Searching for Dark Matter with the DAMIC-SNOLAB Experiment

Ian Lawson

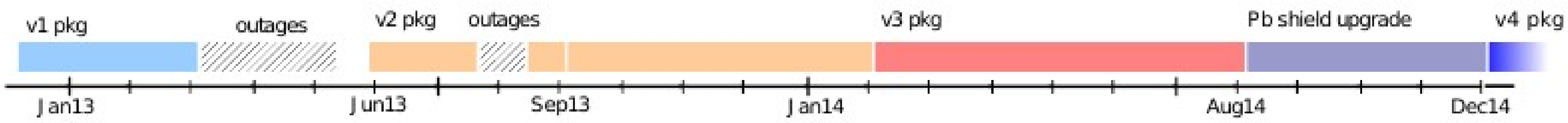
SNOLAB Research Scientist

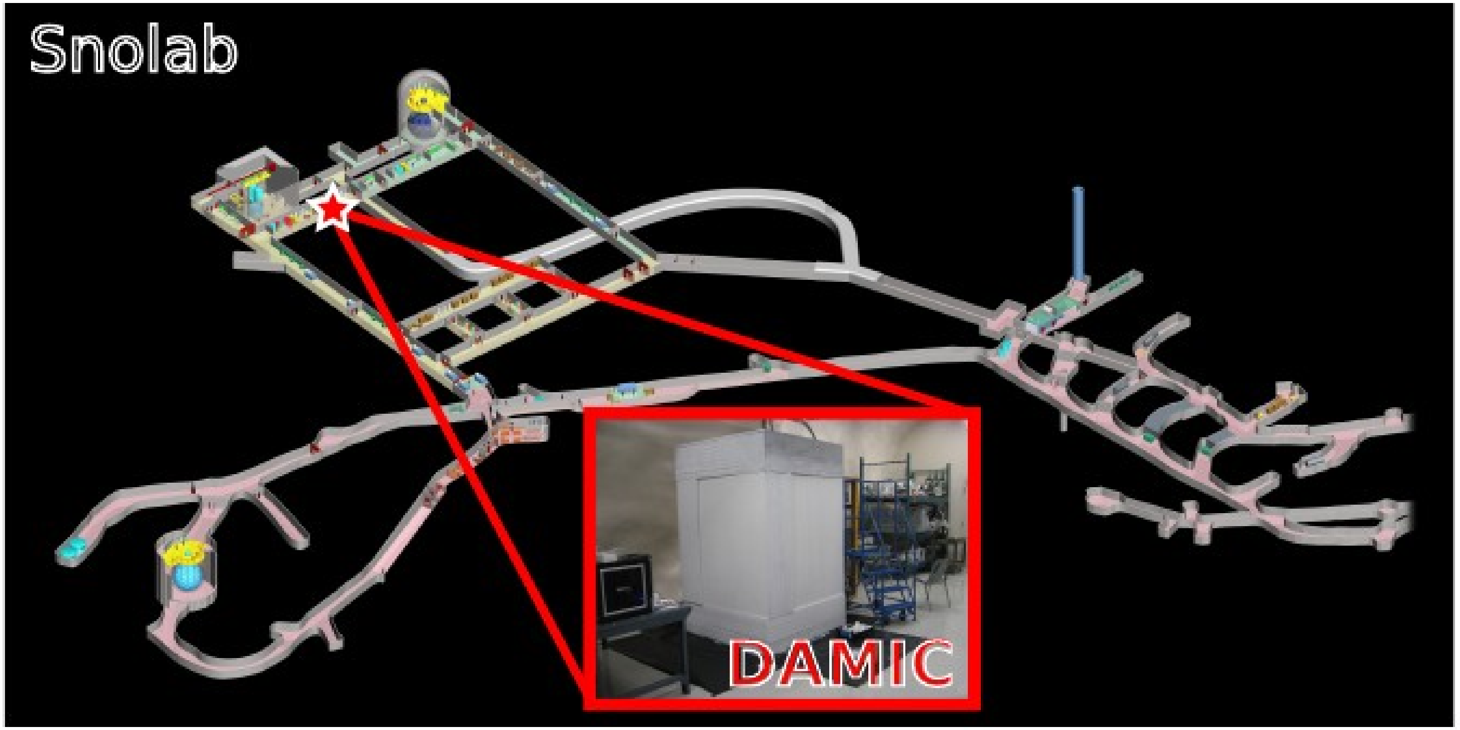
for the DAMIC-SNOLAB Collaboration

TeVPA 2022

August 9, 2022

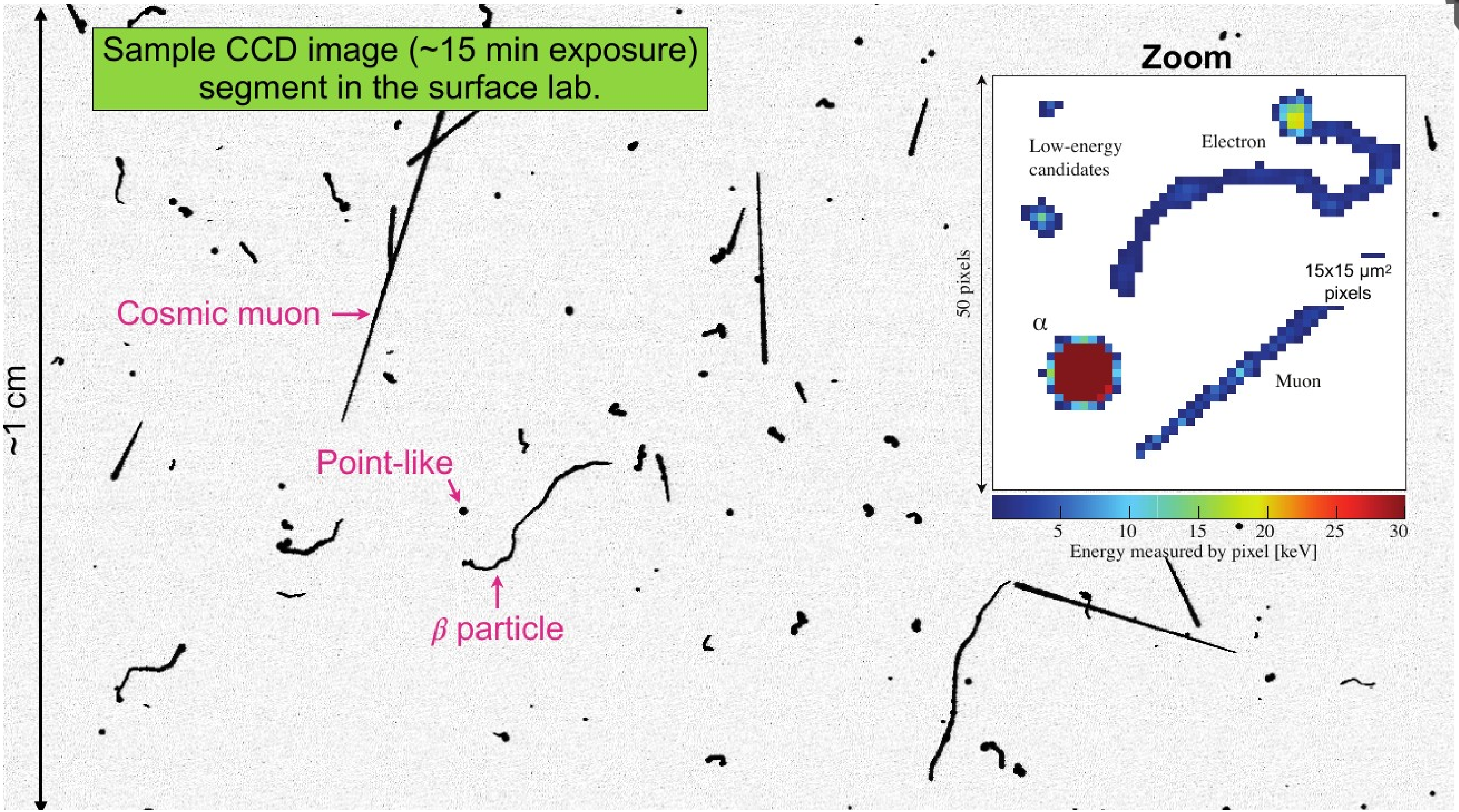
DAMIC-SNOLAB



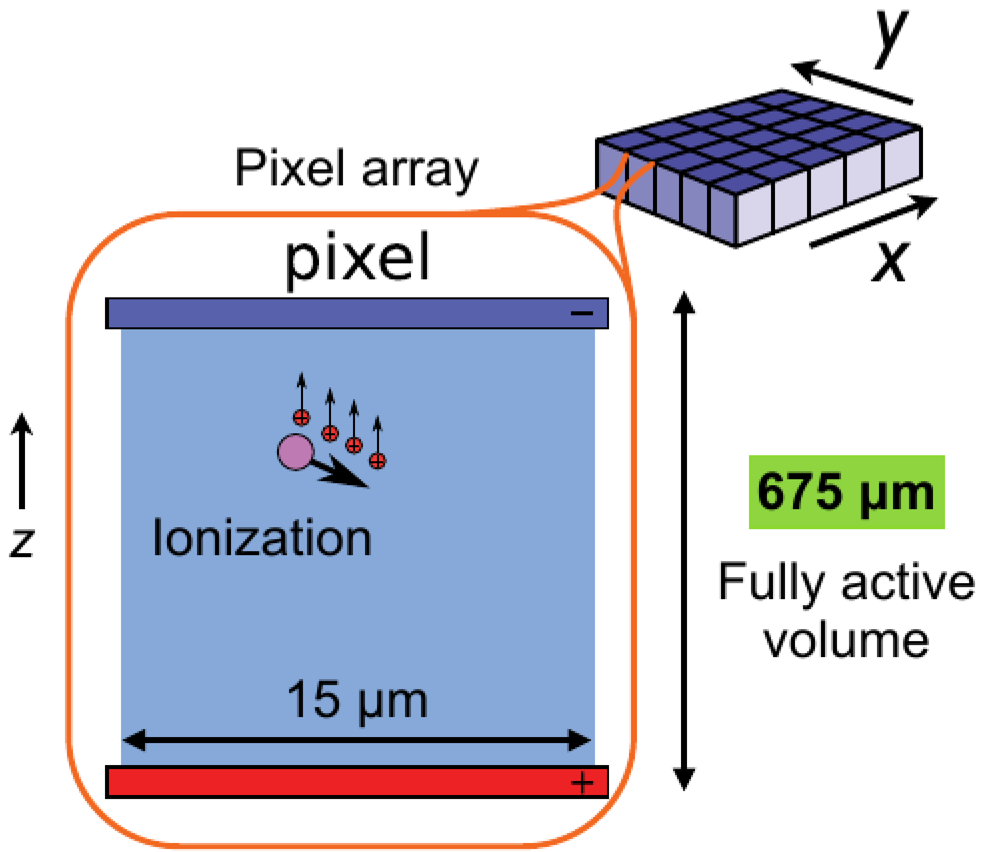


Installed at Snolab: 2km of norite overburden → 6000m water equivalent

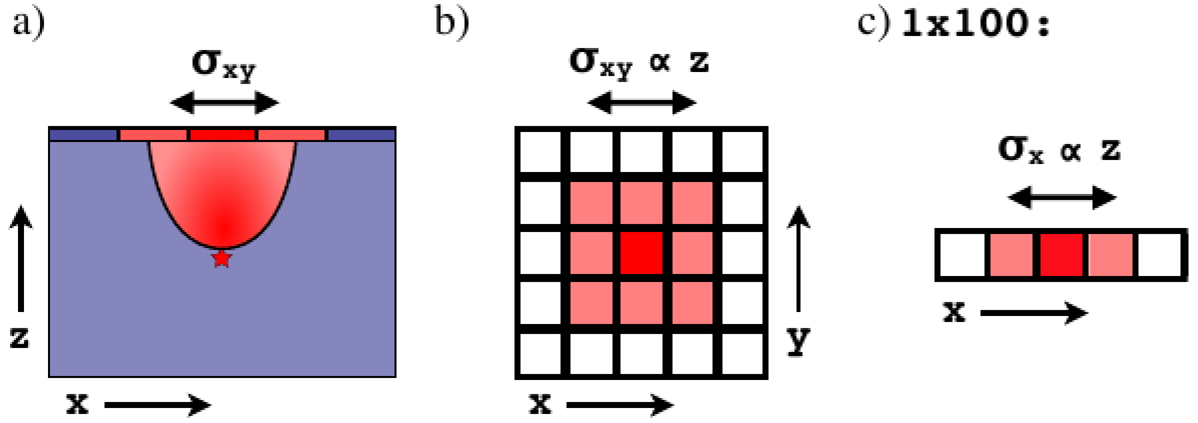
Particle Identification



Charged-Coupled Devices



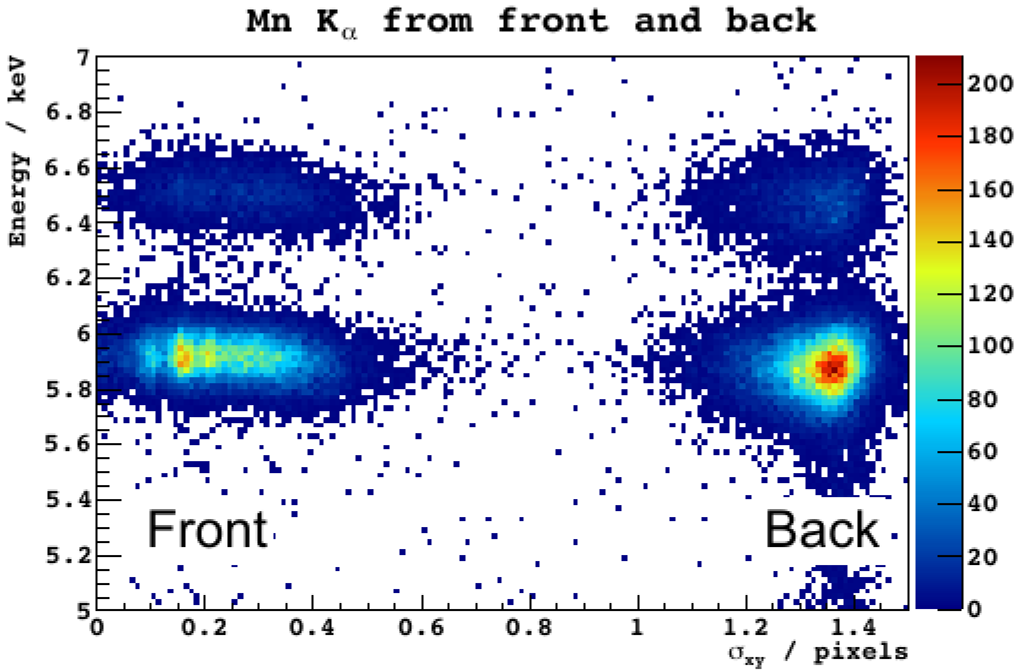
Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

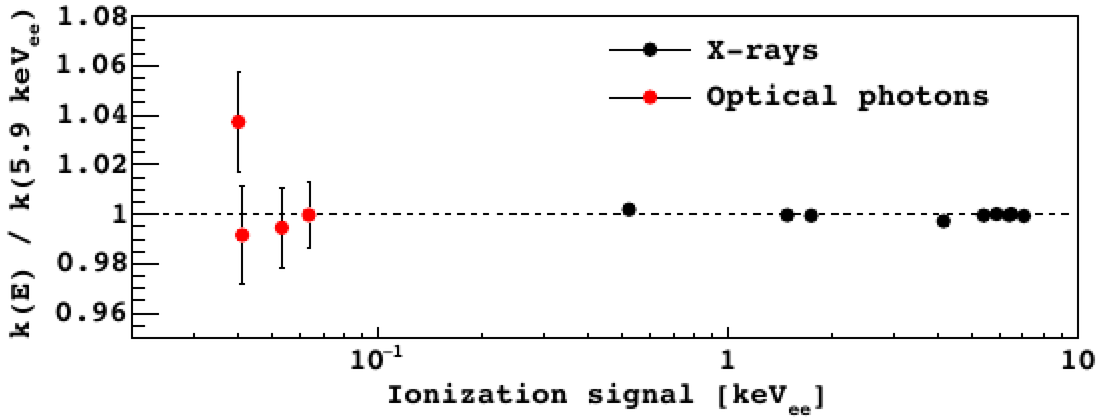


- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is “exposed,” collecting charge until user commands readout.
- Readout can be slow : **low noise (few e-).**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

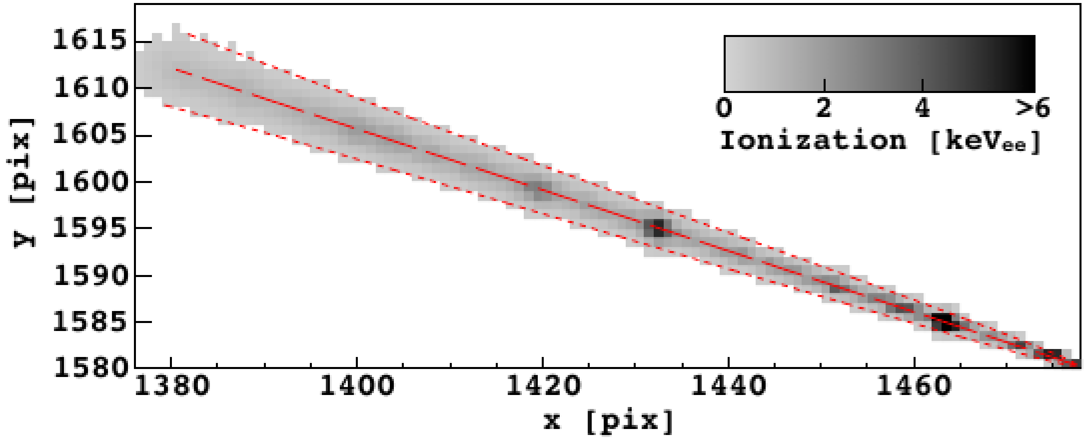
Detector Response

- CCD energy scale calibrated with X rays and photons down to 40 eV$_{ee}$.
- Diffusion model calibrated with cosmic muons on the surface.
- Validated with X-ray cluster reconstruction.



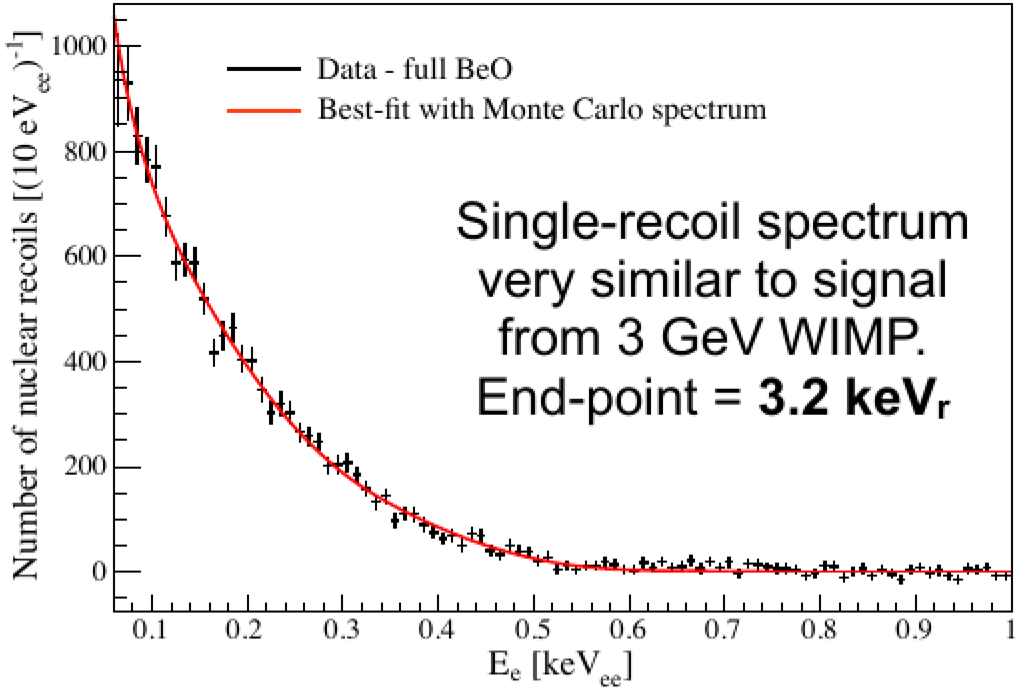


Cosmic muon:

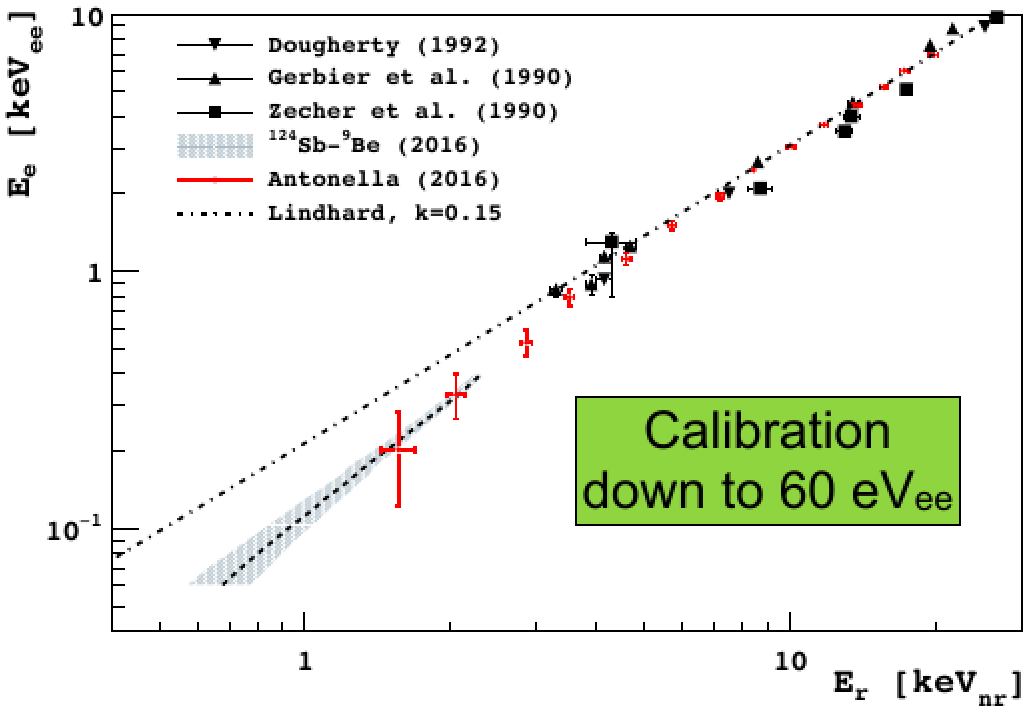


Nuclear Recoil Response

- Detector response calibrated with 24 keV neutrons from $^9Be(\gamma,n)$ reaction.
- By comparing data and Monte Carlo spectra, ionization efficiency was measured to be lower than predicted by Lindhard model.

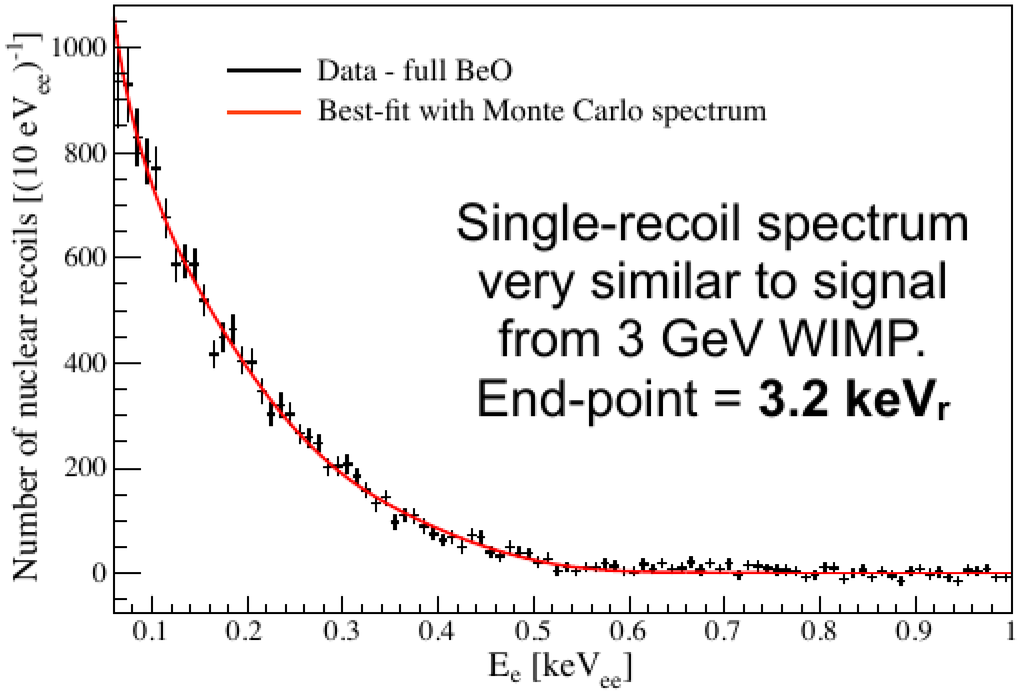


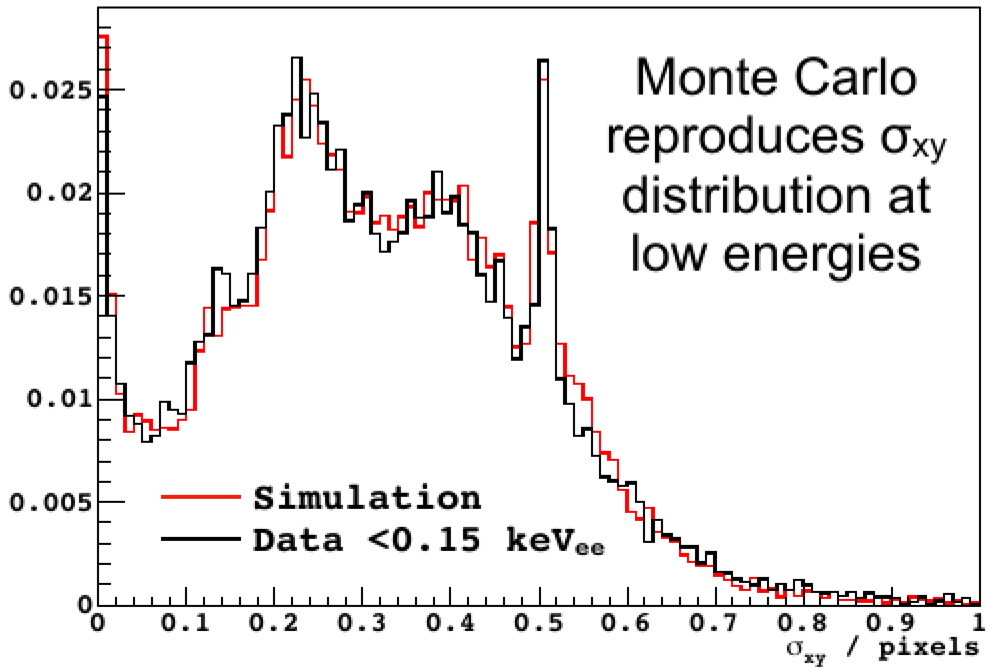
PRD94(2016)082007



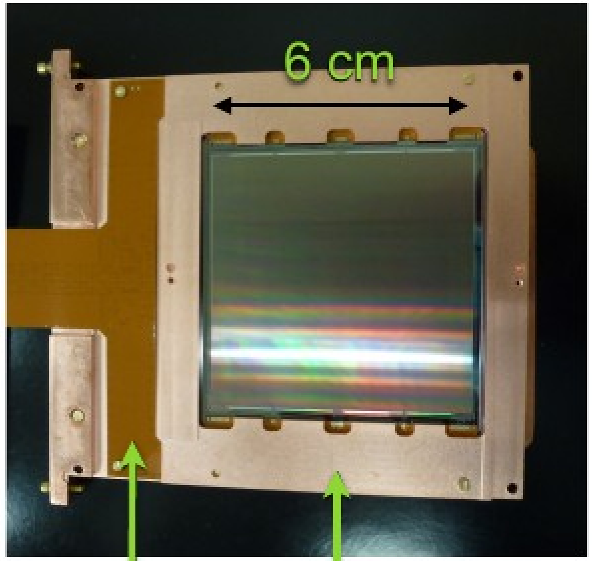
Nuclear Recoil Response

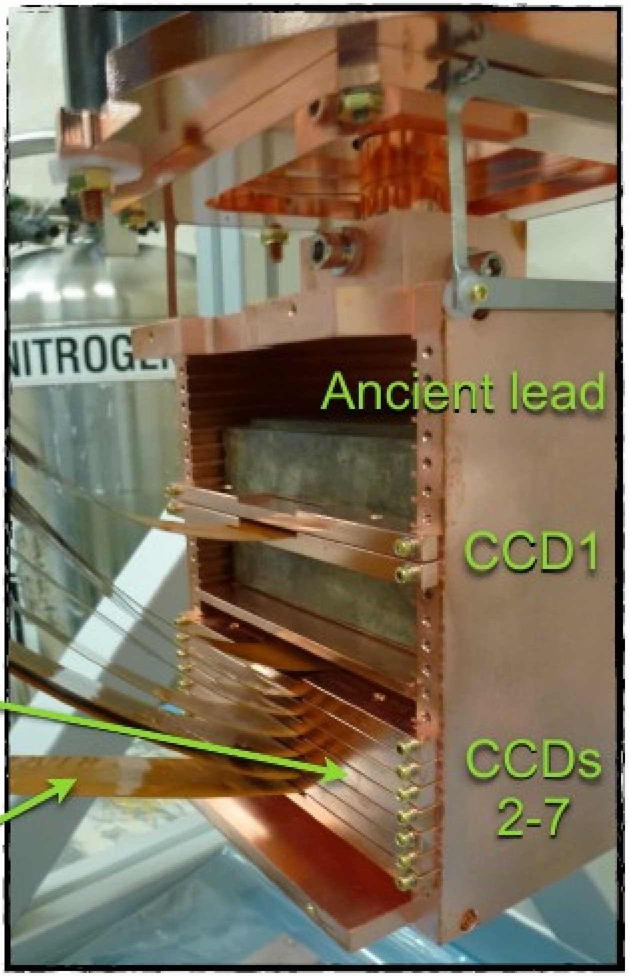
- Detector response calibrated with 24 keV neutrons from $^{9}Be(\gamma,n)$ reaction.
- By comparing data and Monte Carlo spectra, ionization efficiency was measured to be lower than predicted by Lindhard model.
- Validation of diffusion model at low energies.



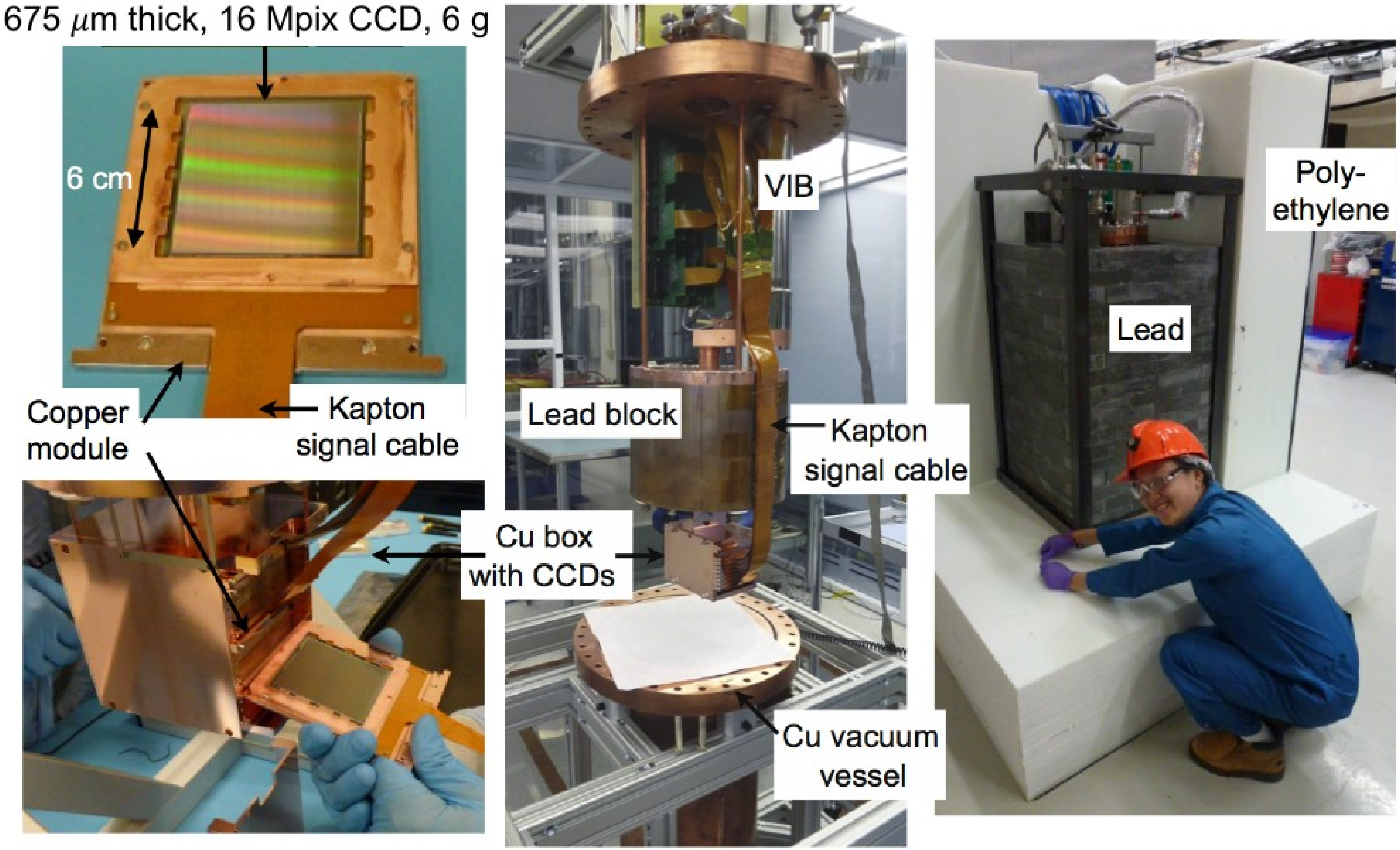


- Located at SNOLAB (6000 m.w.e. overburden).
- 7 CCDs (6.0 g, 16 Mpix) cooled to 140 K.
- Passive shielding: 20 cm of lead (inner 5 cm ancient) and 40 cm of polyethylene.
- Total background rate: ~10 d.r.u.
- Low pixel noise <2 e^-.
- Extremely low leakage current 2×10^{-22} A cm^{-2}.



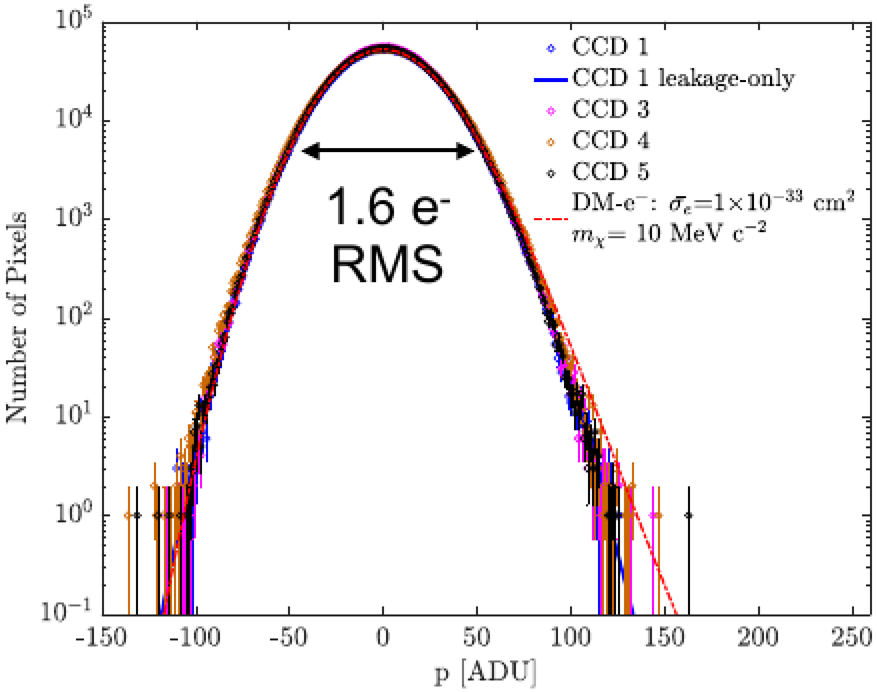


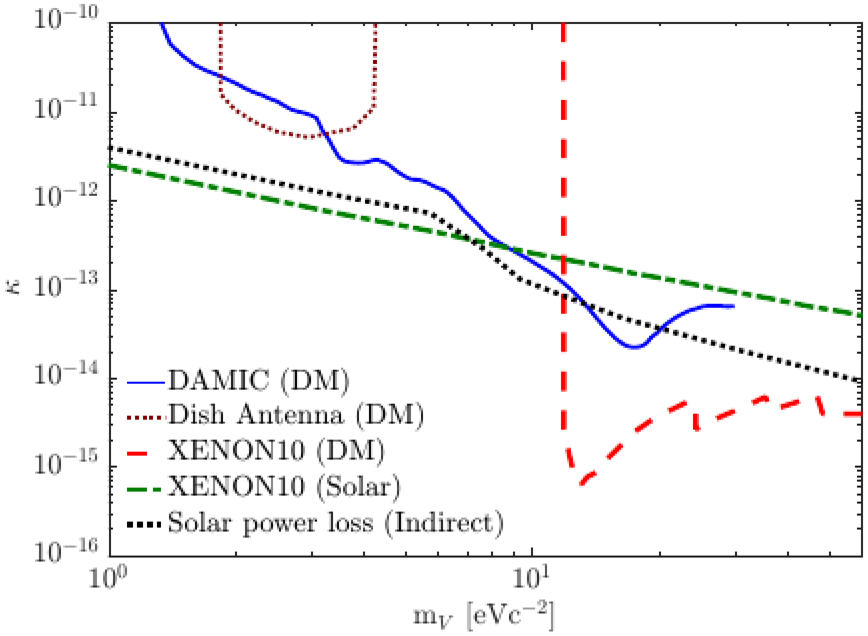
DAMIC-SNOLAB



Selected Results

- **DM-e⁻ interactions:** PRL118(2017)141803
  - First DM search results from ~eV ionization signals.
  - Latest DM-e- scattering results. PRL123(2019)181802





- **WIMP search:** PRL125(2020)241803 PRD105(2022)062003
  - 11 kg-day of data from seven-CCD array.
  - 50 eV_{ee} analysis threshold.
  - First full background model in CCDs.

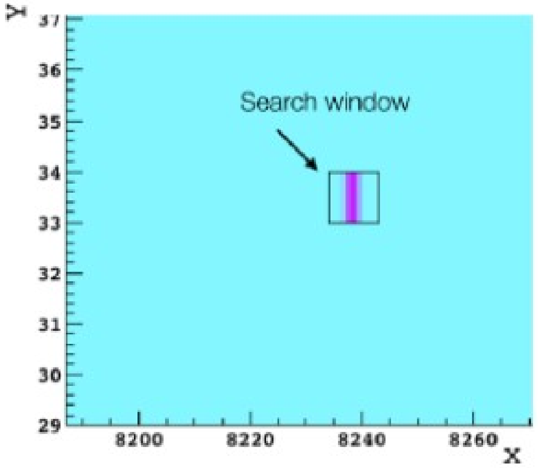
Event Selection

- Pedestal and correlated noise subtraction (hot pixels among several images masked)
- LL fit of the signal in a moving window across the image

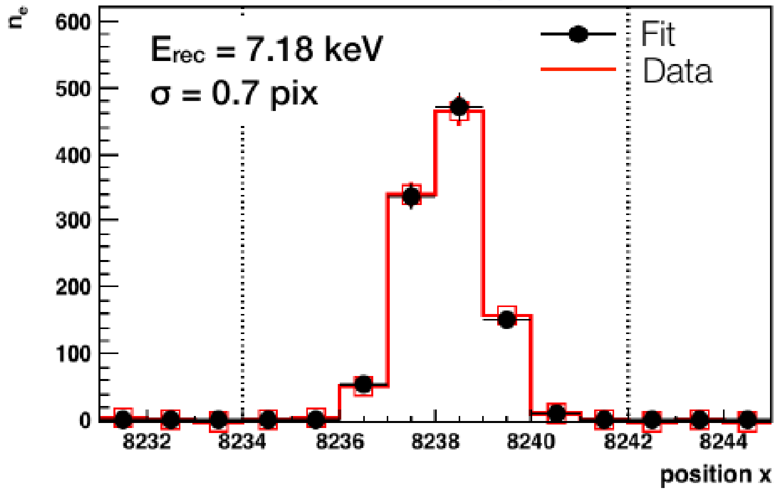
$$\Delta LL = \mathscr{L}_n - \mathscr{L}_S$$

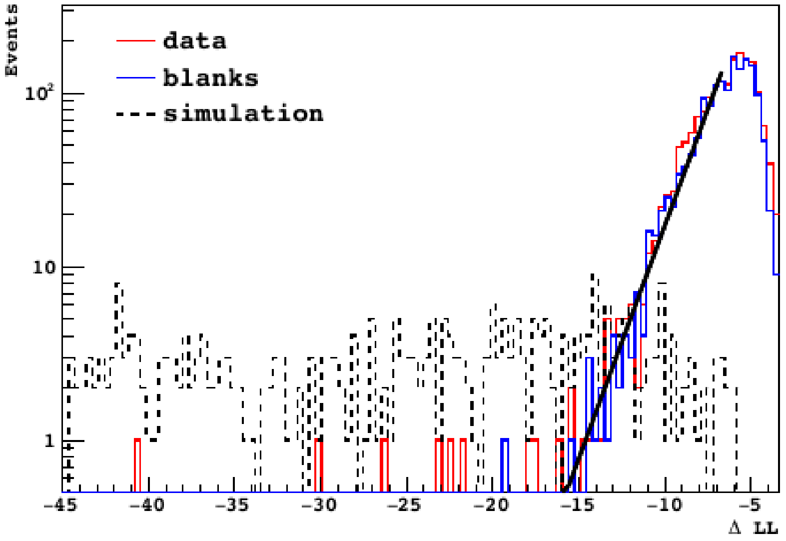
flat noise ($\mathscr{L}_n$) — Gaus signal + flat noise ($\mathscr{L}_S$)

- Best-fit Gaussian parameters provide cluster variables: E, σ_{xy}, x, y
- We select a statistical significance for a Gaussian cluster over noise such that <0.1 noise events in the data.



Example of one event

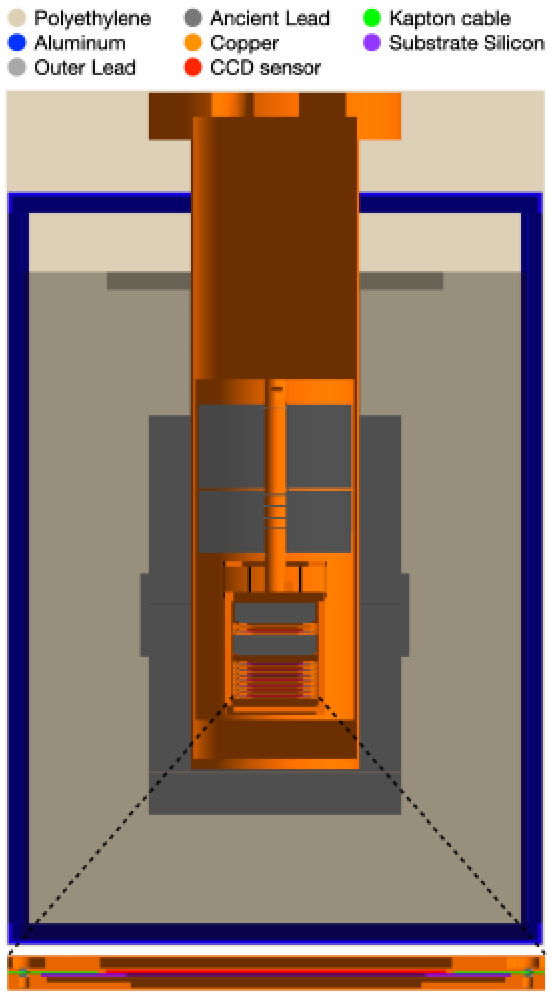




DLL cut : < 0.001 bkg events from exponential fit of the "blanks" distrib

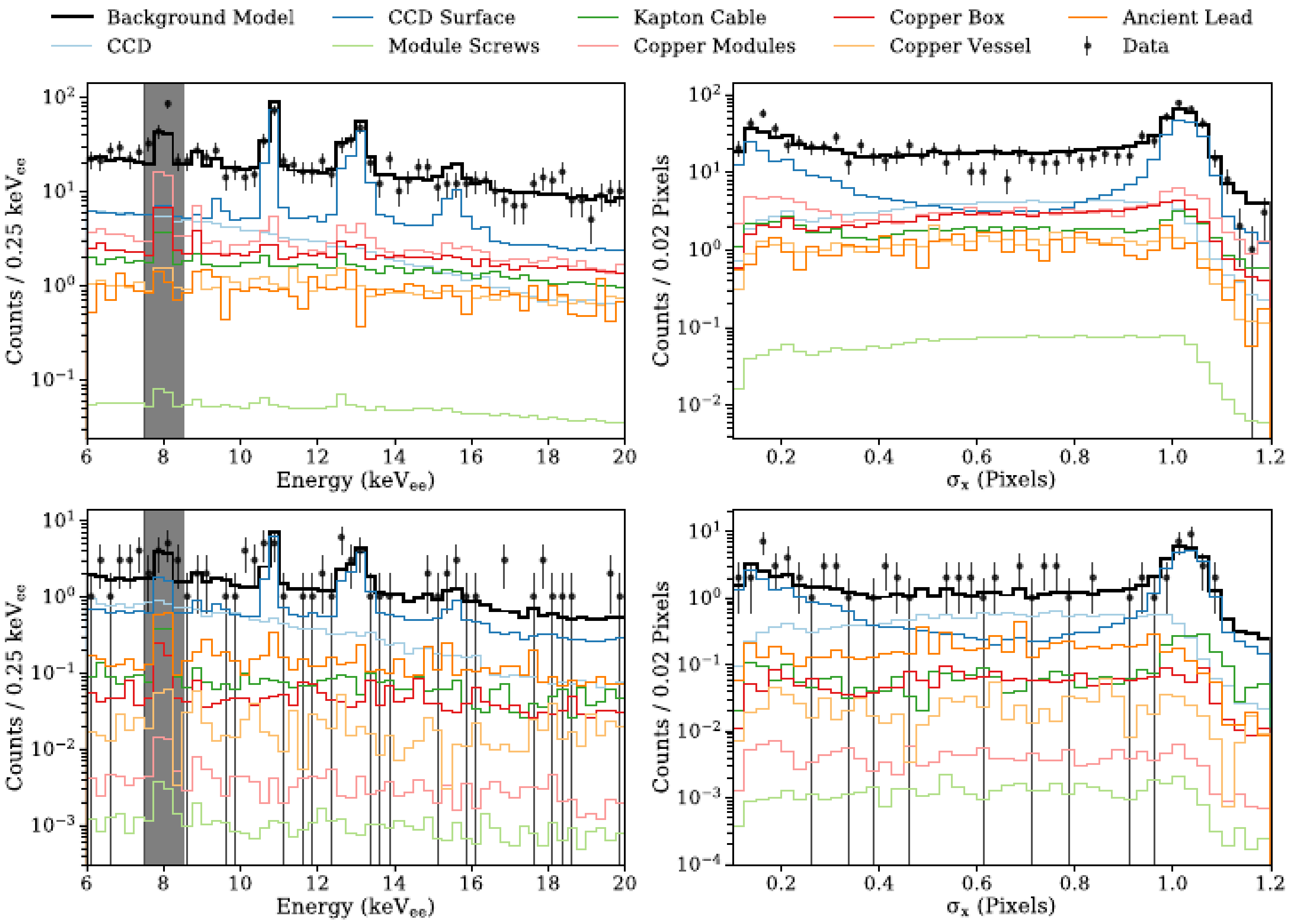
Background Model

- Simulate radioactive decays everywhere inside the detector and track the resulting particles (GEANT4).
- Apply the detector response model to all energy depositions.
- Simulate data reconstruction and selection.
- Perform a fit in (E, σ_{xy}) to clusters with $E > 6$ keV$_{ee}$ for a best-fit background model.
- **Constraints and cross-checks to background model from:**
  - Extensive radioactive materials assay program. **PRD105(2022)062003**
  - Coincidence analysis of decays in bulk silicon. **JINST16(2021)P06019**
  - Independent beam measurement of cosmogenic activation. **PRD102(2020)102006**



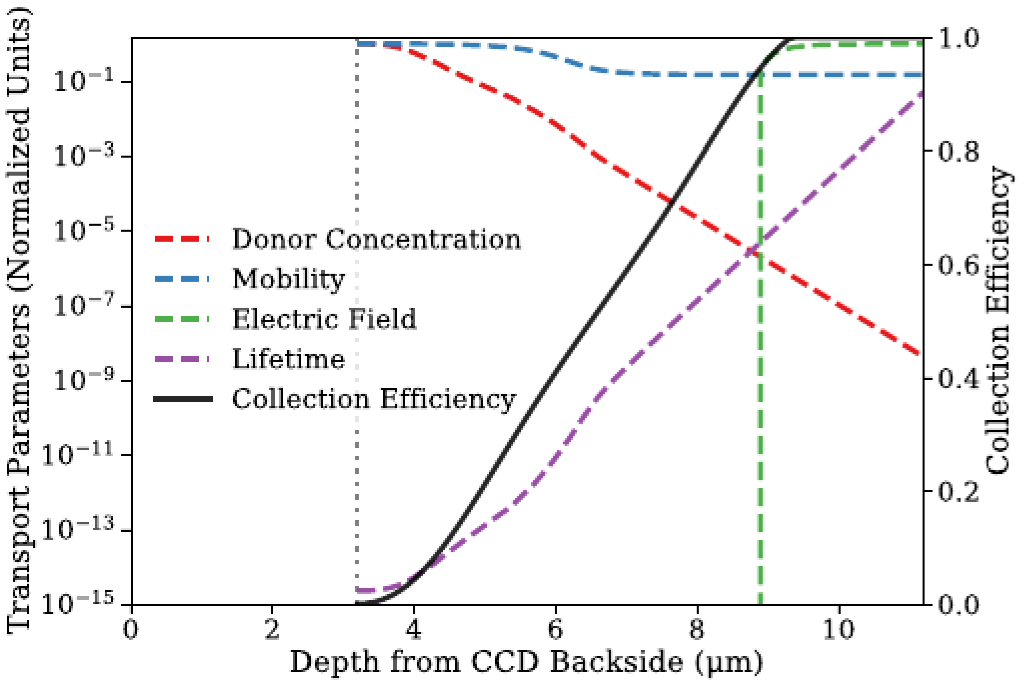
Background Model

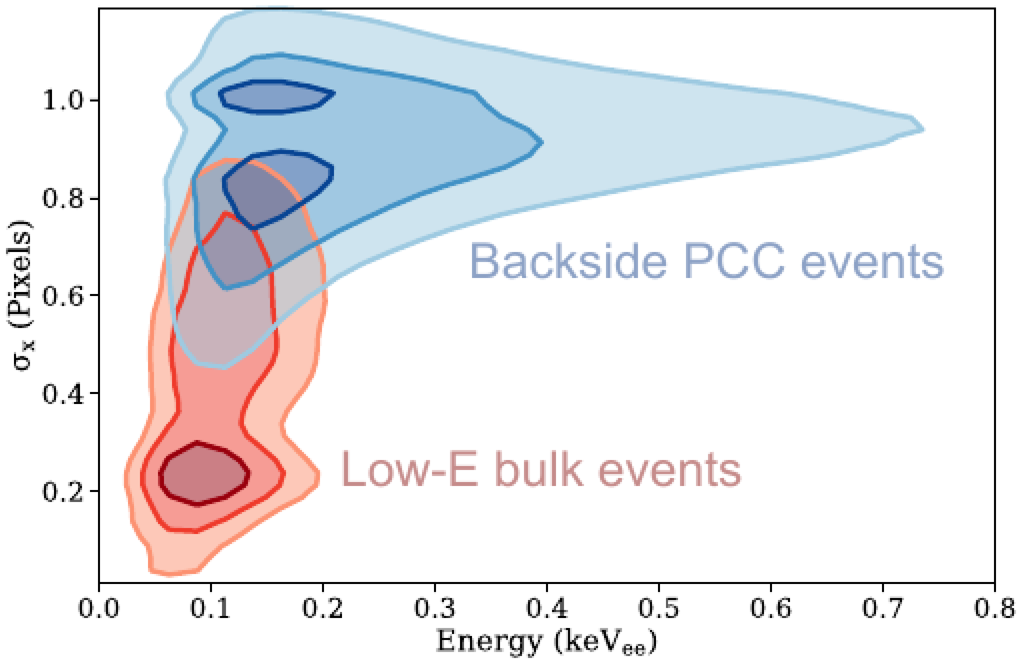
- **Top:** Fit in (E, σ_{xy}) to clusters with E > 6 keV$_{ee}$ to data from CCDs 2-7.
- **Bottom:** Best-fit result compared to data from CCD 1.
- Main background components: ^{210}Pb (surface, bulk Cu), ^{3}H in silicon.
- Extrapolate to low energies for WIMP search.



Partial Charge Collection

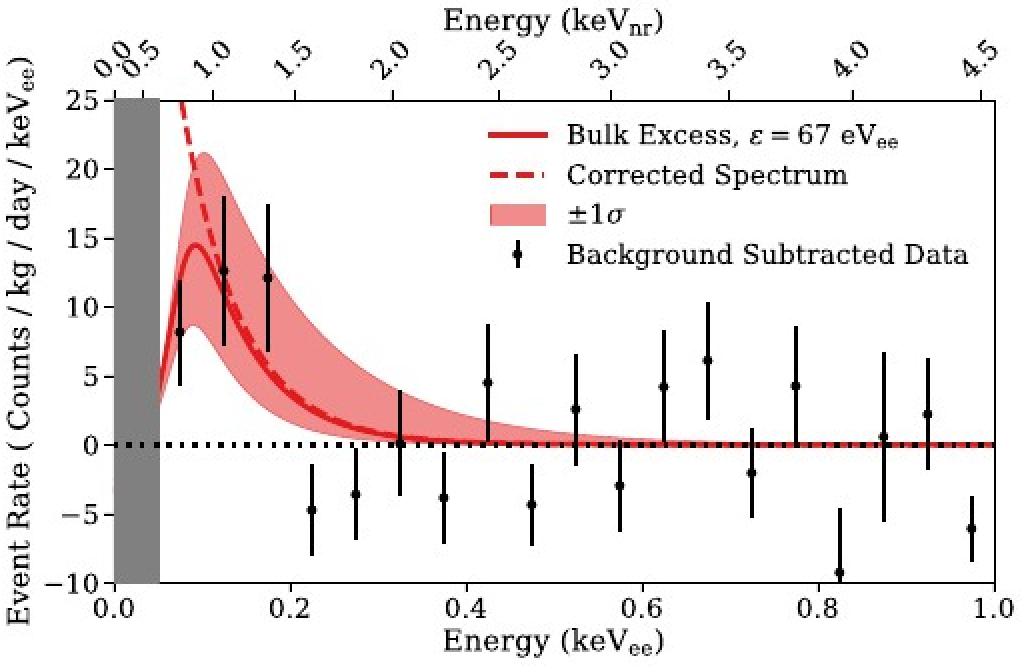
- Dominant systematic uncertainty is the response of the CCD to decays (e.g., ^{210}Pb-Bi) on the backside.
- Simulated CCD backside response and parametrized spectral distortion of backside background components.

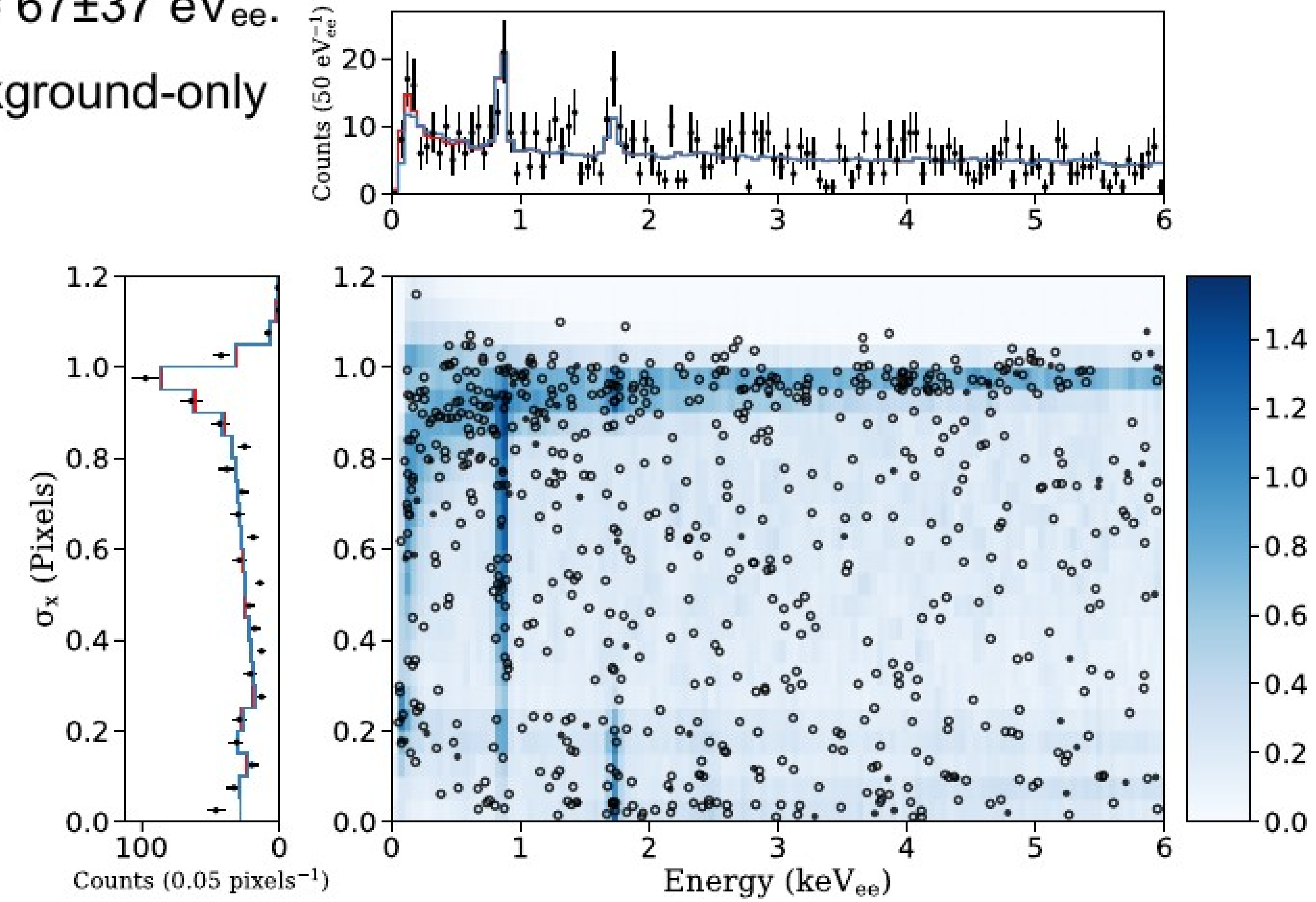




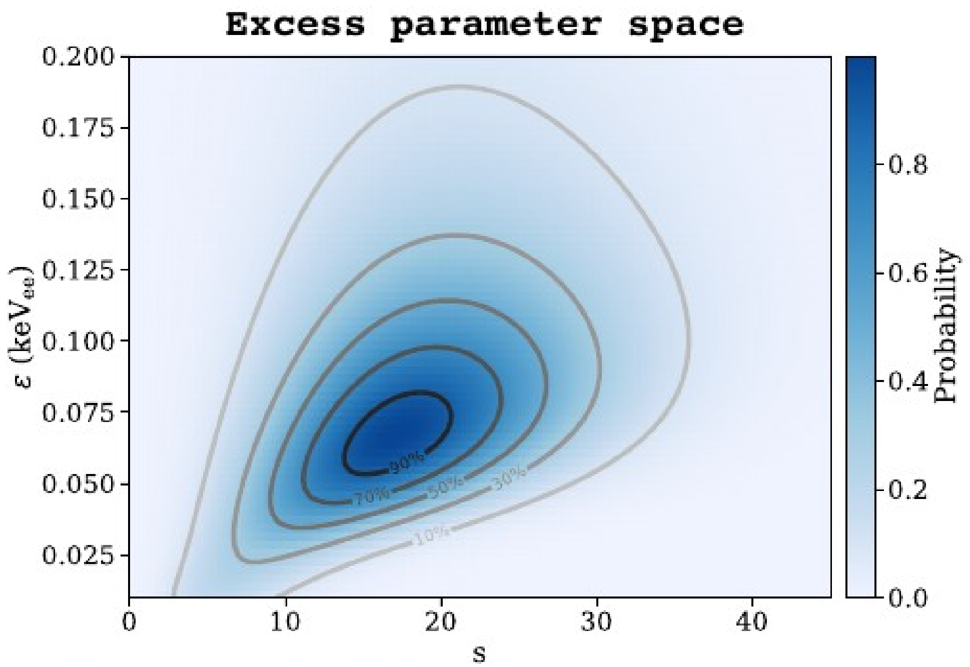
WIMP Search Fit Result

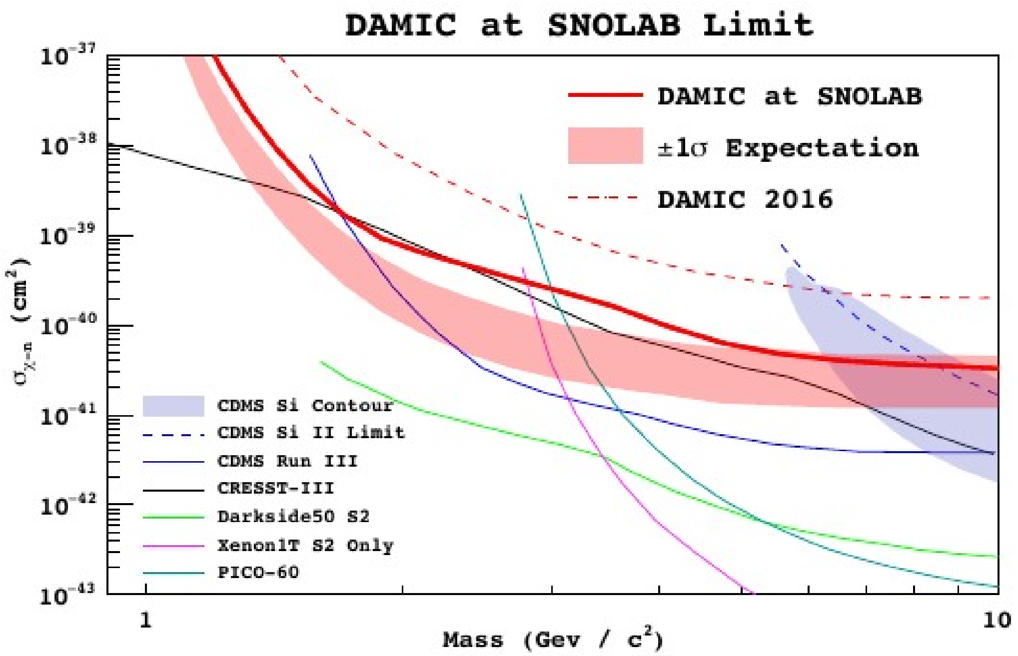
- Unbinned likelihood fit with background model + PCC correction + generic exponential signal.
- Excess of 17.1±7.6 events with decay ε = 67±37 eV_{ee}.
- Fit prefers signal + background over background-only with **p value** 2.2 x 10^{-4}.





Final Results

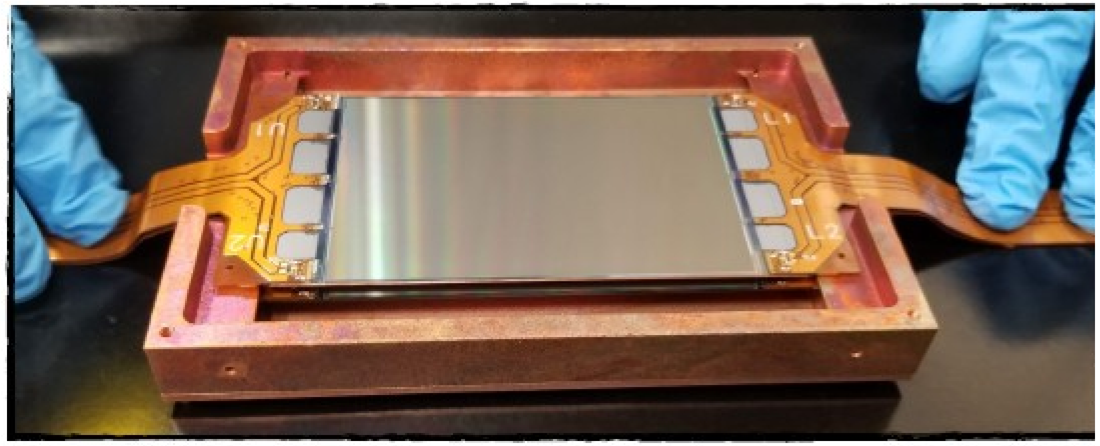


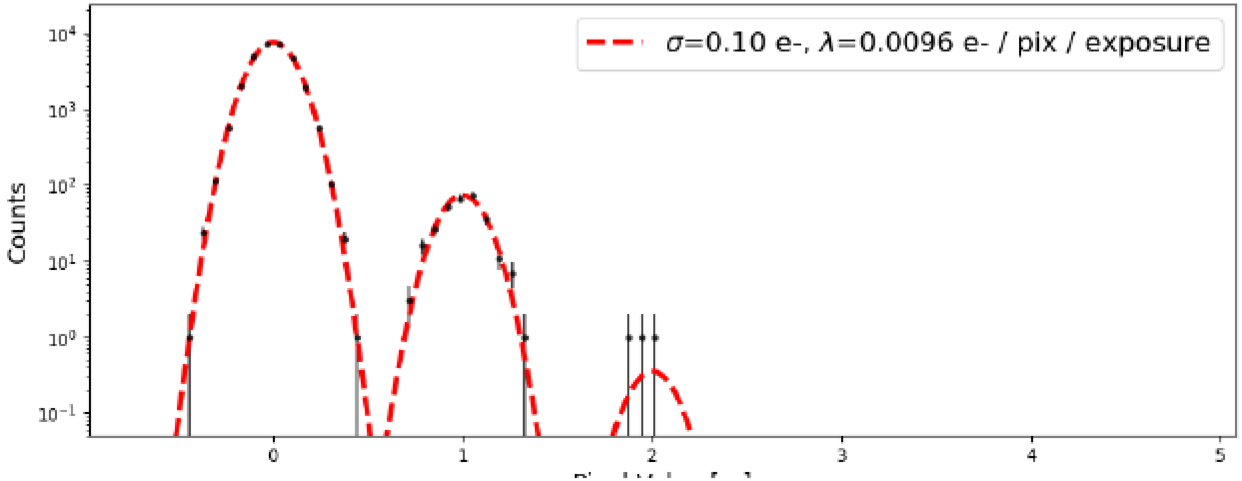


- **Systematic checks:**
  - Events really look like they are in the bulk. Unable to reproduce excess with surface pop.
  - No statistically significant features in the spectrum besides the low energy excess.
  - No known background or detector response hypothesis to explain the excess.
  - Known unknowns: unidentified noise source? imperfect surface background response model?

SNOLAB Upgrade

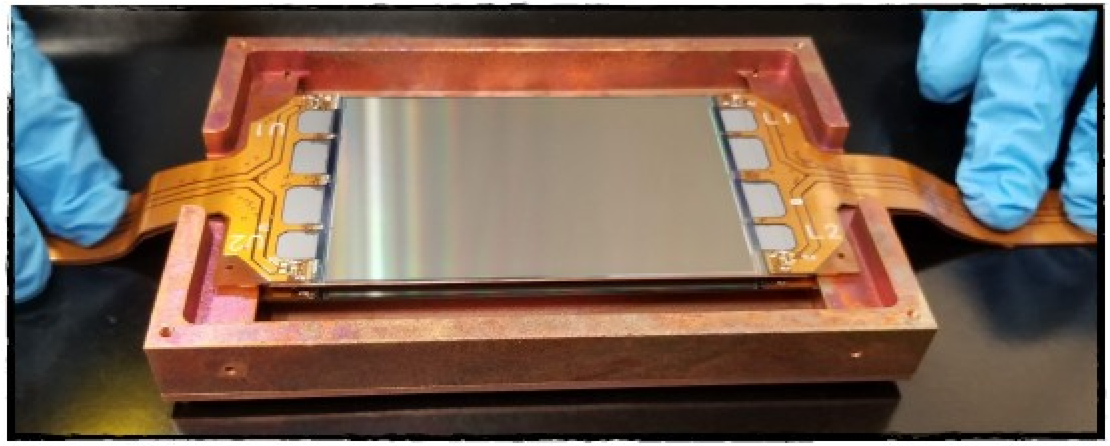
- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) packaged and tested at UW. Installed in Oct-Nov 2021.
- New science run started **in early March 2022**.
- Single-charge resolution (σ_{pix} = 0.16 e^{-}) and low leakage current (2.4 x 10^{-3} e^{-}/pix/day).

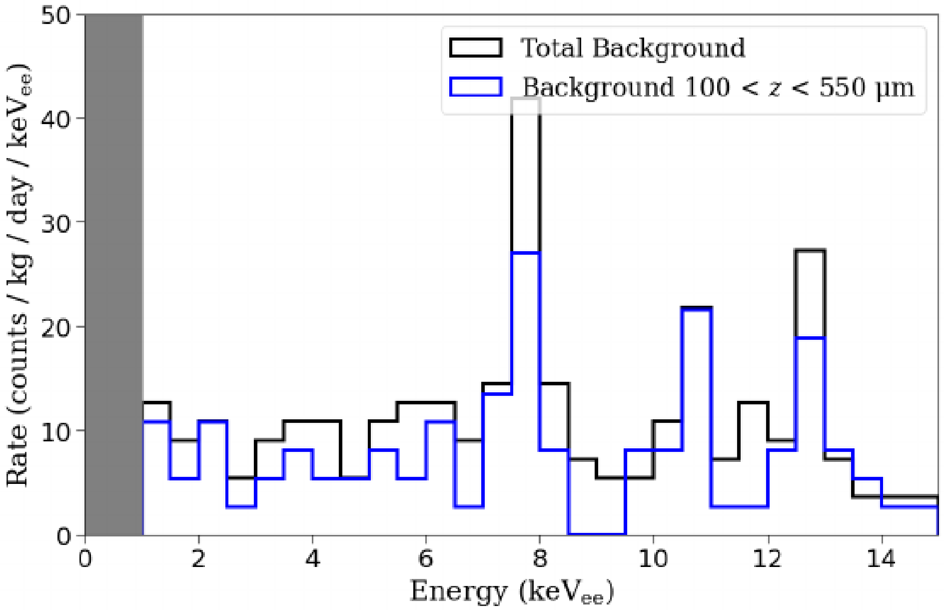




SNOLAB Upgrade

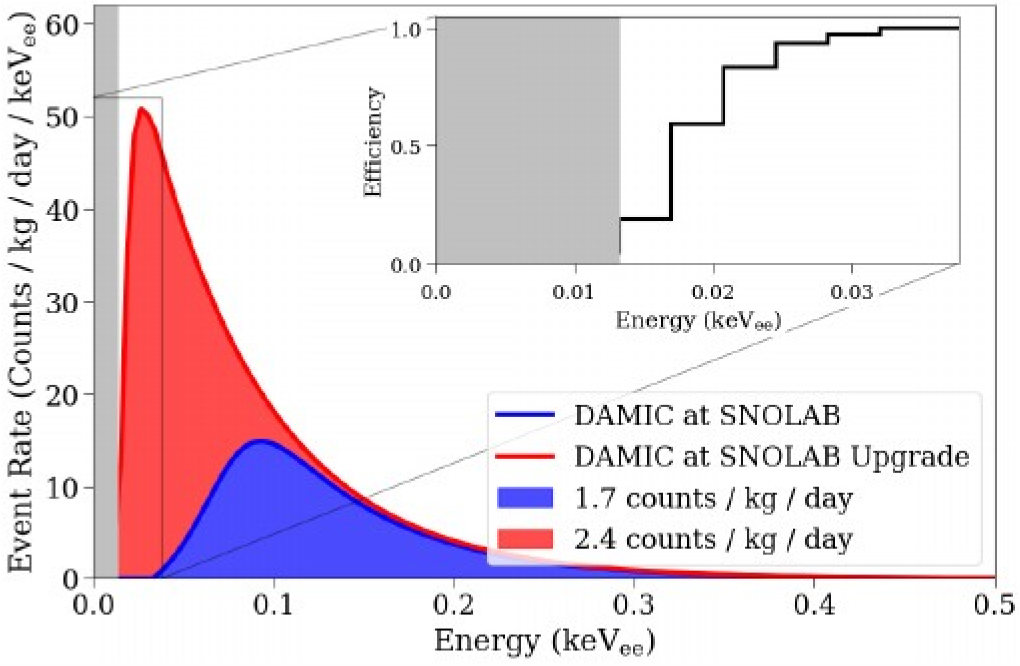
- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) packaged and tested at UW. Installed in Oct-Nov 2021.
- New science run started **in early March 2022**.
- Reproduce background rate from before: 9 ± 1 d.r.u. total and 6 ± 2 d.r.u. bulk.

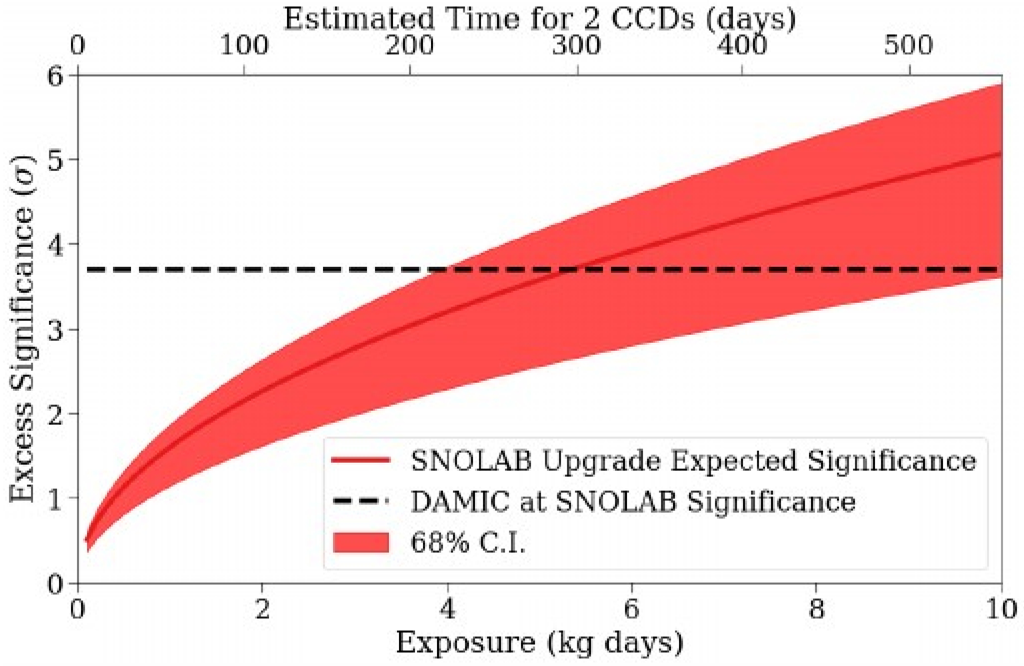




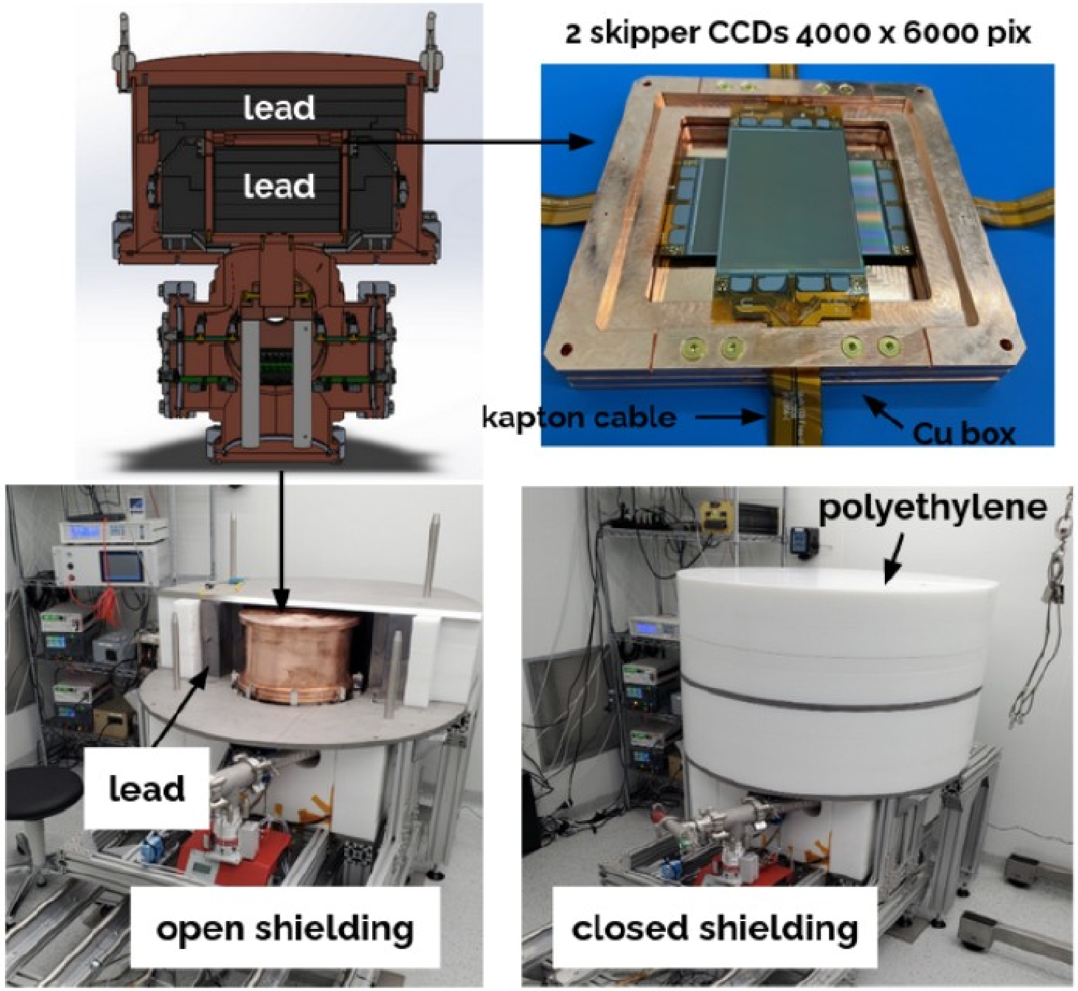
Expected Sensitivity After Upgrades

- Simulated data set with measured detector performance.
- Performed event clustering, reconstruction and selection with methodology from previous analysis.
- Threshold decreased from 50 eV_{ee} to 15 eV_{ee} (4 e-).
- If exponential excess present, should observe with high significance in <1 year.





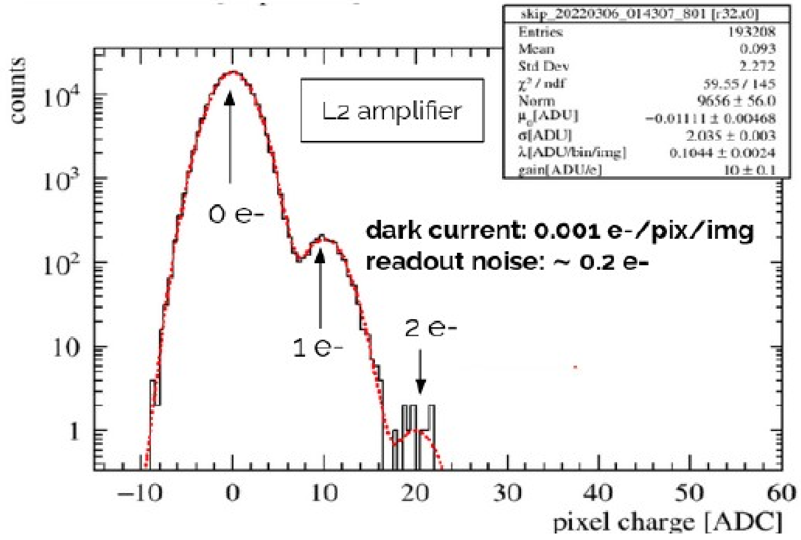
Low Background Chamber (LBC)



DAMIC at the Laboratoire Souterrain de Modane (LSM), or DAMIC-M, is the next generation of the DAMIC experiment.

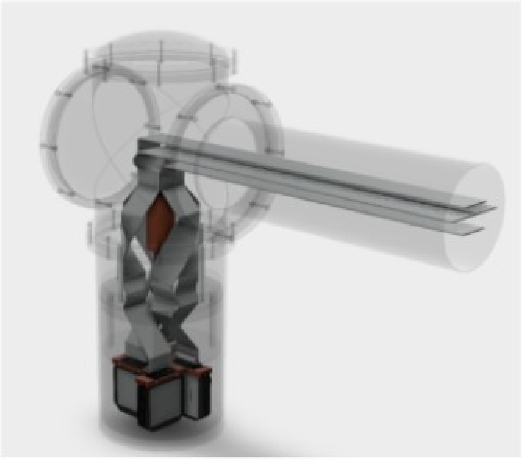
Currently the LBC with two 6k x 4k CCDs (same CCDs as in SNOLAB, also packaged and tested at UW) is actively taking data!

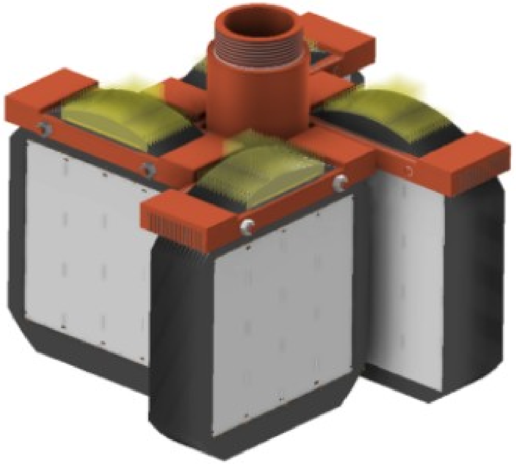
Allows test of electronics and background for the full scale detector and perform dark matter searches.



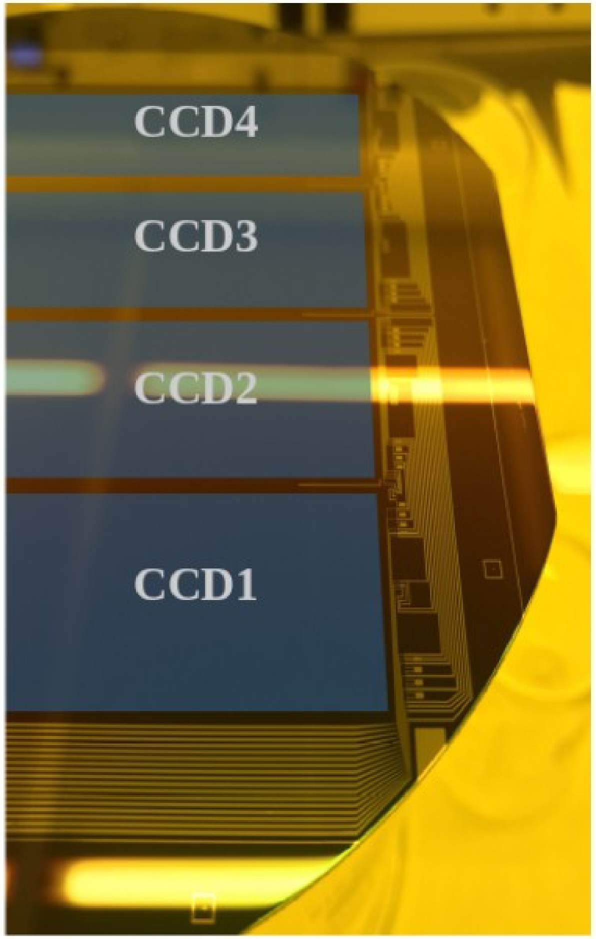
DAMIC-M Detector

- 200 CCD module array located at LSM in France with skipper CCDs for sub electron noise
- Target exposure of 1 kg year
- Background reduction to a fraction of a d.r.u (event / kg / day / keV)
- International collaboration between many institutions!





6K x 1.5k Pixels
(15 x 15 x 675 um^3)



Top Left: DAMIC-M cryostat design. Bottom Left: CCD Array design. Right: Pitch adapter prototype.

Summary

- DAMIC pioneered the use of low-noise CCDs to search for dark matter
- Extensive detector characterization and calibration
- DAMIC-SNOLAB - First CCD array underground, delivered competitive science results
- Developed the first complete background model for a CCD dark matter search.
- Performed the most sensitive search for low-mass WIMPs with a silicon target.
- WIMP search revealed a puzzling excess of events.
- Upgraded DAMIC with skipper CCDs to understand the origin of this excess.

DAMIC-SNOLAB Collaboration