Confirmation of the spectral excess in DAMIC at SNOLAB with Skipper CCDs

Deep Underground Physics (DUPhy) Group Meeting,
Centre Paul Langevin, CAES, CNRS

Michelangelo Traina, on behalf of the DAMIC(-M) collaborations
CENPA, University of Washington, Seattle (US)

Outline:

1. DAMIC at SNOLAB
2. Background model
3. Near-threshold excess
4. SNOLAB skipper upgrade
5. Science data and selections
6. Search results

DAMIC

CENPA
Center for Experimental
Nuclear Physics and Astrophysics
UNIVERSITY *of* WASHINGTON

DAMIC-M

DAMIC AT SNOLAB

DArk Matter In CCDs collaboration (since 2011)

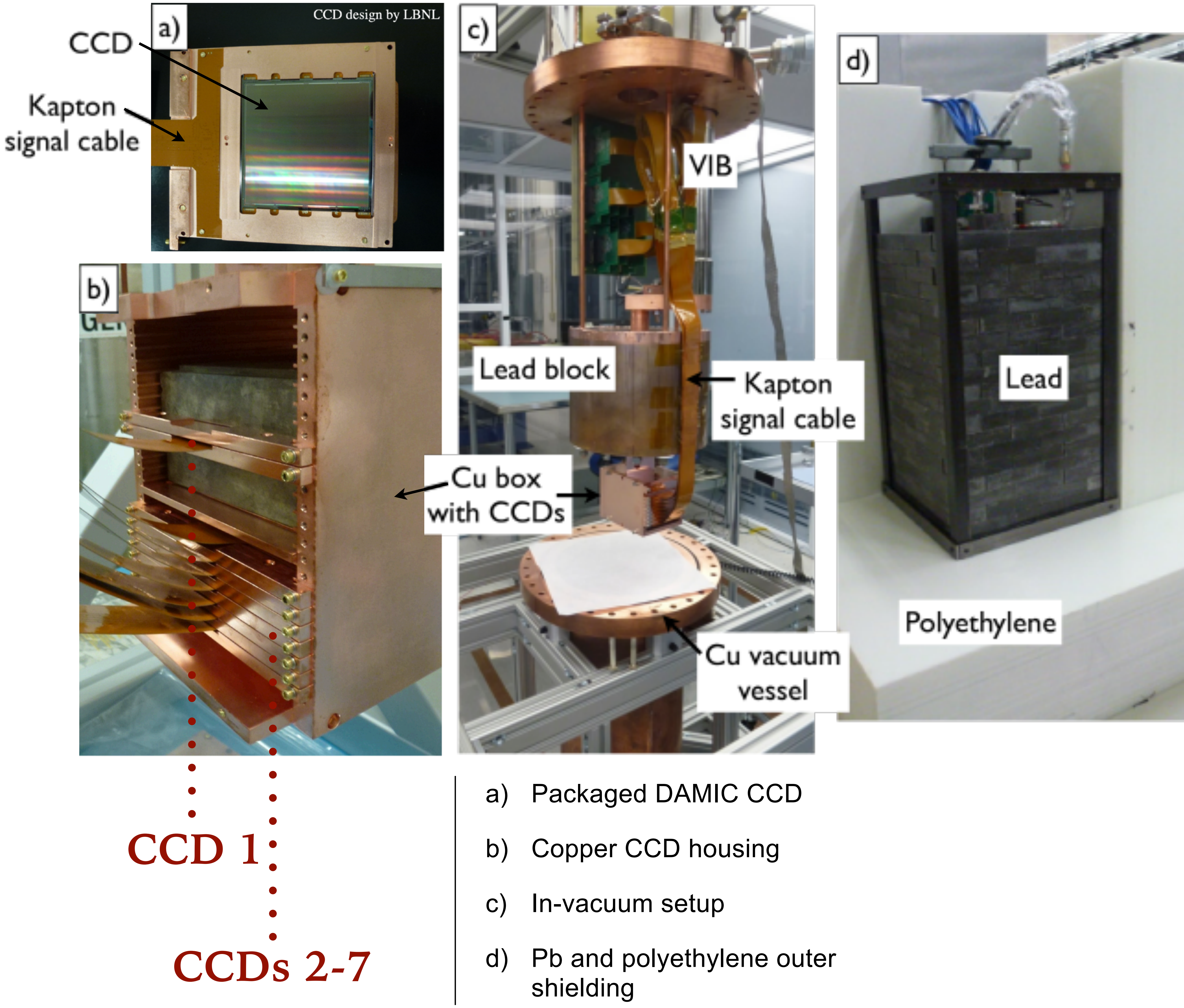
- Setup beneath 2 km of granite **at SNOLAB** (Canada)
- Sensors in cryogenic conditions (10^{-6} mbar, 140 K)

Charge-Coupled Devices

- Very low noise and leakage current: sensitive to e⁻
- 3D track reconstruction and PID capabilities

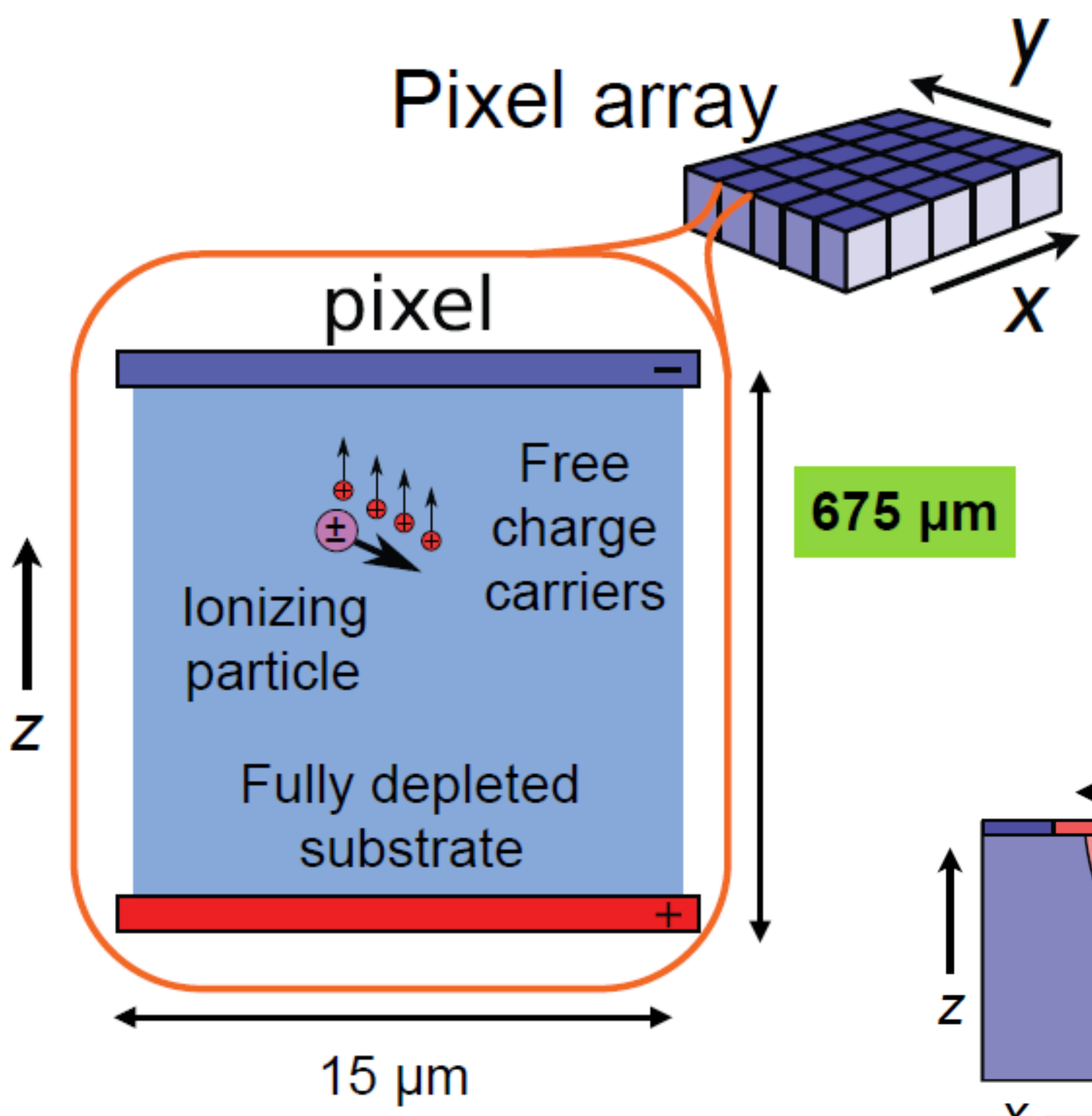
For Dark Matter:

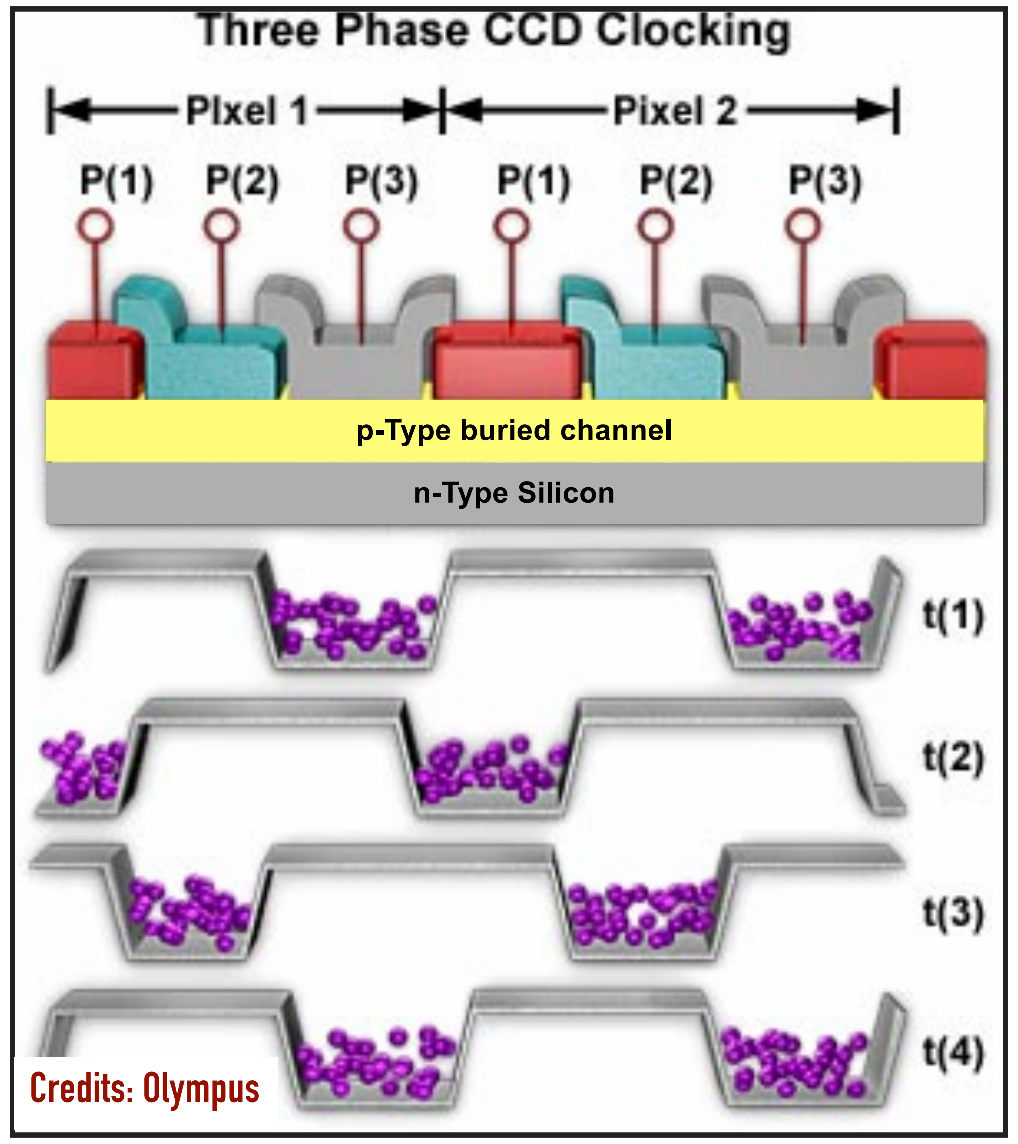
- Several thick CCDs $\Longrightarrow$ massive target
  7 × 675 μm ~ 40 g
- Sensitive to:
  - WIMP-nucleus coherent scattering
  - Hidden sector light DM-e⁻ interactions

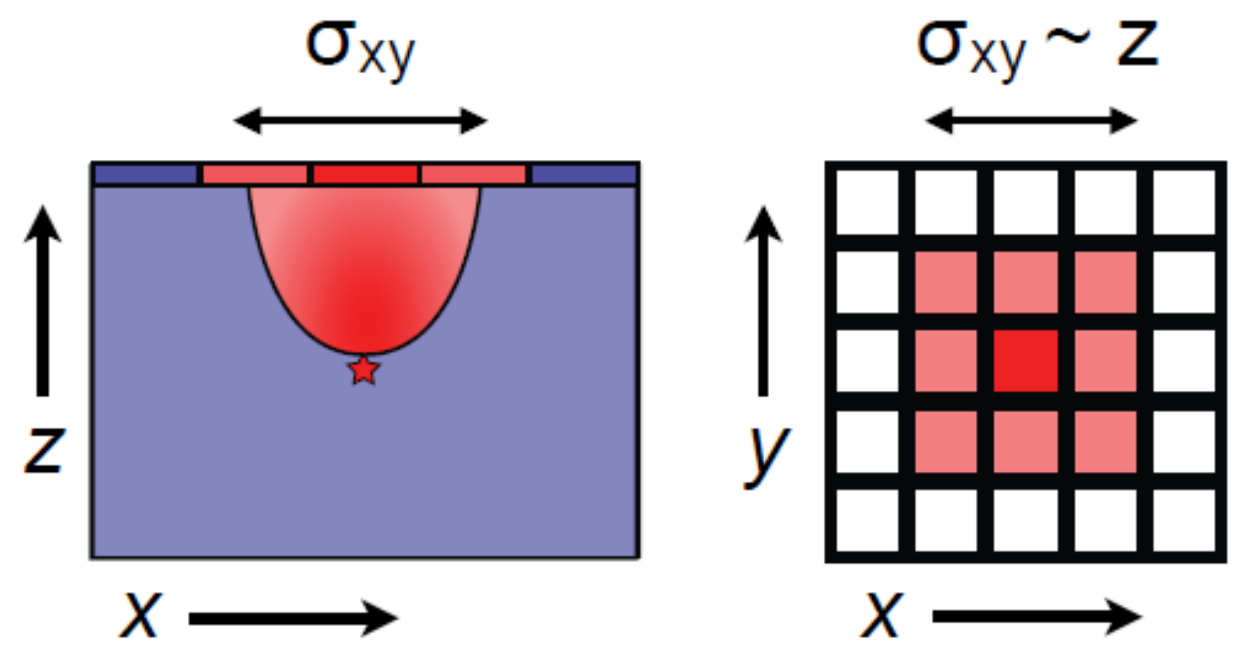


a) Packaged DAMIC CCD
b) Copper CCD housing
c) In-vacuum setup
d) Pb and polyethylene outer shielding

CHARGE-COUPLED DEVICES







DAMIC science-grade CCDs

- PolySi gate, p-type buried channel structure
- Fully depleted at 40 V ($\sim$ 10 k$\Omega \cdot$ cm)

Performance

- Charge transfer inefficiency $< 10^{-6}$
- Readout noise $< 2\ e^{-}$ (6 eV)
- Leakage current $\sim 10^{-4}\ e^{-}$/pix/day


Sample CCD image (~15 min exposure) portion in the surface lab.
~1 cm
Cosmic muon
Diffusion-limited
β particle
$\sigma_{back} > \sigma_{front}$
Image courtesy of Prof. A. Chavarria

BACKGROUNDs IN DAMIC

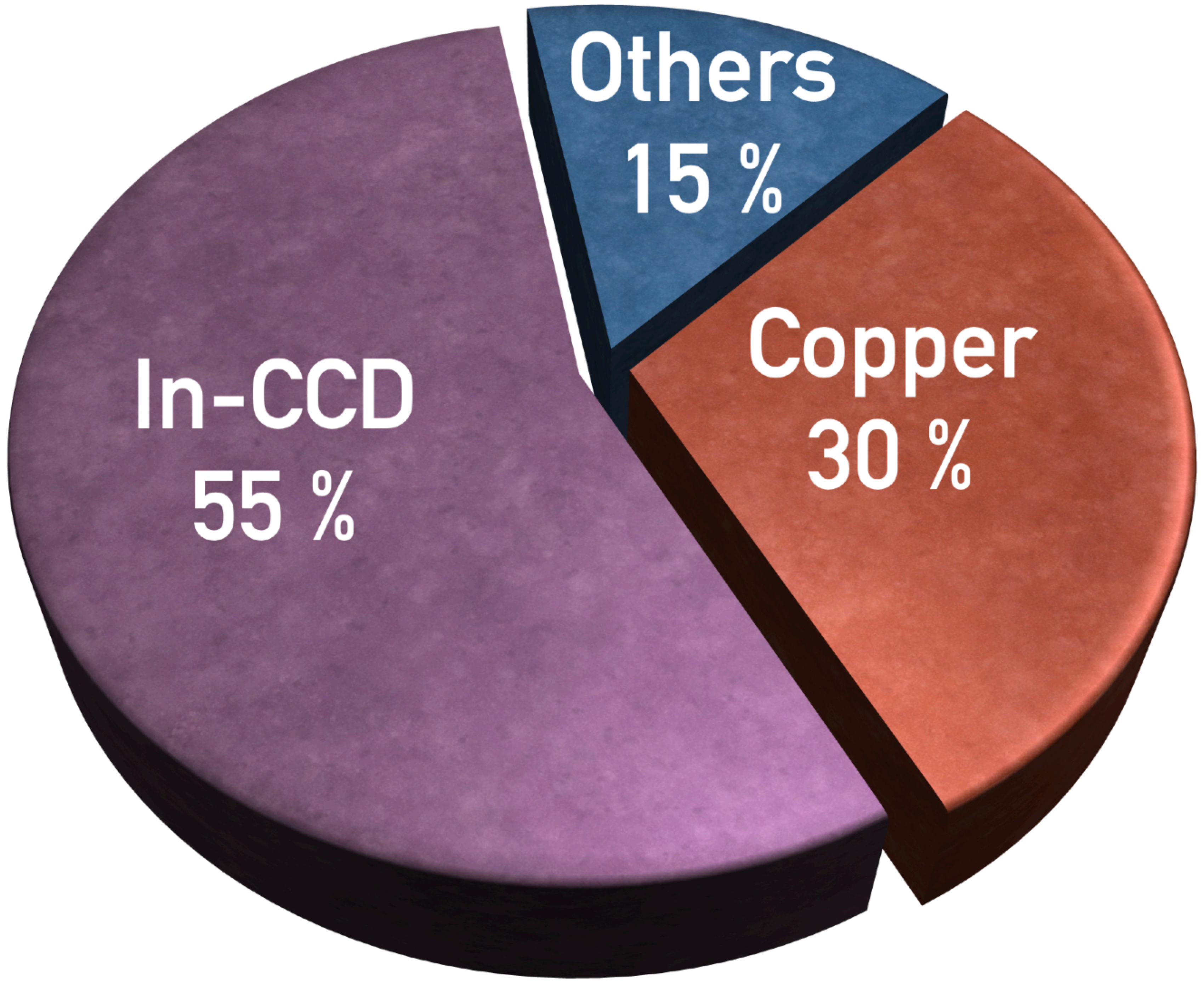
How we deal with backgrounds:

- Underground operation: ~~cosmic radiation~~
- Material selection (assays): ~~apparatus radioactivity~~
- In situ shielding: ~~environmental radioactivity~~
- Discrimination and quantification of residual contaminants $\Longrightarrow$ radioactive background model

Background contributions:

- $\sim 55\,\%$ in-CCD contaminants
- $\sim 30\,\%$ OFHC copper
- $\sim 15\,\%$ from various detector materials (lead, flex cables, etc.)

~ 12 **dru**



1 **dru** $= 1$ **event** $\cdot$ **(keV** $\cdot$ **kg** $\cdot$ **d)**$^{-1}$

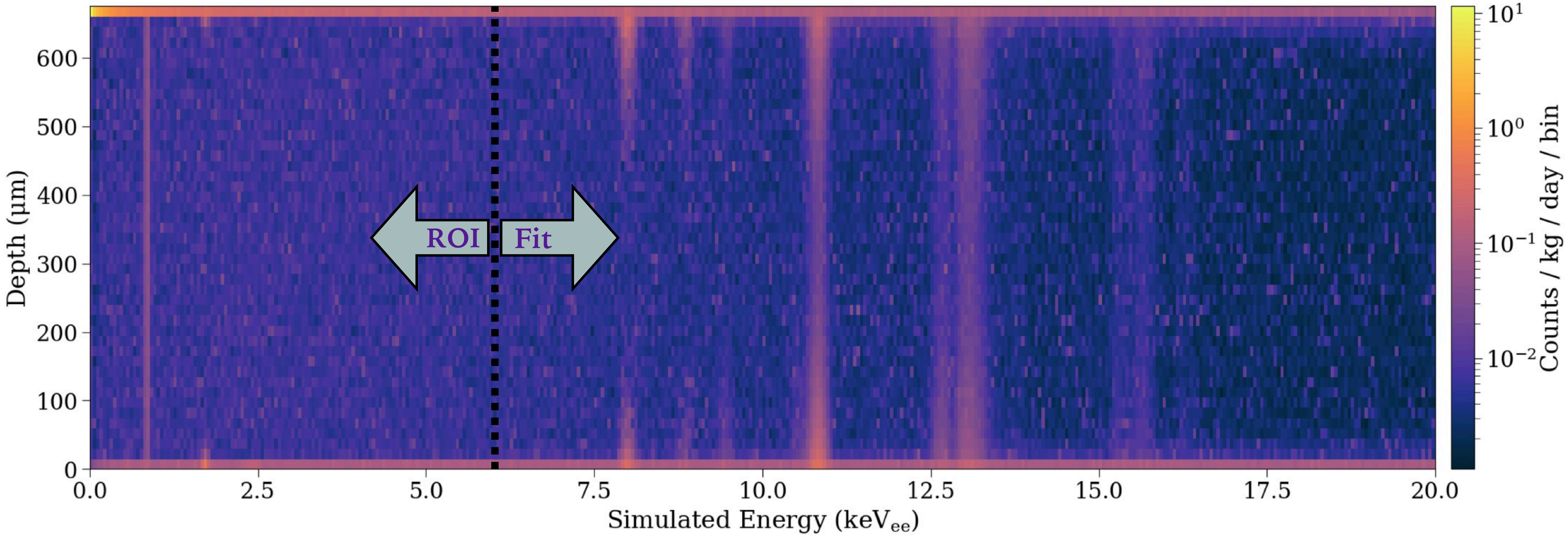
BACKGROUND MODELING

Background model construction: Phys. Rev. D **105**, 062003

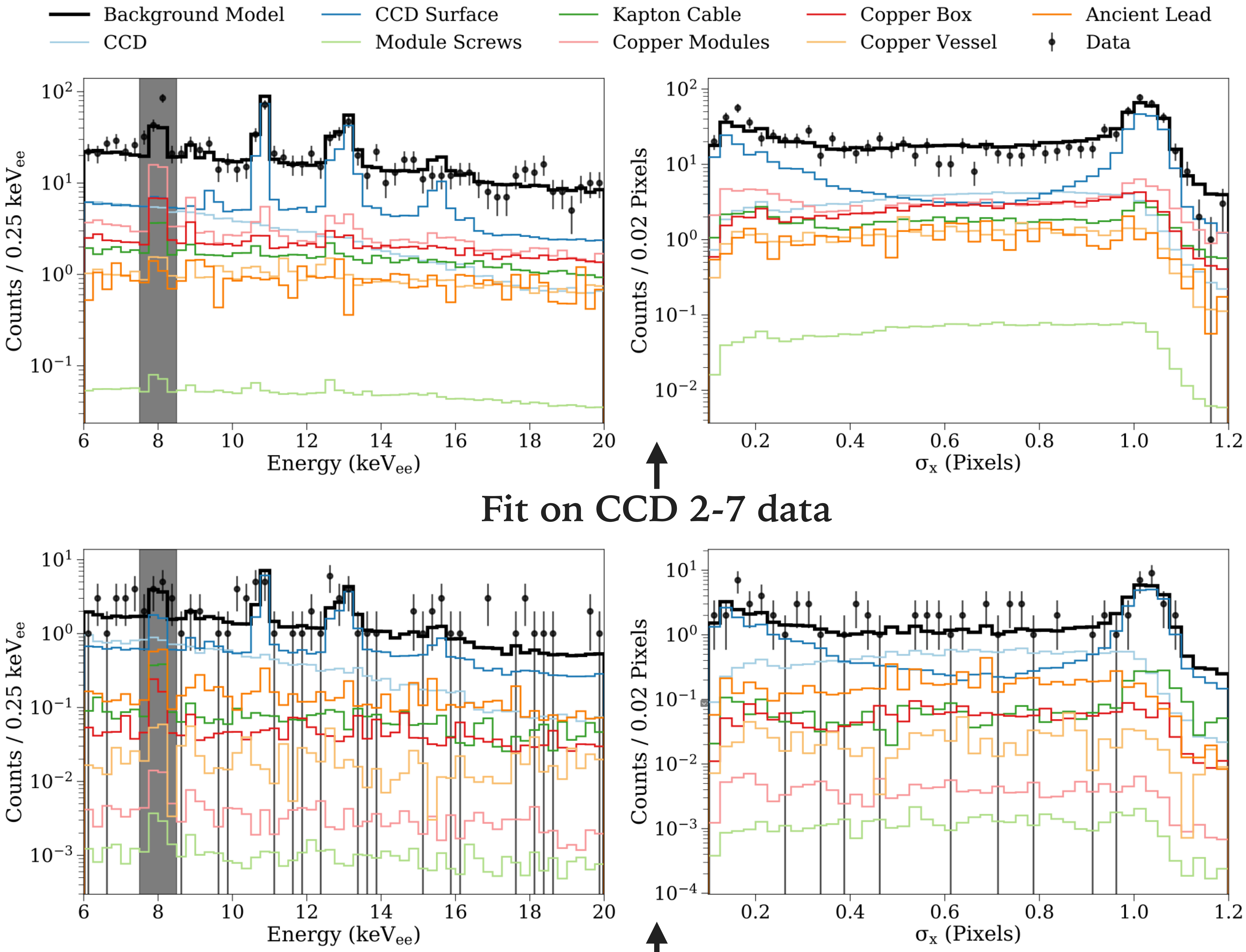
- Decay and tracking across detector geometry with GEANT4
- CCD response simulation
- Reconstruction to (E,σ) analysis space
- Likelihood fit to data in WIMP-free region (6 – 20 keV_{ee}) ⟹ extrapolate in ROI (0.05 – 6 keV_{ee})

eV_{ee} : electron-equivalent energies

Simulated backgrounds for CCDs 2-7 in energy and depth



BACKGROUND TEMPLATE FITTING



Fit on CCD 2-7 data

Validation with CCD 1 data

BACKGROUND TEMPLATE FITTING

Construction of Background Templates

- Group simulations up in templates according to material and decay
- Construct number of expected events per bin, ν_{ij}:

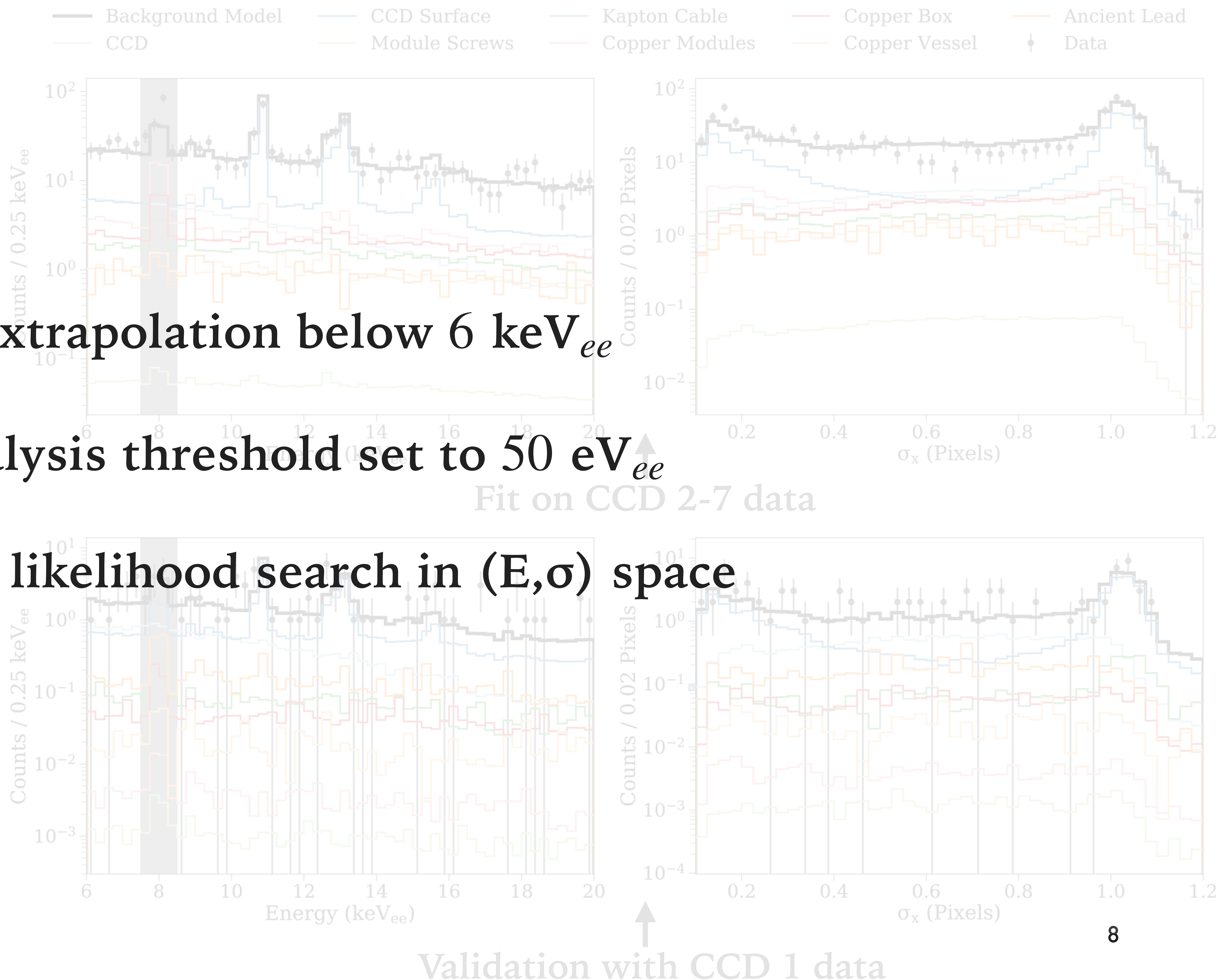
$$\nu_{ijl} = \sum_{m=0}^{N_{det.part}} n_{ijm} \times \frac{A_l M_m(\epsilon_{data} t_{run})}{(\epsilon_{sim} N_m)}, \quad \nu_{ij} = \sum_{l=0}^{N_{templates}} C_l \nu_{ijl}$$

- Compare it to data bin content, by using Poisson two-dimensional likelihood analysis
  - ➡ Best-fit C_l's characterize bkg model

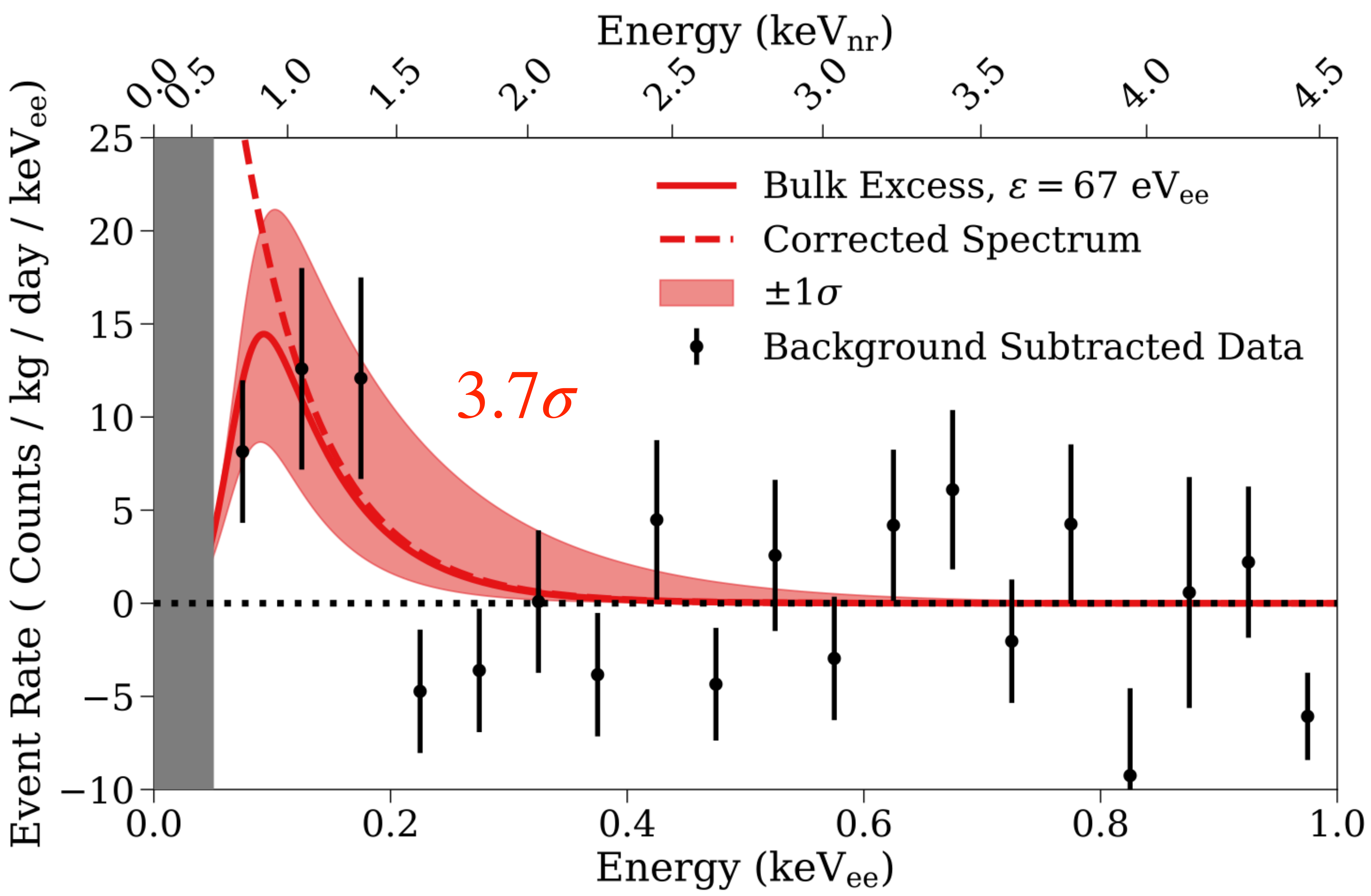
⟹ **Extrapolation below 6 keV$_{ee}$**

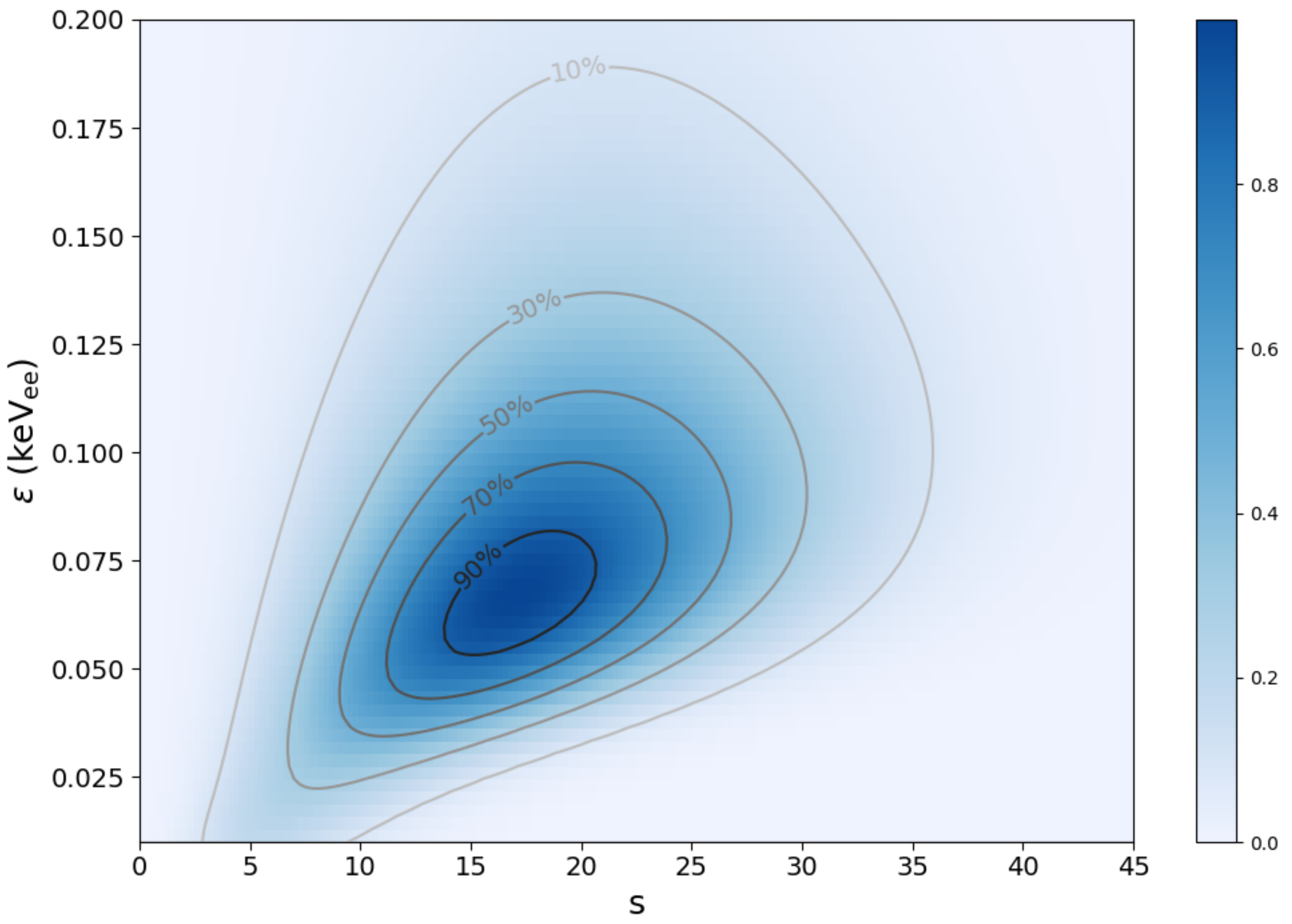
⟹ **Analysis threshold set to 50 eV$_{ee}$**

⟹ **Profile likelihood search in (E,σ) space**



≤200 eV EXCESS





Phys. Rev. Lett. **125**, 241803

Systematic checks: no issue with analysis

Plausible interpretations:

- Unaccounted detector surface effect
- Missing component in background model

DAMIC AT MODANE (DAMIC-M)

Experiment will be deployed at Modane Underground Laboratory (LSM), France.

Main novelties:

- kg-scale detector (~ 200 CCDs)
- Skipper readout: sub-electron resolution $\sim 0.1\ e^-$
- $\sim 100\times$ lower backgrounds: 10 dru → $\mathcal{O}(0.1)$ dru

Status:

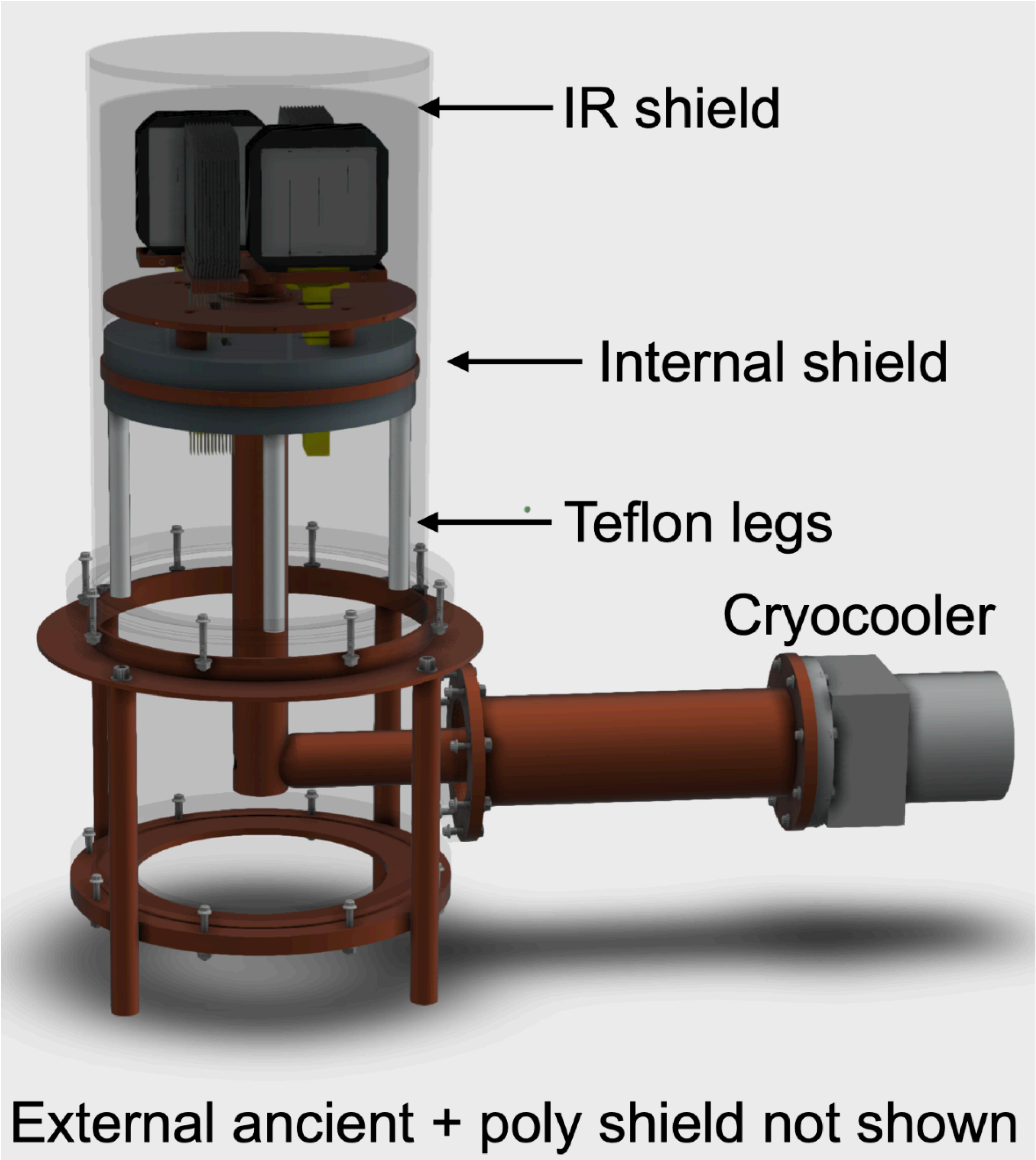
- LBC prototype detector up and running. First DAMIC-M science results published recently

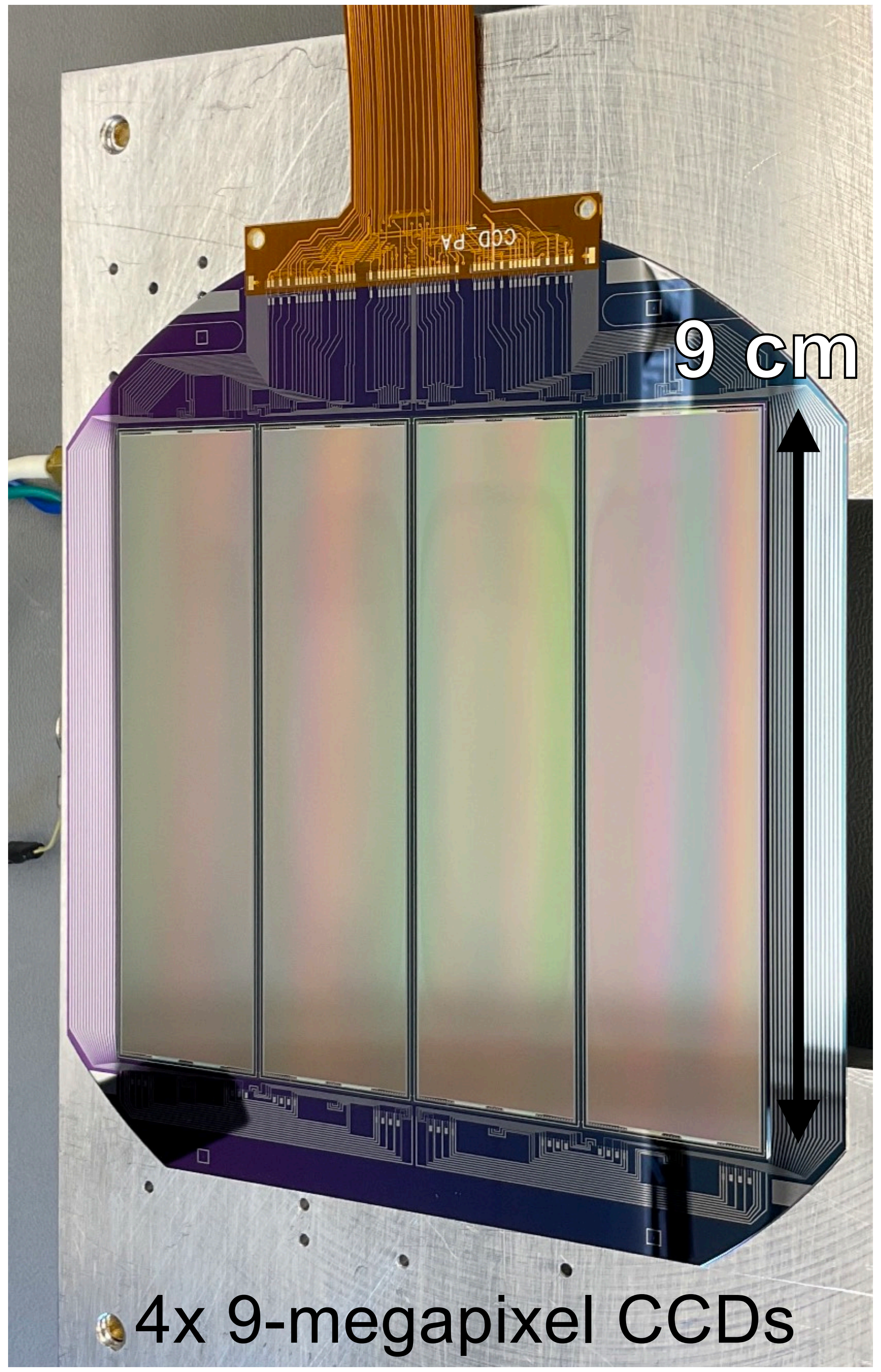
Phys. Rev. Lett. **130**, 171003

See JP Zopounidis presentation

- Construction starting in 2024

Nucl.Instrum.Meth.A 958 (2020) 162933



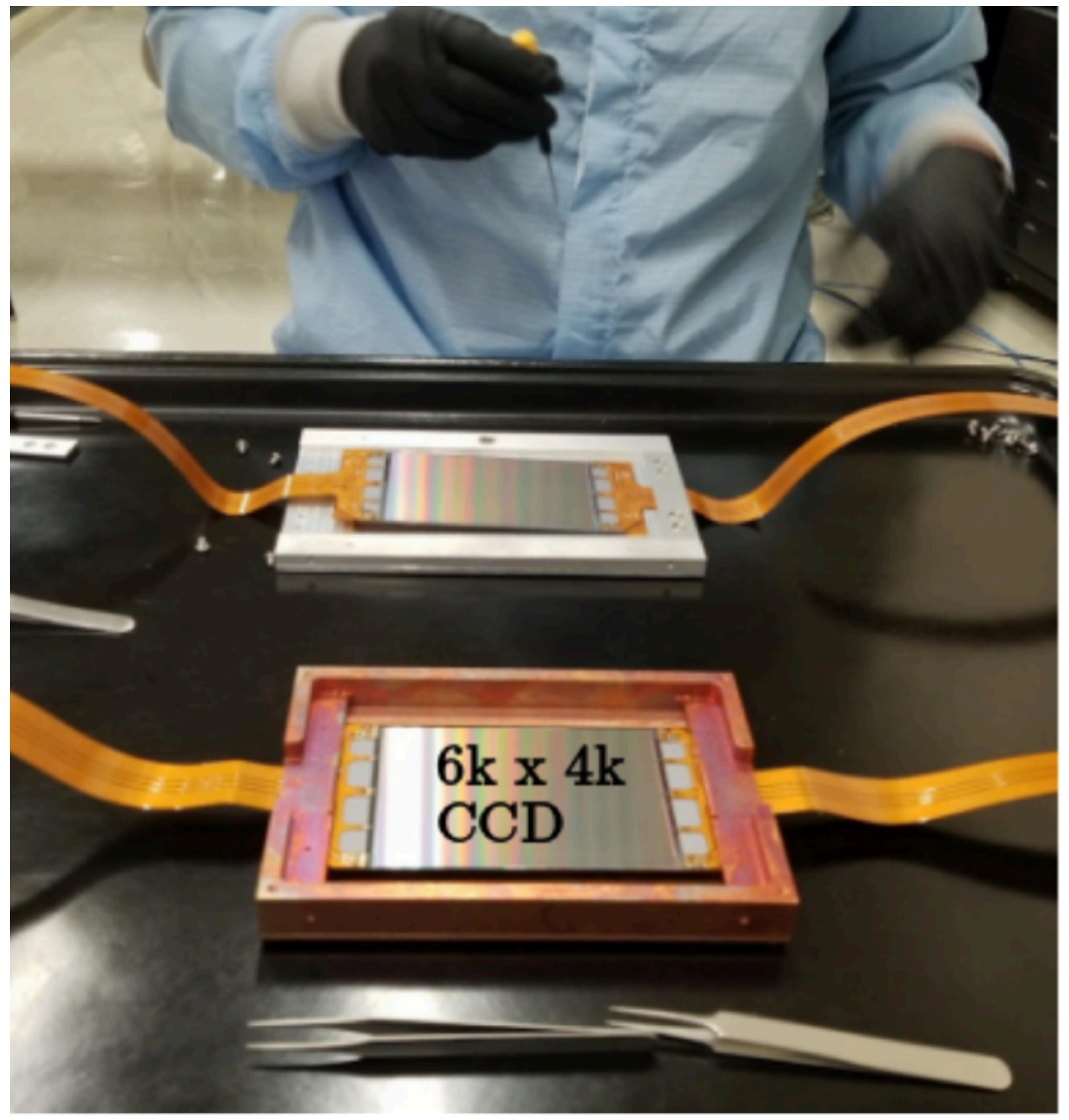


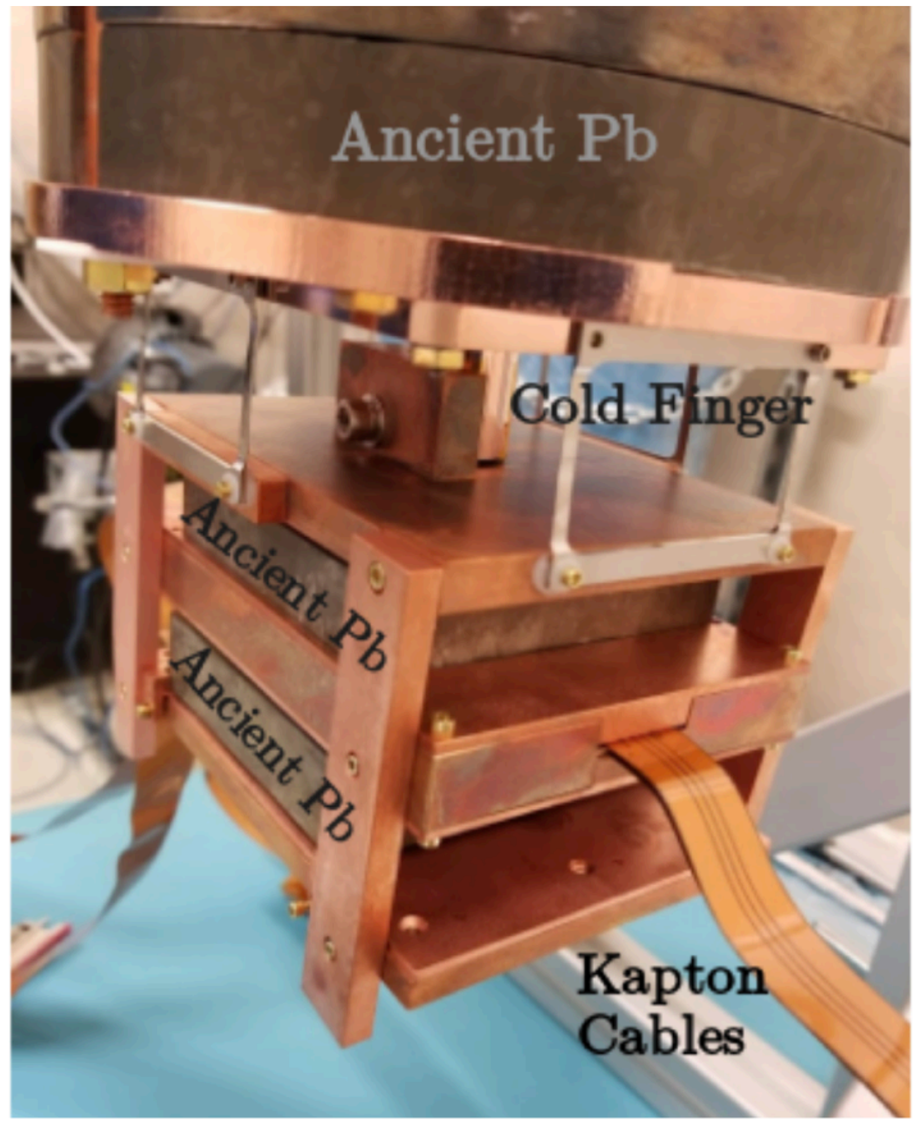
DAMIC-M CCD module packaged at UW

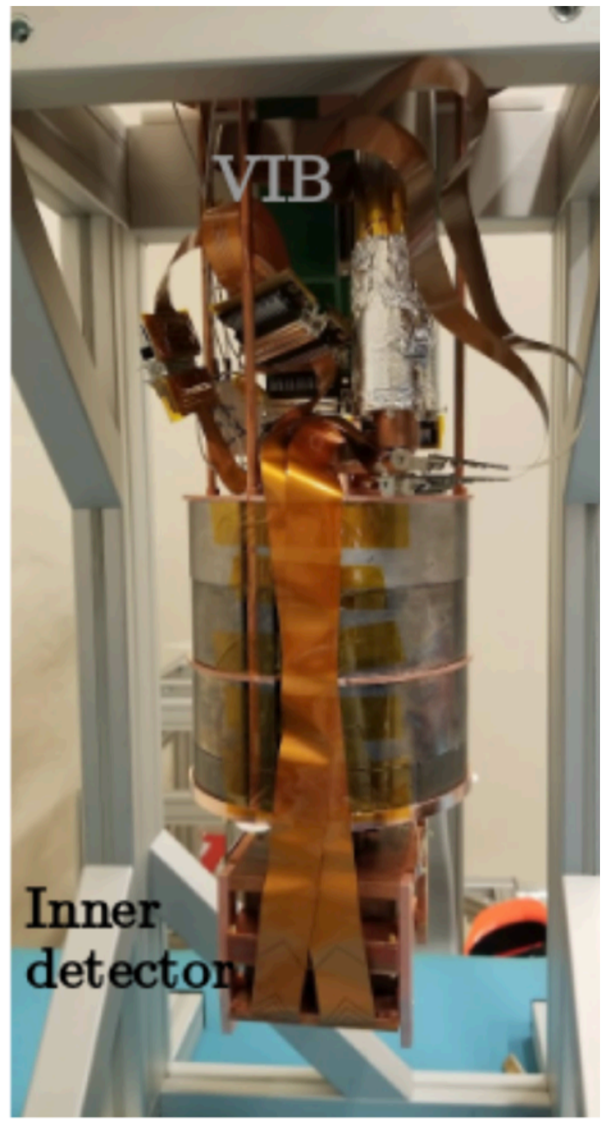
SKIPPER UPGRADE AT SNOLAB

Setup upgraded with two $6k \times 4k$ skipper CCDs

- Same bkg contributions, same rate: ~ 12 dru
- $10\times$ lower noise with skipper readout: $\sim 0.16\ e^-$
- Science run from March 2022 to Jan 2023
- 4.8 kg-day total exposure. 3.1 kg-day after selections
- ROI: $E < 500$ eV$_{ee}$ unblinded in Feb 2023







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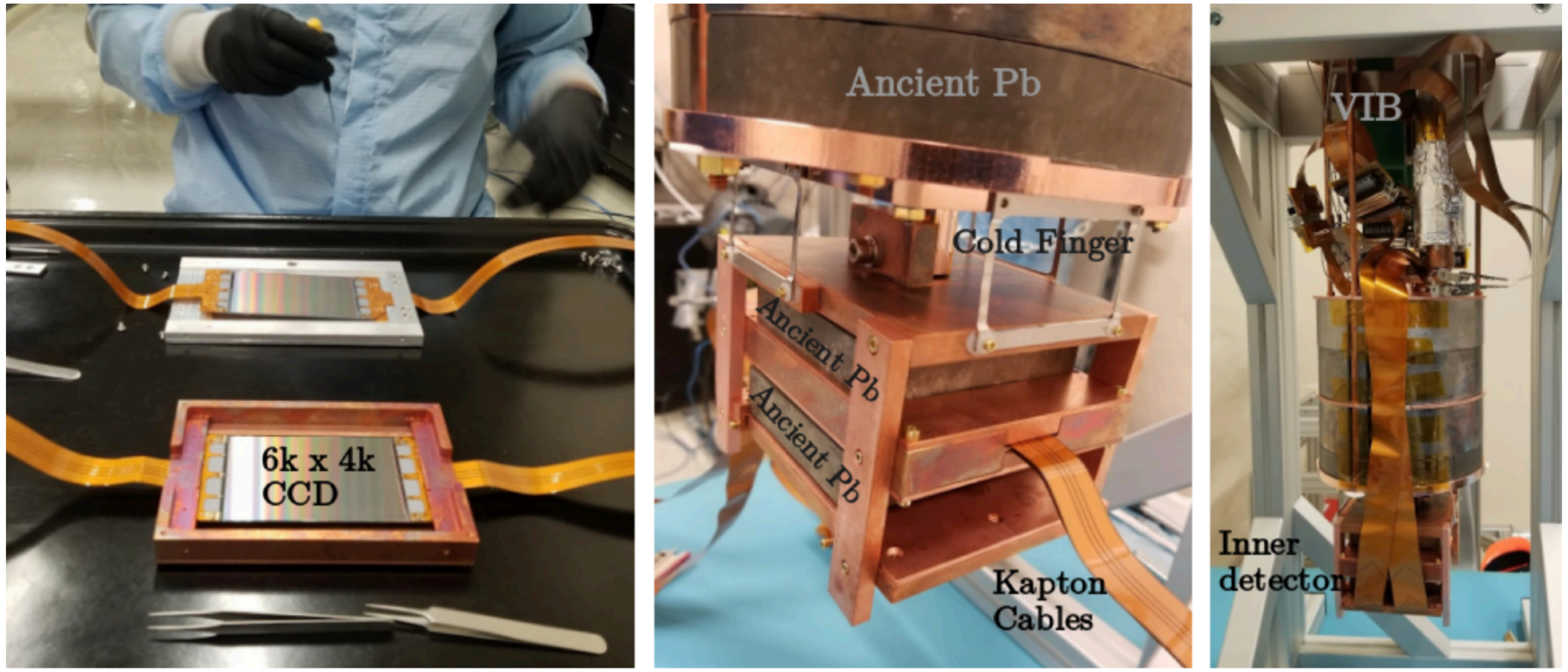
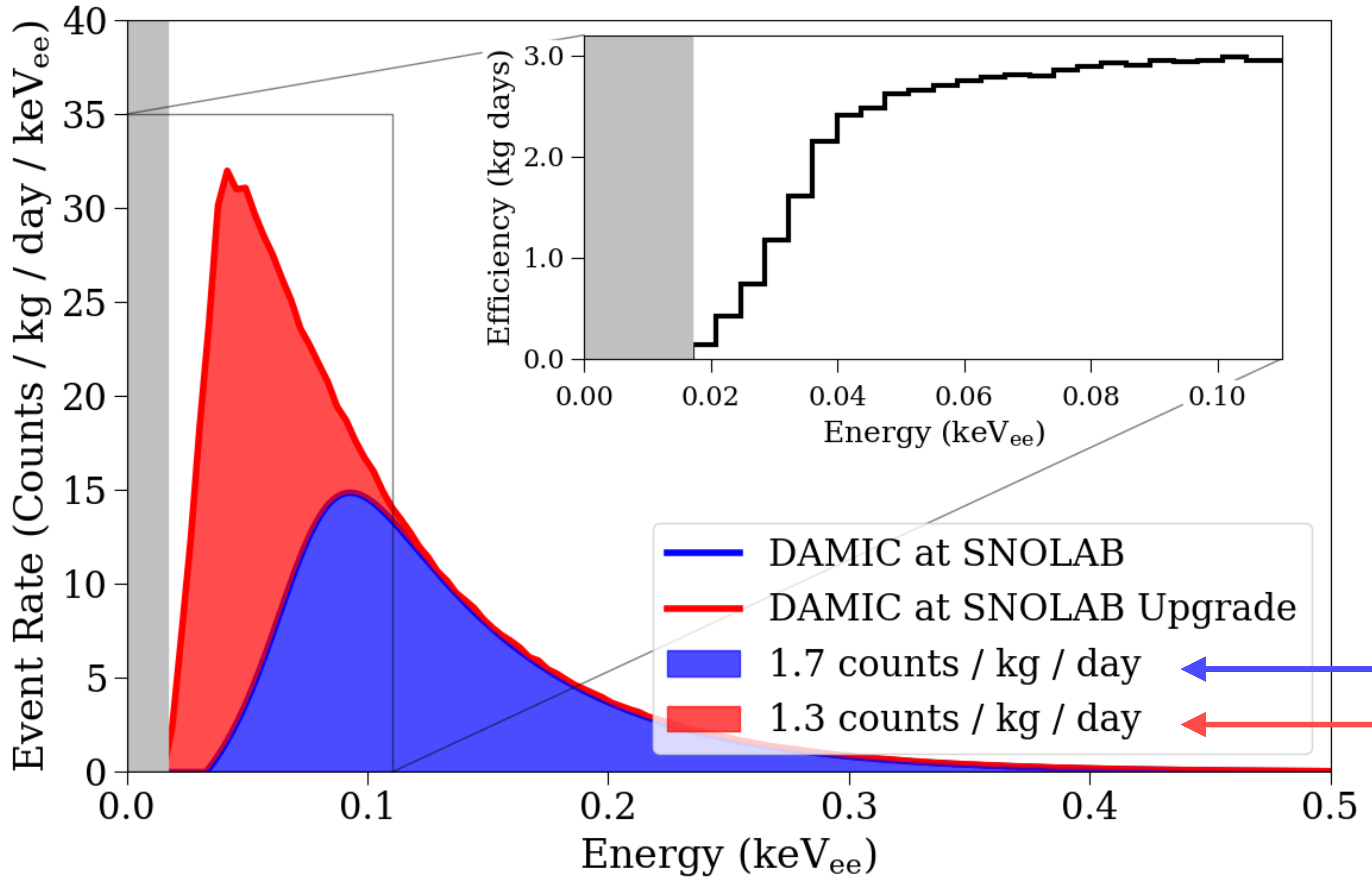


DAMIC, DAMIC-M and SENSEI collaboration



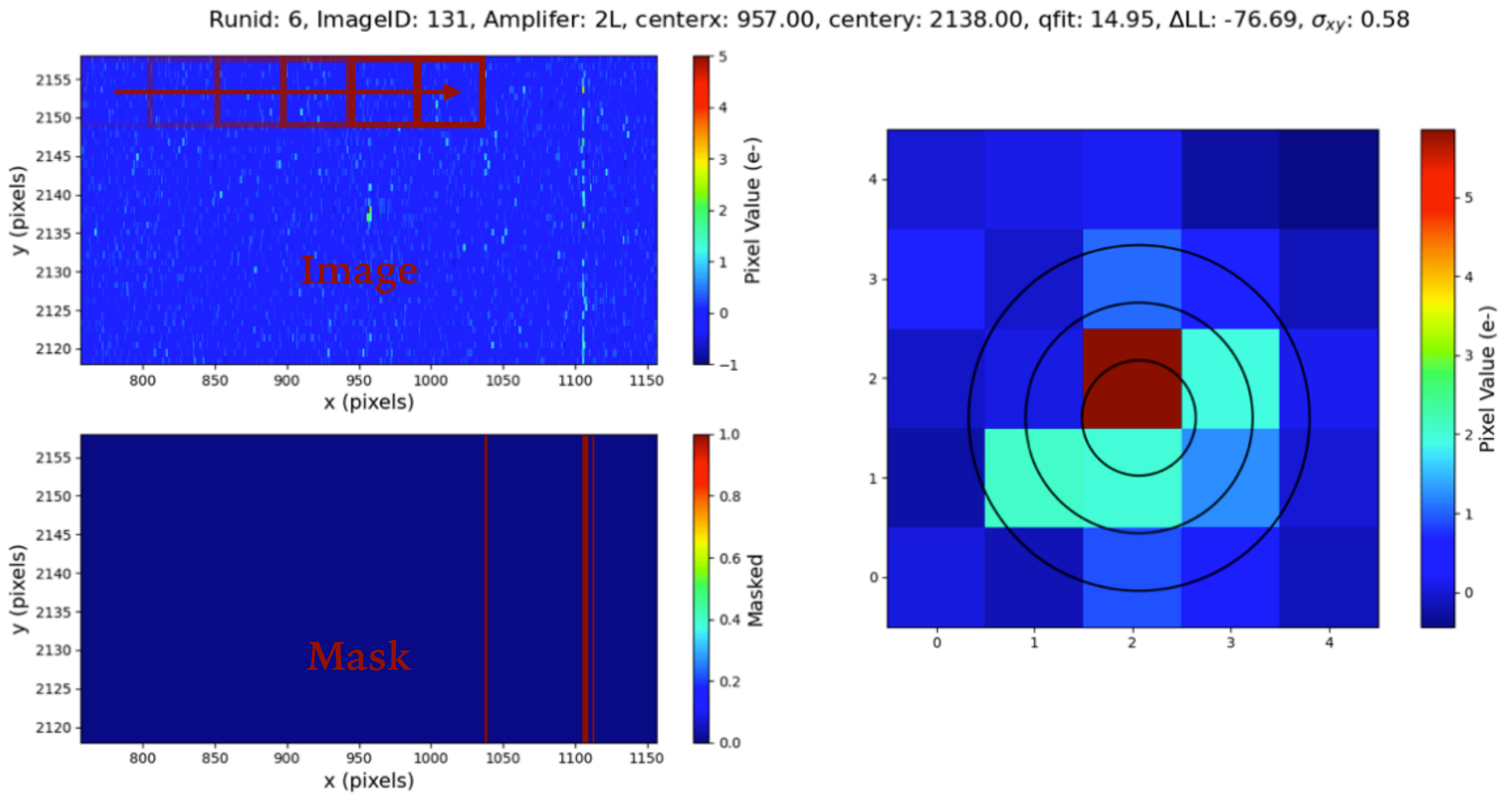
Almost twice as sensitive to previously detected excess

Detected rate in DAMIC at SNOLAB

Expected rate increase in skipper upgrade

LOW-ENERGY CLUSTERS

Likelihood clustering: find low-energy clusters by computing likelihood of ionization event inside moving window…

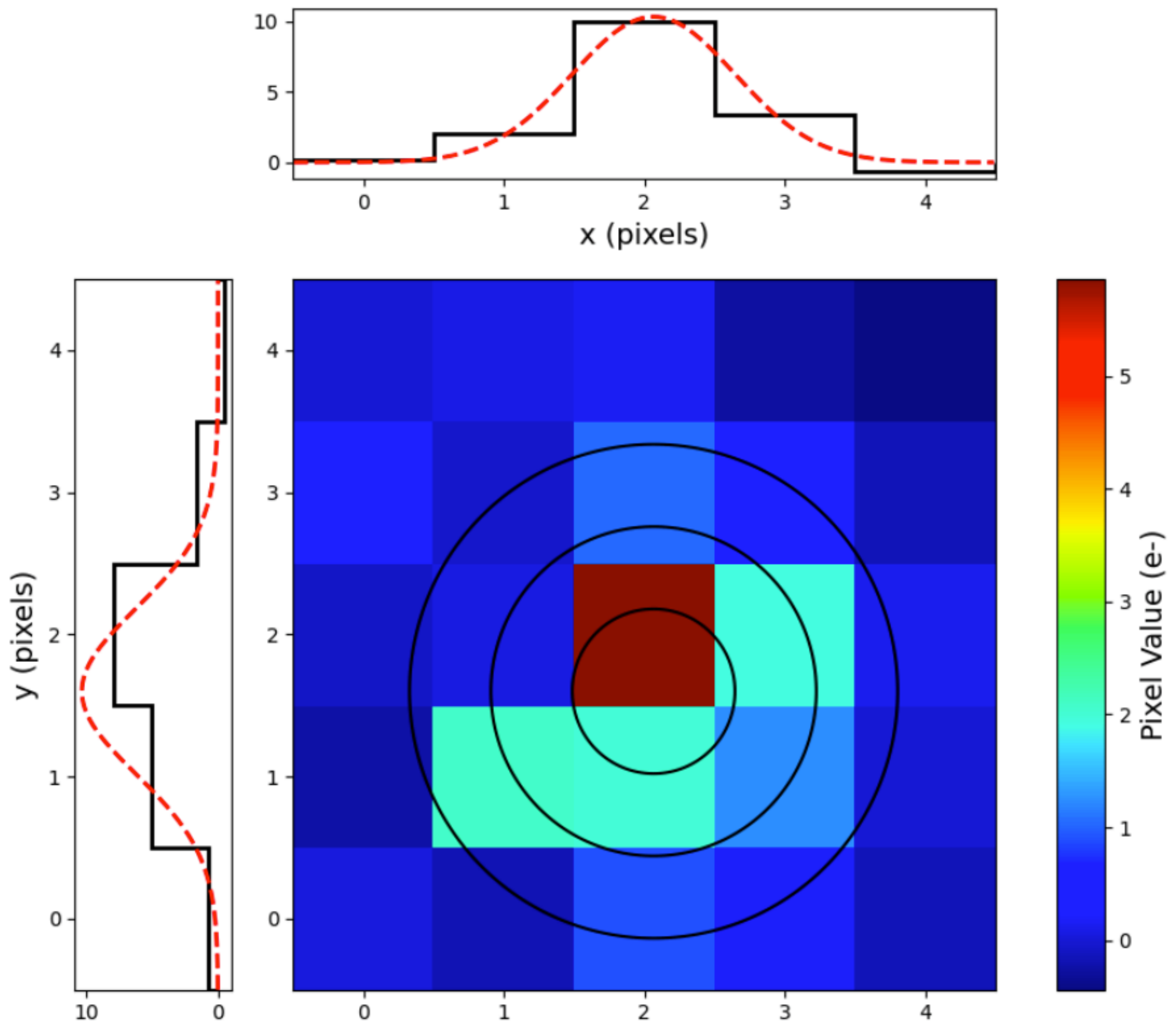


DATA SELECTIONS

Likelihood clustering: find low-energy clusters by computing likelihood of ionization event inside moving window…

$$\log \mathcal{L}(N, \vec{\mu}, \vec{\sigma}, \lambda, \sigma_r | \vec{q}) = \sum_i \sum_j \left(\sum_k^{\infty} \log \left(\frac{\gamma_{ij}^k \exp(-\gamma_{ij})}{k!} \frac{1}{\sqrt{2\pi\sigma_r^2}} \exp\left(\frac{-(q_{ij}-k)^2}{2\sigma_r^2} \right) \right) \right)$$

$$\gamma_{ij} = \lambda_i + N \int_{i-0.5}^{i+0.5} \int_{j-0.5}^{j+0.5} \mathrm{Gaus}(x, y | \mu_x, \mu_y, \sigma_x, \sigma_y) dx dy$$ **: Noise + Ionization**



DATA SELECTIONS

Likelihood clustering: …and efficiently reject noise accidentals down to 23 eV_{ee}

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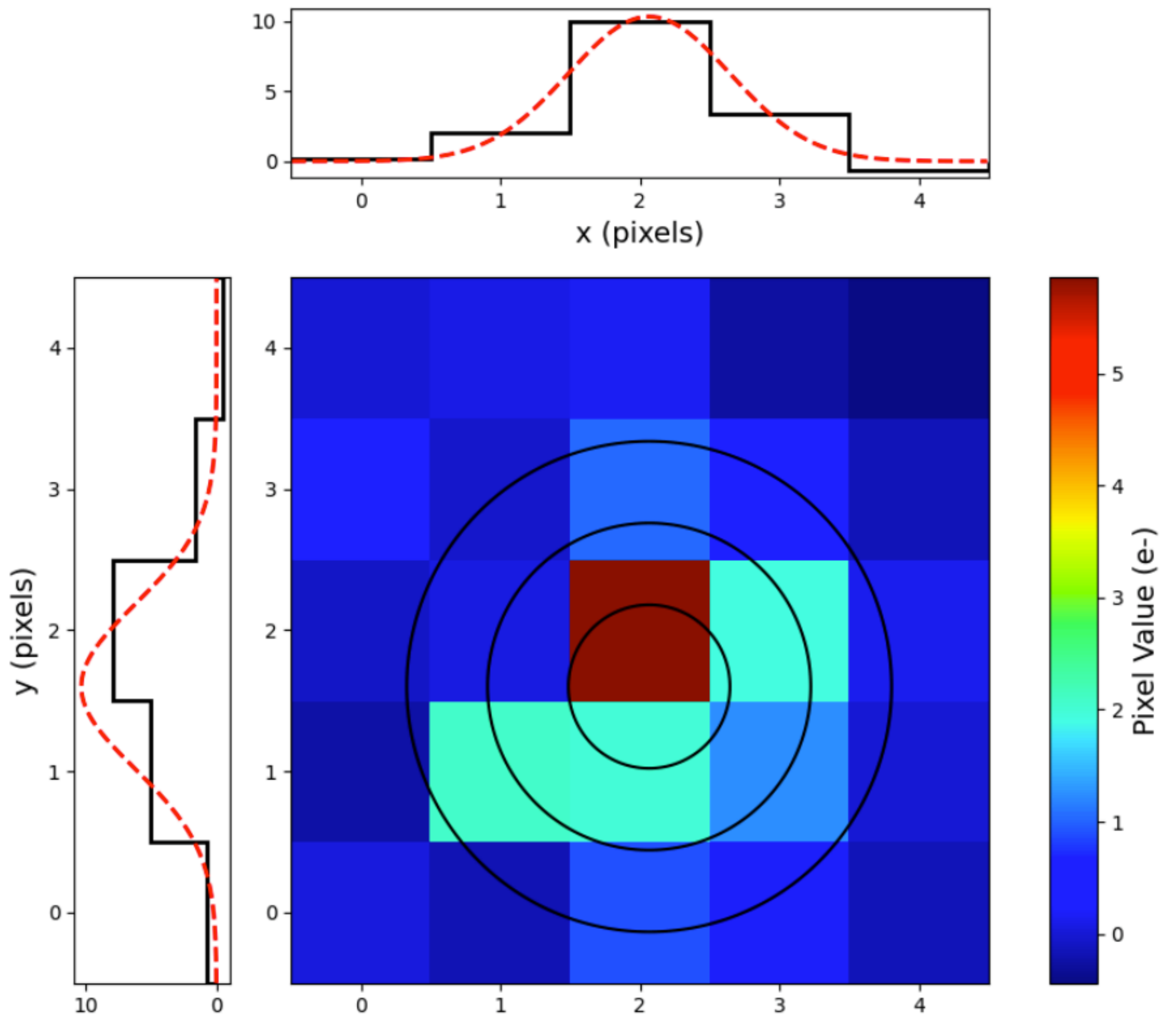
↓

$$\Delta LL = -\log \left(\frac{\tilde{\mathcal{L}}_g}{\mathcal{L}_n} \right)$$ discriminates low-energy events from noise accidentals

$\tilde{\mathcal{L}}_g$: global likelihood under hypothesis of ionization

$\mathcal{L}_n$: local likelihood under noise-only hypothesis



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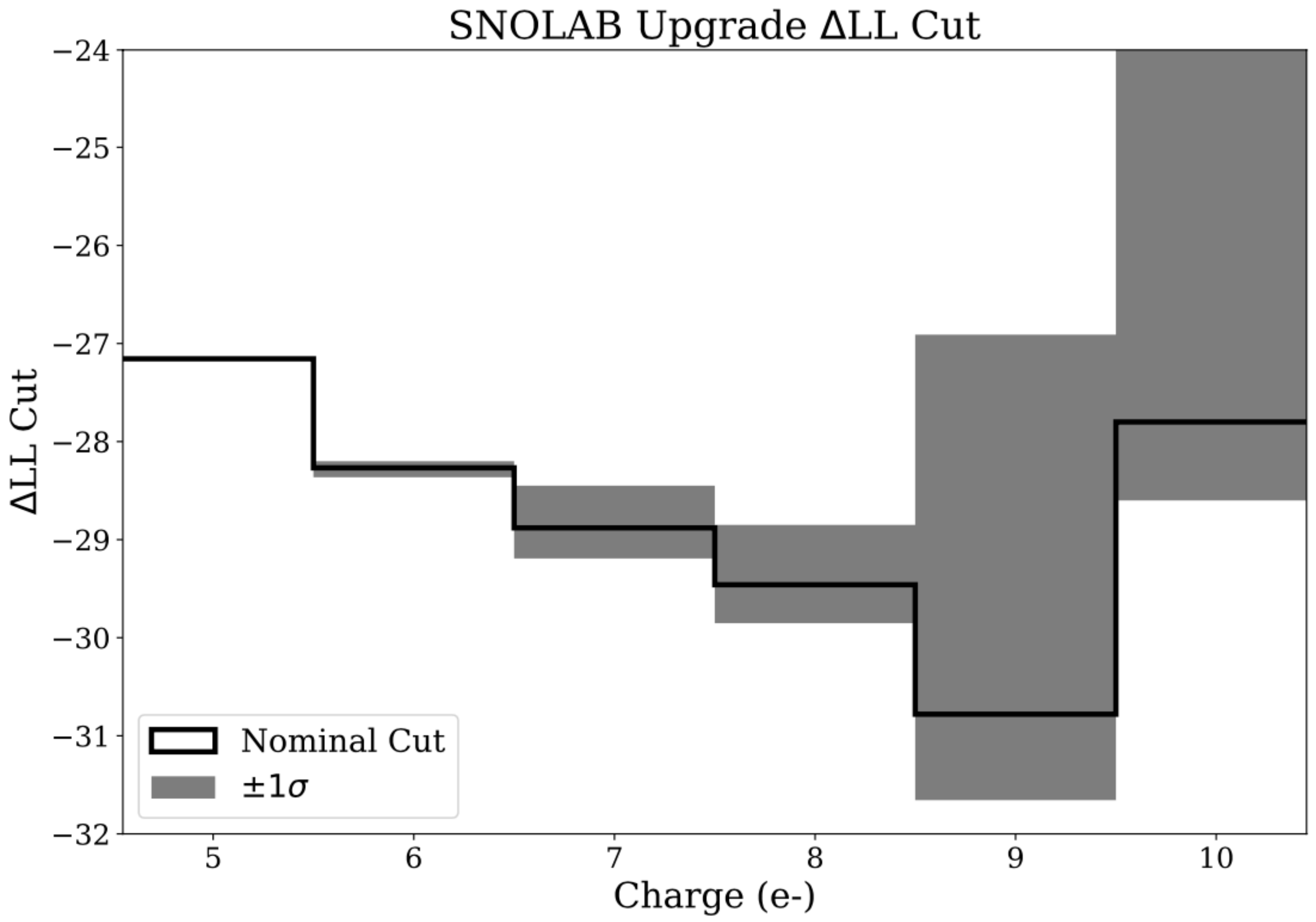

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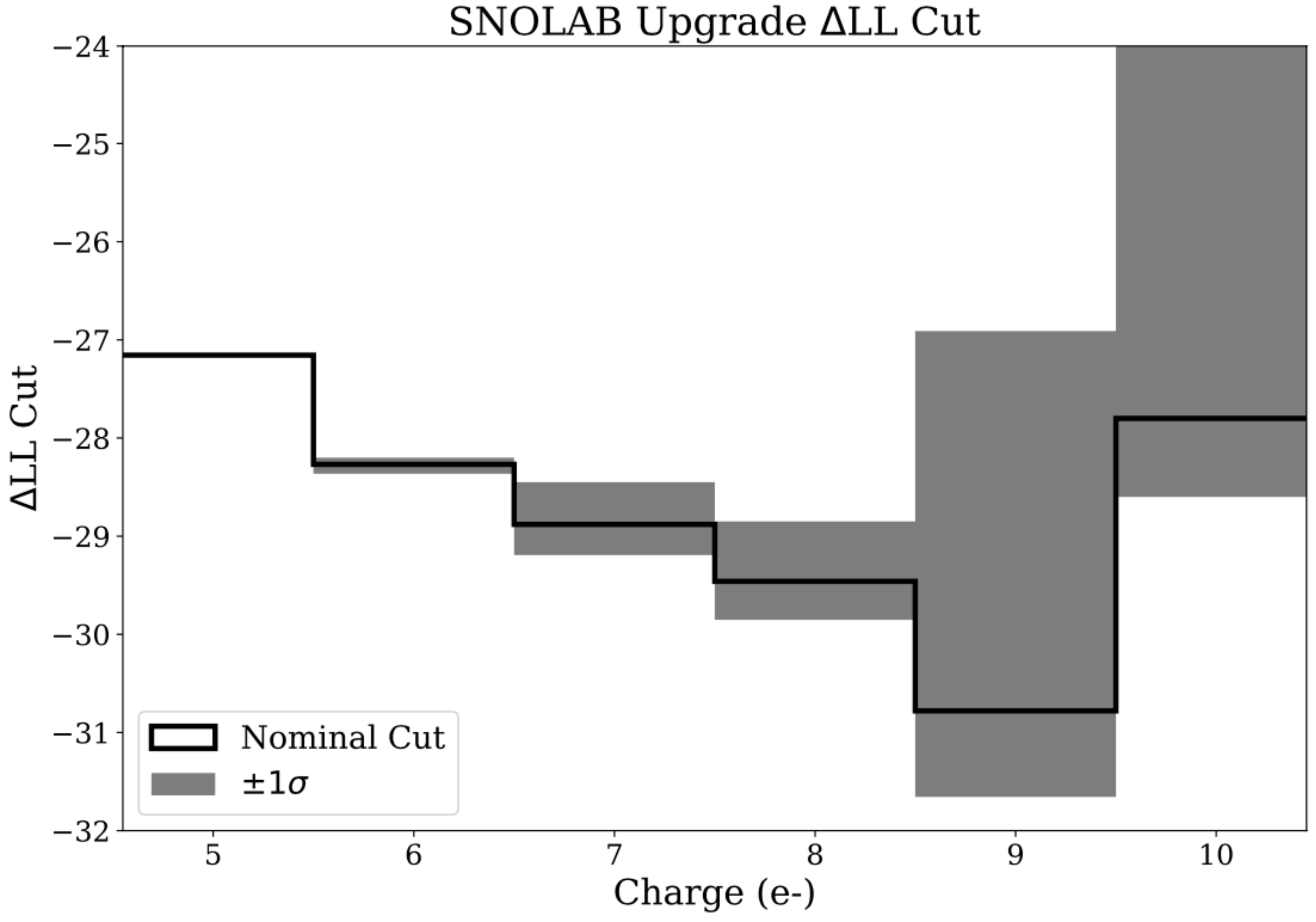

Bulk fiducialization: we also reject CCD surface events, the largest source of systematic uncertainty

We apply a fiducial selection of bulk events, using the diffusion model:

$$\sigma_{xy}(z, E) = \sqrt{-A \ln(1 - bz)}(\alpha + \beta E)$$

σ_{xy} : cluster spread z : depth E : energy

Model validated in the lab

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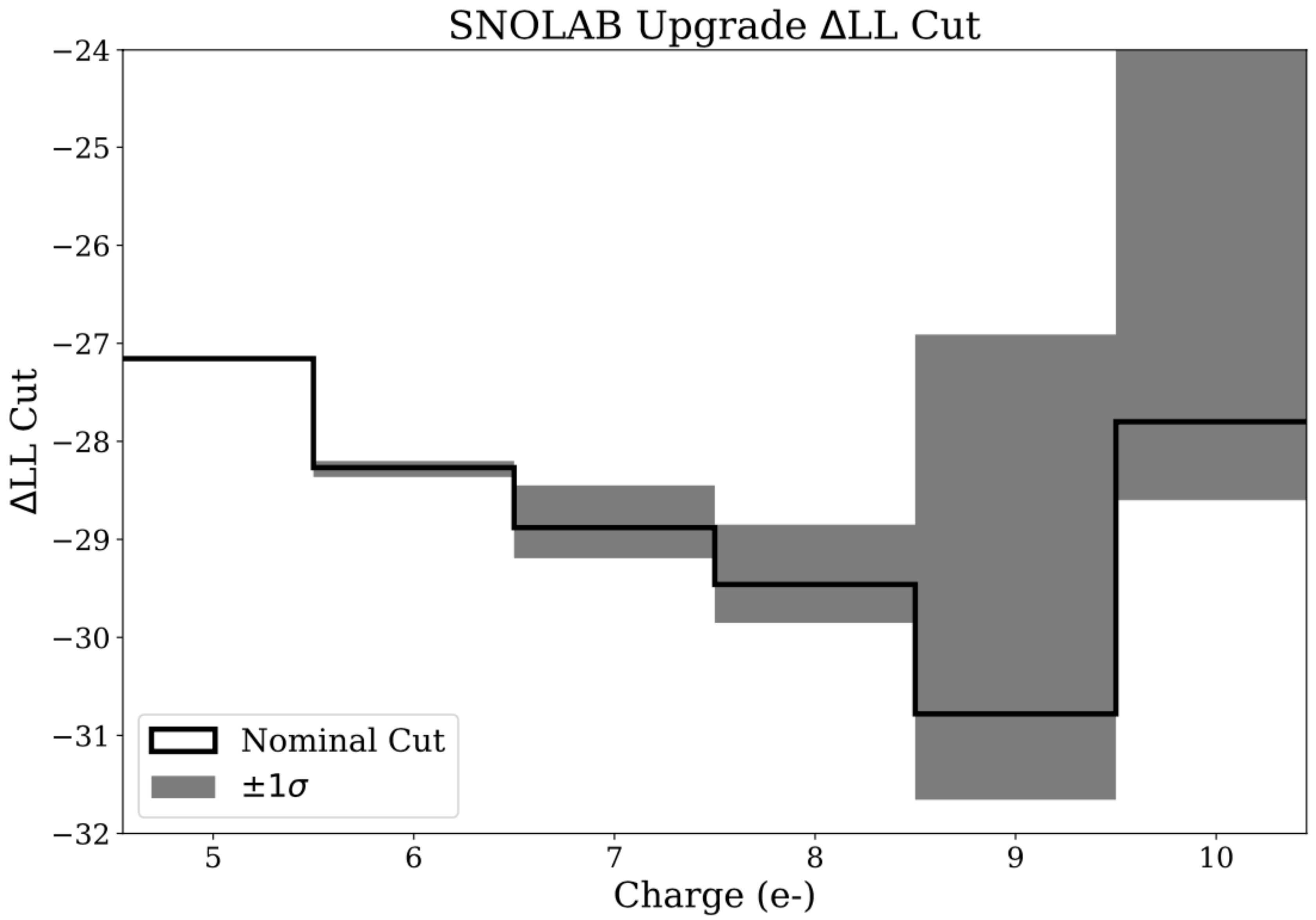

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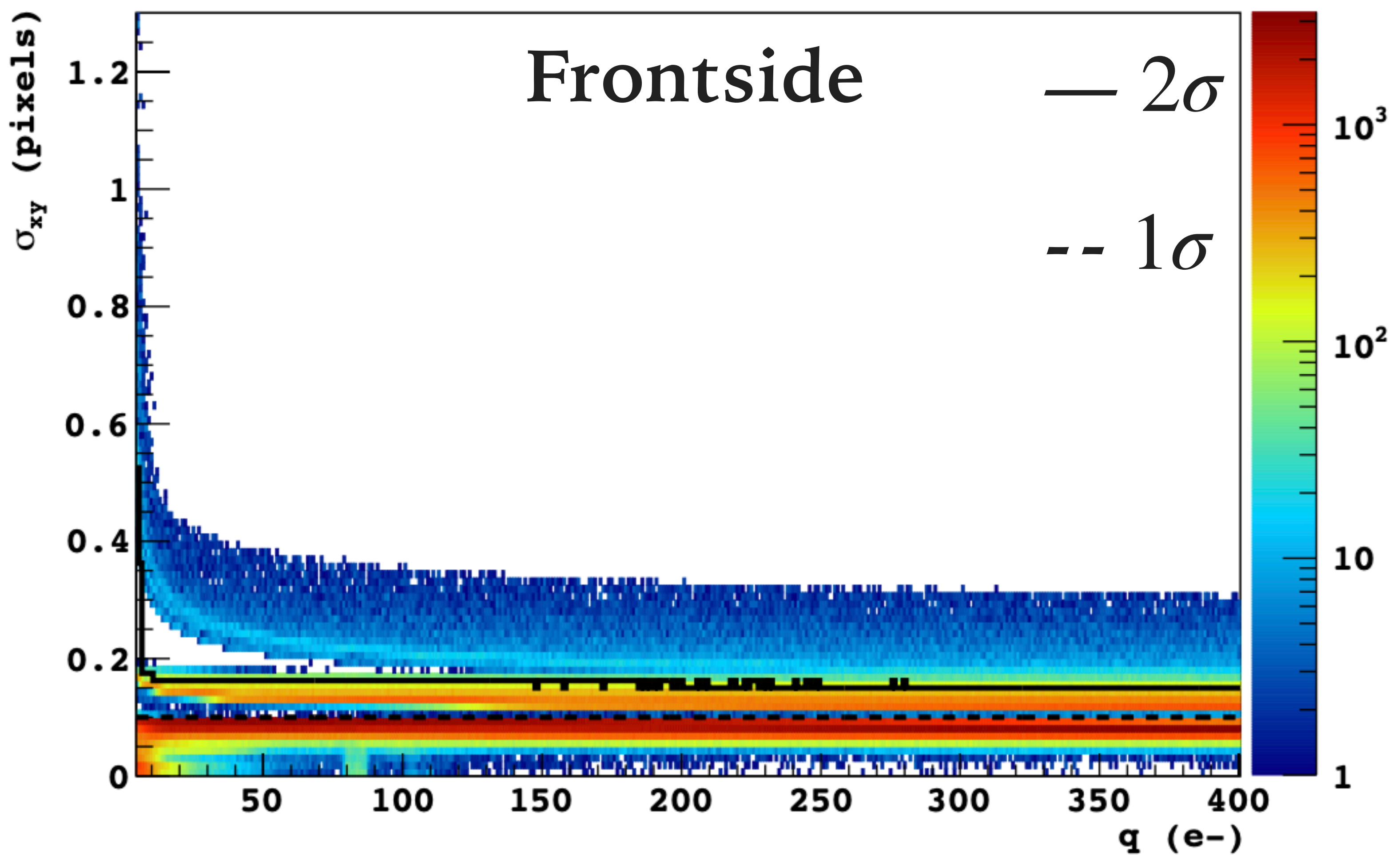

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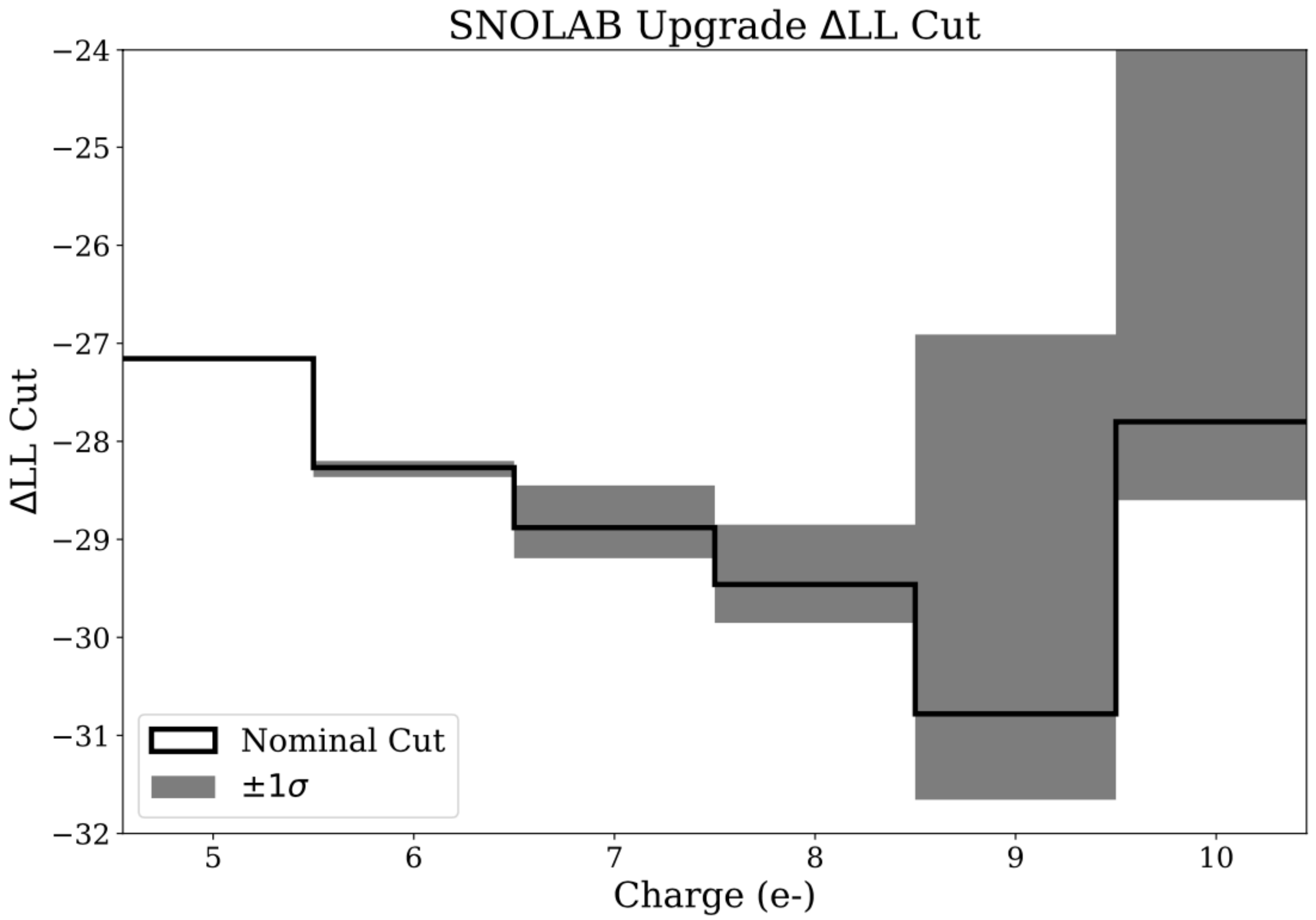

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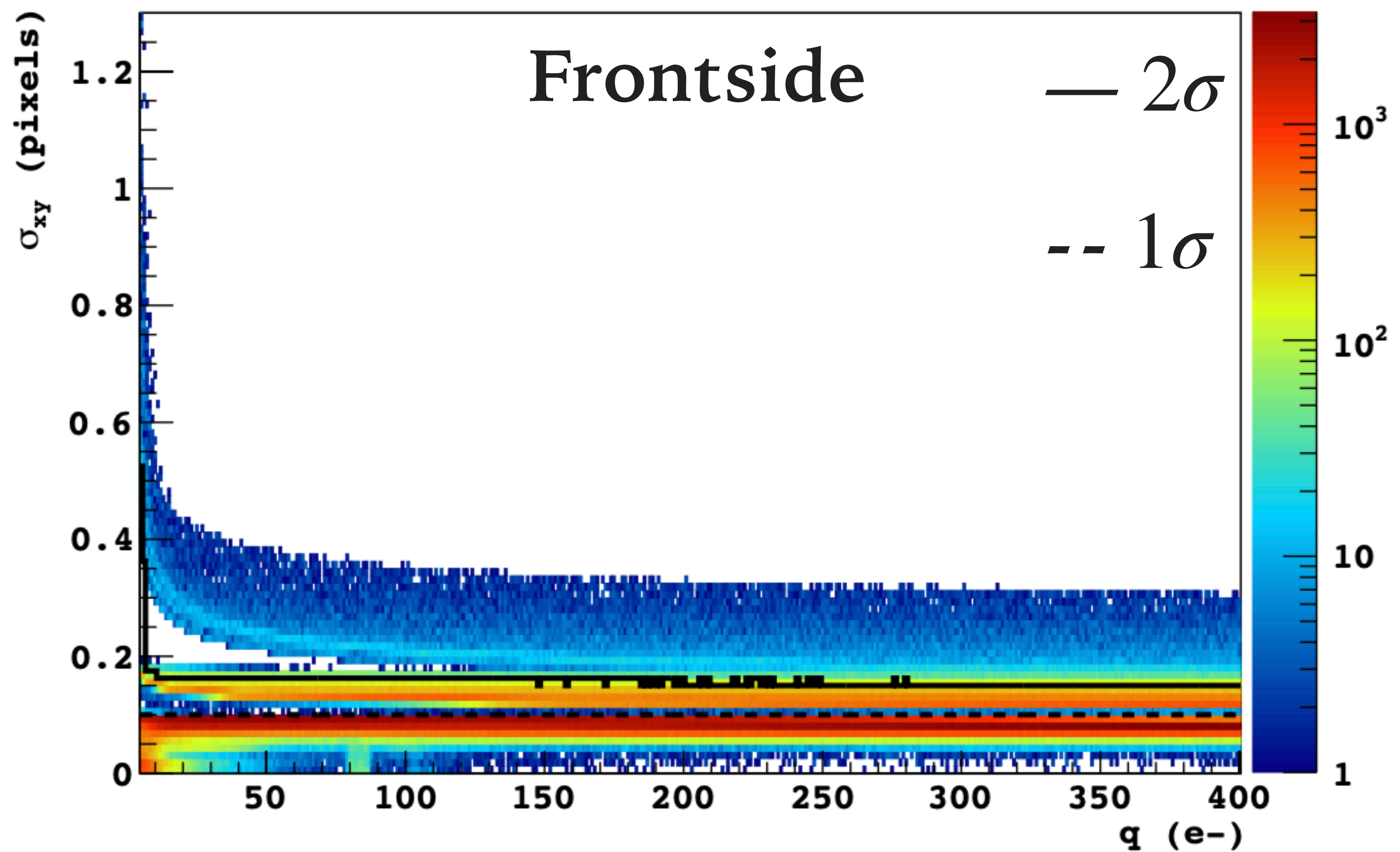
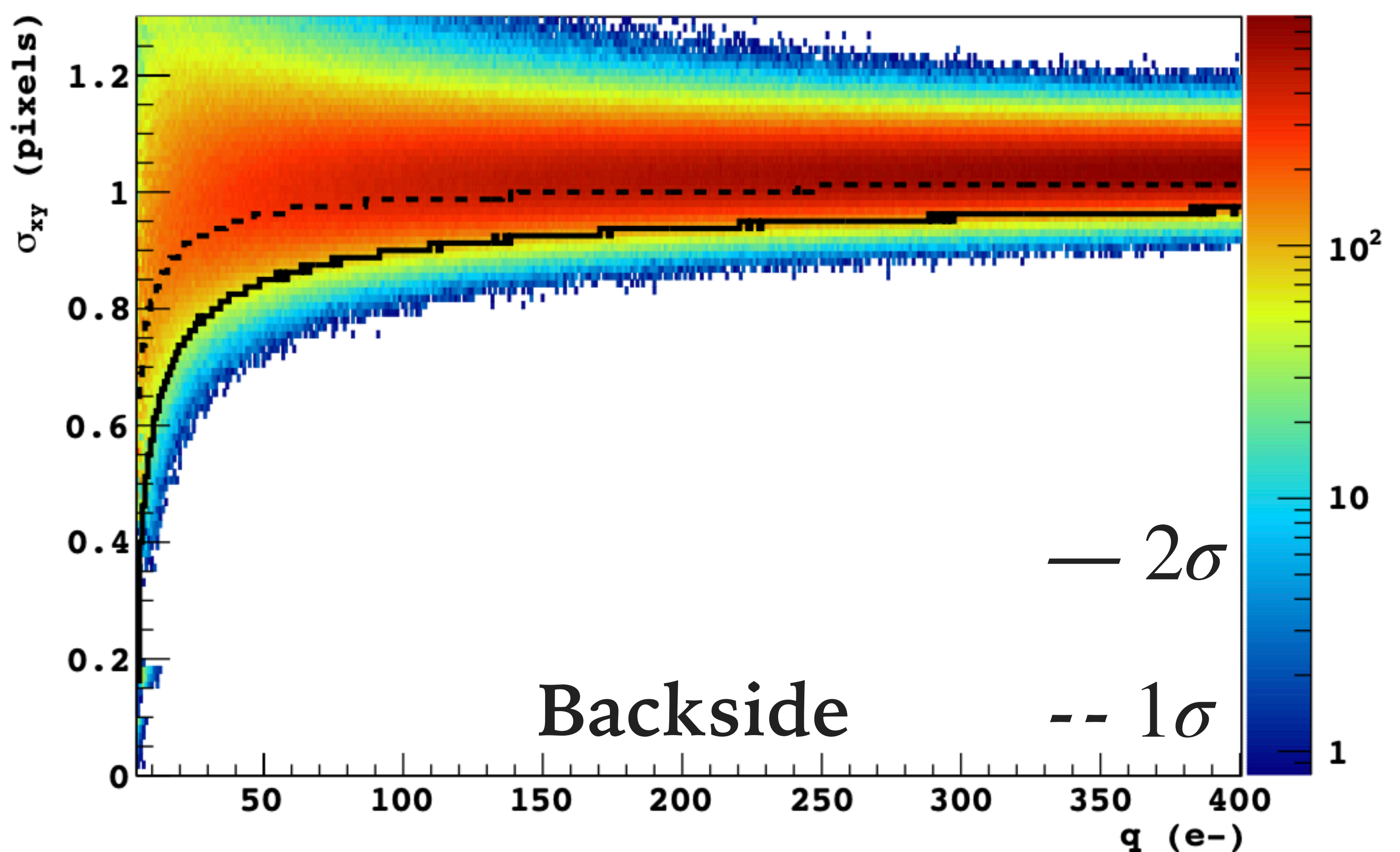
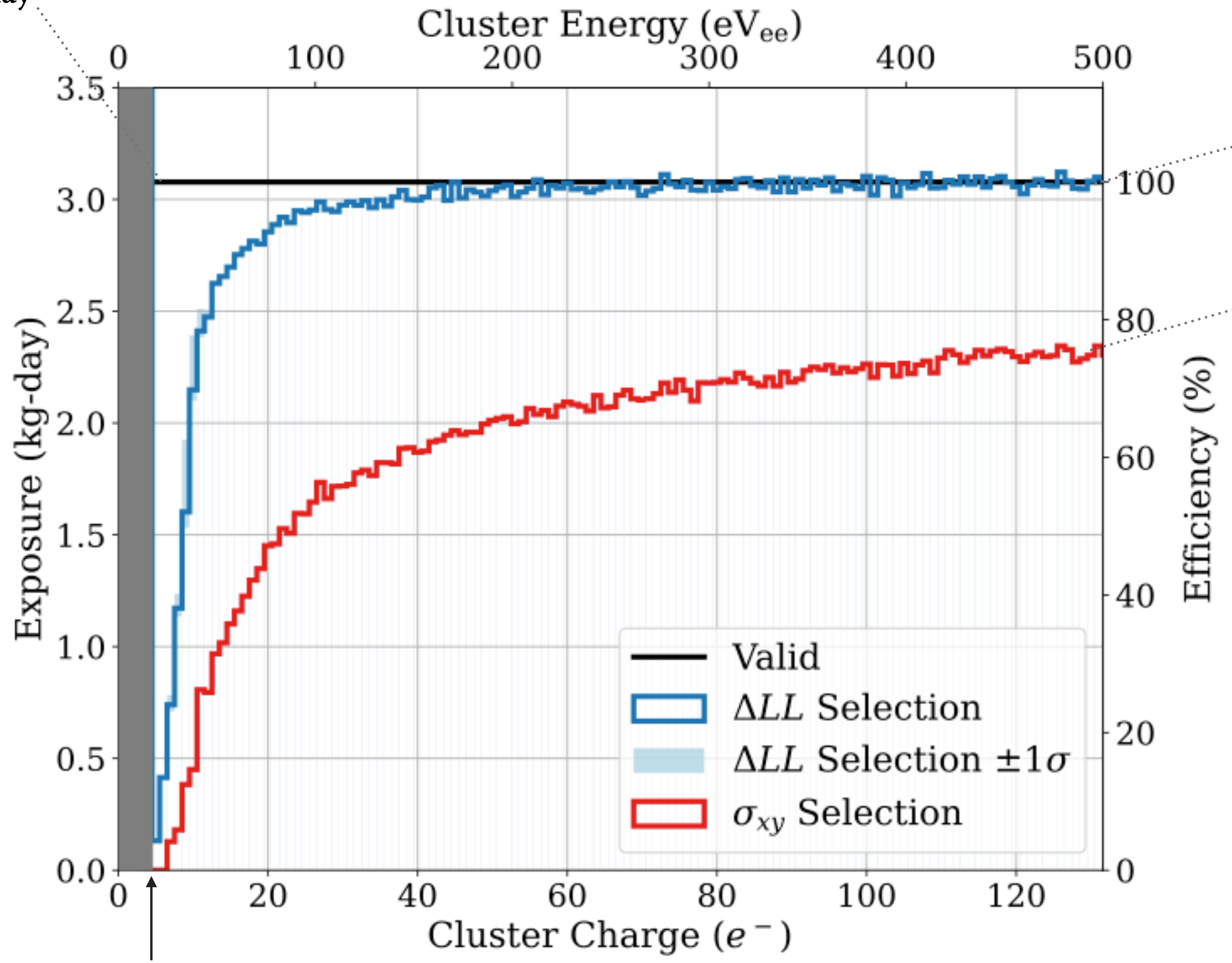




DATA SELECTIONS

Valid clusters: from 4.8 to 3.1 kg-day

- mask defects and hot regions
- mask high-energy clusters
- discard bad images

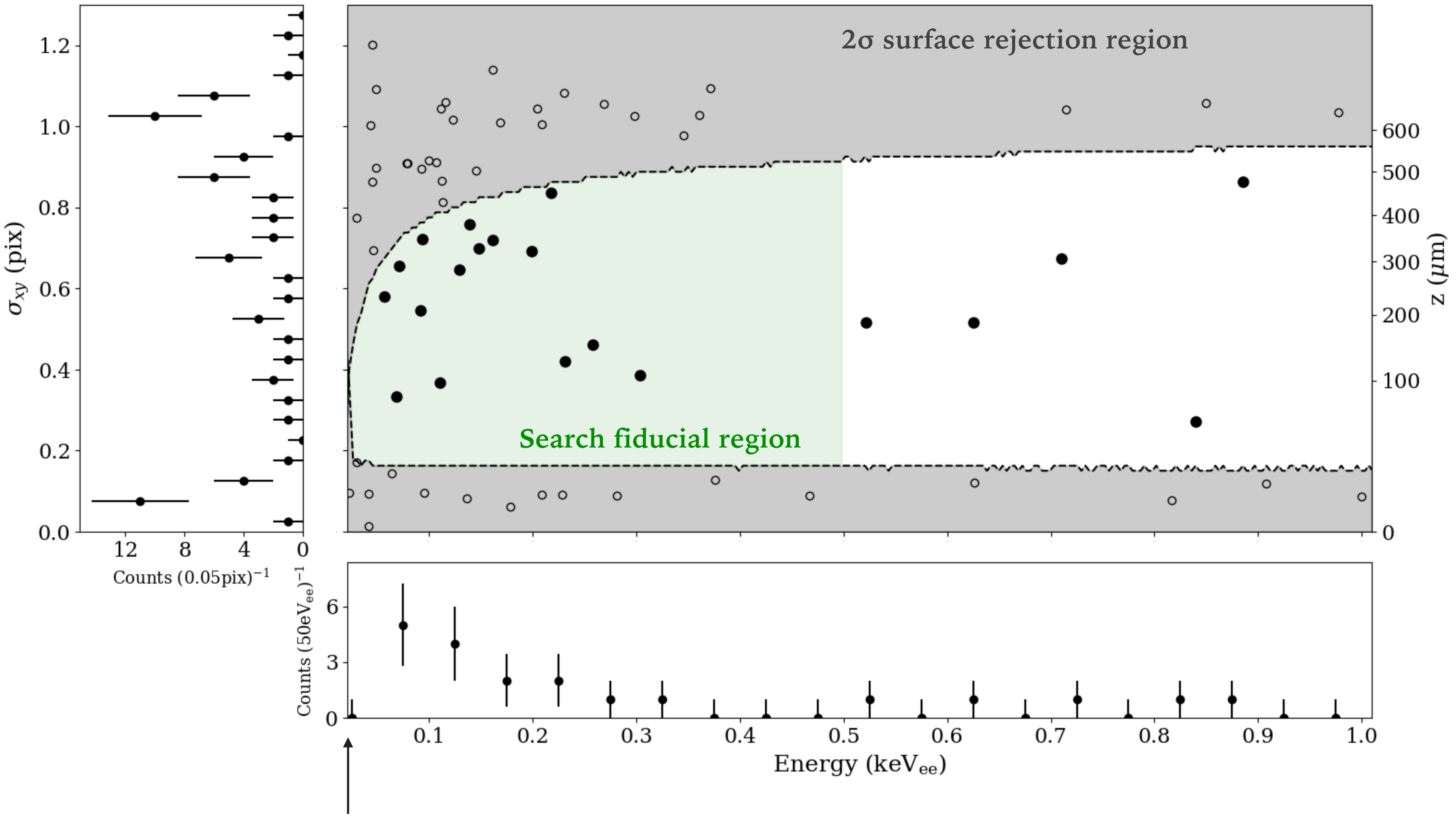


Post accidental rejection

Post surface rejection

threshold: 6 $e^- = 23$ eV_{ee}

FIDUCIALIZED SCIENCE DATA



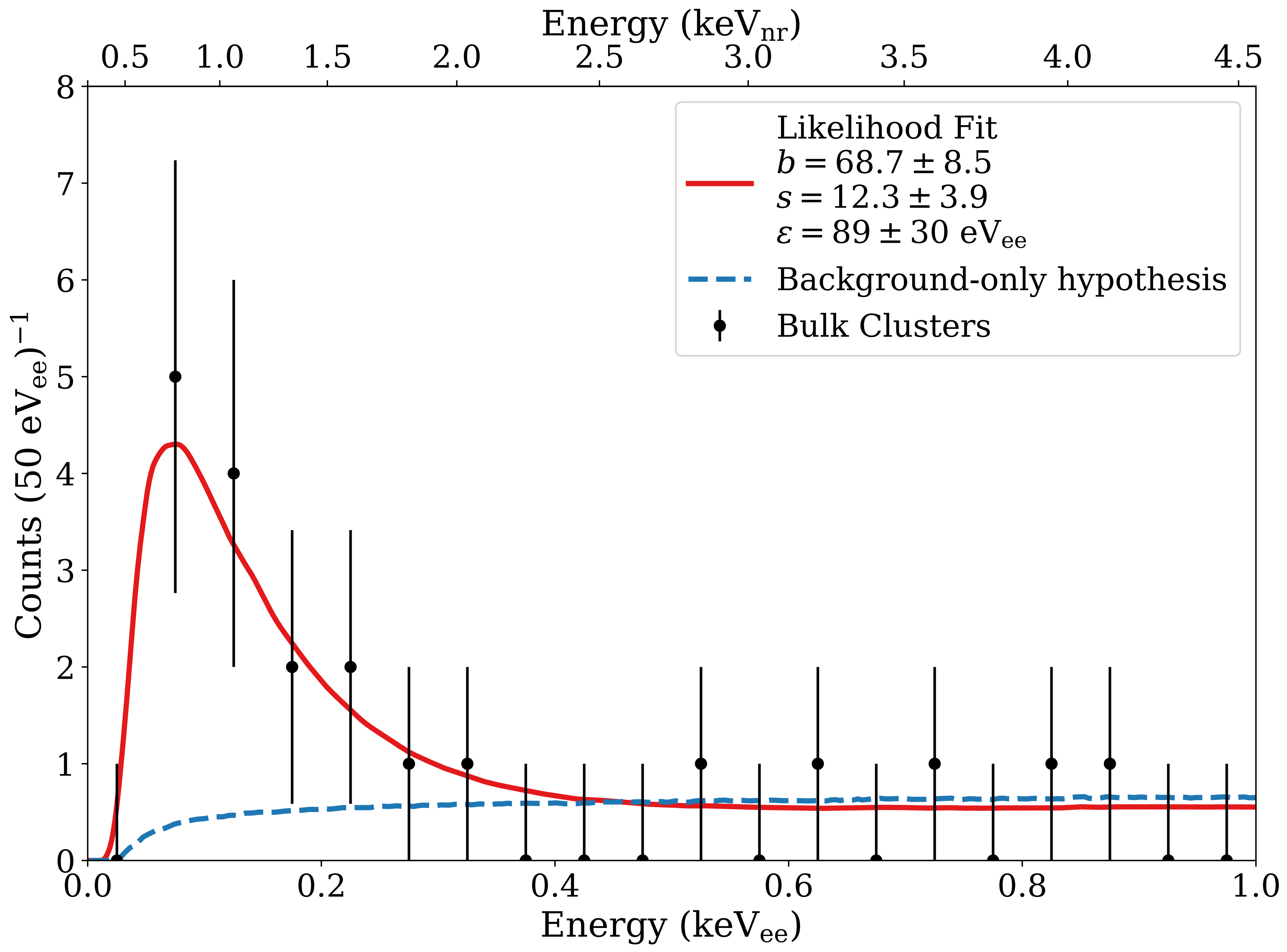
threshold: 6 e^{-} = 23 eV$_{ee}$

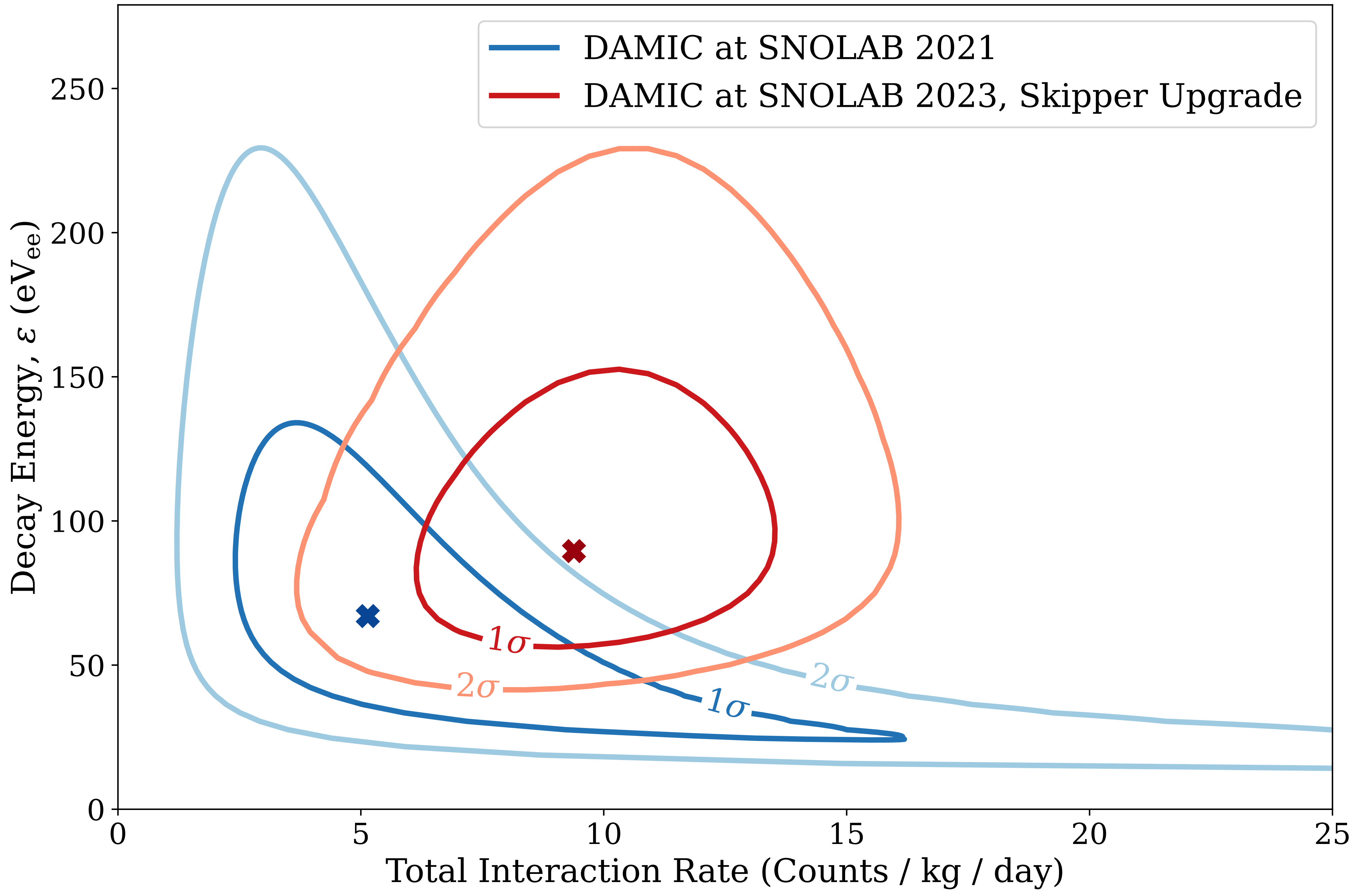
RESULTS

- Fit flat* bkg+exponential signal between 23 eV_{ee} and 6 keV_{ee}

The excess is still there! arXiv:2306.01717

- Increased significance: 5.4σ (expected from lower threshold)
- Statistically compatible with old excess (see contours)





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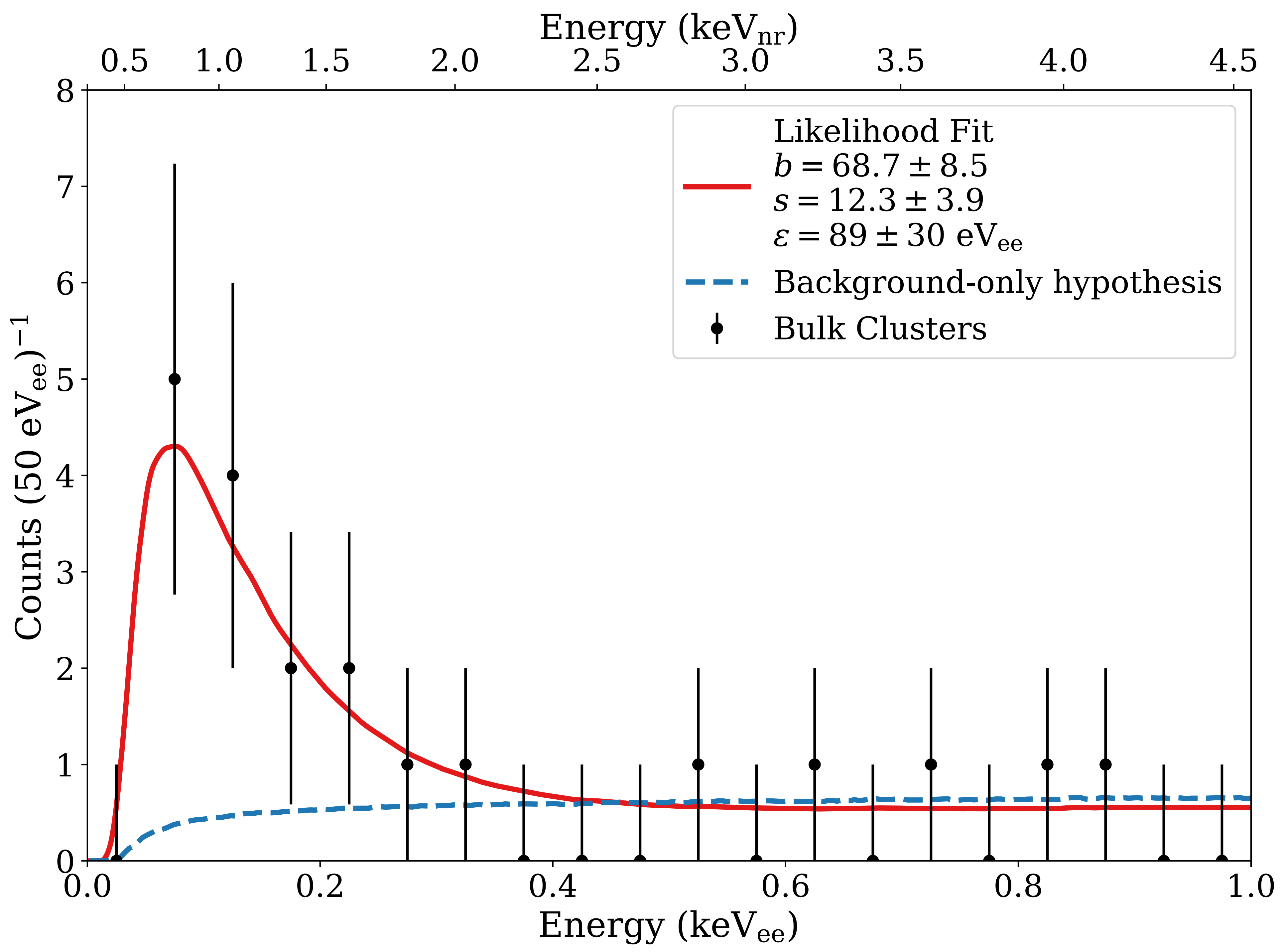
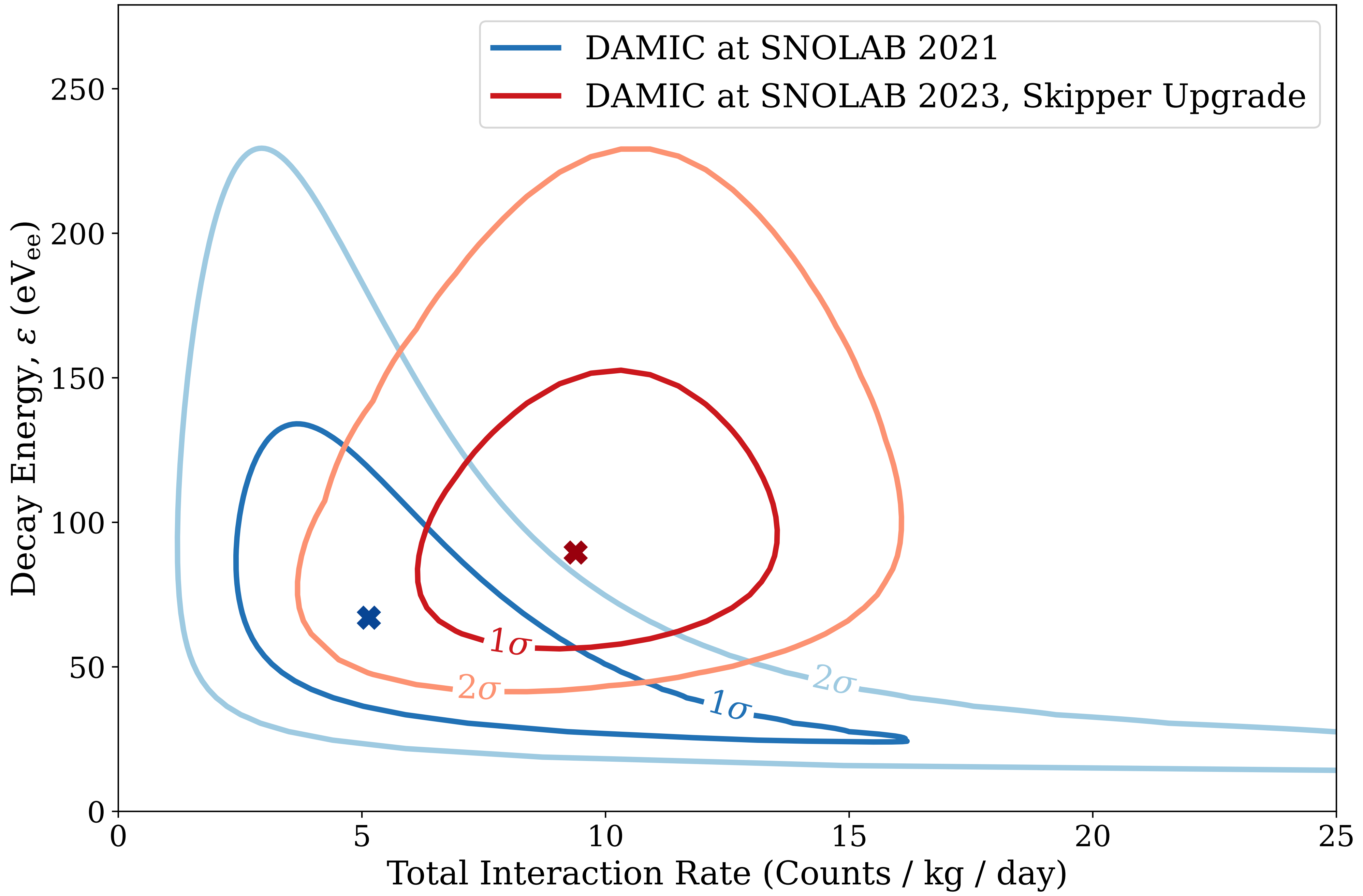
***Flat background**: conservative assumption. Near-threshold drops expected in ROI from Compton and tritium β^- events. Model re-validated above 0.5 keV





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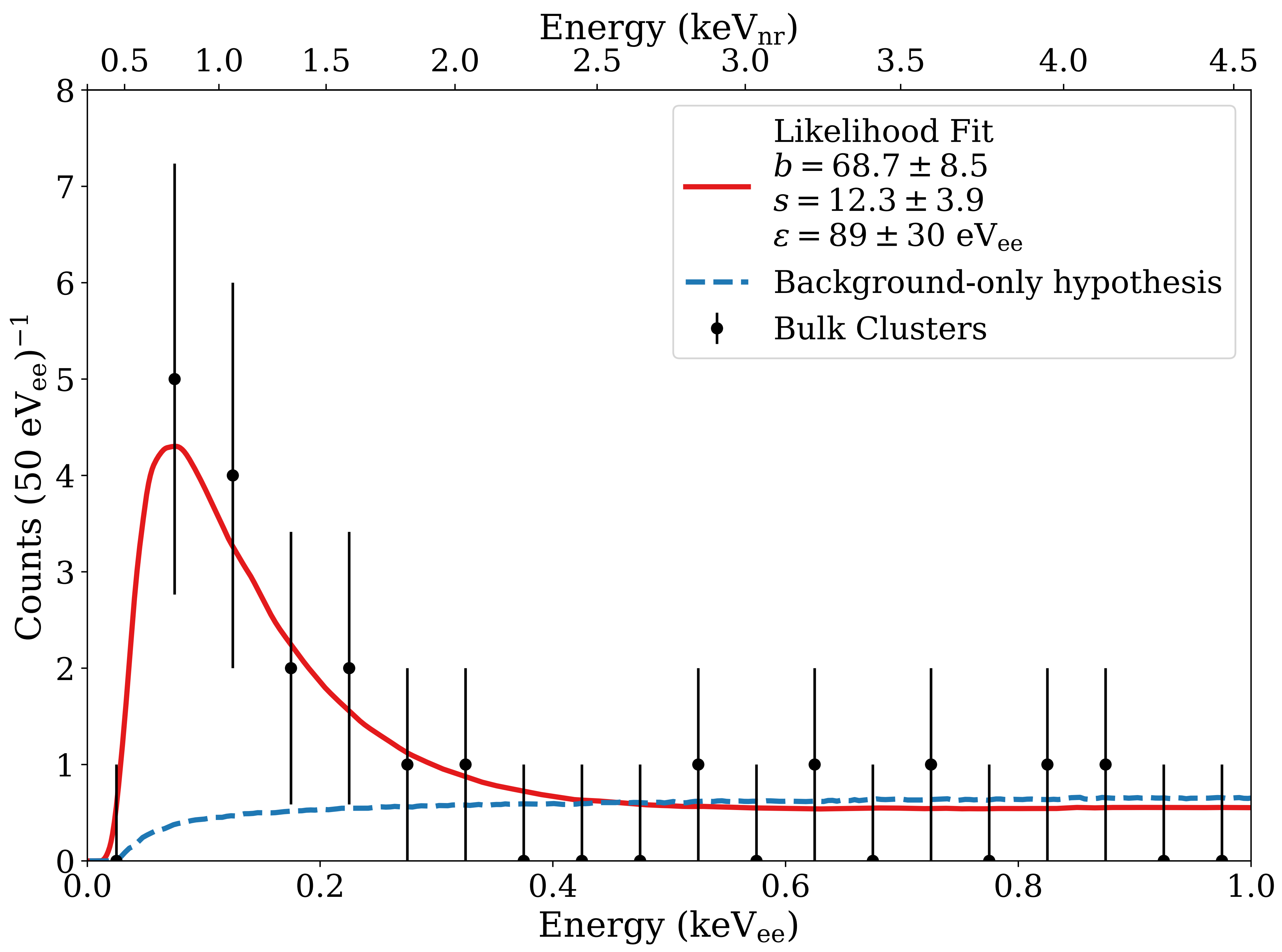
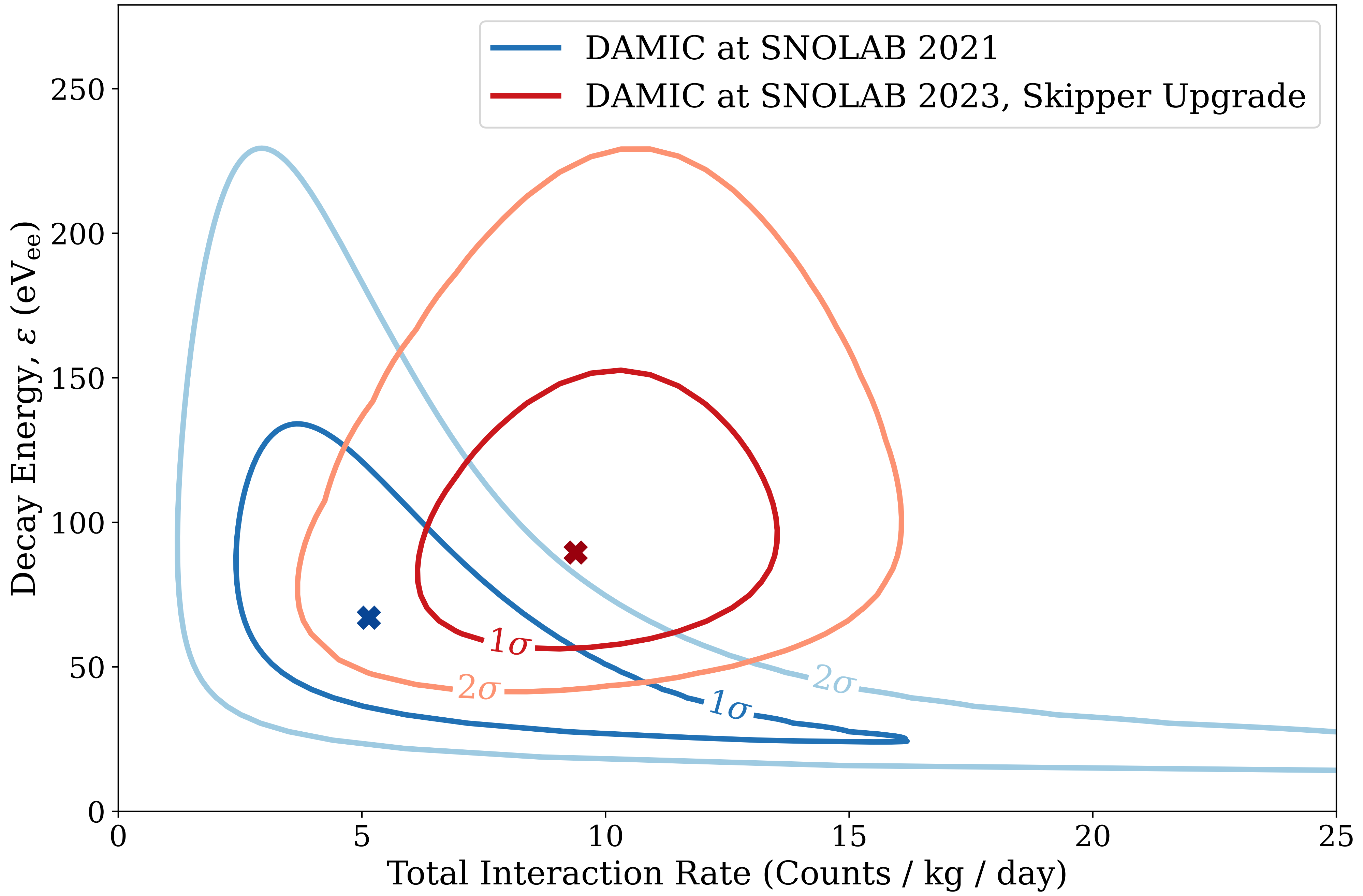
- Probably a source of radiation. Neutrons? No known source could produce this spectrum and rate in our setup. Other source of low-*E* events?





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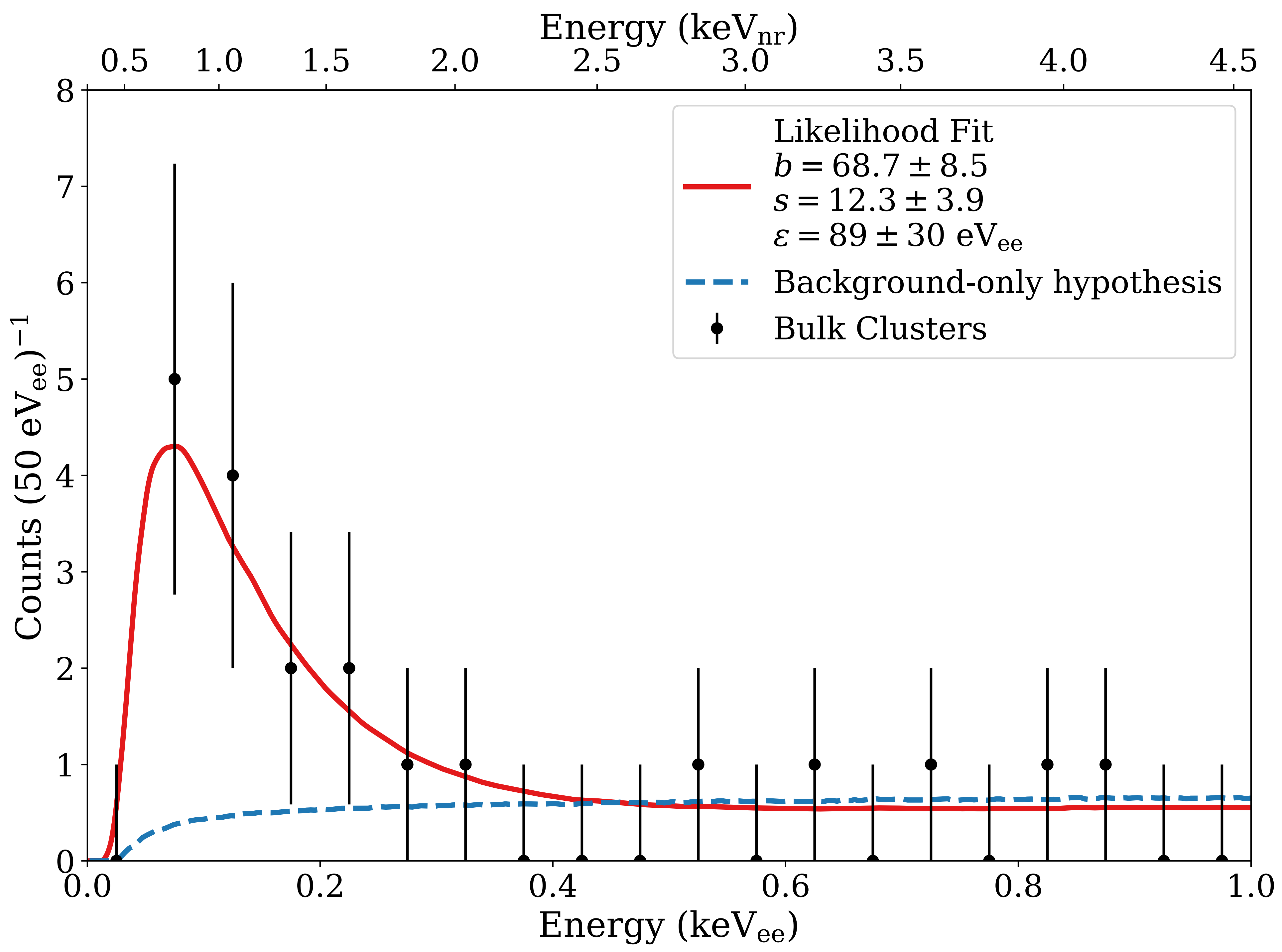

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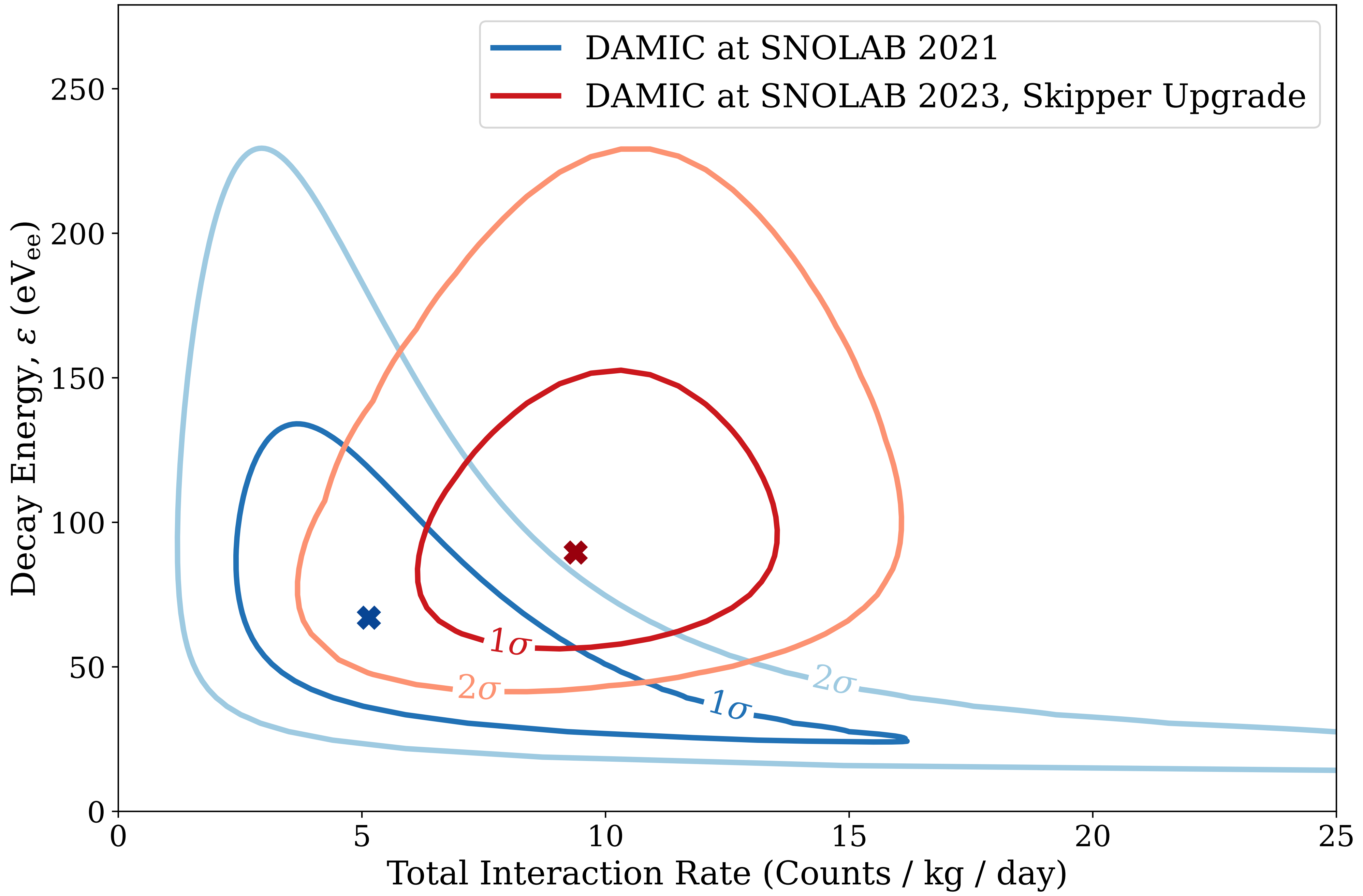
- The finding is in tension with experimental results from CDMSlite and DarkSide-50

$$m_\chi \sim 2.5\ GeV/c^2,\quad \sigma_{\chi n} \sim 3 \times 10^{-40}\ cm^2$$



CONCLUSIONS

- DAMIC at SNOLAB pioneered CCDs as Dark Matter detectors:
  - Constructed first comprehensive CCD background model
  - Detected low-energy excess below 500 eV_{ee}
- DAMIC-M will be deployed in 2024
  - $\sim$200 skipper CCDs: $\mathcal{O}$(kg) detector
  - Low-energy excess <u>confirmed</u> with DAMIC-M skippers at SNOLAB arXiv:2306.01717
    - Lower threshold with sub-electron noise
    - Rejected most prominent systematic: surface events
    - Unchanged background environment
- Will investigate excess in DAMIC-M (different) ultra-low background environment and much higher statistics… Stay tuned! See C. De Dominicis presentation

DAMIC-M

CENPA

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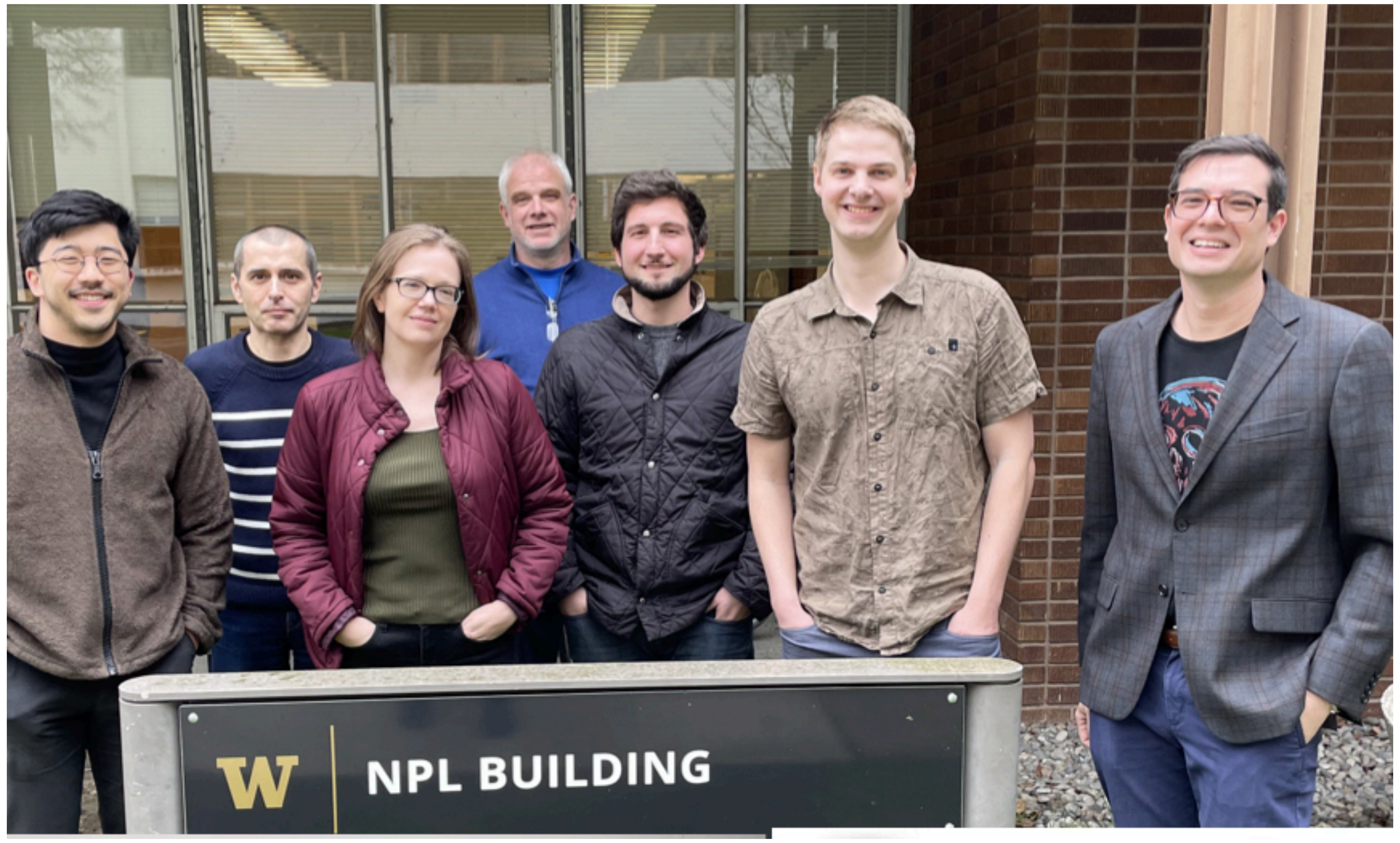
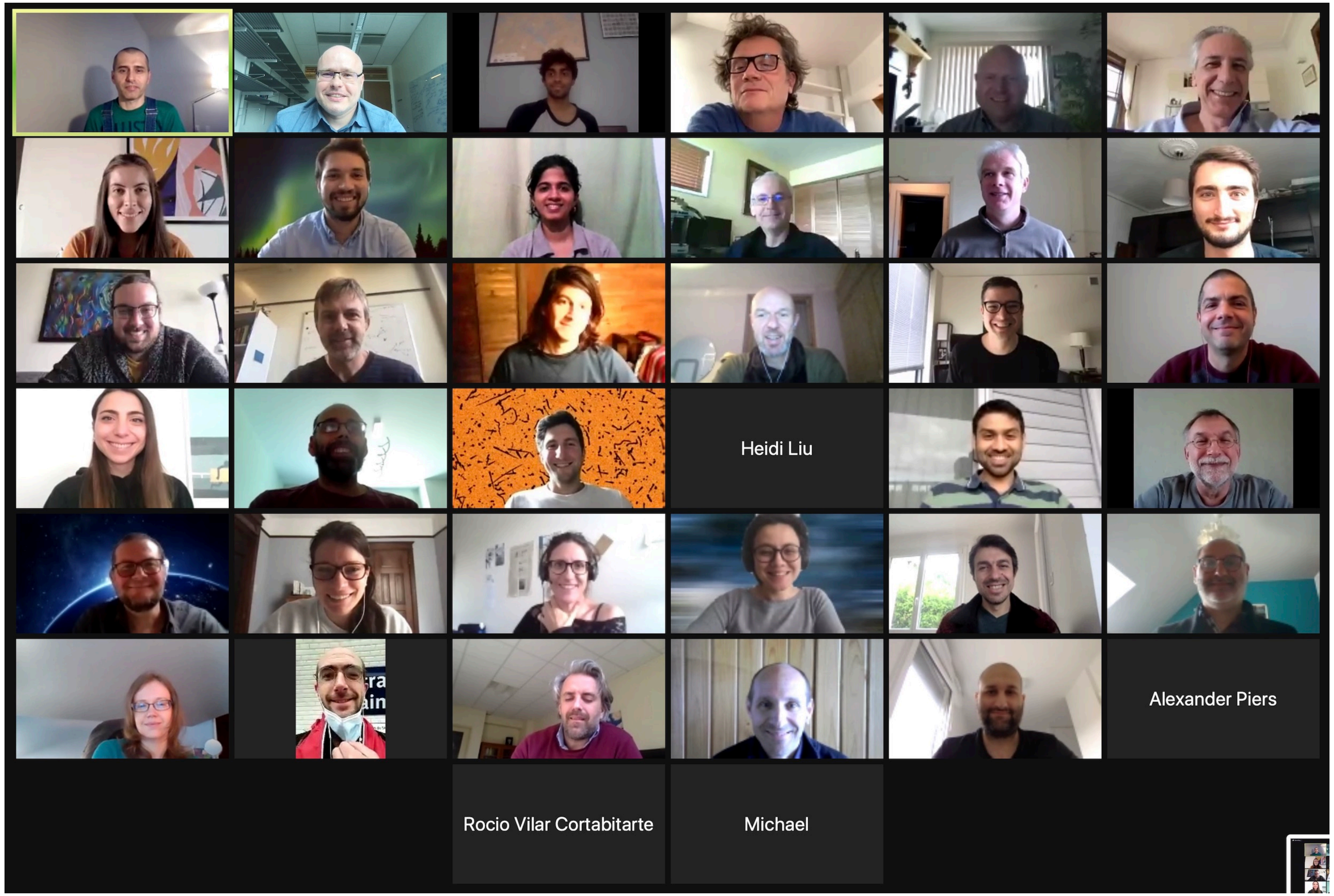
UNIVERSITY *of* WASHINGTON





The DAMIC-M Collaboration

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