Instituto de Física de Cantabria

Consejo Superior de Investigaciones Científicas

Universidad de Cantabria

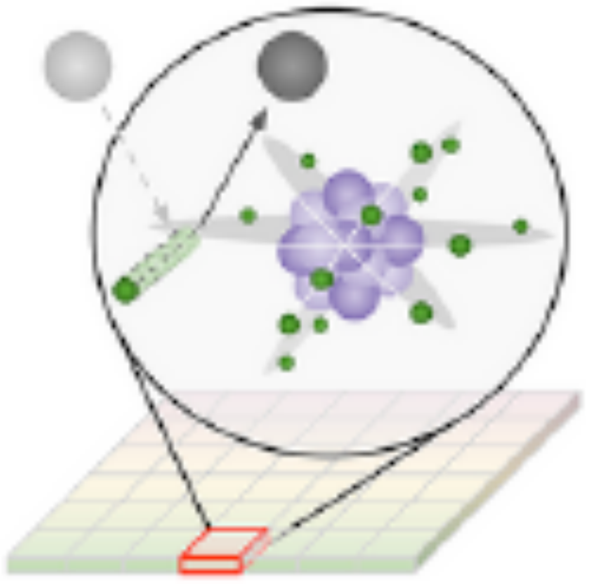
DAMIC-M

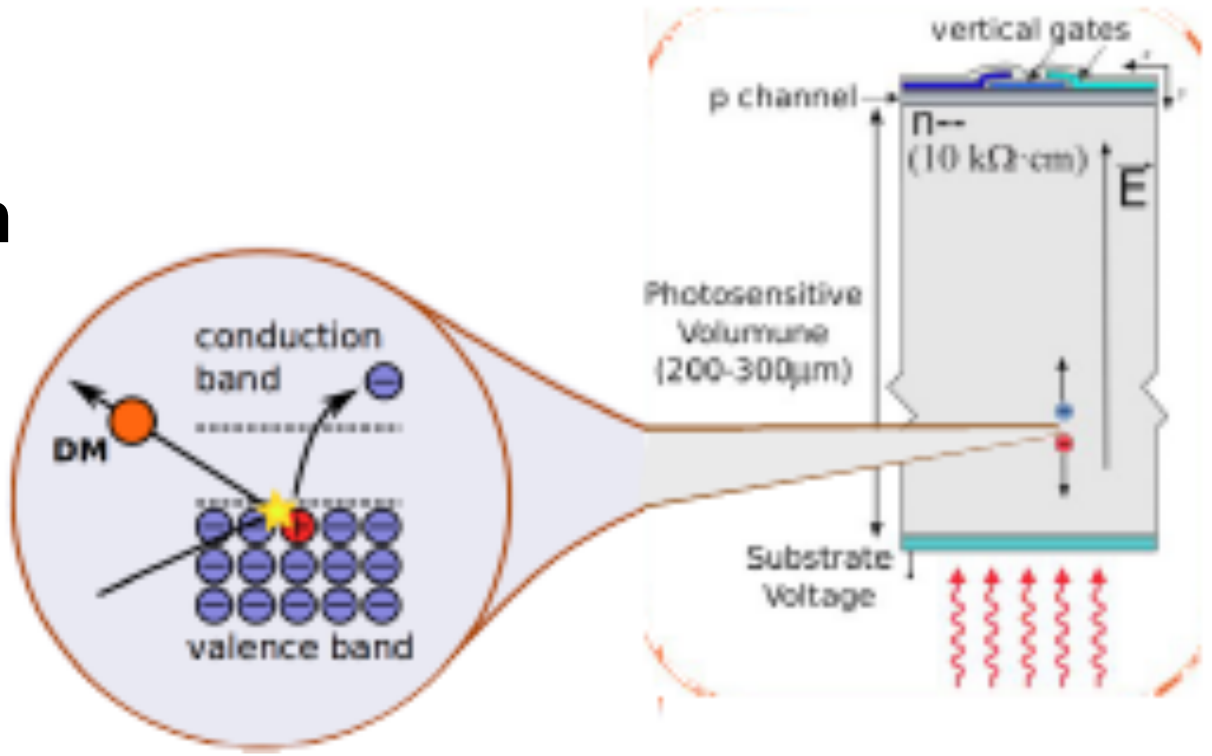
The CCD's experiments to search for Light Dark Matter

DAMIC-M status and first results

AstroHEP-PPCC24
Reunión Nacional: Planes complementarios de Astrofísica y altas Energías
Zaragoza, 5-7 junio, 2025

Rocio Vilar cortabitarte for the DAMIC-M Collaboration





1ª Reunión Nacional
Planes Complementarios de Astrofísica y Altas Energías

Plan de Recuperación, Transformación y Resiliencia

Financiado por la Unión Europea NextGenerationEU

Outline

What we could do with CCDs

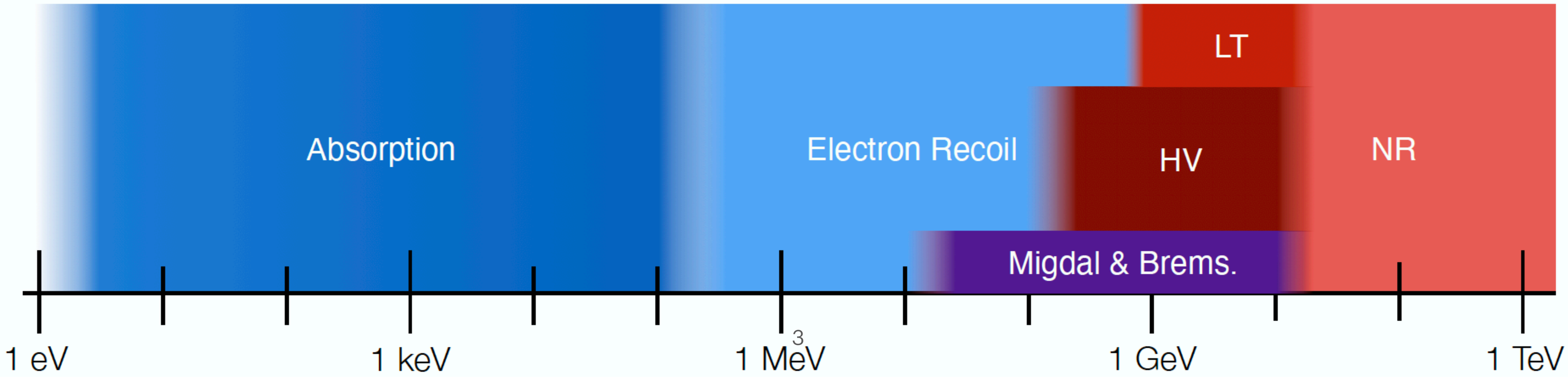
- **Introduction**
  - CCDs as particle detectors for DM
- **DAMIC-M in a nutshell**
  - Design and Background
  - Calibrations
- **Low Background Chamber (LBC)**
  - First results: DM-e scattering / Daily modulation
- **Other initiatives with CCDs**
- **Conclusions**

Introduction

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

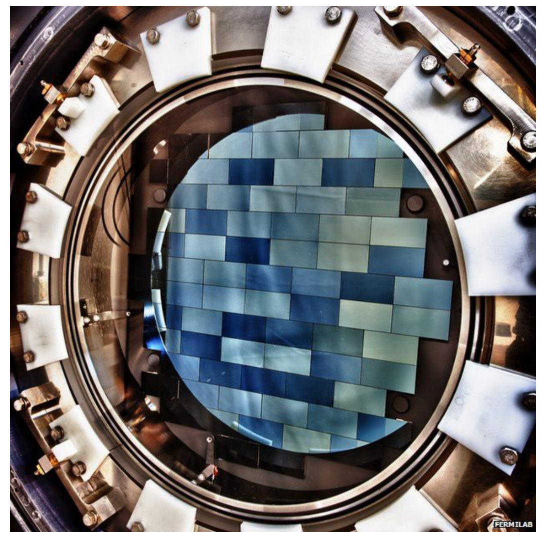
Details in Maria Martinez talk this morning

- Small experiments can have a huge impact in meaningful dark matter models.
- What we need to explore **sub-GeV range**:
  - extremely low thresholds (~few eV) → to access smaller WIMP masses.
  - Scalable technologies to increase the number of interactions in the target.
  - Detectors with and extremely low backgrounds (~sub dru) → Low and controlled backgrounds to identify the rarest signals and probe the smallest cross sections using both nuclear/ electronic recoils from DM-interactions.
- Aim to measure interactions with matter:
  - Elastic scattering off nuclei (standard WIMP scenarios) → m_χ = 1-1000 GeV c^{-2}
  - Inelastic scattering off electrons (dark sector couplings) → m_χ = 1-1000 MeV c^{-2}
  - DM absorption by bound electron (dark sectors and ALPs) → m_χ = 1-1000 eV c^{-2}

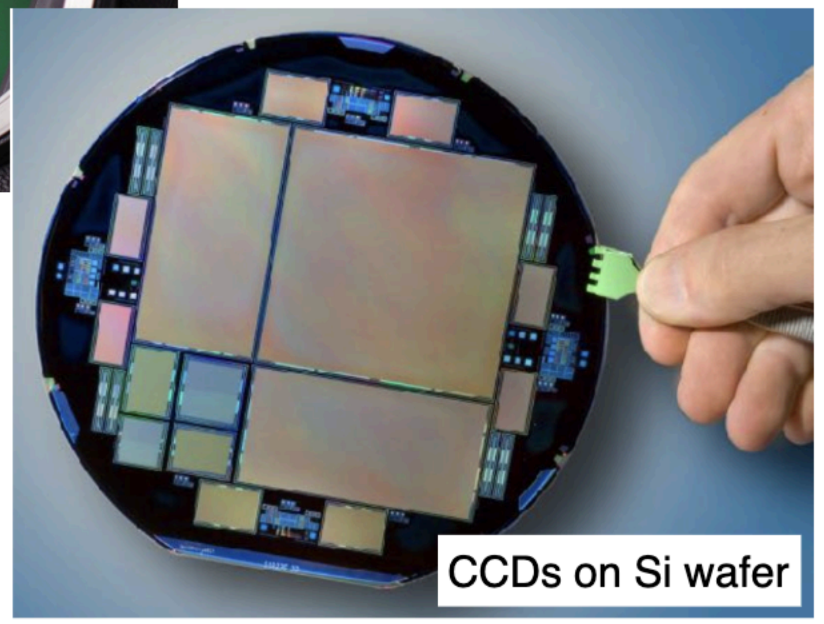


Introduction

CCDs as particle detectors for DM

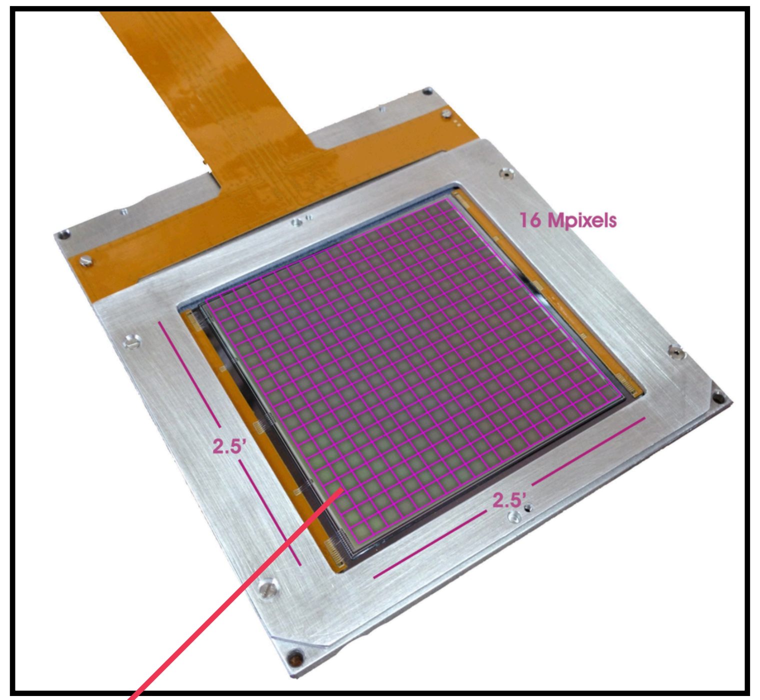


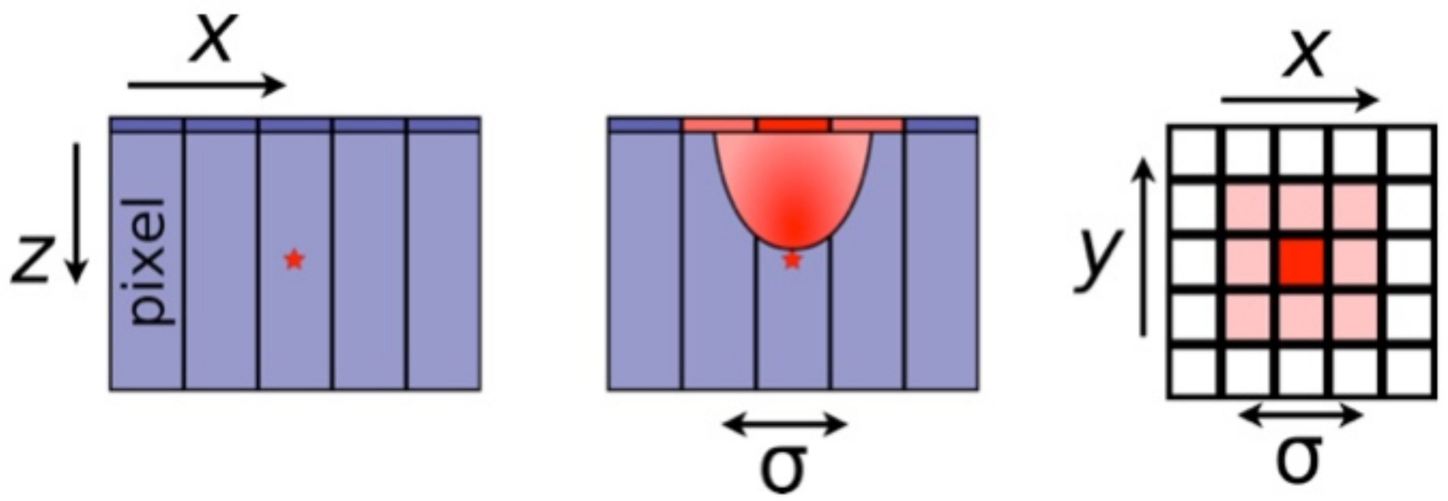
From DES camara

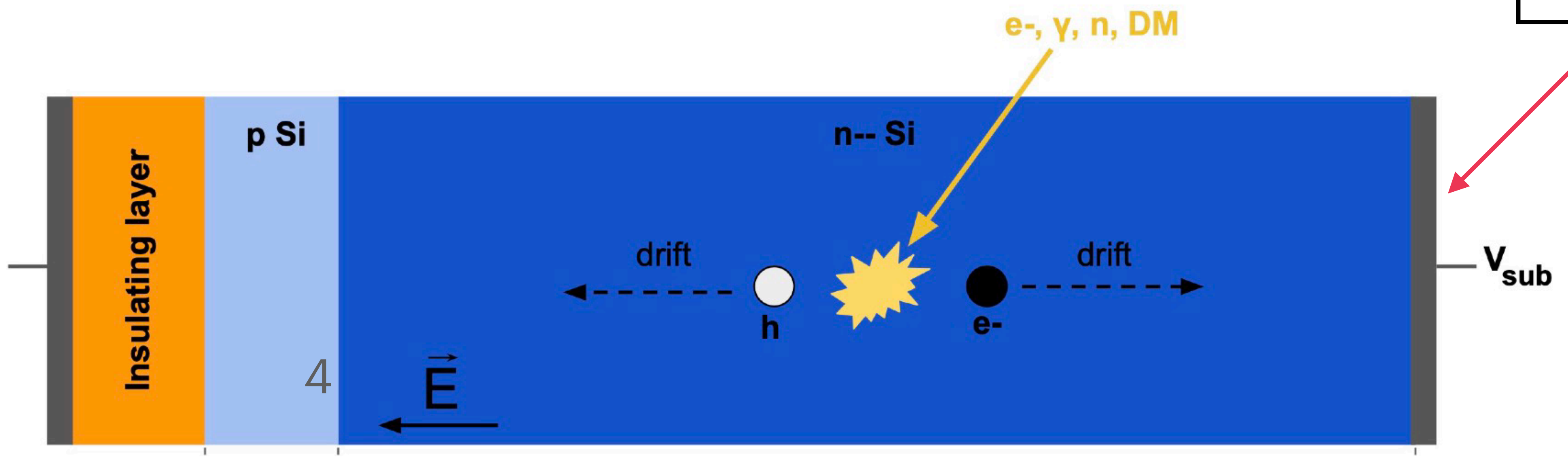


CCDs on Si wafer

- Charge-coupled devices have been used for a long time as telescope cameras (DES,CAHA, JAVALAMBRE,EUCLID, Vera Rubin, etc)
- They were adapted and reimagined for underground Dark Matter detection:
  - demonstrated by DAMIC at SNOLAB
  - on-going experiments DAMIC-M and SENSEI
  - R&D work on OSCURA
- Why? Silicon is a good candidate -> light (A=28), mono-crystalline material is clean, uniform, and can make thick
  - e-h pairs produce (~3.77 ev required) → Charge is collected near the surface
  - Precise spatial resolution and good energy resolution → using the diffusion 3D reconstruction
  - Conventional CCDs are limited to noise of ~2e^- → single electron resolution to ionization signals, 2-3 electron threshold (~ 5-10 eV)
  - Low dark current (2x10^{-22} A/cm^2, <0.001 e/pixel/day (at 140K))



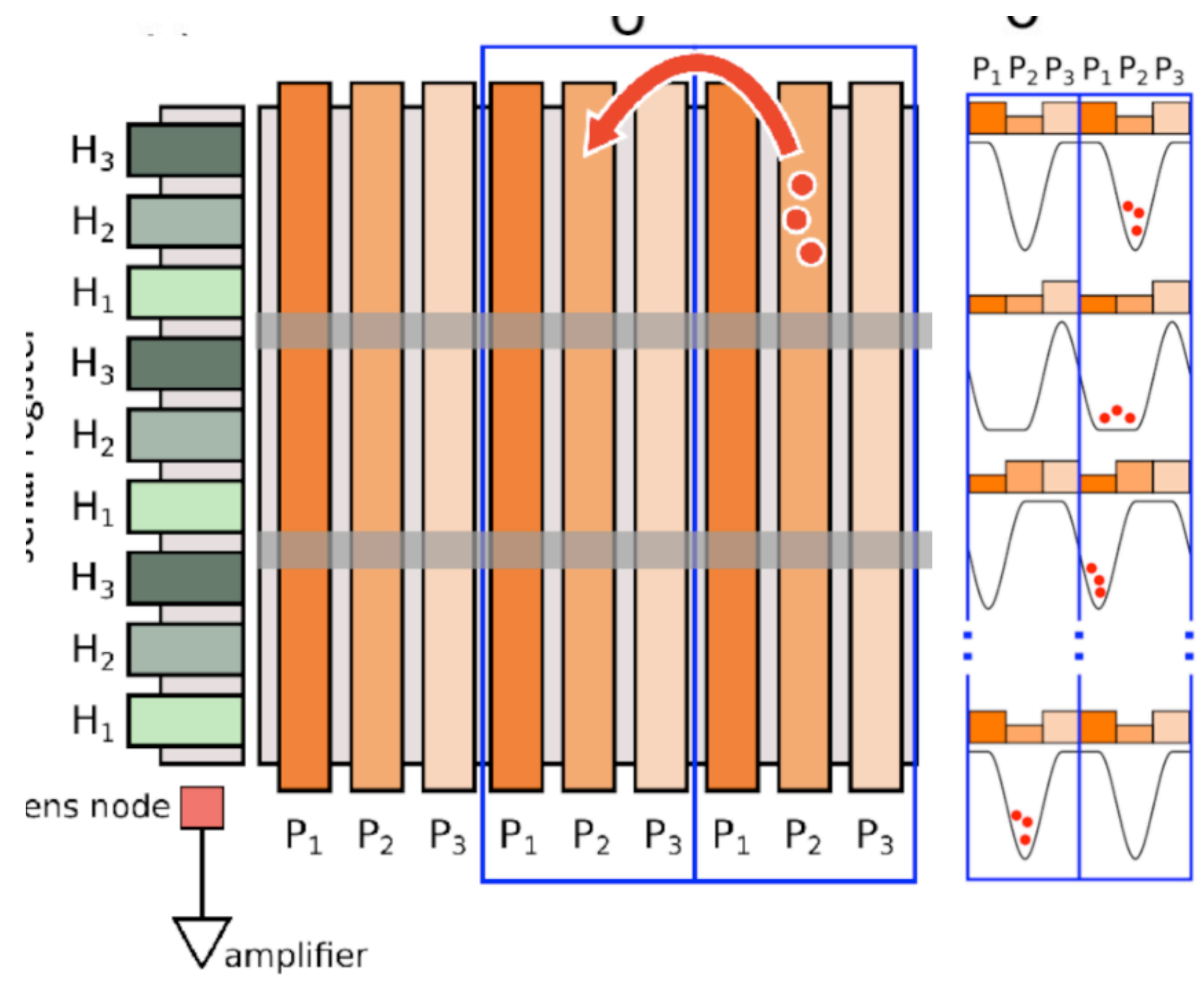




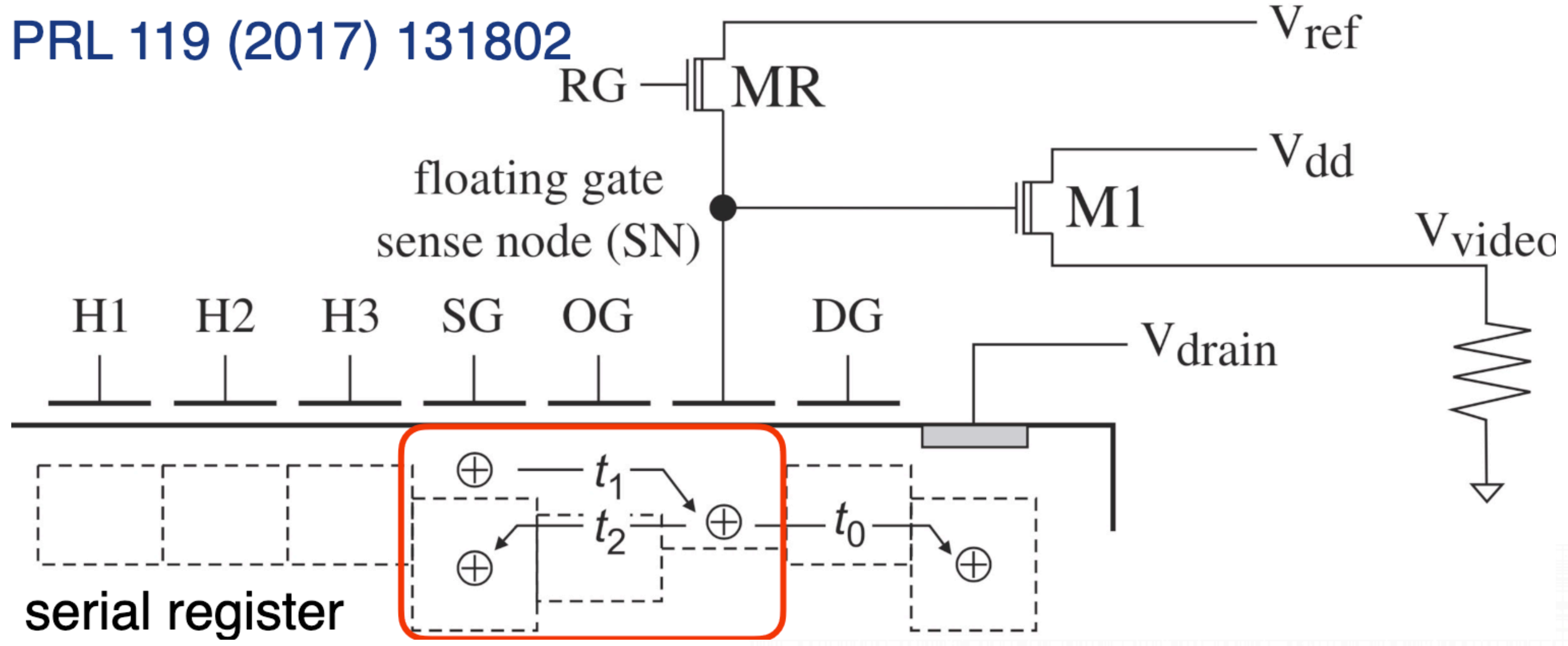
CCDs as particle detectors for DM

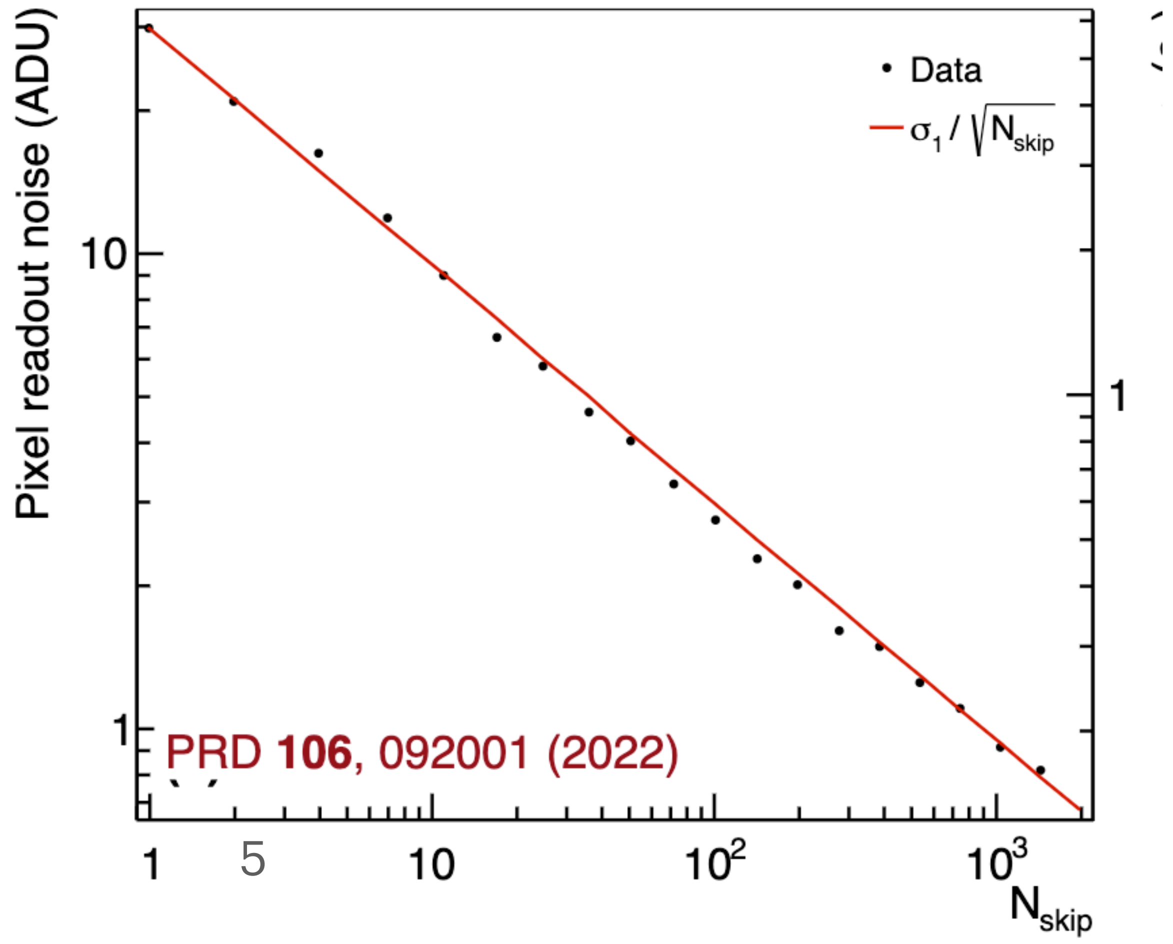
CCDs as particle detectors for DM, improve resolution

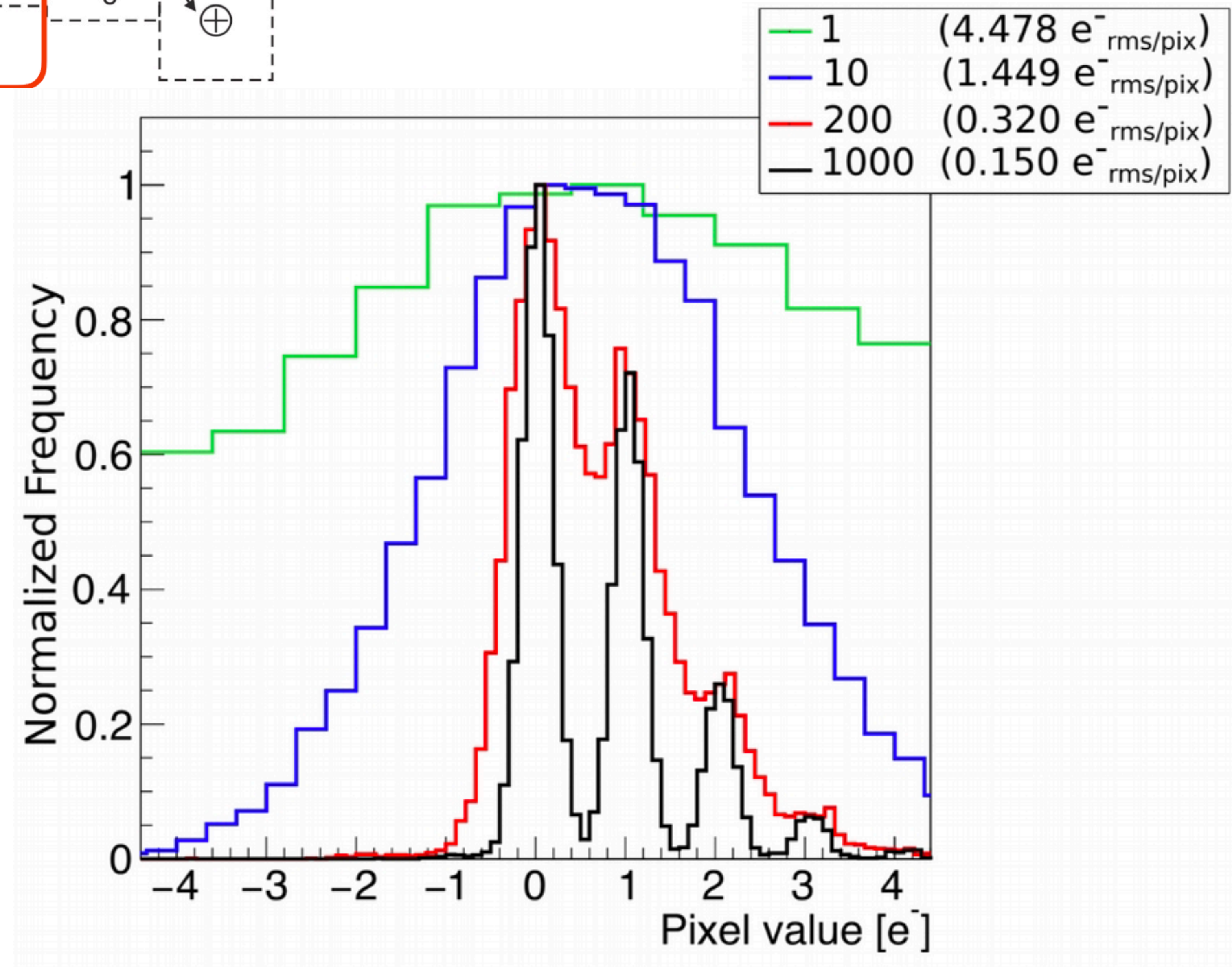
- After exposure of the active target → charge generations and collection, the readout take place
- In a vertical transfer one row of pixels is moved towards the horizontal register
- The horizontal register is moved pixel-by-pixel to a readout amplifier → last horizontal pixel falls into a skipper amplifier
- allows multiple sampling of the same pixel without corrupting the charge packet → Single Electron Resolution (SER)
- Readout noise decrease by a factor 1/sqrt(N)
- Reduce the low frequency noise (1/f) → now subdominant
- But readout time increase ~ Nskip



PRL 119 (2017) 131802



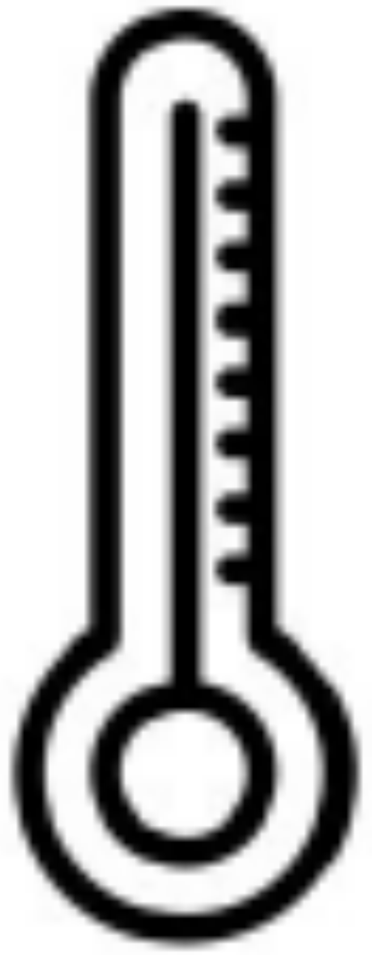




DAMIC-M

In NutShell

DAMIC-M Features: detect Light DM (WIMP, Hidden Sector) signals via interaction with Si-nucleus or e- in the bulk of CCDs



~100 K

Temperature

~1 kg

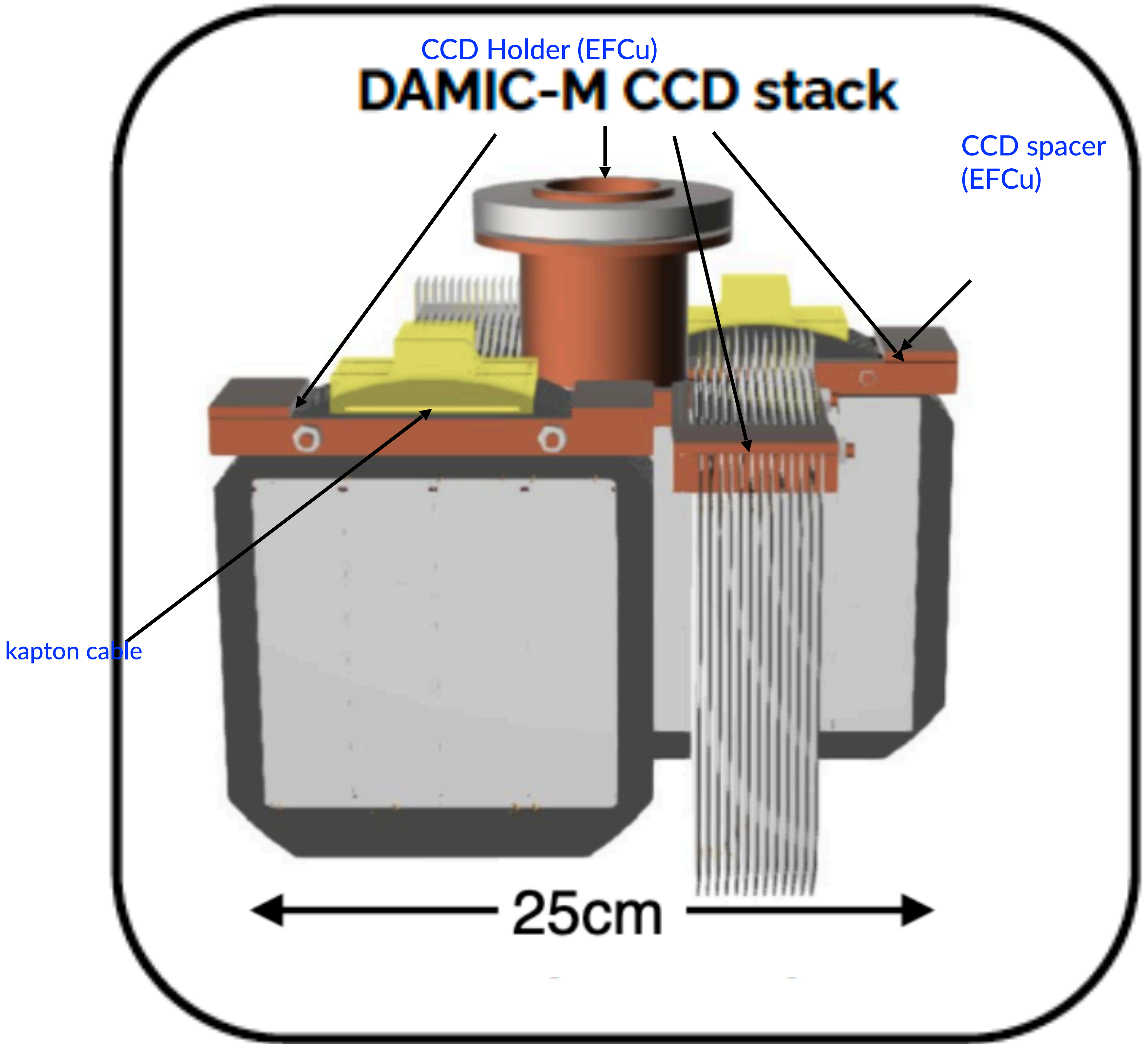
Sensitive Mass

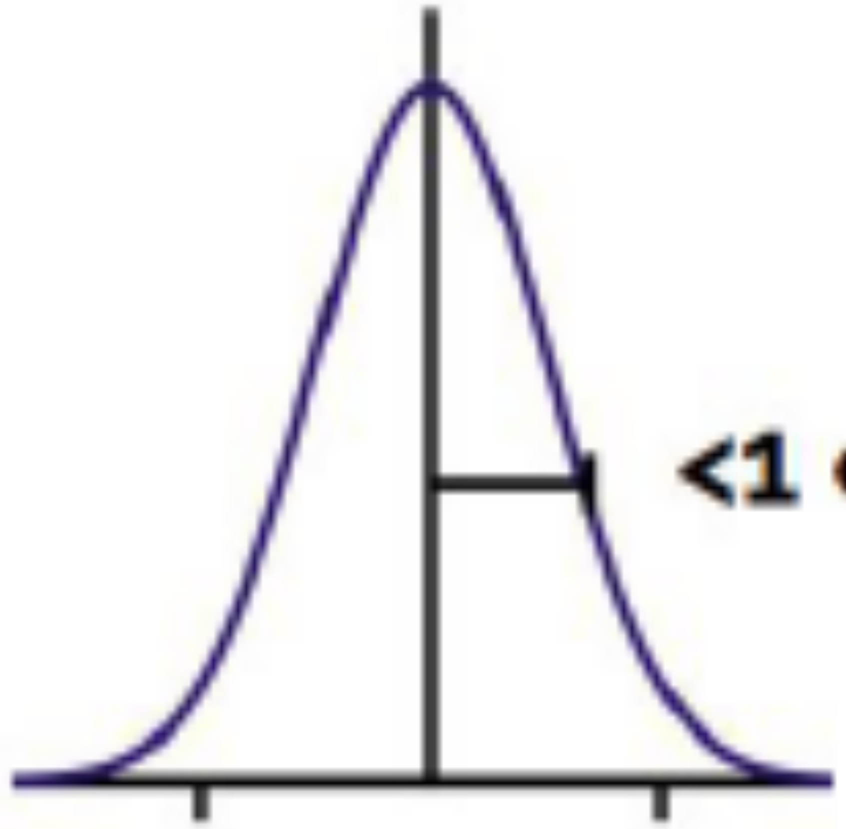
1 d.r.u*

Background Level

O(0.1) d.ru

dru=(events/keV/kg/day)





Resolution (readout noise)

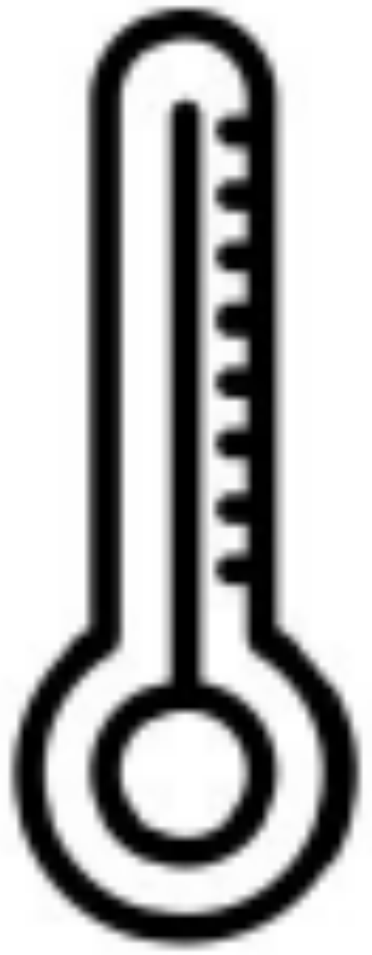
~0.1 eV

2-e electron thresholds (~eV)

52 module, 208 CCDs, total mas of 0,7 kg

DAMIC-M

In NutShell



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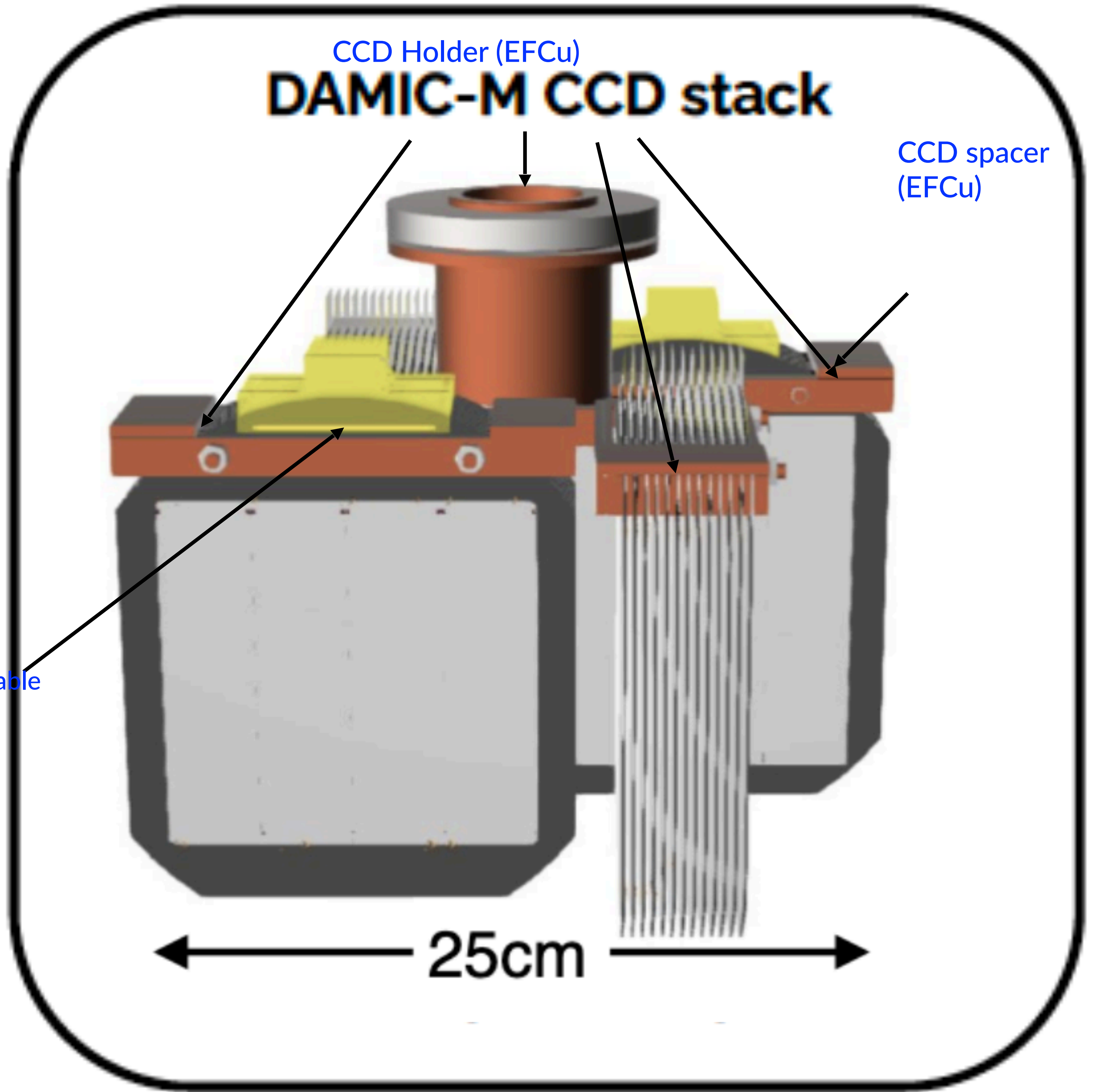

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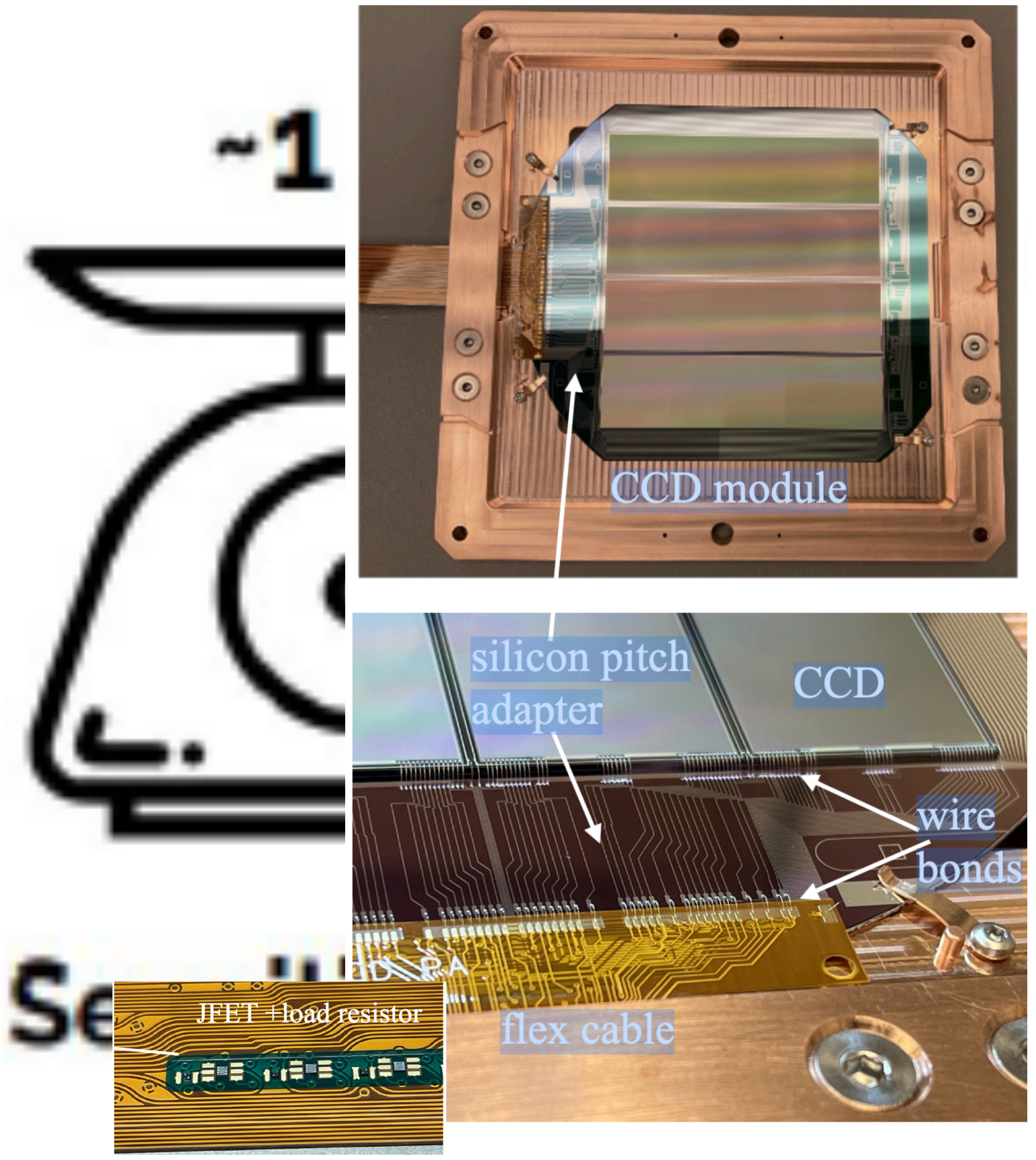
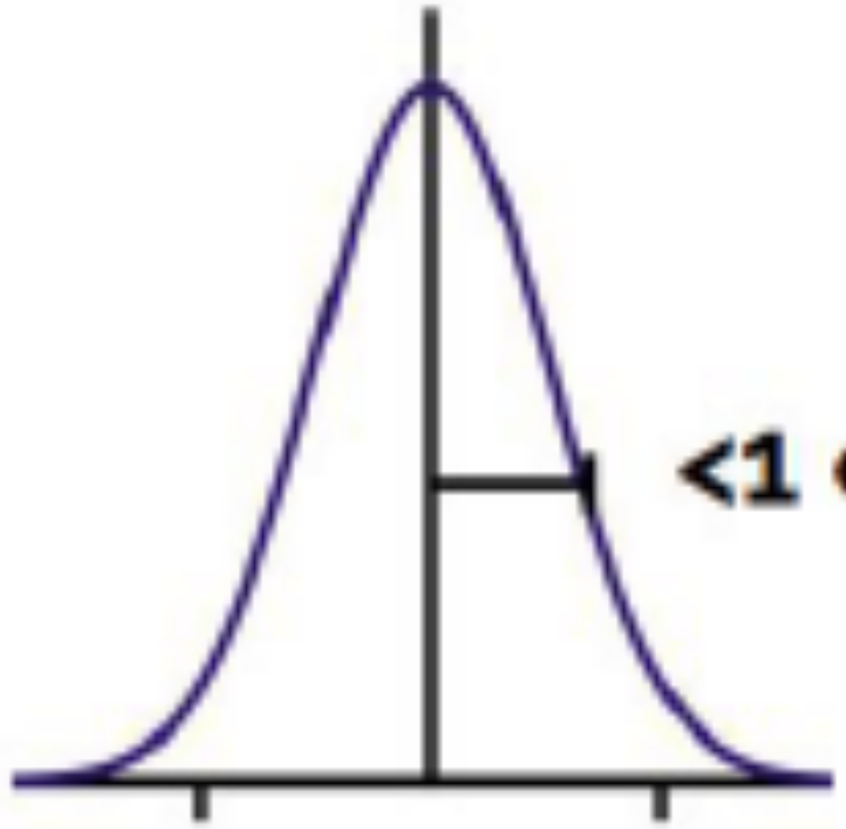
~1





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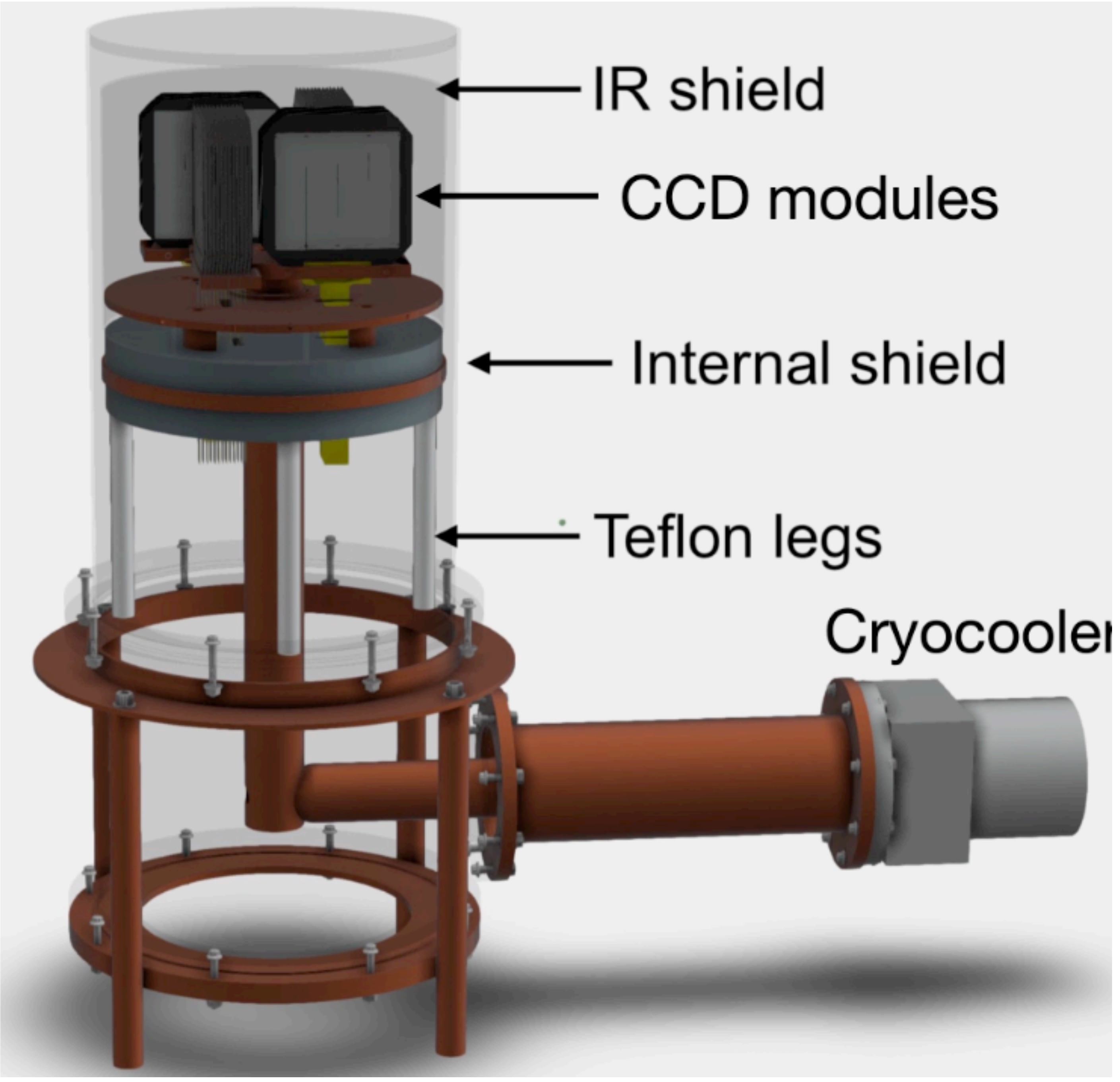

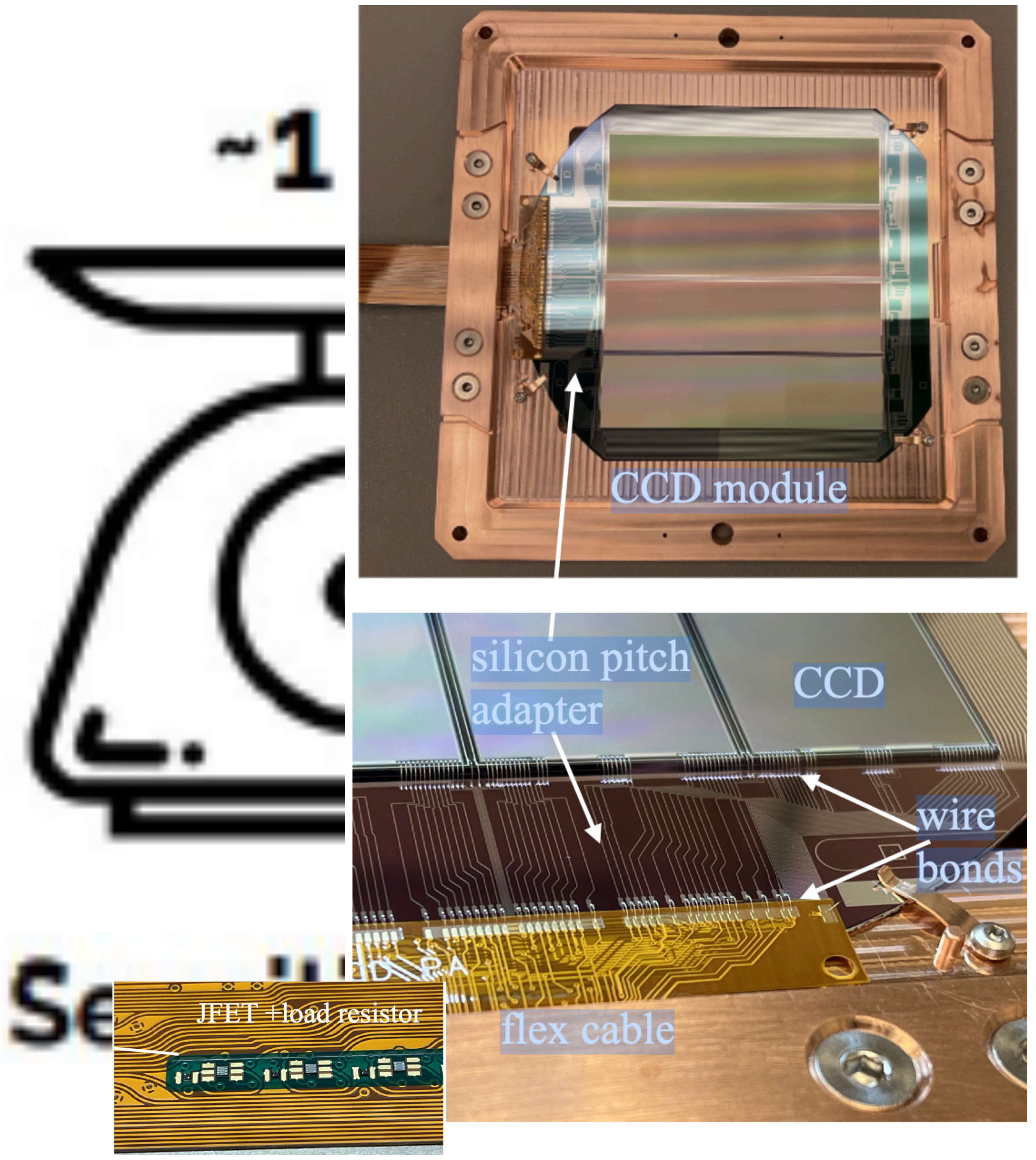

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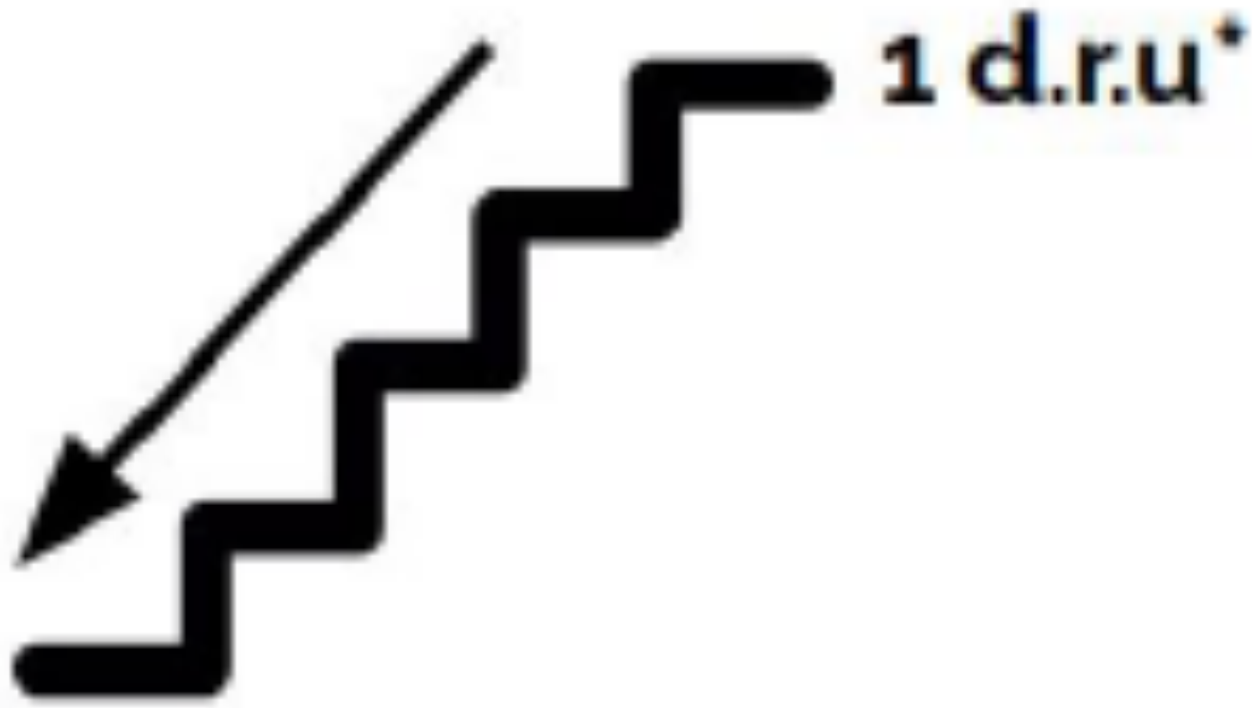

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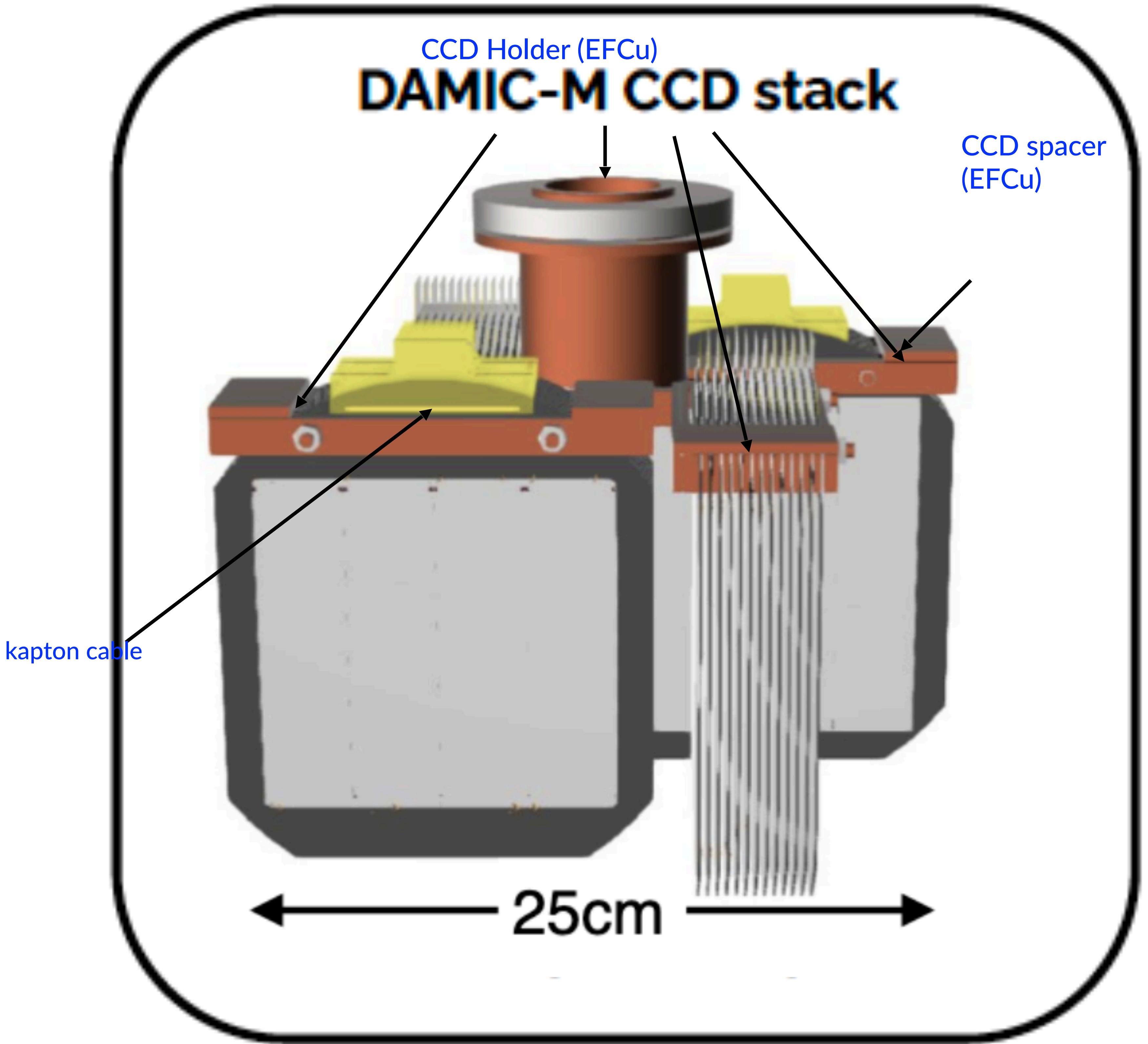

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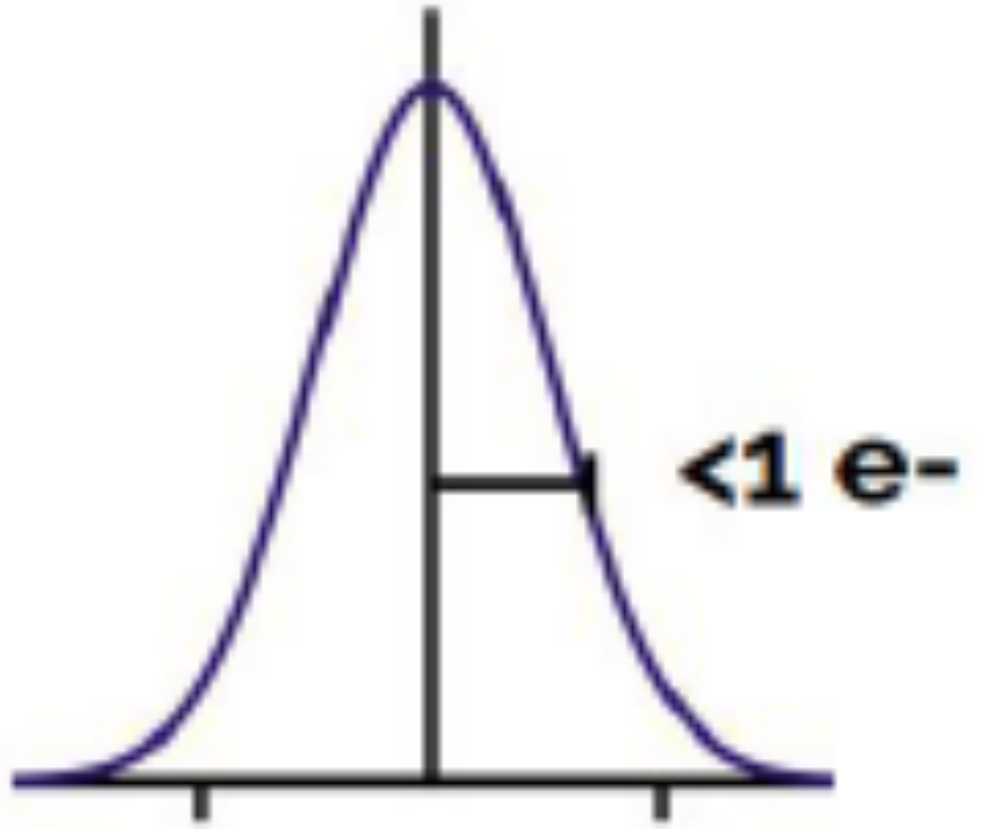

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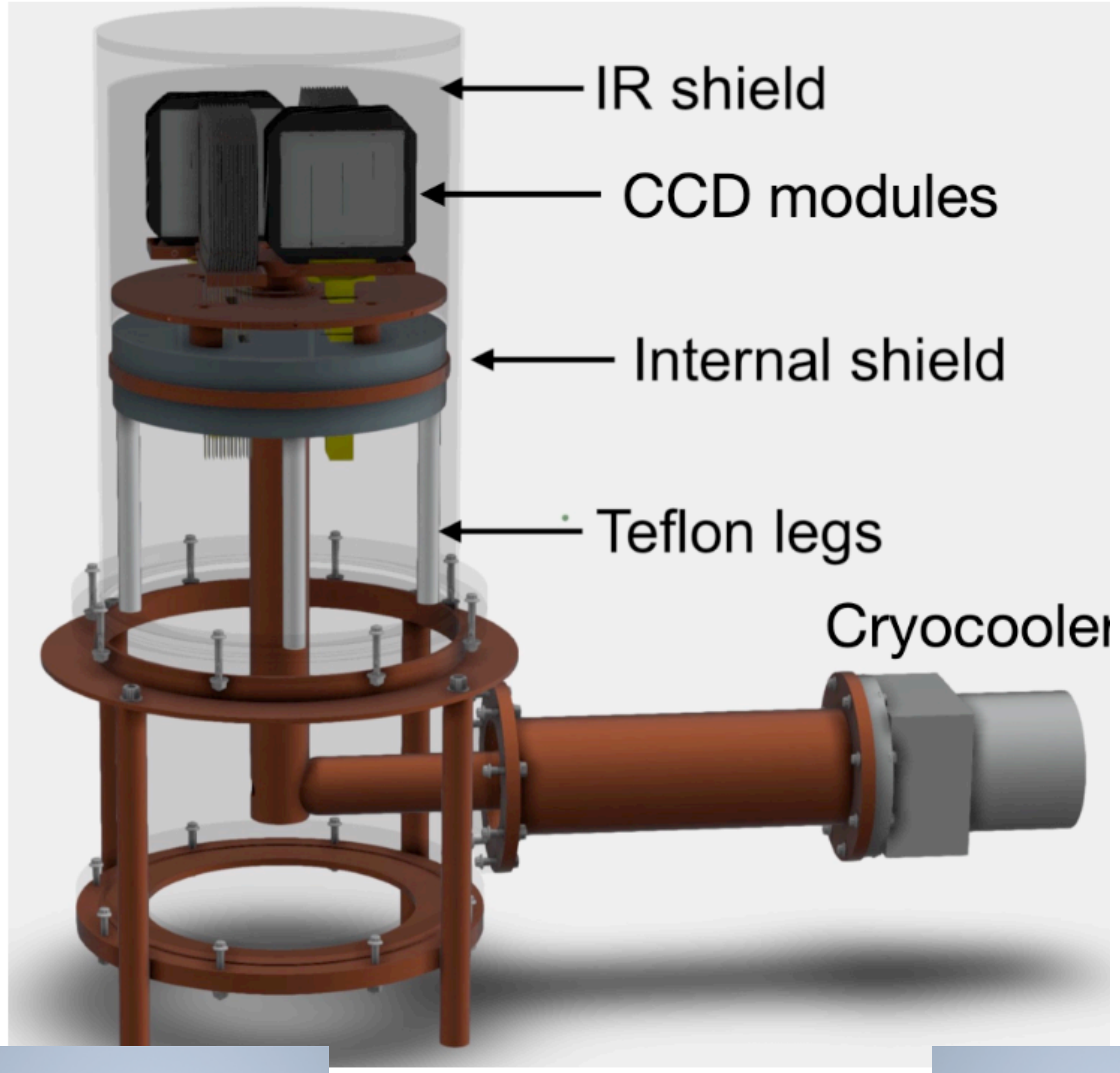

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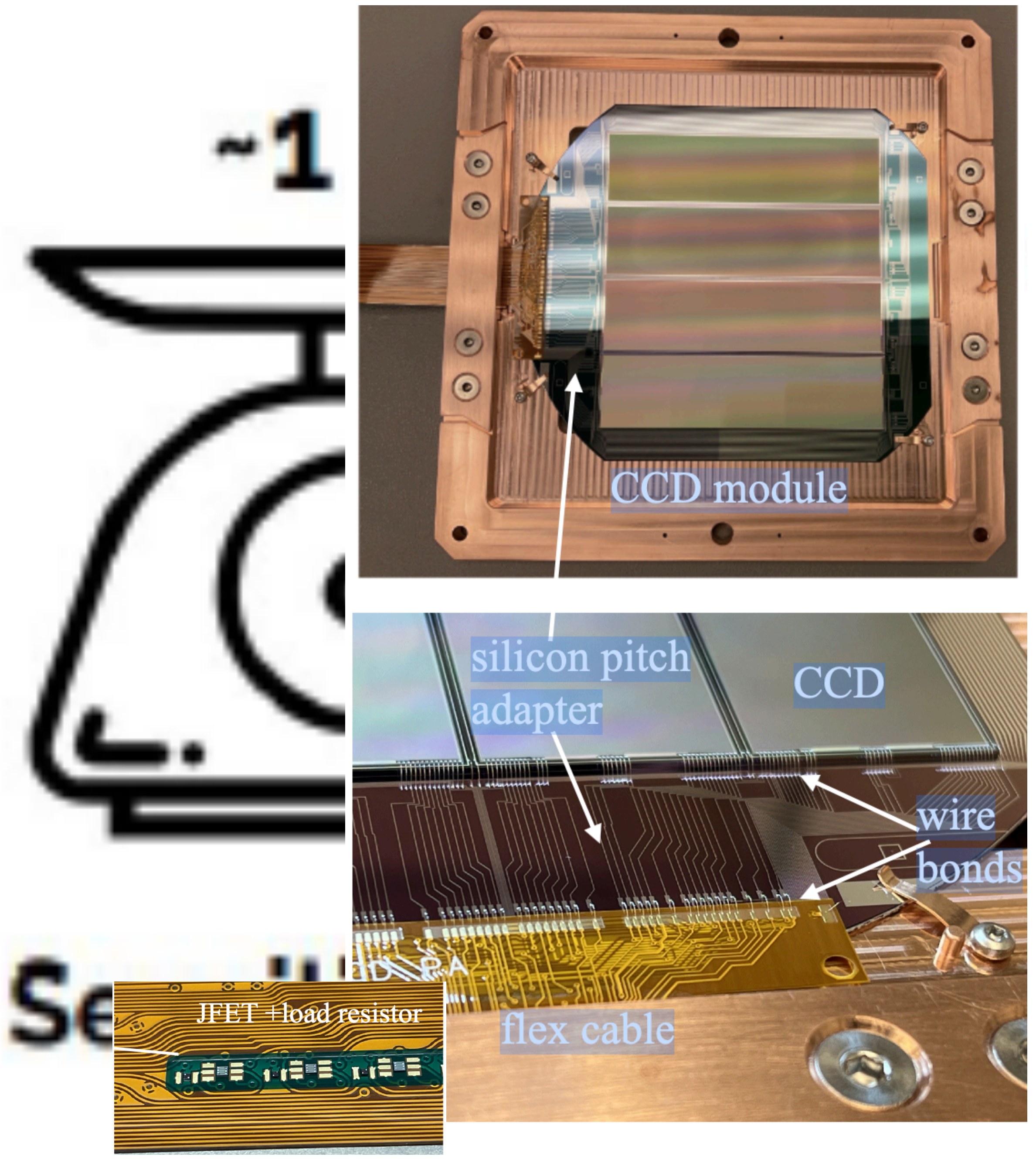

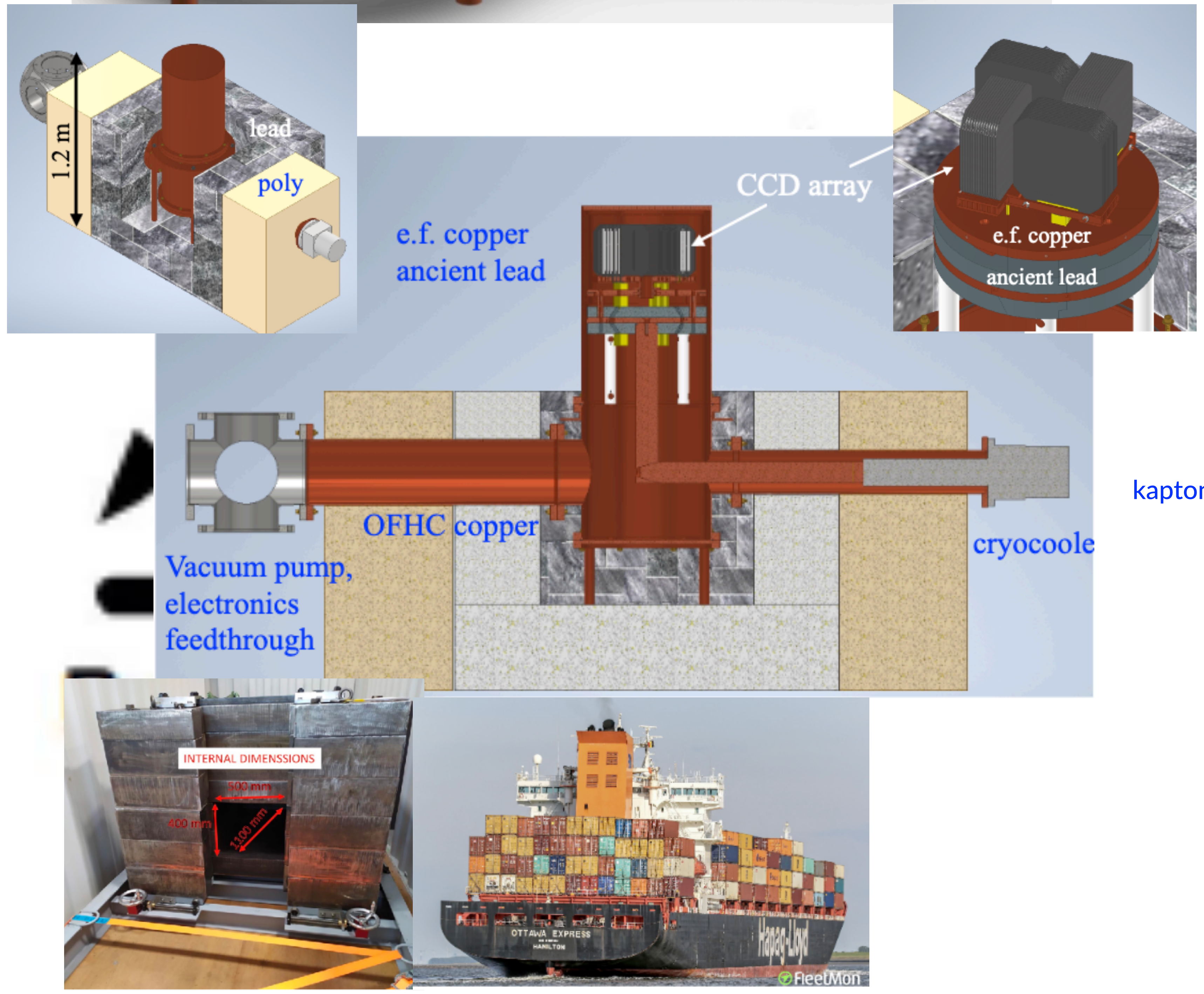

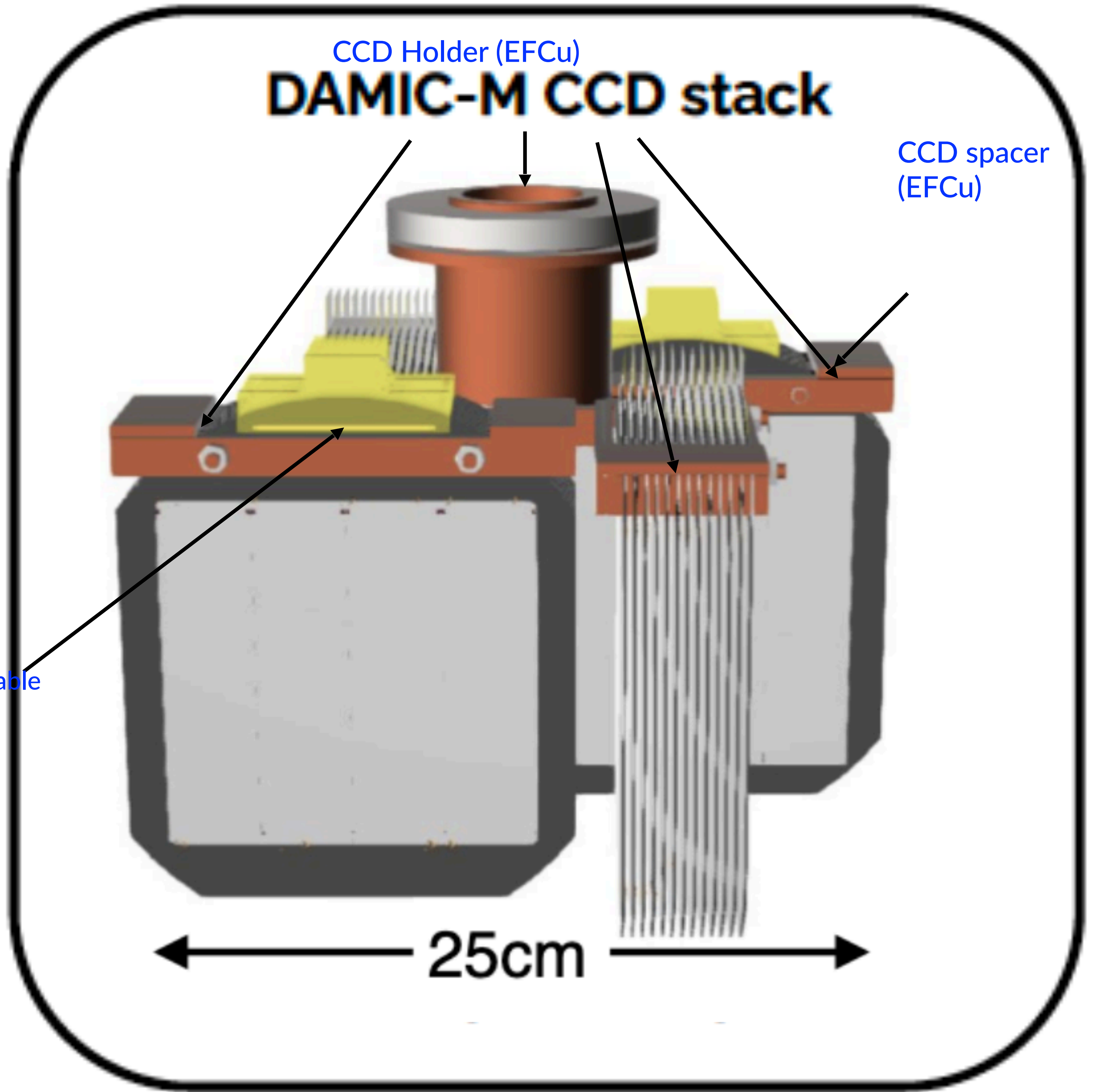

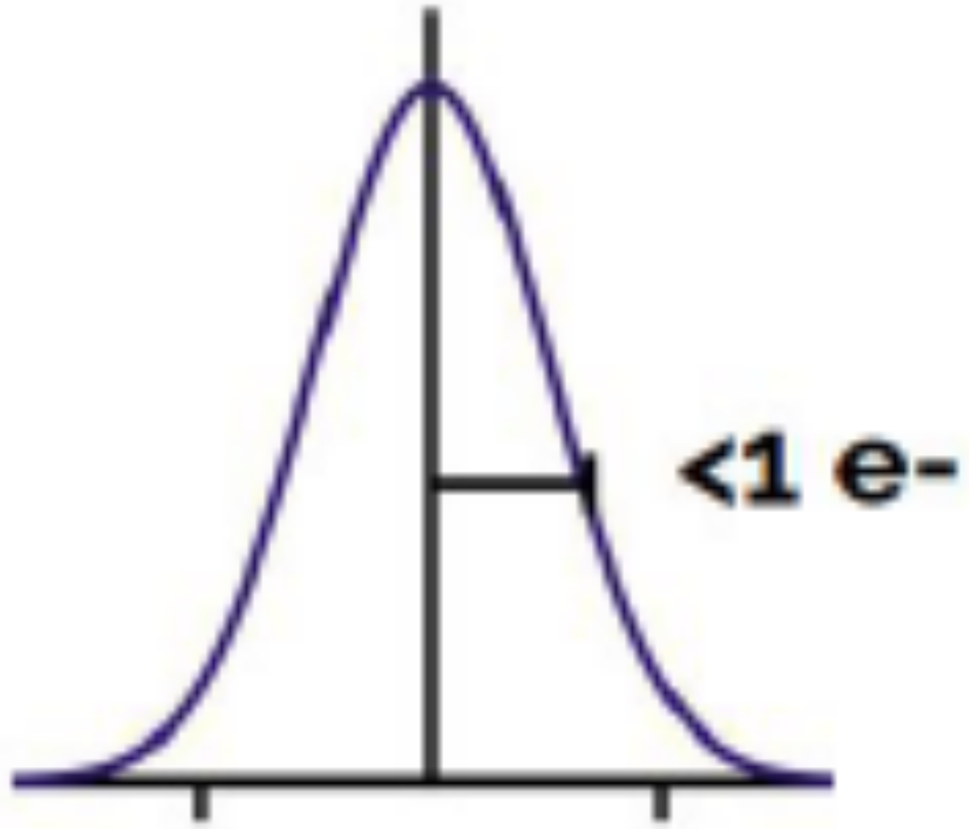

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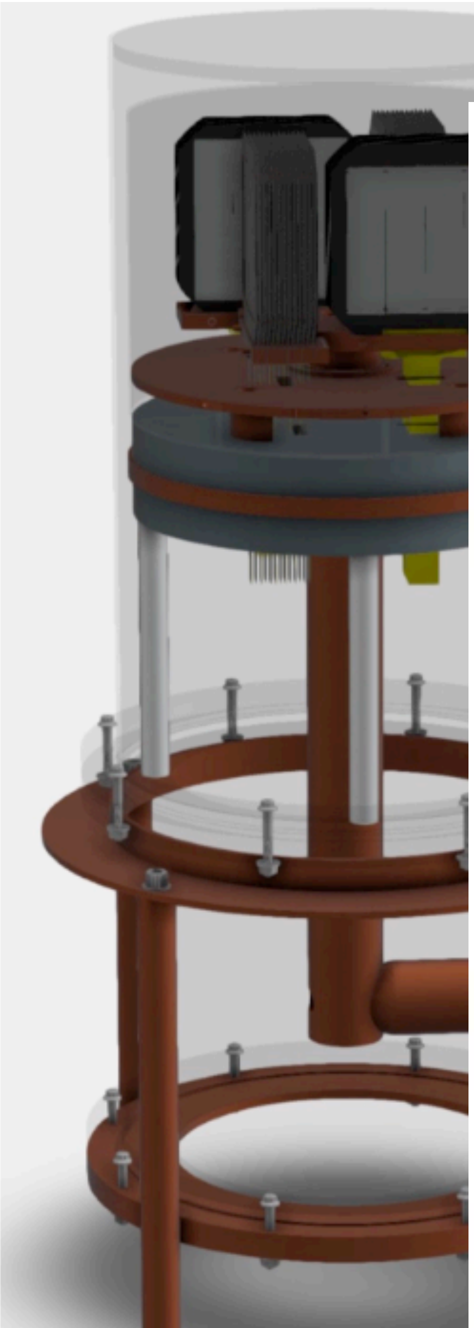
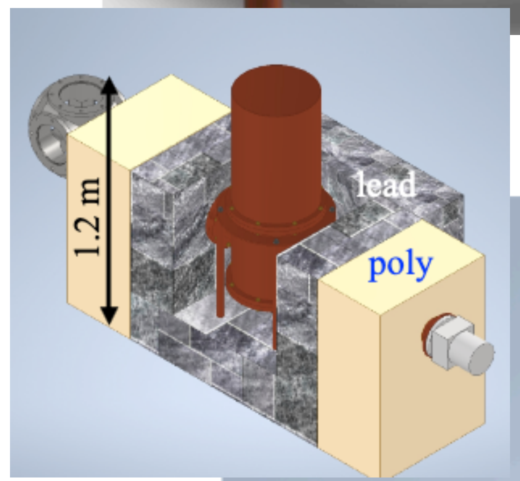
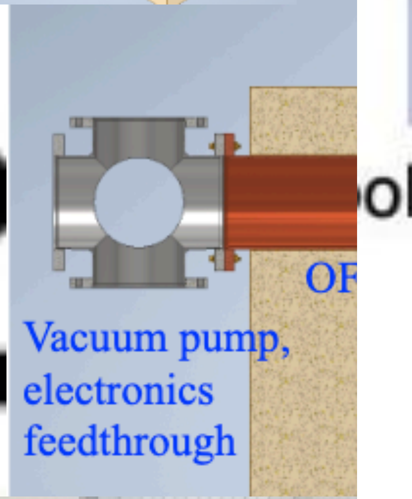
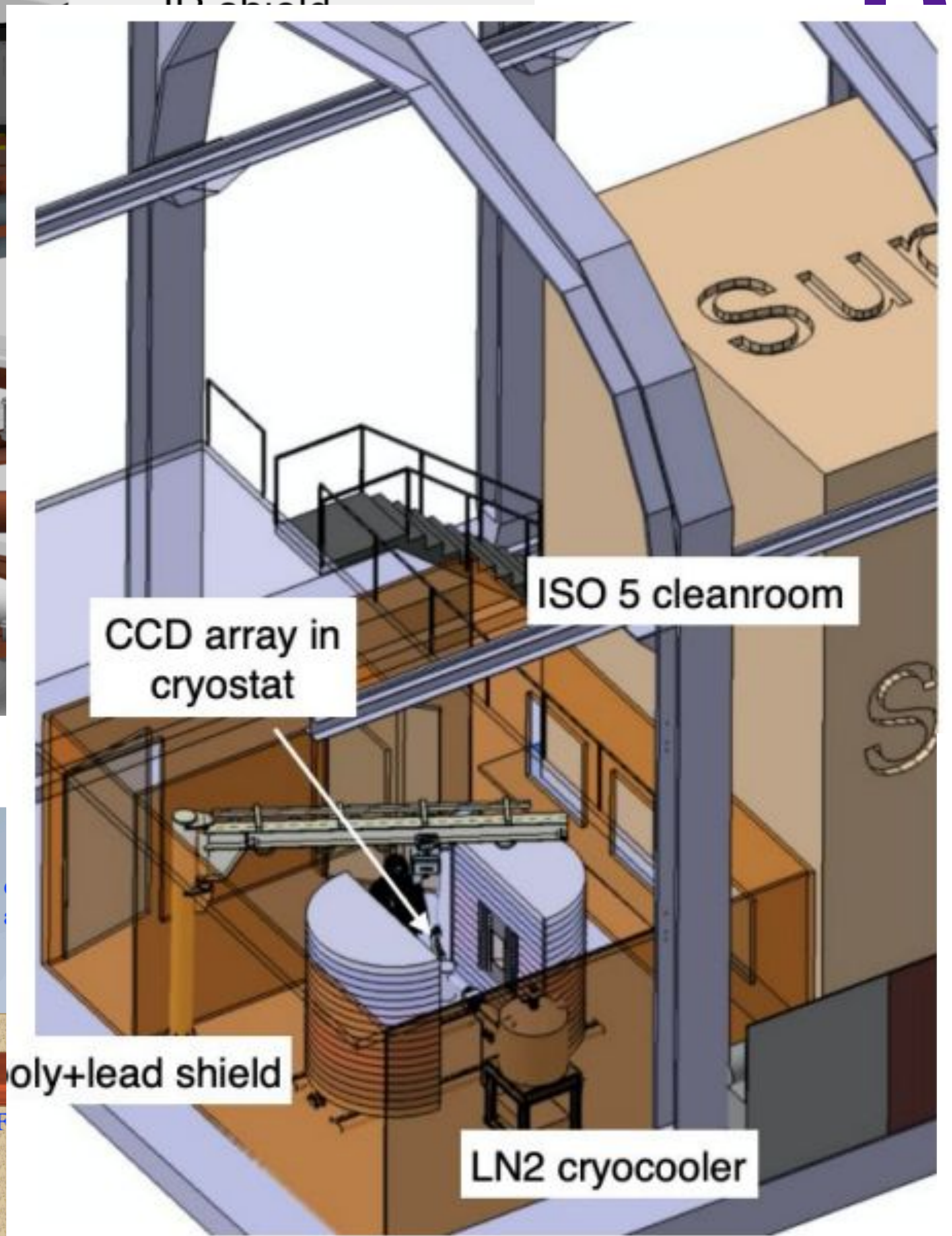
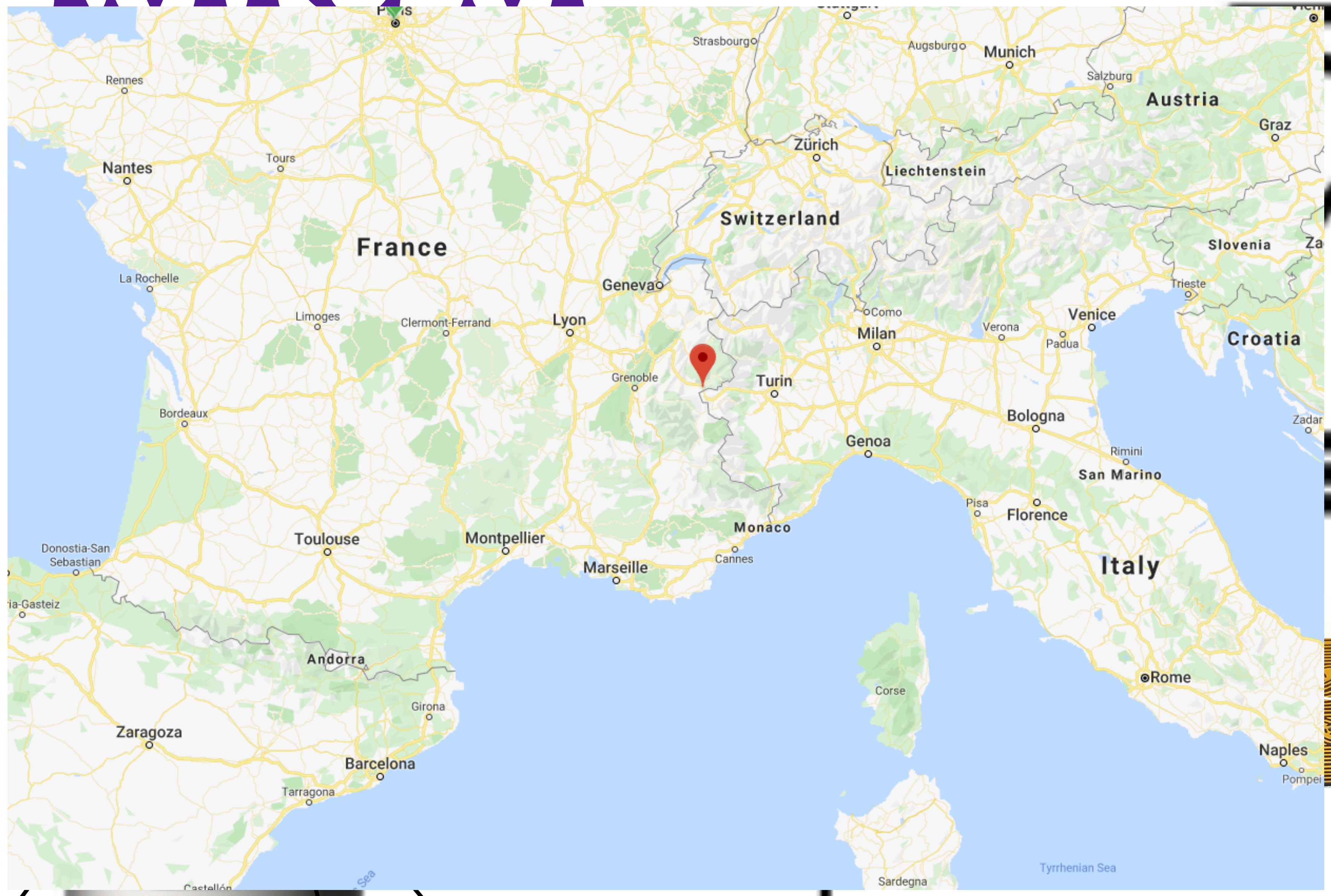


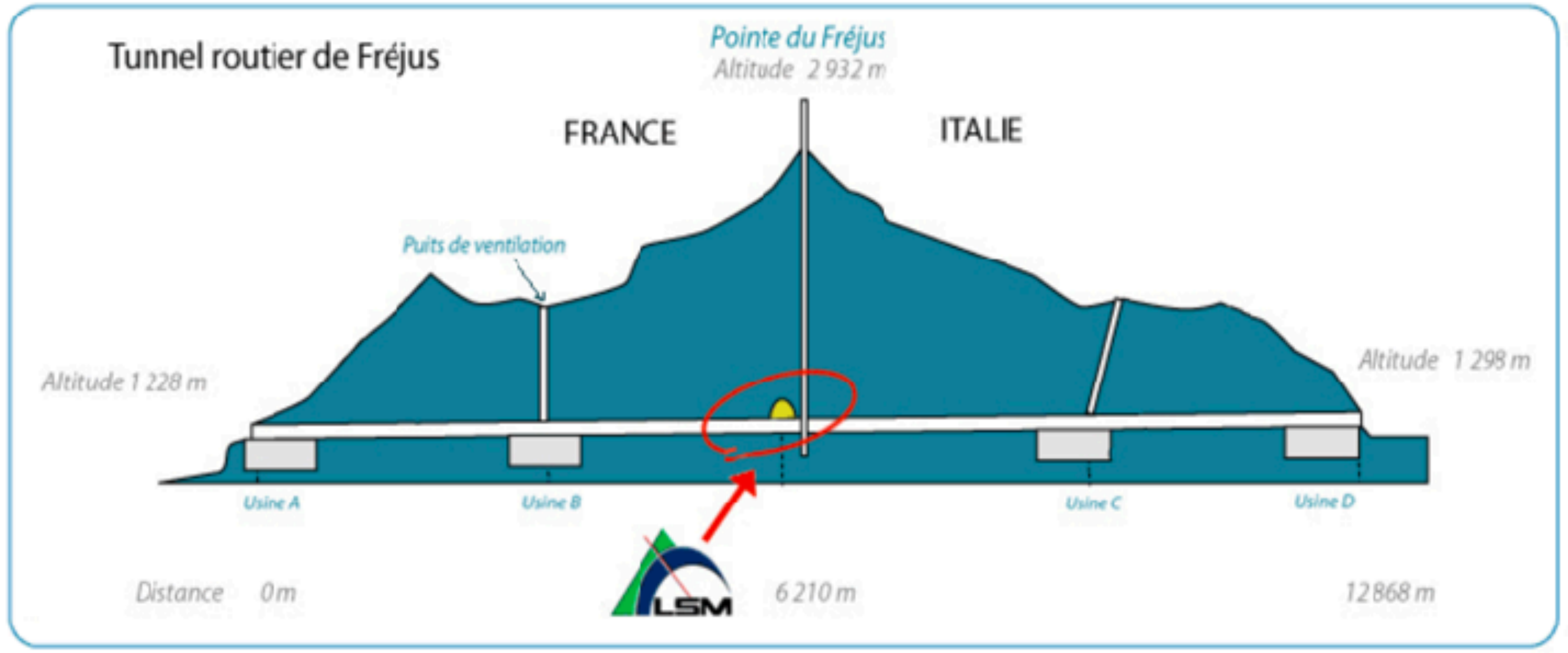


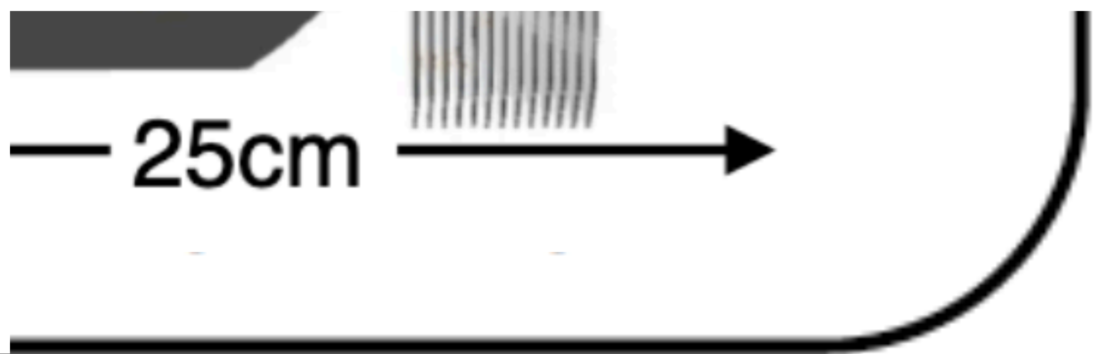


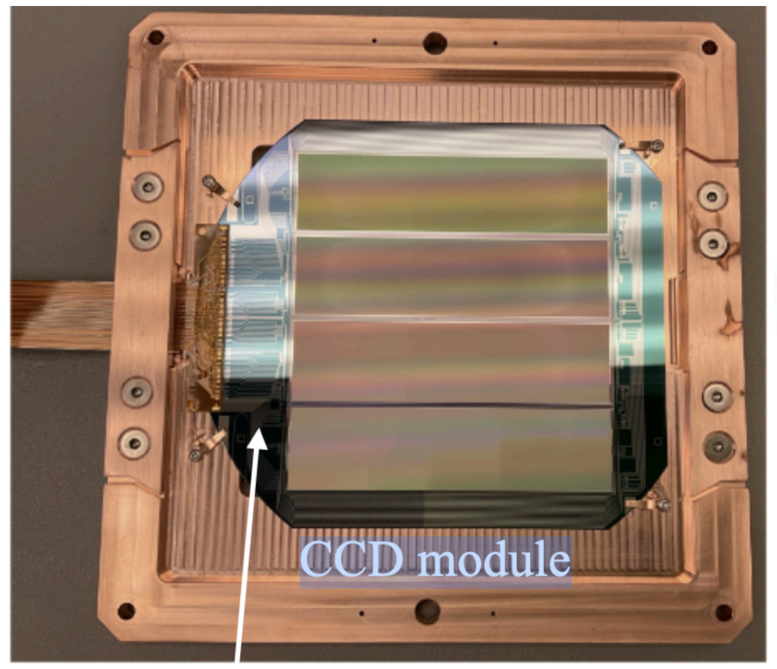


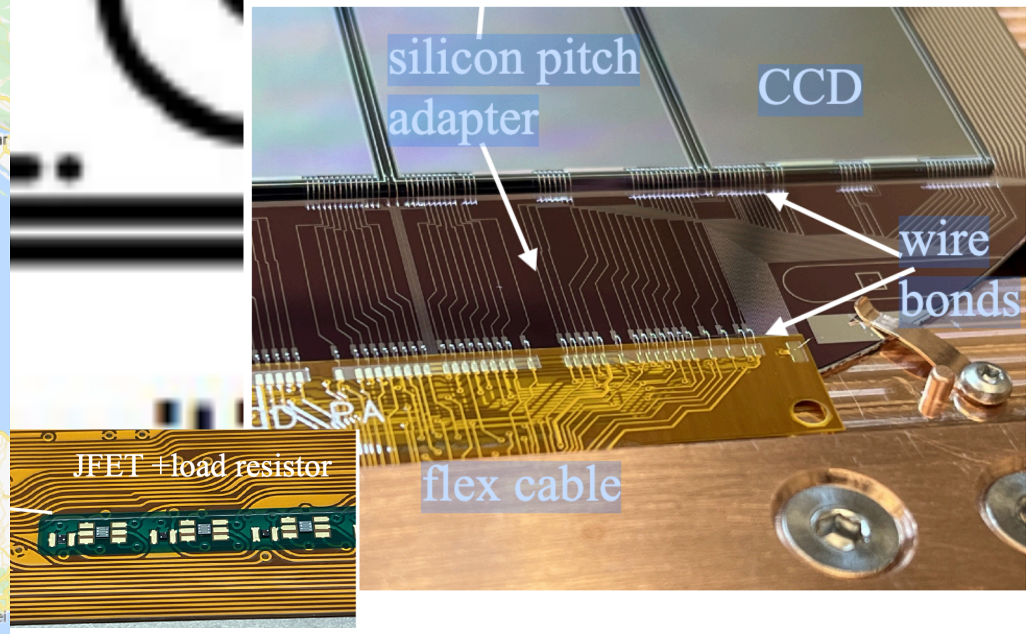
DAMIC-M@LSM
(conceptual design)

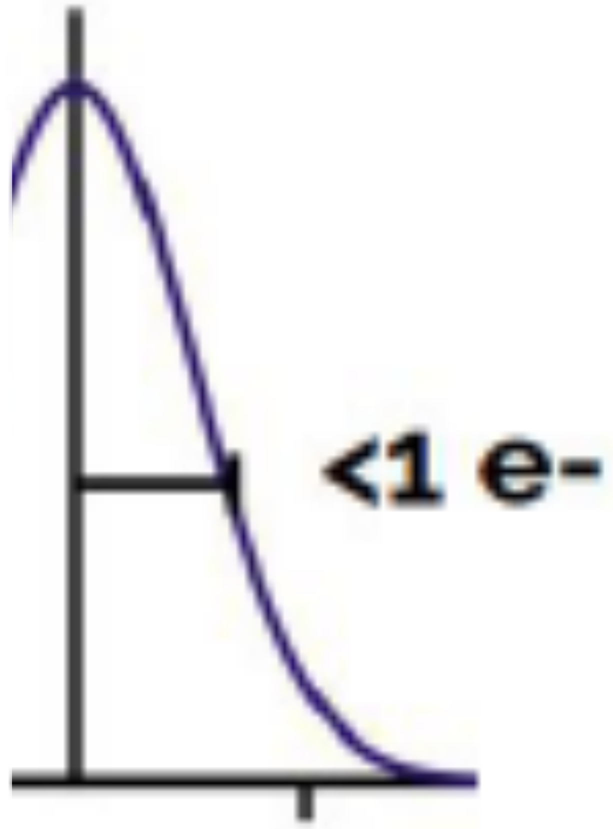












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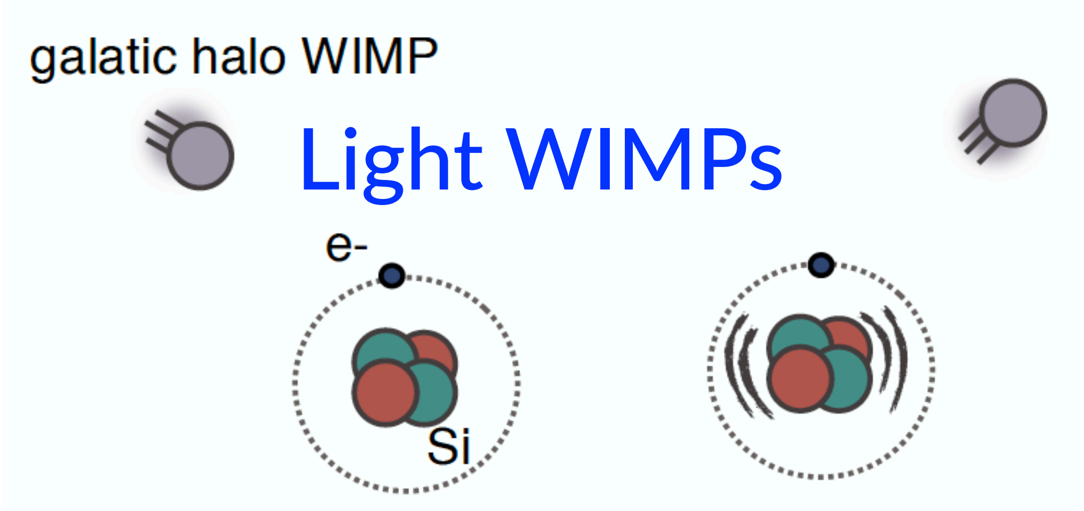
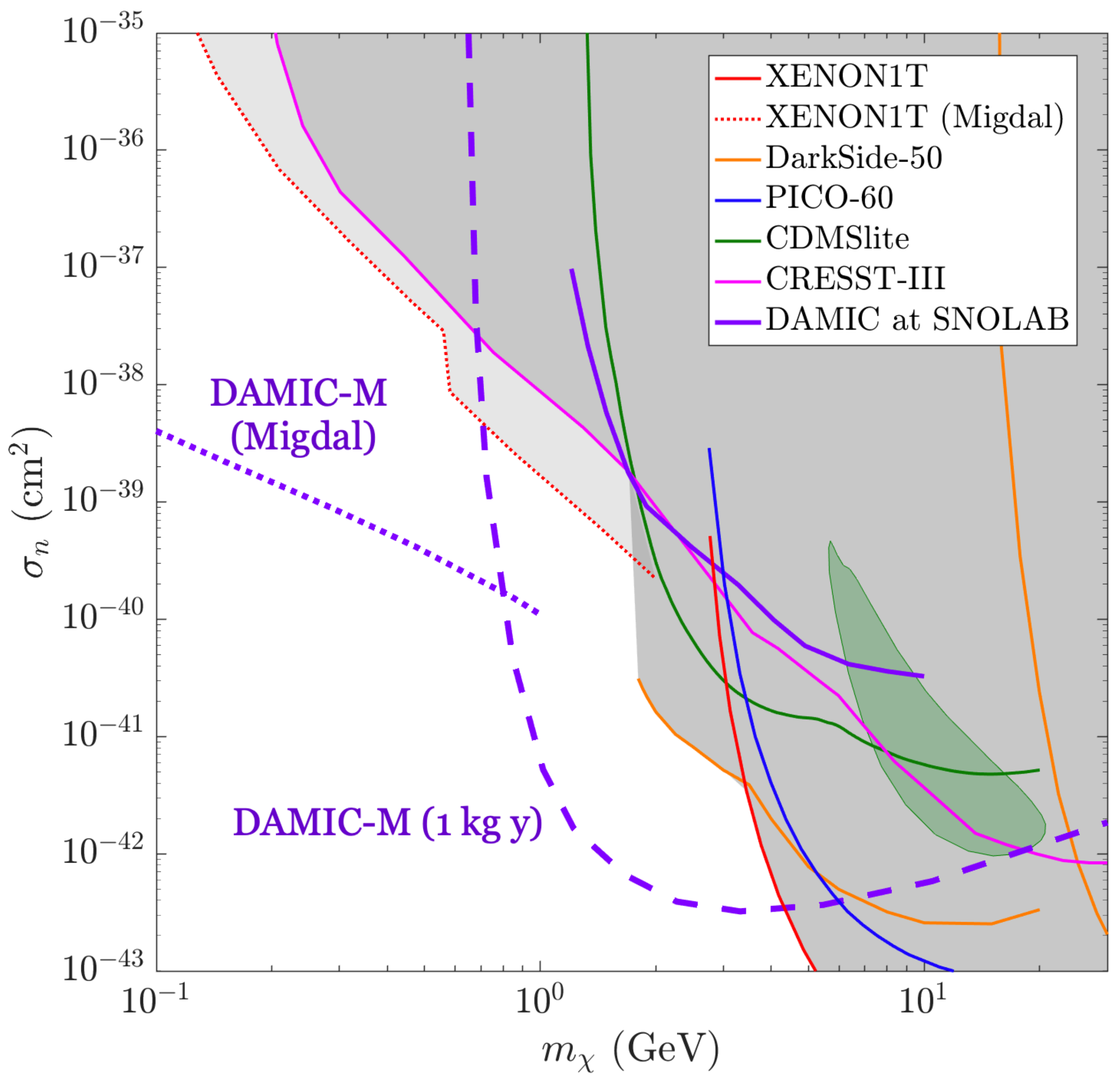
DAMIC-M

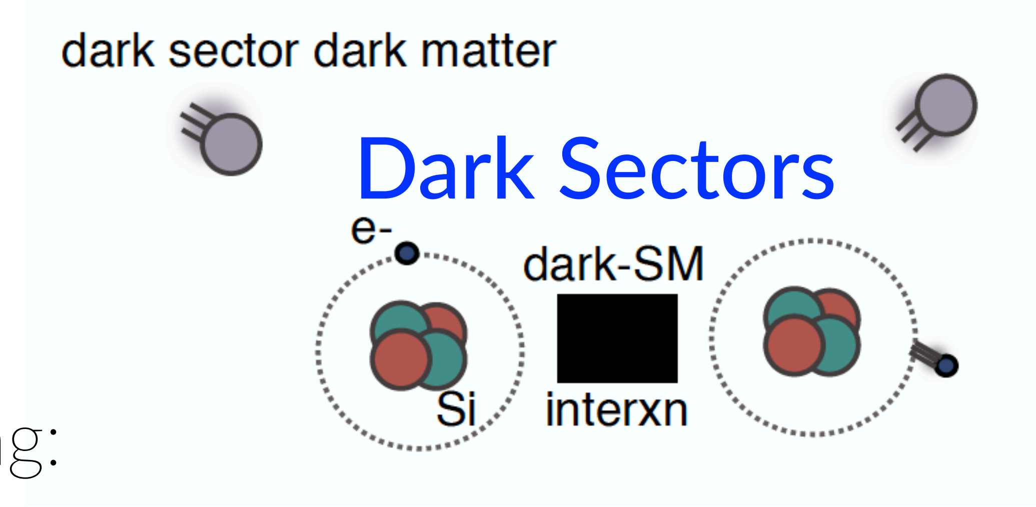
Physics Reach



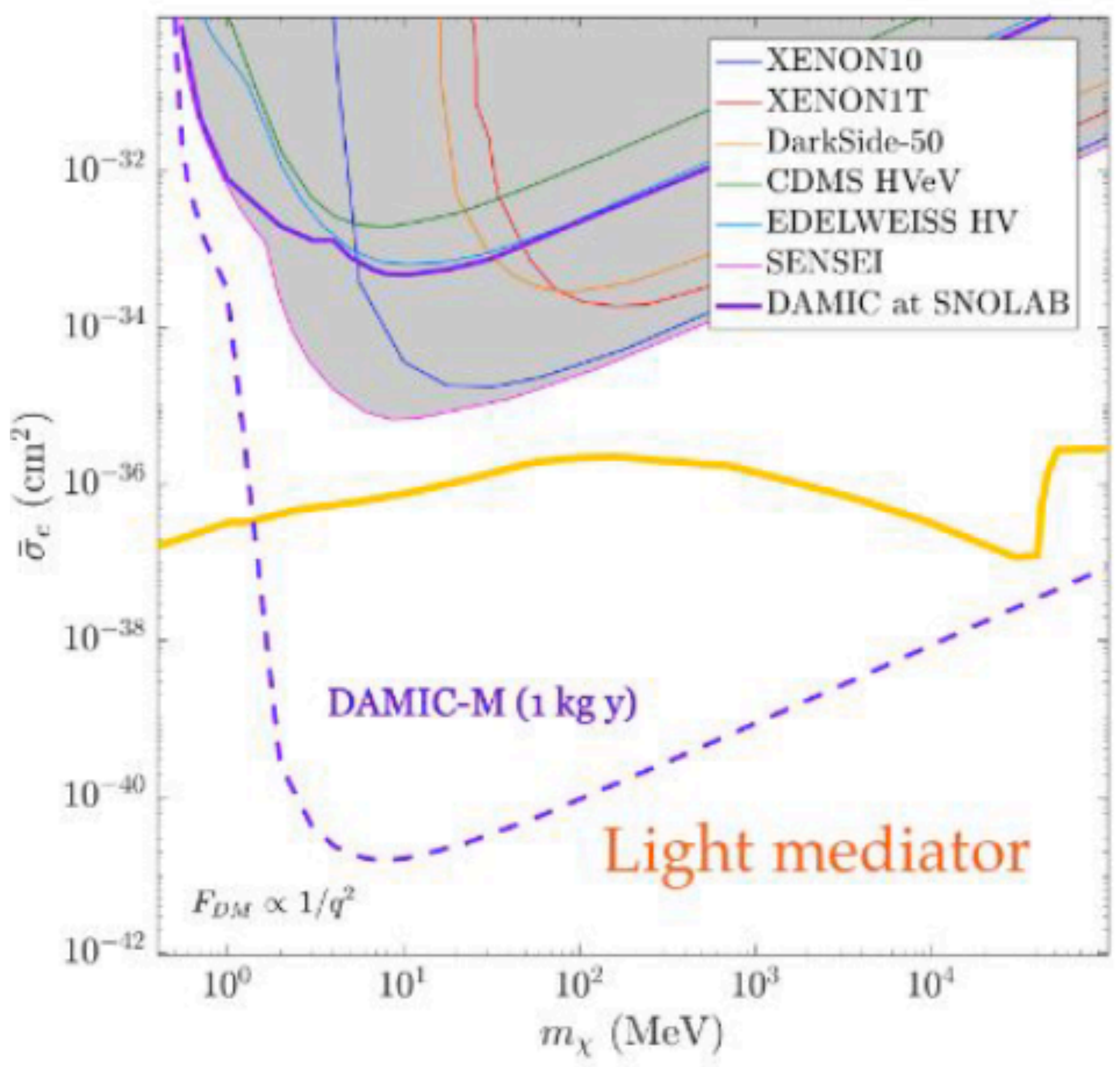
WIMP-nucleus elastic scattering:

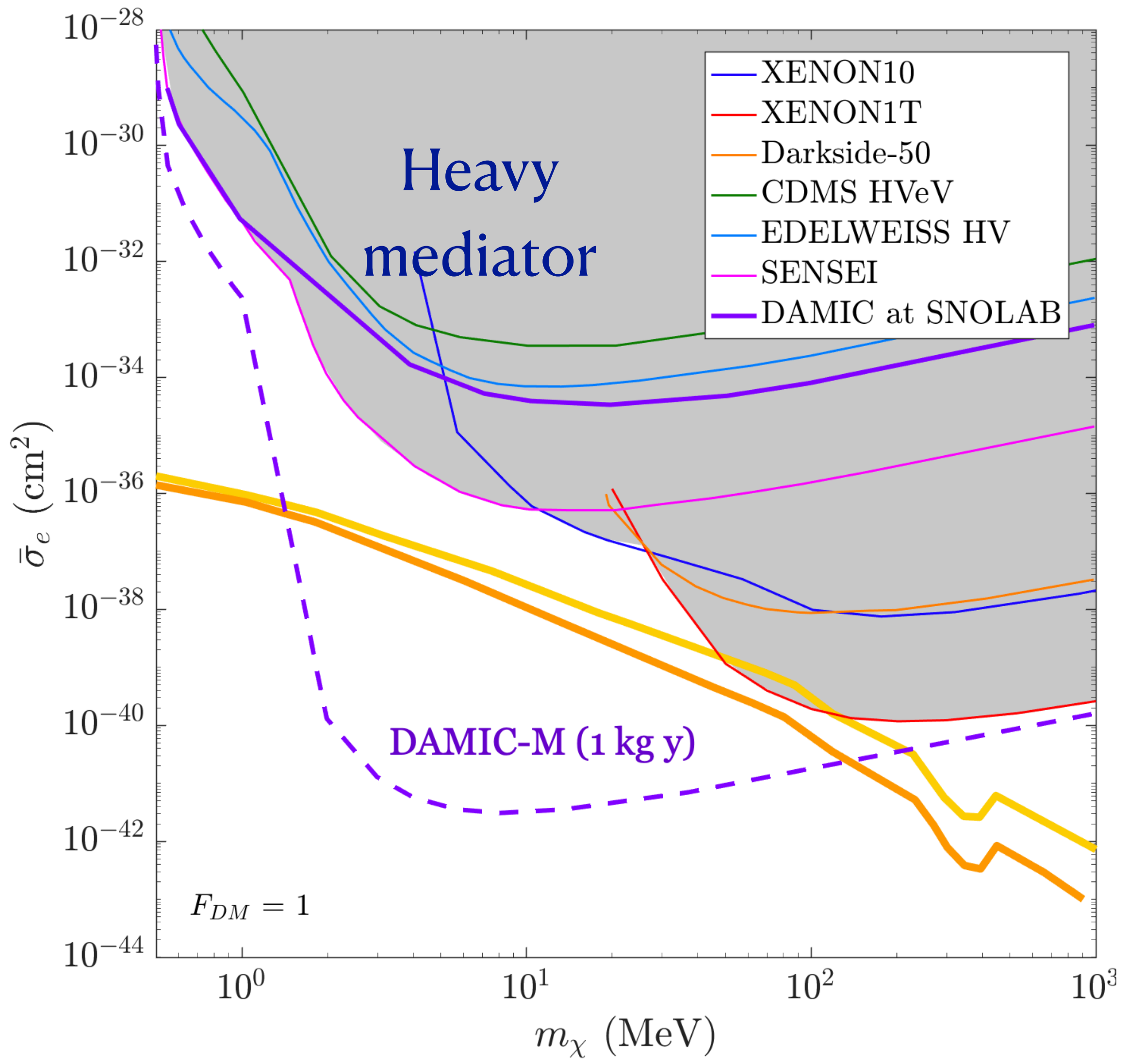
*can also detect secondary electron recoils from inelastic Migdal effect





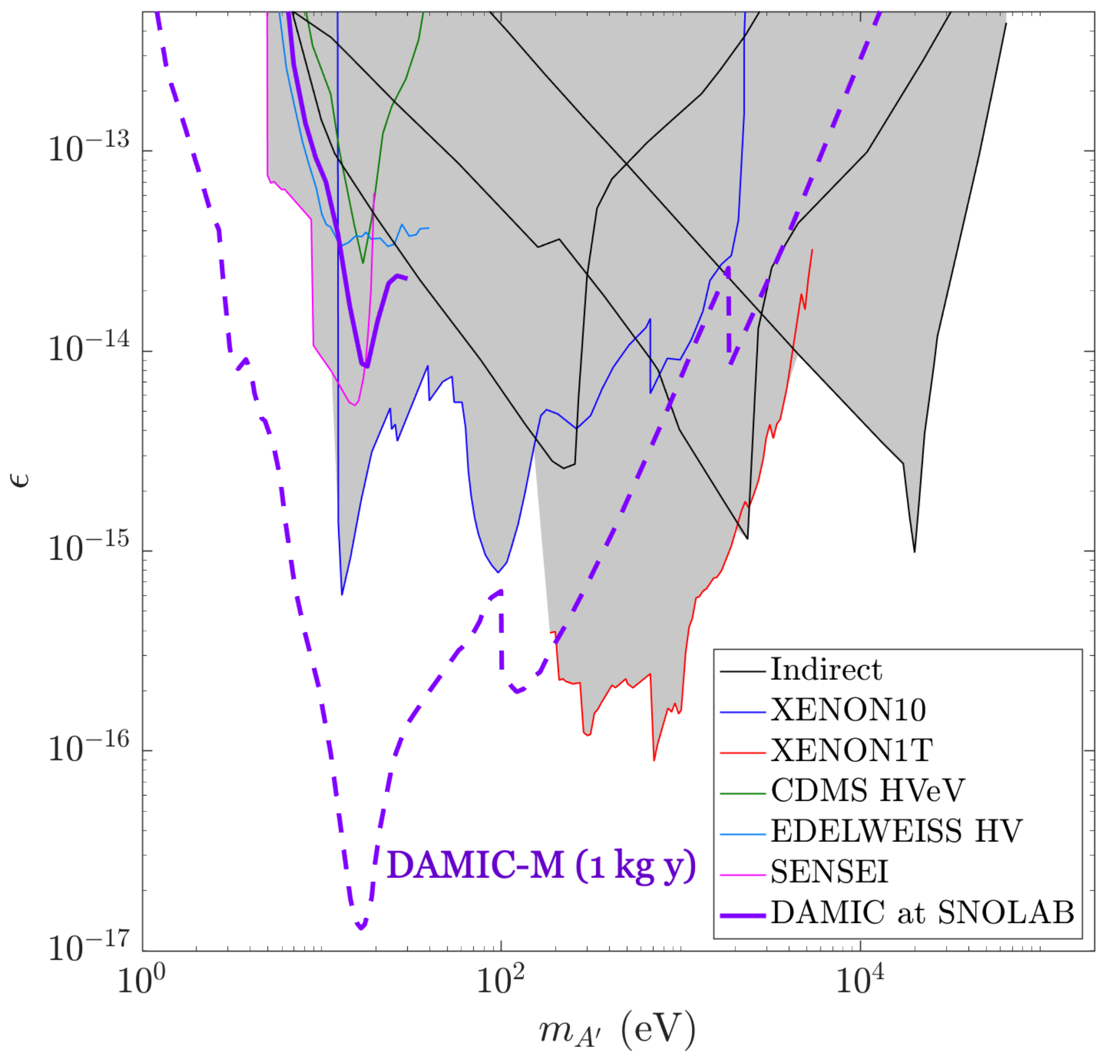
DM - Electron scattering:





DM absorption

Hidden dark photon

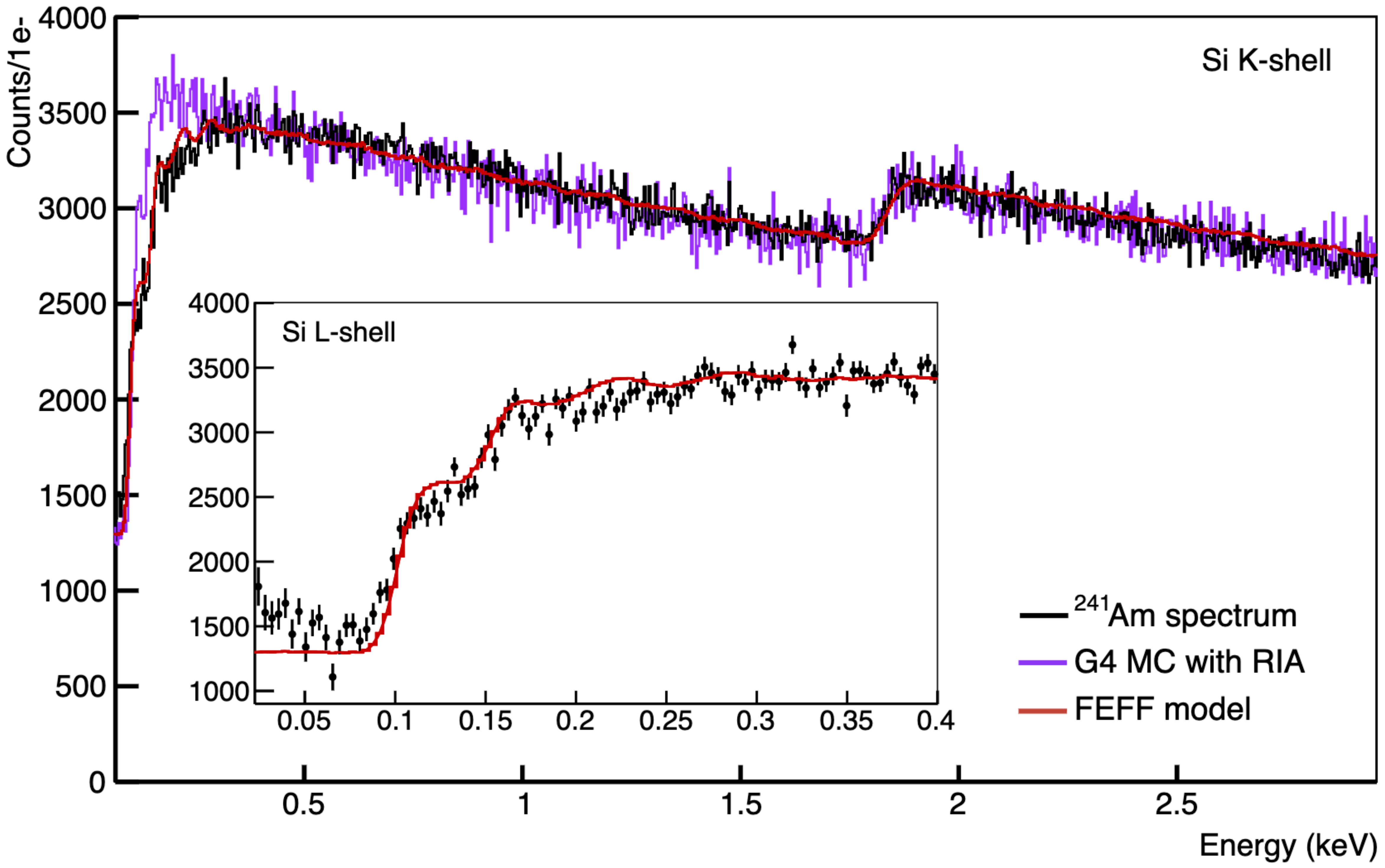


Details in Maria Martinez talk this morning

DAMIC-M progress

Calibrations : Different radioactive sources

- ^{241}Am → Calibration of the low-energy Compton background (PRL 106 (2022) 092001)
  - Understanding Gamma scattering with electrons bound in semiconductors
  - First measurement of Compton scattering on valence e$^-$ below 100 eV
  - Use full QM calculation (FEFF model) better agreement than relativistic impulse approximation (RIA)



DAMIC-M progress

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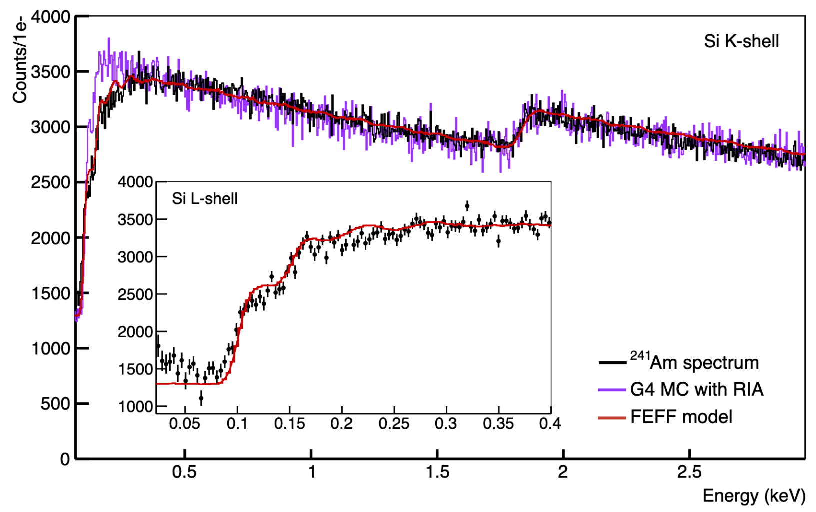

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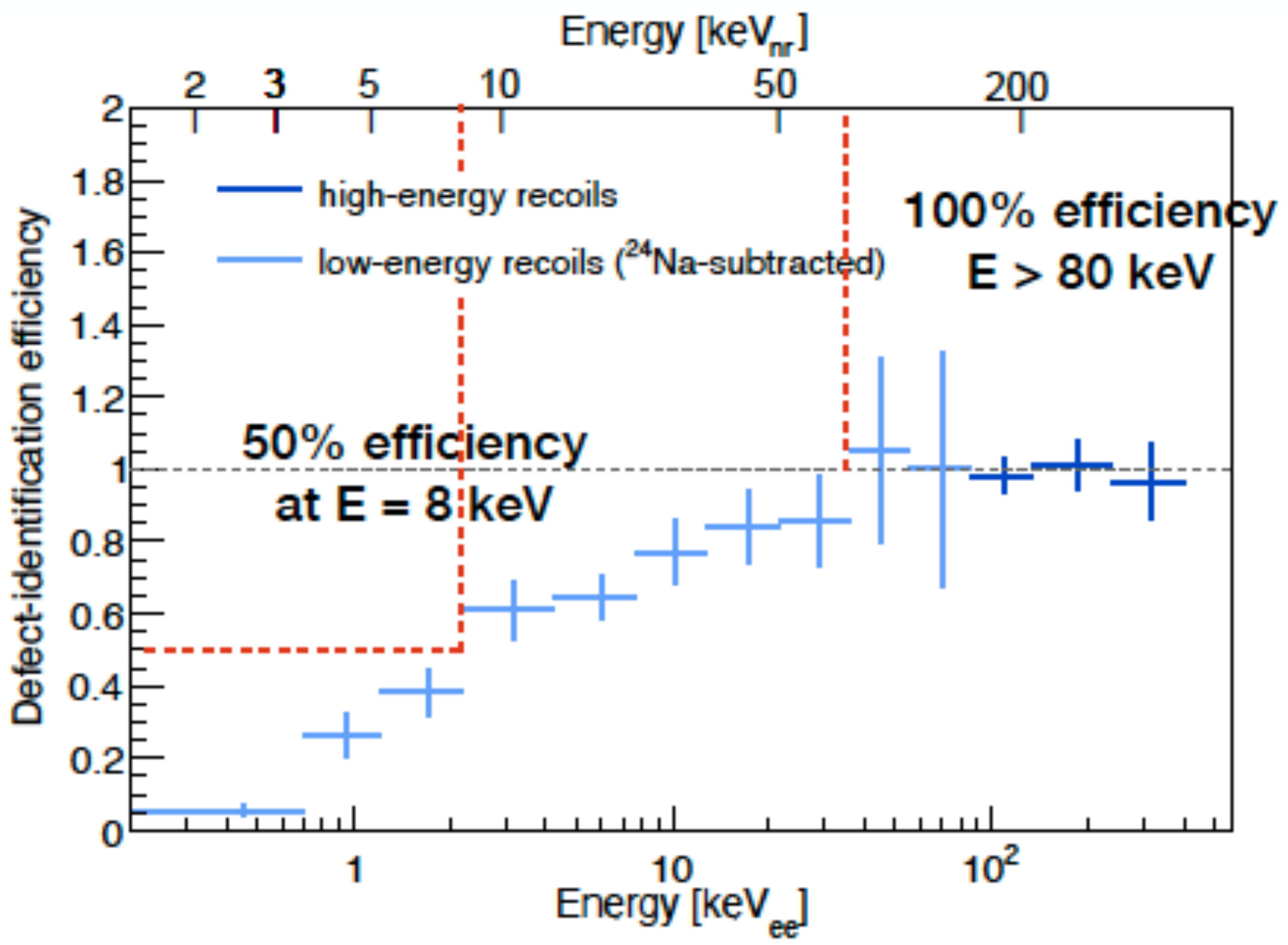
- ^{241}Am ^{9}Be → Distinguishing nuclear recoils signals from electronic recoil backgrounds (arXiv:2309.07869)
  - Induced defect by neutron source → NR dislocates atoms from the crystal lattice, stable for at least 12h
  - 0.1% of ER with E < 85 keV are spatially correlated with a defect. 50% efficiency defect identification at 8 keV.
  - could enhance the sensitivity of future CCD experiments → Still optimize the thermal stimulation strategy, explore optical stimulation, etc



DAMIC-M p

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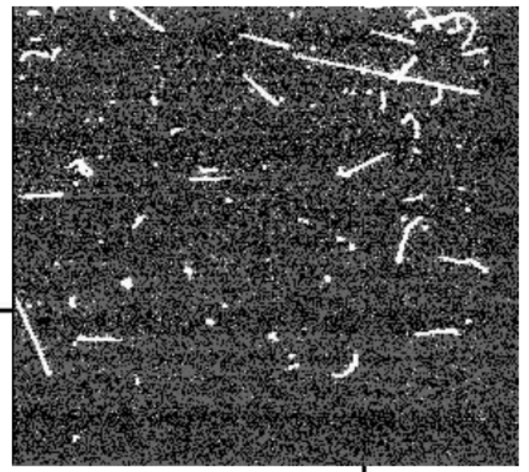
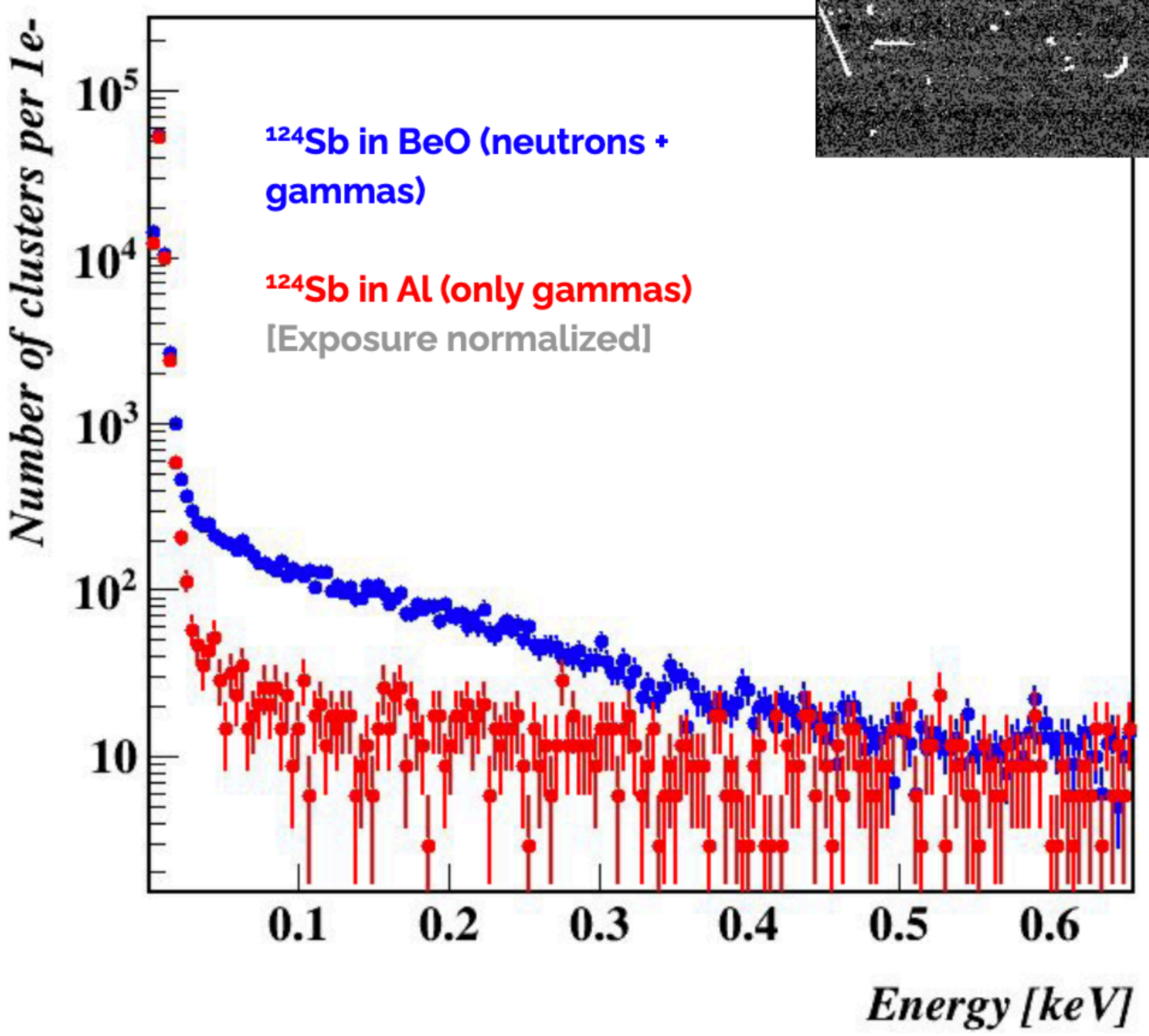
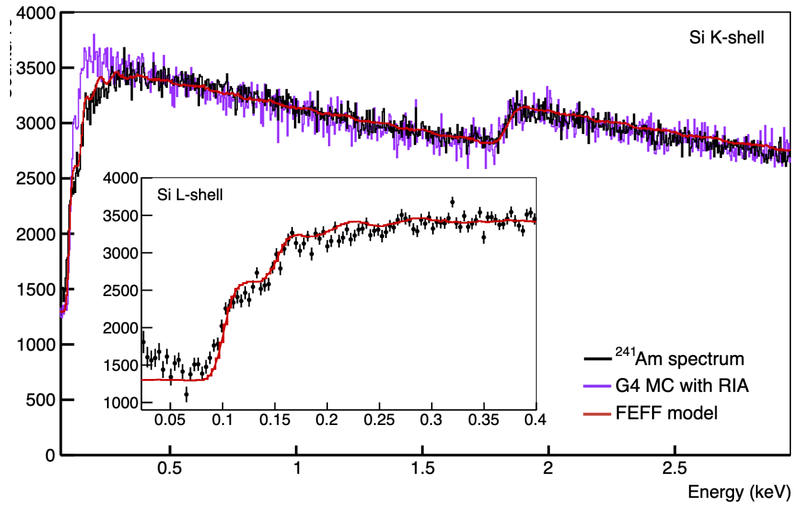
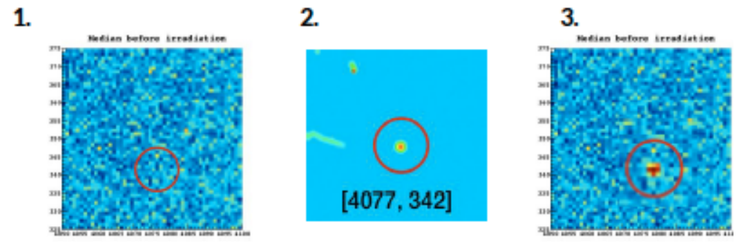
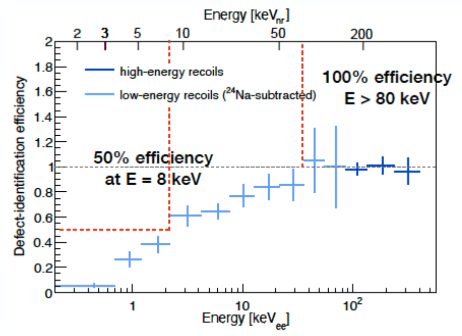
- ^{124}**Sb**/^{9}**BeO**-^{124}**Sb/Al** → Ionisation efficiency of nuclear recoils - Final results will be published soon (previous Phys. Rev. D 94, 082007 (2016))
  - Photoneutron source used to produce mono-energetic neutrons (~23 keV neutrons)
  - **GEANT4** and **MCNP** simulations were used to generate the nuclear recoil spectrum.
  - Measured ionization spectrum and simulated nuclear recoil spectrum were analyzed to produce the ionization efficiency down to > ~ 18 eV ionization energy

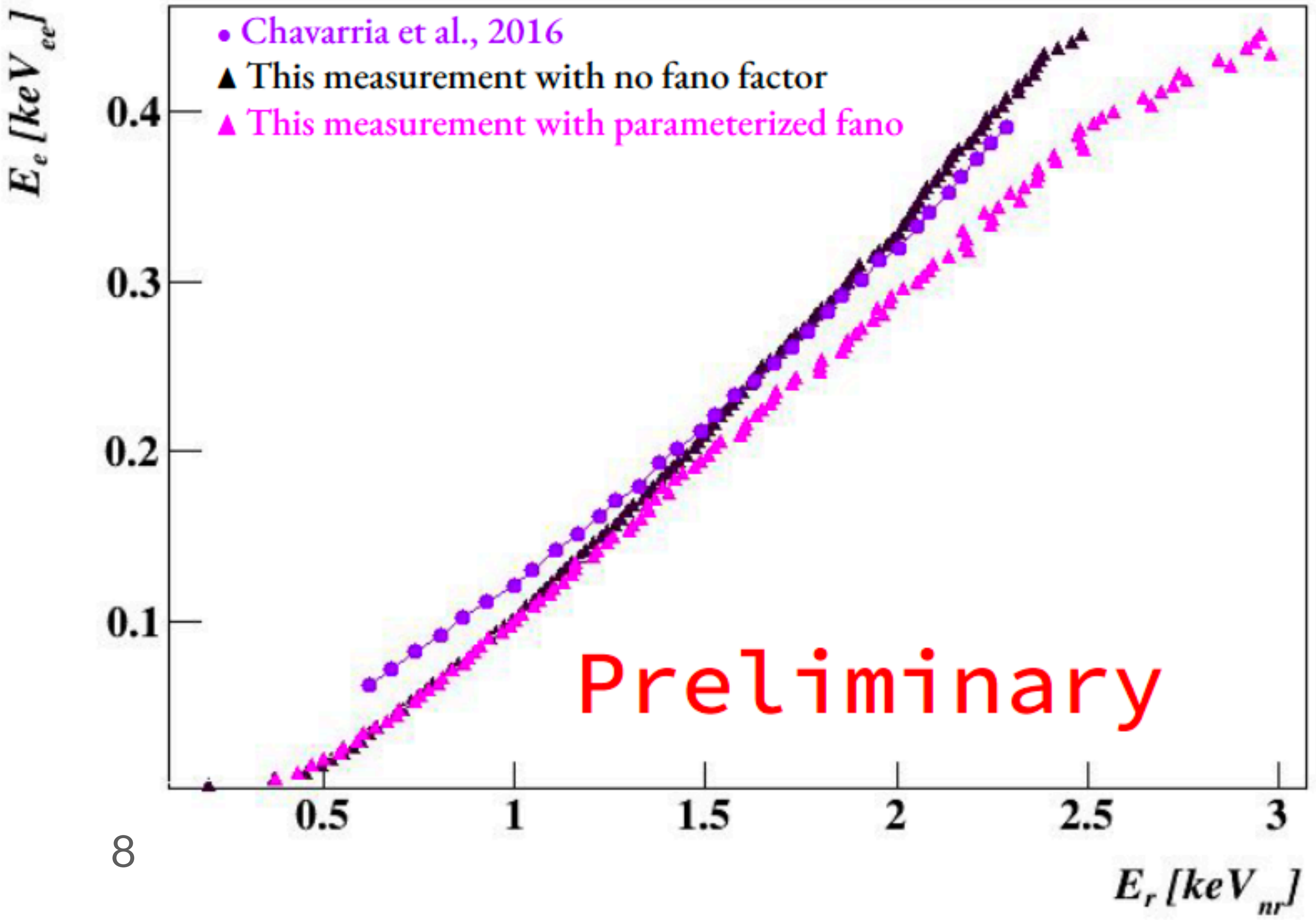








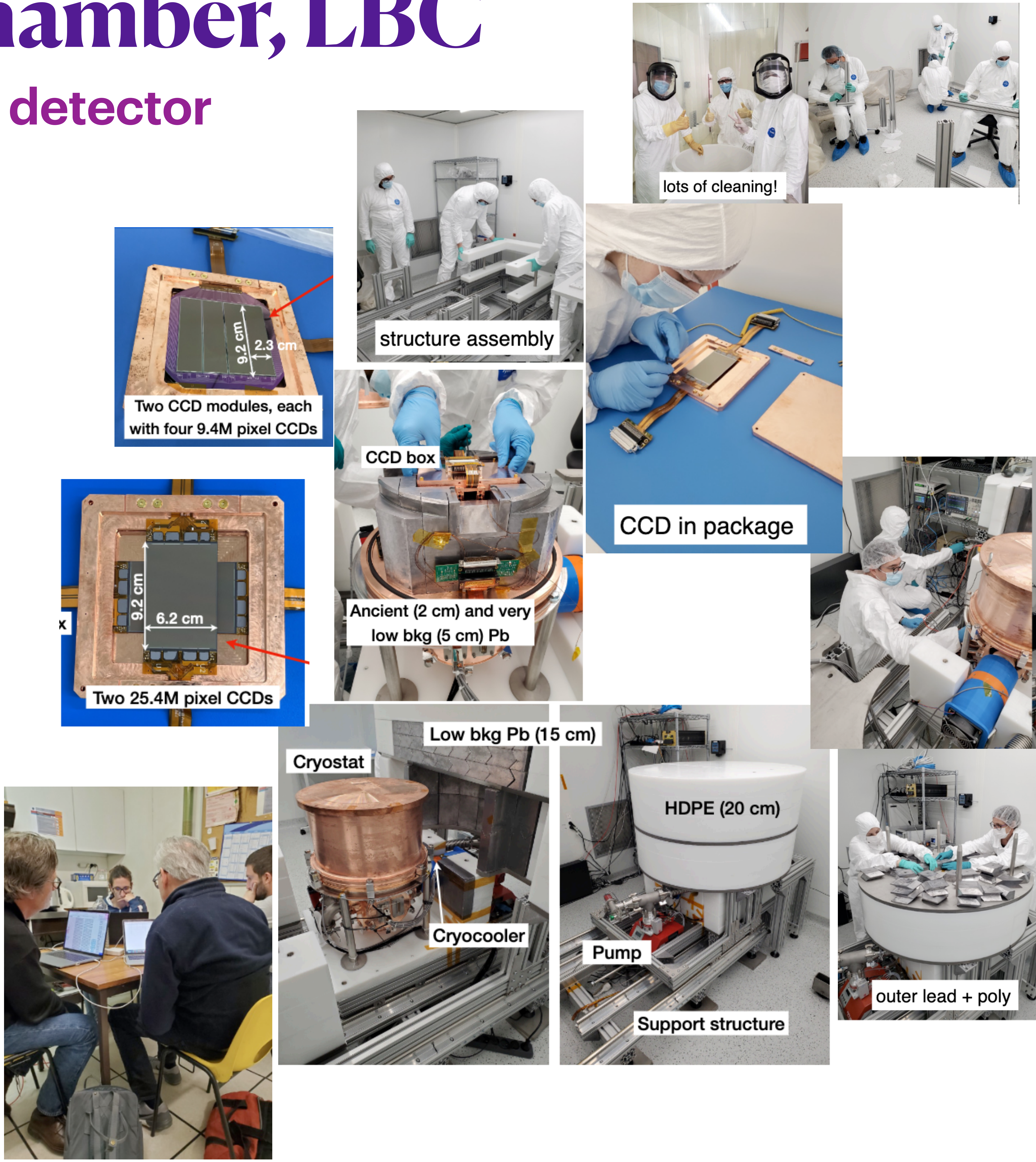




Low Background Chamber, LBC

A DAMIC-M prototype/test detector

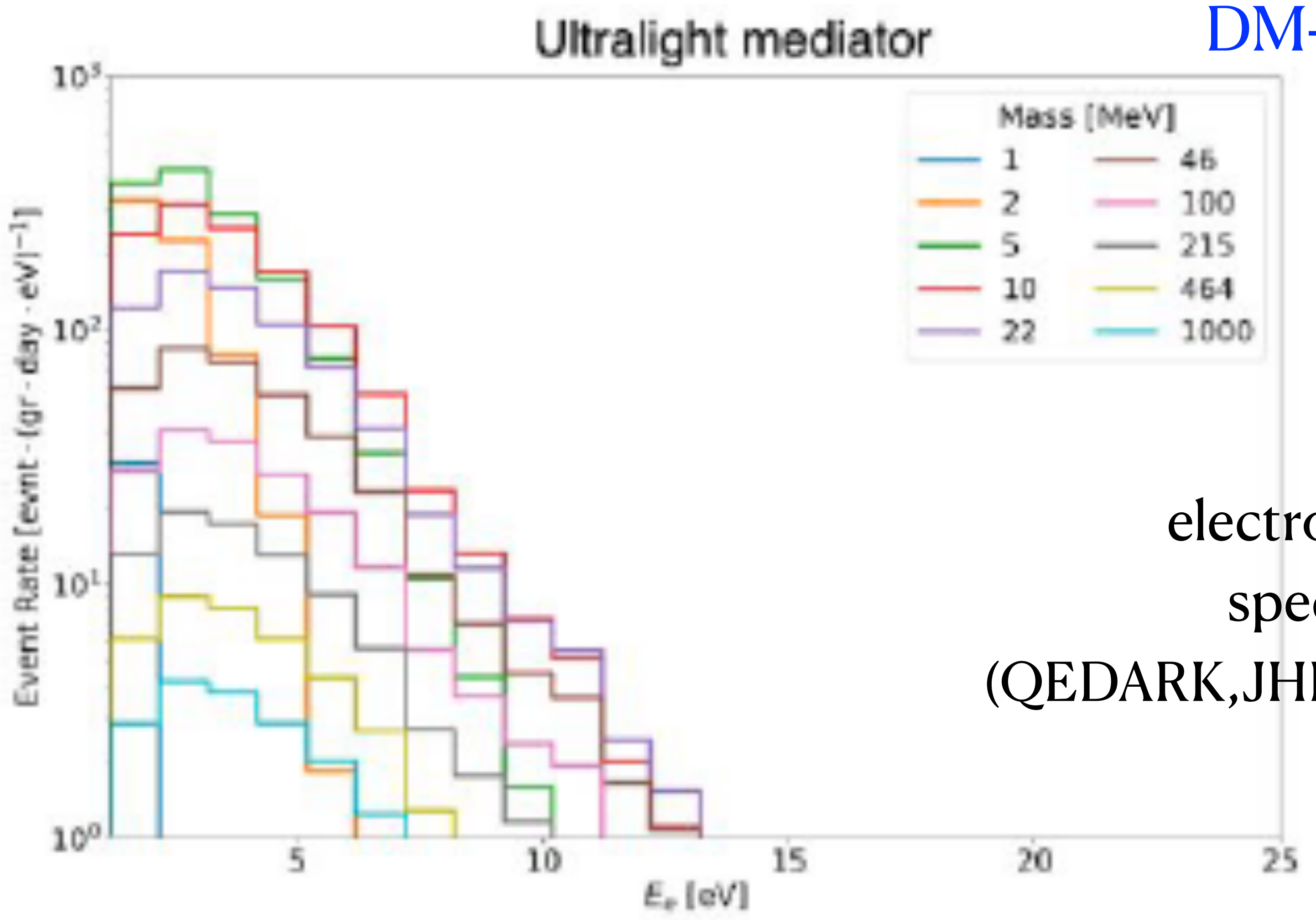
- A low background chamber (~10 dru) apparatus is already operating at the LSM since February 2022
- **Low background studies** (materials, cleaning procedures, surface vs bulk, etc.),
- **Characterisation of CCDs** in low background environment (with a special attention to dark current and noise) and other DAMIC-M components
  - **Test of other subsystems** (CCD controller and electronics, slow control, DAQ software, data transfer and data quality monitoring)
  - Integration/operation of DAMIC-M electronics
- **First Science Data**:
  - DM-electron scattering search
  - daily modulation search



Low Background Chamber, LBC

First science results DM-e scattering (PhysRevLett.130.171003)

- Data collected during LBC commissioning with 6kx4k CCDs and 10x10 bin. Dark current sufficiently low for a first DM search
- 3.68 x 10^8 pixels selected -> Total exposure time of 85.23 g days (SR1,SR2)



DM-e Cross section

DM galactic halo

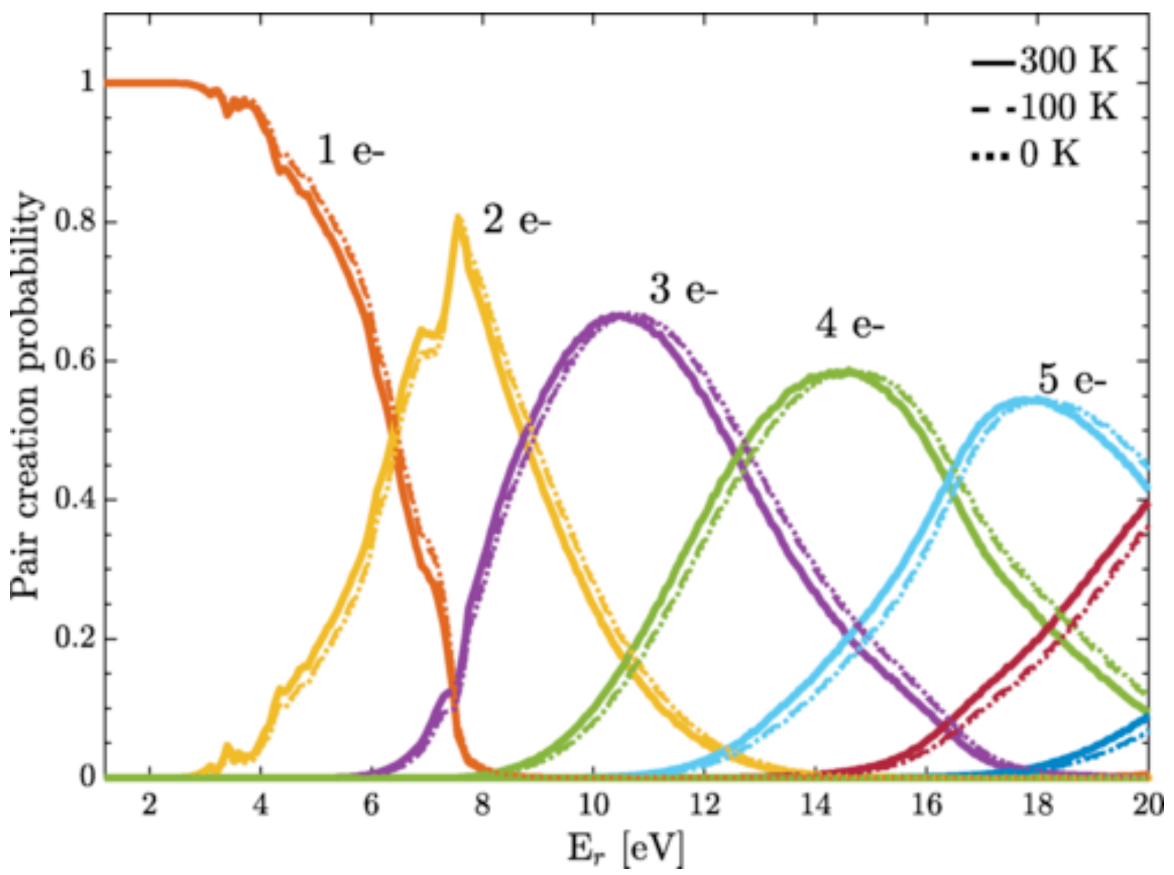
DM form factor

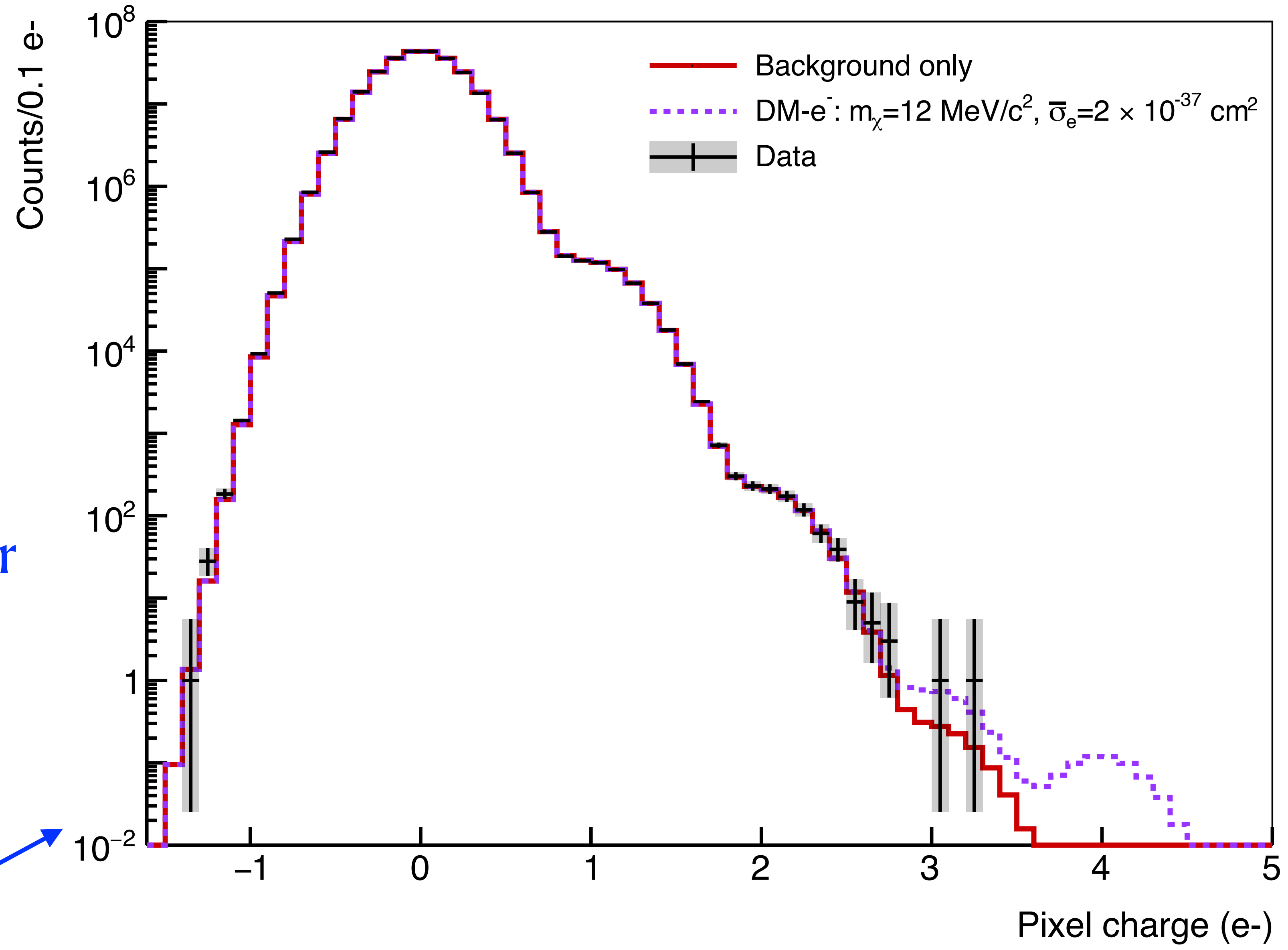
$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2} \eta(m_\chi, q, E_e) \, |f_{DM}(q)|^2 \, |f_c(q, E_e)|^2$$

Crystal form factor

electron recoil spectrum (QEDARK,JHEP05(2016)046))

from recoil energy to ionization charge Phys. Rev. D 102, 063026





Likelihood function for fit to data including charge resolution

$$F(p \,|\, m_\chi, \bar{\sigma}_e, \epsilon_i, \lambda_i, \sigma_{\text{res}}) = \sum_{i=0}^{N_{\text{pix}}} N_{\text{im}} \sum_{n_q=0}^{\infty} \left[\sum_{j=0}^{n_q} S(j \,|\, m_\chi, \bar{\sigma}_e, \epsilon_i) \text{Pois}(n_q - j \,|\, \lambda_i - \lambda_{S,i}) \right] \text{Gaus}(p \,|\, n_q, \sigma_{\text{res}}) \, .$$

Account for the diffusion of the ionization

Add background model (Poisson dark current)

Readout noise

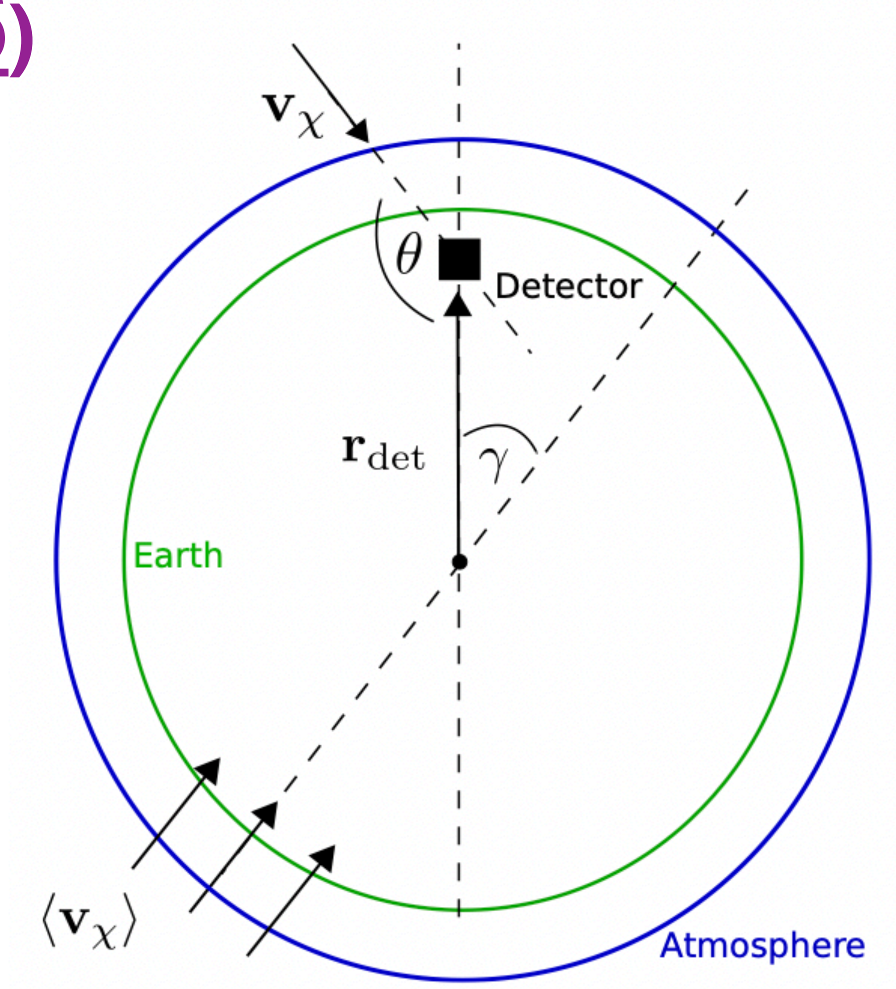
From point-like charge deposit to CCD pixel cluster

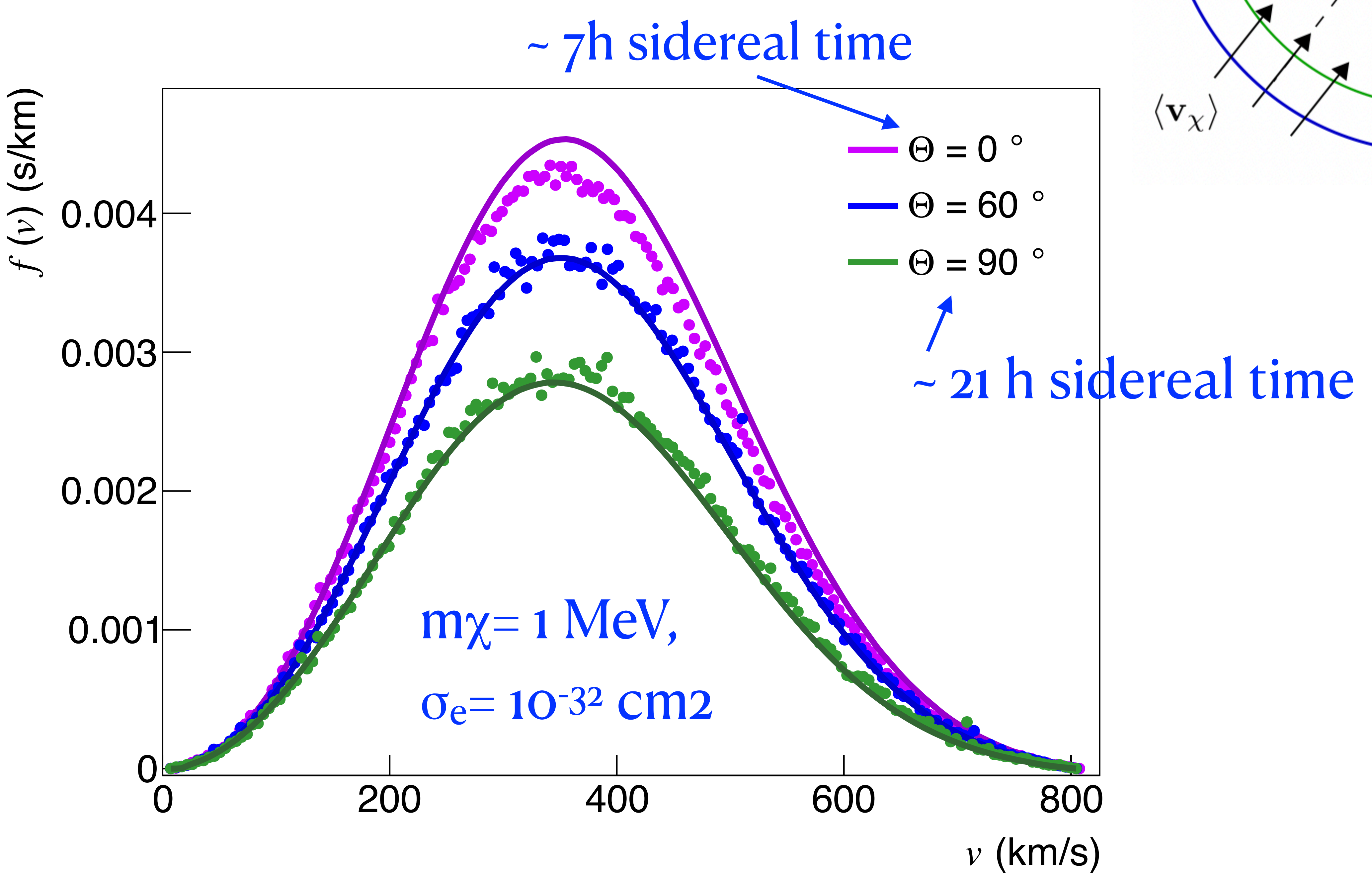
Low Background Chamber, LBC

First Results:Daily modulation (Phys. Rev. Lett. 132, 101006)

- Current cross section constraints for masses < 3 MeV allow for **significant DM interactions** while passing through Earth.
- Modify the DM flux and velocity distribution at the detector, resulting in **daily modulation of the DM** signal
- $$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2} \left[\int \frac{f(\mathbf{v},t)}{\mathrm{v}} d^3\mathrm{v} \right] |F_{\mathrm{DM}}(q)|^2 \, |f_c(q, E_e)|^2$$
- DAMIC-M expected background should be uniform with time.
  - The non-observance of periodicity in the signal will improve the upper limits set for the 1e-
  - The 8779 images used before provide a measurement of the charge distribution every ~10 min, allowing for a meaningful search for a daily modulation

- 0: DM wind from above
- 90: comes from the horizon, ~ SHM
- 180: DM wind goes through the Earth



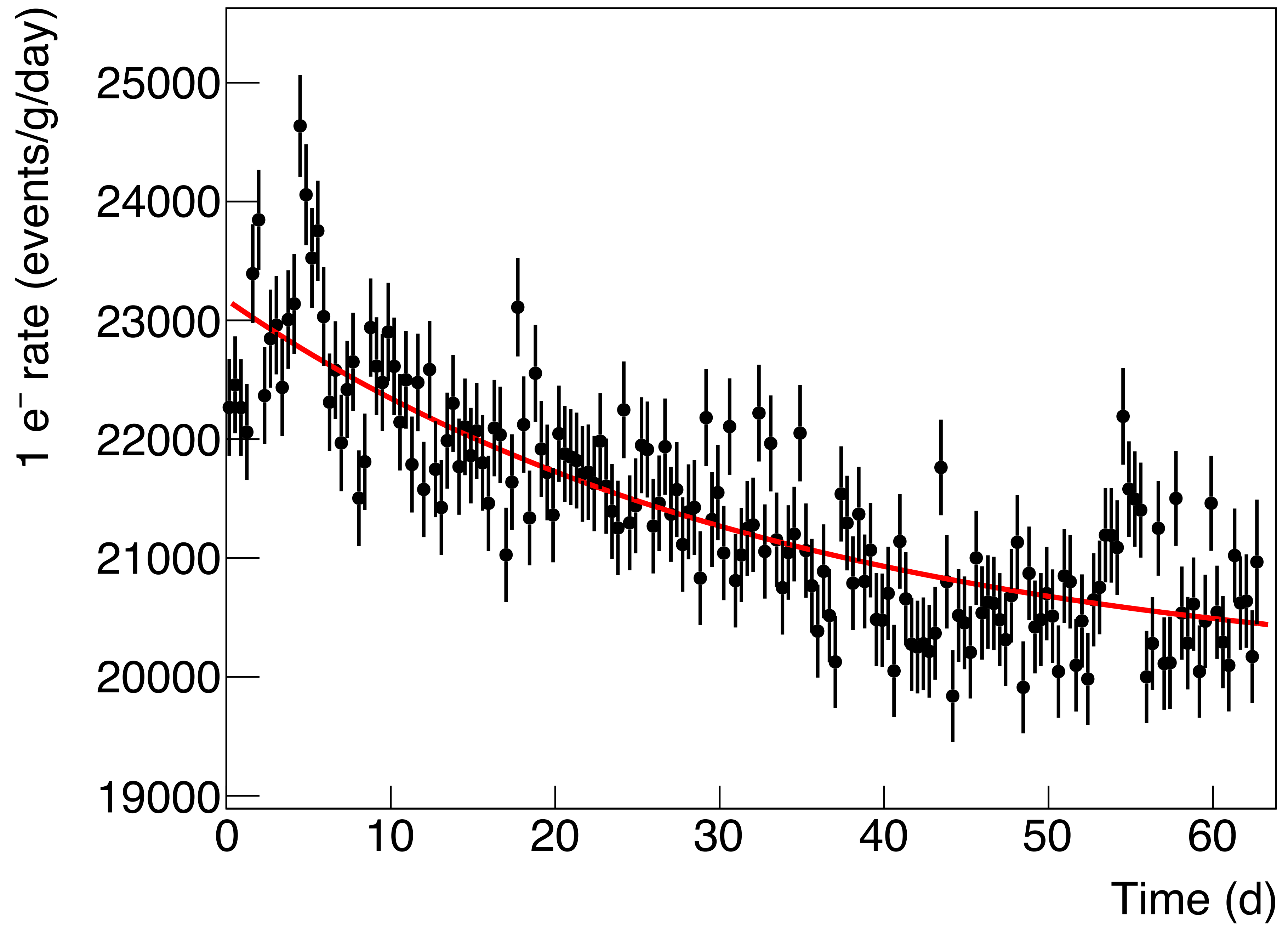


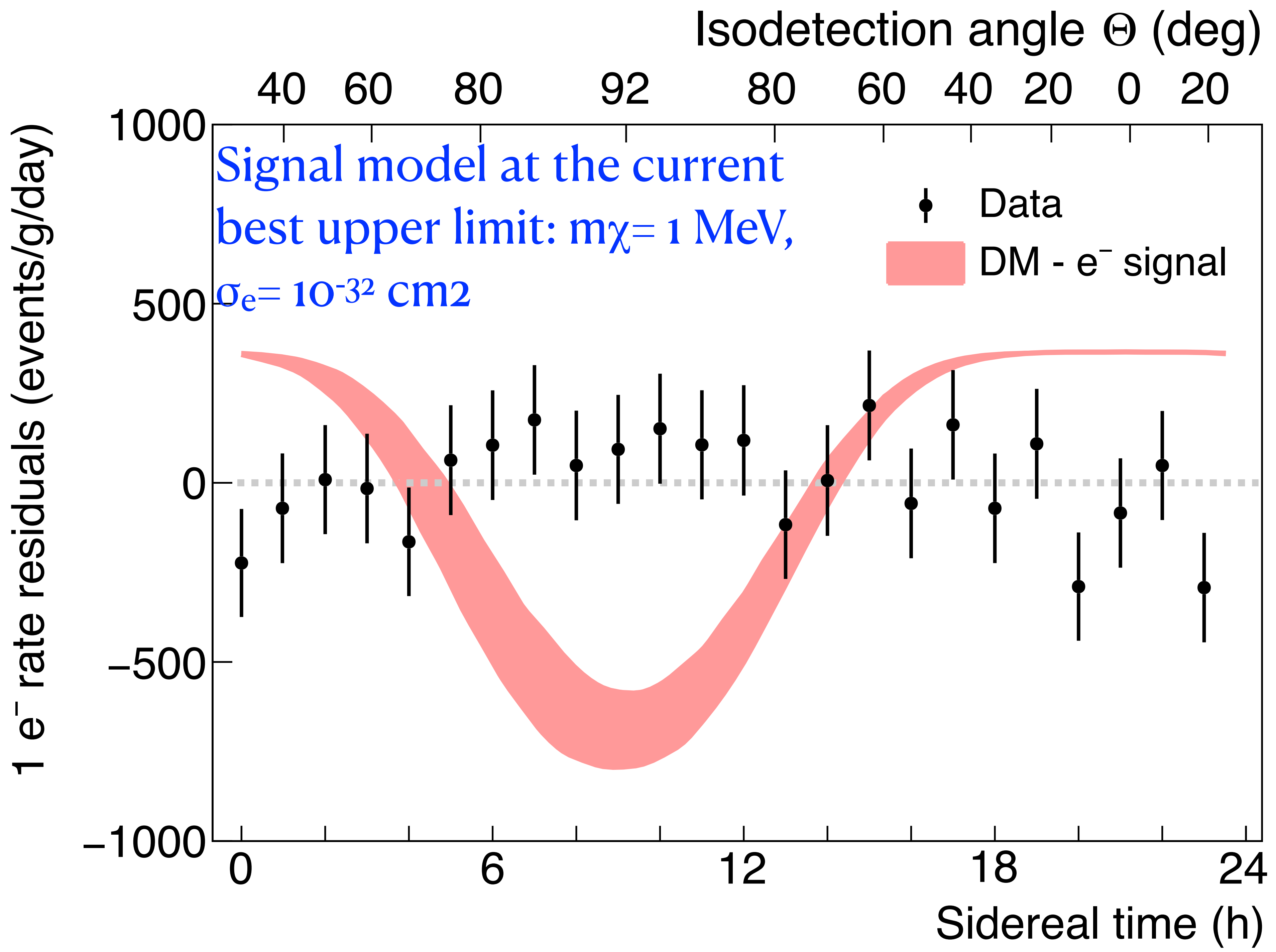
We use a modified version of VERNE (solid line; Lantero-Barreda and Kavanagh) for fast calculation of the DM speed distribution, in excellent agreement with the 3D DAMASCUS (dots) simulation

Low Background Chamber, LBC

First Results: Daily modulation (Phys. Rev. Lett. 132, 101006)

- A **likelihood fit to dat**a is performed using F(ti|θ) for the mass parameter space.
- The fit finds no preference for signal at any mass.
- The correspondent exclusion limits are obtained with a 90% C.L.





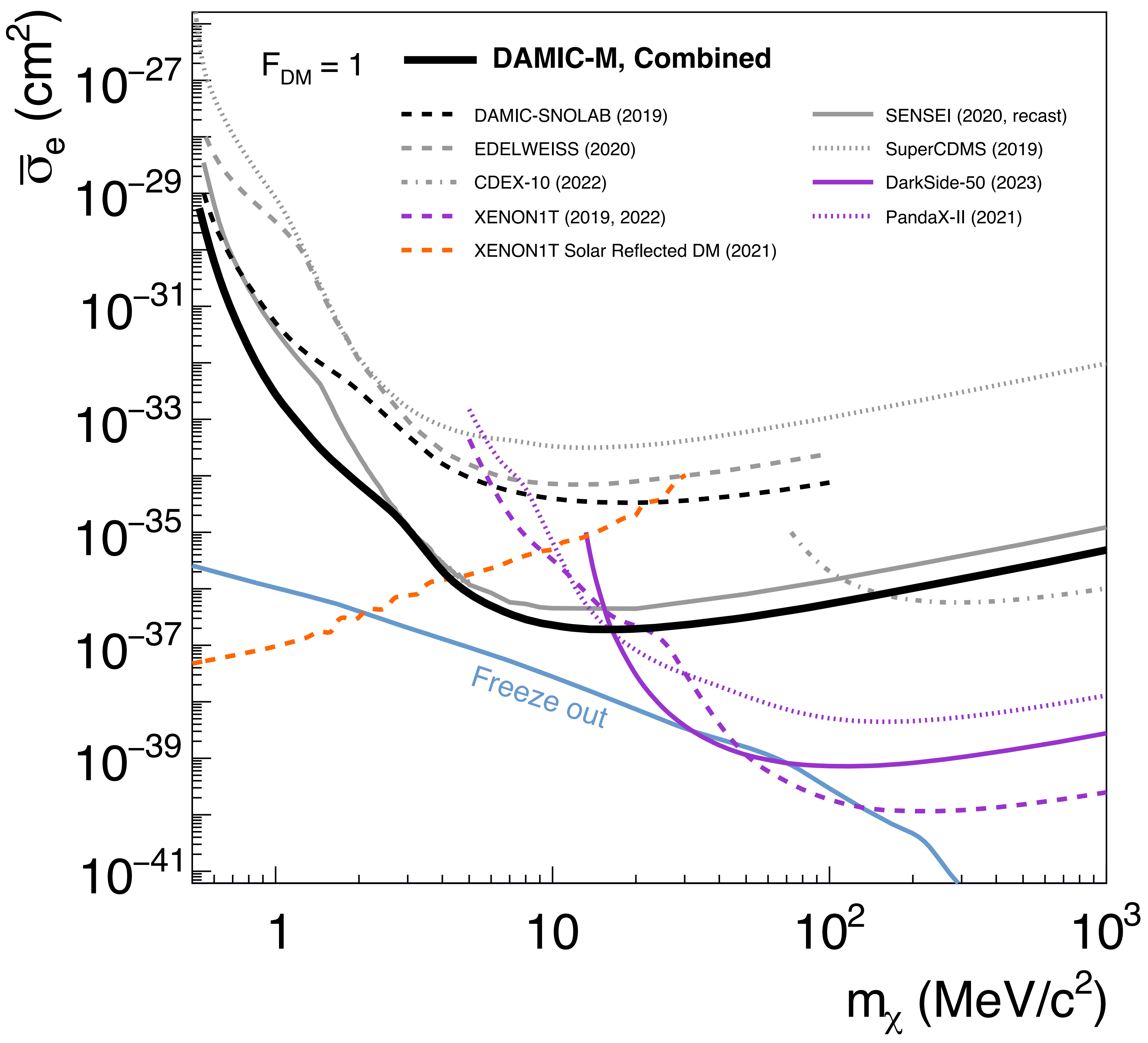
$$F(t_i|\theta) = \frac{1}{t_{\exp} m_{\mathrm{pix}}} \sum_{j=0}^{1} \mathrm{Pois}(1-j|\lambda(t_i))\, S(j|m_\chi, \bar{\sigma}_e, t_i)$$

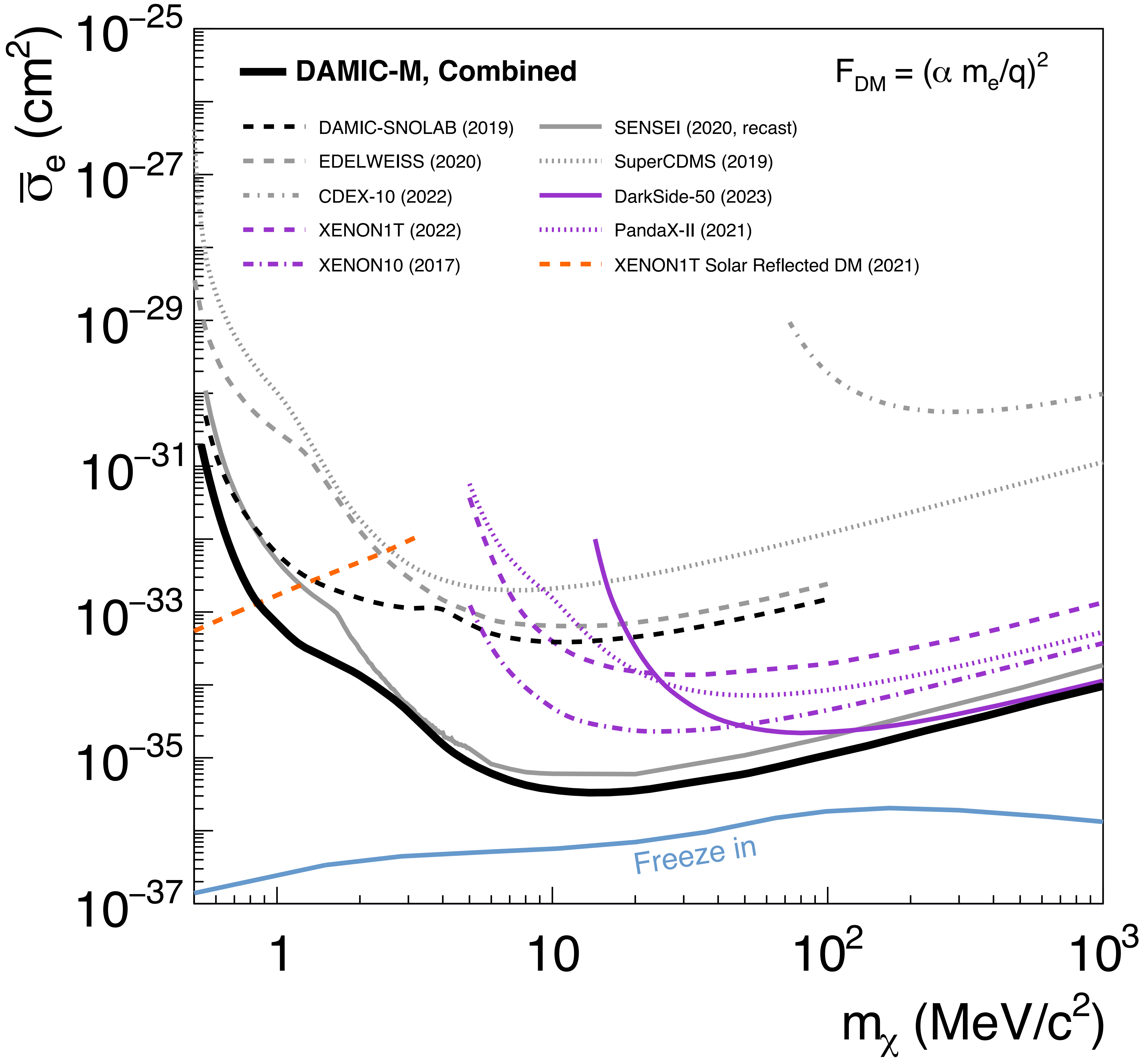
Time dependent background model

Signal time dependent

Low Background Chamber, LBC

First Results:Daily modulation (Phys. Rev. Lett. 132, 101006)





Combined results The daily modulation analysis improves our PRL limits below 3 MeV by up to 2 orders of magnitude

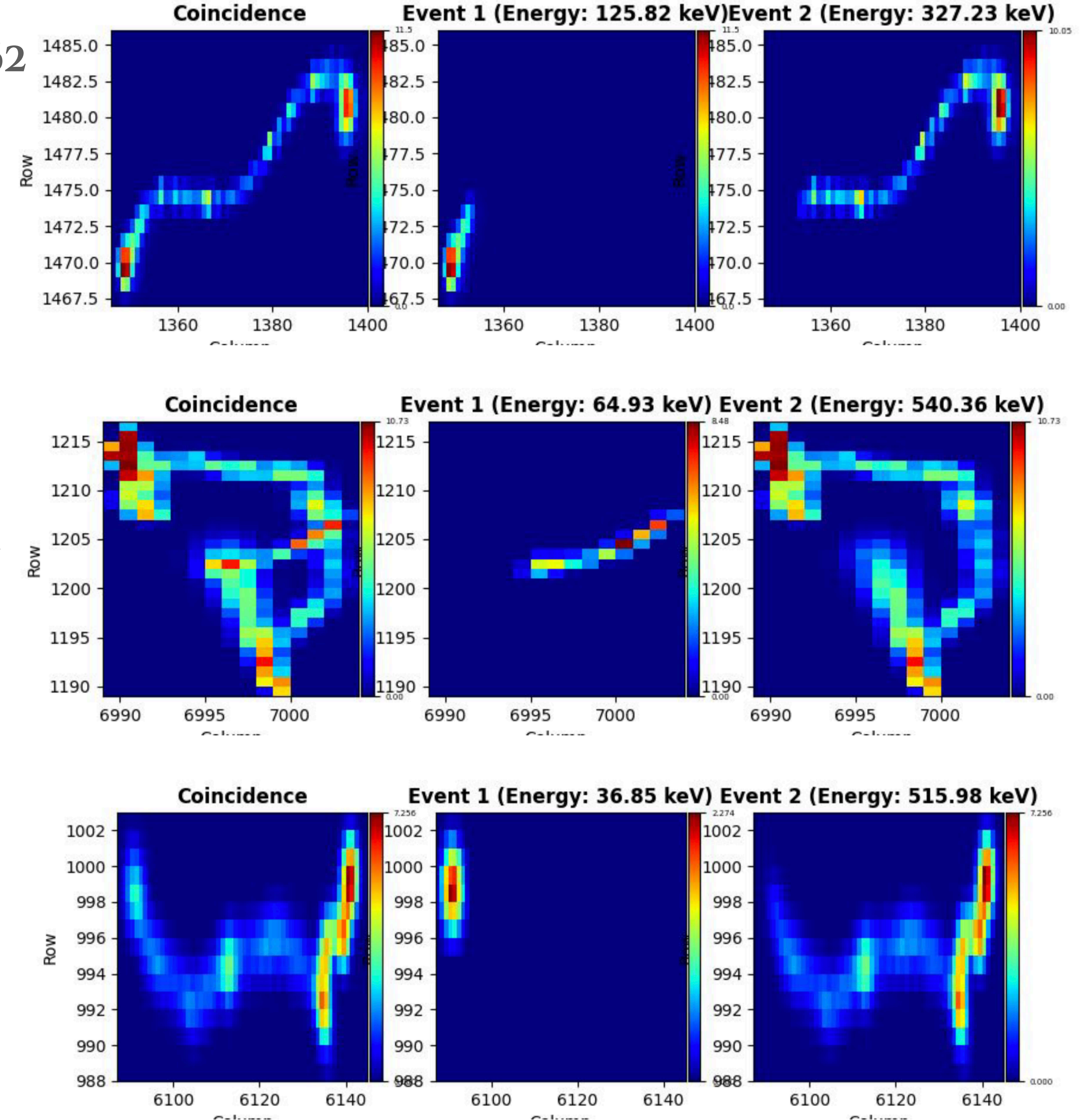
Other initiatives with CCDs

Skipper CCDs Radiopurity mEasurEmeNt sERvice (SCREENER)

- The main goal of the CCD setup at LCS is to characterise radiogenic and cosmogenic backgrounds
- For DAMIC-M Experiments but as installation of radiopurity for LSC: highly sensitive to certain radioisotopes as: ^{32}Si, ^{238}U,^{232}Th and ^{210}Pb using coincidence analysis and Energy spectrum
  - Upper limit is orders of magnitude better than the sensitivity obtained by direct assay techniques

^{32}Si β1-β2

^{210}Pb β_1-β_2



Decay Sequence	$t_{1/2}$	Q-value
$^{210}\text{Pb} \longrightarrow {}^{210}\text{Bi} + \beta^- + \text{IC}/\gamma$	22.3 y	63.5 keV
$^{210}\text{Bi} \longrightarrow {}^{210}\text{Po} + \beta^-$	5.01 d	1.16 MeV
$^{210}\text{Po} \longrightarrow {}^{206}\text{Po (stable)} + \alpha$	138 d	5.41 MeV

Decay Sequence	$t_{1/2}$	Q-value
$^{32}\text{Si} \longrightarrow {}^{32}\text{P} + \beta^-$	150 y	225 keV
$^{32}\text{P} \longrightarrow {}^{32}\text{S (stable)} + \beta^-$	14.3 d	1.71 MeV

Decay	$t_{1/2}$	Q-value
$^{3}\text{H} \longrightarrow {}^{3}\text{He} + \beta^-$	12.3 y	18.6 keV

Limits on radioactive contaminants	
^{210}Pb	< 160 µBq/kg
^{32}Si	140±30 µBq/kg
^{238}U	< 11 µBq/kg
^{232}Th	< 7.3 µBq/kg

Journal of Instrumentation, Volume 16, June 2021

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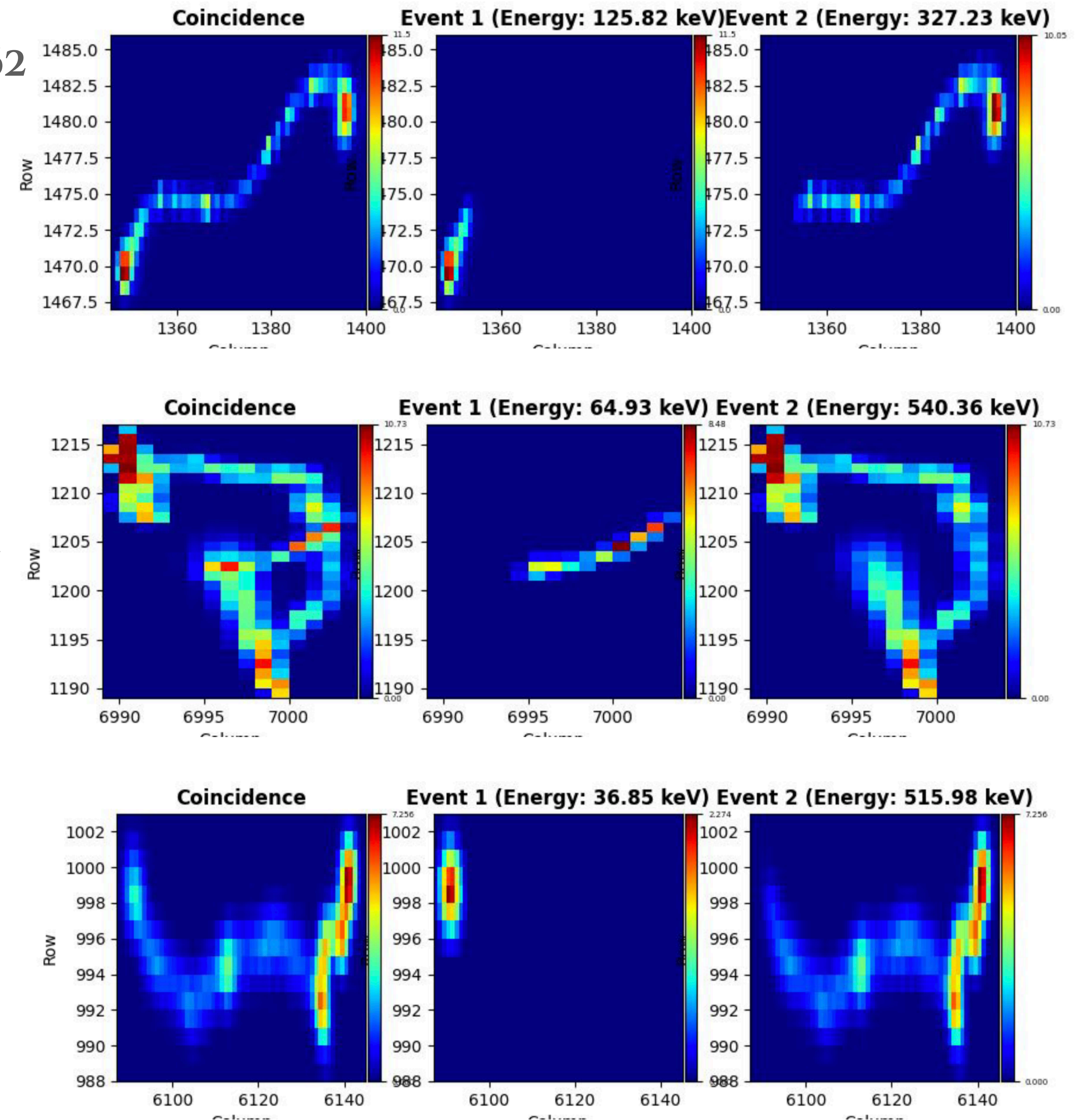

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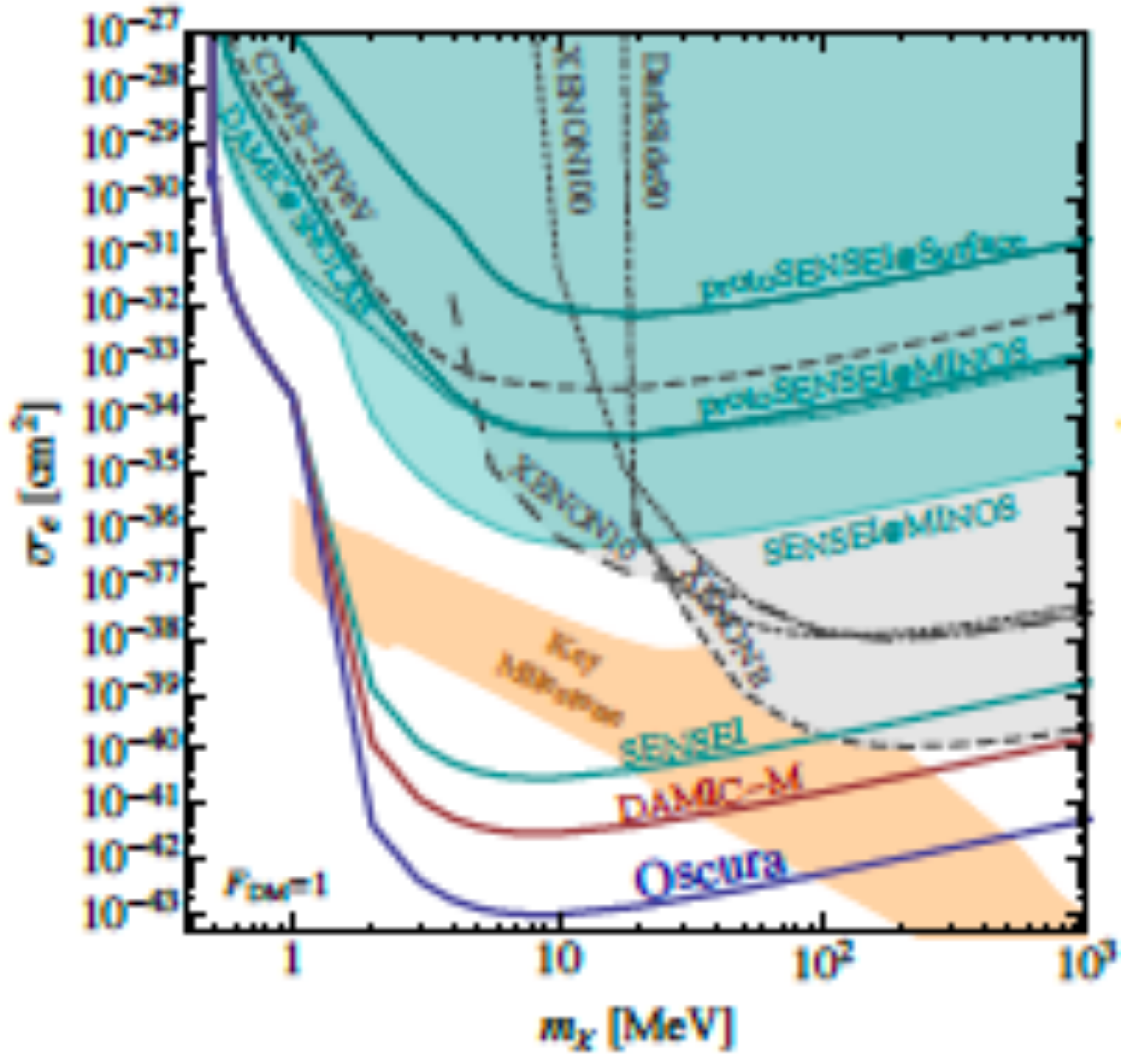
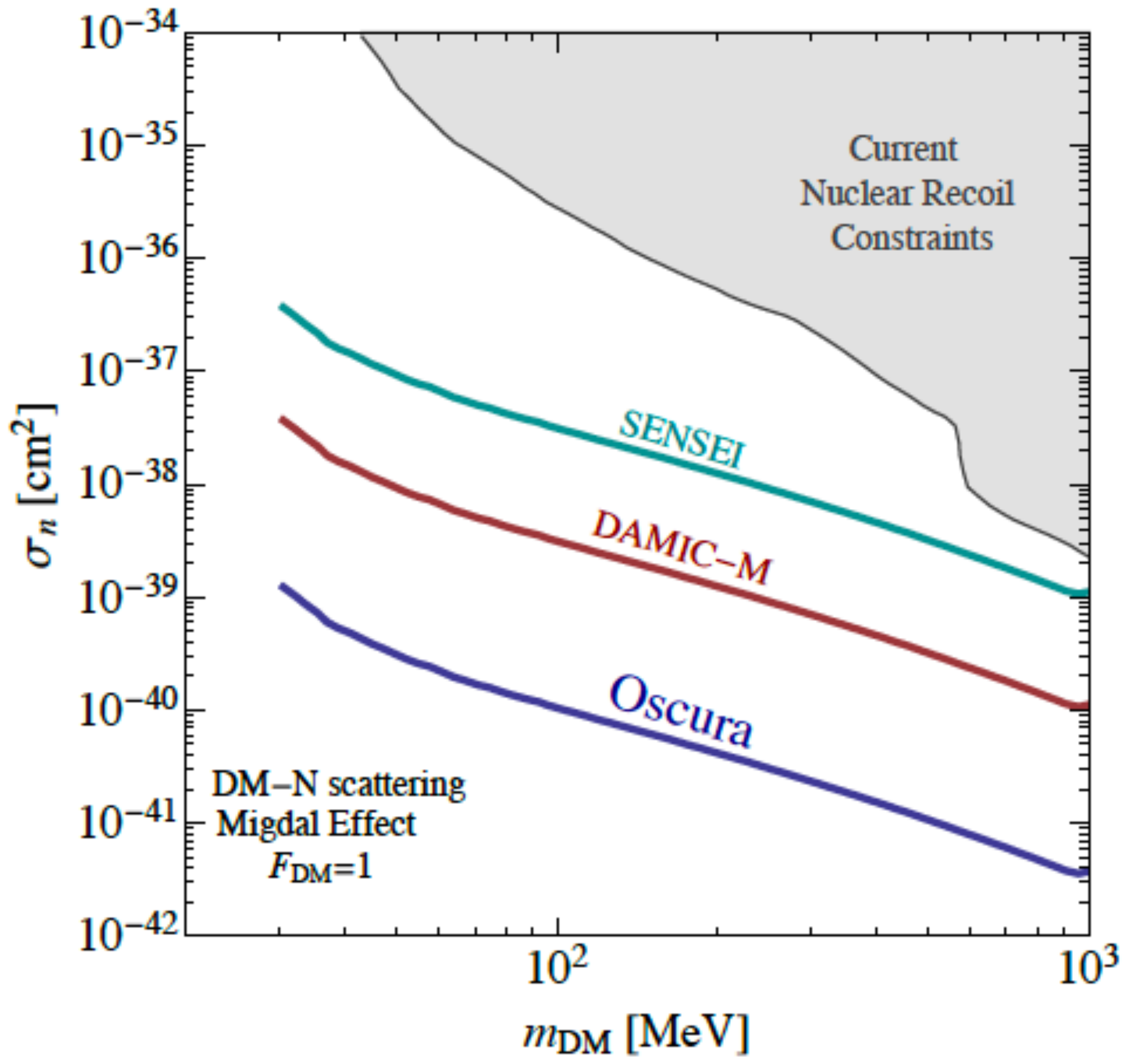
Other initiatives with CCDs

What is next with skipper CCDs

Experiment	Mass(kg)	#CCDs	Radiation bckg [dru]	nstrument bkgc [e-/pix/day]	Commissioninig
SENSEI @MINOS	~0.002	1	3400	1.6x10-4	Late-2019
DAMIC @SNOLAB	~0.02	2 (6k x 4k)	10	3 10-3	Late-2021
LBC (DAMIC-M)	~0.02	2 (6k x 4k) (8 6k x 1.5k)	~10	3 10-3	Early-2022
SENSEI-100	~0.1	50	~10 (goal)		Mid-2022
DAMIC-M	~0.7	208	~0.1 (goal)		Late-2024
Oscura	~10	20000	~0.01 (goal)	1.10-6(goal)	~2028



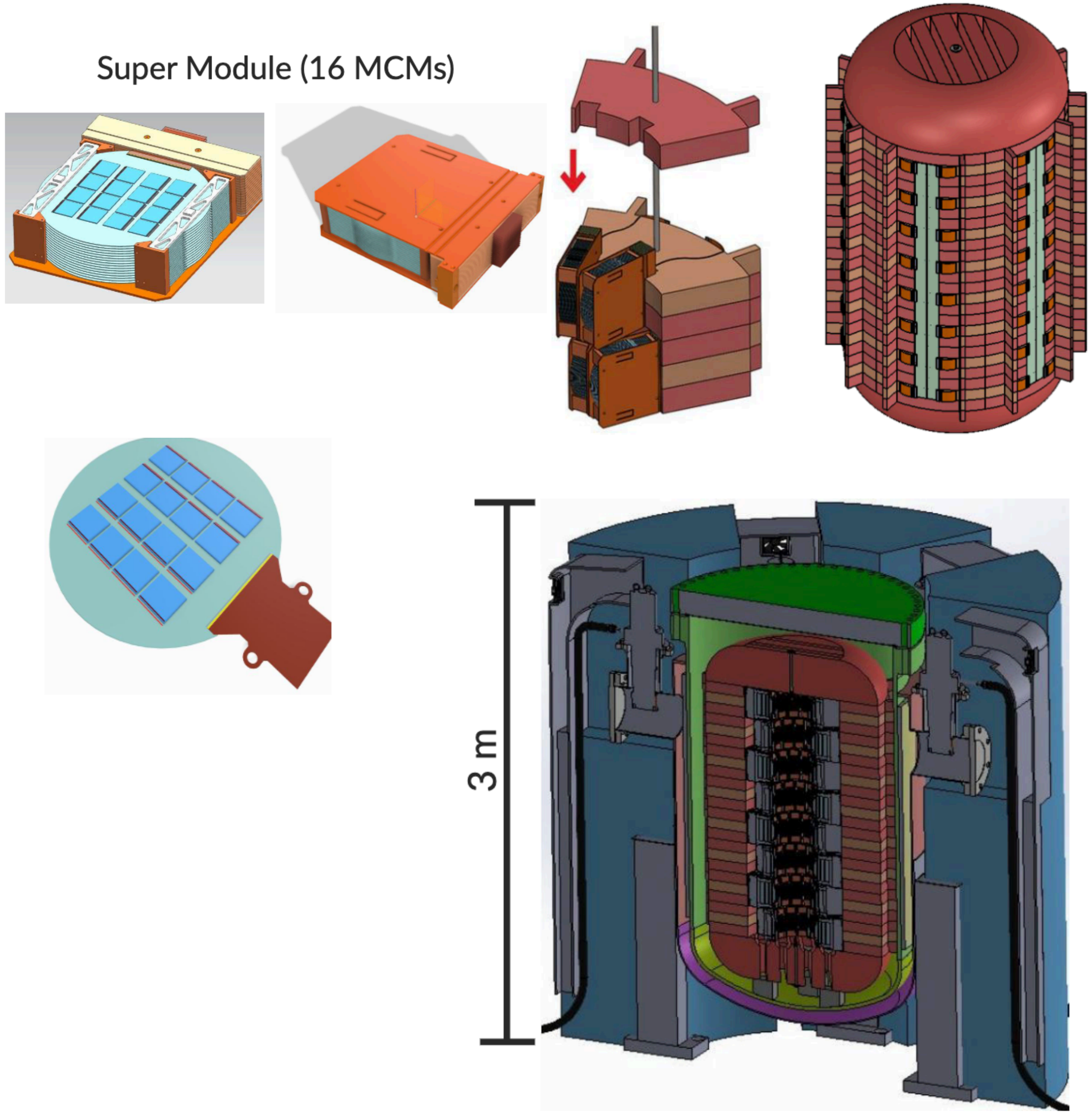


- DAMIC-M builds on existing efforts
  - The challenges are to increase mass (from 1s to 100s) while reducing the background (2 orders of magnitud)
- Oscura builds on existing efforts: DAMIC-M success essential for the Oscura program→ operating kg size detector, understanding of backgrounds, and dark curren
  - The challenges are to increase mass (from 100s to 10,000s CCDs) and to reduce the backgrounds (3 orders of magnitude) → Major R&D- >20,000 CCDs (smaller format), 10kg 20 Gpixels low noise electronics, multiplexing 10x lower background than DAMIC-M goal (0.01 dru)

Other initiatives with CCDs

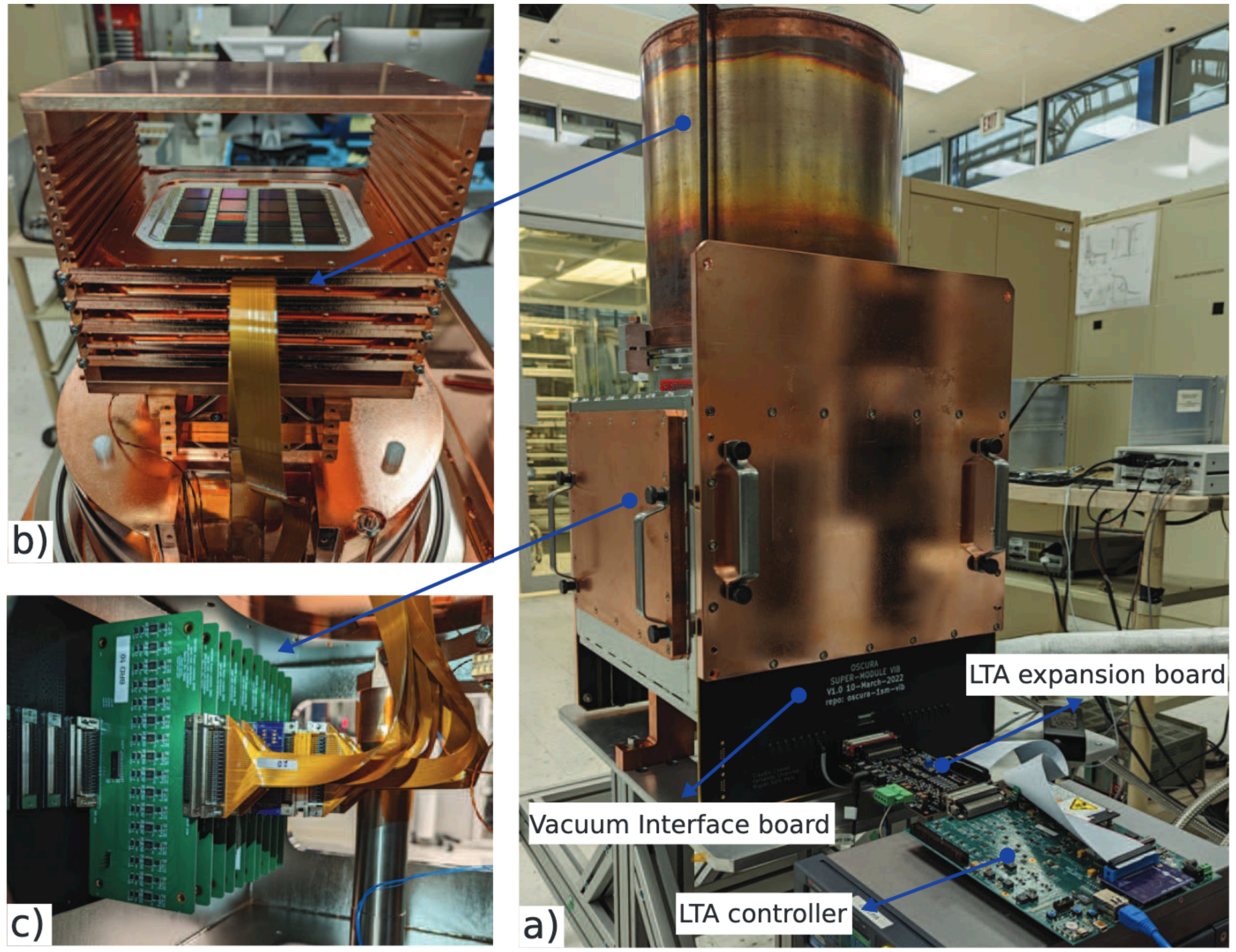
Future Experiments with CCDs: OSCURA (arXiv:2304.04401)

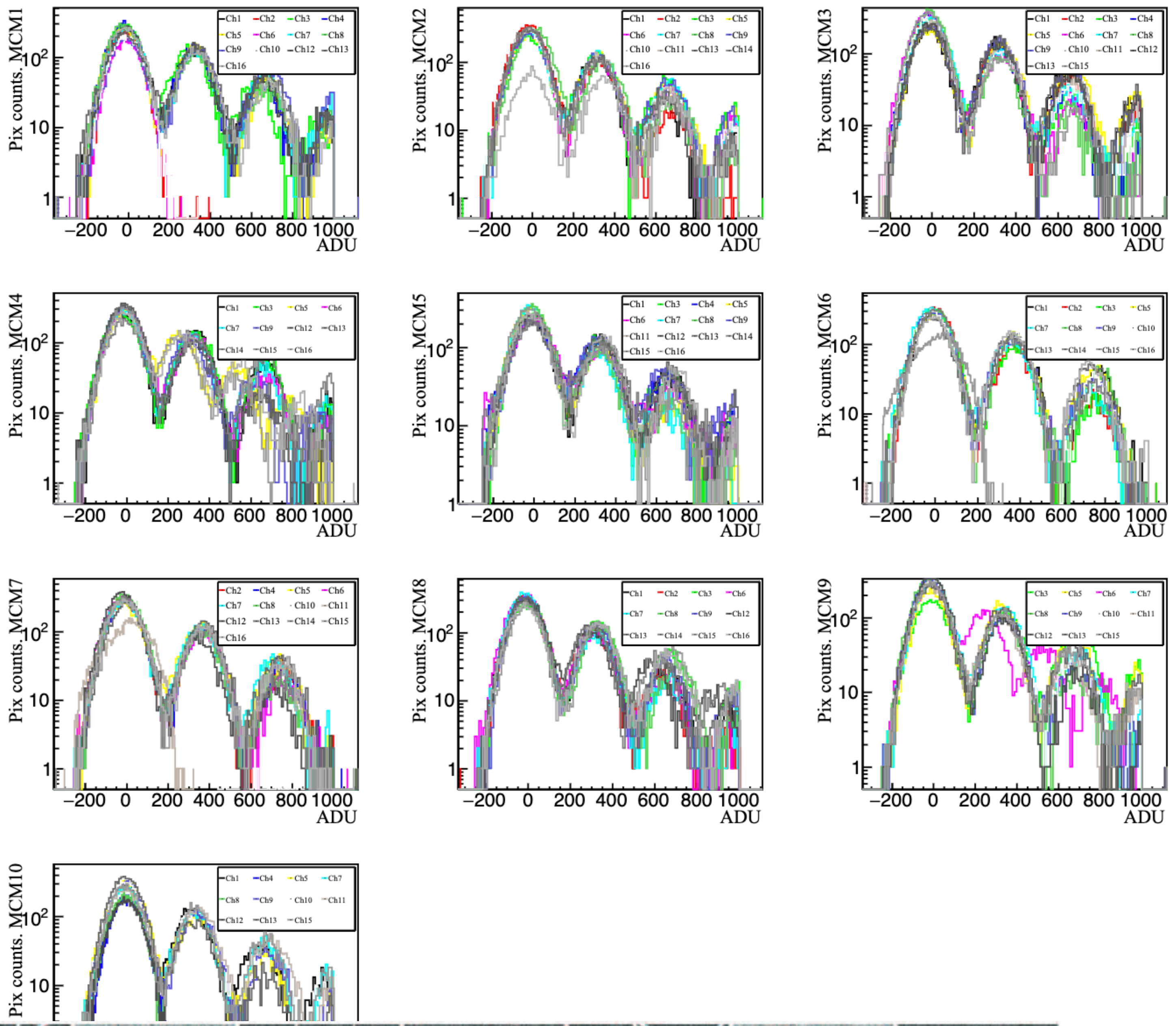
- Oscura conducted a major R&D
- **Mass production** of science-grade skipper-CCDs
- New **sensors packaging and cryogenics** for multi-kg detectors
  - In summer 2021 we received first batch of Oscura prototype skipper-CCDs (1278 x 1058 pix),
  - demonstrated the success of the fabrication
  - Operation in LN2 → Demonstrated stable operation
- New cold front-end electronics for thousands of readout channels
- Low radiation background design
  - isotopic contamination on front-end electronics, cables and components near the sensors
  - External backgrounds
    - Outer shield: lead, polyethylene
    - Inner shield: ancient lead and electroformed copper

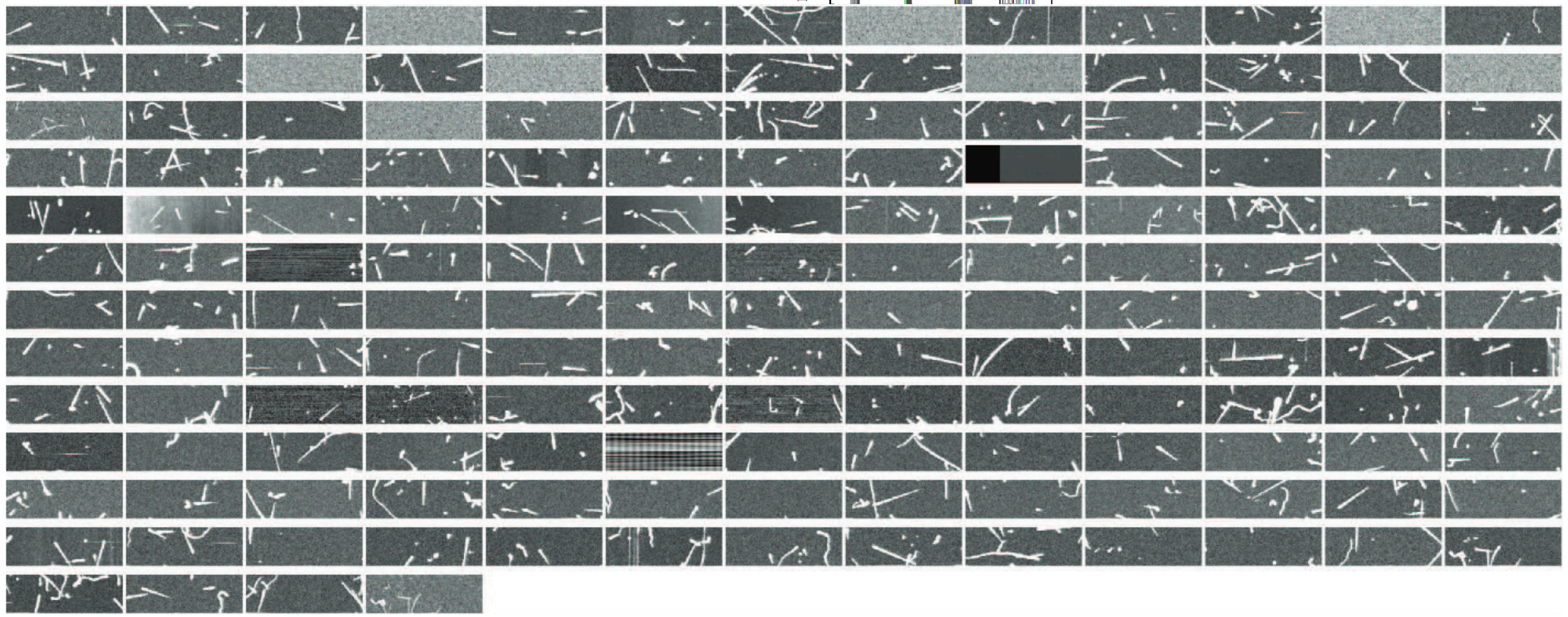


Other initiatives with CCDs

Future Experiments with CCDs: OSCURA (arXiv:2304.04401)





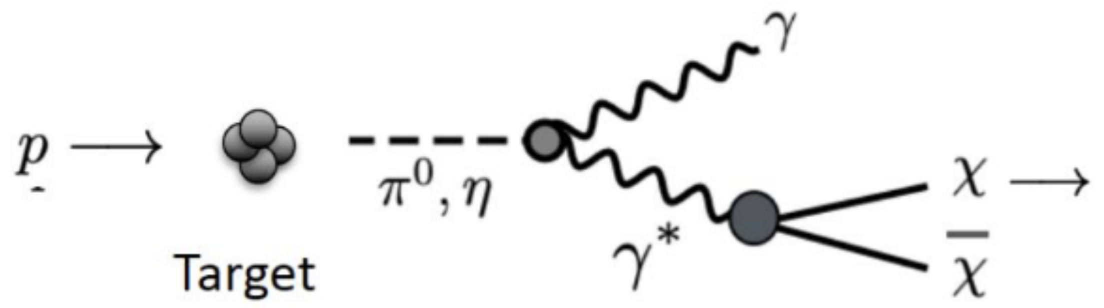


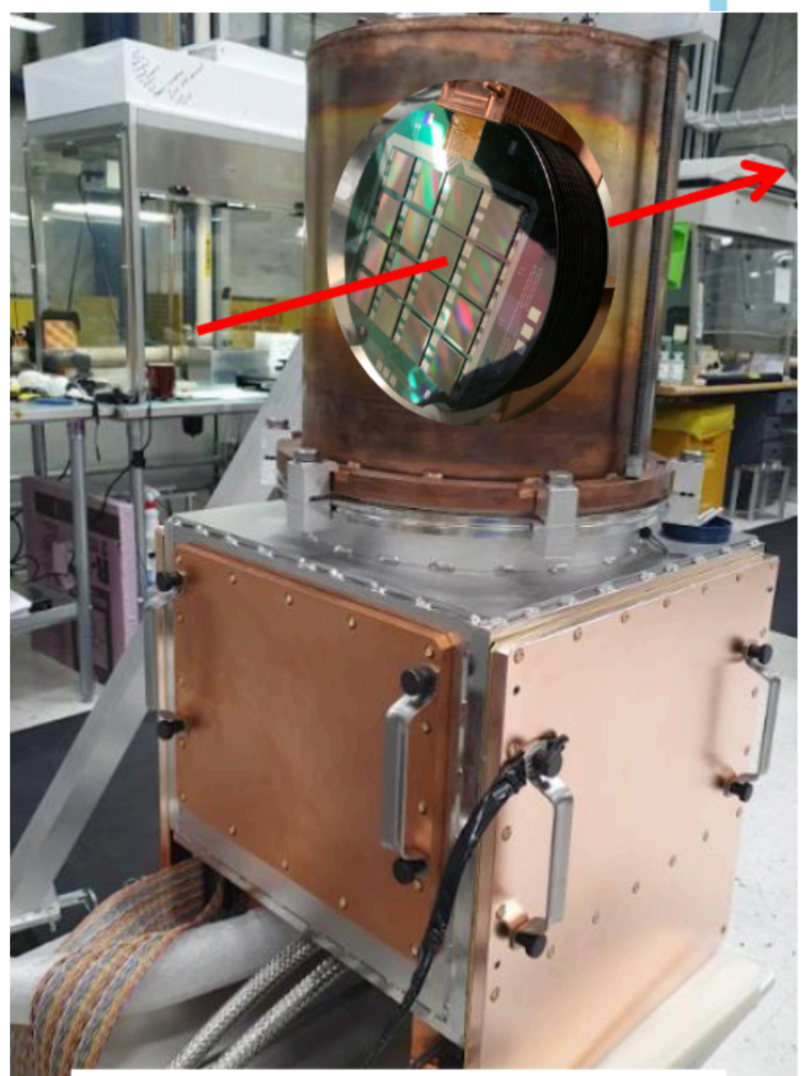
- 10 prototype ceramic MCMs and the discrete readout electronics
- Largest ever built instrument with skipper-CCDs controlled by 1 LTA → Demonstrates electronics solution
- Setup is being used to develop analysis software and could be used for early science

Other initiatives with CCDs

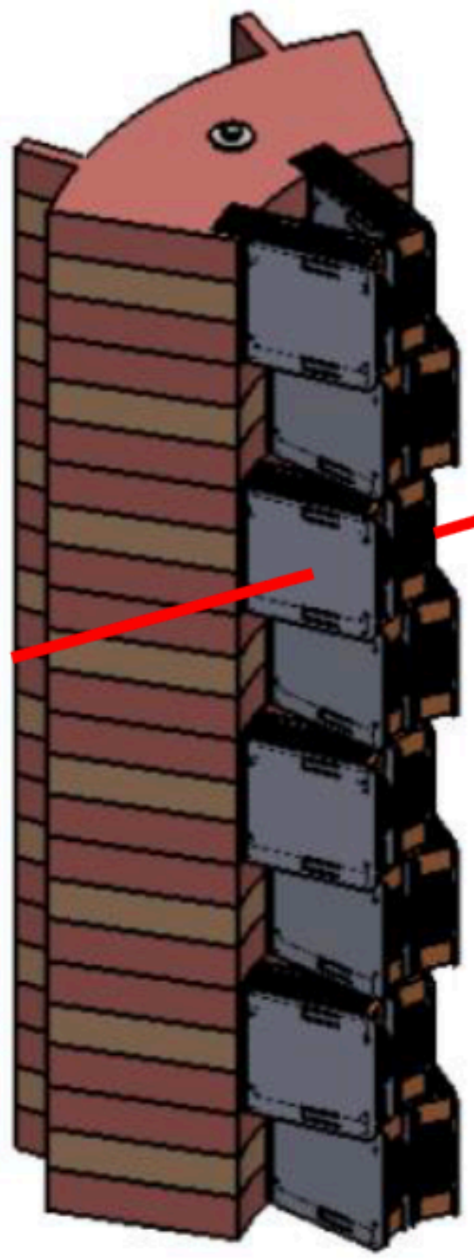
Oscura early science (JHEP02(2024)072)

- With a partial load of the sensors (about 10%) →Science can be done
  - Using the NuMi beam at FNAL → Search for millicharge particles.
  - Multiple-hit search could reduce bkgds
  - Exclusion limits are promising!
- mCPs skipper-CCD detector:
  - Large-mass setup (tracker?)
  - Location @ accelerator facilities

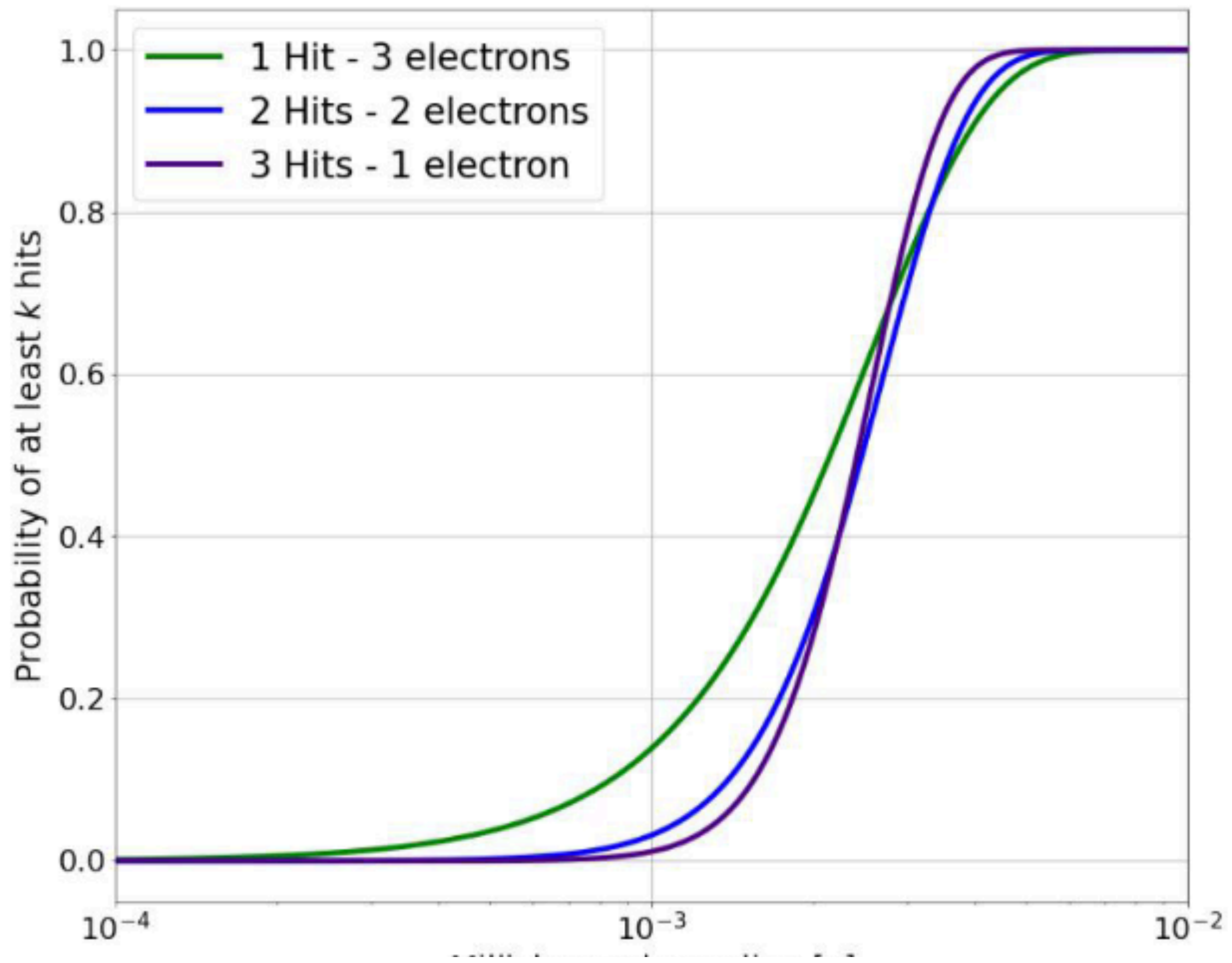


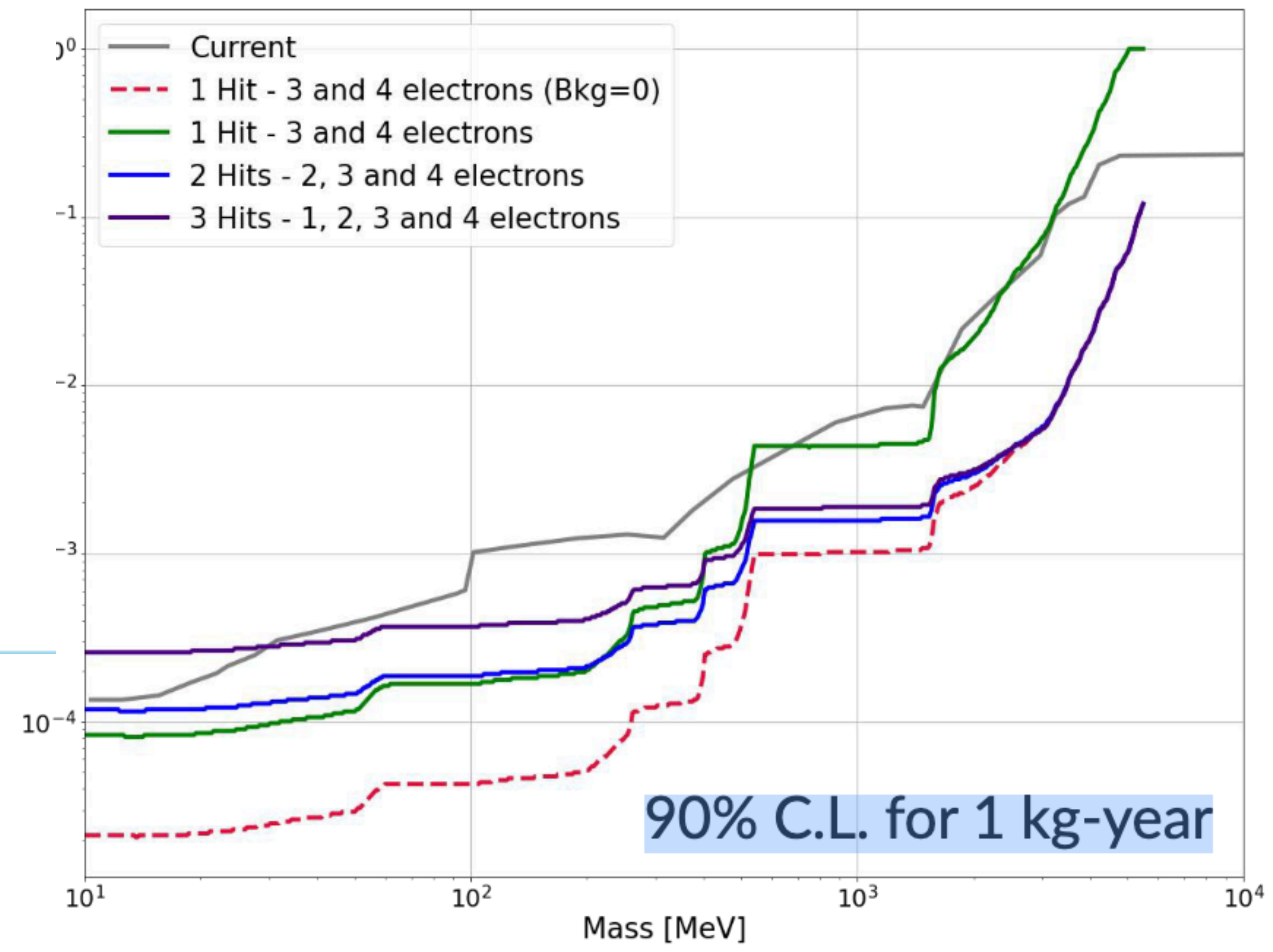


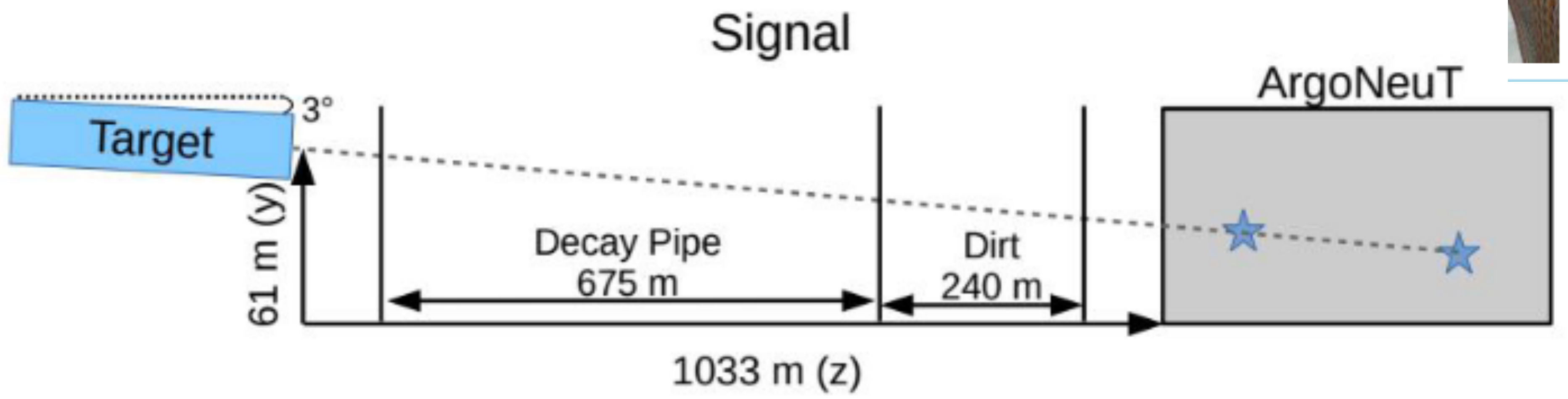
10(16)-layer tracker



32-layer tracker



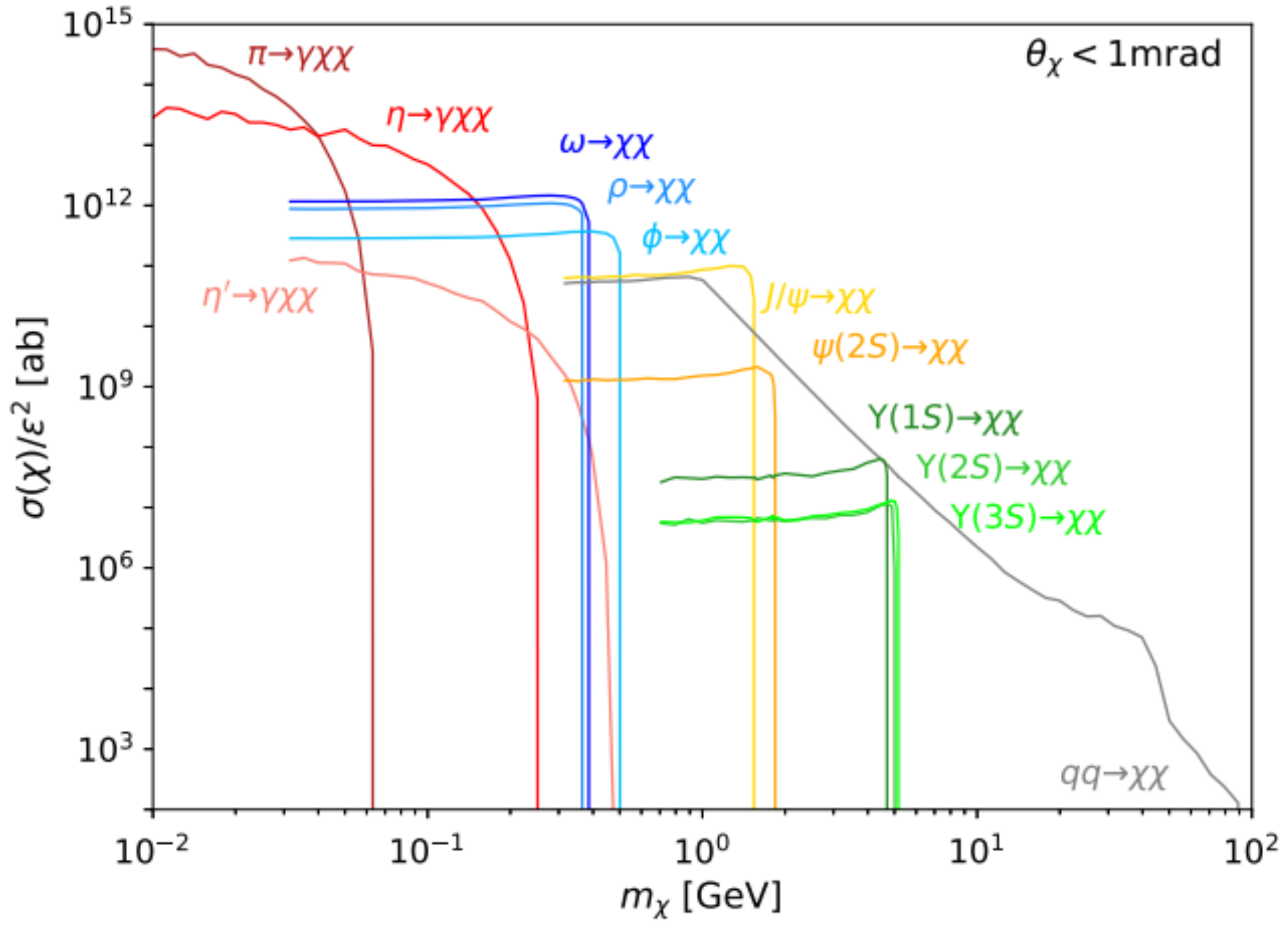




Other initiatives with CCDs

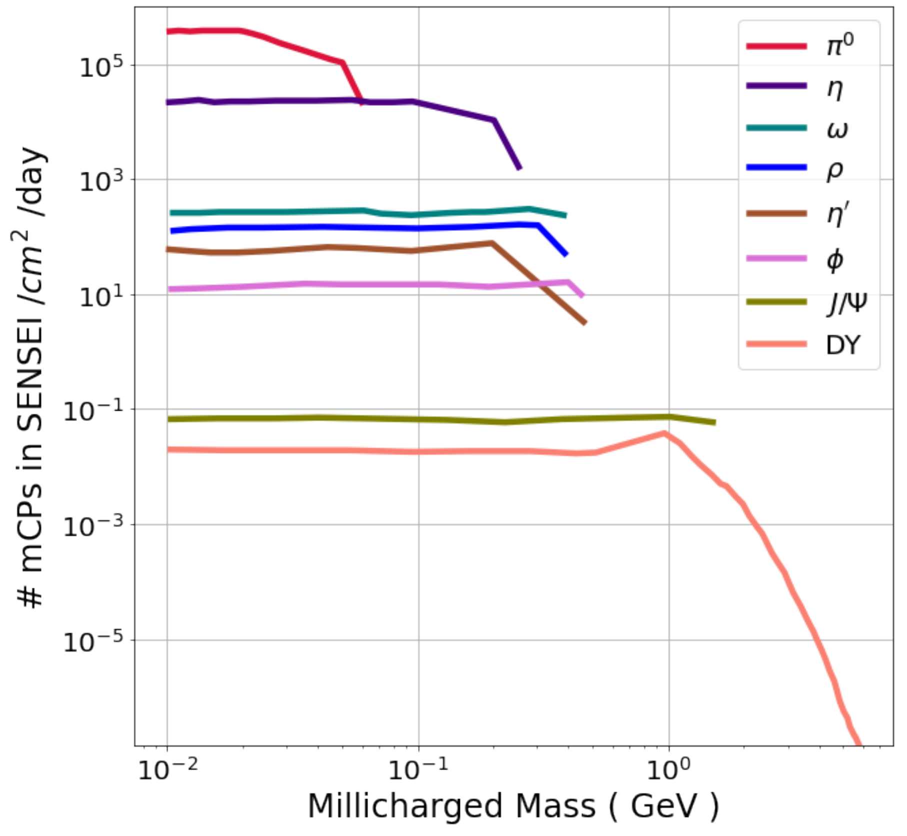
at LHC in the forward side

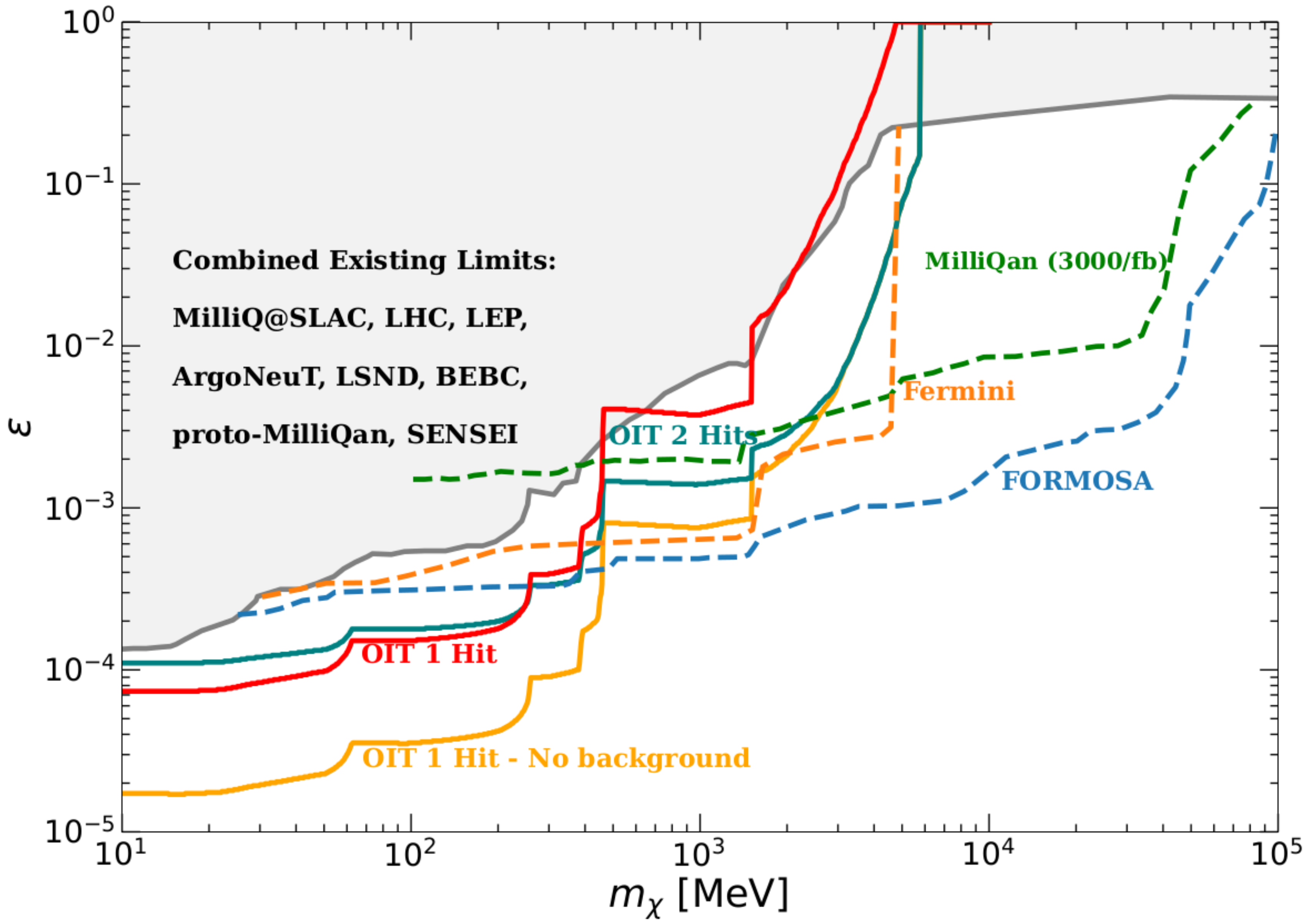
Oscura early science (JHEP02(2024)072)

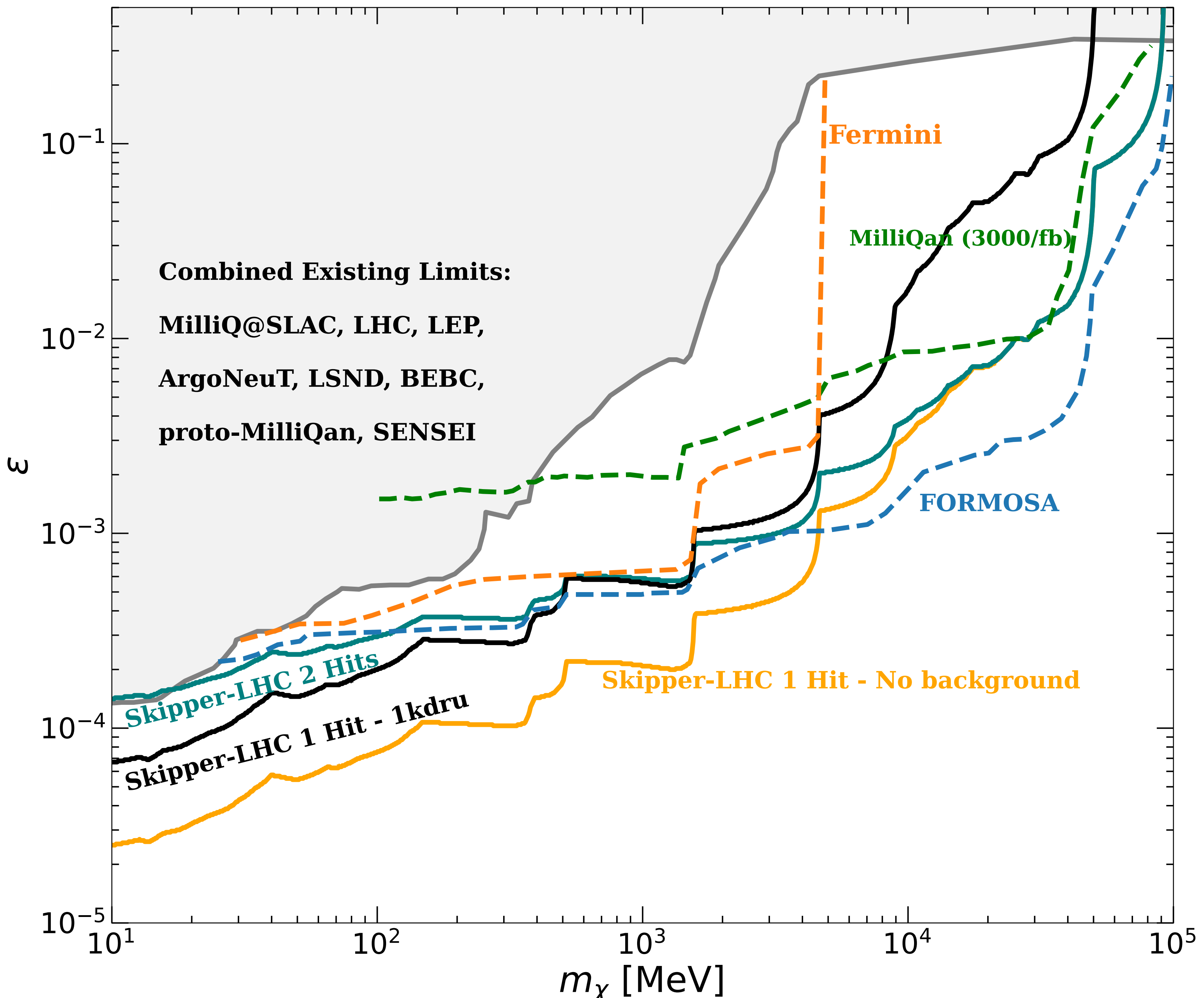


- Assuming a 1 kg detector with 32 layers for tracking, ~1018 POT from the NuMI beam (120 GeV protons) and a flat background of 1000 evts/kg/day/keV
- For higher ε the mean free path of the mCPs is smaller than the width of the tracker, increasing the probability of multiple hits

at NuMI Beam



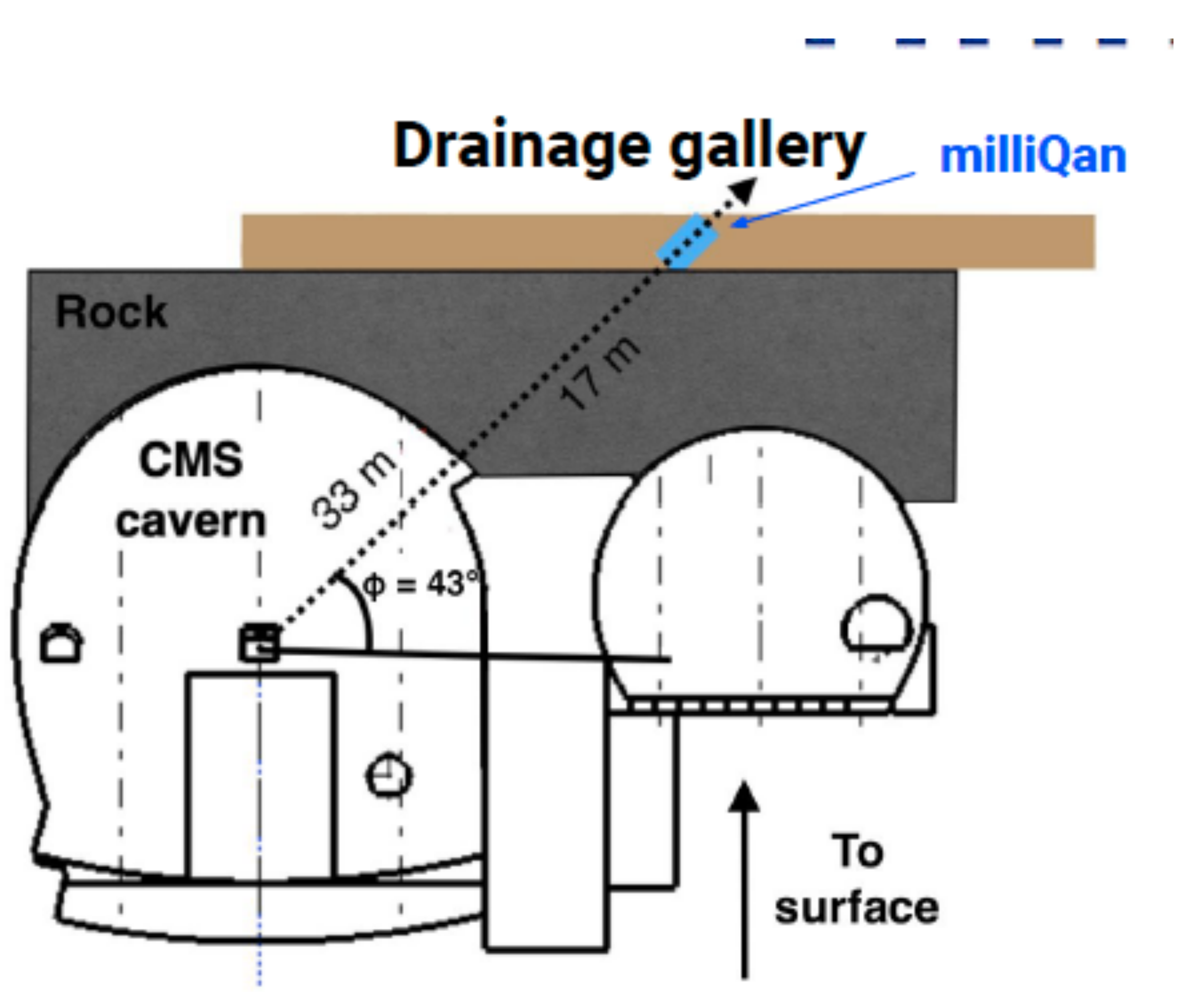


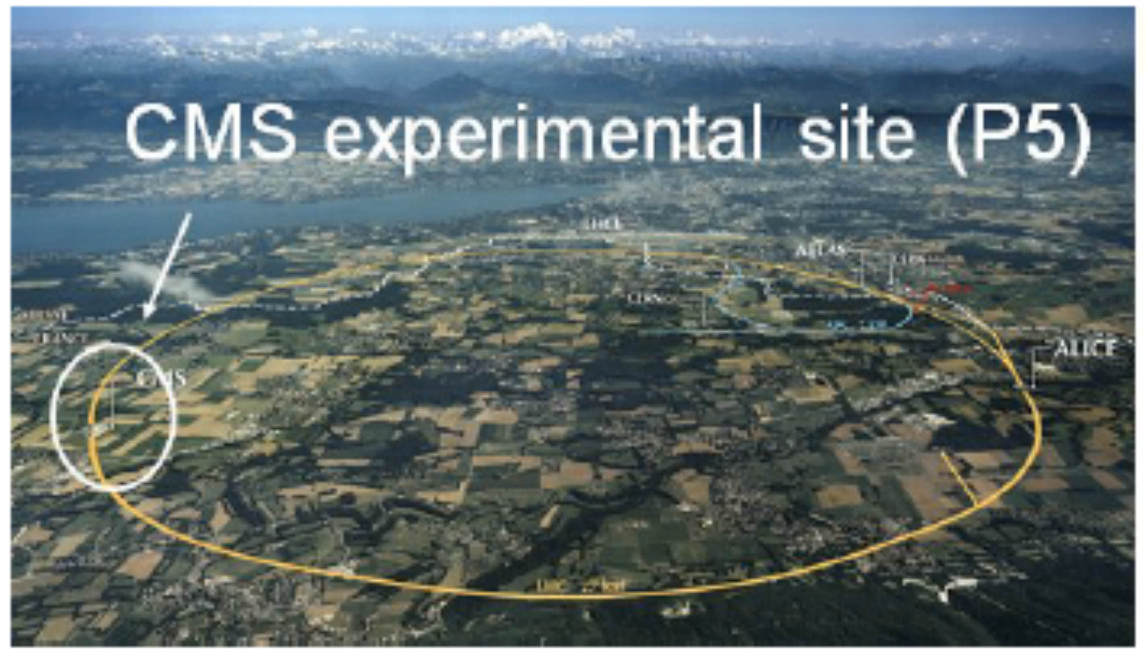


Other initiatives with CCDs

MOSKITA: MObile SKIpper Testing Apparatus

- We are going to test the skipper CCDs at LHC:
  - Measure noise with and without LHC beam(from the beam, the rock and the cosmic among others)
  - Using a setup that it is already working at Fermilab in the MINOS cavern to test the CCDs sensors
  - Located in drainage gallery at LHC collision point 5 near CMS
  - $\eta \sim 0.1$, 17m of rock provide natural shielding from beam particles





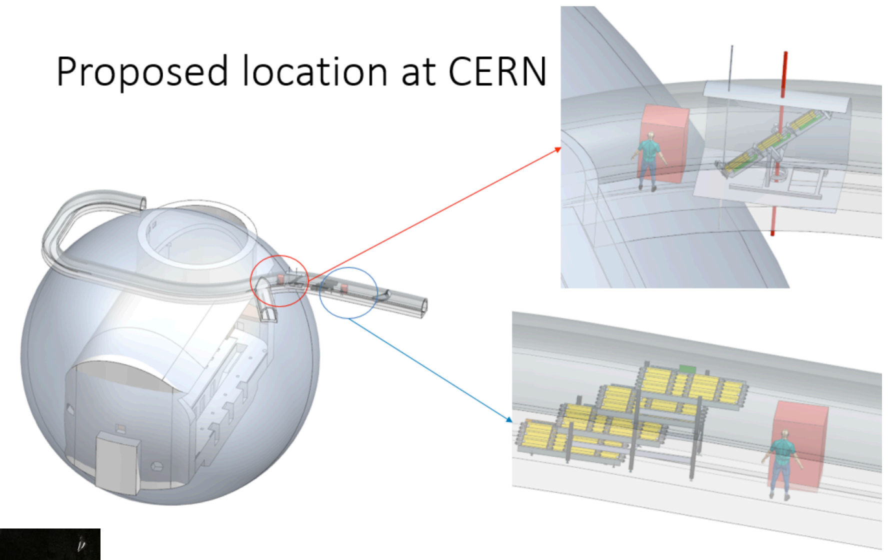
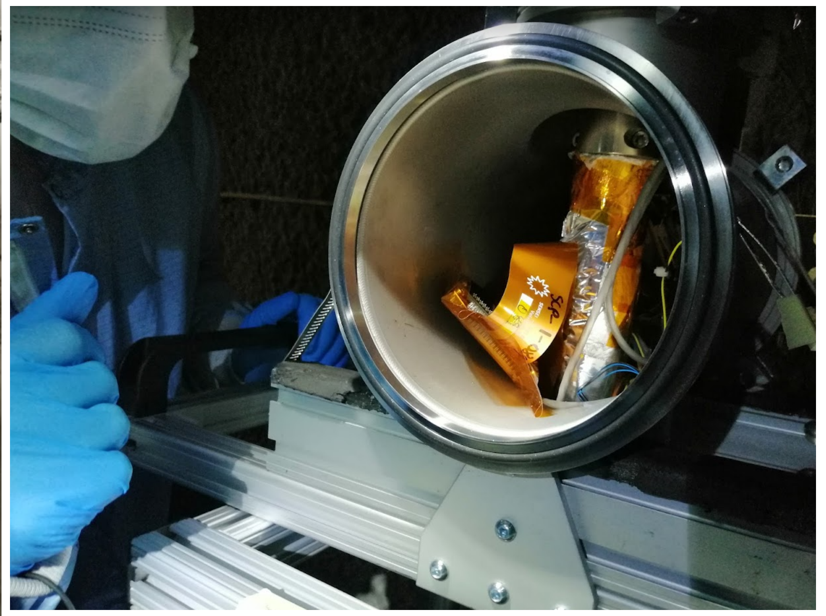


Fig. 3: Envisioned location of MOSKITA at the MilliQAN cavern.



Conclusiones

- Electron-counting skipper-CCD technology allows exploring the dark sector
- Searching for LDM at underground laboratories with skipper-CCDs is a robust experimental program
- DAMIC-M is steadily moving towards its goal of installation, and commissioning at the end of 2024.
- CCD fabrication almost complete (85%) and starting production of the other components of the detector
- Low Background Chamber already produced world leading results on DM searches,
  - currently focus on background and calibration measurements, and characterization of DAMIC-M components
- Development of multi-kg low-background skipper-CCD detectors is ongoing Oscura
  - Millicharged particles search with skipper-CCDs at accelerators seems promising

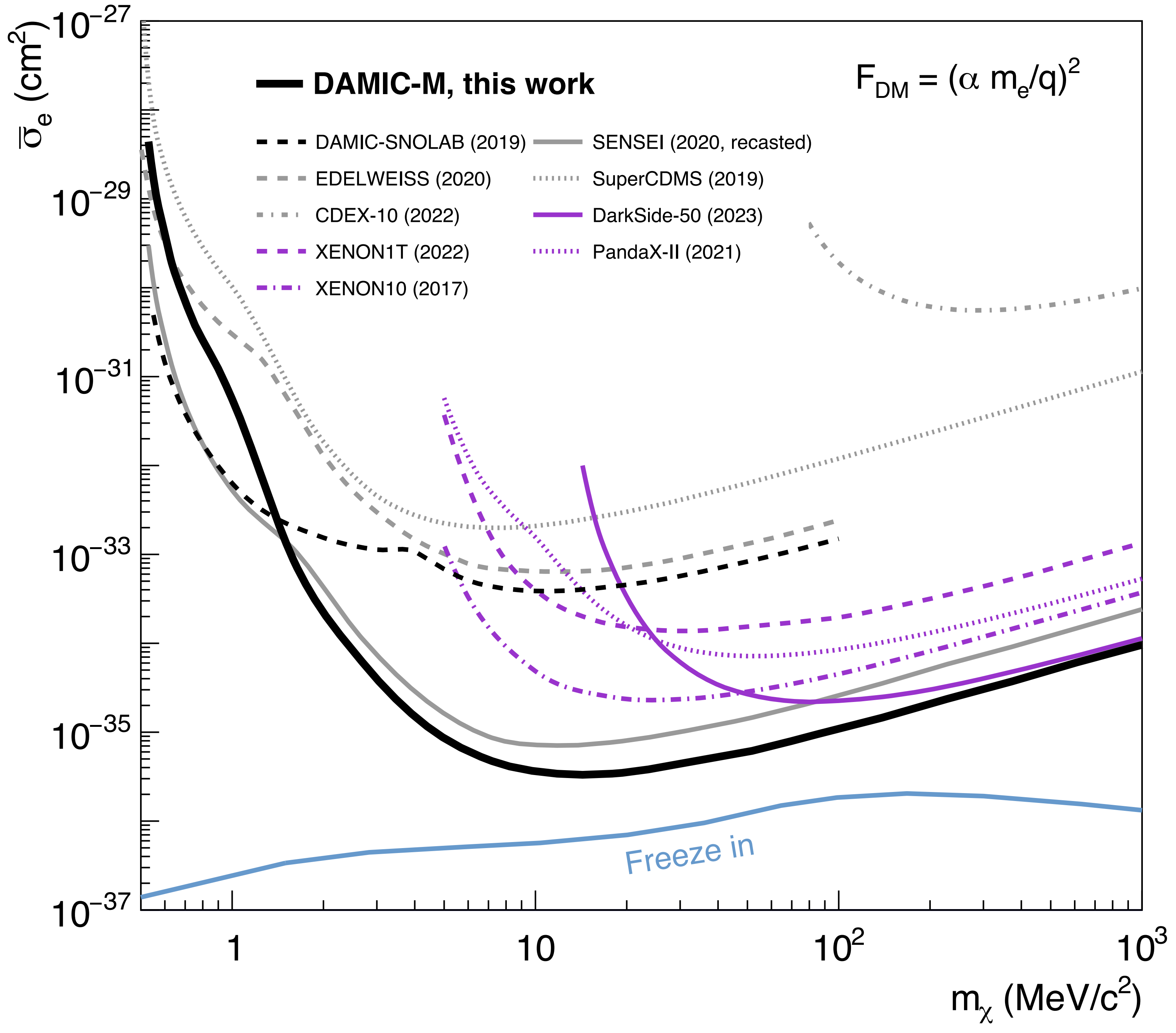
Backup

Details

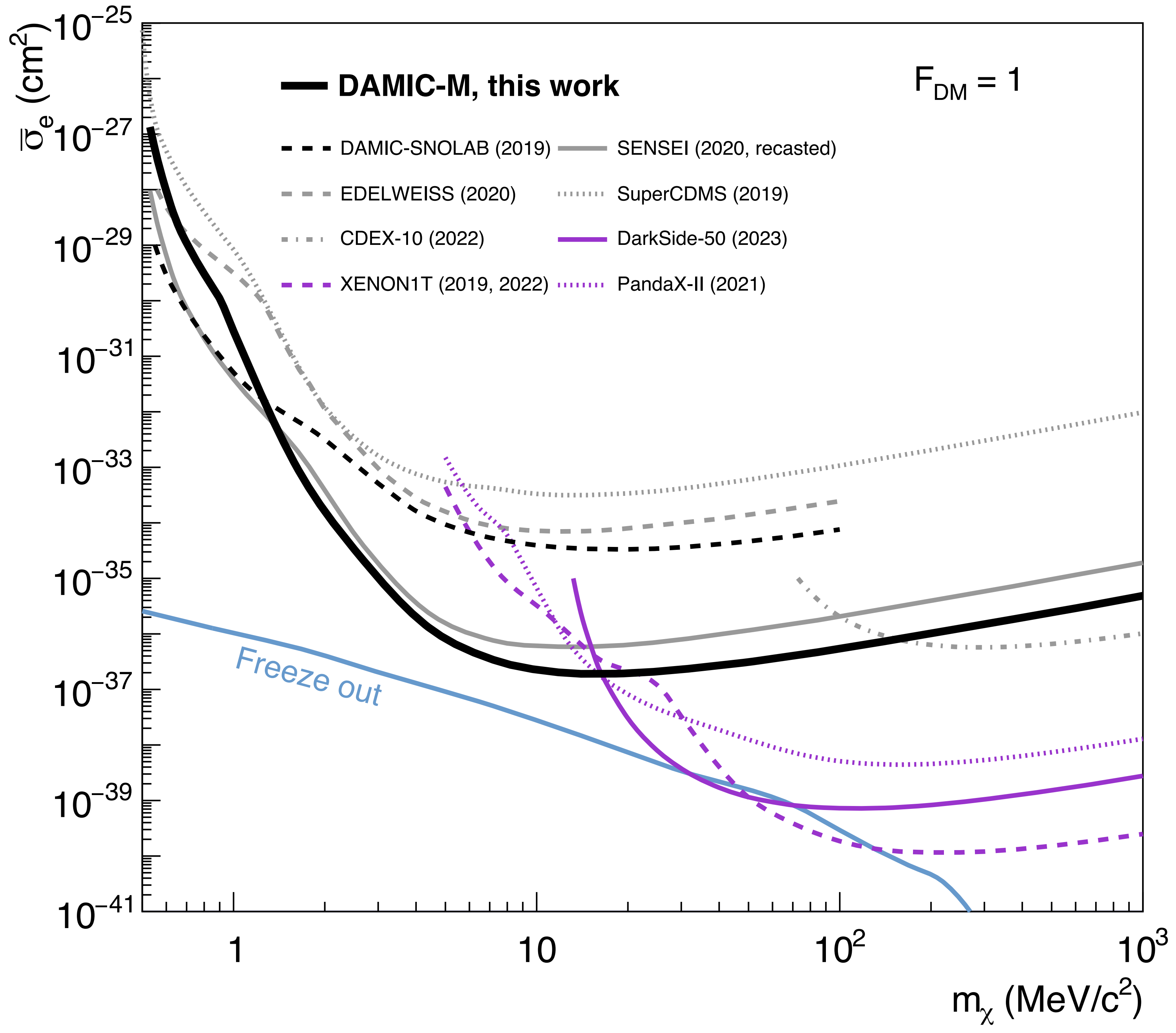
Low Background Chamber, LBC

First science results DM-e scattering (PhysRevLett.130.171003)

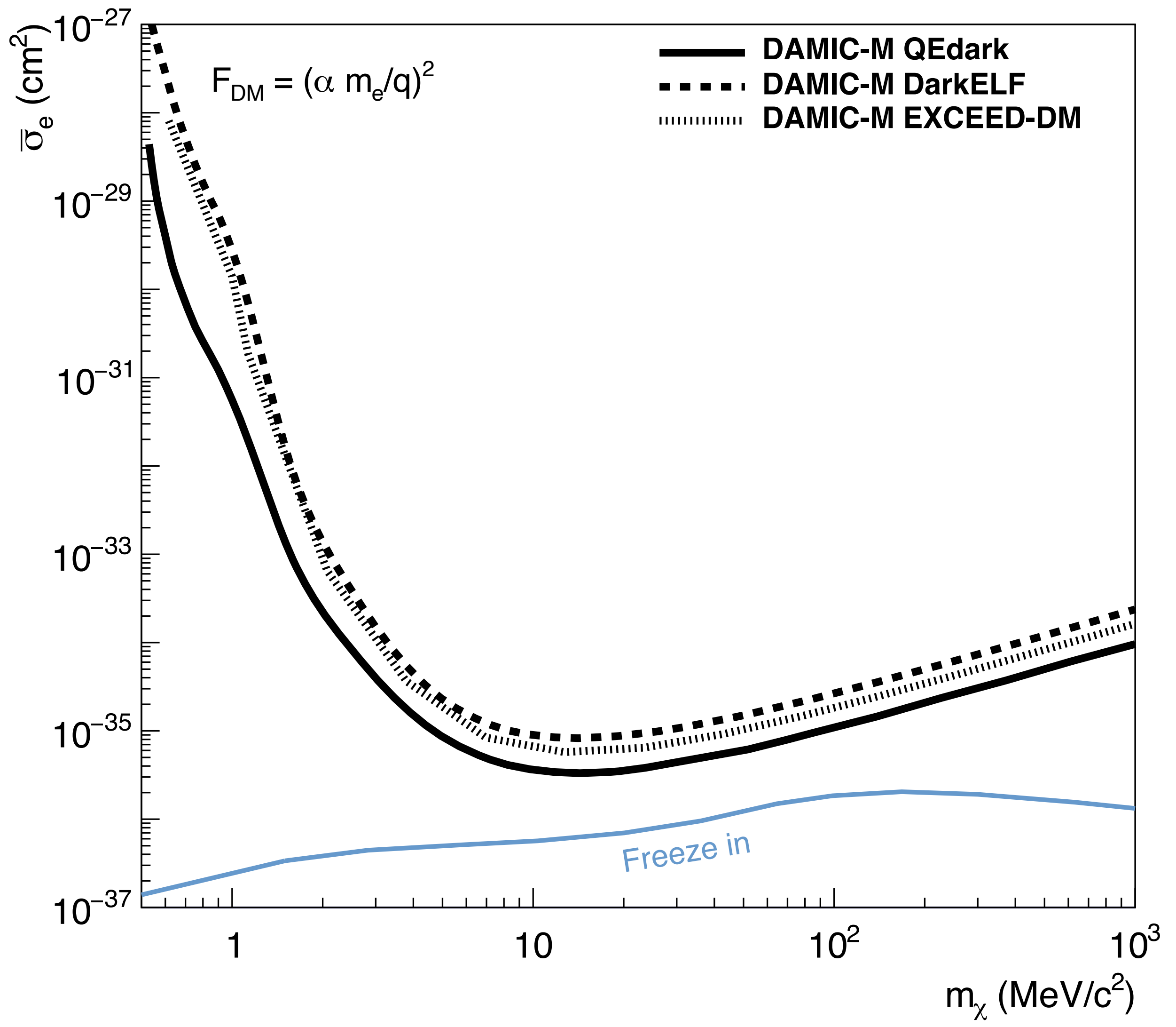
- World leading exclusion limits on DM-electron interactions in the mass ranges [1.6 - 1000 MeV] and [1.5 - 15.1 MeV] for ultralight and heavy mediator interactions with two CCDs in a few months



ultra-light mediator



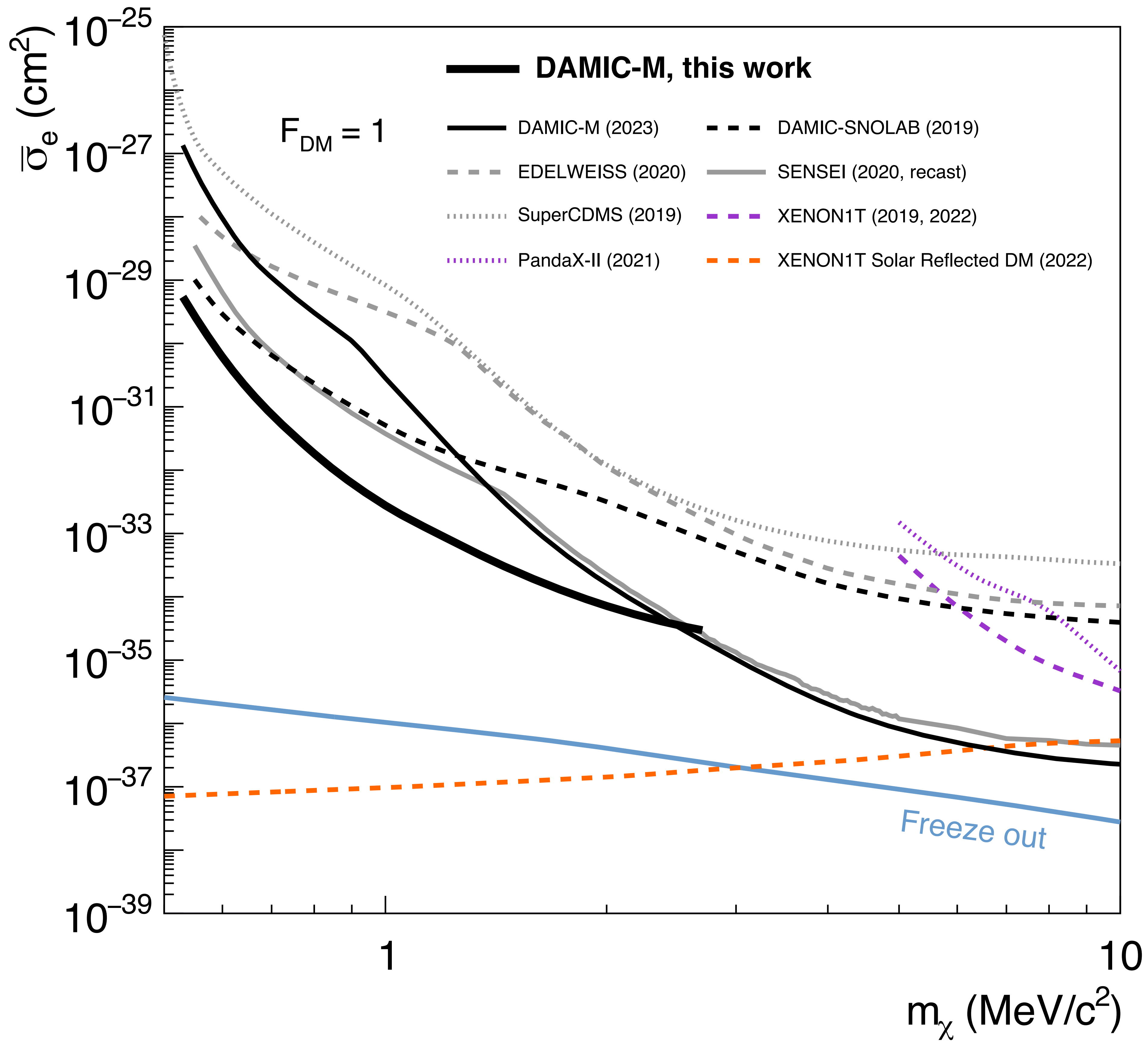
heavy mediator

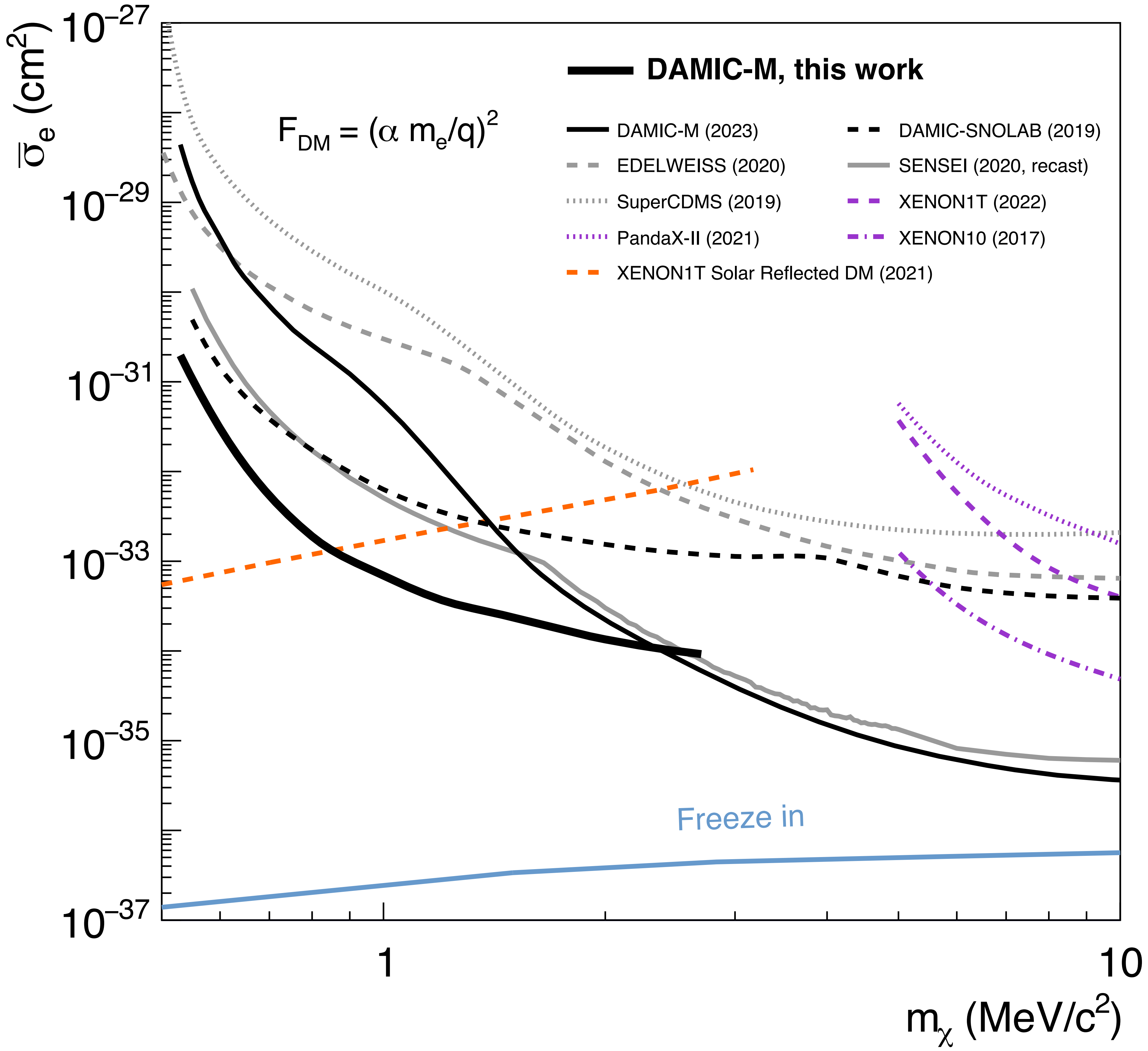


DAMIC-M 90% C.L. upper limits on DM-electron interactions through an ultra-light mediator obtained with QEdark, DarkELF (dashed), and EXCEED-DM theoretical models for the crystal forms

Low Background Chamber, LBC

First Results:Daily modulation (Phys. Rev. Lett. 132, 101006)





The daily modulation analysis improves our PRL limits below 3 MeV by up to 2 orders of magnitude