15th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2025) Madison Wisconsin June 9-13

# The search for Light Dark Matter with DAMIC-M

Paolo Privitera

for the DAMIC-M Collaboration

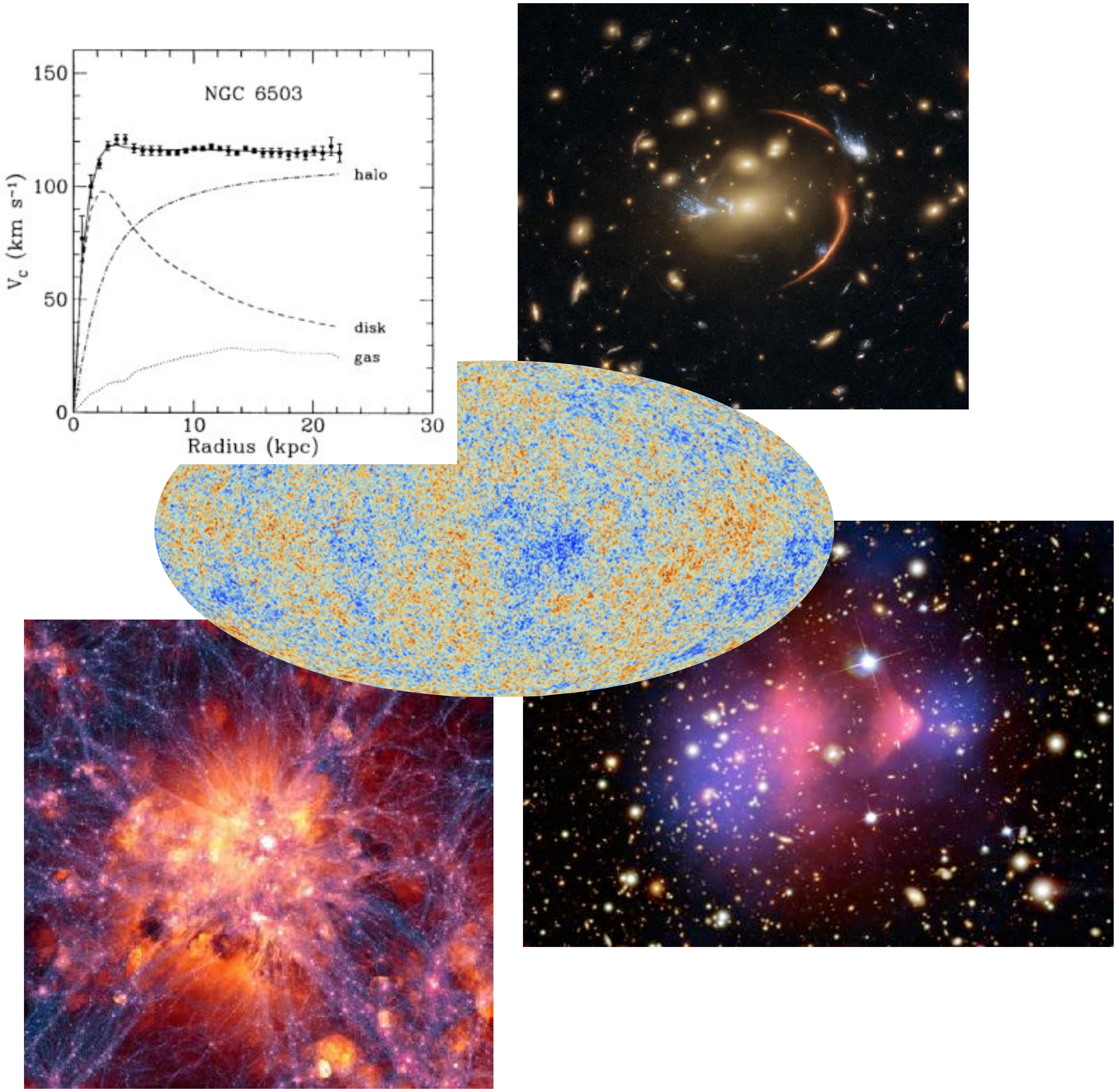
## The DAMIC-M Collaboration


https://damic.uchicago.edu/

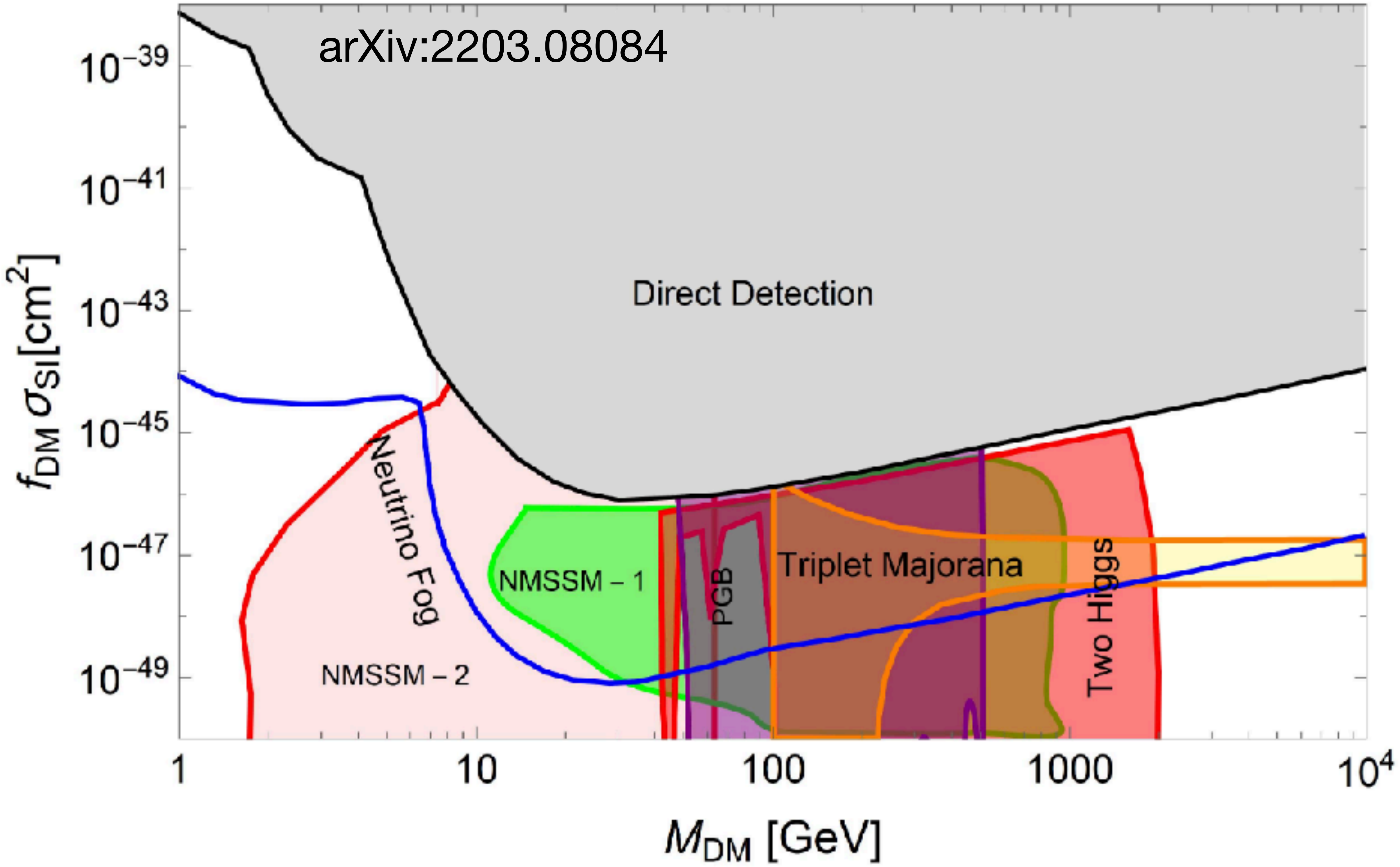
- Sub-GeV Dark Matter
- DAMIC-M and Skipper CCDs
- The Low Background Chamber at LSM
- New results on Hidden-Sector Dark Matter
- Conclusions

# Dark Matter and WIMPs

- A pile of evidence for Dark Matter




- Enormous advance in the search for WIMPs, 5 orders of magnitude in 20 years, but they have not yet been found, despite compelling theoretical motivations - the WIMP "miracle", SUSY,…. The neutrino fog is approaching (see H Lippincot)




"rumors of the WIMP's death have been greatly exaggerated" (J. Feng, SciPost Phys. Lect. Notes 71 (2023) )

but maybe we need another (WIMPless) miracle

# Hidden-Sector Dark Matter

SM


Hidden sector

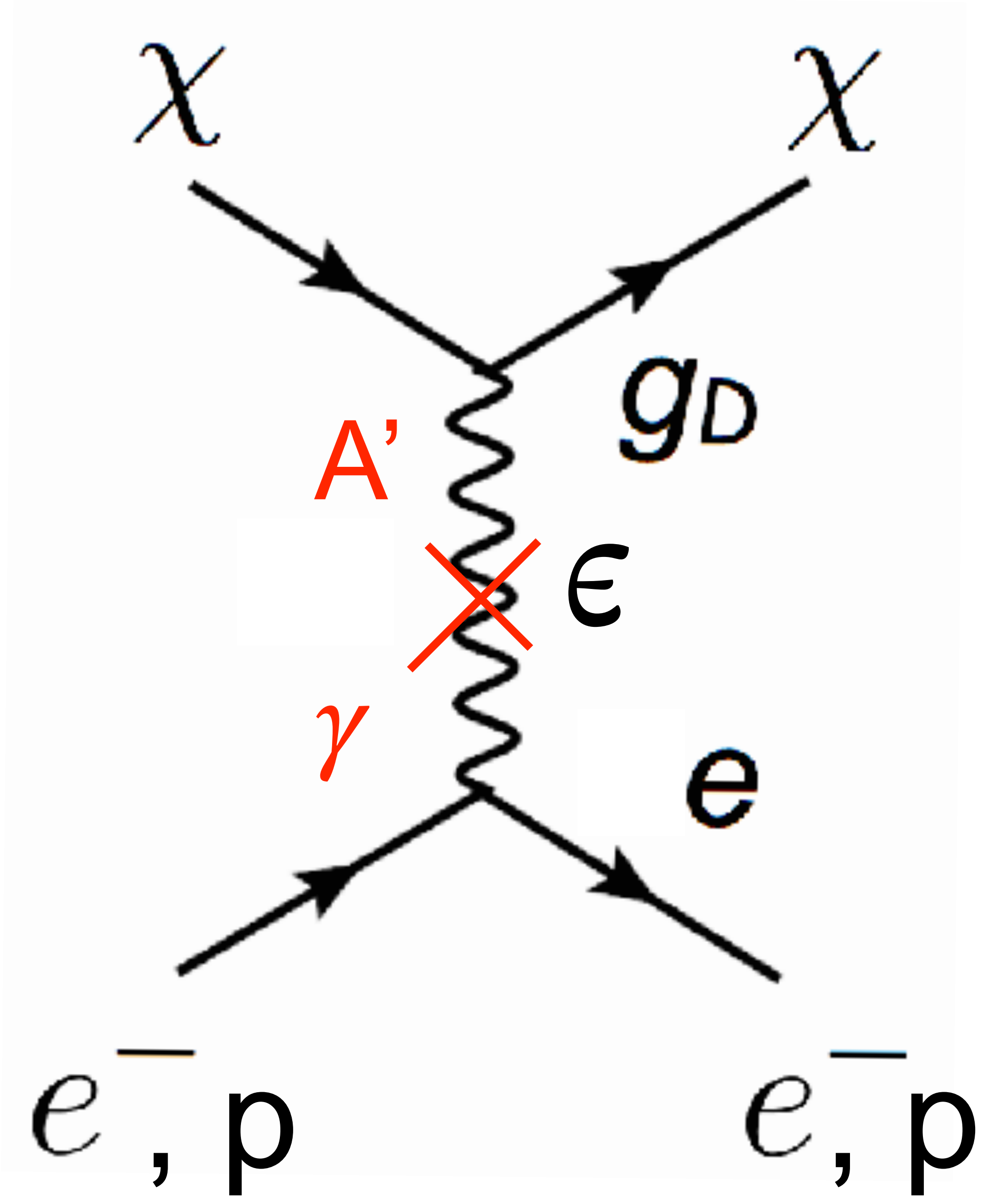
- WIMP miracle:

$$g_X \sim g_{\text{weak}}$$
$$m_X \sim m_{\text{weak}}$$

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

gives the correct DM relic density

- WIMPless miracle: many combinations of couplings and masses in the hidden sector are possible (not bound to be SM *weak)*




- "Dark QED" models

*kinetically mixed dark photon A'*

$$\mathscr{L}_{\text{int}} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\text{EM}}) \quad J^\mu_D = \begin{cases} i\chi^* \partial^\mu \chi + c.c. & \text{Scalar} \\ \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\bar{\chi}_1\gamma^\mu\chi_2 & \text{Pseudo-Dirac} \\ \bar{\chi}\gamma^\mu\chi & \text{Dirac (Asymmetric)} \end{cases}$$

<u>A rich, unexplored DM phenomenology</u>

benchmark models

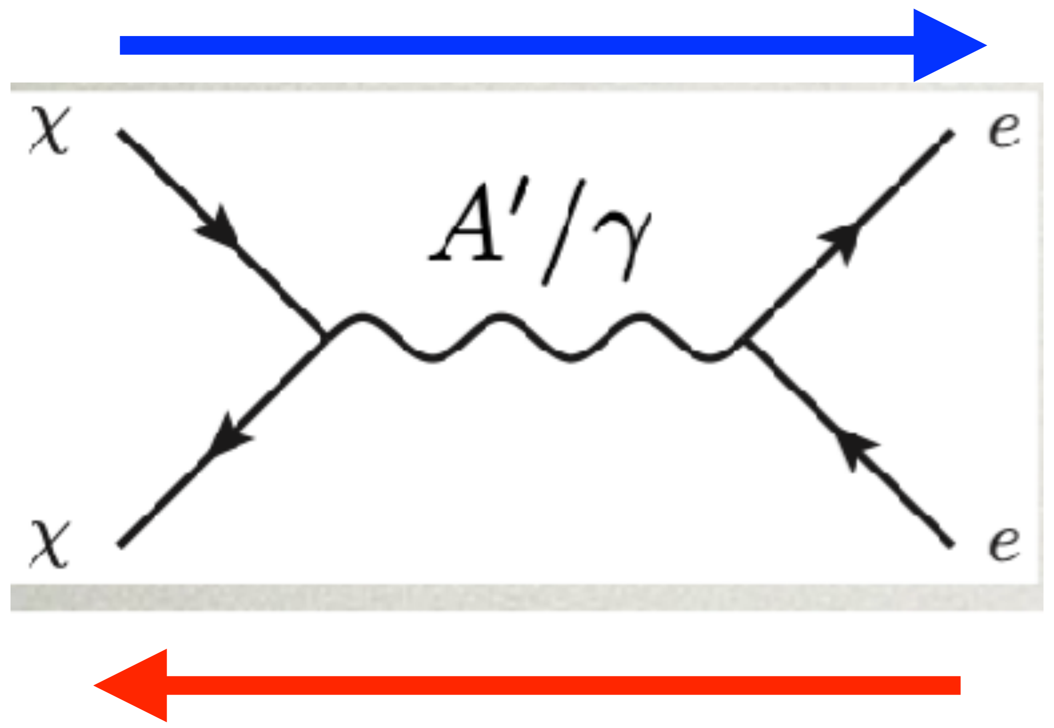
US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

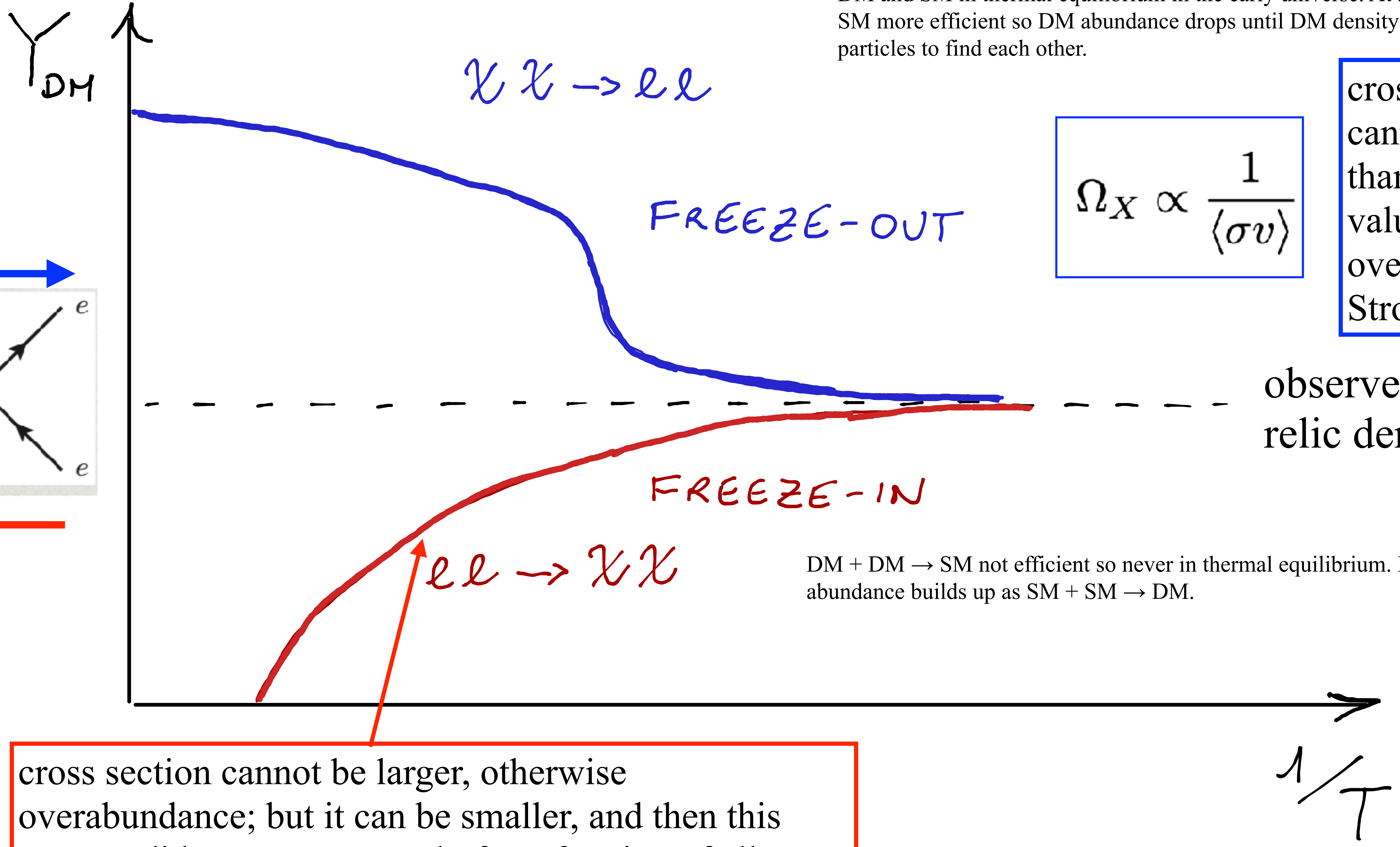
# Freeze-out and -in

DM and SM in thermal equilibrium in the early universe. At some point DM + DM → SM more efficient so DM abundance drops until DM density is too low for DM particles to find each other.

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle}$$

cross section cannot be smaller than a minimum value, otherwise overabundance. Strong constraint!



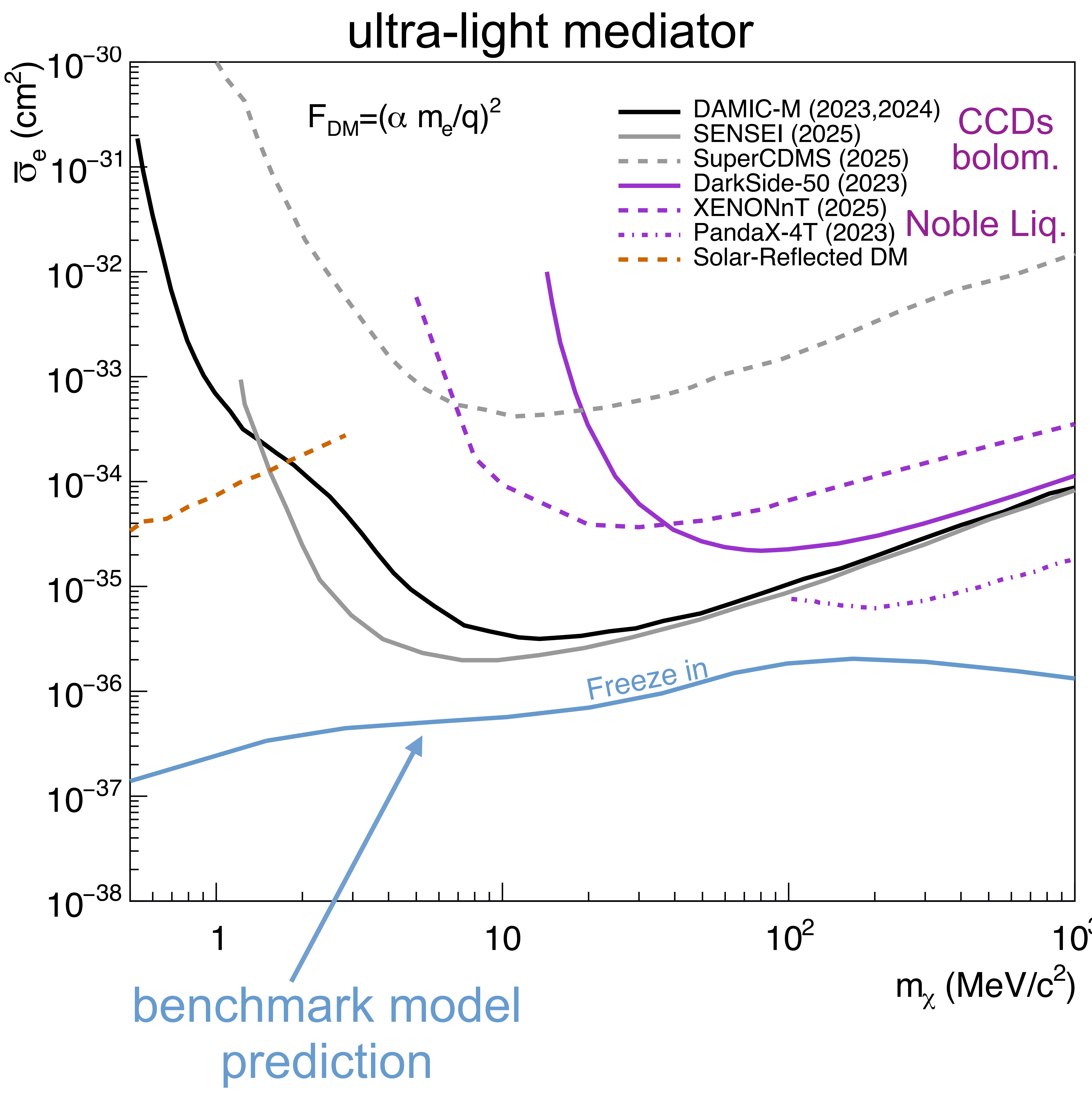



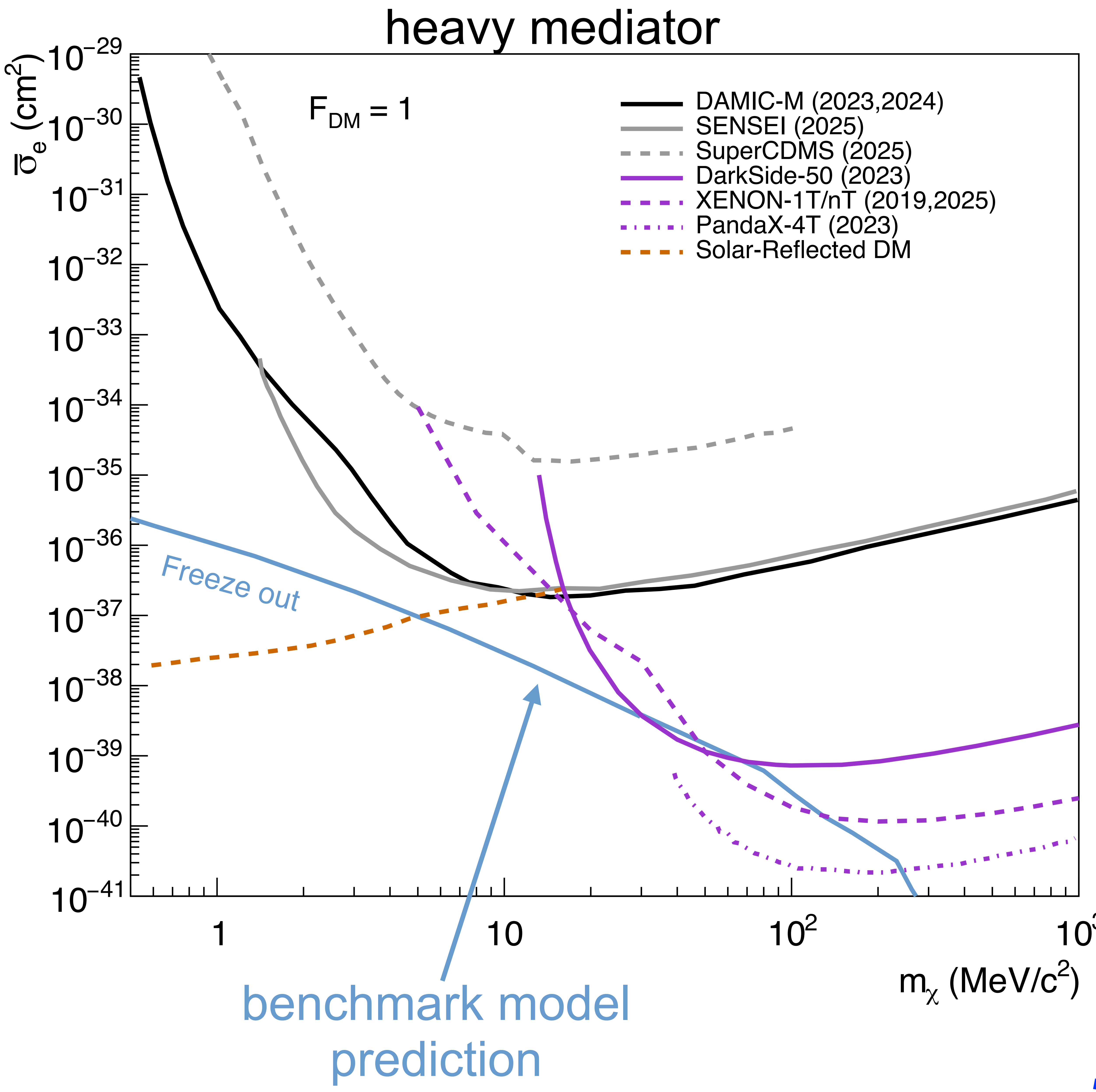

observed DM relic density

DM + DM → SM not efficient so never in thermal equilibrium. DM abundance builds up as SM + SM → DM.

cross section cannot be larger, otherwise overabundance; but it can be smaller, and then this DM candidate can count only for a fraction of all DM

# Status February 2025



# Detection of Hidden-Sector DM

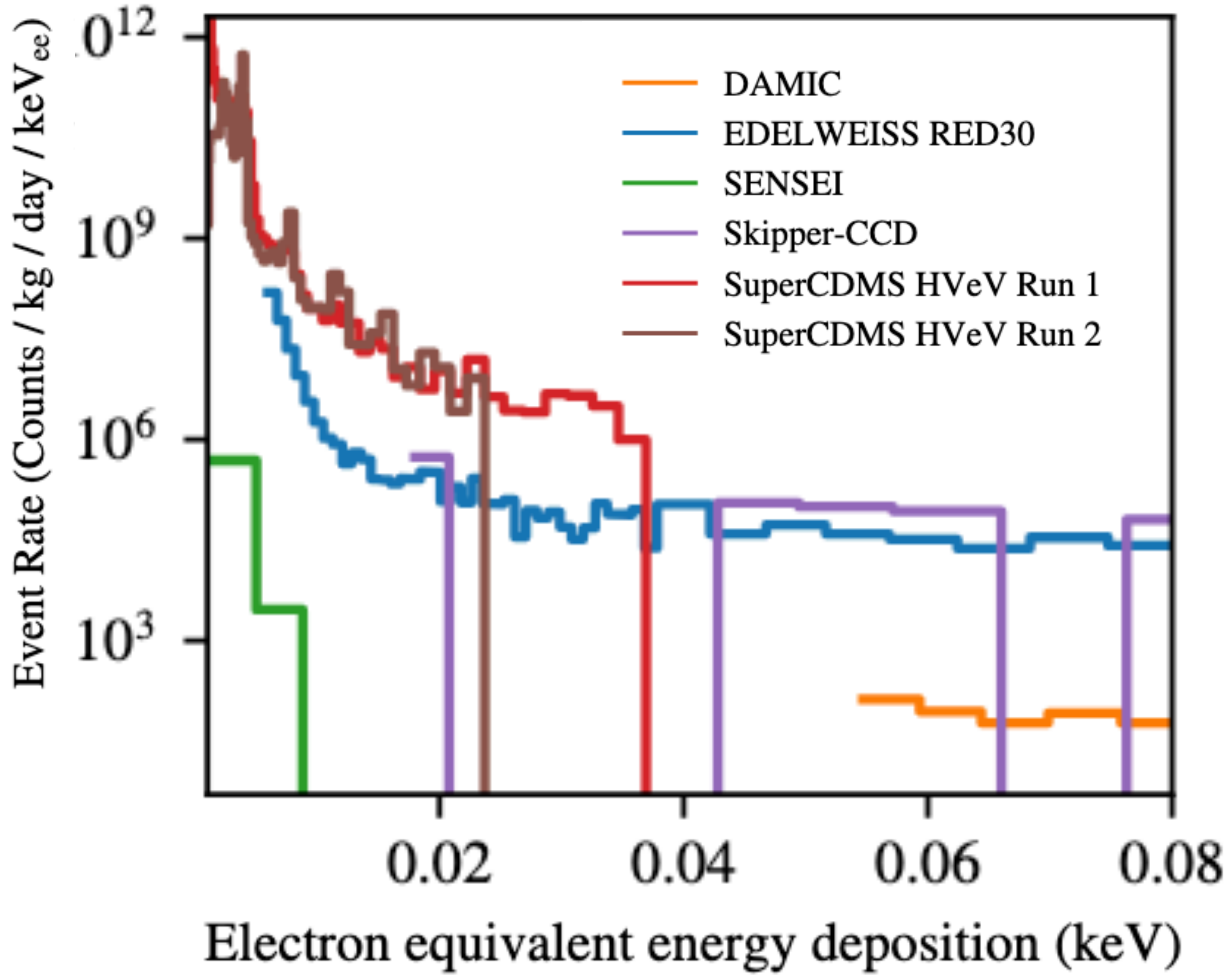
- Electron recoils:
  the e⁻ (not $\chi$) sets the typical momentum transfer

$$v_e \sim \alpha \gg v_o \quad \sim 10^{-3} \quad \text{(outer shell electron)}$$

$$q_{\rm typ} \simeq \mu_{\chi e} v_{\rm rel} \sim \alpha m_e \sim 4 \text{ keV}$$

$$\Delta E_e \simeq q_{\rm typ}\, v_o \simeq \text{few eV}$$

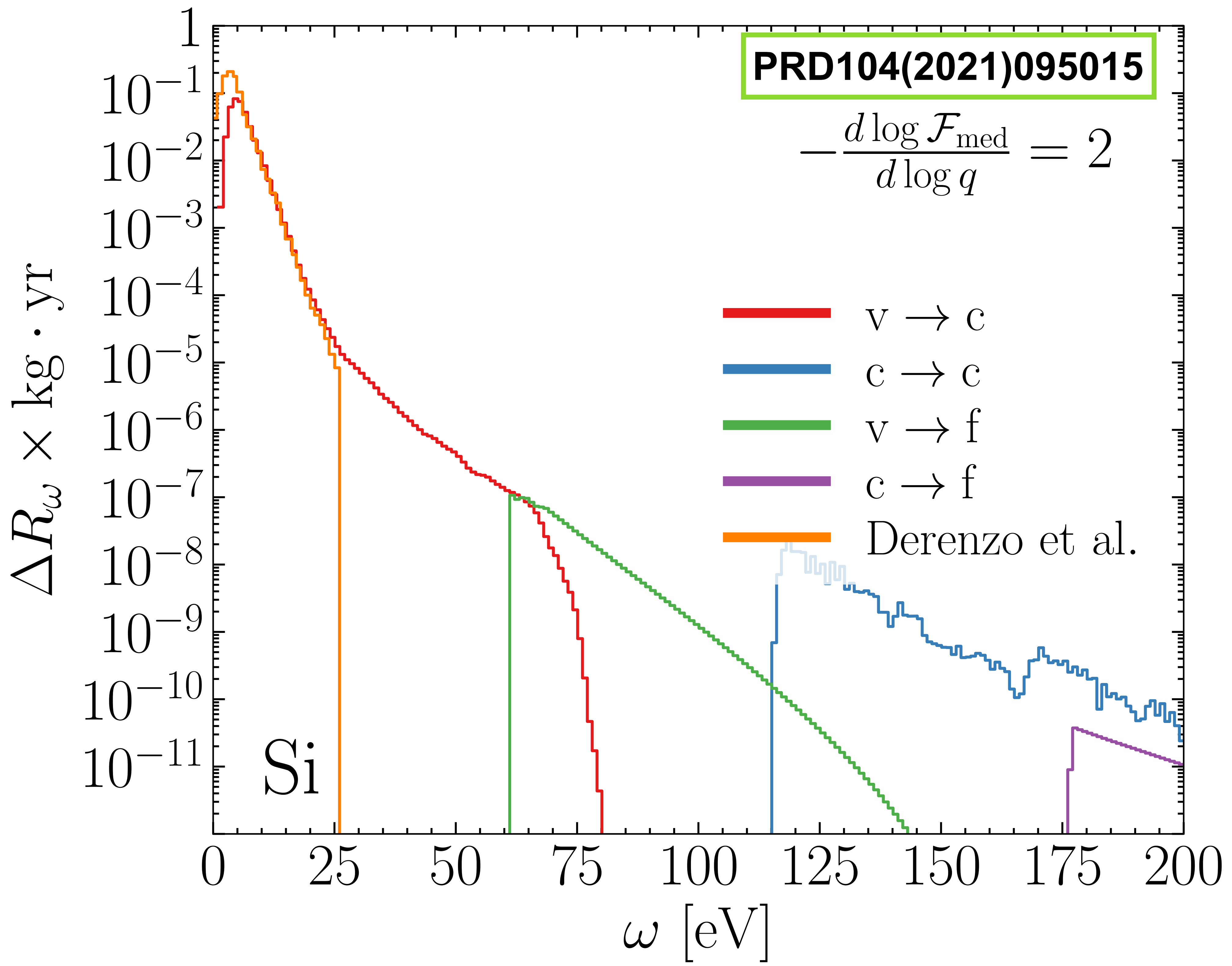
EXCESS Wkshop 2022




MeV scale DM accessible to detectors with single-electron resolution

(much more difficult with nuclear recoils)

- Your detector must also have very low intrinsic dark current




Required a theory effort to calculate rates: QEDARK, DarkELF, EXCEED-DM, QCDARK

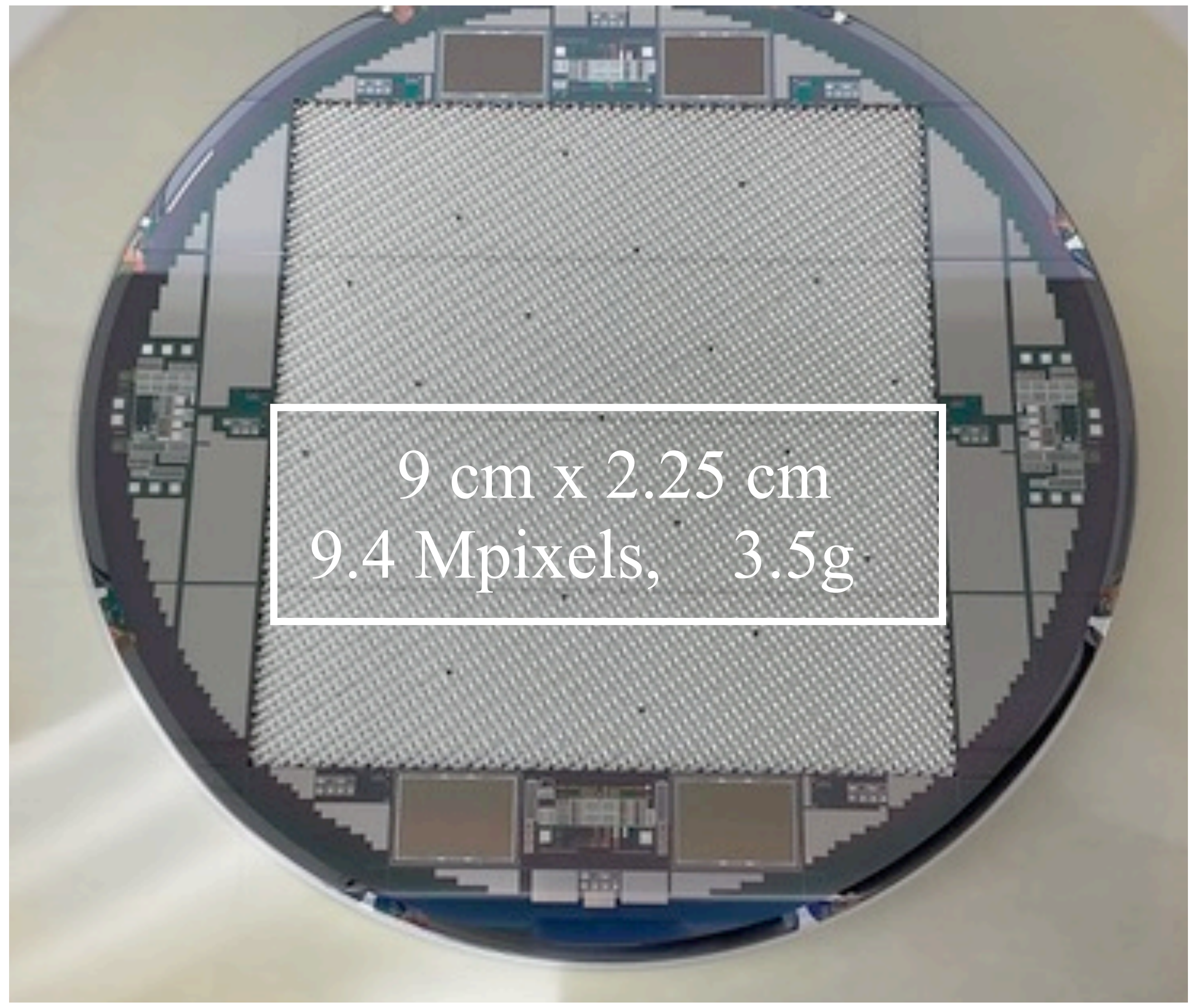
3.7 eV to produce an e-h pair in Si,

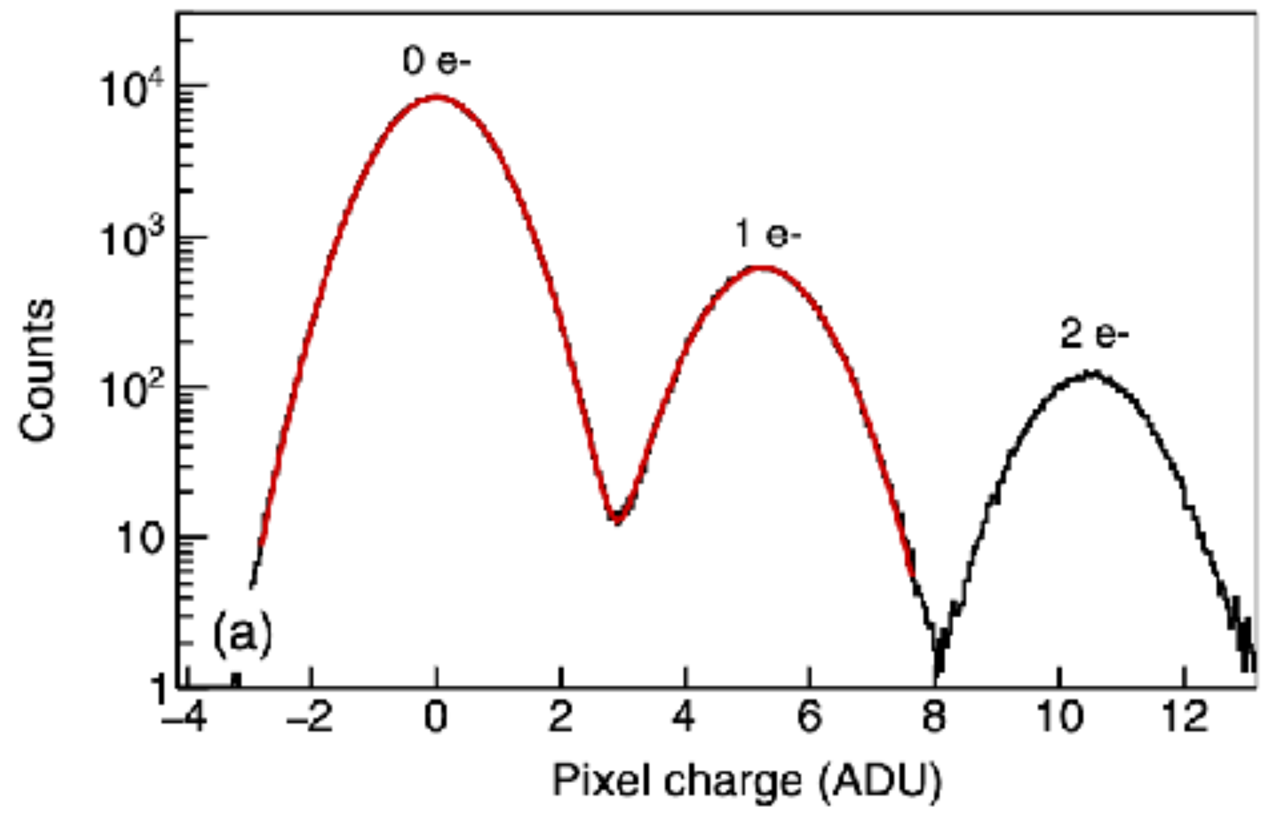
1.2 eV band gap

# DArk Matter In CCDs at Modane

**DAMIC-M in a nutshell**

- detect nuclear and electron recoils to search for light dark matter candidates (eV to GeV), particularly sensitive to “hidden-sector” dark matter candidates that interact with electrons
- target exposure ~ **1 kg yr** with CCD detectors
- **single electron resolution** to ionization signals, **2-3 electron threshold** (~eV)
- dark current < **100s e-/g/day**
- background rate goal of **~0.1 dru** (events/keV/kg/day)
- scheduled for installation at the Laboratoire Souterrain de Modane (LSM) end of 2025

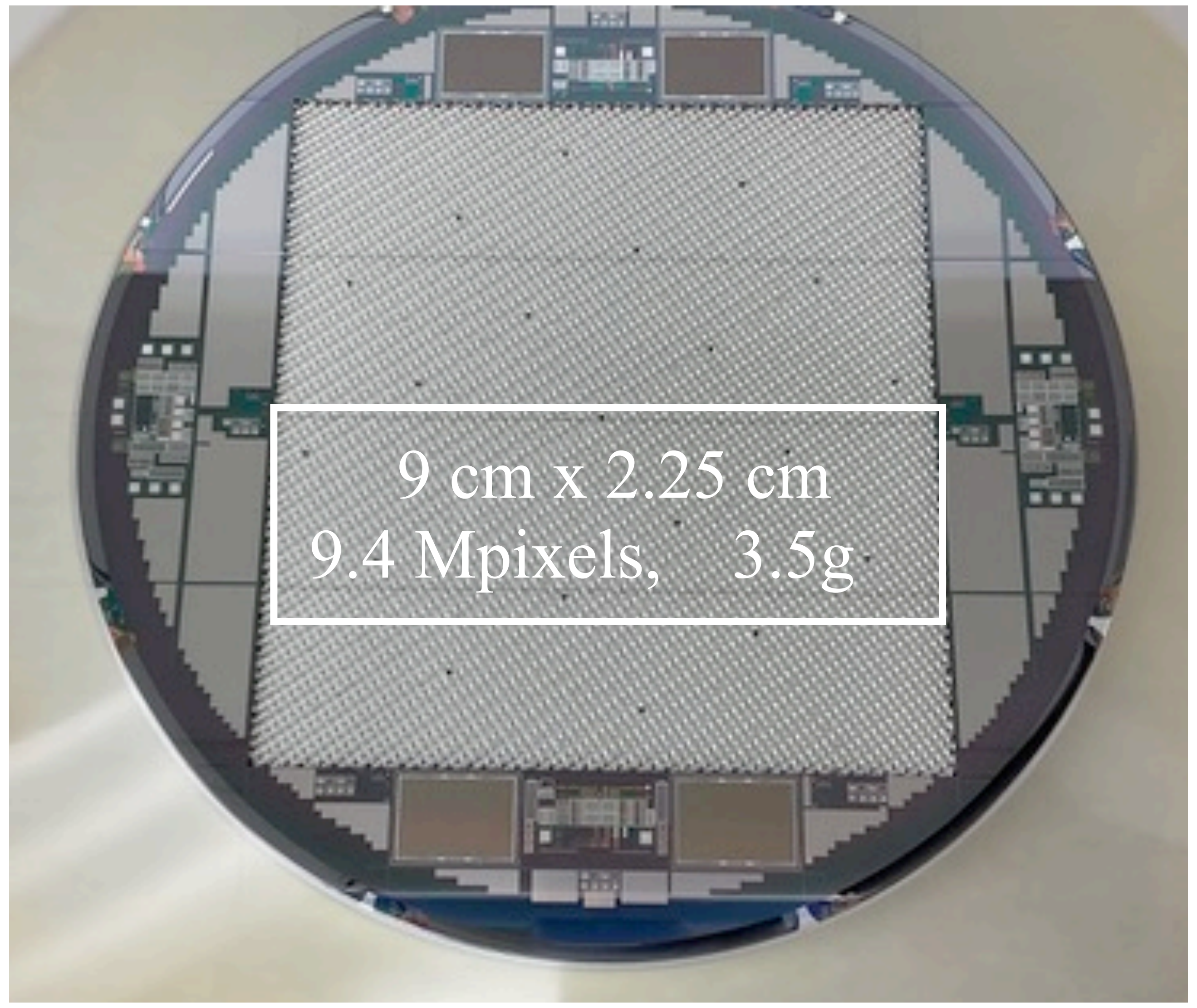


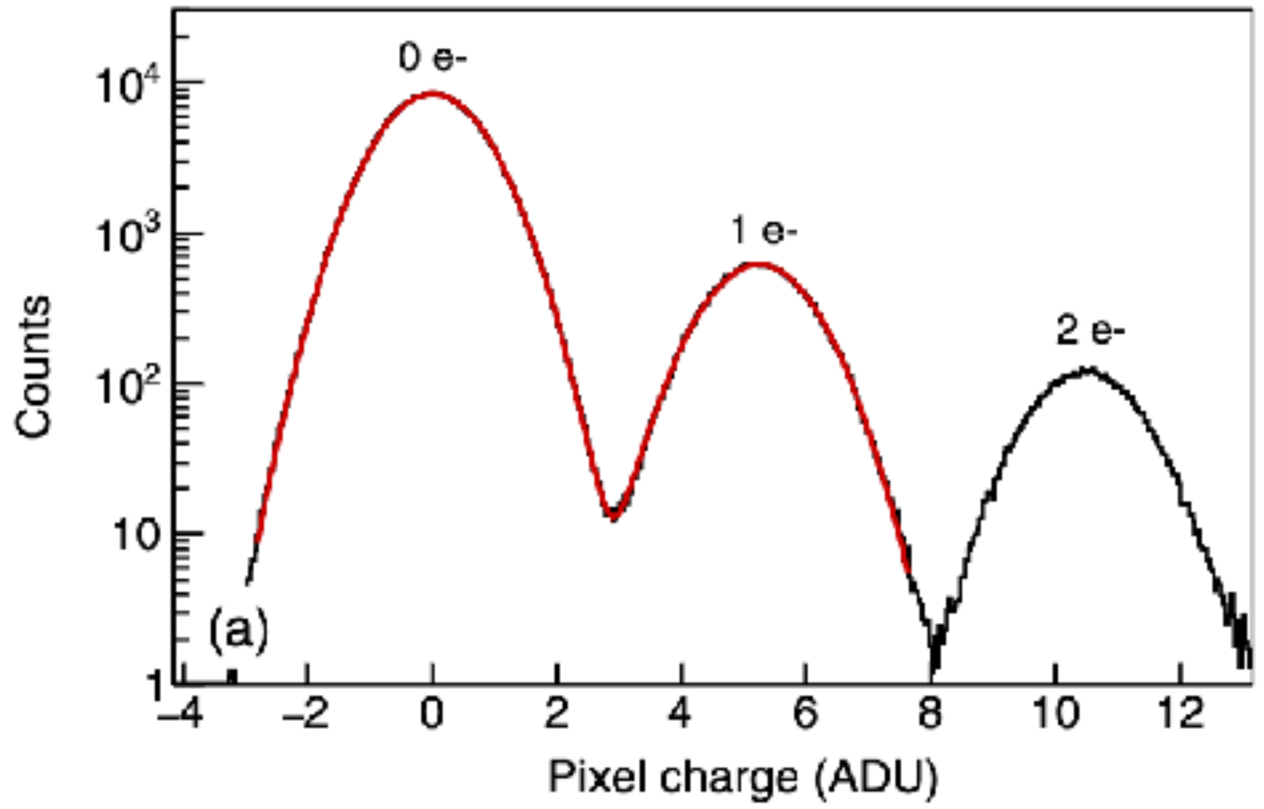



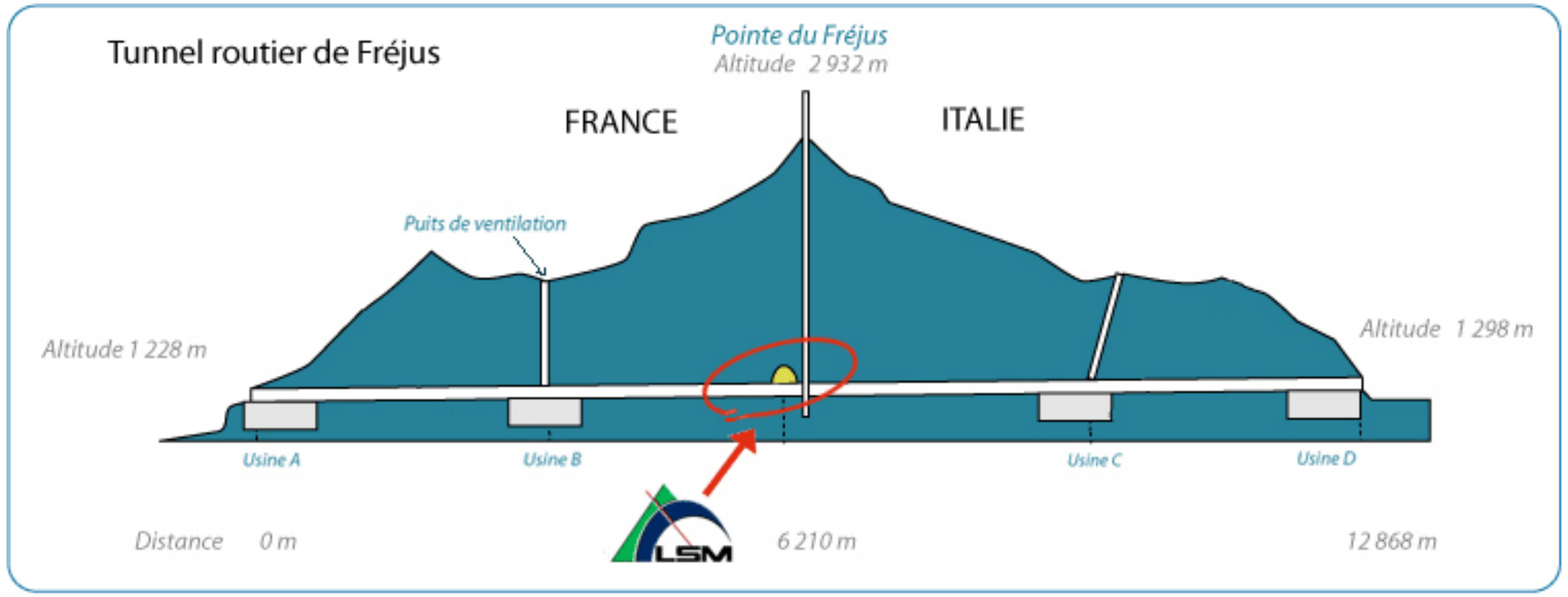

# DArk Matter In CCDs at Modane

**DAMIC-M in a nutshell**

- detect nuclear and electron recoils to search for light dark matter candidates (eV to GeV), particularly sensitive to “hidden-sector” dark matter candidates that interact with electrons
- target exposure ~ **1 kg yr** with CCD detectors
- **single electron resolution** to ionization signals, **2-3 electron threshold** (~eV)
- dark current < **100s e-/g/day**
- background rate goal of **~0.1 dru** (events/keV/kg/day)
- scheduled for installation at the Laboratoire Souterrain de Modane (LSM) end of 2025



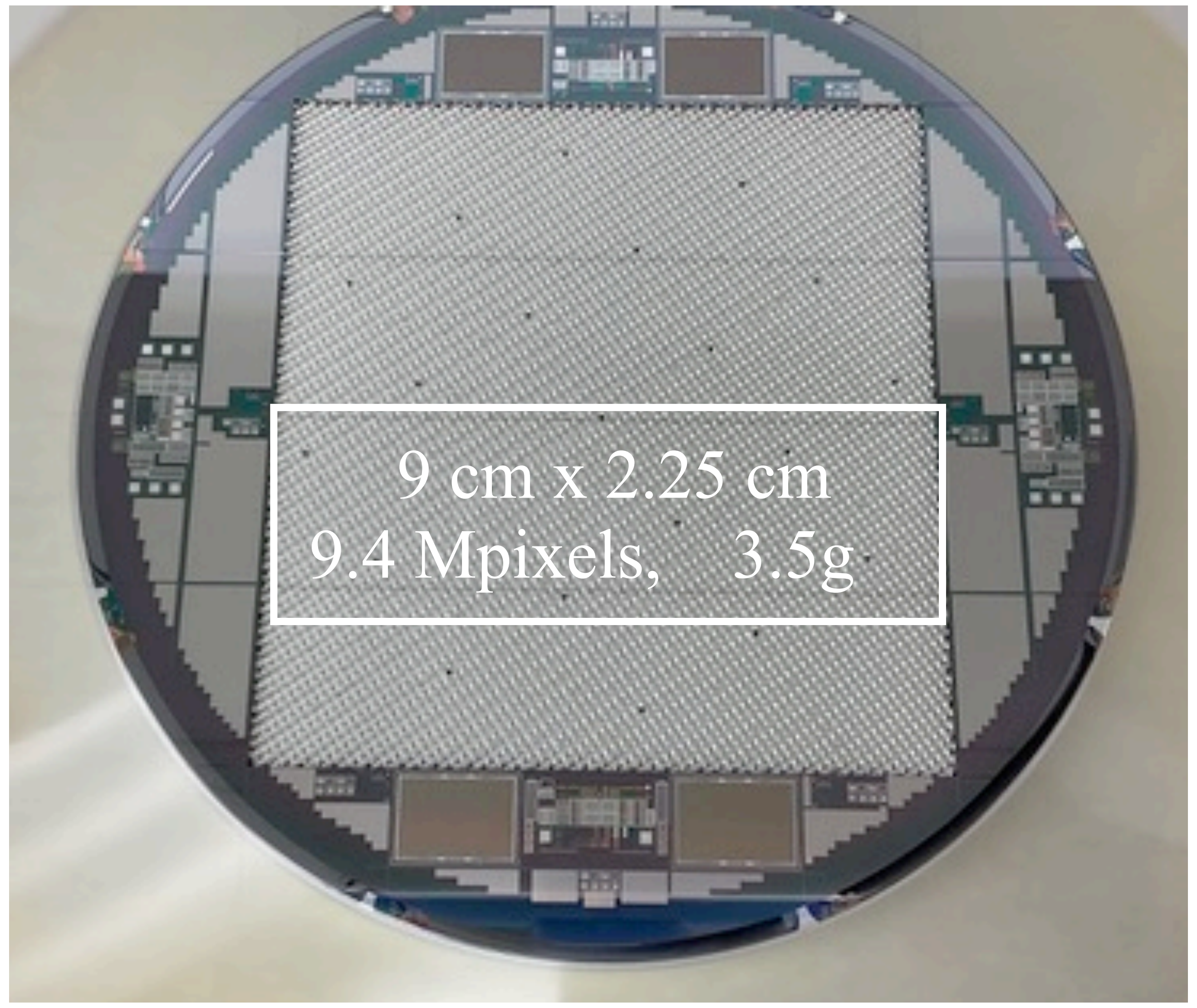



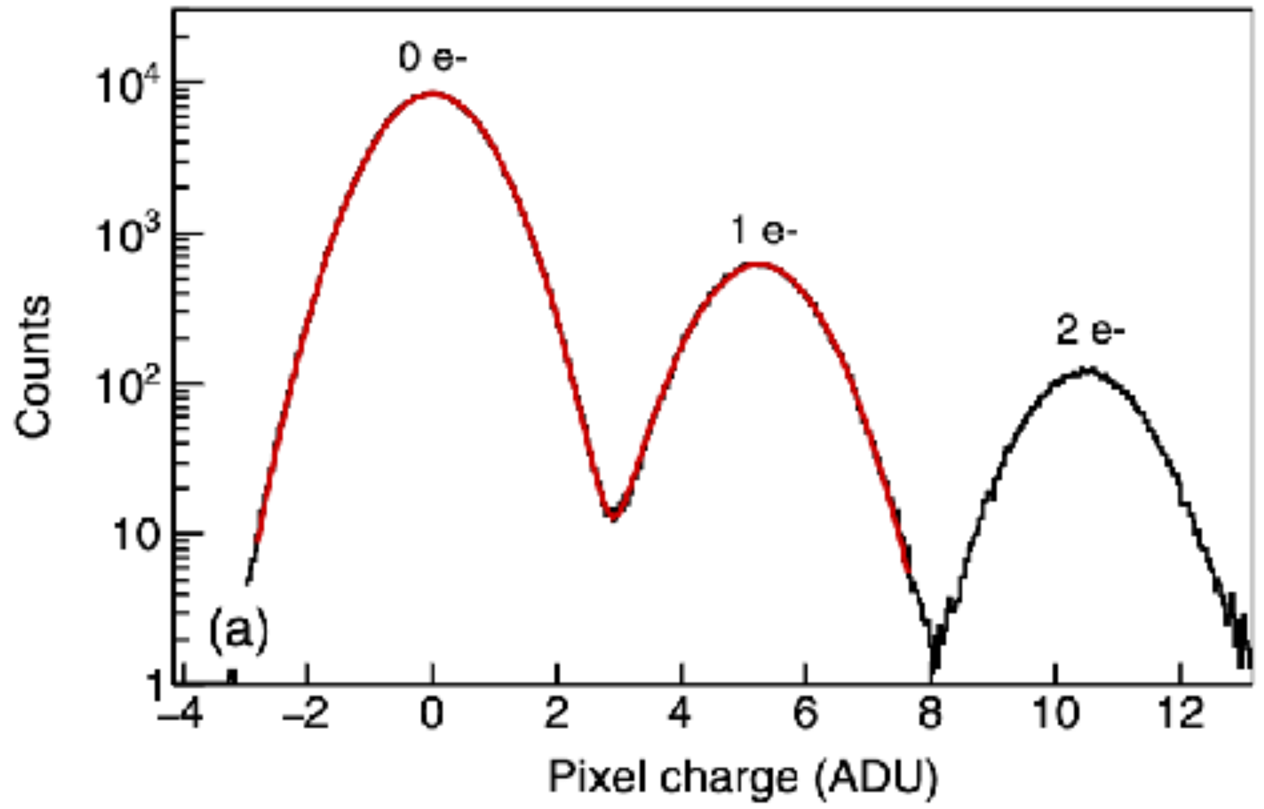



# DArk Matter In CCDs at Modane

**DAMIC-M in a nutshell**

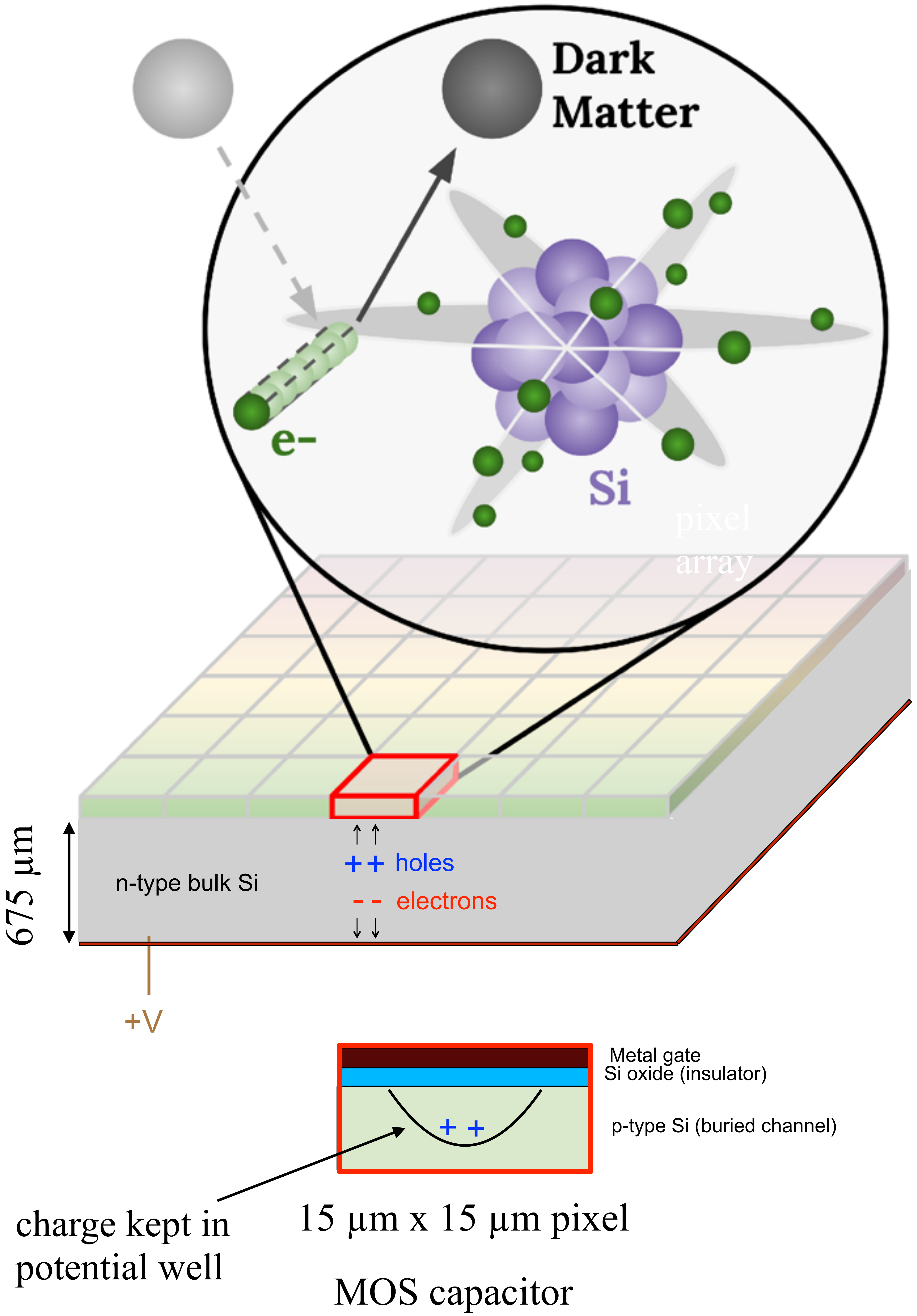
- detect nuclear and electron recoils to search for light dark matter candidates (eV to GeV), particularly sensitive to “hidden-sector” dark matter candidates that interact with electrons
- target exposure ~ **1 kg yr** with CCD detectors
- **single electron resolution** to ionization signals, **2-3 electron threshold** (~eV)
- dark current < **100s e-/g/day**
- background rate goal of **~0.1 dru** (events/keV/kg/day)
- scheduled for installation at the Laboratoire Souterrain de Modane (LSM) end of 2025

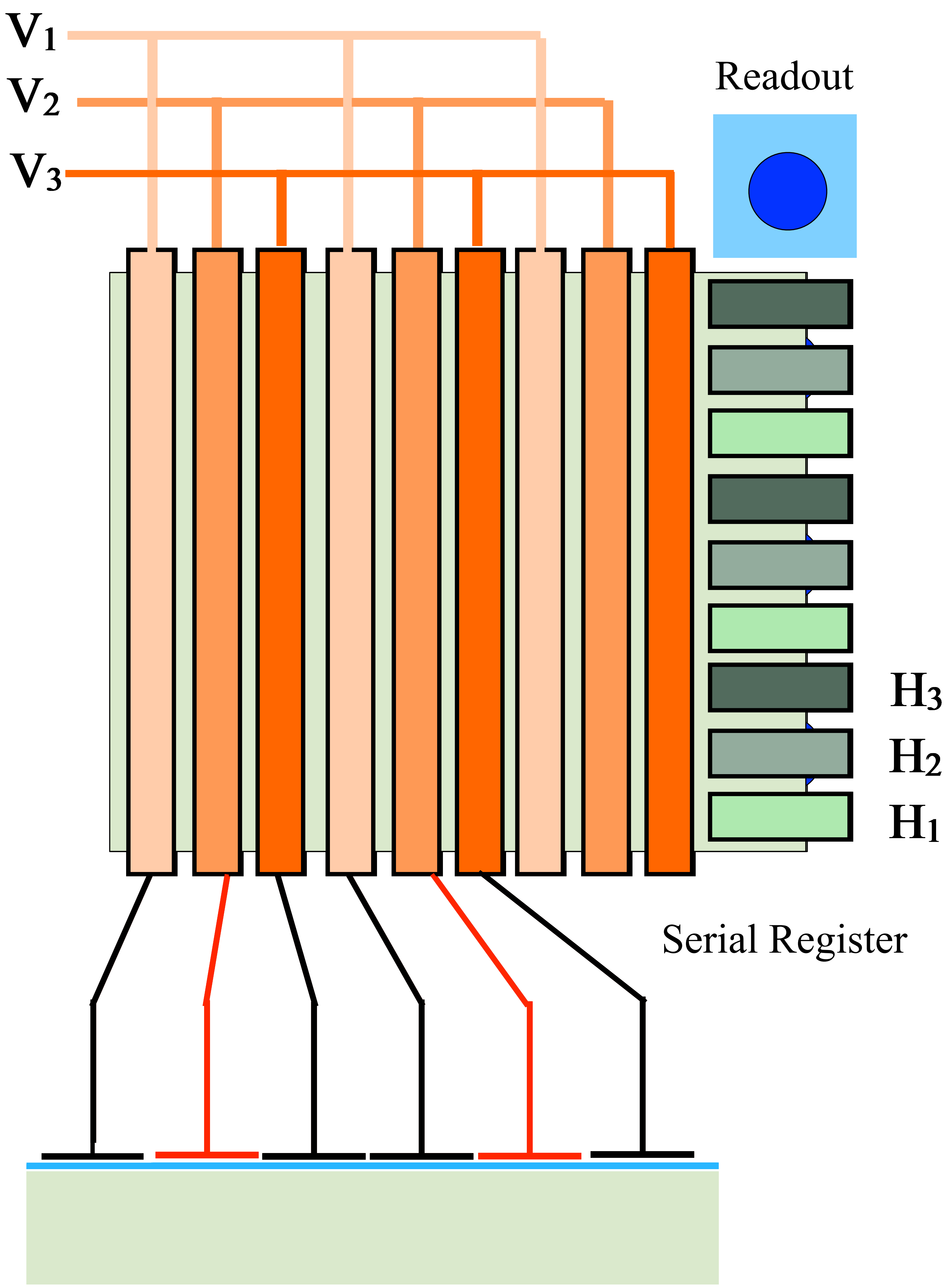


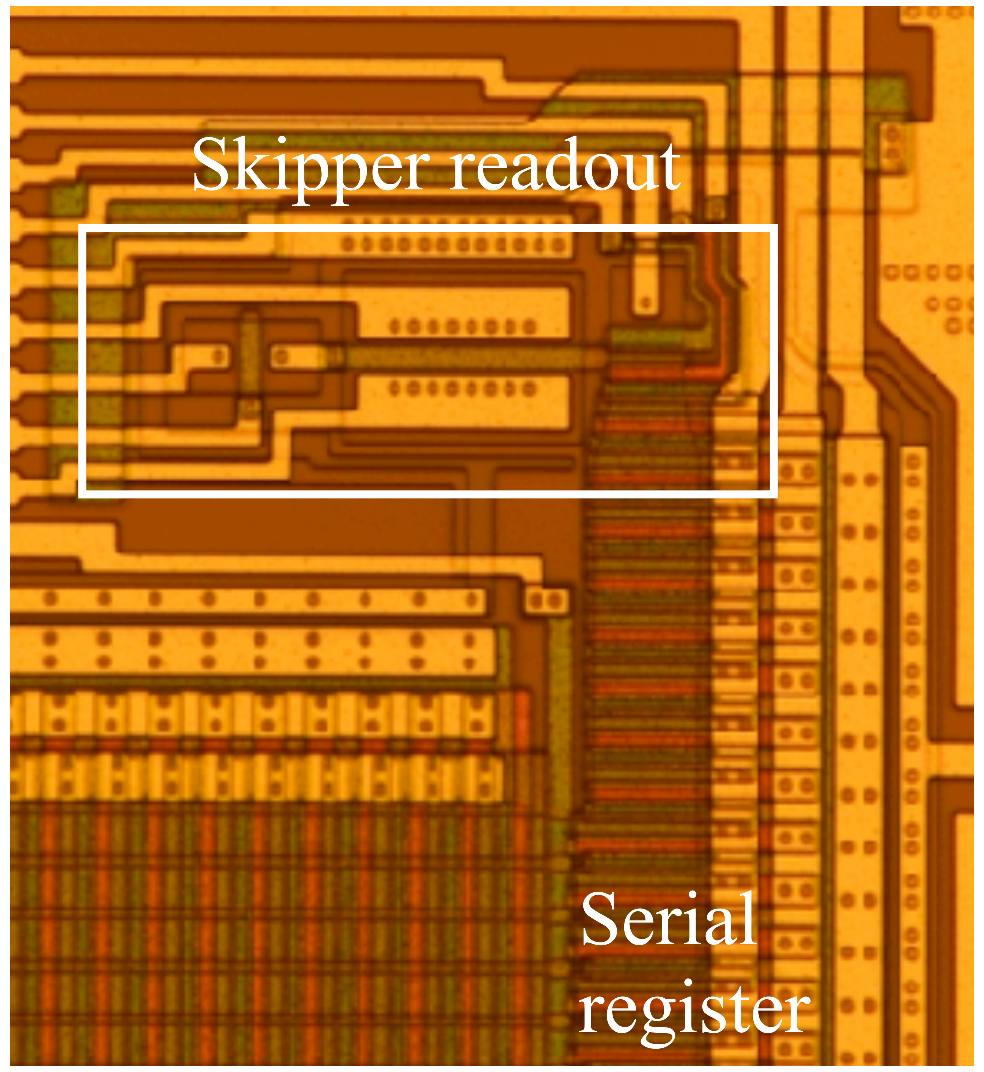




commuting to work

# DM detection with CCDs

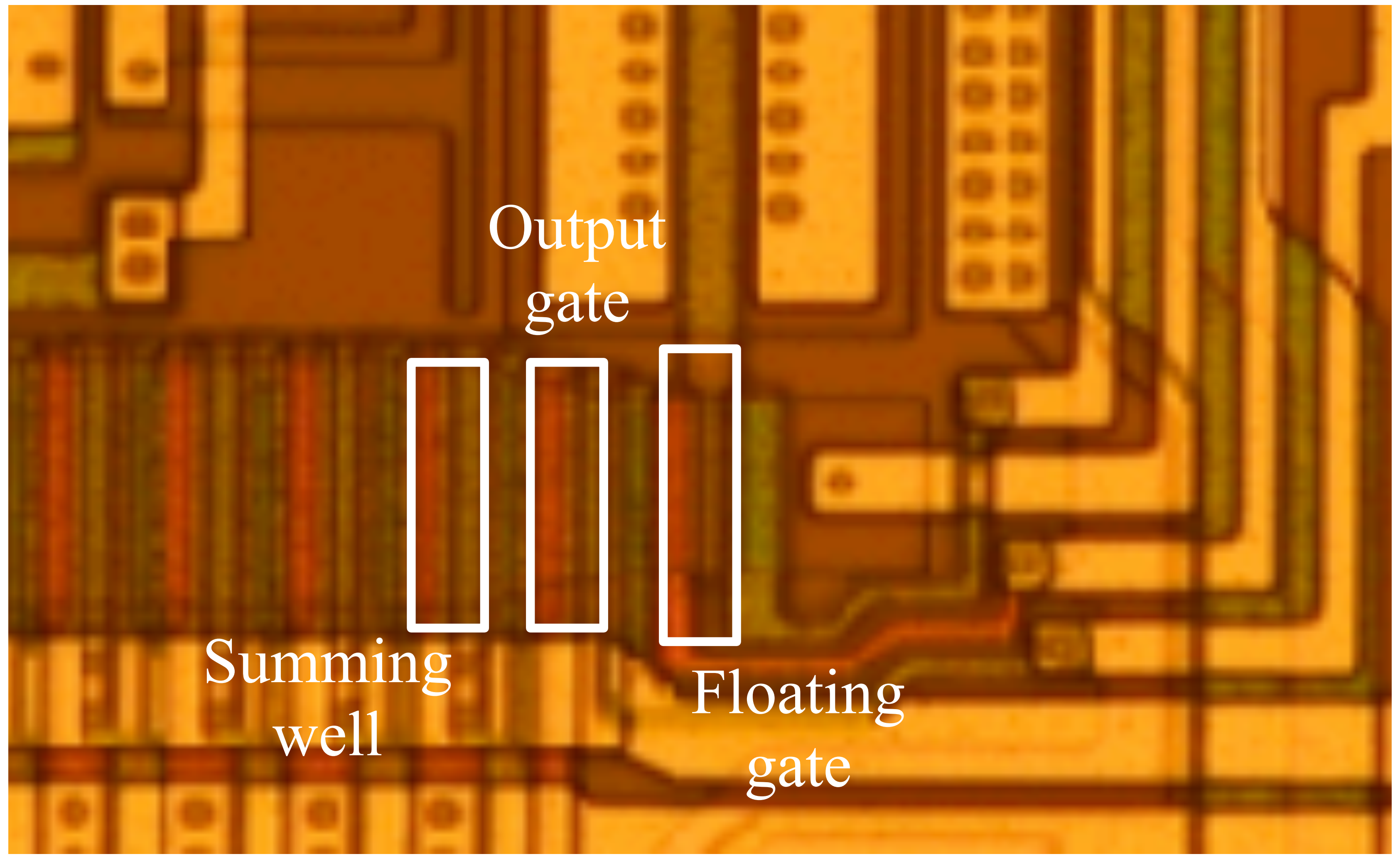


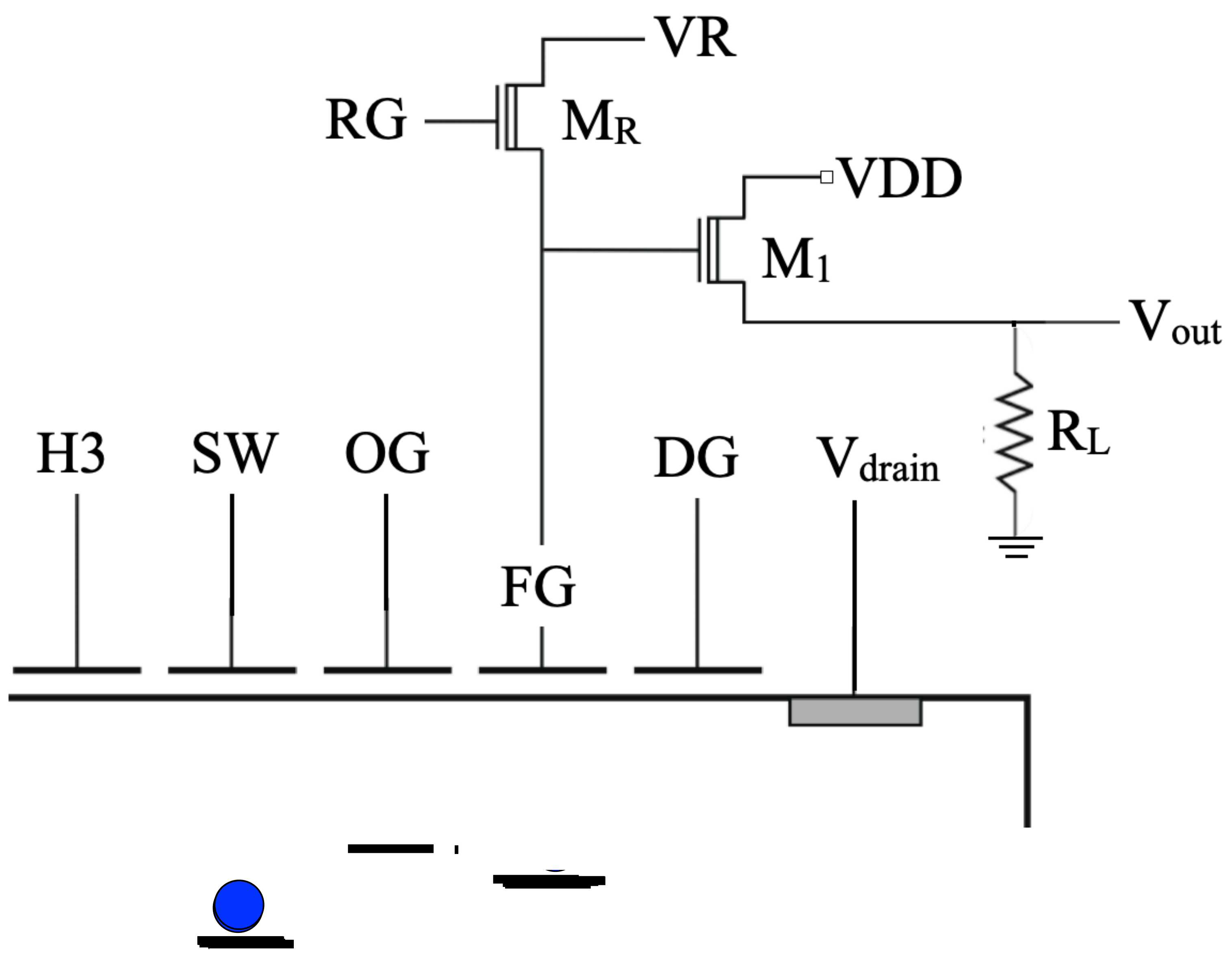



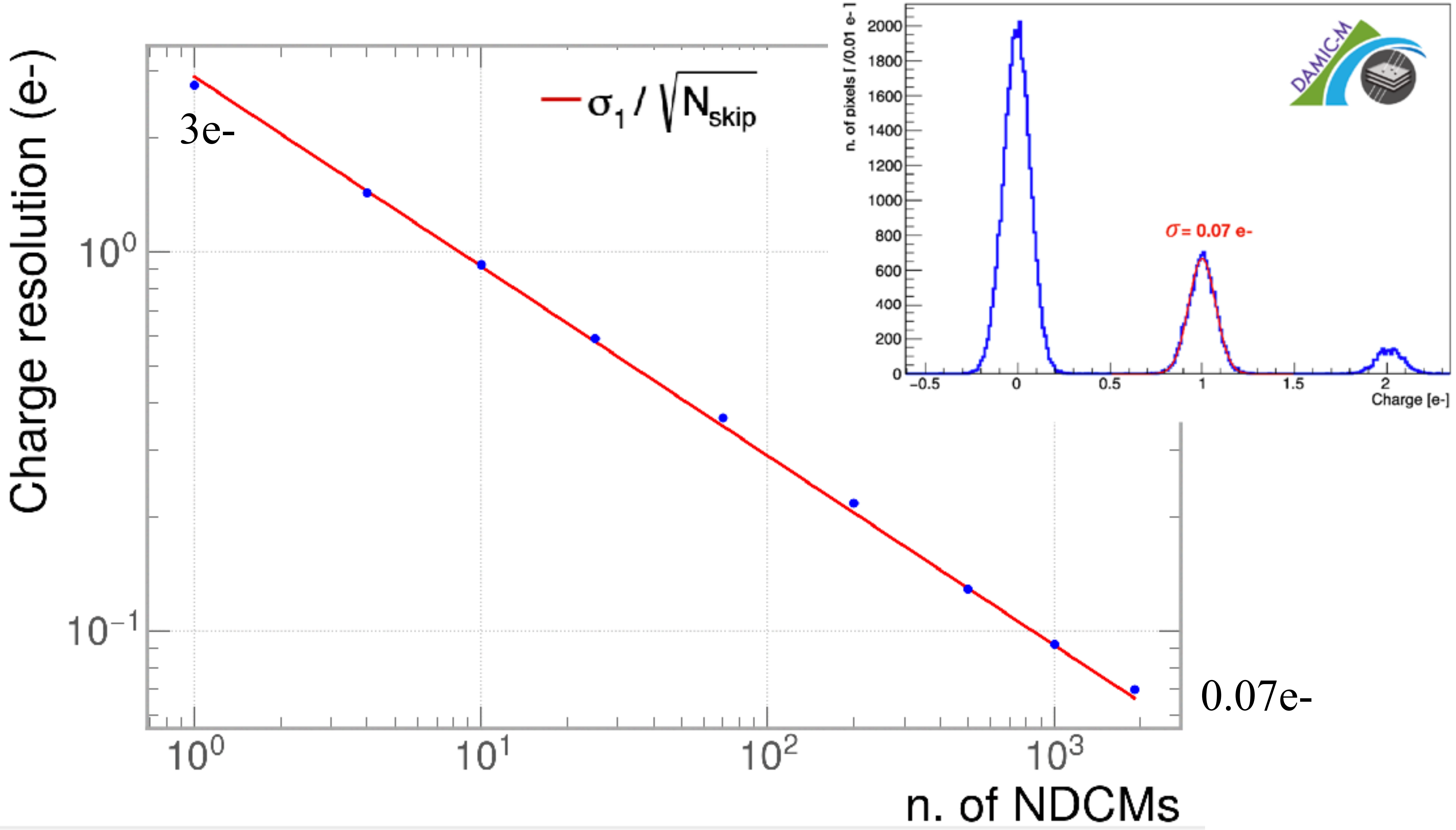

- High voltage, high-resistivity (>10 MOhm cm), fully depleted, p-channel CCD technology (originally developed at LBNL for astronomy)

# Skipper CCD Readout



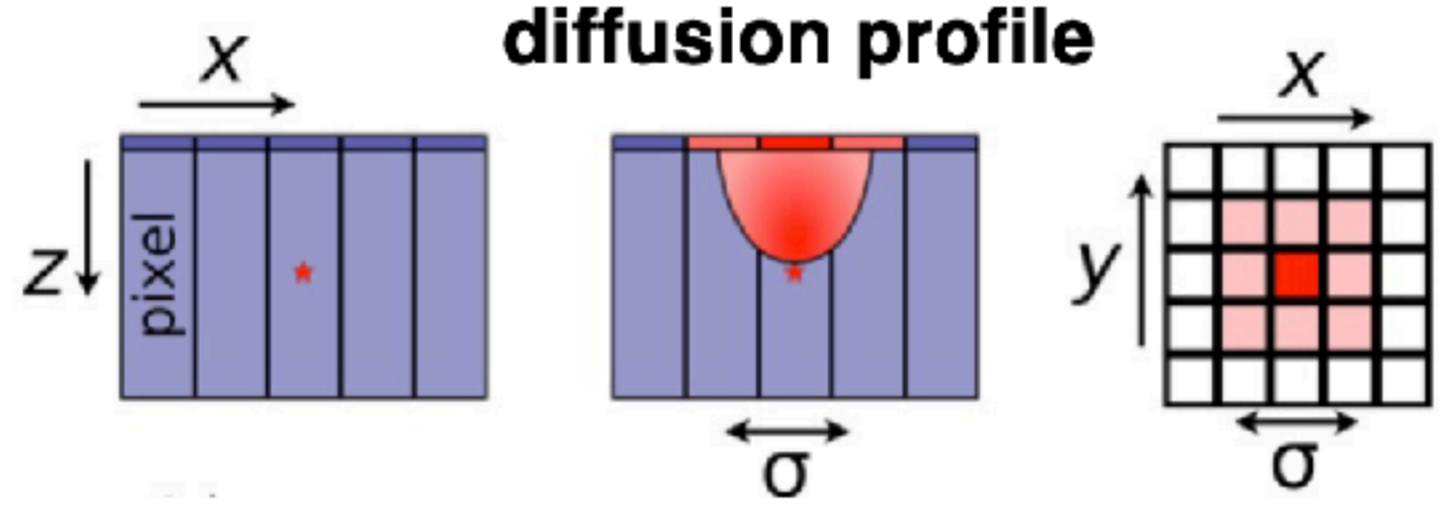



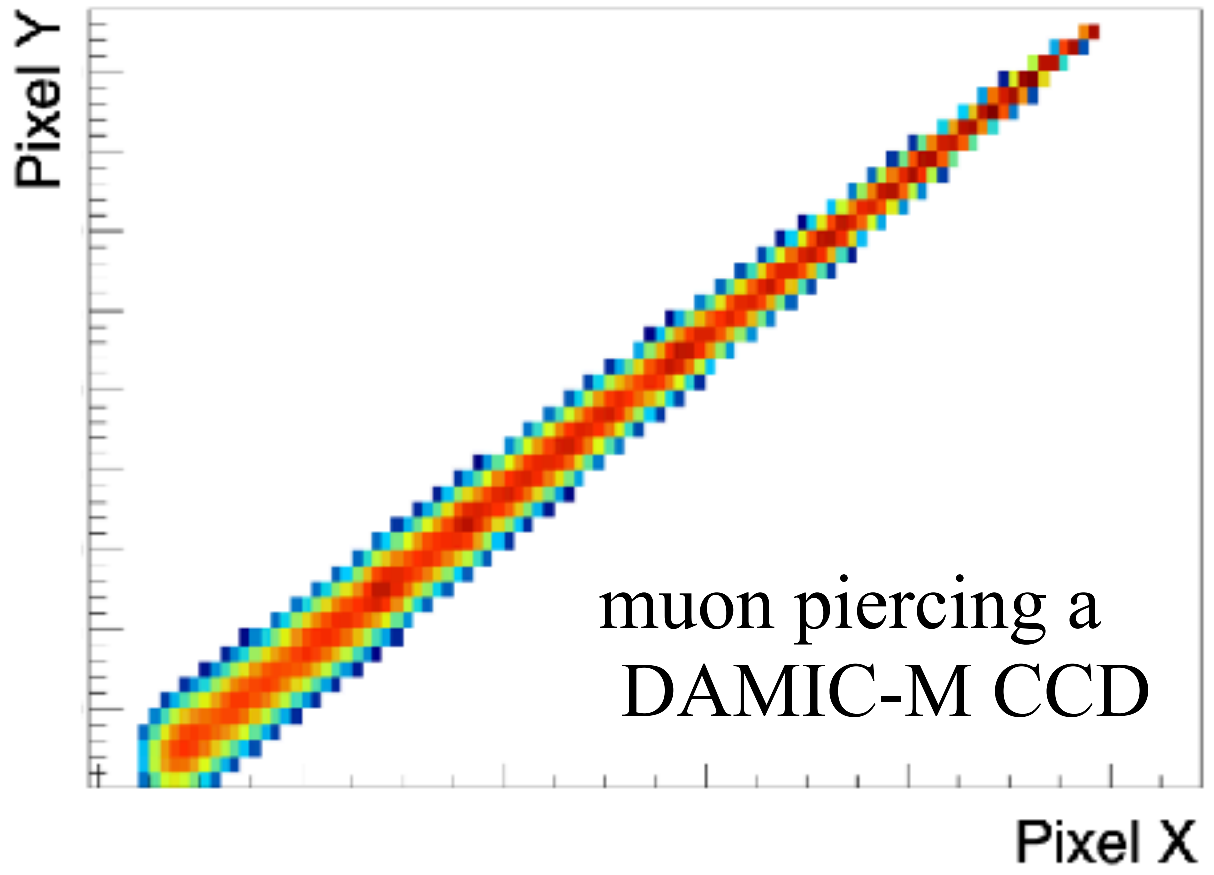

- **Non-destructive charge measurement**, Janesick et al. (1990)
- Re-engineered for LBNL CCDs, Tiffenberg et al. (2017)
- **Single electron resolution** by multiple NDCMs

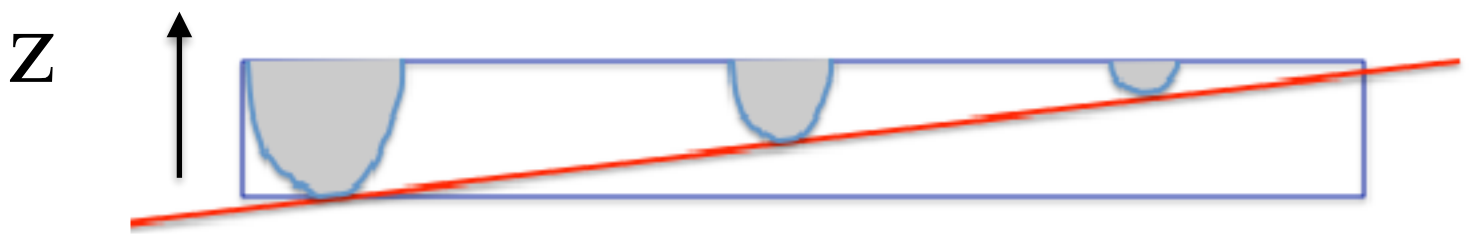



- Pixel readout time O(10 ms) for 0.15e-; ok for DM searches

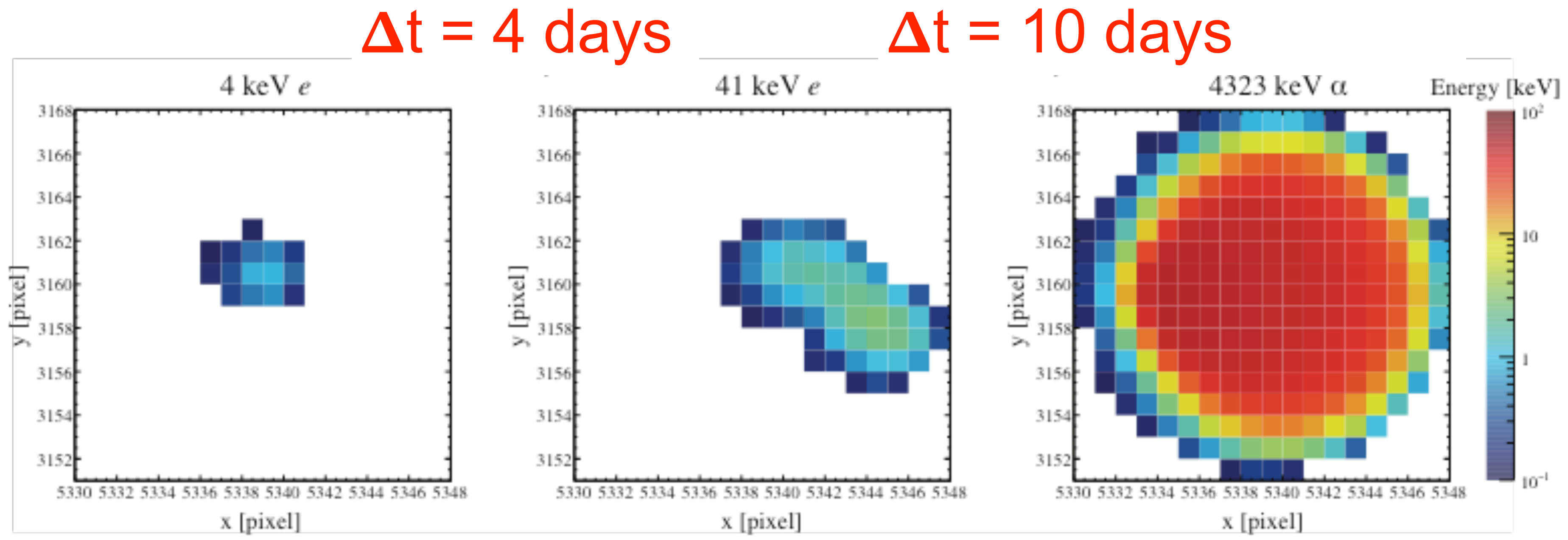
# 3-D spatial reconstruction



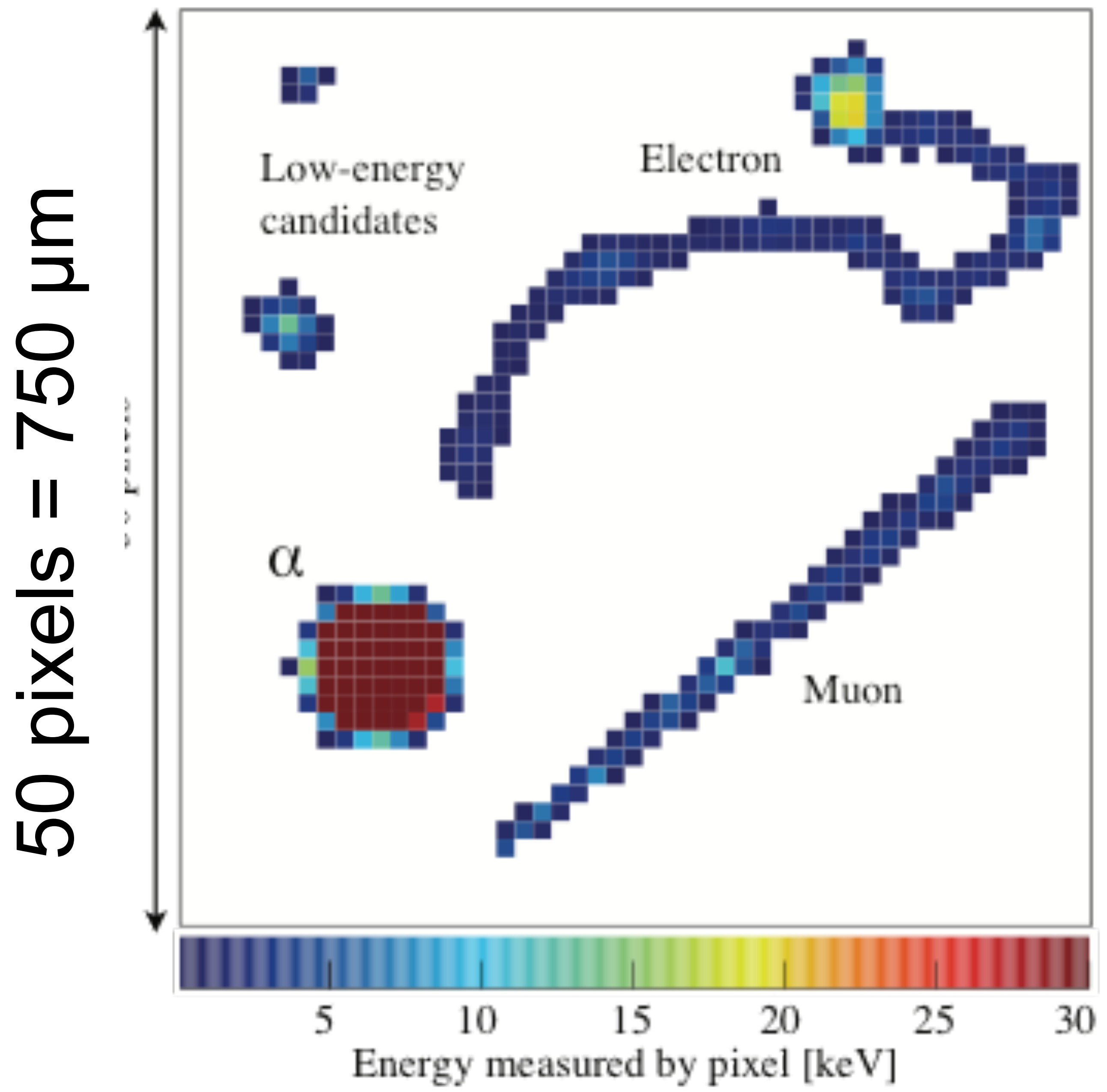




3D reconstruction of energy deposit within the silicon bulk using charge diffusion



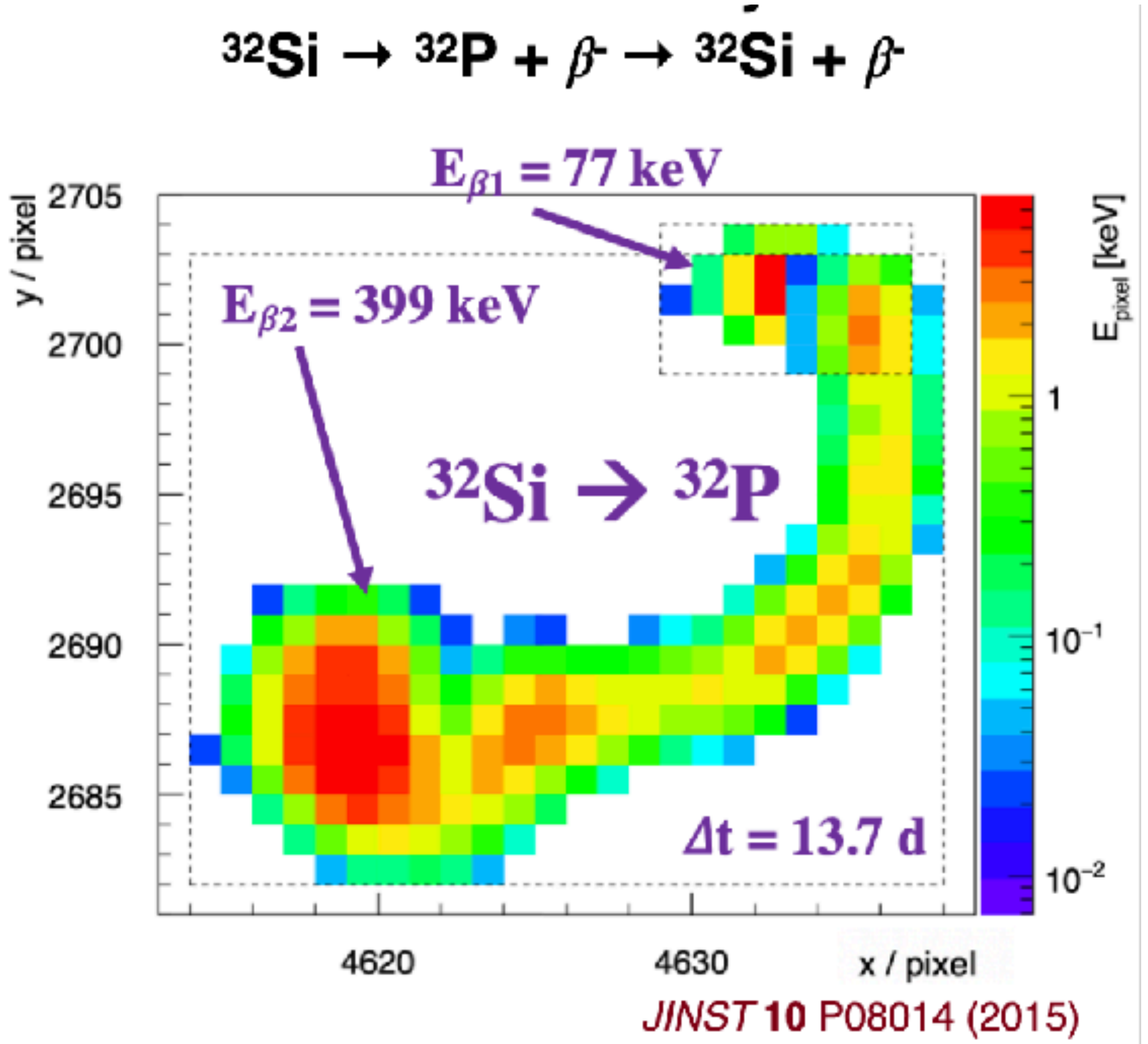

candidate $^{210}$Pb decay chain

measure particle ionization with exquisite spatial resolution



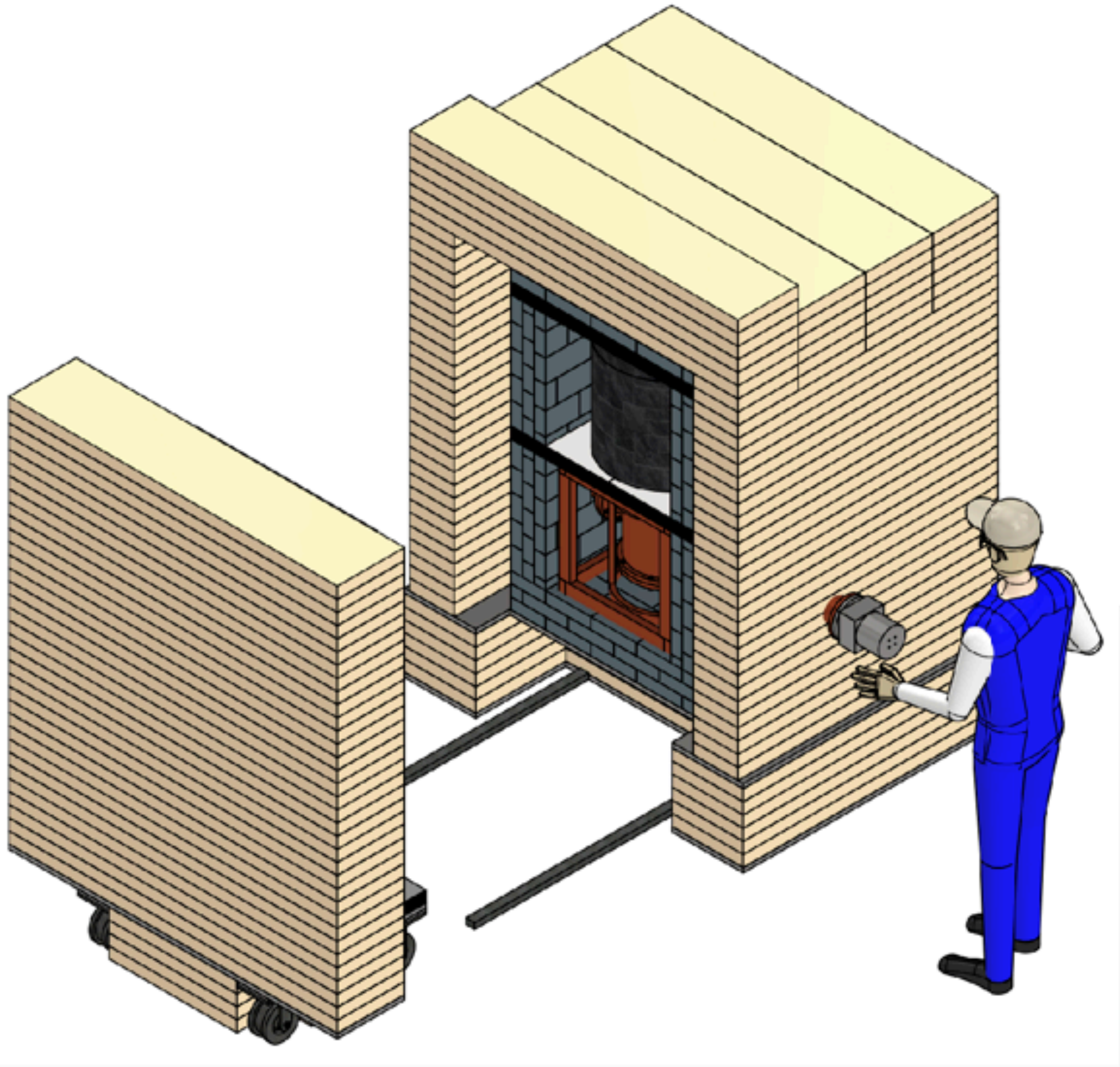

# particle ID

# Background rejection

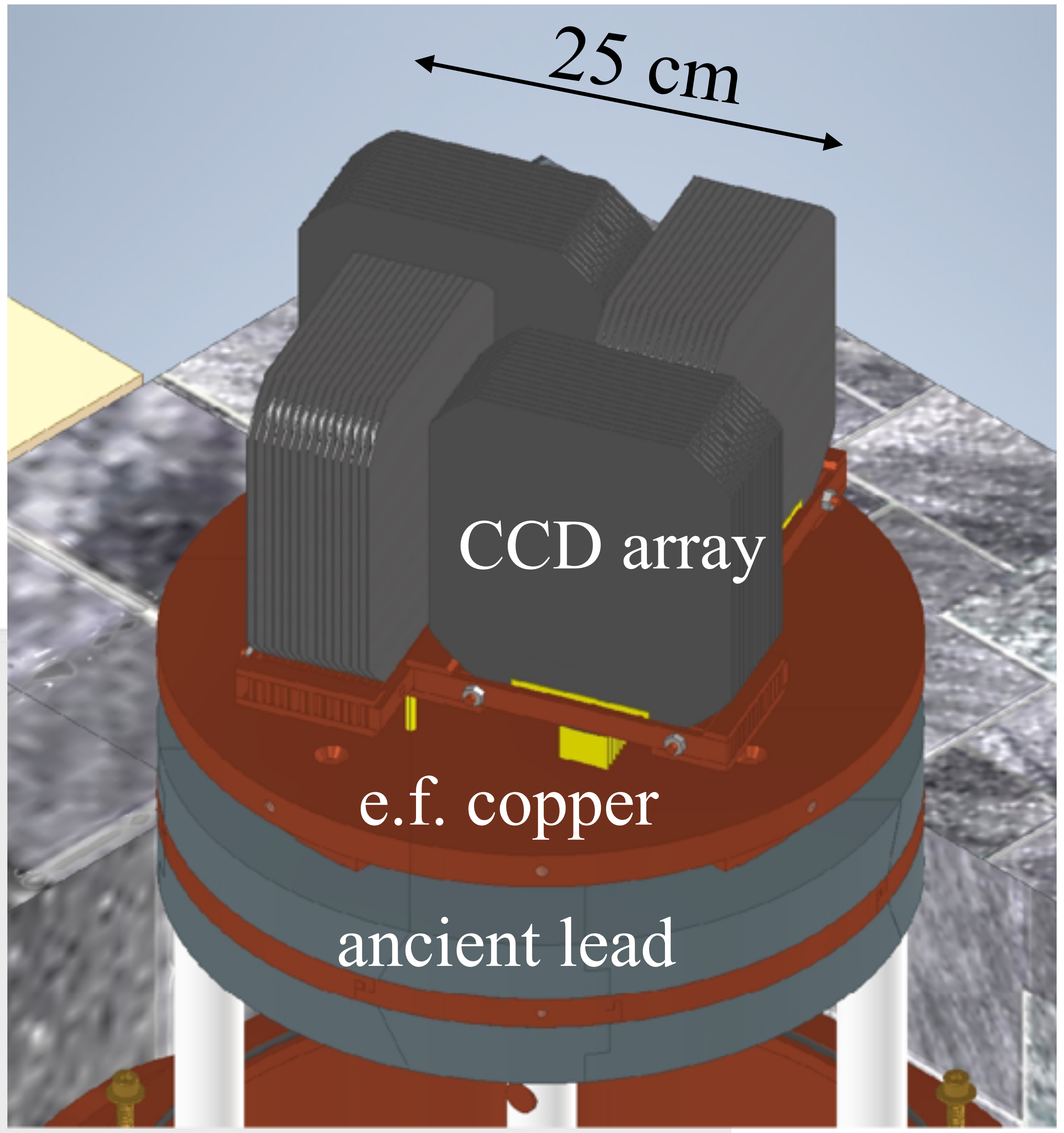


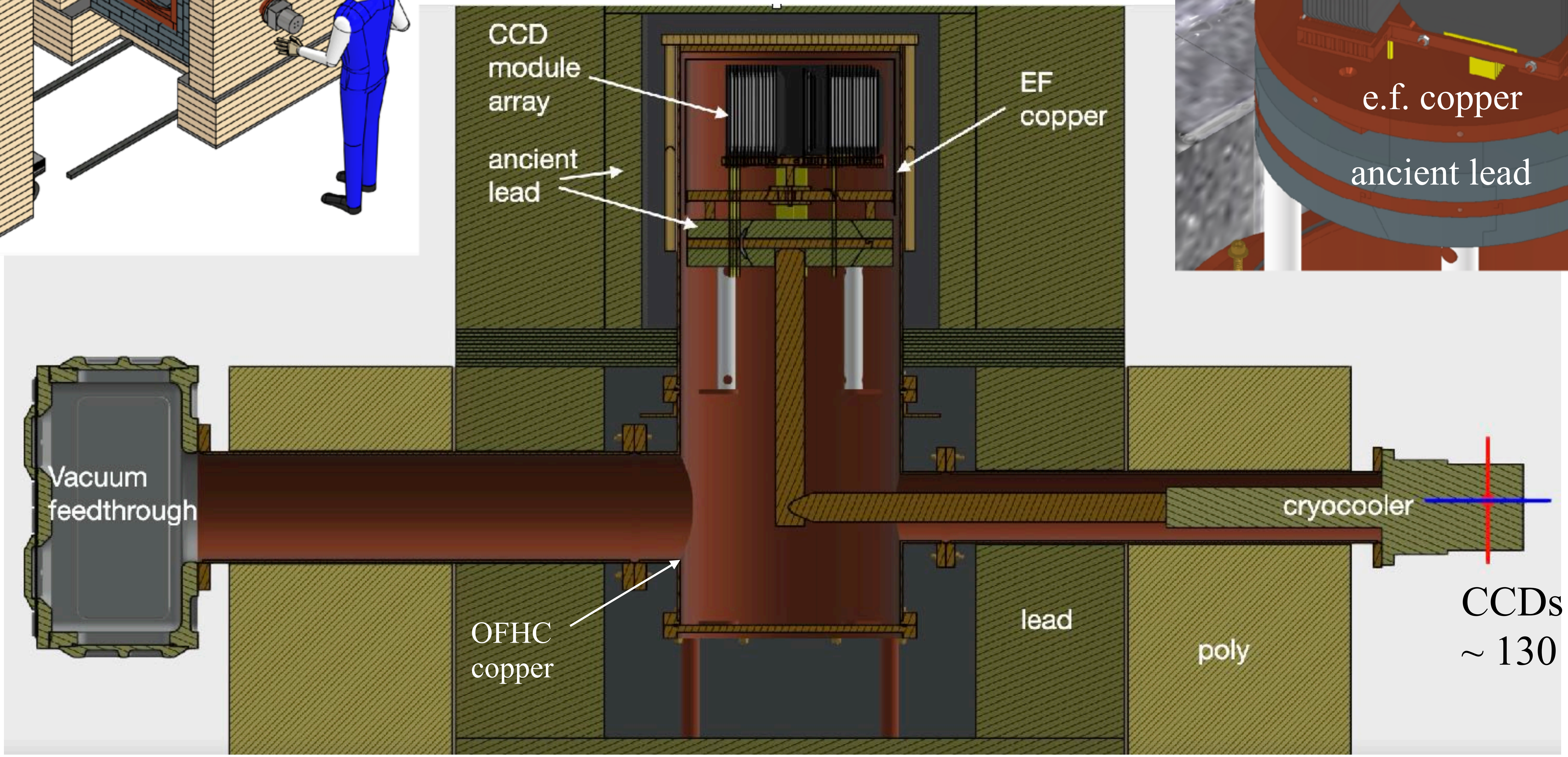

measurement (and rejection) of surface and bulk backgrounds: decay chains detected as spatially correlated, time separated energy clusters

# DAMIC-M



design driven by the stringent requirements on background

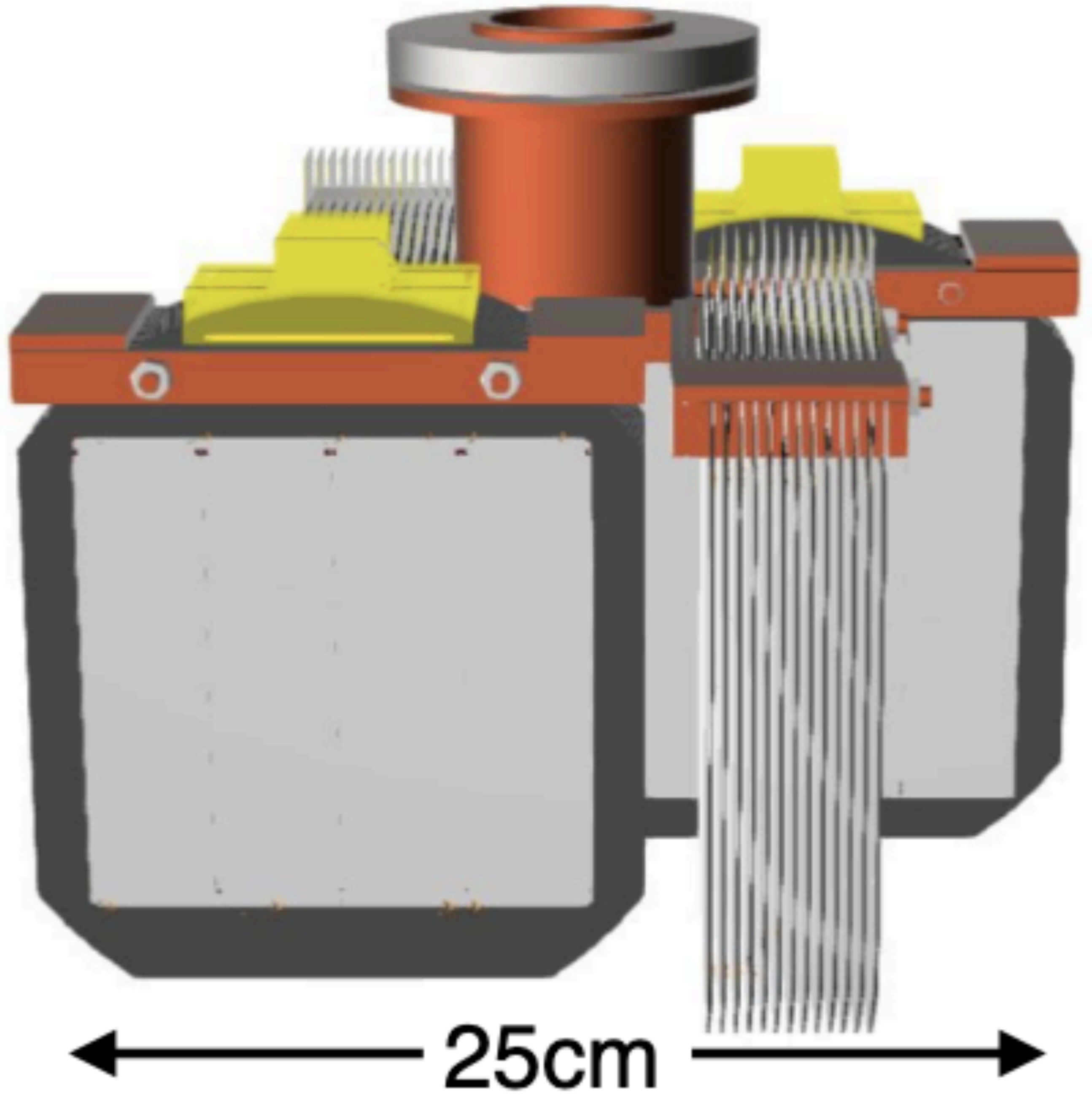



CCDs operated at ~ 130 K

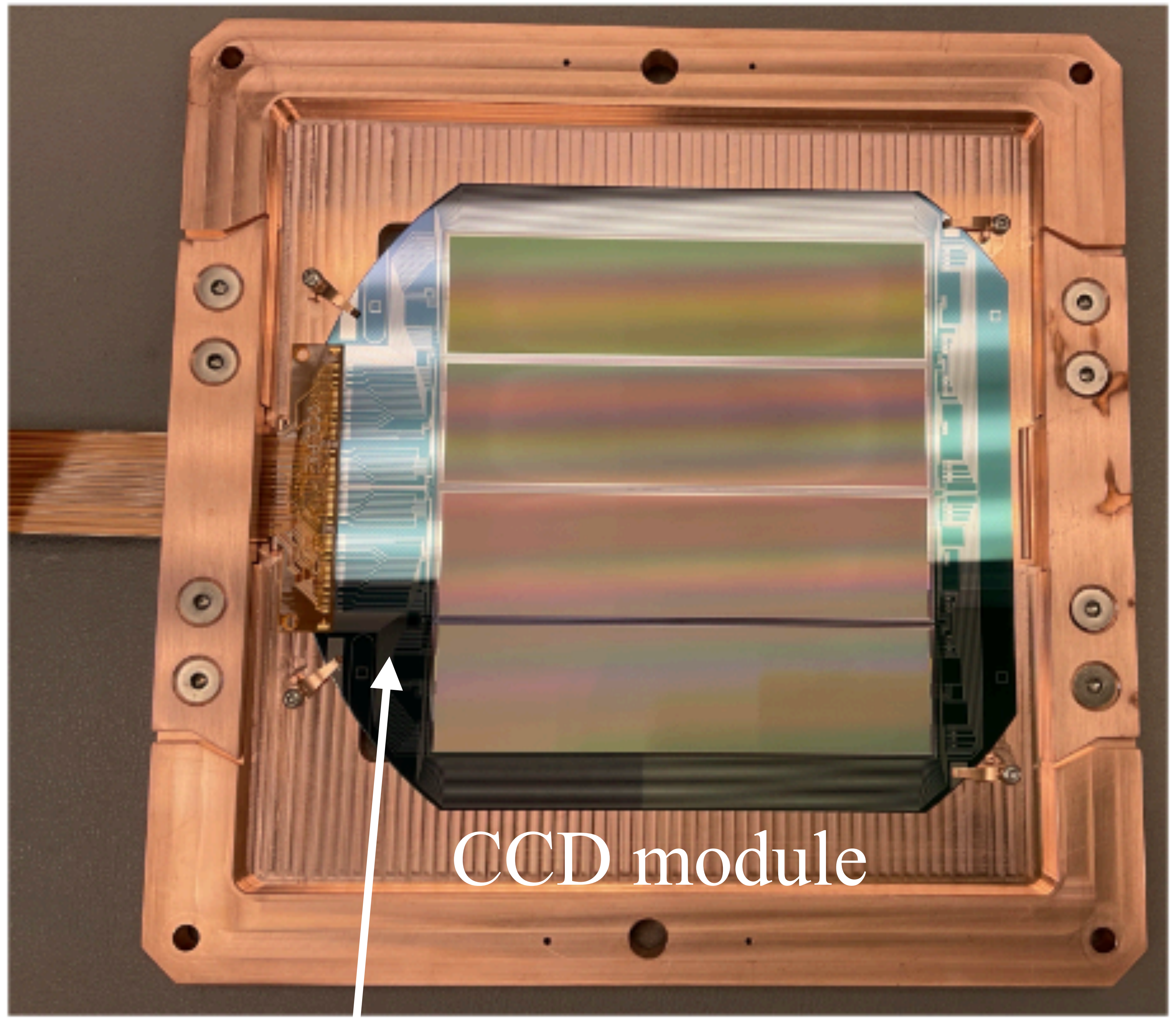
# CCD Module

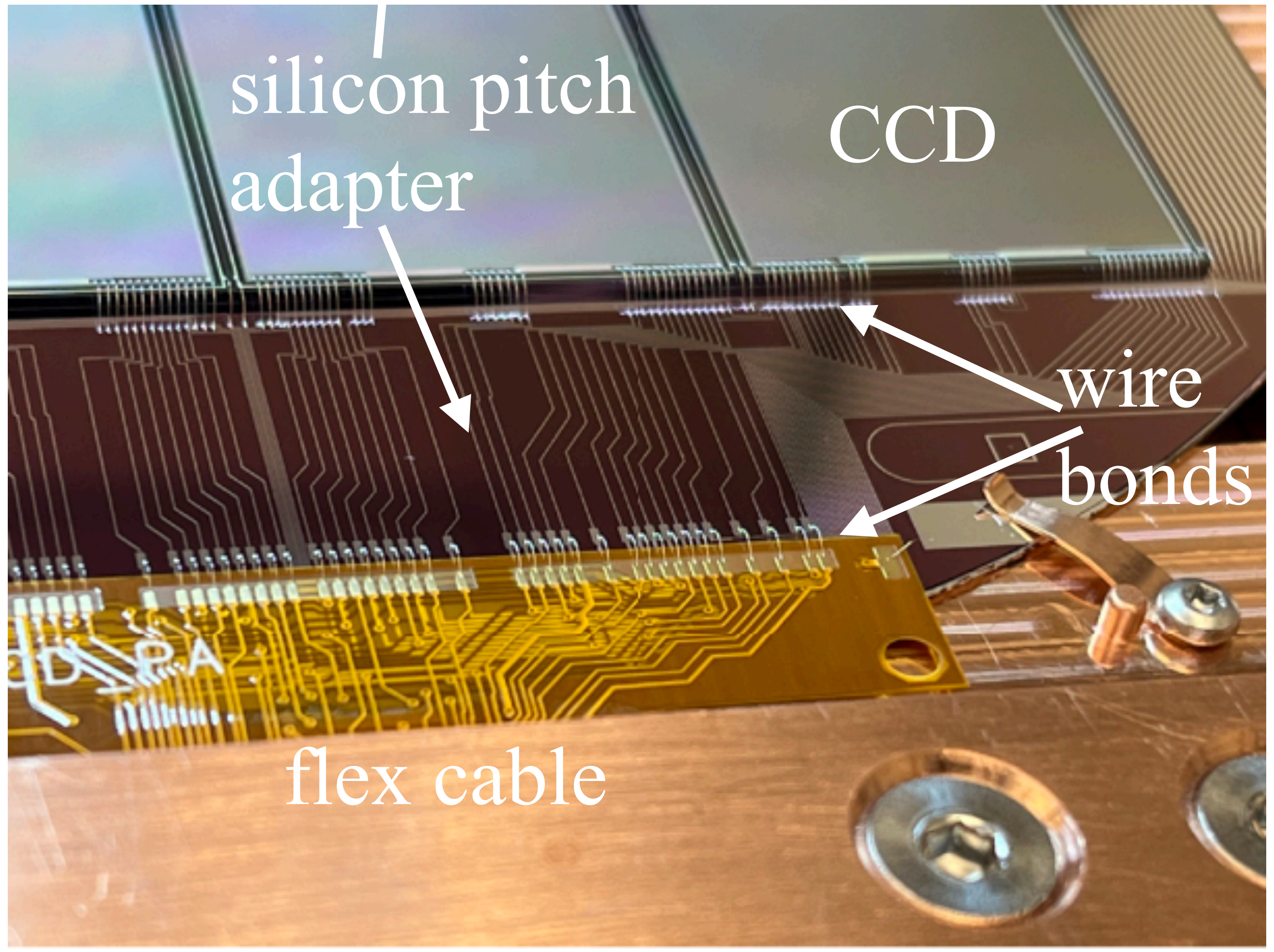
CCD module array

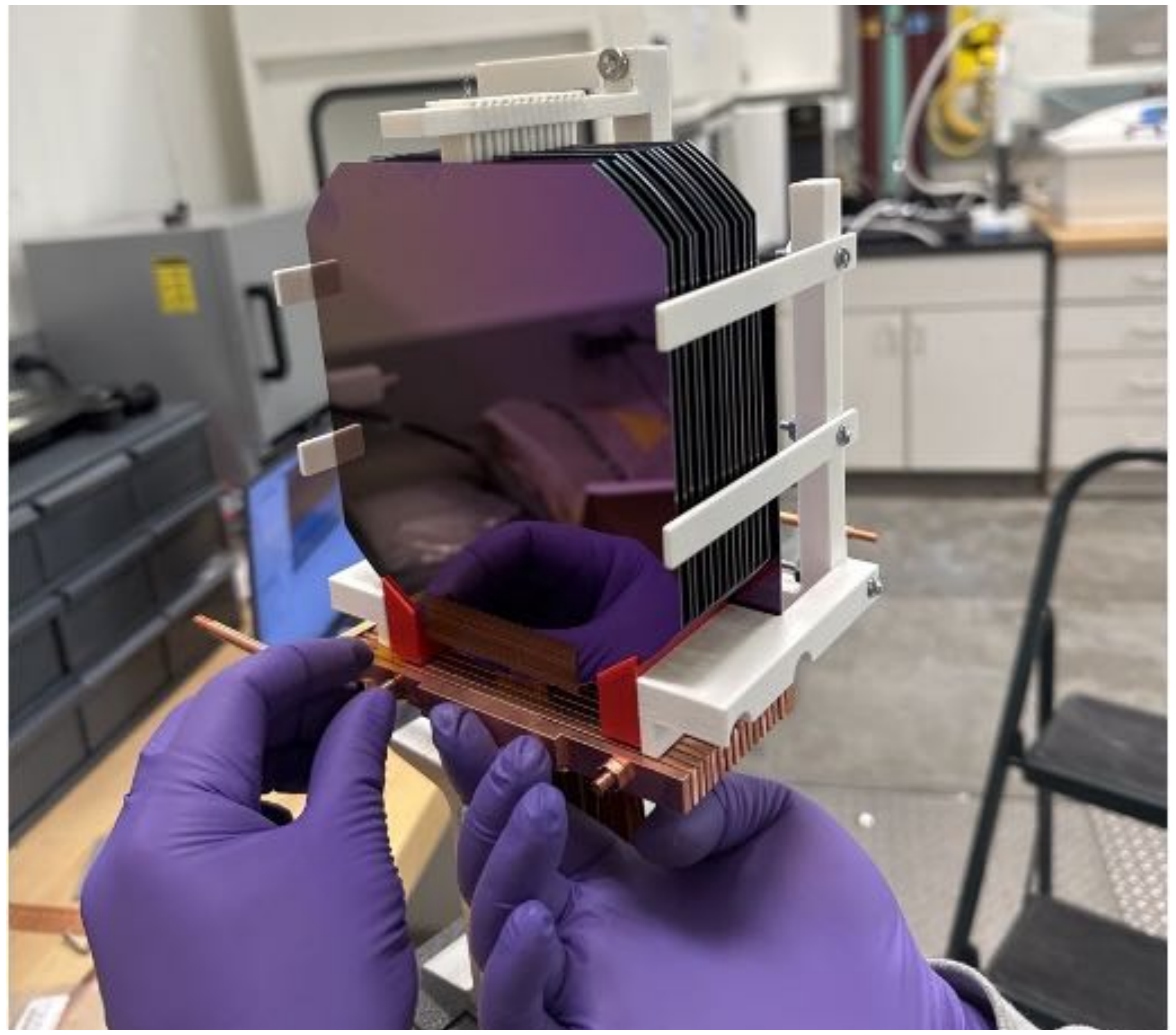



52 CCD modules
208 CCDs, total mass ~ 0.7 kg

- 4 CCDs glued on a silicon pitch adapter. A flex cable, also glued on the silicon pitch adapter, brings the voltage biases and clocks



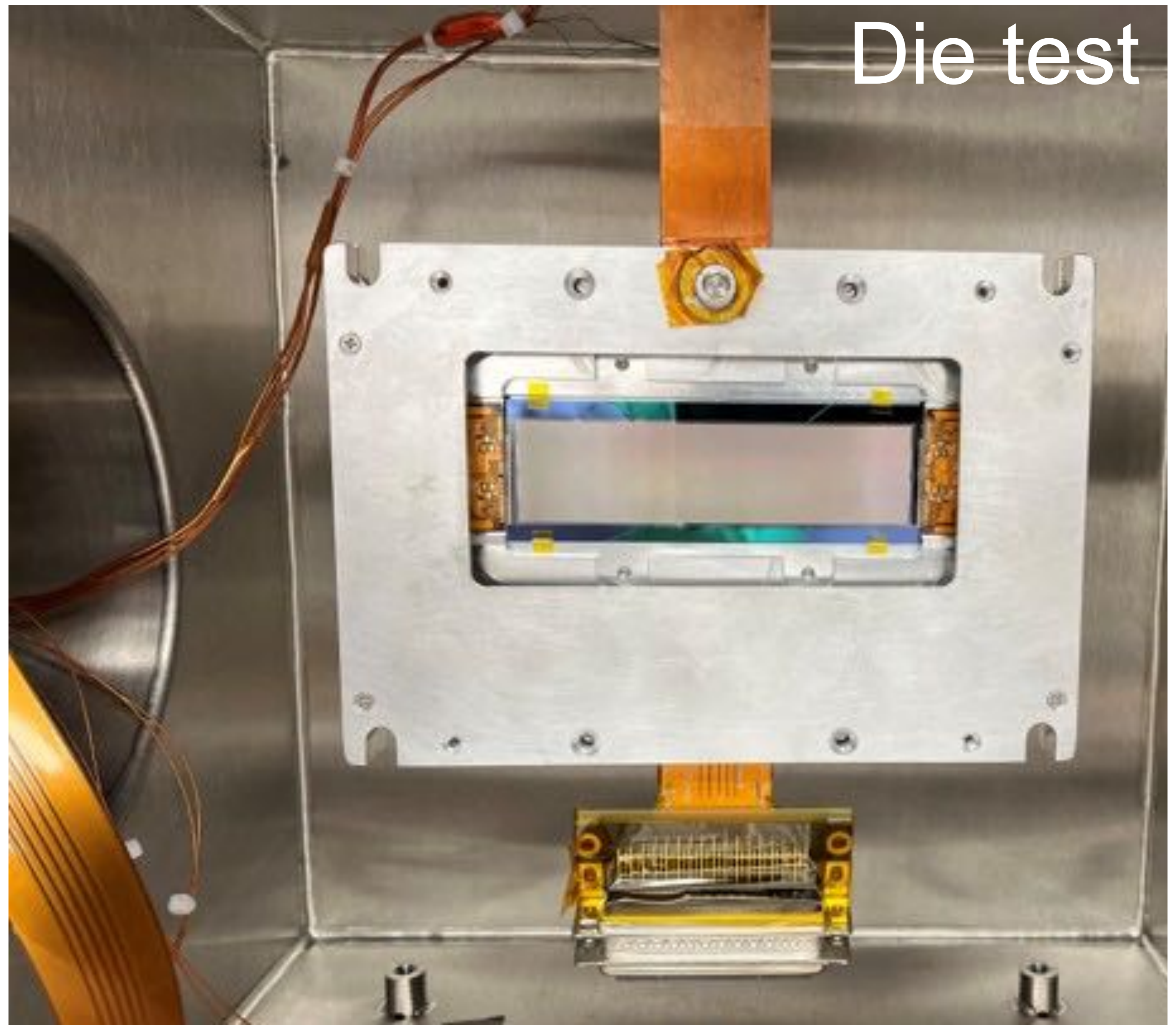



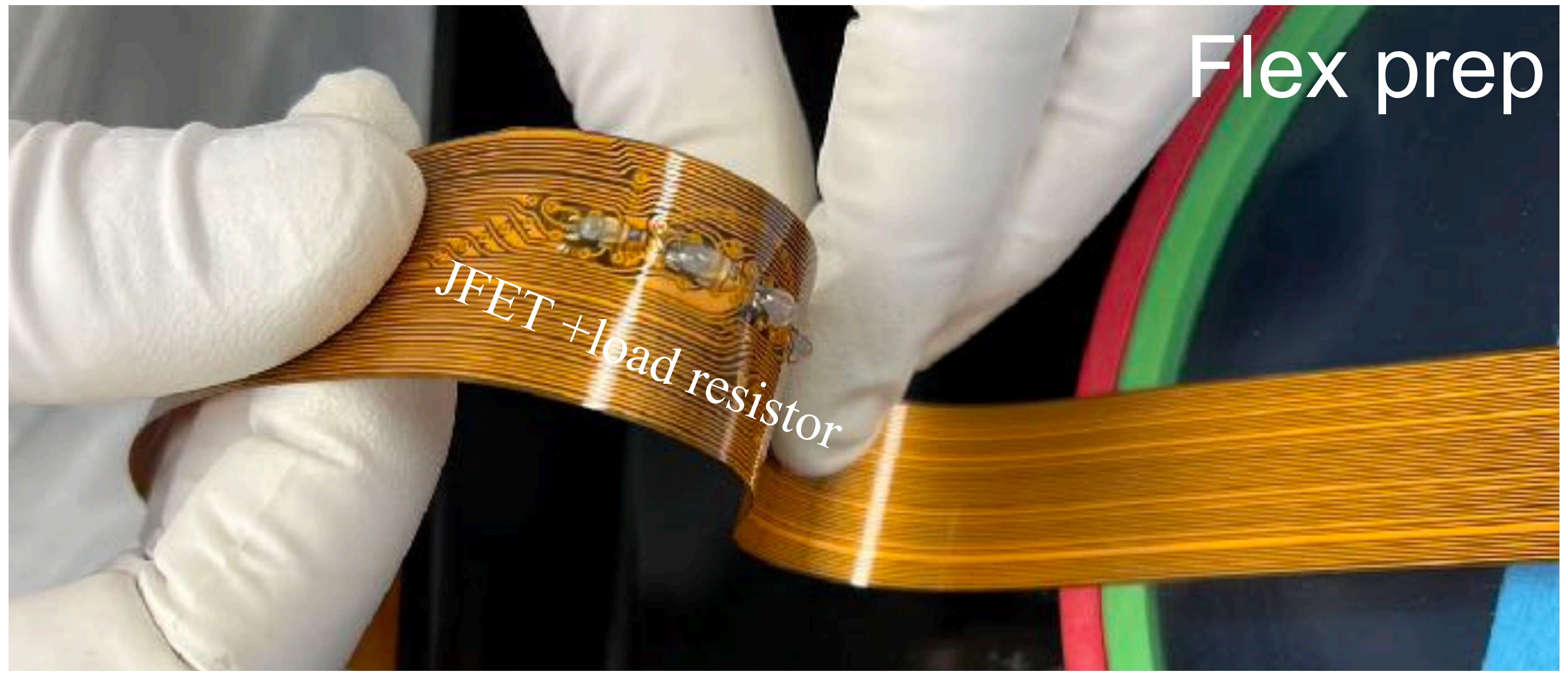



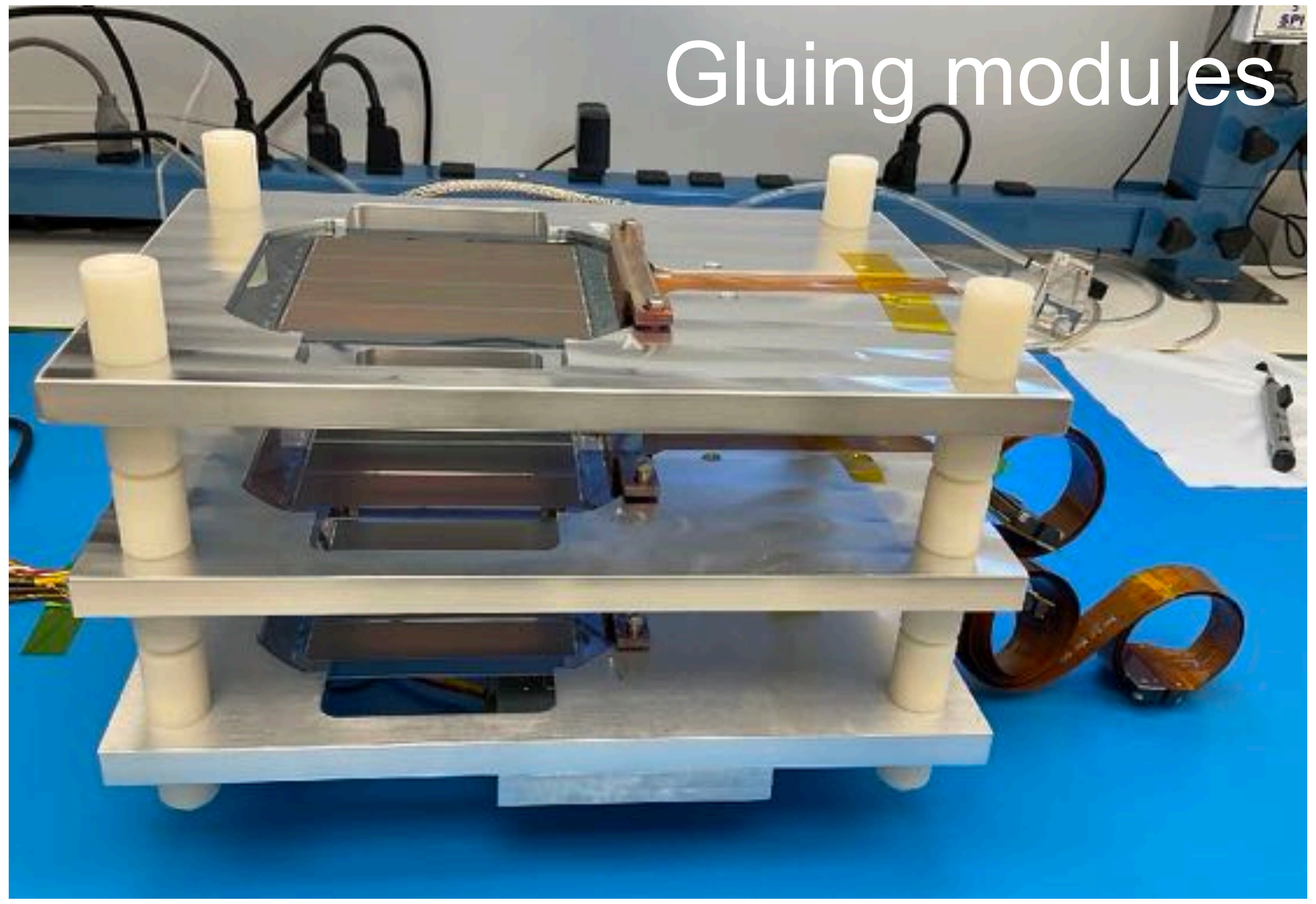
CCD module array mock-up assembly

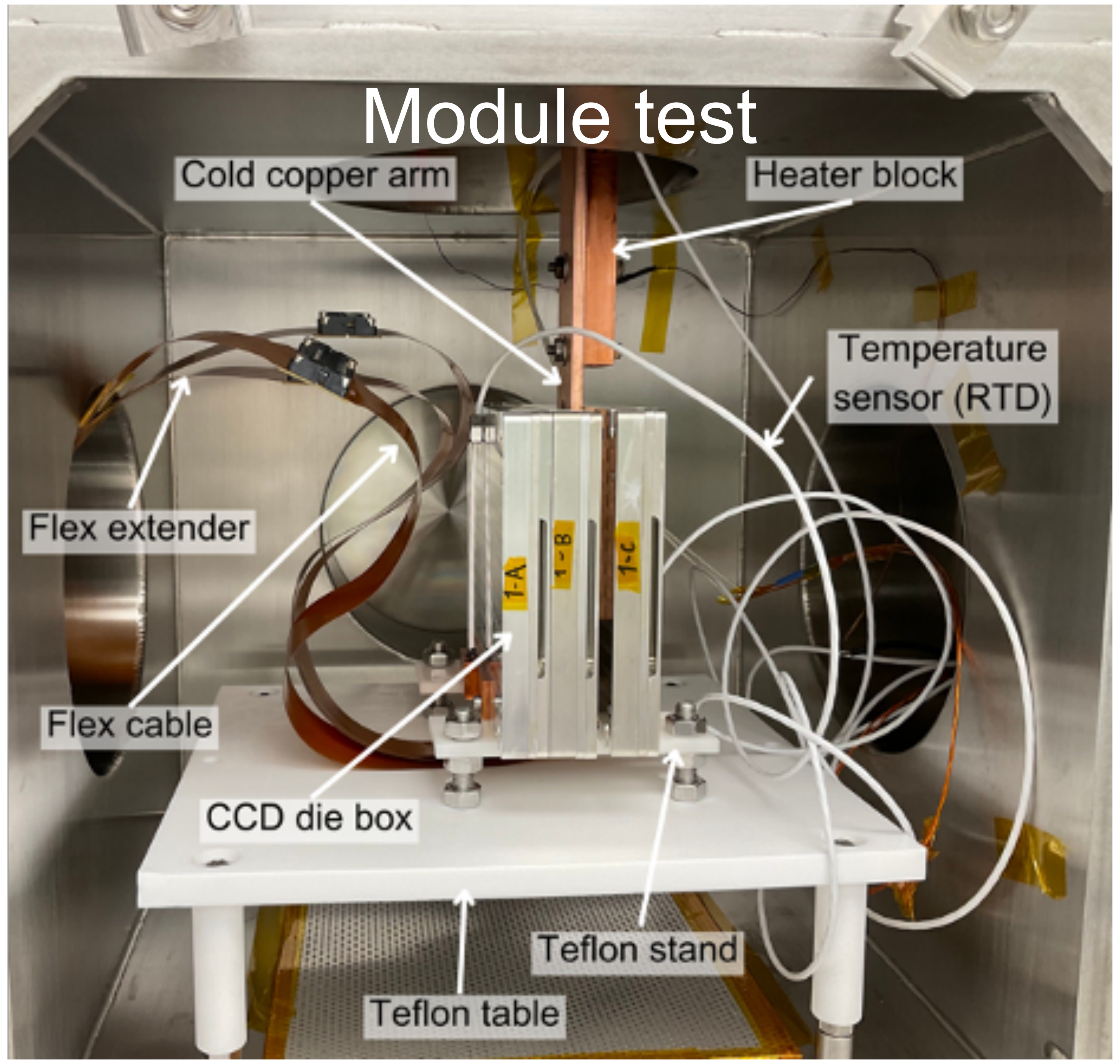
- 1.5 K max temperature difference between modules

# CCD Module production

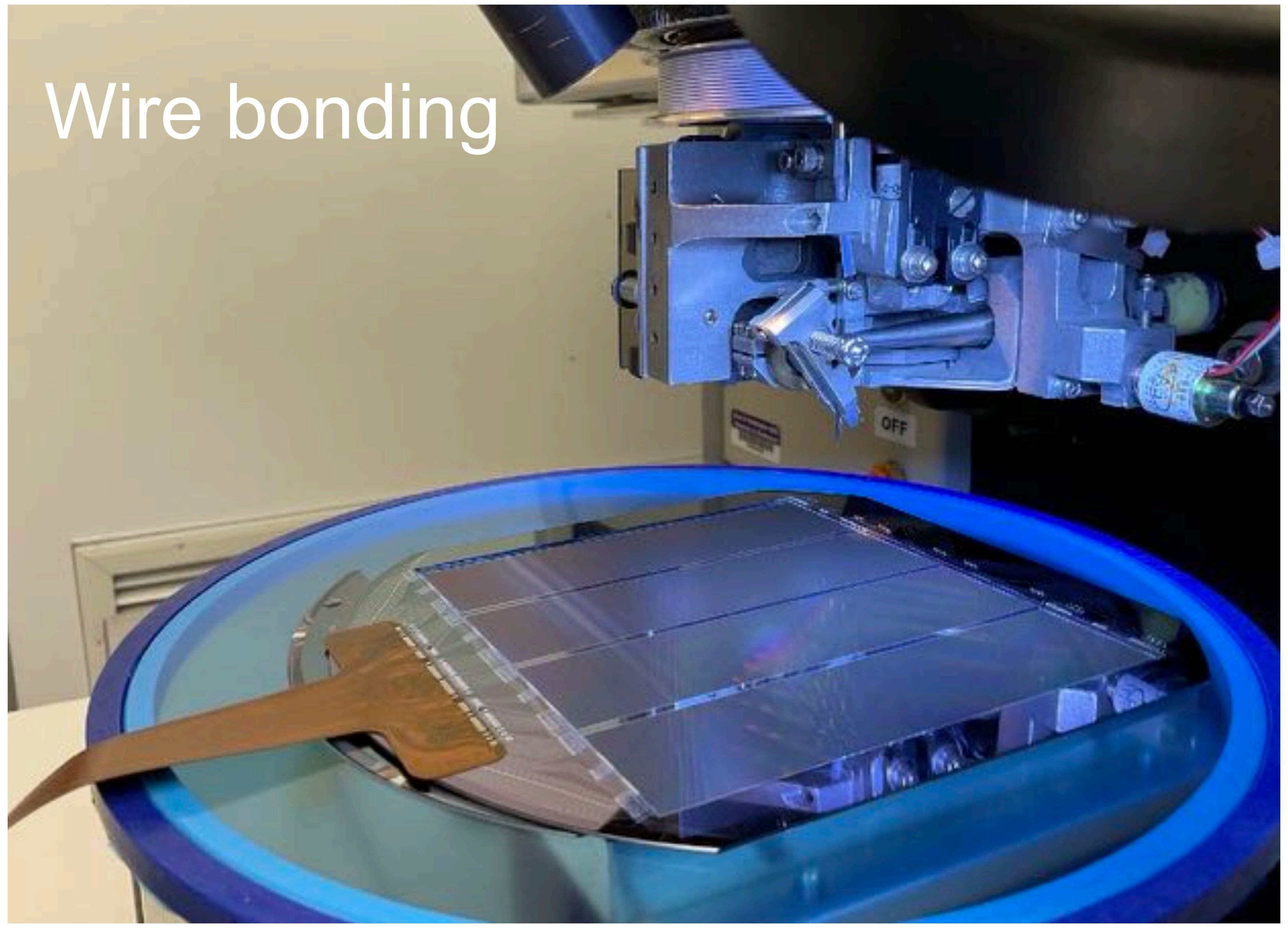


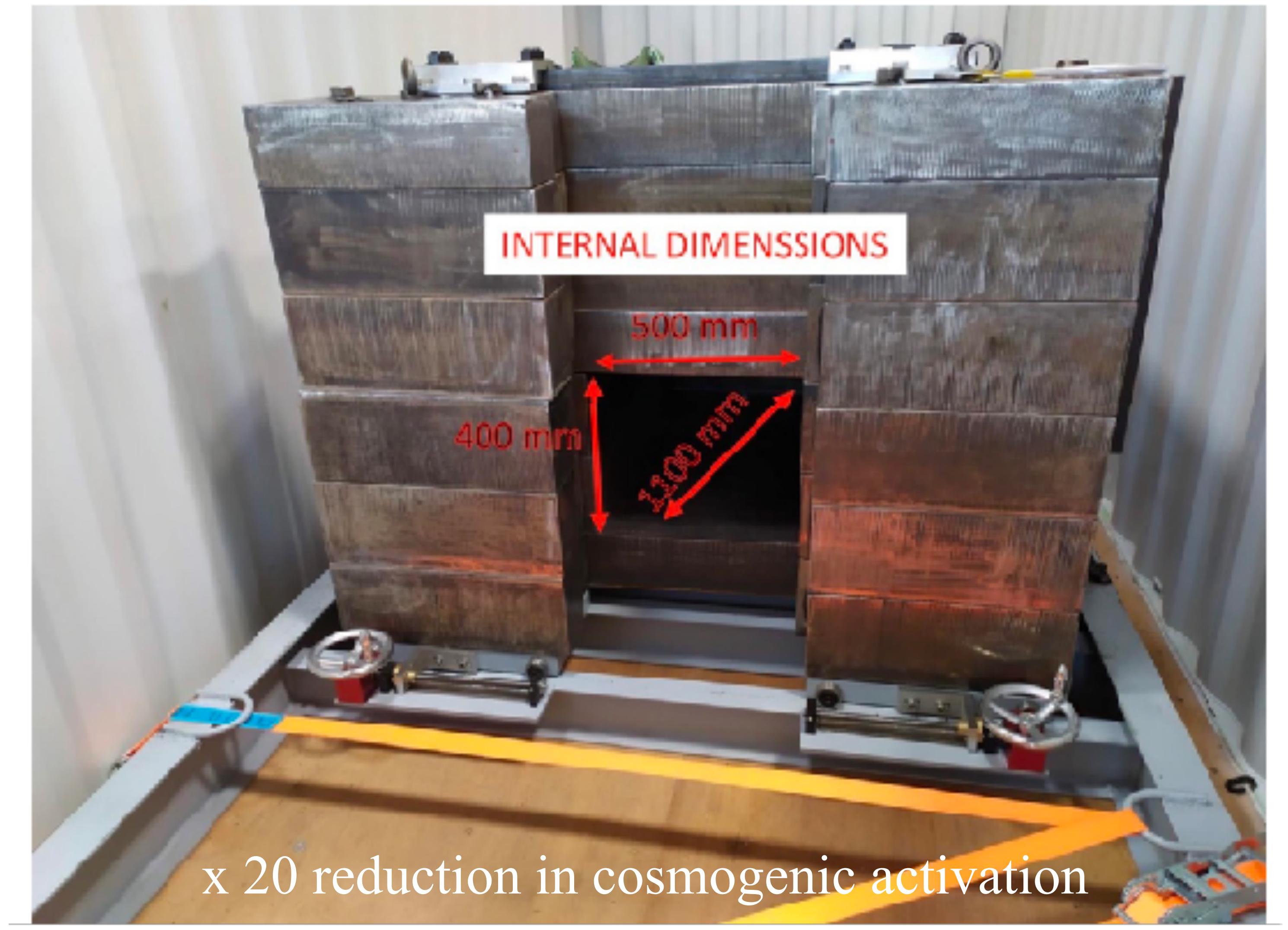





Packaged and tested ~ 200 CCDs, excellent quality; minimal exposure to cosmic neutrons (underground storage at University of Washington)

# Mitigating backgrounds

5-ton shielding in the CCD fab clean room at DALSA (Bromont, Canada)




18-ton shielding in shipping container to transport silicon and e.f. copper


container leaving Canada


- Cosmogenic activation of materials

Cosmic rays spallation in silicon results in tritium (12.3 yrs half-life, 5.7 keV average beta energy)
To meet our background goal, we can afford at most a few months of exposure.

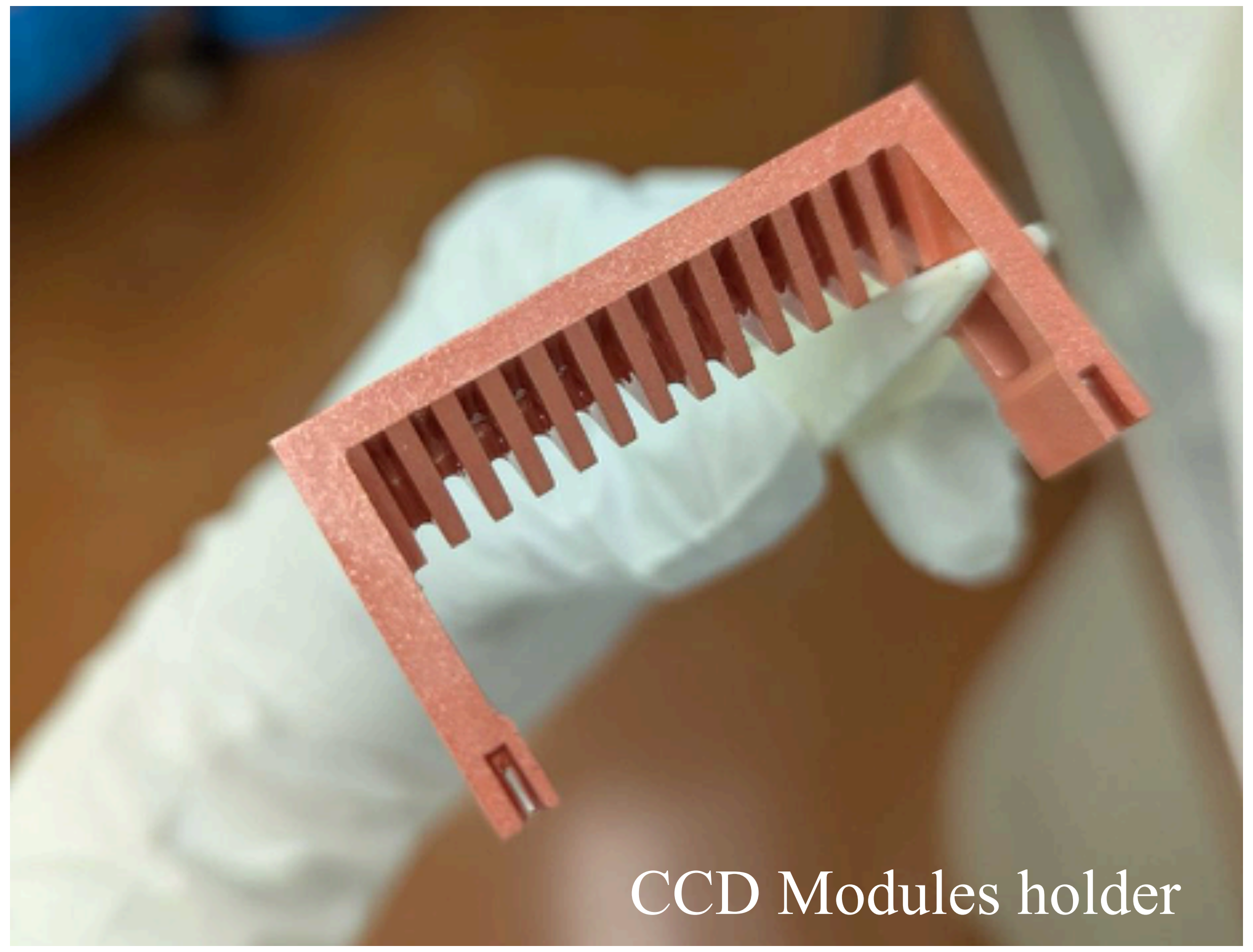



underground labs

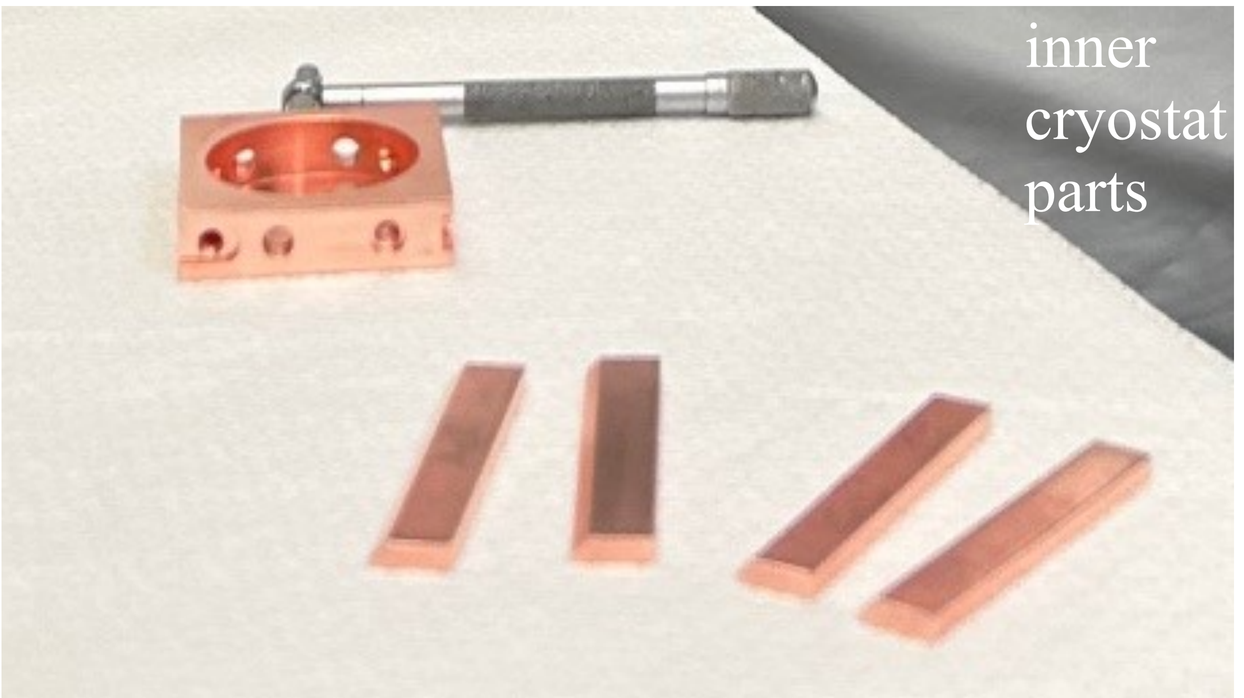
Strict shielding protocols for all transports/storage, complex logistics: Europe (silicon ingot);
Europe -> Canada <-> California (wafers) ;
Canada -> Europe (CCD Modules);
Europe <-> US (e.f. copper)

CCD Modules underground at LSM

# Radiopurity

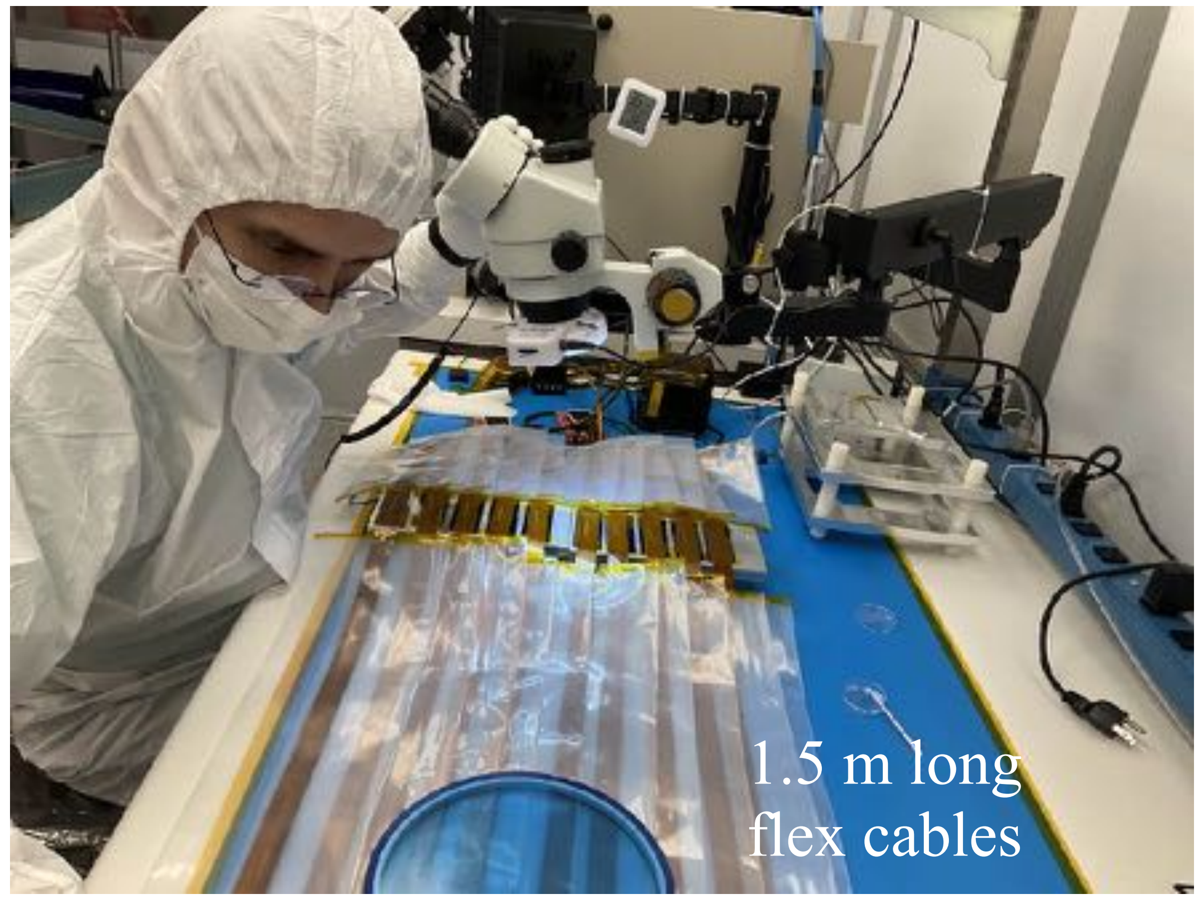




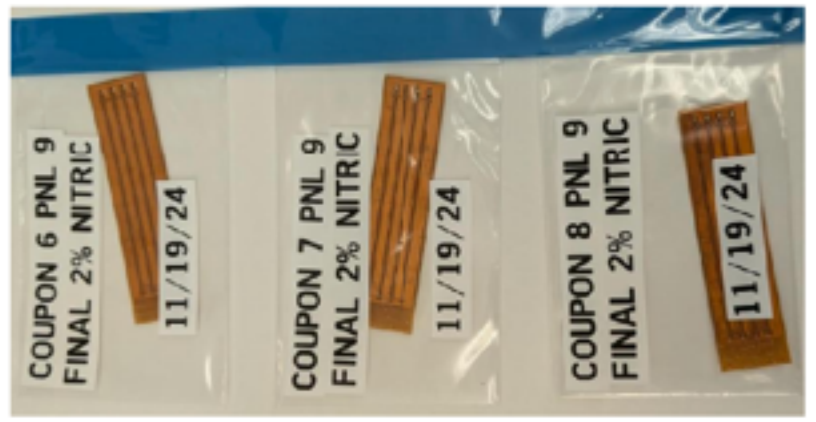



- Copper is the material closest to the CCDs, imposing stringent radiopurity requirements. Its cosmogenic activation (Co) must be limited to max few weeks to meet our background goal.

- We use electroformed copper produced underground at the Sanford Underground Research Facility (thanks to the MAJORANA Collaboration). Machined underground at SURF for DAMIC-M. Now ready for pick-up by our shielded container.




- Commercial flex cables are too “dirty”. A dedicated R&D, led by PNNL, with the US company QFlex resulted in a radiopure flex (up to 20x better than a commercial flex)




| Ethanol Wipe | $^{232}$Th [pg/g] | | $^{238}$U [pg/g] | | nat K [ng/g] | |
|---|---|---|---|---|---|---|
| | mean | sd | mean | sd | mean | sd |
| Panel 9 Coupon 8 | 46 | 4 | 66 | 6 | 135 | 43 |
| Panel 11 Coupon 8 | 38 | 13 | 65 | 25 | 271 | 57 |
| Panel 12 Coupon 8 | 70 | 23 | 59 | 5 | 328 | 117 |
| **All subsamples** | **51** | **20** | **63** | **13** | **245** | **110** |
| DAMIC-M target | 60 | | 150 | | 1500 | |

# Radio purity


lead recovered from a galleon ship

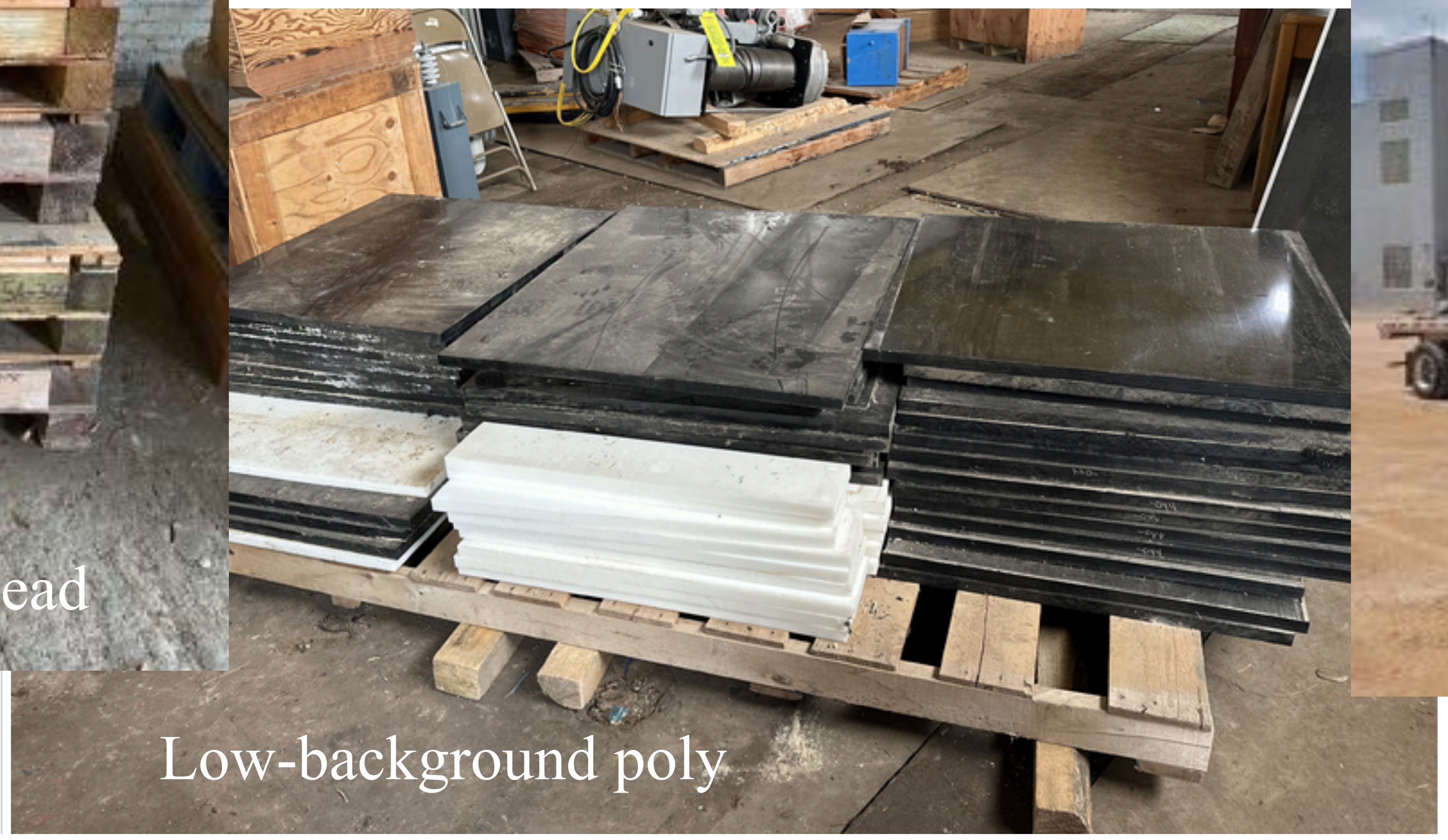

MTH, Germany
Chevron brick casted from ancient lead


DAMIC-M ancient lead shielding

- We use ancient lead, where Pb-210 has mostly decayed (half life 22yrs; beta decay producing bremsstrahlung) for the innermost part of our shielding


Low-background lead

- Low-background lead and poly for the external shield, from SURF


Low-background poly


Leaving SURF

- DAMIC-M is in its final stage of construction, with most critical components completed and shipped to LSM. The schedule foresees installation by end of 2025.

# The Low Background Chamber at LSM

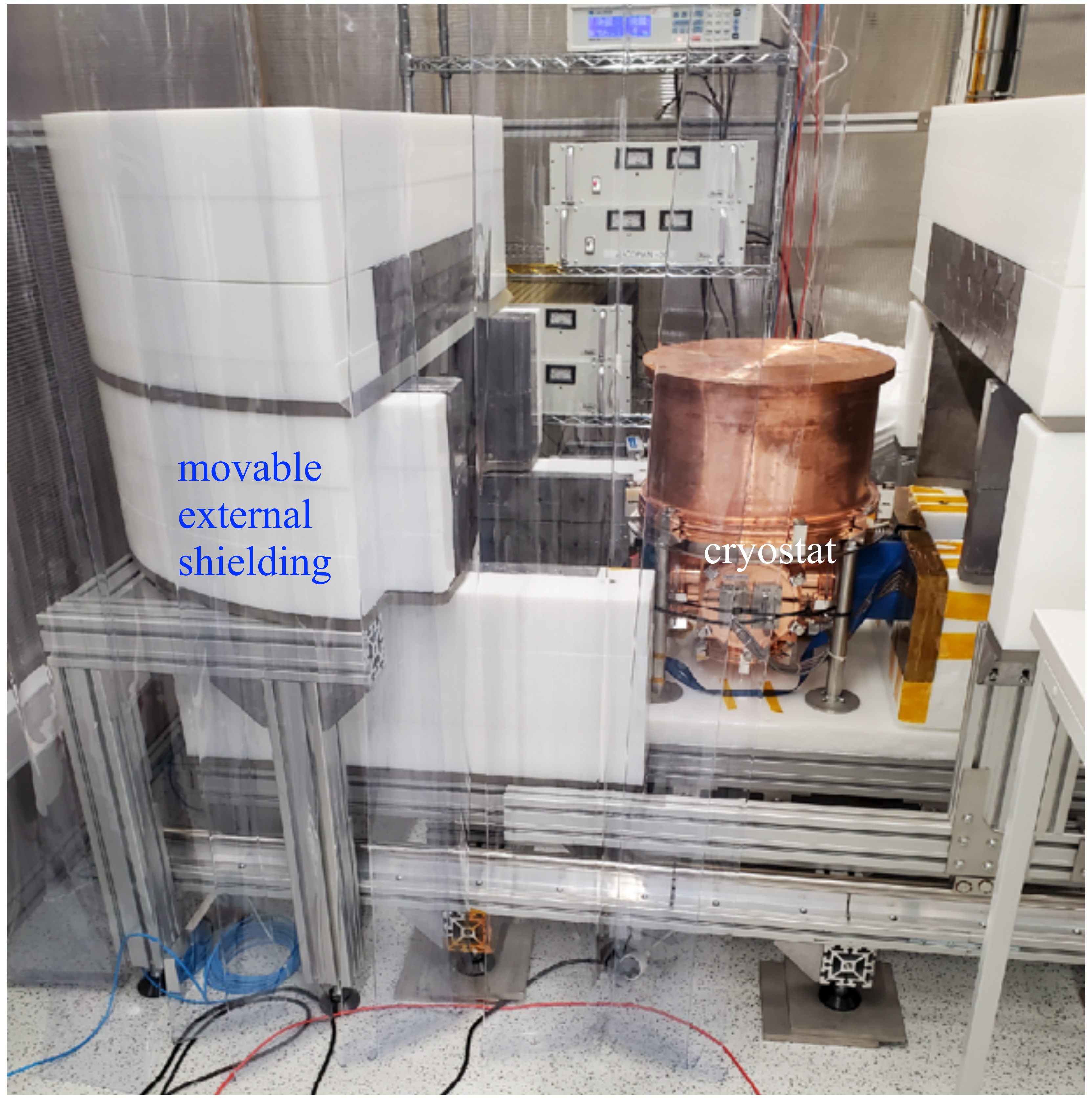
- A low background (~7 dru) test setup operating at the LSM since 2022

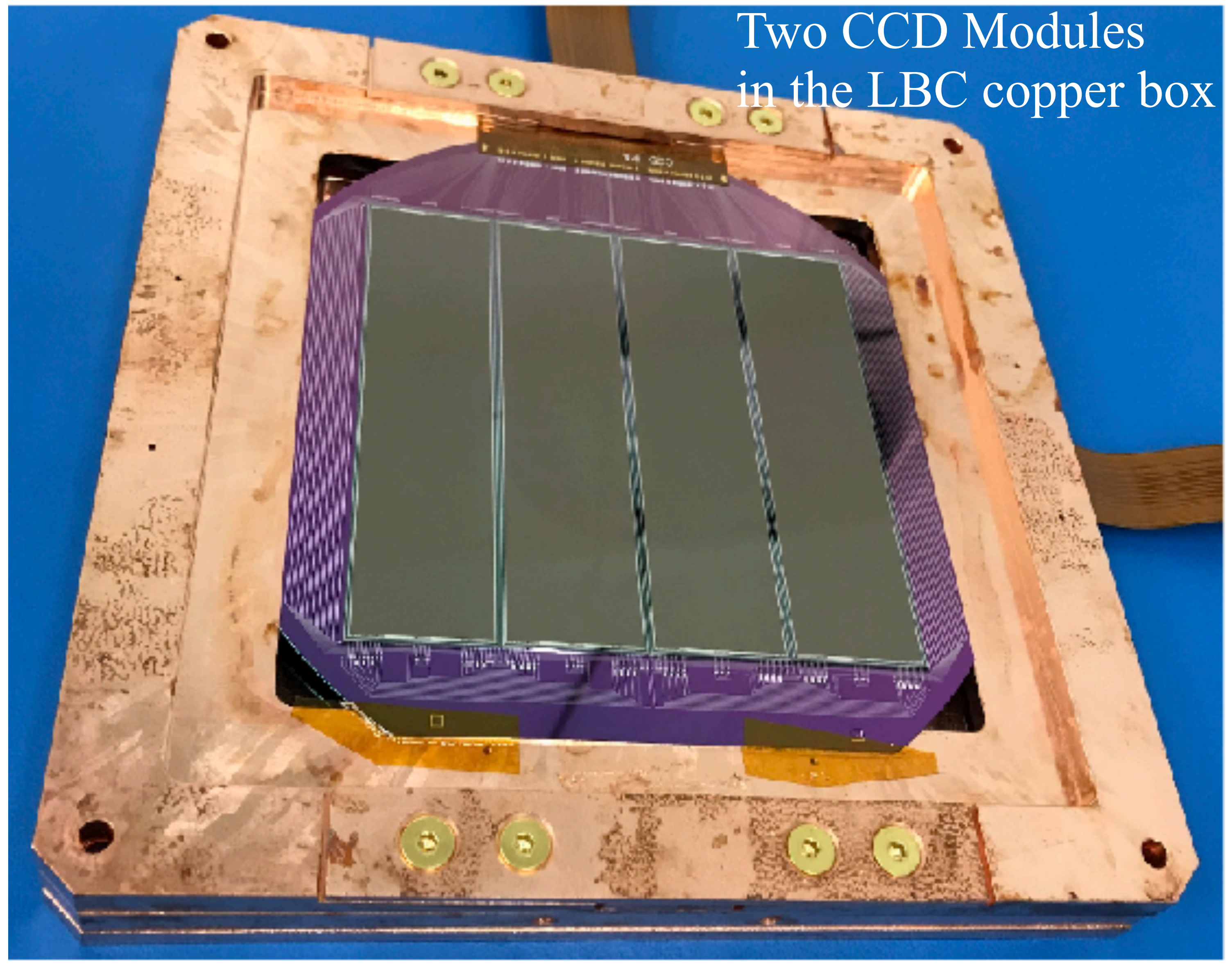
- Objectives: CCD performance and background studies, components validations for DAMIC-M

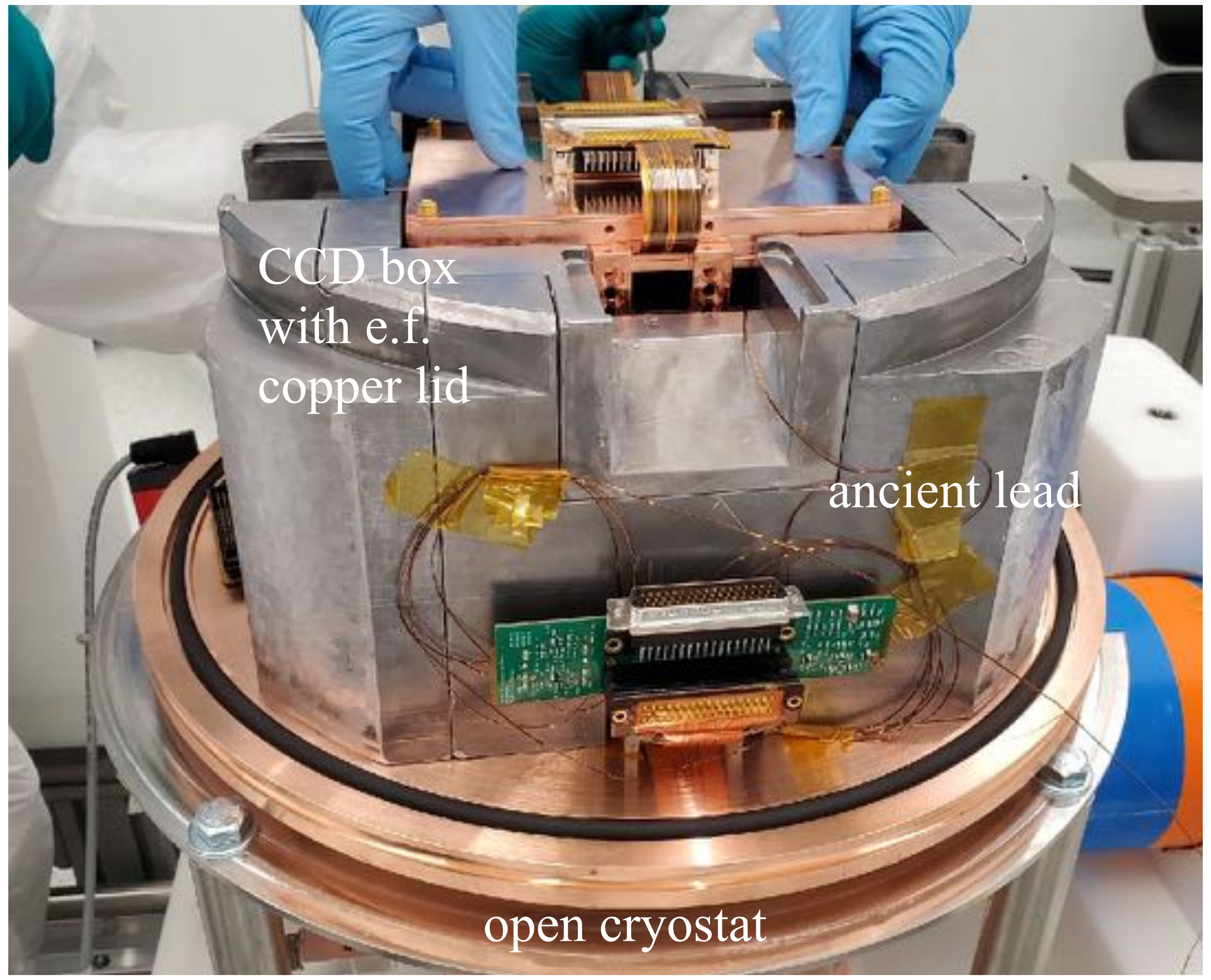
- First science with prototype skipper CCDs: search for DM-e-scattering through charge spectrum and daily modulation PRL130(2023)171003 PRL132(2024)101006

- Today will present new results from Science Run 2, taken with DAMIC-M CCD Modules

JINST19(2024)T11010

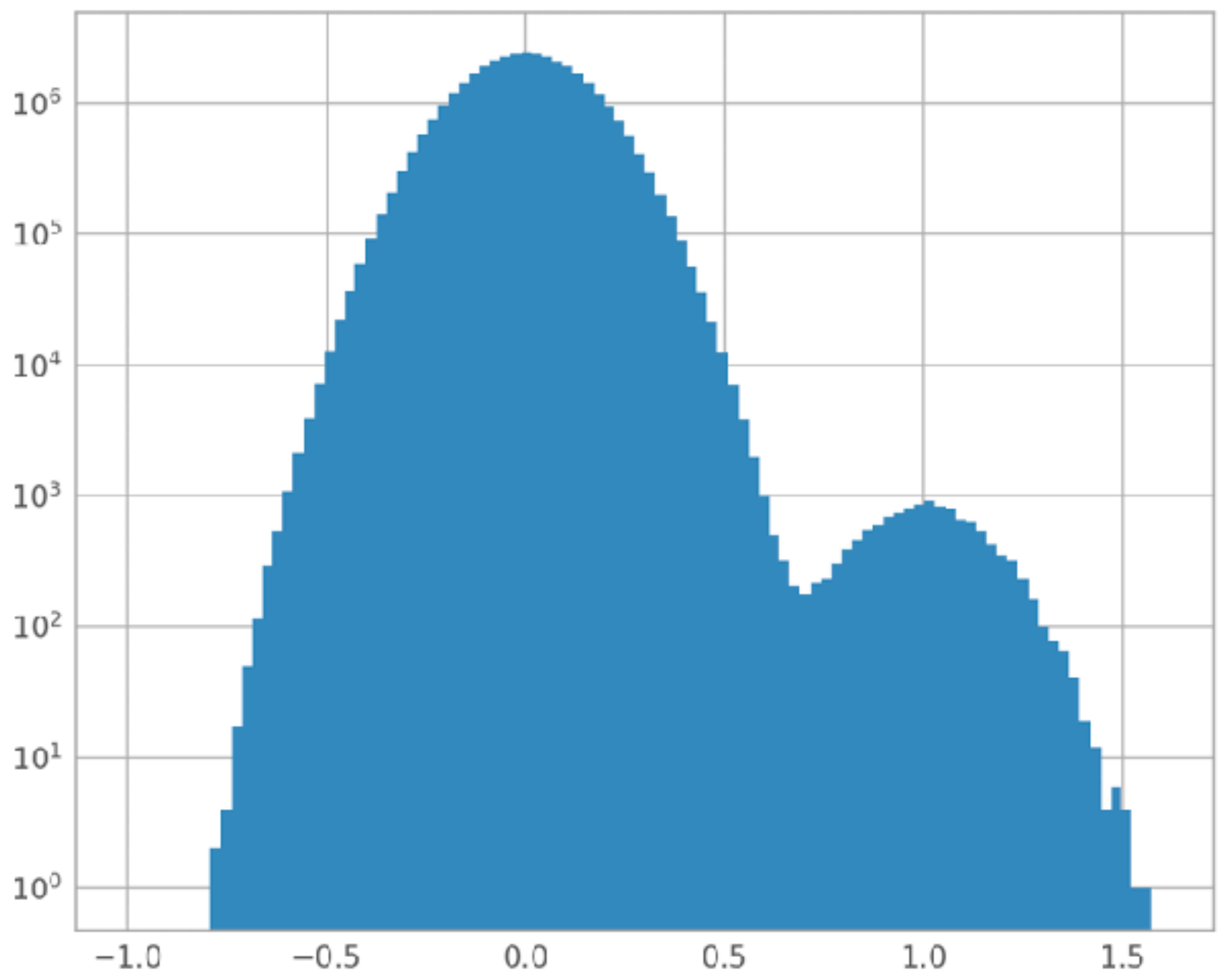


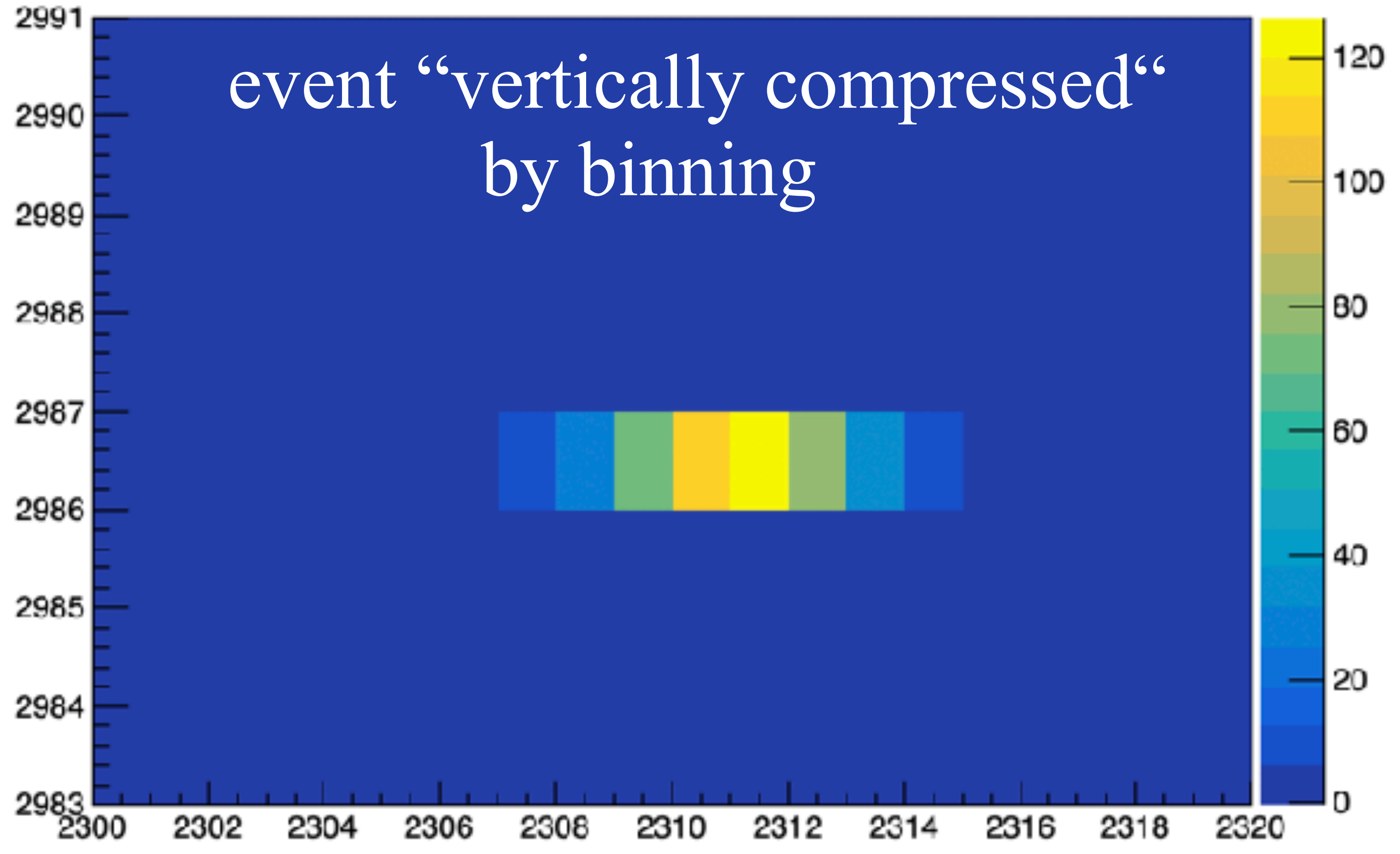



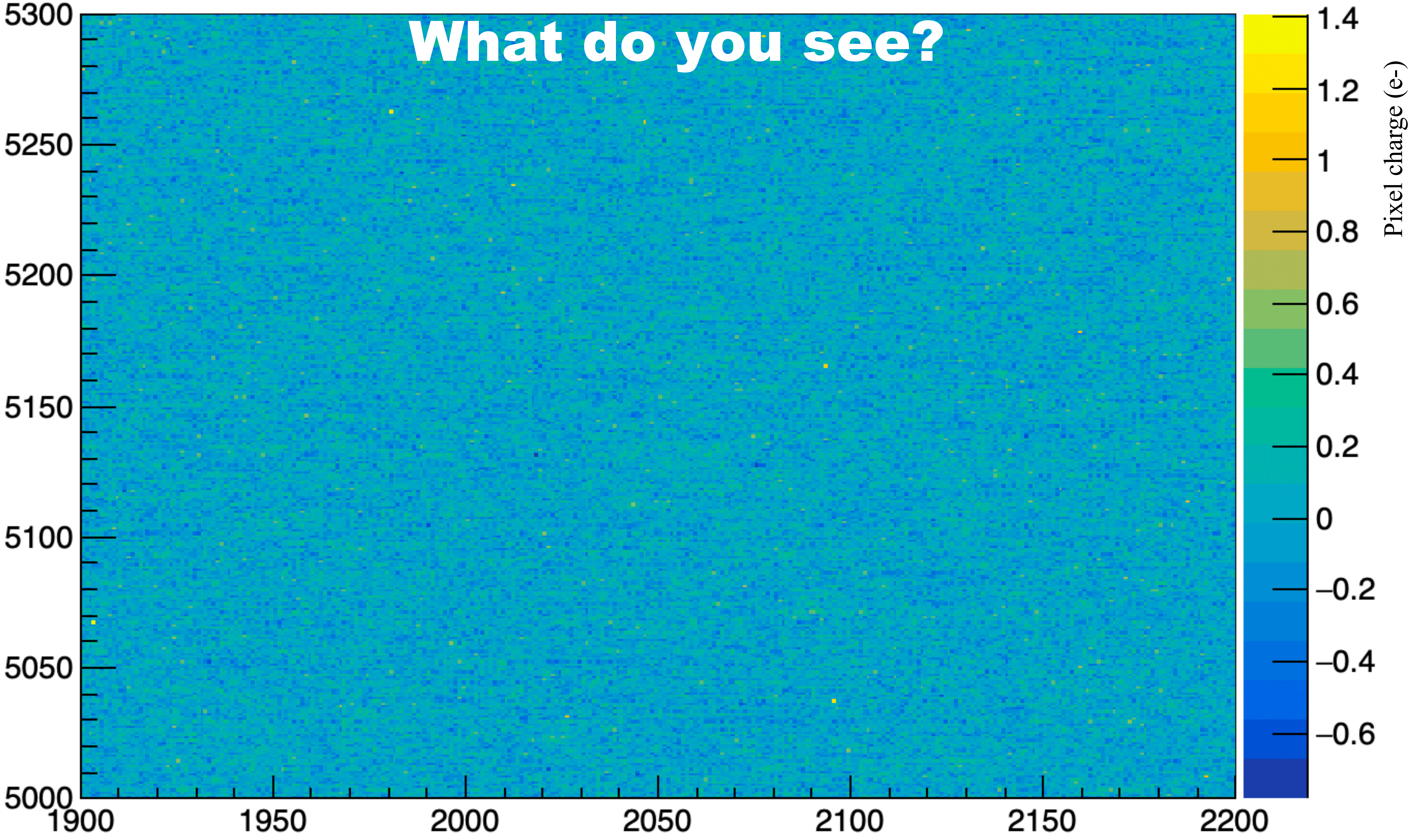



# Search for Hidden-Sector DM with SR2

- Two CCD Modules, each with 4 skipper CCDs, total 26.4g
- Notable improvements thanks to low-noise electronics and better box light tightness:
  - ✴ **0.16e-** charge resolution (~0.2e- in SR1)
  - ✴ **~1.3x10$^{-4}$ e-/pix/day** (400 e-/g/day) dark current (x50 lower than SR1)
- Collected data October 2024-January 2025: total exposure after selection **1.3 kg day** (0.086 kg day SR1)
- **Blind analysis:** pixel selection and DM search criteria defined with 7 days of unblinded data (~10% of total)
- Continuous readout with 100 vertical binning, which compresses the 1.5kx6k CCD into images of 16 rows x 6300 columns. 28 min to read one image, allowing for daily modulation analysis.

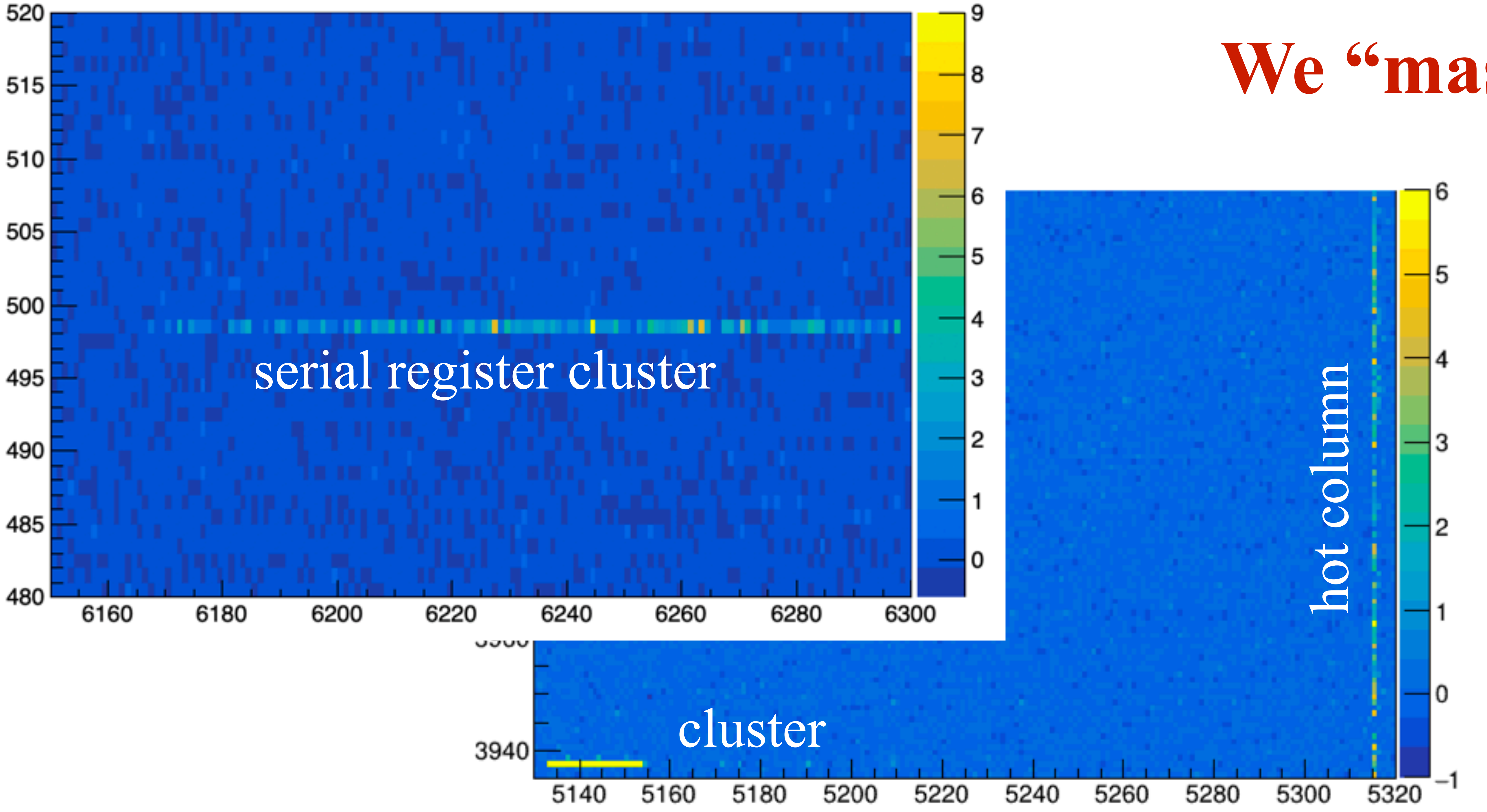



What do you see?
5300
5250
5200
5150
5100
5050
5000
1900
1950
2000
2050
2100
2150
2200
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
Pixel charge (e-)

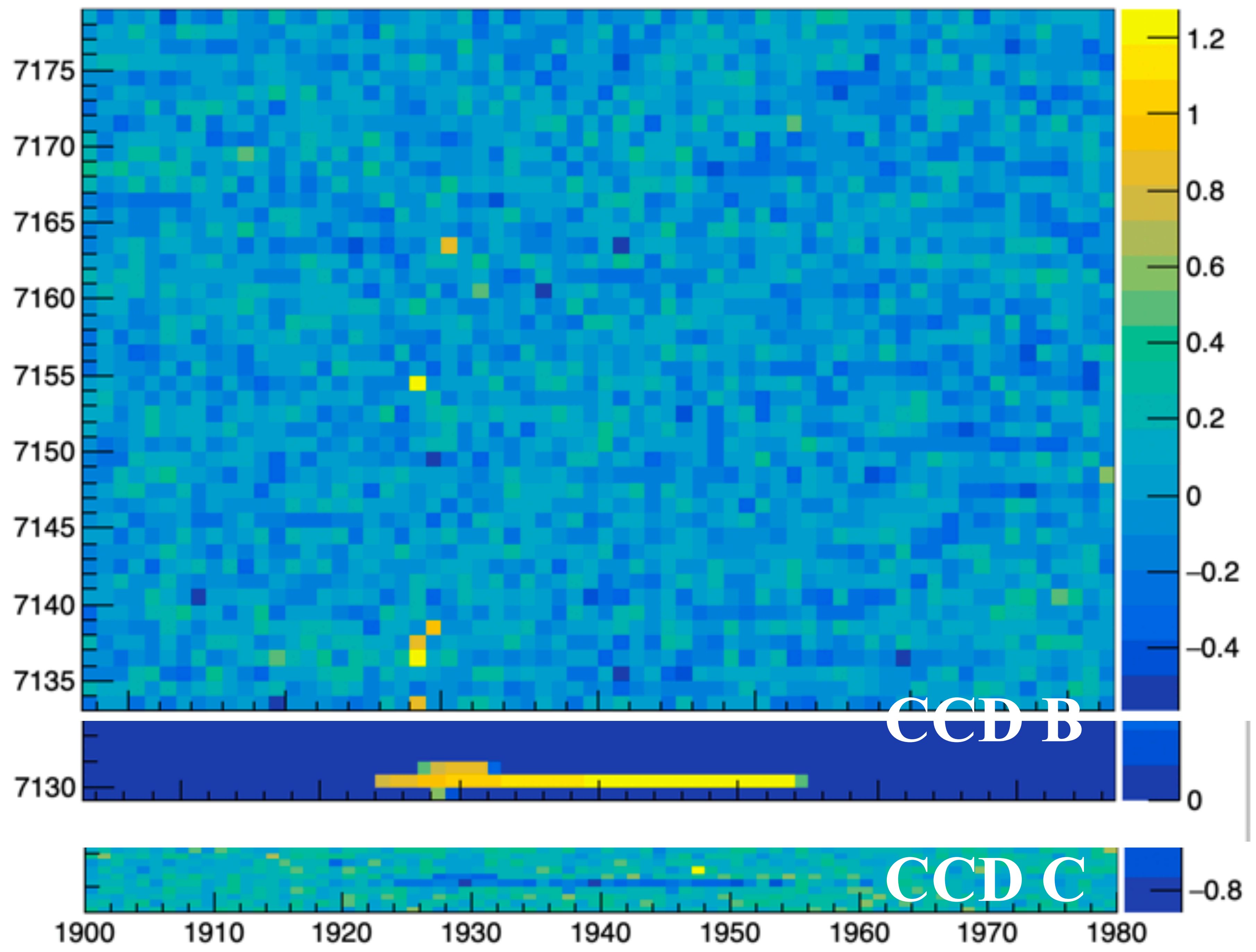
# Pixel Selection Criteria

- “hot columns” and serial register clusters



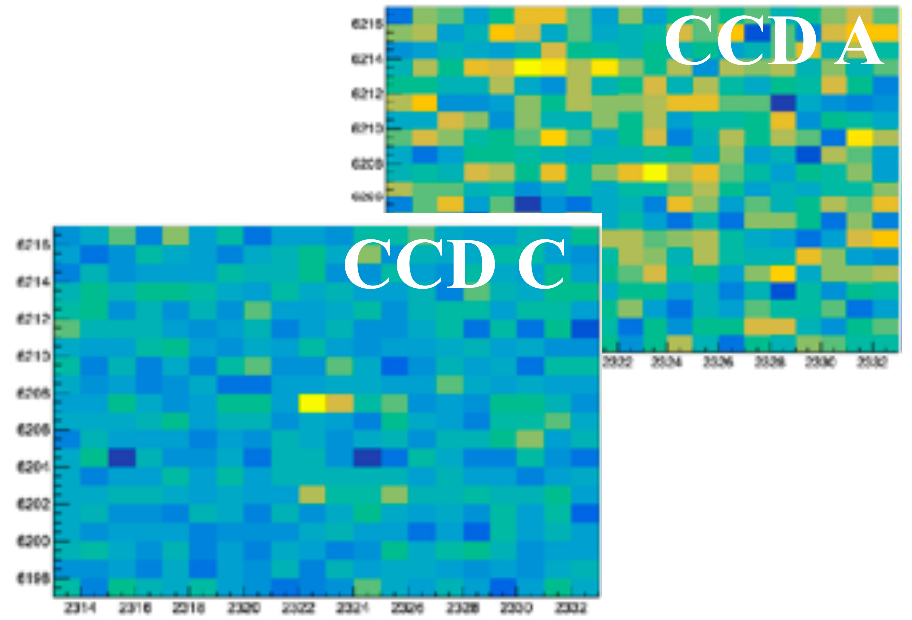

We “mask”

- Charge-Transfer Inefficiency (CTI): a high-charge pixel may leave charges behind while being transferred vertically or horizontally




- Clusters with total charge > 5e- (since their contribution to the DM-e- signal is small; kept blind for future searches)

- Correlated-noise pixels, resulting in the same pixel *(i,j)* having a small signal in several CCDs; or in a pixel with large RMS of the NDCMs due to noise occurring during the NDCMs.




- Cross-talk: a high-charge pixel *(i,j)* in one CCD may induce small signals in the corresponding *(i,j)* pixels of the other CCDs of the same Module through cross-talk in the electronics chain (the 4 CCDs are readout synchronously)

**efficiency ~95%**

# DM Candidates Search

- Dark matter candidates are searched for as **patterns of two or three consecutive pixels** with charge (in e-): {11}, {21}, {111}, {22}, {31}, {211}

- Backgrounds:

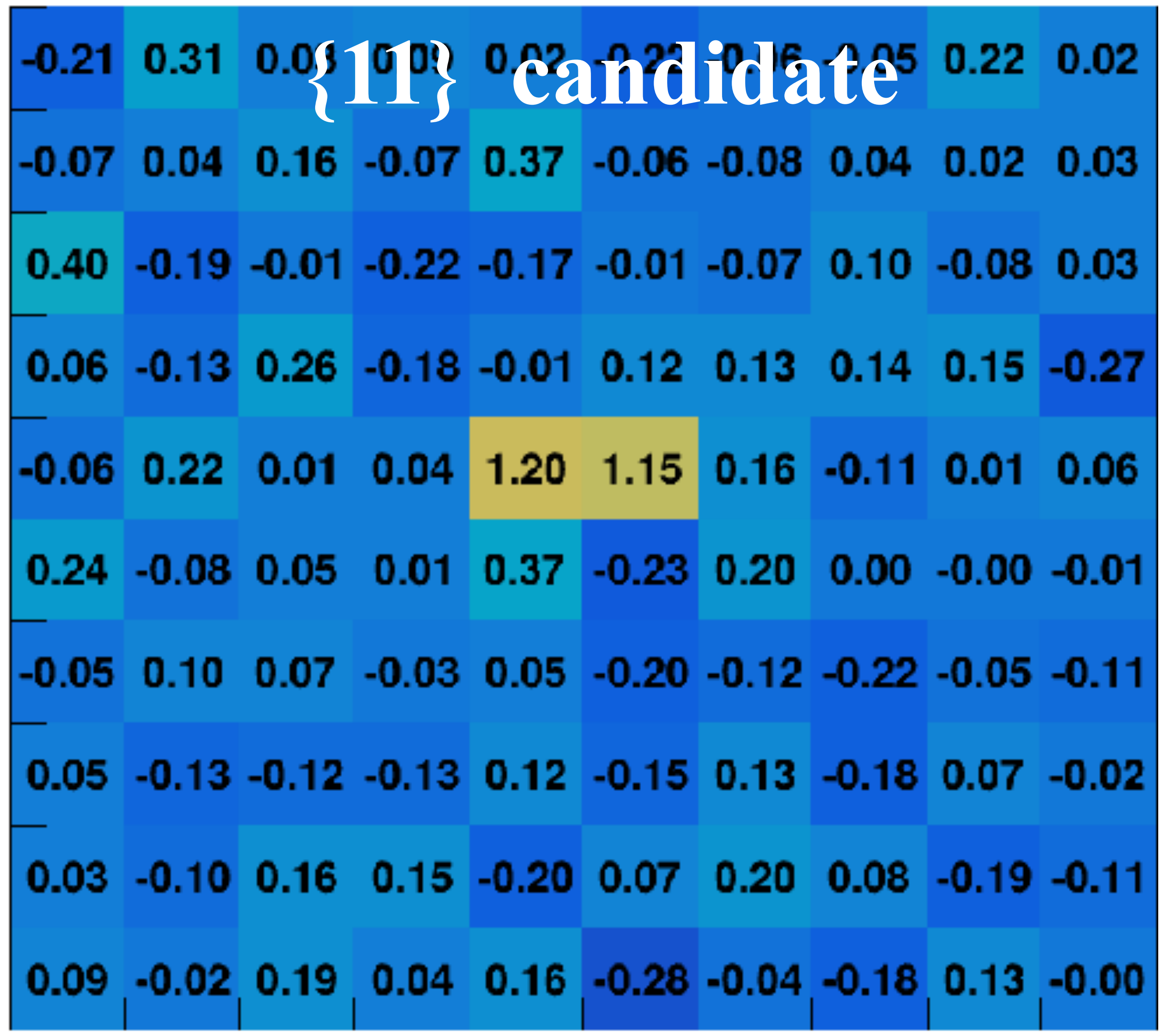
$B_p^{\mathrm{rc}}$ - random coincidences, estimated from measured rates of 1, 2, 3 e- pixels; e.g. {11} ~ $R_{1e}$ x $R_{1e}$

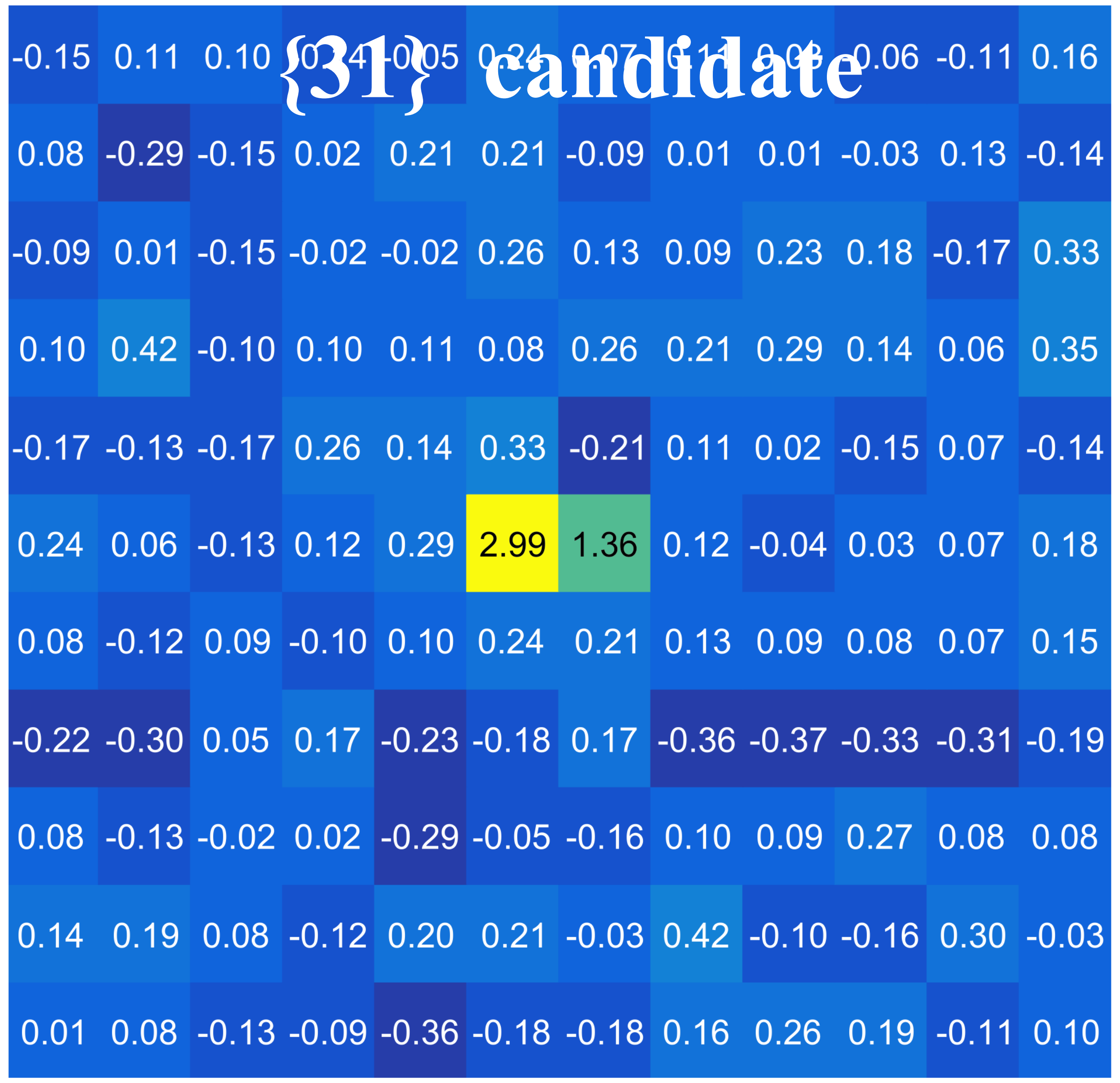
$B_p^{\mathrm{rad}}$ - radiogenic backgrounds: estimated from measured n. of clusters $N_{rad}$ (2.5<E<7.5 keV) and simulations (Geant4, charge diffusion, pattern id)

- "Box opened"

| | found<br>{11} | {21} | {111} | found<br>{31} | {22} | {211} |
|---|---|---|---|---|---|---|
| $D_p$ | **144** | 0 | 0 | **1** | 0 | 0 |
| $B_p^{\mathrm{rc}}$ | 141.4 | 0.111 | 0.042 | 0.019 | $2.5 \cdot 10^{-5}$ | $5.8 \cdot 10^{-5}$ |
| $B_p^{\mathrm{rad}}$ | 0.039 | 0.039 | 0.016 | 0.052 | 0.011 | 0.035 |
| | 141.44<br>expected | | | 0.071<br>expected | | |

**No evidence for a signal**



# Signal Model and Limit Setting

**theory input**

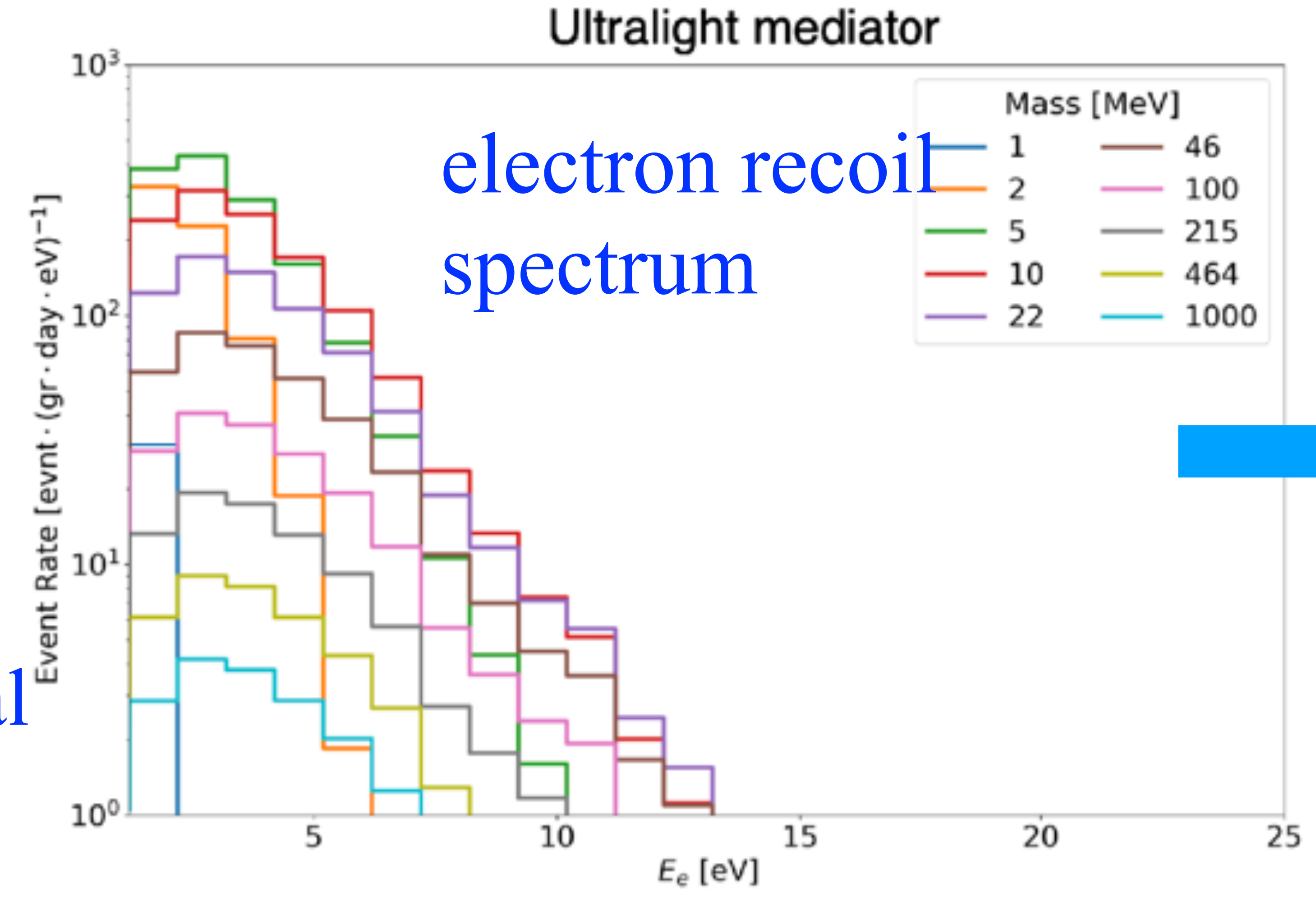
DM galactic halo

DM-e cross section

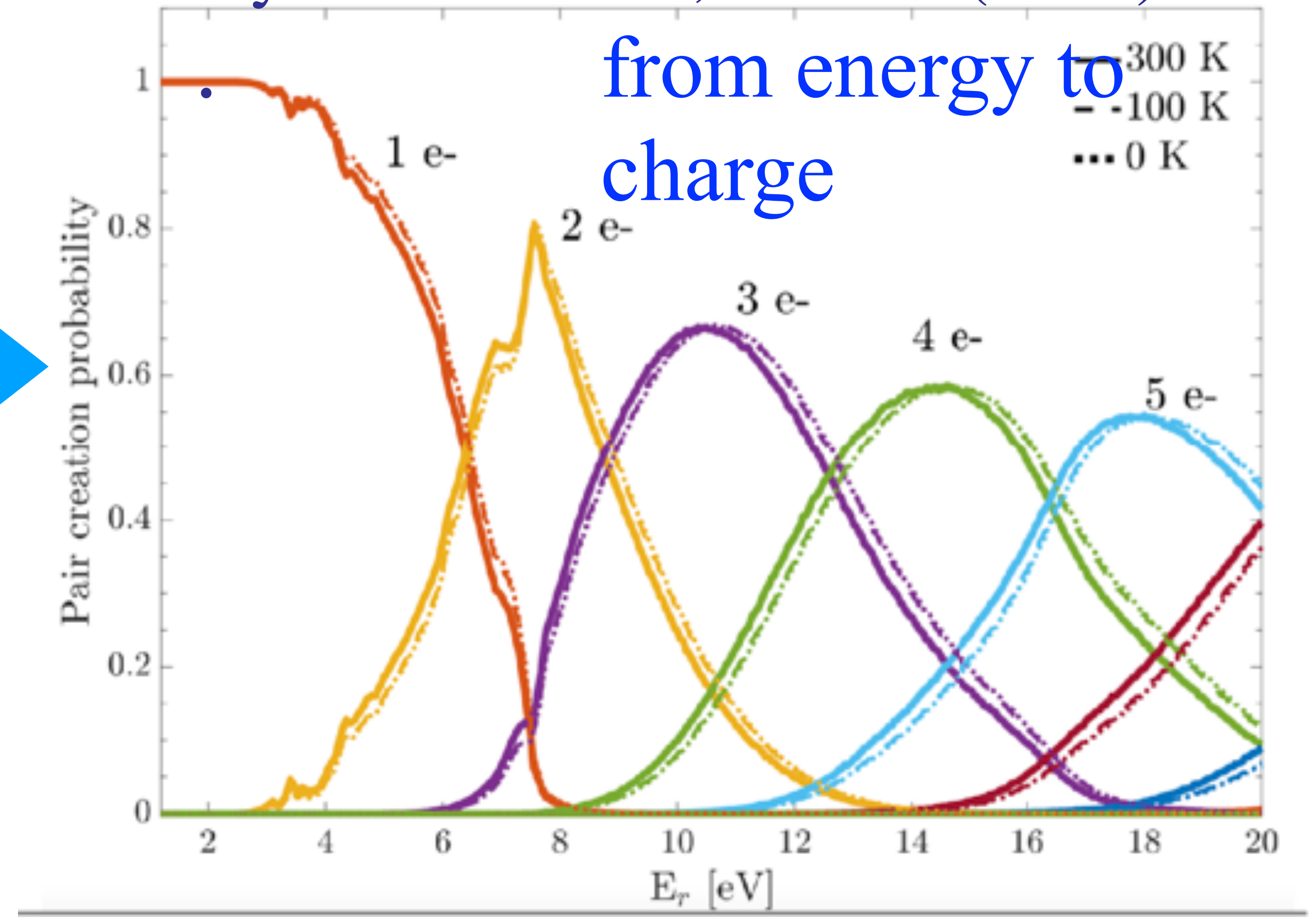
DM form factor

crystal

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




Phys. Rev. D 102, 063026 (2020)



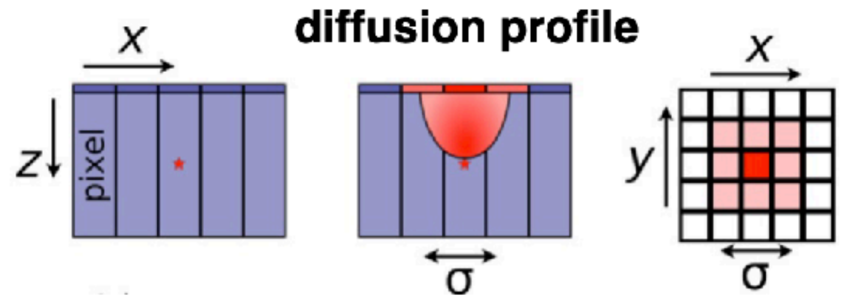

**N. of patterns p**

**number of DM interactions resulting in $q_e$ ionization charges**

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

**Probability that $q_e$ charges result in a pattern p**

from MC simulation, including charge diffusion and pattern selection



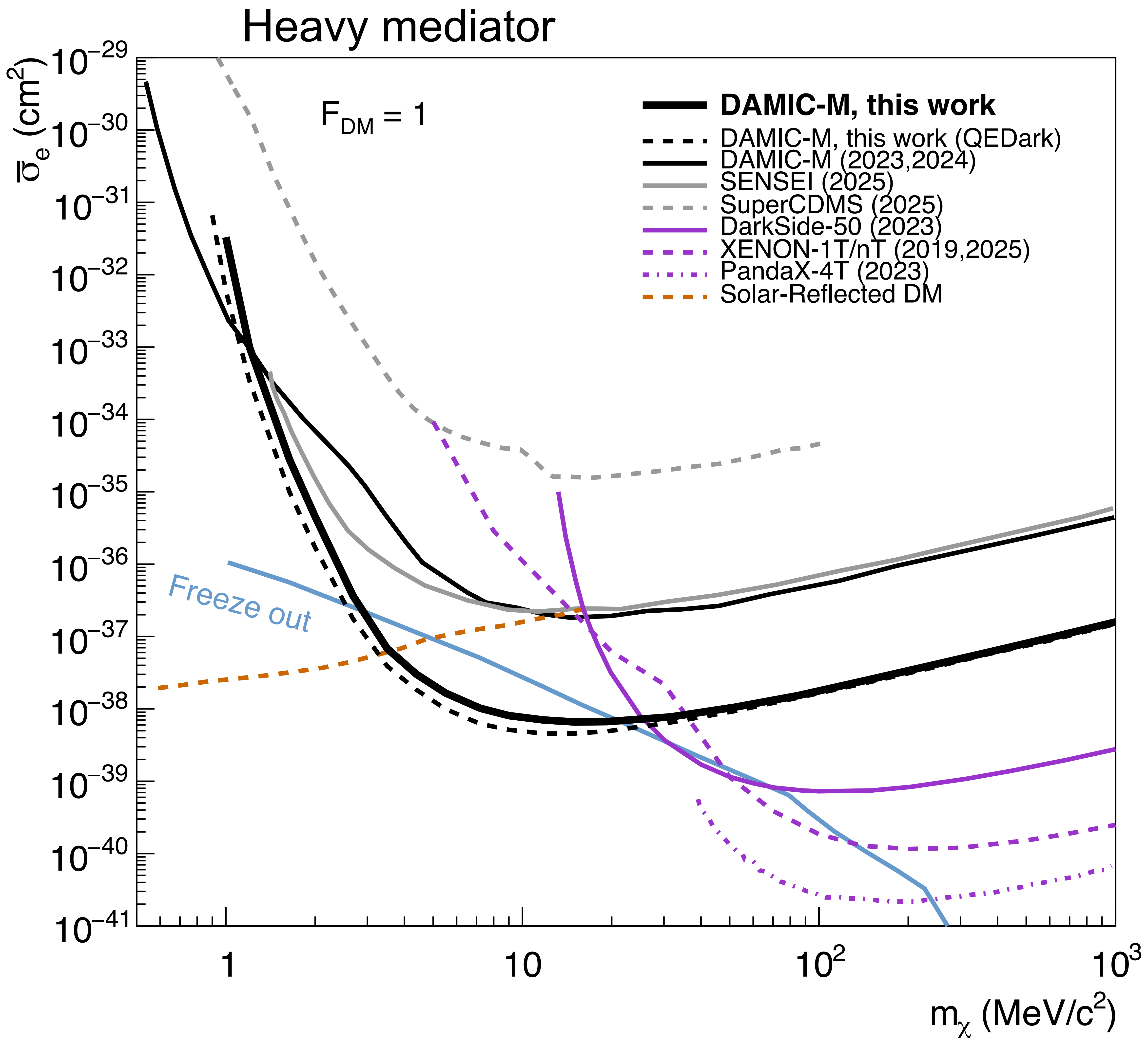

$\bar{\sigma}_e$ nuisance

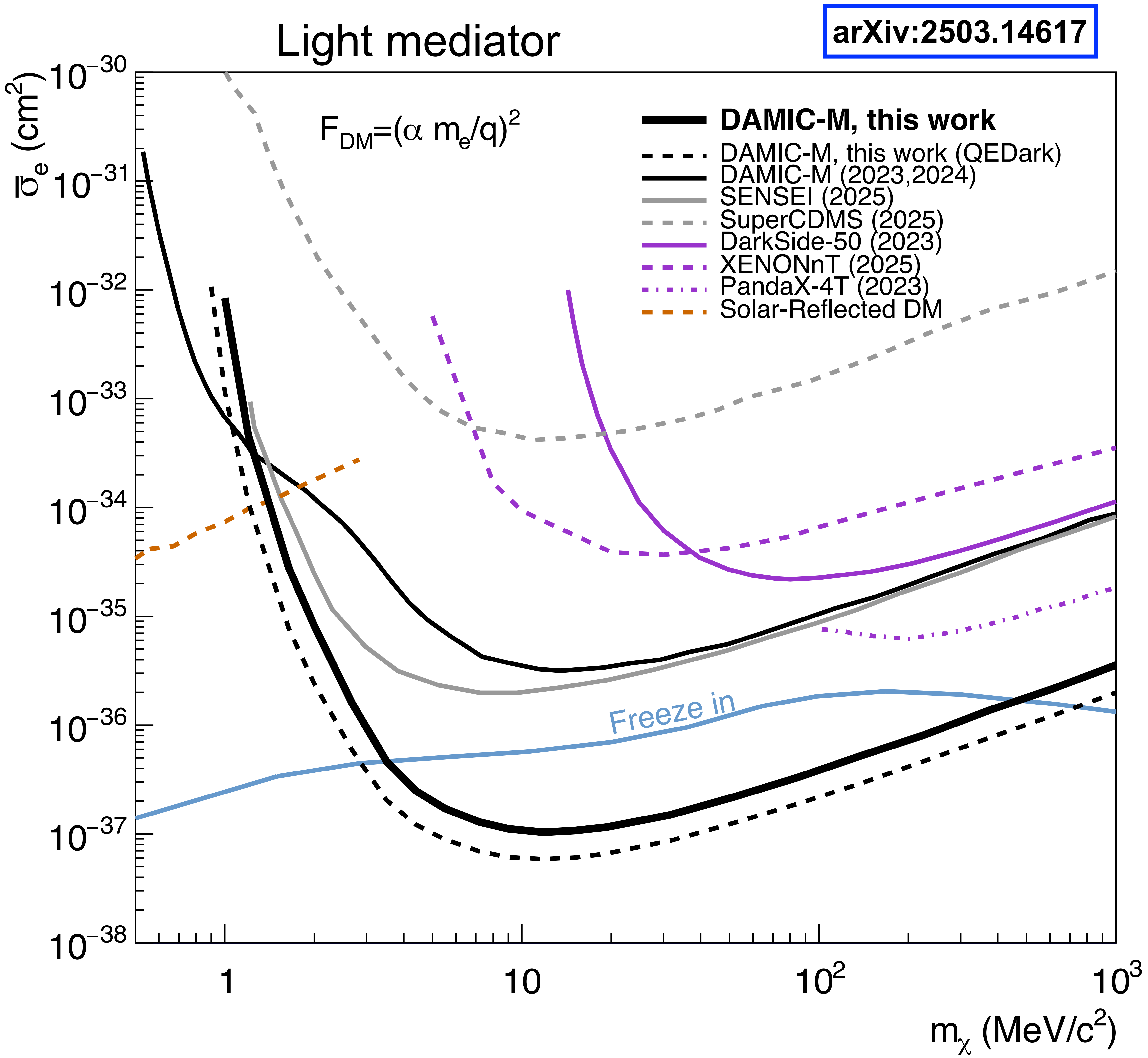
$$\mathcal{L}(\mu, \theta) = \prod_p \frac{\left(S_p(\mu) + B_p^{rc} + \theta B_p^{rad}\right)^{D_p} e^{-\left(S_p(\mu)+B_p^{rc}+\theta B_p^{rad}\right)}}{D_p!} \prod_p \frac{\left(\theta \tau_p B_p^{rad}\right)^{N_{rad}} e^{-\left(\theta\tau_p B_p^{rad}\right)}}{N_{rad}!}$$

"control sample"

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

# DM-e exclusion limits

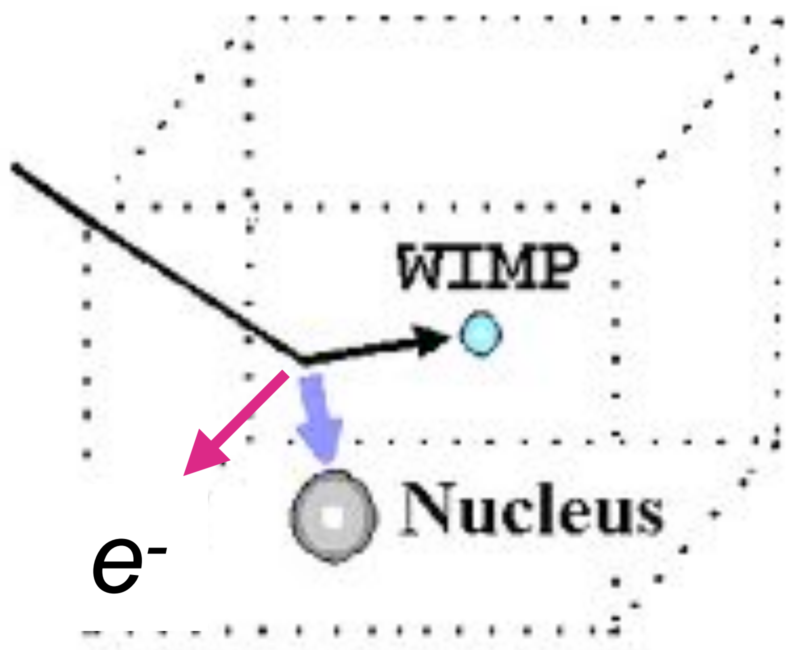


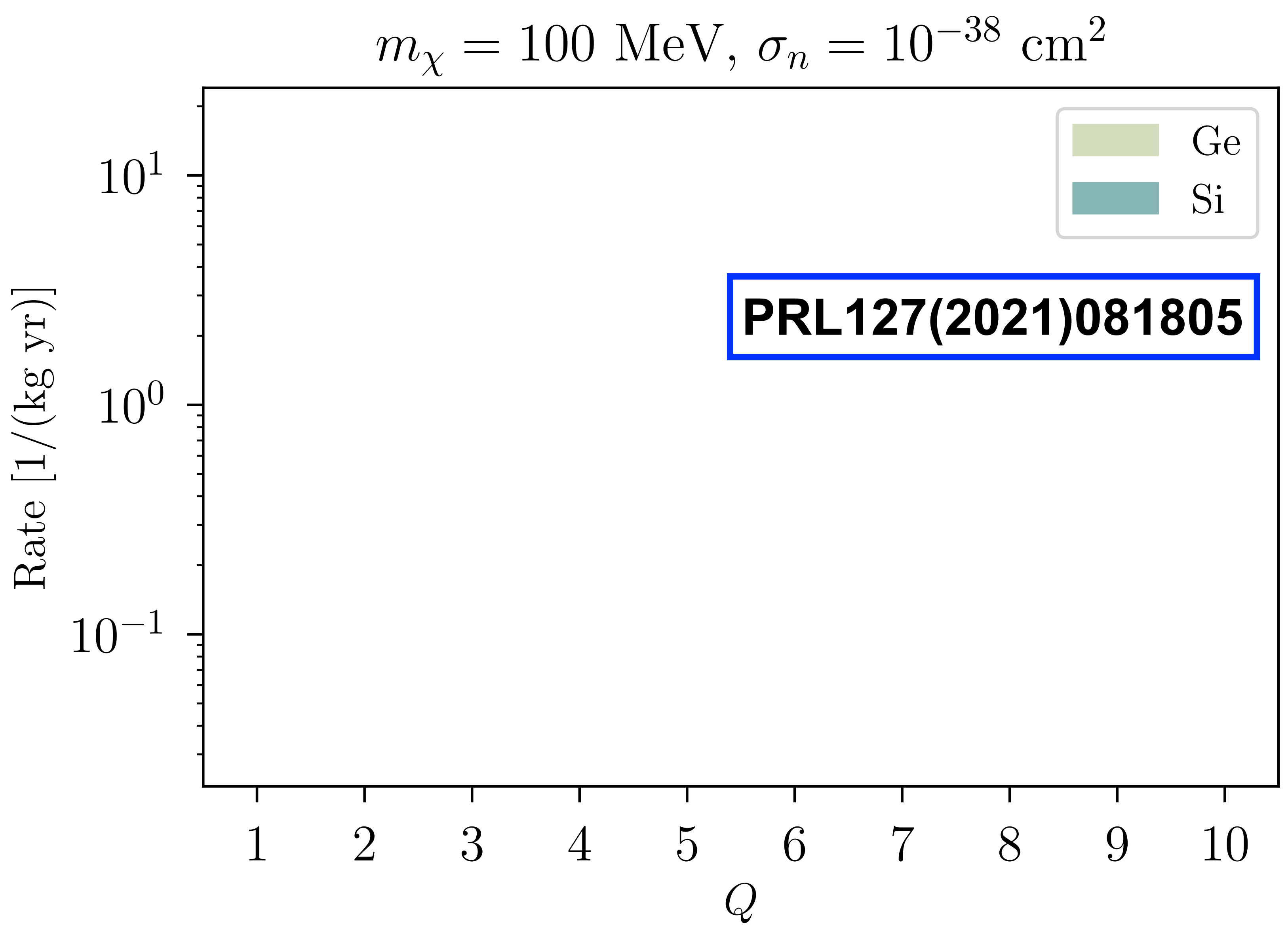

**DAMIC-M probes benchmark hidden-sector dark-matter models!**

# Other e-recoils

**Migdal effect:**




- Three-body final state: 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, see V. Azad talk tomorrow



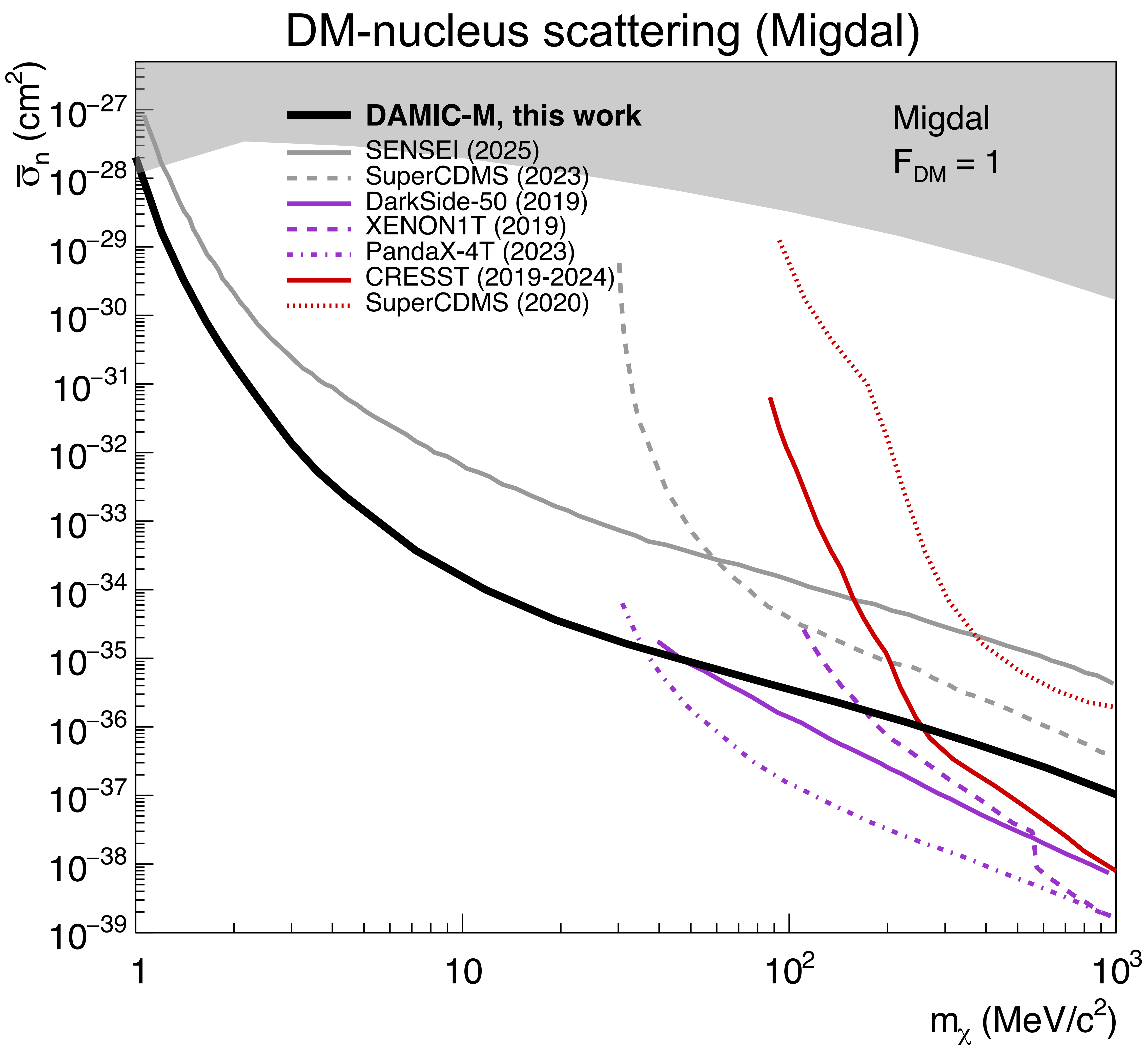

**Bosonic DM absorption:**

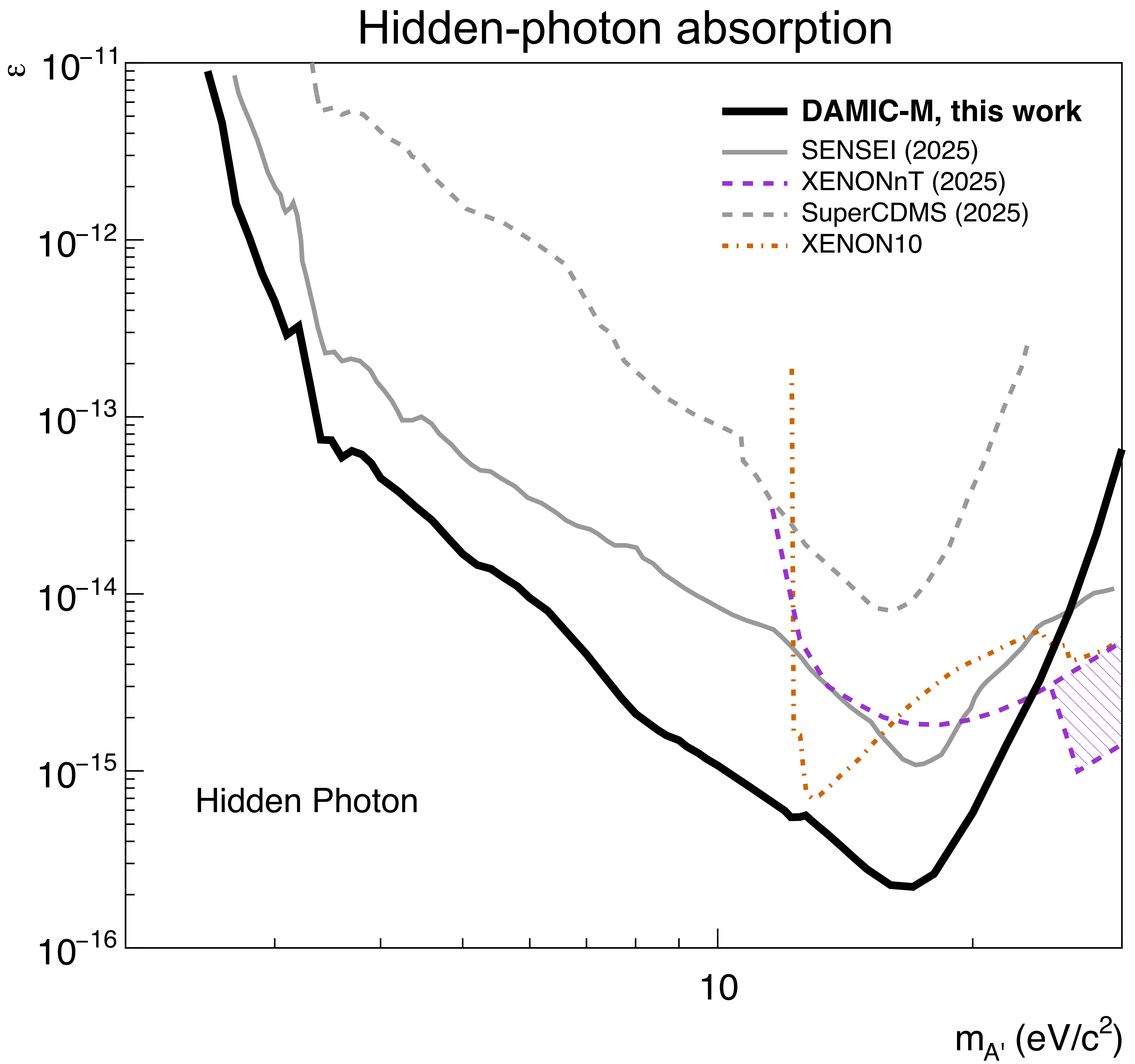
- DM particle is a boson that couples to the electron, e.g., a "dark" or "hidden" photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

➡ spectral line search

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

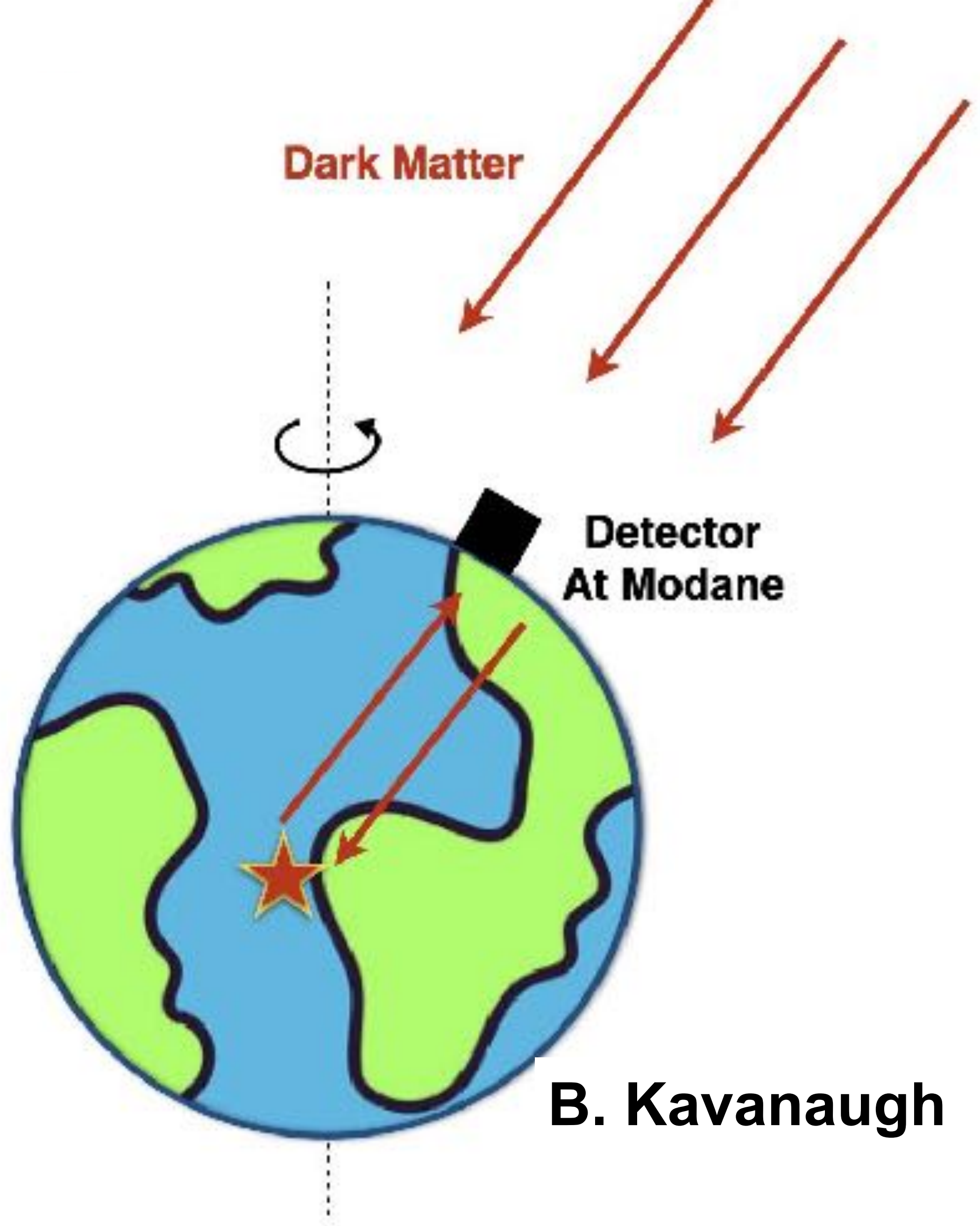
# Other exclusion limits



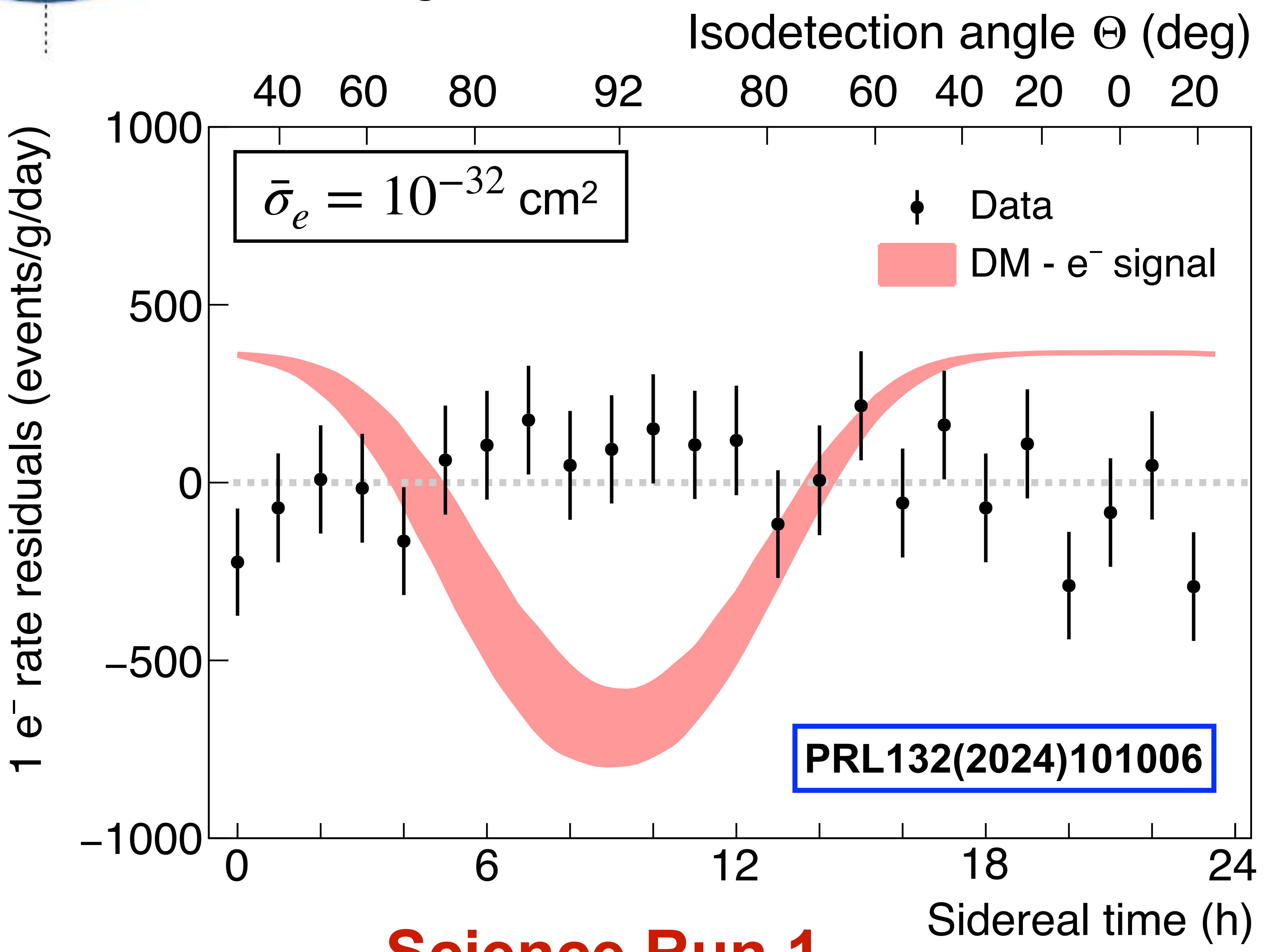




**More world-leading DM exclusion limits from DAMIC-M!**

# A peek to Daily Modulation

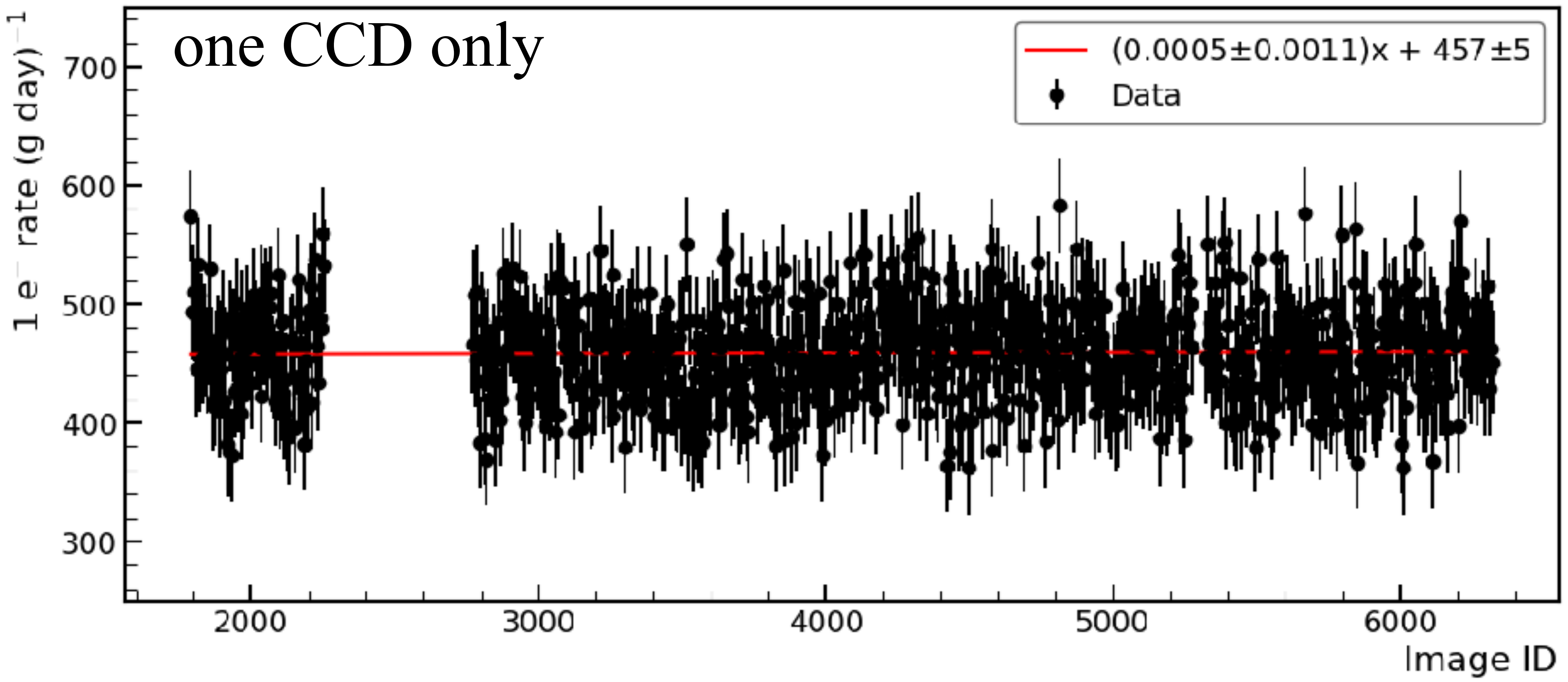



- At large enough σ, DM scatterings in the Earth cause a daily modulation of the flux in the lab. In Science Run 1 data, we searched for a daily modulation of the 1e- rate, improving our previous limits in the MeV DM mass range by up to x100.
- Science Run 2 data show excellent detector stability, and we expect further improvements in our sensitivity below 3 MeV




Science Run 1

Science Run 2



# Conclusions

- CCDs, pioneered by DAMIC at SNOLAB, are now established as the leading technique in the search for sub-GeV hidden-sector DM, thanks to the steadfast progress in the development of skipper CCDs by SENSEI and DAMIC-M

- DAMIC-M has already put a dent in hidden-sector dark matter with its prototype detector, challenging benchmark models with both heavy and ultra-light mediators. <u>Scalar dark matter is essentially excluded</u>

- More results to be expected from the SR2 data set (daily modulation, solar reflected DM,..)

- DAMIC-M is in advanced stage of construction, on track to be completed by the end of this year, with further improvements in sensitivity guaranteed by the reduction of radiogenic and cosmogenic backgrounds. In addition, a tenfold reduction in dark current may be possible.

- This talk focused on DM-e, but DAMIC-M is also sensitive to light WIMPs, through nuclear recoil ionization and possibly novel techniques (defects from nuclear recoils, see V. Azad talk tomorrow)

zoom in of the “question mark” particle

# DAMIC-M CCD image at a surface lab