The search for dark matter with DAMIC-M

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DAMIC-M

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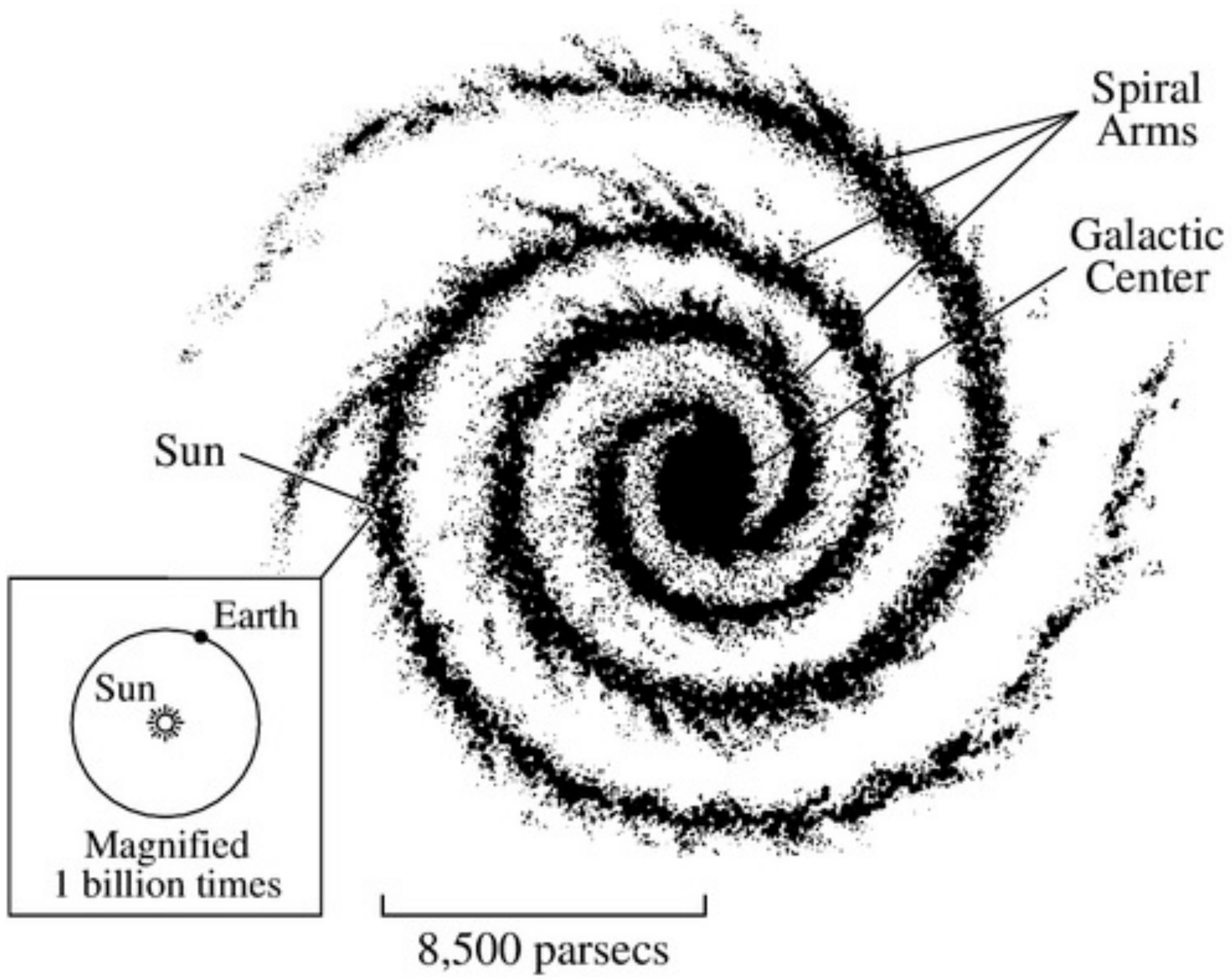
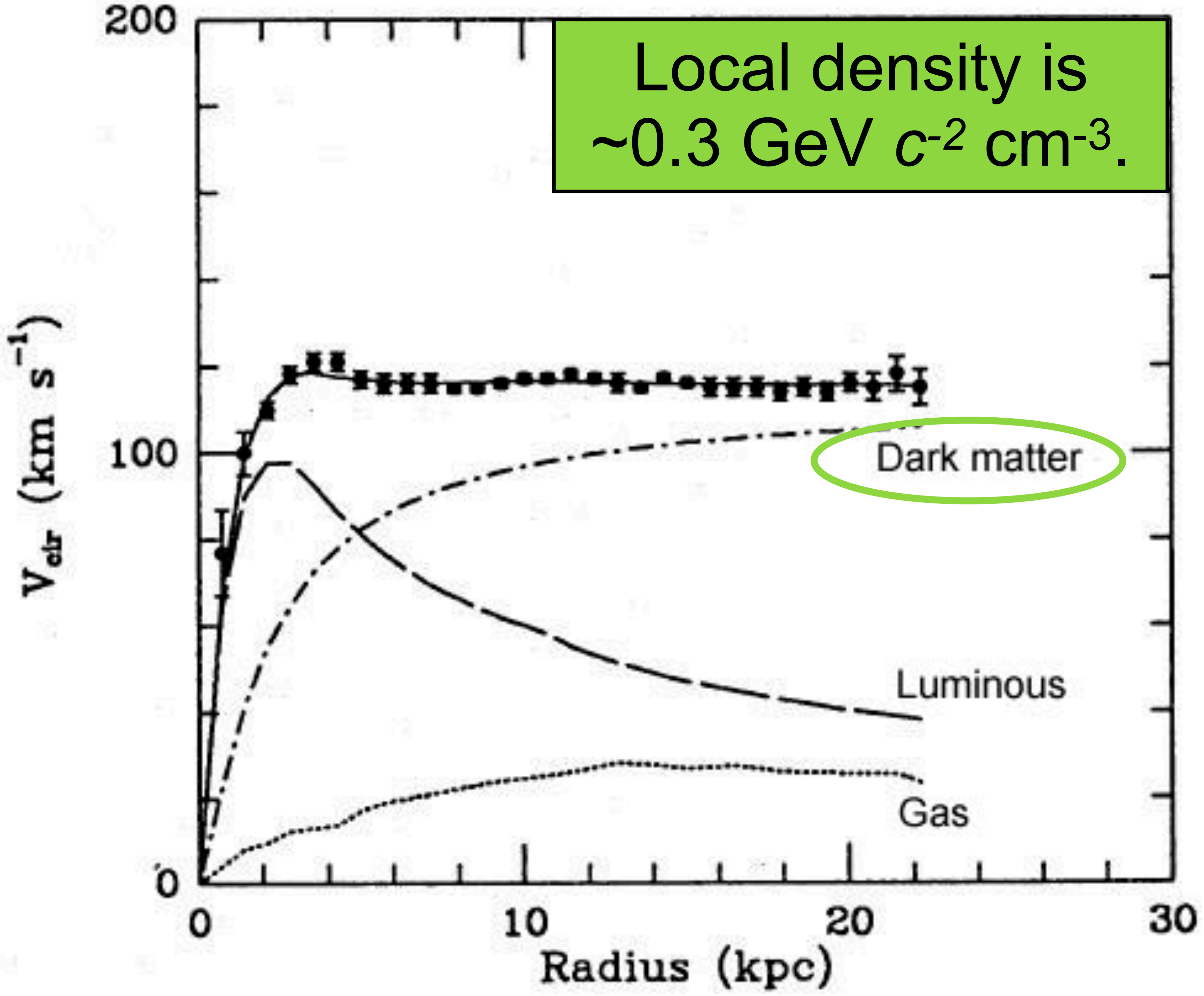
Outline

- Dark matter particles and direct detection.
- Charge-coupled devices (CCDs) for dark matter direct detection.
- The DAMIC-M program.
- Results from the Low Background Chamber (LBC).
- The upcoming full-scale DAMIC-M detector.
- R&D for the future.

Dark matter (DM)

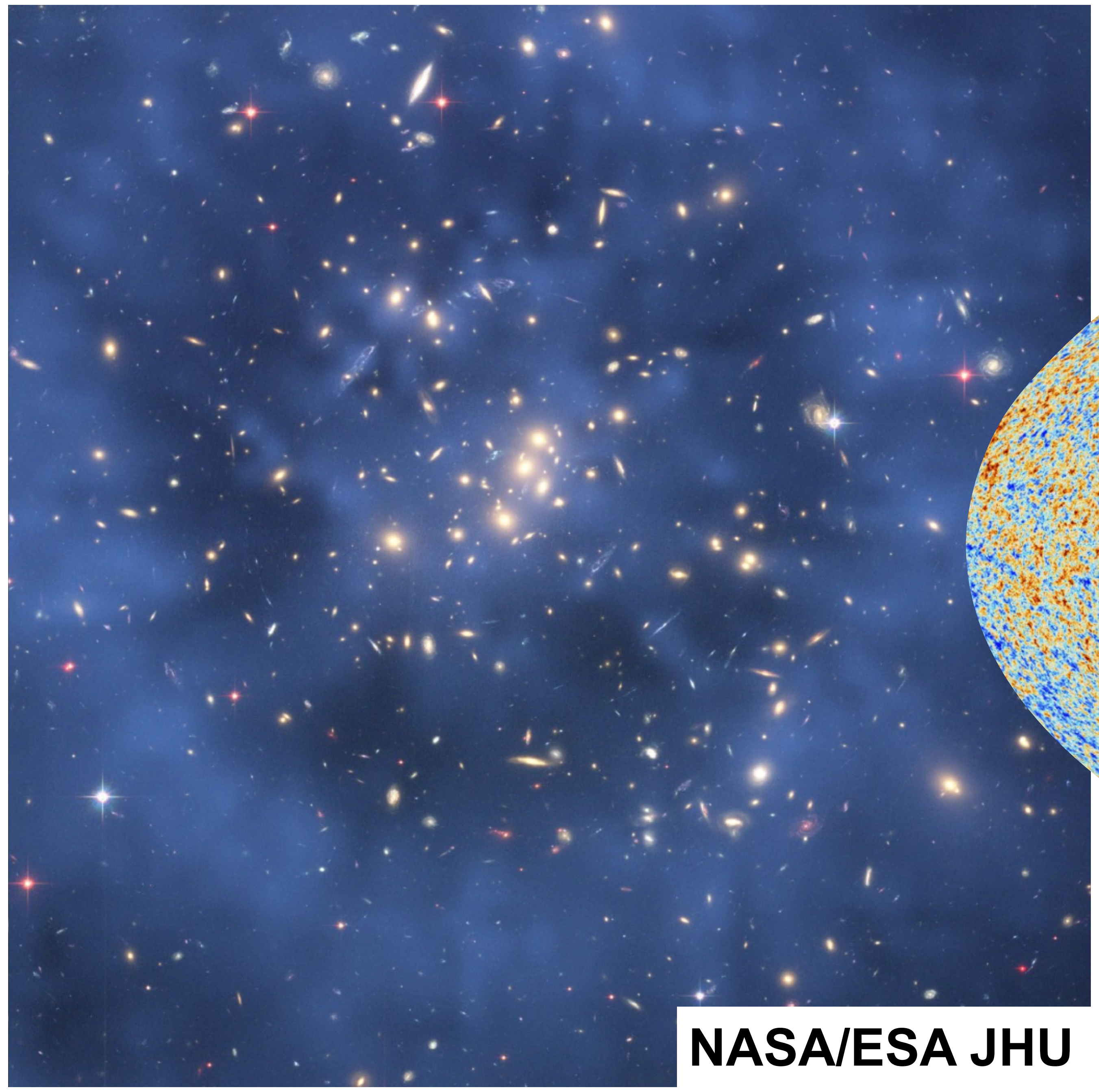


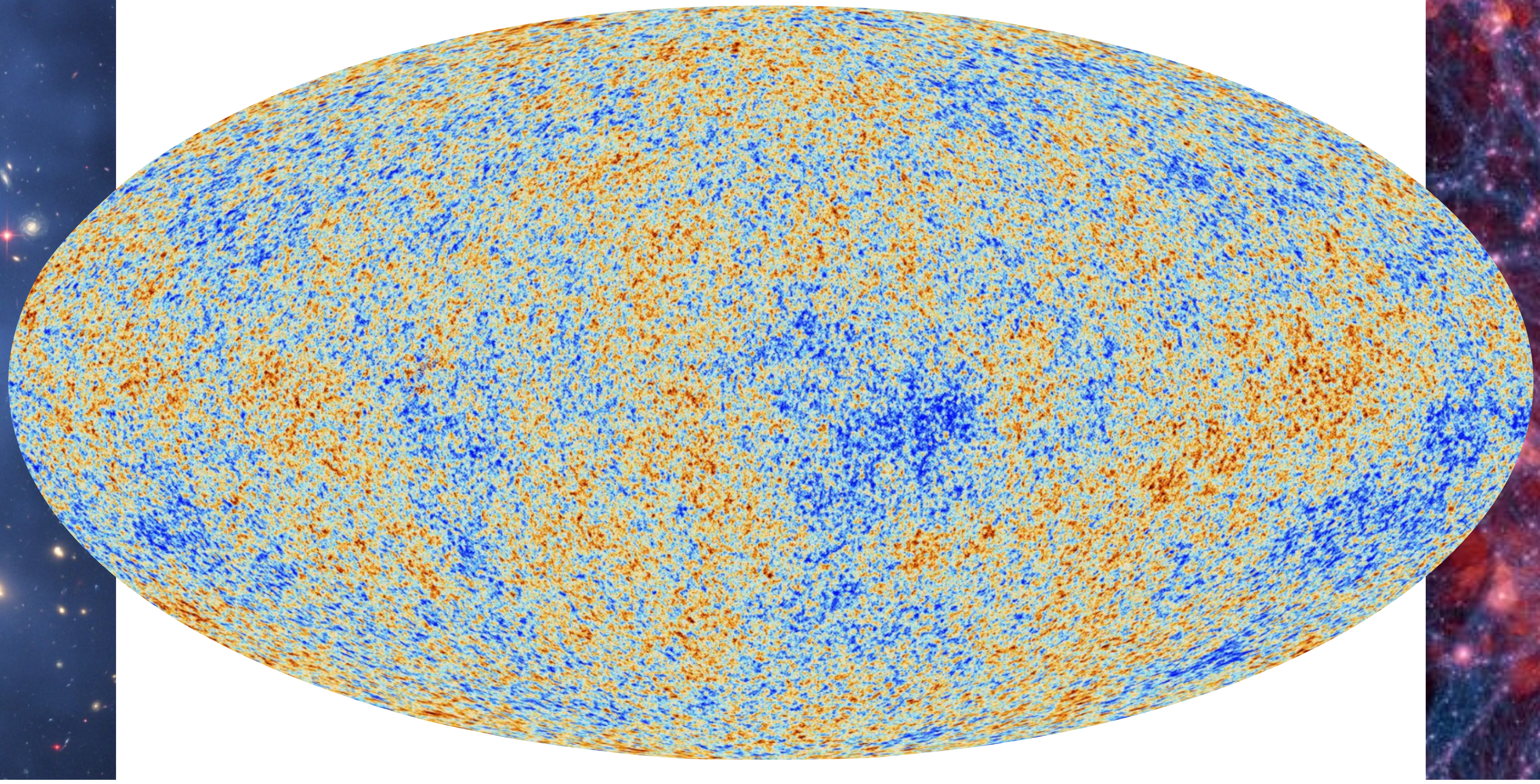


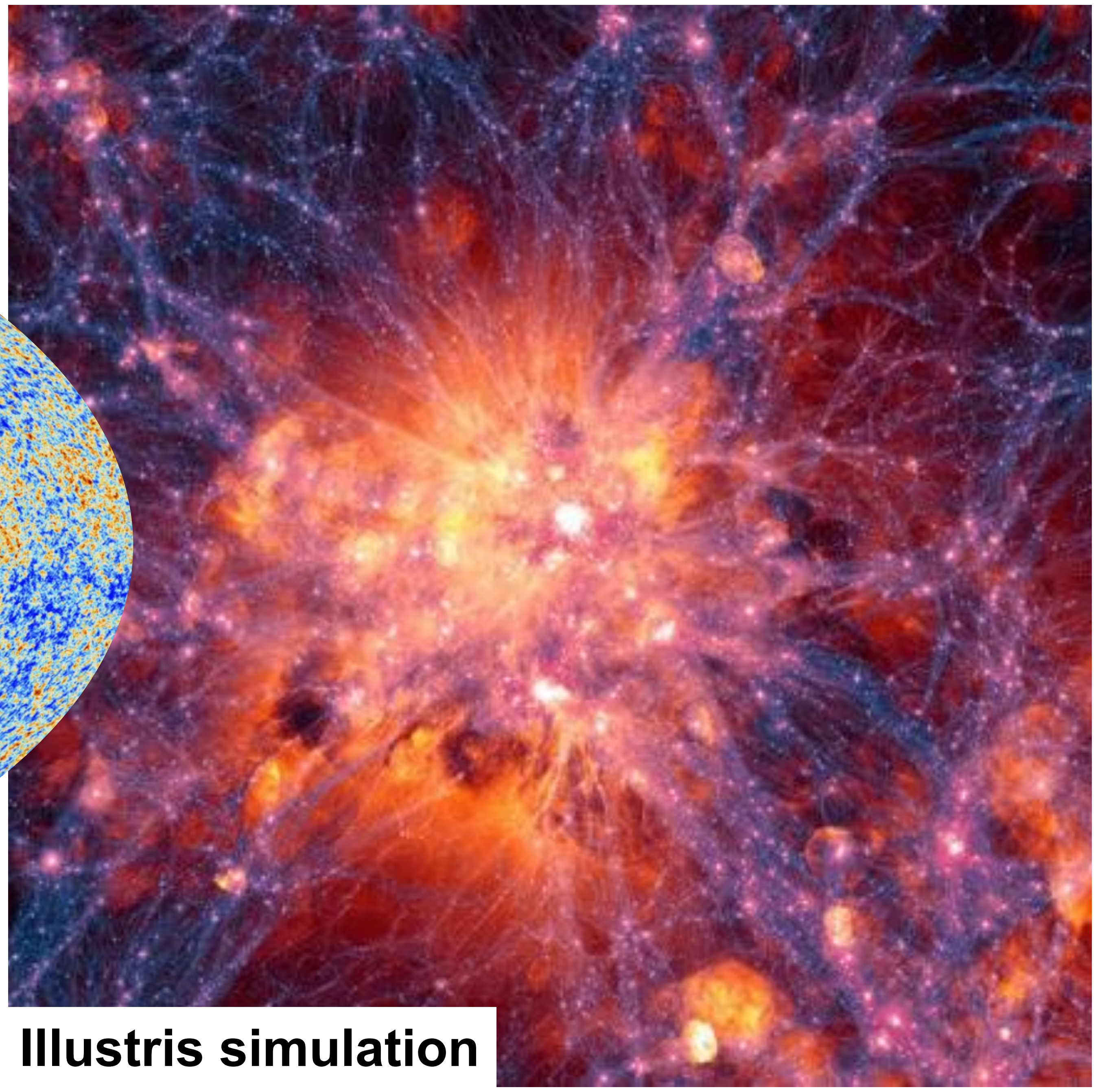
The centripetal force exerted on the "Sun" cannot be explained by stars and gas.

Introduce massive "dark matter" in a halo around the galaxy, that we can't see but can *feel* gravitationally.

Cosmological evidence


NASA/ESA JHU


Planck


Illustris simulation

Dark matter from gravitational lensing

Cosmic microwave background (CMB)

Universe’s large-scale structure

Dark matter *is needed* to explain astronomical observations from galactic to cosmological scales!

Dark matter particles

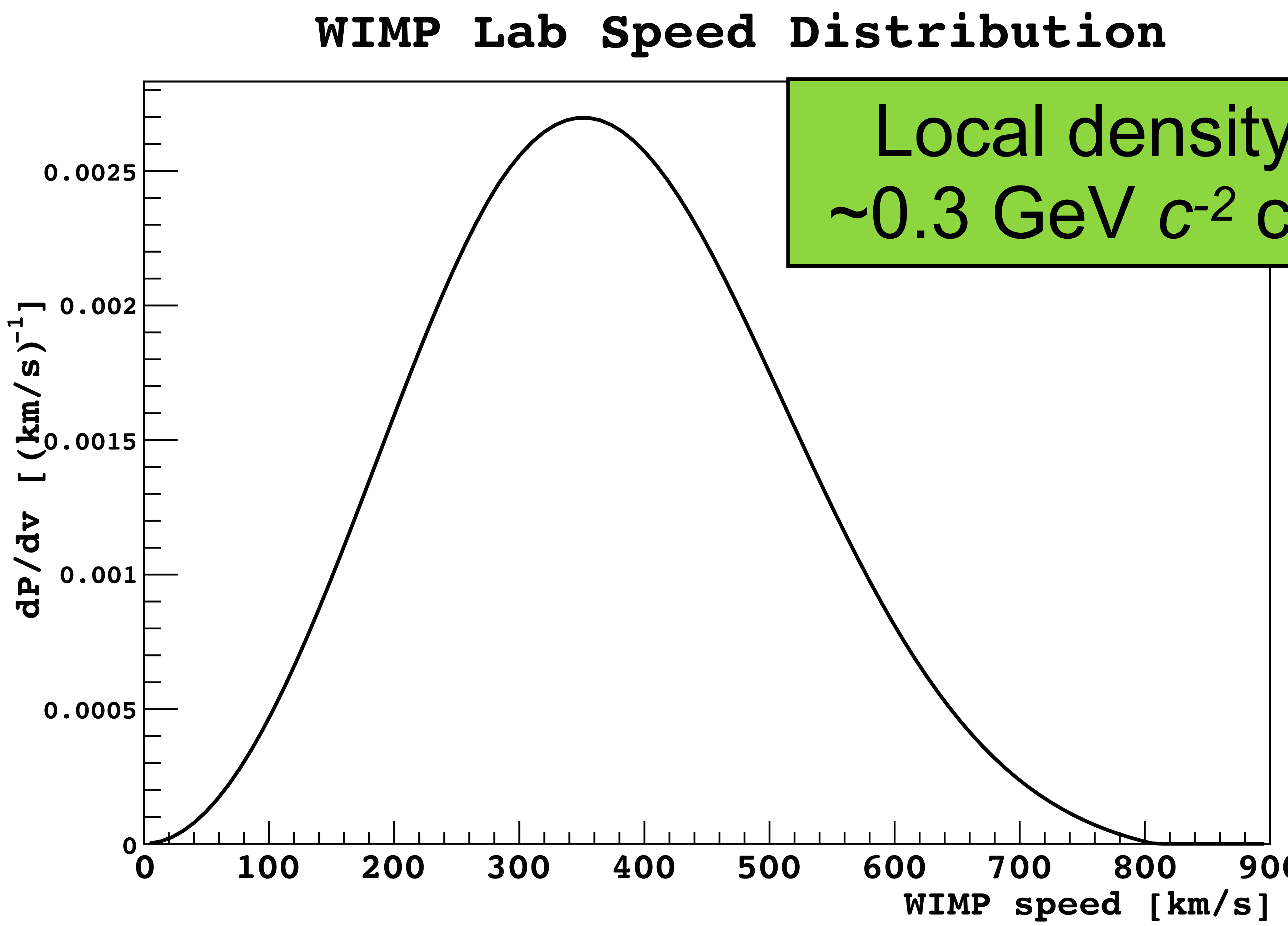
Dark matter is *cold*, i.e., it is bound to the galaxy.

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

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

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

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

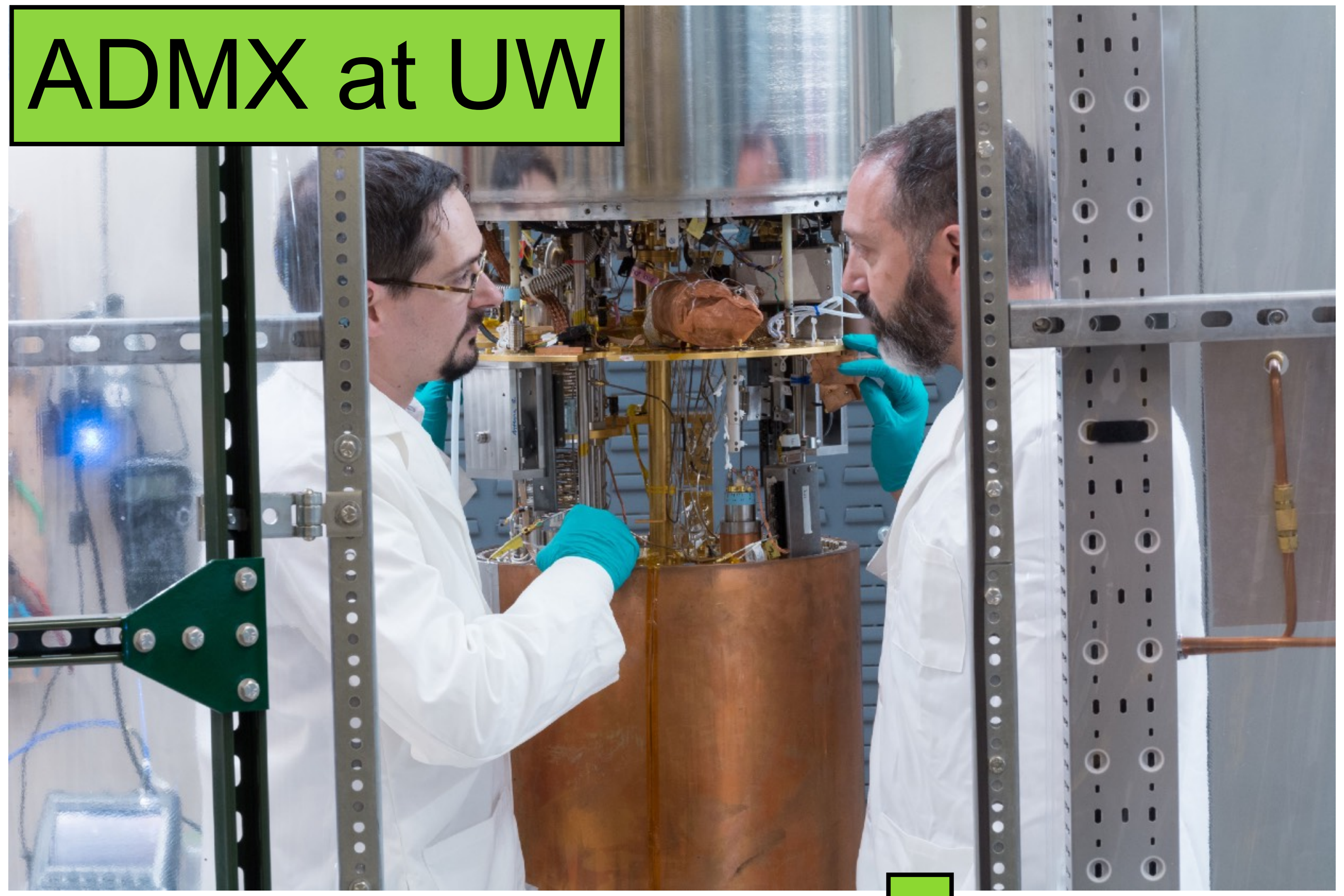


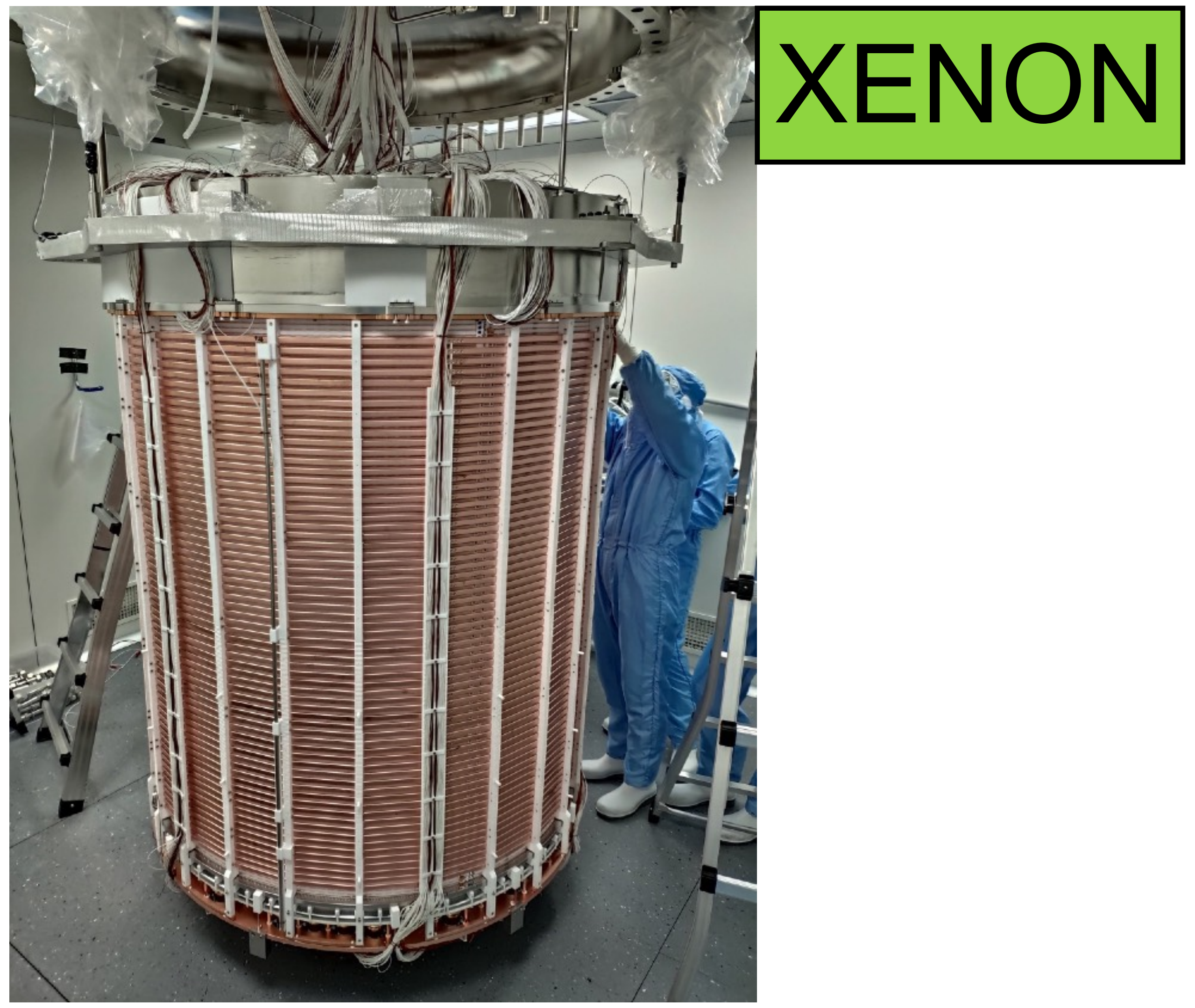
Local density is ~0.3 GeV c^{-2} cm^{-3}.

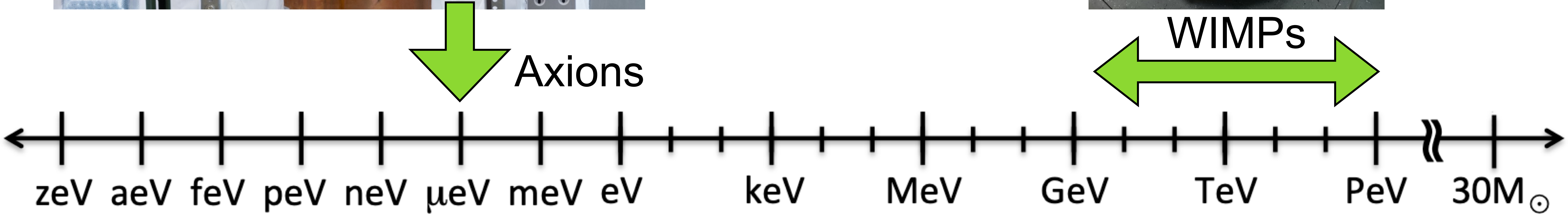
We do not know the particle mass (M_χ)

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

DM particle candidates







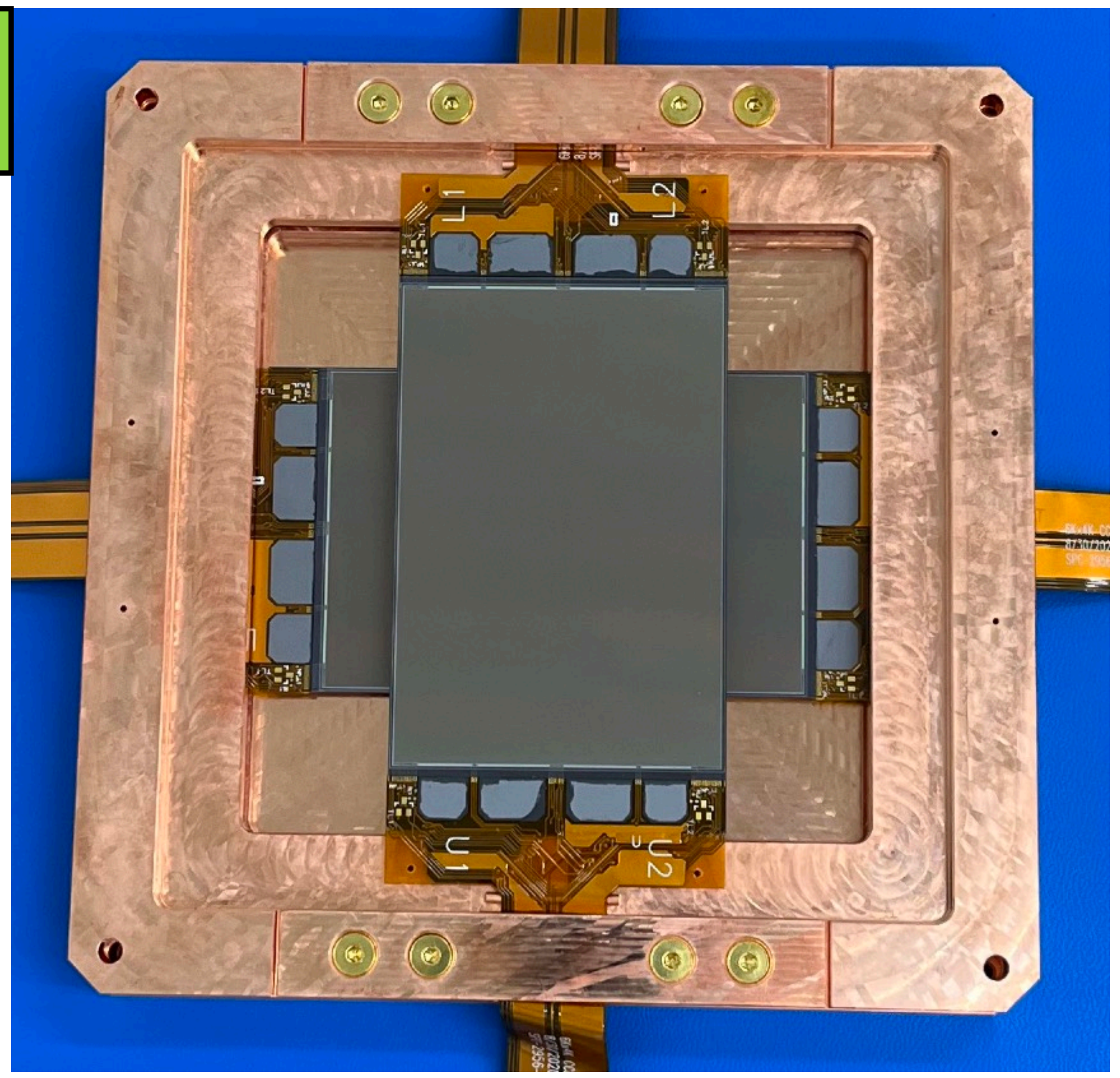
“wave-like” dark matter

“particle-like” dark matter

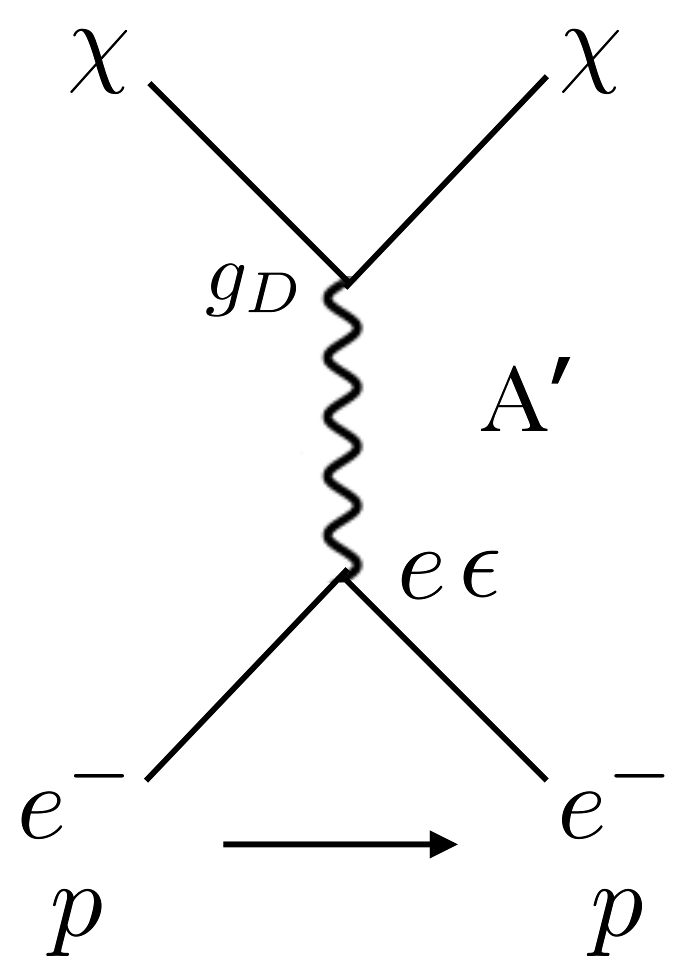
black holes

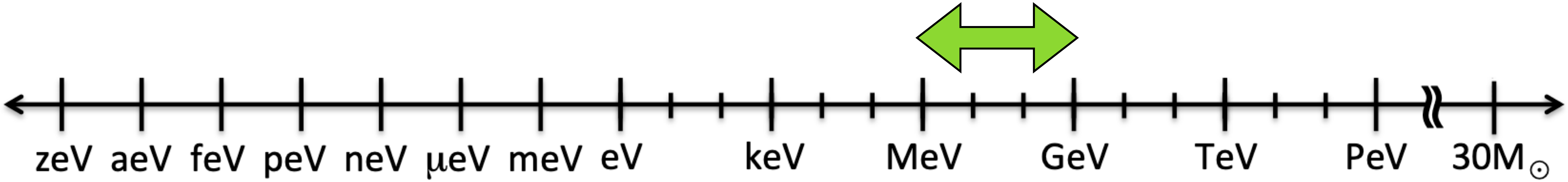
DM particle candidates

DAMIC-M



Sub-GeV
Hidden-sector
Dark matter





"wave-like" dark matter

"particle-like" dark matter

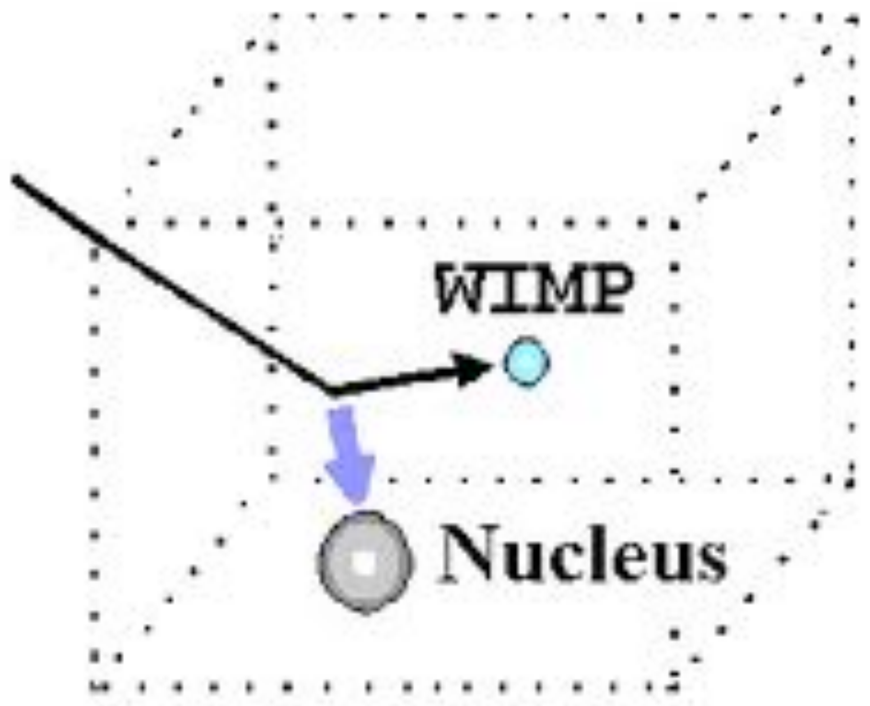
black holes

Dark matter signal

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

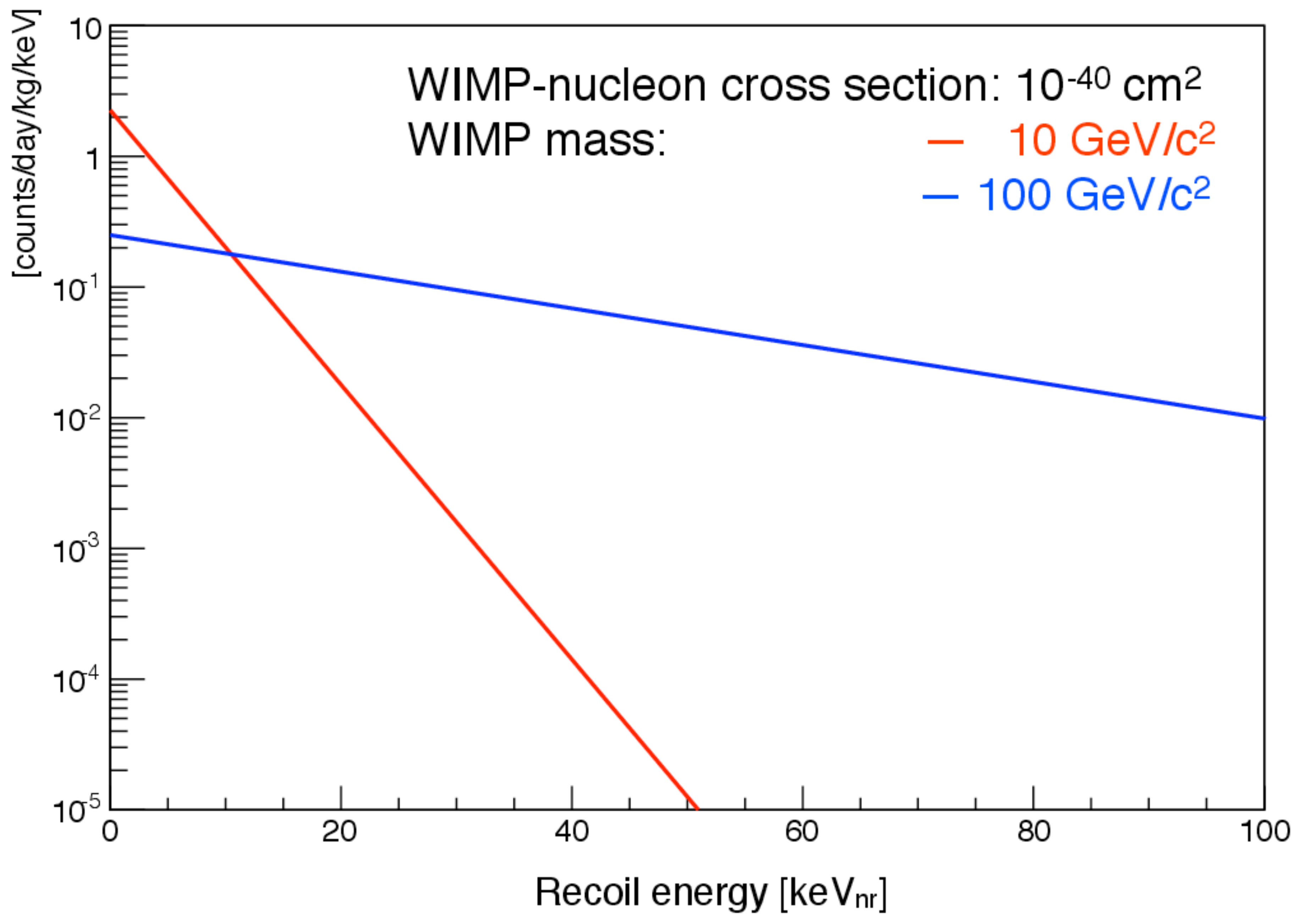
Traditional mechanism for WIMP searches:

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



Maximum energy transfer when *M* ~ *A*

Recoil spectrum in Si target

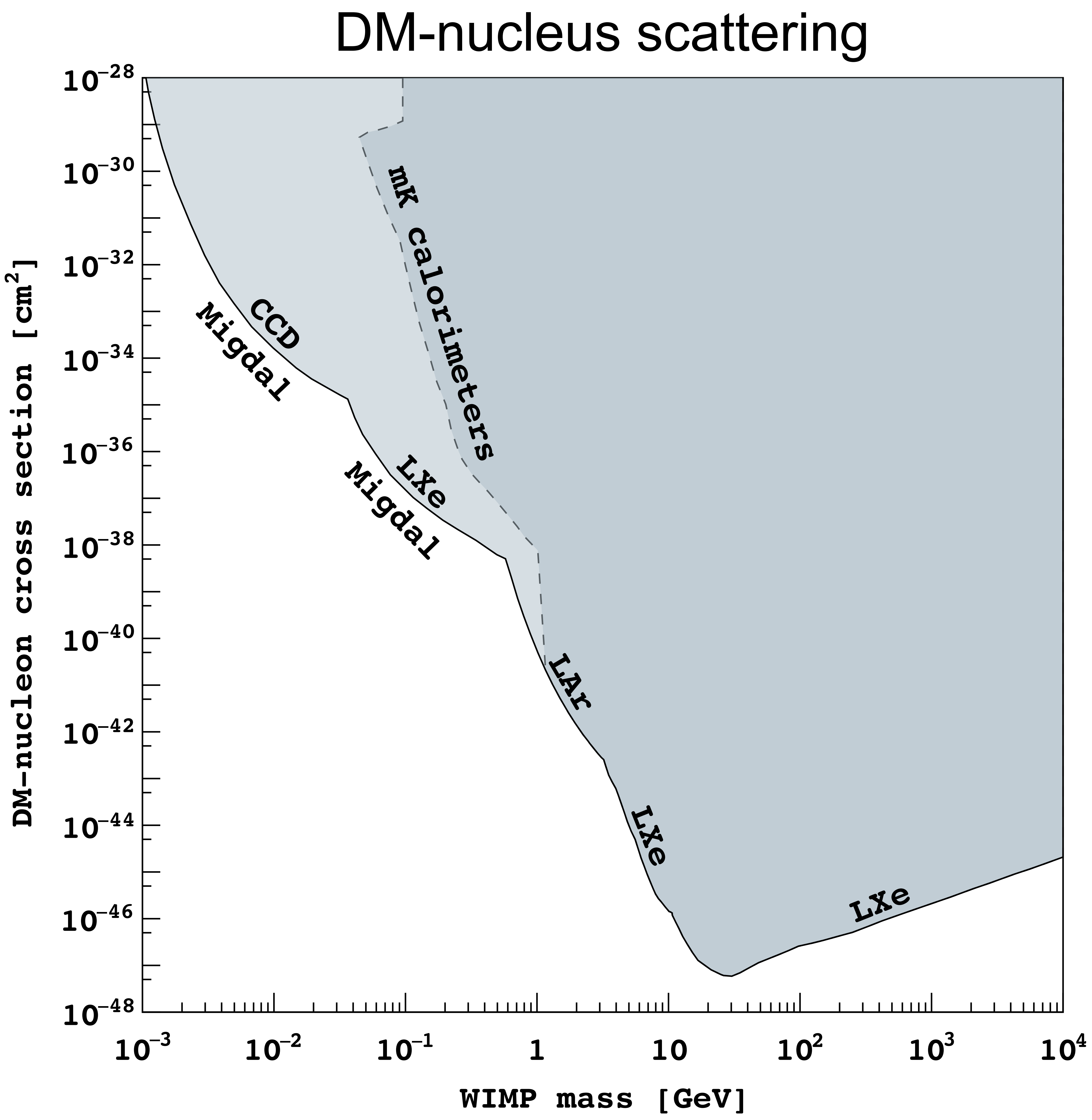


For low-mass WIMP: $M_T \gg M_\chi$

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

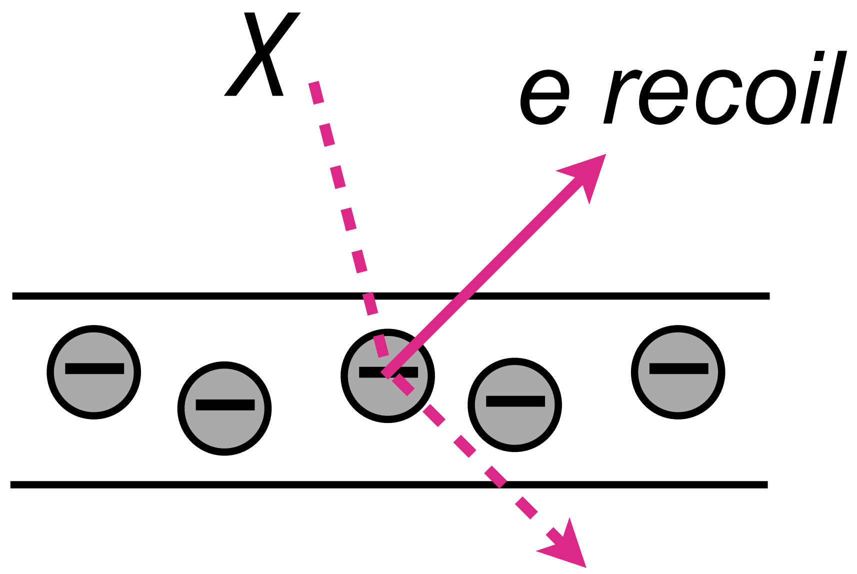
World Status

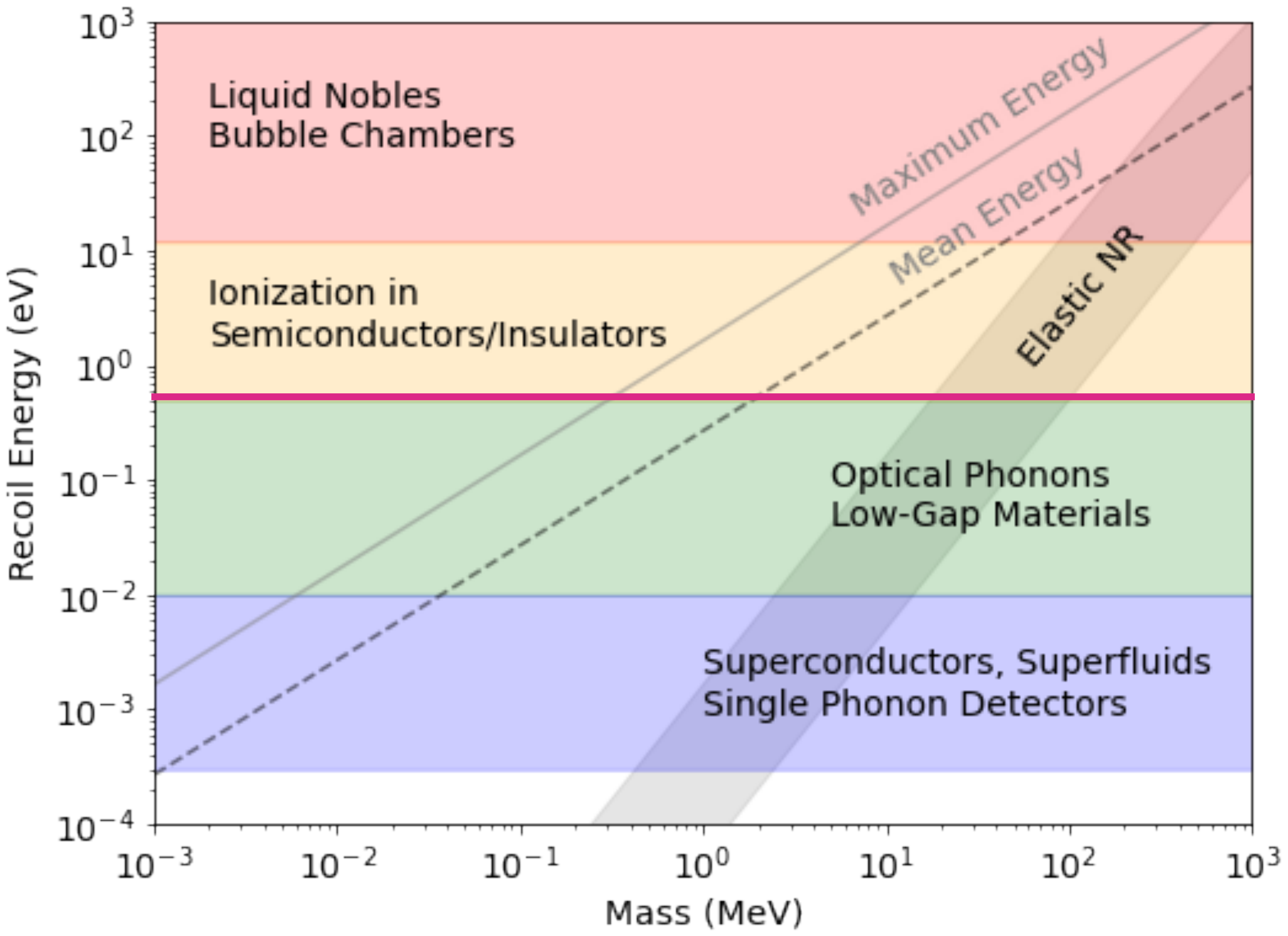
- World-wide effort to directly detect DM signals.
- For “particle” DM the search currently spans from ~1 MeV to the Planck mass.
- Different technologies target different mass ranges.
- CCDs have greatest sensitivity below 35 MeV*
- *Depends on the Migdal effect (very small probability of ionization)



DM-e scattering

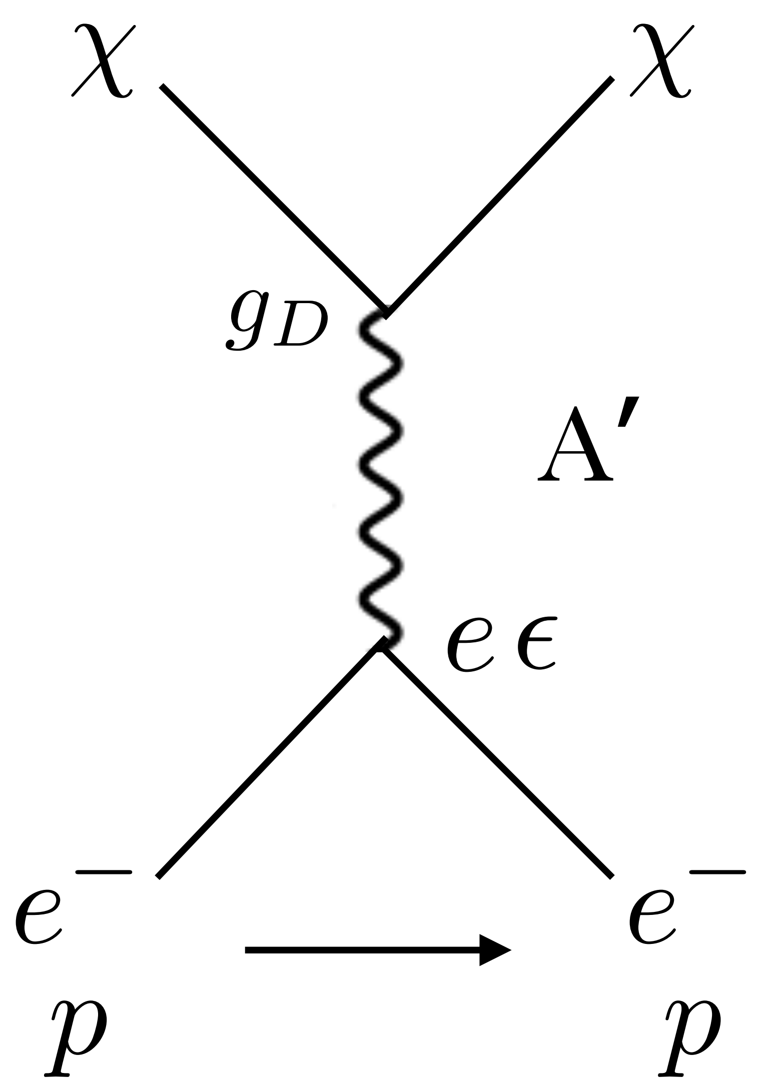
- Electrons are a lighter target and *ER visible as ionization*.
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.





- 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.

- Mediator A’ mixes with SM photon.



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

DM-e scattering

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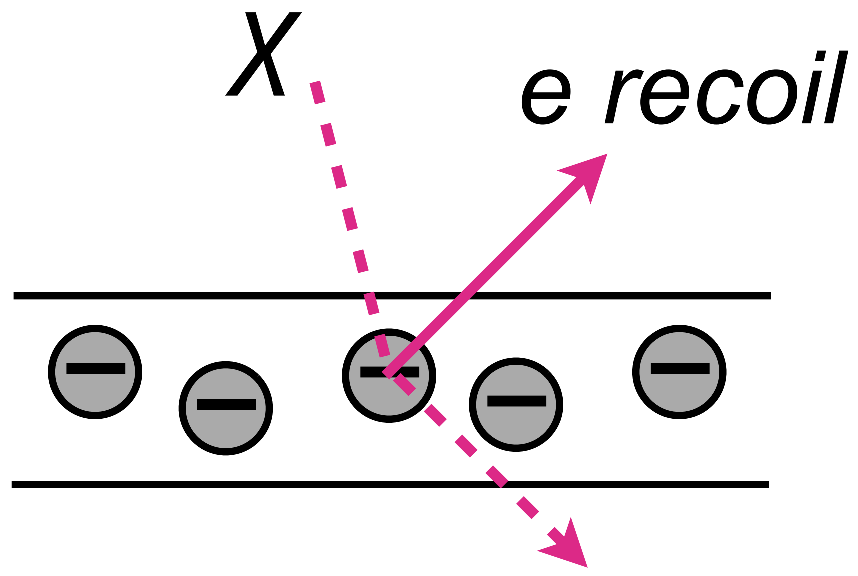
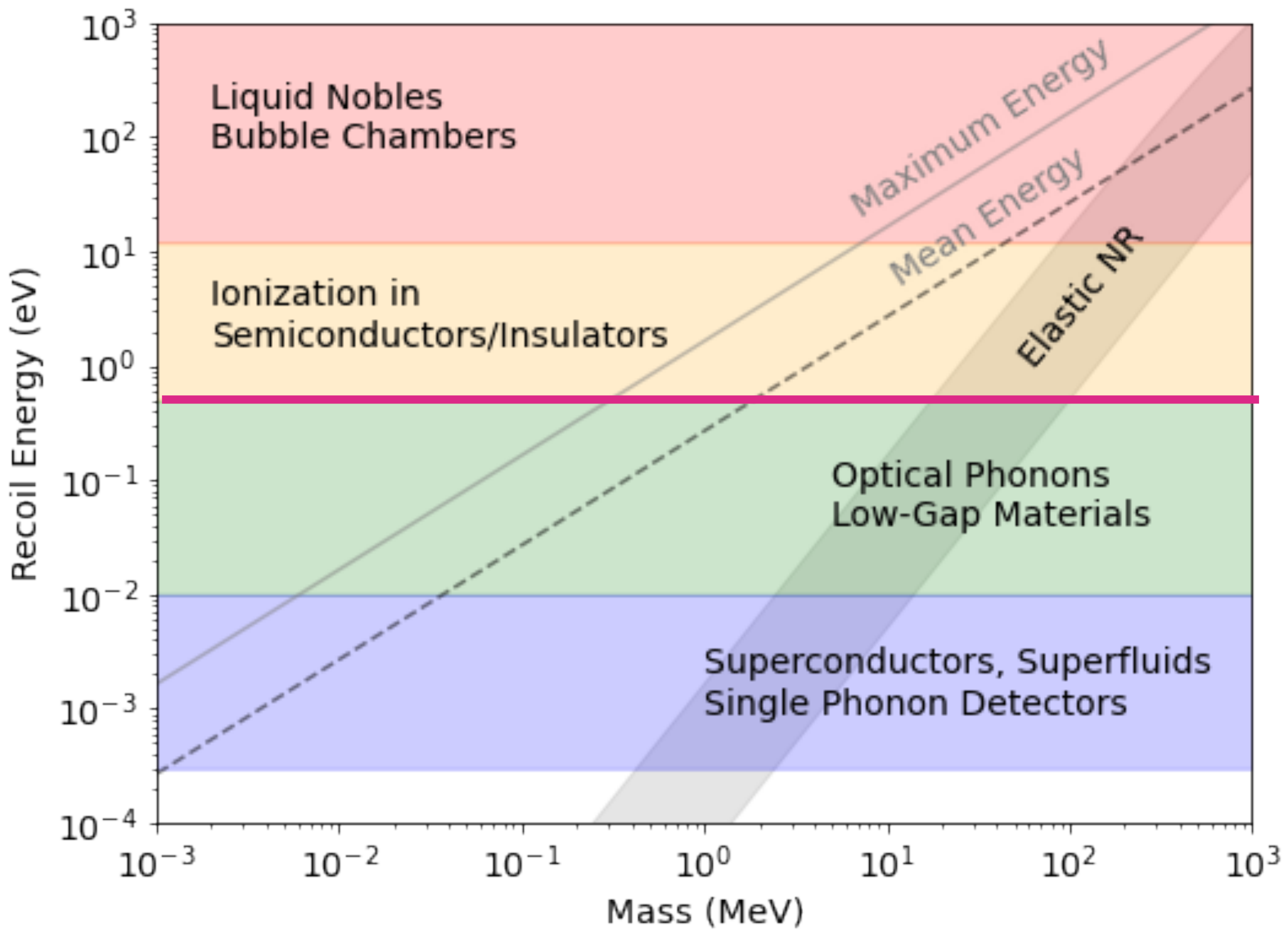
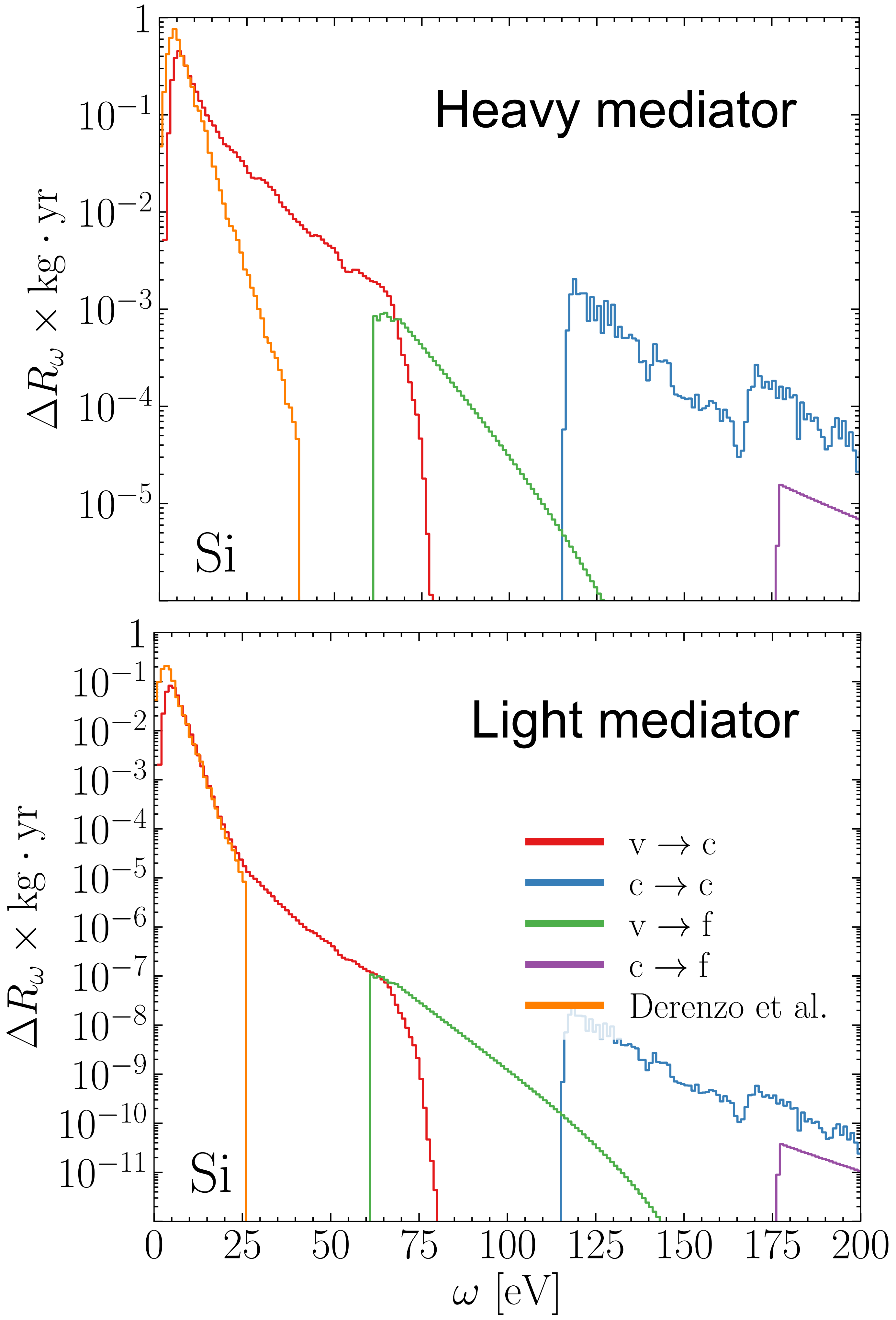
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.





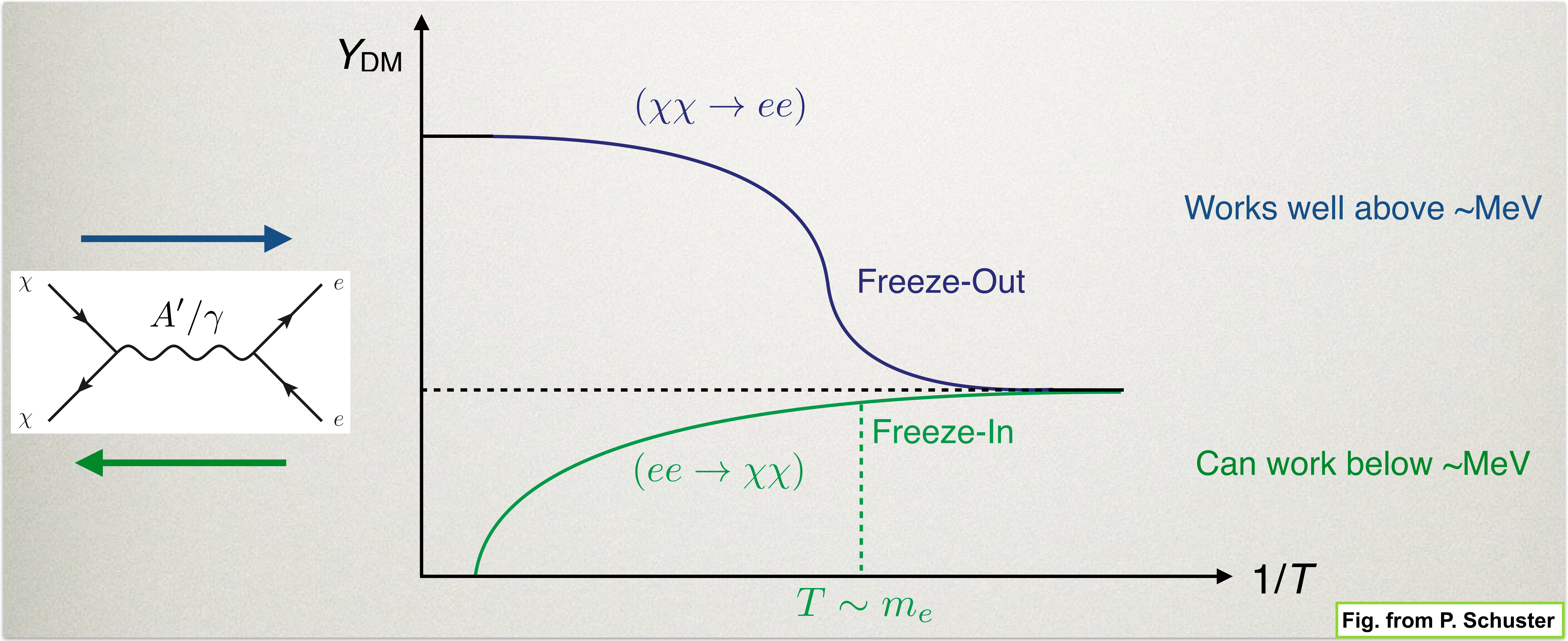
1 GeV PRD104(2021)095015



- 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.

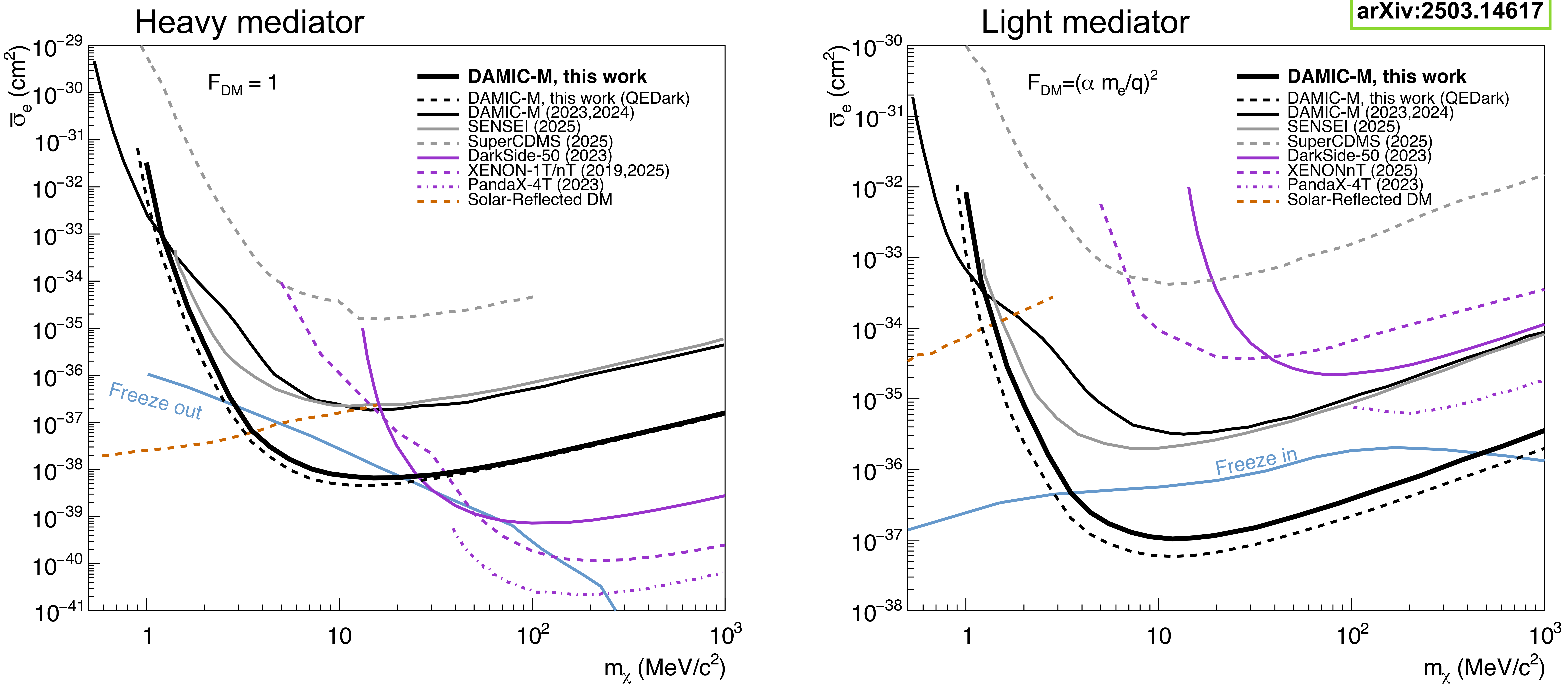
Freeze-out and -in

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



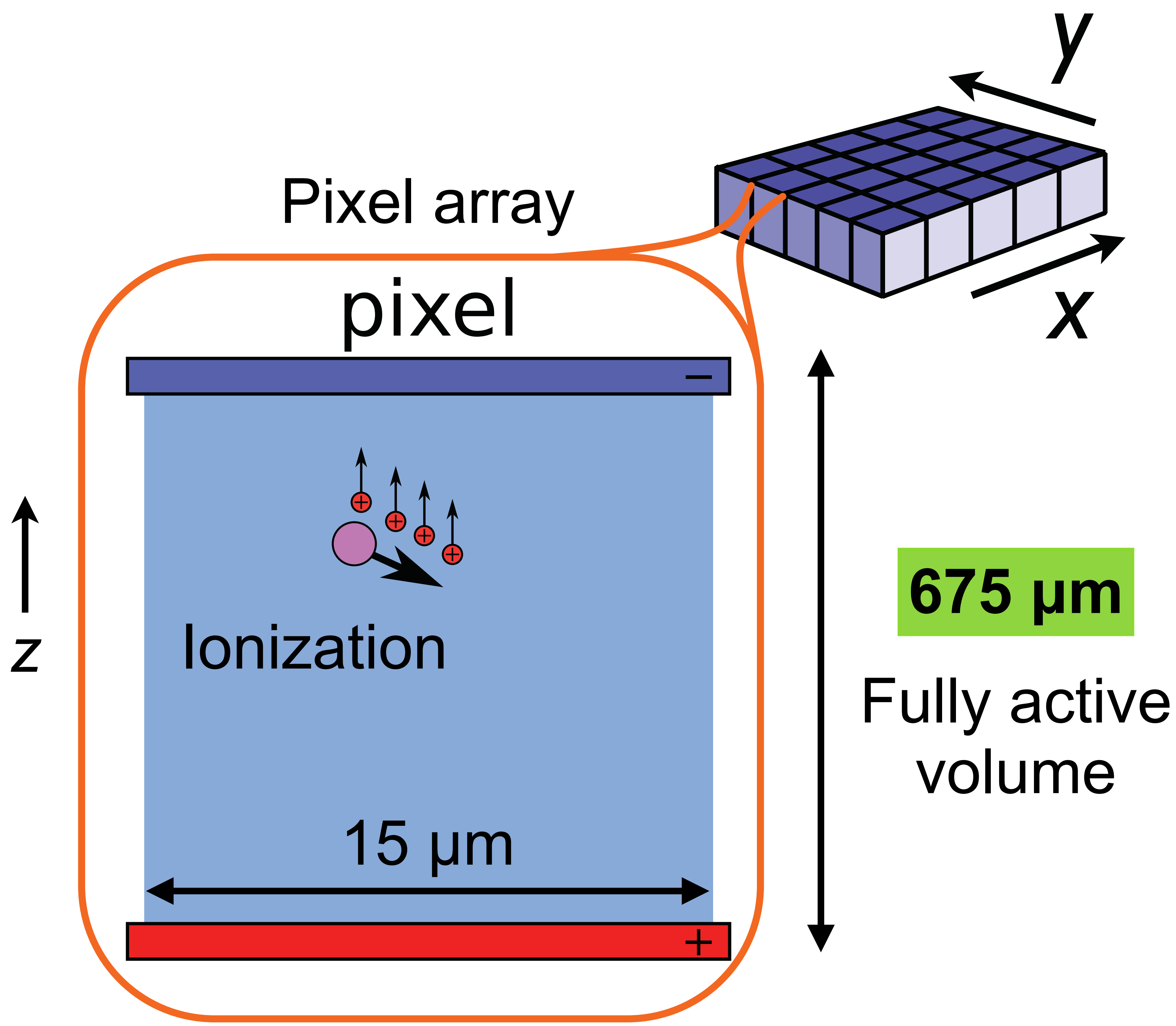
DM-e exclusion limits

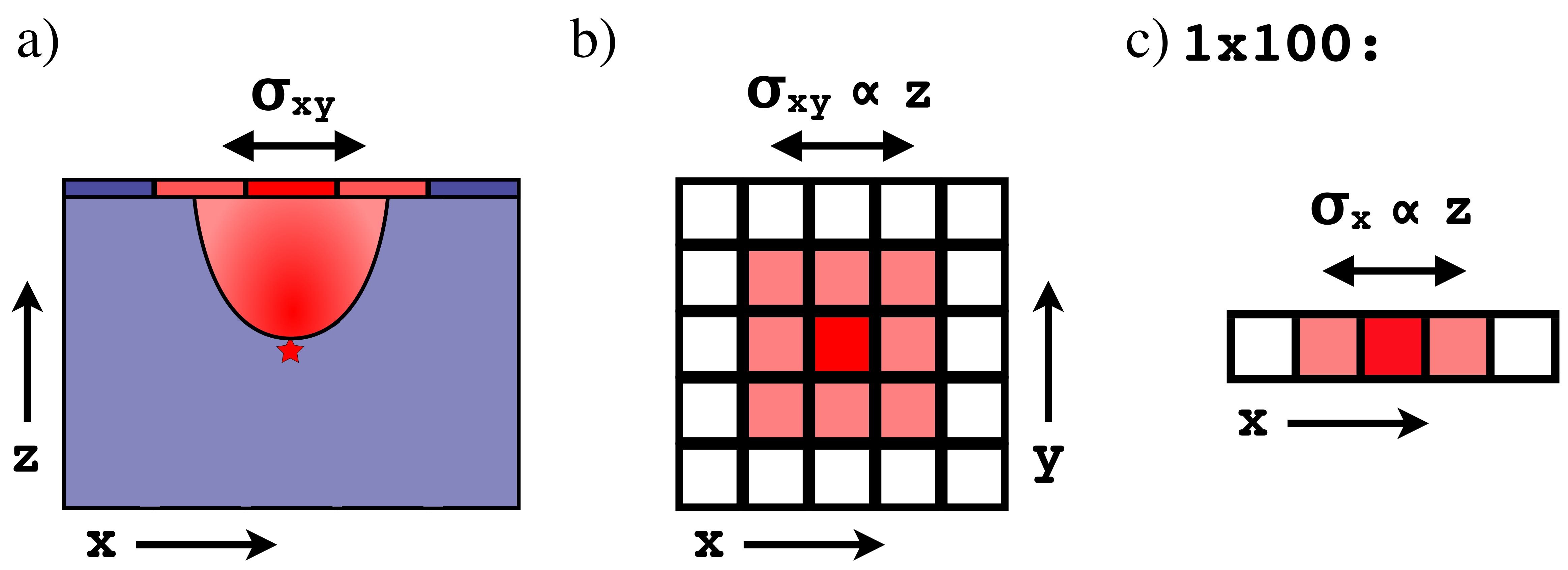
arXiv:2503.14617



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

Charge-coupled devices



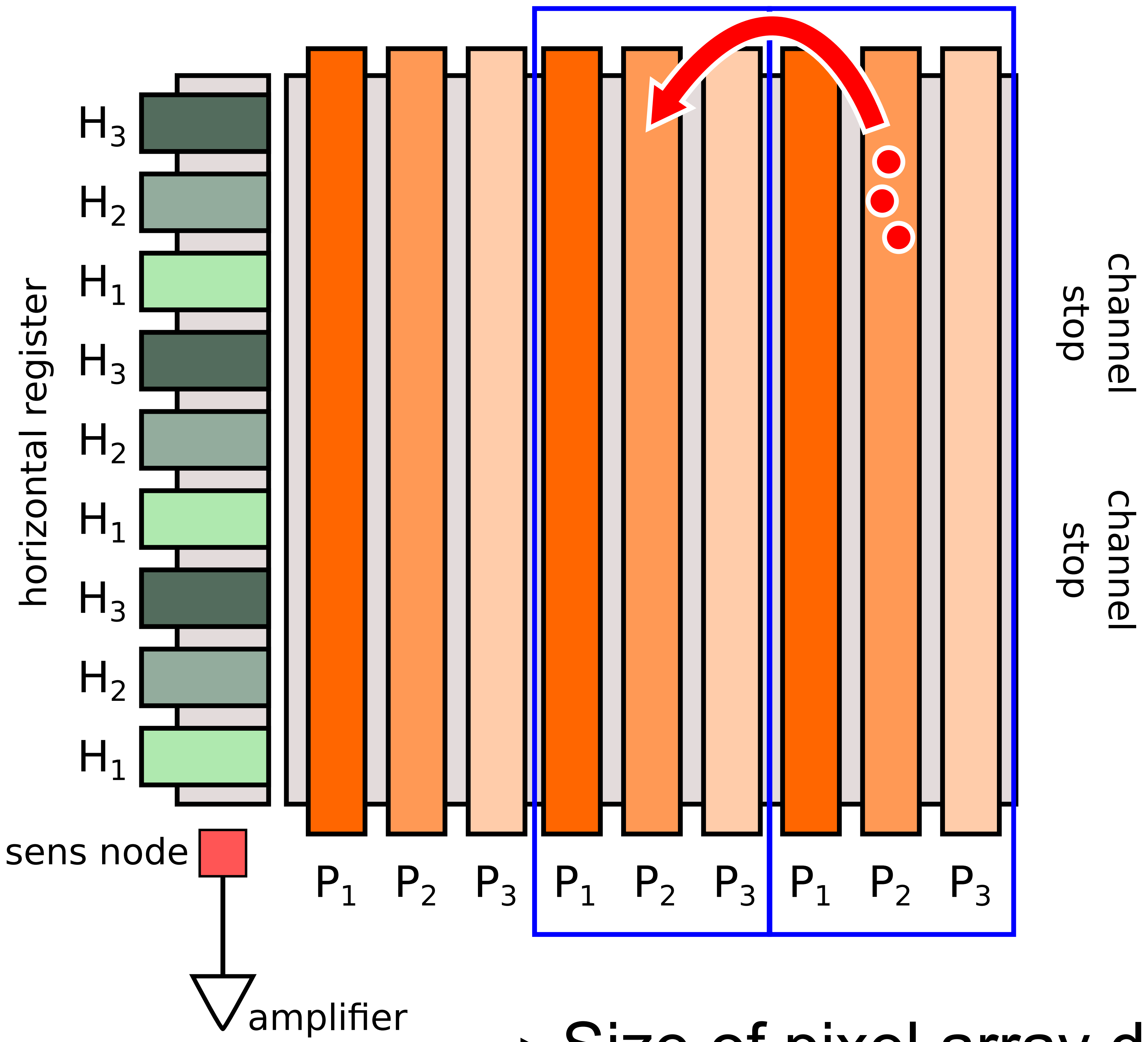


Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

- 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).

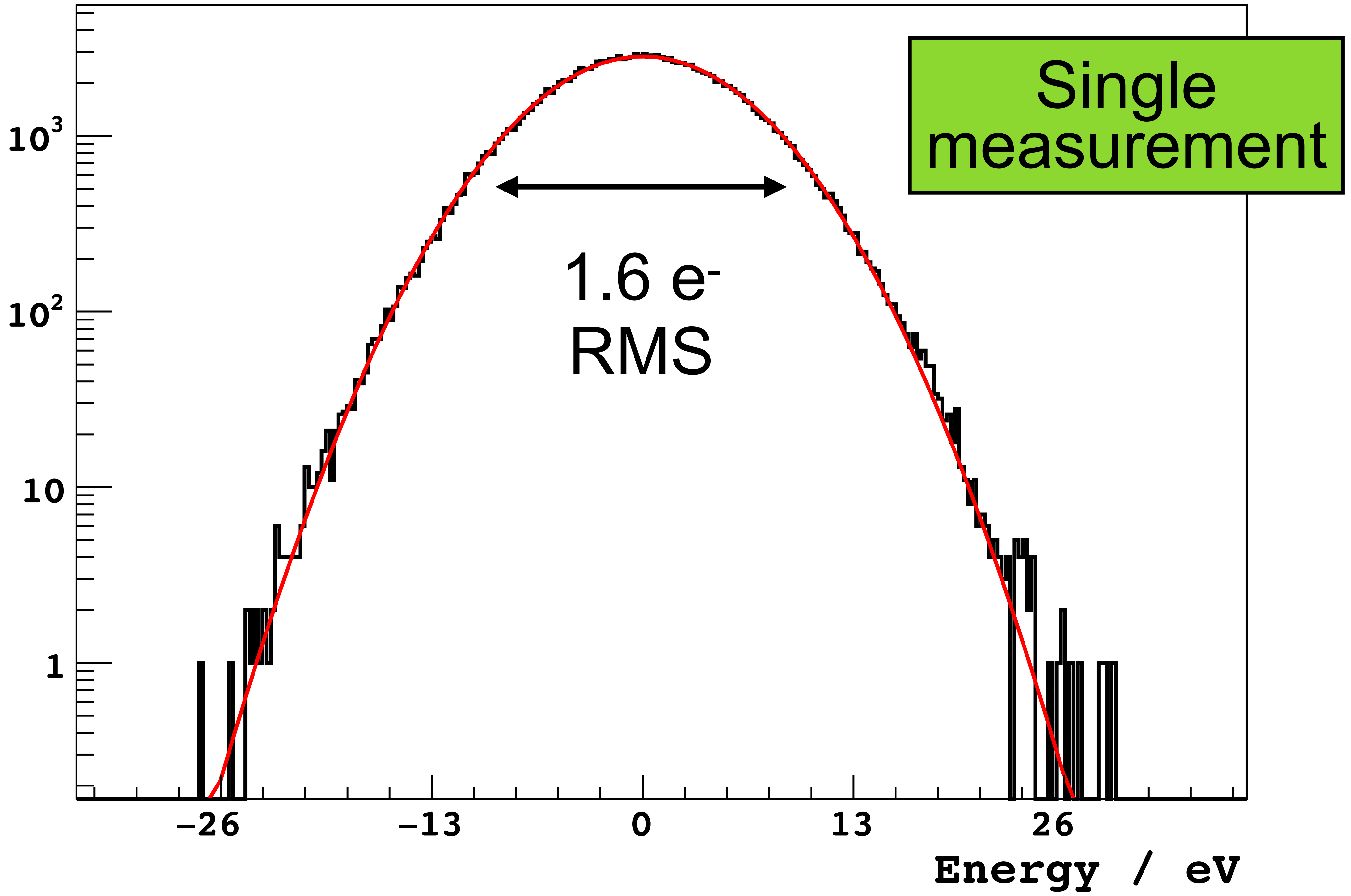
CCD readout

3x3 pixels CCD



$C \sim 10$ **fF**

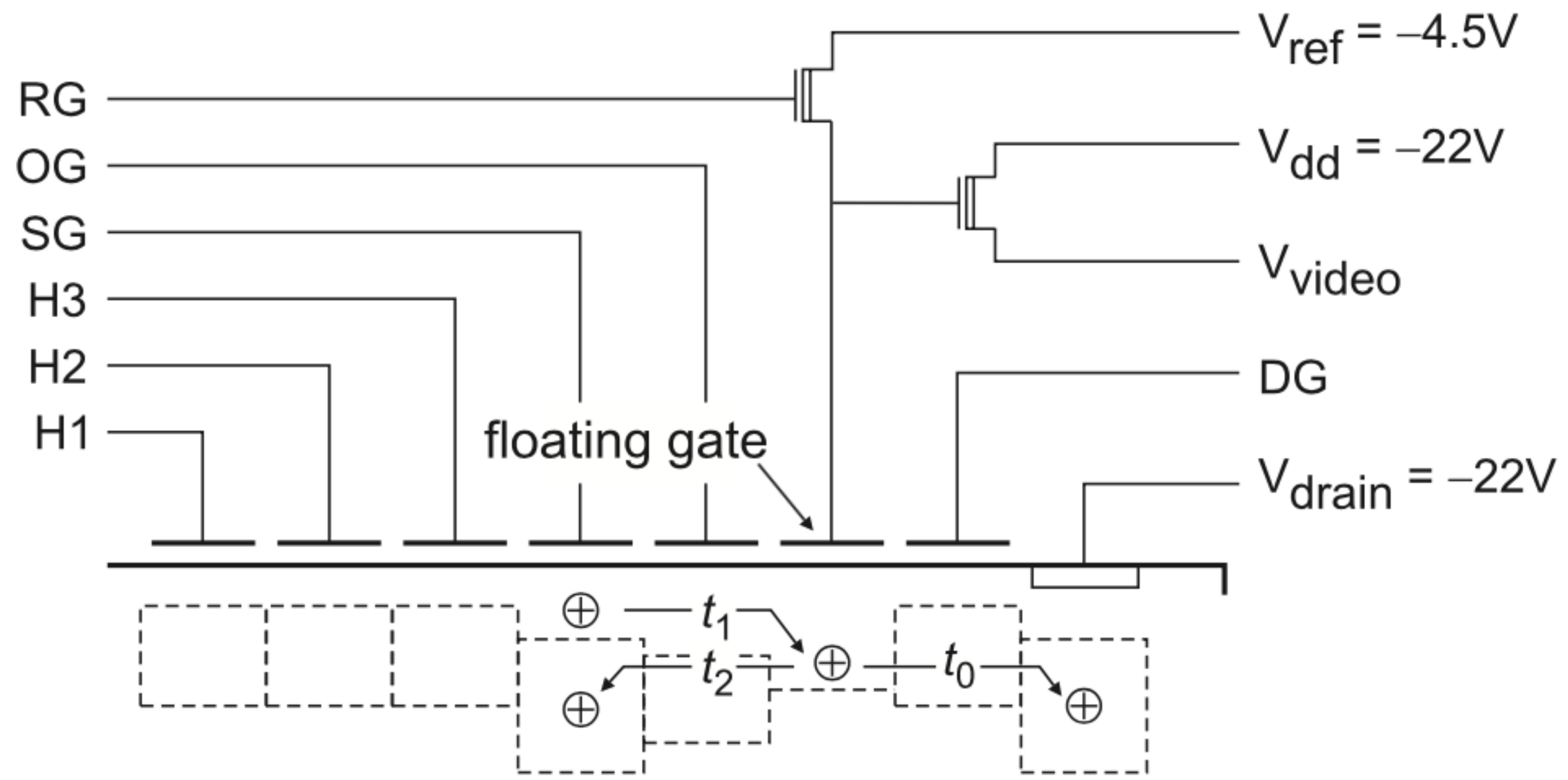
- Size of pixel array decoupled from capacitance of output node (device noise).



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

Skipper readout

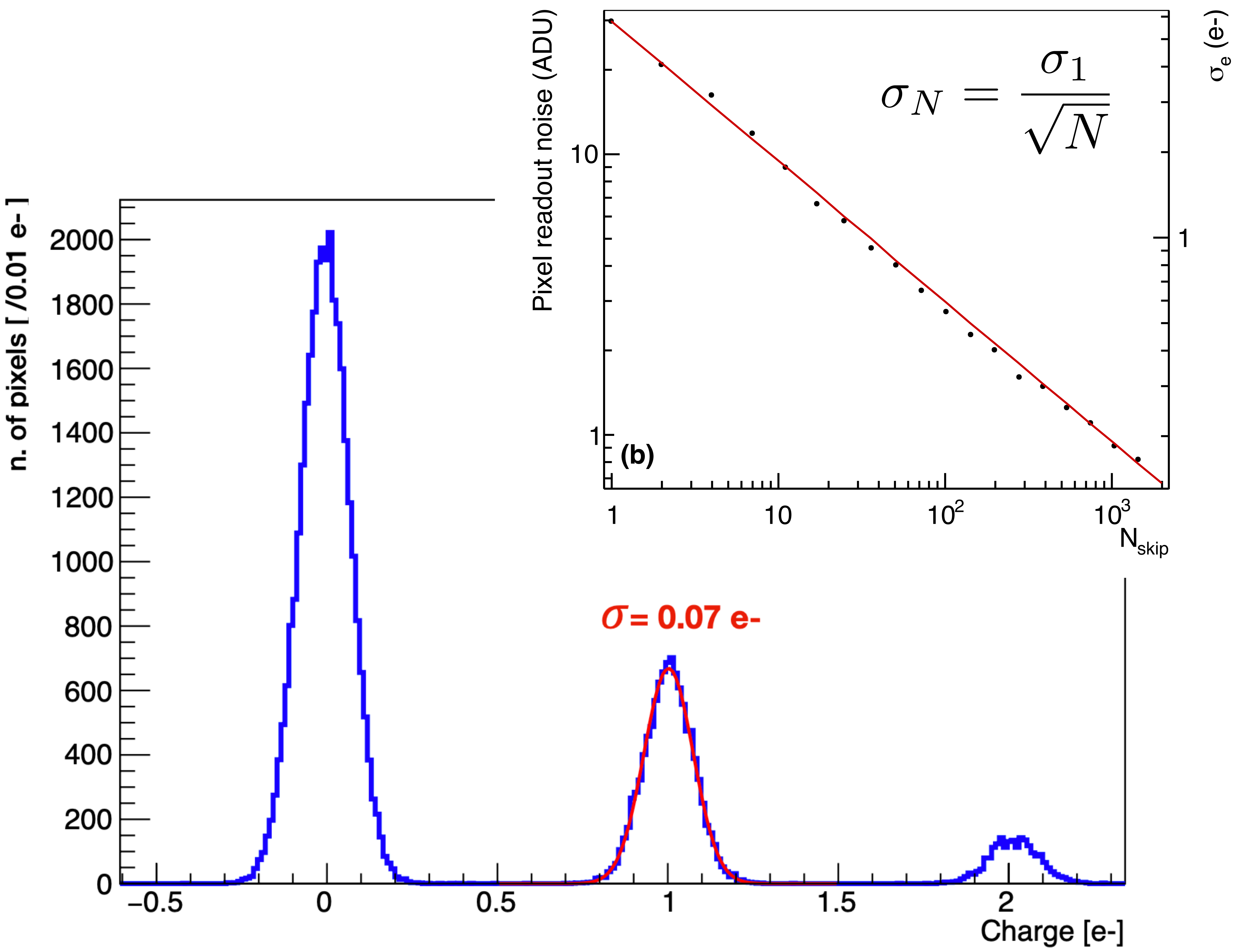
"Skipper" readout:
Perform *N* uncorrelated measurements of the same pixel.



⟷ move charge back and forth

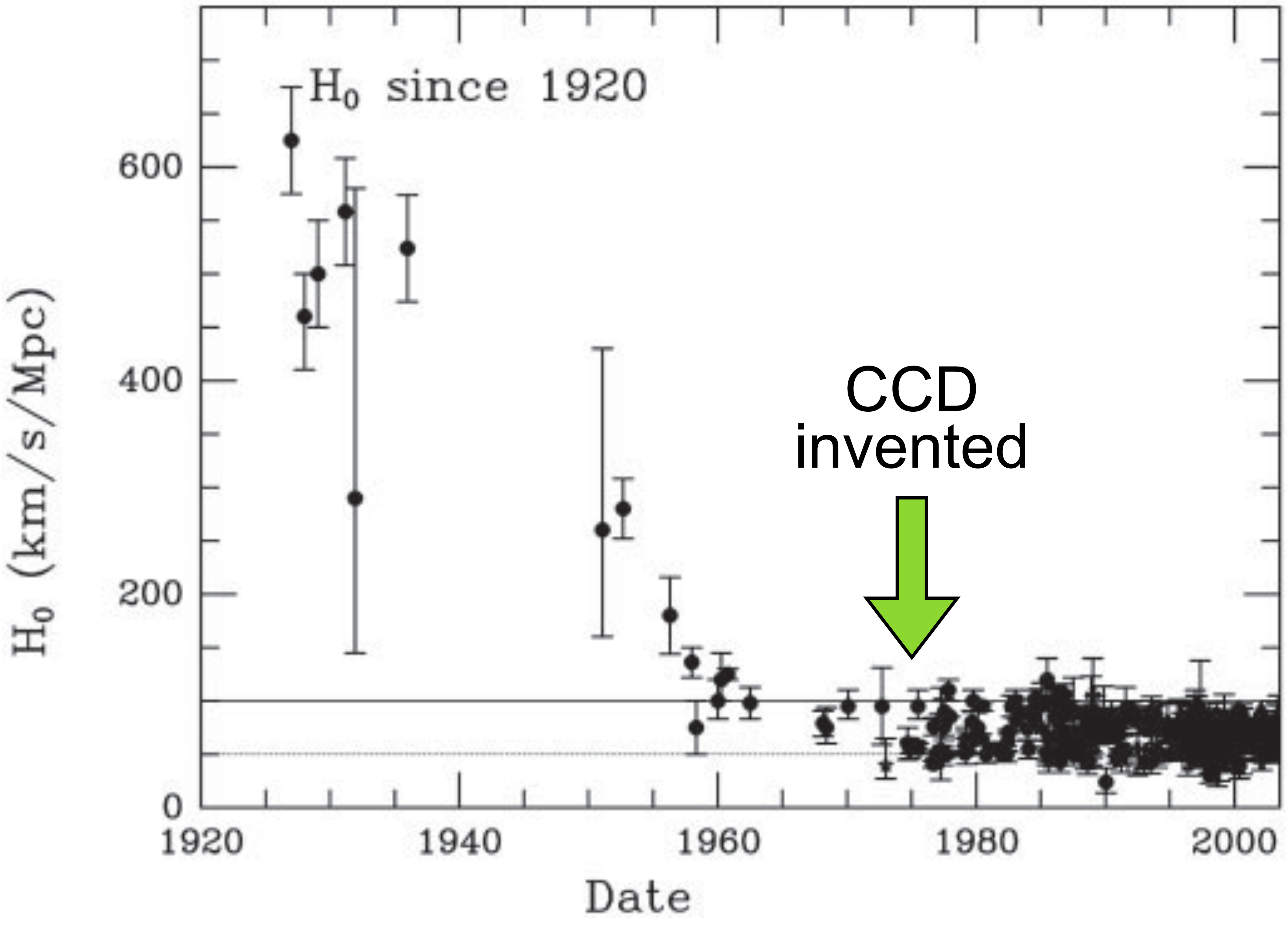
Introduced to particle physics in 2017

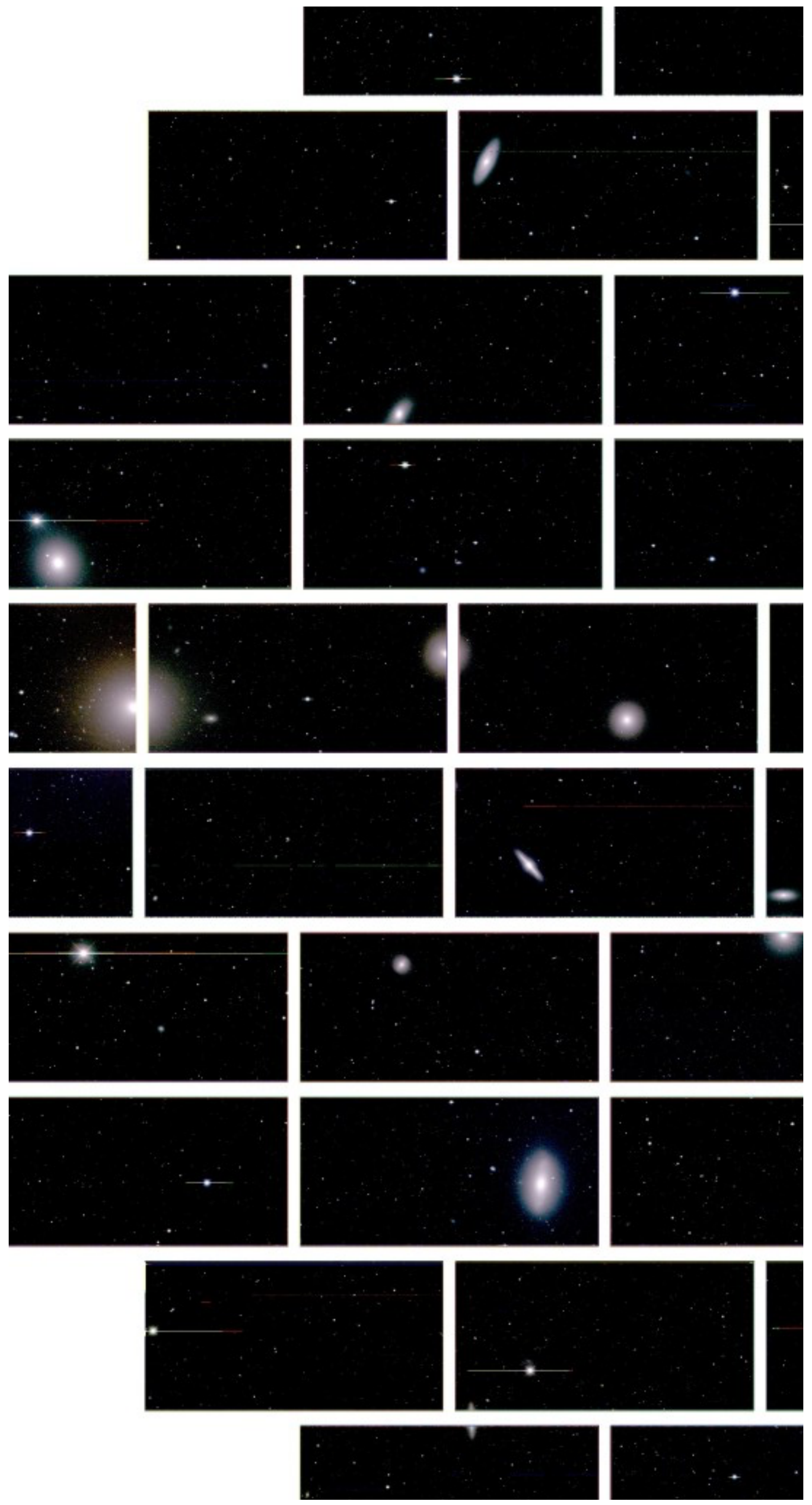
PRL119(2017)131802

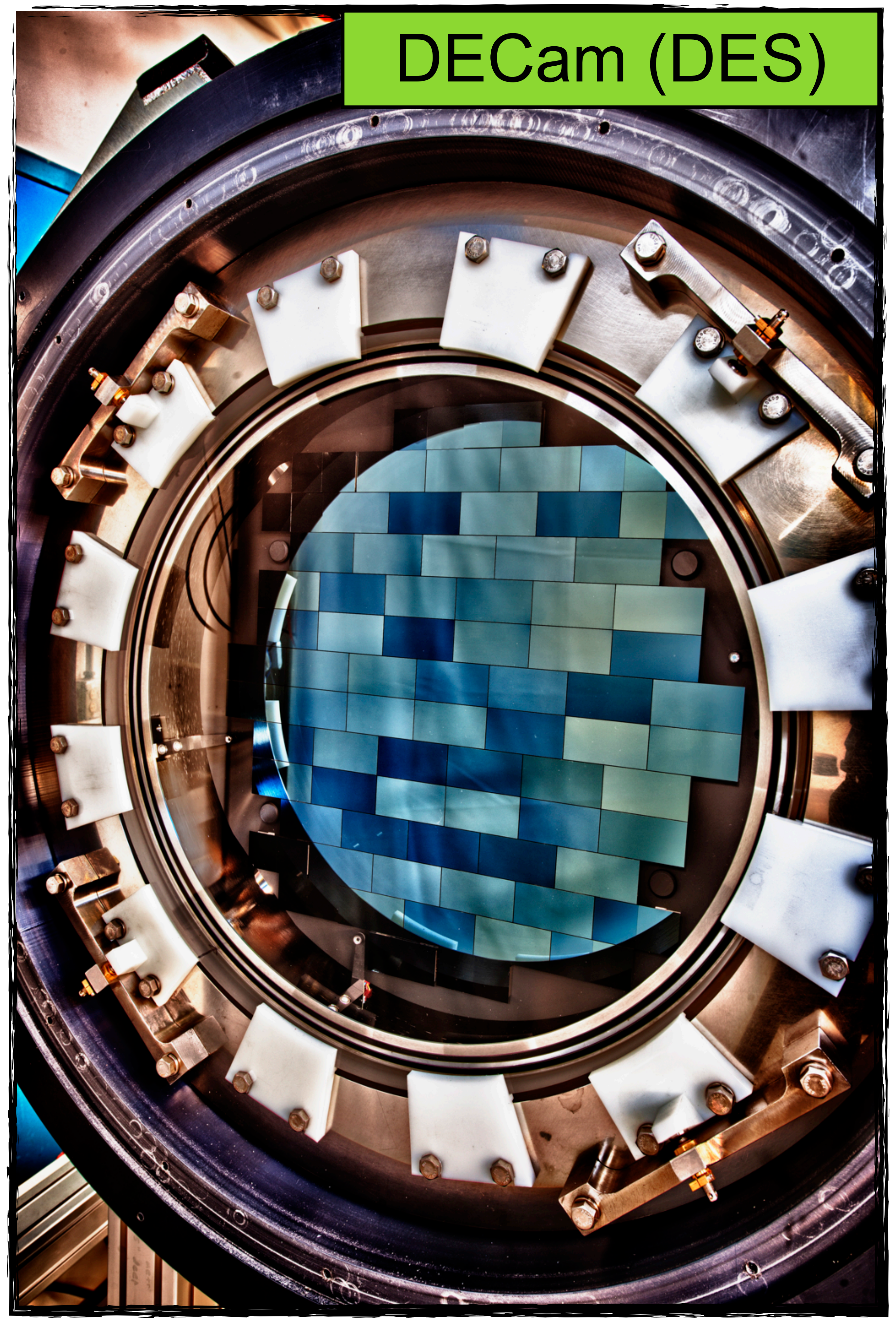


CCD: digital imaging

Boyle and Smith (inventors of the CCD) won the **Nobel Prize** in **2009** for revolutionizing astronomy!





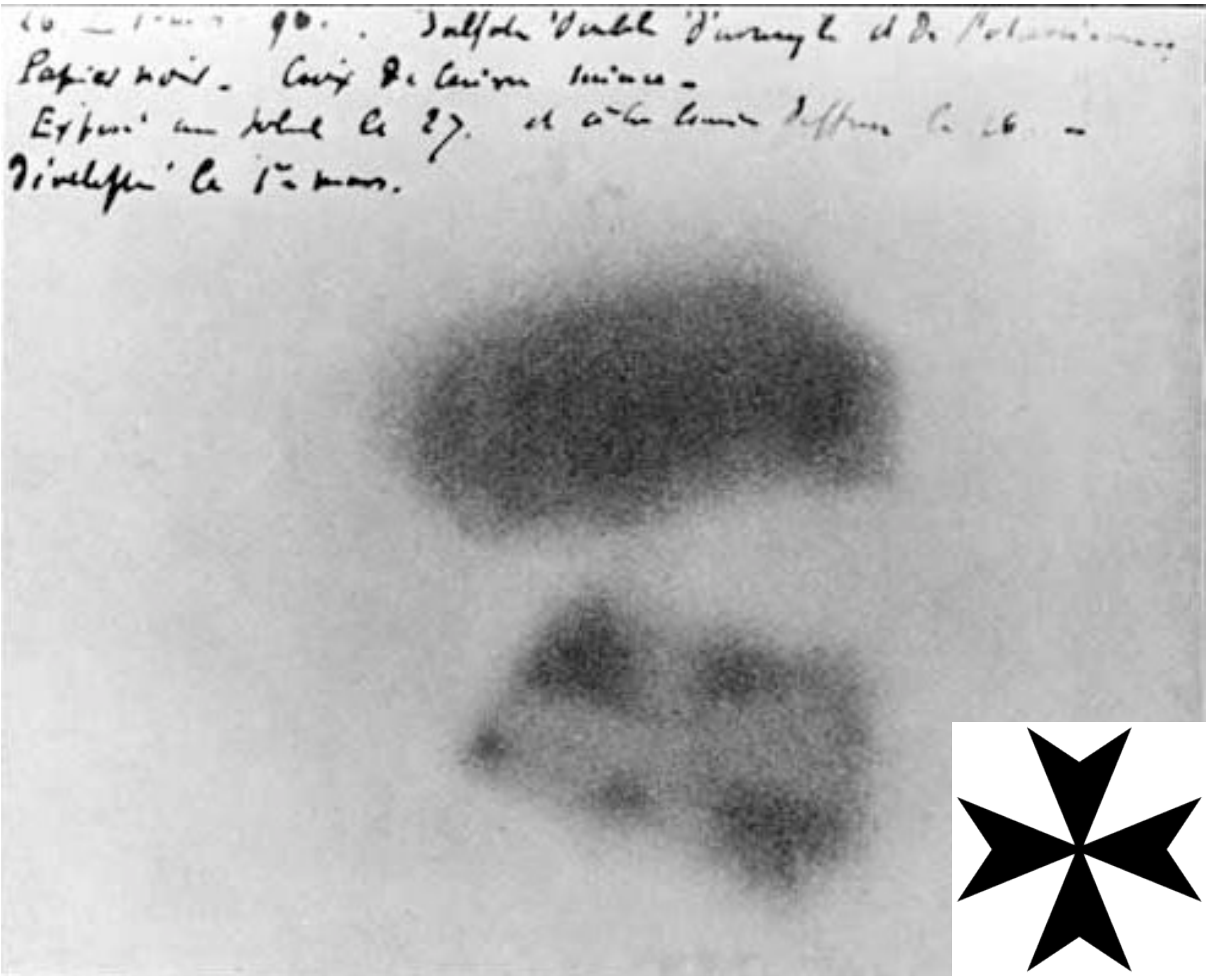


Particle detection

This is not the first time that imagers are used to detect ionizing particles…

In 1896 Becquerel left some uranium salt next to a photographic plate in a dark drawer. A few days later he saw an image on a plate.

The discovery of radioactivity



Today we take photographs in the dark with modern digital imagers to search for dark matter!


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

Spatial resolution

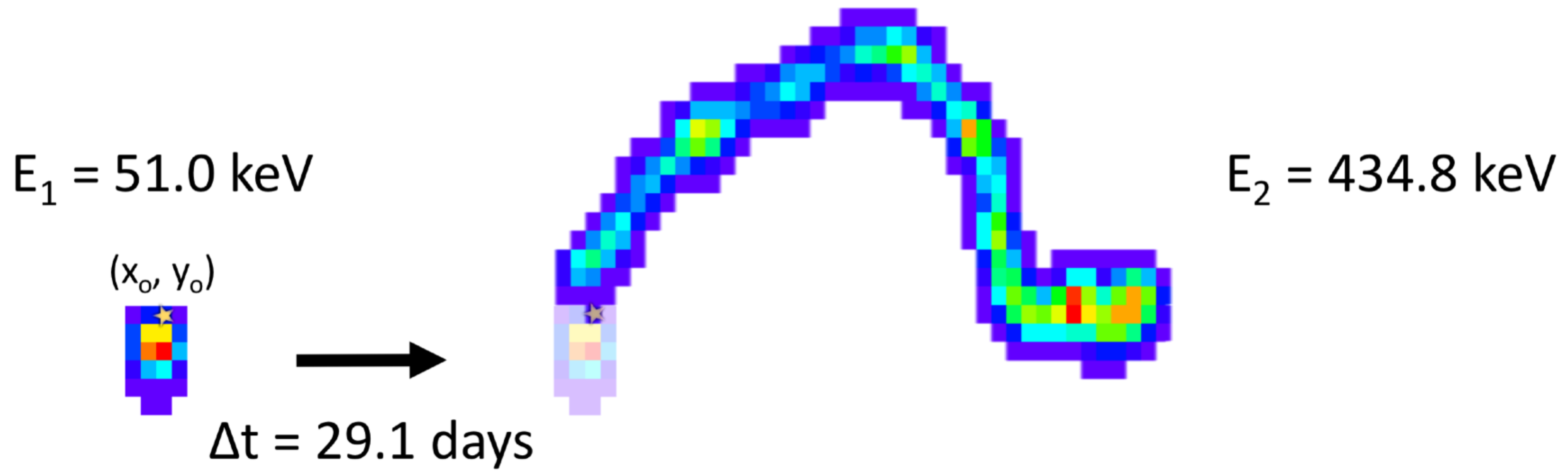
- Surface background rejection by depth (z) reconstruction, and classification (α, β, NR) by track topology (at high E>80 keV_{ee}).

- 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.

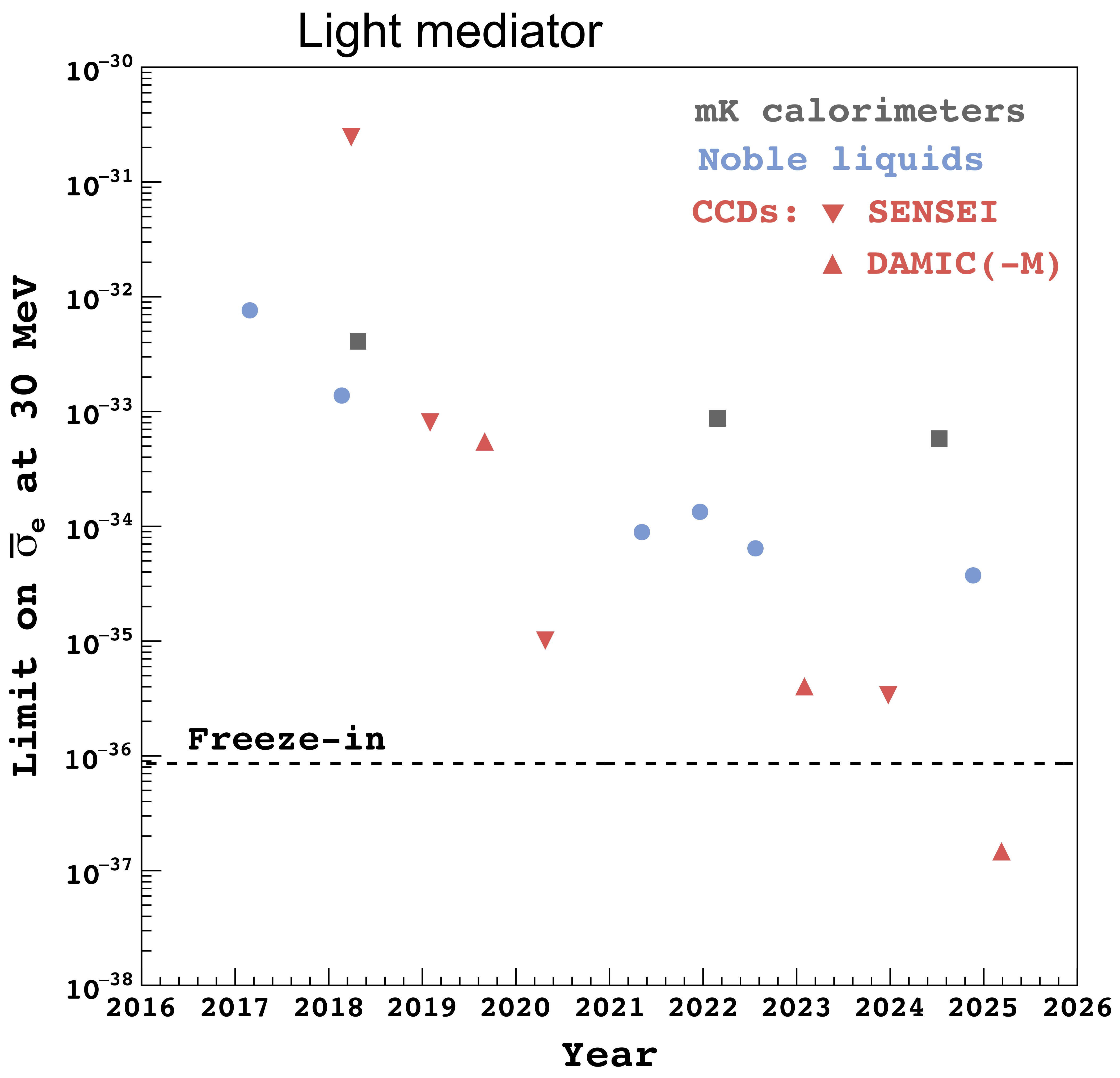


- Reject crystal defects “hot spots” that dominate device leakage current.

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

CCD timeline

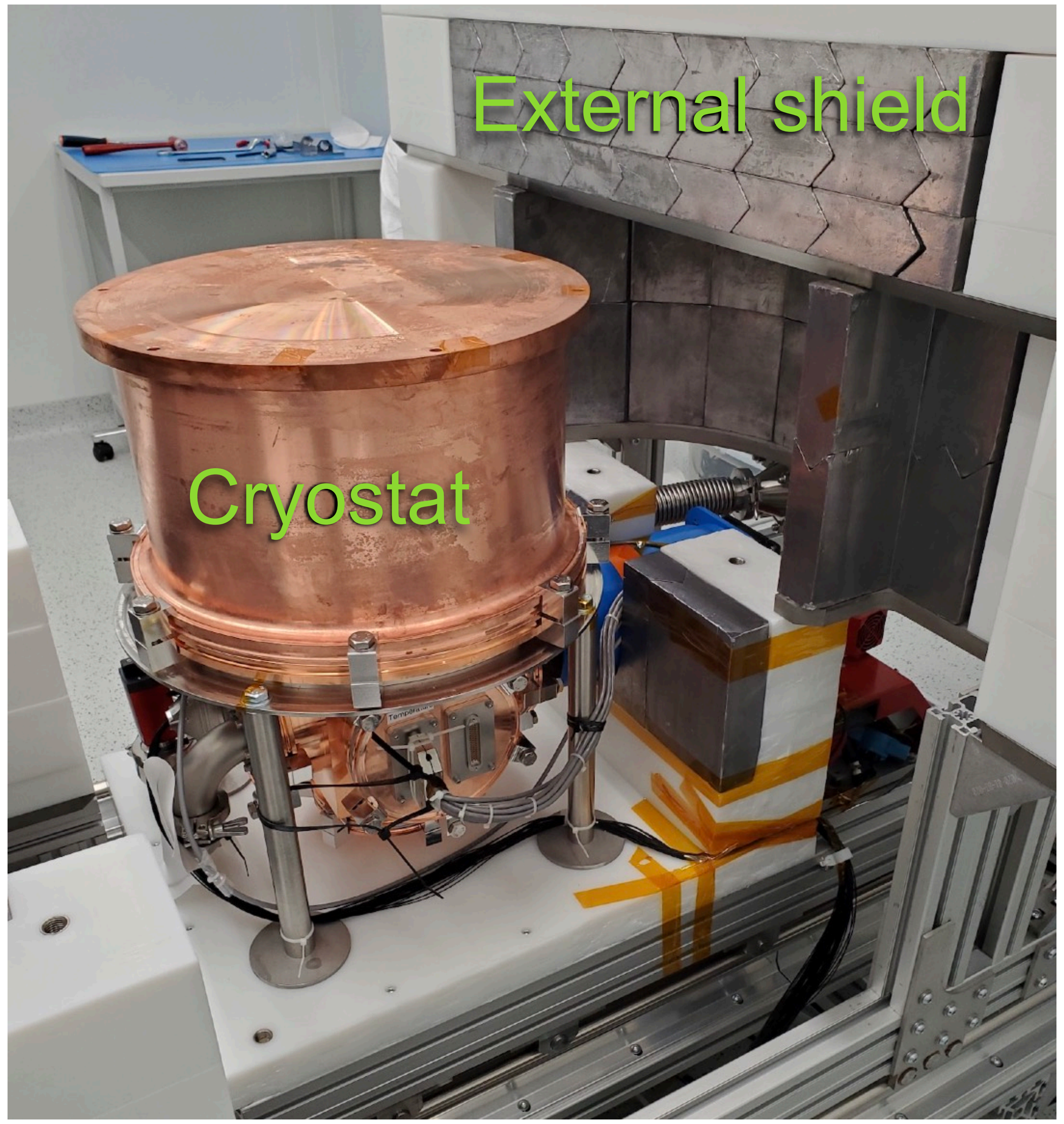
- **2012–2017:** we built DAMIC at SNOLAB, the first low background CCD array for DM searches.
- **2017:** DAMIC releases first DM search results from ~eV ionization signals.
- **2017:** "Skipper" CCDs are introduced for 10x improvement in noise to provide increased sensitivity for DM-e searches.
- Two 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!

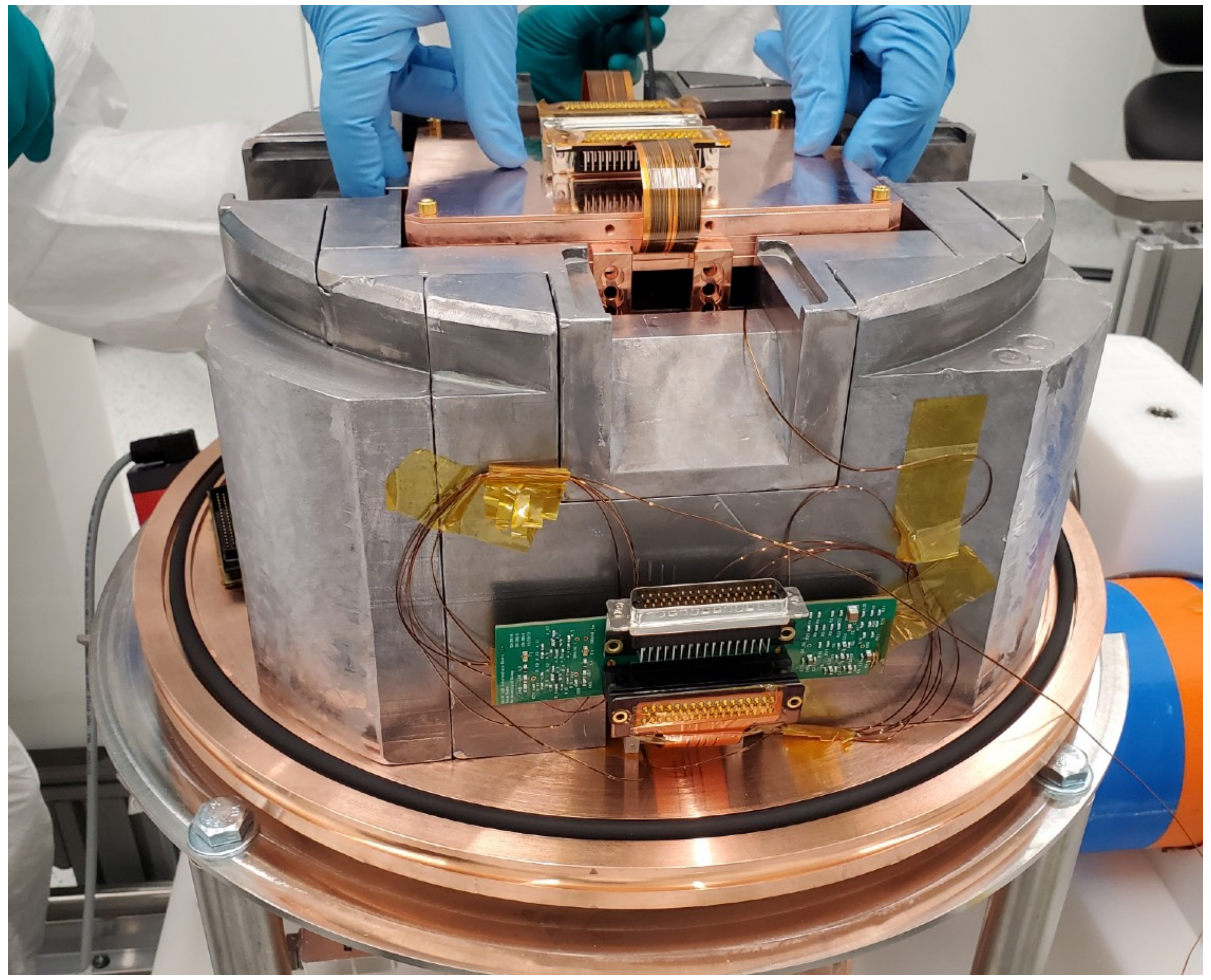


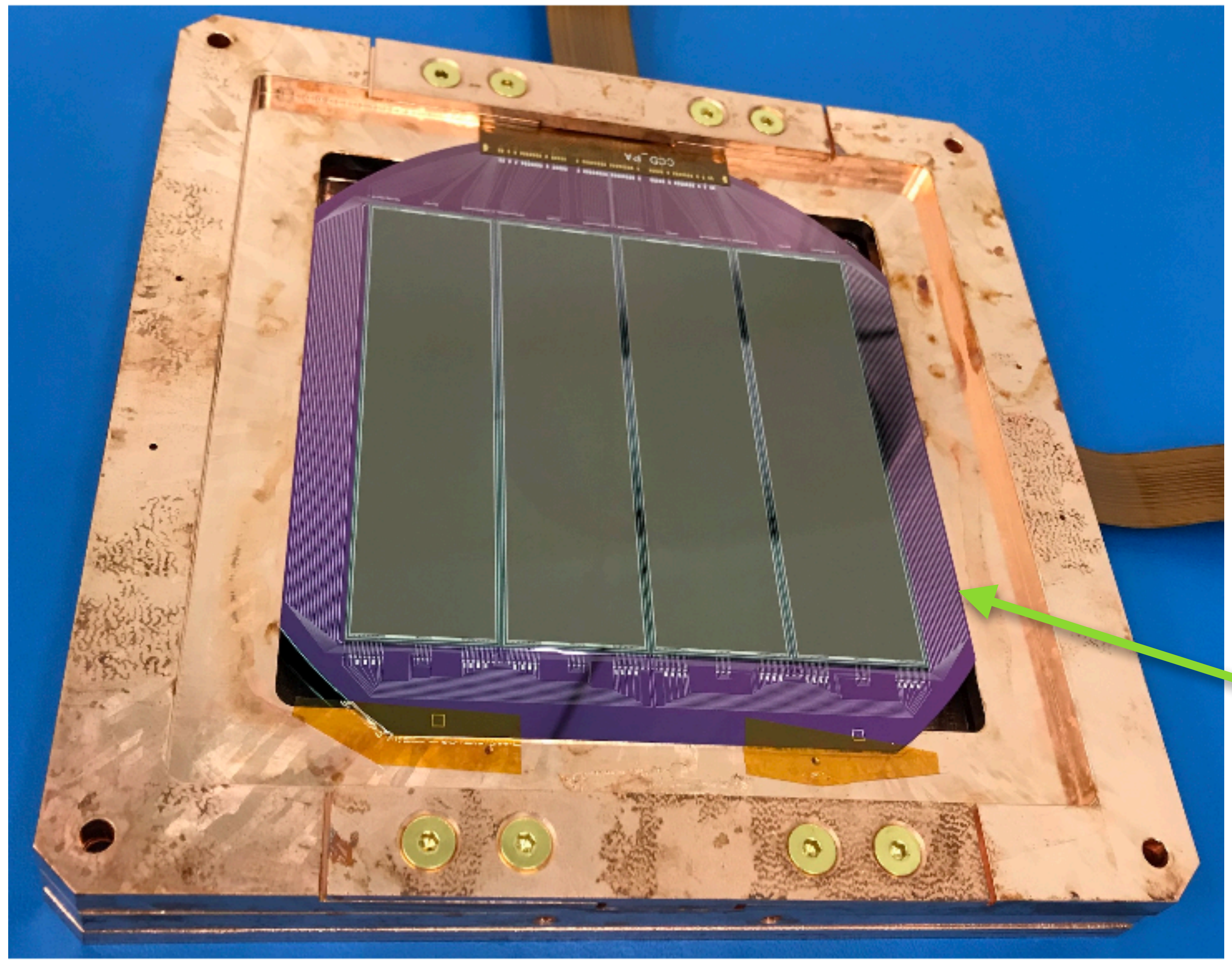
DAMIC-M

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**



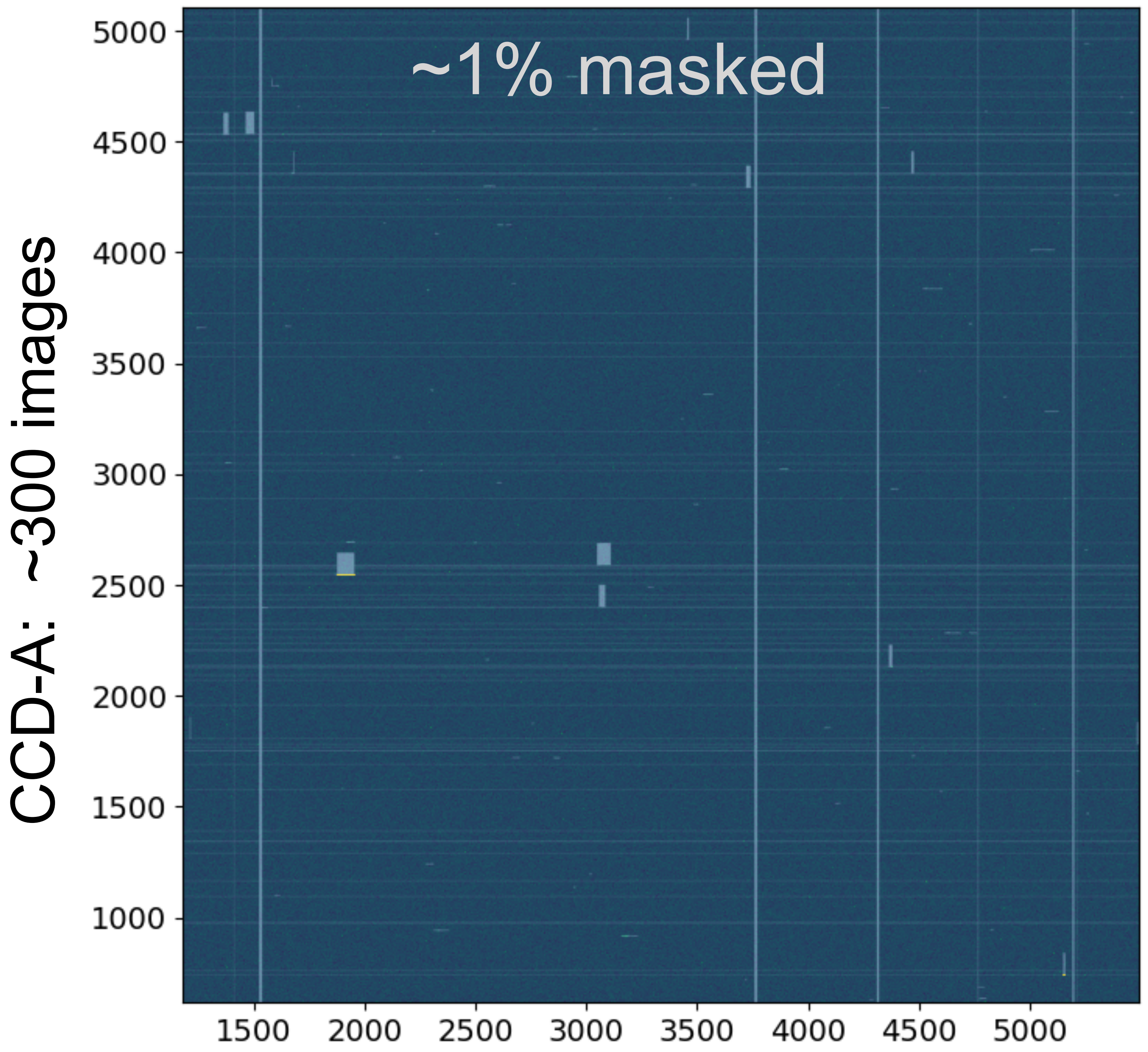




Prototype CCD module packaged and tested at UW

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)

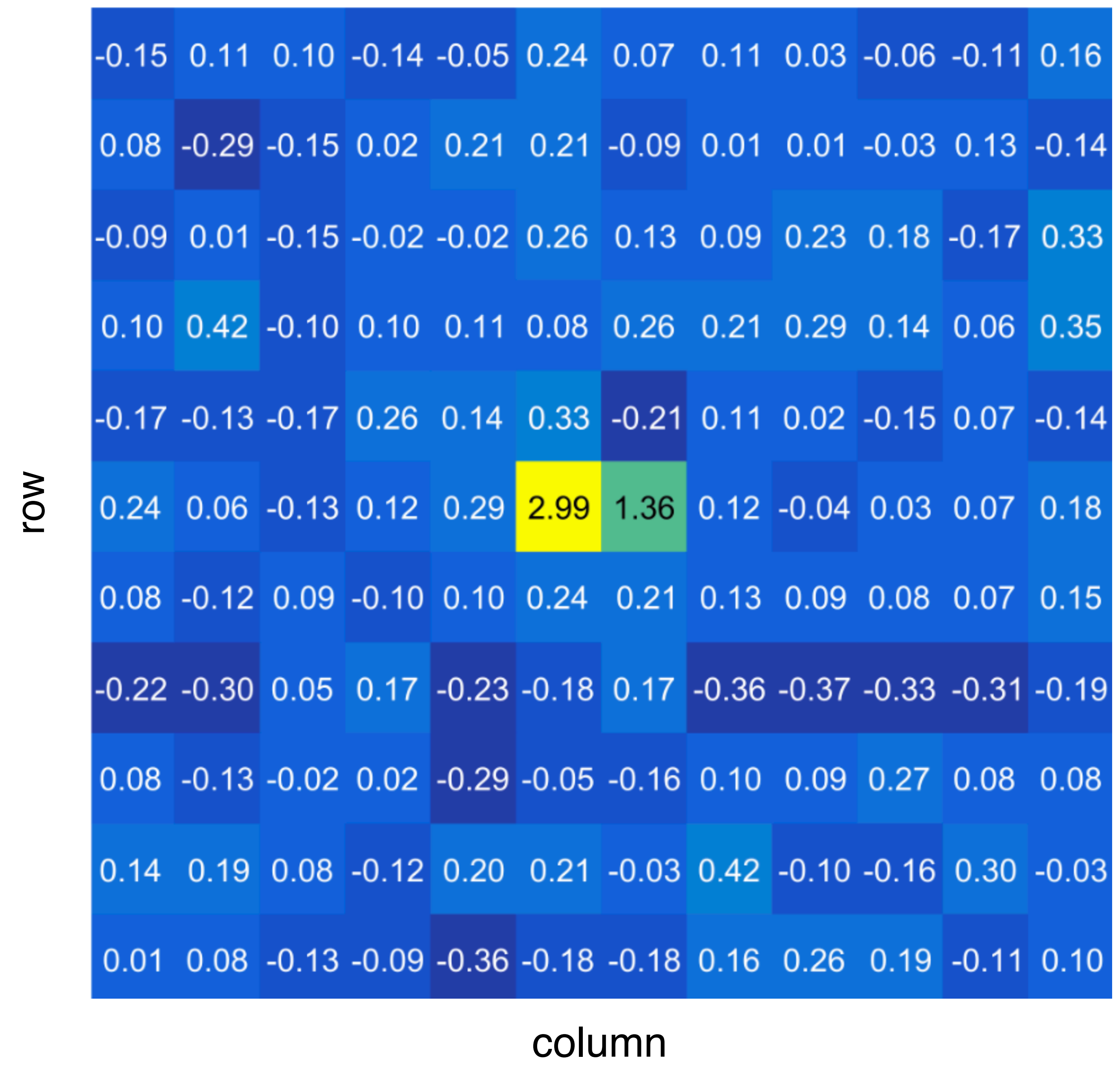
Backgrounds

- 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 with toy MC

	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

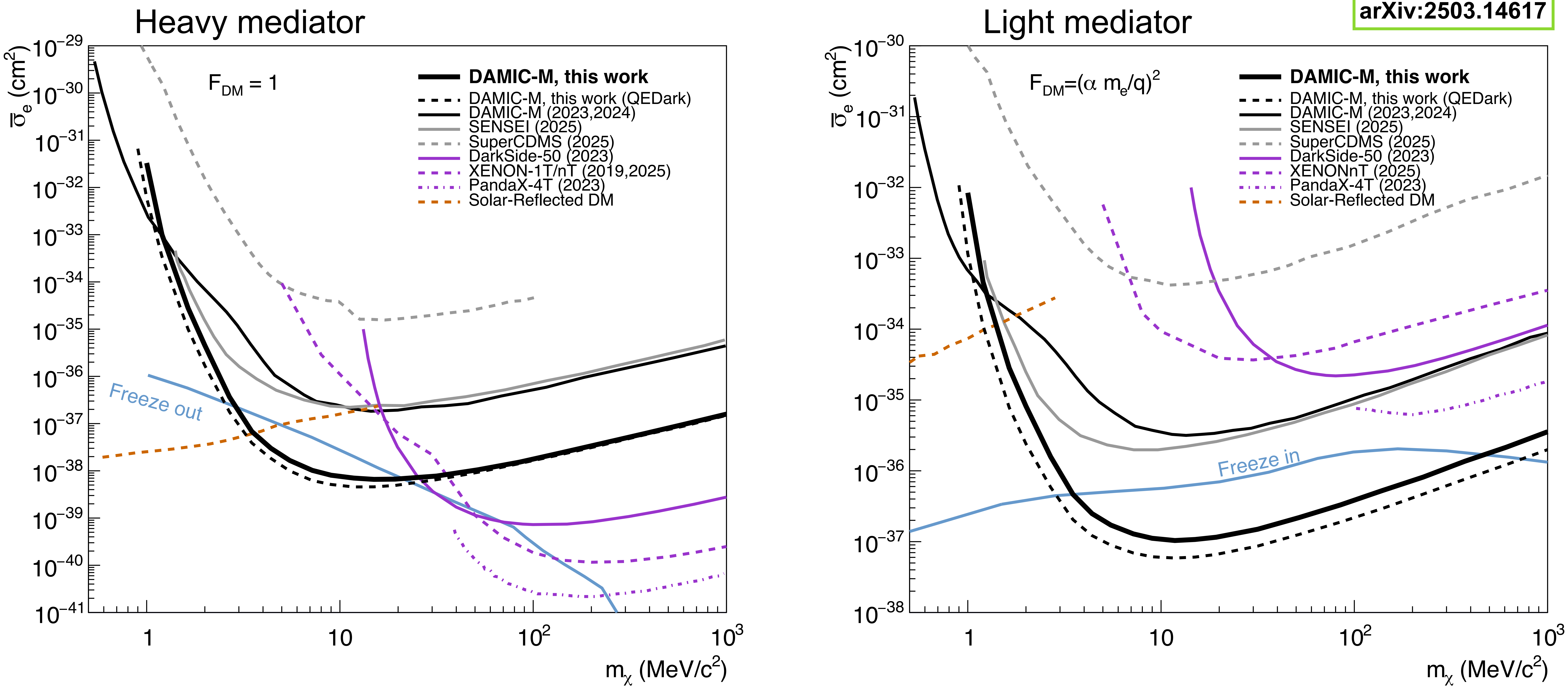
TABLE I. The number of candidates D_p in the D2 data set, and the number expected from backgrounds due to random coincidences, B_p^{rc}, and to radioactive decays, B_p^{rad}.

{31} candidate



DM-e exclusion limits

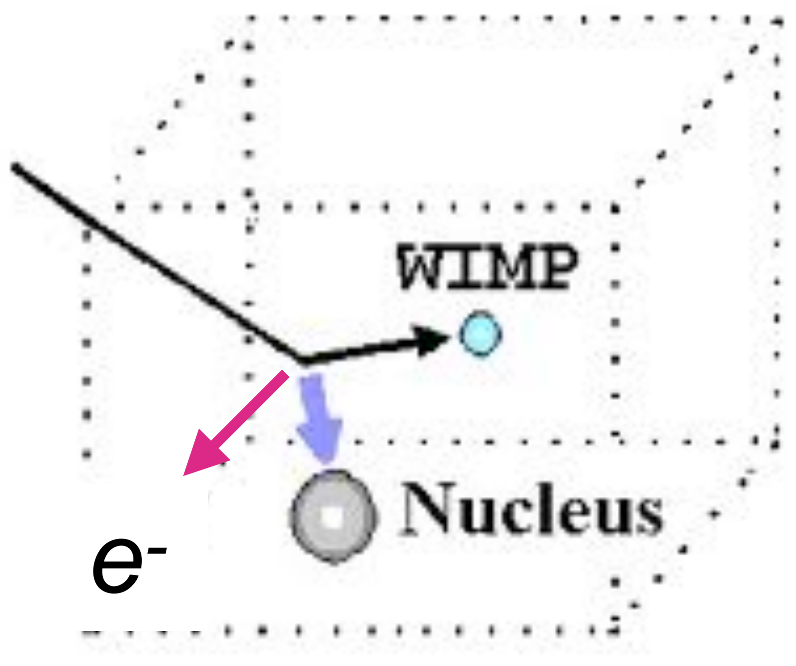
arXiv:2503.14617



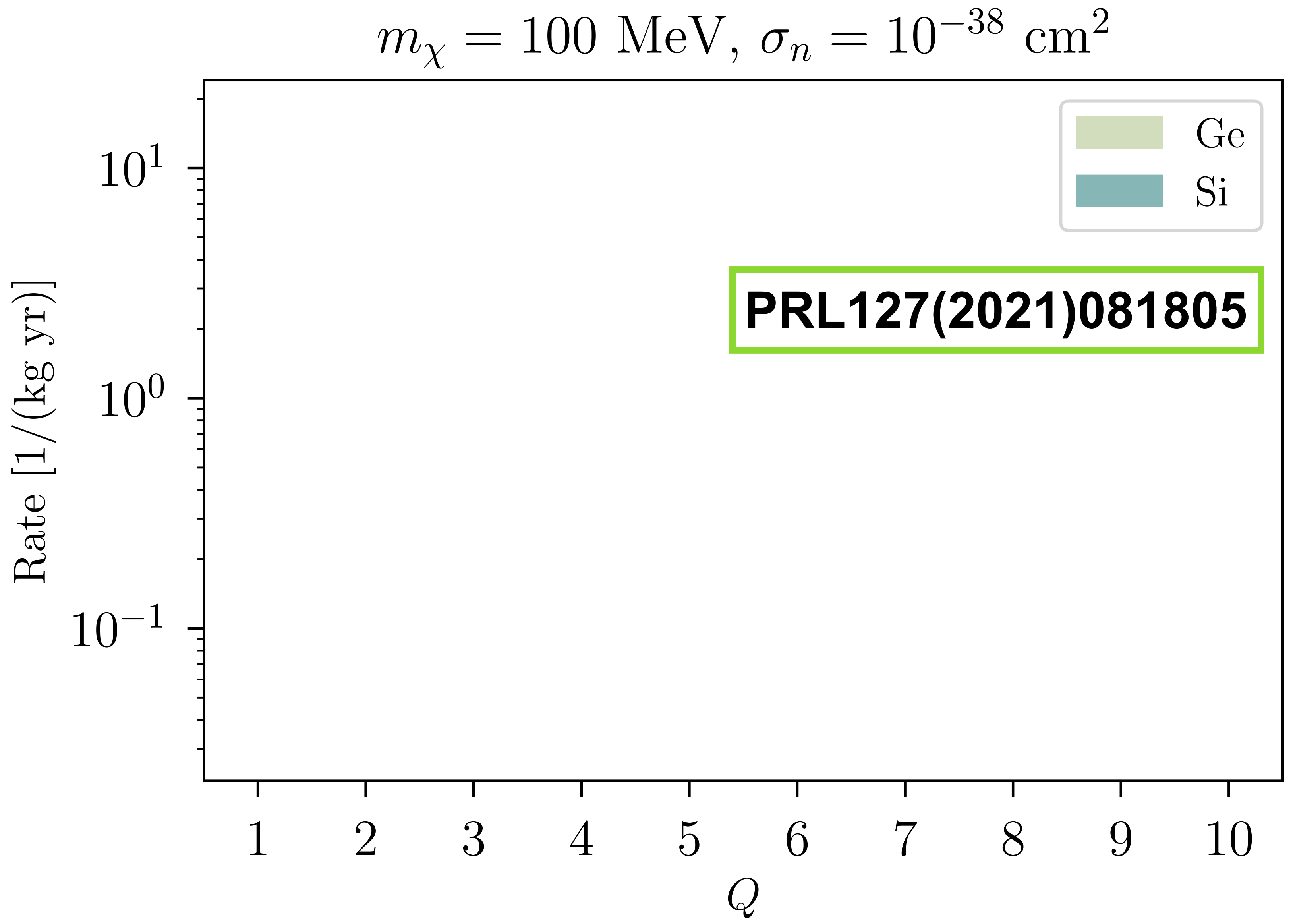
▸ **DAMIC-M probes benchmark hidden-sector dark-matter models!**

Other e-recoils

Three-body final state:



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



Bosonic DM absorption:

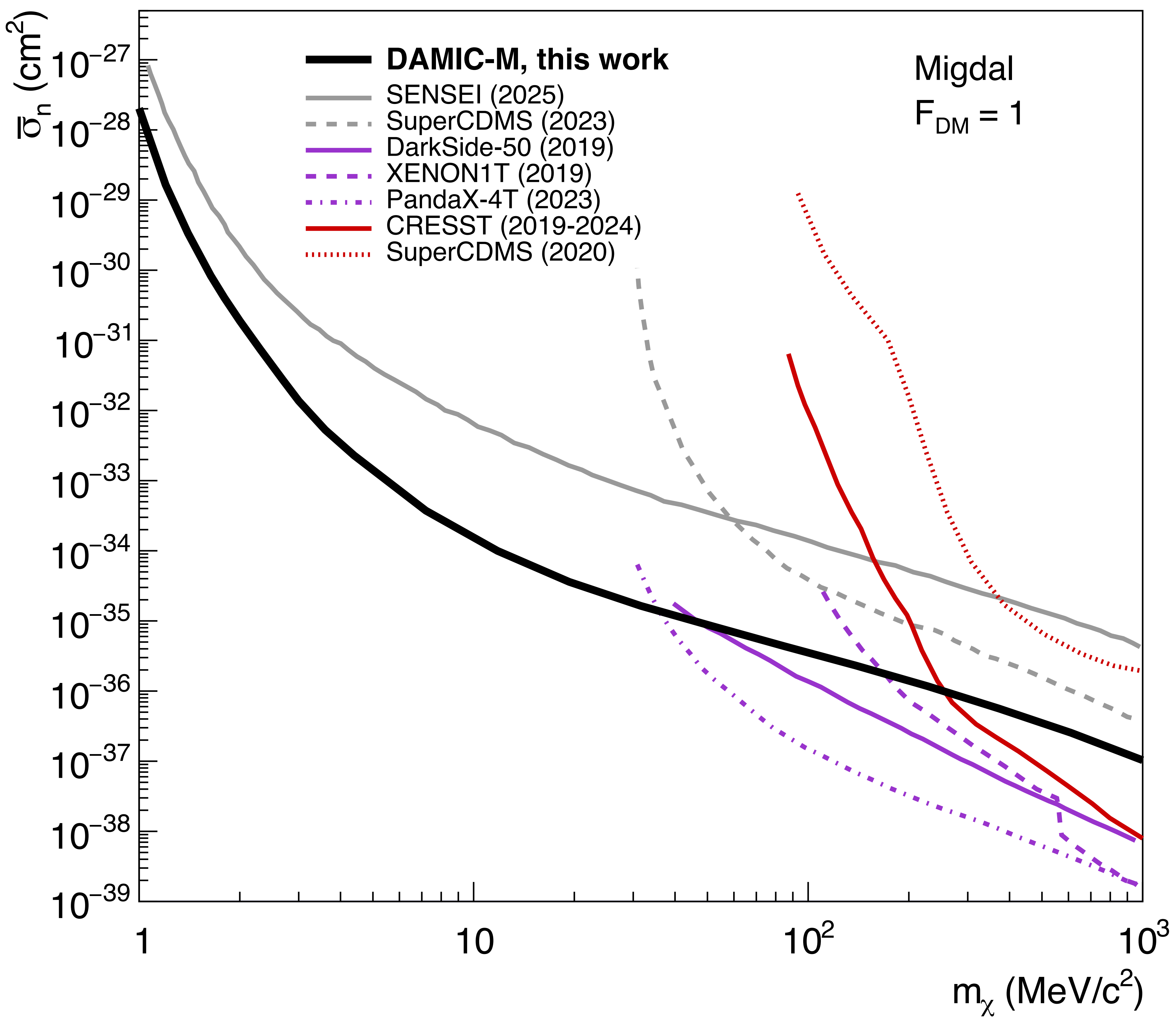
- DM particle is a boson that couples to the electron, e.g., a “dark” or “hidden” photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

➡ spectral line search

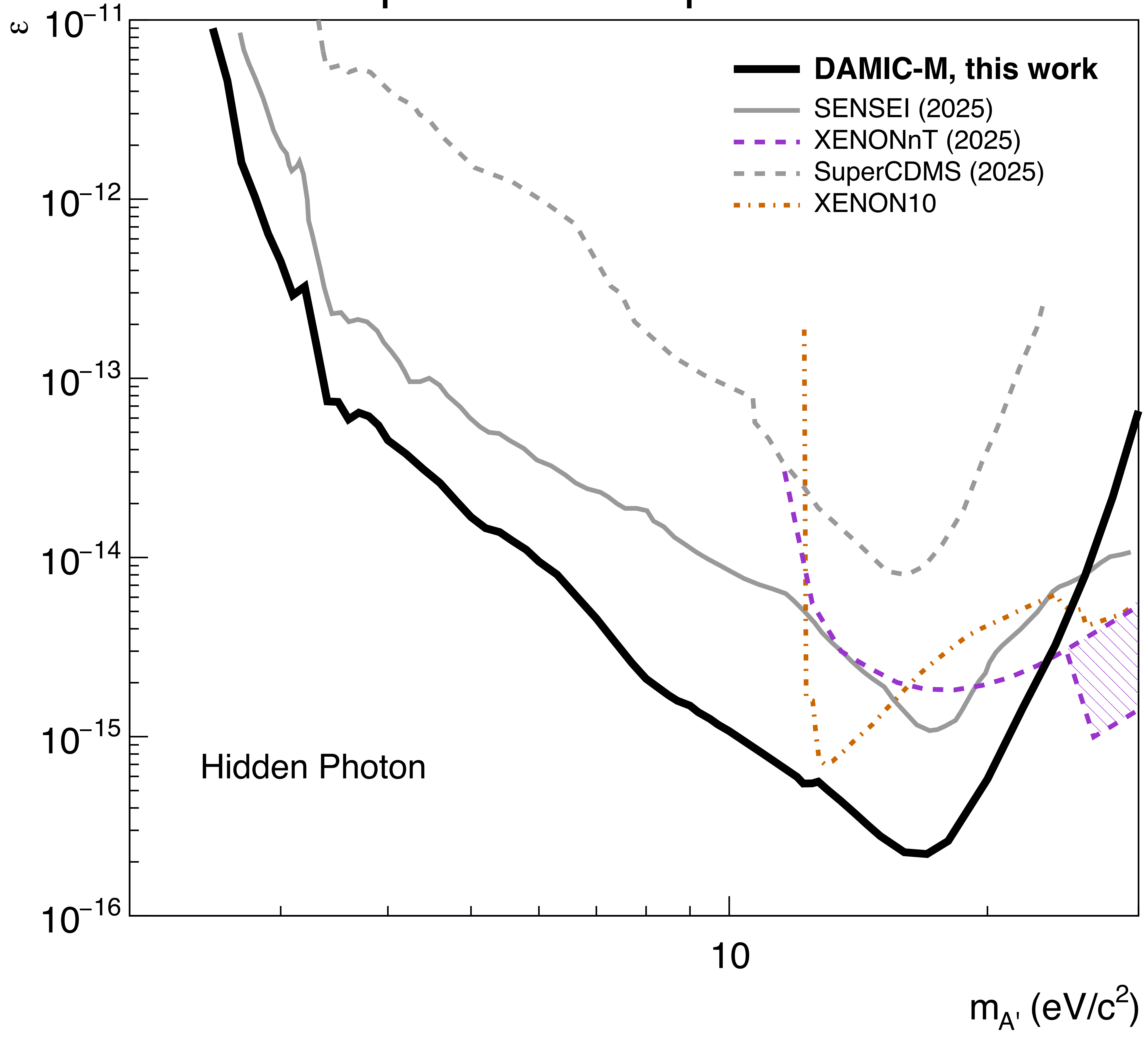
Electronic recoil result re-interpreted as limit on DM-N scattering (Migdal) or DM absorption

Other exclusion limits

DM-nucleus scattering (Migdal)



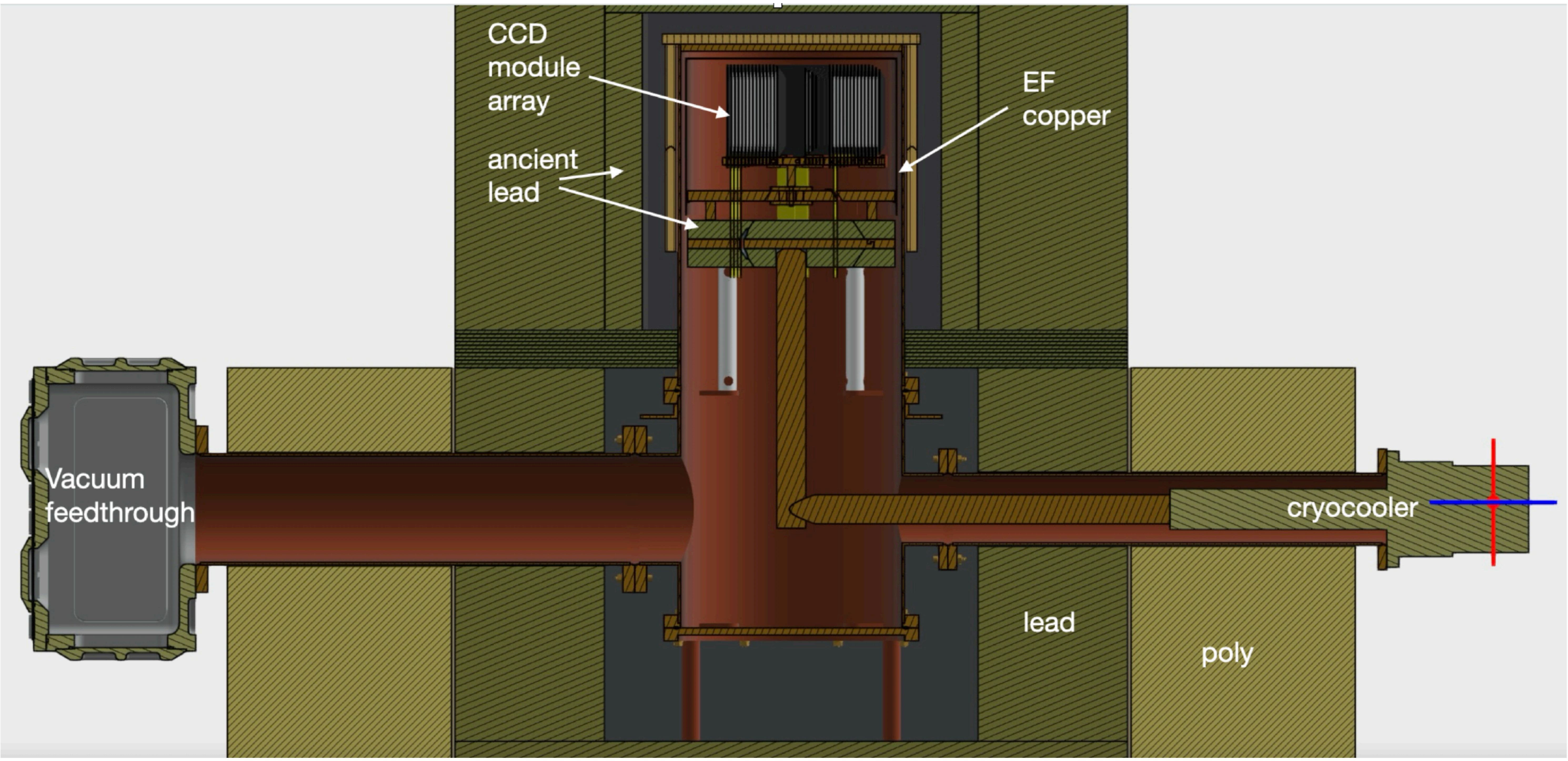
Hidden-photon absorption

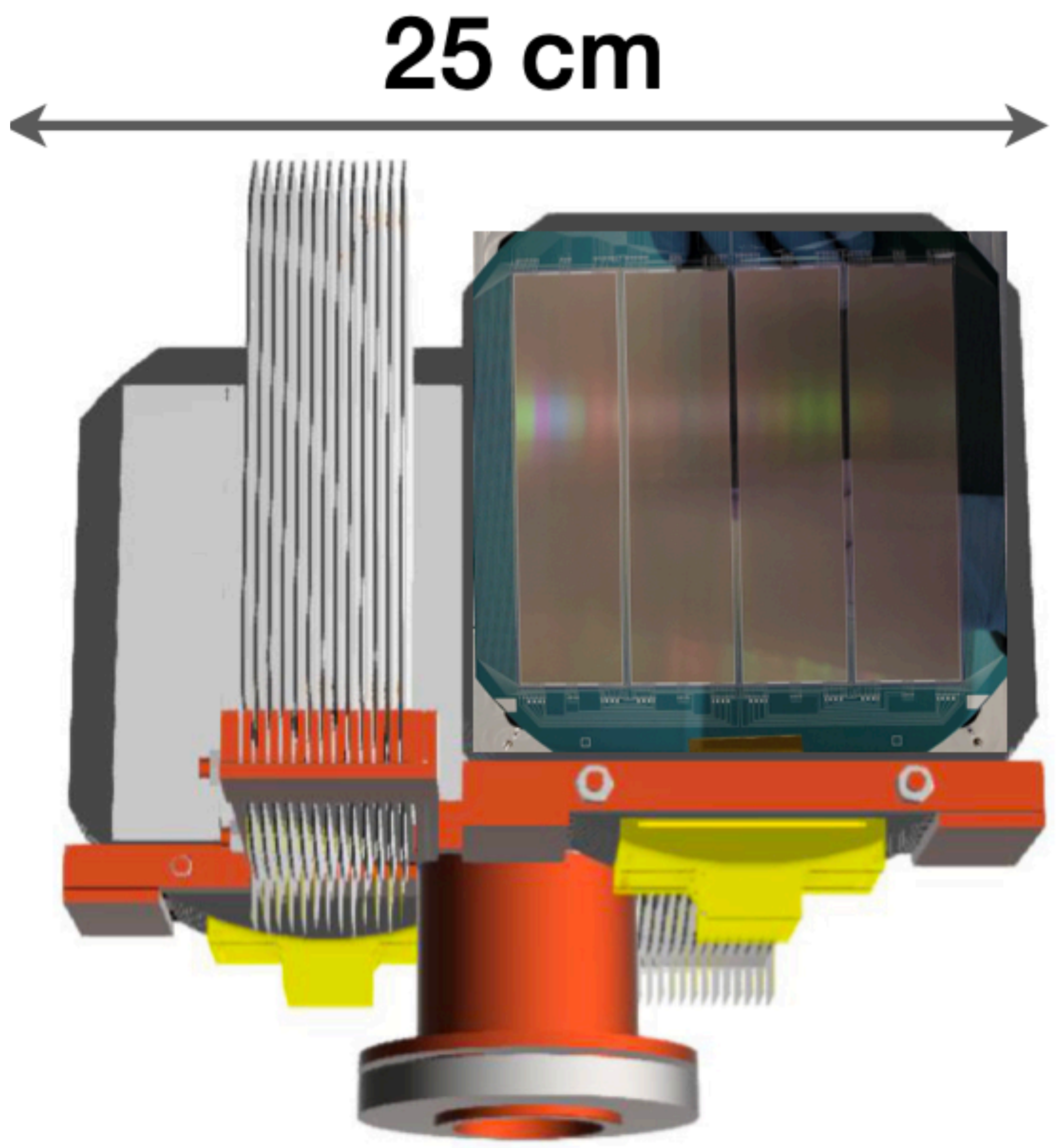


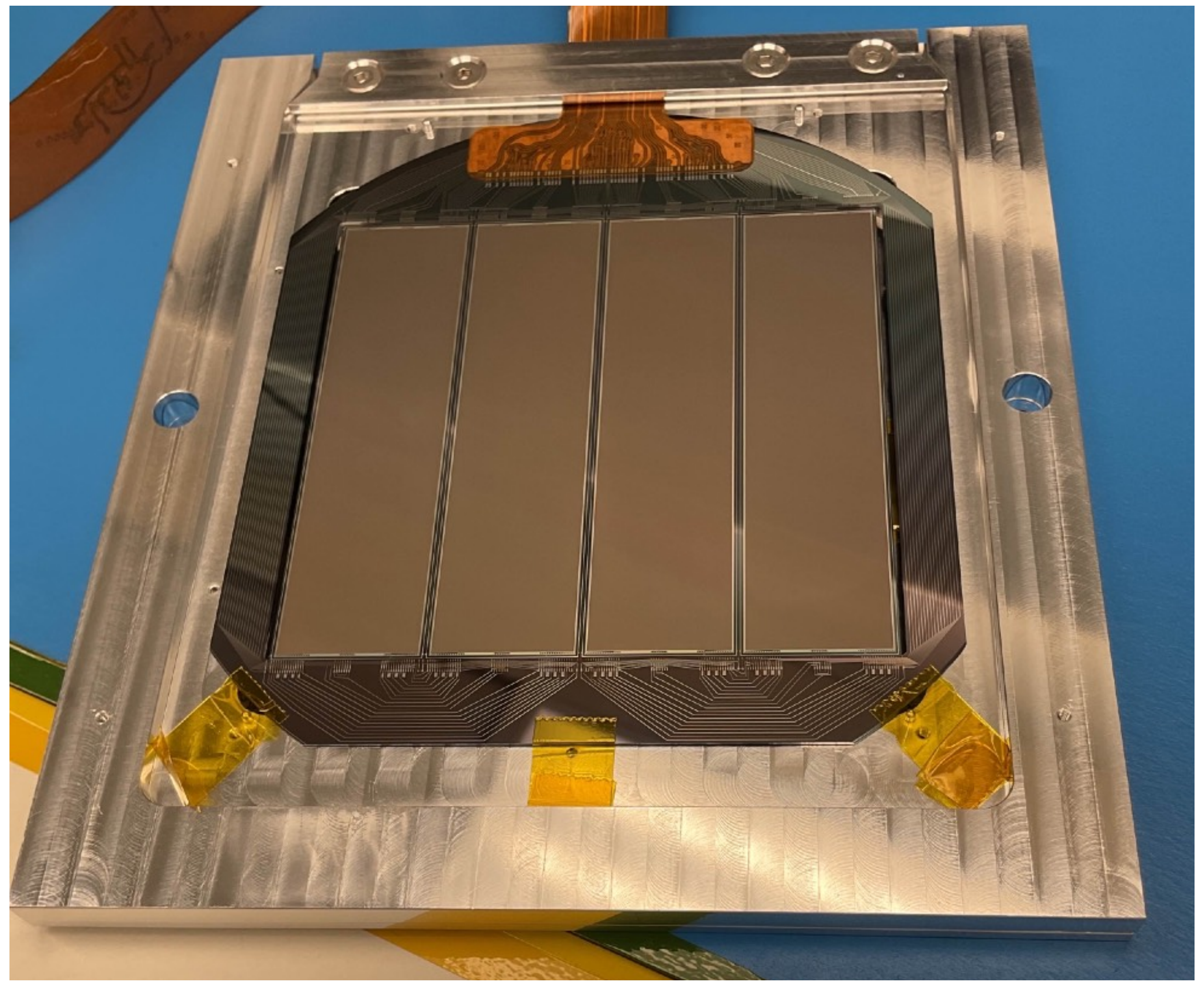
▸ **More world-leading DM exclusion limits from DAMIC-M!**

DAMIC-M

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

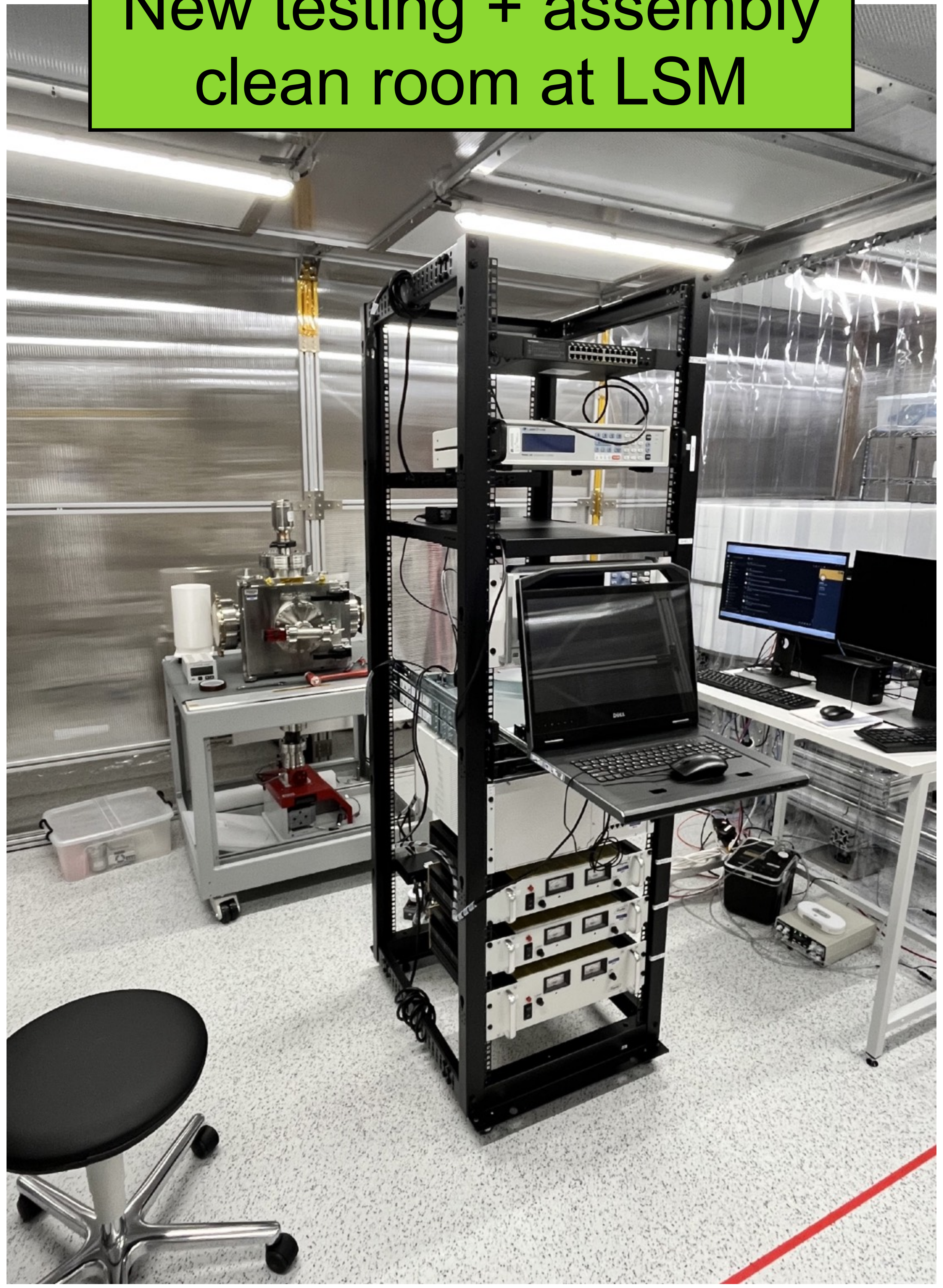






DAMIC-M Status

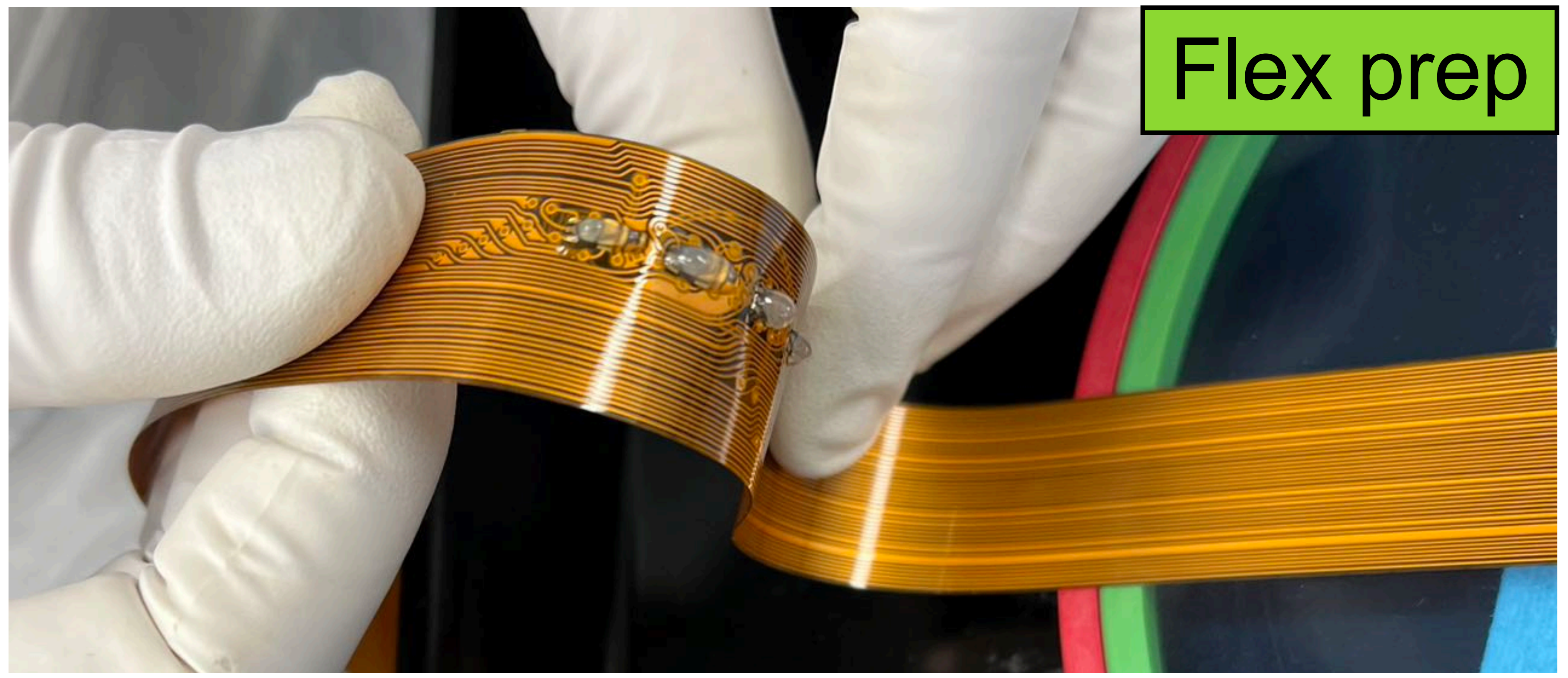
- CCD module production completed and shipped to LSM.
- LBC relocated to second clean room at LSM.
- Test systems being assembled for final module validation.
- Reconditioning clean rooms for CCD array assembly and detector installation.
- Copper machining ongoing, lead and poly for shield ready for shipment.
- Custom electronics under procurement and testing.
- Detector installation in second-half 2025, commissioning by end of 2025.

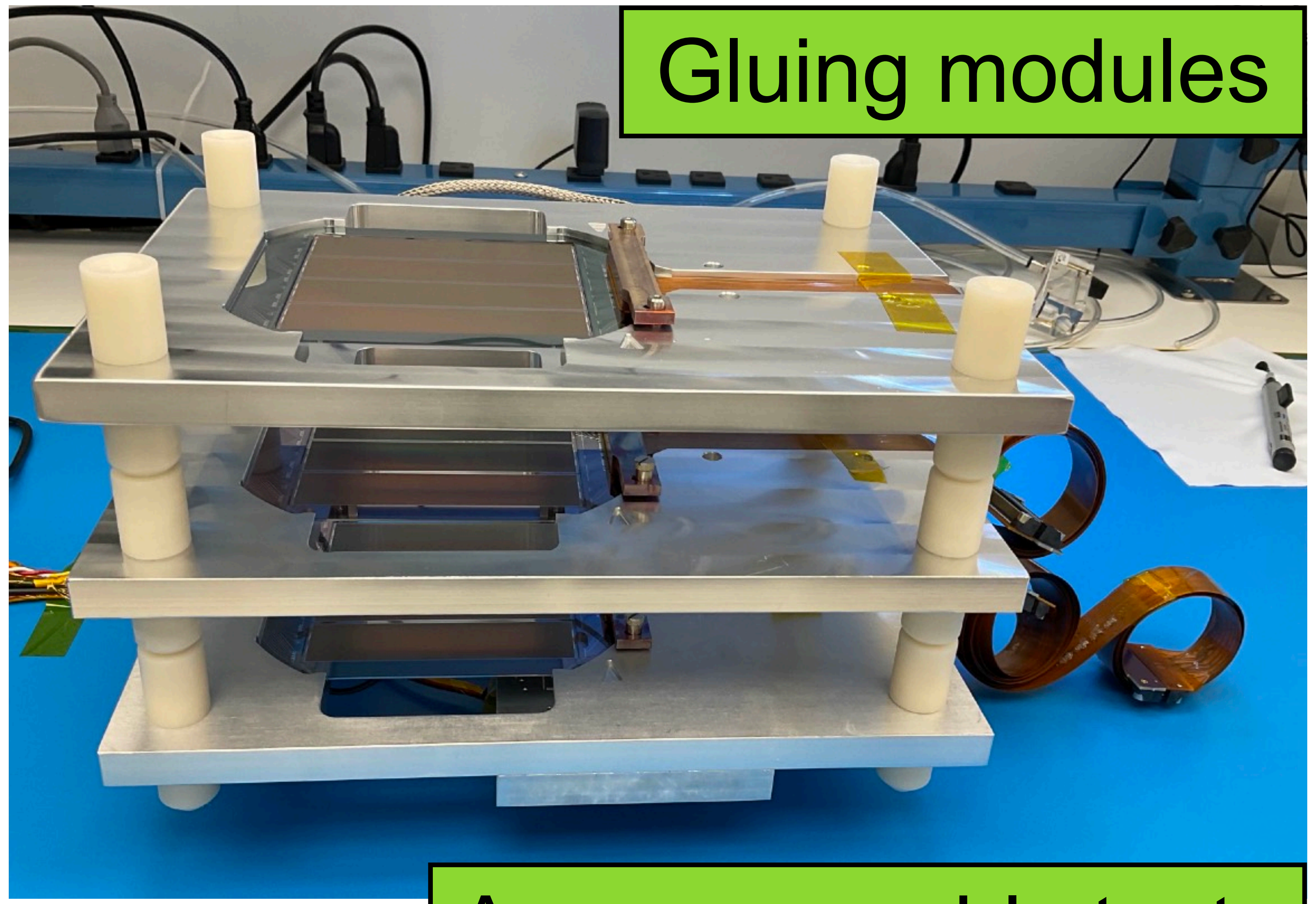


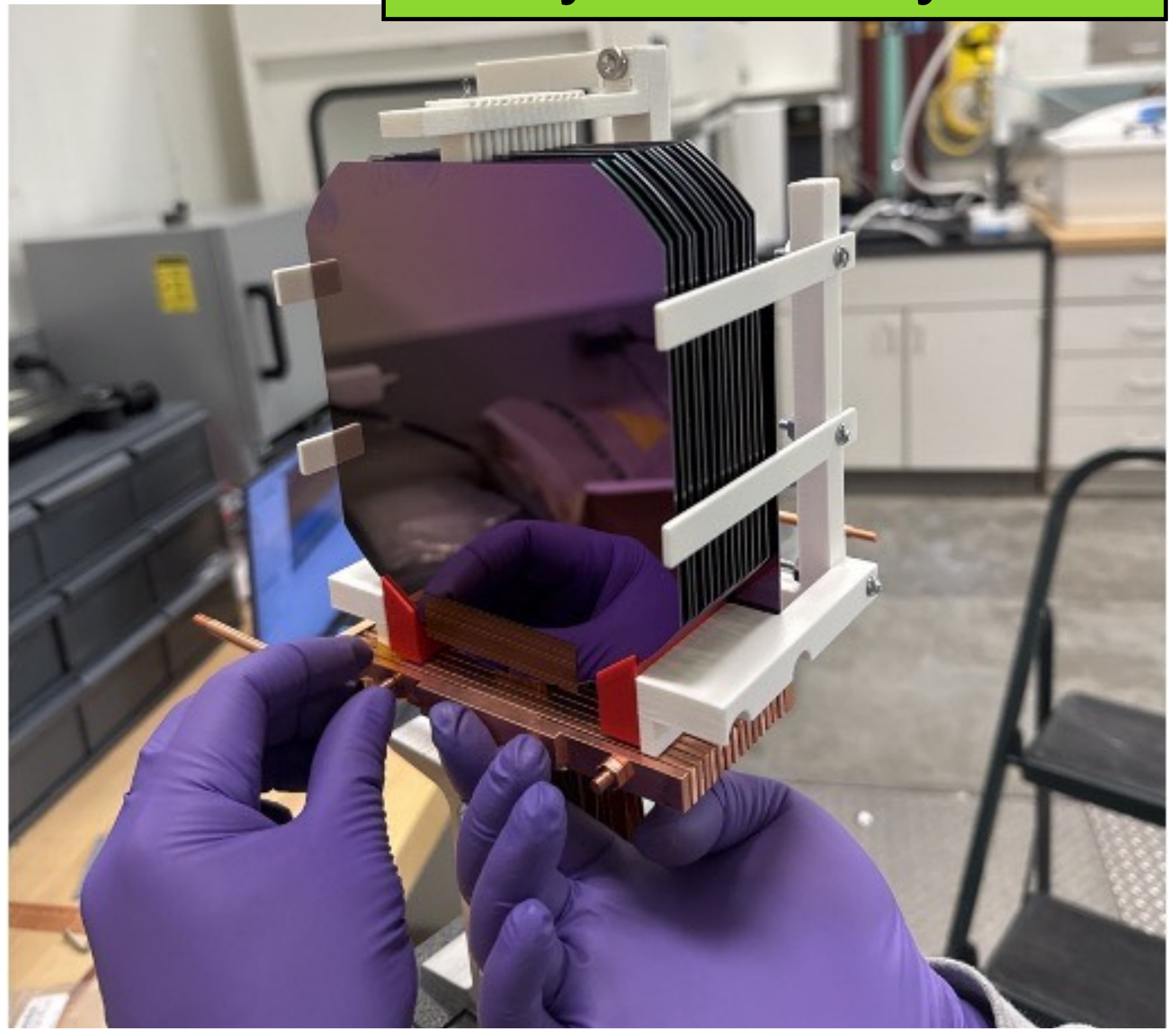
New testing + assembly clean room at LSM

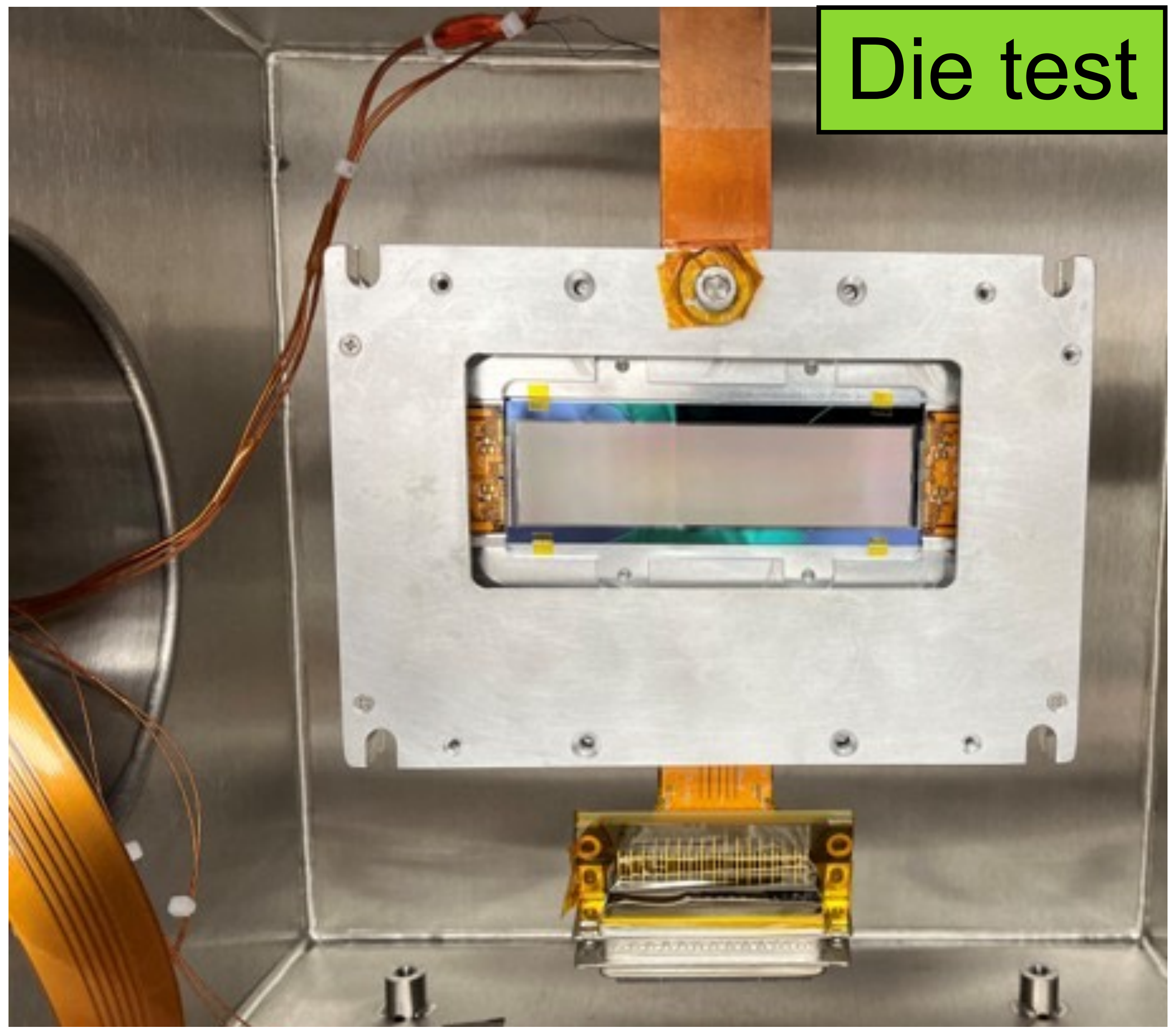
Module Production

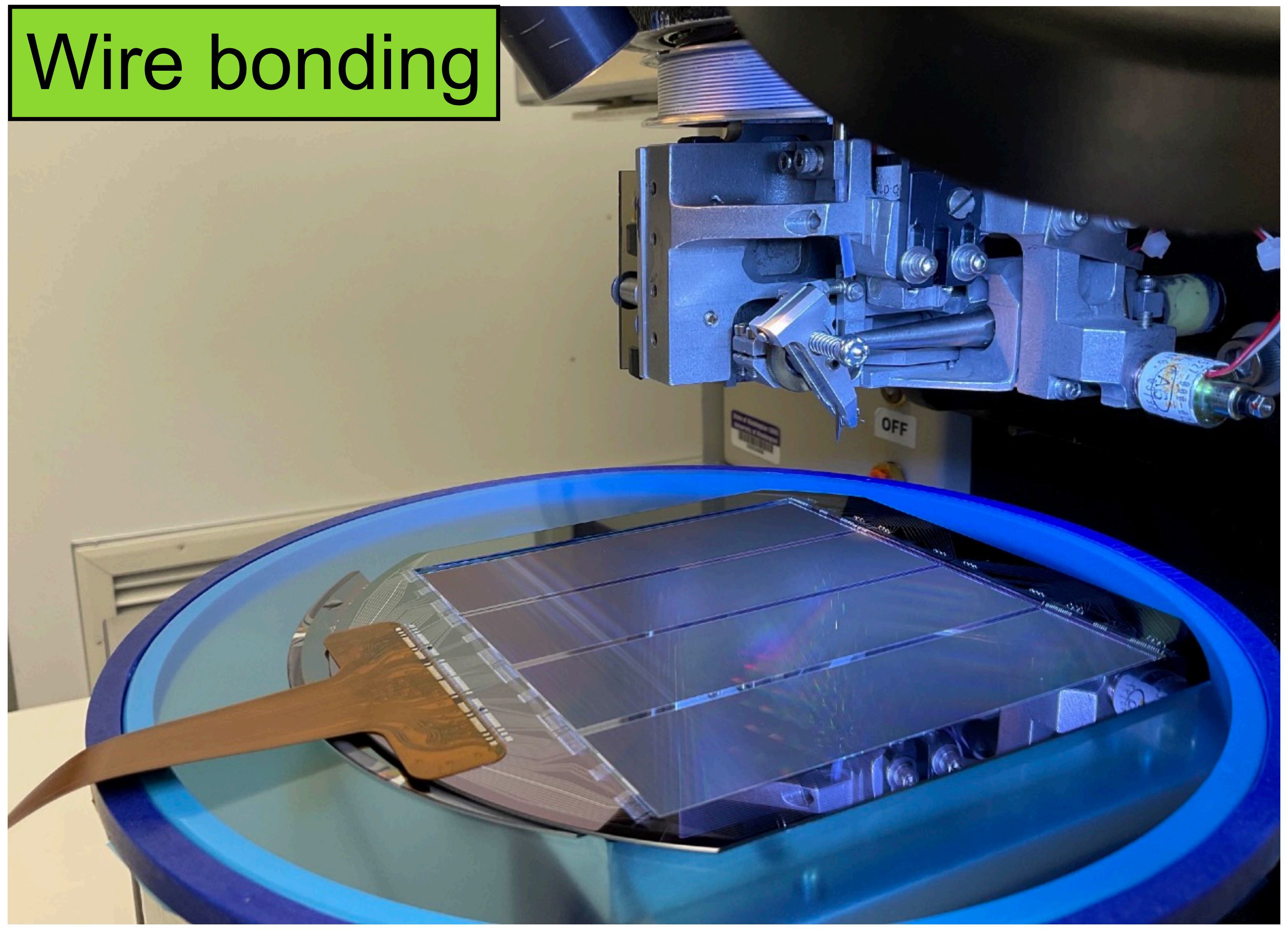
- UW Seattle in Autumn 2024.
- Tested 188 CCDs and selected the best to fabricate 28 modules.


Flex prep


Gluing modules

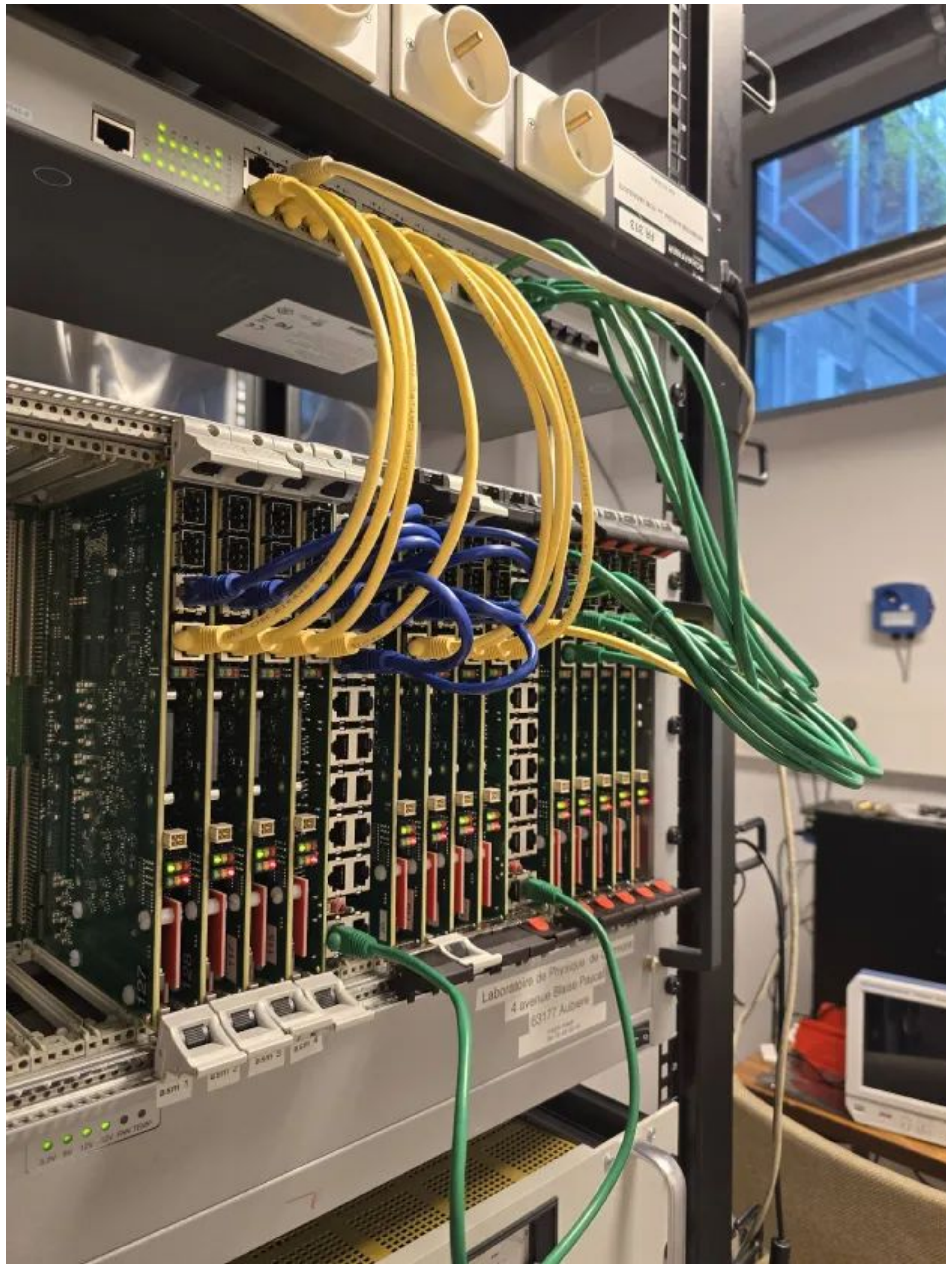

Array assembly tests


Die test


Wire bonding

DAMIC-M Electronics

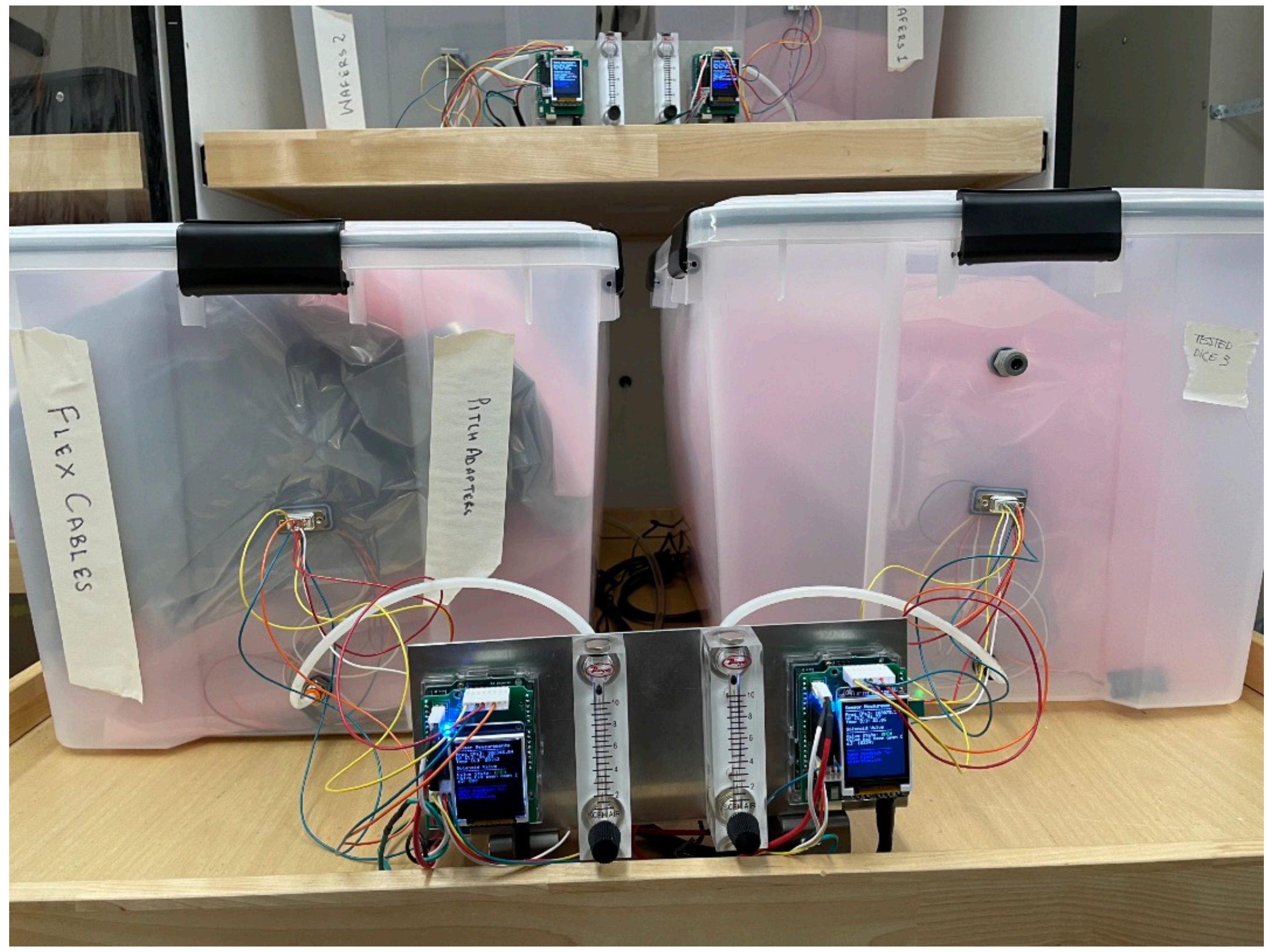
- Developed in collaboration by LPNHE and UChicago.
- Scalable, low noise, custom electronics for synchronized readout of 52 CCD modules.
- 1x Acquisition Control Module (ACM) per CCD module + synchronization boards.
- Digitize CCD output signal, can operate in "minimum bias" mode.
- Boards fabricated, more than 26 tested + ready for first deployment.
- Preparing for final stress test at LPNHE.

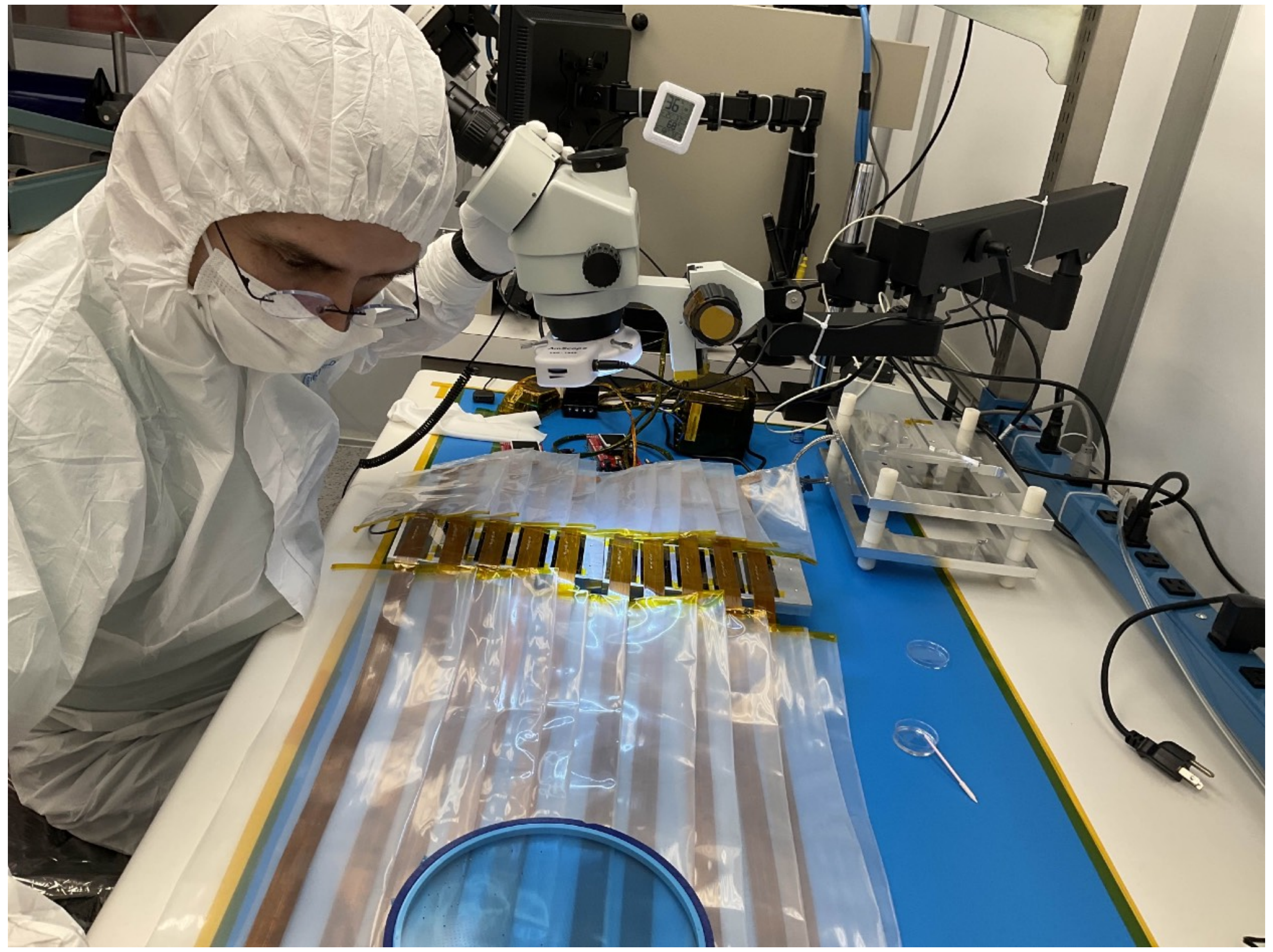


Low-background

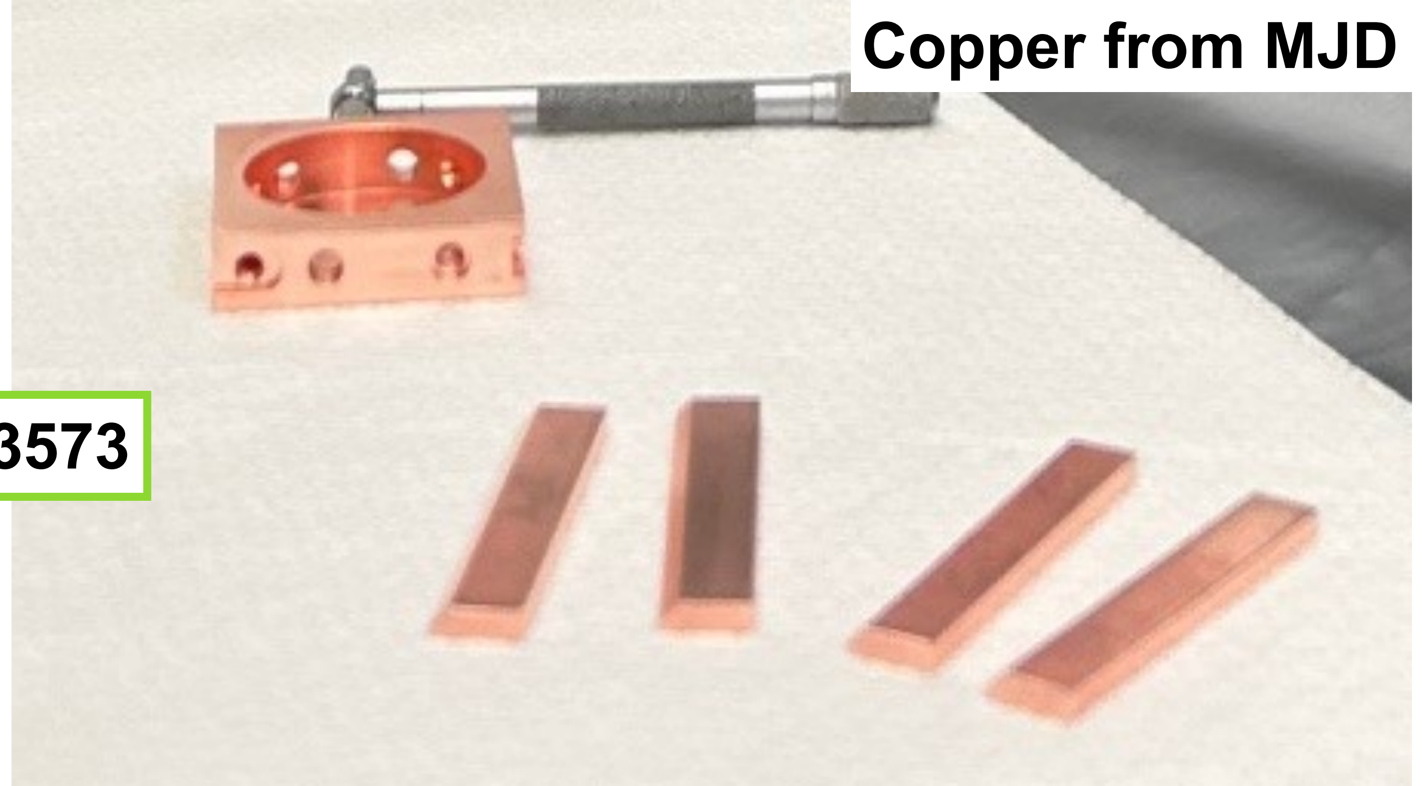
20x reduction in ^{3}H activation

PRD102(2020)102006



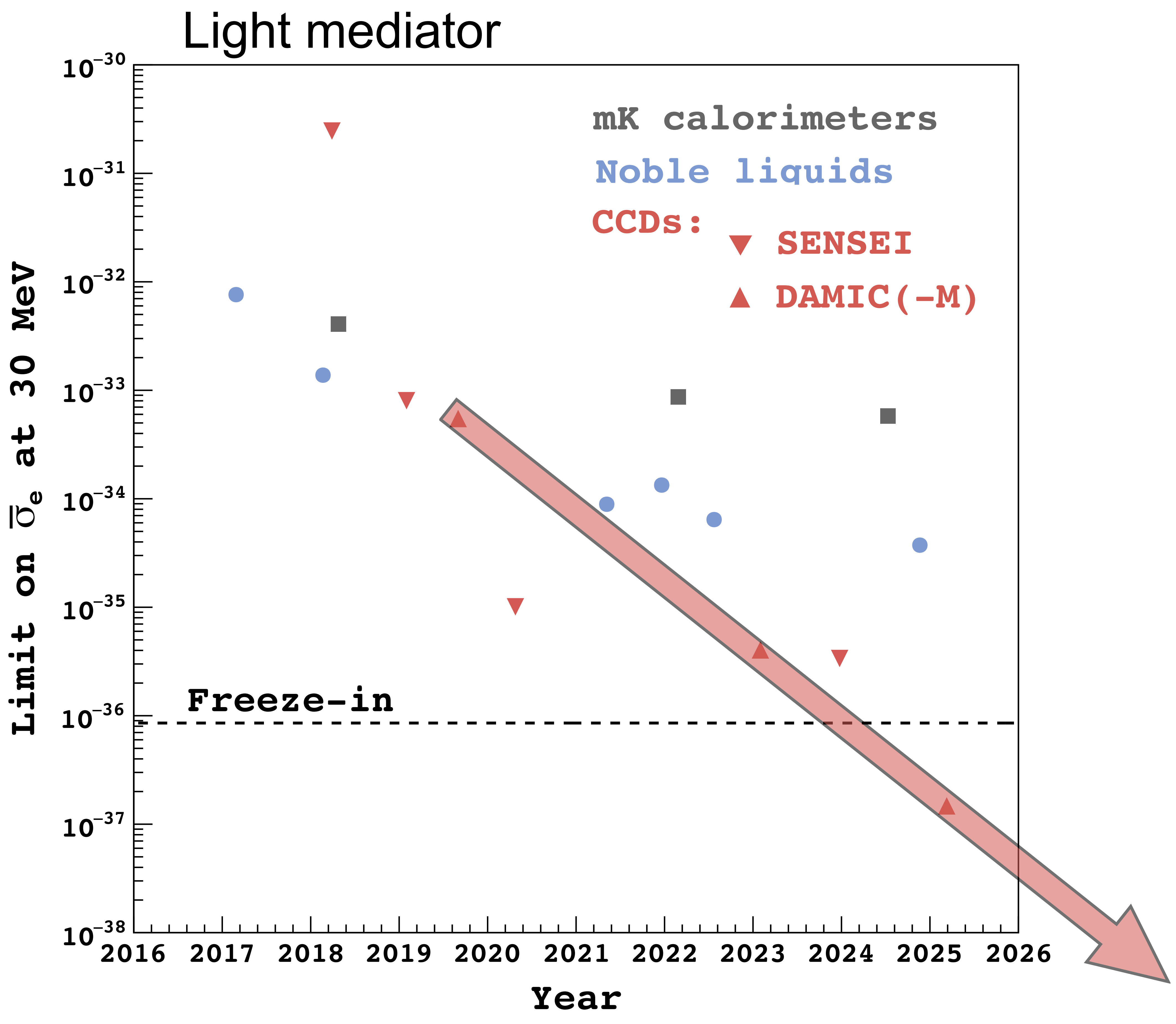


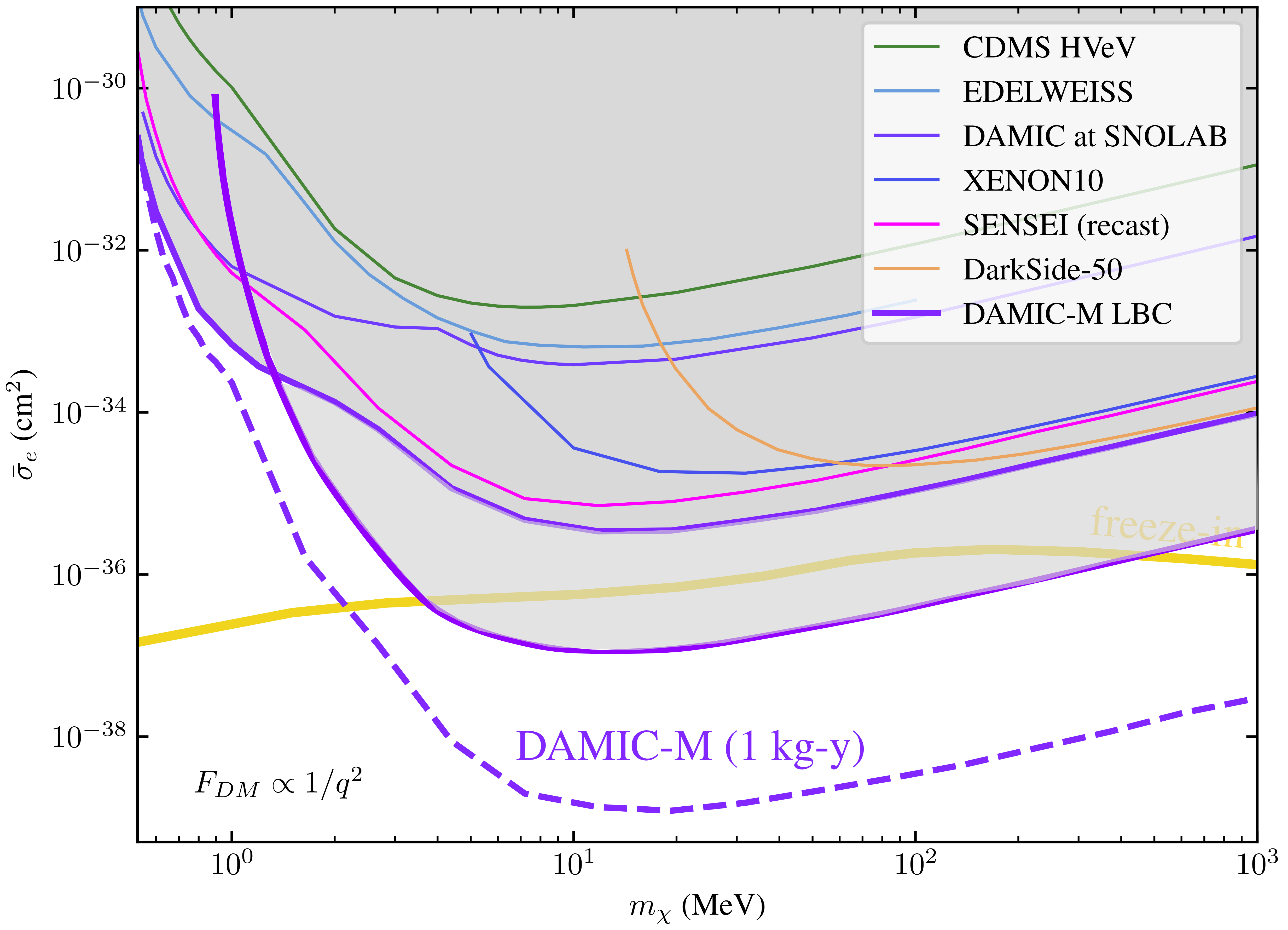
- Transport in shielded container.
- Shielded, Rn-free storage.
- Clean room operations.
- Low-radioactivity flexes. NIMA959(2020)163573
- Copper electroformed underground.
- Light-tight infrared shield.



Copper from MJD

DAMIC-M Forecast

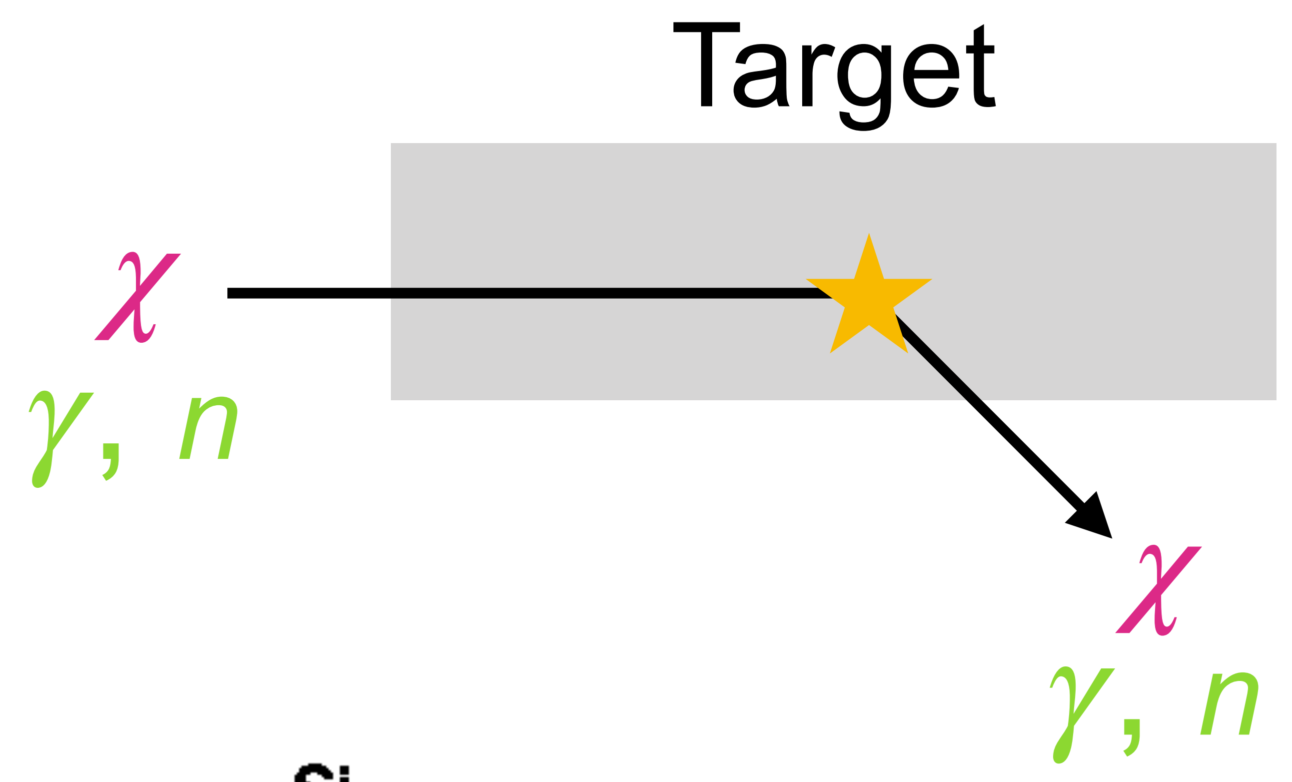


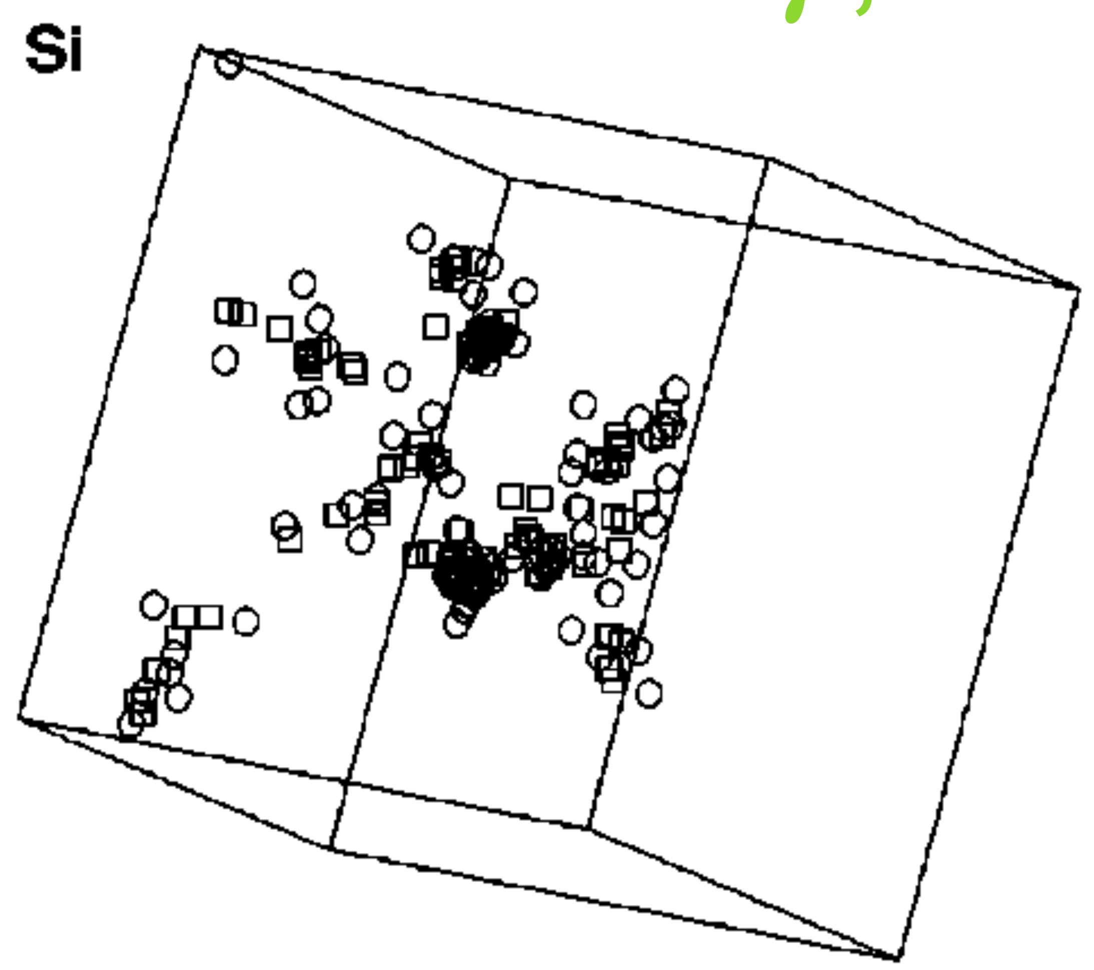


R&D for Future

Nuclear recoil identification

- So far, CCDs cannot distinguish interactions with nuclei vs. interactions with electrons in the target.
- Microscopically, electronic (ER) and nuclear recoils (NR) disrupt the silicon lattice differently.
- Low-energy NR dislocate atoms to create “defects,” ER do not (kinematically forbidden).
- Nuclear recoil events can be identified by the spatial correlation between the primary ionization event and the defect.

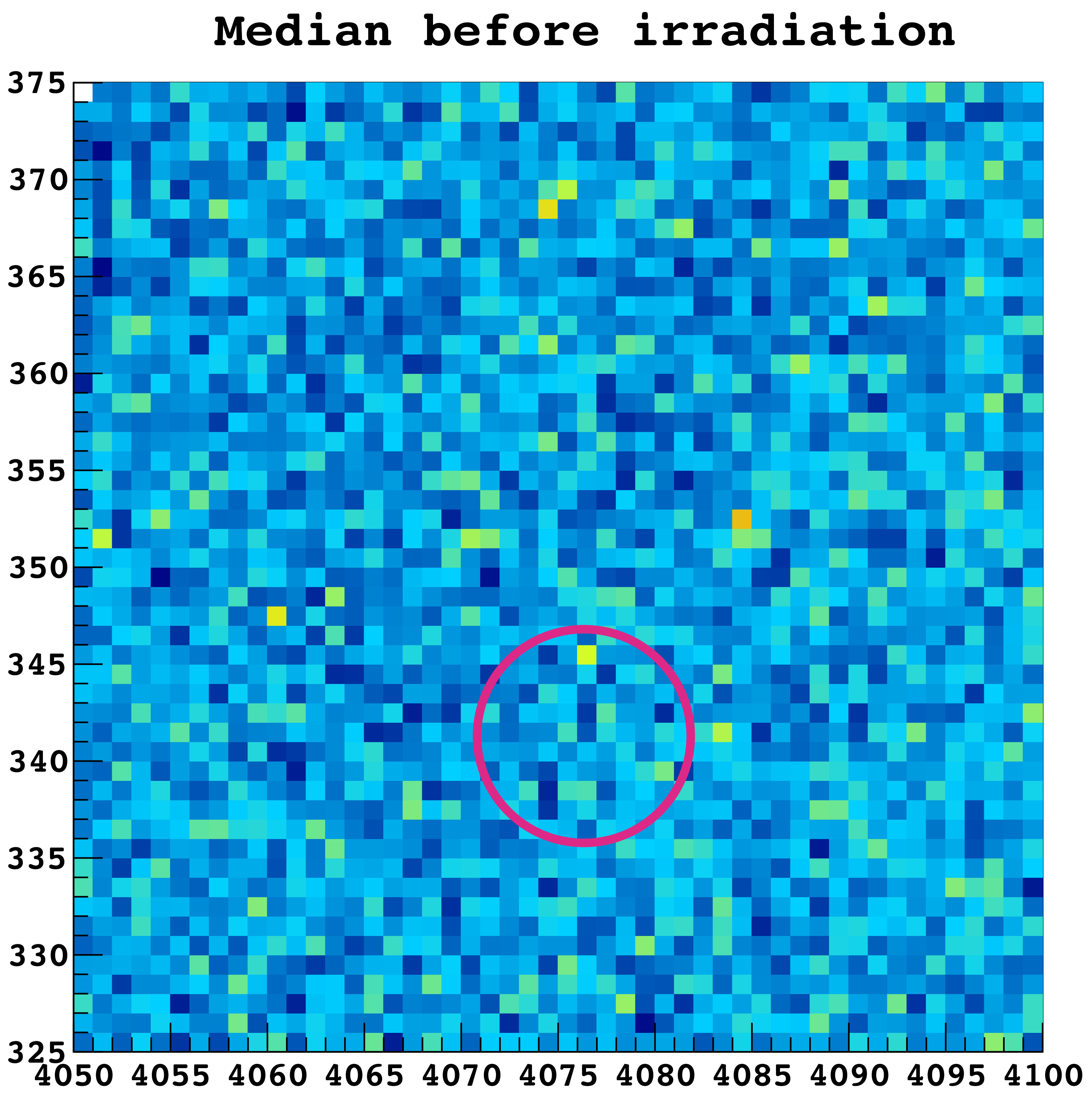


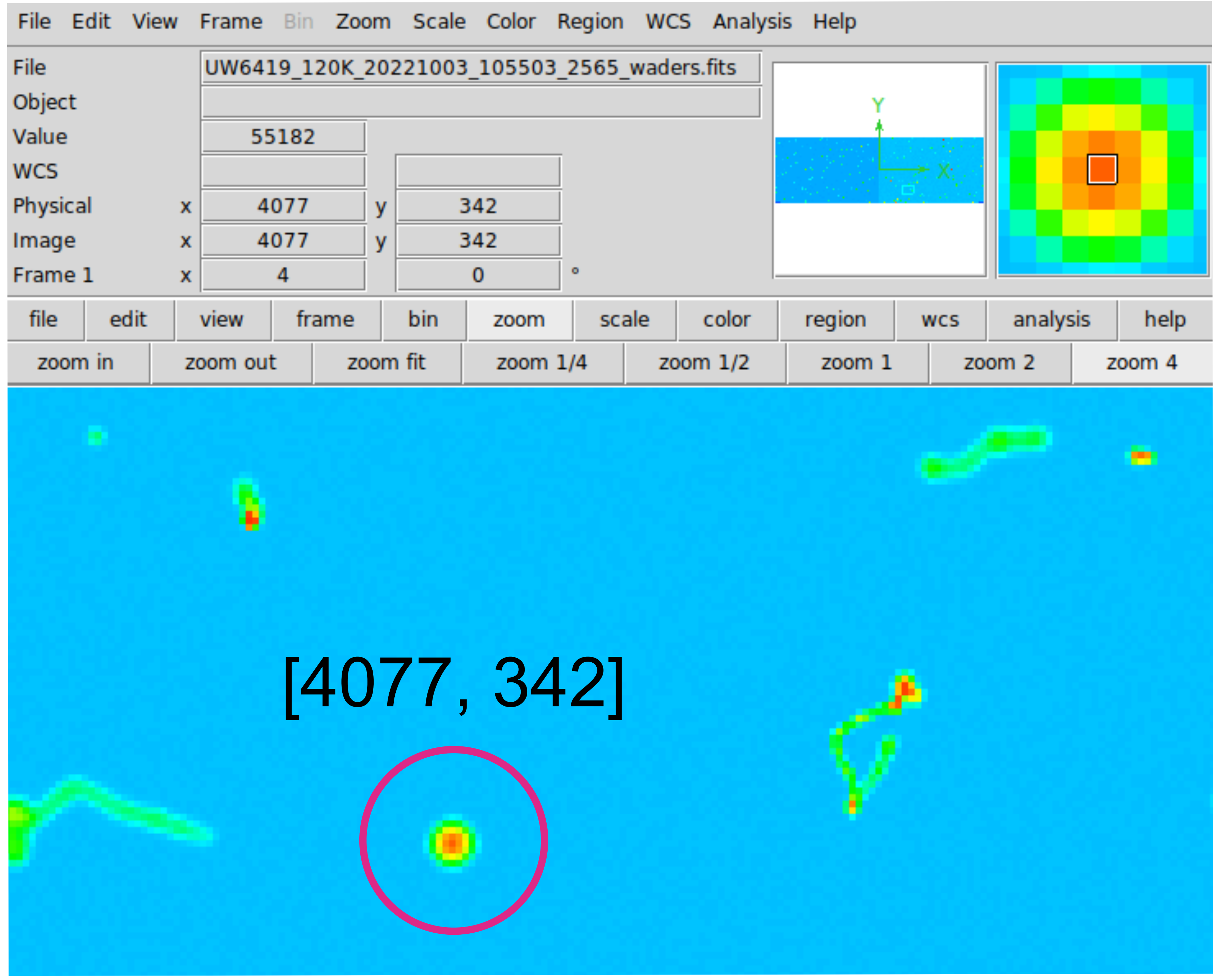


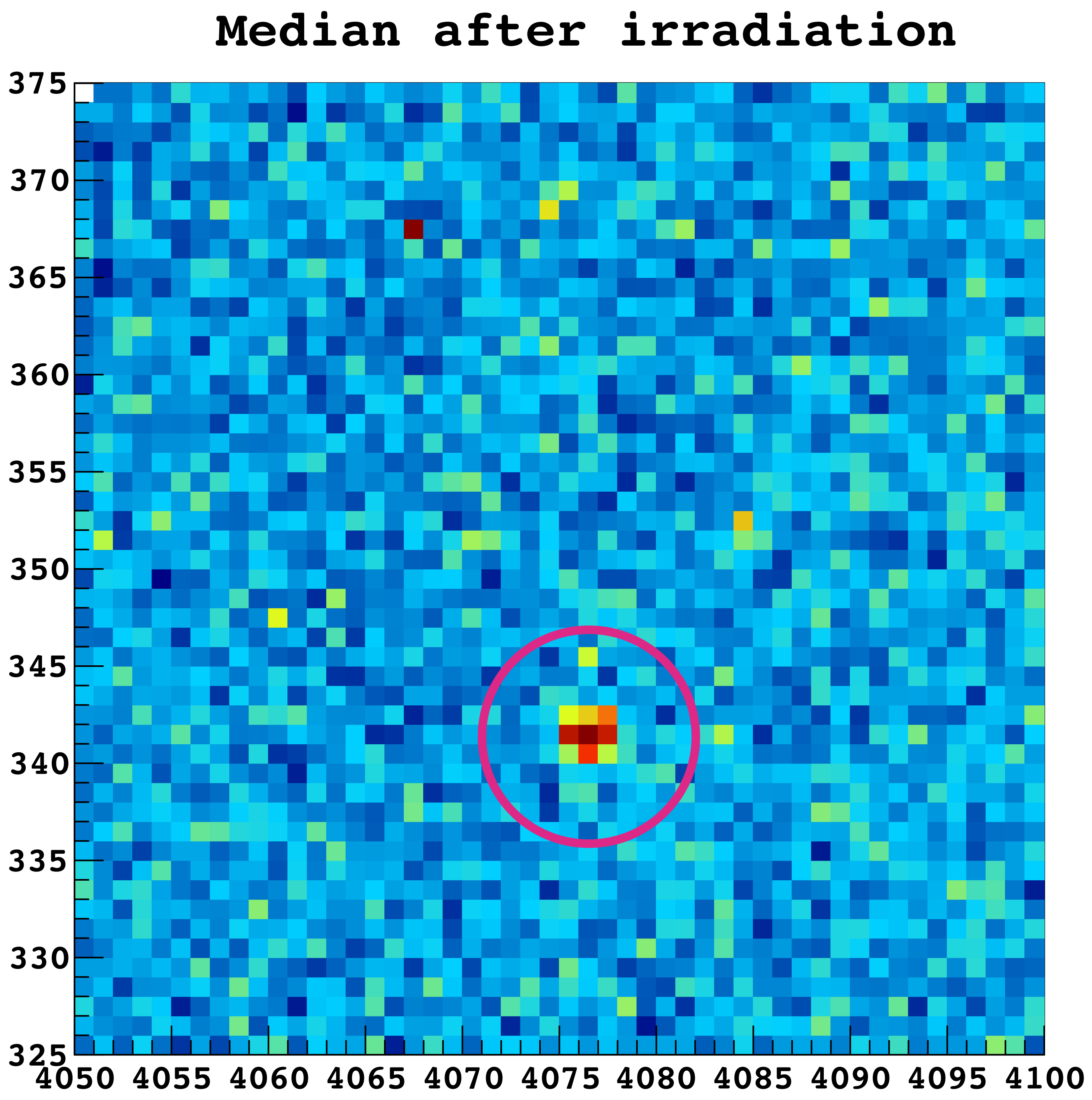
Defects from 10 keV NR

Experiment at UW:

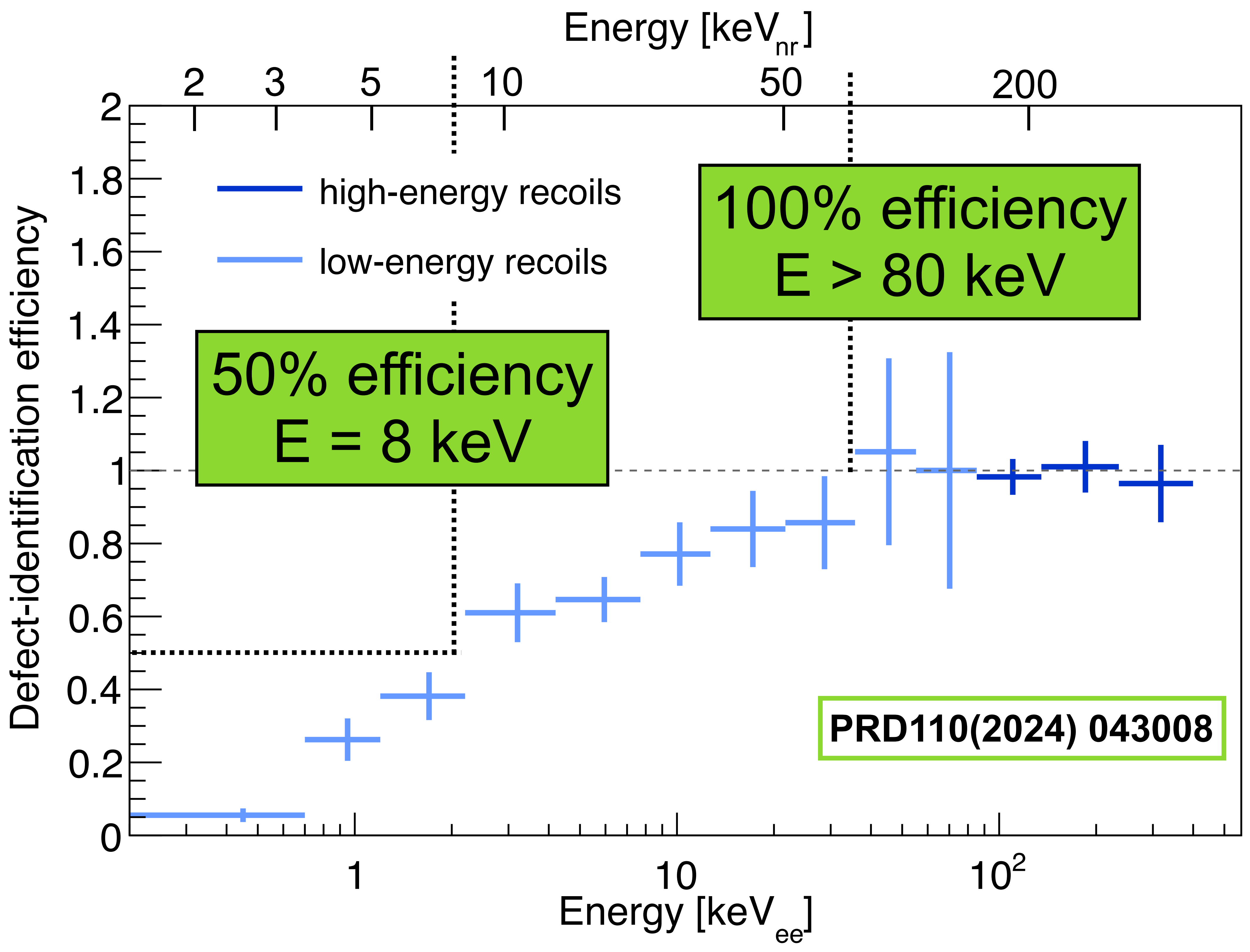
Series of warm images (223 K) to identify existing defects → Cold images (147 K) during irradiation with a neutron source to identify primary ionization events → Series of warm images (223 K) to identify new defects







Results



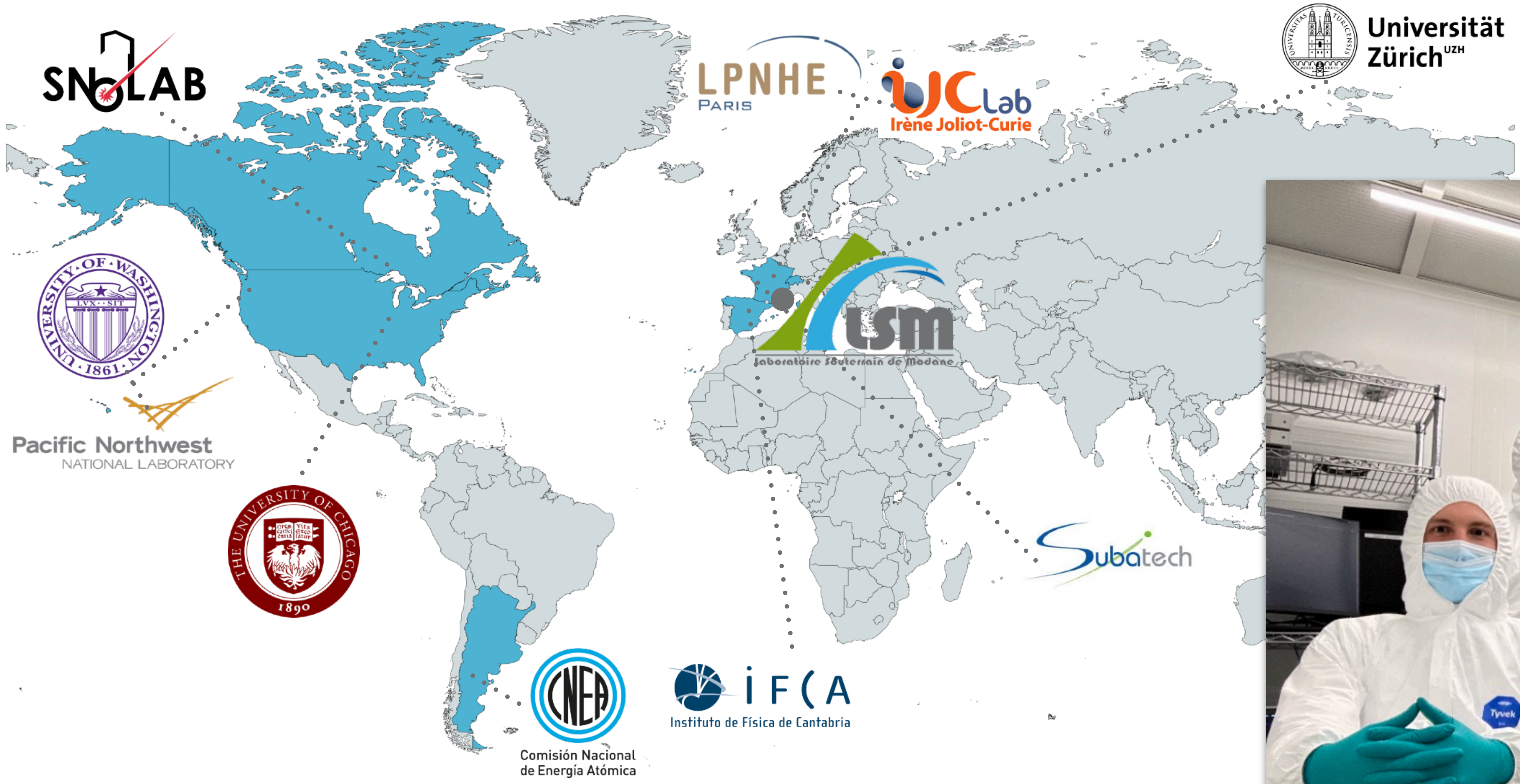
<0.1% of electronic recoils with E < 85 keV are spatially correlated with a defect

- We demonstrated that CCDs can distinguish between interactions with nuclei and electrons!
- We have a proposal to extend the sensitivity toward to sub-keV recoil energies.
- This will allow DAMIC-M to perform ER and NR dark-matter searches independently, for significantly increased sensitivity and discovery potential.

Conclusions

- The range of DM particles 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 in the last 8 years.
- DAMIC-M’s LBC now probes several hidden-sector benchmark models.
- Progress should continue for at least one more generation with DAMIC-M full-scale detector.

Thank you!



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