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

TAUP VIENNA 2023

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Outline:

1. DAMIC at SNOLAB
2. Background model
3. Low-energy excess
4. SNOLAB skipper upgrade
5. Science data and selections
6. Confirmation of the excess

DAMIC

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

DAMIC-M

DAMIC AT SNOLAB

DArk Matter In CCDs collaboration

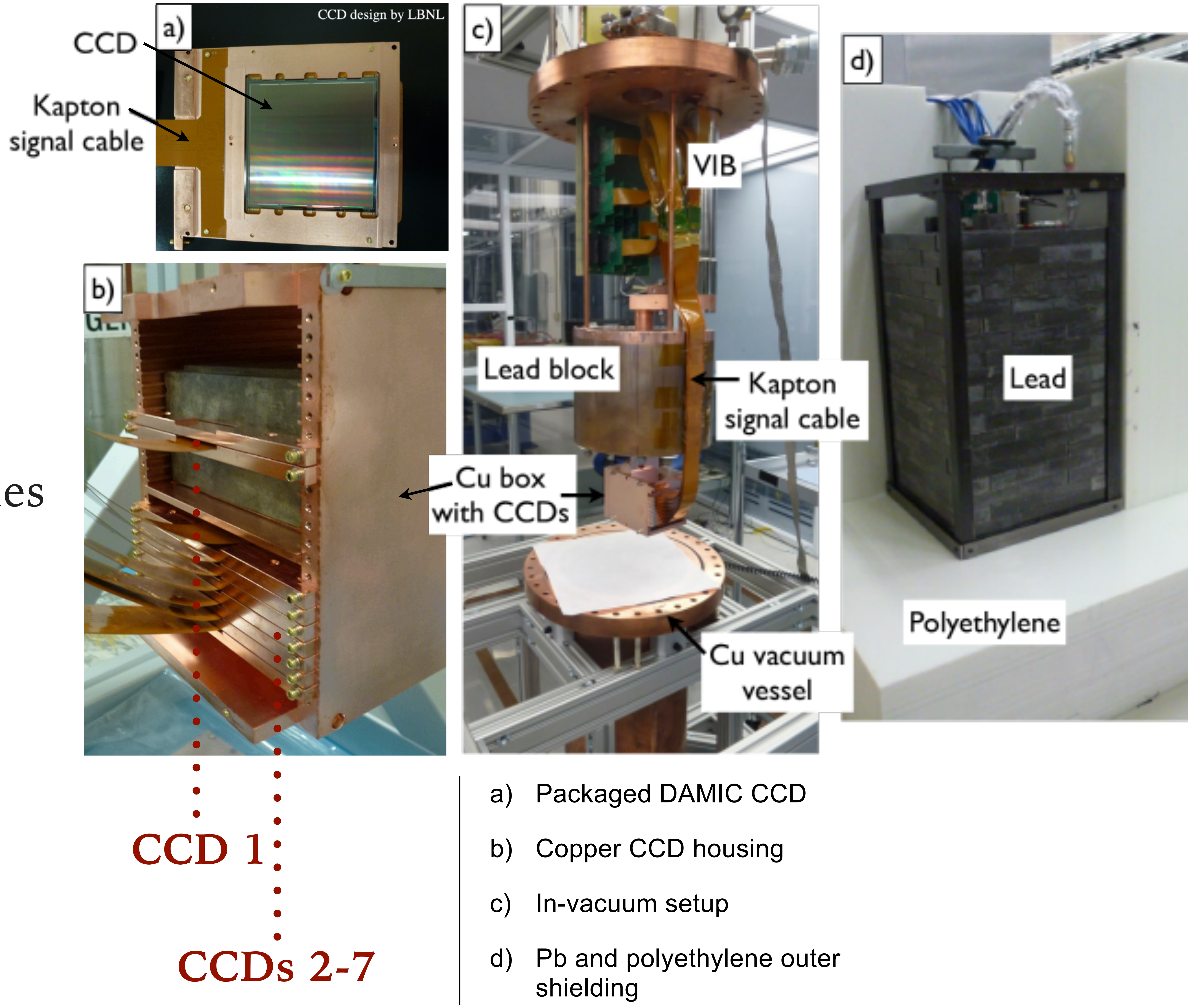
- Setup beneath 2 km of granite **at SNOLAB** (Canada)
- Sensors in cryogenic conditions (10^{-6} mbar, 140 K)

Charge-Coupled Devices

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

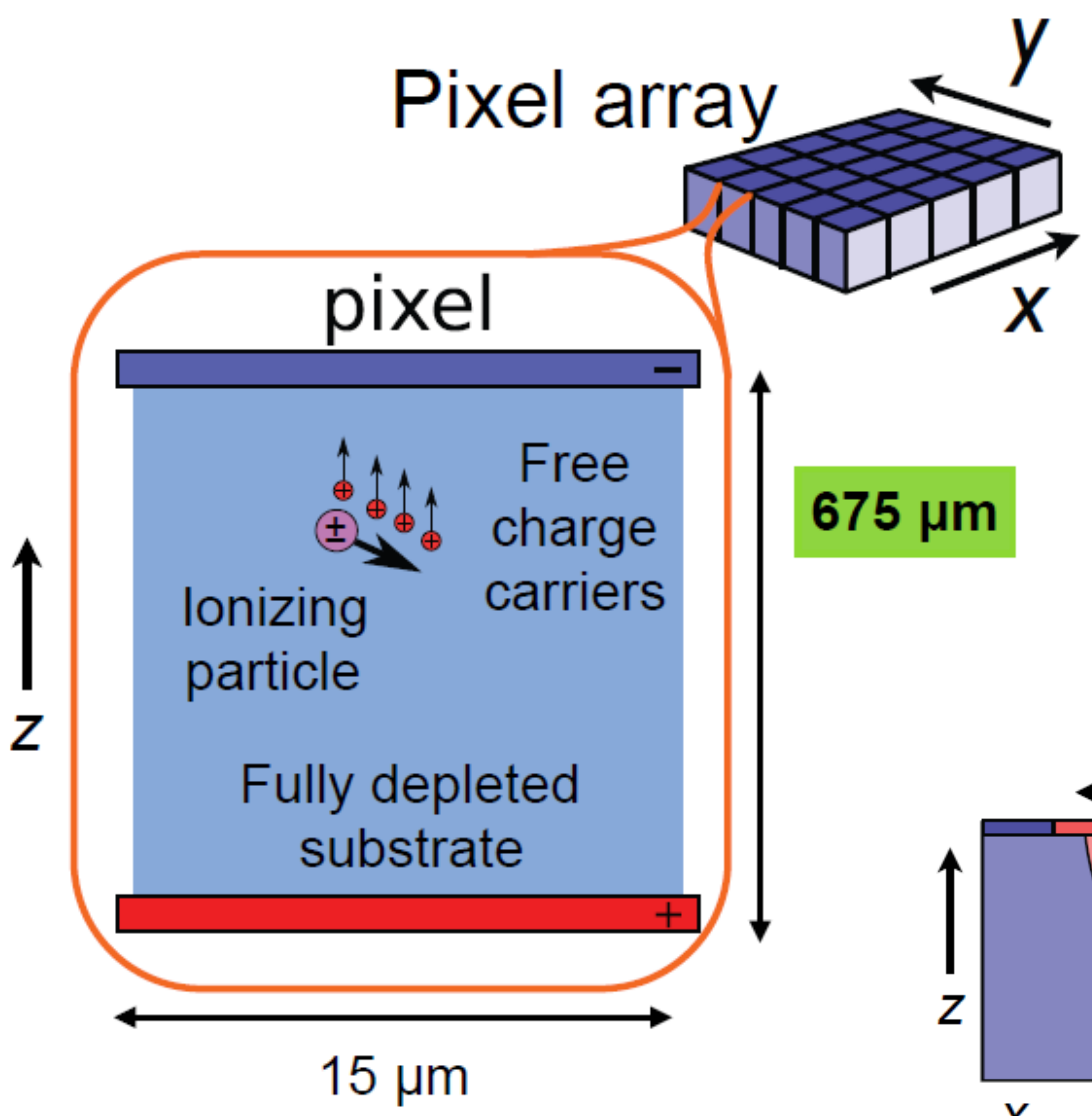
DAMIC apparatus in 2018:

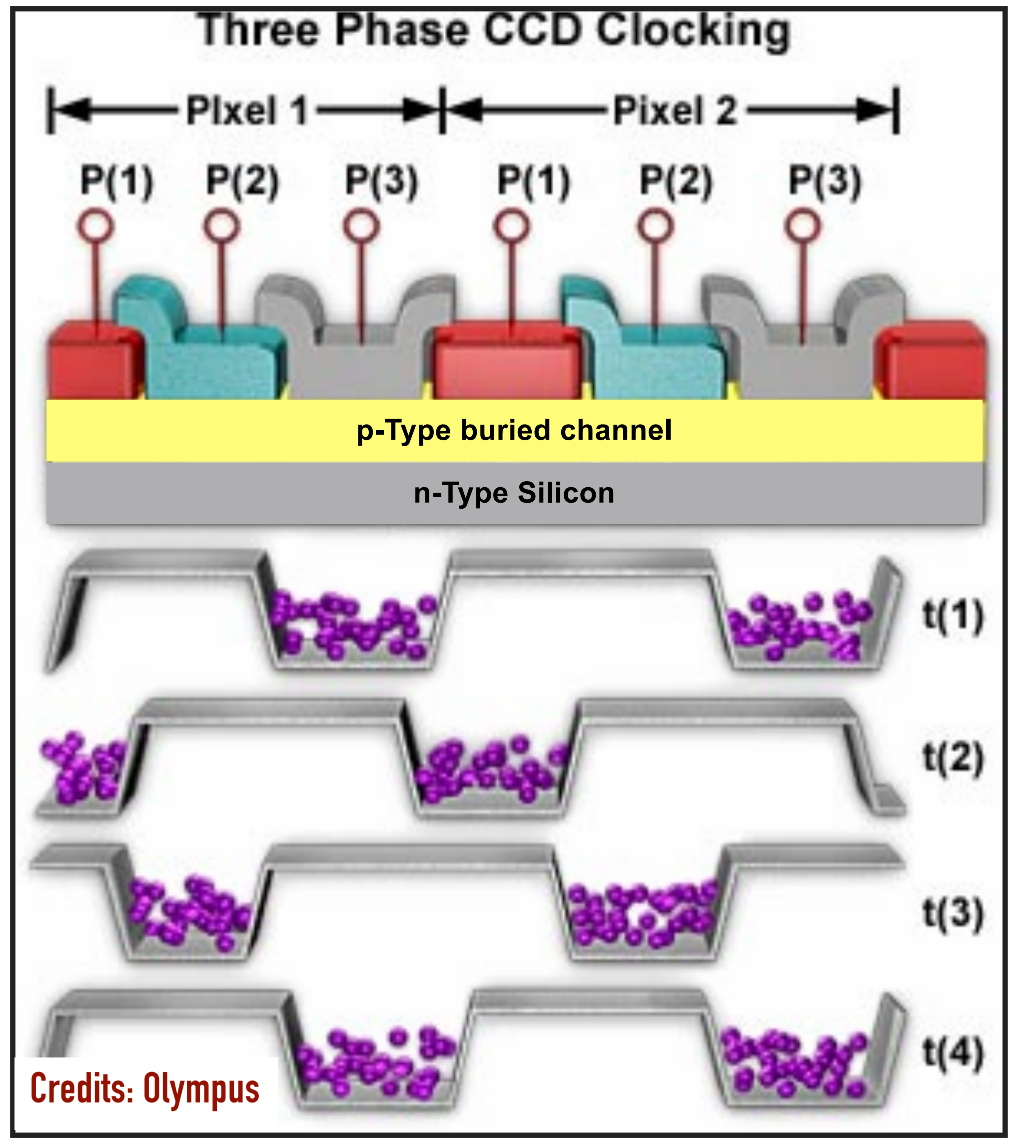
- Seven thick CCDs $\Longrightarrow$ massive target
  675 μm ~ 40 g
- Sensitive to:
  - WIMPs (nucleus coherent scattering)
  - Hidden sector DM (e^- interactions)

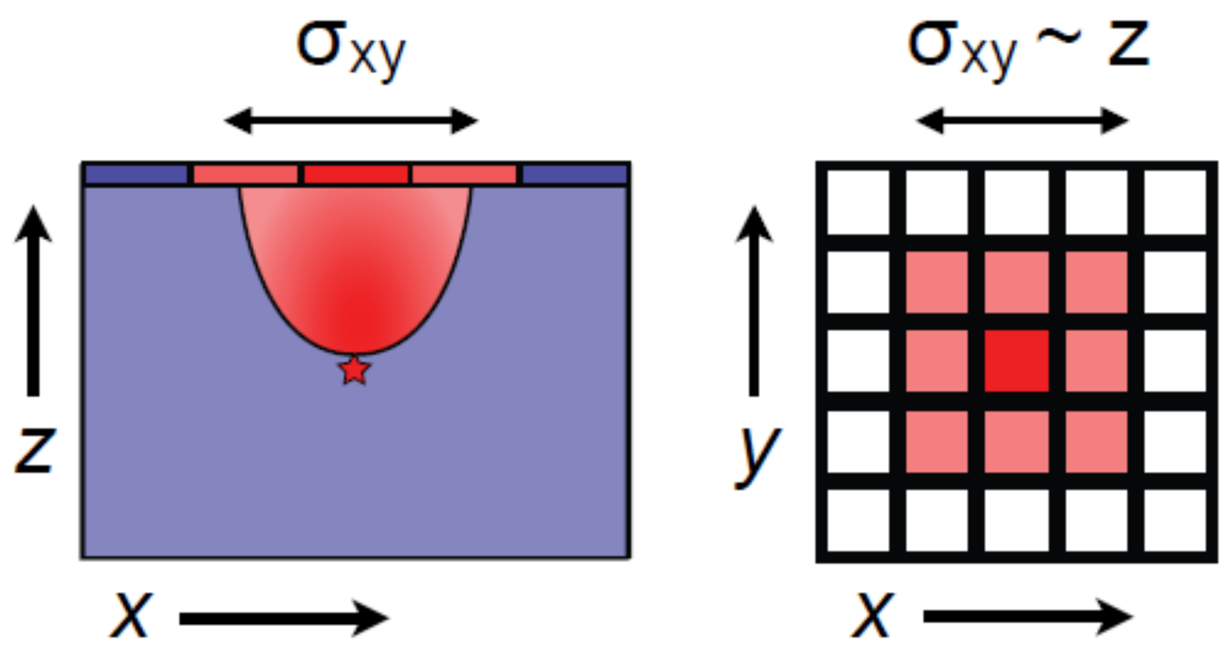


a) Packaged DAMIC CCD
b) Copper CCD housing
c) In-vacuum setup
d) Pb and polyethylene outer shielding

CHARGE-COUPLED DEVICES

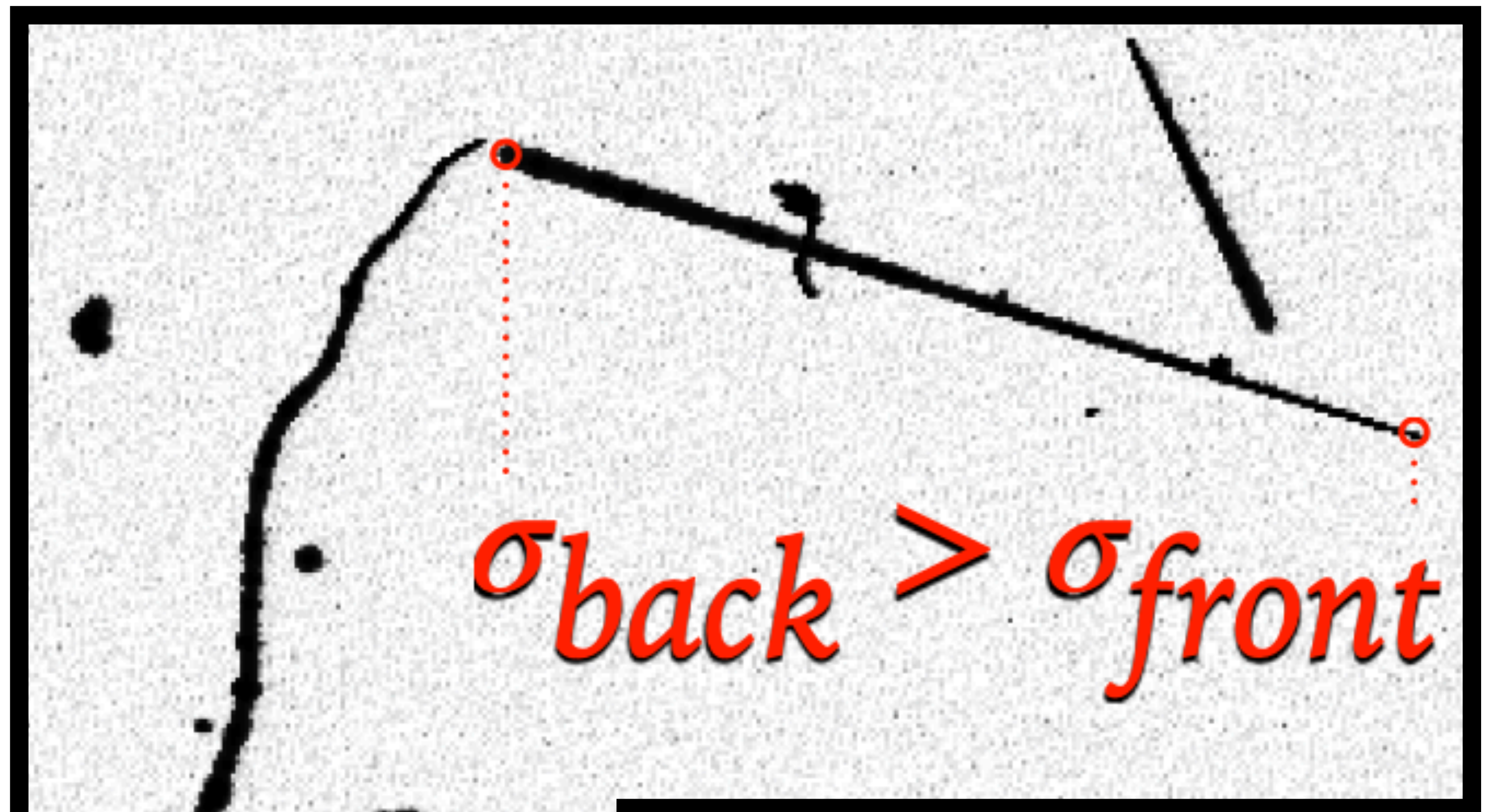






DAMIC science-grade CCDs

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



Portion of CCD image taken on surface

BACKGROUNDs IN DAMIC

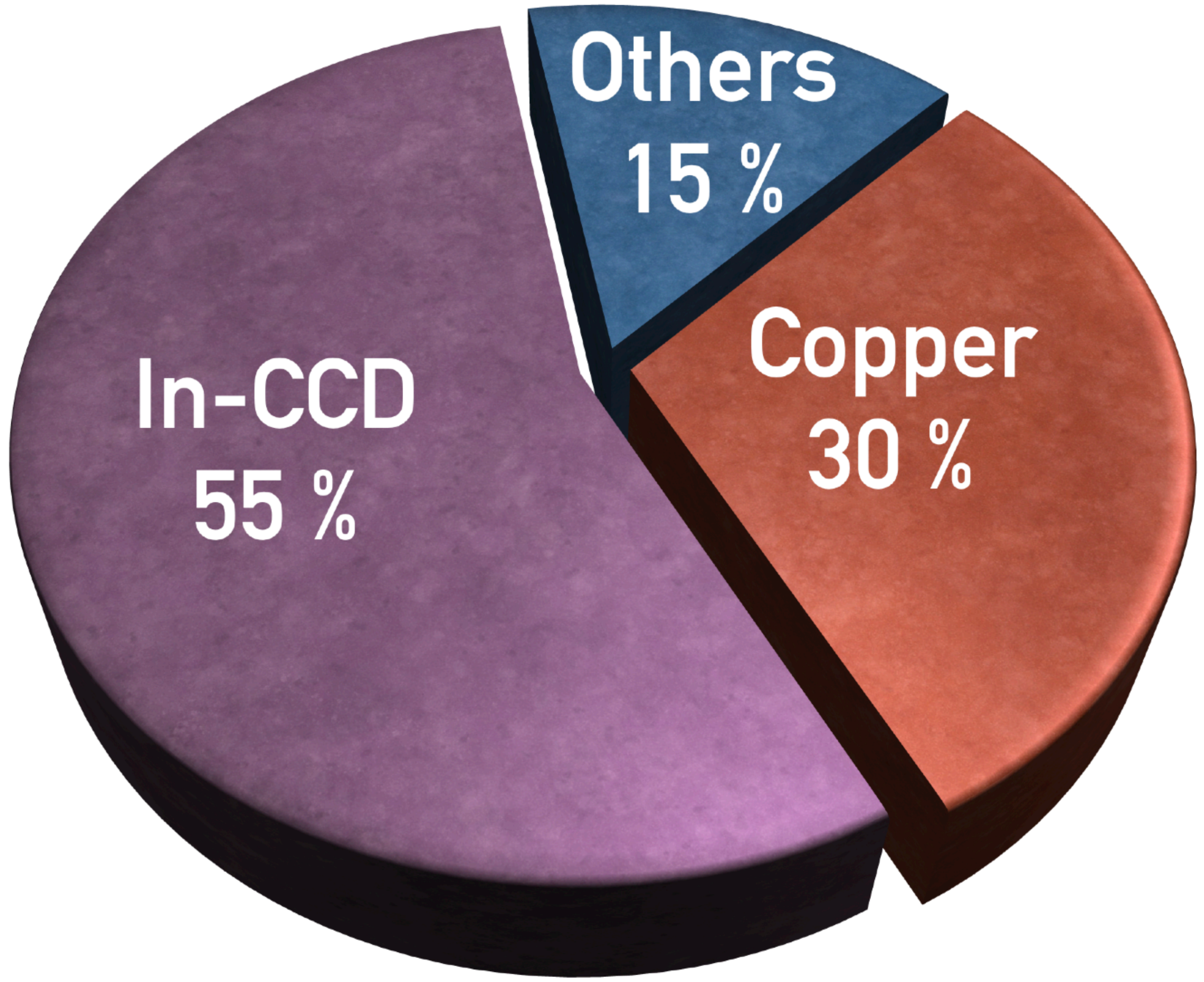
How we deal with backgrounds:

- 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:

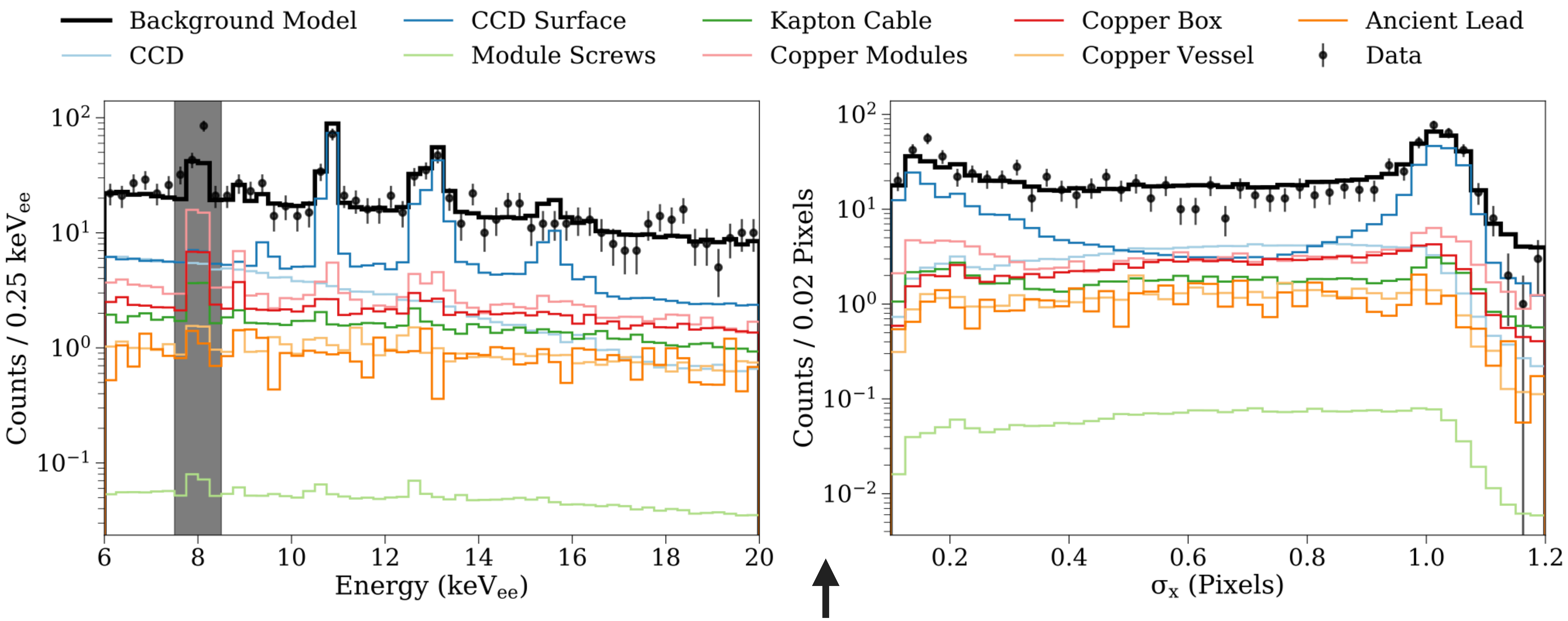
- $\sim 55\,\%$ in-CCD contaminants
  - Surface ^{210}Pb from Rn deposition
  - Bulk ^{3}H from cosmogenic activation
- $\sim 30\,\%$ OFHC copper
  - Bulk ^{210}Pb in copper
  - Cobalt isotopes from cosmogenic activation
- $\sim 15\,\%$ from various detector materials (lead, flex cables, etc.)

~ 12 **dru**

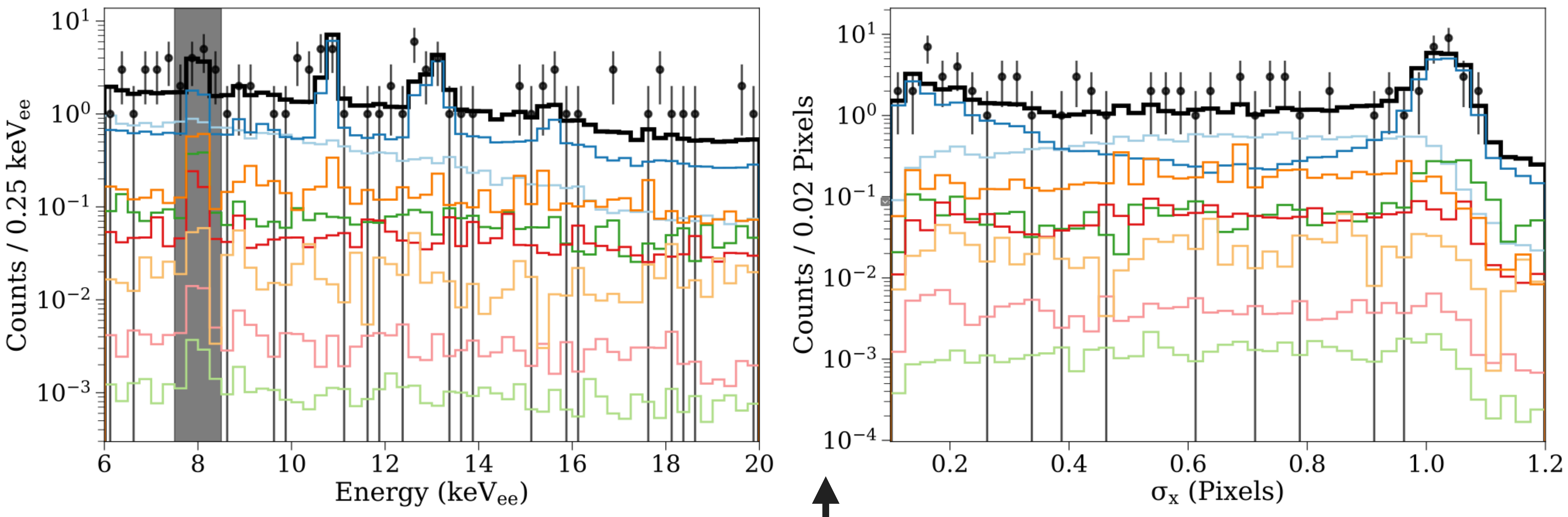


$1\ \mathbf{dru} = 1\ \mathbf{event} \cdot (\mathbf{keV} \cdot \mathbf{kg} \cdot \mathbf{d})^{-1}$

BACKGROUND TEMPLATE FITTING



Fit on CCD 2-7 data



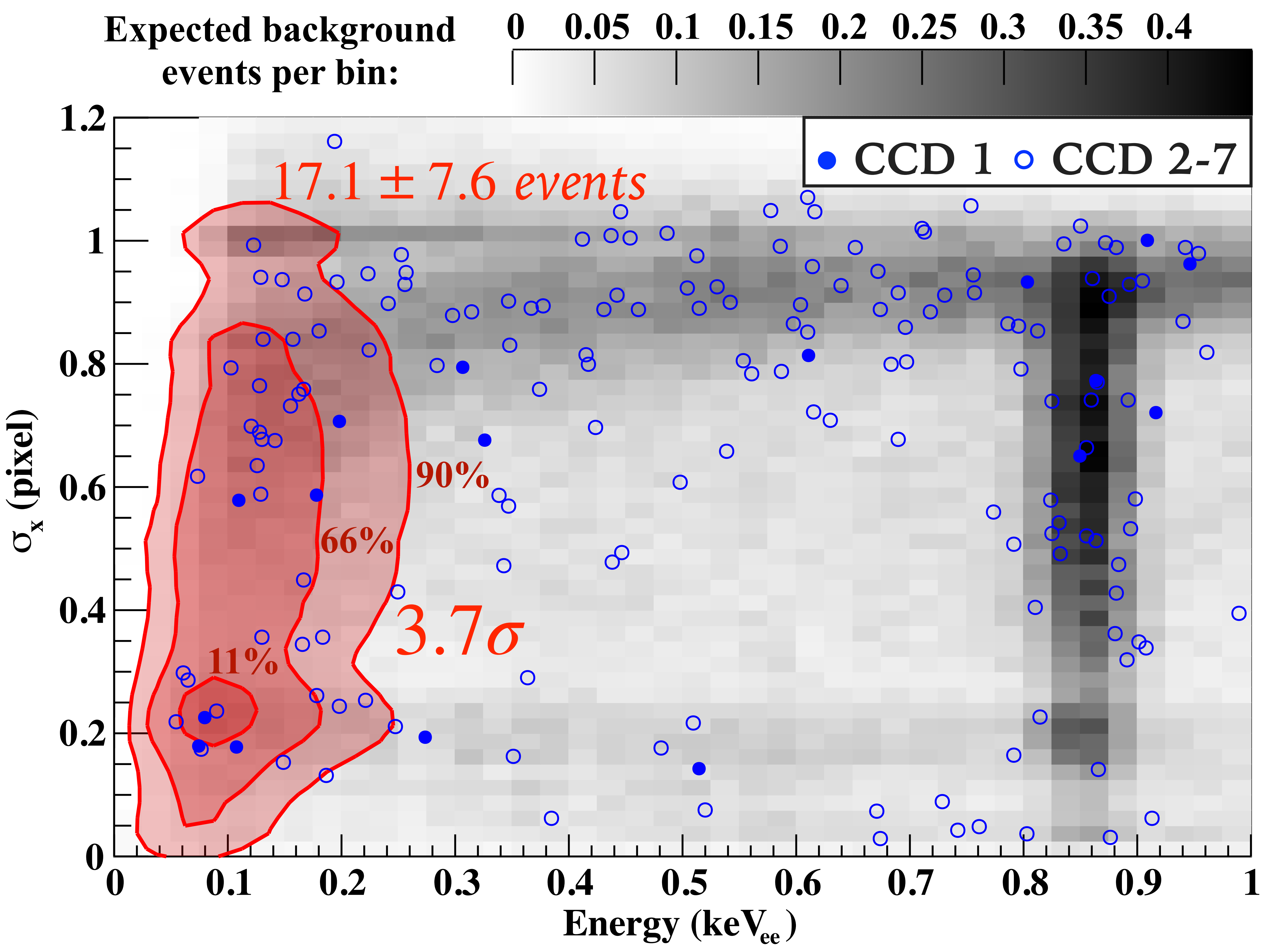
Validation with CCD 1 data

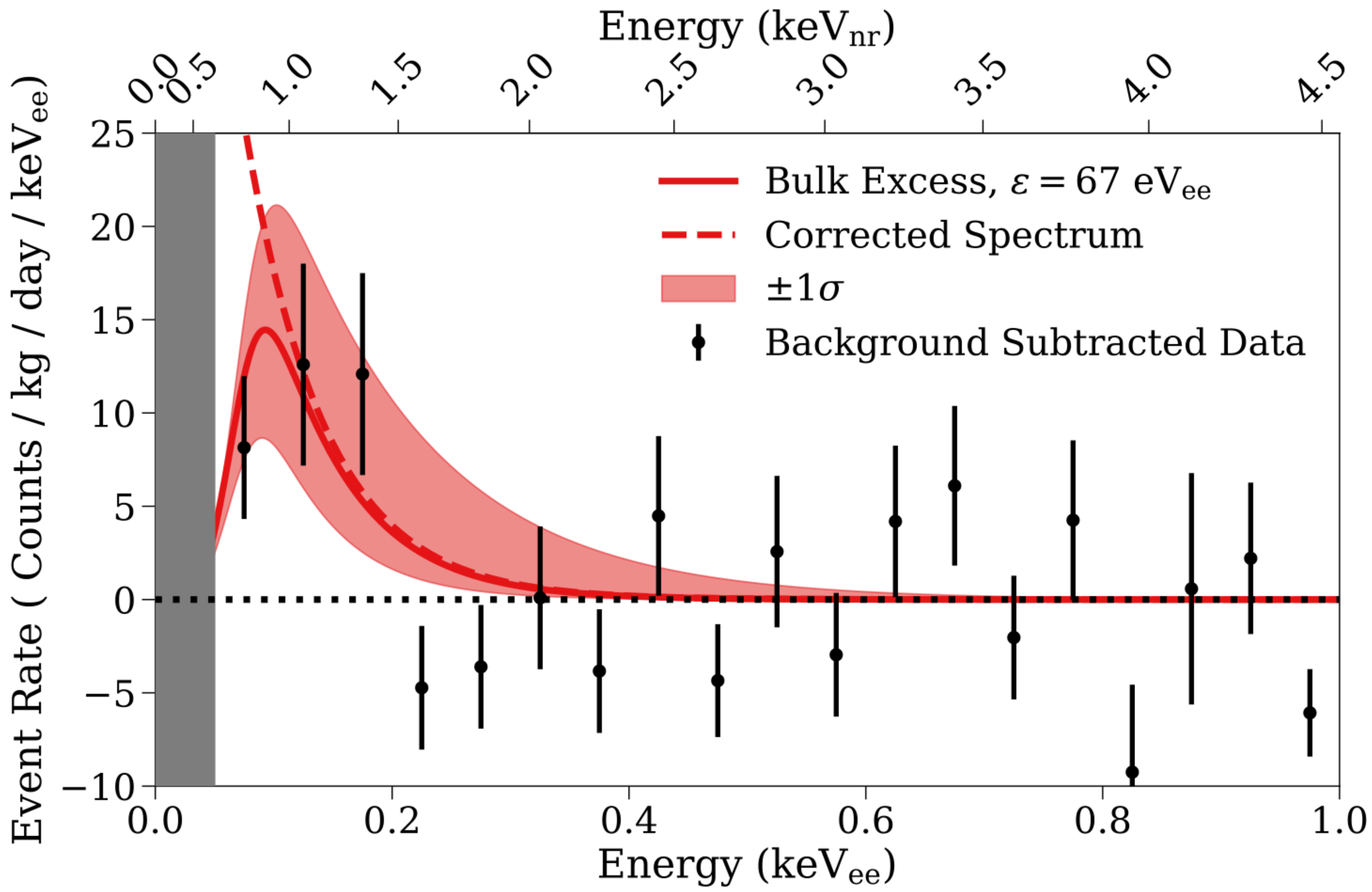
- Model constructed above 6 keV_{ee} in the (E, σ_{xy}) space

⟶ WIMP search below 6 keV_{ee} in the (E, σ_{xy}) space

Phys. Rev. D **105**, 062003 JINST **16** P06019

≤200 eV EXCESS





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

Systematic checks: no issue with analysis

Plausible interpretations:

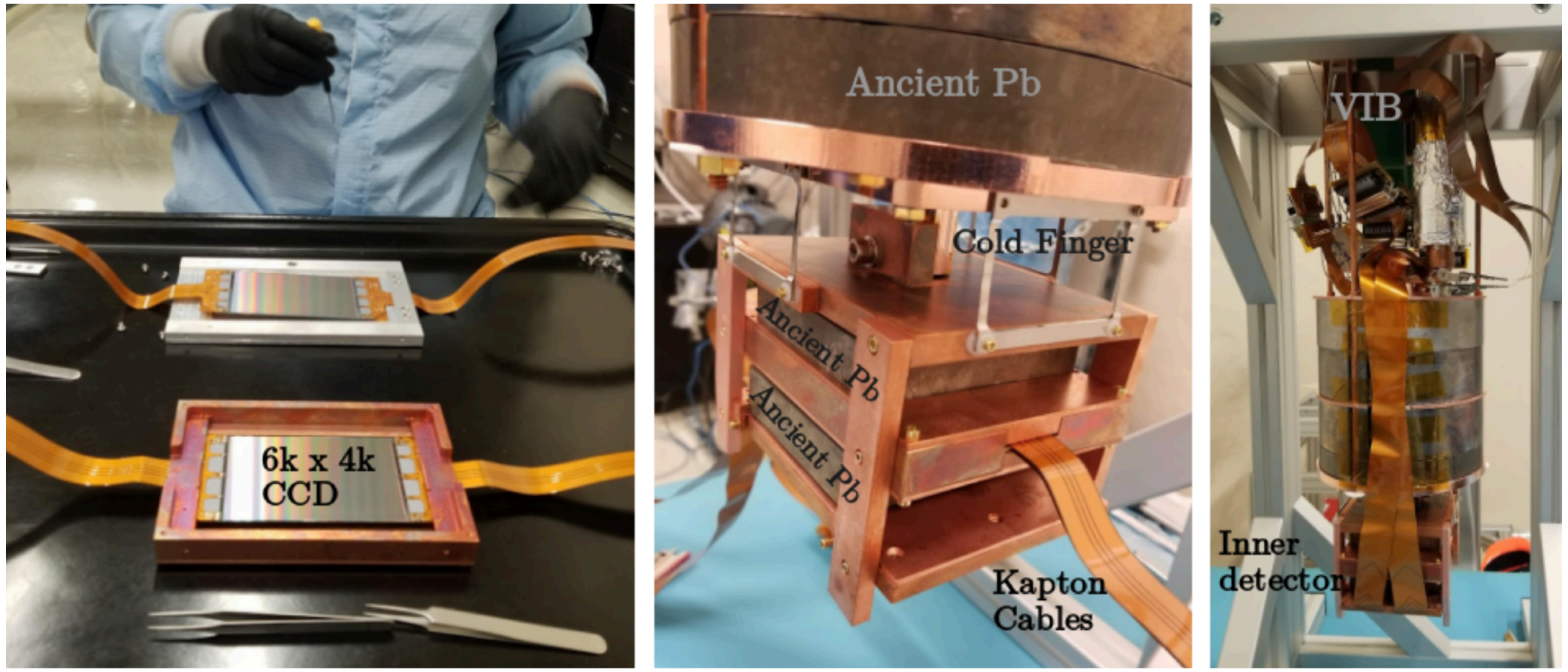
- Unaccounted detector effect
- Missing background component

SKIPPER UPGRADE AT SNOLAB

DAMIC, DAMIC-M and SENSEI collaborations

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

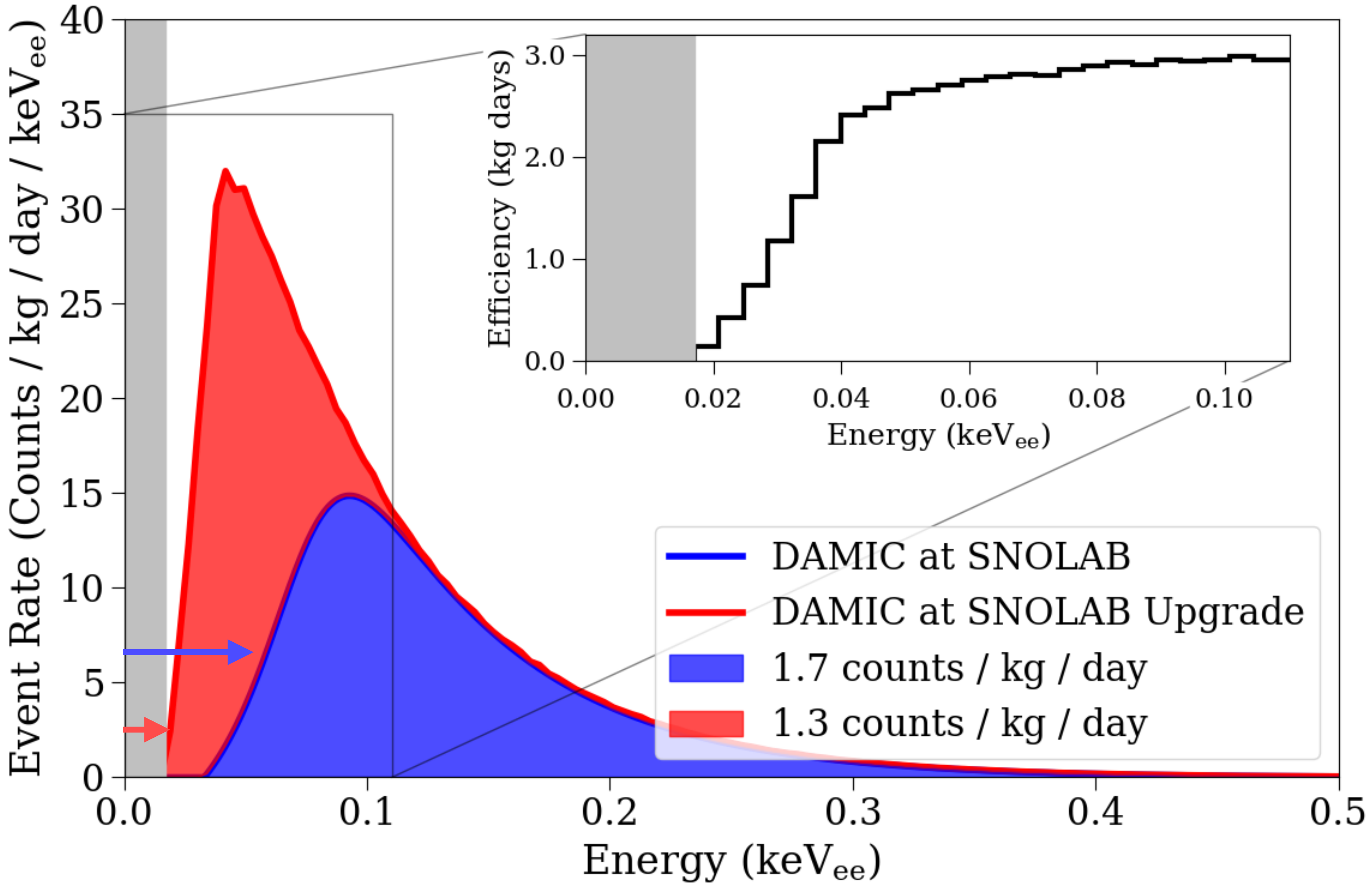
- Same bkg contributions, same rate: ~ 10 dru
- $10\times$ lower noise with skipper readout: $\sim 0.16\ e^-$
- Science run from March 2022 to Jan 2023
  - Different readout → different noise response
  - Improved $\sigma_{xy}(z)$ reconstruction for depth fiducialization
  - 4.8 kg-day total exposure. 3.1 kg-day after selections



Almost twice as sensitive to previously detected excess

Detected rate in DAMIC at SNOLAB

Expected rate increase in skipper upgrade

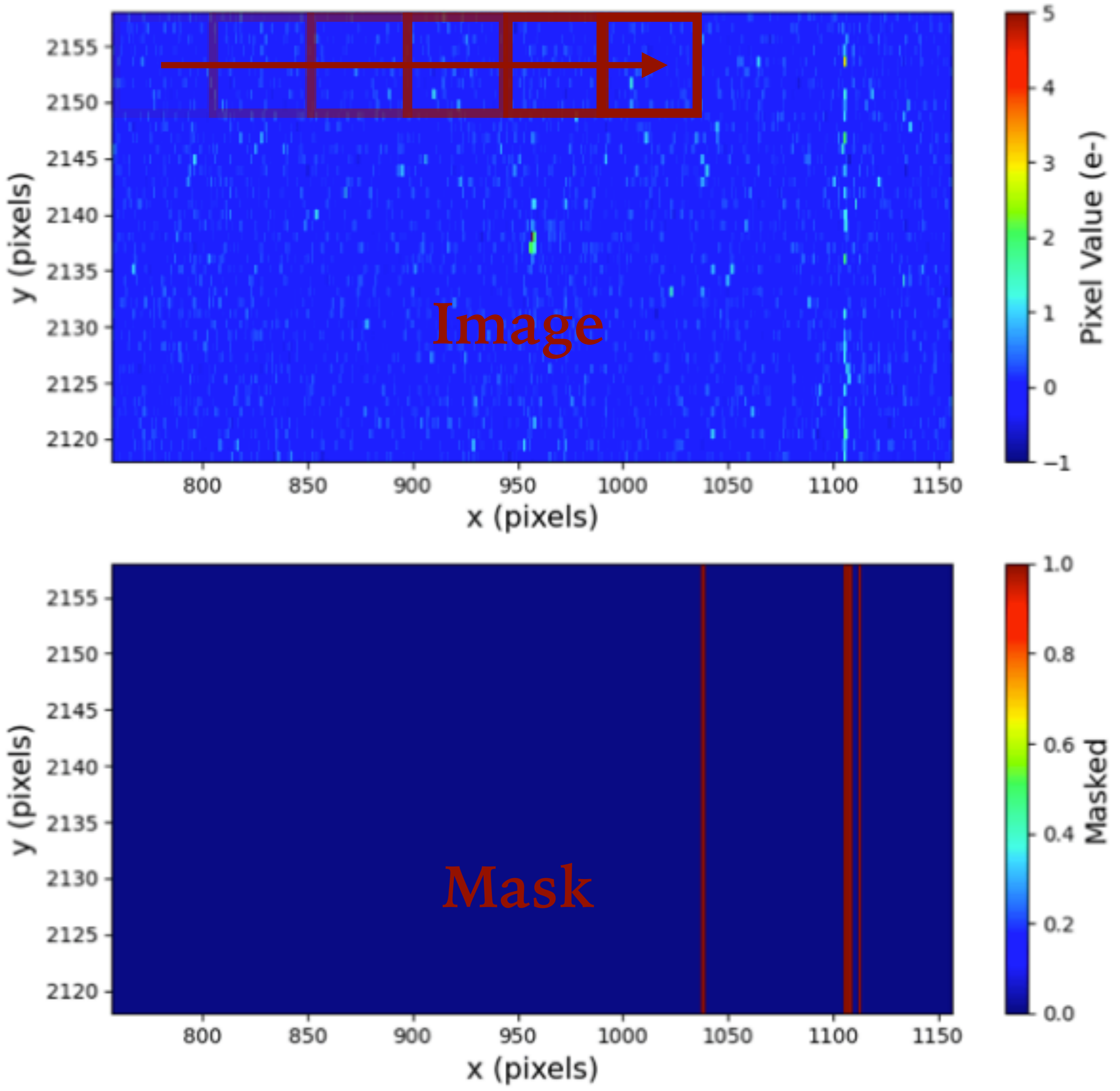


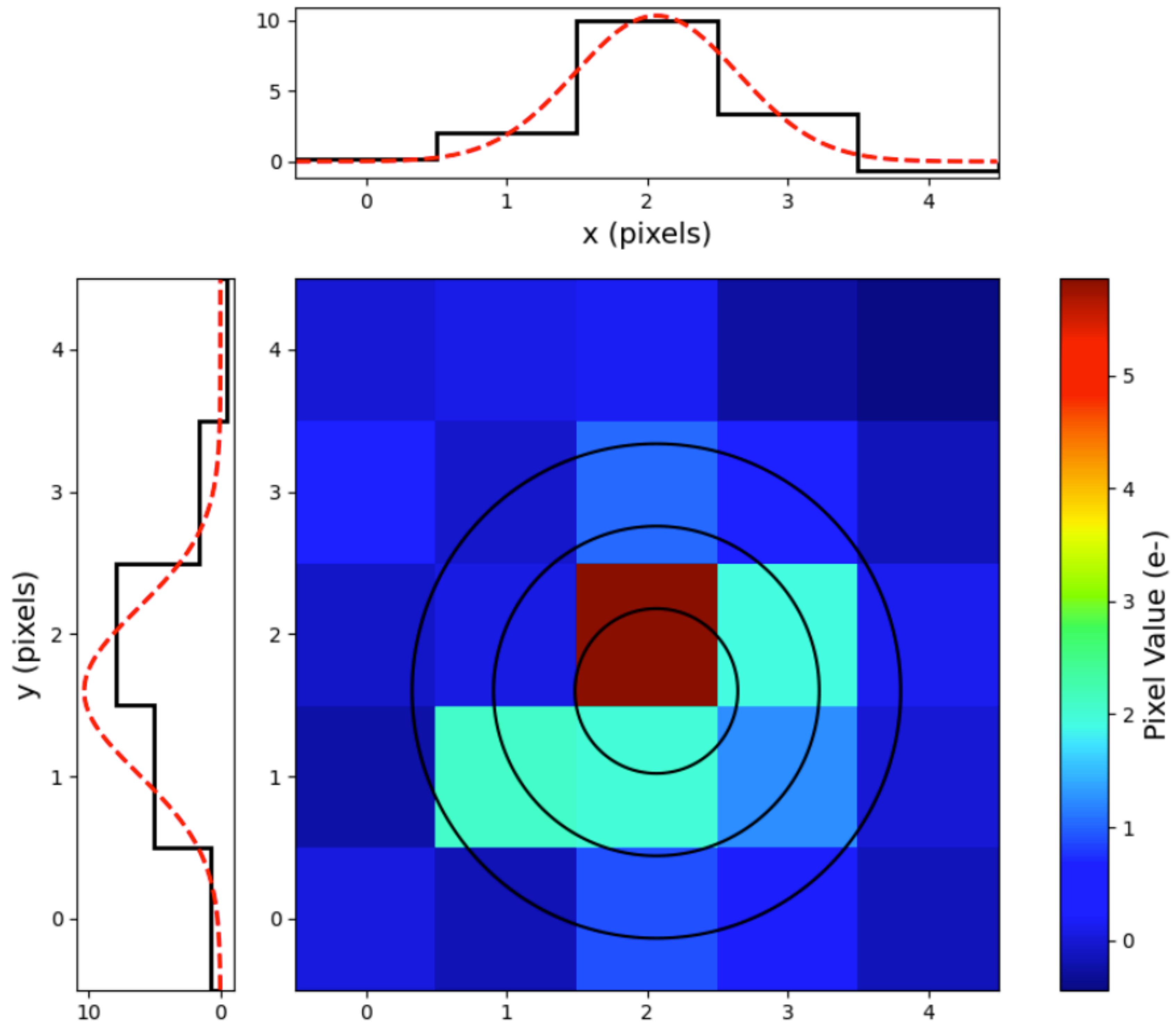
LOW-ENERGY CLUSTERS

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

$< 6\ keV$

Runid: 6, ImageID: 131, Amplifer: 2L, centerx: 957.00, centery: 2138.00, qfit: 14.95, ΔLL: -76.69, σ_{xy}: 0.58





We expect a 2D Gaussian spatial distribution for ionization events.

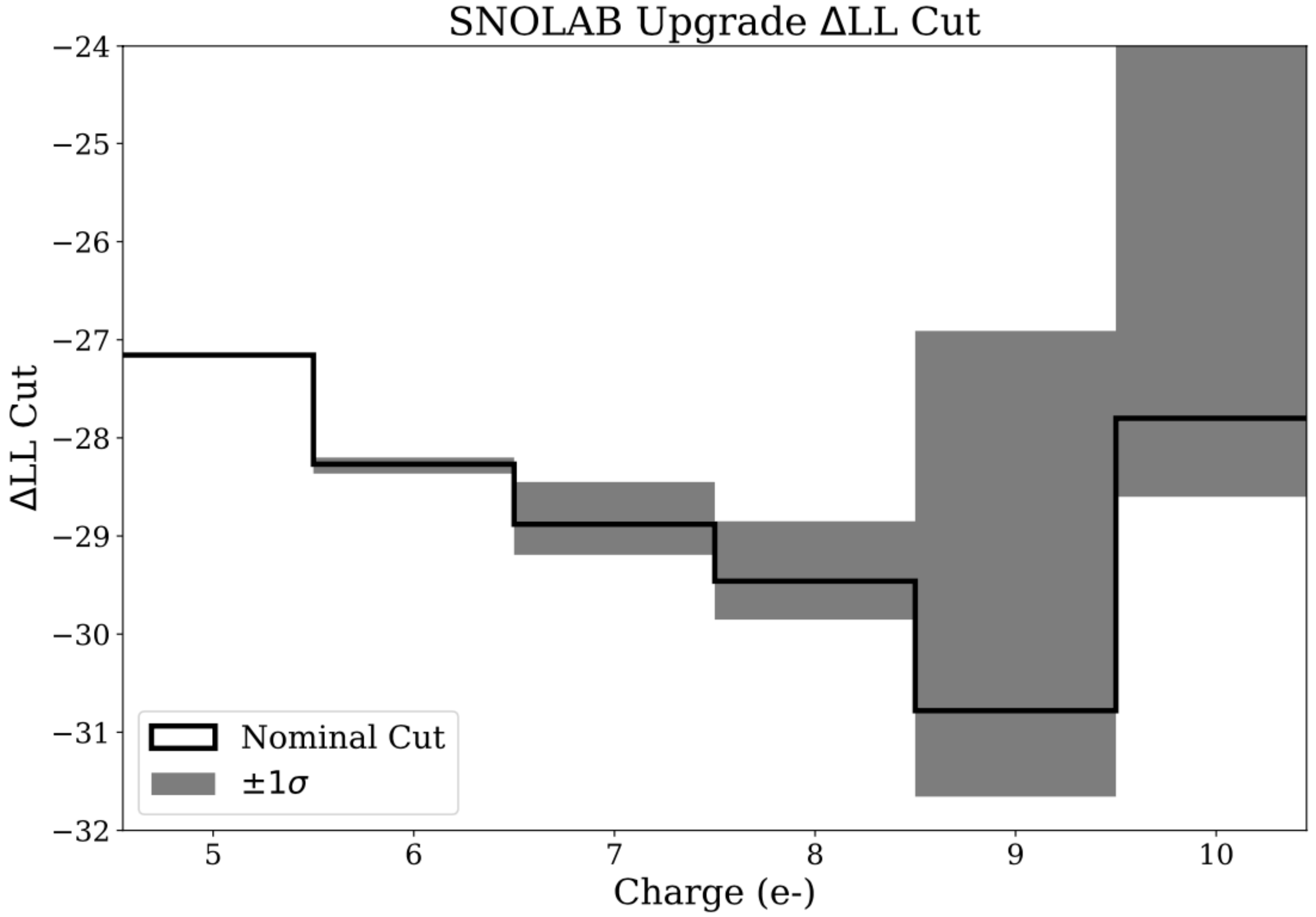
DATA SELECTIONS

ΔLL selection: efficiently reject noise accidentals down to 23 eV_{ee}

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

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

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

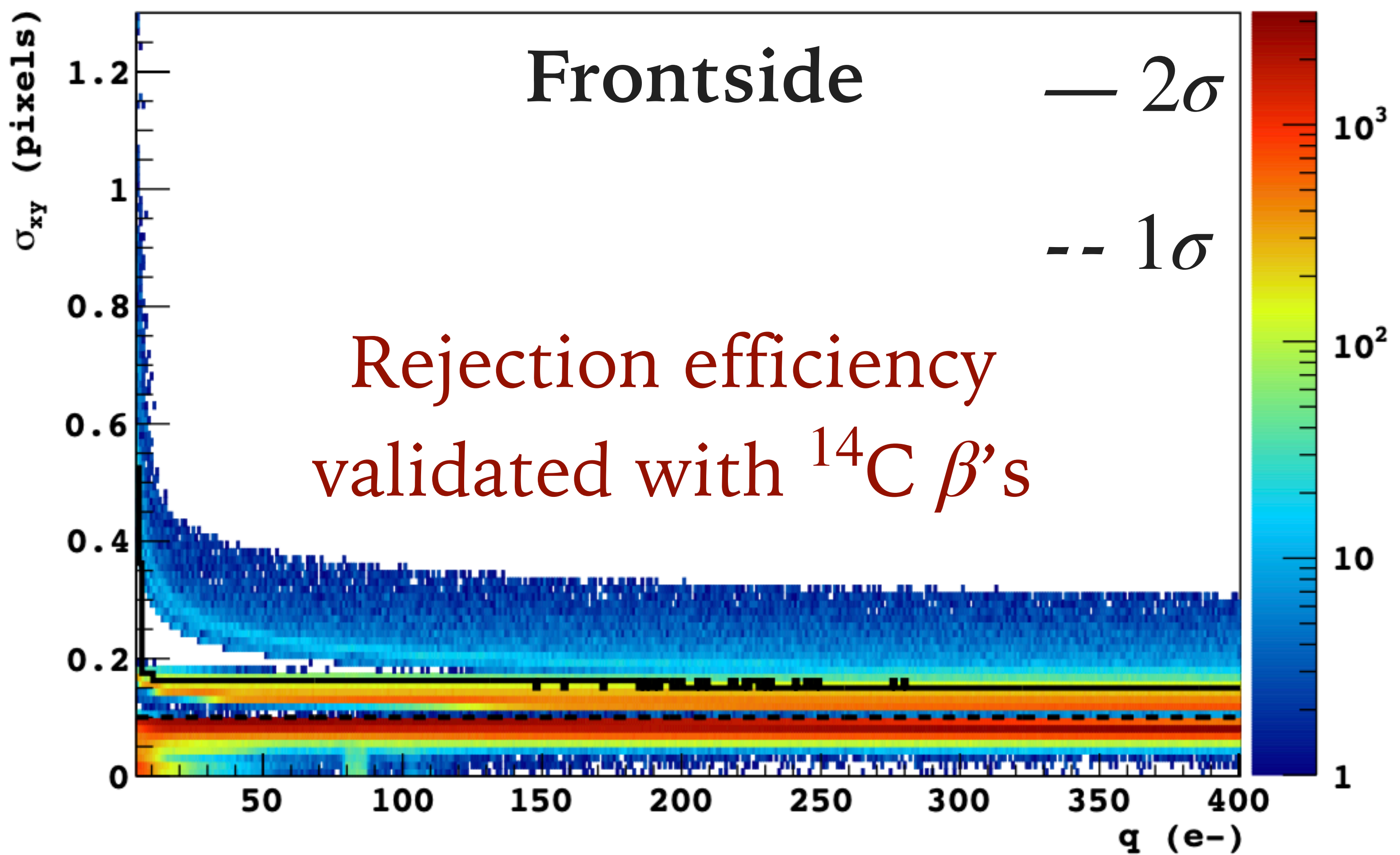


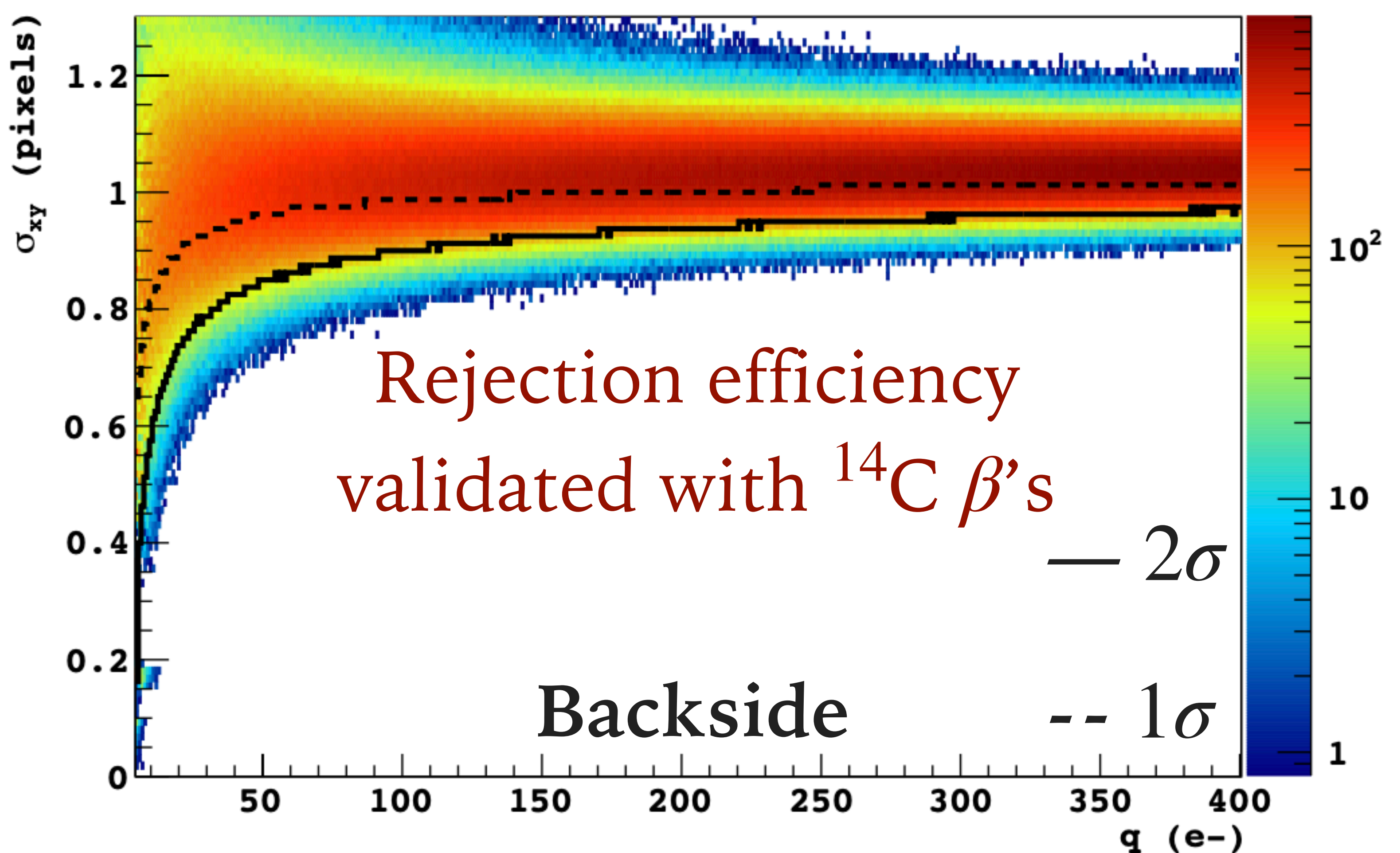
Bulk fiducialization: we also reject CCD surface events, the largest source of systematic uncertainty

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

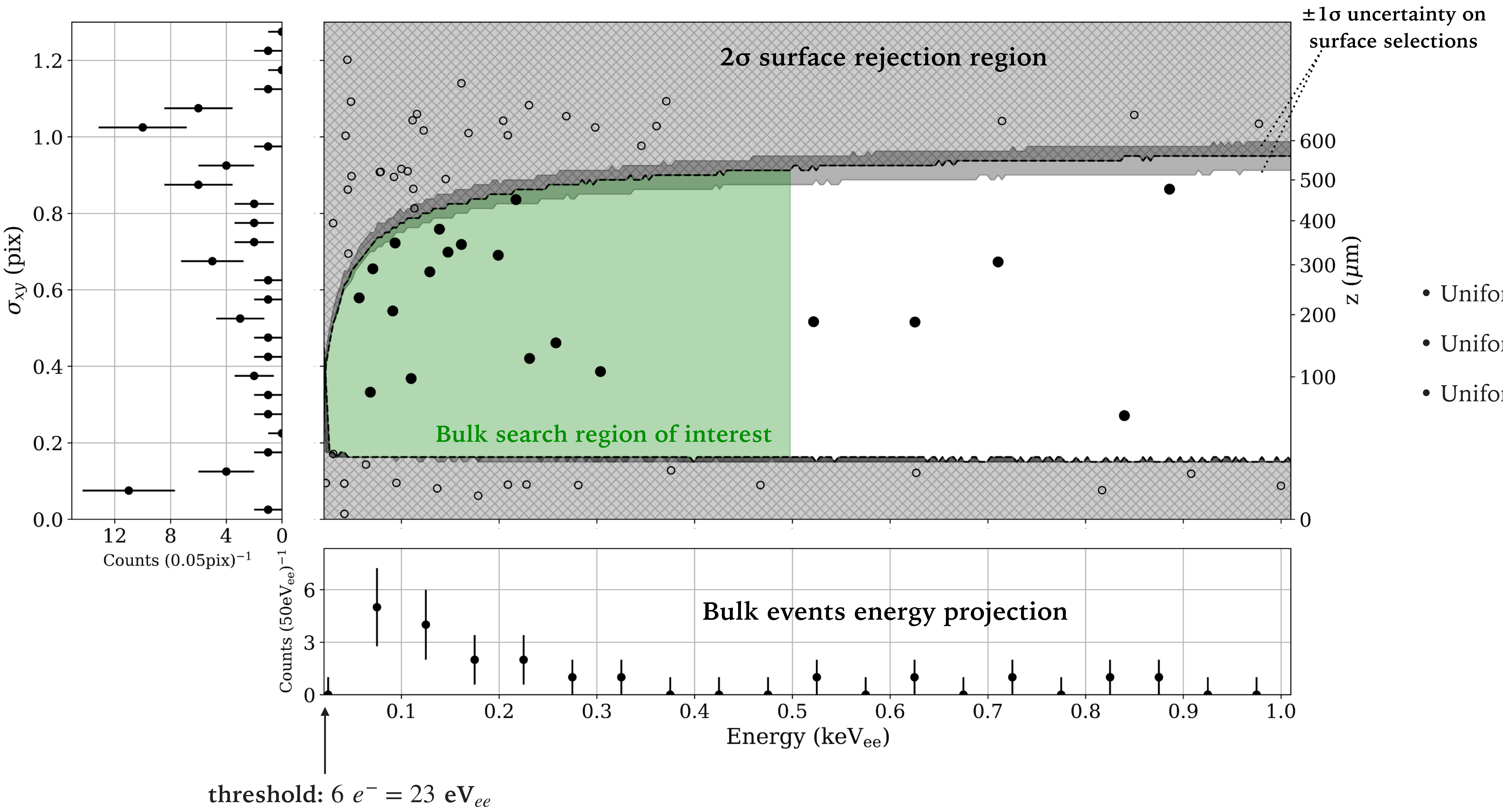
$$\sigma_{xy}(z, E) = \sqrt{-A \ln(1 - bz)(\alpha + \beta E)}$$

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





FIDUCIALIZED SCIENCE DATA



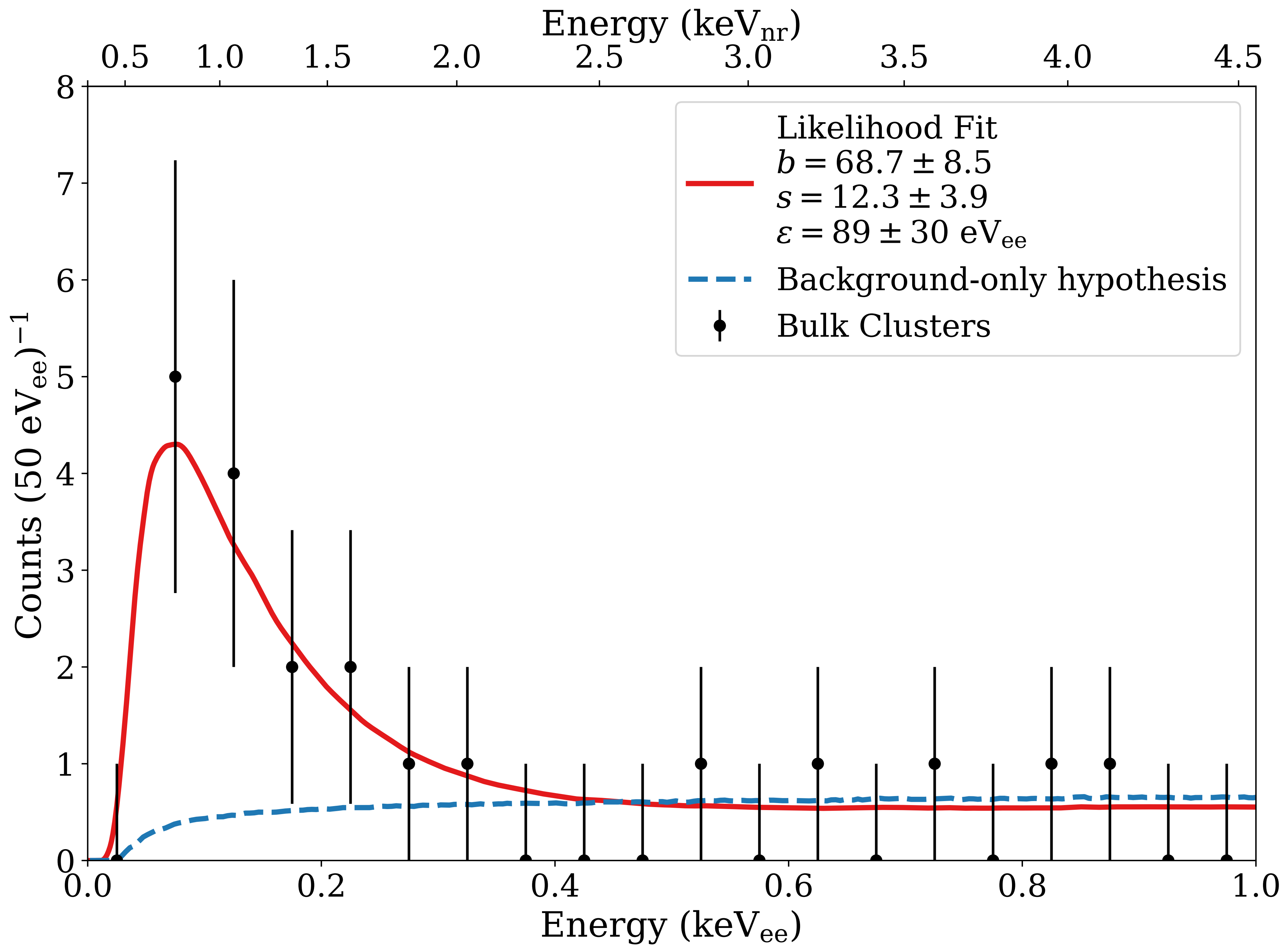
- Uniform spatial distribution
- Uniform amplifier distribution
- Uniform time distribution

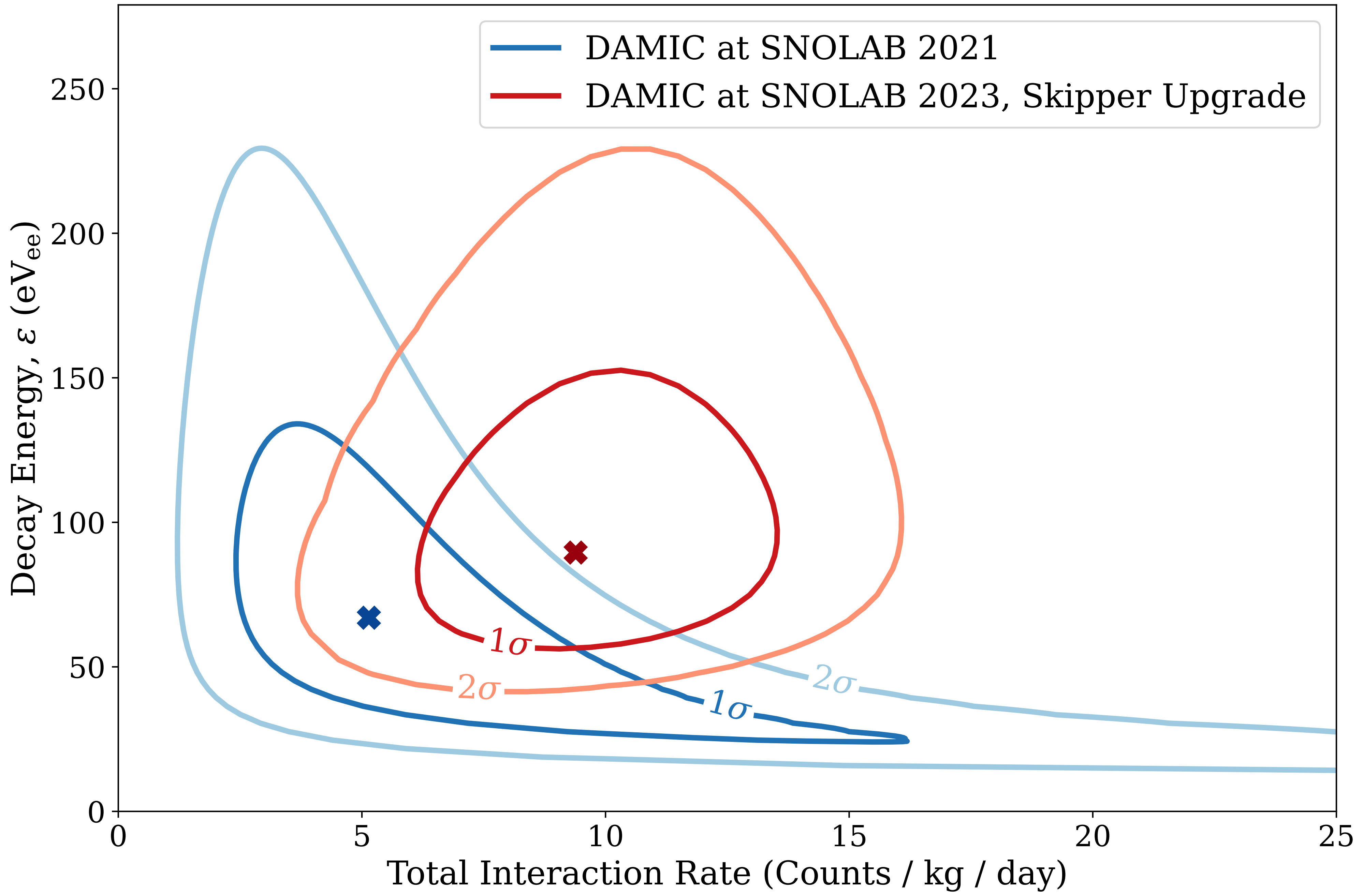
RESULTS

- 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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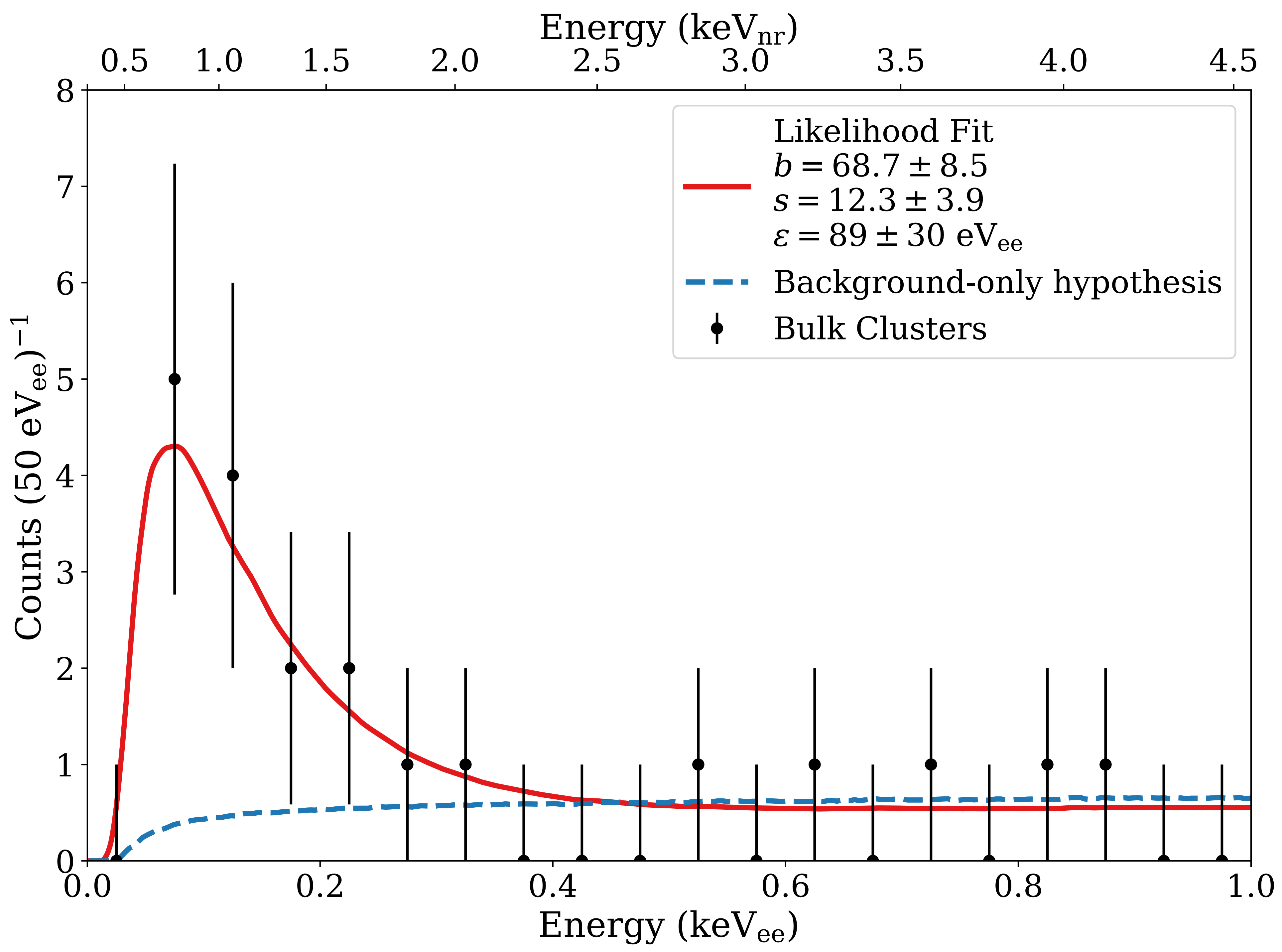
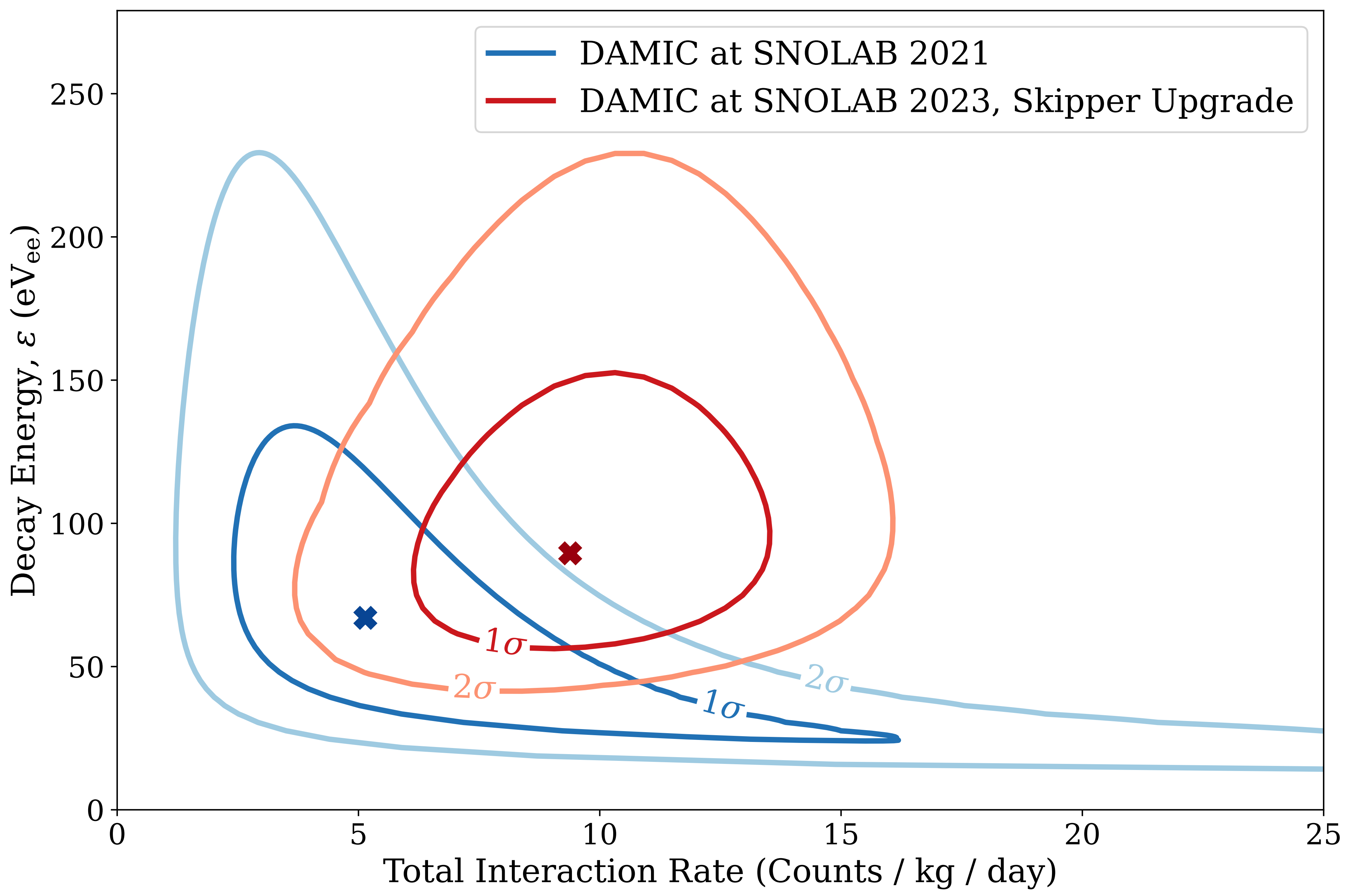
***Flat background**: conservative assumption. Low-energy drops expected in ROI from Compton and tritium β^- events. Data consistent with background model above 0.5 keV





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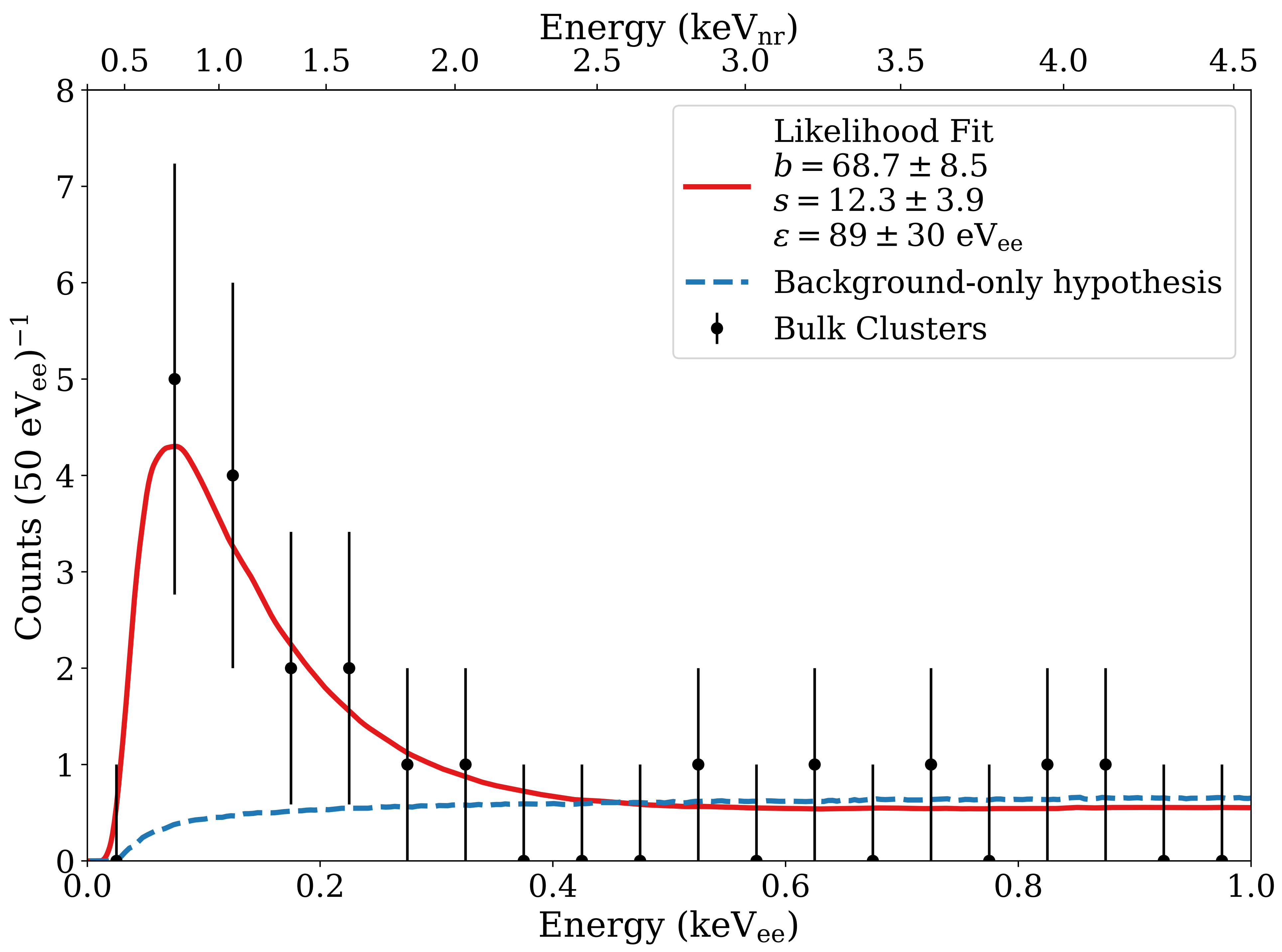
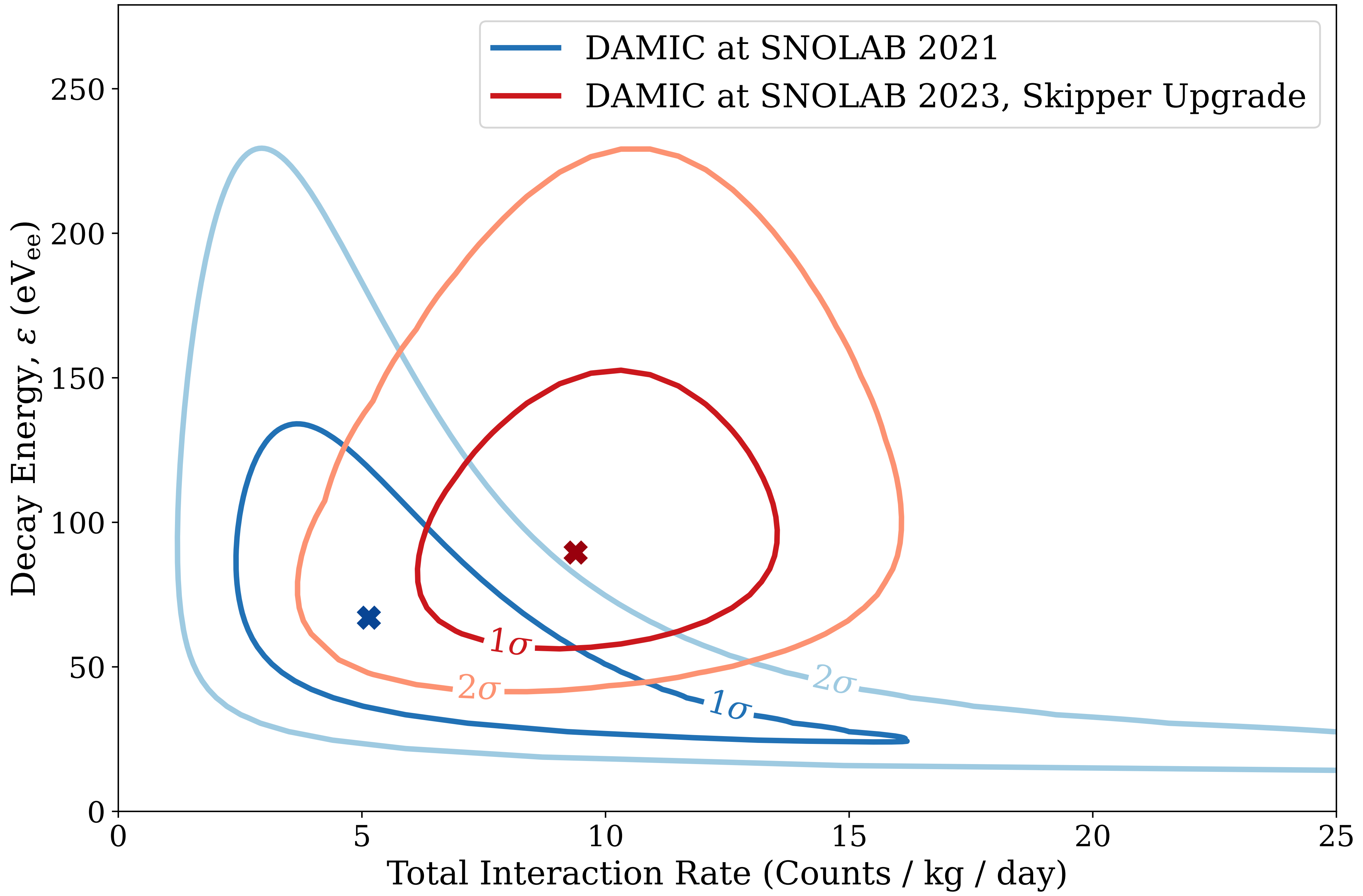
What is it?

- Probably a source of radiation. Neutrons? Required flux: 0.2 $cm^{-2}\,day^{-1}$ ~ total flux in SNOLAB cavern. We expect ~ 100 × lower.

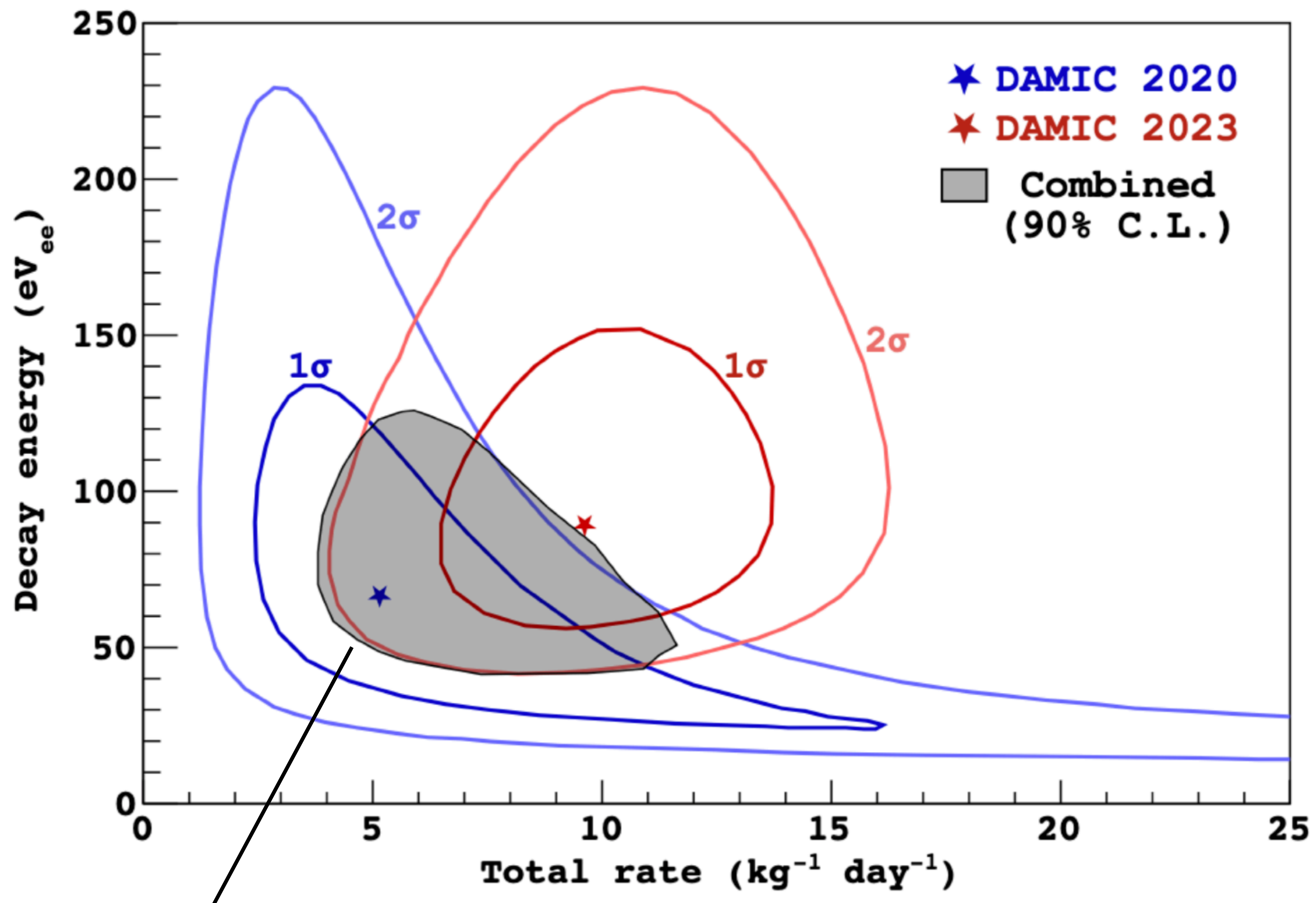




EXCESS CONTOURS

arXiv:2308.12176

Linear interpolation of excess contours

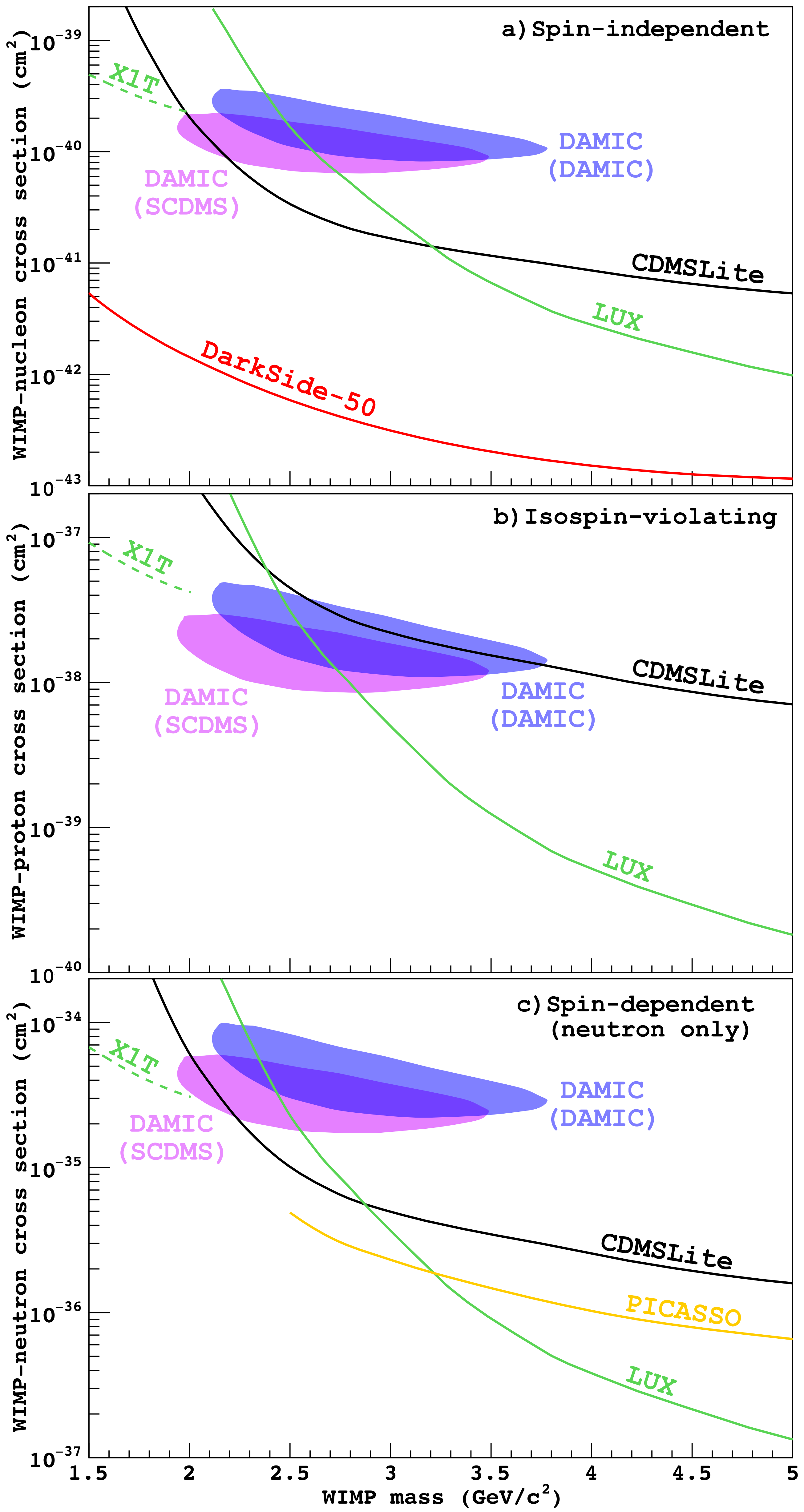


Points of combined p-value $= 0.1$

Each point (R, ε) uniquely identifies a point in the $(m_\chi, \sigma_{\chi N})$ space

Take-home message:

- Comparison between different materials should be taken with a grain of salt. Investigations with silicon detectors are now most important to understand the DAMIC excess



- NRIE largest systematic: compare DAMIC and SCDMS measurements
  arXiv:2303.02196

$$\sigma_{\chi N} \sim [f_p Z + f_n (A - Z)]^2$$

- In general, no reason to assume $f_n = f_p$
  - ➡ Isospin-violating dark matter
  - Destructive interference can suppress cross section

- ^{40}Ar has nuclear spin $J = 0$.
- ^{28}Si (92% n.a.) has $J = 0$ too, ^{29}Si (5% n.a.) has $J = 1/2$

➡ Spin-dependent dark matter interaction is possible (neutron-only)

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 deploy a kg-scale skipper CCD detector in 2024
  - **Low-energy excess <u>confirmed</u> with DAMIC-M skippers at SNOLAB** arXiv:2306.01717
    - Sub-electron noise
    - Different readout strategy
    - Rejected most prominent source of systematic: surface events
    - Unchanged background environment
  - **Will investigate excess in DAMIC-M (different) ultra-low background environment, much higher statistics and NR/ER discrimination** See TAUP talks from R.Smida and P.Privitera on Aug 28th and 31st
    - If confirmed, excess will have significant implications on the next generation of CCD dark matter experiments

Thanks!

DAMIC-M

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Center for Experimental
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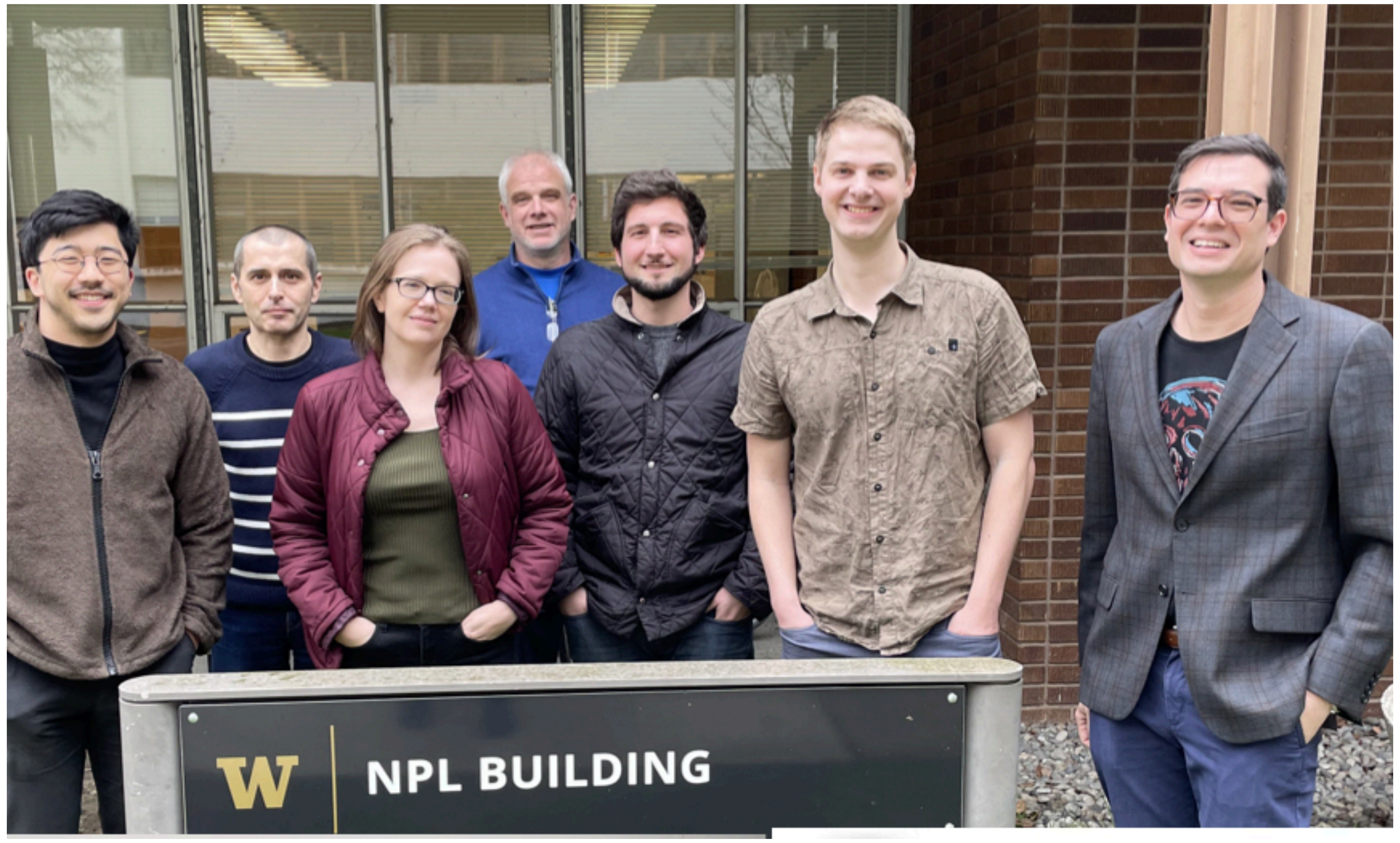
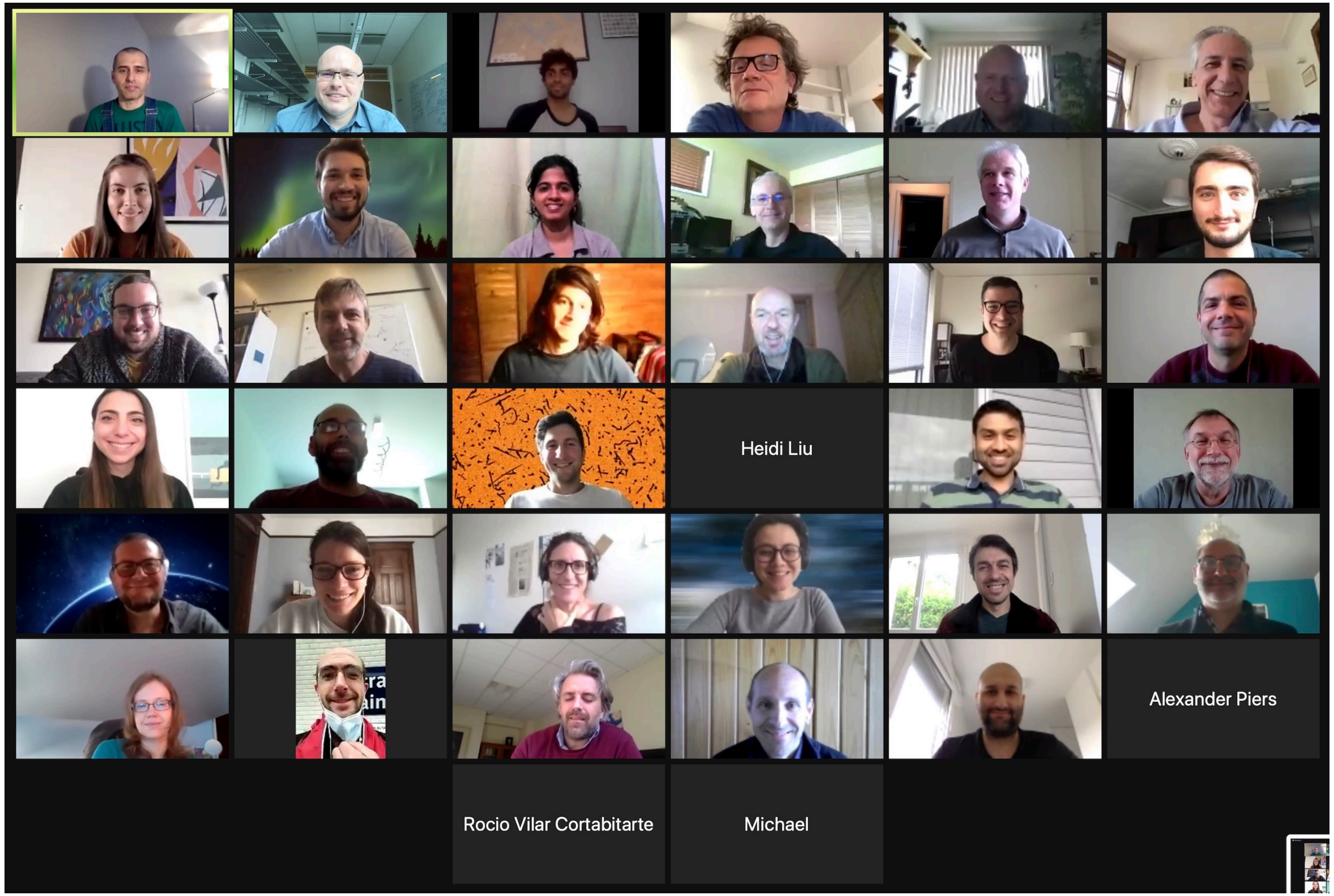




The DAMIC-M Collaboration

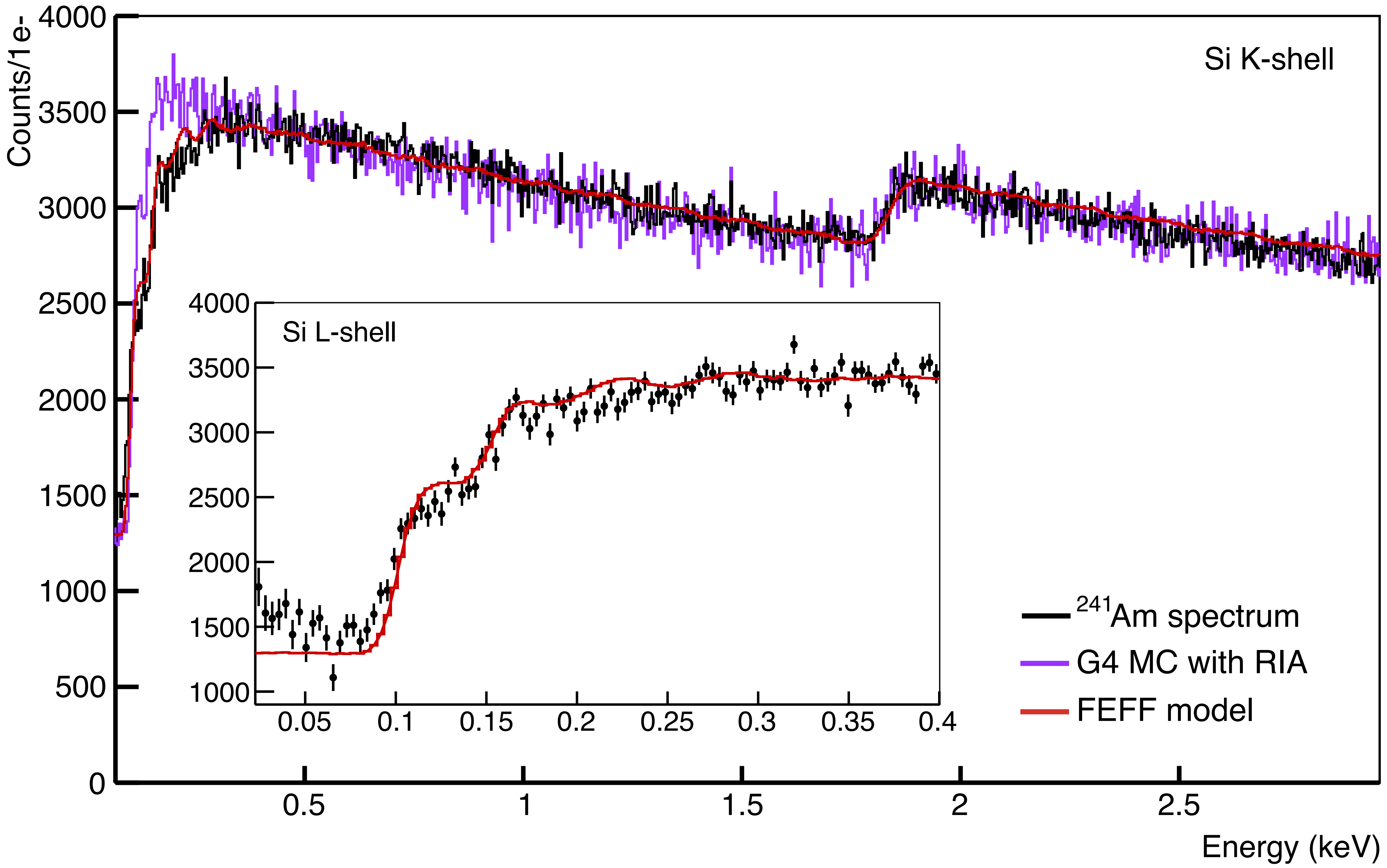
European Research Council
Established by the European Commission

https://damic.uchicago.edu/

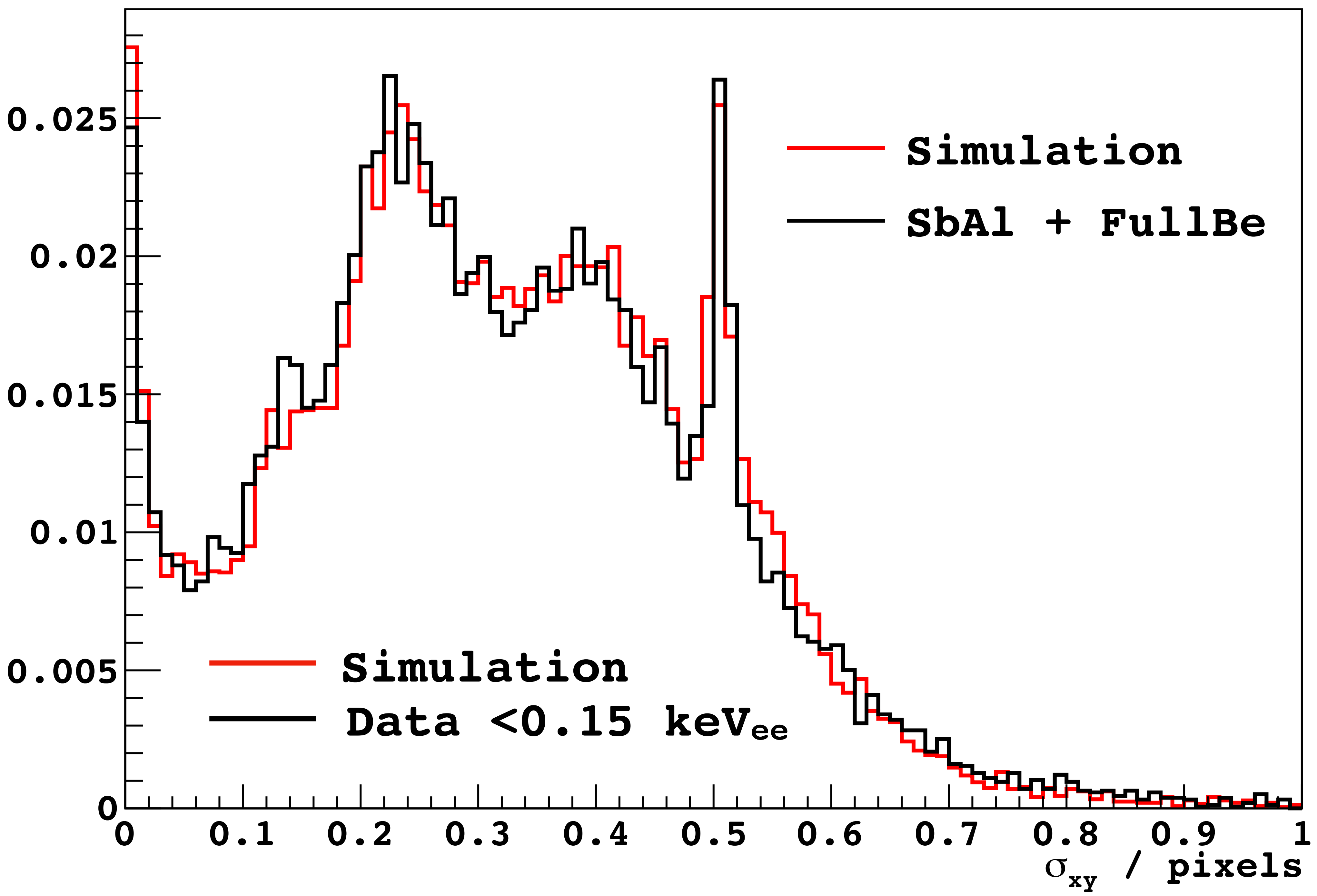
ENERGY AND DEPTH RESPONSE

Energy response validated with Compton scatterings from ^{241}Am down to 23 eV$_{ee}$

Depth response validated with low-energy neutrons from SbBe



PRD106(2022)092001

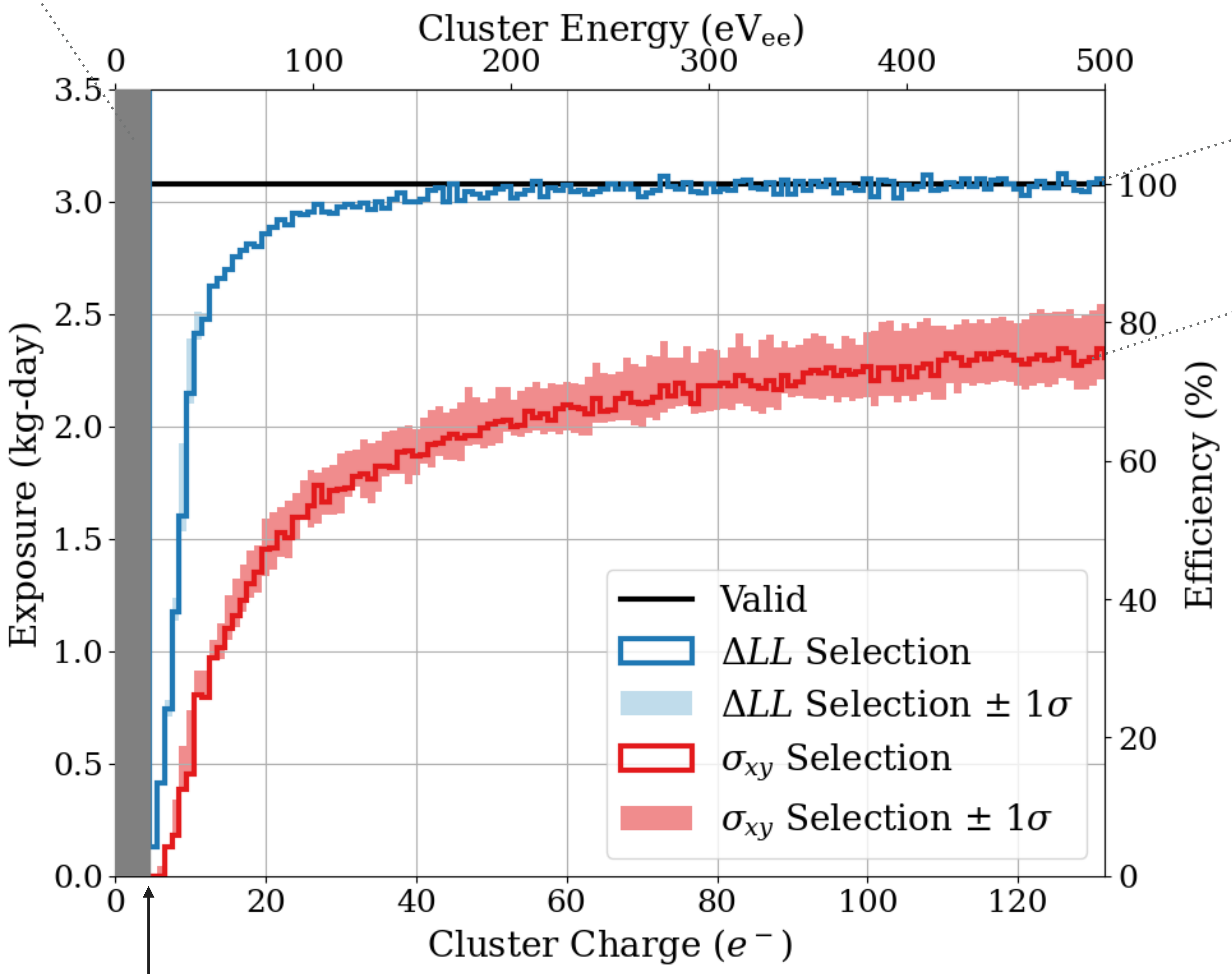


J. Phys.: Conf. Ser. **1468** 012024

DATA SELECTIONS

Valid clusters: from 4.8 to 3.1 kg-day

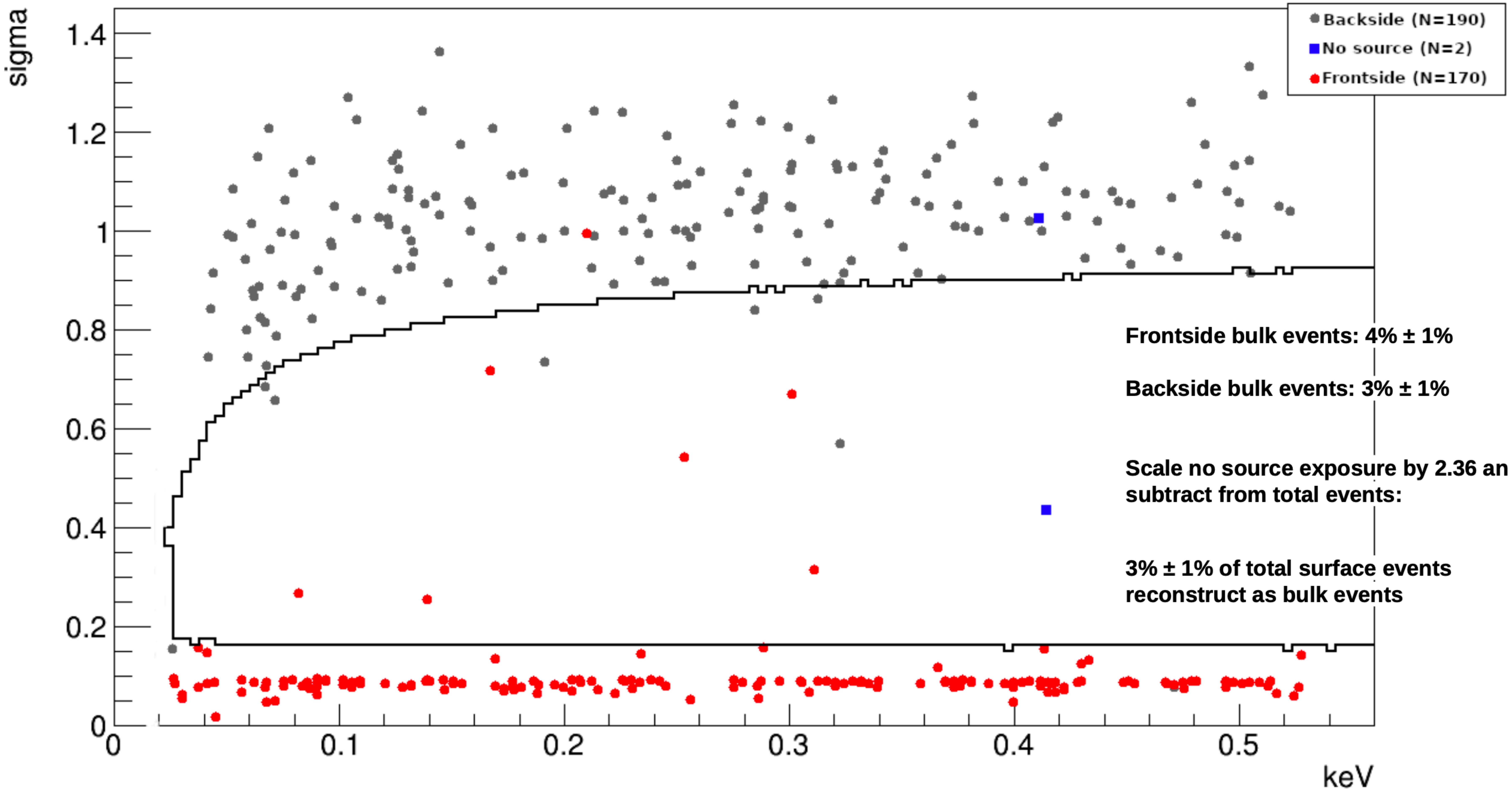
- discard bad images
- mask high-energy clusters
- mask defects, hot regions and instrumental artifacts



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

DIFFUSION SYSTEMATICS

Validation of surface rejection with ^{14}C pure β source (Q_β = 156.476 keV)



Frontside bulk events: 4% ± 1%

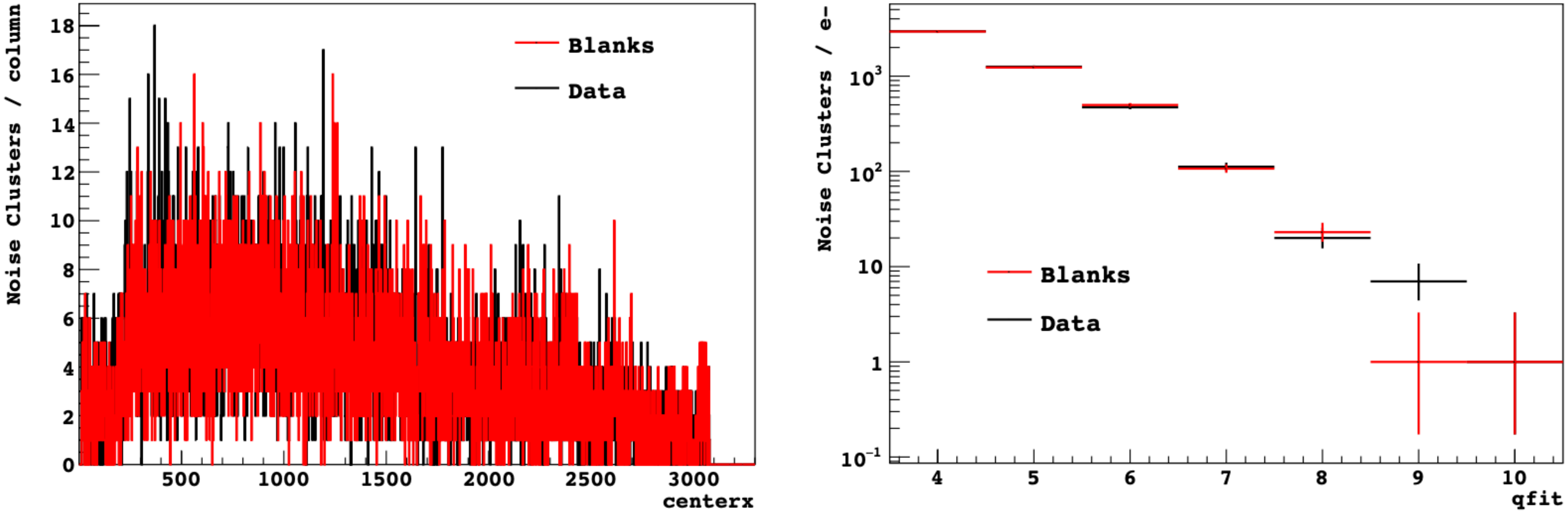
Backside bulk events: 3% ± 1%

Scale no source exposure by 2.36 an subtract from total events:

3% ± 1% of total surface events reconstruct as bulk events

ALL CUT SYSTEMATICS

Validation of likelihood clustering selections: comparing data and noise simulations

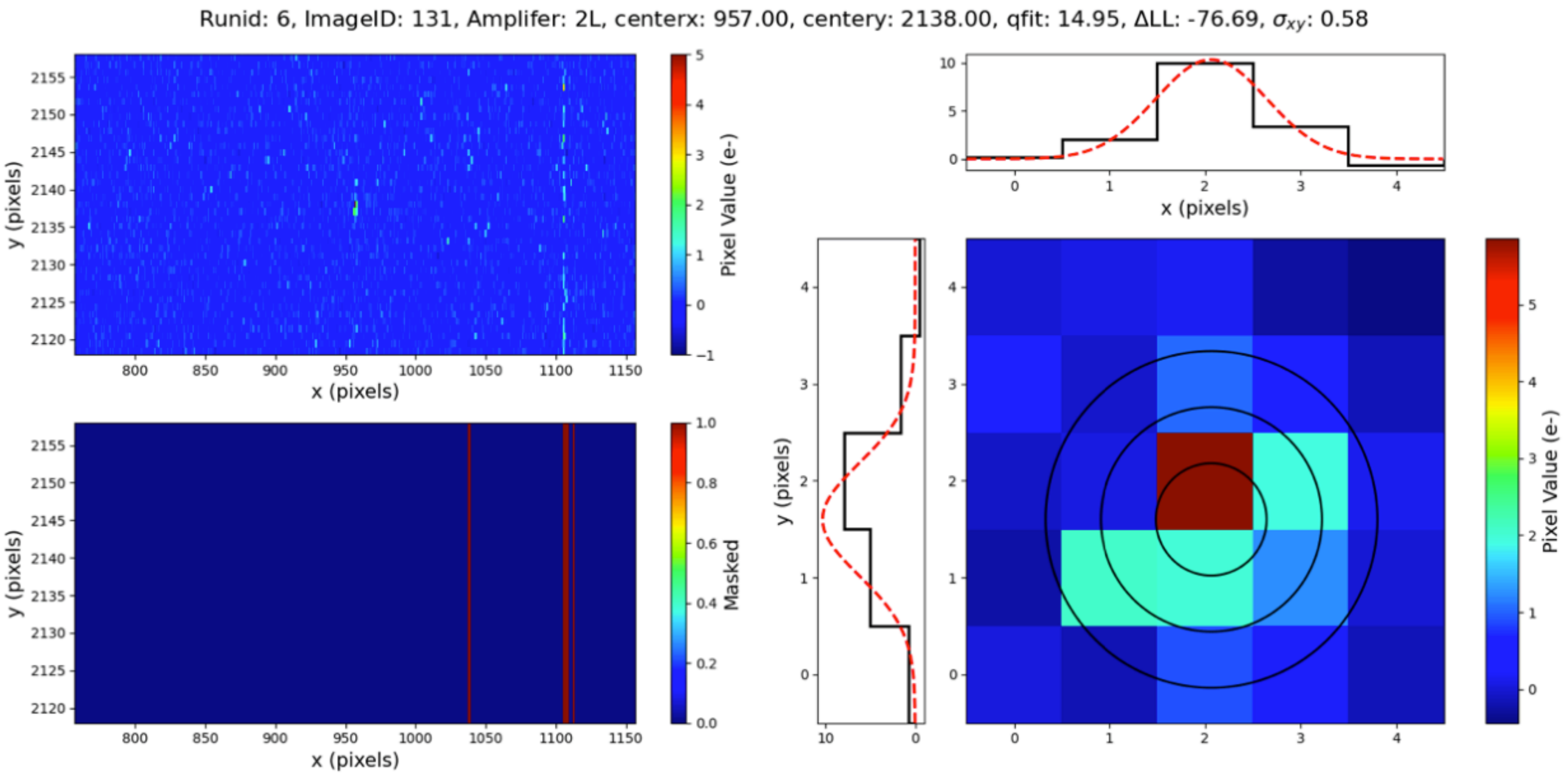


(a) Cluster **centerx** comparison.

(b) Cluster charge comparison.

LOW-E CLUSTERS

Visual inspection event by event for quality assessment



ΔLL CUT INGREDIENTS

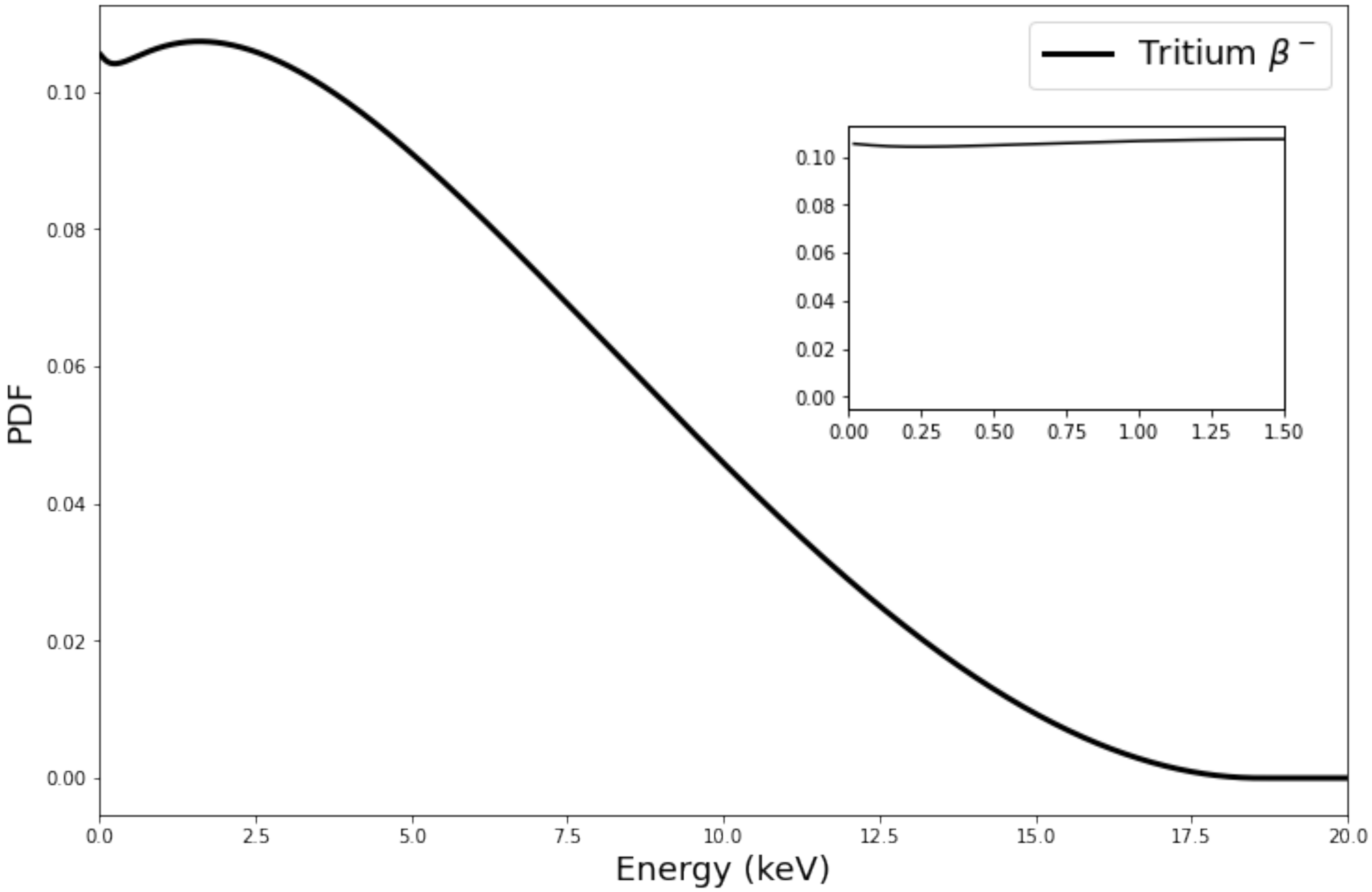
Figure 3.12: Components needed to compute the ΔLL cut values. (a) The accidental rate, $R_a(q, \lambda)$, of clusters (in counts / kg / day) as a function of the local λ value from the blank images. We simulated $\sim$ 30 kg days of images. (b) The CDF, $\alpha(\Delta LL, \lambda|q)$, of the ΔLL distribution for $q = 7$. (c) The distribution of λ values across all images. We convert the exposure to a probability distribution $P(\lambda)$. (d) Finally the ΔLL cut as a function of charge to allow < 0.01 accidental event / kg / day. The uncertainty in the shaded band comes from the uncertainty of the bin content in (a).

MAIN BACKGROUNDS

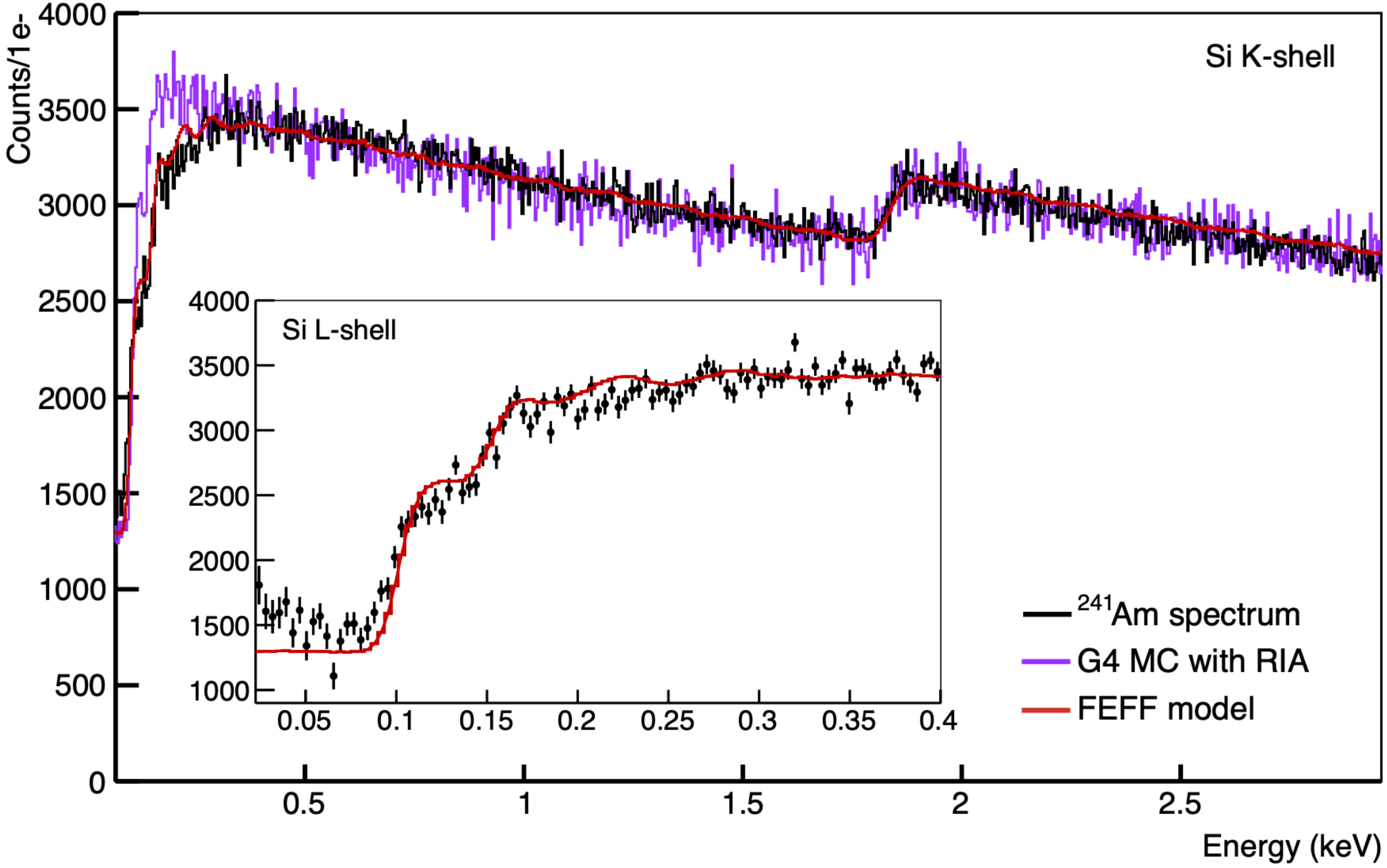
	Detector part	Chain	C_l	Best-fit activity	Rate (dru): CCDs 2–7		Rate (dru): CCD 1	
					1–6 keV$_{ee}$	6–20 keV$_{ee}$	1–6 keV$_{ee}$	6–20 keV$_{ee}$
1	CCD	^{238}U	0.897	$\lesssim$9.86 μBq/kg	0.01	0.01	<0.01	<0.01
2	CCD	^{226}Ra	0.900	$\lesssim$4.79 μBq/kg	0.01	0.01	<0.01	<0.01
3	CCD	^{232}Th	0.900	$\lesssim$6.56 μBq/kg	0.01	0.03	0.01	0.02
4	CCD	^{40}K	0.910	$\lesssim$0.42 μBq/kg	<0.01	<0.01	<0.01	<0.01
5	CCD	^{22}Na	1.066	340 ± 60 μBq/kg	0.17	0.16	0.10	0.09
6	CCD	^{32}Si	1.042	150 ± 30 μBq/kg	0.19	0.17	0.15	0.13
7	CCD	^{3}H	1.131	330 ± 90 μBq/kg	2.86	0.78	2.40	0.66
8	CCD (front surface)	^{210}Pb	1.658	69 ± 12 nBq/cm^2	1.45	1.67	0.53	0.88
9	CCD (back surface)	^{210}Pb	$<10^{-4}$	<0.1 nBq/cm^2	<0.01	<0.01	<0.01	<0.01
10	CCD (wafer surface)	^{210}Pb	1.343	56 ± 8 nBq/cm^2	2.43	1.84	1.98	1.18
11	Copper Box	^{238}U	0.900	$\lesssim$110 μBq/kg	0.01	0.01	<0.01	<0.01
12	Copper Box	^{226}Ra	0.900	$\lesssim$120 μBq/kg	0.19	0.15	0.03	0.02
13	Copper Box	^{210}Pb	0.380	10 ± 6 mBq/kg	0.33	0.20	0.02	0.01
14	Copper Box	^{232}Th	0.900	$\lesssim$36 μBq/kg	0.08	0.06	0.01	0.01
15	Copper Box	^{40}K	0.900	$\lesssim$28 μBq/kg	<0.01	<0.01	<0.01	<0.01
16	Copper Box	Act.	1.015	280 ± 30 μBq/kg	0.63	0.49	0.10	0.08
17	Copper Modules	^{238}U	0.900	$\lesssim$110 μBq/kg	0.05	0.03	<0.01	<0.01
18	Copper Modules	^{226}Ra	0.900	$\lesssim$120 μBq/kg	0.21	0.17	<0.01	<0.01
19	Copper Modules	^{210}Pb	0.557	15 ± 4 mBq/kg	1.18	0.71	<0.01	<0.01
20	Copper Modules	^{232}Th	0.900	$\lesssim$36 μBq/kg	0.10	0.08	<0.01	<0.01
21	Copper Modules	^{40}K	0.900	$\lesssim$28 μBq/kg	<0.01	<0.01	<0.01	<0.01
22	Copper Modules	Act.	1.006	130 ± 10 μBq/kg	0.30	0.23	0.01	0.01
23	Kapton Cable	^{238}U	1.016	59 ± 5 mBq/kg	0.51	0.30	0.23	0.11
24	Kapton Cable	^{226}Ra	1.362	7 ± 5 mBq/kg	0.24	0.18	0.05	0.03
25	Kapton Cable	^{232}Th	1.010	32 ± 0.5 mBq/kg	0.17	0.13	0.04	0.02
26	Kapton Cable	^{40}K	1.003	29 ± 2 mBq/kg	0.09	0.05	0.04	0.02
27	Kapton Cable	Act.	1.000	140 ± 10 μBq/kg	0.01	0.01	<0.01	<0.01
28	Ancient Lead	^{238}U	0.911	$\lesssim$21 μBq/kg	<0.01	<0.01	<0.01	<0.01
29	Ancient Lead	^{226}Ra	0.900	$\lesssim$230 μBq/kg	0.44	0.36	0.21	0.18
30	Ancient Lead	^{210}Pb	1.000	~33 mBq/kg	0.04	0.03	0.24	0.18
31	Ancient Lead	^{232}Th	1.000	~2.3 μBq/kg	<0.01	<0.01	<0.01	<0.01
32	Ancient Lead	^{40}K	0.916	$\lesssim$5.3 μBq/kg	<0.01	<0.01	<0.01	<0.01
33	Outer Lead	^{238}U	0.916	$\lesssim$12 μBq/kg	<0.01	<0.01	<0.01	<0.01
34	Outer Lead	^{226}Ra	0.909	$\lesssim$190 μBq/kg	<0.01	<0.01	<0.01	<0.01
35	Outer Lead	^{210}Pb	1.000	18 ± 5 Bq/kg	<0.01	<0.01	<0.01	<0.01
36	Outer Lead	^{232}Th	0.907	$\lesssim$4.2 μBq/kg	<0.01	<0.01	<0.01	<0.01
37	Outer Lead	^{40}K	0.906	$\lesssim$200 μBq/kg	<0.01	<0.01	<0.01	<0.01
38	Module Screws	^{238}U	1.000	20 ± 40 mBq/kg	<0.01	<0.01	<0.01	<0.01
39	Module Screws	^{226}Ra	0.900	$\lesssim$1.4 mBq/kg	0.01	0.01	<0.01	<0.01
40	Module Screws	^{210}Pb	1.000	27 ± 8 mBq/kg	<0.01	<0.01	<0.01	<0.01
41	Module Screws	^{232}Th	1.024	2.4 ± 1.6 mBq/kg	0.02	0.01	<0.01	<0.01
42	Module Screws	^{40}K	1.000	28 ± 15 mBq/kg	<0.01	<0.01	<0.01	<0.01
43	Module Screws	Act.	1.000	89 ± 9 μBq/kg	<0.01	<0.01	<0.01	<0.01
44	Copper Vessel	^{238}U	0.903	$\lesssim$110 μBq/kg	<0.01	<0.01	<0.01	<0.01
45	Copper Vessel	^{226}Ra	0.900	$\lesssim$120 μBq/kg	0.10	0.09	0.01	0.01
46	Copper Vessel	^{210}Pb	0.731	20 ± 8 mBq/kg	0.06	0.03	<0.01	<0.01
47	Copper Vessel	^{232}Th	0.900	$\lesssim$36 μBq/kg	0.04	0.03	<0.01	<0.01
48	Copper Vessel	^{40}K	0.901	$\lesssim$28 μBq/kg	<0.01	<0.01	<0.01	<0.01
49	Copper Vessel	Act.	0.486	400 ± 440 μBq/kg	0.33	0.27	0.05	0.04
	Total				12.28	8.29	6.22	3.70

(Table continued)

MAIN BACKGROUNDS: TRITIUM



MAIN BACKGROUNDS: COMPTON



BKG MODEL VALIDATION

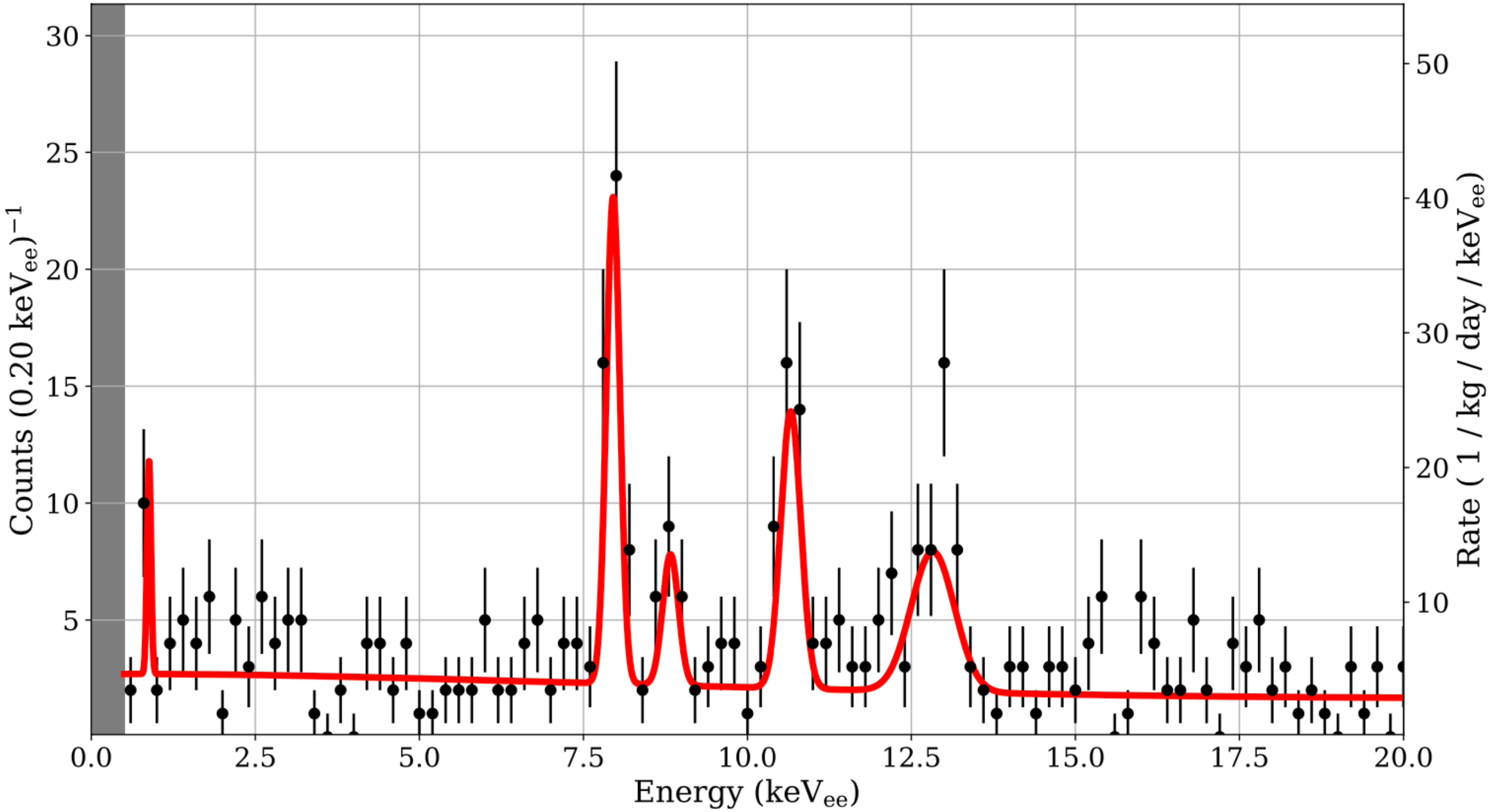
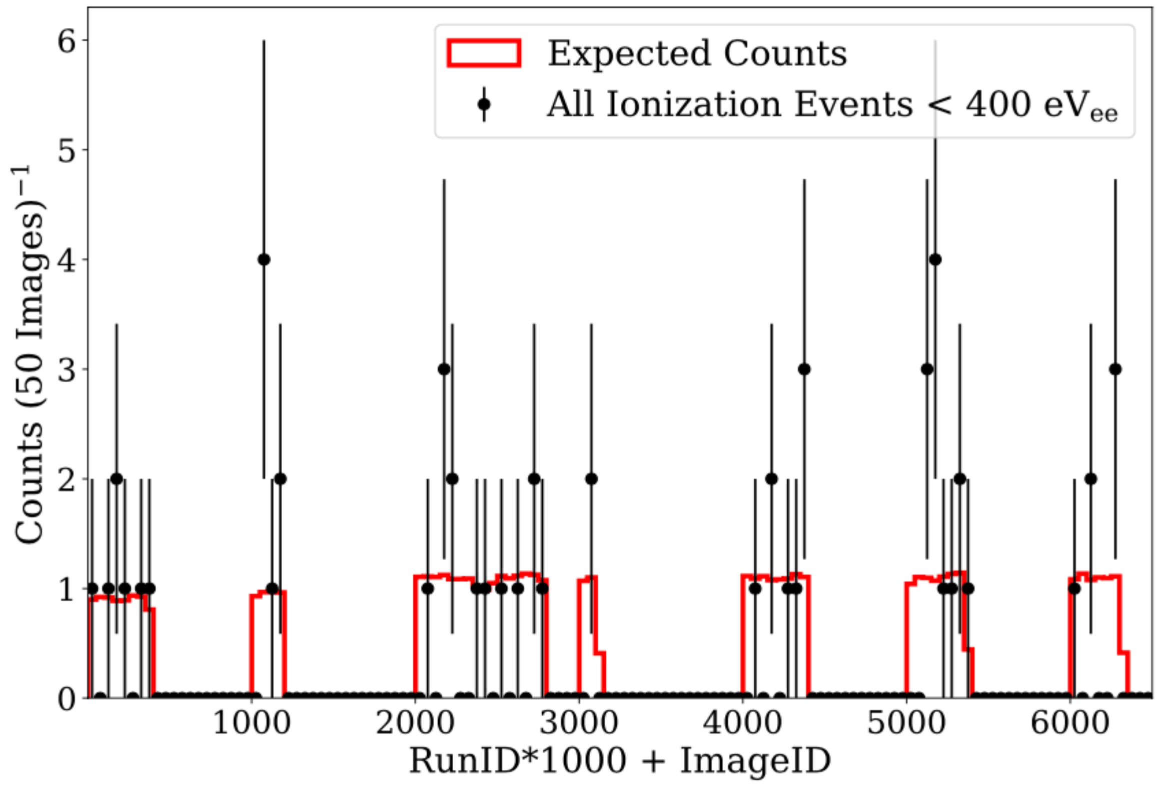


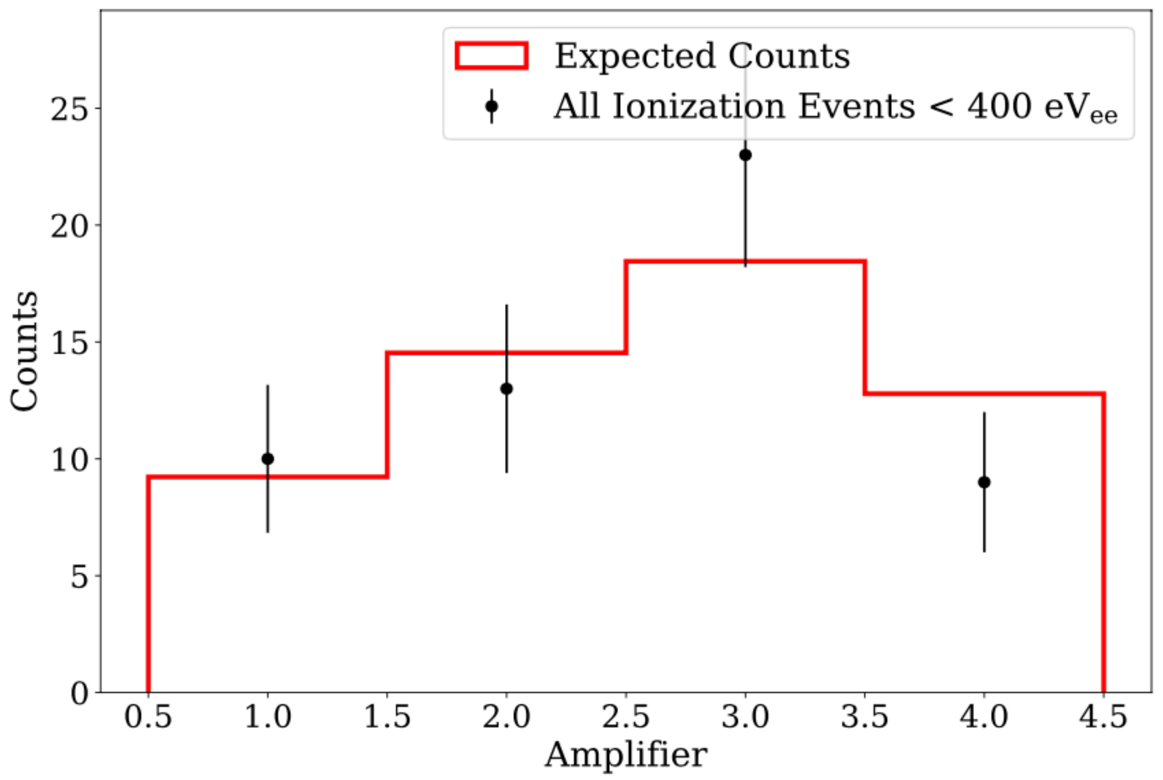
Figure 3.9: The bulk (after σ_y cuts) background rate above 0.5 keV$_{ee}$ for a bulk exposure of $\sim$ 3 kg days.

MAIN SYSTEMATICS

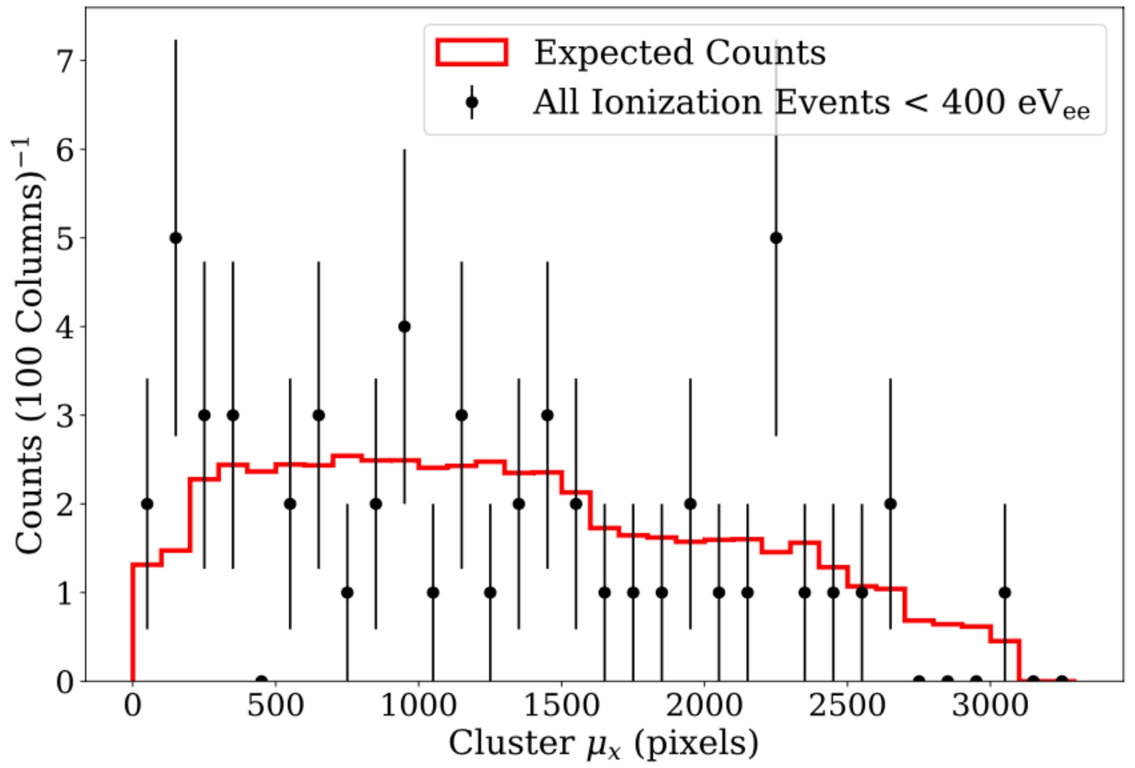
Validation of statistical properties of dataset



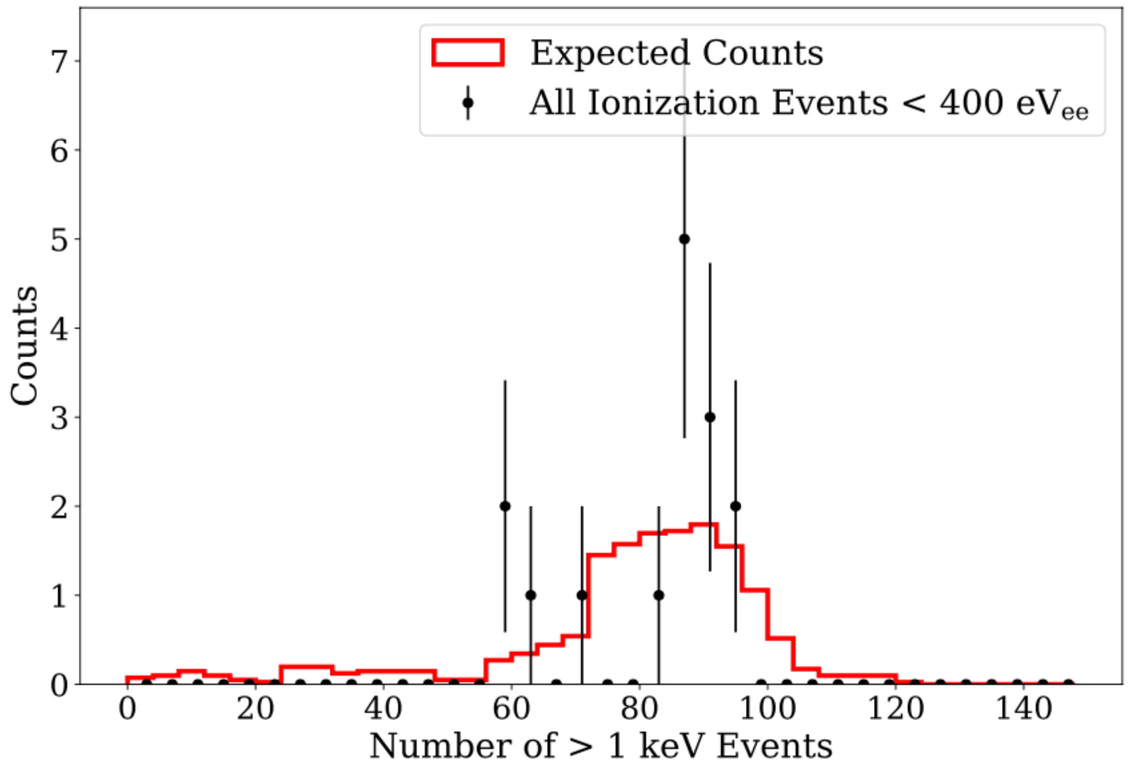
(a) Time distribution of events.



(b) Amplifier distribution.

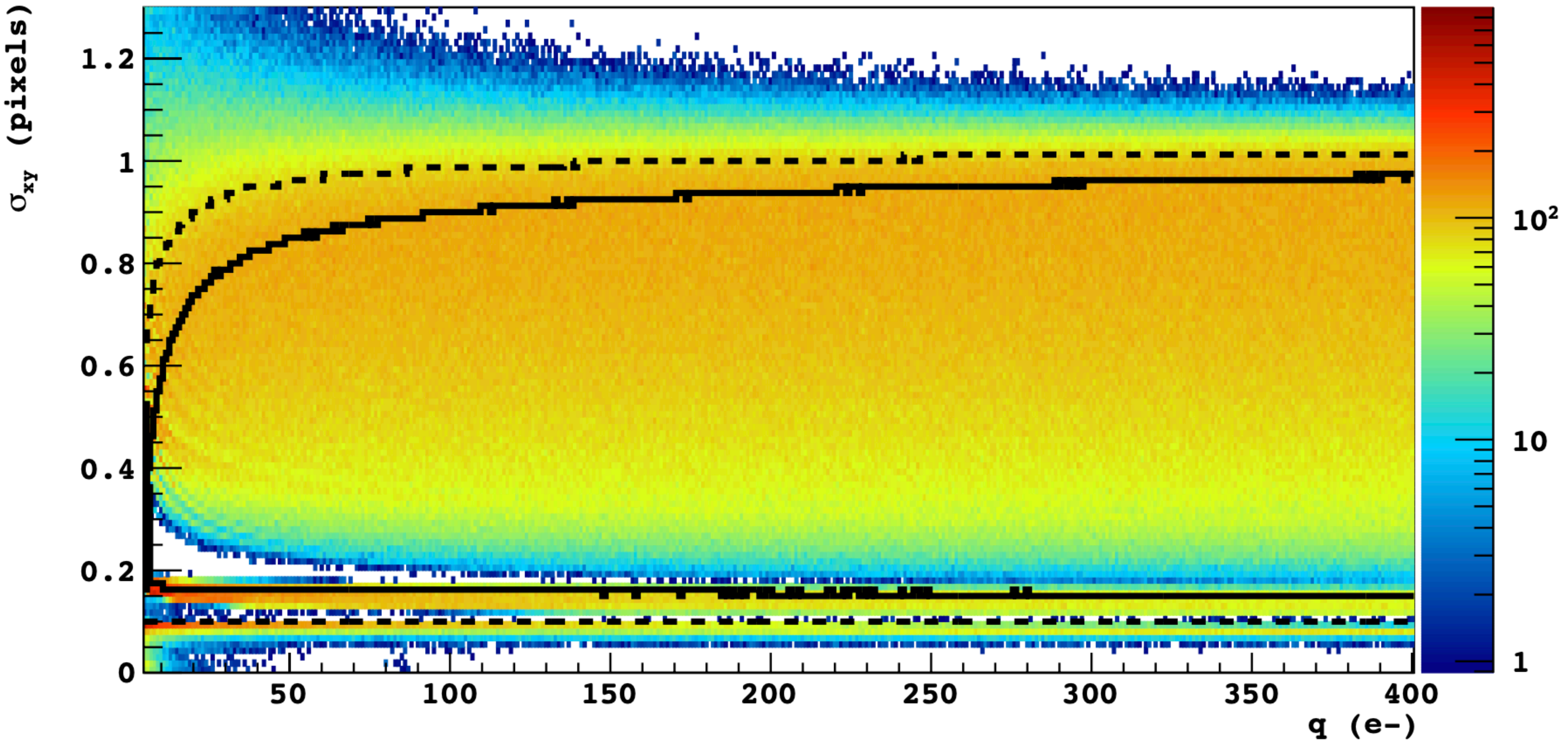


(c) Position distribution.



(d) Number of possible time coincident events.

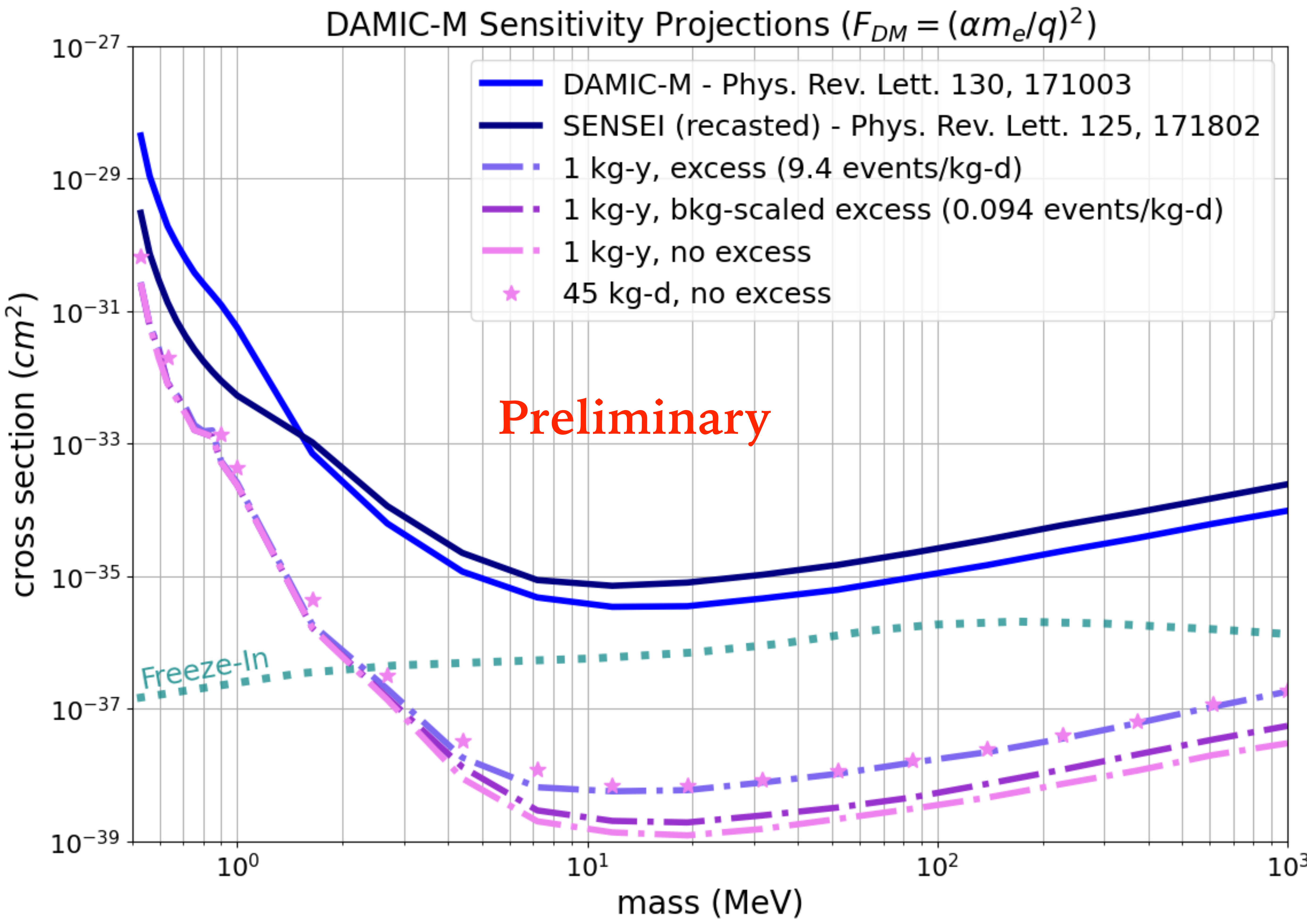
BULK EVENTS SIMULATIONS



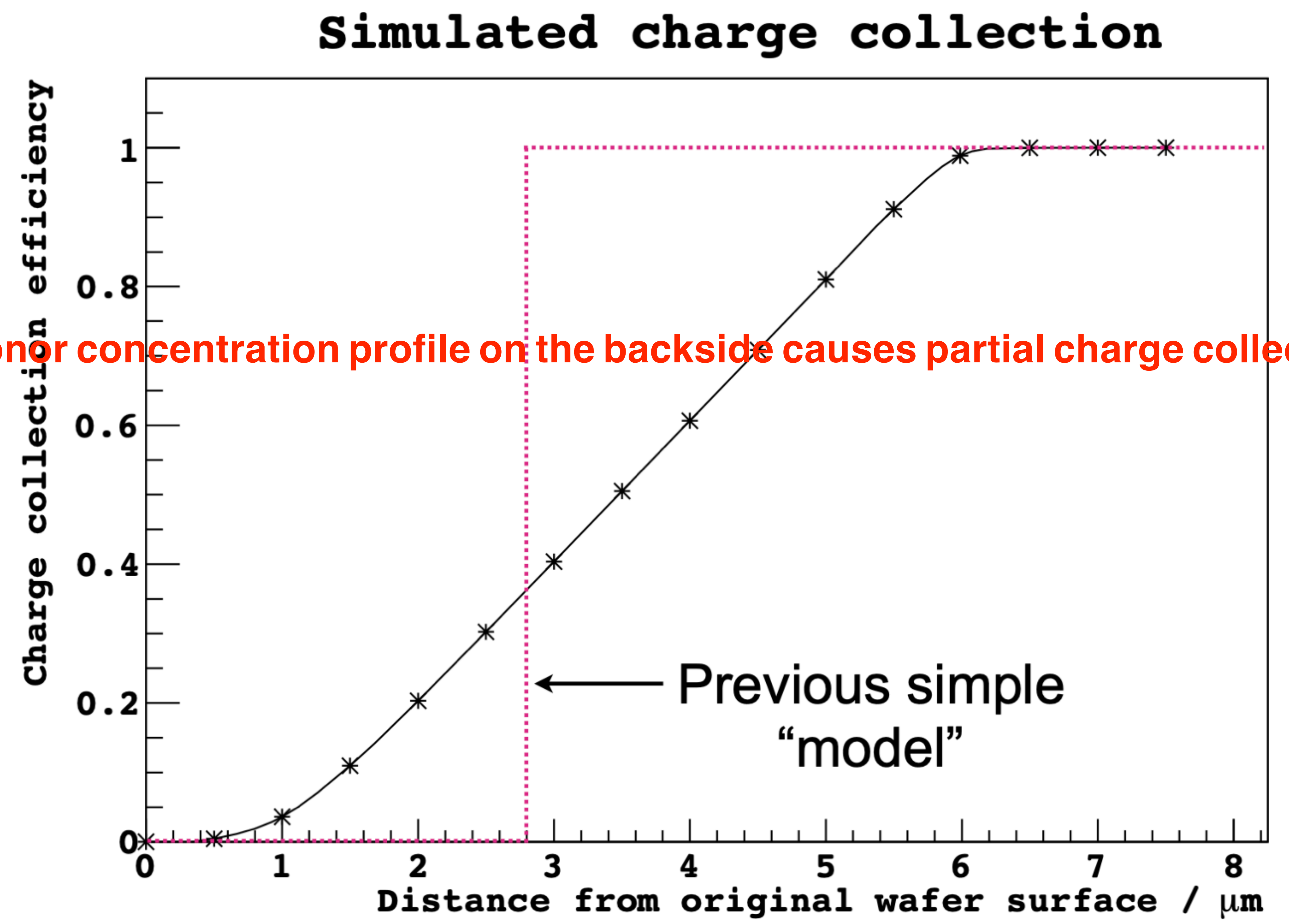
EXCESS AS A BACKGROUND

Sensitivity projections for DM-e^- scattering:
How the excess might affect DAMIC-M sensitivity.

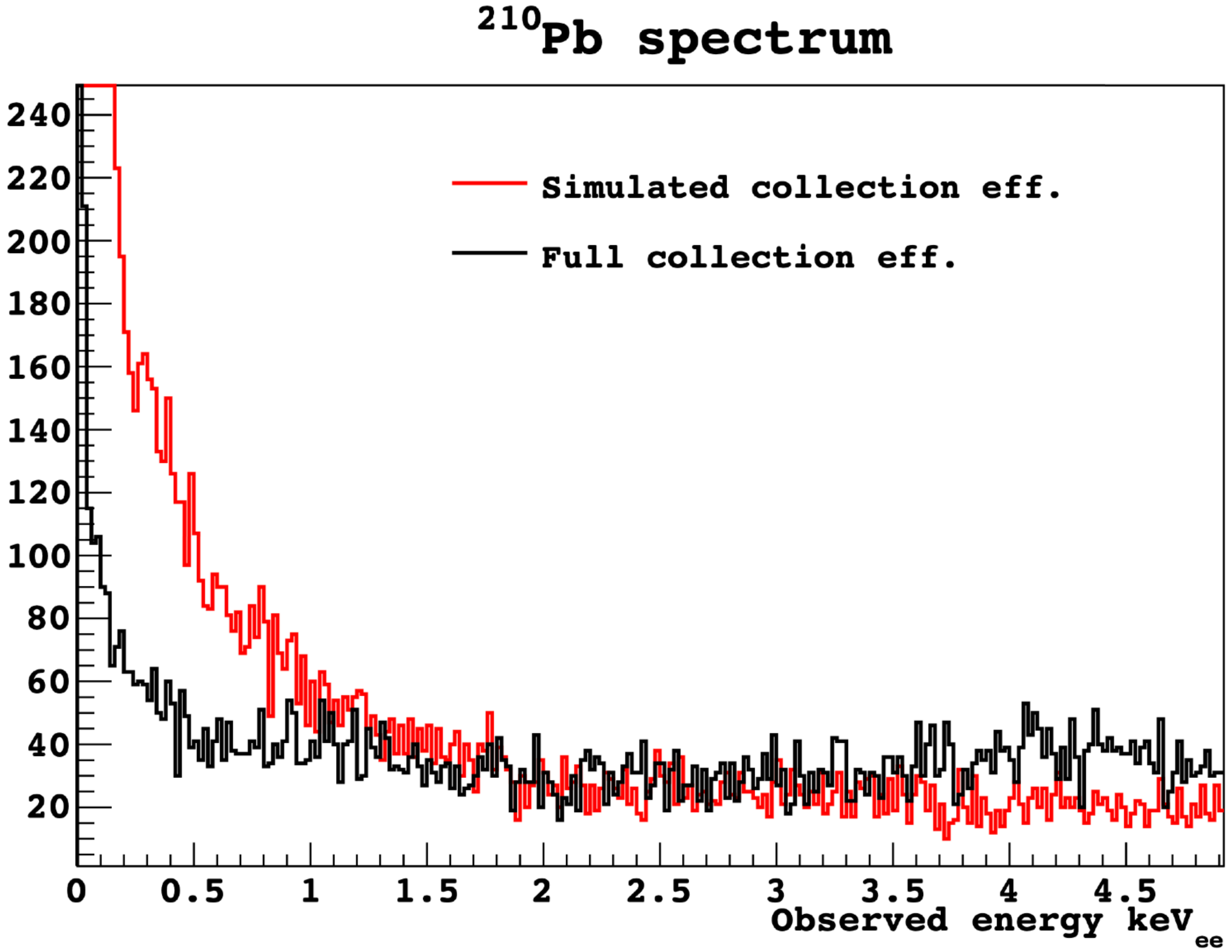
- We extrapolate the exponential physical signal down to $1e^-$ and simulate it as a background for hidden sector DM searches
- Conservative assumptions on noise and leakage current ($\sigma = 0.23\ e^-$ and $\lambda = 10^{-3}\ e^-$/pix/day), and readout strategy (continuous)
- We consider two scenarios:
  - The excess event rate is fixed to 9.4 (kg-d)$^{-1}$ and does not depend on the total background rate
  - The excess event rate scales with the background rate
    - ➡ 2 order of magnitude reduction in DAMIC-M

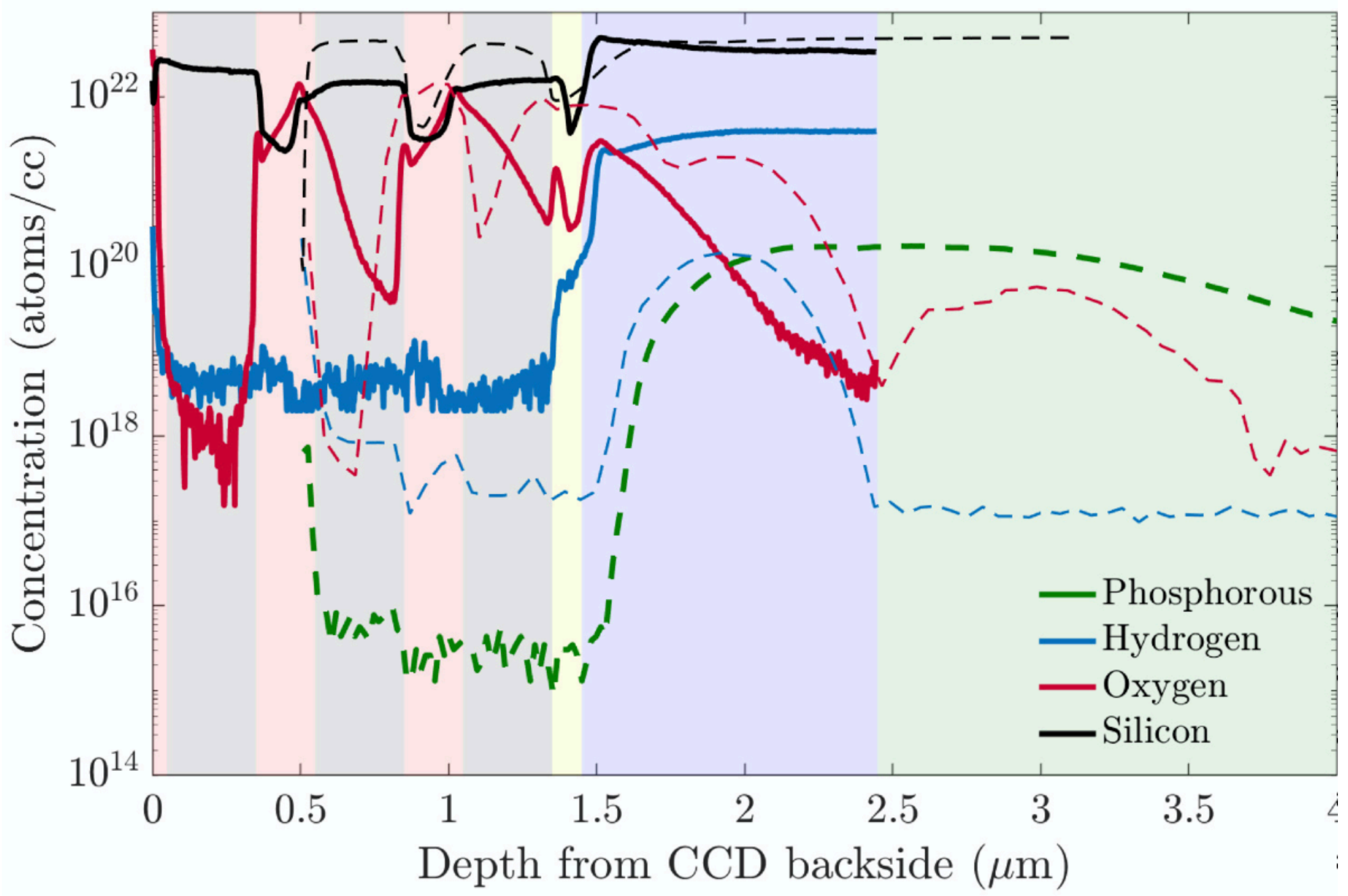


BACKSIDE ANALYSIS: PARTIAL CHARGE COLLECTION



Donor concentration profile on the backside causes partial charge collection





largest uncertainty in our response model

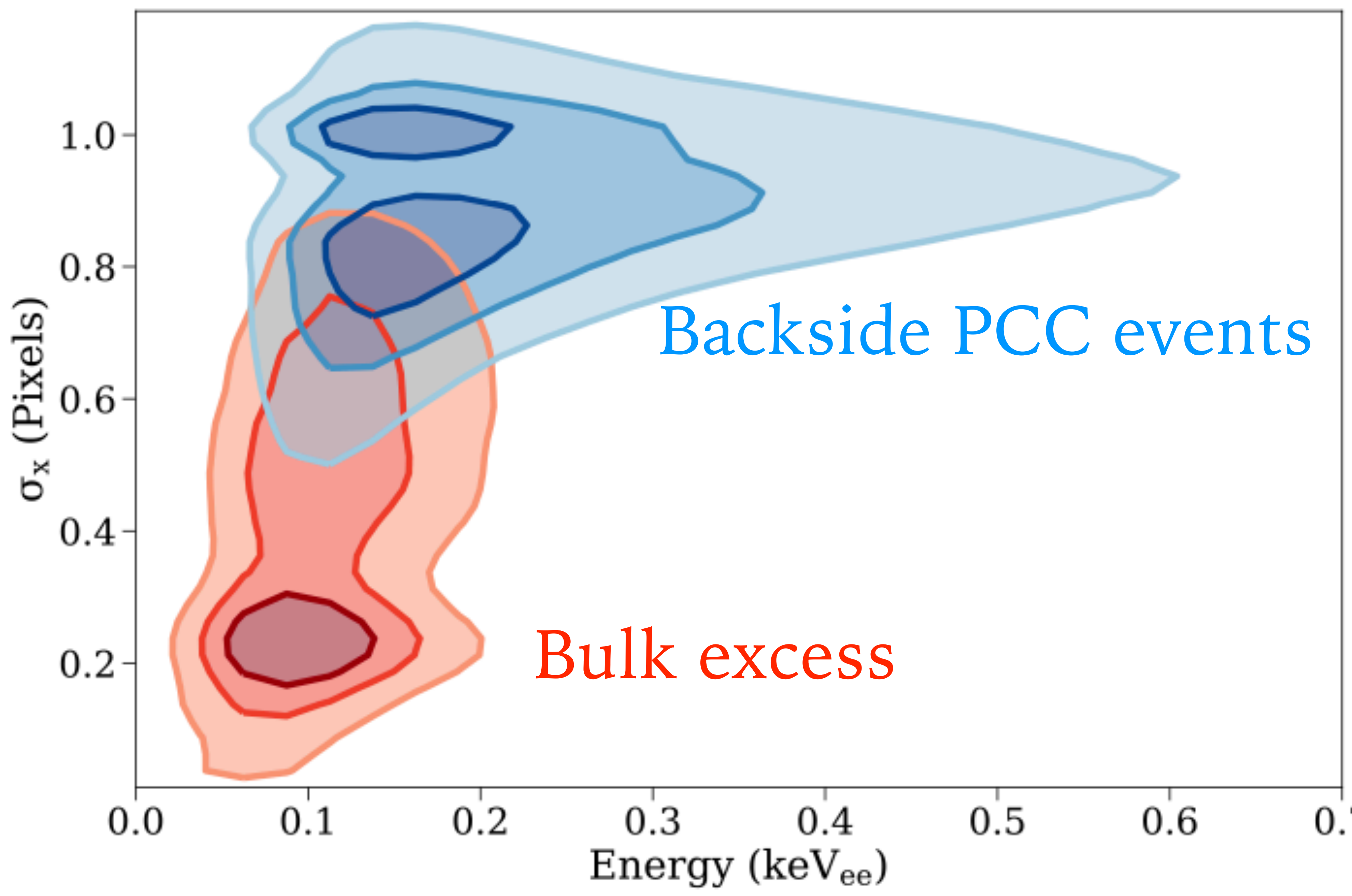
Incorporate it as systematic via back exponential in log-likelihood fit

$$f_{pcc}(E[keV_{ee}];\alpha_{pcc}) = N_{pcc}e^{-\frac{\sqrt{E}}{\alpha_{pcc}}}$$

SYSTEMATIC CHECKS

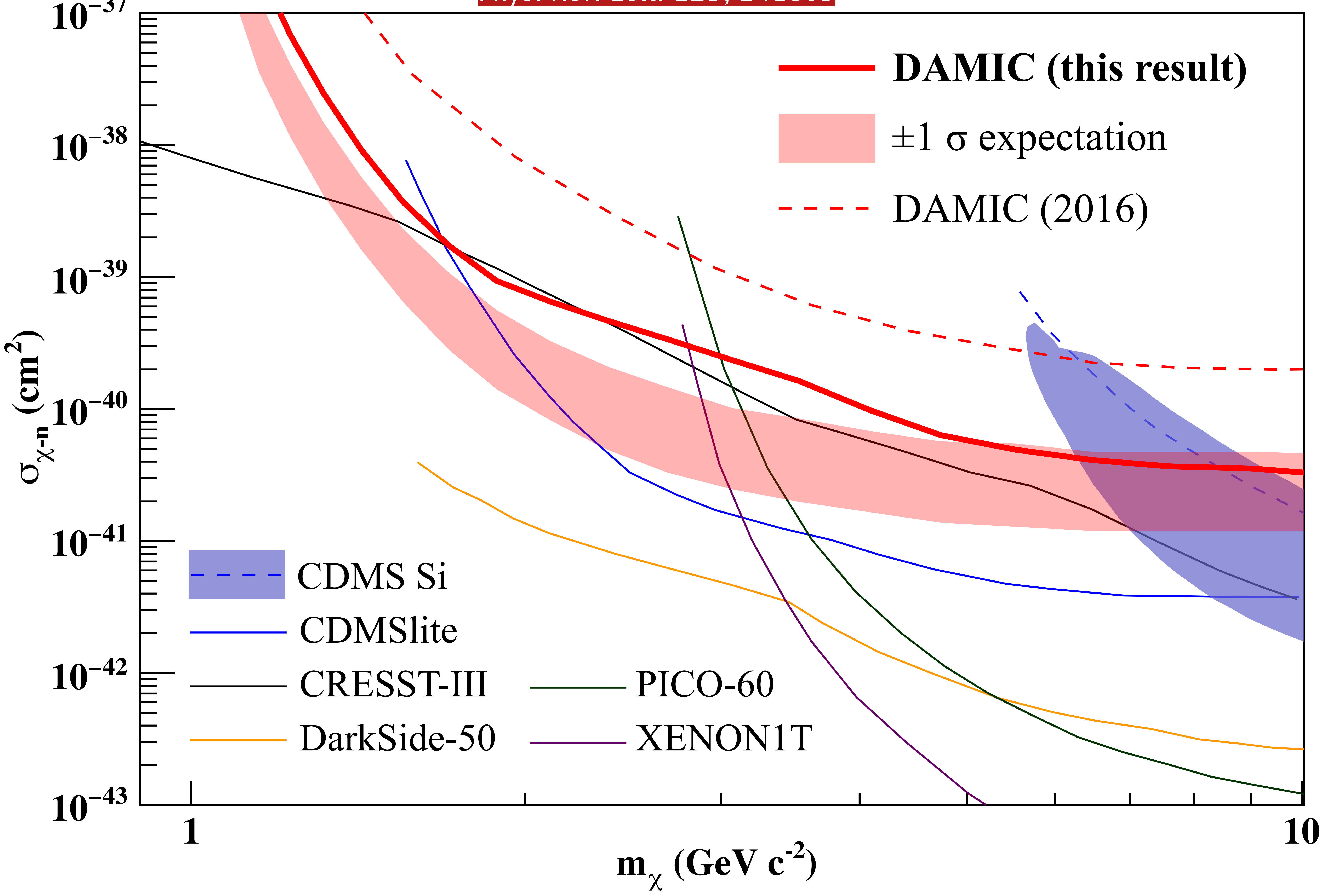
Systematic Checks

- Fit above 200 eV_{ee} consistent with null hypothesis
- Fit to CCD1 and CCD2-7 data sets separately consistent with joint analysis (excess more significant in CCD 1)
- Partial Charge Collection (PCC) systematic cannot account for the excess
- Front-surface events alone cannot account for the excess
- Local vs Global significance tests: excess is by far the most significant feature in data
- Serial register events excluded as possible source of excess (0.01% of overall exposure)

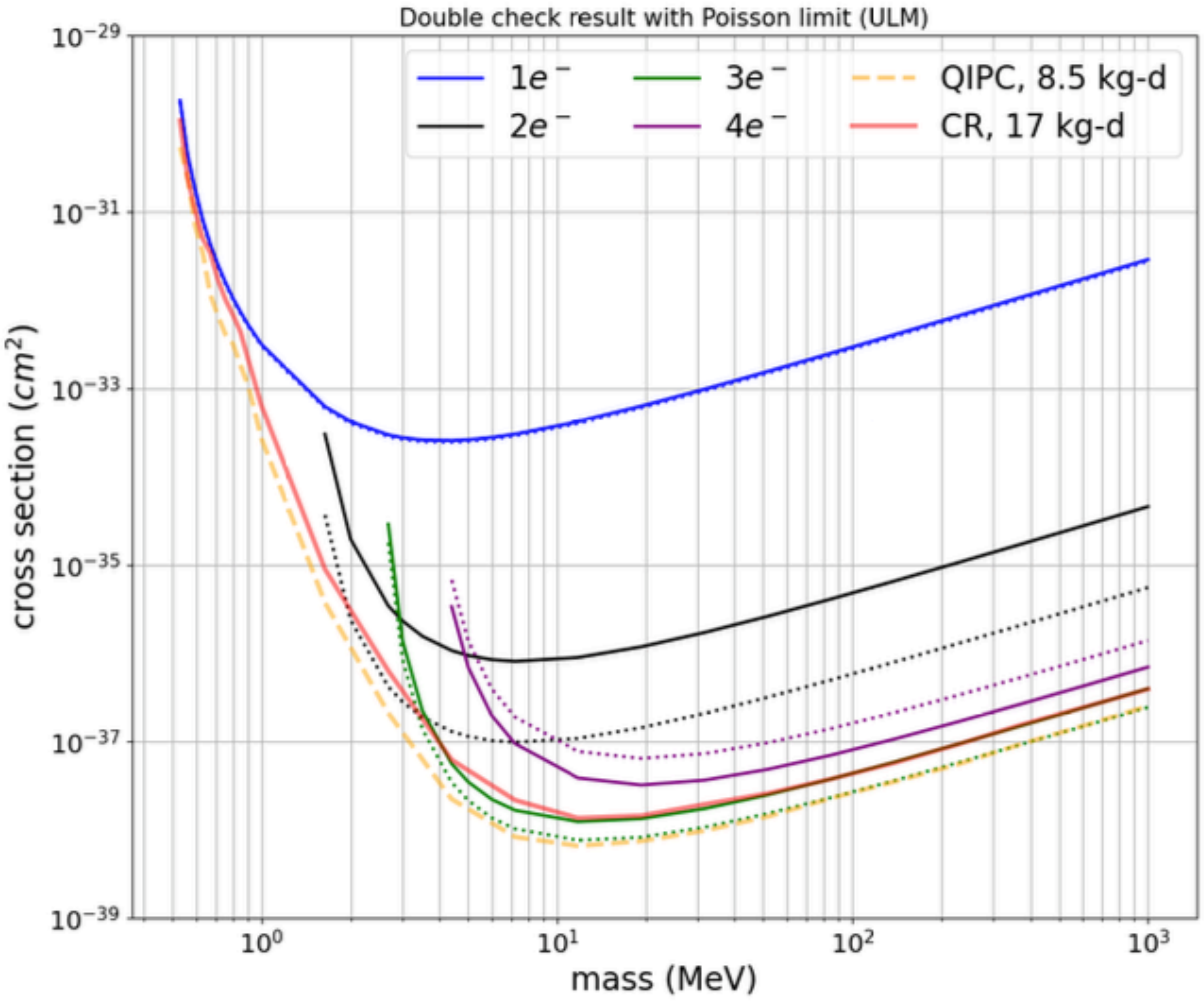


11 KG-DAY WIMP SEARCH LIMITS

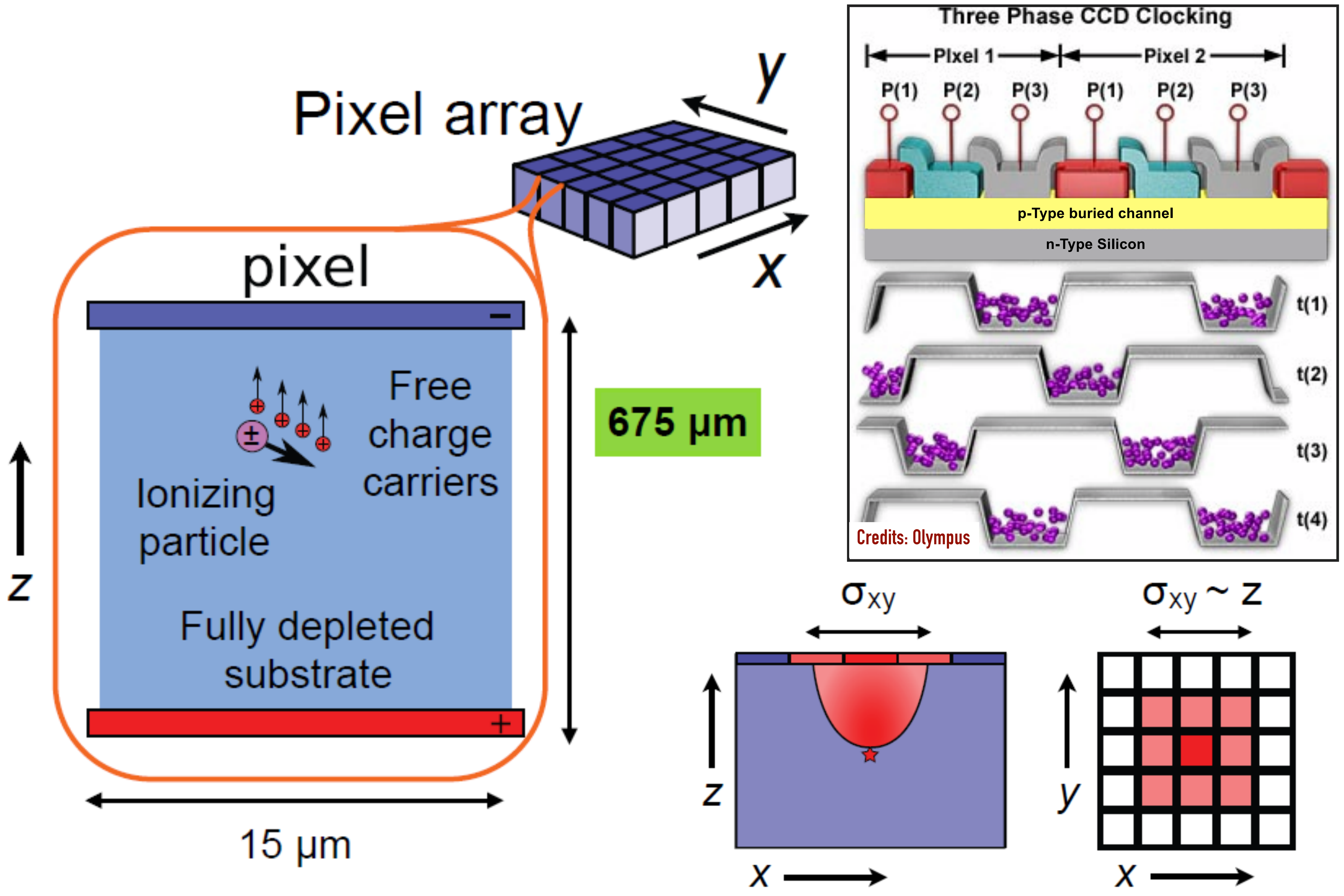
Phys. Rev. Lett. **125**, 241803



POISSON-PLR LIMITS



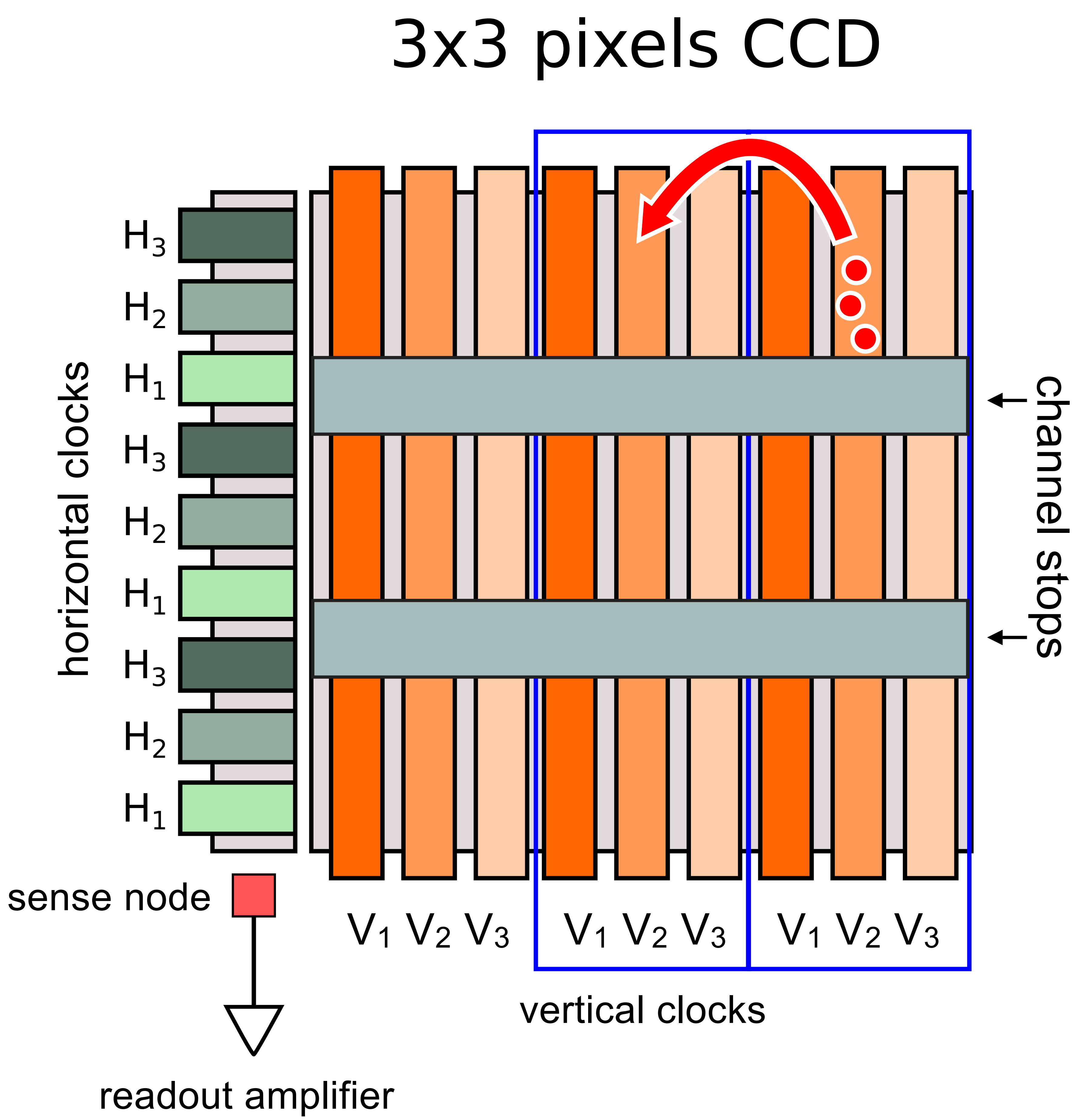
CHARGE-COUPLED DEVICES



DAMIC science-grade CCDs

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

CHARGE-COUPLED DEVICES



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

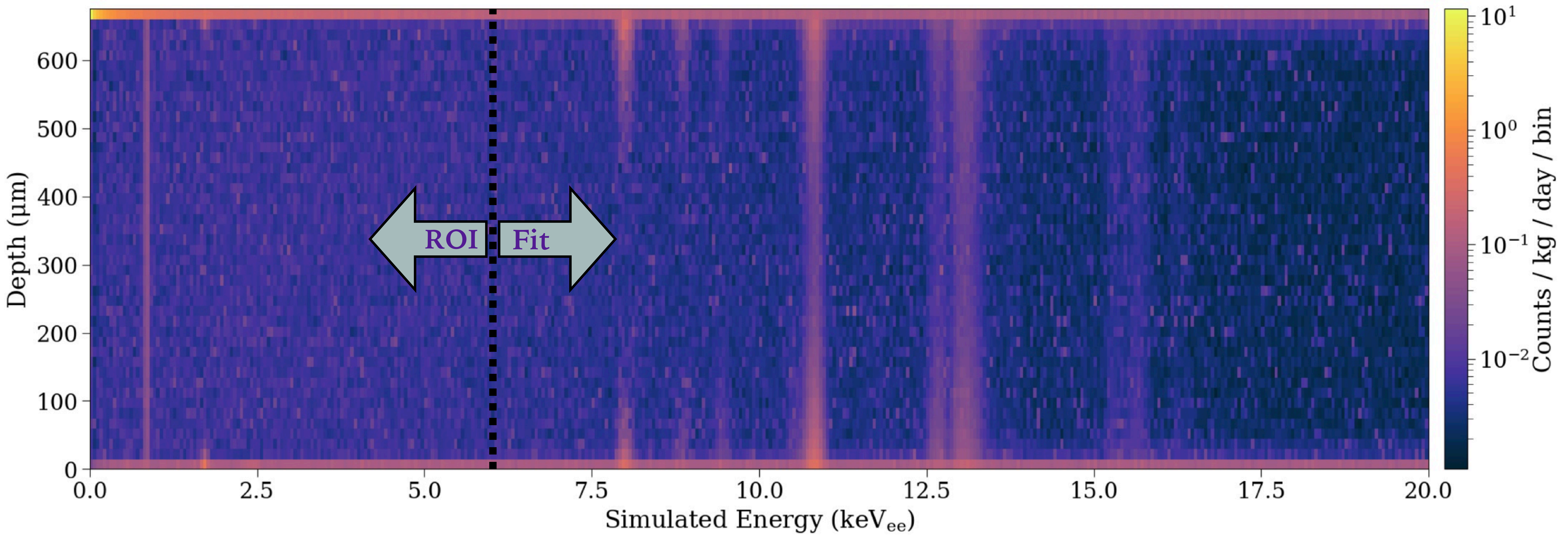
BACKGROUND MODELING

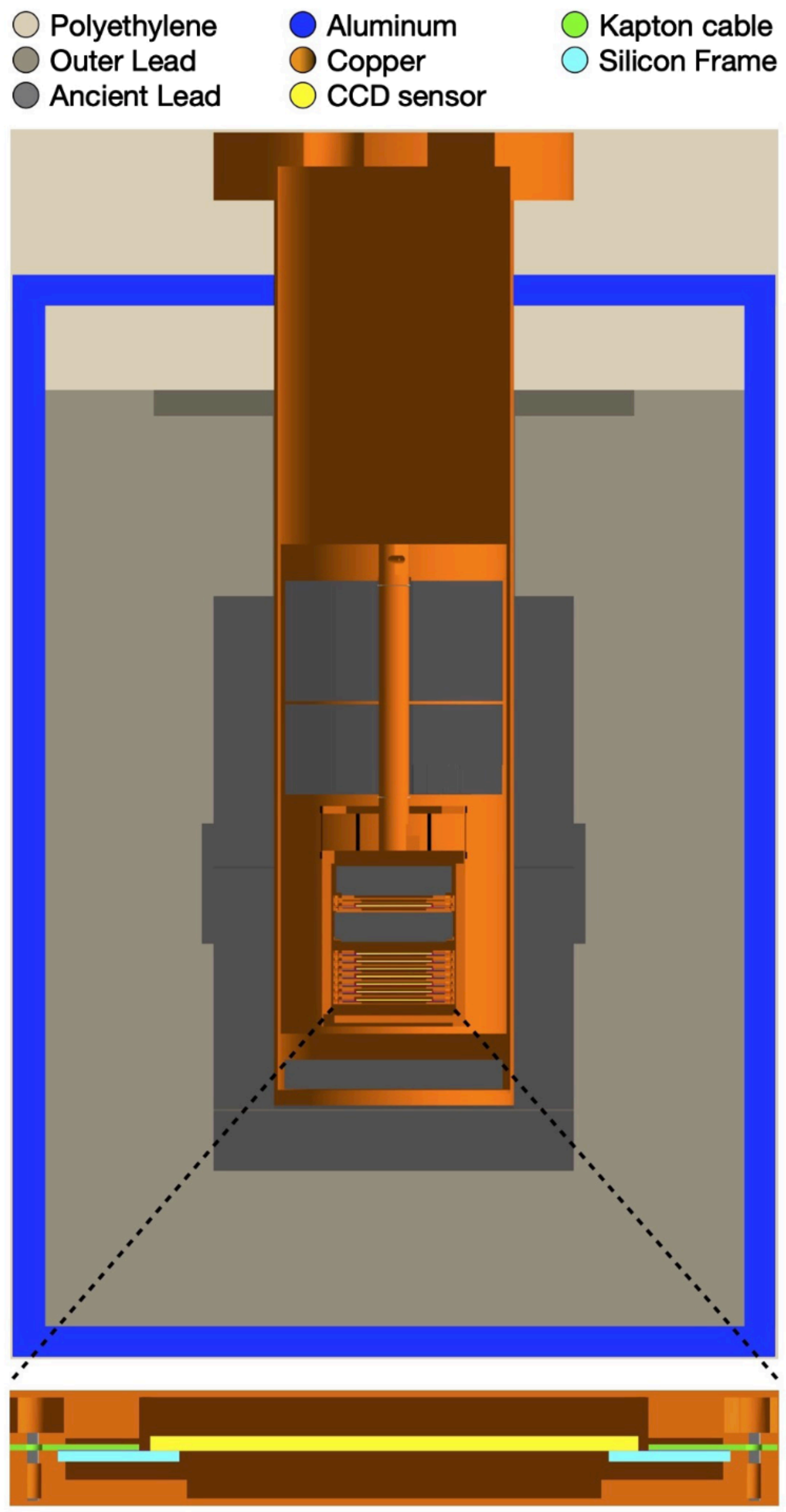
Background model construction: Phys. Rev. D **105**, 062003 JINST **16** P06019

- Decay and tracking across detector geometry with GEANT4
- CCD response simulation
- Reconstruction to (E, σ_{xy}) analysis space
- Likelihood fit to data in WIMP-free region $(6 - 20\ \mathrm{keV}_{ee})$
  $\Longrightarrow$ extrapolate in ROI $(0.05 - 6\ \mathrm{keV}_{ee})$

eV_{ee} : electron-equivalent energies

Simulated backgrounds for CCDs 2-7 in energy and depth





DETECTOR RESPONSE

- Charge generation: $\langle E_{eh} \rangle = 3.8\ \text{eV}_{ee}$ j.nima.2021.165511

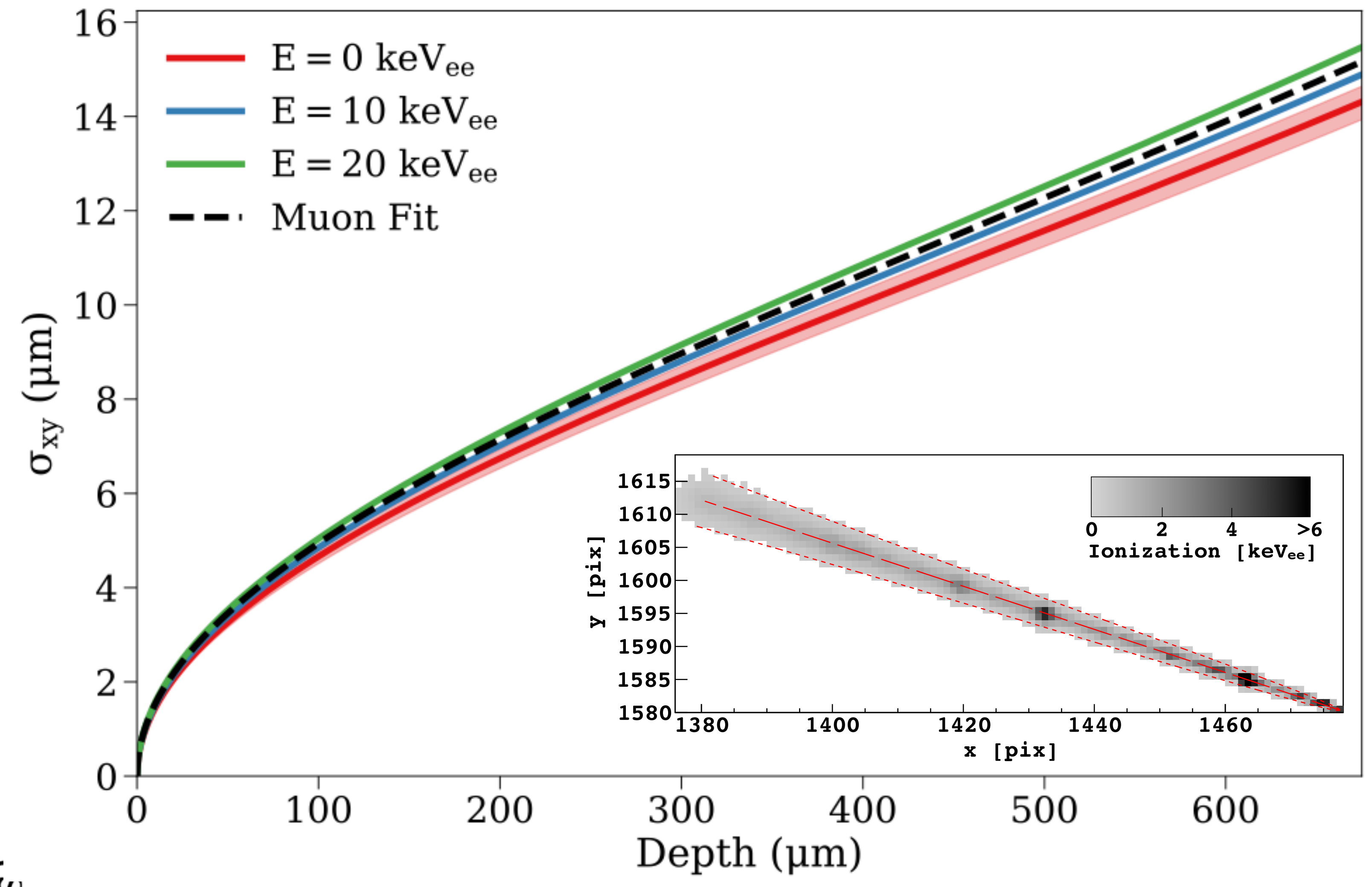
- Diffusion model calibrated on muon surface data

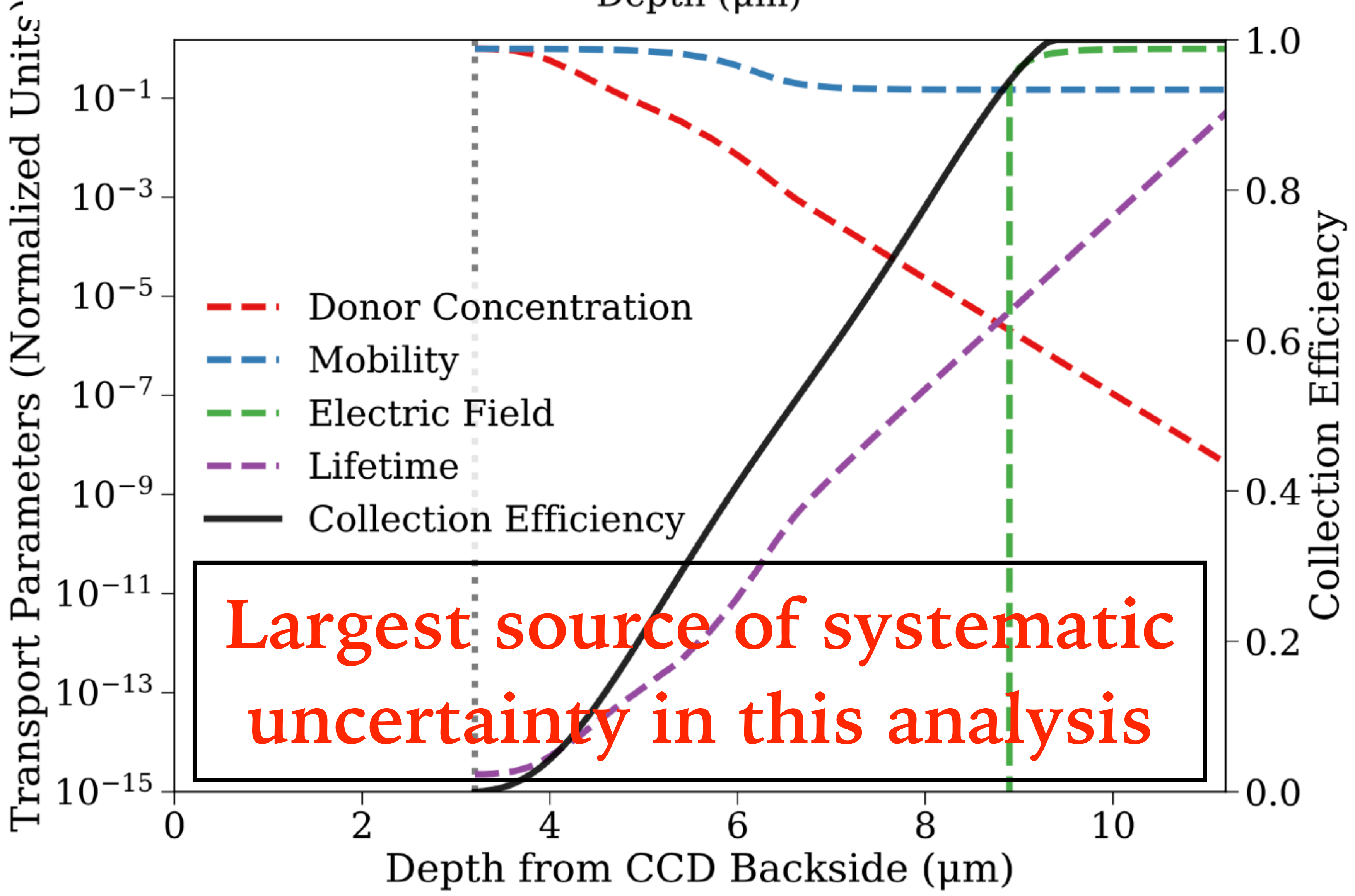
- Charge collection efficiency based on secondary ion mass spectrometry measurements (SIMS)
  - Consistent with later calibration
    Phys. Rev. Applied **15**, 064026

- Pixelation and noise addition

$\Longrightarrow$ **Reconstruction into (E, σ_{xy}) distribution**

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





DAMIC AT MODANE (DAMIC-M)

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

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

Main novelties:

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

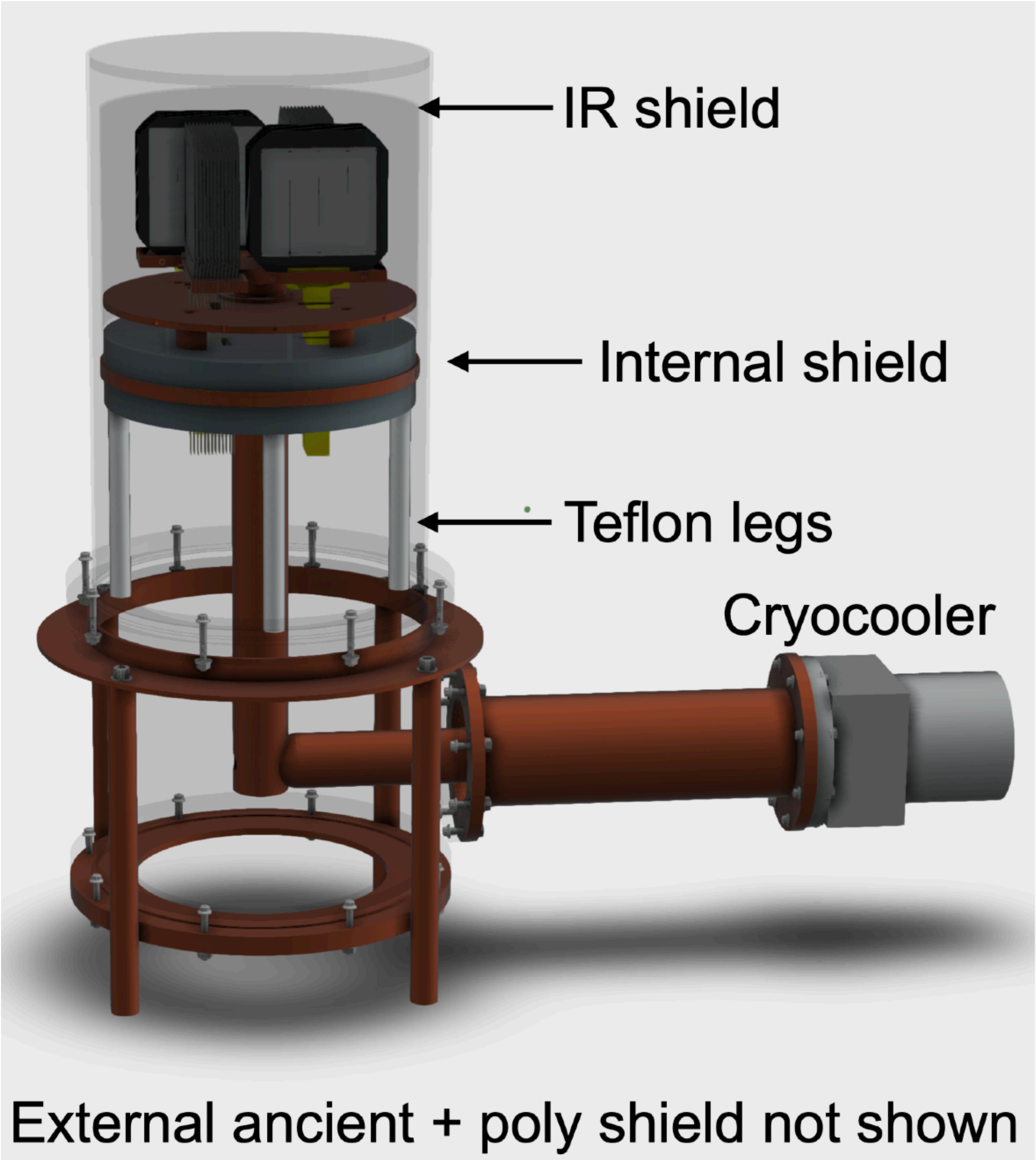
Status:

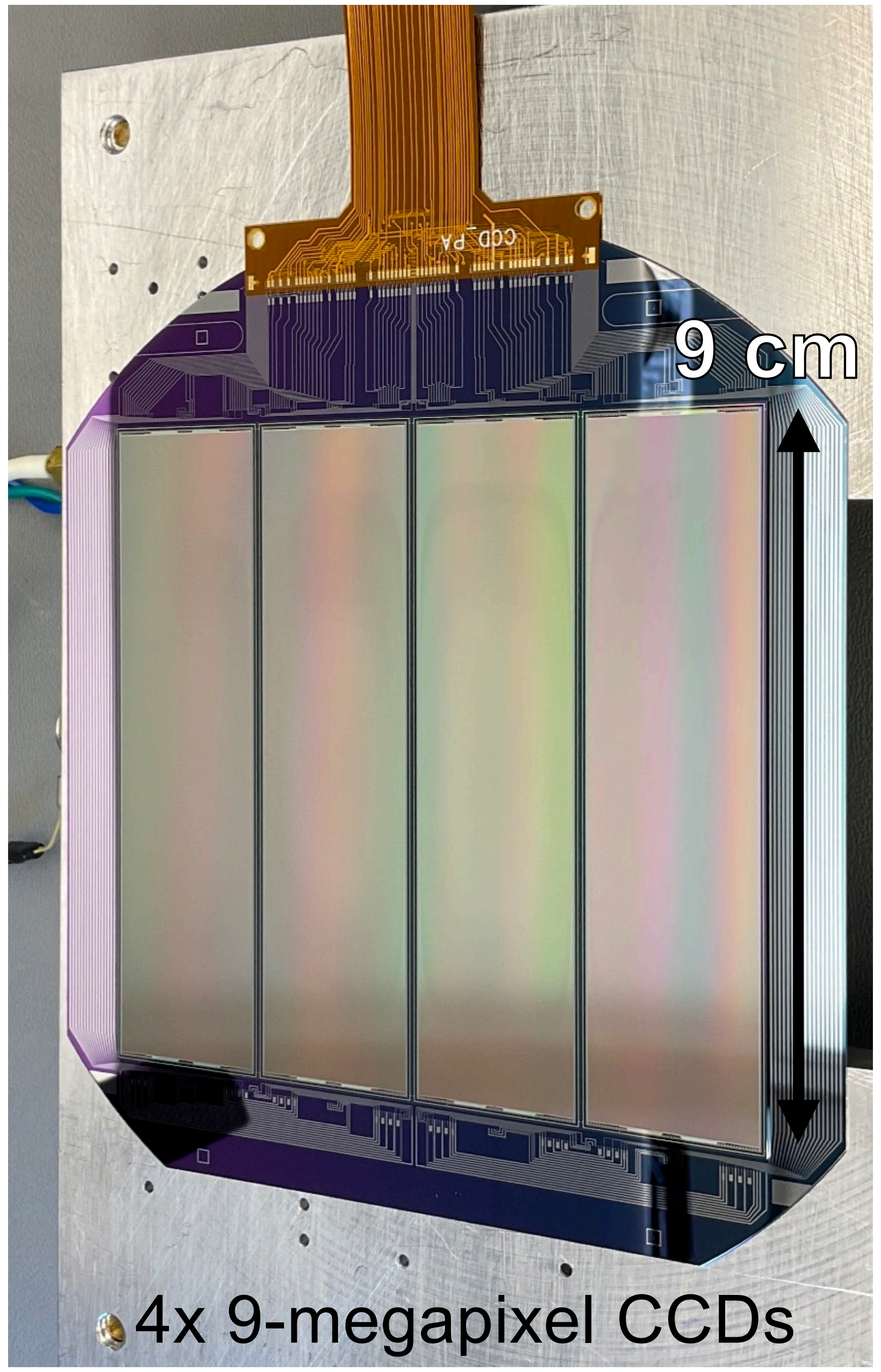
- LBC prototype detector up and running. First DAMIC-M science results published recently

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

- Construction starting in 2024

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





DAMIC-M CCD module packaged at UW