ICHEP 2024 | PRAGUE

The search for light dark matter with DAMIC-M

Radomir Smida
smida@kicp.uchicago.edu

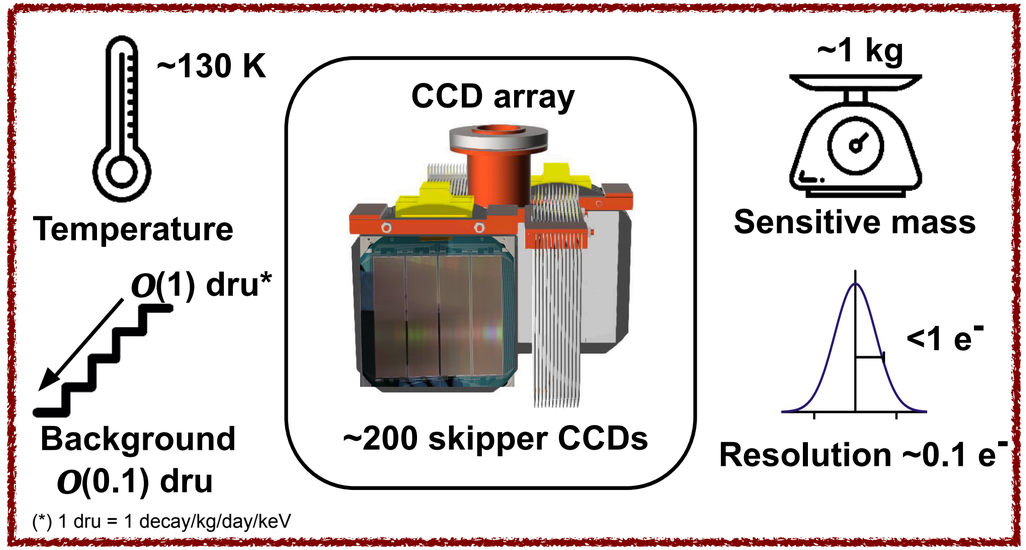
- DAMIC-M goals,
- Skipper CCDs,
- Low Background Chamber,
- Dark matter-electron scattering,
- Outlook.

European Research Council
Established by the European Commission

Dark Matter in CCDs at Modane (DAMIC-M)

DAMIC-M will deploy an array of skipper CCDs and its design goals are

- exposure of $1\,\mathrm{kg\,year}$,
- single electron resolution $\sigma < 1\,\mathrm{e}^-$,
- low background $O(0.1)\,\mathrm{dru}$,
- low dark current $< 0.5\,\mathrm{e}^-/\mathrm{mm}^2/\mathrm{day}$.



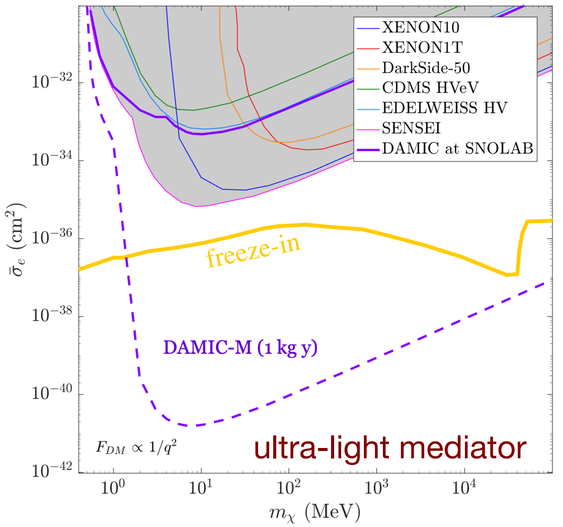
Located at the Modane underground laboratory (LSM) in France

- Prototype takes data since early 2022,
- DAMIC-M installation in early 2025.

Science goals:

- Detects both nuclear & electronic recoils,
- Explore wide range of DM models, i.e. DM masses starting from 1.2 eV (hidden-sector mediators) to light WIMPs (<10 GeV).

DAMIC-M projected sensitivity



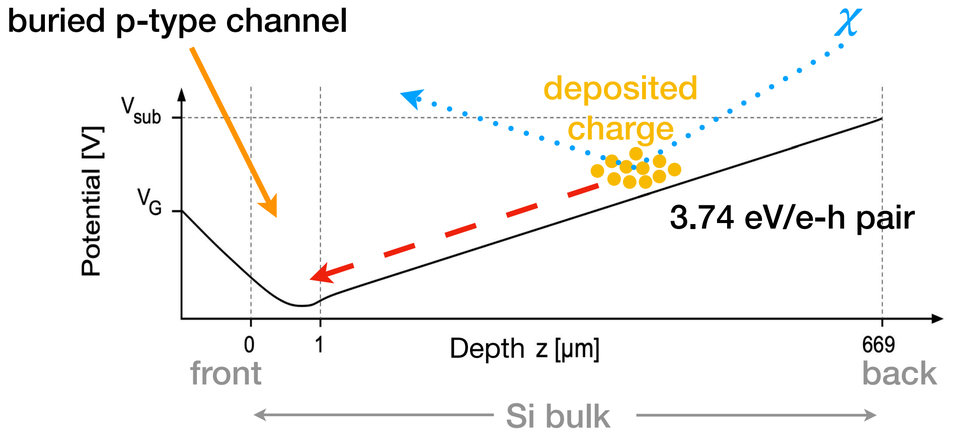
Charge-coupled devices (CCDs)

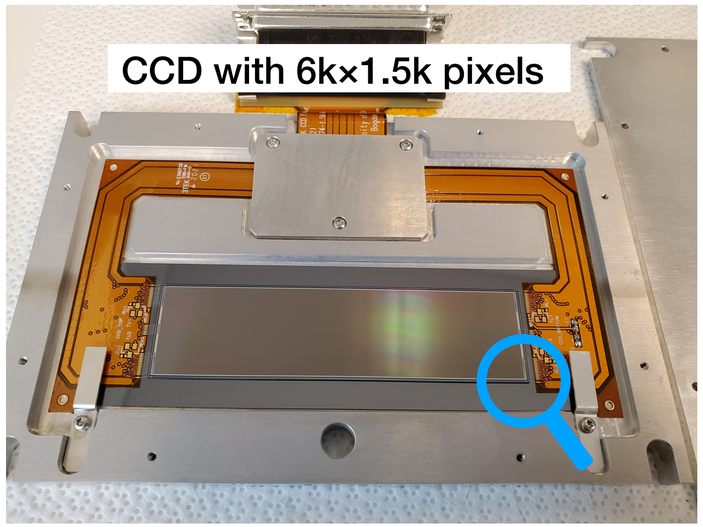
Semiconductor device made from mono-crystalline Si

- Clean material (but cosmogenically activated ^{3}H, ^{7}Be, ^{22}Na),
- thickness 670 μm,
- high resistivity (>10 kΩ-cm) and fully depleted with the substrate voltage $V_{\mathrm{sub}} \geq 40\ \mathrm{V}$,
- pixel size 15 μm × 15 μm.

DAMIC-M CCD has ~9M pixels and 3.3 grams

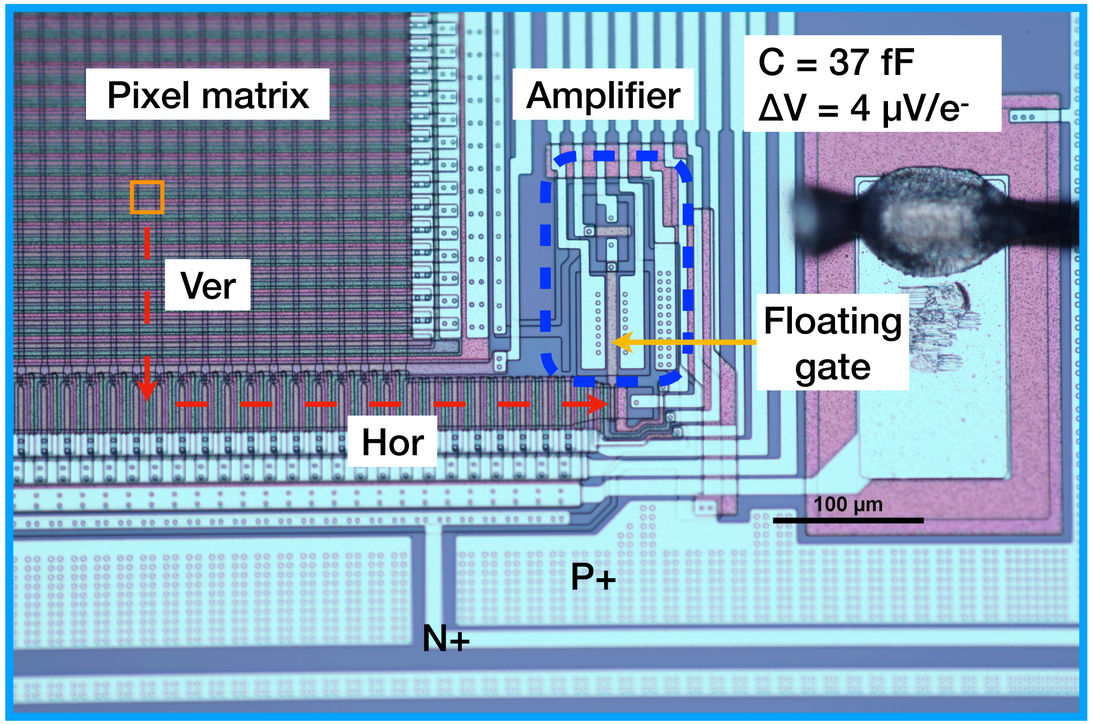
Three-phase vertical and horizontal clocks move charge





Developed by BERKELEY LAB

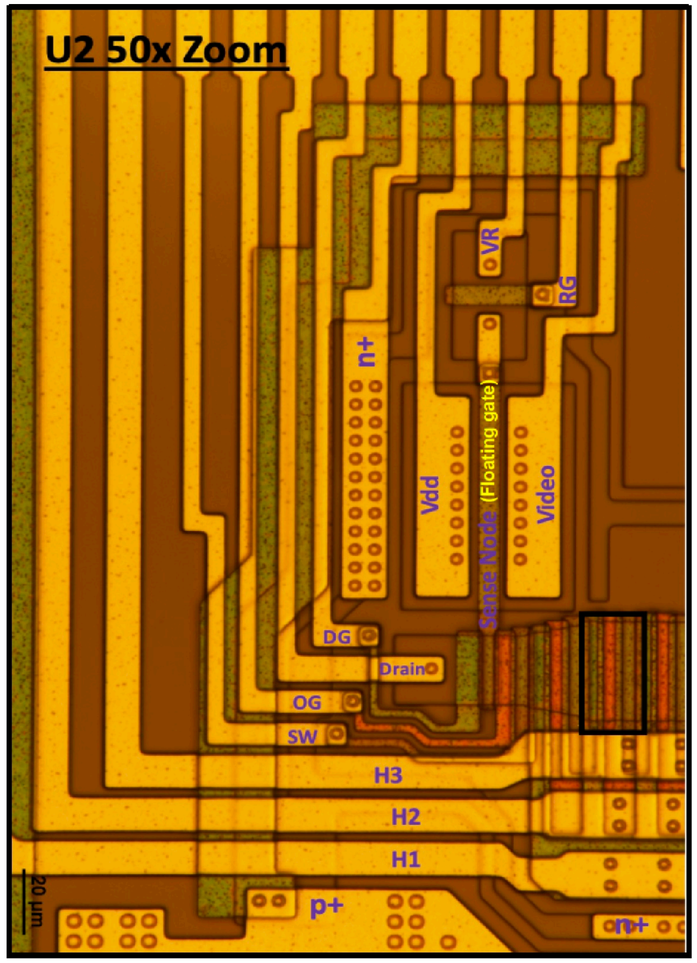
20× zoom

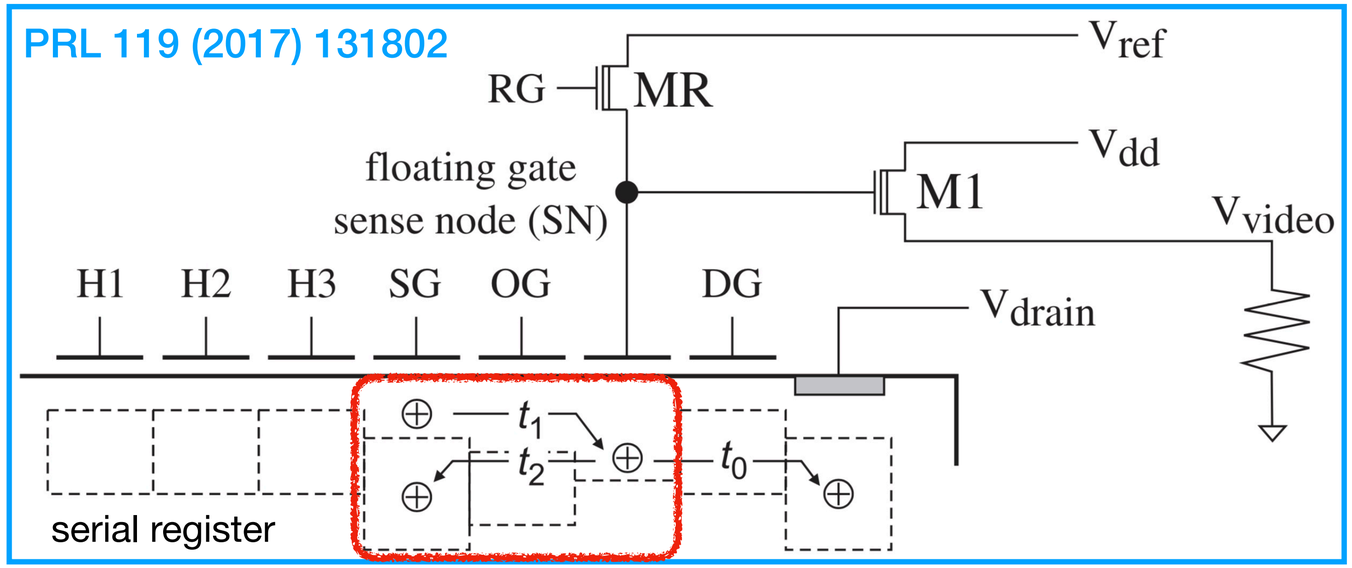


Skipper CCD

DAMIC-M CCDs have floating-gate (skipper) amplifiers

- Skips = multiple non-destructive charge measurements by moving pixel charge between the summing well and floating gate



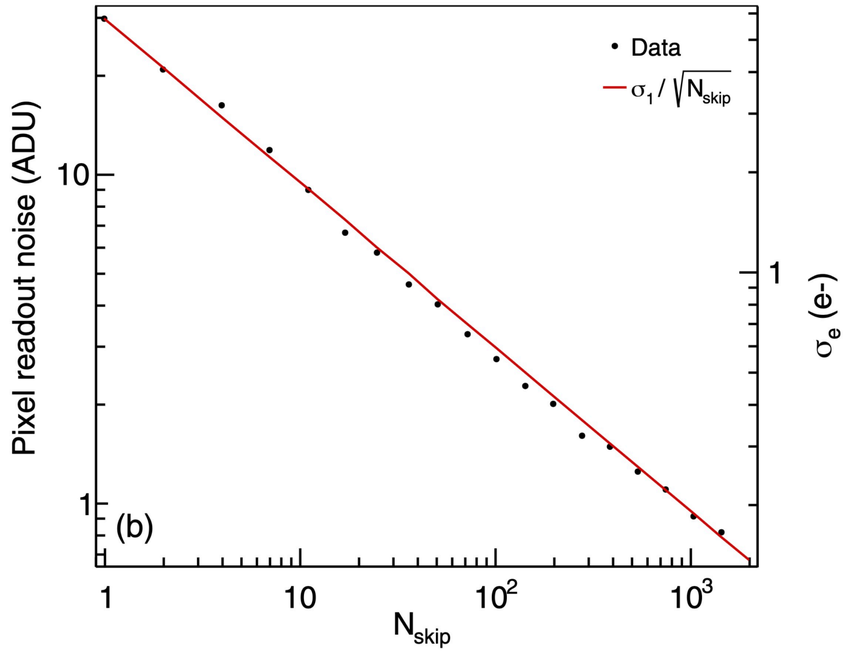


H1,2,3 horizontal clocks
SG summing well
OG output gate
DG dump gate
RG reset gate
V_{ref} reference voltage

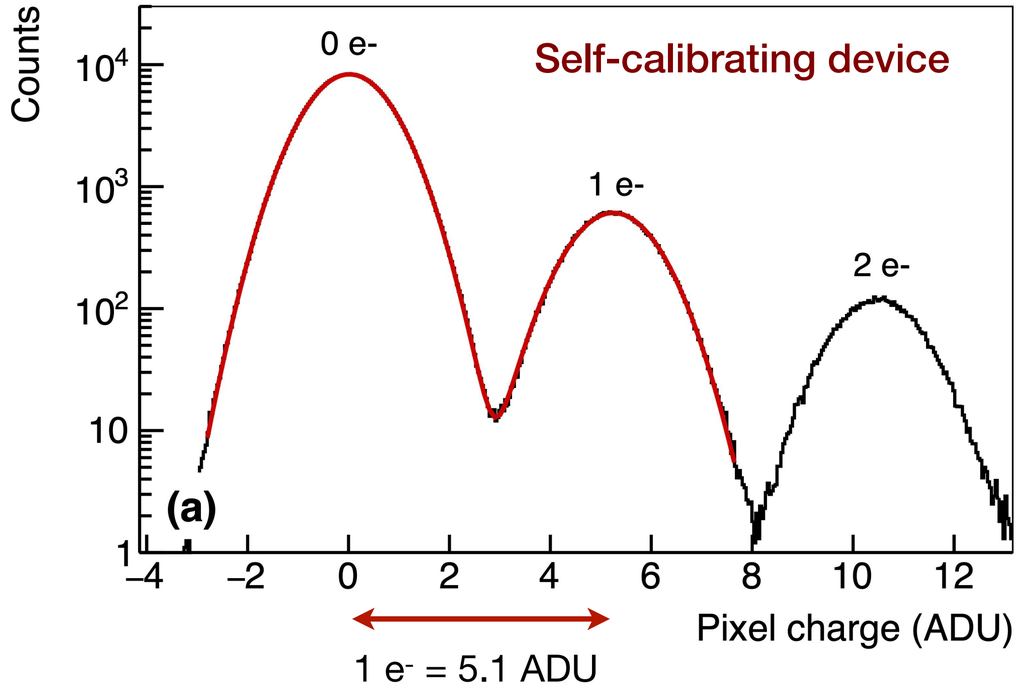
Skipper CCD

DAMIC-M CCDs have floating-gate (skipper) amplifiers

- Skips = multiple non-destructive charge measurements by moving pixel charge between the summing well and floating gate
- The readout noise decreases to $\sigma = \sigma_1/\sqrt{N_{skip}}$ for N_{skip} and typically $N_{skip} > 200$ is required to achieve good single-electron resolution



PRD 106, 092001 (2022)



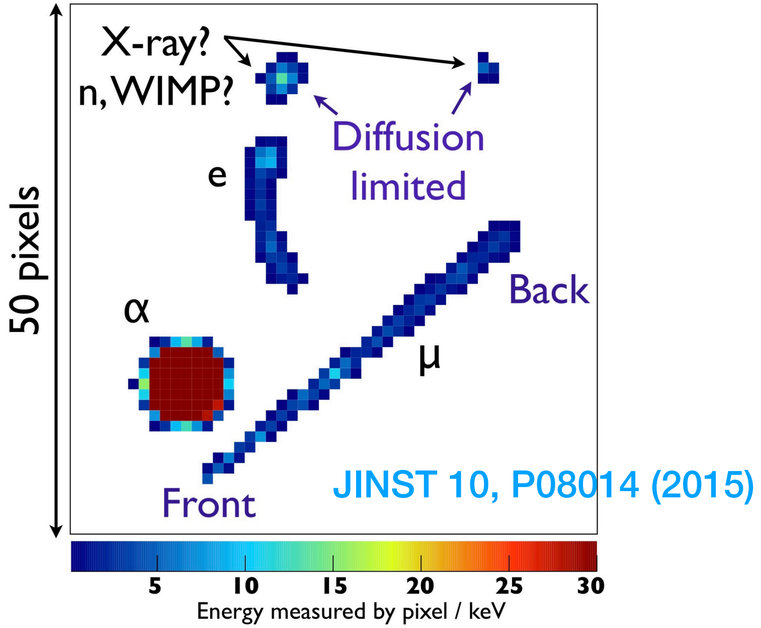
Unfortunately, pixel readout time is much longer than in a standard CCD. This is an issue on the surface, because we have almost no events in a low background environment. We can shorten it by summing charge from more pixels (i.e. binning).

Particles in CCDs

Excellent spatial (x, y) reconstruction due to pixelization

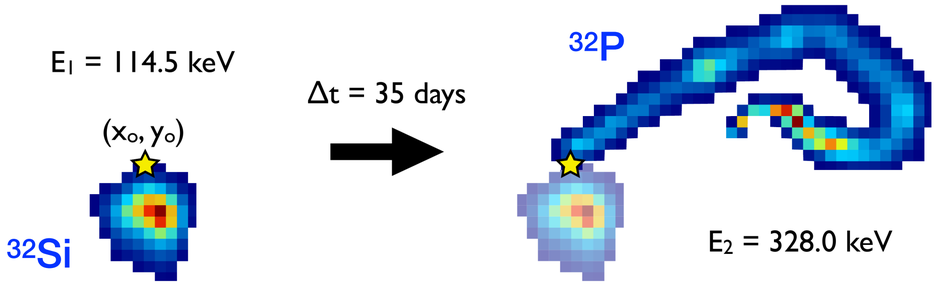
The depth (z) thanks to charge diffusion
CCDs are calibrated by atmospheric muons

1. Particle identification



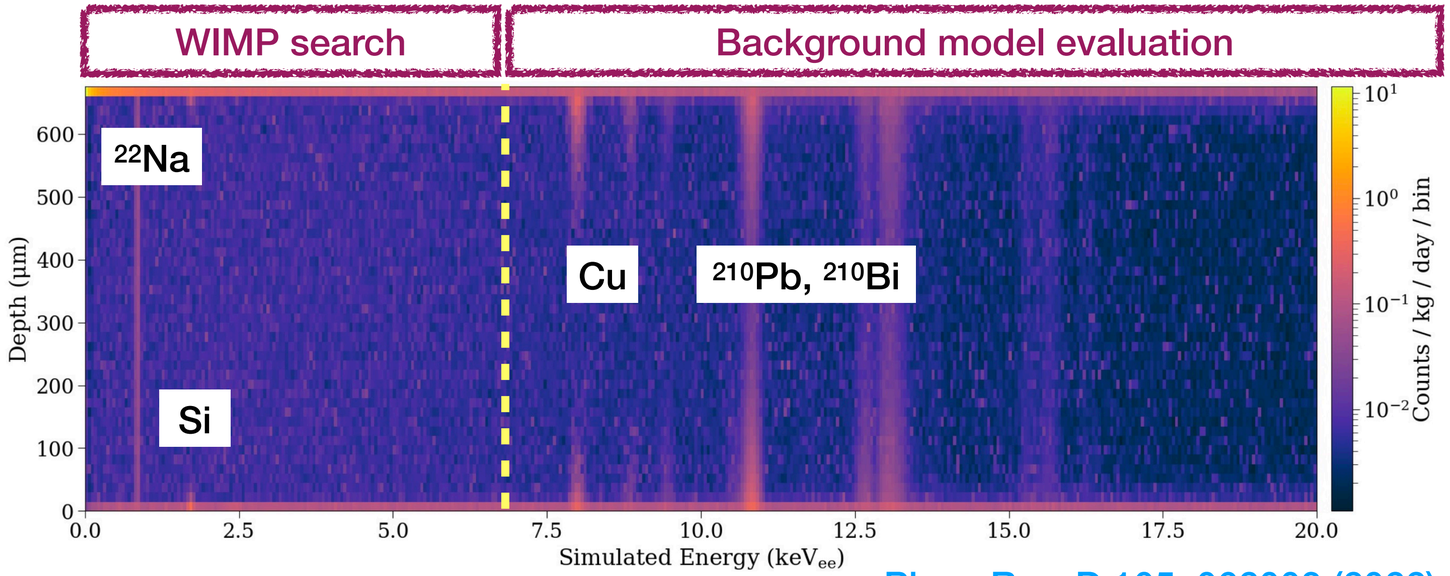
JINST 10, P08014 (2015)

2. Spatial and time coincidences (e.g. ^{32}Si, ^{210}Pb)



JINST 16, P06019 (2021)

3. Background model by DAMIC at SNOLAB



Phys. Rev. D 105, 062003 (2022)

Calibration measurements

PRD 106, 092001 (2022)

Precision measurement of Compton scattering in Si down to E_{ee} = 23 eV, experiment at UChicago with ^{241}Am γ source

Measurement of the nuclear recoil ionization efficiency in Si, experiment at UChicago with low-energy neutrons (<24 keV) from a ^{124}Sb-^{9}Be photoneutron source, ongoing analysis

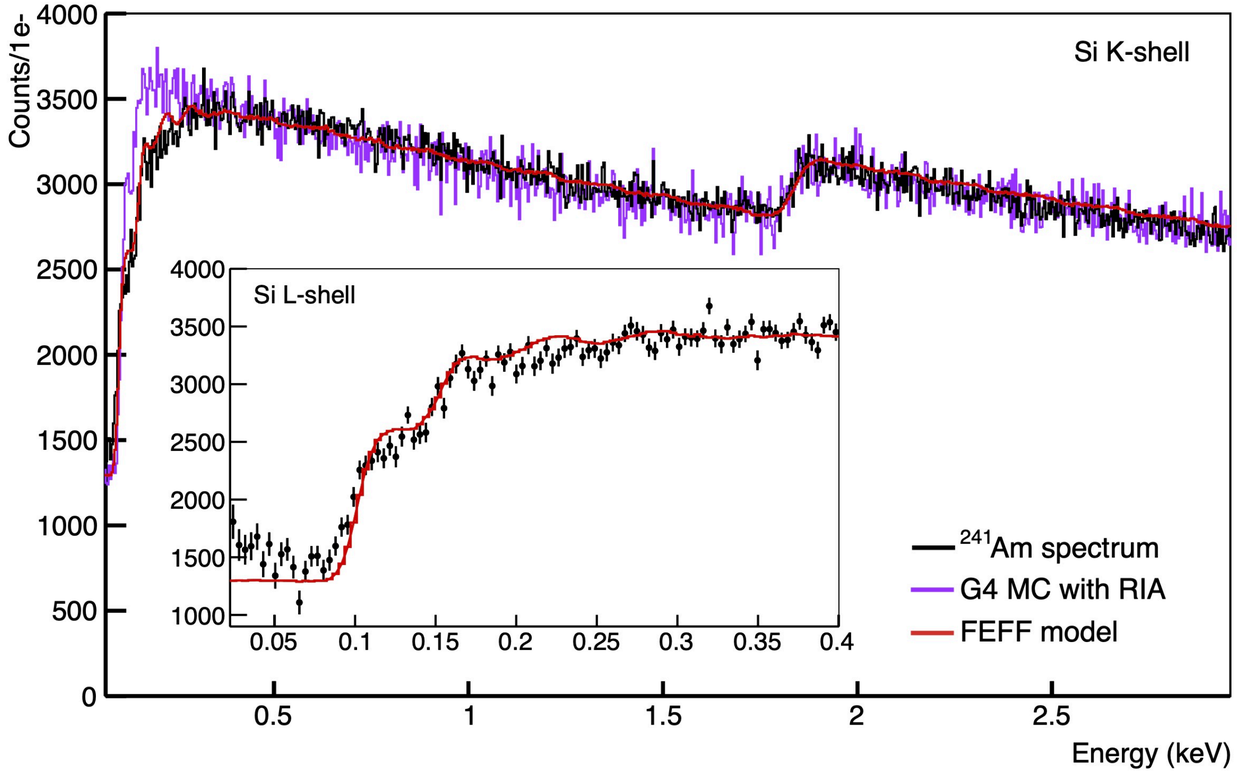
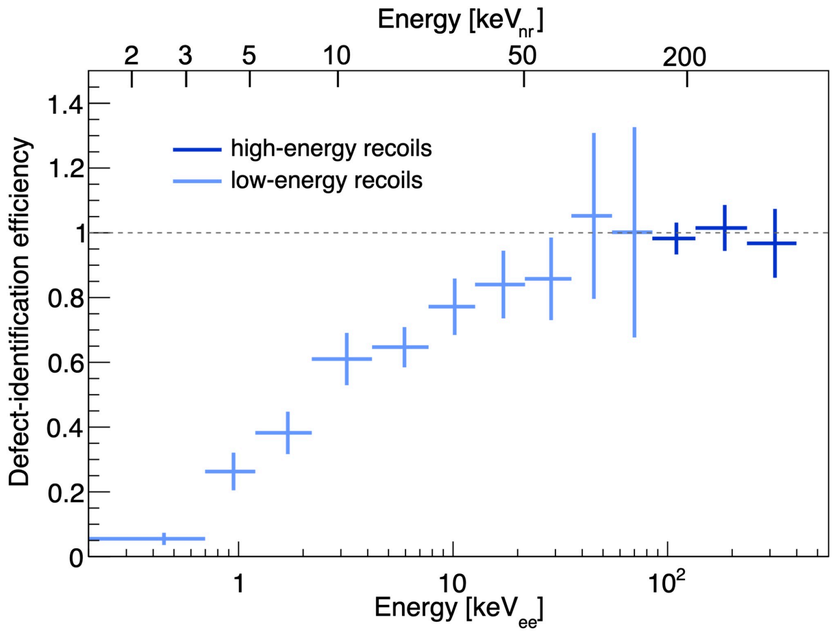


FIG. 10. The measured ^{241}Am Compton spectrum (black) from the 23 eV detection threshold to 2.1 keV. The K-step is observed at 1.8 keV. The GEANT4 simulated spectrum (purple) that is based on the relativistic impulse approximation is also shown. In red is the *ab initio* calculation from the FEFF code, with detector response taken into account. The inset shows the data comparison to the FEFF prediction in the L-shell energy range.



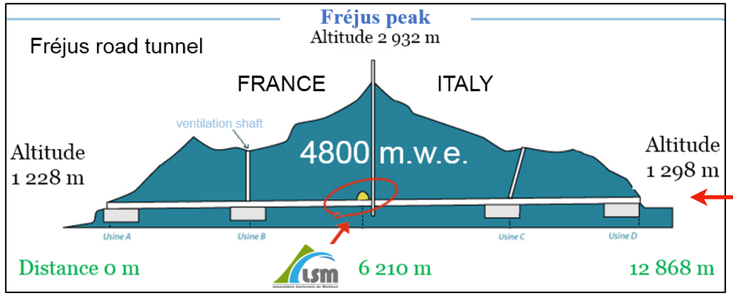
Distinguishing nuclear recoil signals from electronic recoil background, CCD irradiated with ^{241}Am-^{9}Be neutron source at UWashington, arxiv:2309.07869, accepted by PRD

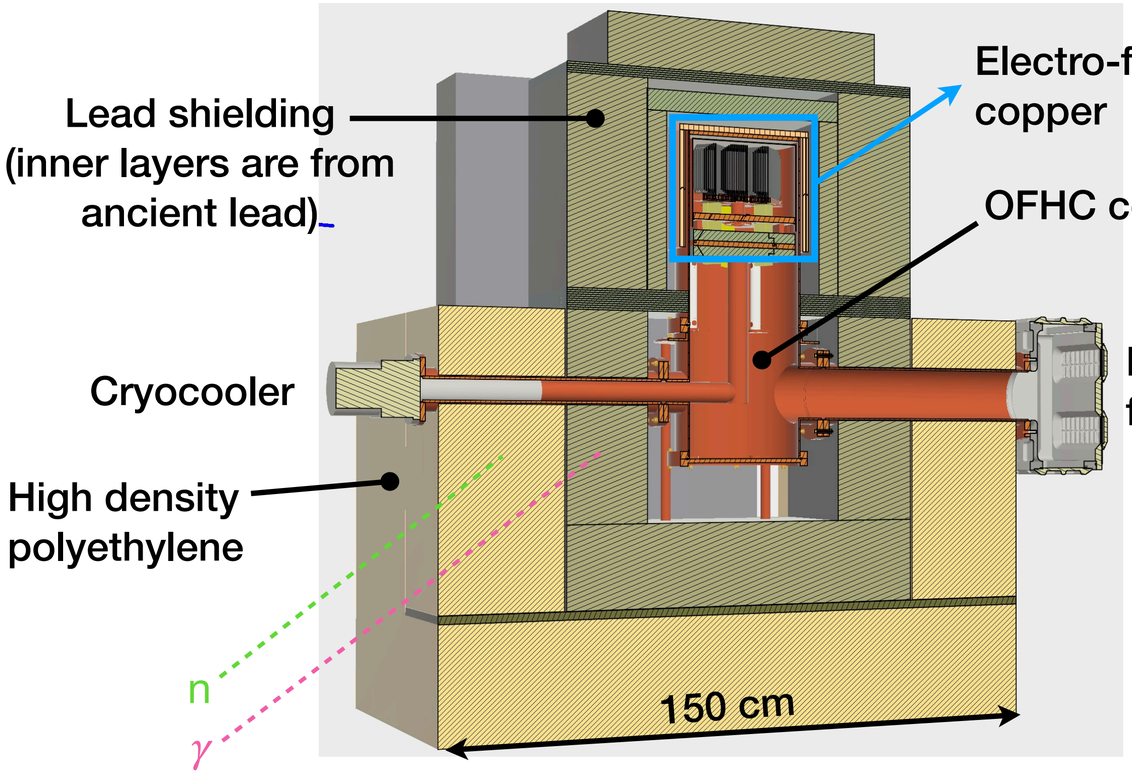
DAMIC-M detector at LSM

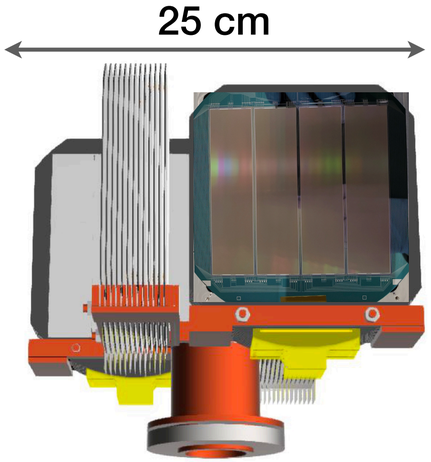
Modane Underground Laboratory Modane (LSM)

- 1700 m of rock overburden or 4800 m.w.e.,
- muon flux reduced ~10^6 times to only 5 μ/m^2/day,
- road tunnel, i.e. convenient access.

Detector clean room (class ISO 5) plus clean room for testing and assembly

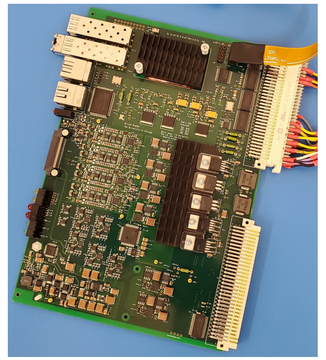






CCD array

- 208 science-grade skipper CCDs,
- 4 devices on a Si pitch adapter with a flex cable
- cosmogenic activation ~3 months,
- IR shield around.



Custom electronics for fast readout and low noise

DAMIC-M background mitigation steps

CCD cosmogenic activation (no flights, expedite production, storage underground, transport in a container with 16-ton iron shielding)
PRD 102, 102006 (2020)

Strict control of exposure to Radon and dust

Ultra-clean CCD flex cables, further away from CCDs
EPJ Tech. Inst. 10, 17 (2023)

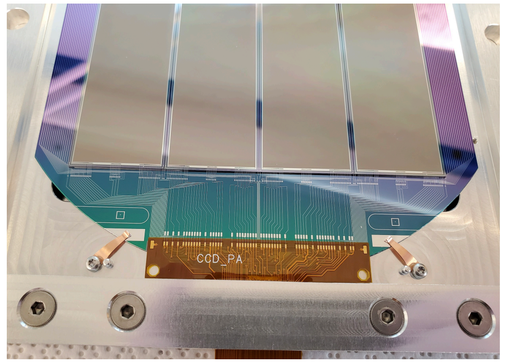
Copper electro-formed and machined underground, cosmogenic activation below 10 days
NIM A 828, 22 (2016)
AIP Conf. Proc. 1921, 020001 (2018)

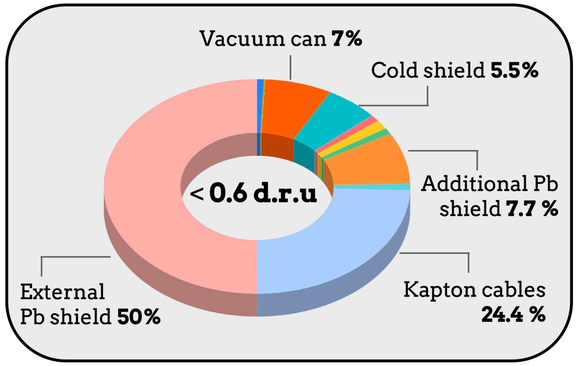
Ancient lead shielding

Chemical cleaning
NIM A 579, 486 (2007)

Design validation with Geant4 simulations

Expected total background $O(0.1)$ dru.

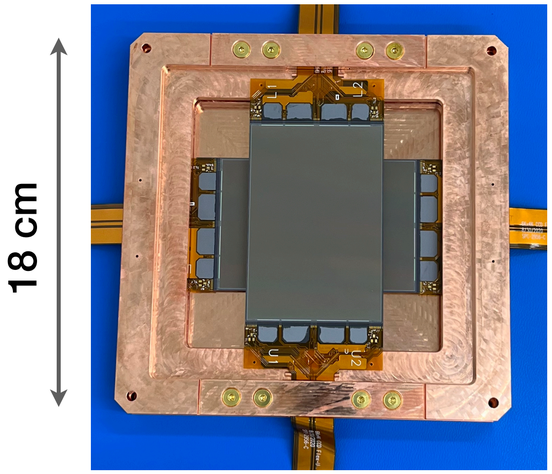




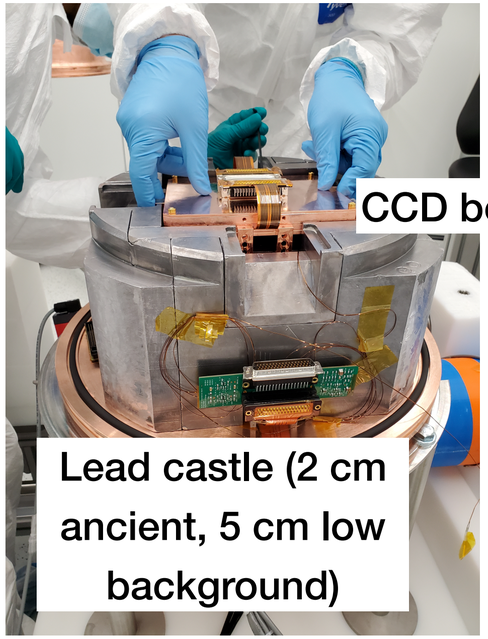
CCDs are not included

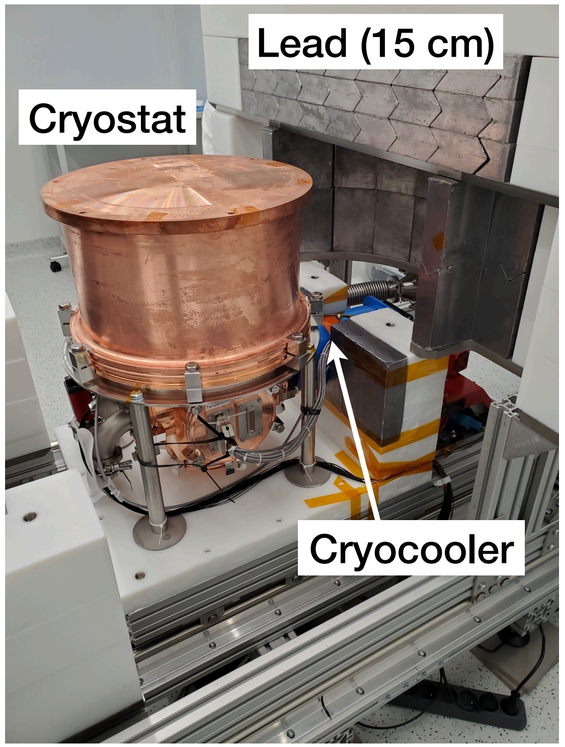
Low Background Chamber (LBC)

DAMIC-M prototype commissioned in early 2022

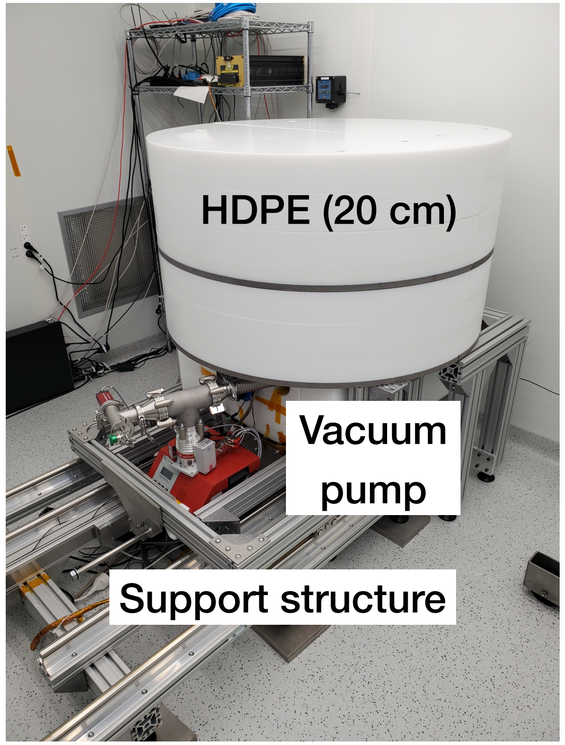


Two 6k x 4k pixel CCDs





Electronics, slow control



- CCDs in the copper box are at ~130 K,
- the box provides cooling and shielding (radioactive and IR background),
- cleanest materials are closest to CCD devices,
- pressure <10^{-5} mbar.

LBC goals:

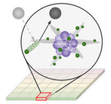
1. Gain working experience at LSM, ✔
2. characterize DAMIC-M components in a low background environment, ✔
3. test of other subsystems (electronics, SC, DAQ, data transfer, etc.), ✔
4. science results with small detector. ✔

Editors' Suggestion

First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

I. Arnquist *et al.* (DAMIC-M Collaboration)

Phys. Rev. Lett. **130**, 171003 (2023) – Published 28 April 2023



World-leading constraints are placed on electron interactions with dark matter in the MeV to GeV range by the first underground operation of a new CCD detector.

Show Abstract +

PHYSICAL REVIEW LETTERS **132,** 101006 (2024)

Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M

I. Arnquist,[1] N. Avalos,[2] D. Baxter,[3,*] X. Bertou,[2] N. Castelló-Mor,[4] A. E. Chavarria,[5] J. Cuevas-Zepeda,[3] A. Dastgheibi-Fard,[6] C. De Dominicis,[7] O. Deligny,[8] J. Duarte-Campderros,[4] E. Estrada,[2] N. Gadola,[7] R. Gaïor,[7] T. Hossbach,[1] L. Iddir,[5] B. J. Kavanagh,[4] B. Kilminster,[9] A. Lantero-Barreda,[4] I. Lawson,[10] S. Lee,[9] A. Letessier-Selvon,[3] P. Loaiza,[8] A. Lopez-Virto,[4] K. J. McGuire,[3] P. Mitra,[5] S. Munagavalasa,[3] D. Norcini,[3,11] S. Paul,[3] A. Piers,[3] P. Privitera,[3,†] P. Robmann,[9] S. Scorza,[4] M. Settimo,[12] R. Smida,[3] M. Traina,[3,‡] R. Vilar,[4] G. Warot,[6] R. Yajur,[7] and J-P. Zopounidis[6]

(DAMIC-M Collaboration)

DM-electron scattering data

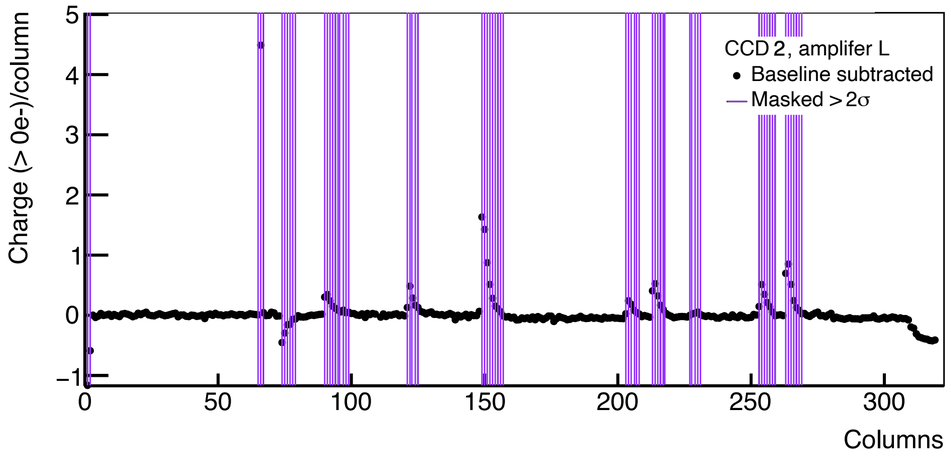
Data taken during the commissioning phase

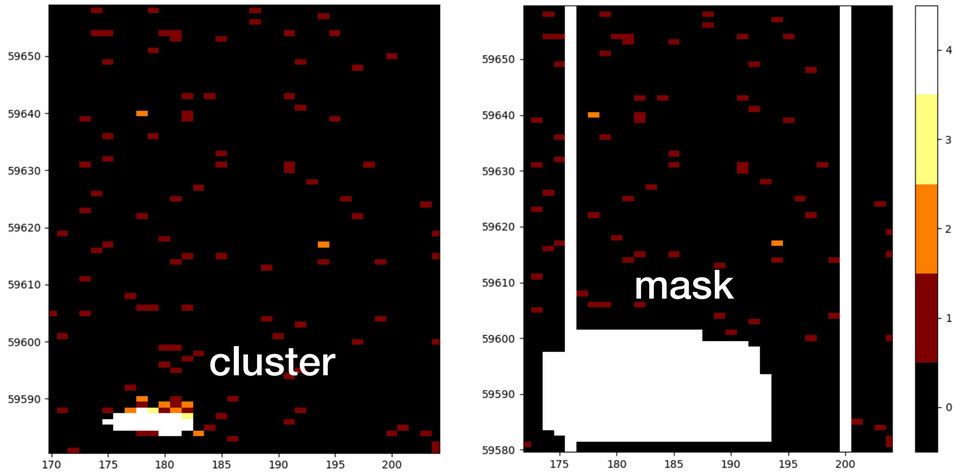
- Resolution 0.2 e^- (N_{skip} = 650), dark current ~20 $e^-/mm^2/day$,
- two runs over three months in 2022,
- remote operation.

"Minimum-bias" selection criteria:

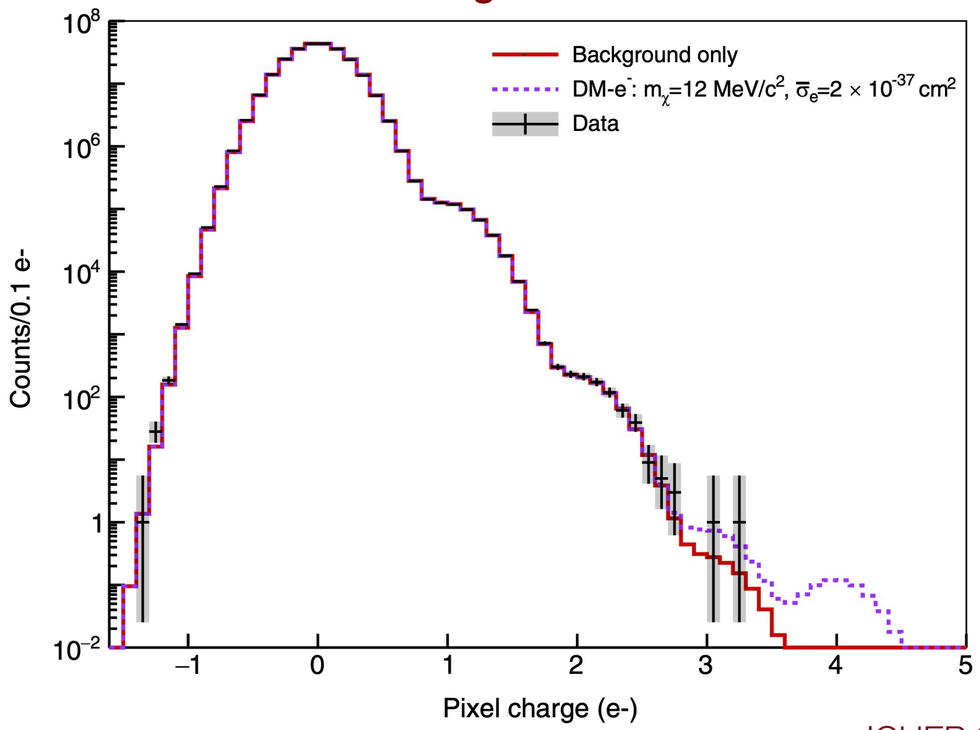
- Identify high energy clusters and reject those with >7 e^- (negligible contribution to DM signal),
- mask around clusters for charge transfer inefficiency (only 6×10^{-5} of the pixels are excluded),
- reject hot pixels/columns (20% of the pixels are excluded),
- exclude regions with charge traps in the serial register.

Total exposure 85.2 g-days



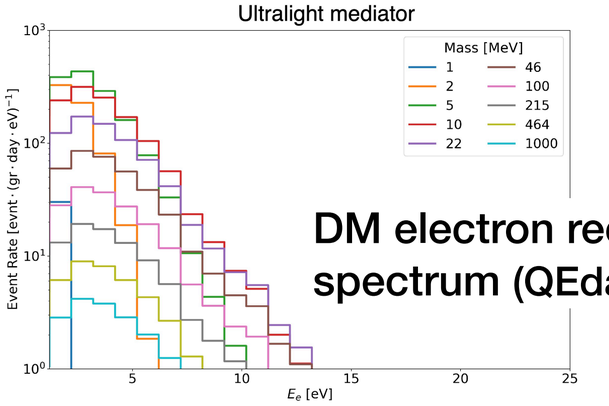


Pixel charge distribution

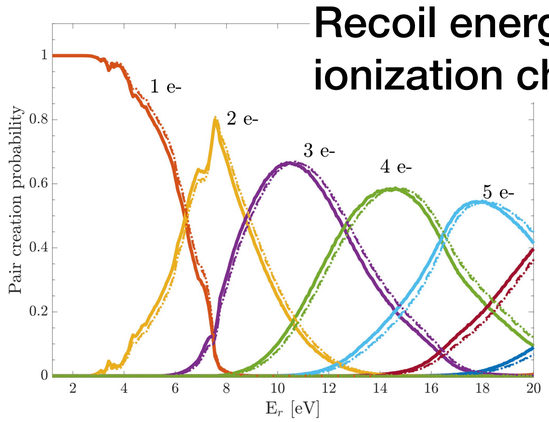


PRL 130, 171003 (2023)

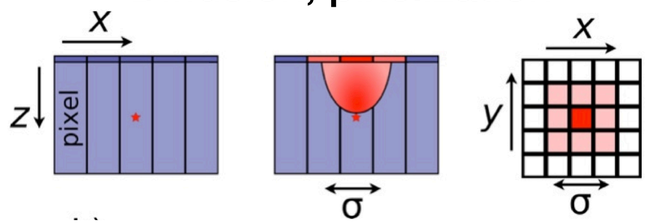
DM-electron scattering upper limit setting



DM electron recoil spectrum (QEdark)



Recoil energy to ionization charge



Add dark current to the DM signal

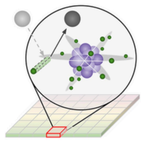
Binned likelihood function fit to the LBC data

Editors' Suggestion

First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

I. Arnquist *et al.* (DAMIC-M Collaboration)

Phys. Rev. Lett. **130**, 171003 (2023) – Published 28 April 2023

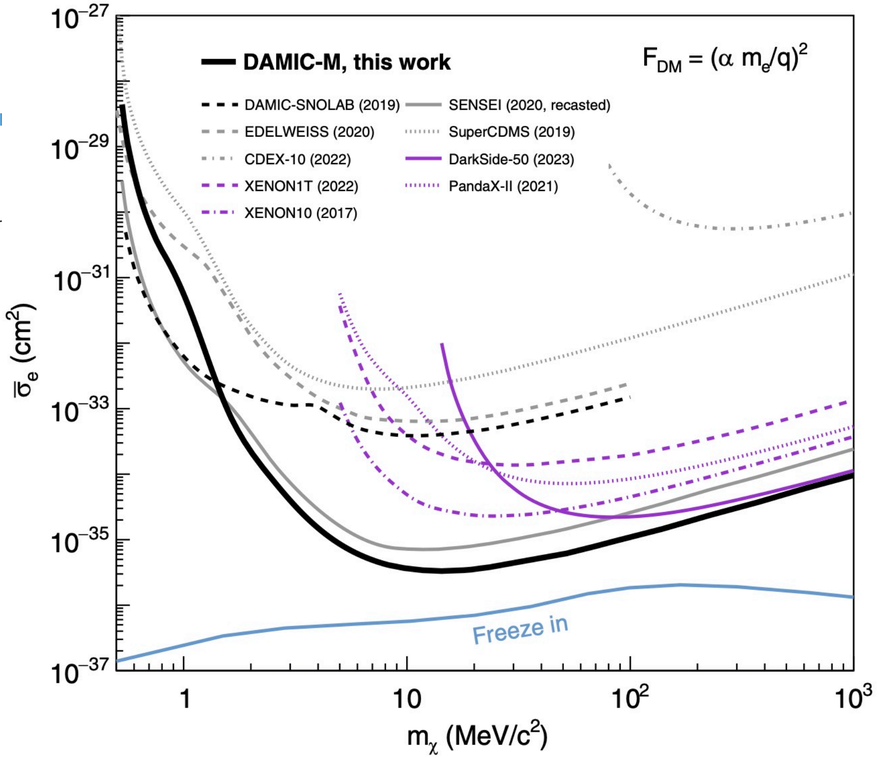


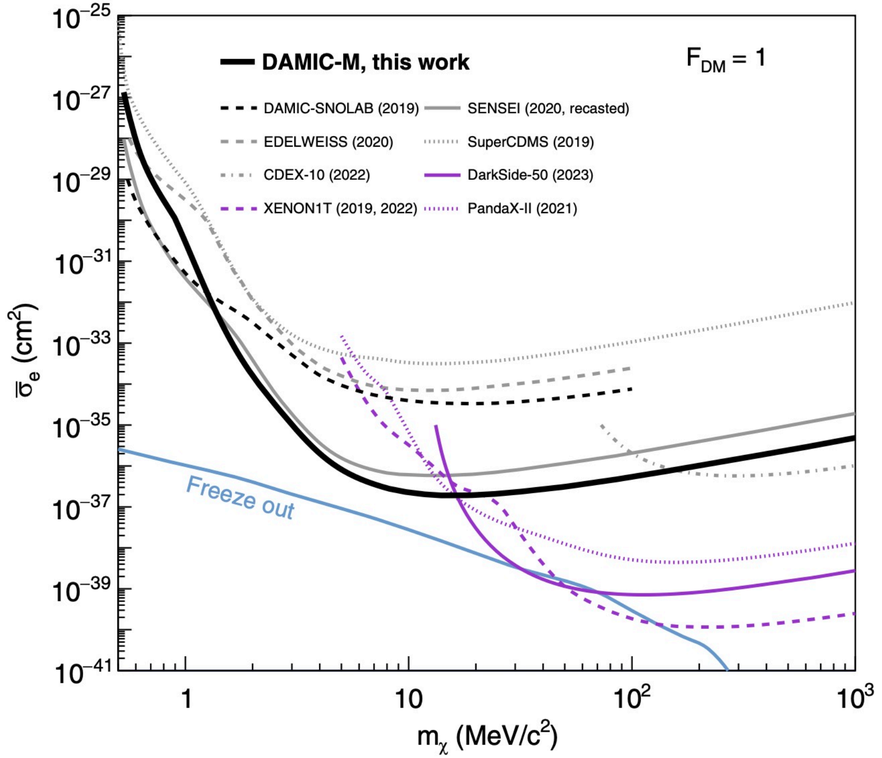
World-leading constraints are placed on electron interactions with dark matter in the MeV to GeV range by the first underground operation of a new CCD detector.

Show Abstract +

The best constraints at the time of publication

PRL 130, 171003 (2023)





Search for daily modulation of MeV DM signals

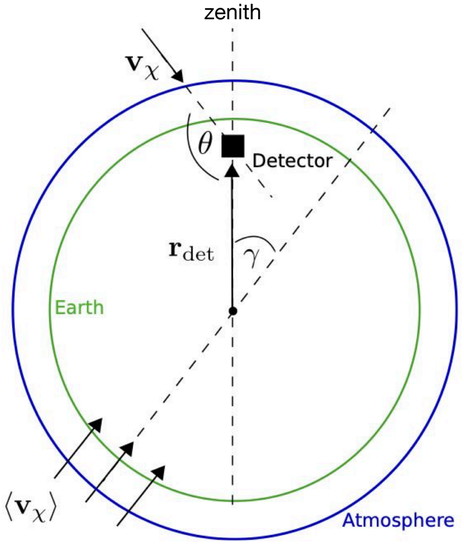
We have improved at lowest energies corresponding to the 1e⁻ bin

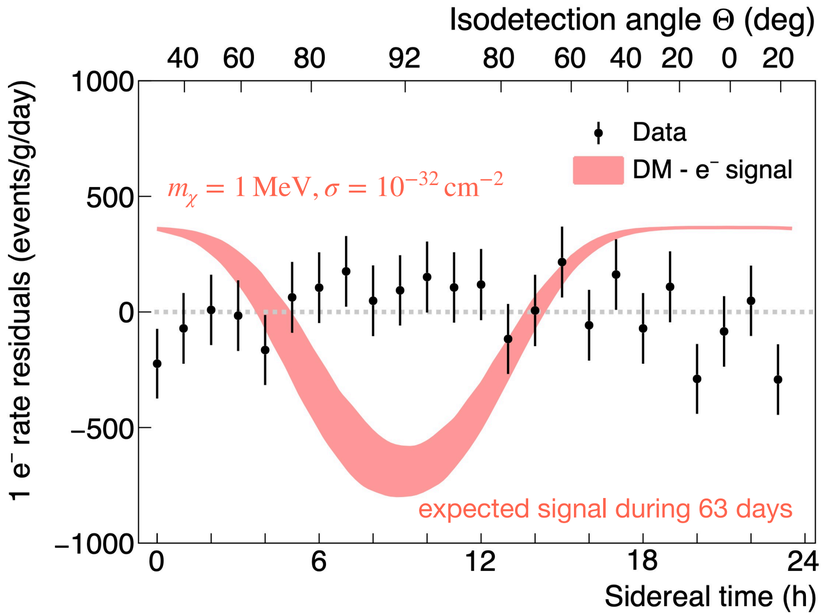
Motivation:

- Scattering in Earth's bulk modifies the DM flux and velocity distribution, resulting in daily modulation of the DM signal.
- In LBC, time-dependent signal vs. independent background strong discriminating power.
- New approach for constraining DM-electron scattering.

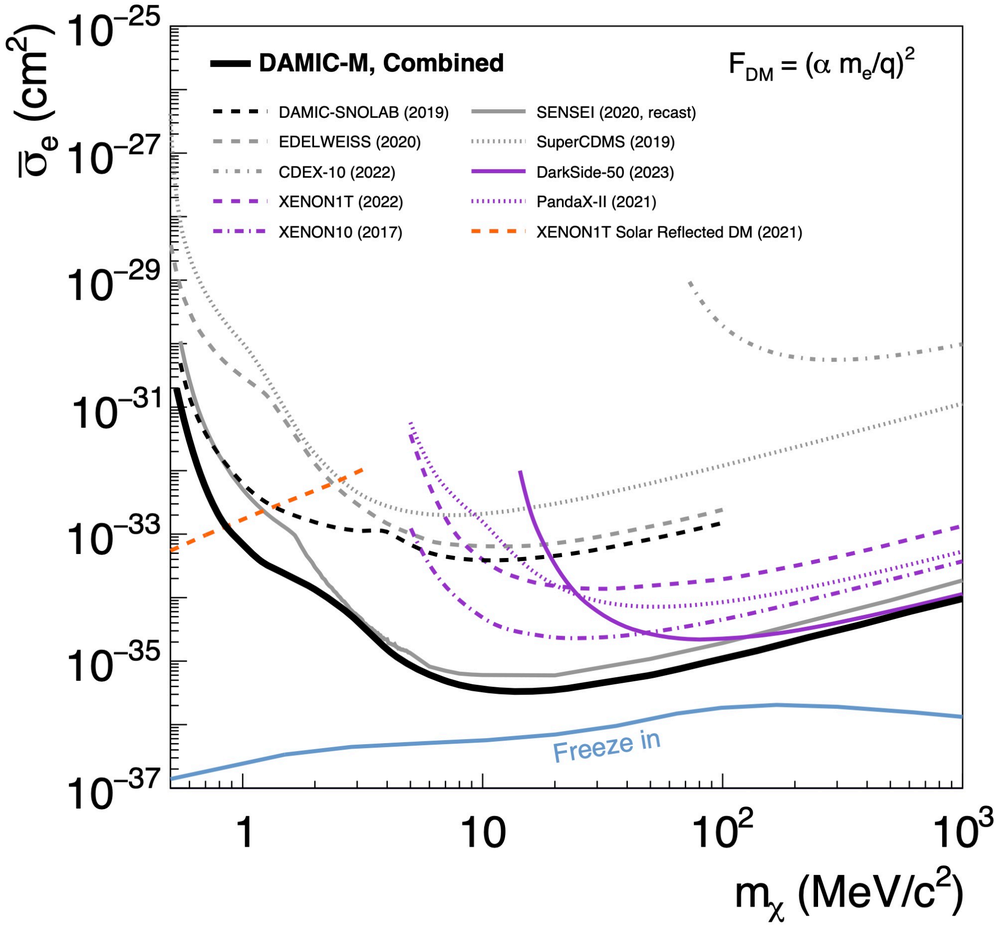
LBC result:

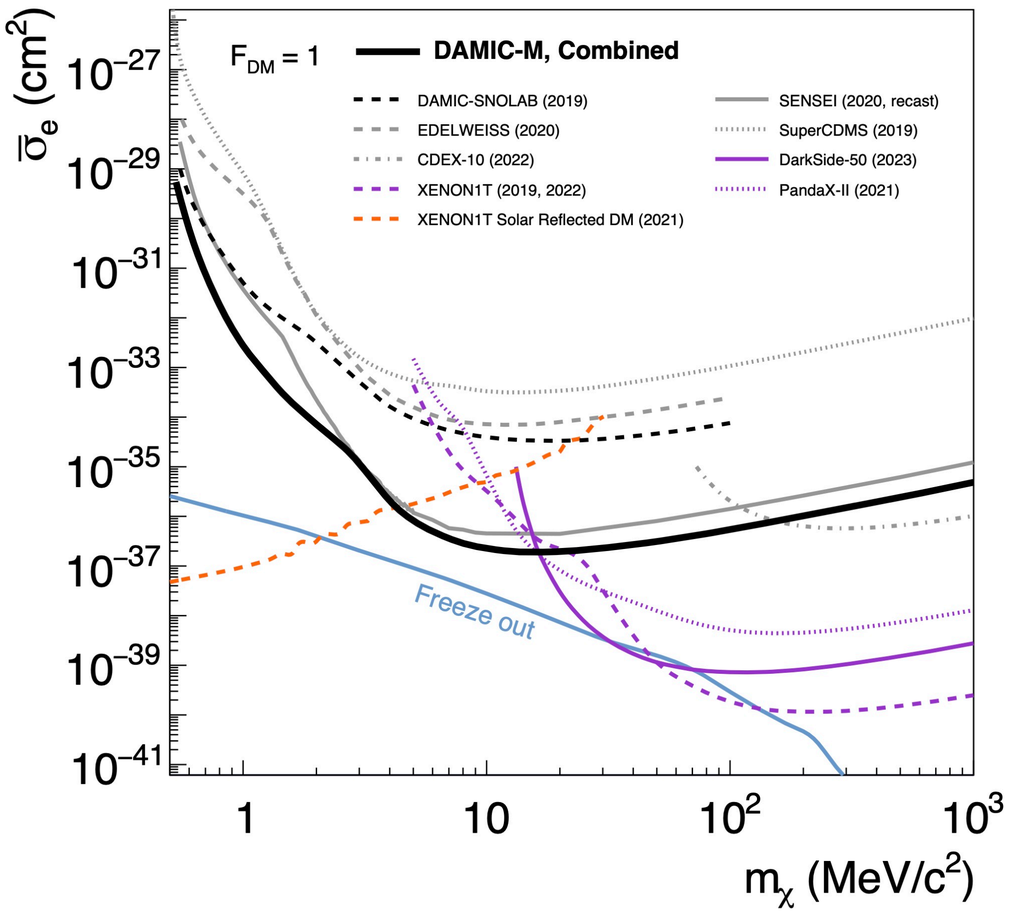
- Search in 1e⁻ bin, because bins >1e⁻ are already constrained,
- A subset of the data used in the previous work, the images were taken consecutively every 10 min during 63 days,
- No modulation signal found for periods of 1-48 hr.





LBC daily modulation constraints on DM-e scattering





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

PRL 132, 101006 (2024)

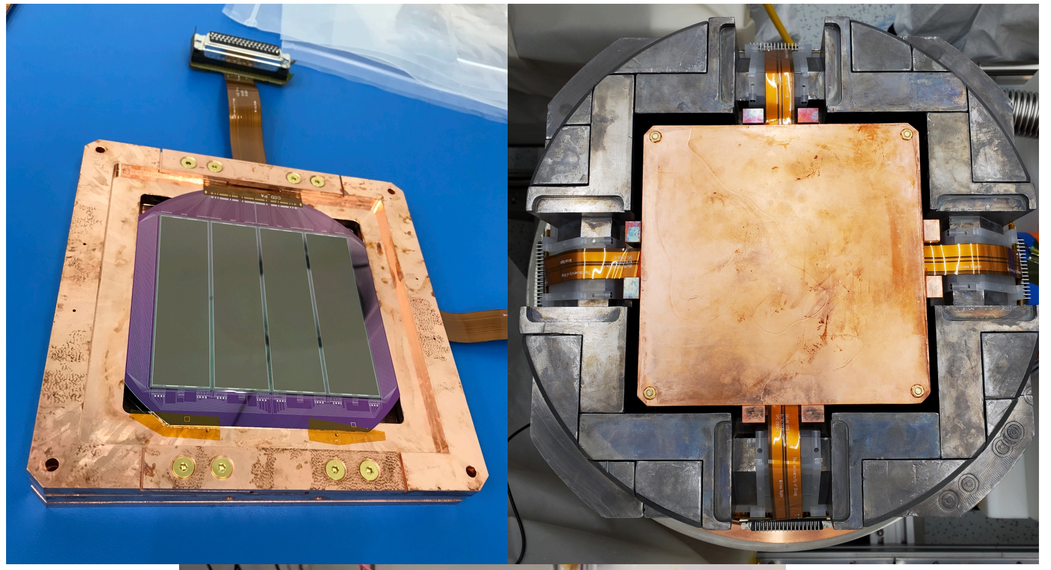
LBC upgrades after DM-e papers

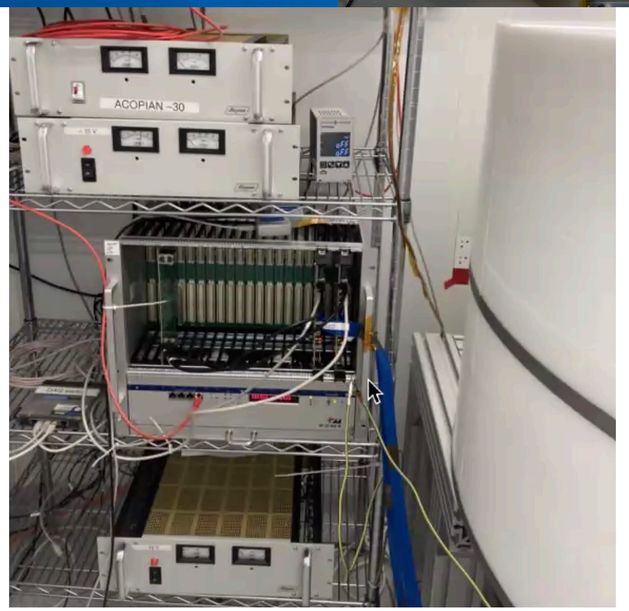
1. Two DAMIC-M CCD module prototypes were installed, CCDs are from the DAMIC-M pre-production run,

2. Lids of the CCD box from copper electro-formed and machined at LSC in Spain,

3. Background rates decreased after installing less activated CCDs and copper grown and machined underground at LSC,

4. New electronics: two times lower noise, lower dark current thanks to clock shaping and other modifications





Data analysis:

- Studying α rates,
- Coincidences, e.g. $\beta - \beta$ for ^{32}Si and ^{210}Pb,
- Low energy clusters,
- Dark current studies, etc.

Technical design publication is forthcoming

Outlook

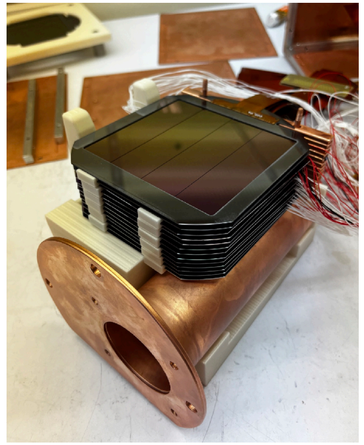
Happening right now!

- CCDs are being shipped from their underground storage at SNOLAB to the Univ. of Washington,
- (Extremely) busy with preparing for packaging and testing CCDs,
- Radiopure CCD flex cables are being fabricated,
- Testing new electronics,
- Issuing purchase orders for commercial and electro-formed copper, pitch adapters, etc.,
- Plans for new clean room at LSM,

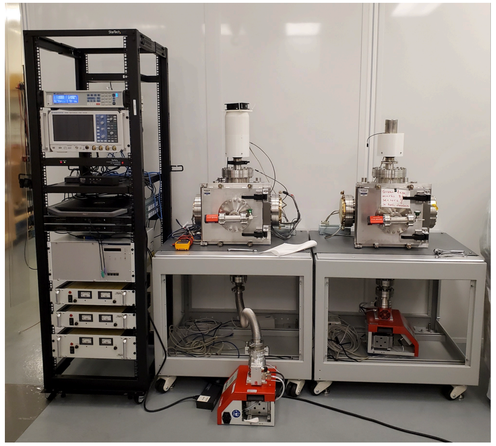
- We continue to take new data with the LBC at LSM,
- ongoing data analysis (the nuclear recoil ionization efficiency and the LBC)

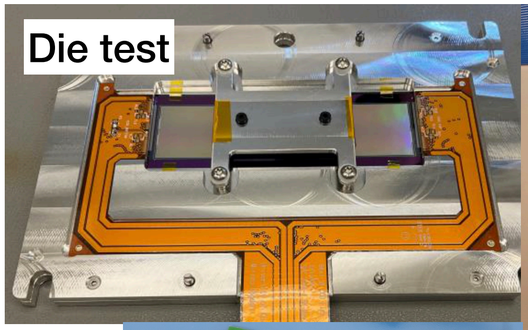
DAMIC-M will be online in 2025 and will push the search for dark matter into new, unexplored regions that were previously non-accessible due to detector limitations. Skipper CCDs have the potential for new discovery.

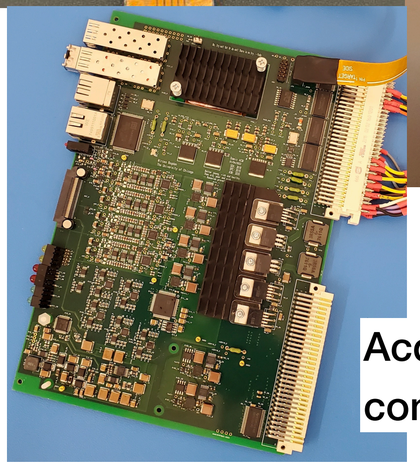
Prototyping



New test chambers







Acquisition and control module

Dark Matter in CCDs in Modane (DAMIC-M)

https://damic.uchicago.edu/