Status of DAMIC-M and related experiments

Kellie J. McGuire
CENPA Monday Meeting
May 1, 2023

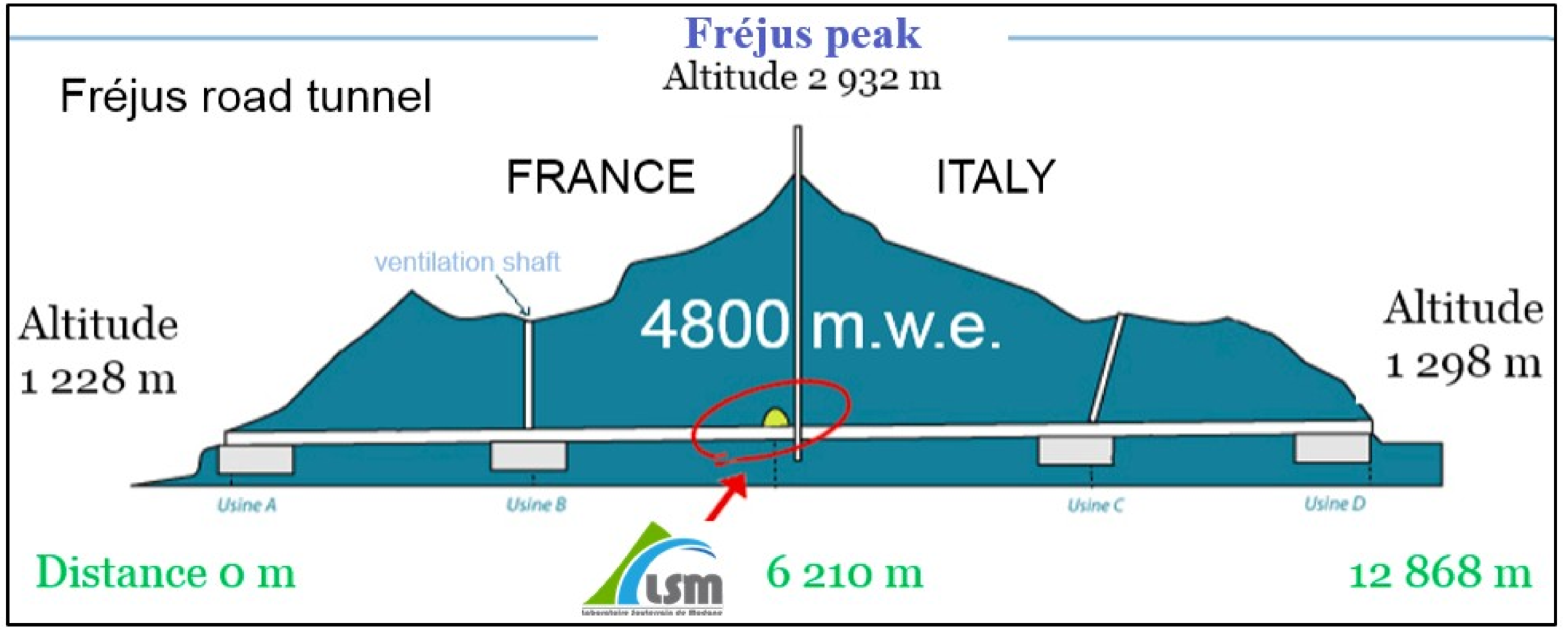
Outline

- DAMIC-M
  - Overview
  - Status
  - Recent results
- Electron/nuclear recoil discrimination in CCDs
- CCD surface calibrations

DArk Matter In CCDs at Modane

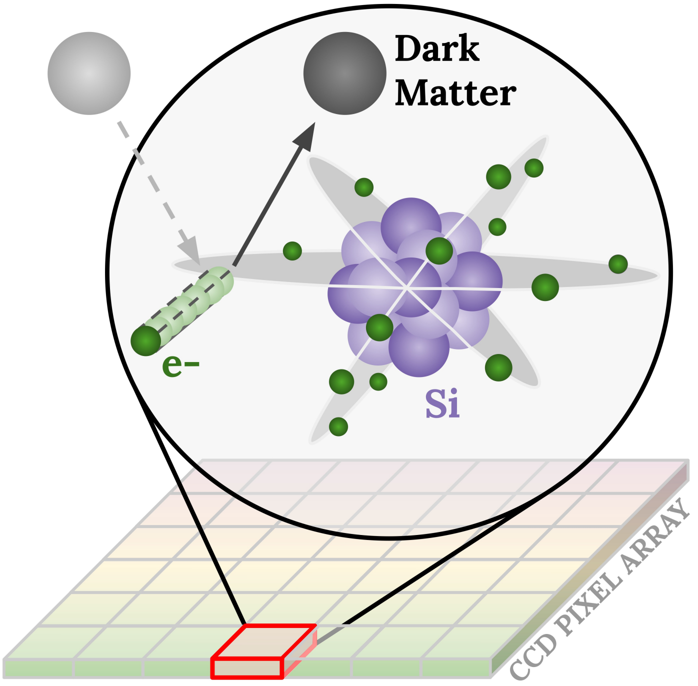
DAMIC-M: A kg-scale detector using silicon charge-coupled devices (CCDs) to search for light (sub-GeV) dark matter.

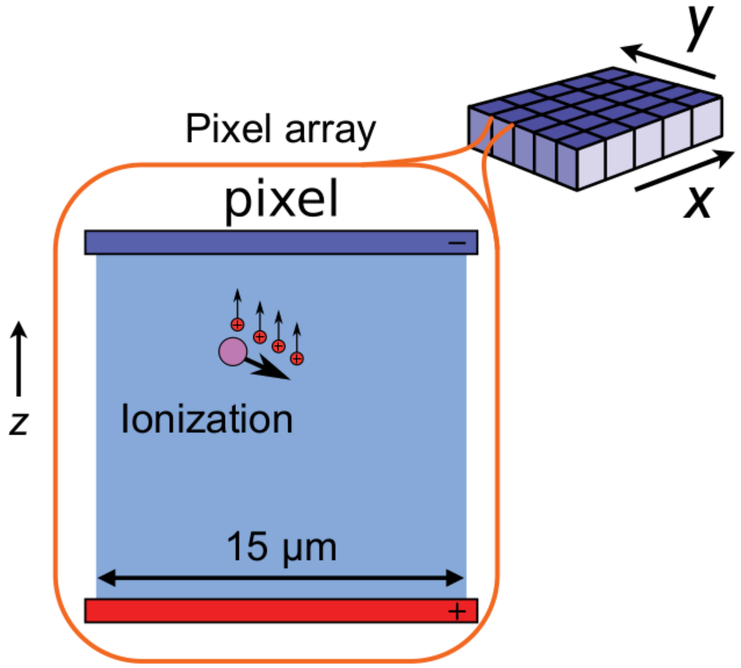
Located at the Laboratoire Souterrain de Modane (LSM) 1,700 meters below the Fréjus peak in Modane, France.



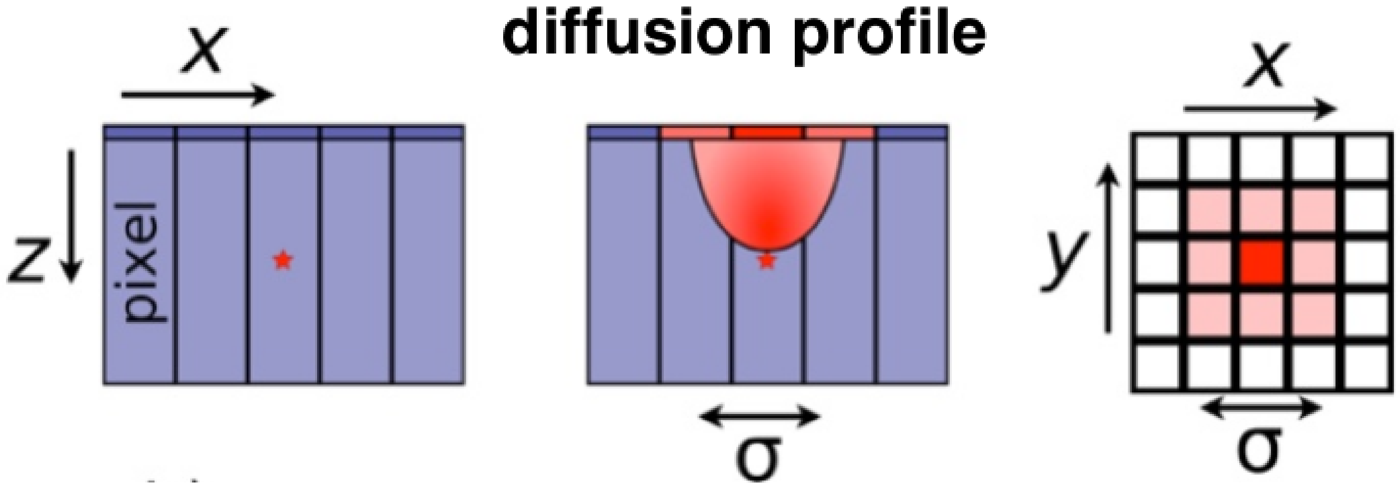
<u>Commissioning and data acquisition to begin in 2024.</u>

CCDs as dark matter detectors

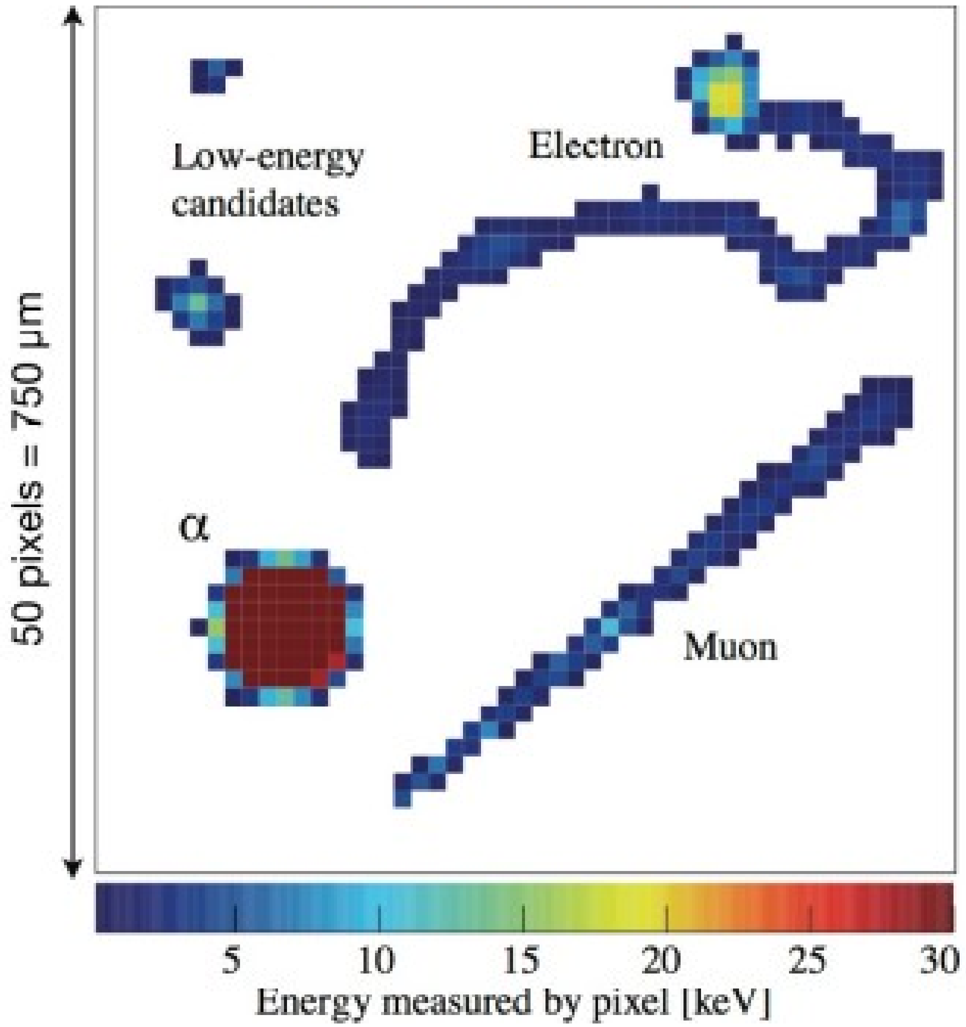




- DM particle scatters off Si nucleus or valence electron, creating ionization
- one e-h pair produced per 3.77eV (avg) deposited
- bias voltage drifts charge to readout plane
- lateral diffusion of charge proportional to drift time (3D spatial resolution)
- pixelation allows for particle identification via cluster shape
- backgrounds rejection via spatially and temporally correlated decay products



CCDs as dark matter detectors



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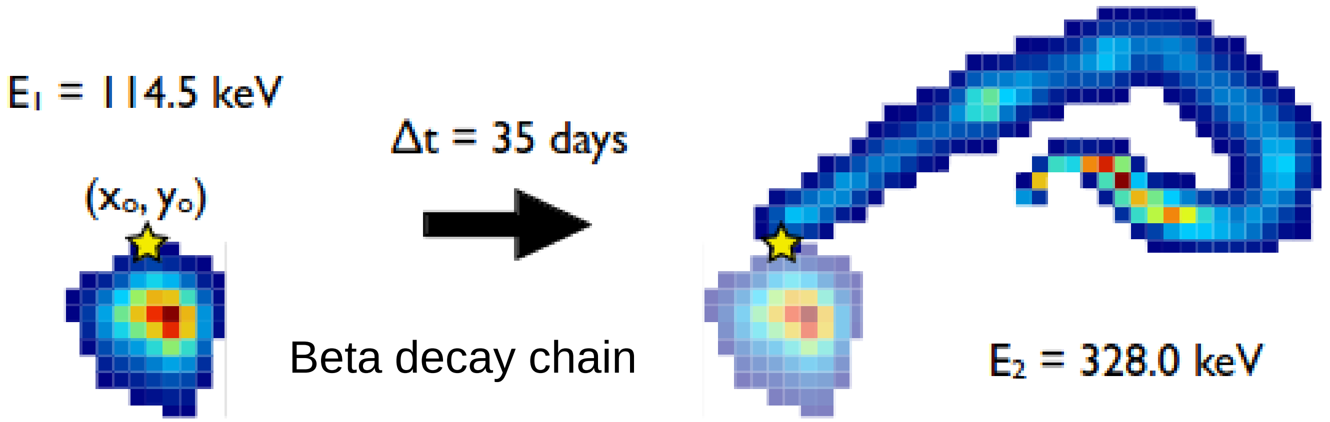
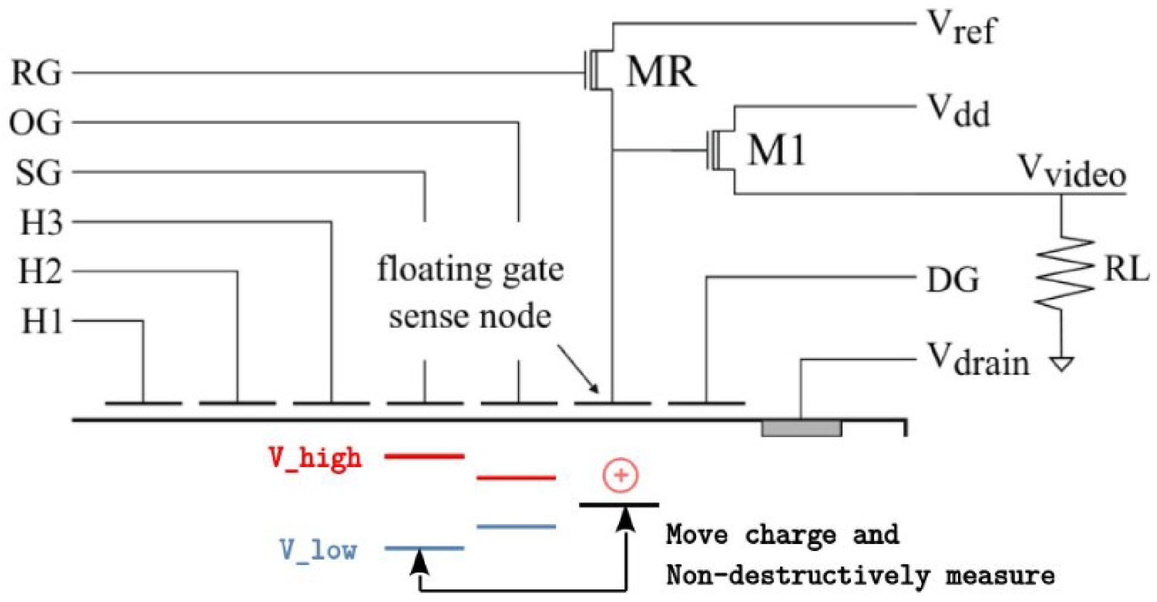


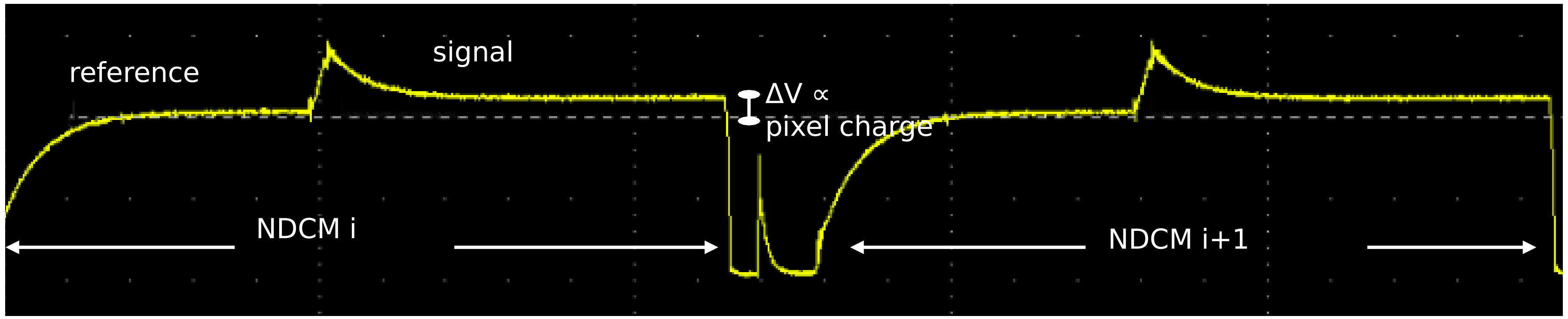
JINST 16(2021)P06019

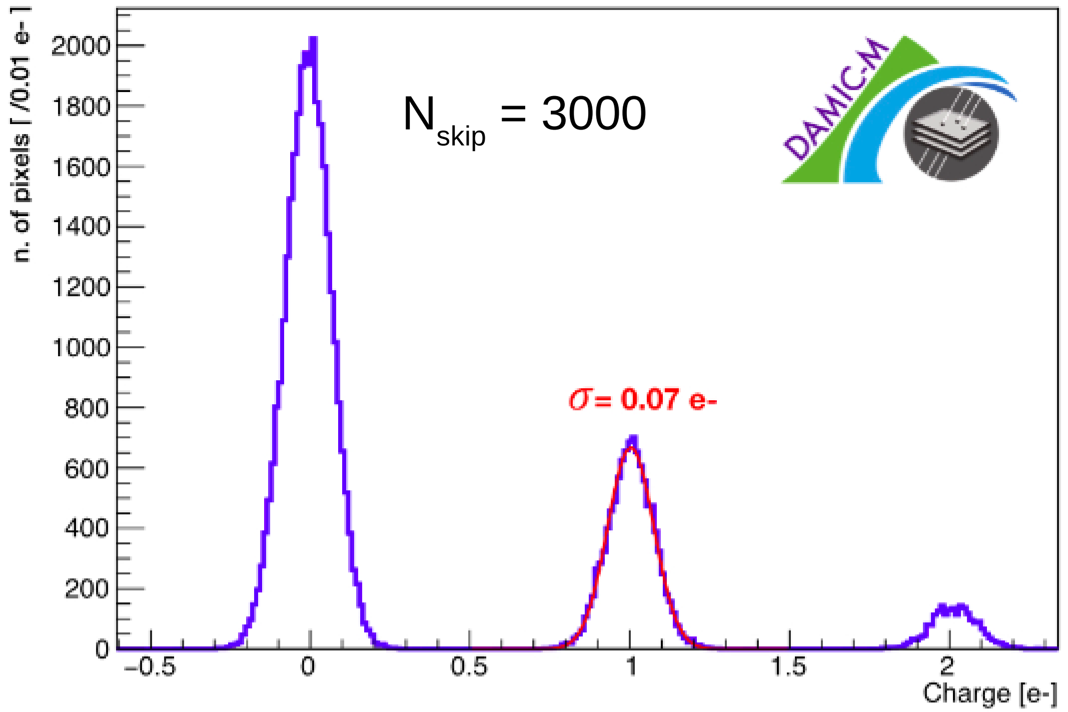
Skipper CCDs for sub-electron noise

- DAMIC-M CCDs equipped with floating gate "skipper" readout stage
- Floating gate allows for repeat non-destructive pixel charge measurements (NDCMs)
- Measure each pixel N_{skip} times for $1/\mathrm{sqrt}(N_{skip})$ noise suppression
- Achieve sub-electron resolution after a few hundred N_{skip}



Correlated double sampling (CDS)



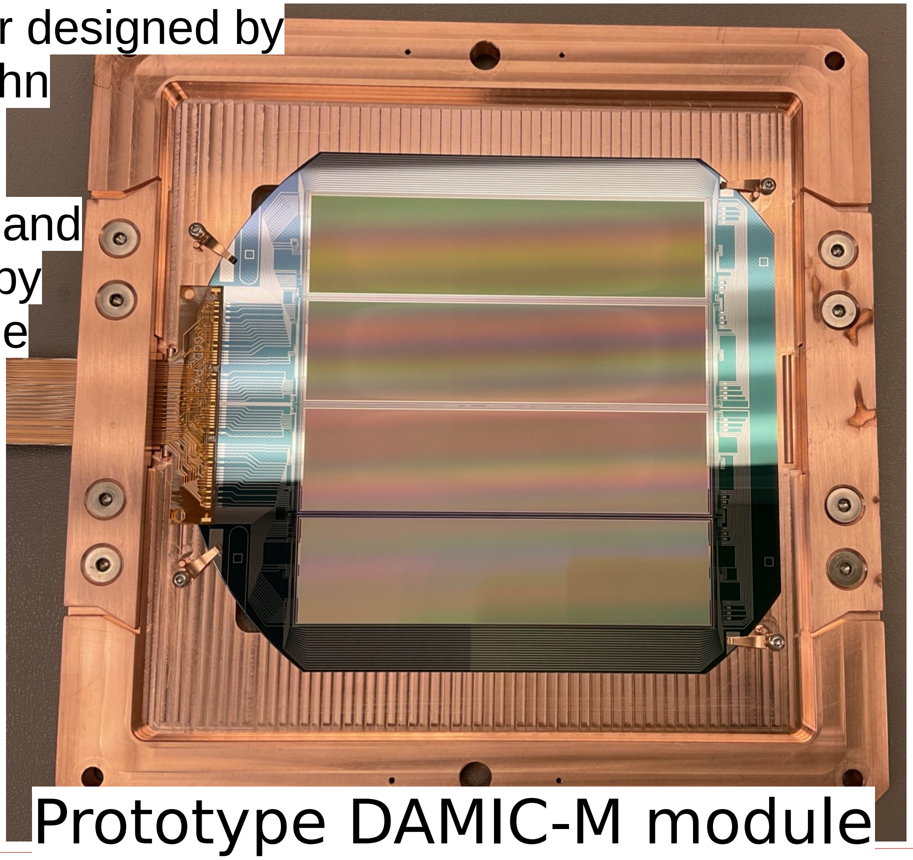


The DAMIC-M Detector

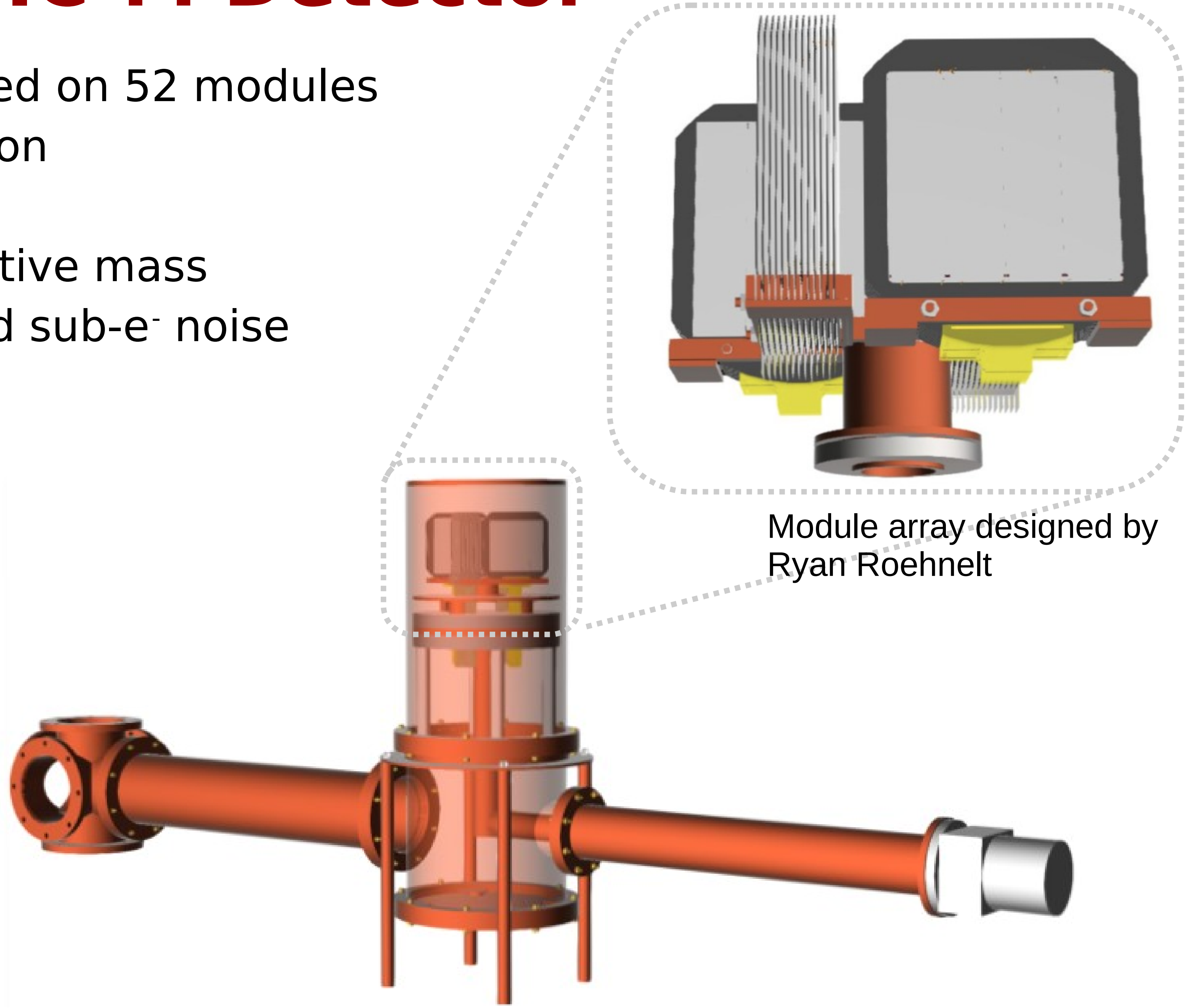
- 208 9-Mpixel (6k x 1.5k) CCDs packaged on 52 modules
- high-resistivity (>10kΩcm) n-type silicon
- pixel size: 15 x 15 x 675 um^3
- each CCD 3.5 grams --> 700 grams active mass
- custom electronics for fast readout and sub-e^- noise

Pitch adapter designed by Michael Huehn

CCDs glued and wirebonded by Marcel Conde



Prototype DAMIC-M module



Module array designed by Ryan Roehnelt

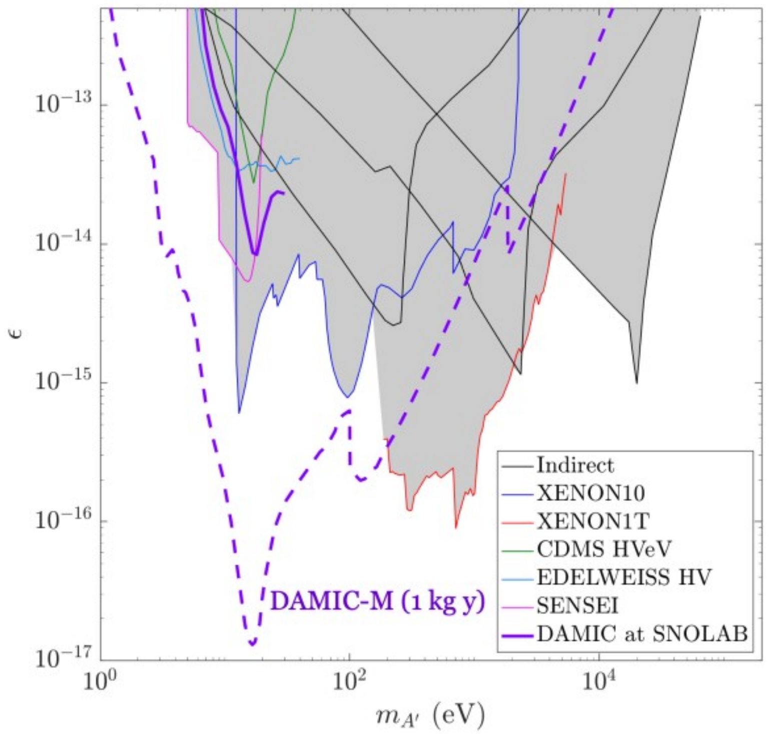
Science reach

DAMIC-M will be sensitive to...

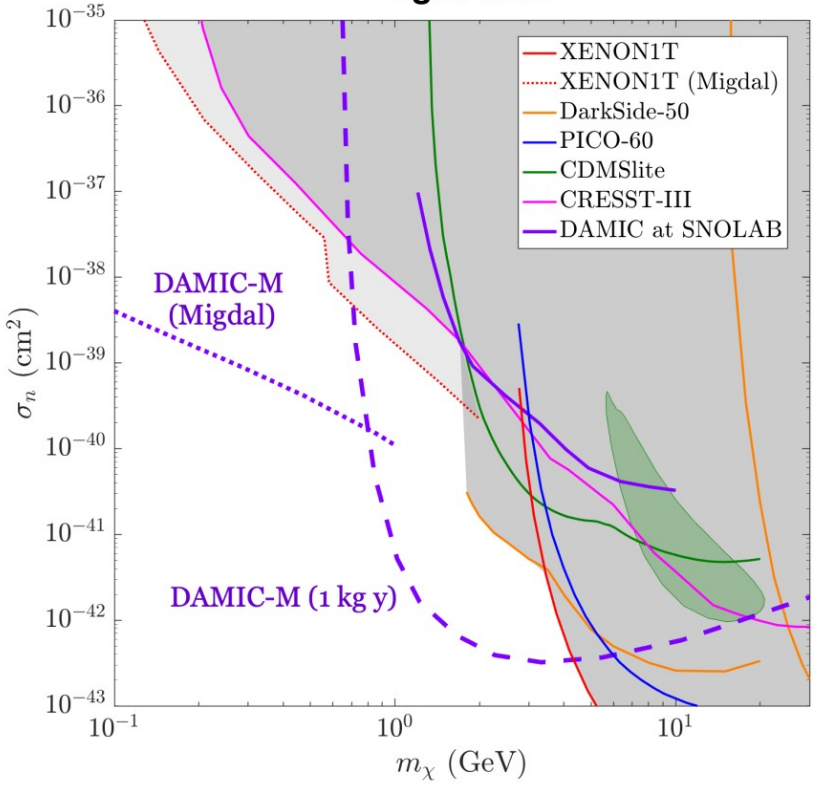
light WIMPs via DM-nucleus elastic scattering and inelastic scattering (Migdal effect)
[PRL 127, 081805 (2021)]

hidden-sector candidates via DM-electron scattering and DM absorption
[arXiv:1707.04591v1]

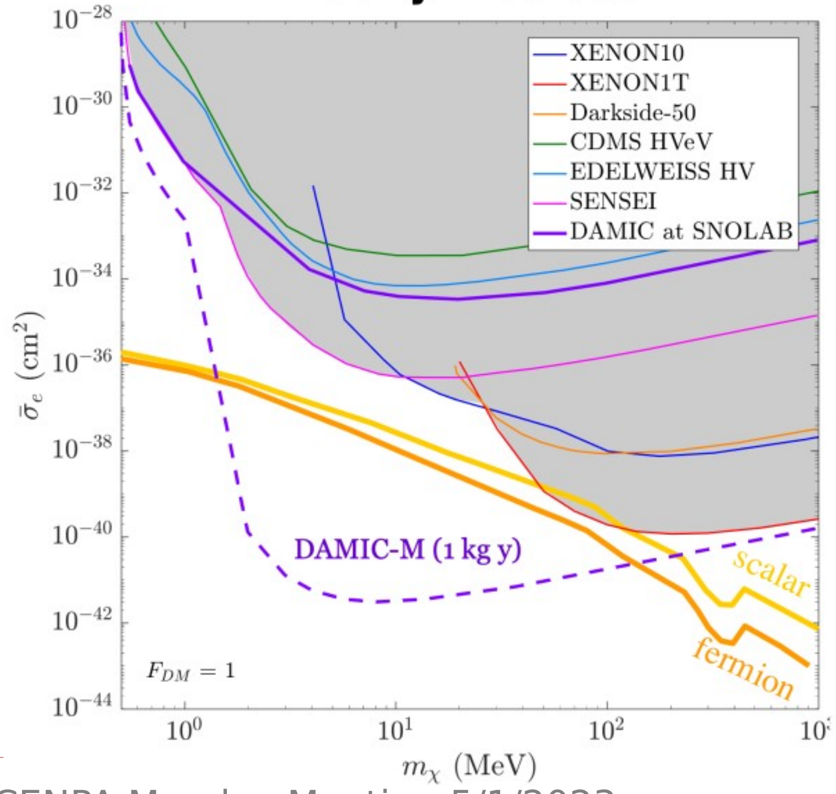
hidden photon



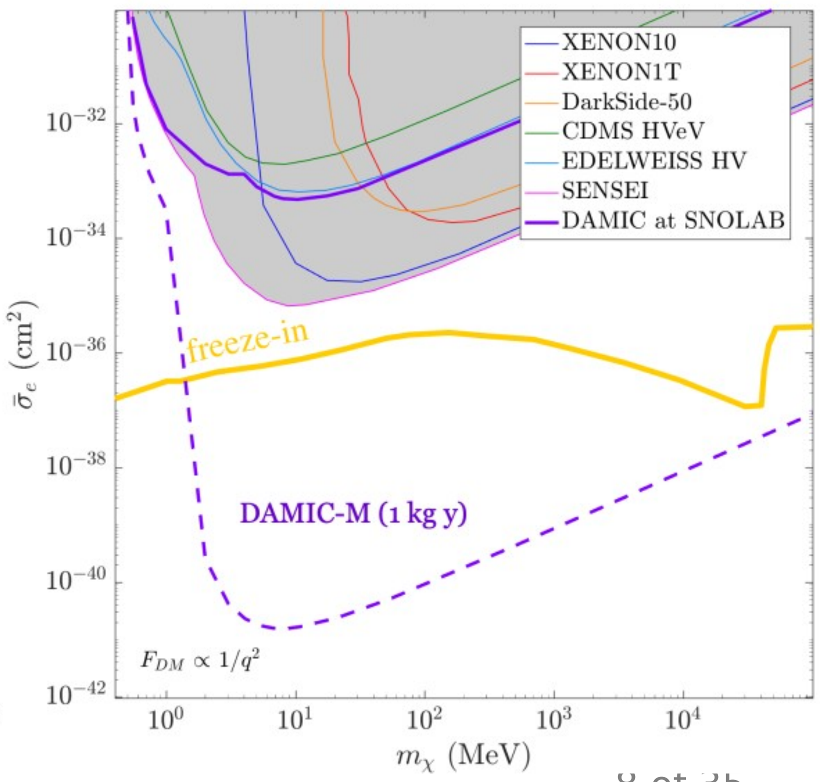
light WIMP



heavy mediator

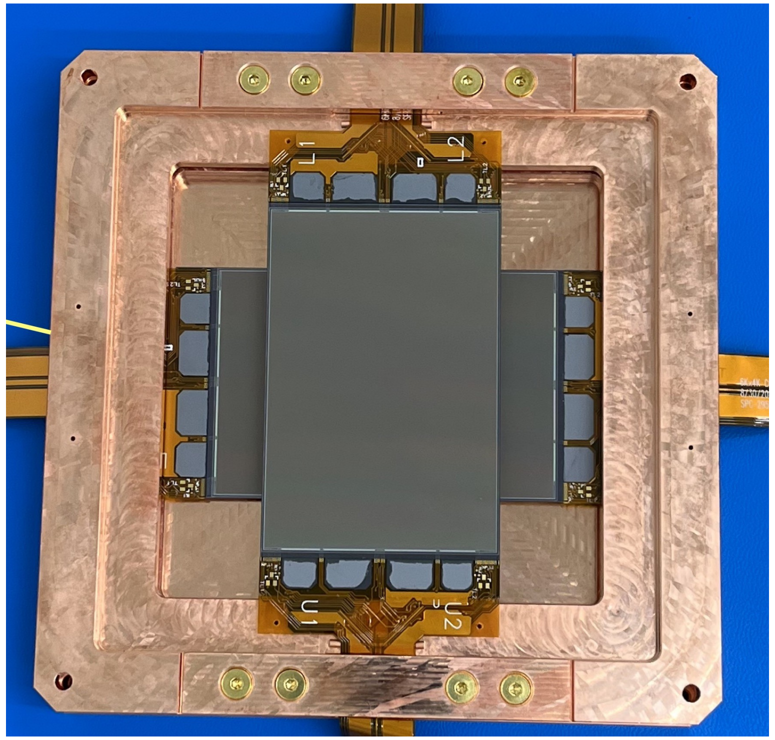


light mediator

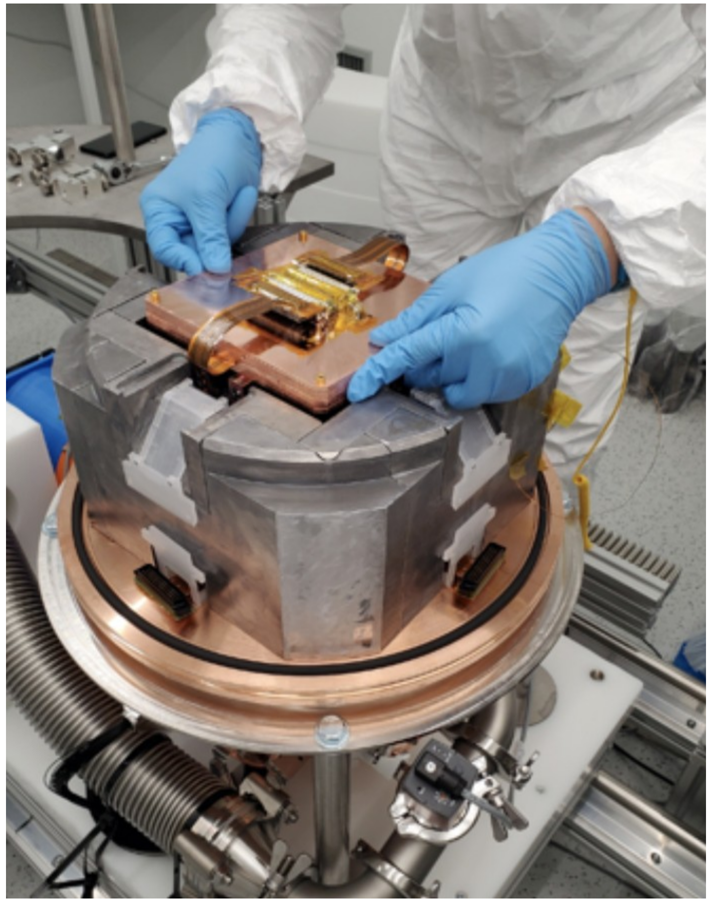


Low-Background Chamber

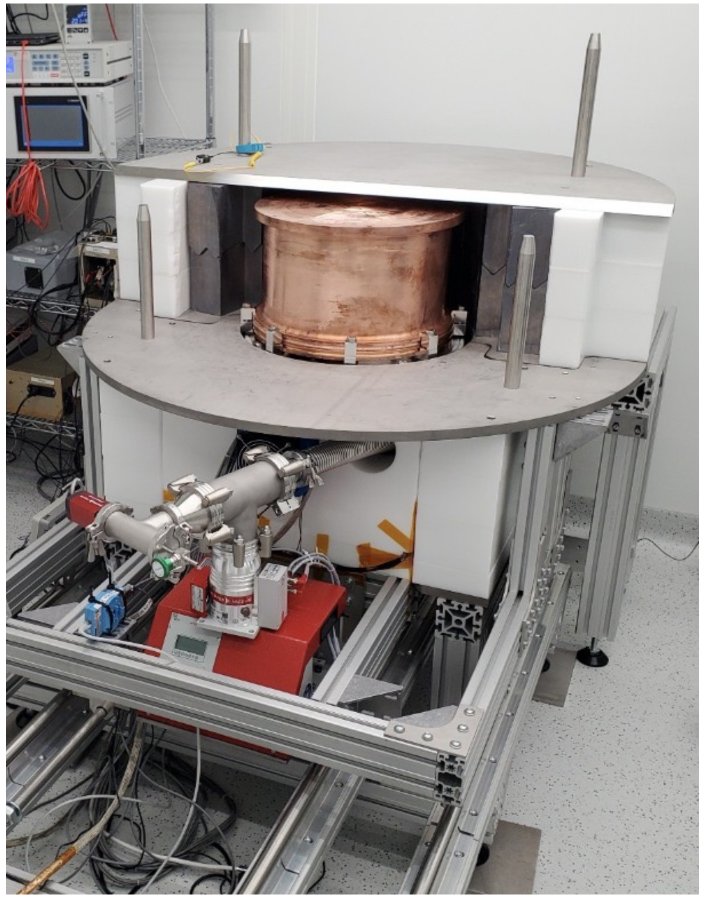
Prototype detector located underground at LSM in operation since early '22



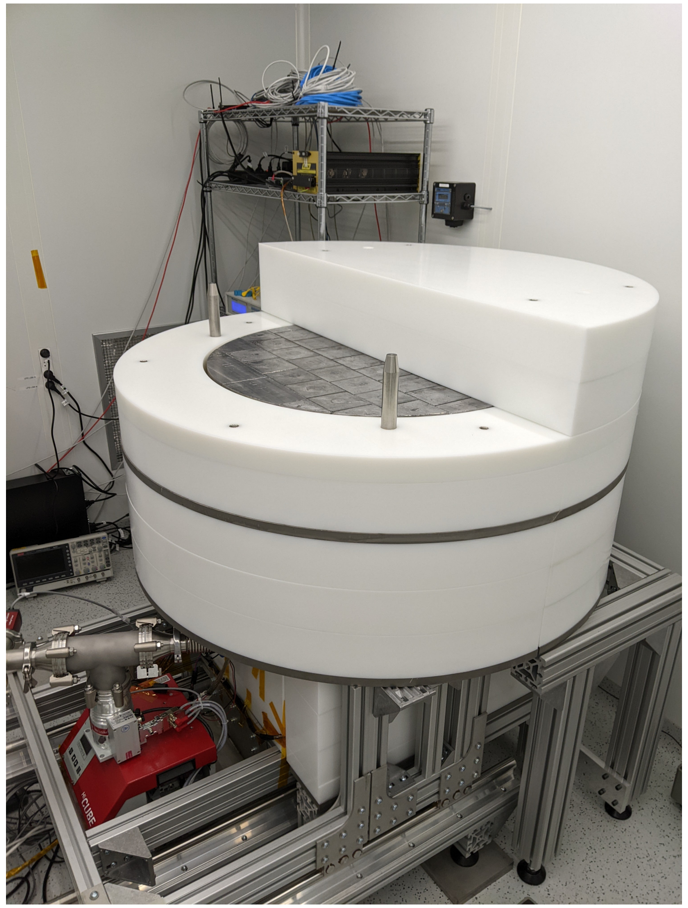
Two 6kx4k skipper CCDs (18 grams active mass) installed in high-purity, oxygen-free copper box



Copper box surrounded by 7.5+ cm low-background lead, innermost ancient



Detector enclosed in copper cryostat, external shield open

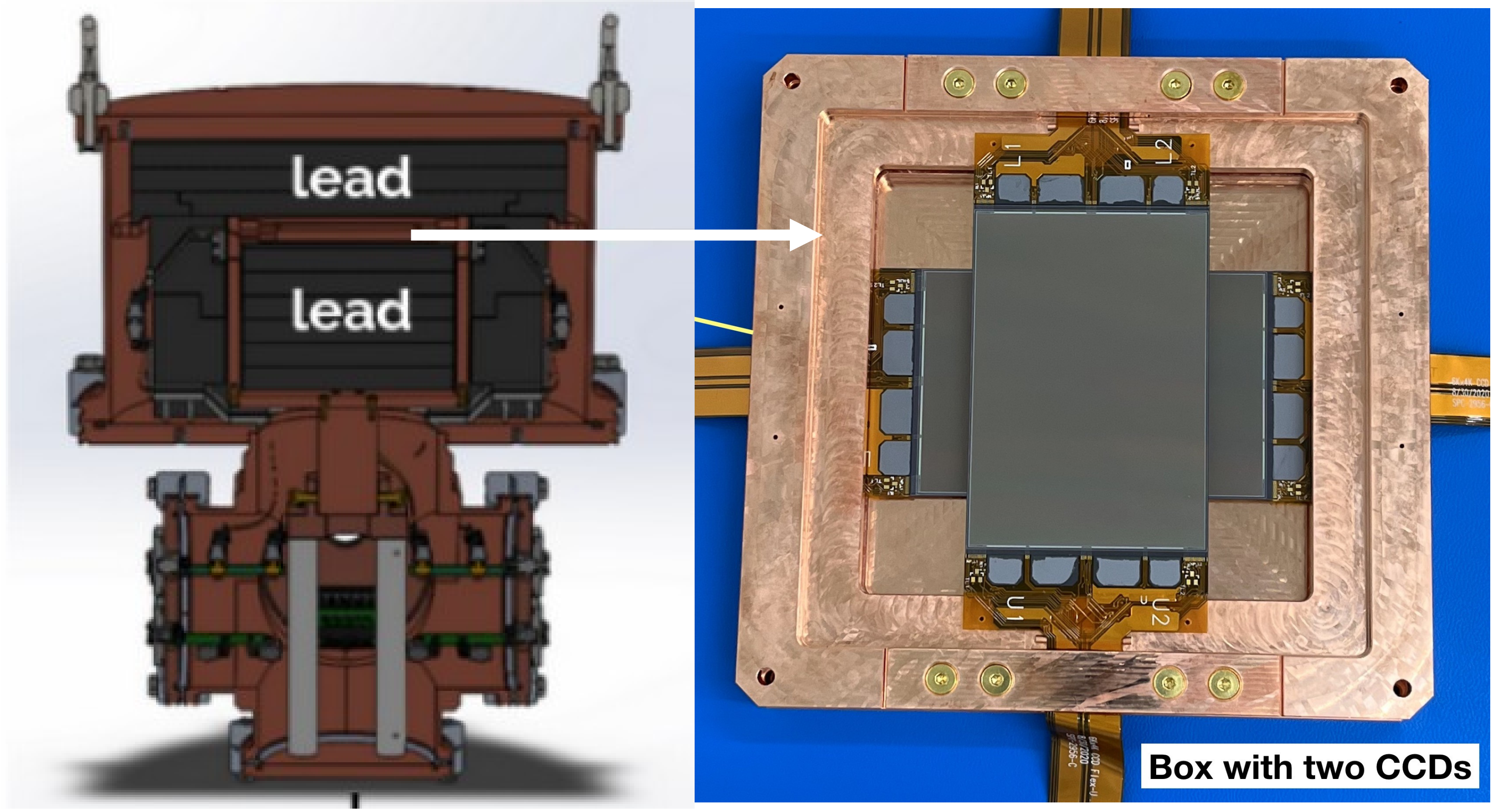


Low-background lead and polyethylene external shield in place

Low-Background Chamber

LBC objectives

- Demonstrate skipper CCD performance
- Characterize backgrounds and inform mitigation strategies
- Provide test bench for dark current studies and reduction stategies
- Determine sensitivity to light dark matter



Prototype performance

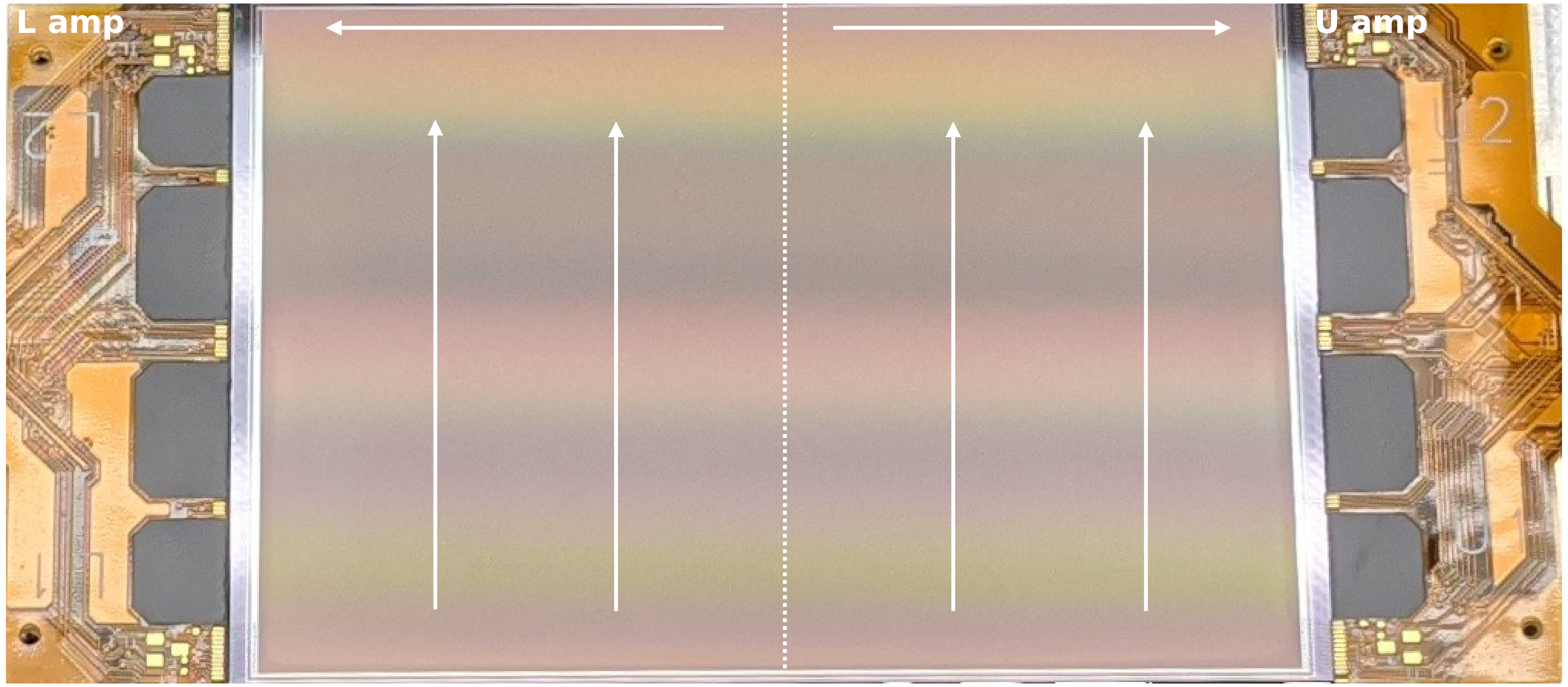
- ~10 dru background rate
- Dark current ~4.5 x 10^{-3} e^-/pixel/day (~20e^-/mm^2/day)
- 0.2 e^- noise at N_{skip} = 650
  (using commercial readout electronics)

Sensitive to unexplored DM-e^- scattering parameter space...

LBC DM-electron scattering

Operation

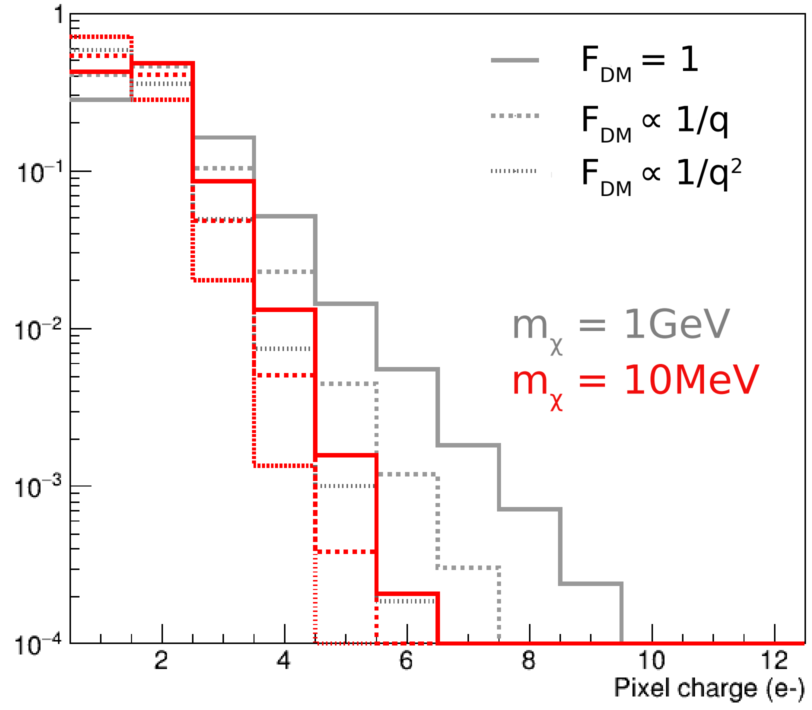
- Substrate voltage: 70V
- CCD temperature: 130K
- Vacuum pressure: 5×10^{-6} mbar
- Each CCD half read through a separate skipper amplifier



Data sets

- Two science runs, both using 10x10 hardware binning (pixels summed before readout) → **Pixel-based analysis**
- SR1: continuous readout
- SR2: read first 110 (binned) rows; CCD cleared of charge before readout
- Total SR1 + SR2 exposure: 85.23 g-days

LBC DM-electron model



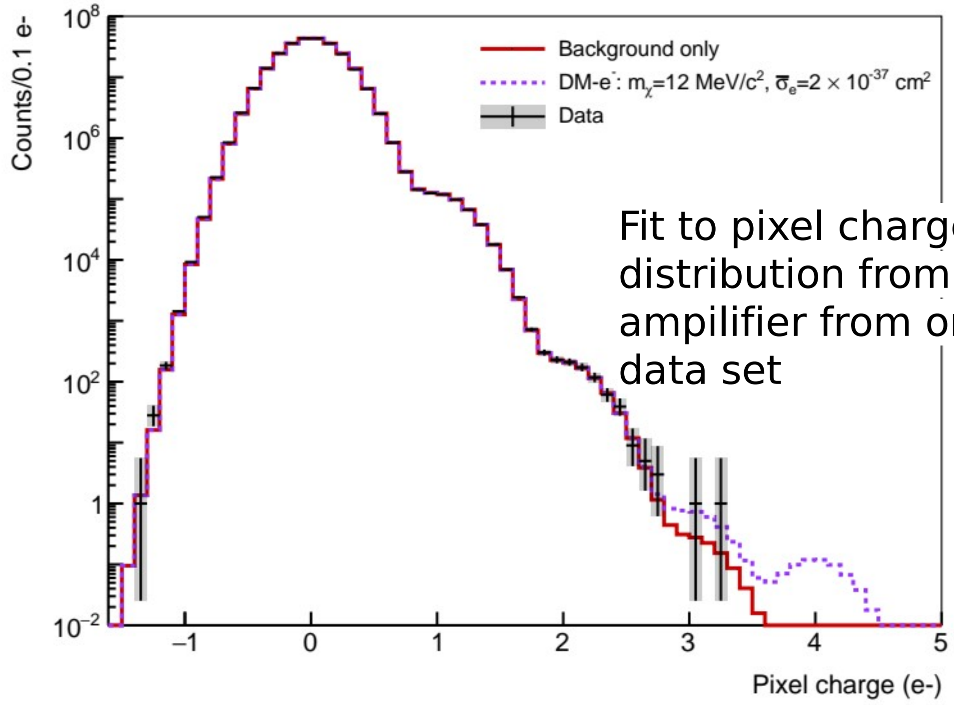
Generate DM signal templates

- DM halo parameters
- DM form factor
- ionization efficiency
- detector response

Build pixel charge distribution

DM signal component, Poisson background, readout noise

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

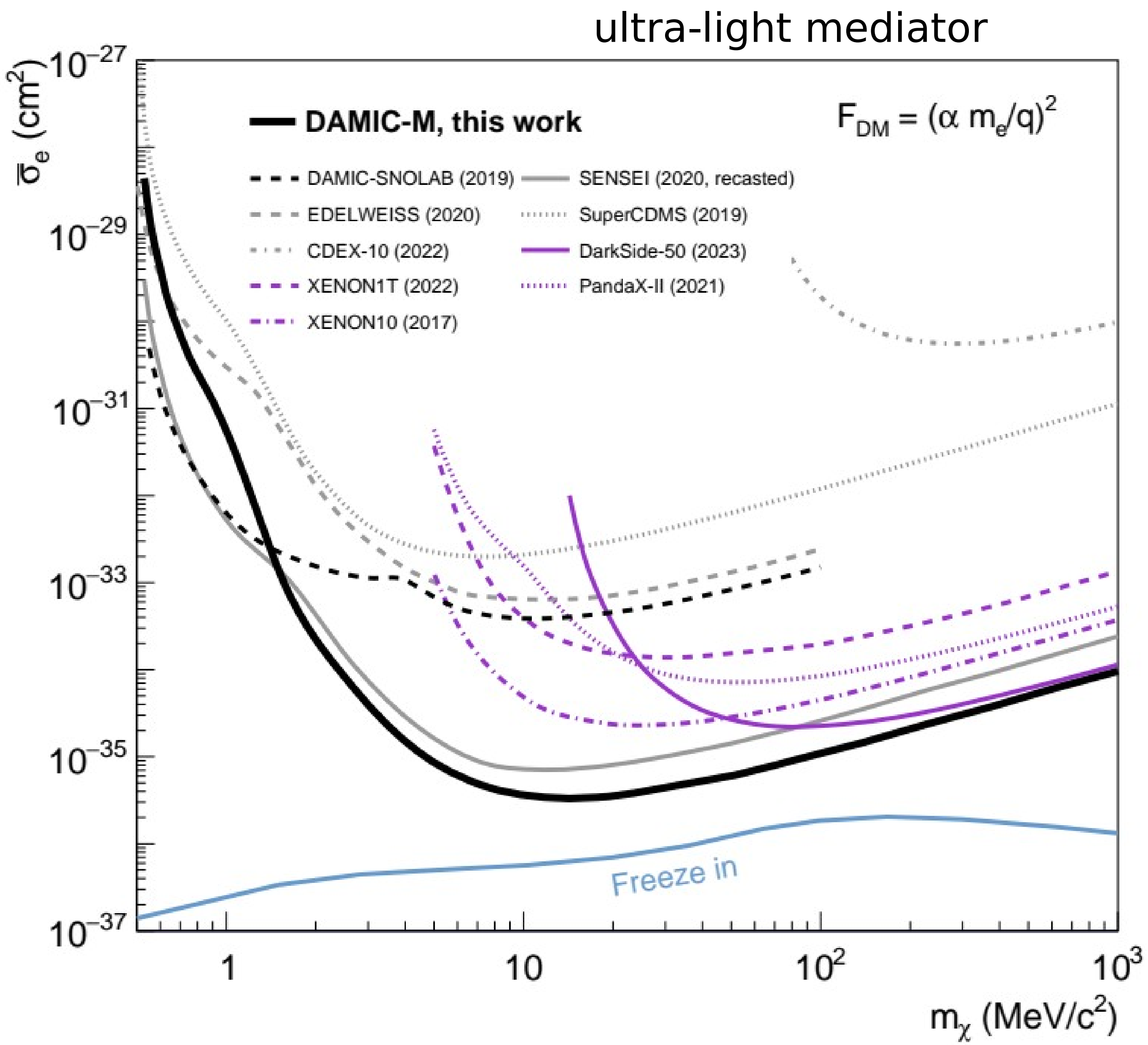


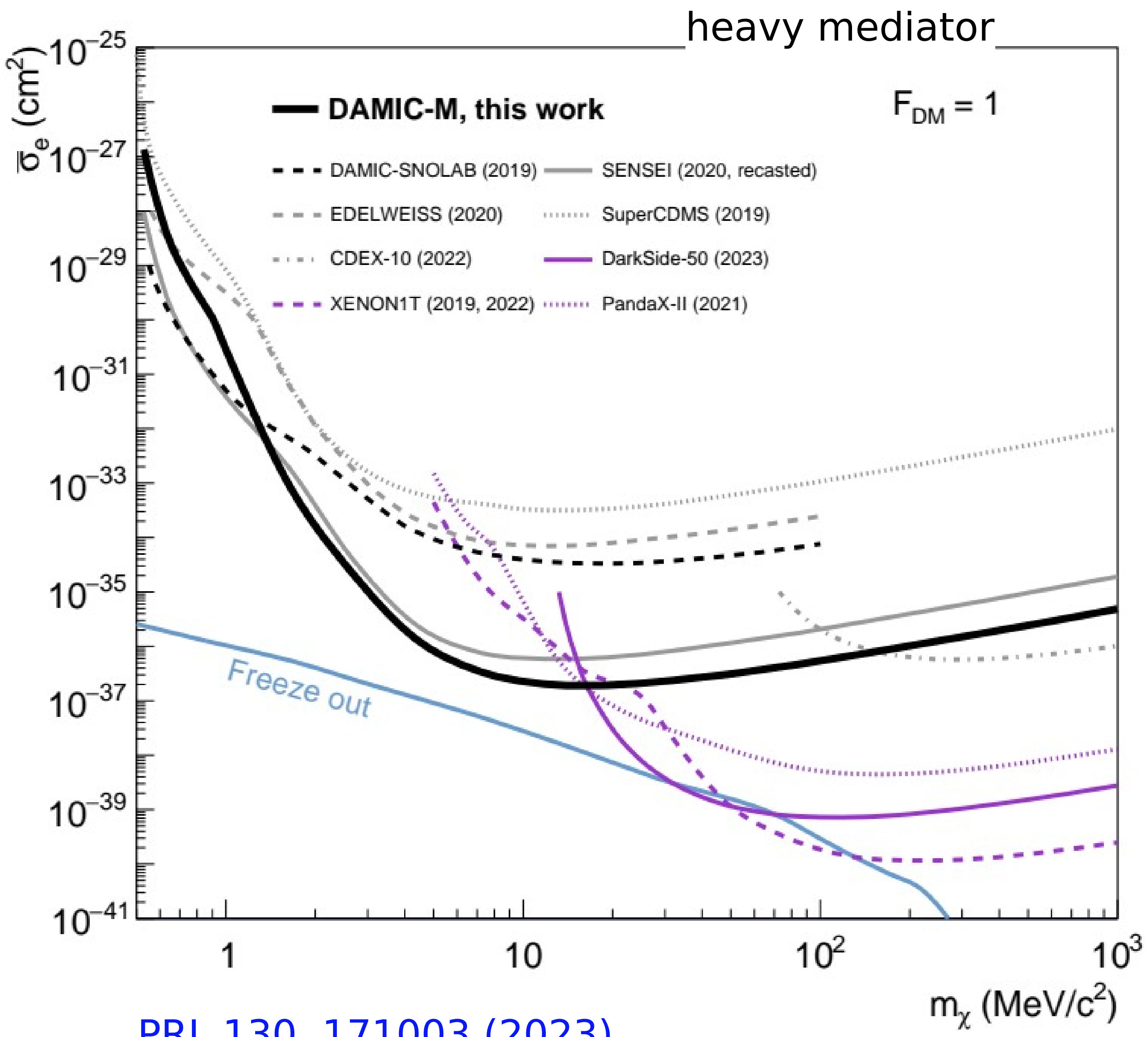
Fit to pixel charge distribution from one amplifier from one data set

Perform joint binned likelihood fit

One term for each amplifier for each data sets

LBC 90% CL upper limits





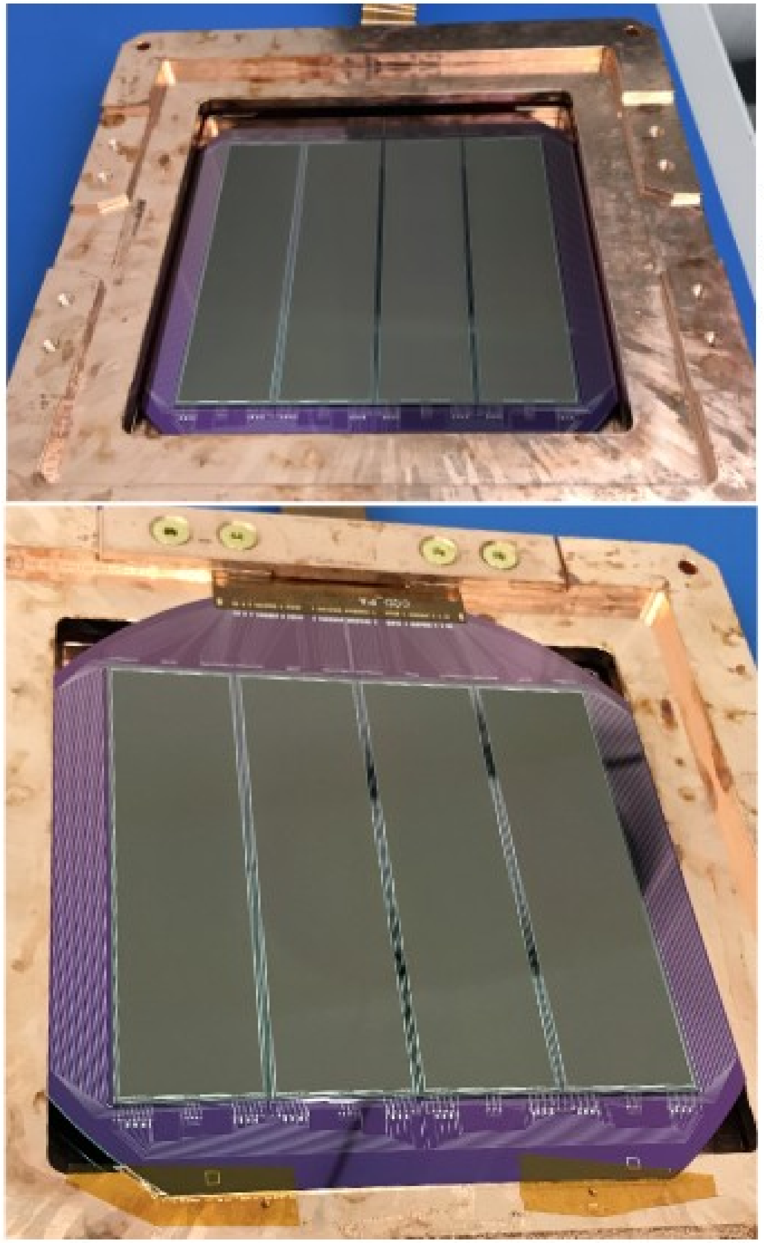
PRL 130, 171003 (2023)

Toward DAMIC-M's sensitivity goals...

Improve sub-electron resolution
- Custom readout electronics for lower noise with fewer N_{skips}

Lower backgrounds
- Cleaner CCDs (shorter surface exposure)
- More electroformed copper parts
- Low-activity cables

Lower dark current levels
- Smaller-format CCDs (two DAMIC-M CCD modules with 8 6k x 1.5k CCDs are installed and operating at LSM; immediate 3x improvement in DC)
- Improved cooling
- Studies into sources of few-electron events (e.g., charge traps, transition radiation, Cherenkov)
- Optimization of operating parameters



DAMIC-M modules installed at LSM

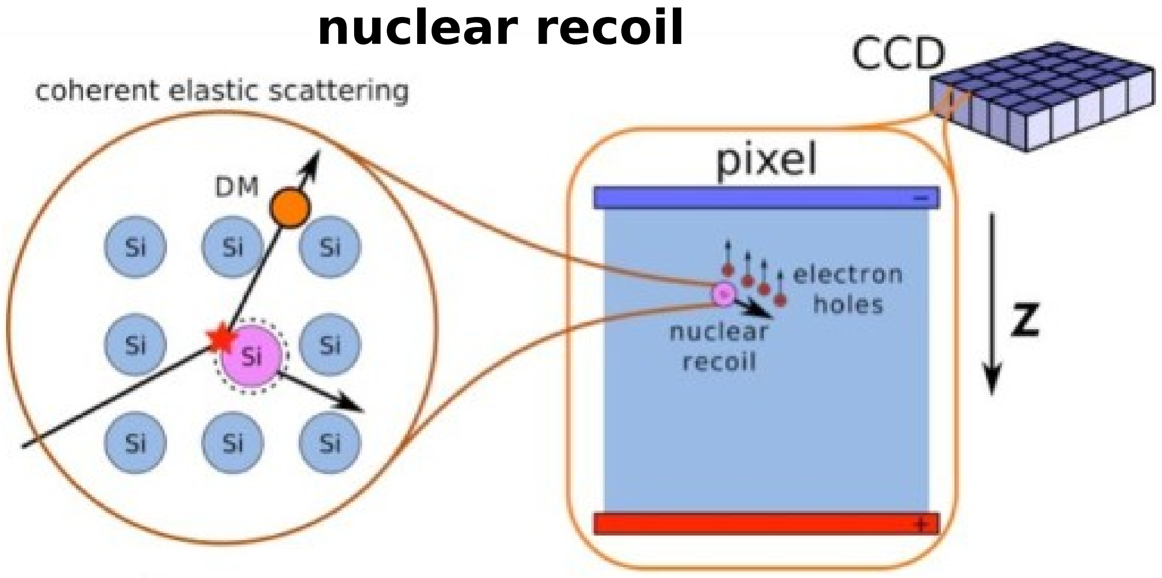
Nuclear/electron recoil discrimination in CCDs

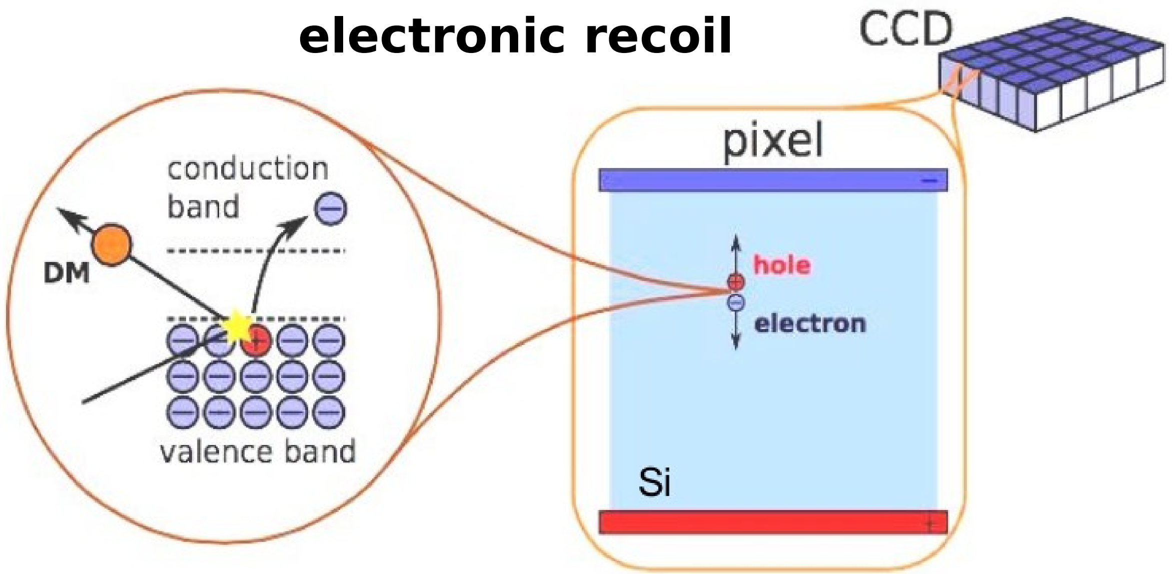
Motivation

Electron recoils a major background for low-energy rare event search for which scattering off neutrons is dominant interaction:

- Low-mass WIMP search ($m_\chi < 10GeV \rightarrow E_{nr} < 10keV \rightarrow E_{ee} < 3keV$)
- CEνNS

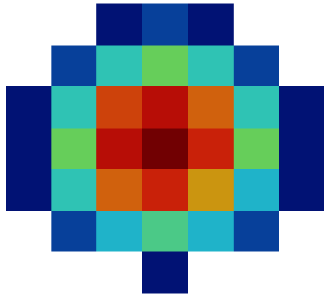
Nuclear/electron recoil discrimination not previously demonstrated in CCD.



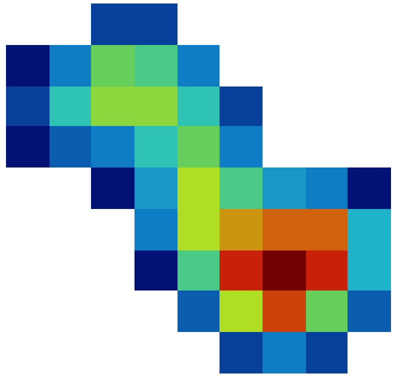


Recoil ionization in CCDs

At sufficiently high energy, NRs can be easily identified by cluster topology alone.

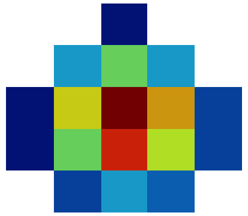


200 keV$_{ee}$ nuclear recoil

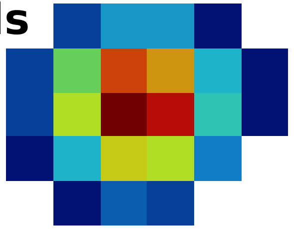


200 keV$_{ee}$ e- recoil

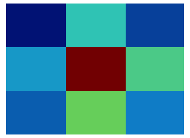
At lower energies, ERs begin to resemble nuclear recoils.



50 keV$_{ee}$ e- recoils



Eventually it becomes impossible to tell just by cluster shape...

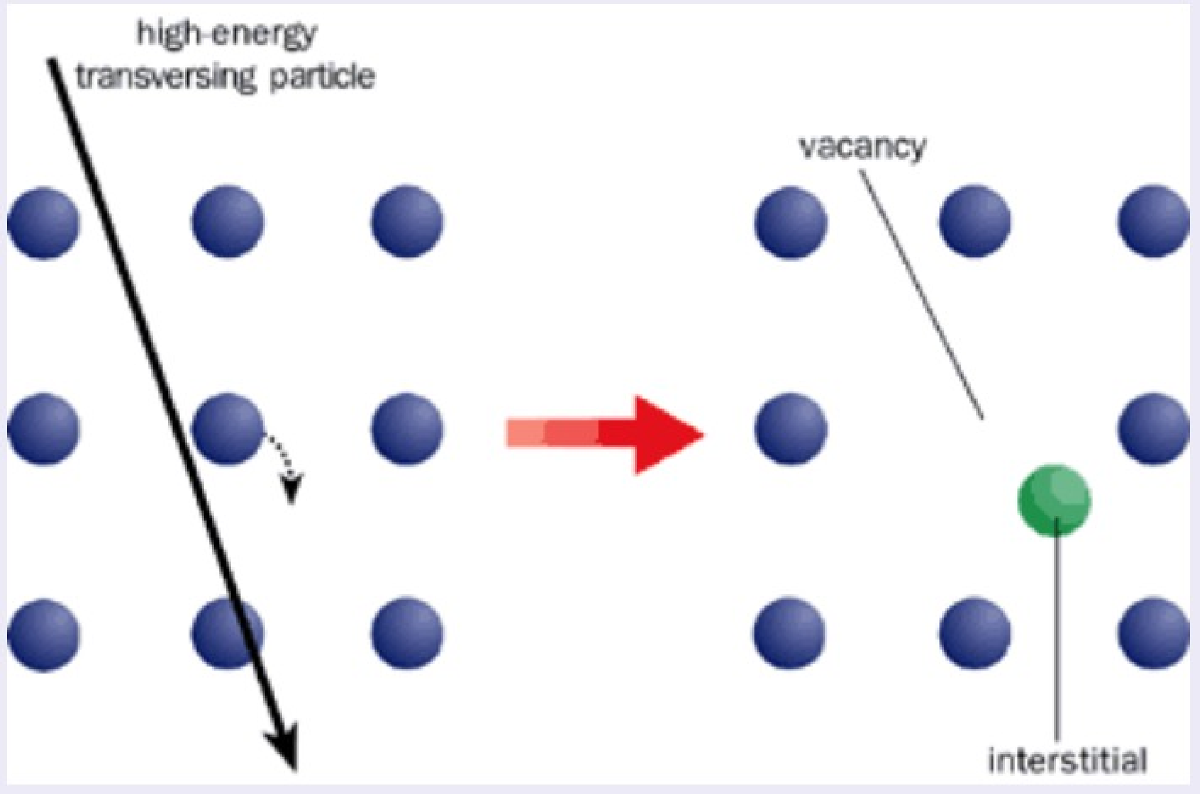


2 keV$_{ee}$ e- recoils

...for competitive rare event searches, these are the energies we care about.

Nuclear/electron recoil discrimination in CCDs

Key Difference
Recoiling nuclei leave defects in the CCD silicon.
Recoiling electrons (generally) do not.



defects
↓
intermediate energy states
↓
excess thermally stimulated leakage current

Strategy: Irradiate CCD with neutron source to create nuclear recoils and search for new defects at "high" temp (e.g., 225K).

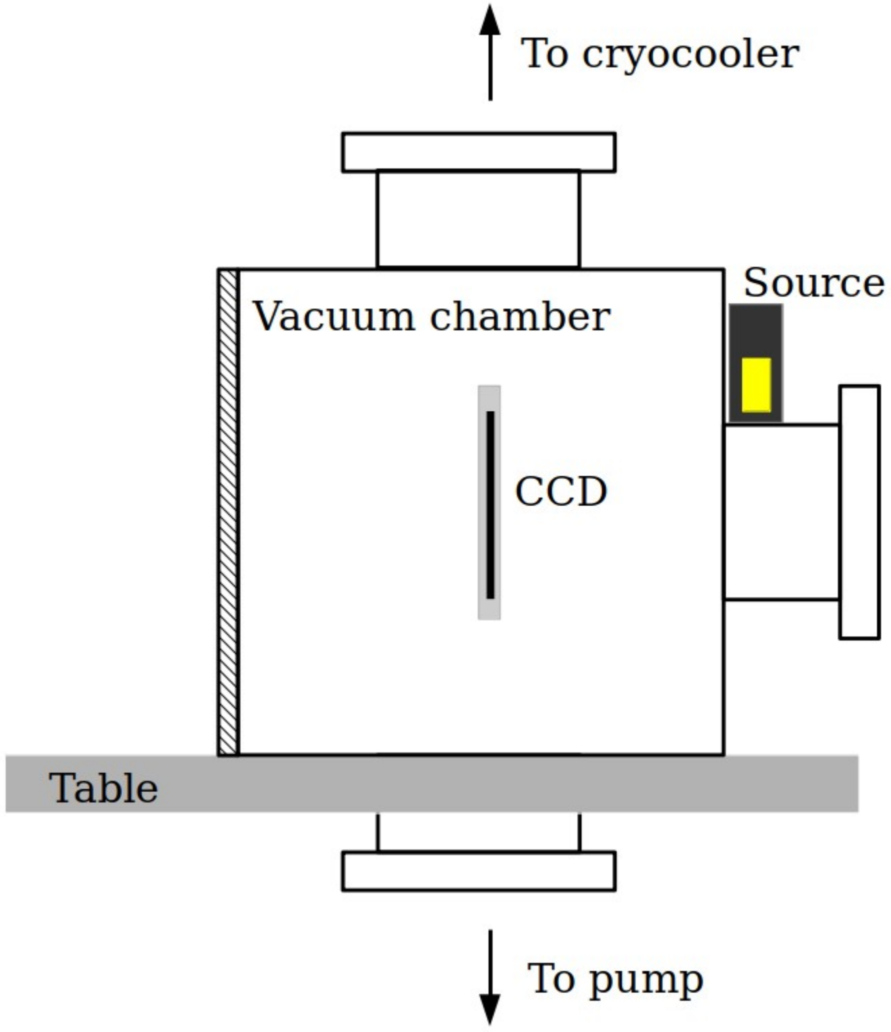
CCD Irradiaton

Three irradiations:

$^{241}Am^{9}Be$: 4.2 MeV neutrons
4.4 MeV gammas
<u>generate nuclear recoils</u>

^{24}Na: 1.37 MeV gammas
2.75 MeV gammas
<u>electron recoil background</u>

Bkgd: no source
<u>environmental background</u>



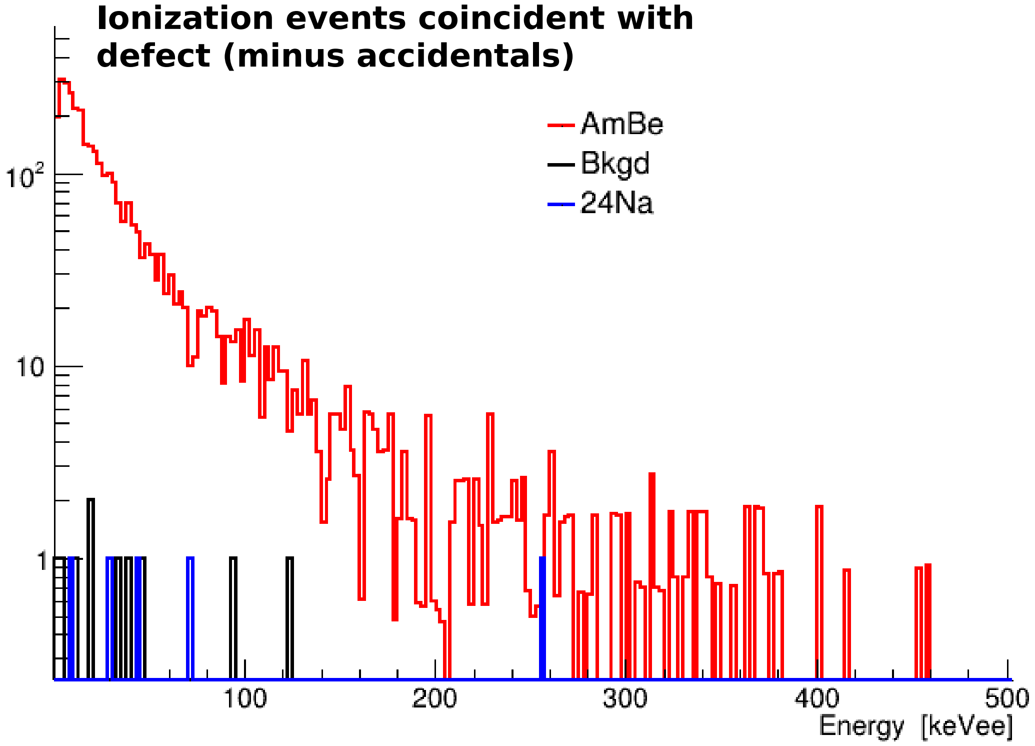
Remove source during readout to preserve spatial correlation.

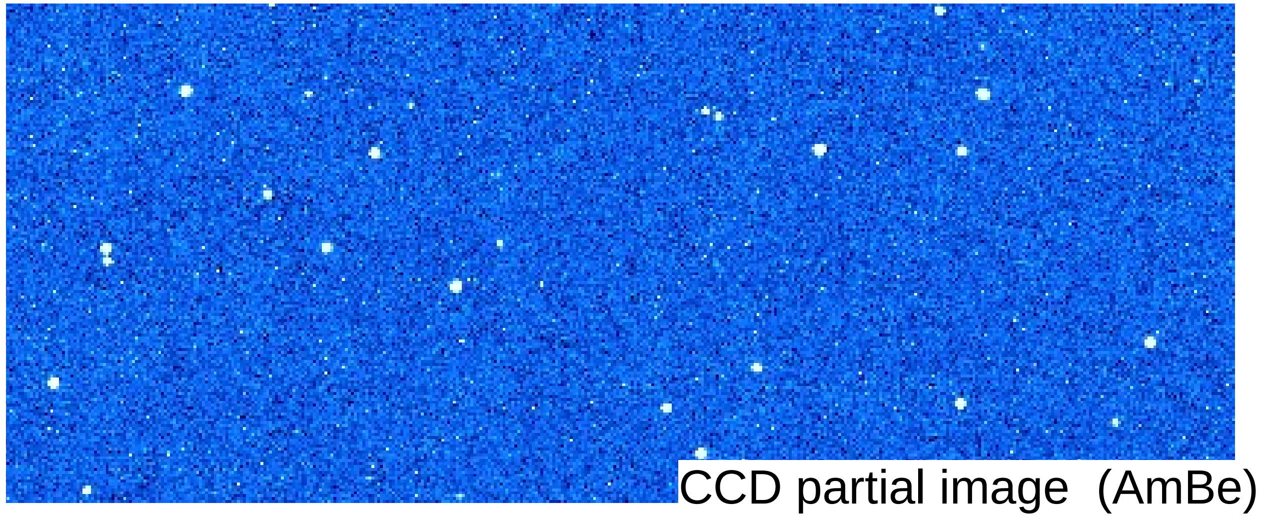
Defect Search

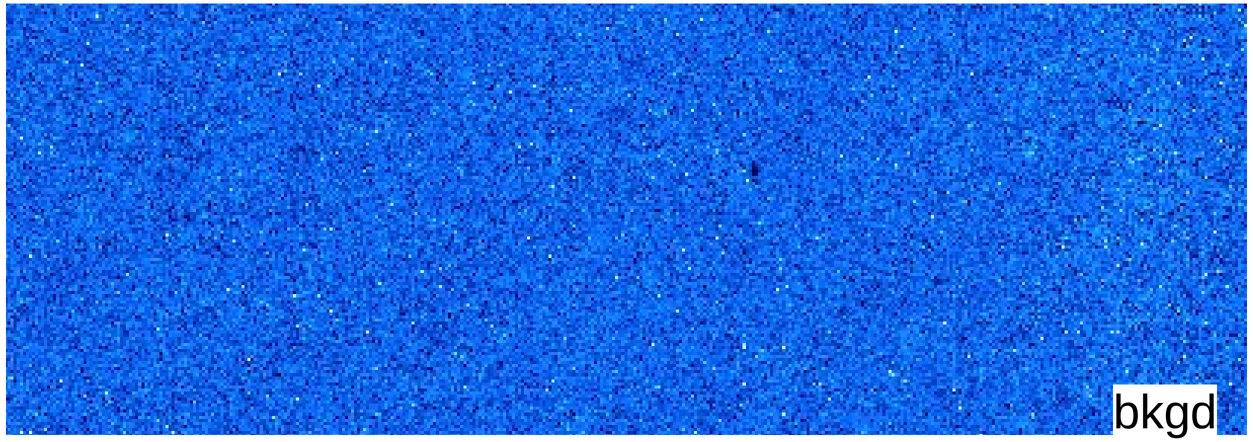
Generate a median of dozens of CCD images taken at “high temp” before and after each irradiation to suppress ionization events.

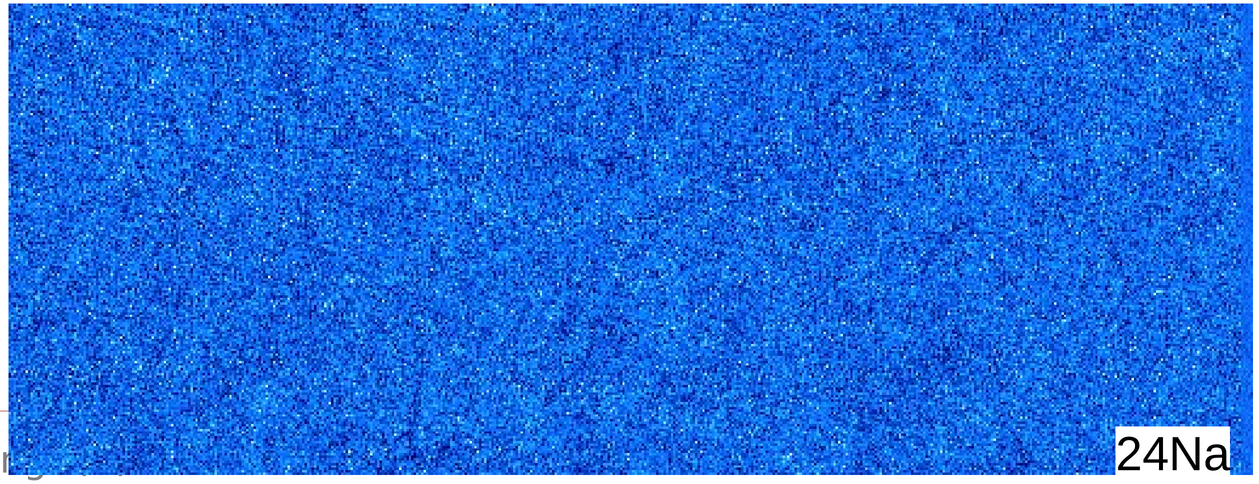
The difference in the two medians reveals the defects that arose during the radiation.

<u>Defects disappear after annealing to room temp.</u>



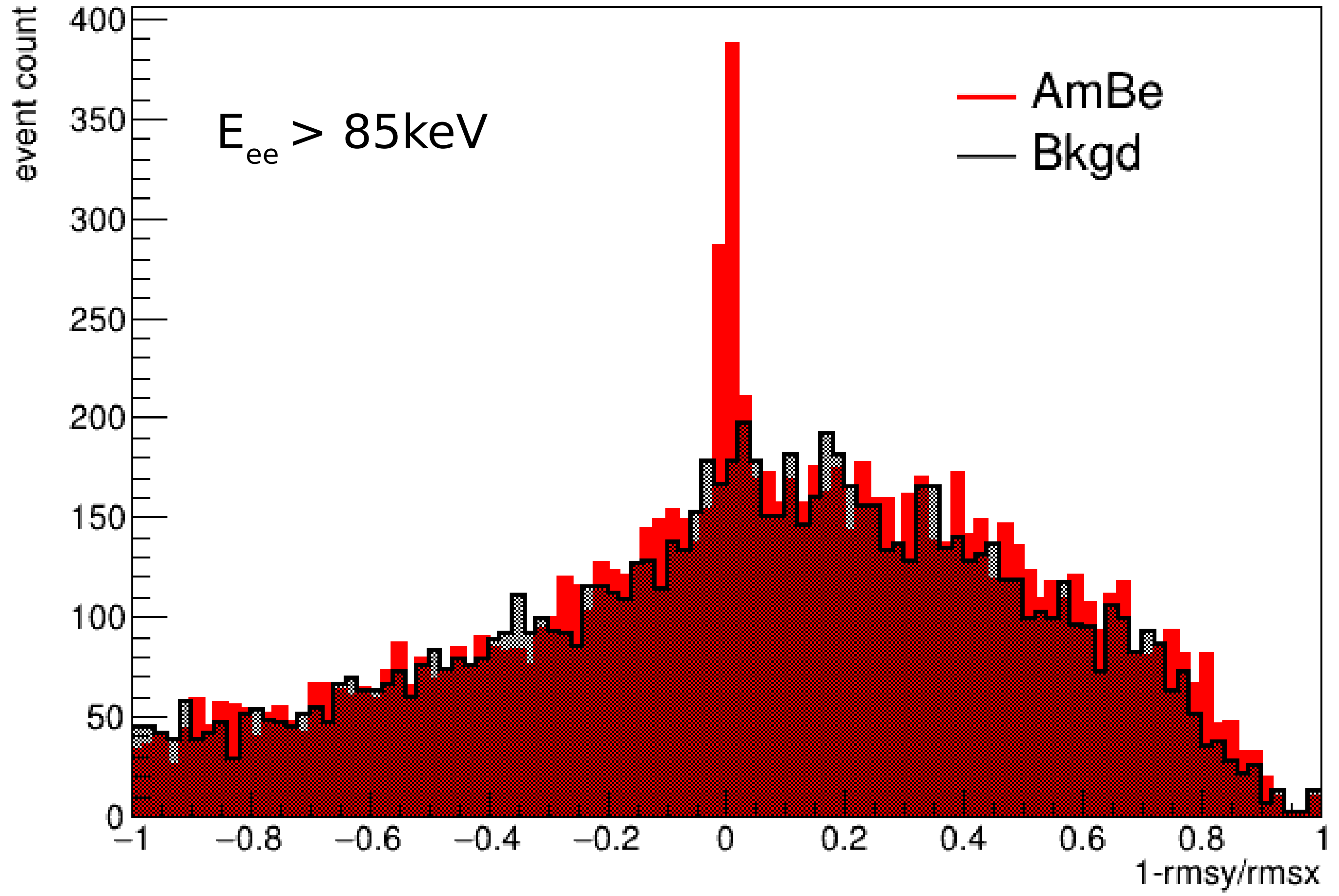




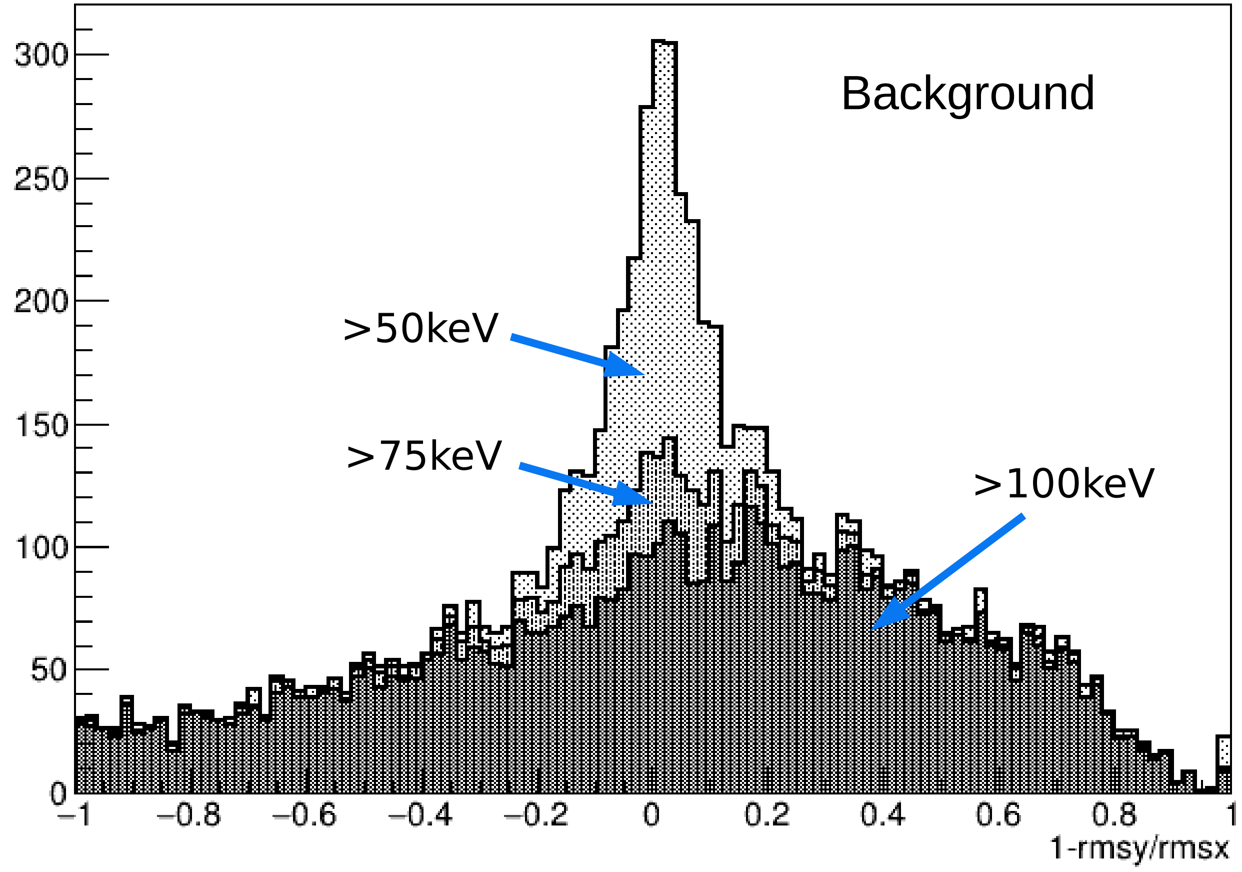


High-energy NR ID by topology

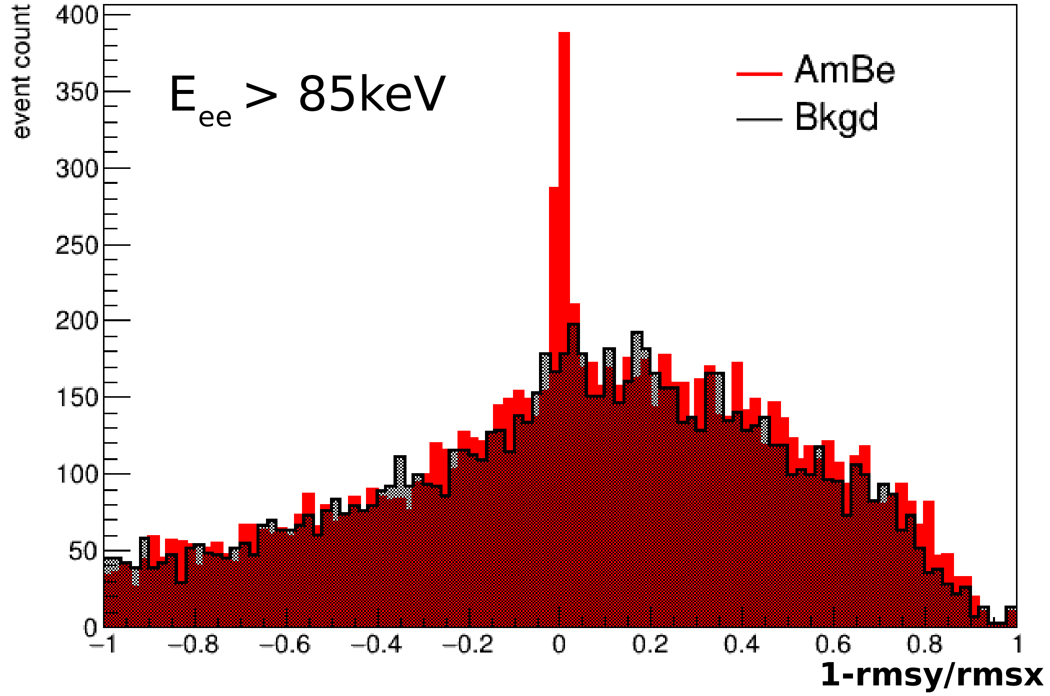
Parameterize cluster symmetry using σ_y/σ_x from Gaussian fit to cluster

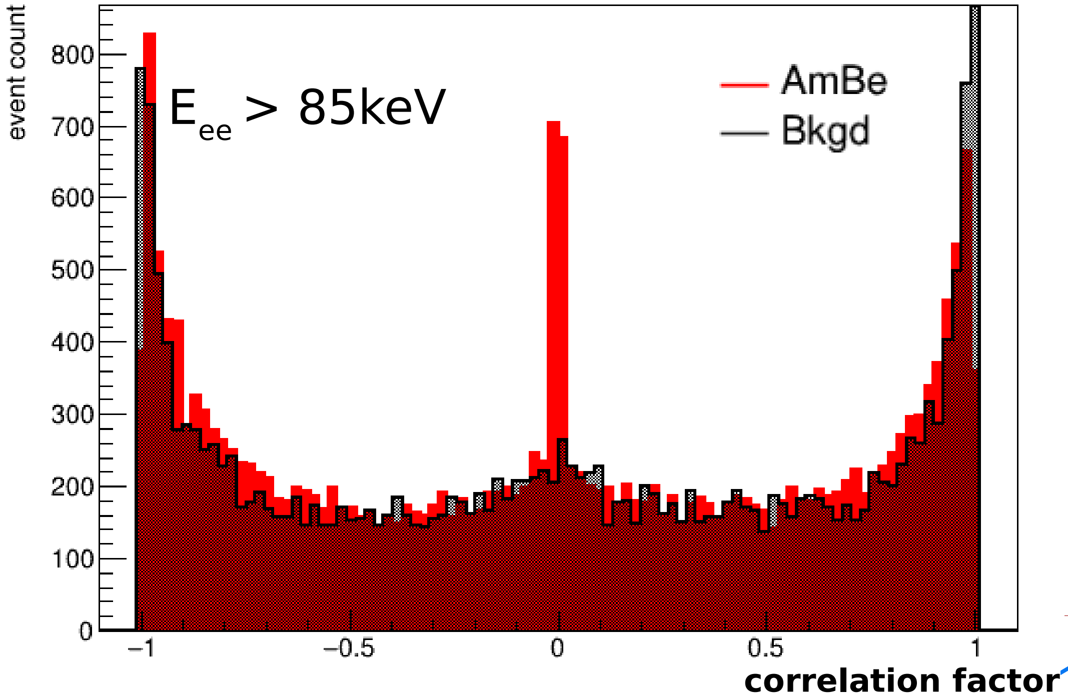


Breaks down at lower energies...

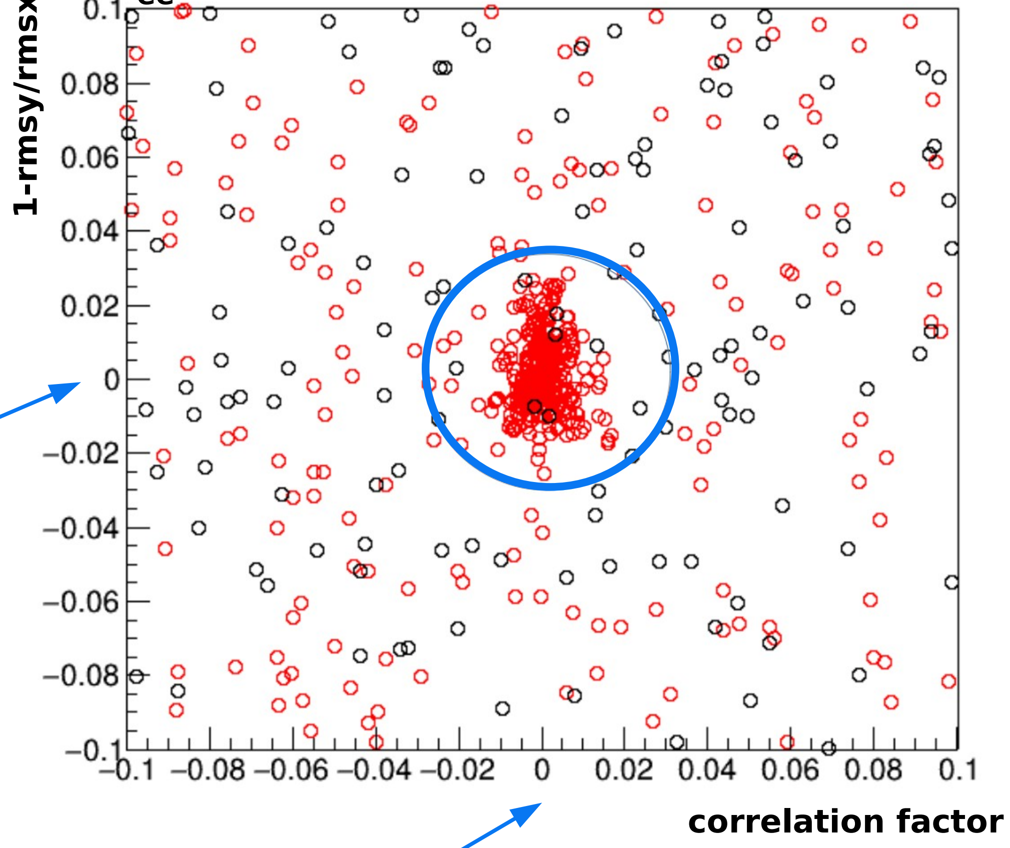


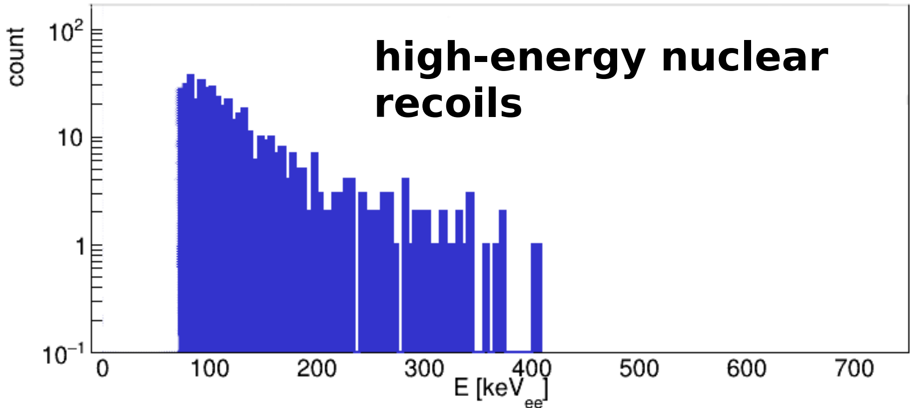
High-energy NR ID by topology





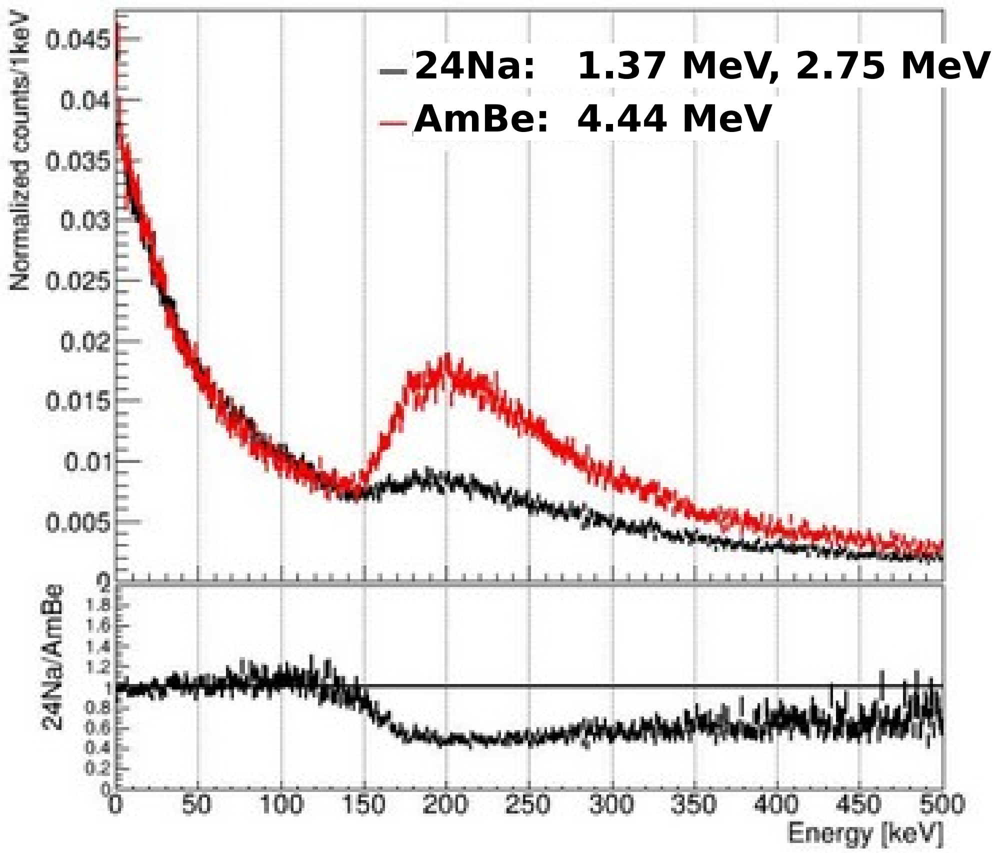
Is high-energy NR
if
E_{ee} > 85keV and radius = < 0.03

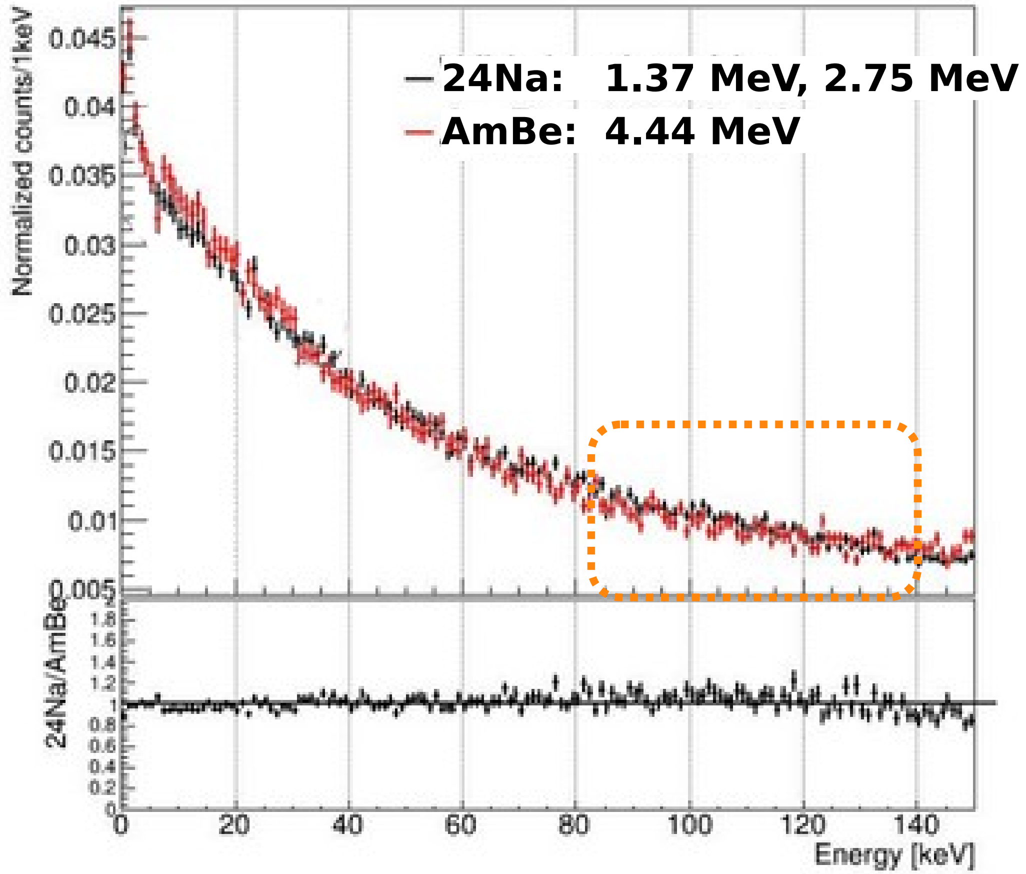




Low-energy NR spectrum using ^{24}Na

Below 200 keV peak, simulated gamma spectra are qualitatively identical…





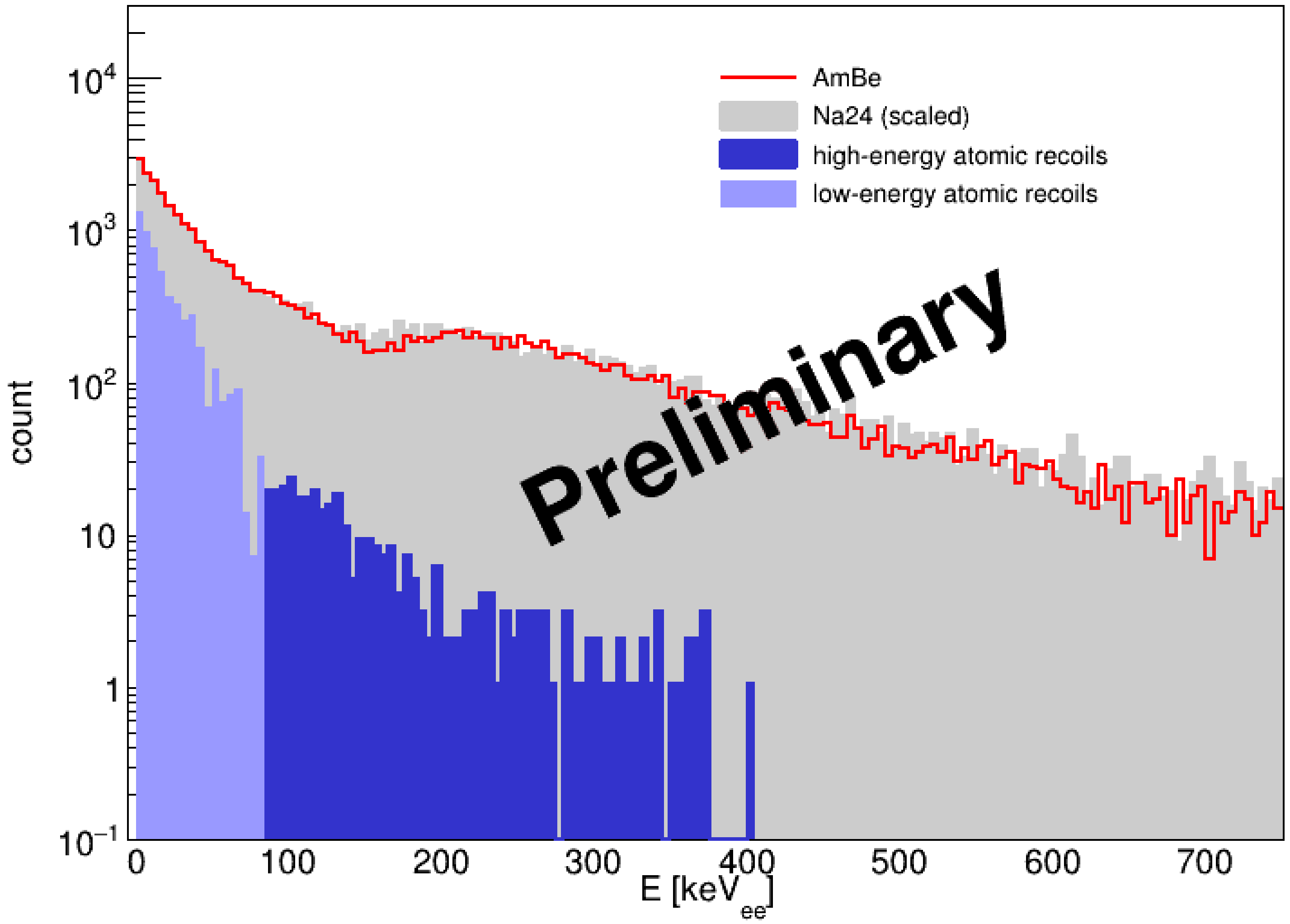
Scale ^{24}Na to NR-subtracted AmBe spectrum in "high-energy" range…

Difference in the two spectra gives AmBe nuclear recoil spectra at low energy.

Low-energy NR spectrum using ^{24}Na

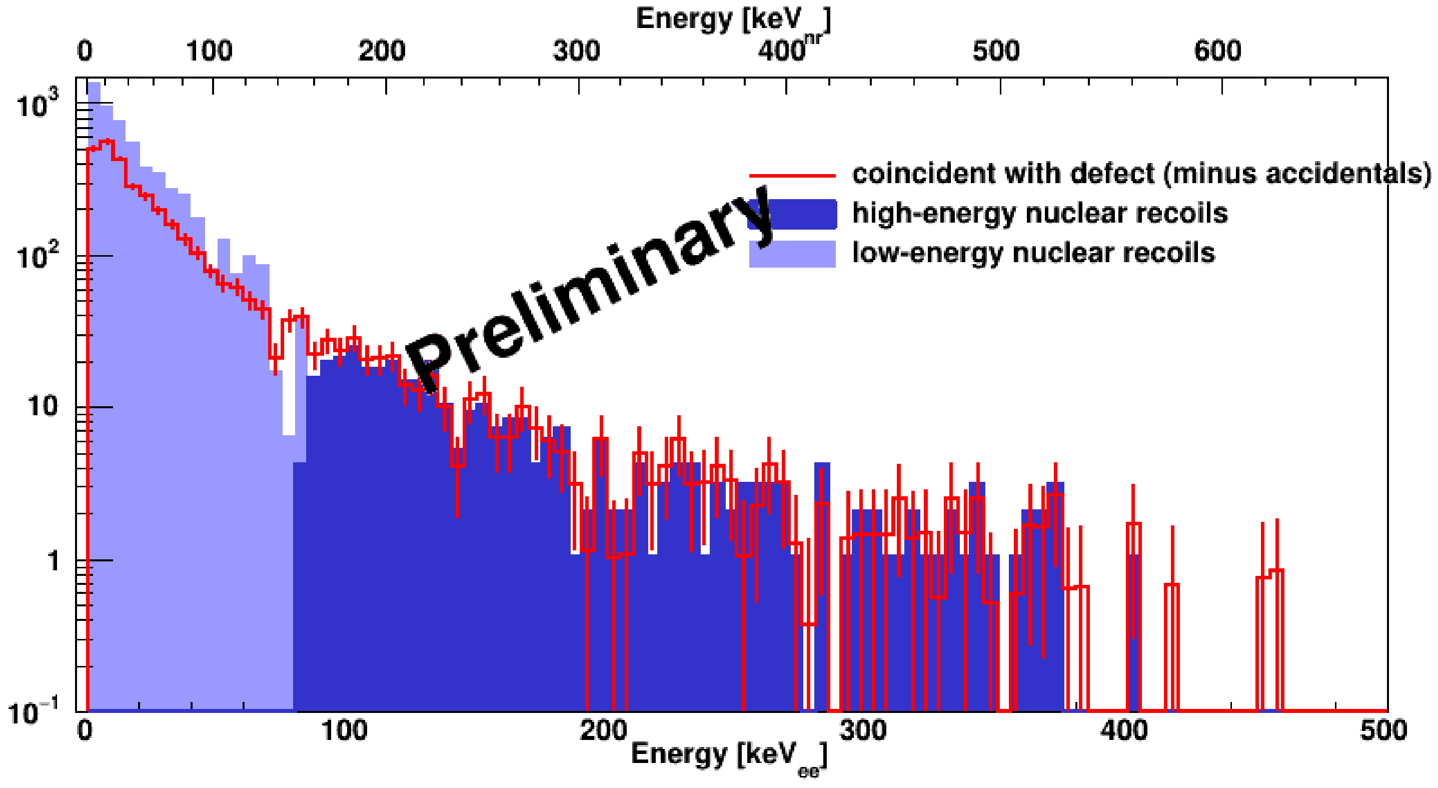
Scale ^{24}Na to NR-subtracted AmBe spectrum in “high-energy” range…

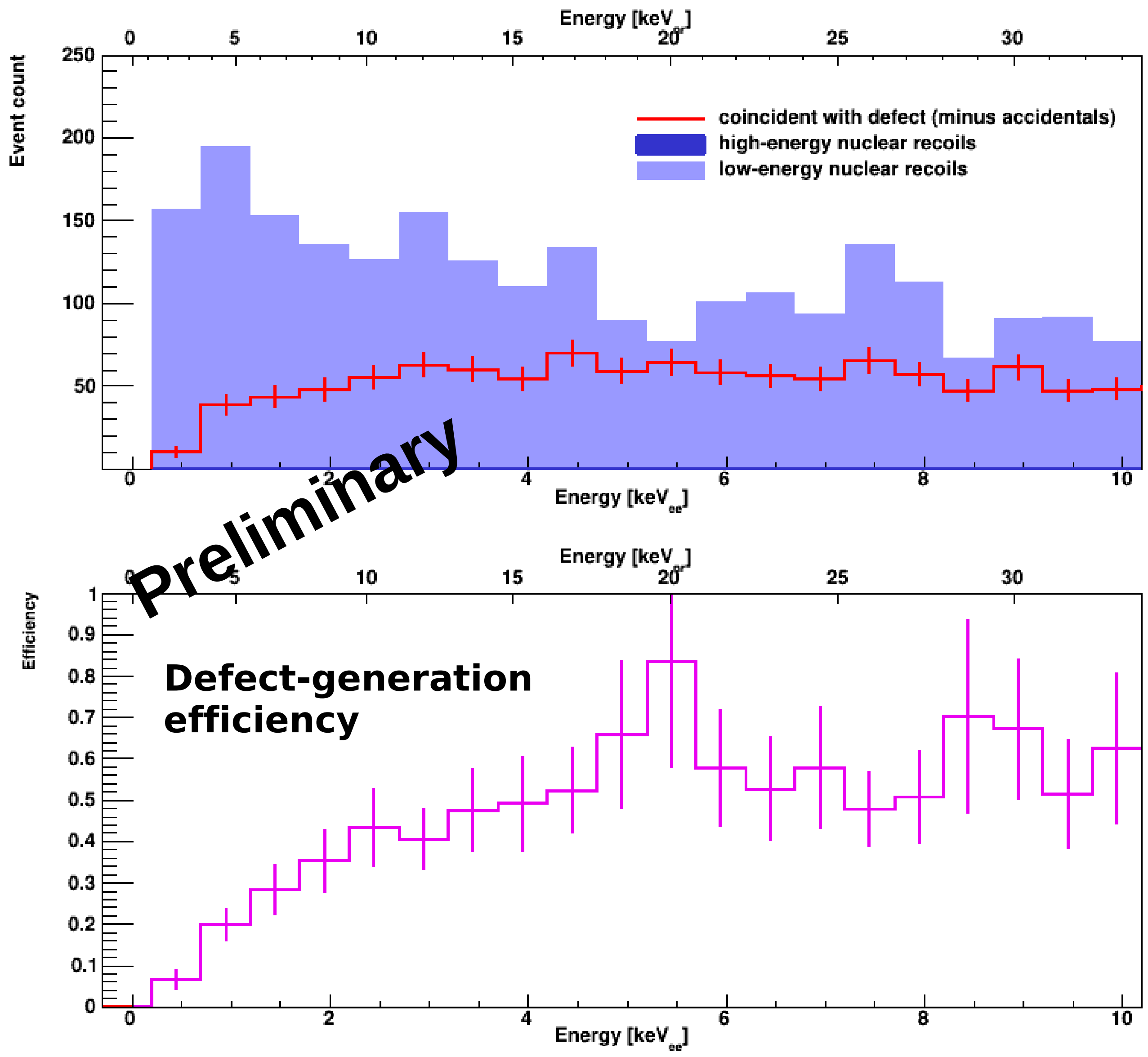
Difference in the two spectra gives AmBe nuclear recoil spectra at low energy.



NR defect-generation efficiency

Perform coincidence search to correlate ionization events with defects...



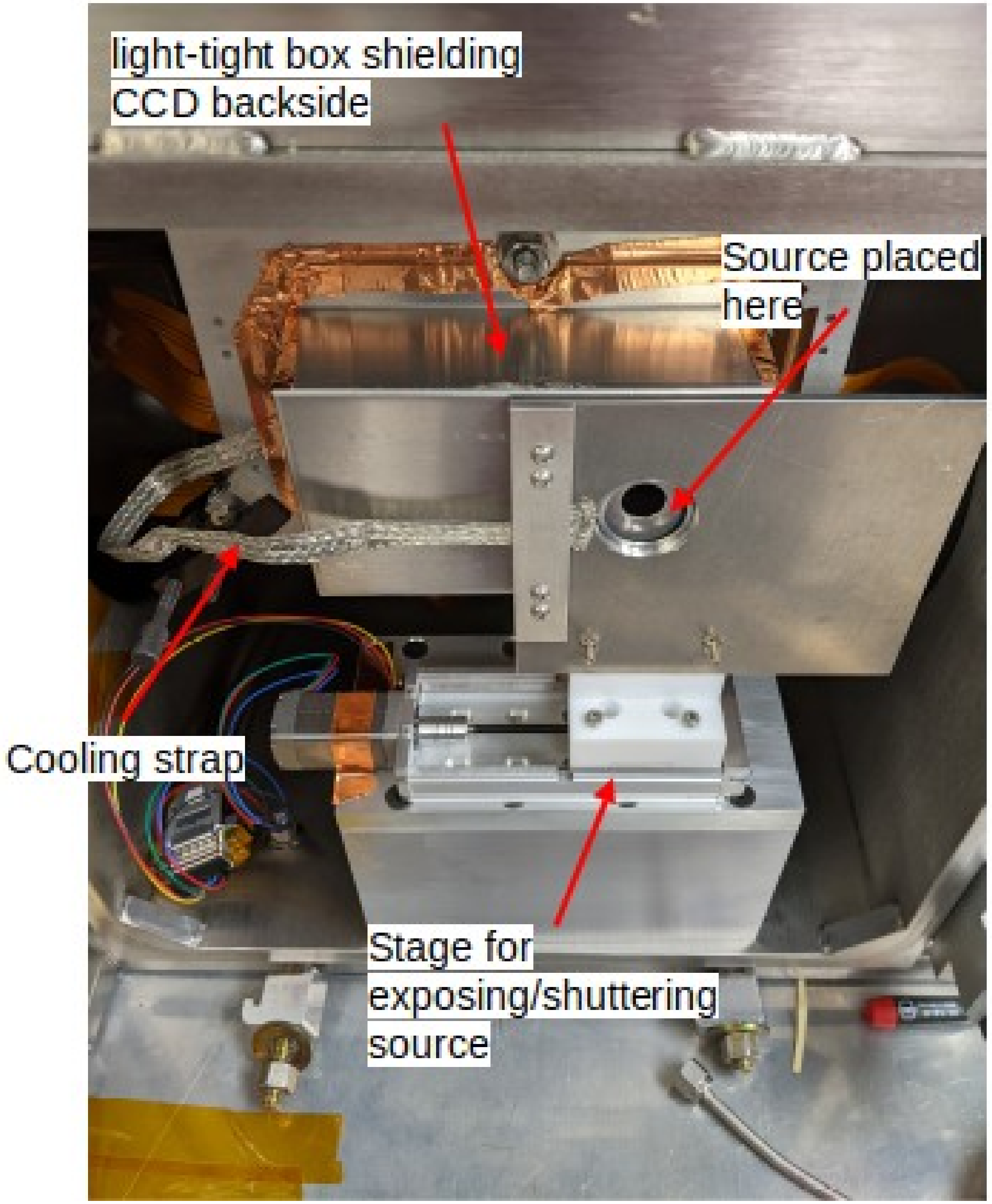


Paper forthcoming

CCD Surface Calibrations

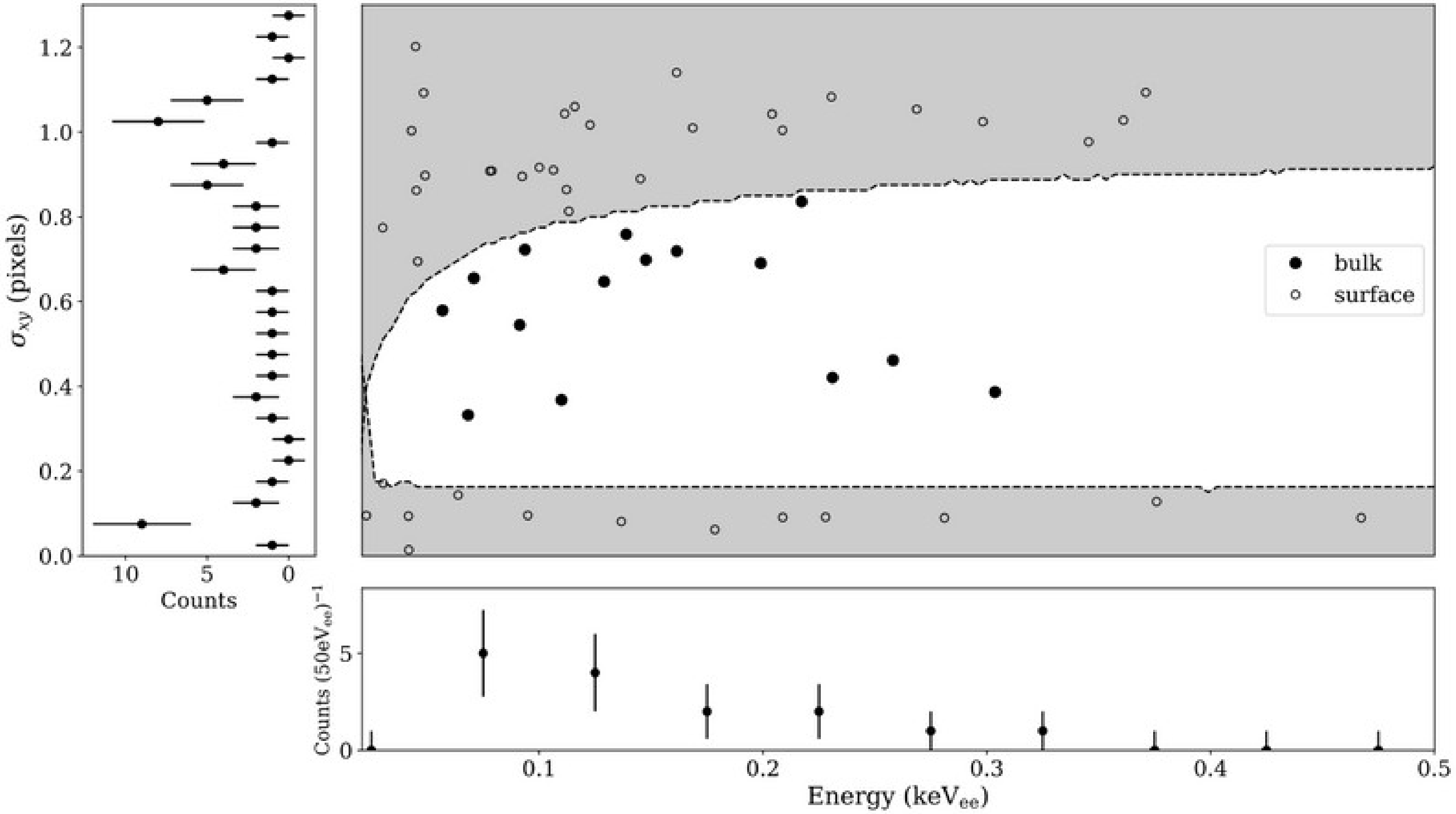
Perform controlled irradiations of front or back surface of CCD:

- Test effects of CCD back-thinning process
- Explore DAMIC@SNOLAB upgrade excess



DAMIC@SNOLAB UPGRADE EXCESS

From Alex Piers' thesis defense on March 10...



Paper under collaboration review

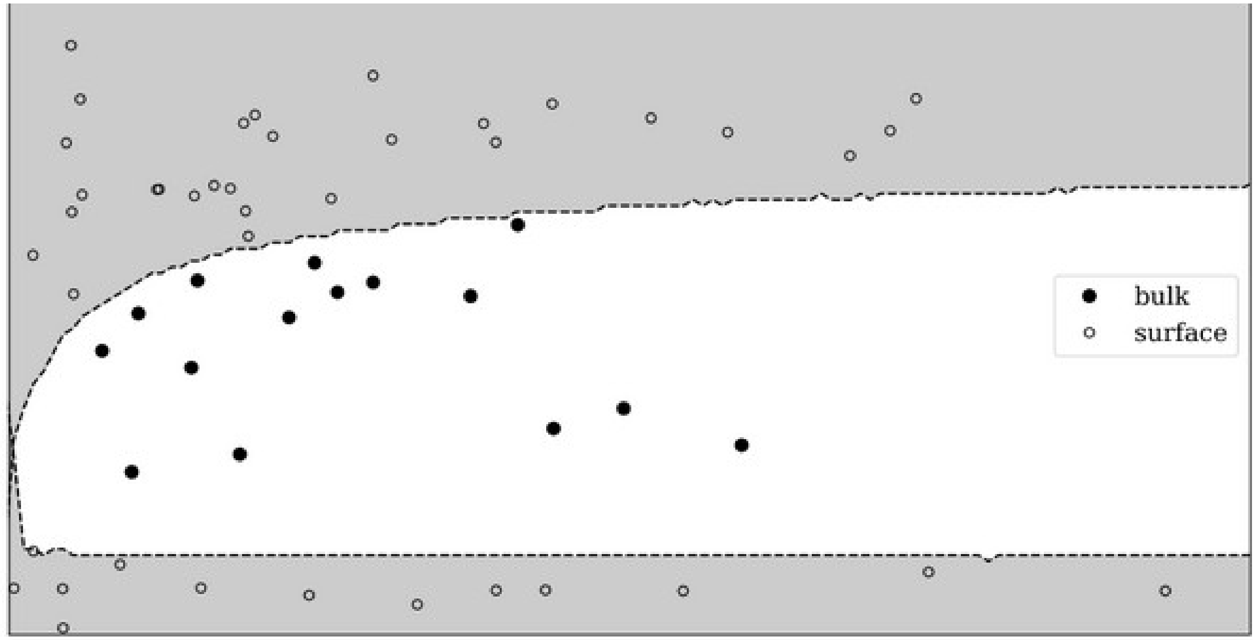
Based on simulations, expect ~5% of surface events to survive fiducial cut.

DAMIC@SNOLAB UPGRADE EXCESS

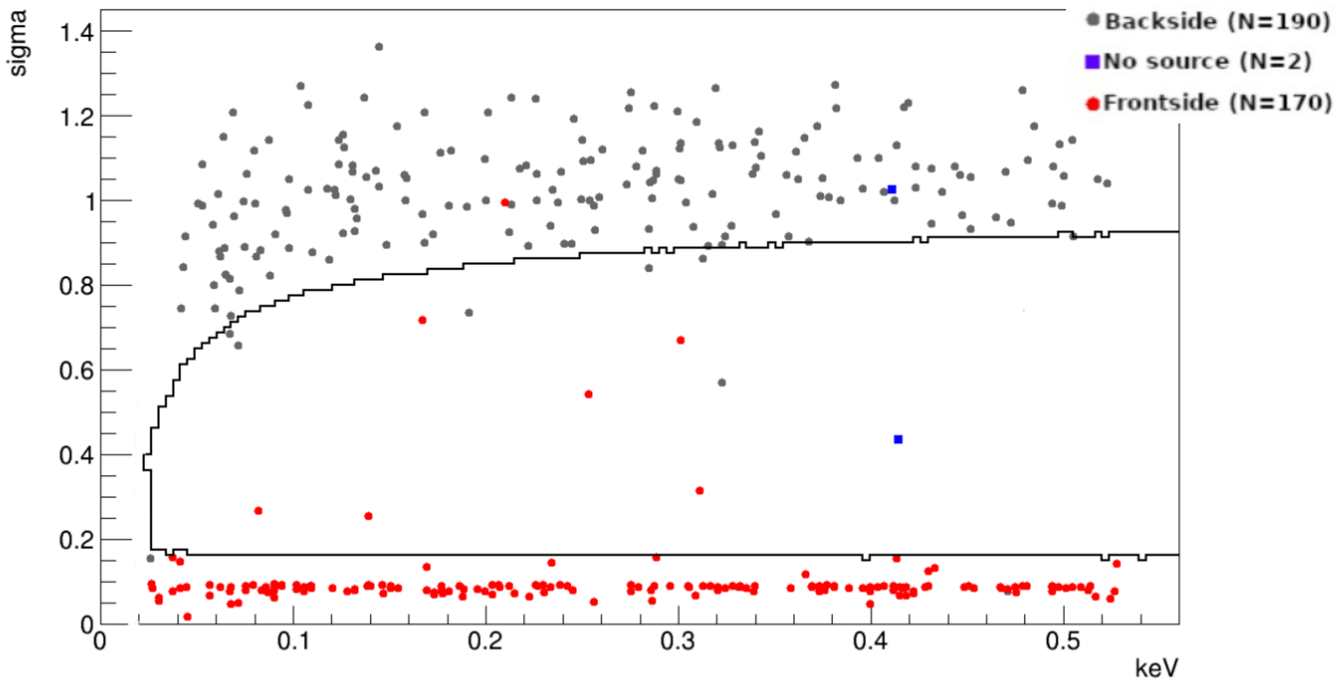
Problem with the diffusion model? Surface events reconstructing as bulk events?

Using similar CCD and same operating parameters as SNOLAB, generate low-energy surface events by irradiating CCD using ^{14}C source (49 keV betas).

SNOLAB



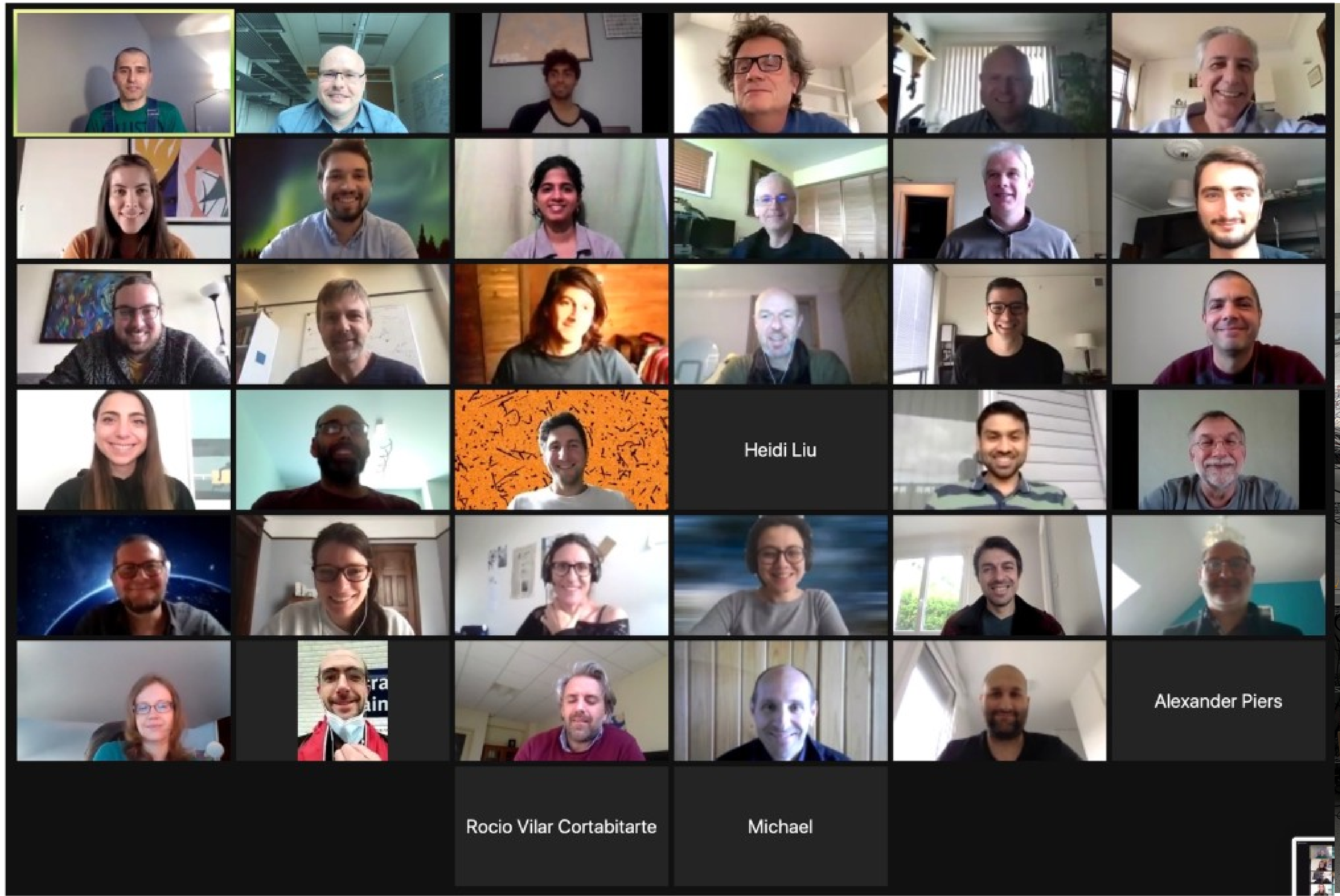
UW

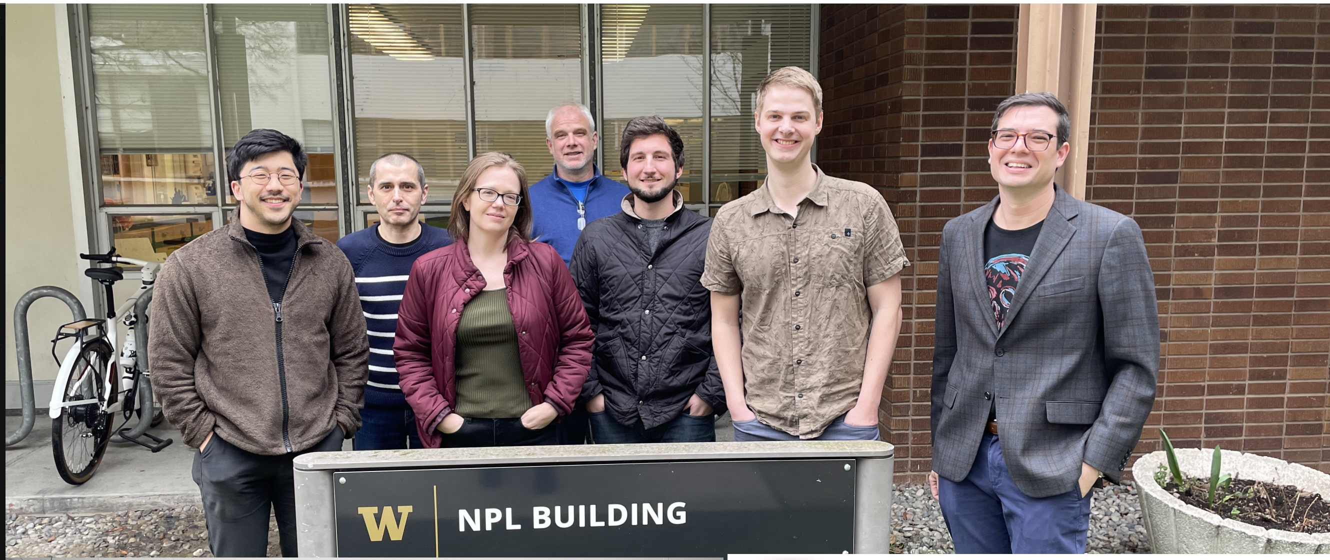


Frontside bulk events: 4%
Backside bulk events: 3%

<u>Consistent with simulation</u>.

Thank you!





CENPA
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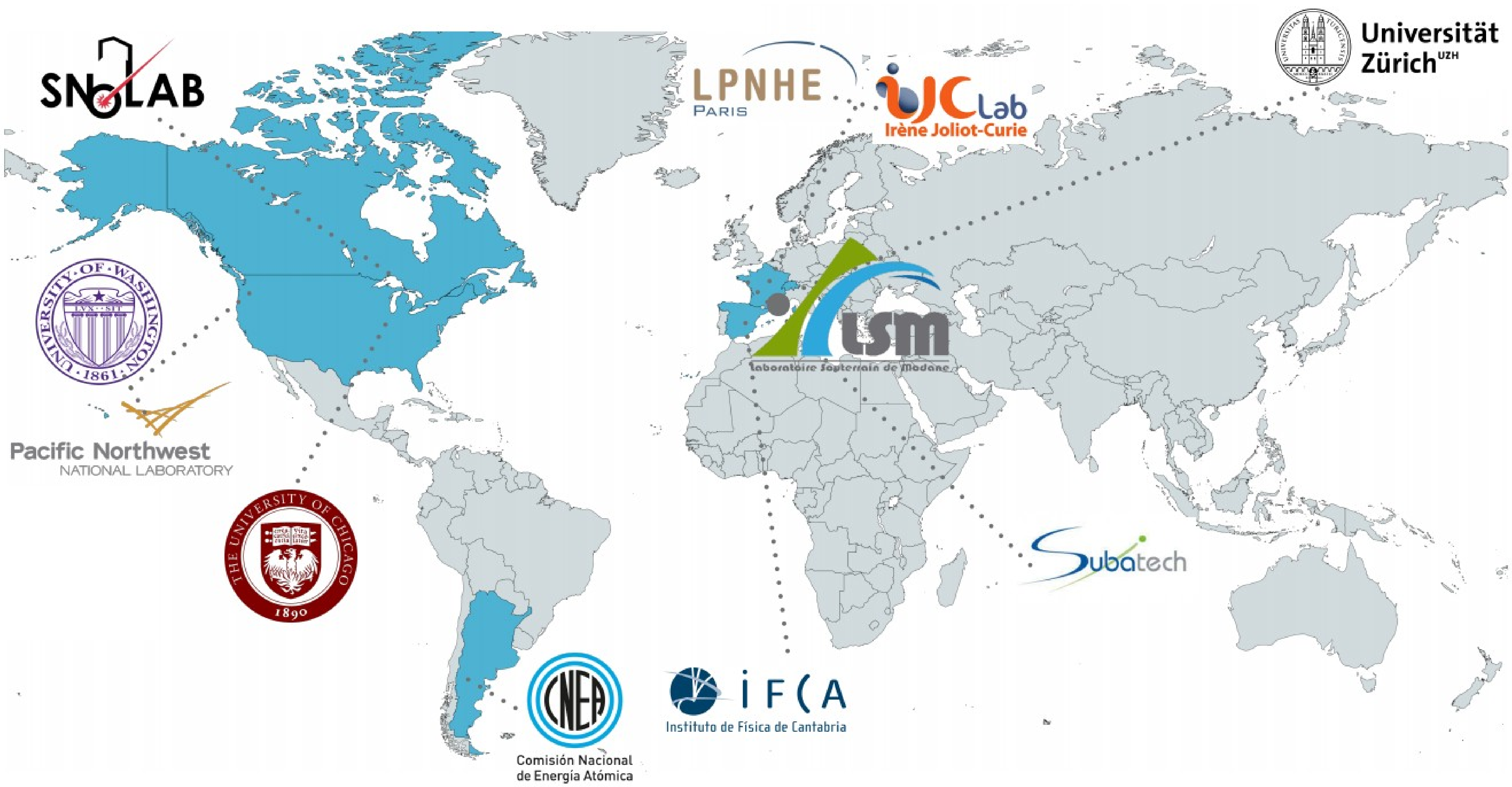
Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

The DAMIC-M Collaboration



European Research Council
Established by the European Commission

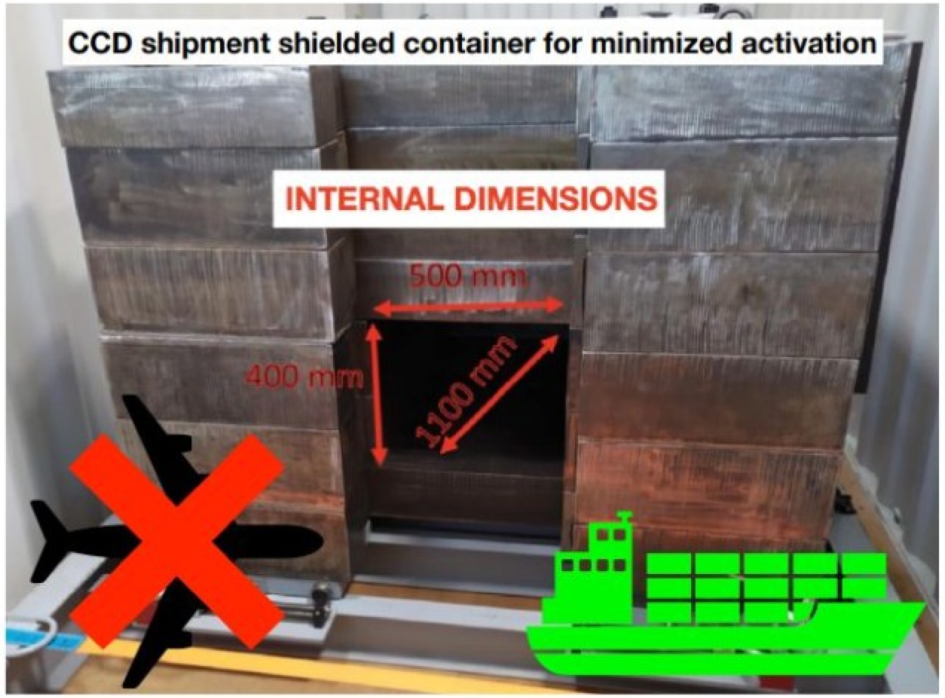
Additional slides...

Background reduction

DAMIC-M backgrounds target < 1 dru

Mitigation

- Silicon wafers stored underground
- Minimal total surface exposure
- CCDs to be packaged and tested underground onsite
- Nitrogen storage to minimize radon deposition



Shielding

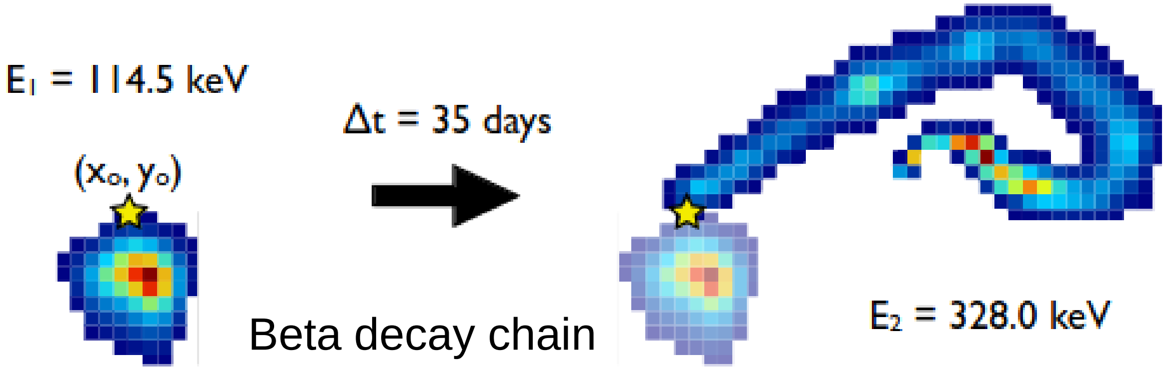
- External shield: polyethylene + low-background lead
- Internal shield: ancient lead

Materials Selection

- Electroformed copper: vacuum chamber, IR shield
- High-purity OFHC copper: parts outside IR shield
- Low-background flex cables arXiv:2303.10862

Rejection

- Topology cut: a DM interaction would be pointlike
- Identify surface events from diffusion
- Spatially correlated decay products



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LBC DM-electron model

Generate DM signal templates

- QEDark to get differential rate for DM-e^- interactions
- Halo parameters from [Phystat-DM]
- Detector response:
  - Readout noise -- different for each amplifier
  - Electron recoil ionization yield from [PRD 102, 063026 (2020)]
  - Diffusion model from [PRD 94, 082006 (2016)] using LBC parameters

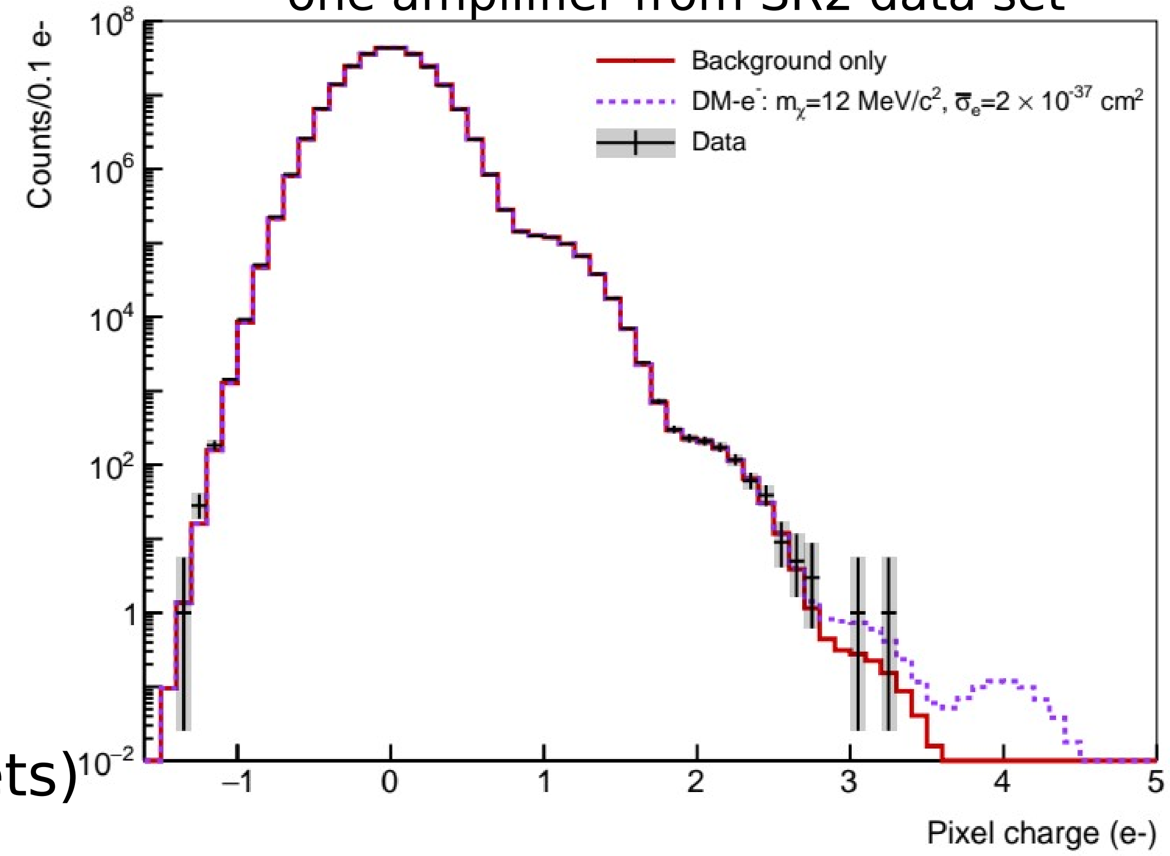
Build pixel charge distribution

- DM signal component
- Poisson background (dark current estimated per pixel)
- Gaussian noise

Perform joint binned likelihood fit

- four separate pixel distributions (2 amplifiers + 2 data sets)

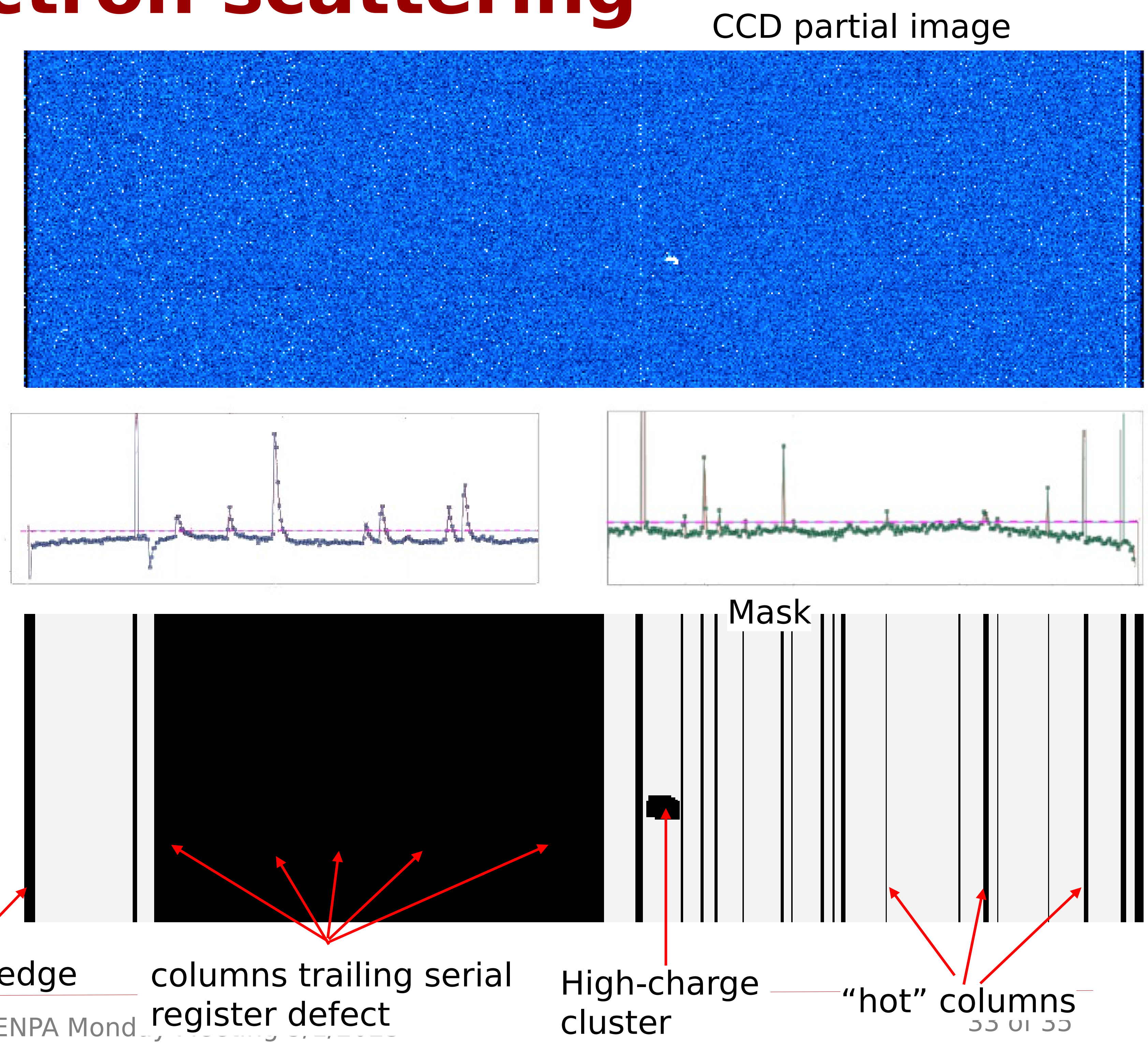
Fit to pixel charge distribution from one ampilifier from SR2 data set



LBC DM-electron scattering

Mask

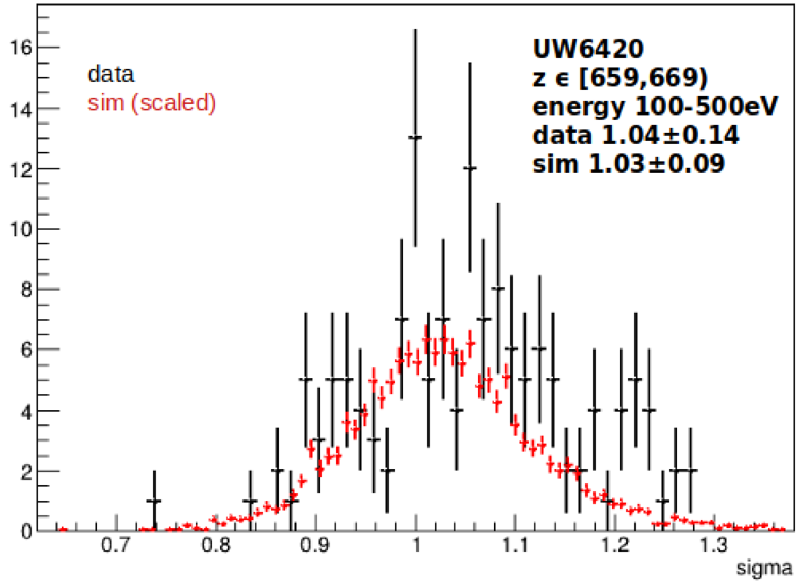
- All pixel clusters ≥ 7 e^-, plus 10 trailing horizontal and vertical pixels (charge-transfer inefficiencies)
- Columns containing defects, indentified by:
  - Excess of $1e^-$ pixels ($1e^-$ rate a function of column number)
  - High-charge pixels appearing in multiple 3-hour exposures
  - Deficit of $1e^-$ pixels (indication of serial register defect); mask all trailing columns
- Five-pixel window surrounding image

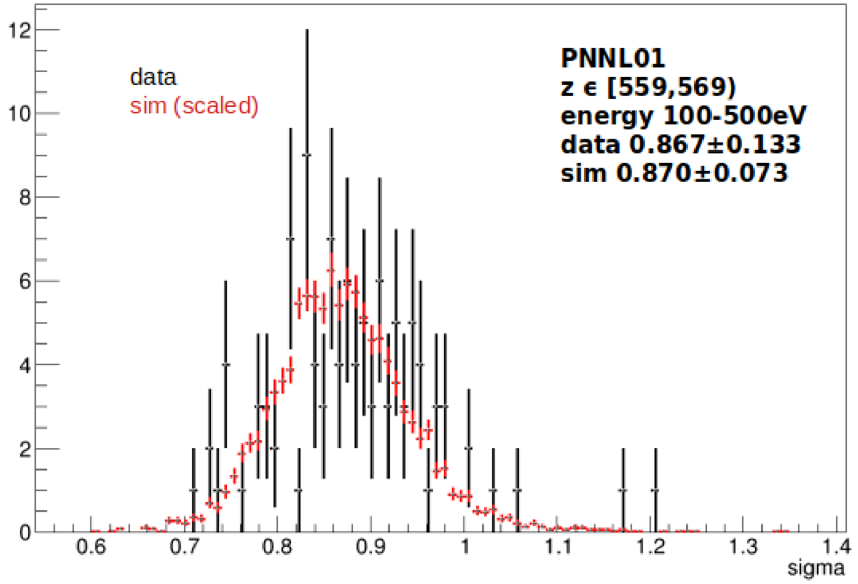


Fun with back-thinned CCDs

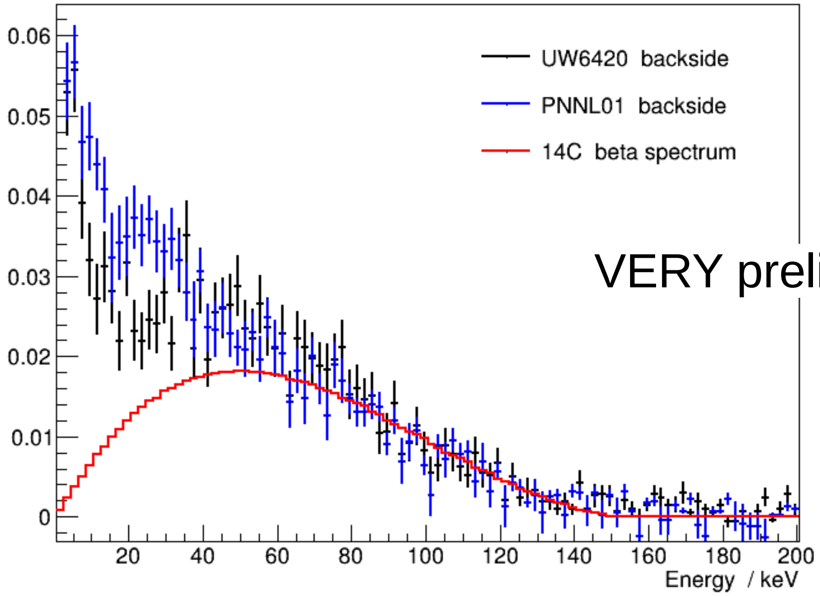
Processed to remove backside partial charge collection region (major source of systematic uncertainty).

Test diffusion model, correcting for CCD thickness (back-thinned are 100 µm thinner)





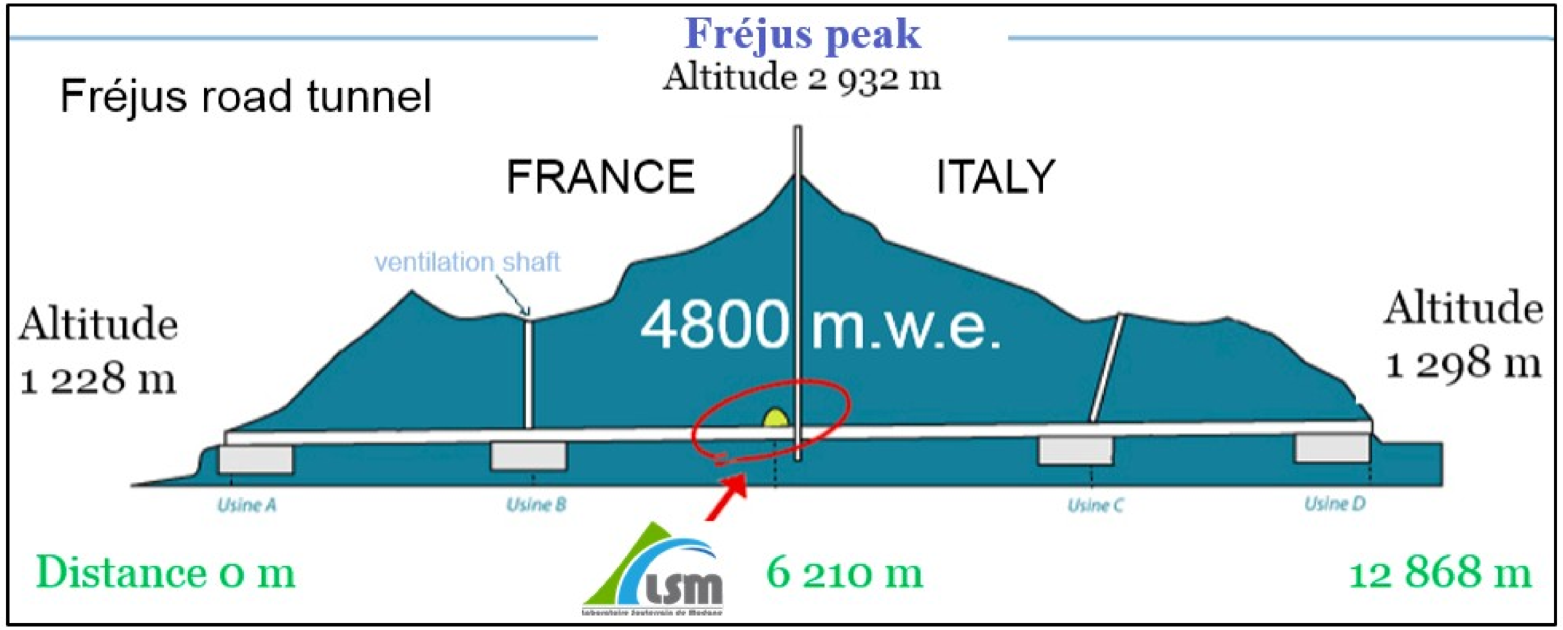
Explore effects of back-thinning process on CCD event spectra.



VERY preliminary!

DArk Matter In CCDs at Modane

DAMIC-M: A kg-scale detector using silicon charge-coupled devices (CCDs) to search for light (sub-GeV) dark matter.



Located at the Laboratoire Souterrain de Modane (LSM) 1,700 meters below the Fréjus peak in Modane, France.

- sub-electron resolution
- 2-3 e^- energy threshold
- dark current ~10^{-4} e^-/pixel/day
- background rate < 1 dru

    (1 differential rate unit = 1 event/kg/keV/day

<u>Commissioning and data acquisition to begin in 2024.</u>