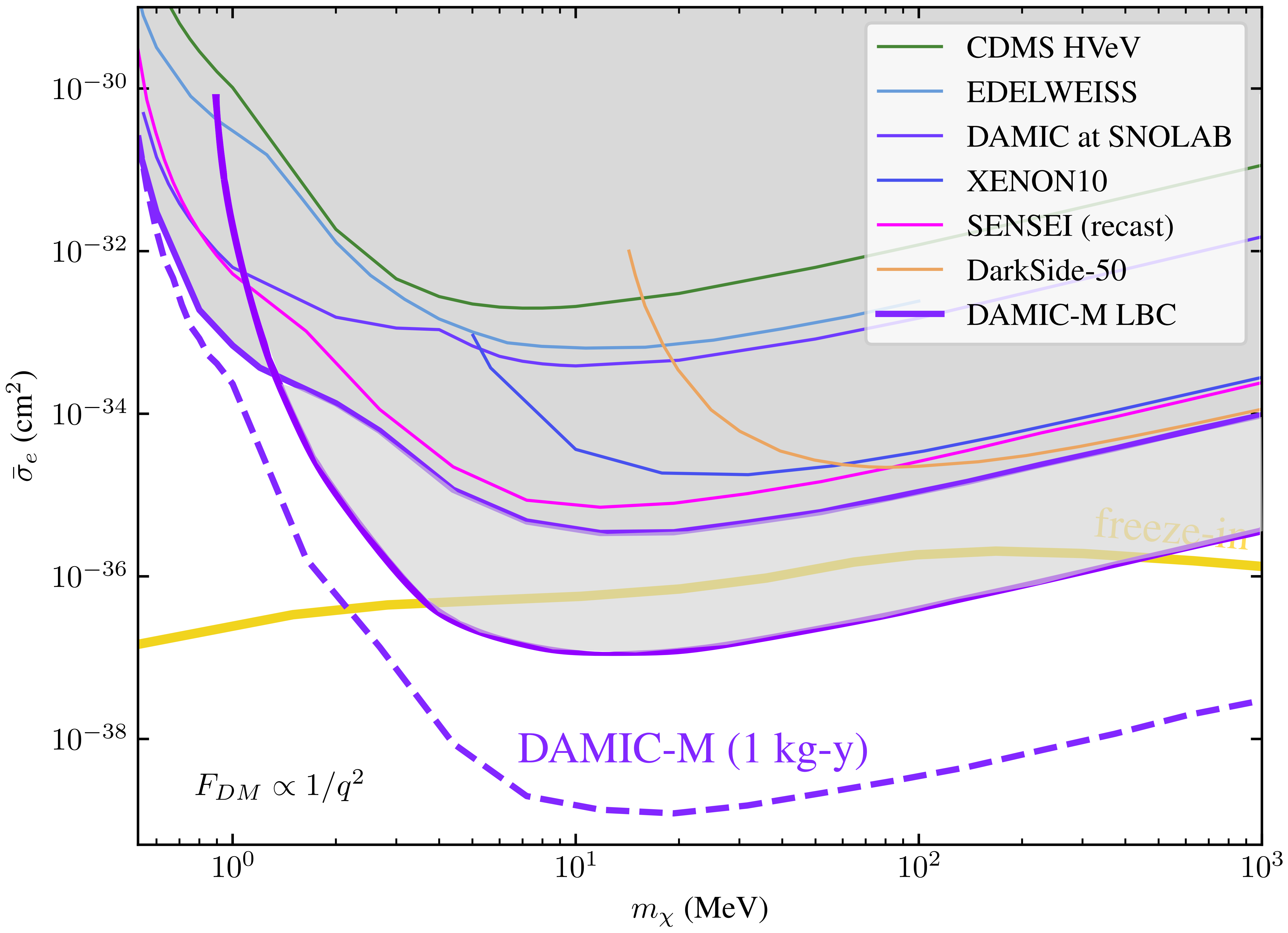


- Transport in shielded container.
- Shielded, Rn-free storage.
- Clean room operations.
- Low-radioactivity flexes. NIMA959(2020)163573
- Copper electroformed underground.
- Light-tight infrared shield.



DAMIC-M Forecast

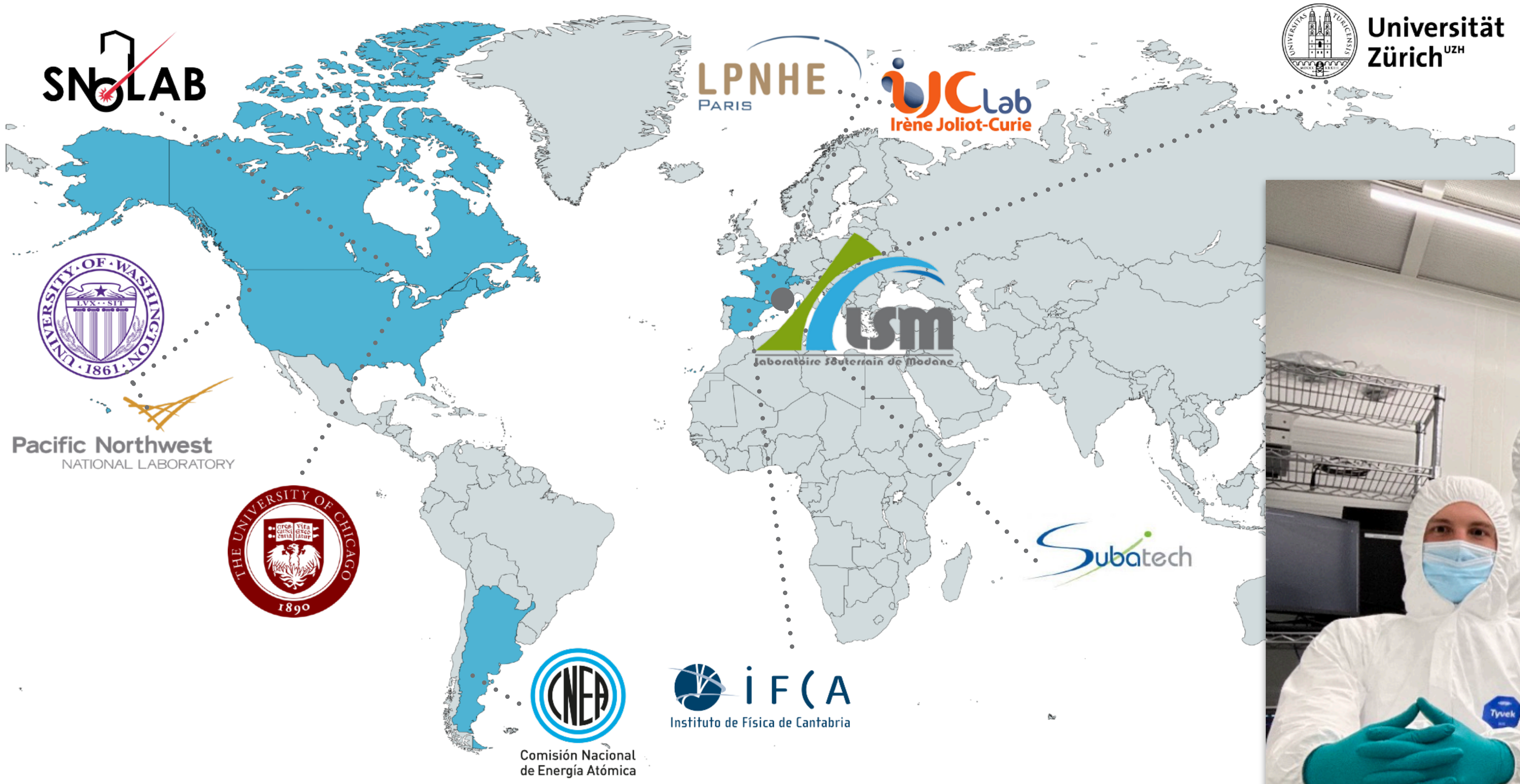




Conclusions

- The range of DM particle masses searched for by direct detection has expanded greatly in recent years.
- DM-e^- scattering is a powerful probe for sub-GeV DM particles.
- Charge-coupled device (CCD) experiments lead the sub-GeV mass window.
- DAMIC pioneered the use of CCDs to search for dark matter.
- Steadfast progress by skipper-CCD experiments SENSEI and DAMIC-M in the last 8 years.
- DAMIC-M's LBC now excludes several hidden-sector benchmark models.
- Progress should continue for at least one more detector generation with DAMIC-M.

Thank you!



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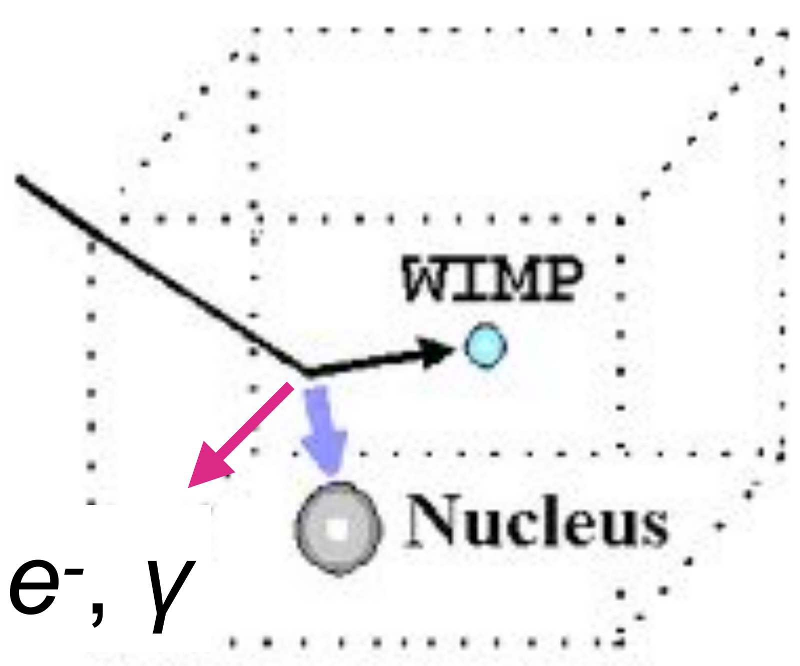
European Research Council
Established by the European Commission
NSF
DAMIC-M

Backup Slides

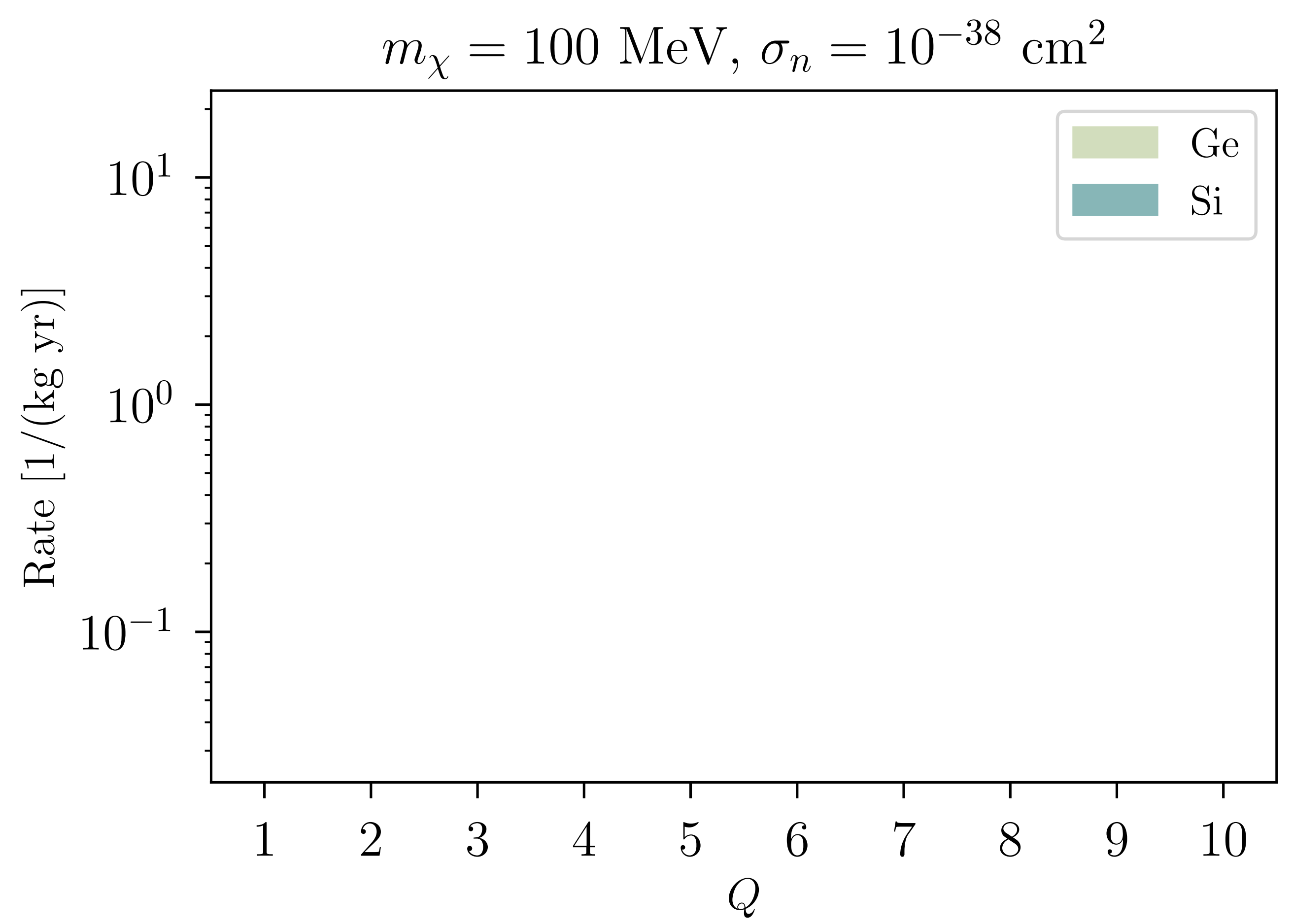
Other e-recoils

Three-body final state:



- An additional e^- or γ in the final state.
- Migdal effect (atomic e^-) or Bremsstrahlung (γ).
- *E* and *p* can be conserved even when e^- or γ take most of the WIMP kinetic energy.
- Probability of e^- or γ emission $<10^{-6}$. Rare.
- Never observed for recoils with keV energies. Uncalibrated.

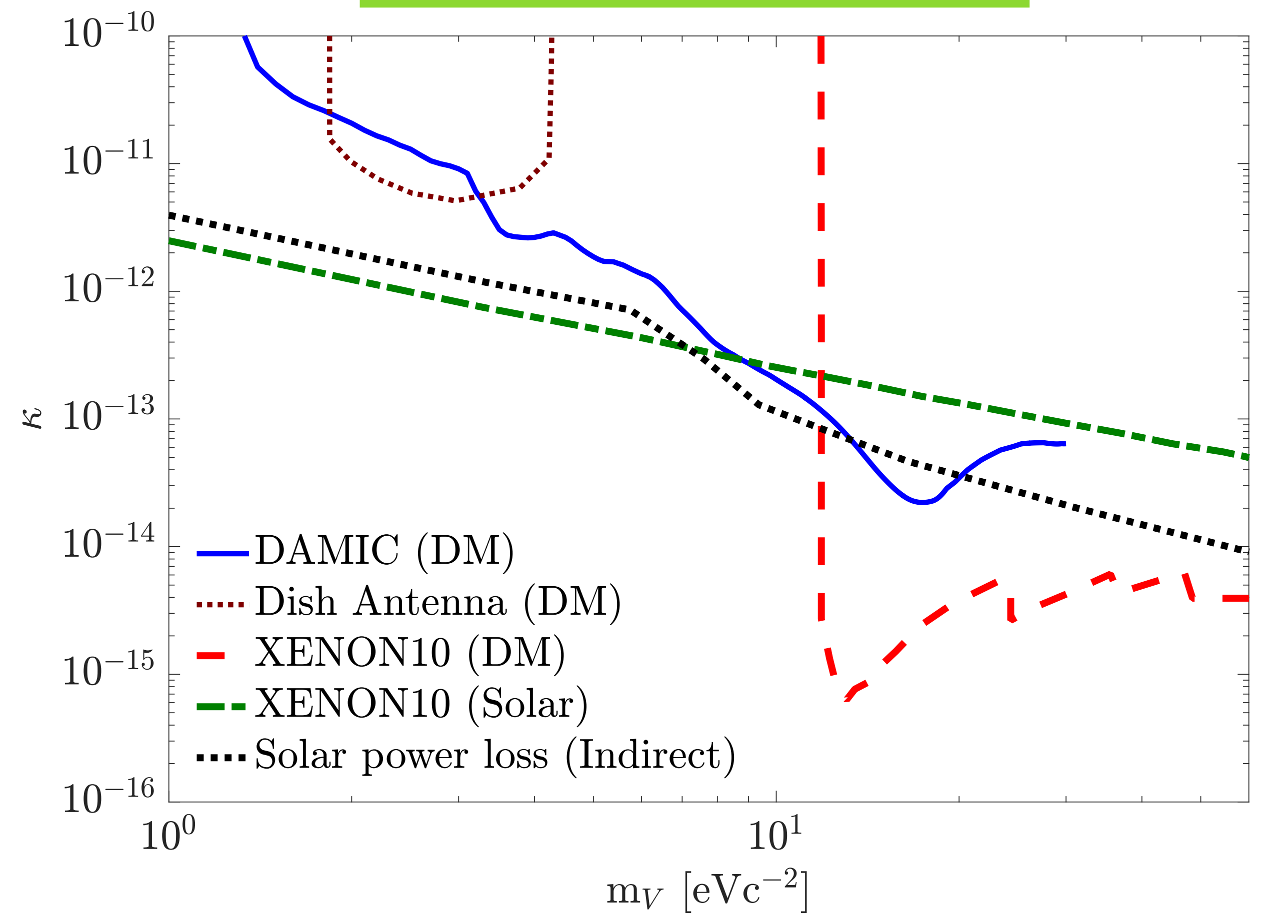
PRL127(2021)081805



Bosonic DM absorption:

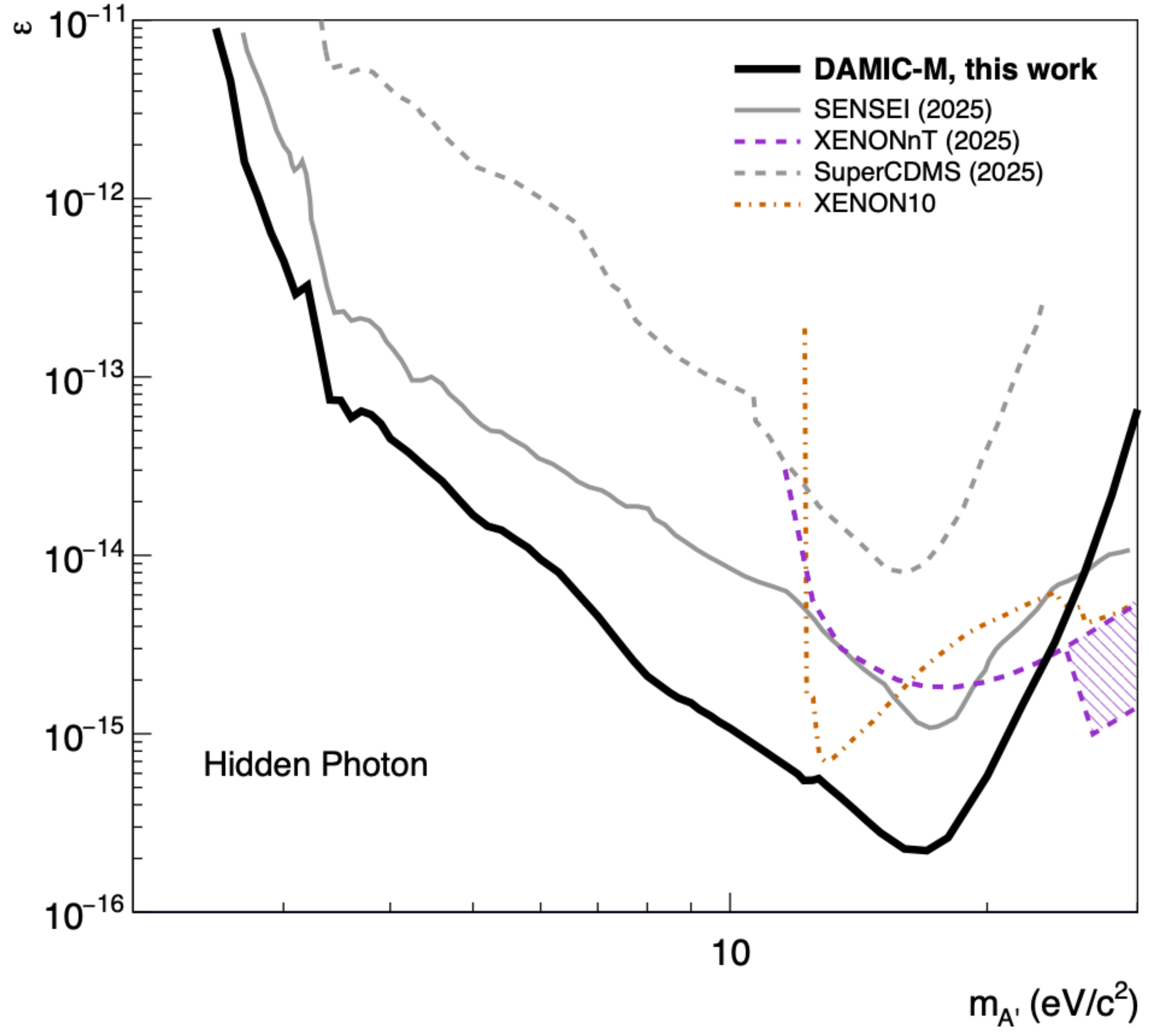
- DM particle is a boson that couples to the electron, e.g., a "dark" or "hidden" photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

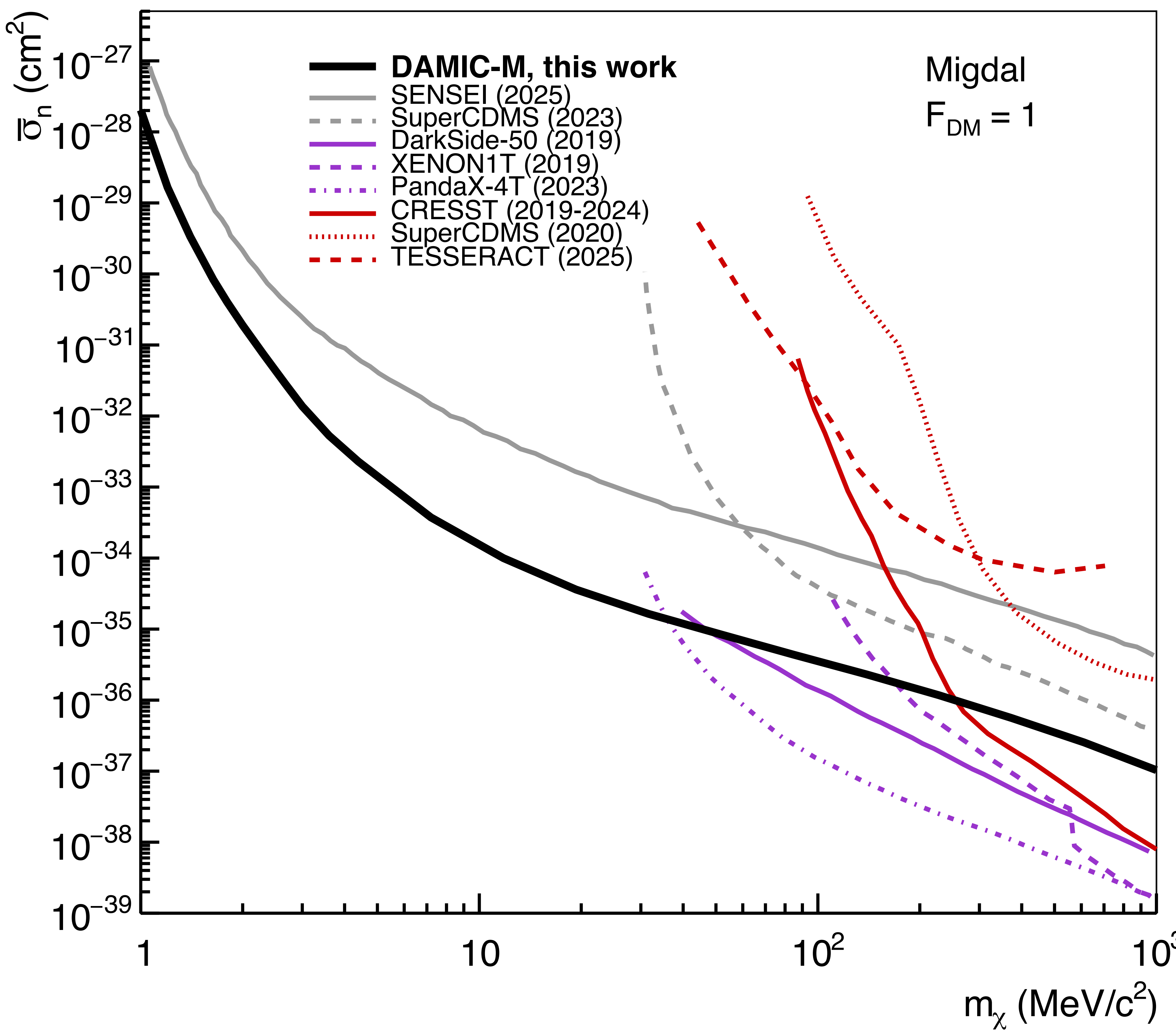
PRL118(2017)141803



Electronic recoil result could also be interpreted as limit on DM-N scattering (Migdal) or DM absorption
I will use DM-e scattering parameter space as benchmark

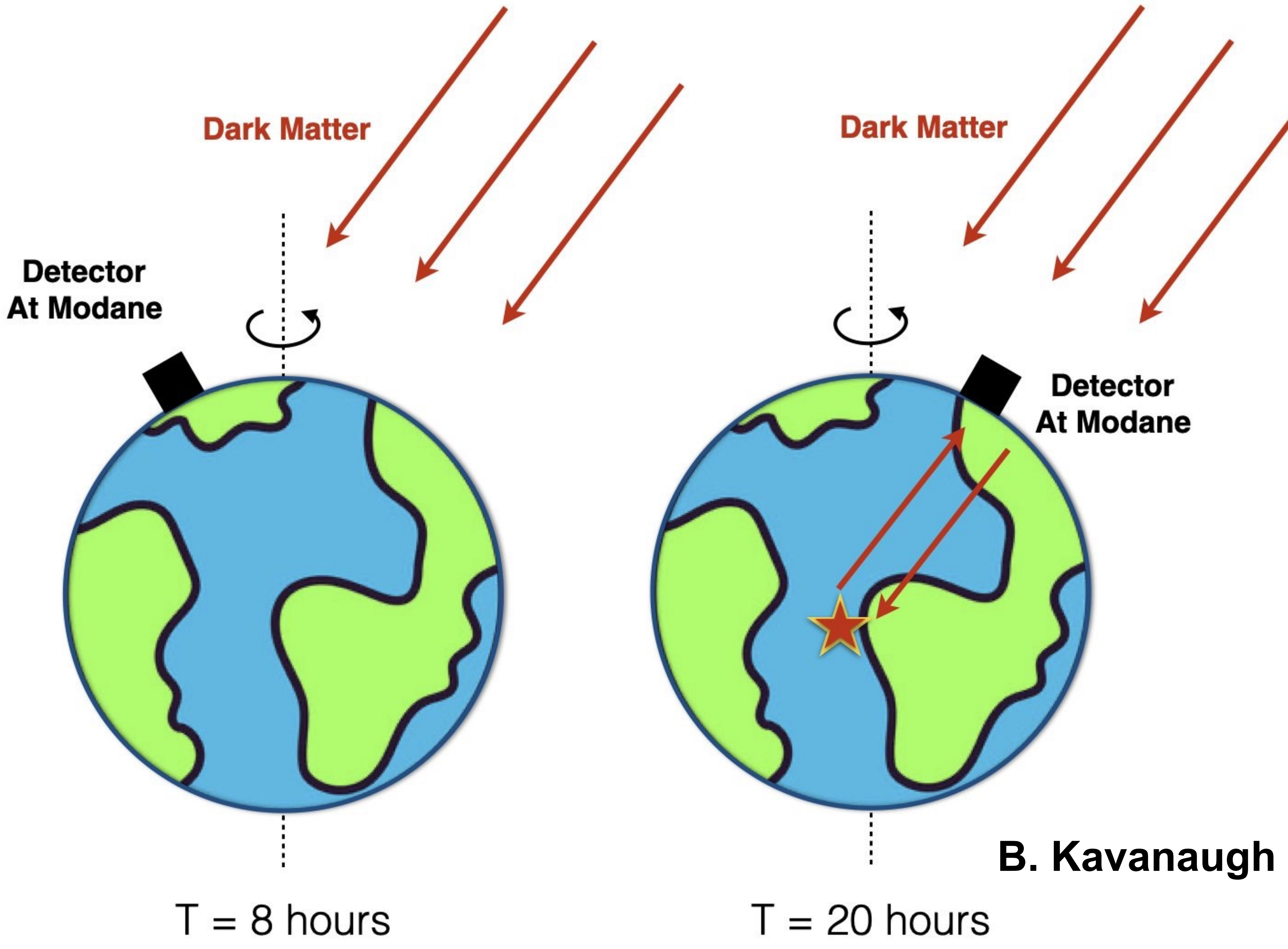
Other exclusion limits

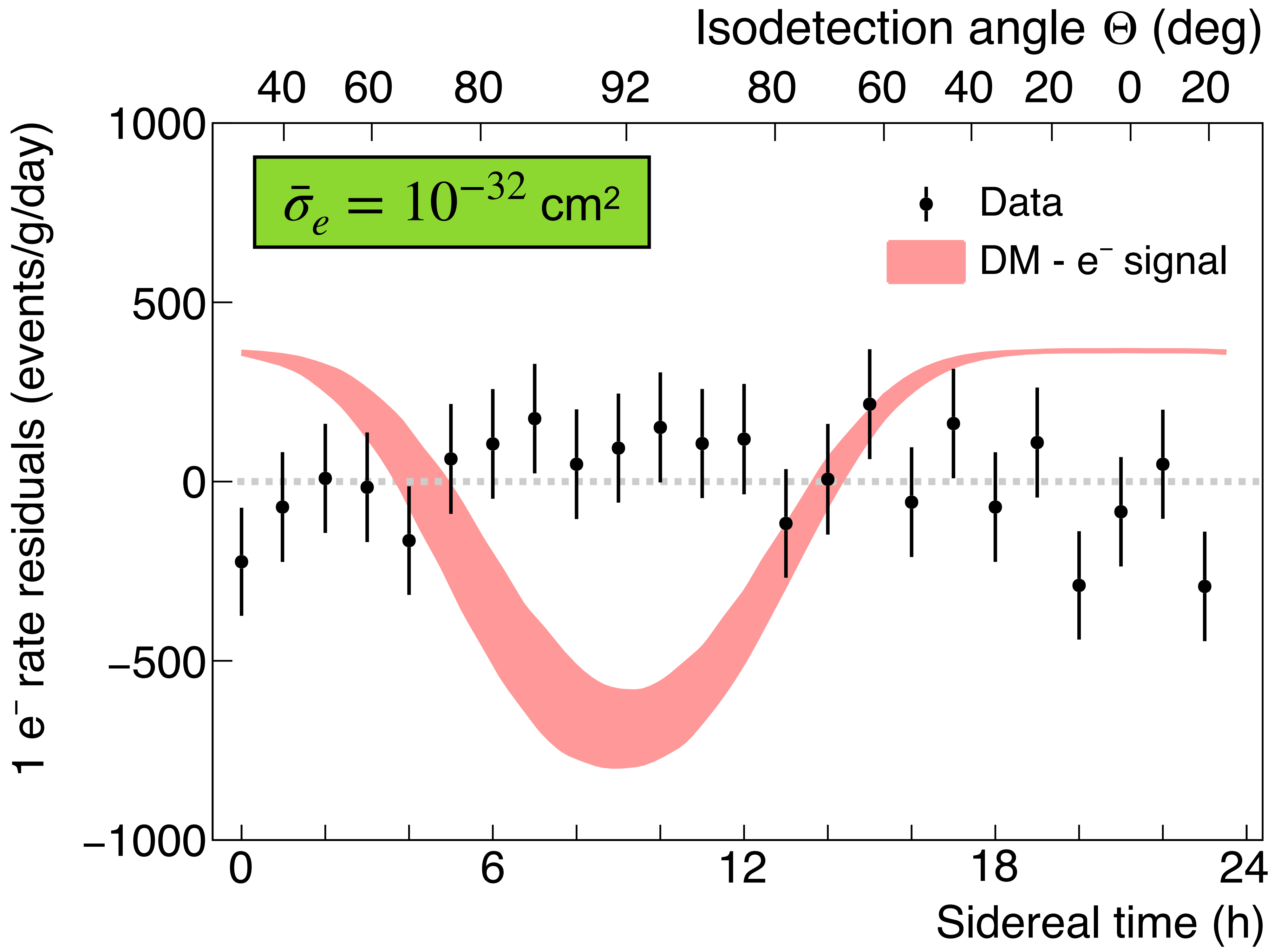




- DAMIC-M also sets stringent constraints on **absorption of relic hidden photon** by atomic electron on silicon and **DM-nuclear scattering via Migdal** effect (see End Matter arXiv:2503.14617). All limits available as text on linked Github.

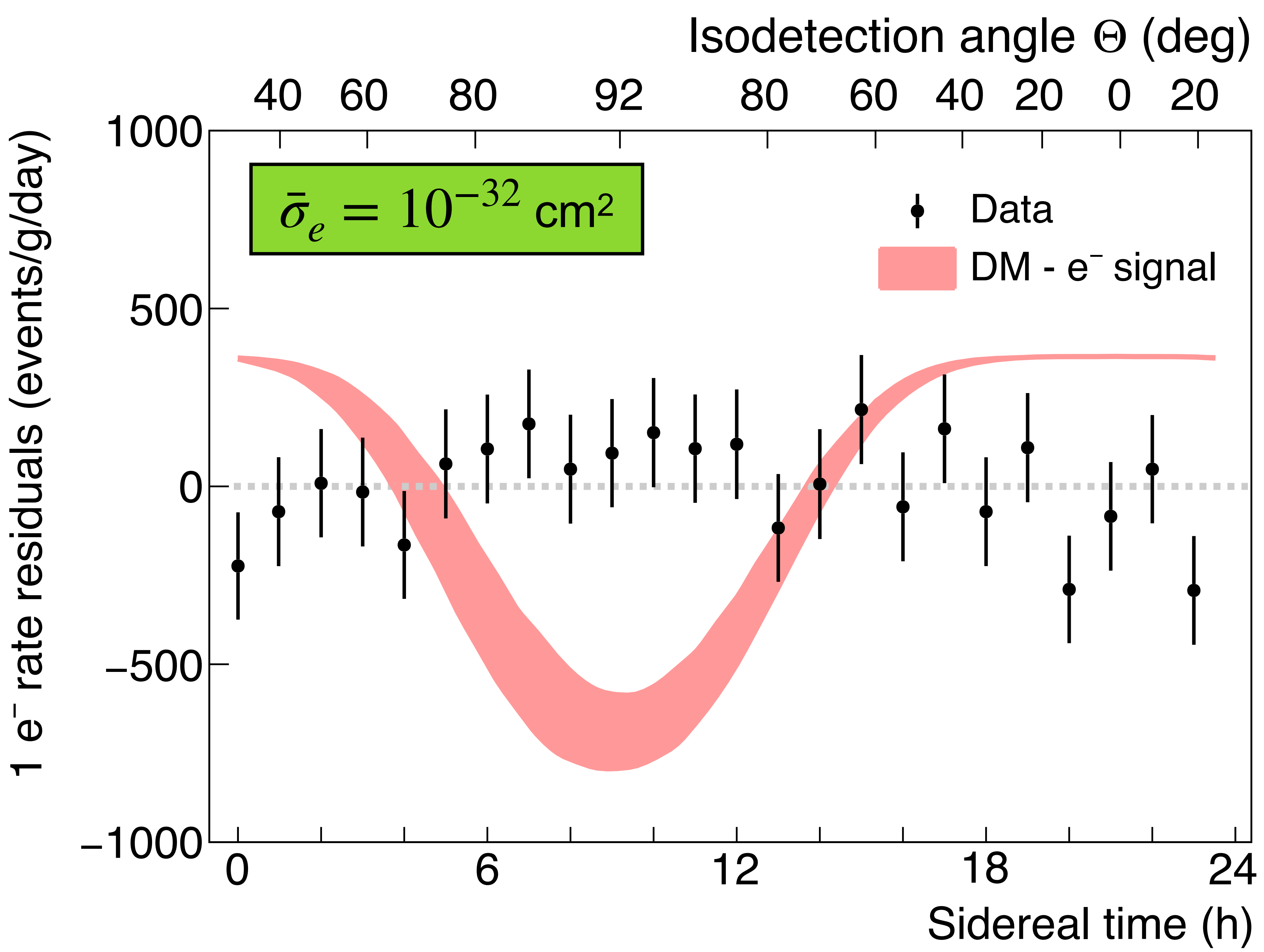
Daily modulation

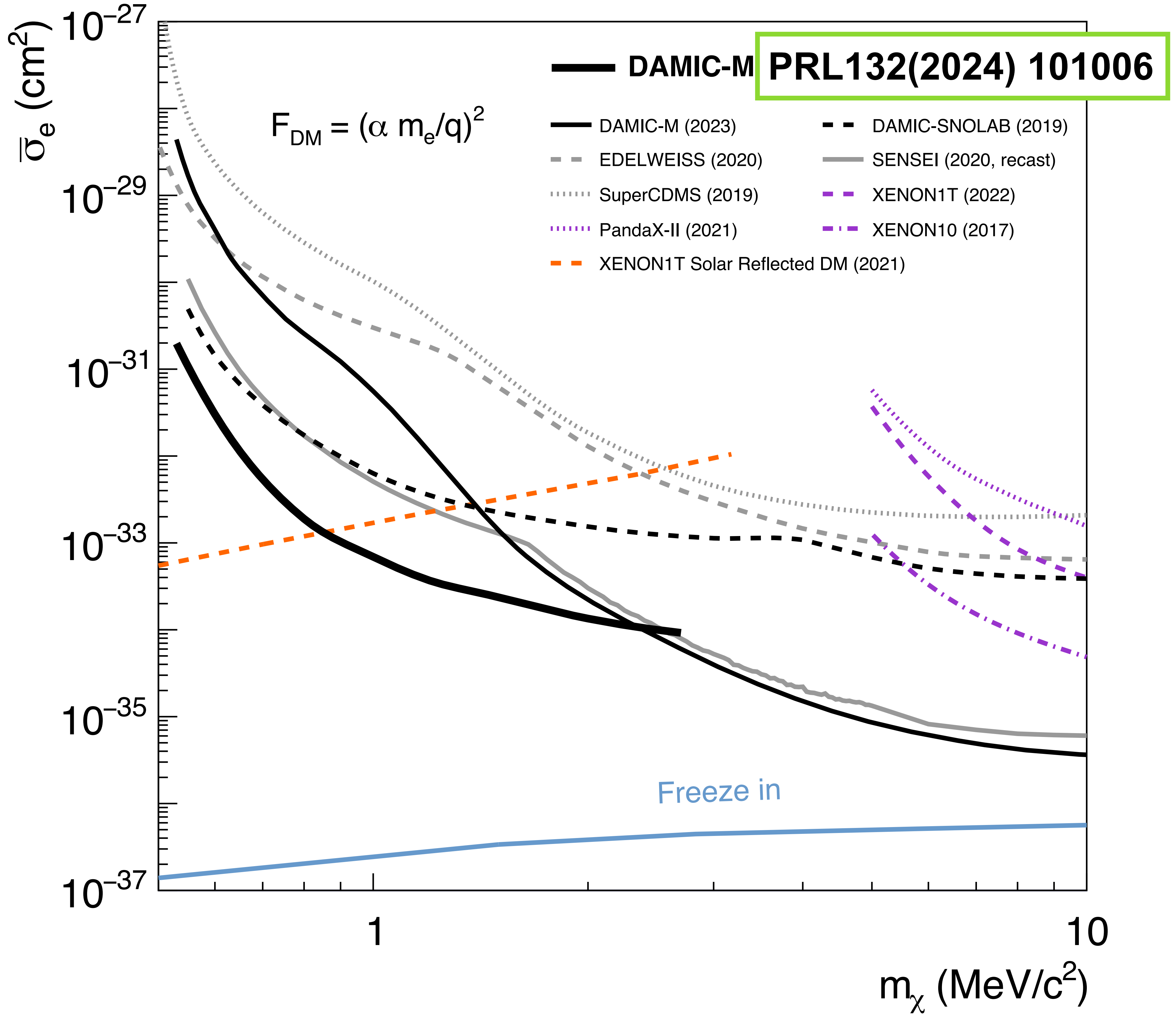




- At large enough σ, DM scatterings in the Earth cause a daily modulation of the flux in the lab.
- Although “large,” these σ had never been probed for ~1 MeV DM.

Daily modulation





- Previous daily modulation analysis x100 more sensitive than spectral analysis for m_χ ~ 1 MeV.
- Currently updating daily modulation analysis with latest data set.

Spectroscopy

- Calibrations to confirm CCDs can measure spectral features near threshold.
- Precision measurement with a skipper CCD of electronic recoil spectrum from Compton scattering: PRD106(2022)092001
- “Steps” at the binding energies of the atomic shells in silicon.
- Spectral features not well-reproduced by Geant4.
- Spectrum down to 23 eV_{ee} reproduced with *FEFF* code, which performs full atomic physics treatment.