The low-energy spectrum in DAMIC at SNOLAB

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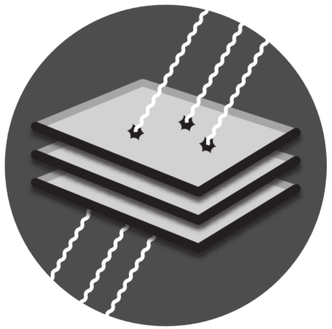
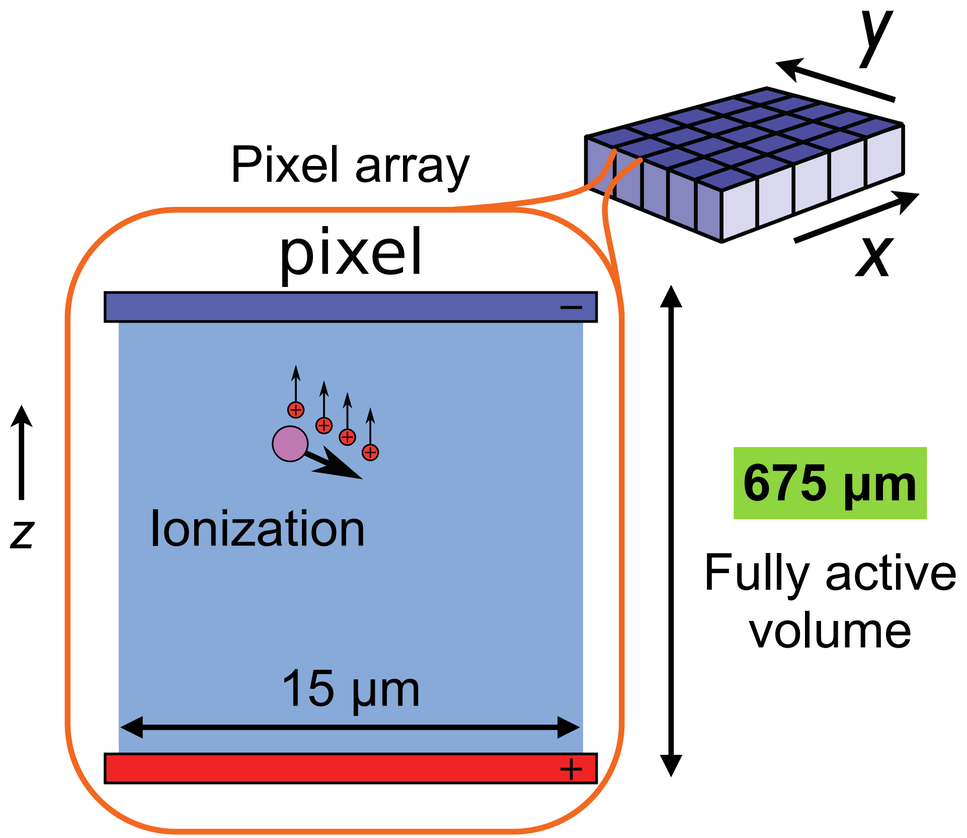


CENPA
Center for Experimental
Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

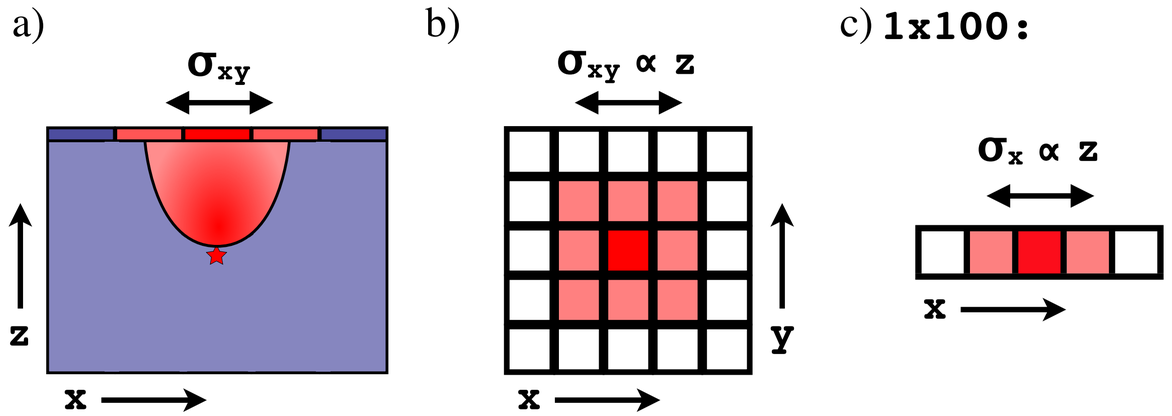
Outline

- Charge-coupled devices (CCDs).
- CCD detector response.
- DAMIC at SNOLAB.
- Data reconstruction.
- Background model.
- WIMP search results / low-energy excess.
- DAMIC upgrade with skipper CCDs.

Charge-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).

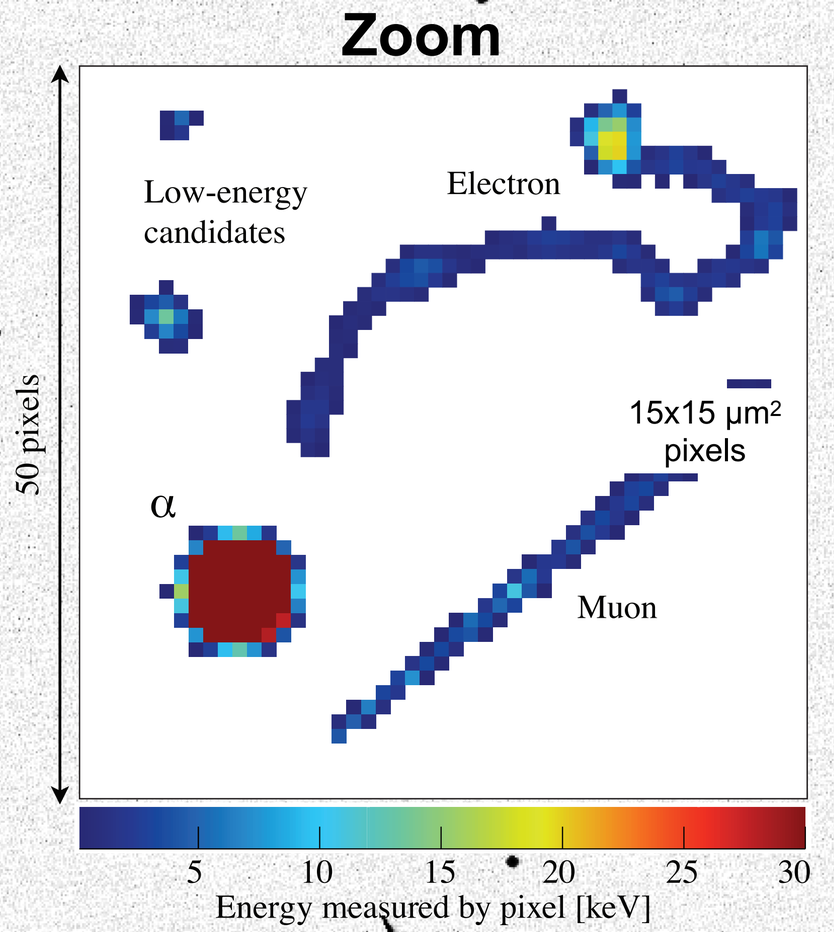
Sample CCD image (~15 min exposure) segment in the surface lab.

~1 cm

Cosmic muon

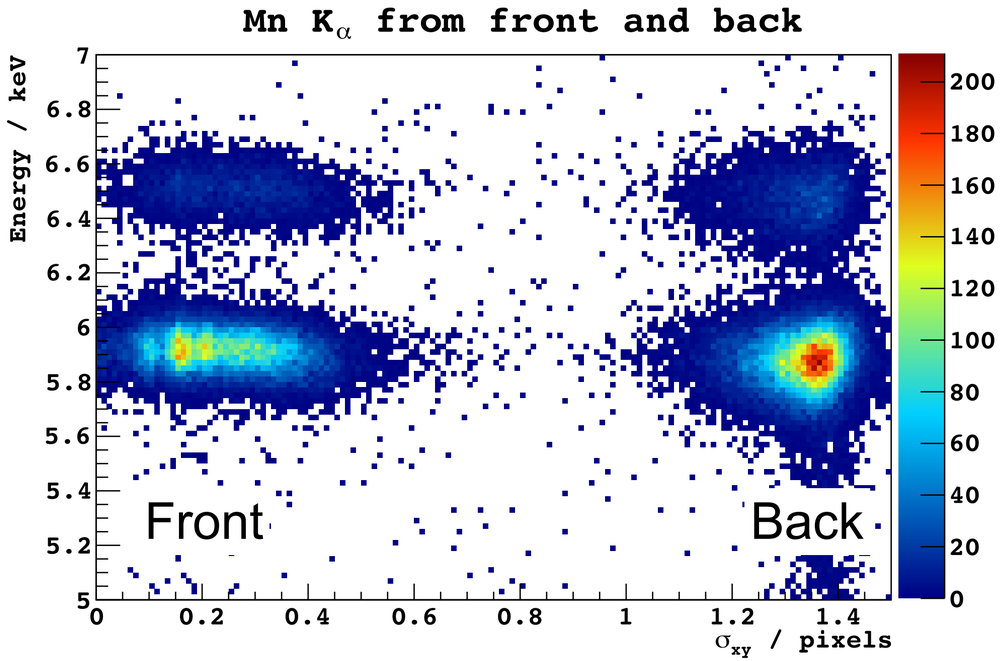
Point-like

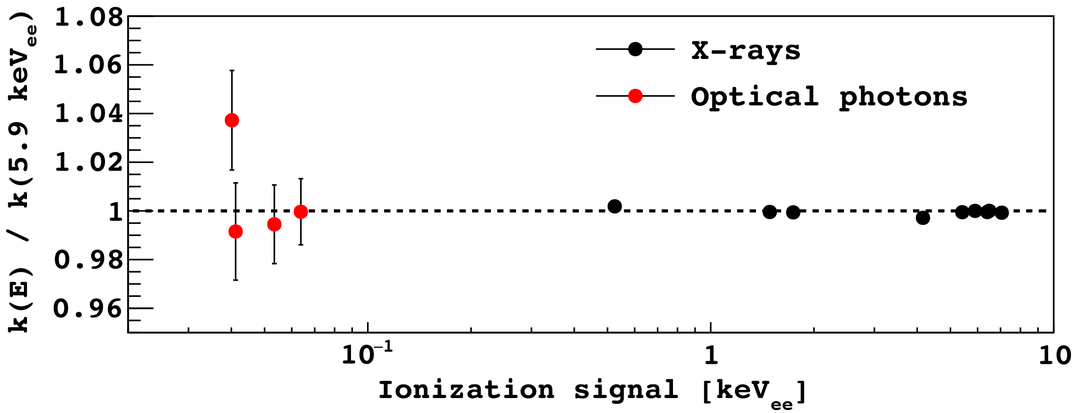
β particle



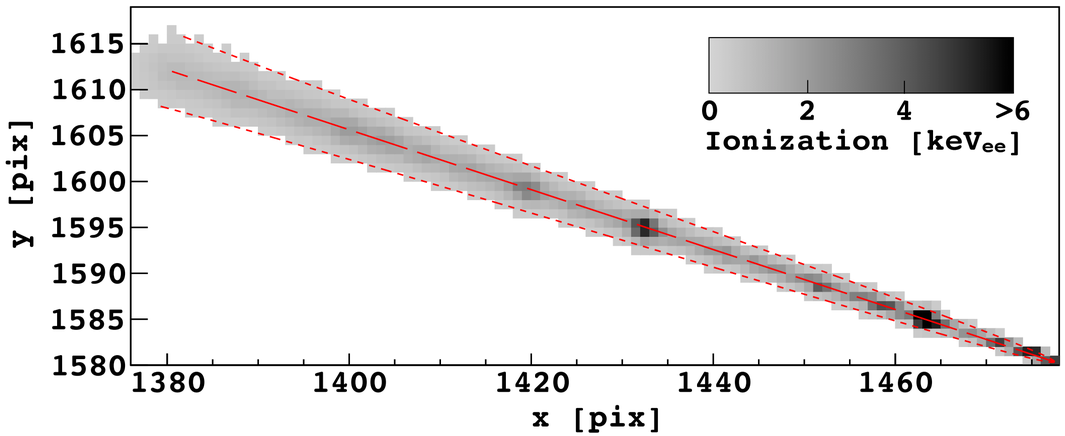
Detector response

- 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 ^{9}Be(γ,n) reaction.
- By comparing data and Monte Carlo spectra, ionization efficiency was measured to be lower than predicted by Lindhard model.
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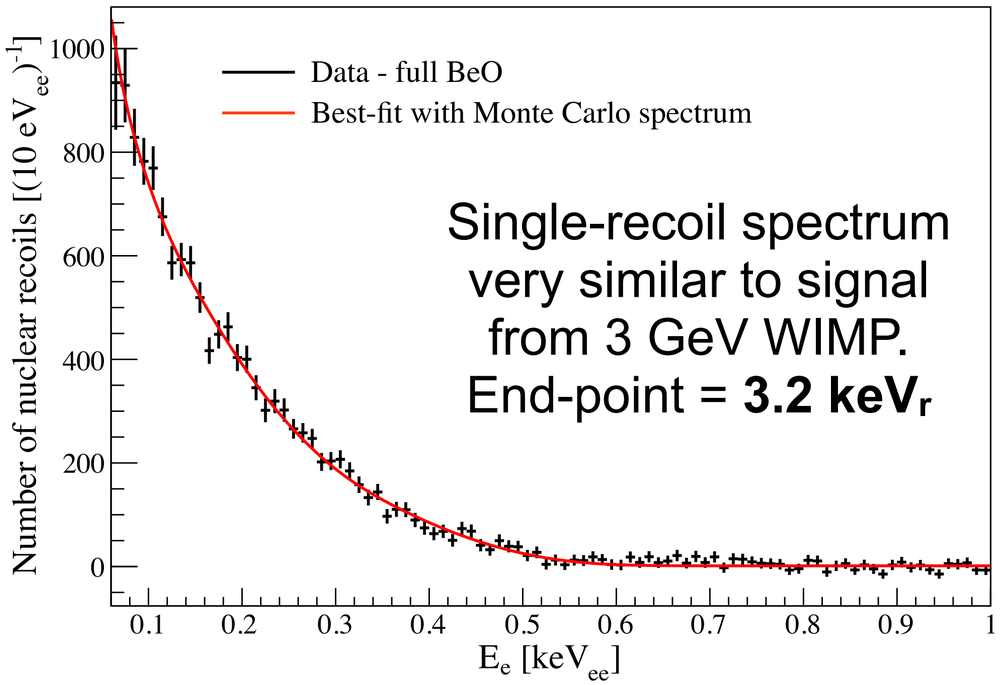

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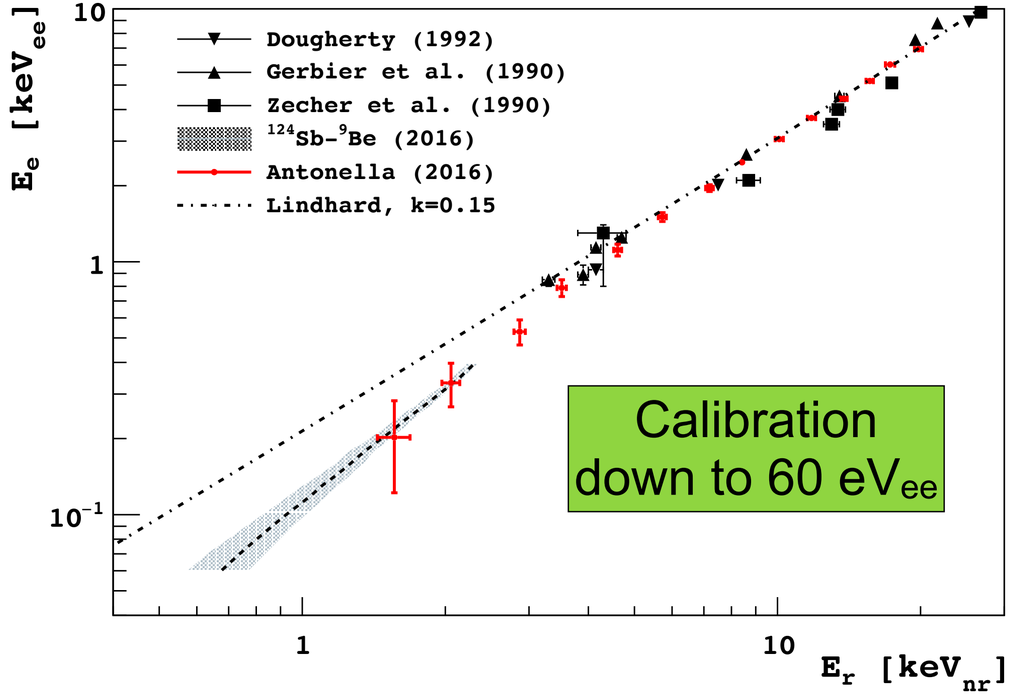
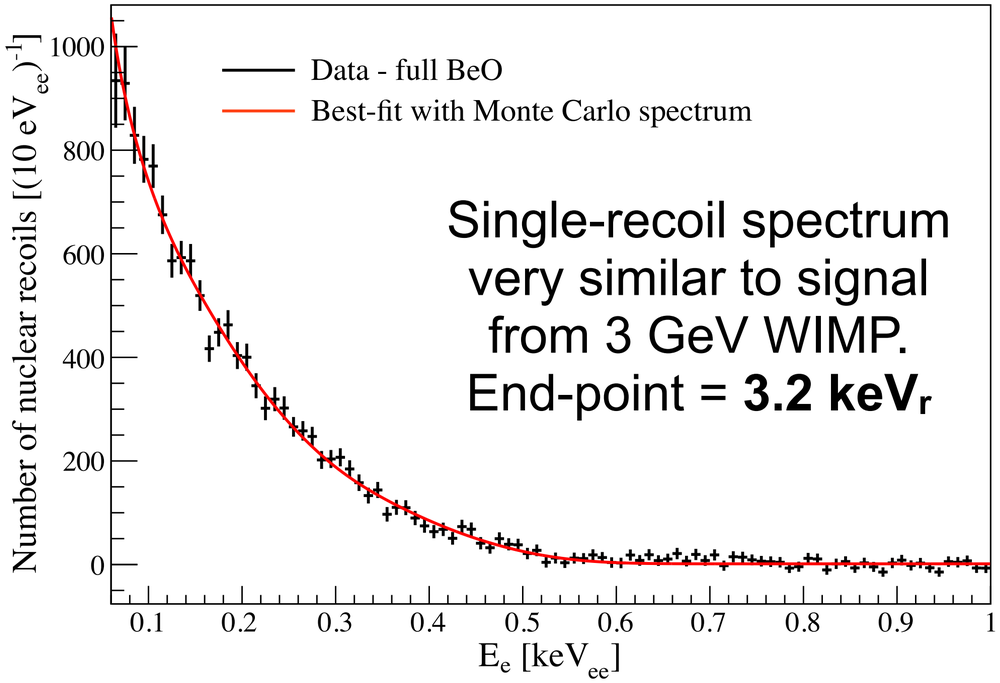
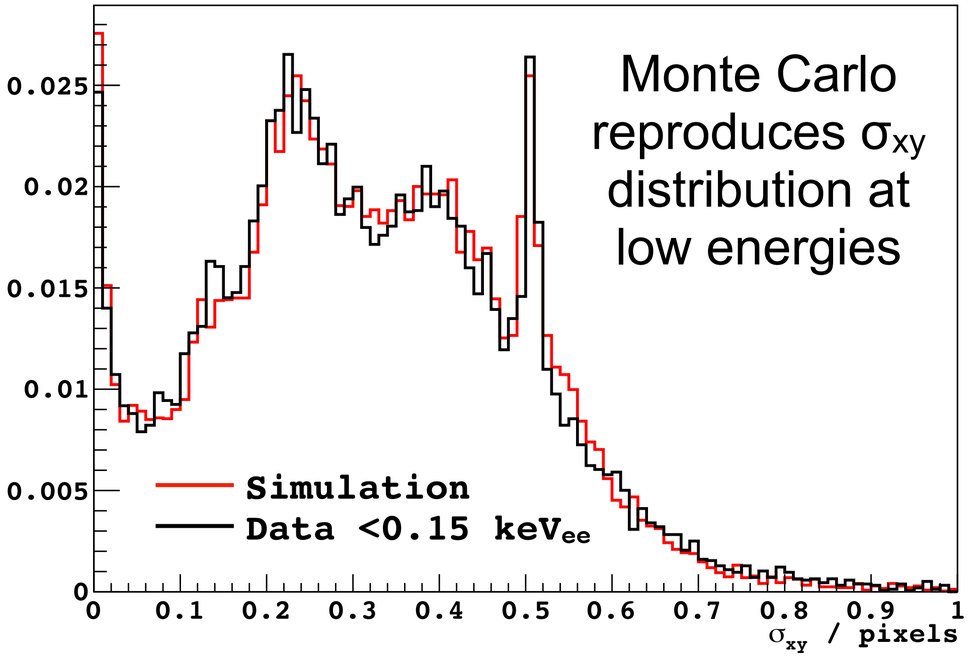


Nuclear recoil response

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



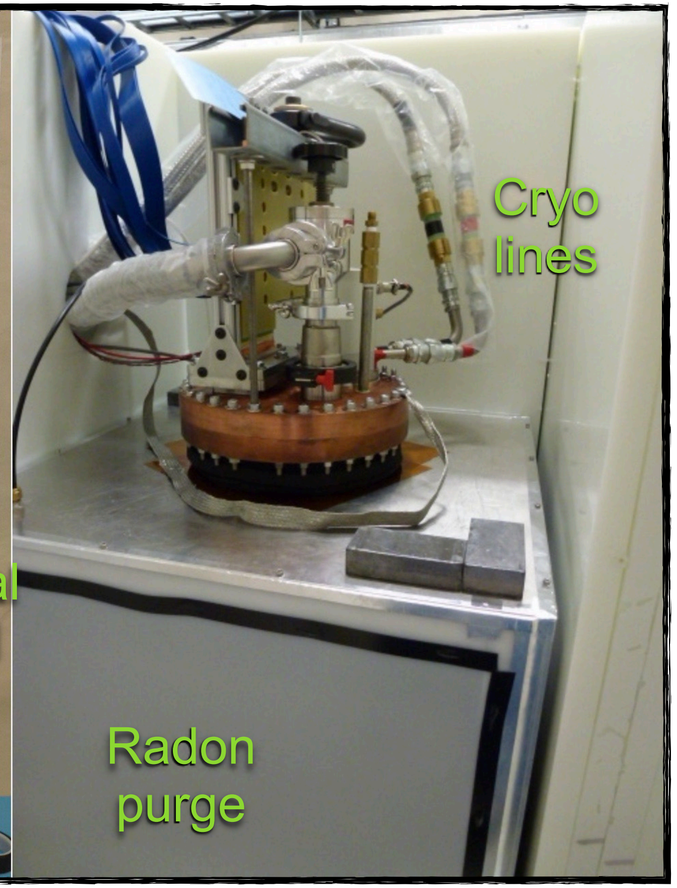


DAMIC at SNOLAB

CCD Box

Cryostat insert

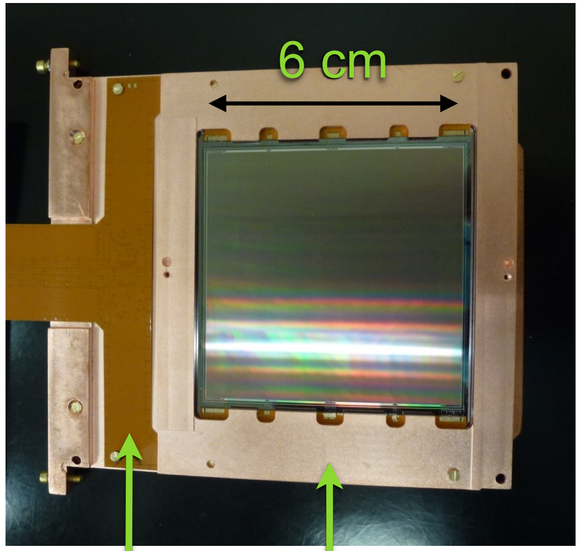
In shield

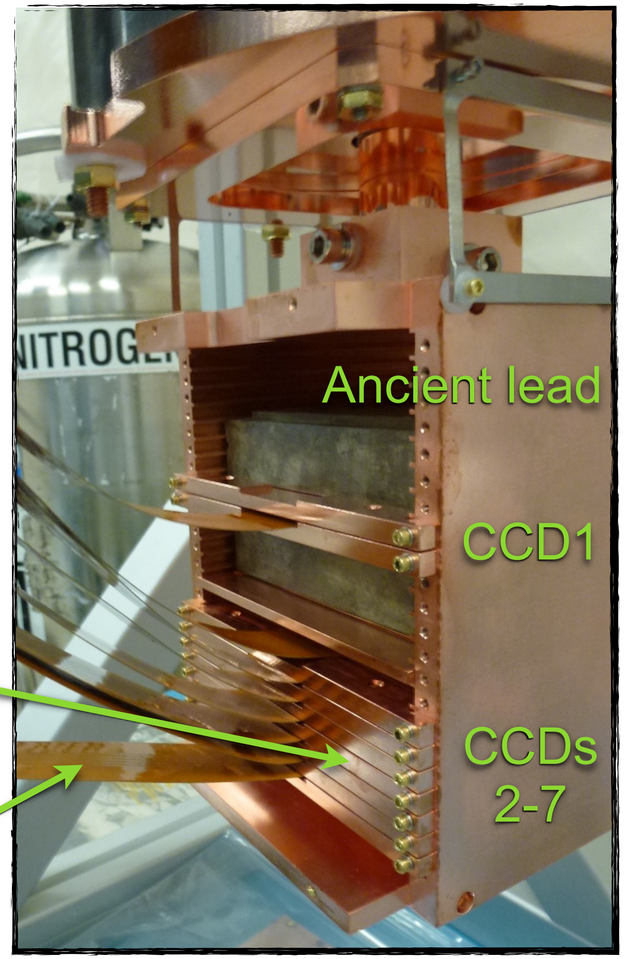


External shield

DAMIC at SNOLAB

- 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}.



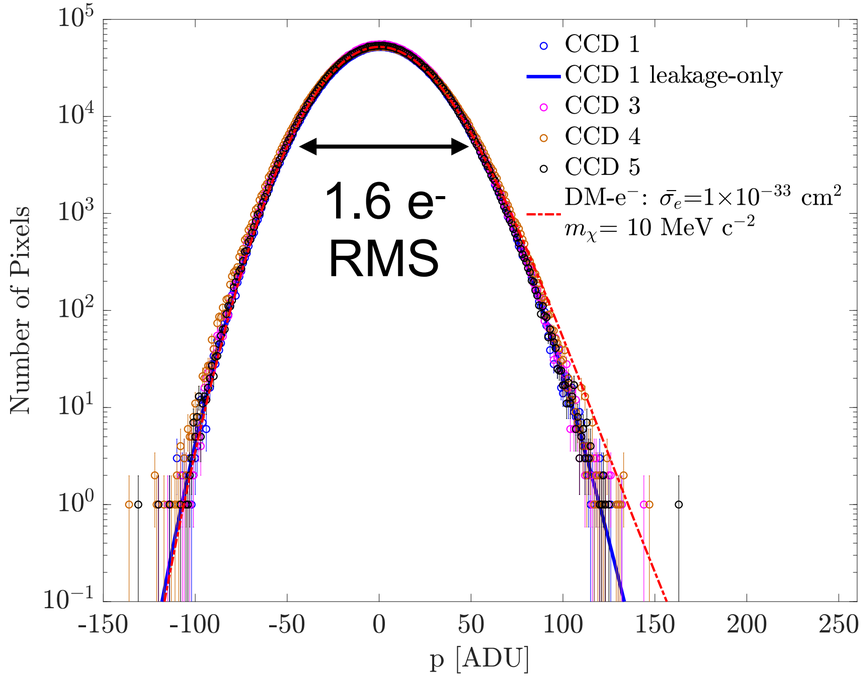


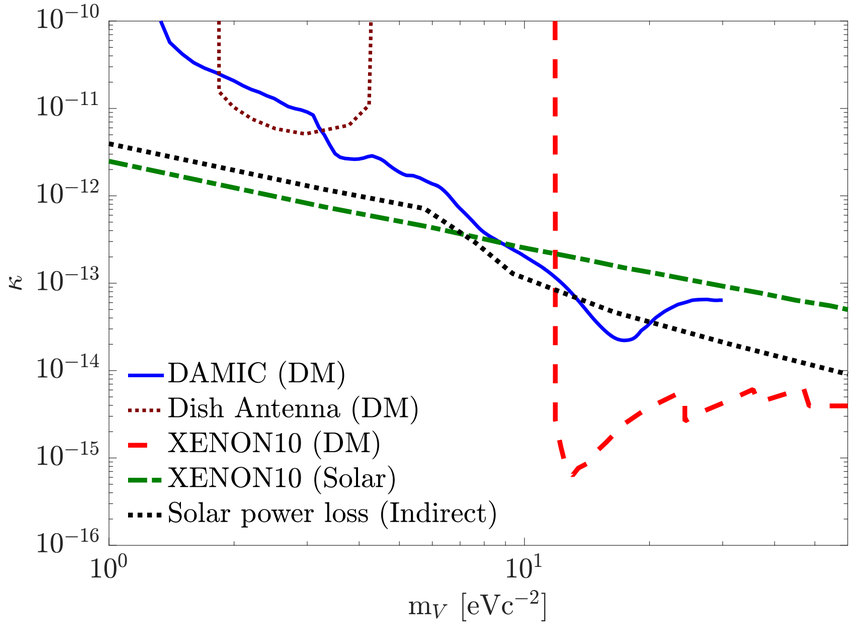
Copper trays
(EF for CCD1)

Kapton signal flex

Results summary

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

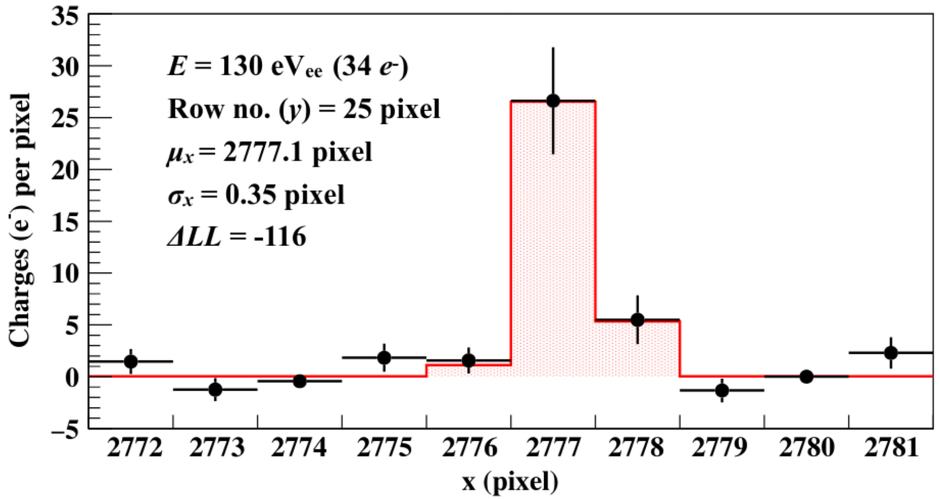


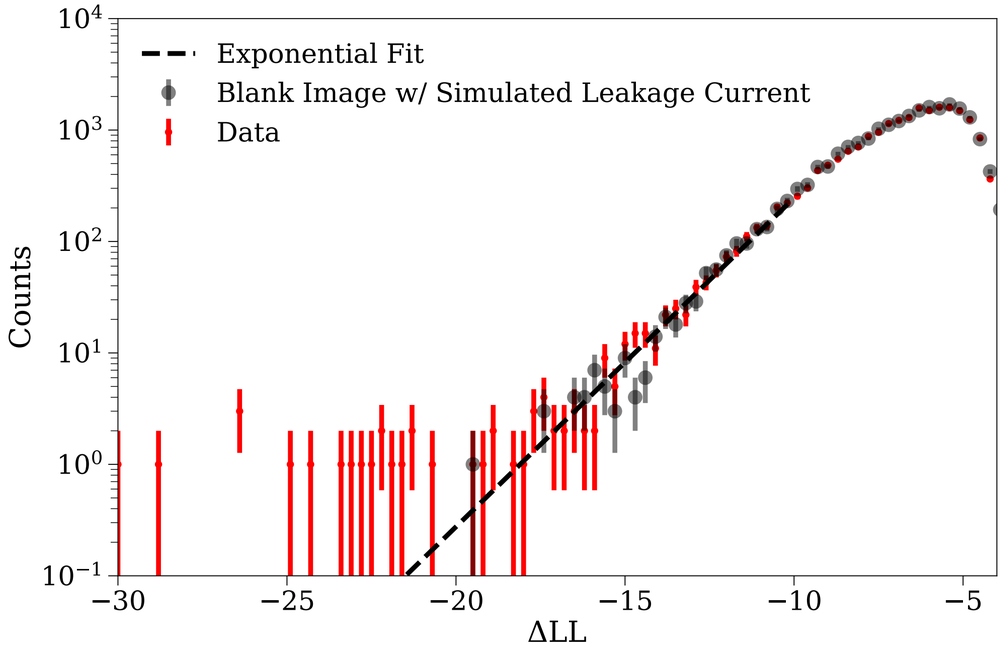


- **WIMP search:** PRL125(2020)241803 PRD105(2022)062003
  - 11 kg-day of data from seven-CCD array.
  - 50 eV_{ee} analysis threshold.
  - First full background model in CCDs.

Data recon

- Mask “hot” regions of the CCD which contain higher dark current (remove ~16% mass) or high-E depositions.
- Scan over the image and perform a likelihood ratio test of Gaussian vs. flat to find event clusters.
- Best-fit Gaussian parameters provide cluster variables (E, σ_{xy}, x, y).
- We select a statistical significant for a Gaussian cluster over noise such that <0.1 noise events in our data.





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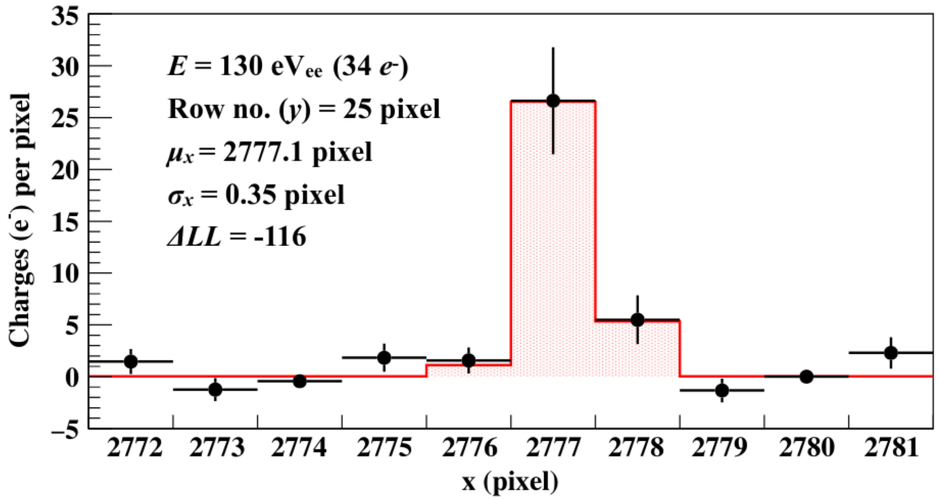
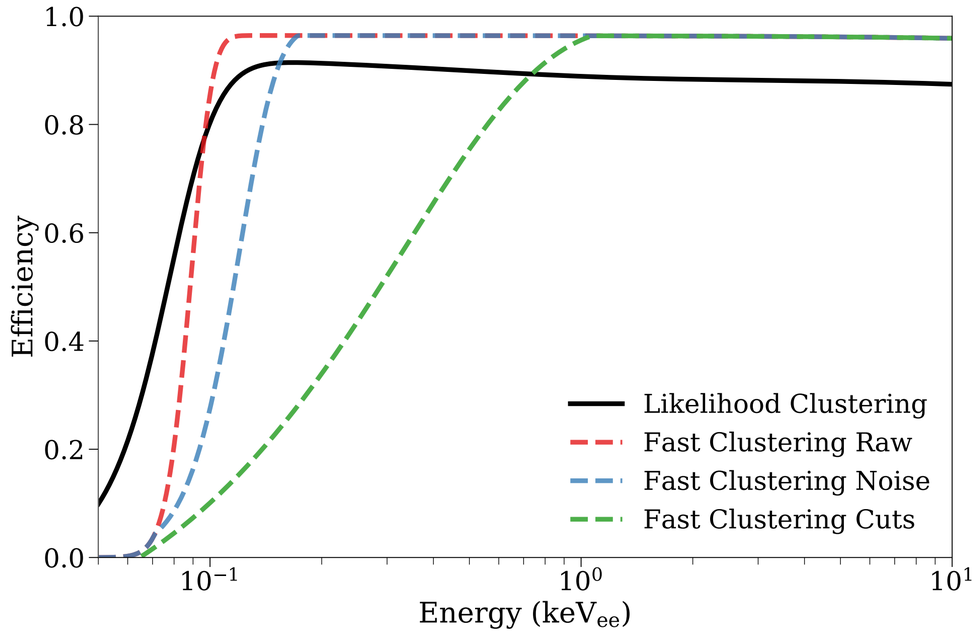
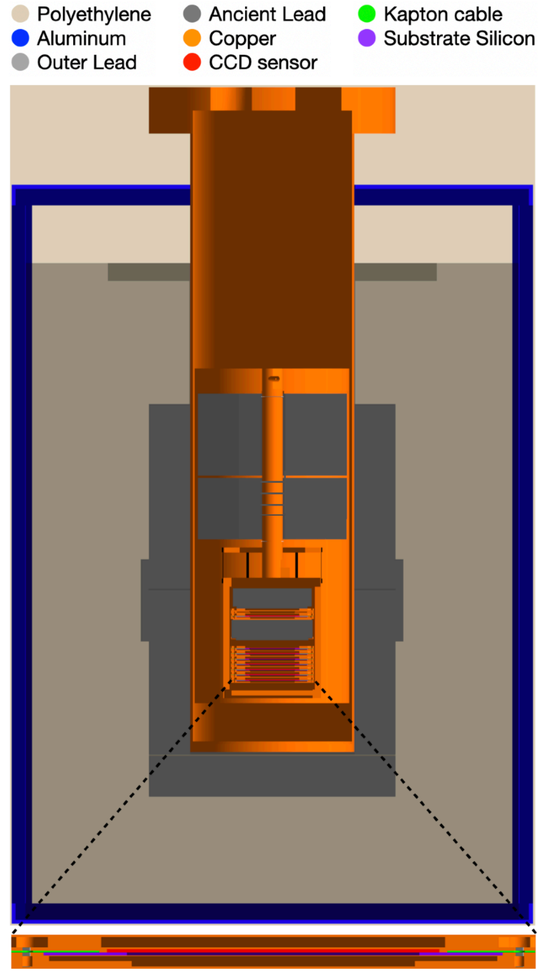




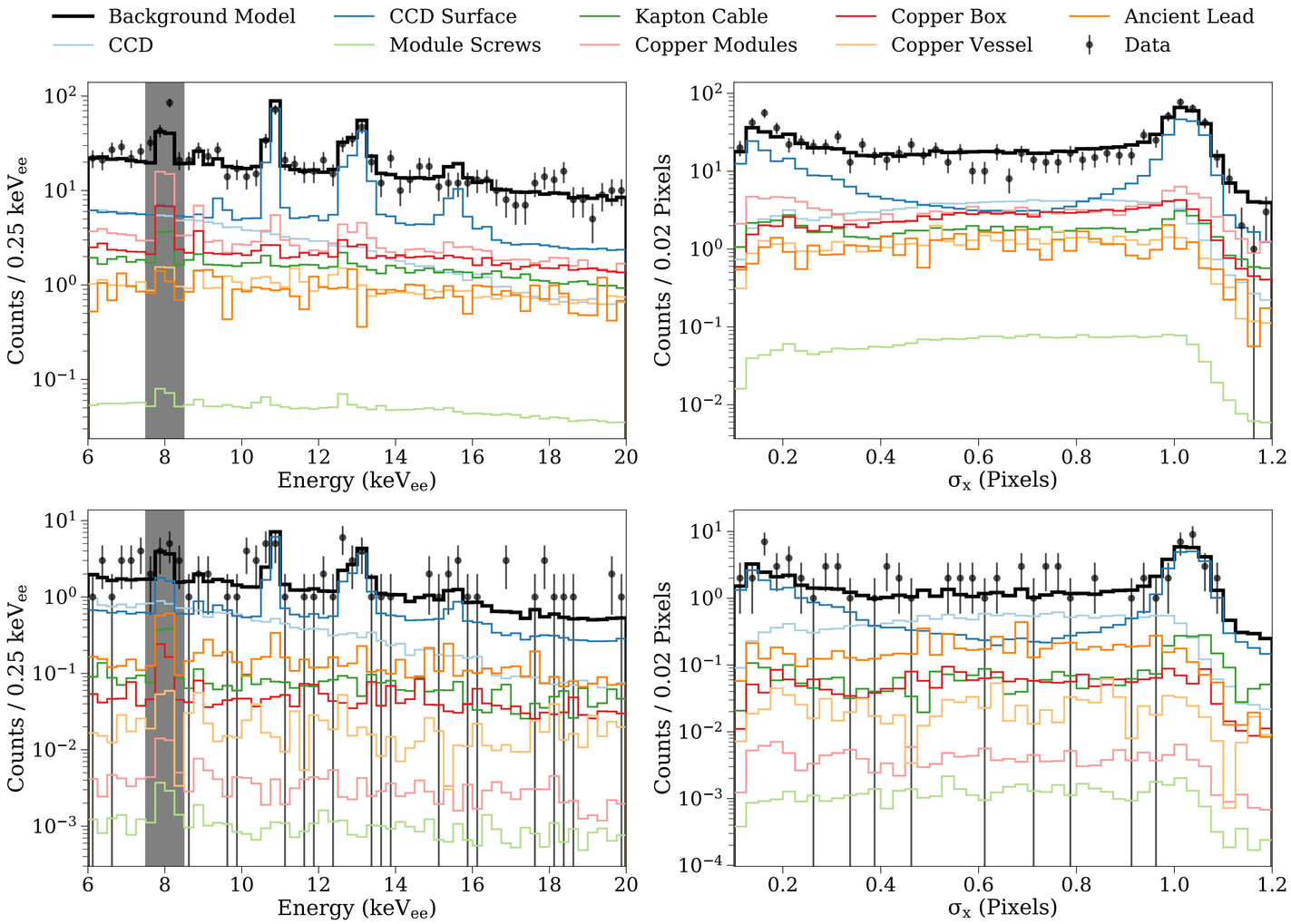
Background model

- 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**



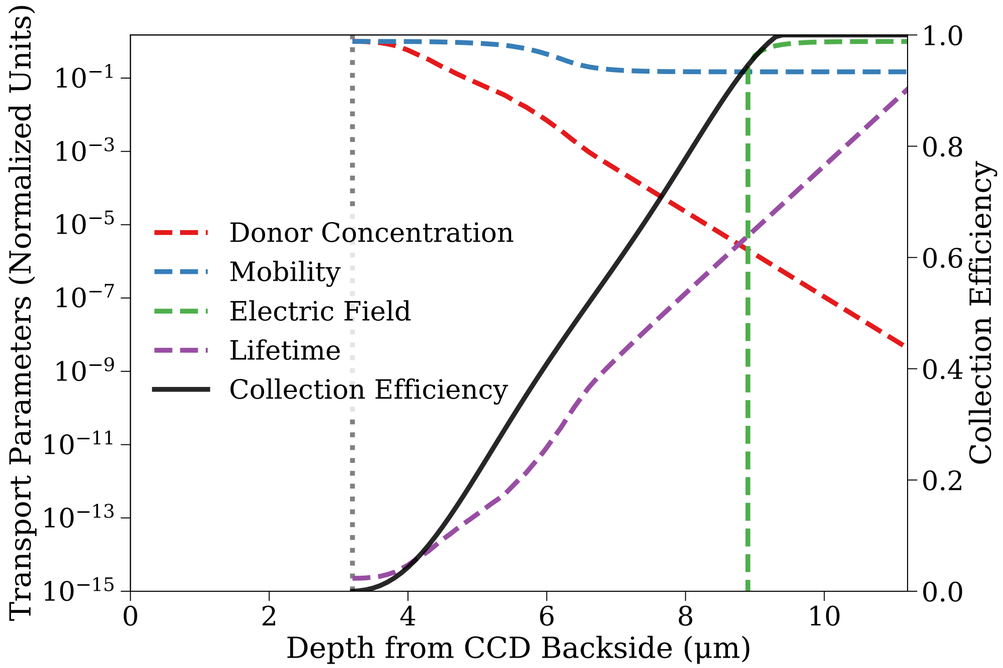
Background model

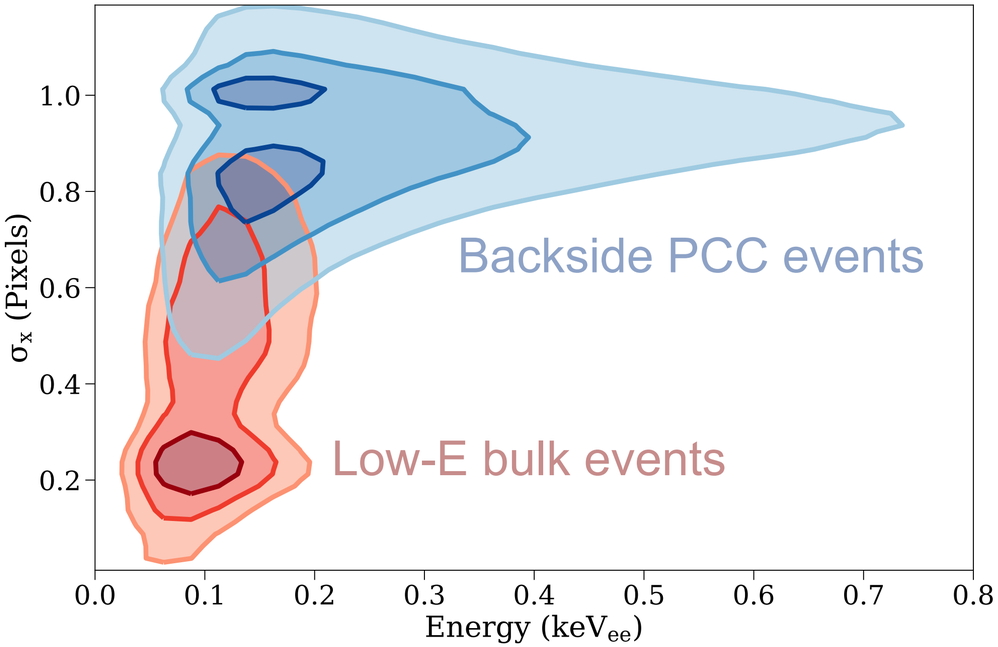
- **Top:** Fit in (E, σ_{xy}) to clusters with $E > 6$ keV$_{ee}$ to data from CCDs 2-7.
- **Bottom:** Best-fit result compared to data from CCD 1.
- Main background components: ^{210}Pb (surface, bulk Cu), ^{3}H in silicon.
- Extrapolate to low energies for WIMP search.



Partial charge collection

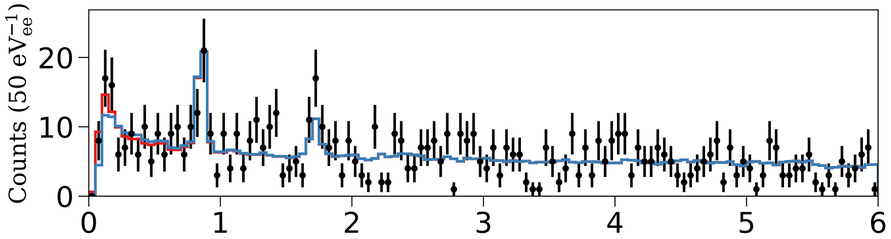
- Dominant systematic uncertainty is the response of the CCD to decays (e.g., ^{210}Pb-Bi) on the backside.
- Simulated CCD backside response and parametrized spectral distortion of backside background components.

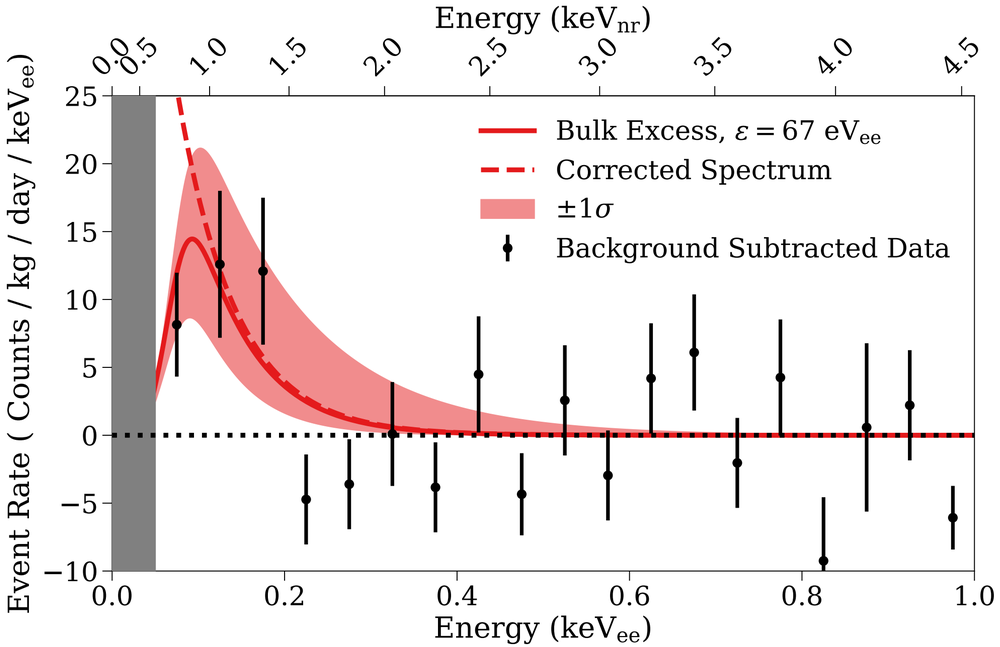


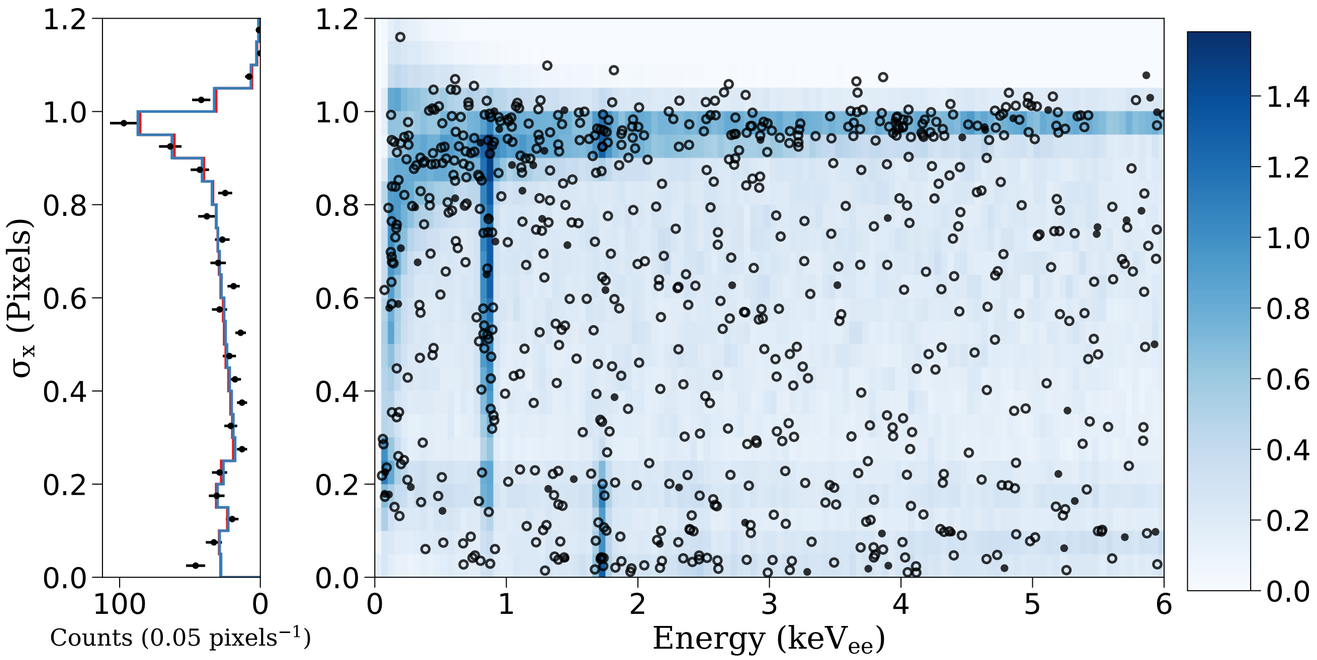


WIMP search fit result

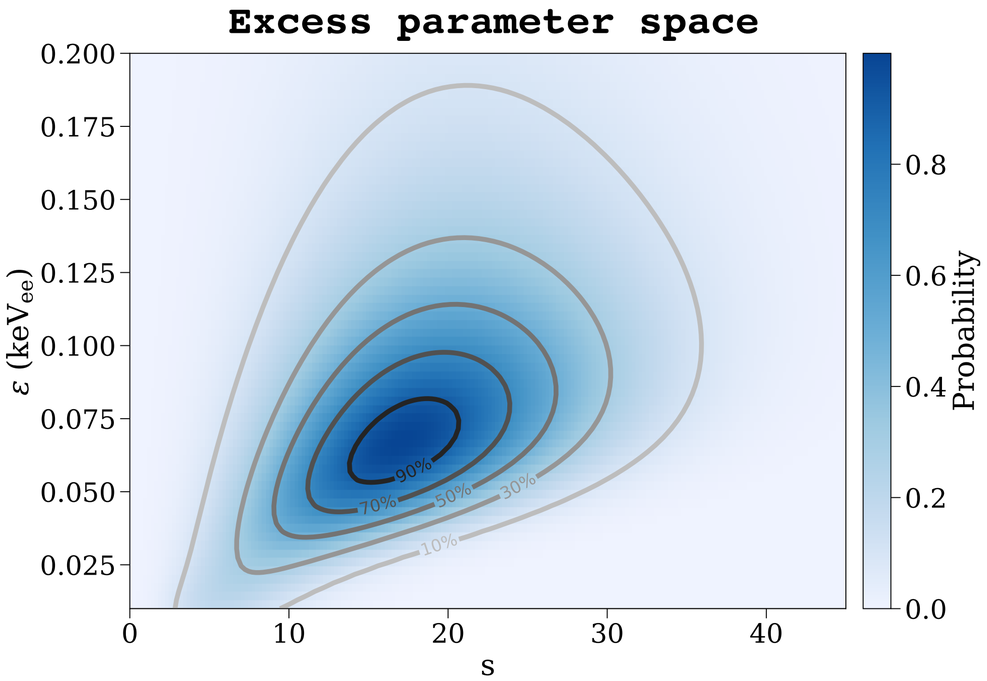
- Unbinned likelihood fit with background model + PCC correction + generic exponential signal.
- Excess of 17.1±7.6 events with decay ε = 67±37 eV_{ee}.
- Fit prefers signal + background over background-only with **p value** 2.2 x 10^{-4}.

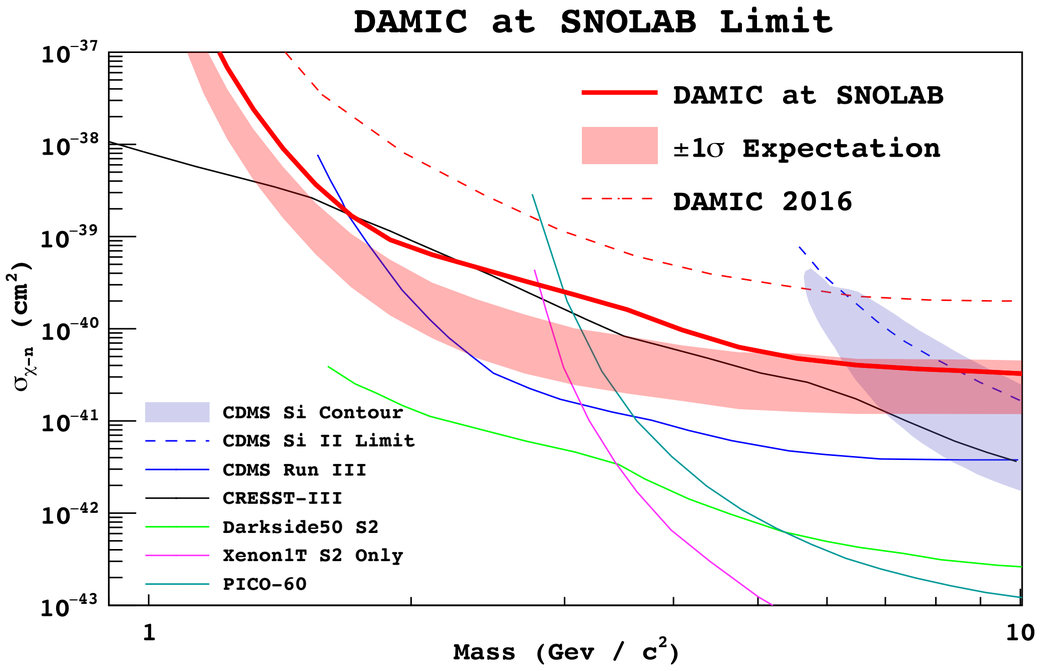






Final results

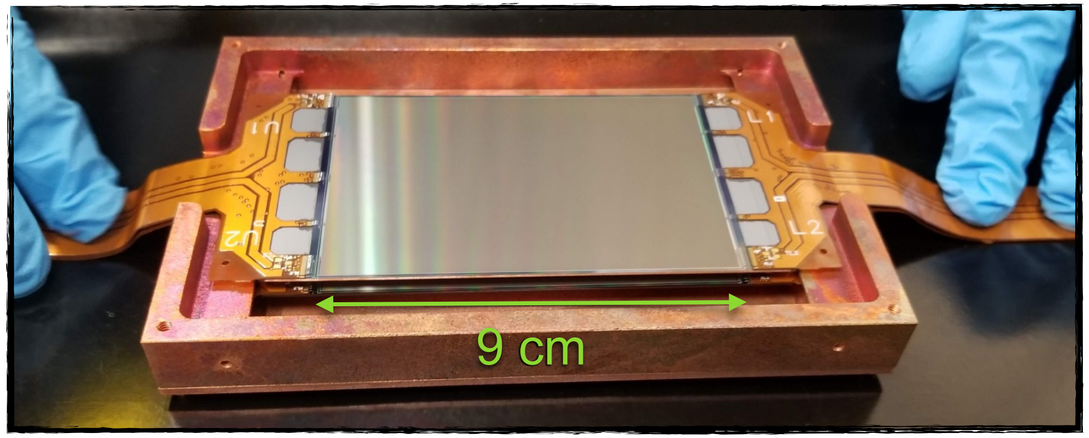


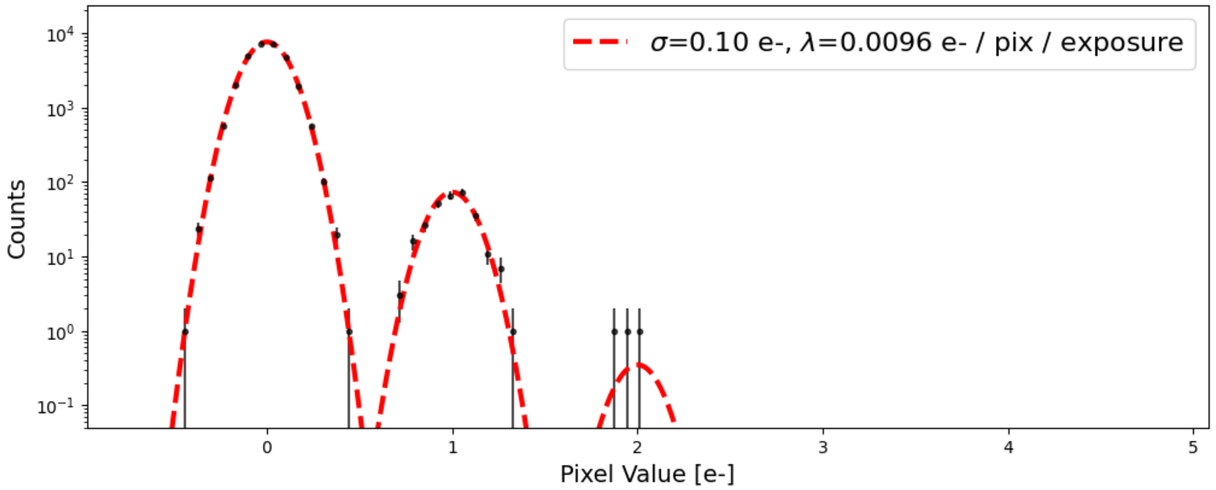


- **Systematic checks:**
  - Events really look like they are in the bulk. Unable to reproduce excess with surface pop.
  - No statistically significant features in the spectrum besides the low energy excess.
  - No known background or detector response hypothesis to explain the excess.
  - Known unknowns: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





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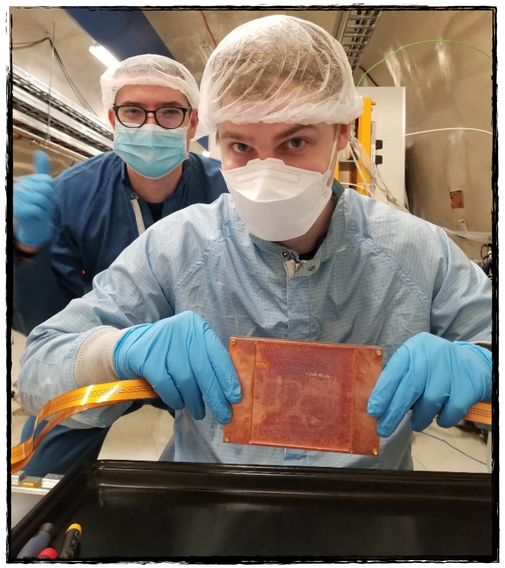
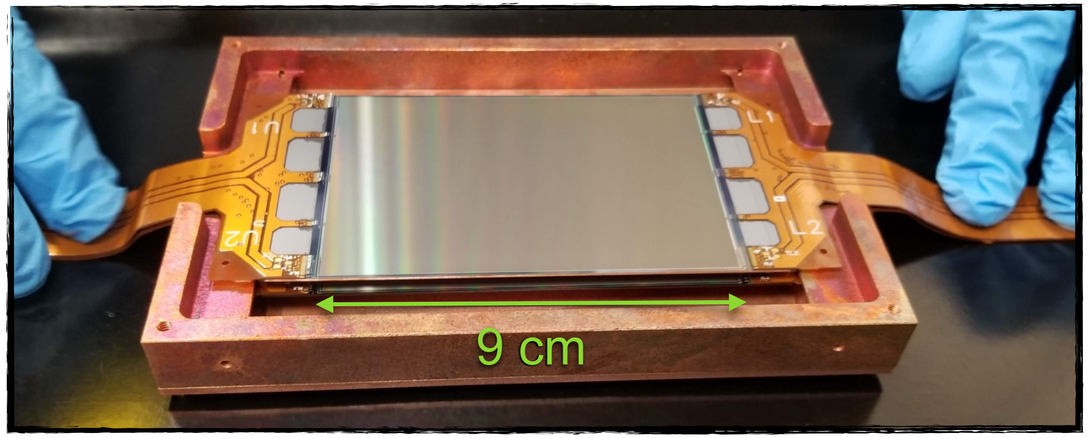
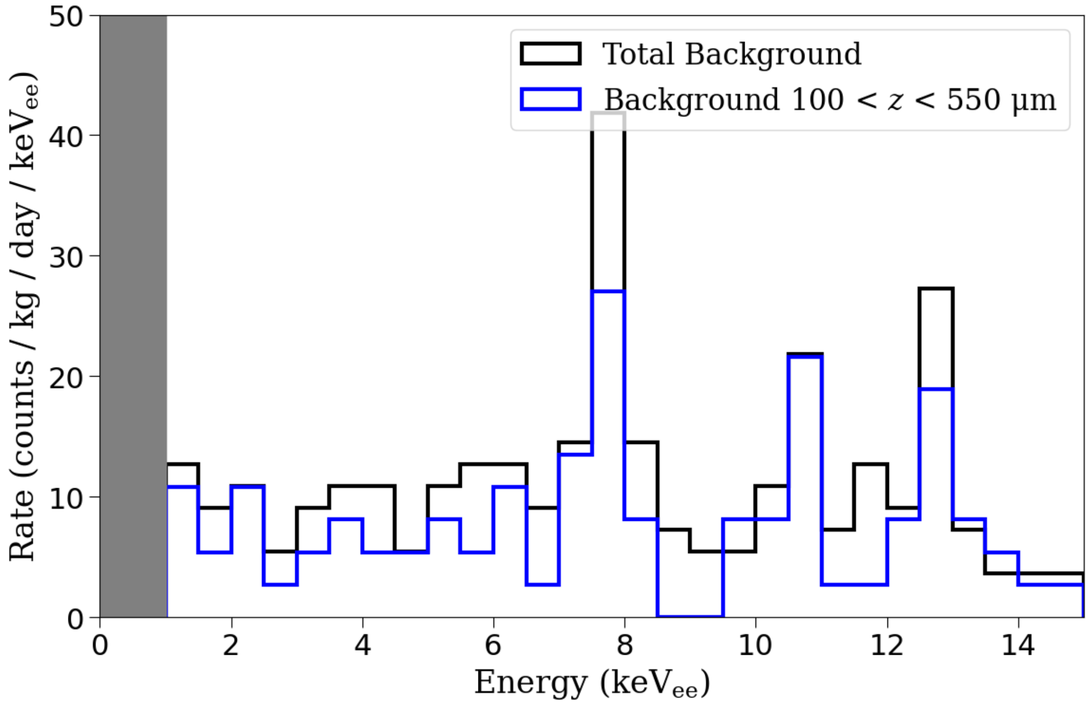


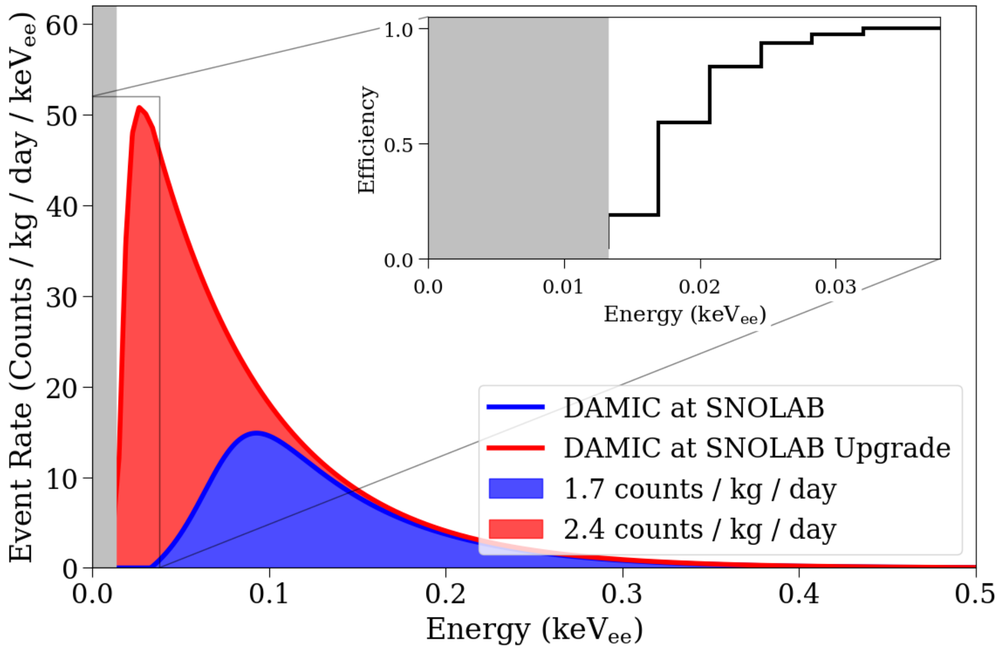
- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) packaged and tested at UW. Installed in Oct-Nov 2021.
- New science run started **in early March 2022**.
- Reproduce background rate from before:
  9 ± 1 d.r.u. total and 6 ± 2 d.r.u. bulk.

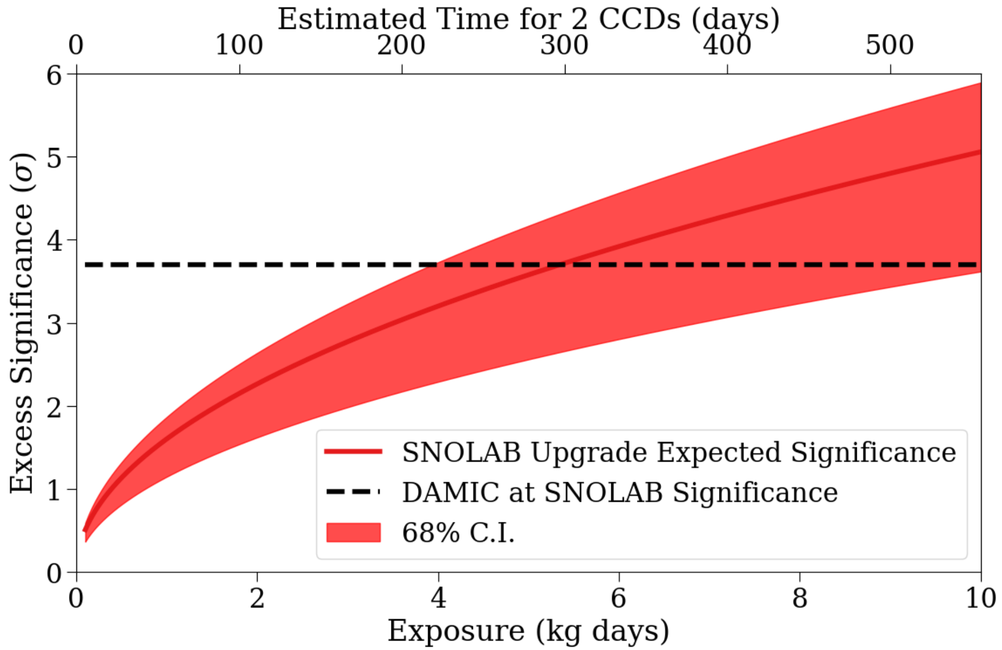




Upgrade sensitivity

- 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.





Conclusions

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

Thank you!

DAMIC Collaboration