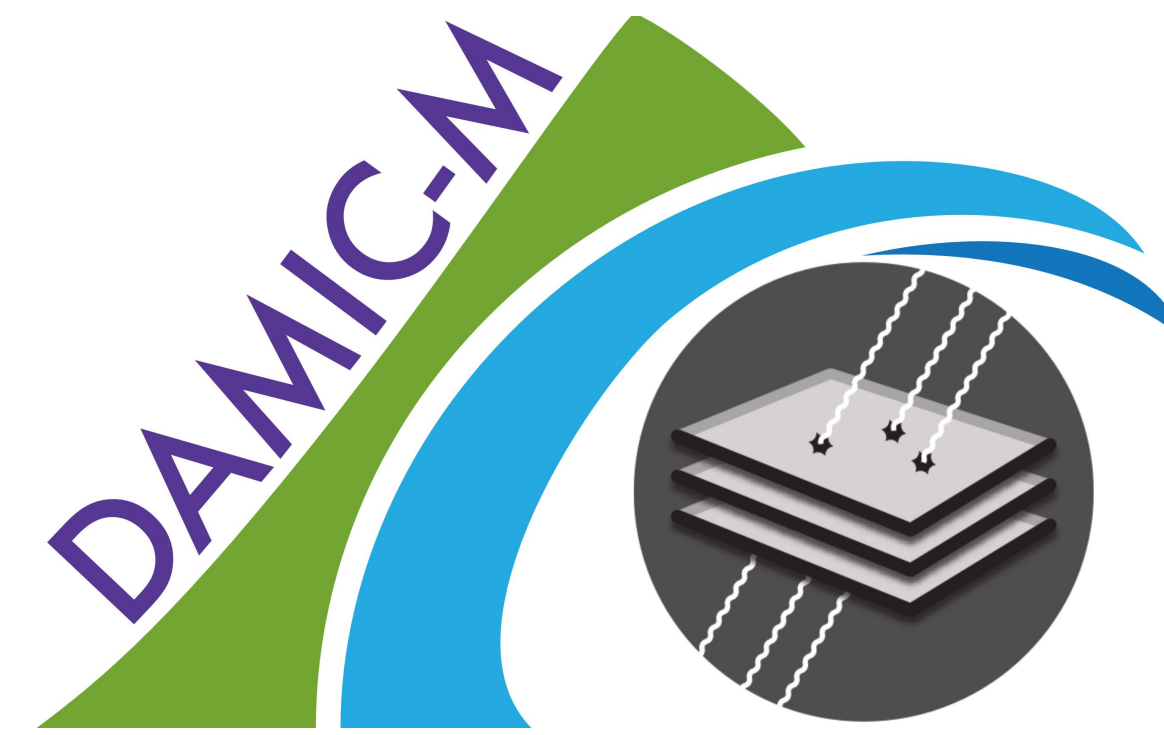




The DAMIC-M experiment: A skipper CCD detector at LSM

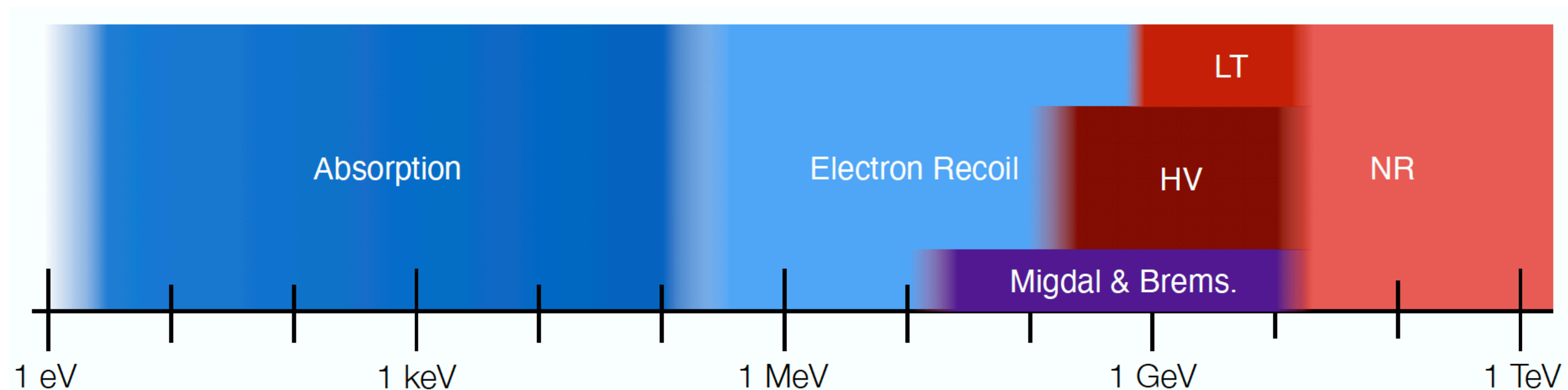
Rocio Vilar Cortabitarte
On behalf of the DAMIC-M Collaboration

Weight
14 tons

Introduction

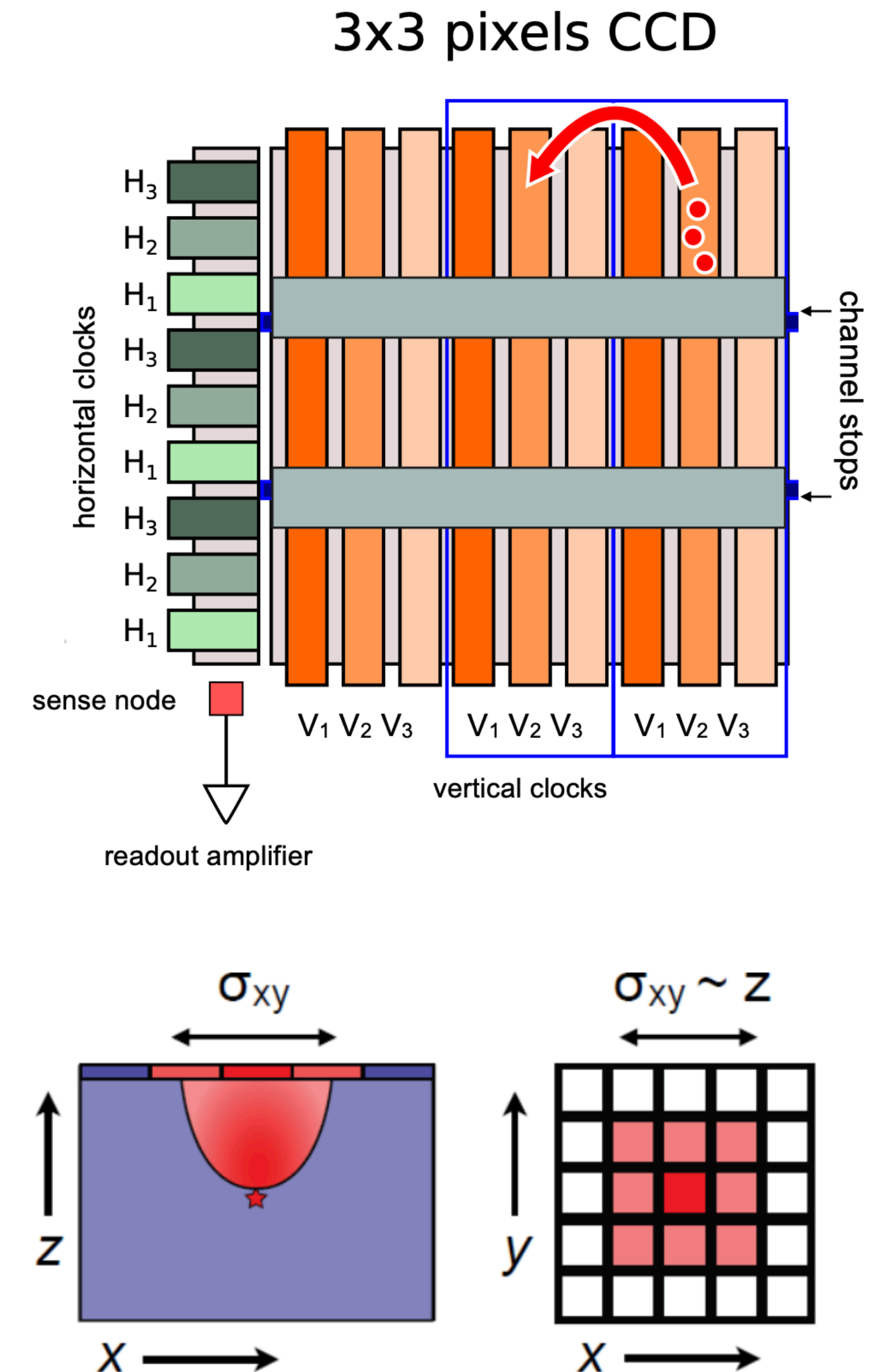
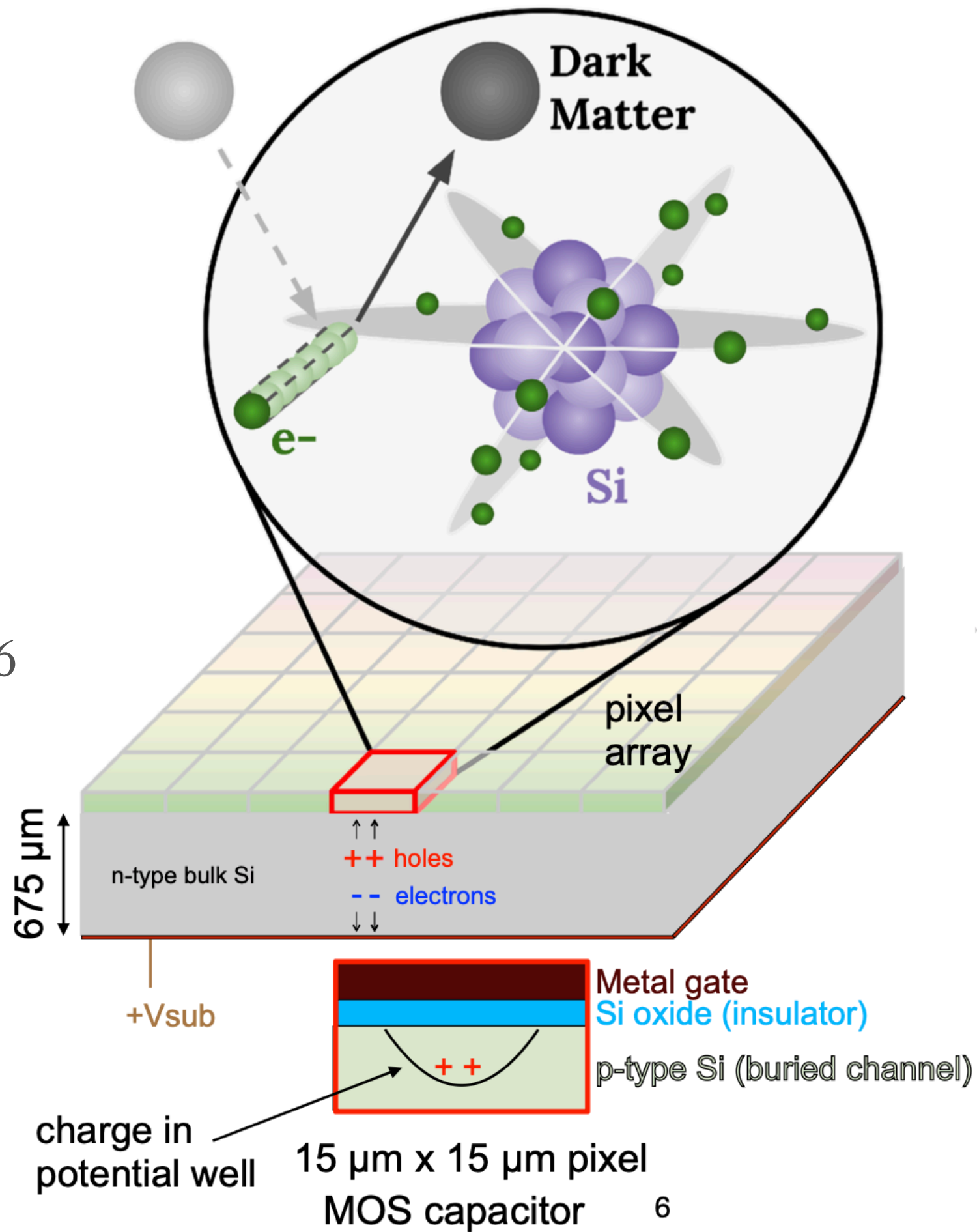
Theoretical motivation combined with technological opportunities makes the moment right for the search below 1 GeV.

- **Small experiments can have a huge impact in meaningful dark matter models.**
- **What we need to explore sub-GeV range:**
 - Extremely low thresholds ($\sim$ few eV) $\rightarrow$ to access smaller DM masses.
 - Scalable technologies to increase the number of interactions in the target.
 - Detectors with an extremely low backgrounds ($\sim$ sub dru) $\rightarrow$ Low and controlled backgrounds
- **Aim to measure interactions with matter:**
 - Elastic scattering off nuclei (standard WIMP scenarios) $\rightarrow m_\chi = 1\text{-}1000 \text{ GeV } c^{-2}$
 - Inelastic scattering off electrons (dark sector couplings) $\rightarrow m_\chi = 1\text{-}1000 \text{ MeV } c^{-2}$
 - DM absorption by bound electron (dark sectors and ALPs) $\rightarrow m_\chi = 1\text{-}1000 \text{ eV } c^{-2}$



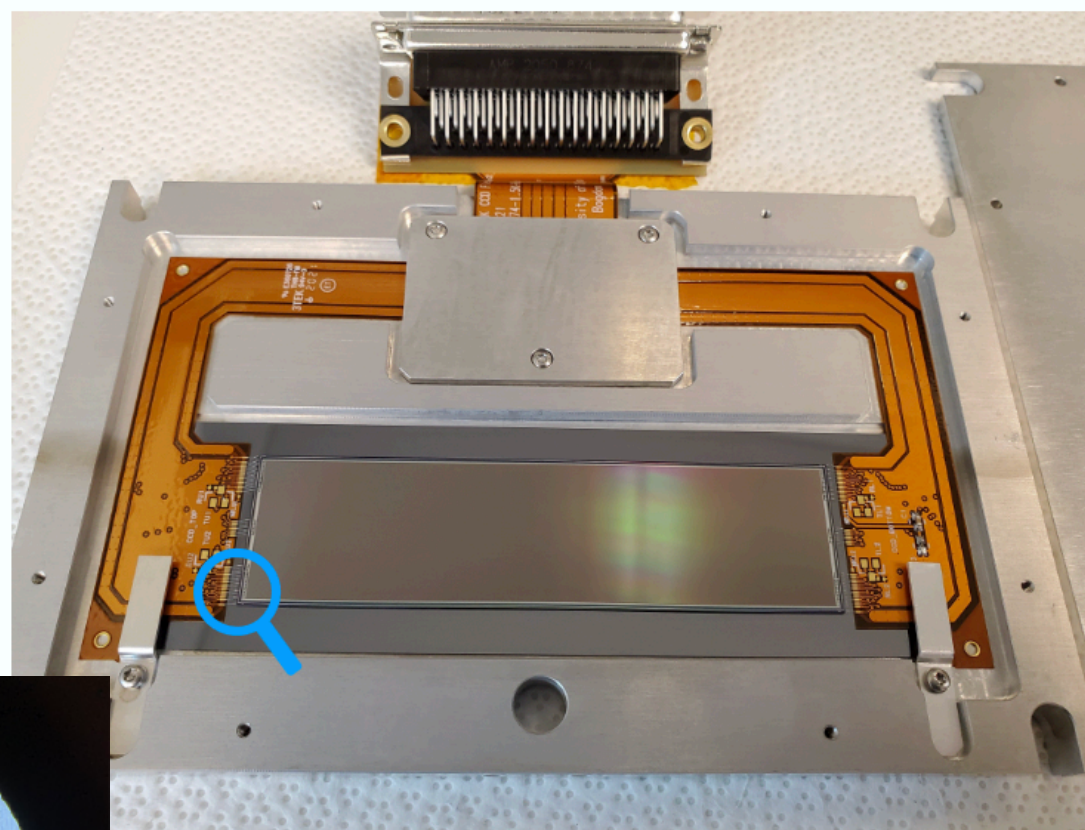
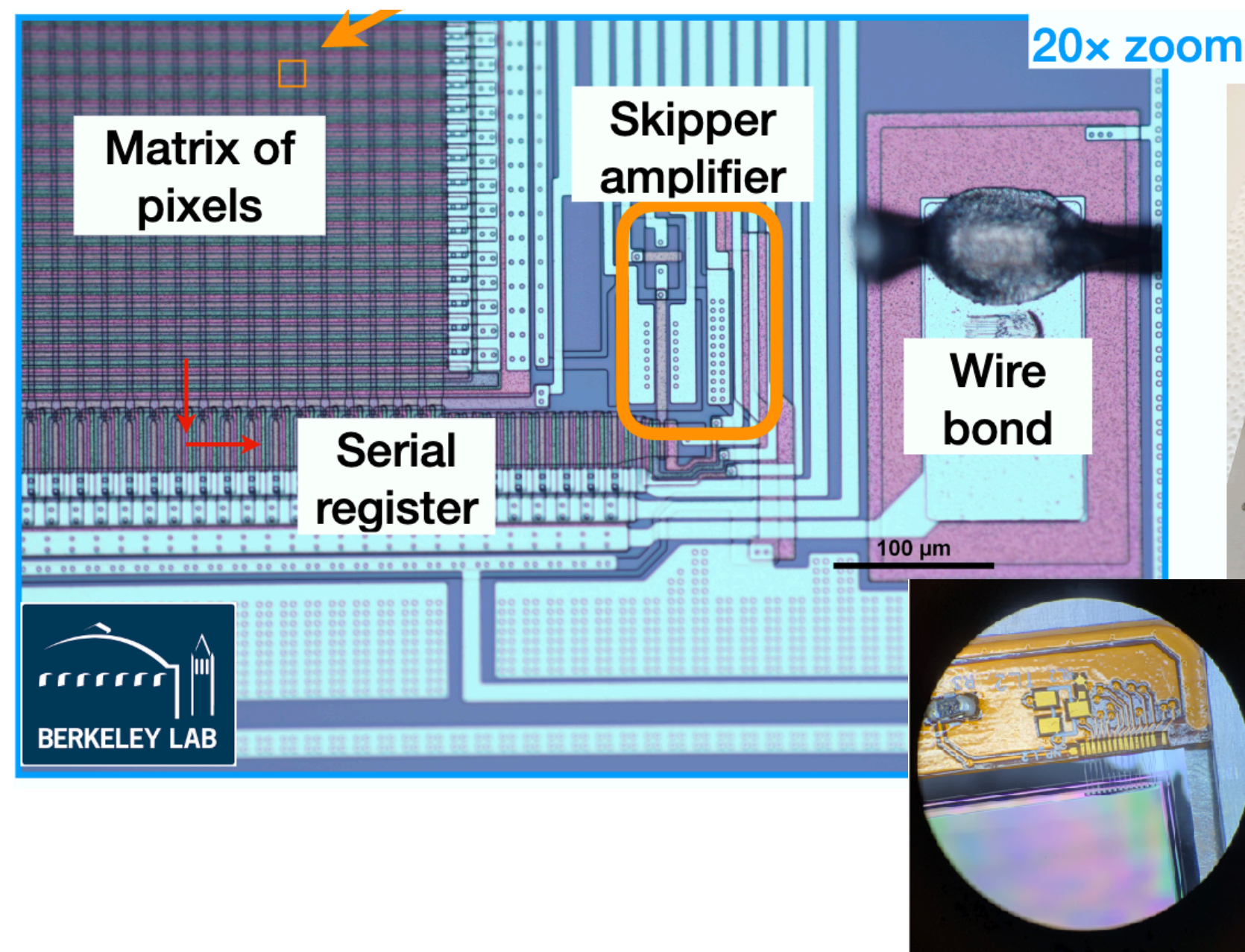
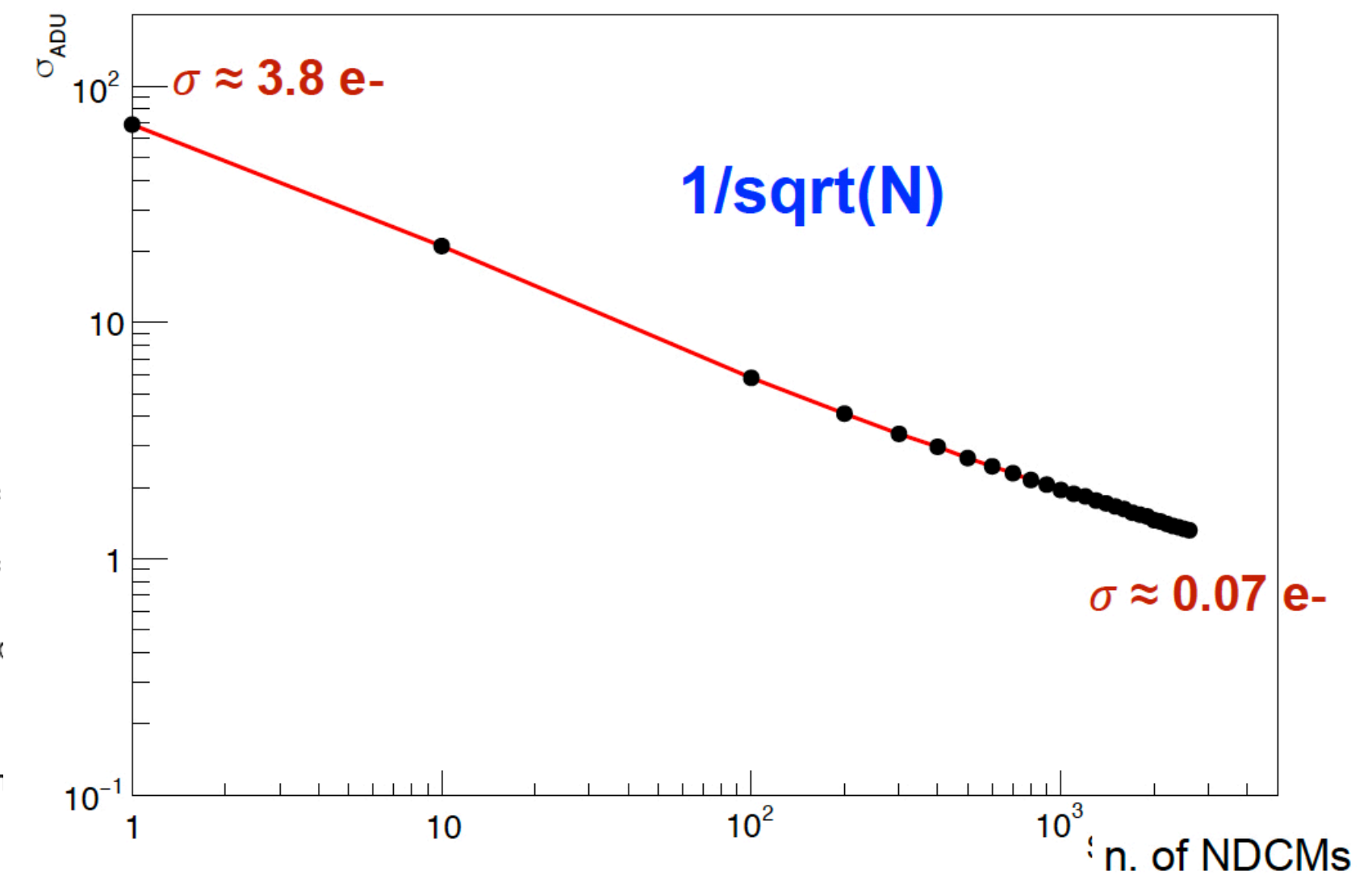
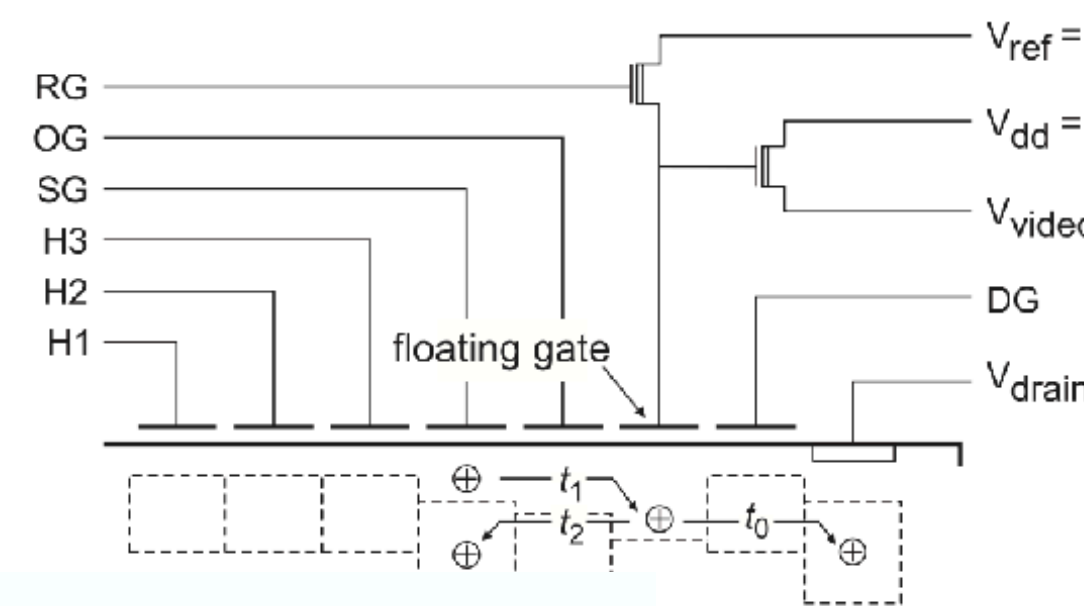
CCD technology

- **P-type** buried channel structure (LBNL).
- Fully depleted at 40 V ($> \sim 10 \text{ k}\Omega \cdot \text{cm}$)
- $15 \text{ }\mu\text{m} \times 15 \text{ }\mu\text{m} \times 670 \text{ }\mu\text{m}$ pixel
- Charge transfer inefficiency(CTI): $< 10^{-6}$
- **Dark Current**: $< 100 \text{ e}^-/\text{g}/\text{day}$
- **Thresholds**: $\sim 2 \text{ e}^-$ (6 eV)
- Depth (z) reconstructed from lateral distribution of charge on pixel array.

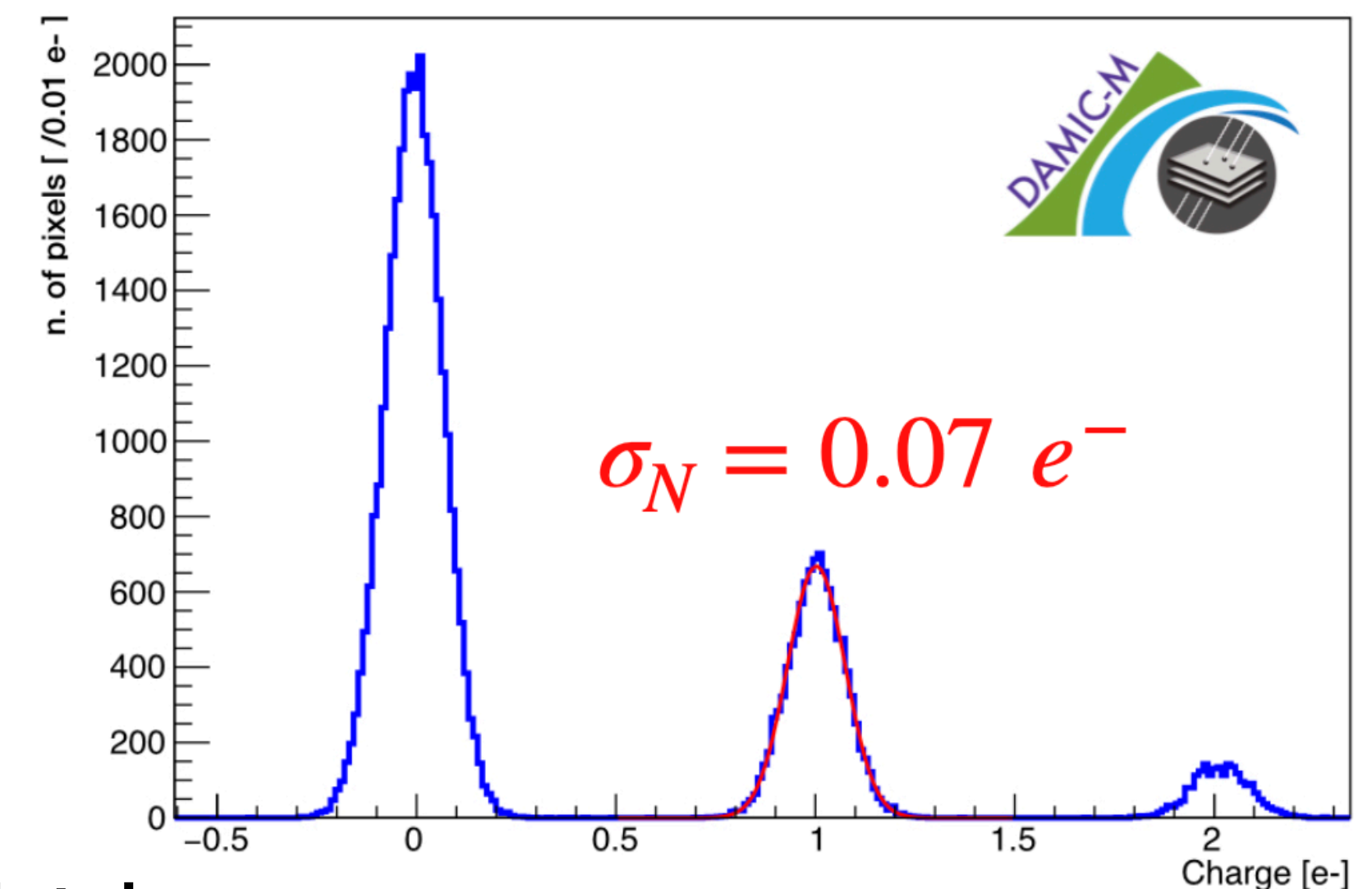


CCD technology

- The **skipper-CCD** is a modification of the output stage (Janesik et al -1990).
- Allows **multiple non-destructive** charge readout of a pixel.
- Re-engineered from LBNL CCDs, Tiffenberg et al. (2017)
- **Single electron resolution** by multiple NDCMs
- Pixel readout time $O(10 \text{ ms})$ for $0.15e^-$; ok for DM searches



DAMIC-M prototype device



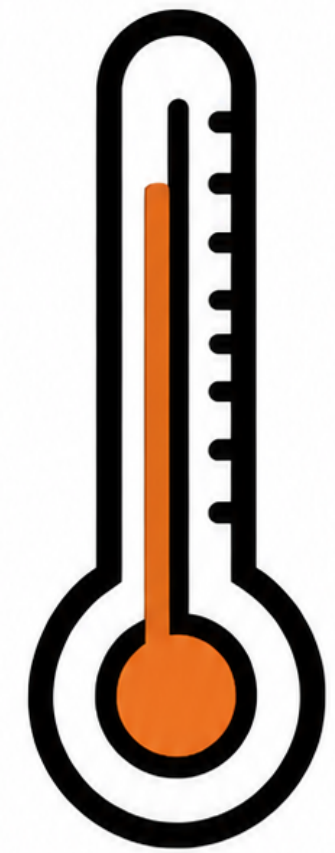
More on Nuria Castello and Ans Desai talks today
and Brenda Cervantes talk's on Thursday

What is DAMIC-M?

DAMIC-M

In NutShell

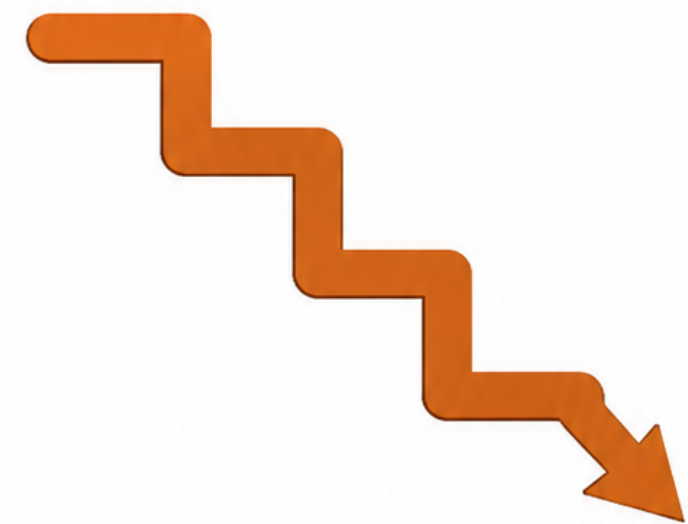
Detect **Light DM** (WIMP, Hidden Sector) signals via interaction with Si-nucleus or e- in the bulk of CCDs



130 K

Temperature

10 d.r.u.

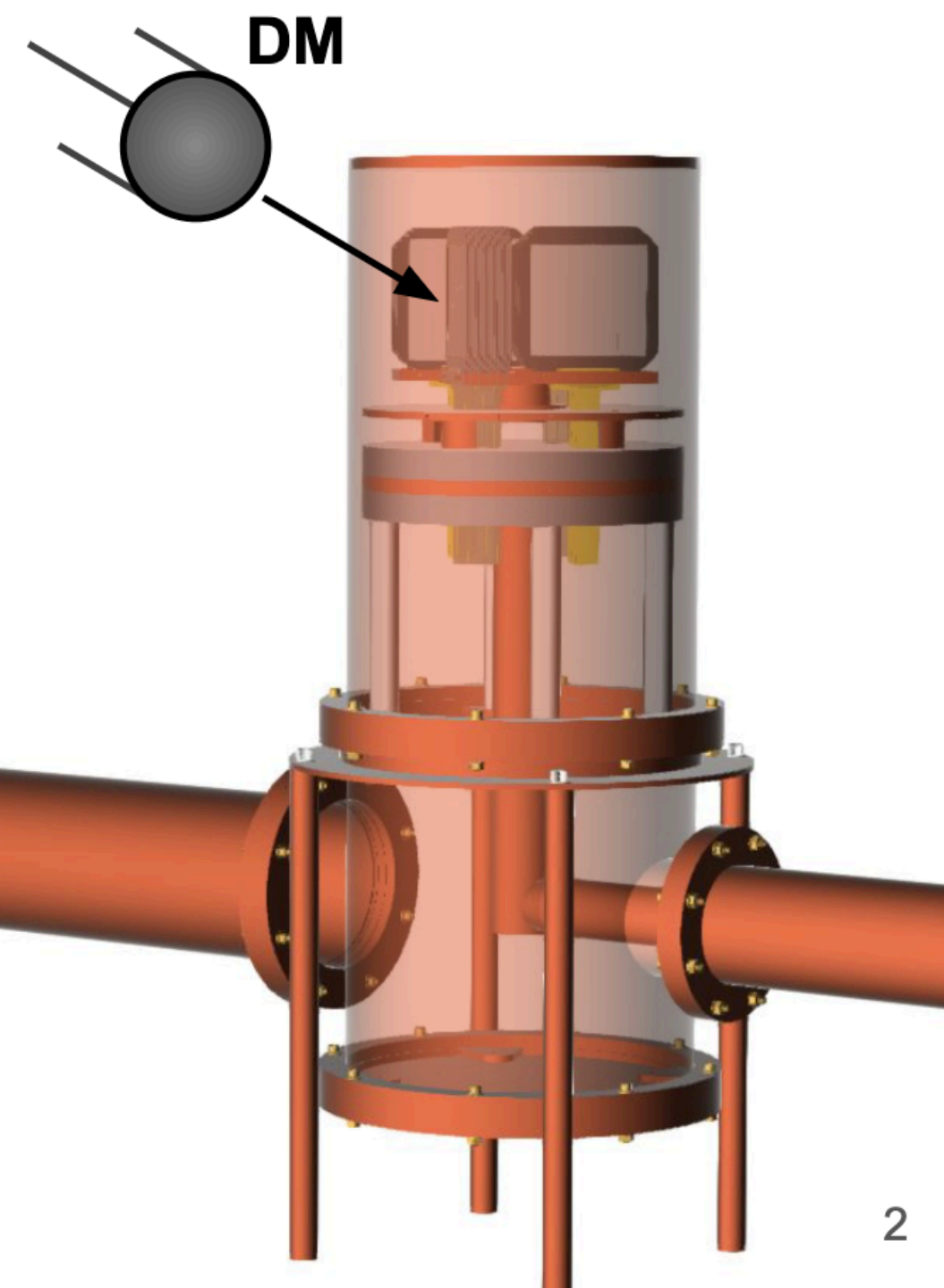


$O(<1 \text{ d.r.u.})$

Background Level

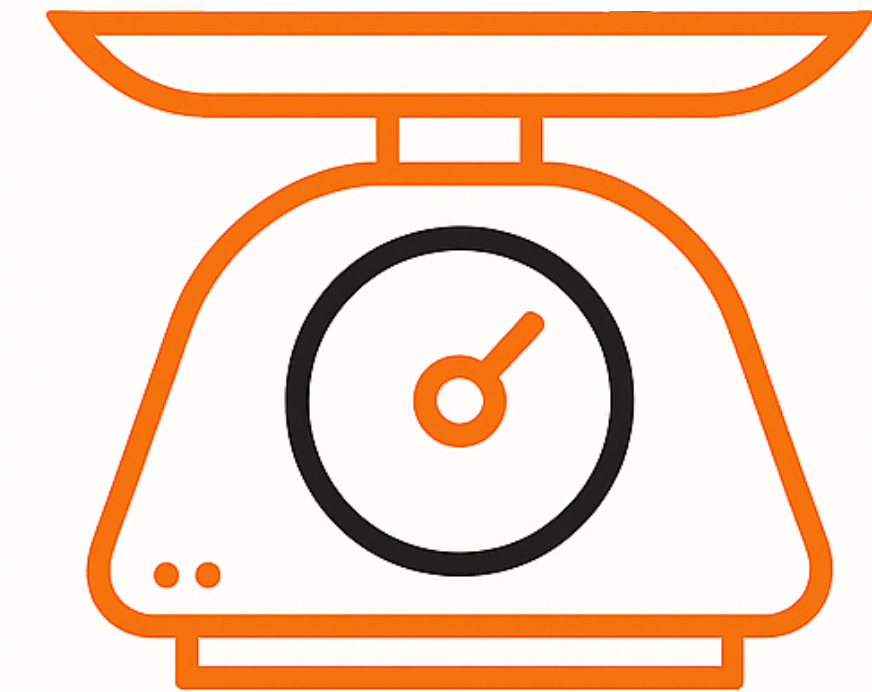
$O(<1 \text{ d.r.u.})$

$\text{dru}=(\text{events/keV/kg/day})$

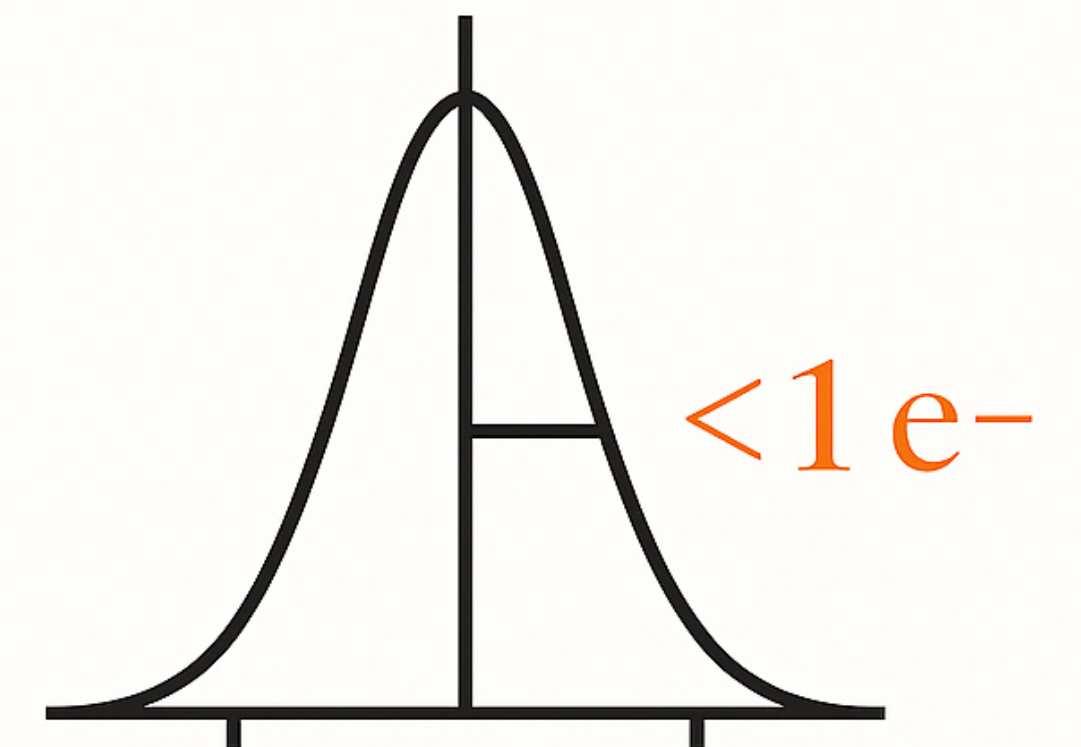


2

$\sim 350 \text{ gr}$



Sensitive Mass



Resolution (readout noise)

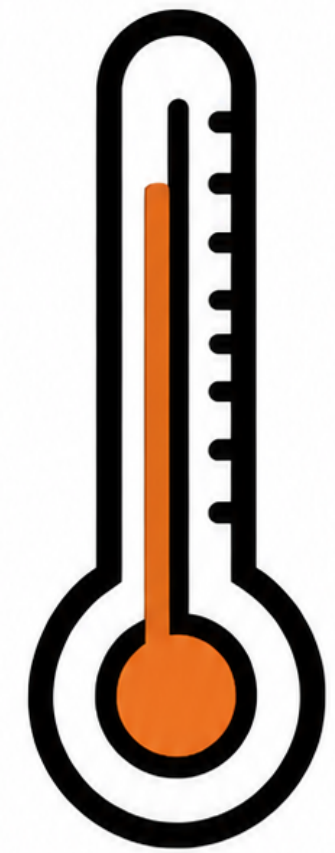
$\sim 0.1 \text{ eV}$

2-e electron thresholds ($\sim \text{eV}$)

DAMIC-M

In NutShell

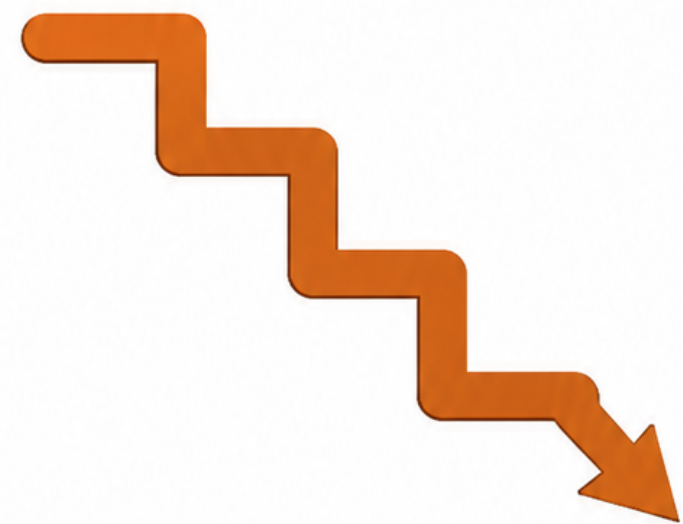
Detect **Light DM** (WIMP, Hidden Sector) signals via interaction with Si-nucleus or e- in the bulk of CCDs



130 K

Temperature

10 d.r.u.

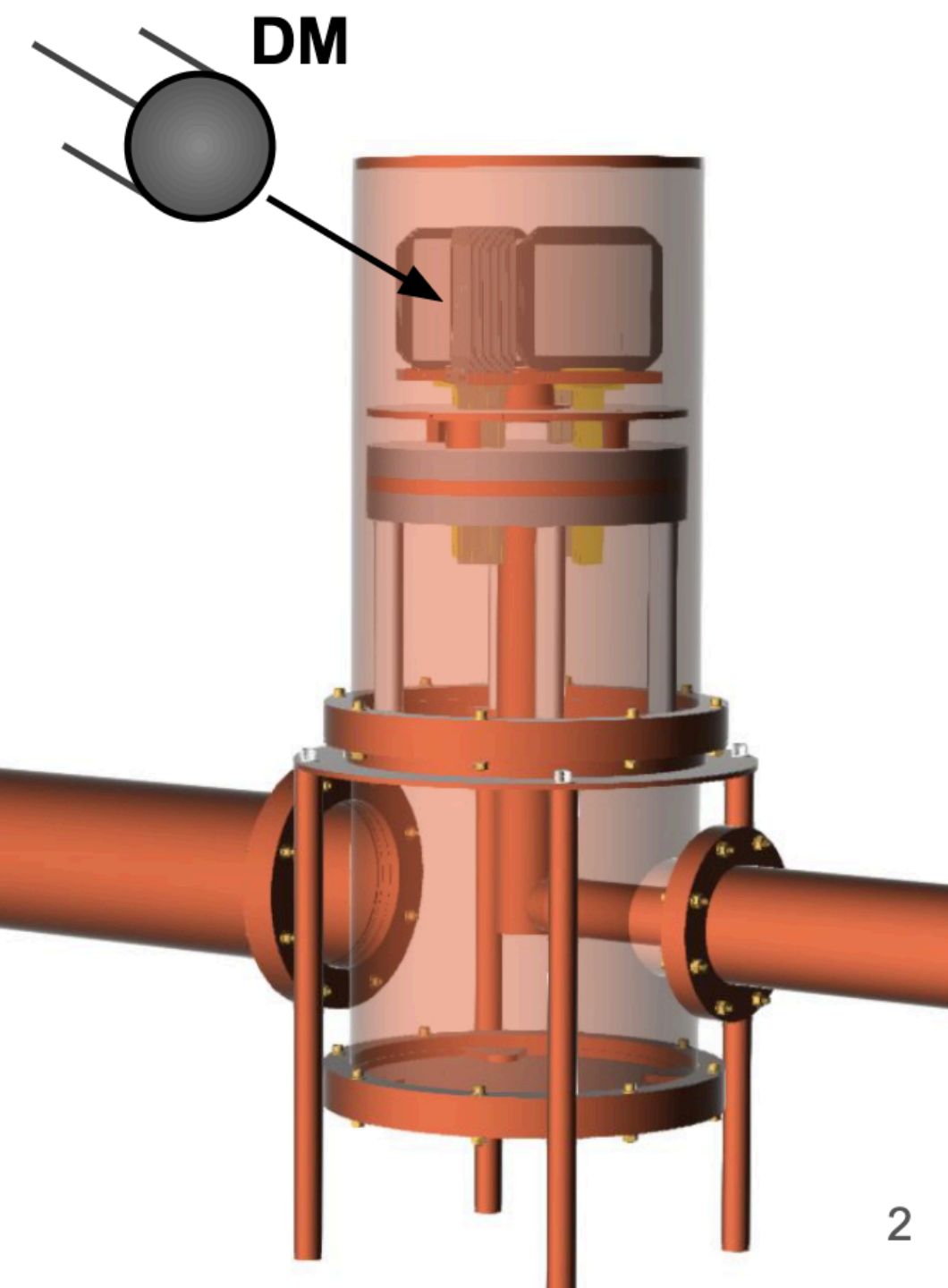


$O(<1 \text{ d.r.u.})$

Background Level

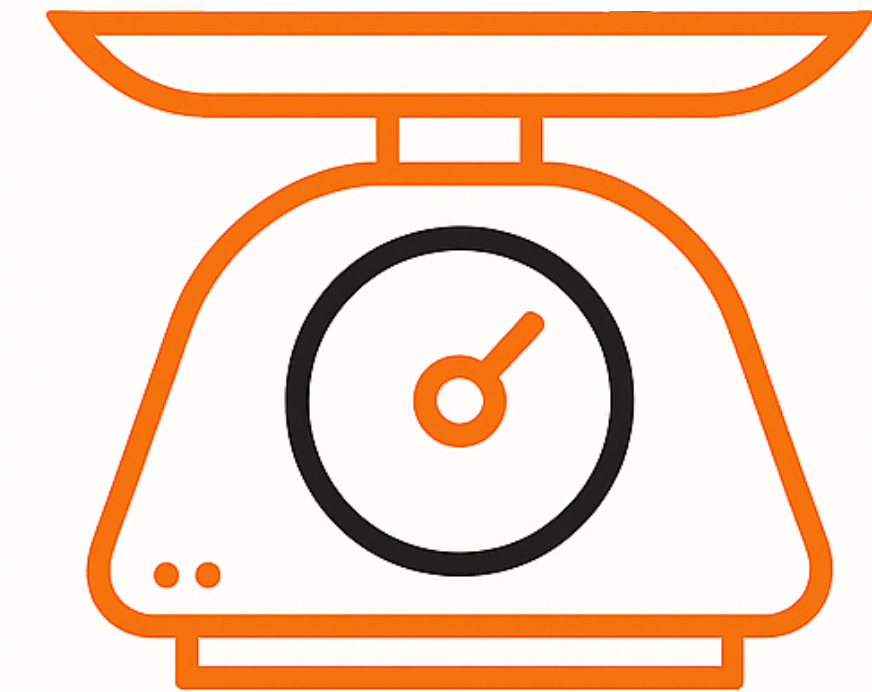
$O(<1 \text{ d.r.u.})$

dru=(events/keV/kg/day)

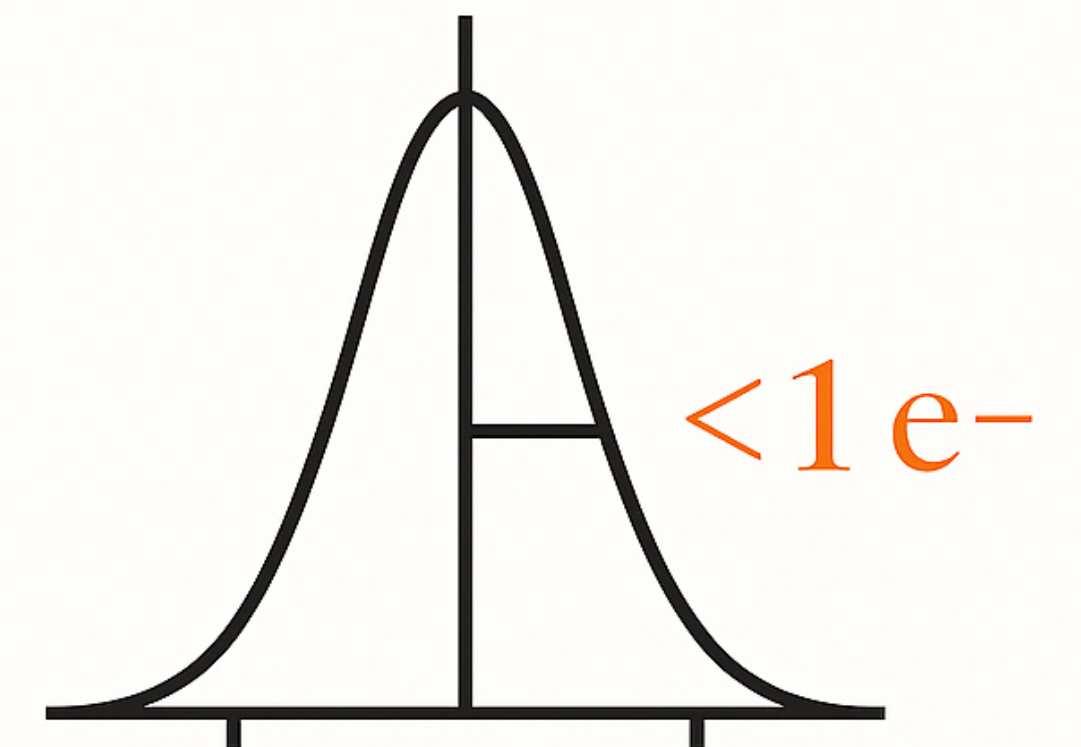


See's Nuria Talk on the prototype

$\sim 350 \text{ gr}$



Sensitive Mass



Resolution (readout noise)

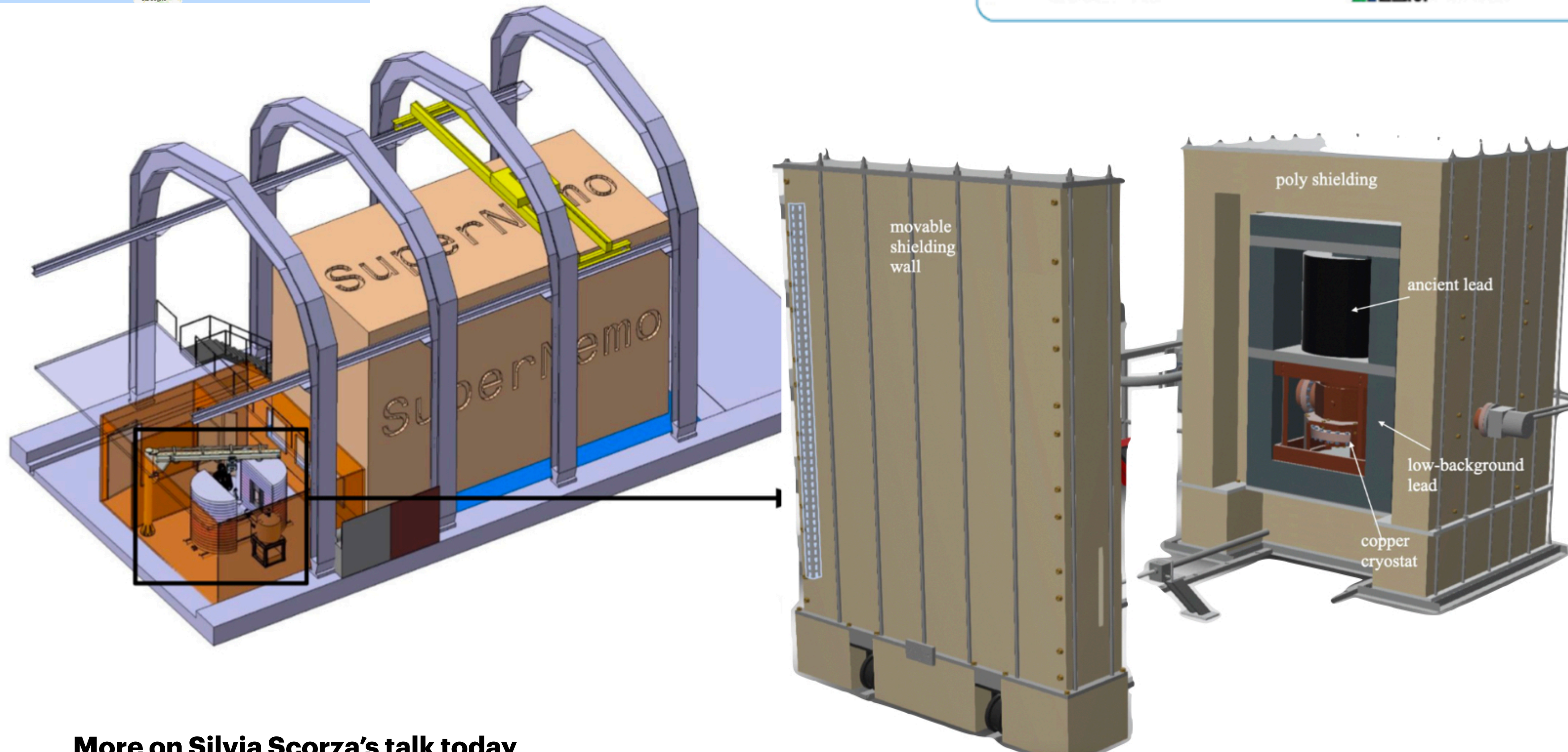
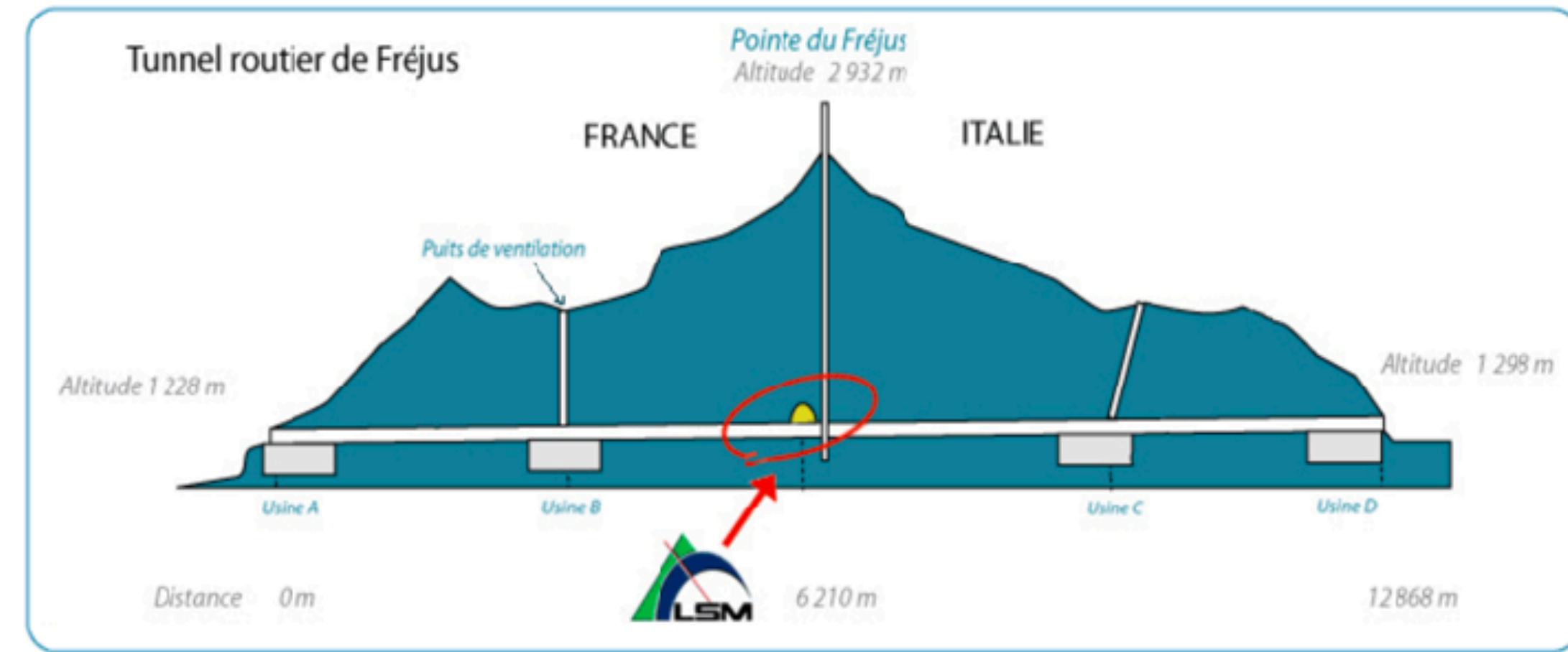
$\sim 0.1 \text{ eV}$

2-e electron thresholds ($\sim \text{eV}$)



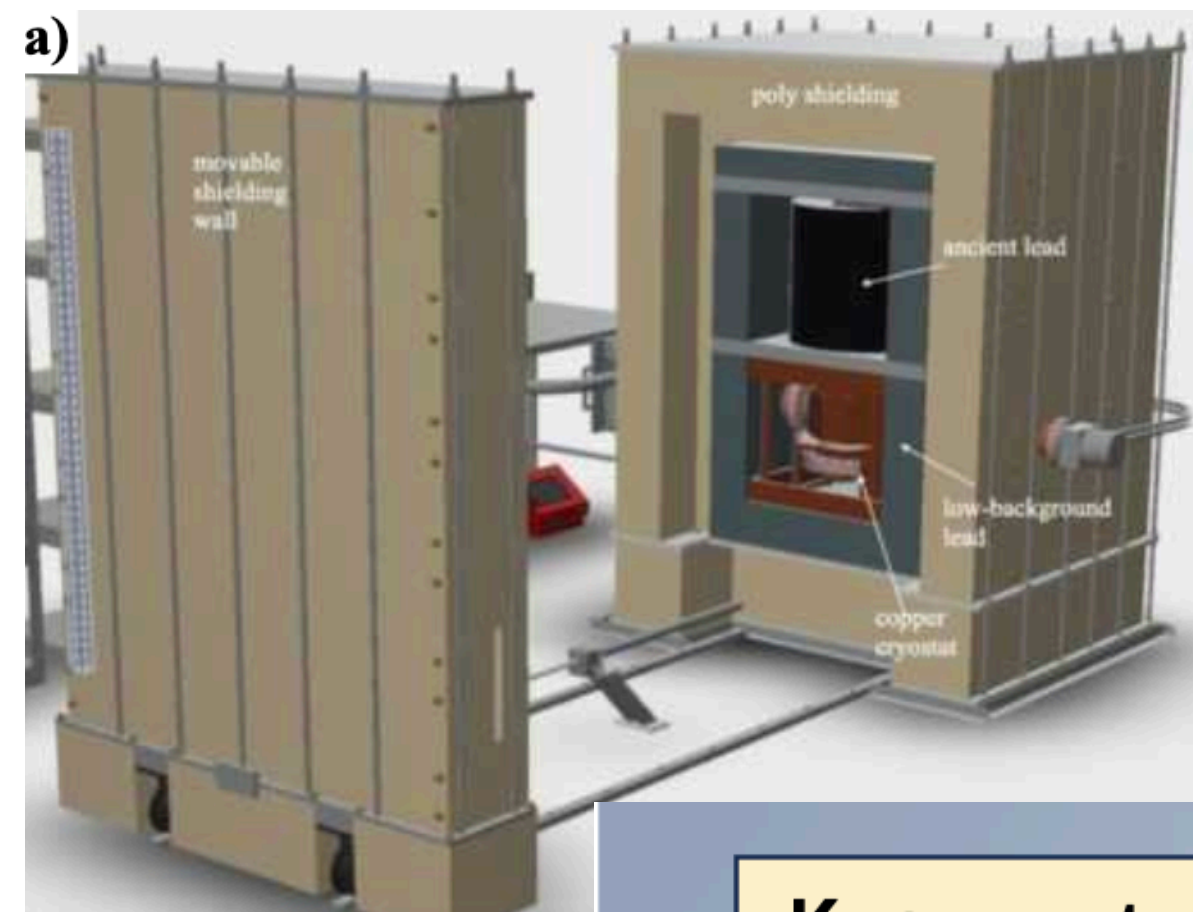
DAMIC-M

In NutShell



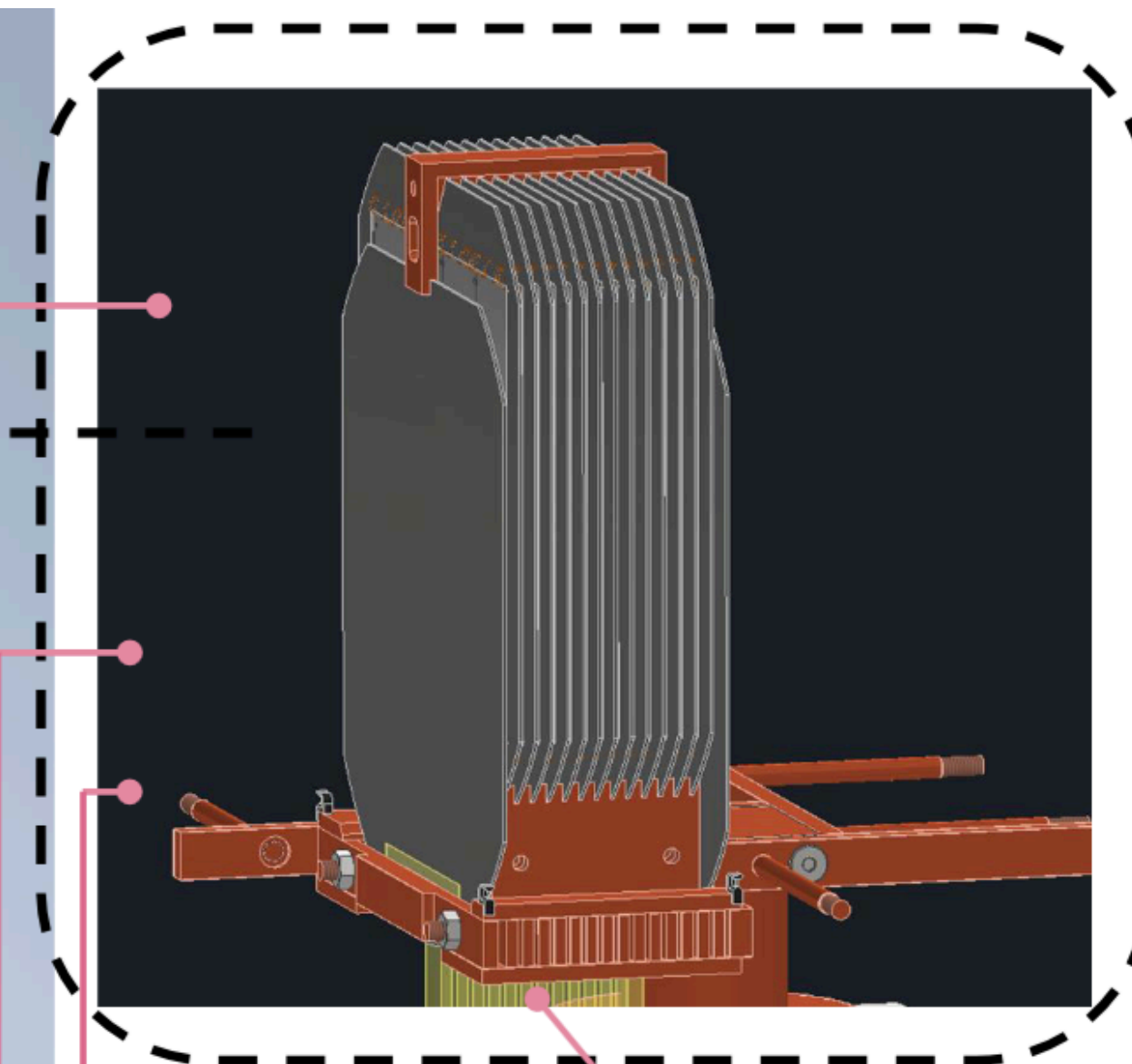
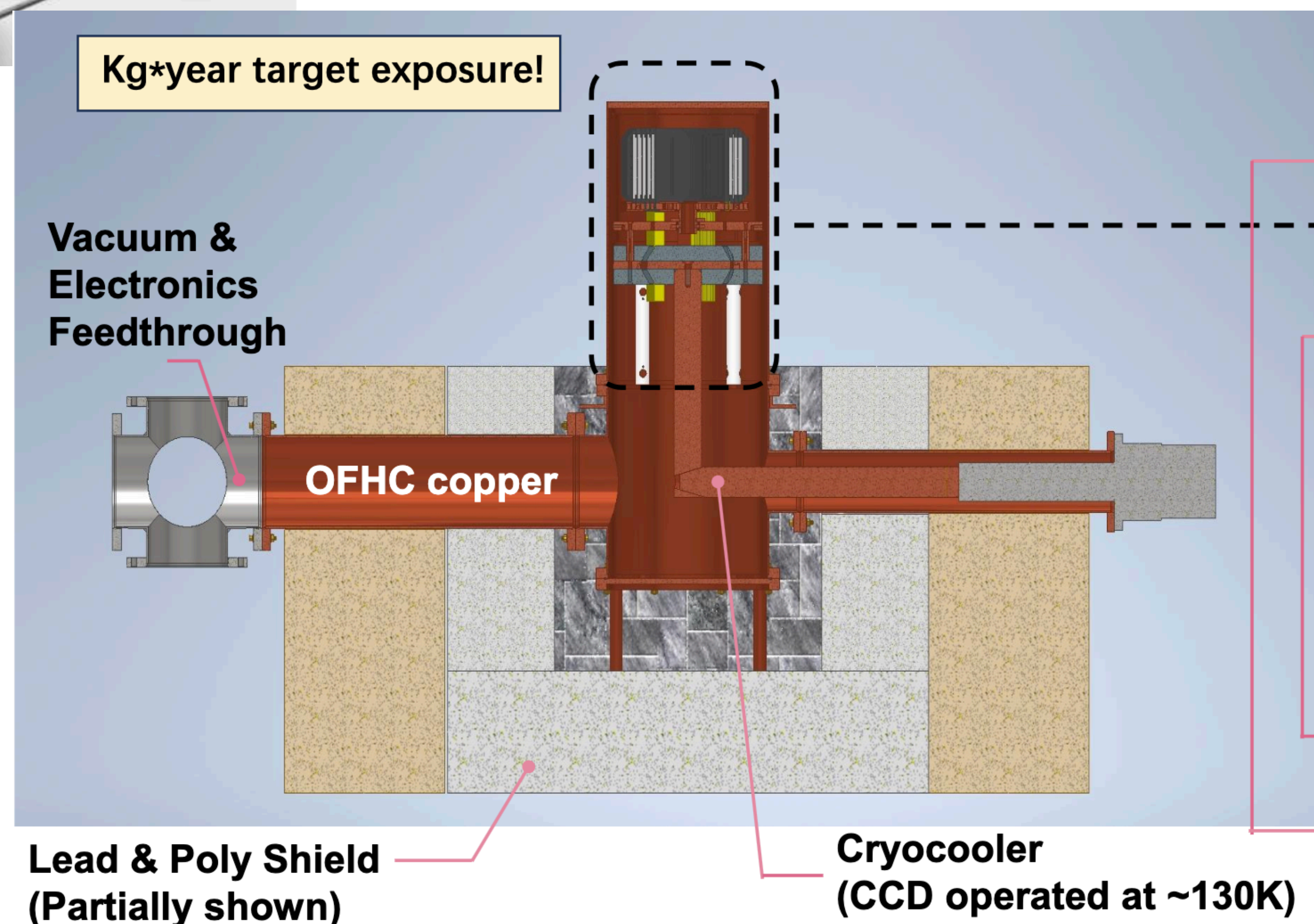
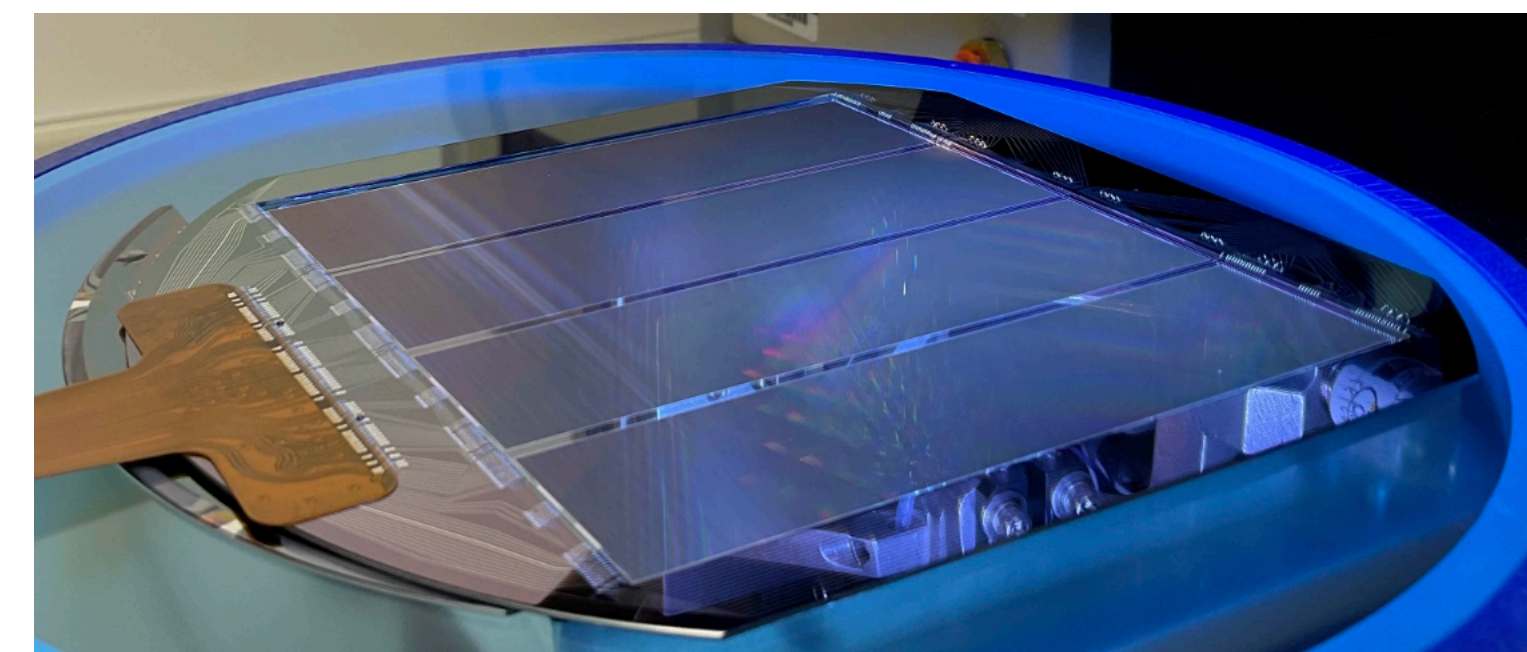
More on Silvia Scorza's talk today

a)



DAMIC-M

**4 Ccd (6144X1536) Pixels Glued On
Si Pitched Adapter And 2-Layer Qflex
Kapton Cable**



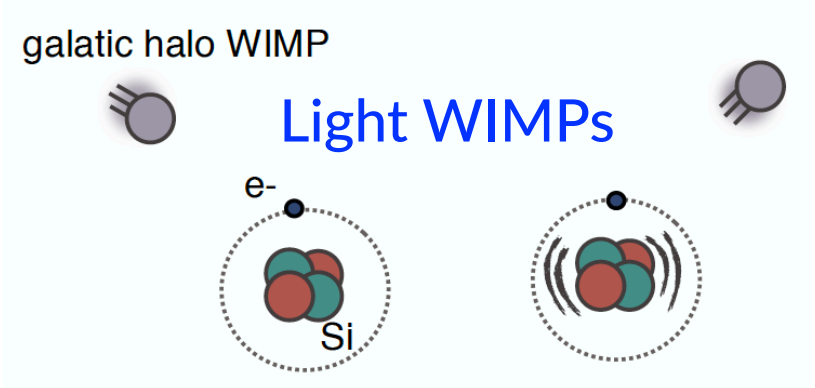
Radio-pure flex
EPJ Tech. Instrum., 10(1):17, 2023.

Ancient Lead

E.F. Copper

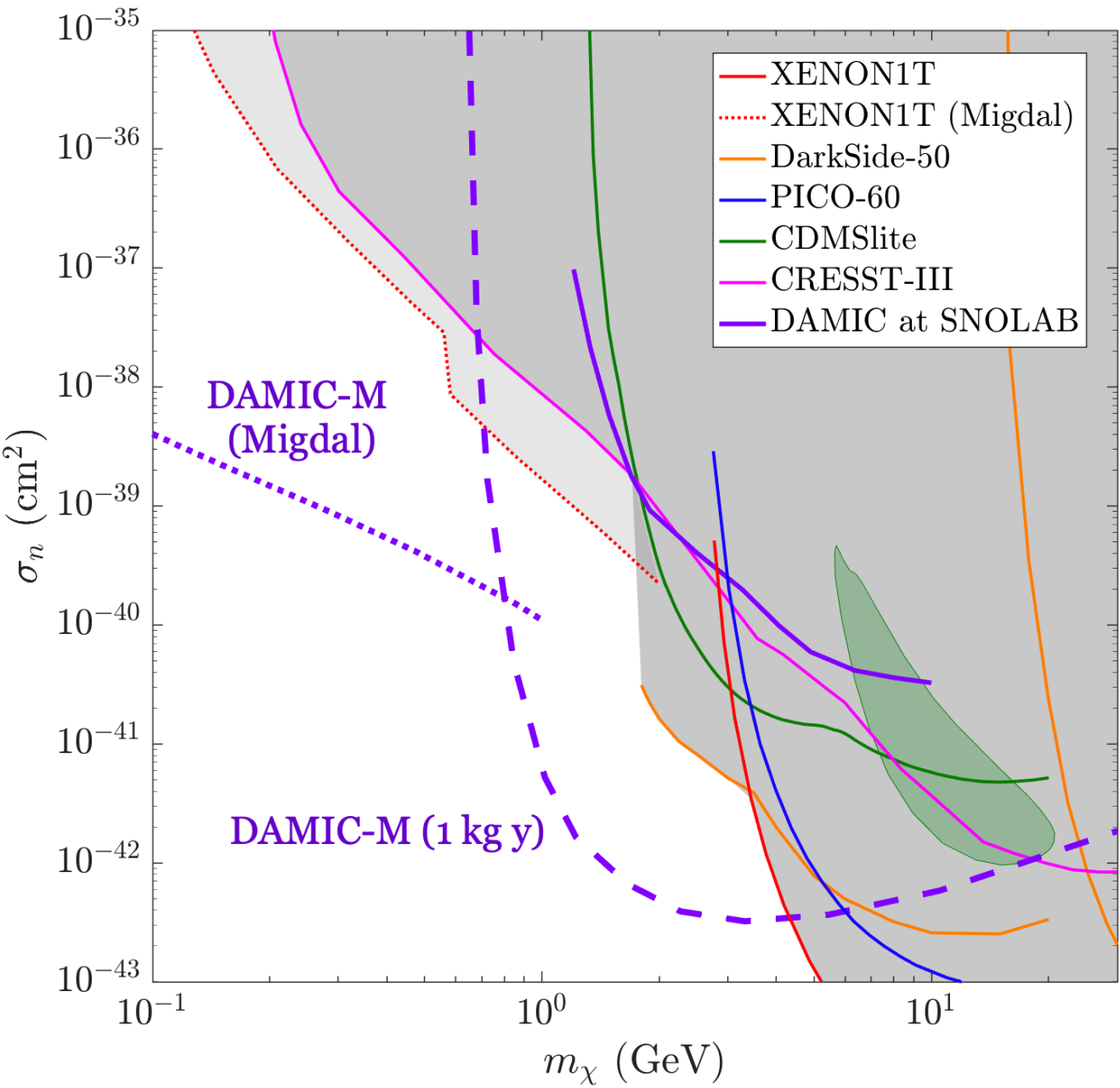
**Phase I: Array of 26 CCD Modules
(340 g silicon target)**

DAMIC-M Sensitivies

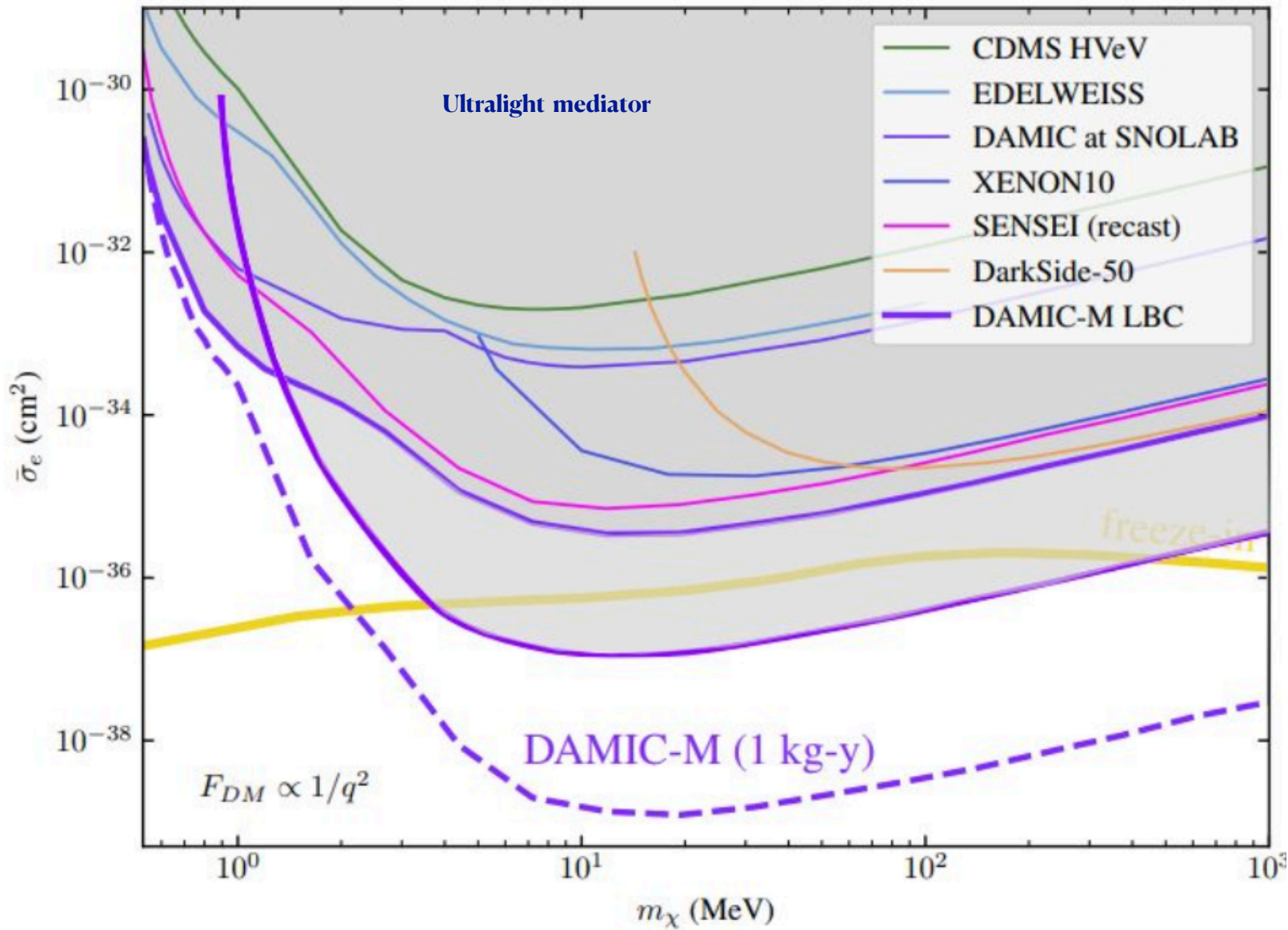


WIMP-nucleus elastic scattering:

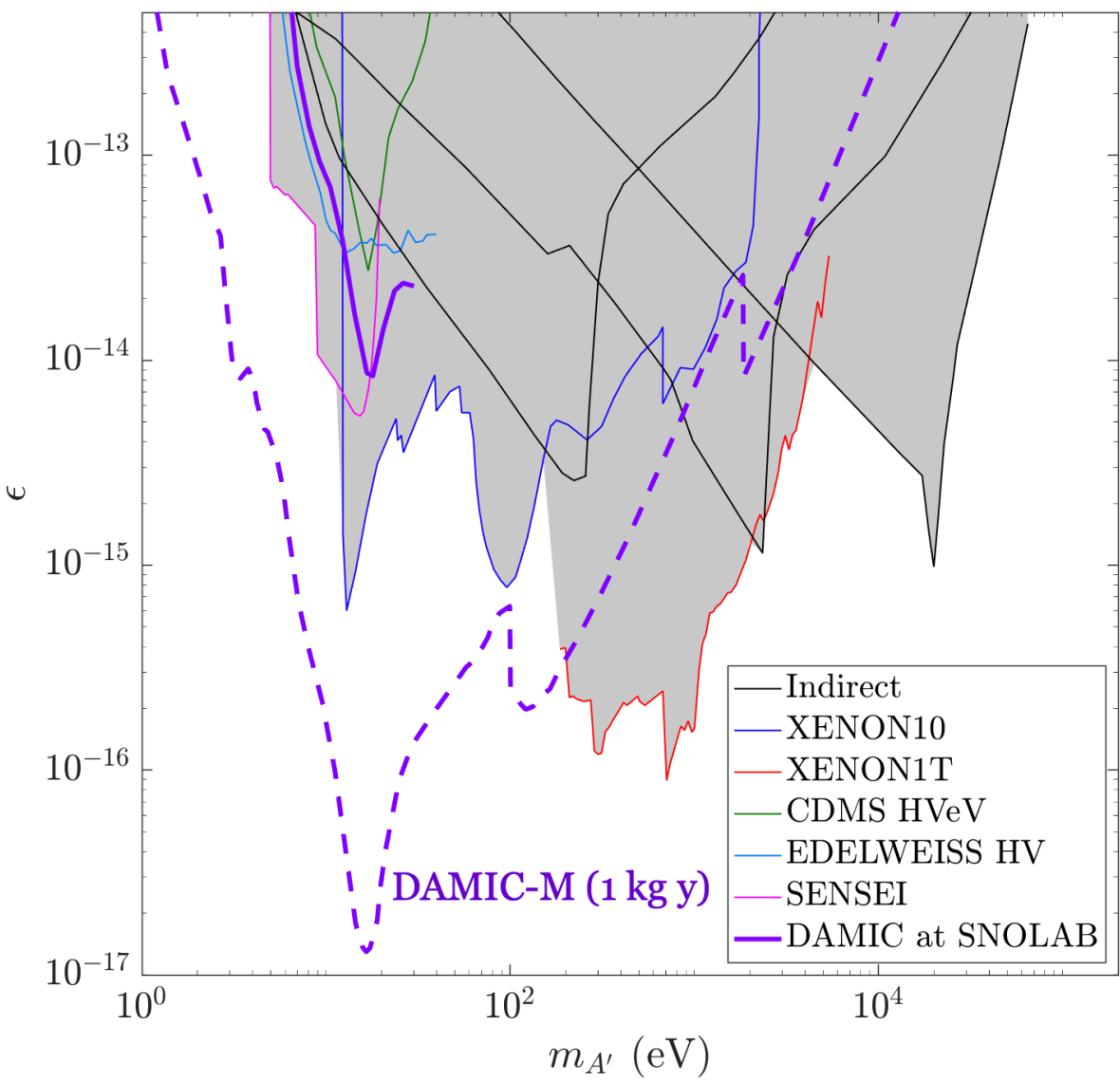
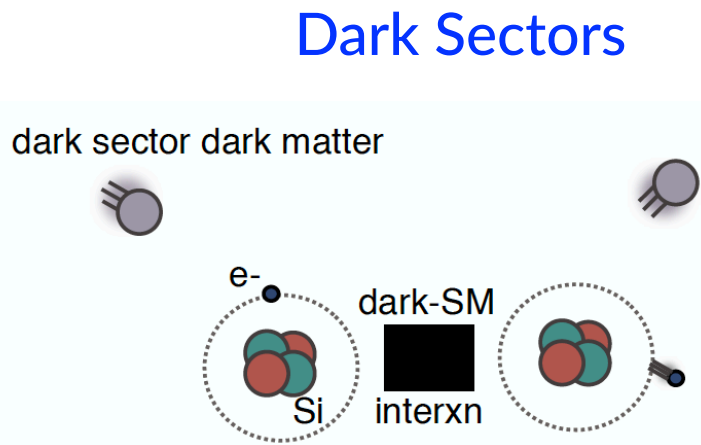
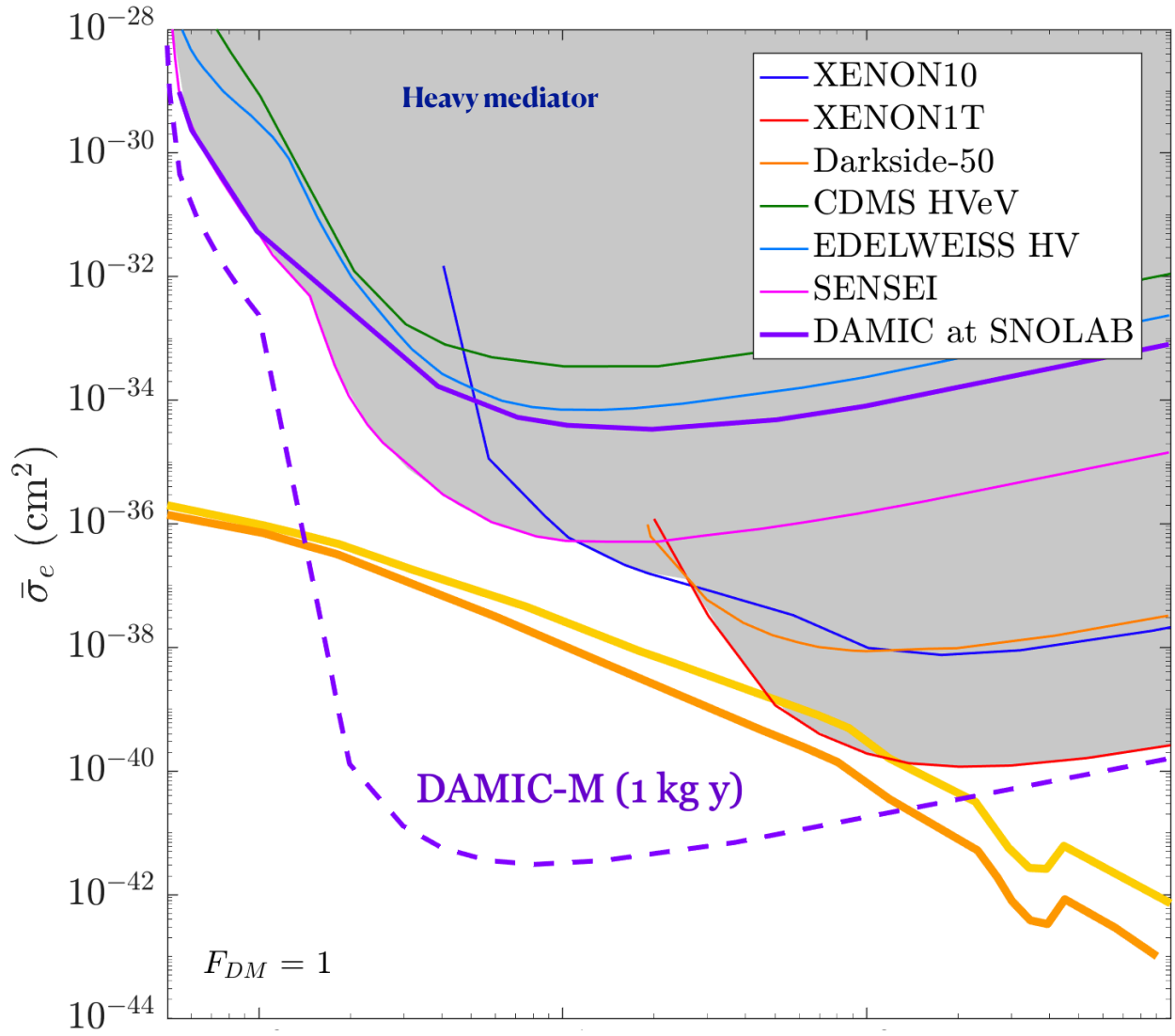
*can also detect secondary electron recoils from inelastic Migdal effect



Physics Reach

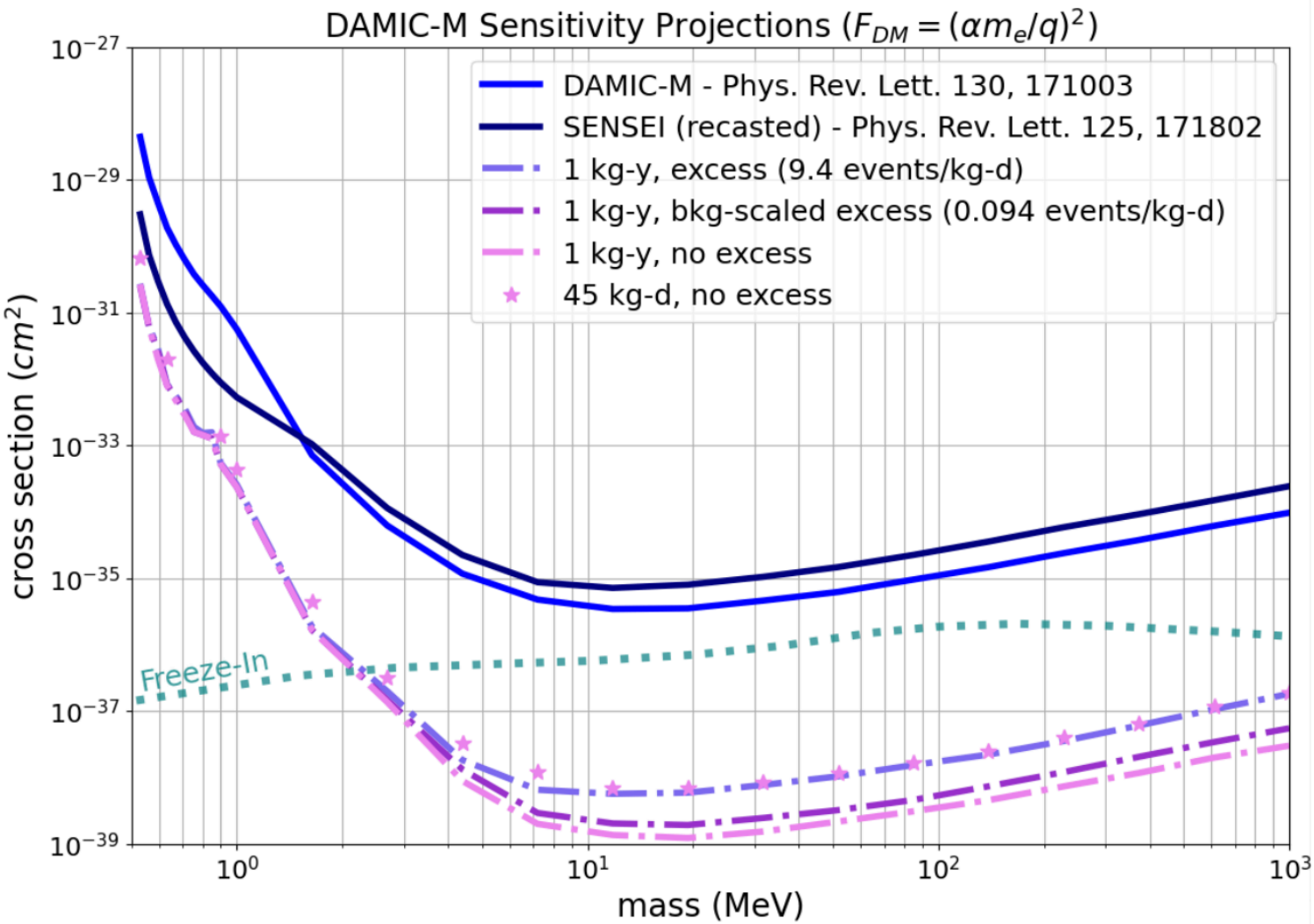


DM - Electron scattering:



DM absorption

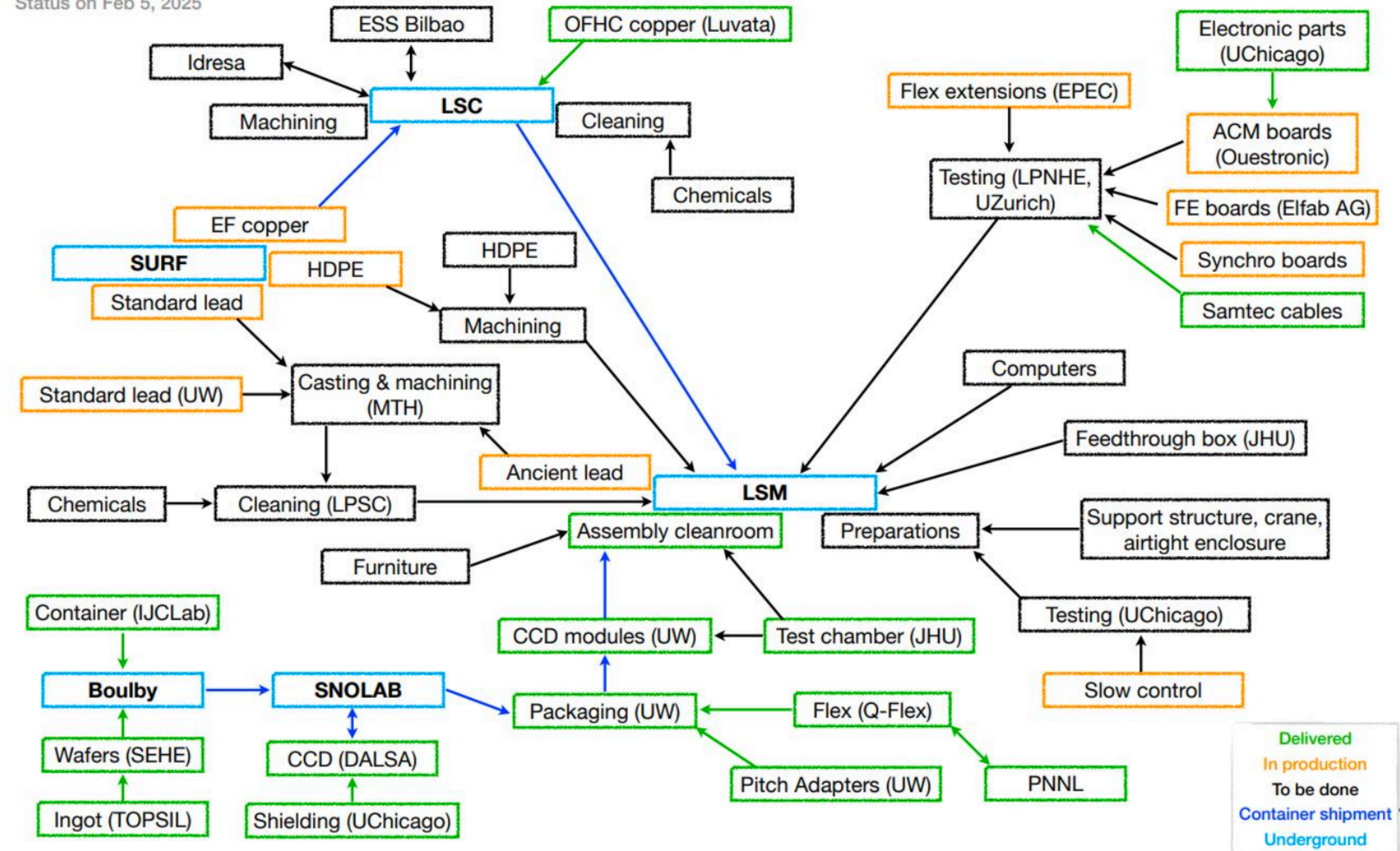
Hidden dark photon



Towards DAMIC-M

Coming End of this year

Status on Feb 5, 2025

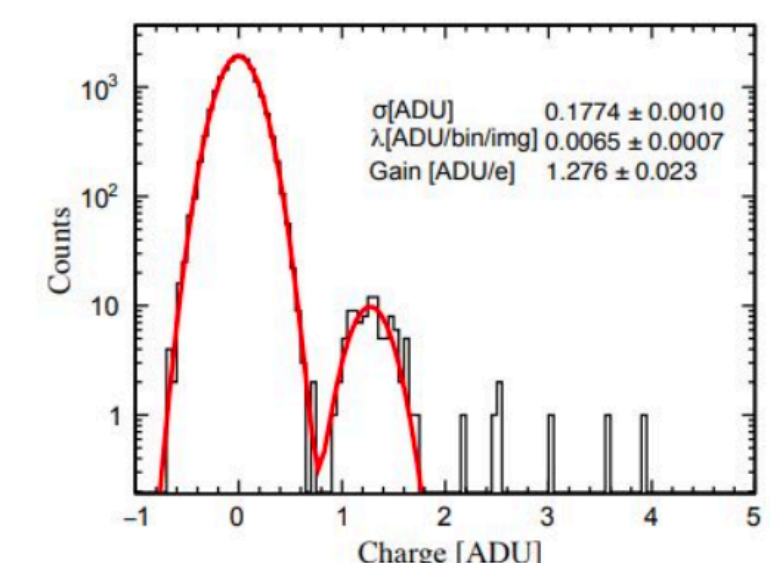
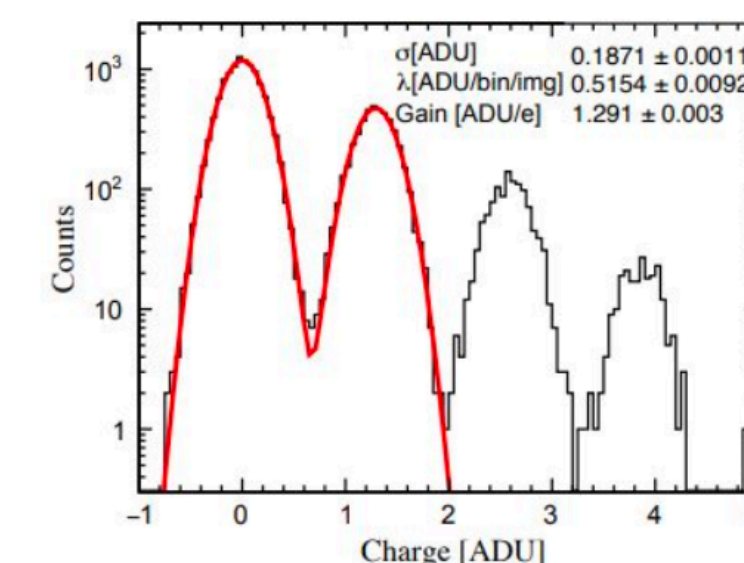
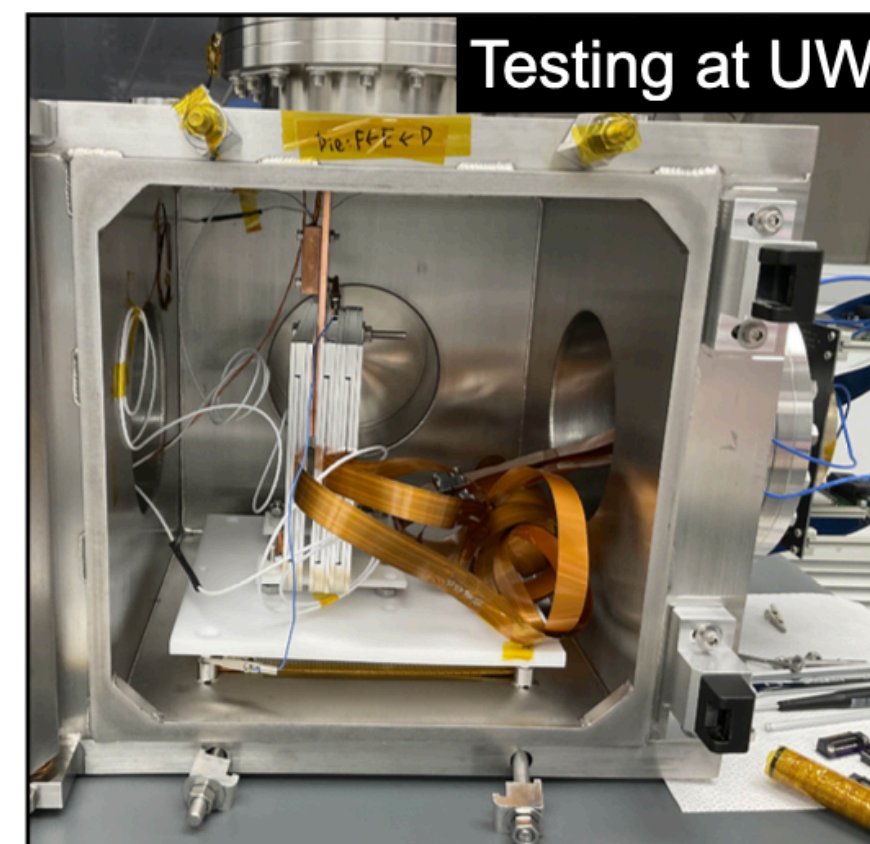
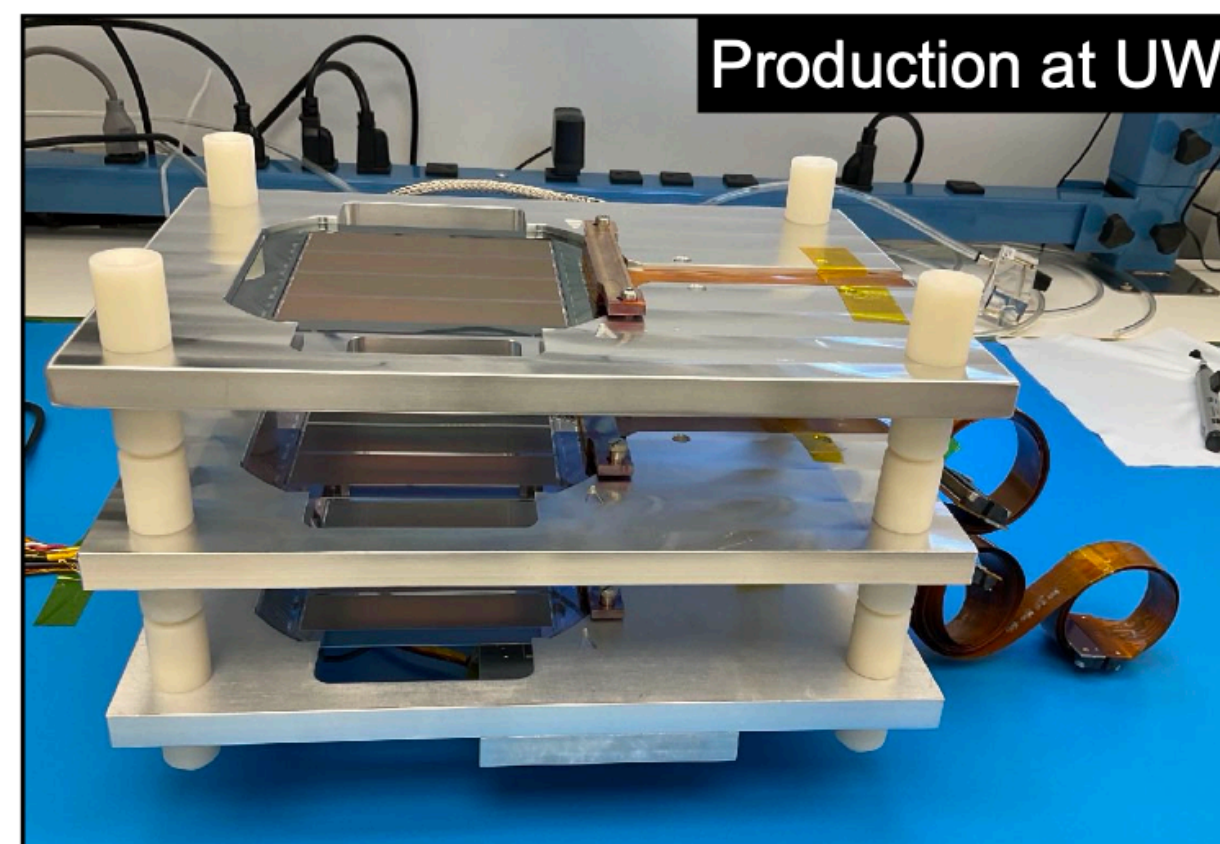
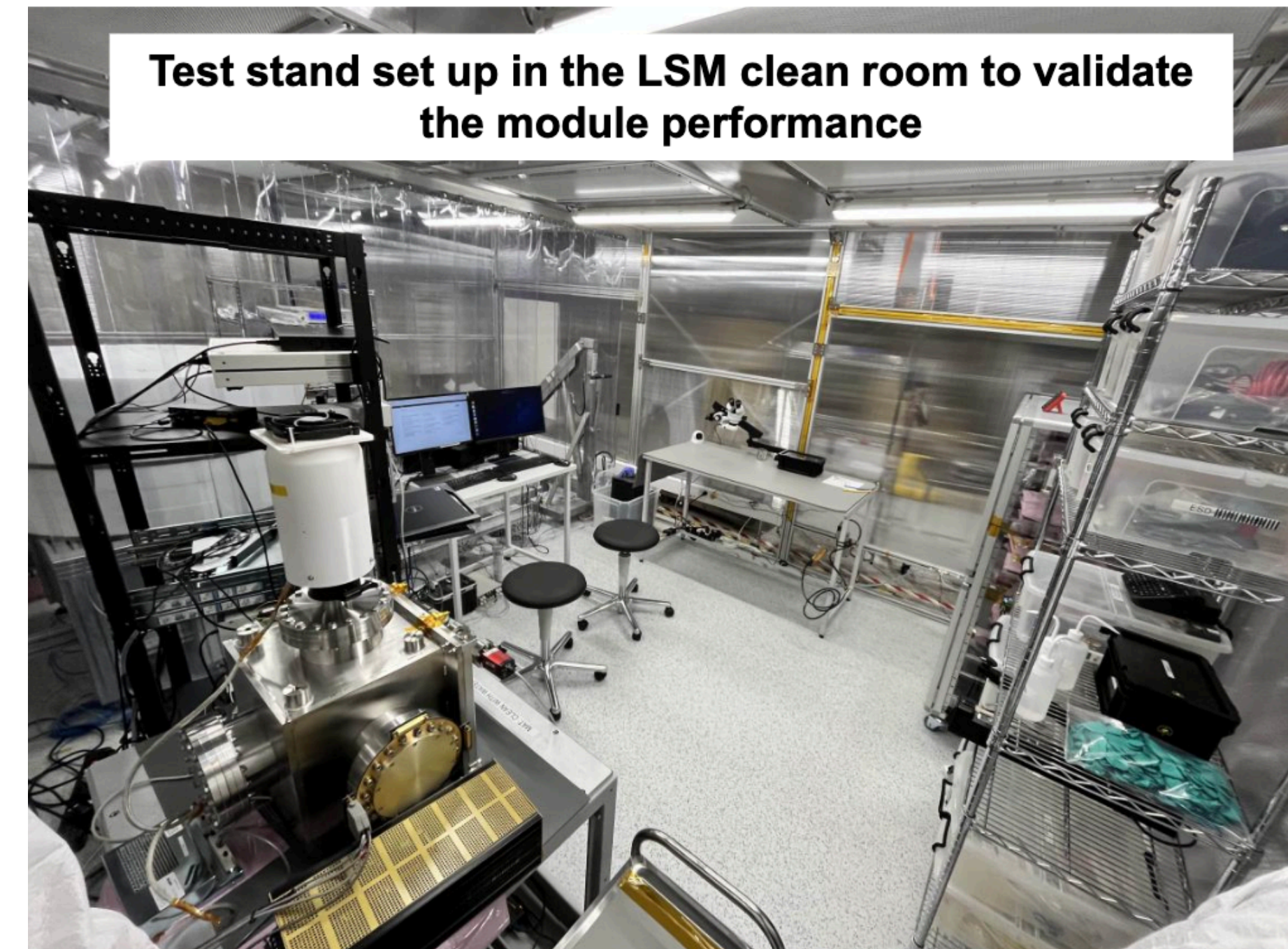


Delivered
In production
To be done
Container shipment
Underground

CCDs status

Tested and built 26 CCD modules (340g of Silicon target) for DAMIC-M

- CCD module production/test at UW completed.
- Underground characterisation before array assembly at LMS.
- Energy Calibrations on going at test chambers at LSM
- Use of LBC to measure Dark Current, test final electronics and DAQ



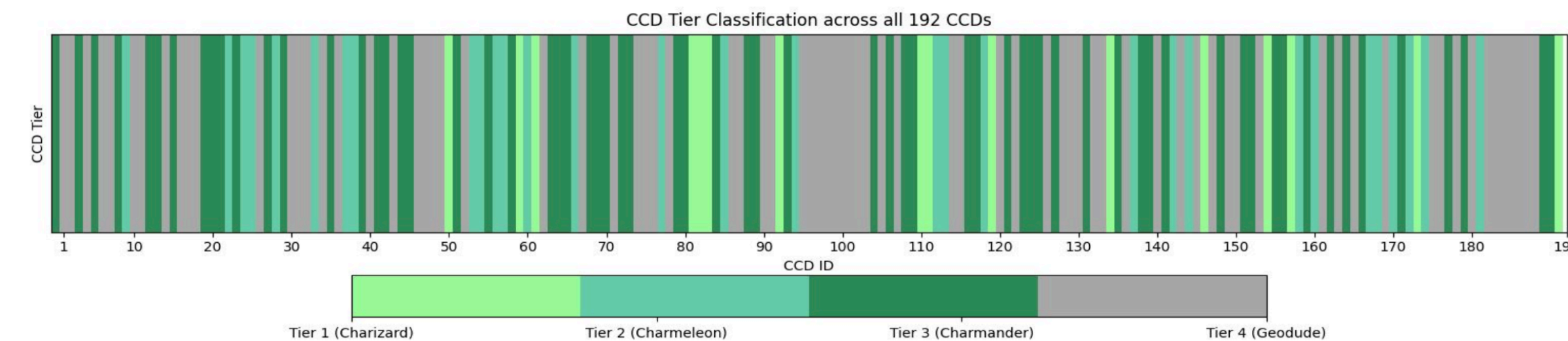
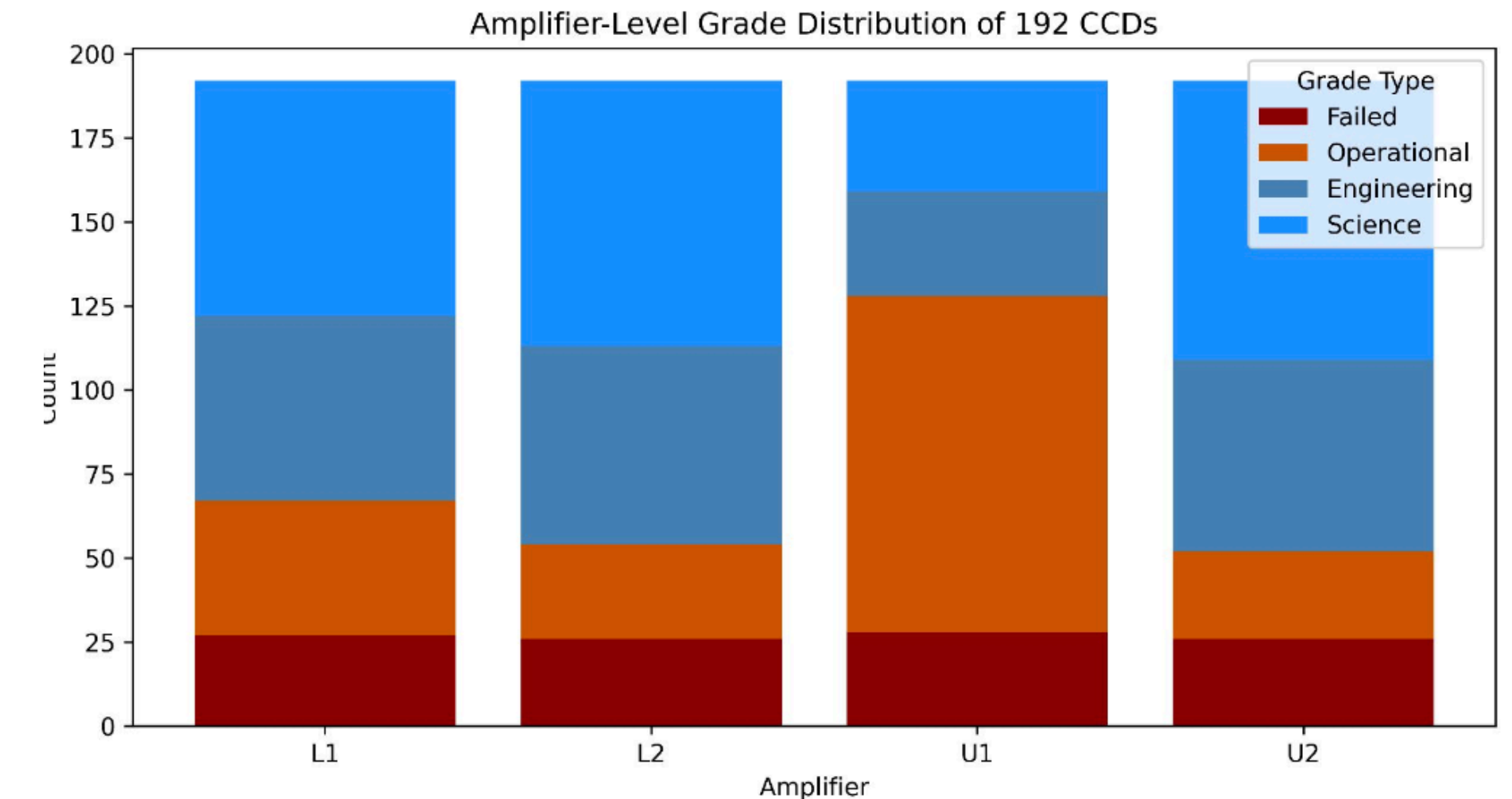
CCD testing

Long Way to final installation

[First Production of Skipper-CCD Modules for the DAMIC-M Experiment. H. Lin et al. DAMIC-M coll. \(arXiv:2509.06943\)](#)

• Stage 1: Die Testing to find science-grade die, and identify amplifiers to be glued for pitch adapter module

- Perform intensive tests on 6 dice a day
- Tests @185 K, characterisation of:
 - CTI, Single Electron Resolution, Gain, Defects
- Science grade amplifier criteria:
 - Defects < 20, Stress test didn't introduce defects
 - CTI within a few percent and within uncertainty range
 - Gain ~ 1.3 ADU/e
 - Skipper resolution ~ 0.1 e- (with 1000 skips)
- Results store in a DB for each amplifier of each CCD
- Choose the CCD (only one amplifier will be use):
 - Tier-1 (Charizard): four science-grade amplifiers.
 - Tier-2 (Charmeleon): Two science-grade amplifiers.
 - Tier-3 (Charmander): Only one science-grade amplifier,
 - Tier-4 (Geodude): No science-grade amplifiers

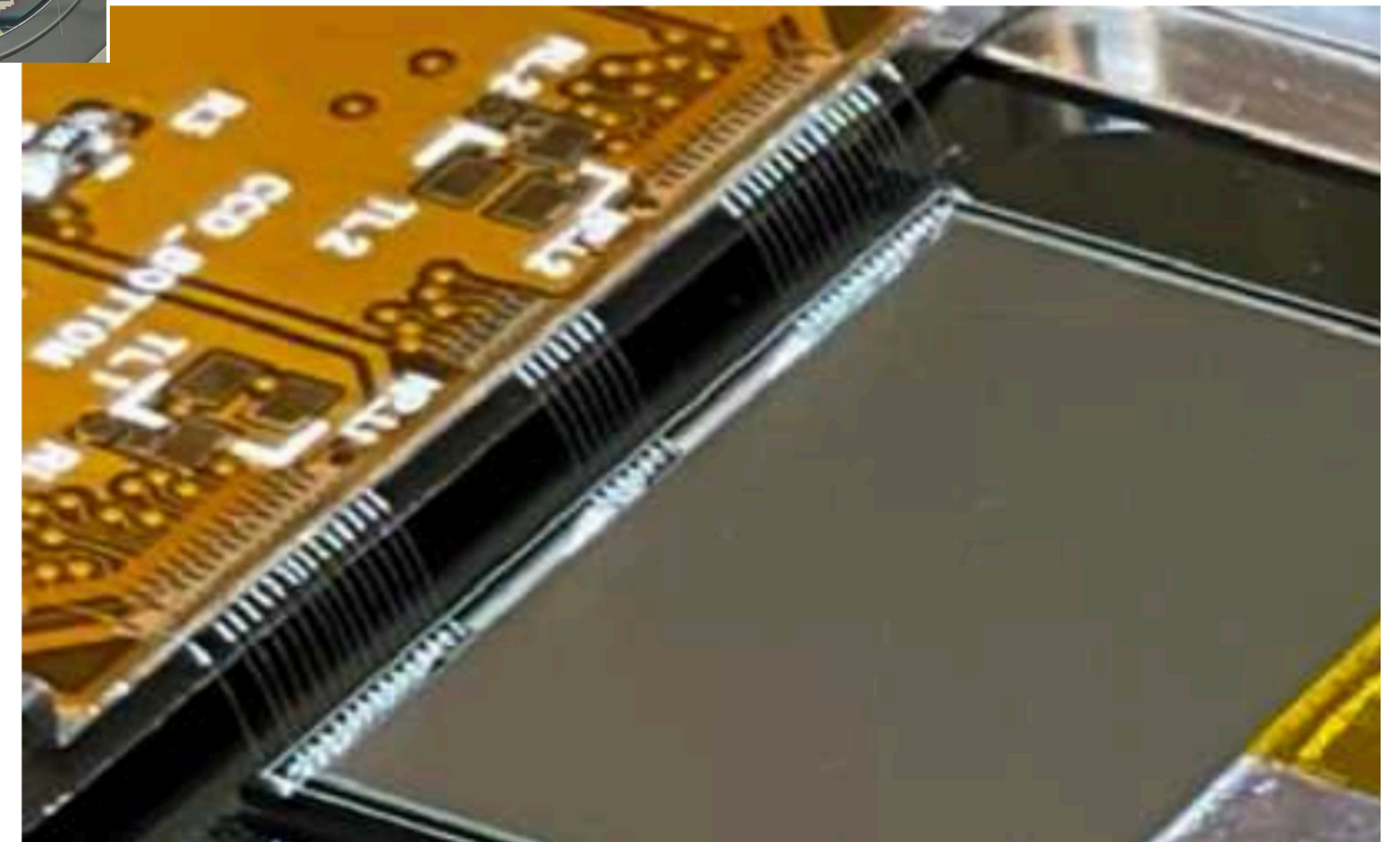
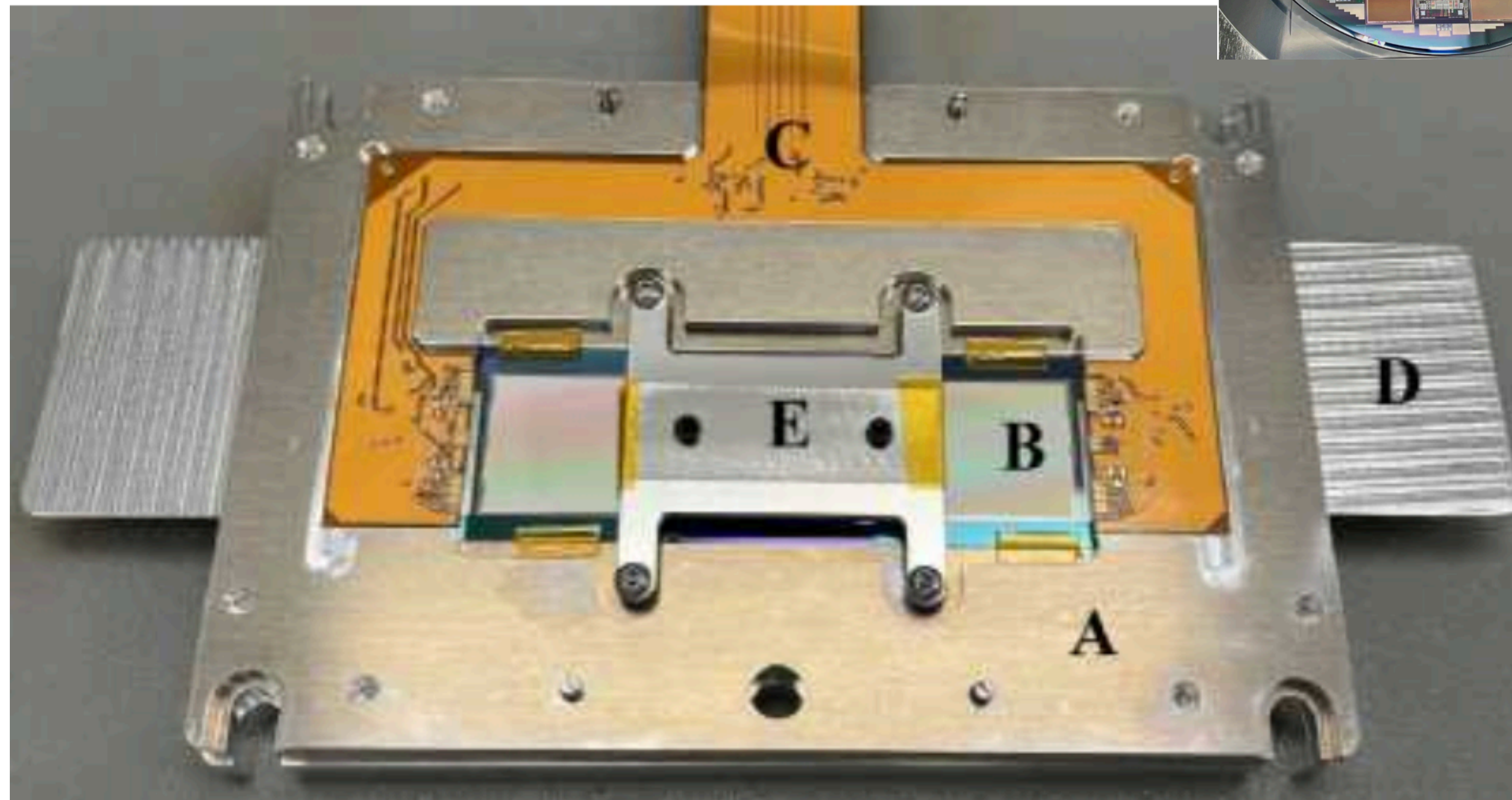
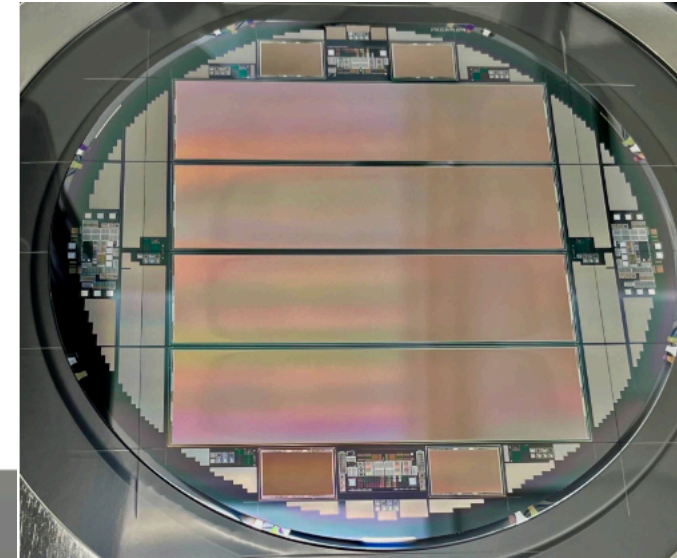


- Found 113 CCDs from around 200 CCDs

CCD testing

Long Way to final installation

[First Production of Skipper-CCD Modules for the DAMIC-M Experiment. H. Lin et al. DAMIC-M coll. \(arXiv:2509.06943\)](#)



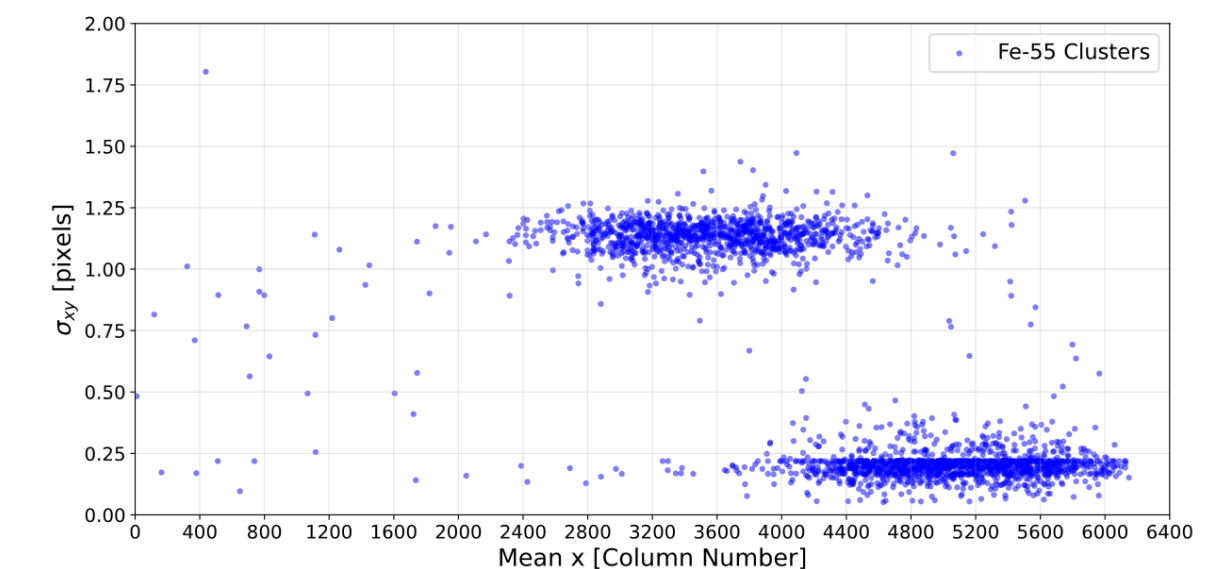
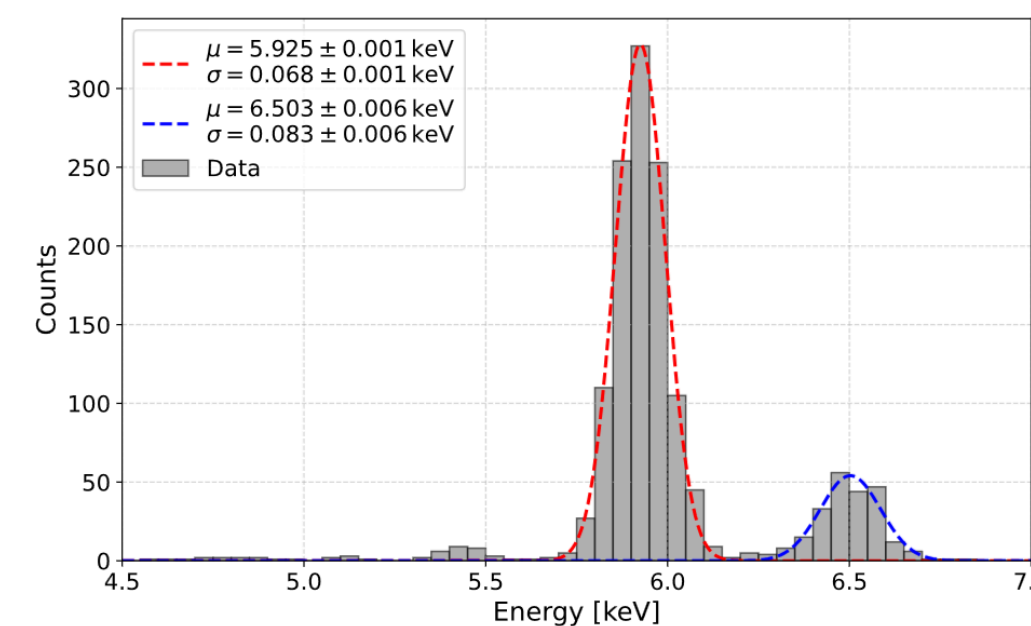
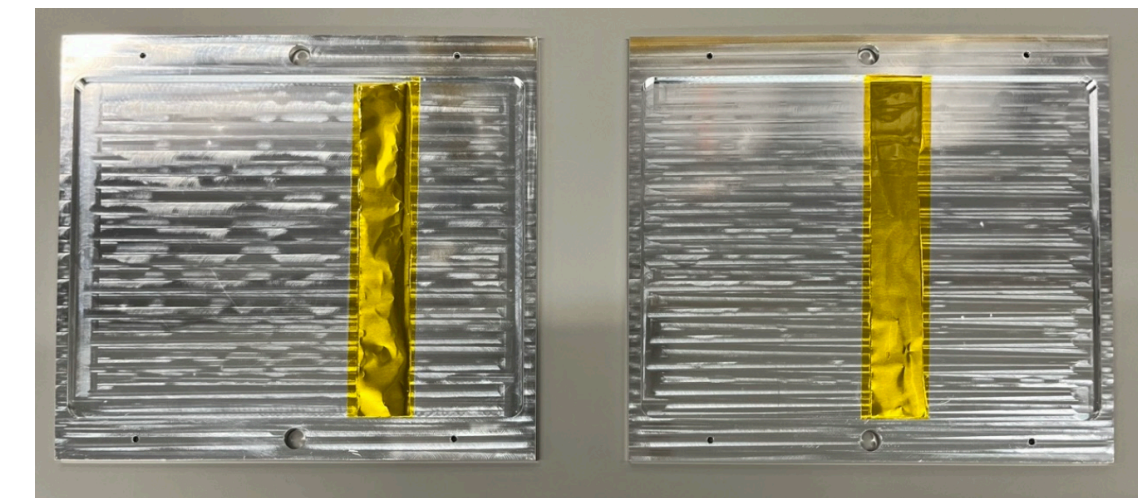
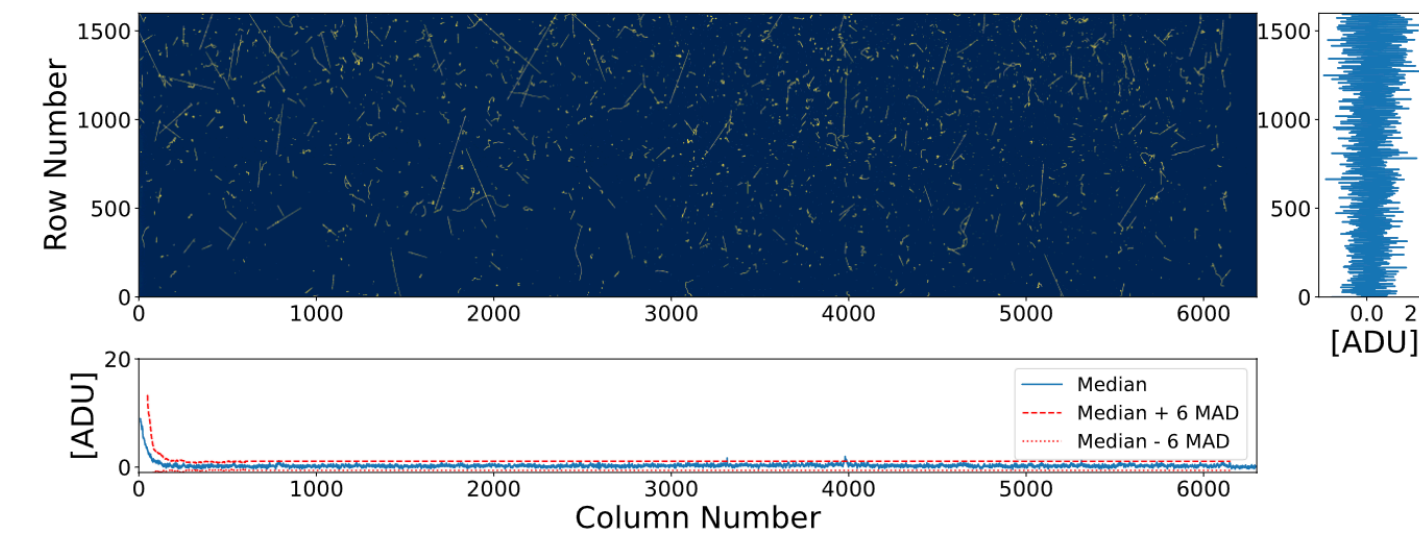
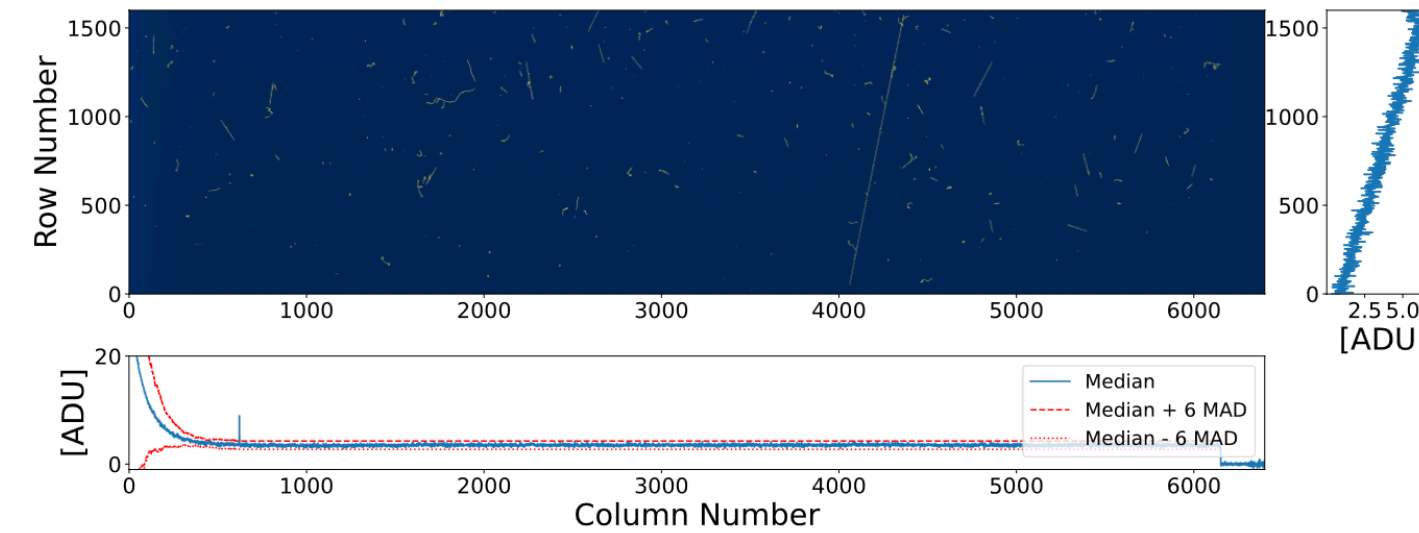
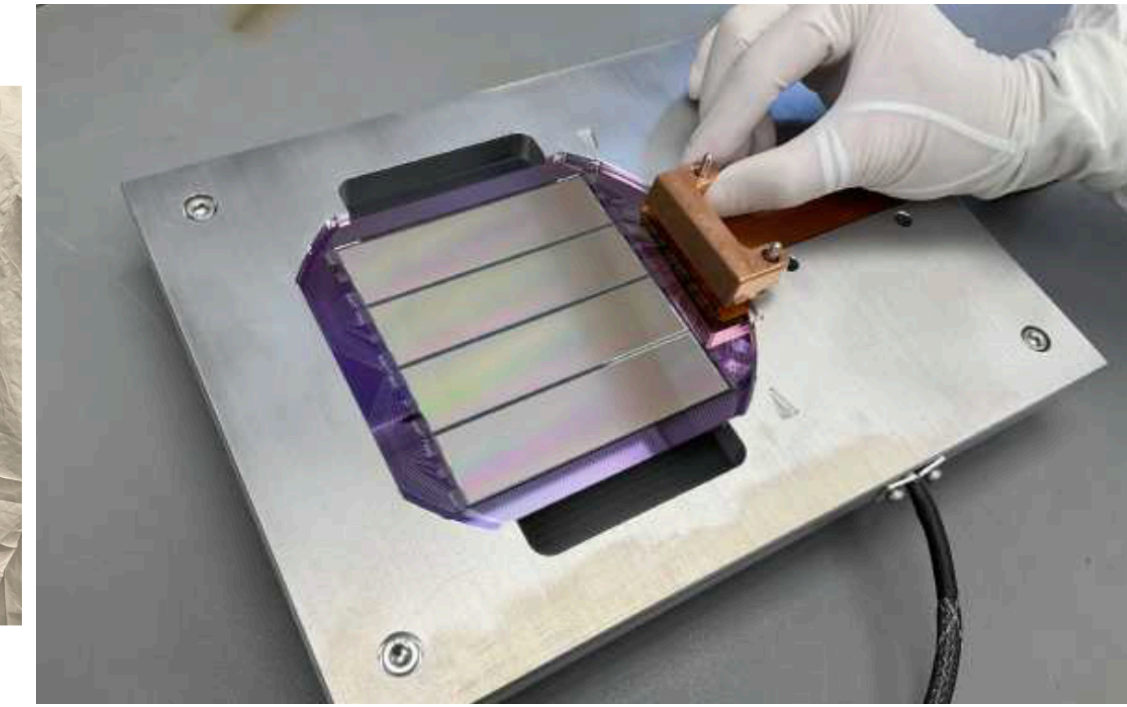
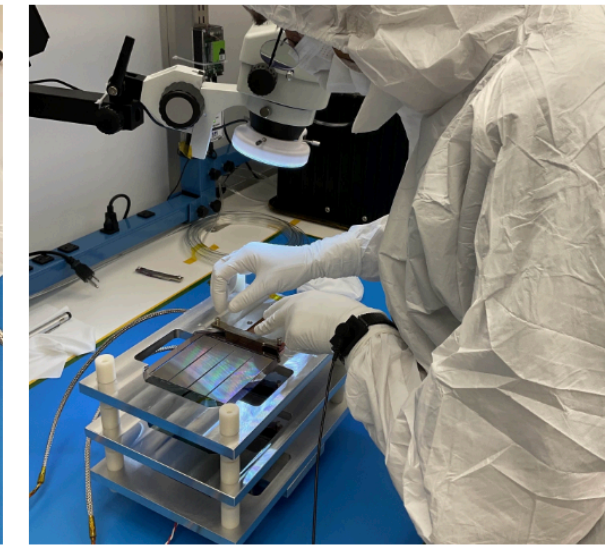
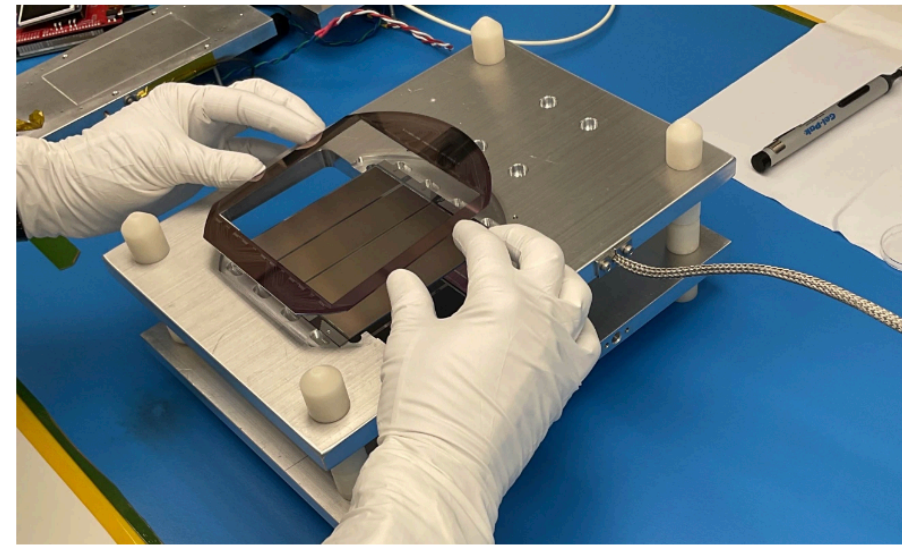
- Found 113 CCDs from around 200 CCDs

CCD testing

Long Way to final installation

• Stage 2: Module Testing characterize science-grade modules to installed at DAMIC-M

- Testing of the new electronics
- Perform intensive tests on 3 modules every 2 days
 - @ 185K
 - All amplifier were wirebonded correctly pertaining to the die amplifier identified
 - All amplifiers showed same feature as stage 1, with some deflections
 - @135K
 - Characterization of lateral spread of events (diffusion), CTI, SER, noise, gain...
 - Energy calibration with Fe-55 clusters
 - Verify most defects disappear at low temperature

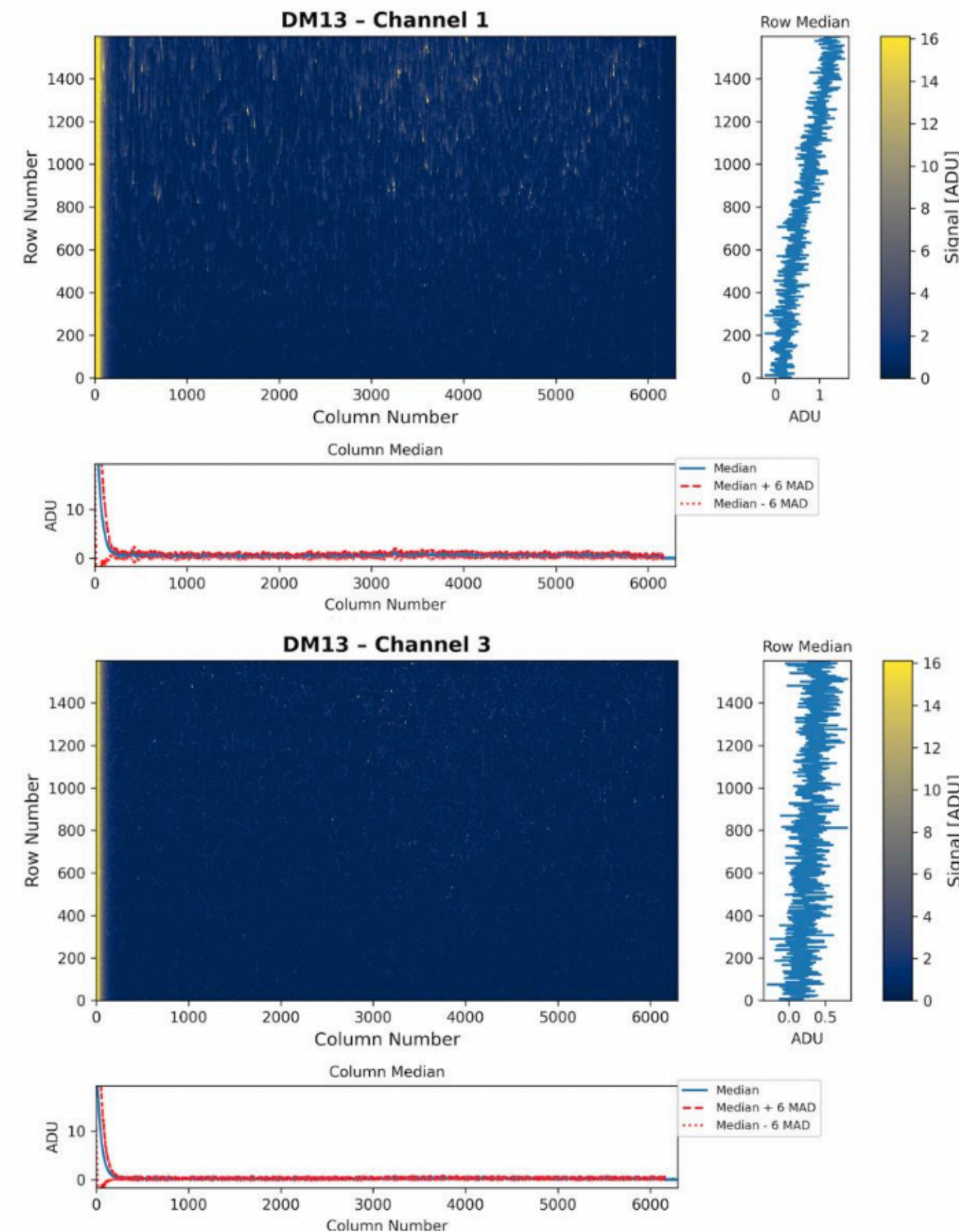
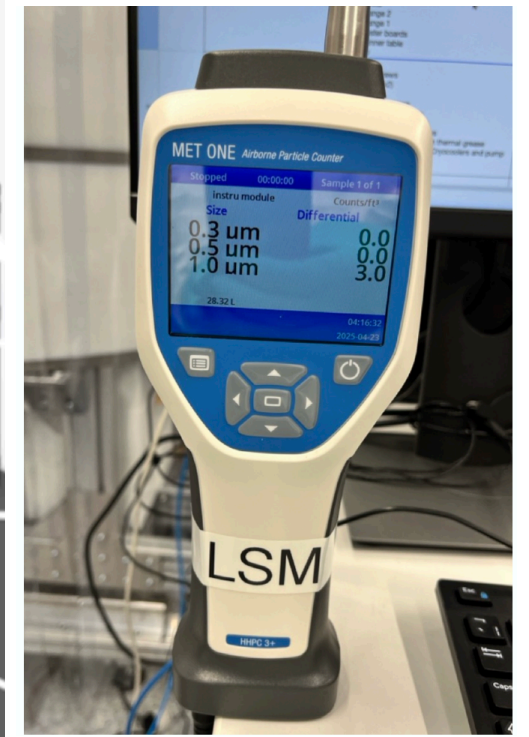
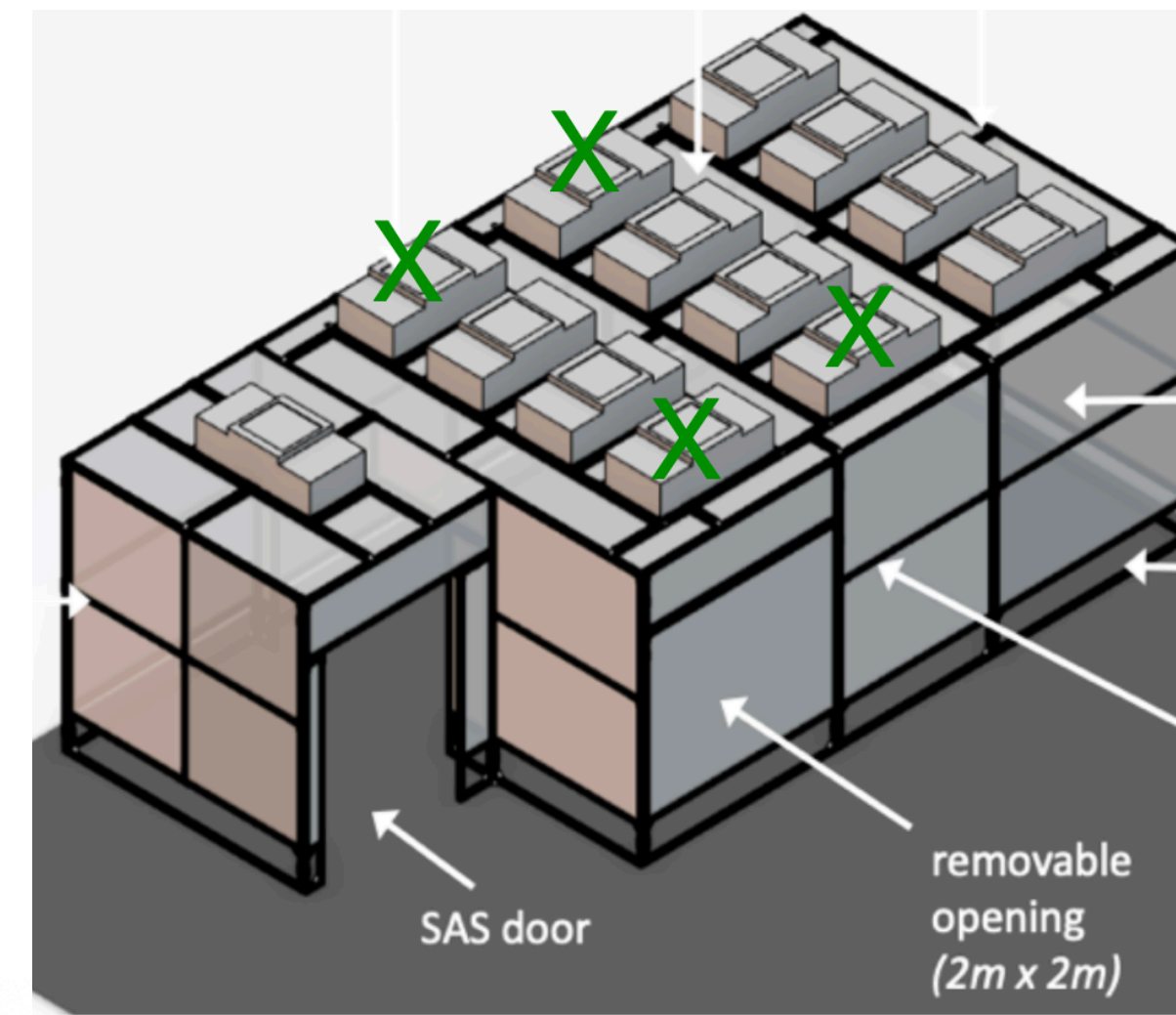


CCD testing

Long Way to final installation

• Stage 3: Module Testing at Modane

- Visually check modules after transport
- Confirm same high temperature performance as on surface
- Confirm module defect map at low temperatures
- Optimisation of clocks for individual modules/CCDs
- Determine module arrangement in the array
- Module testing inside the LBC (very low background measurements)
 - Dark current studies
 - Testing electronics and DAQ modes
 - Sequencers and firmwares
- Checking the optimisation parameters



testing + assembly
clean room at LSM



Electronics, DAQ, SC status

Long Way to final installation

• Electronics

- Acquisition and Control Module
+FE+synchronisation
- Based on FPGAs boards
- Desing to reduce electronic noise
- System complexity, uses μV signal amplitudes

• DAQ

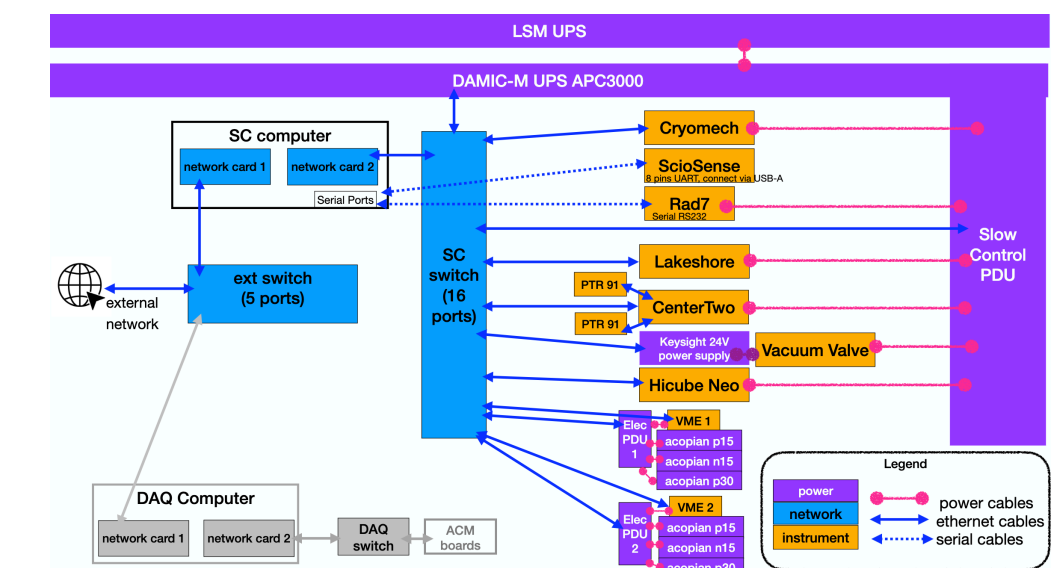
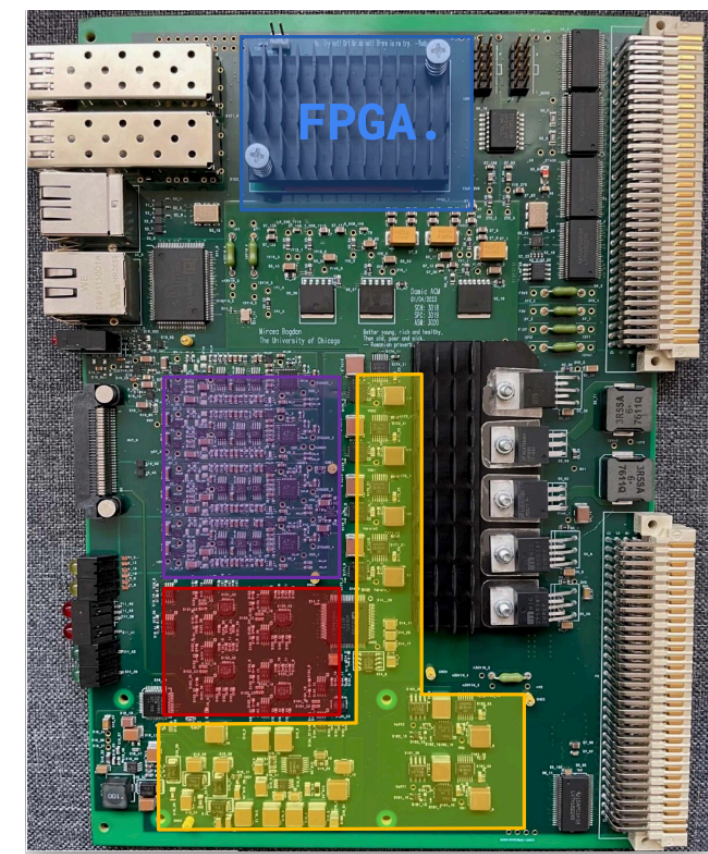
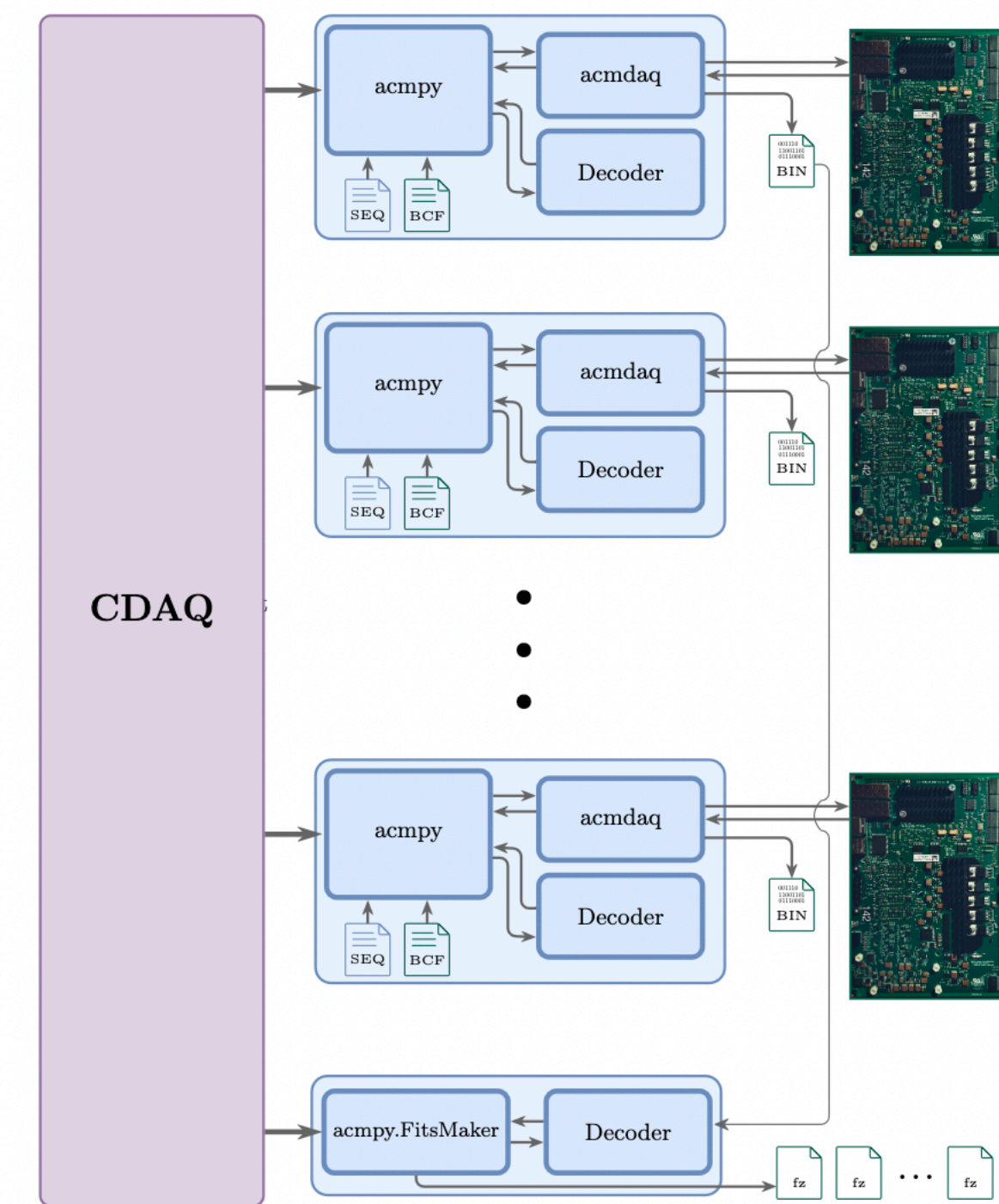
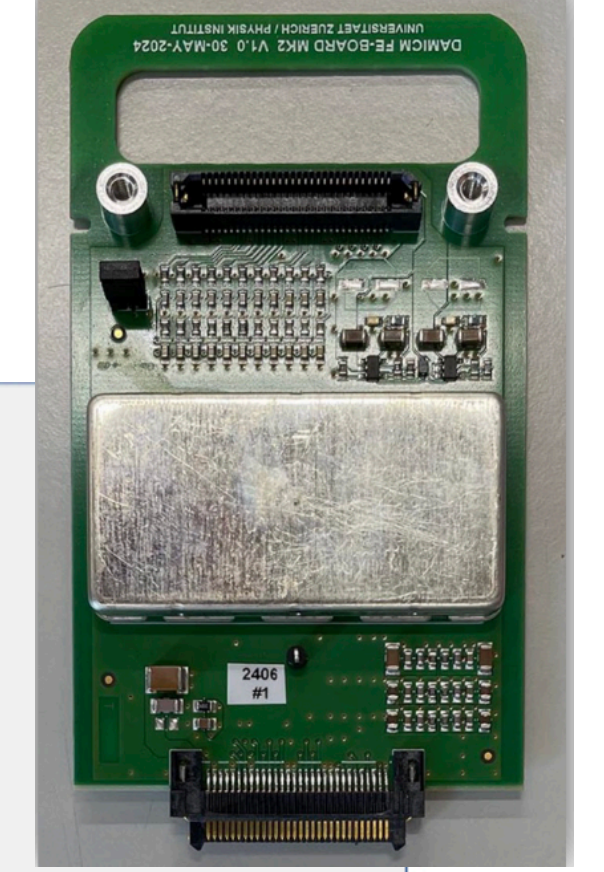
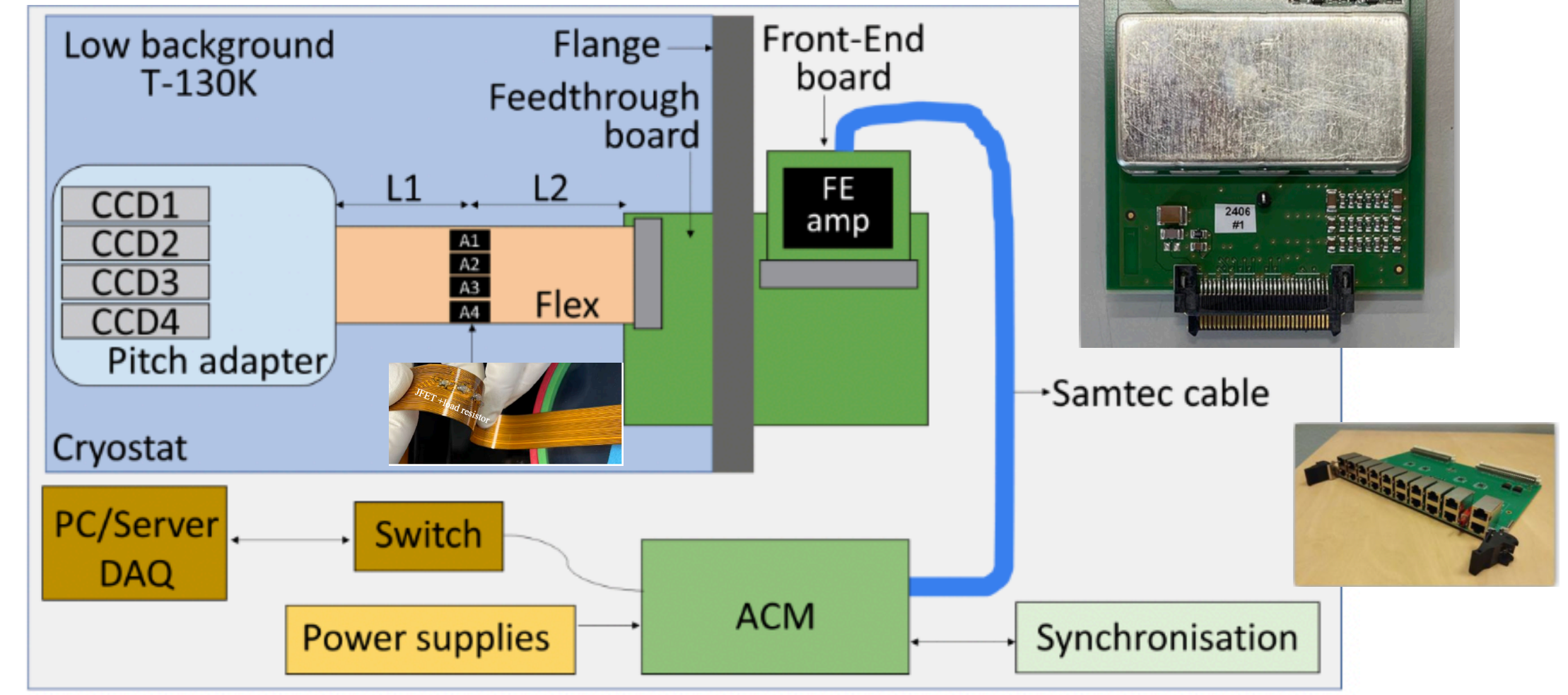
- LDAQ $\rightarrow$ Python user interface
- CDAQ $\rightarrow$ LDAQ/ODAQ broker

• Slow Control

- Design to be low-cost, able to interface with many different instruments ([Adapted open-source SC package by J. Nikkel \(Yale\)](#))
- C-based instrument backend, MySQL db, php web interface.

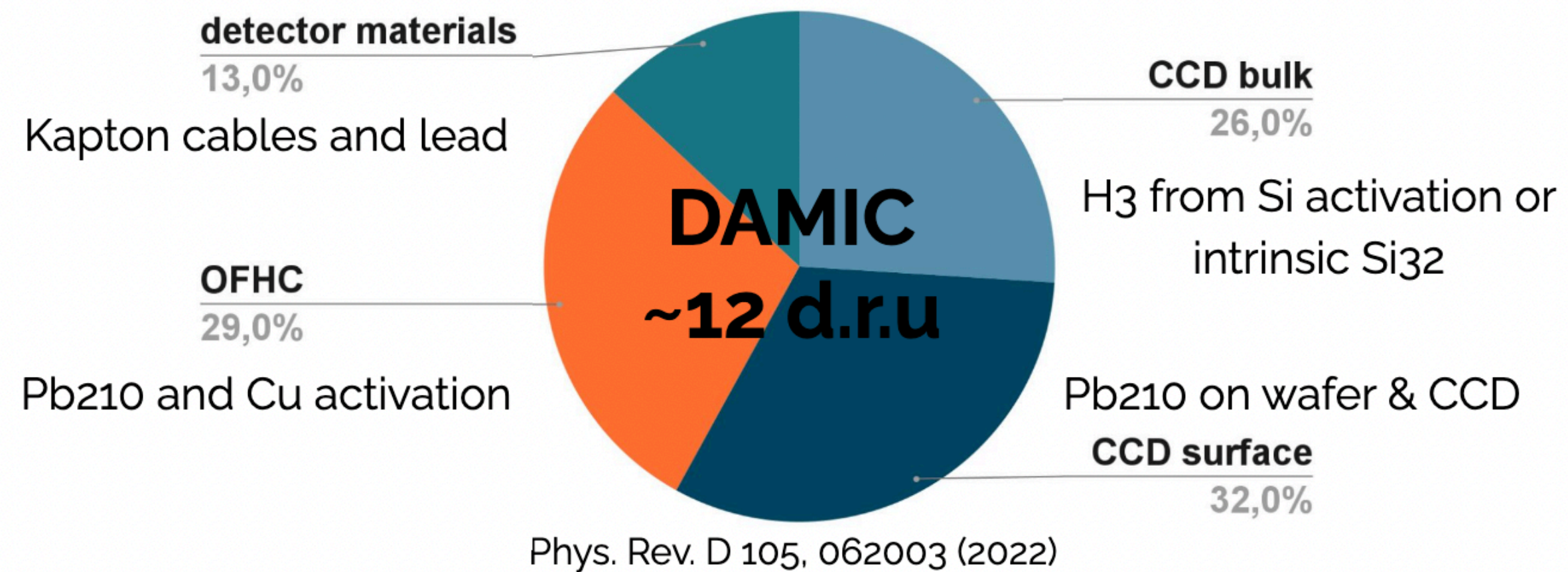
• DQM

- Ensure detector functionality and operation efficiency
- Provides tools to generate, store and visualised elements



Backgrounds at LSM

Ultra Low background (goal: < 1 d.r.u)



● Better material selection and handling:

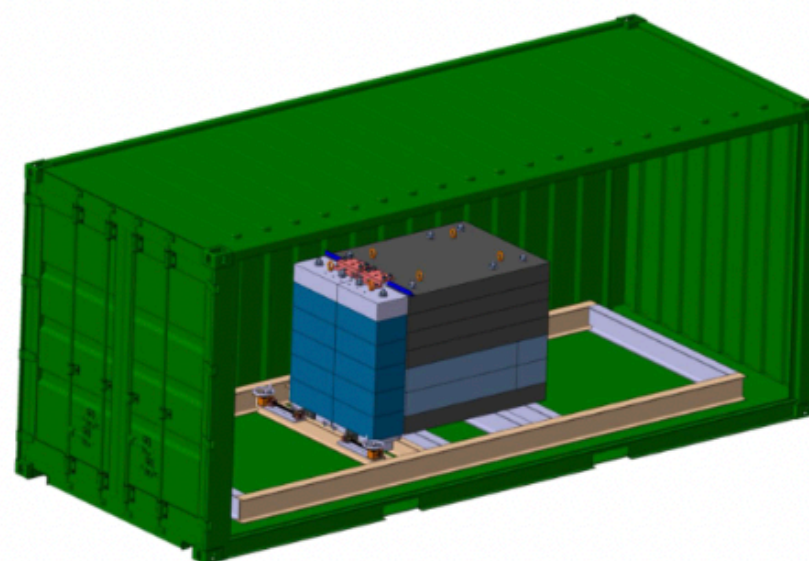
- **Limit exposure time** to cosmic rays (mostly Cu and Si)
 - Cosmic rays spallation in Si results in ^3H → FEW months of exposure.
- **Limit the detector surfaces' exposure to Rn**
- Remove Si wafer surface (to reduce surface ^{210}Pb)
- Chemical treatments of Cu, Pb components to remove surface ^{210}Pb
- Use of **ultra pure materials**
 - Electro-Formed copper, low-background cables
- Careful **design of the shielding** based on detail **simulations**:
 - Ancient lead
 - Lead and Polyethylene



Rn free storage



Rn free clean-room



shielded transportation
(activation rate/20)



shield during
CCD production
(act. rate /7)

Radiopurity

Copper is the material closest to the detector

- **Stringent radio purity requirements**

- Cosmogenic **activation limits** to below 90 days/
20 days
- Use of **EfCu** produced at **SURF** for Majorama
 - Machined at SURF sent to LSC
 - E-beam welded at Spanish Companies
(ESSBilbao)
- **OFHC copper** from Luvata sent to LSC
 - Machined at ESSBilbao, Idresa
- **Chemical cleaning** following PNNL procedure at
LSC and IFCA
- Store underground

Cleaning and passivation of copper surfaces to remove surface radioactivity and prevent oxide formation
[E.W. Hoppe et al. Nuclear Instruments and Methods in Physics Research A 579, 486 \(2007\).](#)



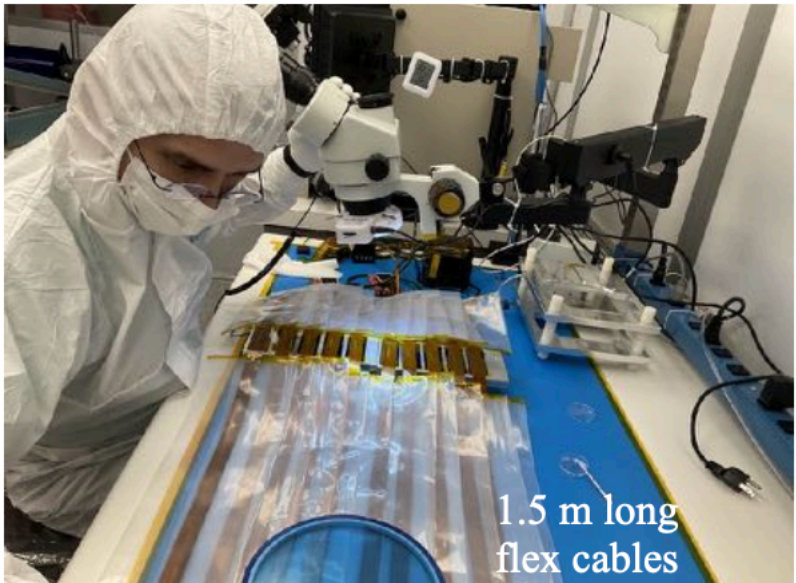
Radiopurity

Ultra-low radioactivity flexible printed cables

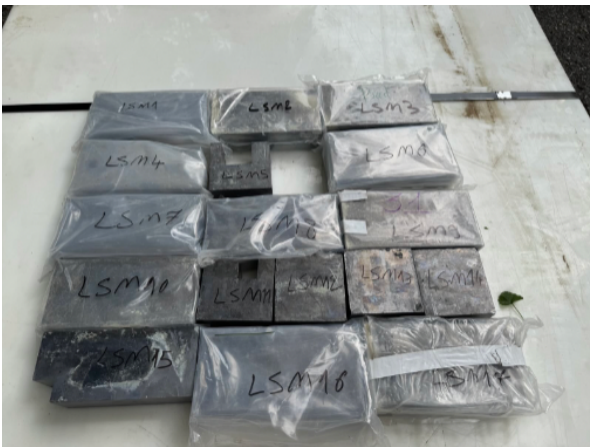
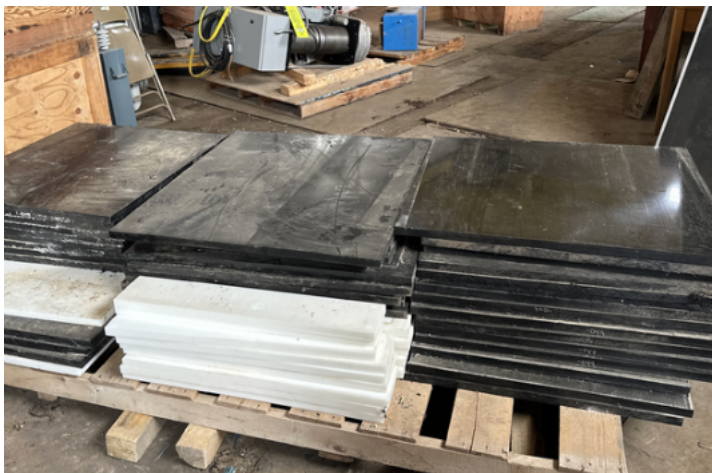
Isaac J. Arnquist et al. EPJ Techn Instrum 10, 17 (2023)

Lead and flexes

- Commercial flex cables are “dirty”.
 - R&D, led by PNNL, with the US company QFlex resulted in a radiopure flex (up to 20x better than a commercial flex)
- Ancient lead use for the innermost part of our shielding
 - CAST at MTH in germany and chemically clean in Grenoble , France
- Low-background lead and poly for the external shield, from SURF
 - Bricks chemically clean at France by ONET
 - re-CAST plates by LEMER will be clean at LSM only with API and wipes
 - Poly will be clean LSM with wipe and water



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	

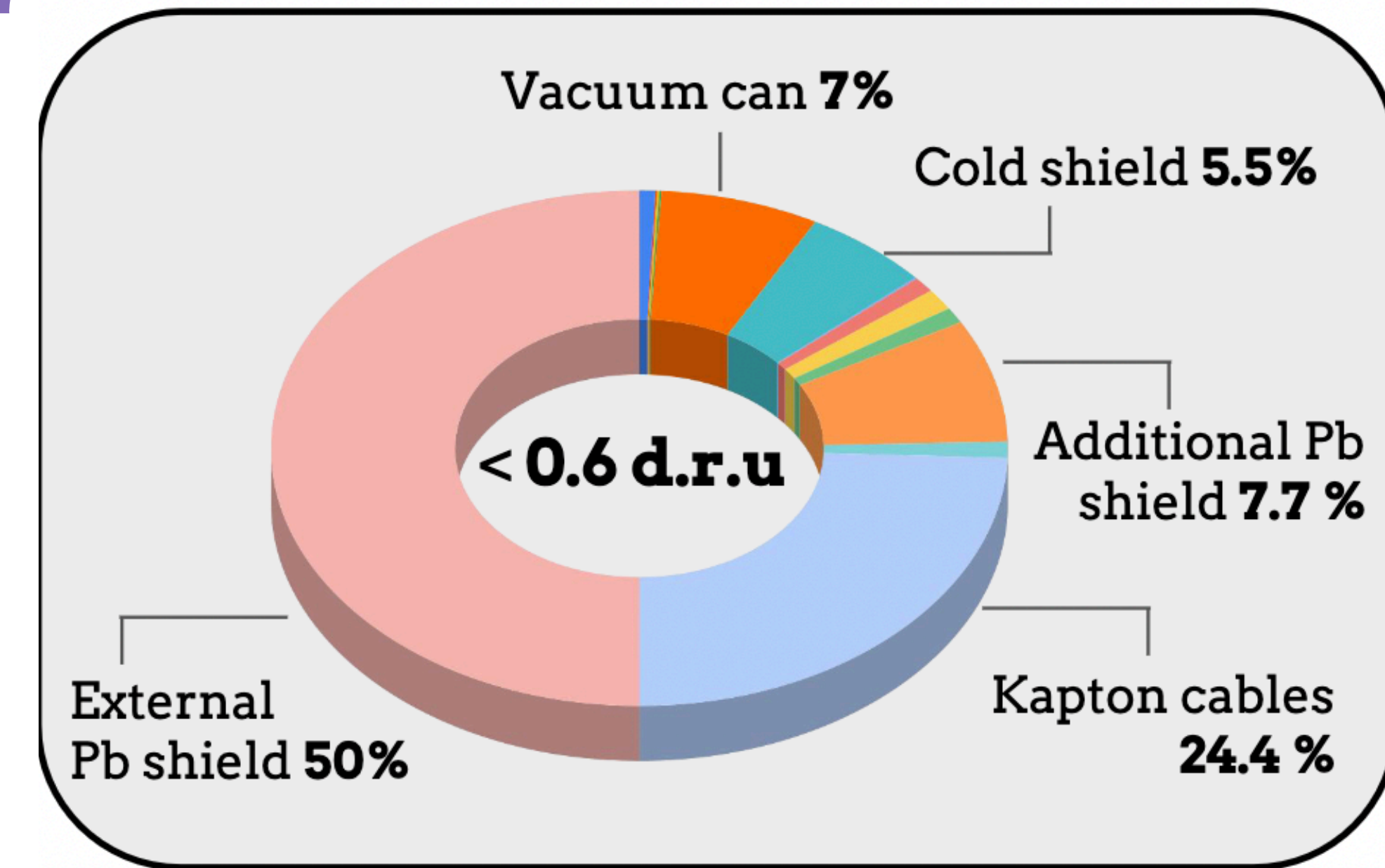
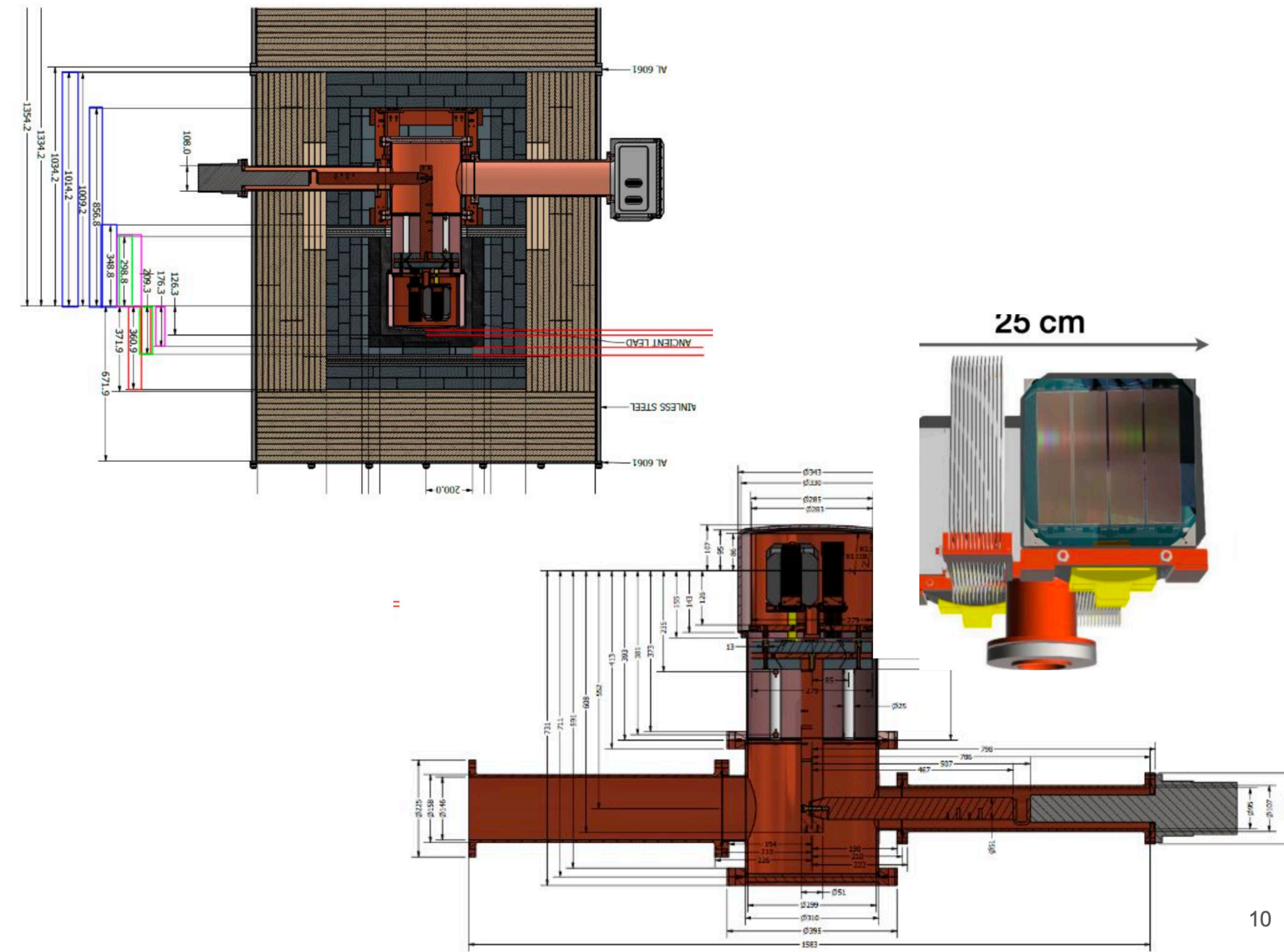


The Majorana Demonstrator Radioassay Program

MAJORANA COL. N. Abgrall et al., Nucl. Instrum. Meth. A 828, 22 (2016), 1601.03779.

Backgrounds at LSM

Ultra Low background



Cosmogenic isotopes in Electro-Formed Cu assuming:

exposure time= 10 d ,
cooling time underground = 180 d ,
Experiment running time = 1 yr
No CCD contamination's is included yet

Background level goal within reach

TOWARDS DAMIC-M

Coming soon

Dec 2024

CCD Module array (4 CCDs) tested at UW

Feb 2025

Preparation of the Testing Clean Room and new host for LBC

May 2025

Arrival of the CCDs. Modules from UW in the 18Tn steel container.
Start CCD Module testing underground

Fall 2025

Mechanised of the Luvata Copper pieces for the cryostat.
Arrival of the EfCu from SURF
Mechanised and E-beam welding of EfCu

Spring 2026

Chemical cleaning of the pieces and the shielding.
Preparation at LSM of DAMIC-M clean room for installation
Preparation at LSM of the electronics space

Summer 2026

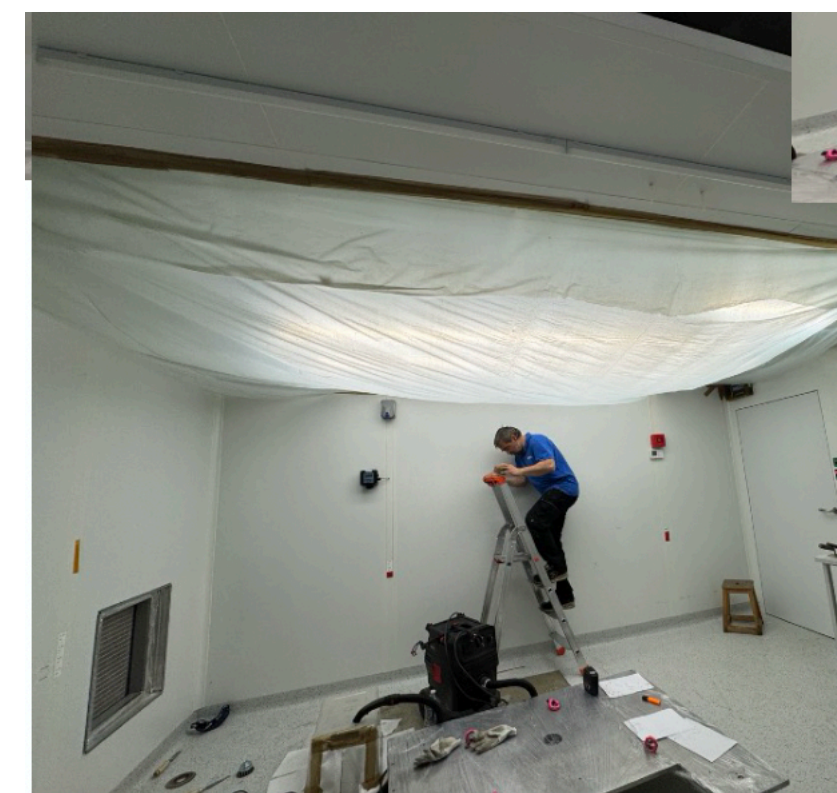
Construction and installation of DAMIC-M

Fall 2026

Commissioning of DAMIC-M

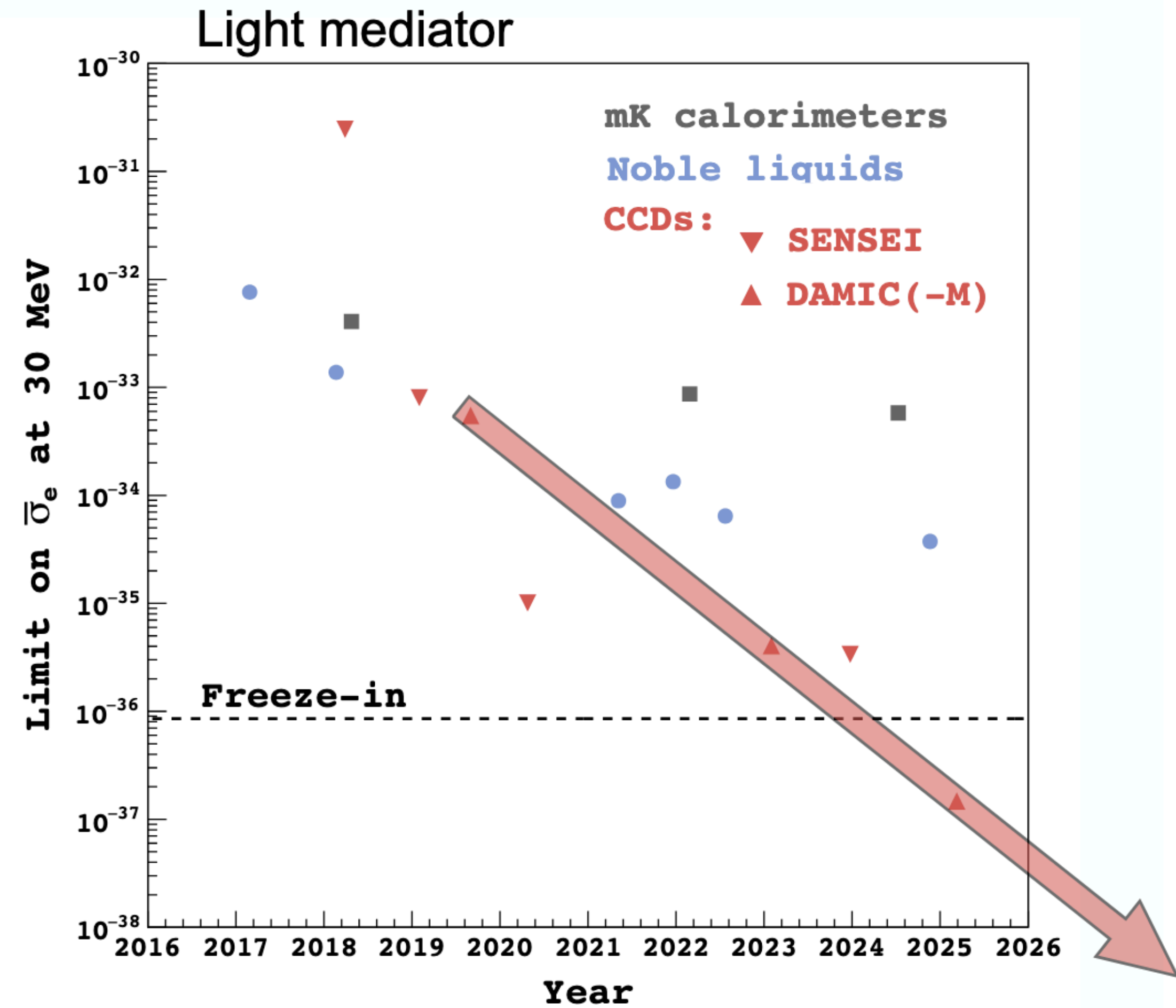
2027

DATA TAKEN



Conclusions

- Skipper CCDs are **unique detectors** with single electron detection capability and sub-electron reading noise
- Searching for LDM at underground laboratories with skipper-CCDs is a **robust experimental program**
- They provide **world-leading sensitivity**, outperforming other technologies by orders of magnitude in sensitivity
- The **LBC prototype** of DAMIC-M has explored the expected freeze-in (and freeze-out) parameter space and excluded it
 - Currently **focus on Dark Current and Characterization** of DAMIC-M Modules
- **DAMIC-M** should **improve by 2 orders** of magnitude the LBC sensitivity over the next 3 years
 - DAMIC-M is also sensitive to light WIMPs, through nuclear recoil ionization and other possibly novel techniques



Plot from A. Chavarria, U of Washington.

The DAMIC-M Collaboration



**THANKS!!!
STAY TUNED
ANY QUESTIONS?**

<https://damicm.cnrs.fr/en/home/>

<https://damic.uchicago.edu/>

<https://damicm.hubweb.ifca.es/>

