Latest Results from the full exposure of DAMIC at SNOLAB

Daniel Baxter

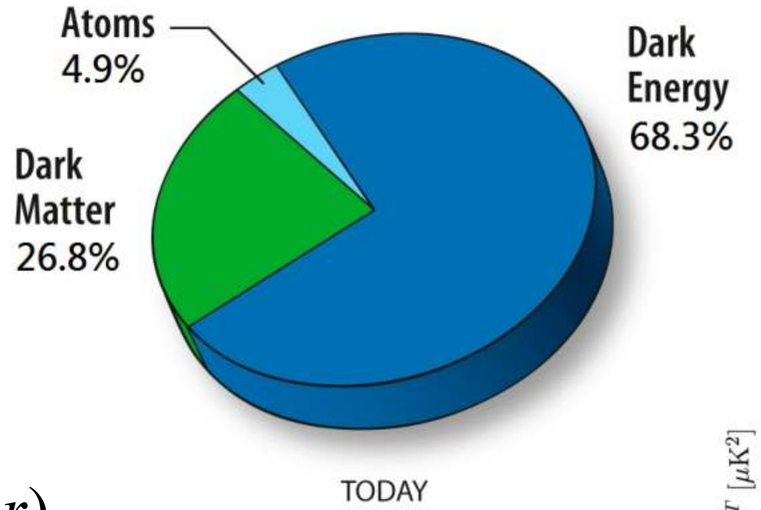
…on behalf of the DAMIC at SNOLAB collaboration

Cosmology from Home

August 24 - September 4, 2020

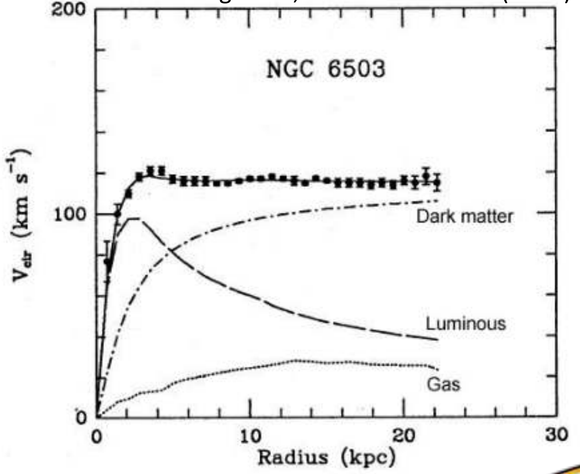
Dark Matter

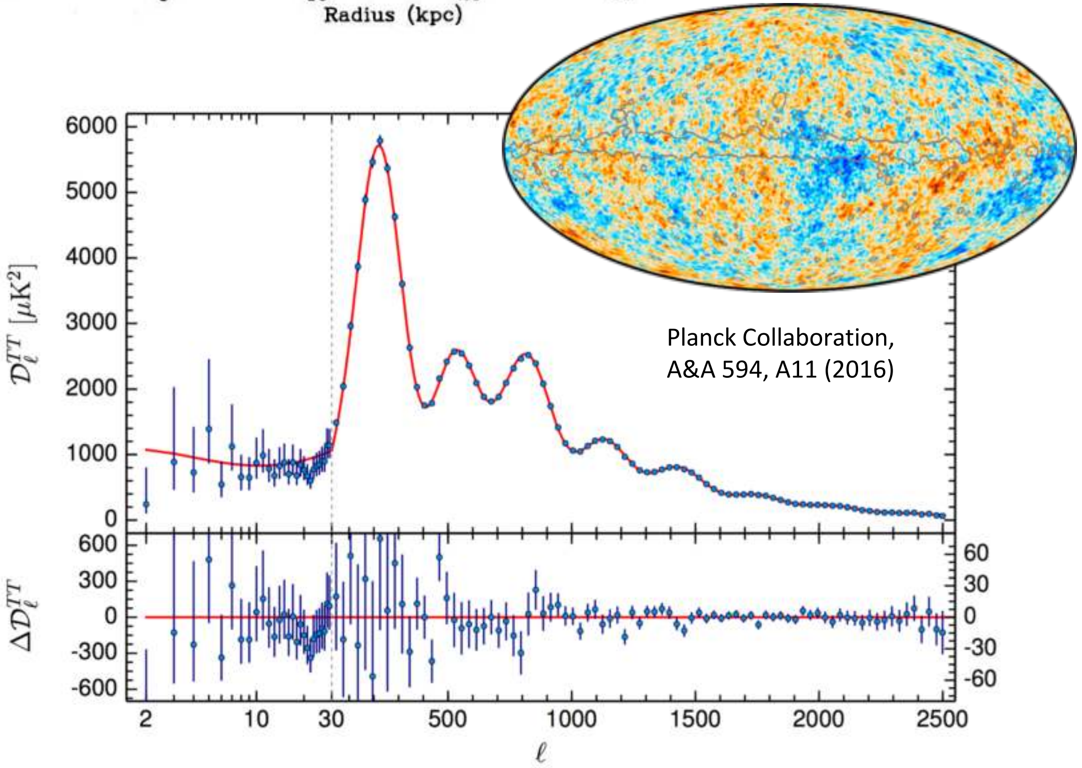
Evidence:
- **Galaxy Rotation**
- **CMB**
- Lensing
- …and many more



Interactions:
- Gravity: YES (*matter*)
- EM: NO (*dark*)
- other: maybe?
  - **Weakly Interacting Massive Particles**
  - Axions

Begeman, et al. MNRAS 249 (1991)

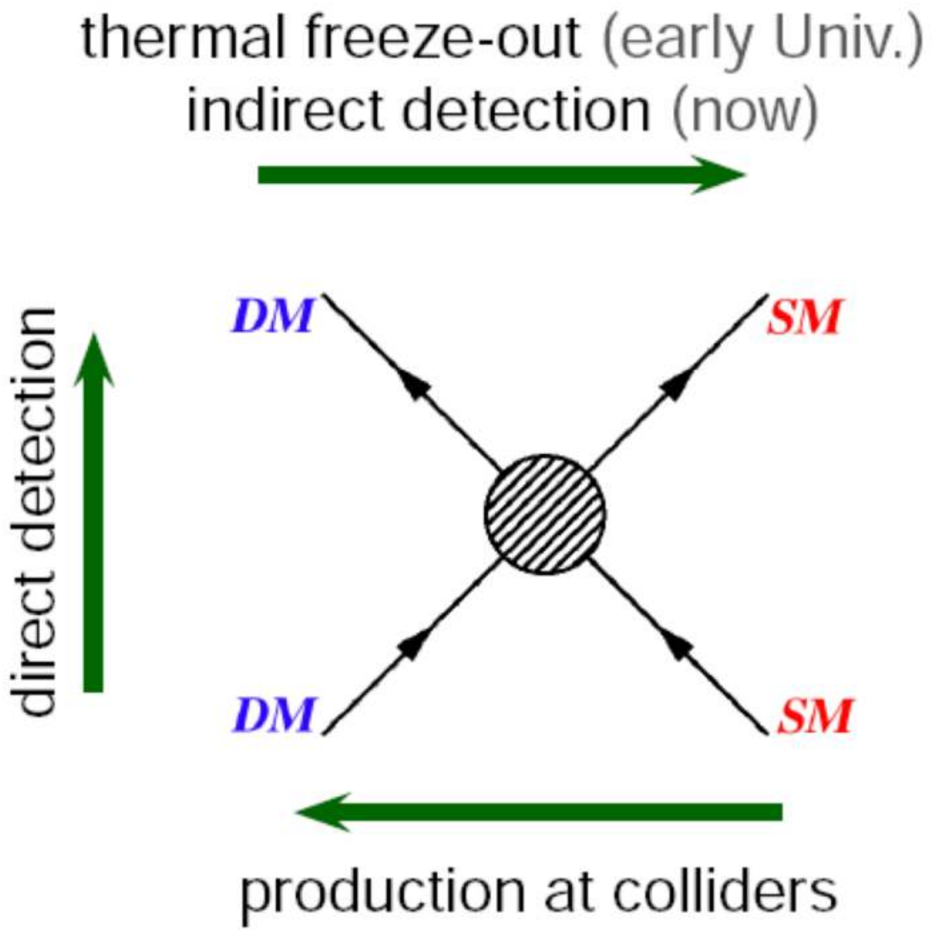




Planck Collaboration, A&A 594, A11 (2016)

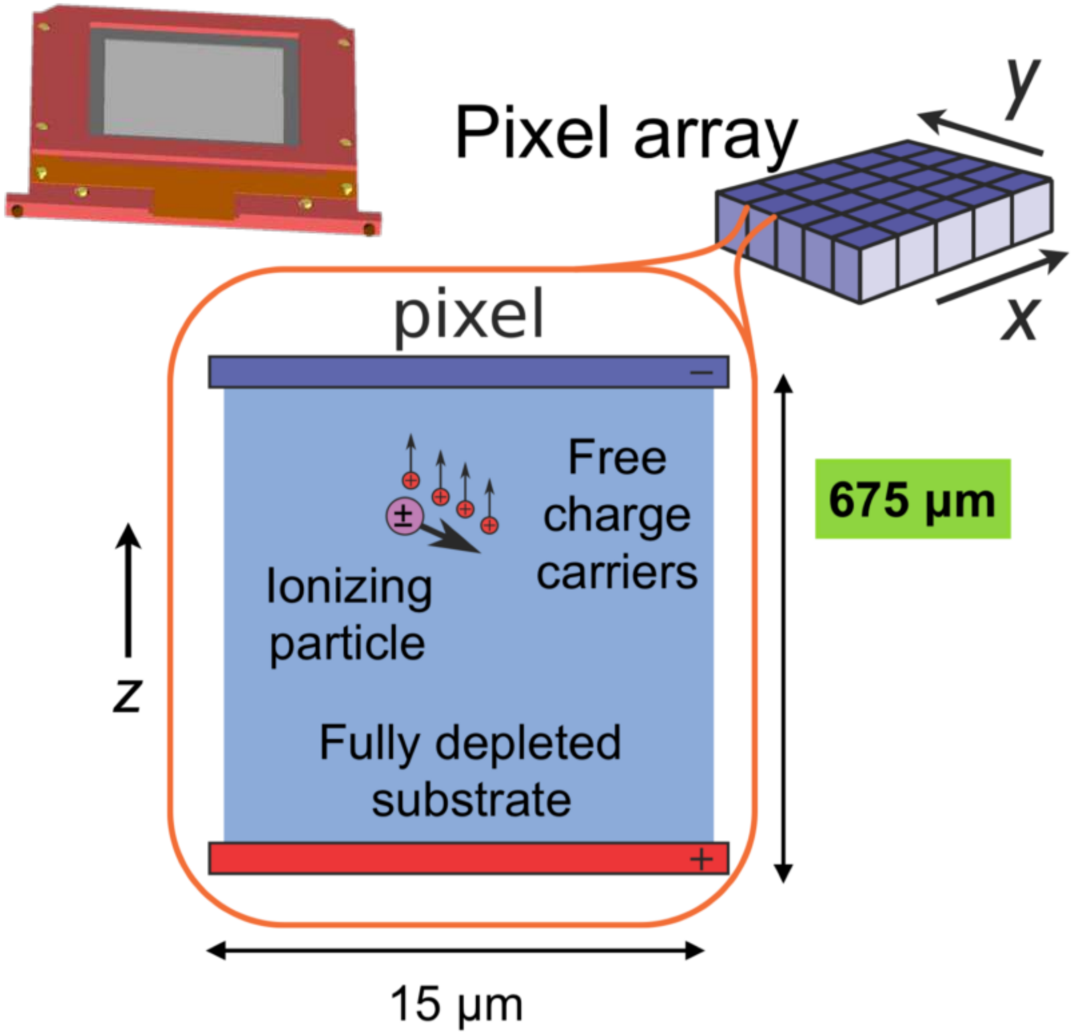
Direct Detection

- Build a detector to identify the small energy deposition of dark matter scattering off SM particles
- Scattering off nuclei (elastic):
  - The standard WIMP paradigm
  - 1-1000 GeV DM masses
  - 0.3-300 keV recoil energy
- Scattering off electrons (inelastic):
  - As in the case of a dark photon
  - 1-1000 MeV DM masses
  - 1-100 eV recoil energy



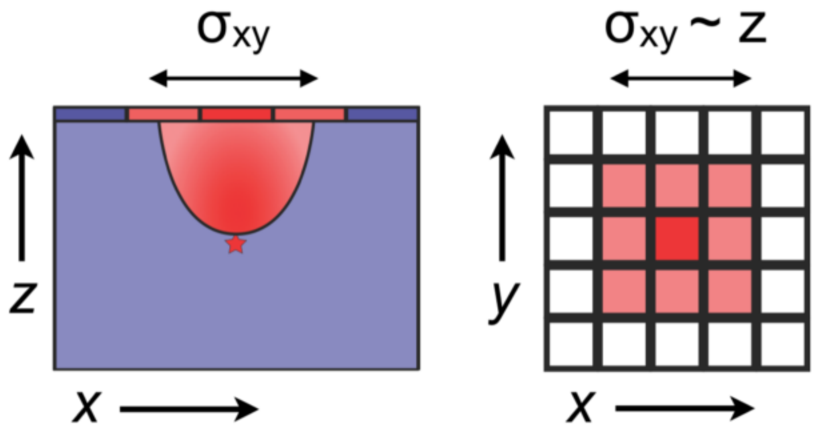
DAMIC Collaboration

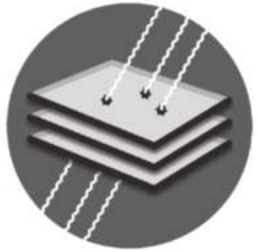
Charge Coupled Devices



- Interaction with silicon produces free charge carriers…
  - …which are drifted across fully-depleted region… → *very little loss of charge*
  - …and collected in 15 micron square pixels… → *exceptional position resolution*
  - …to be stored until a user-defined readout time after many hours. → *large exposures*
- The method of read-out can be optimized to improve read-out noise at the cost of position resolution (1x100 binning)

Pixelization

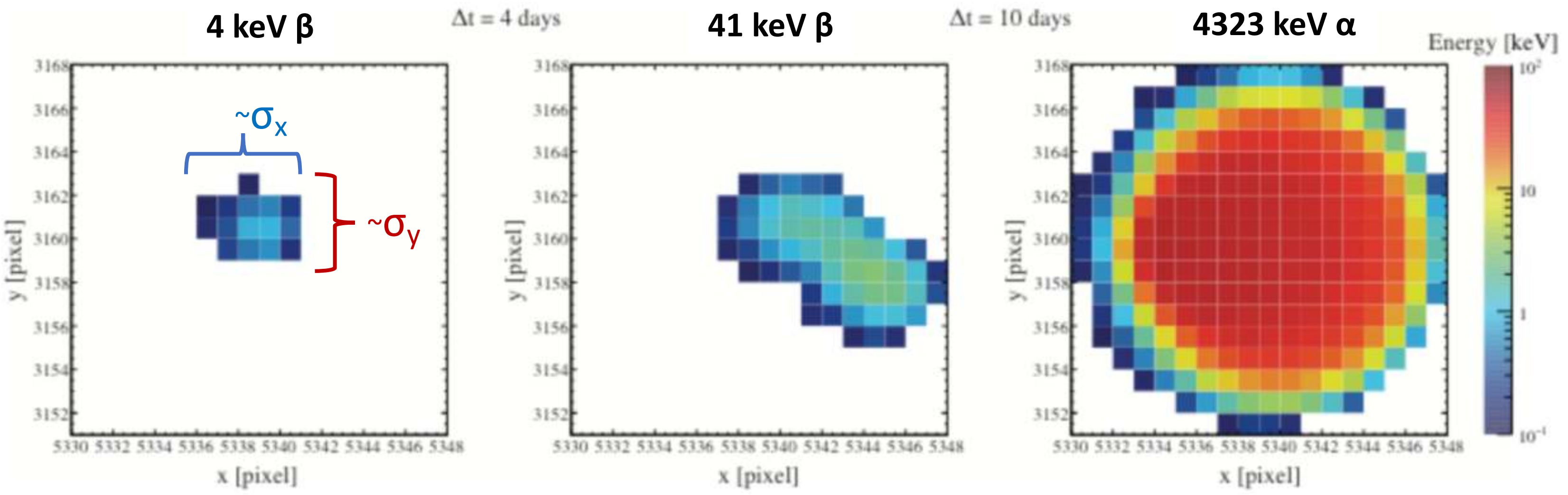




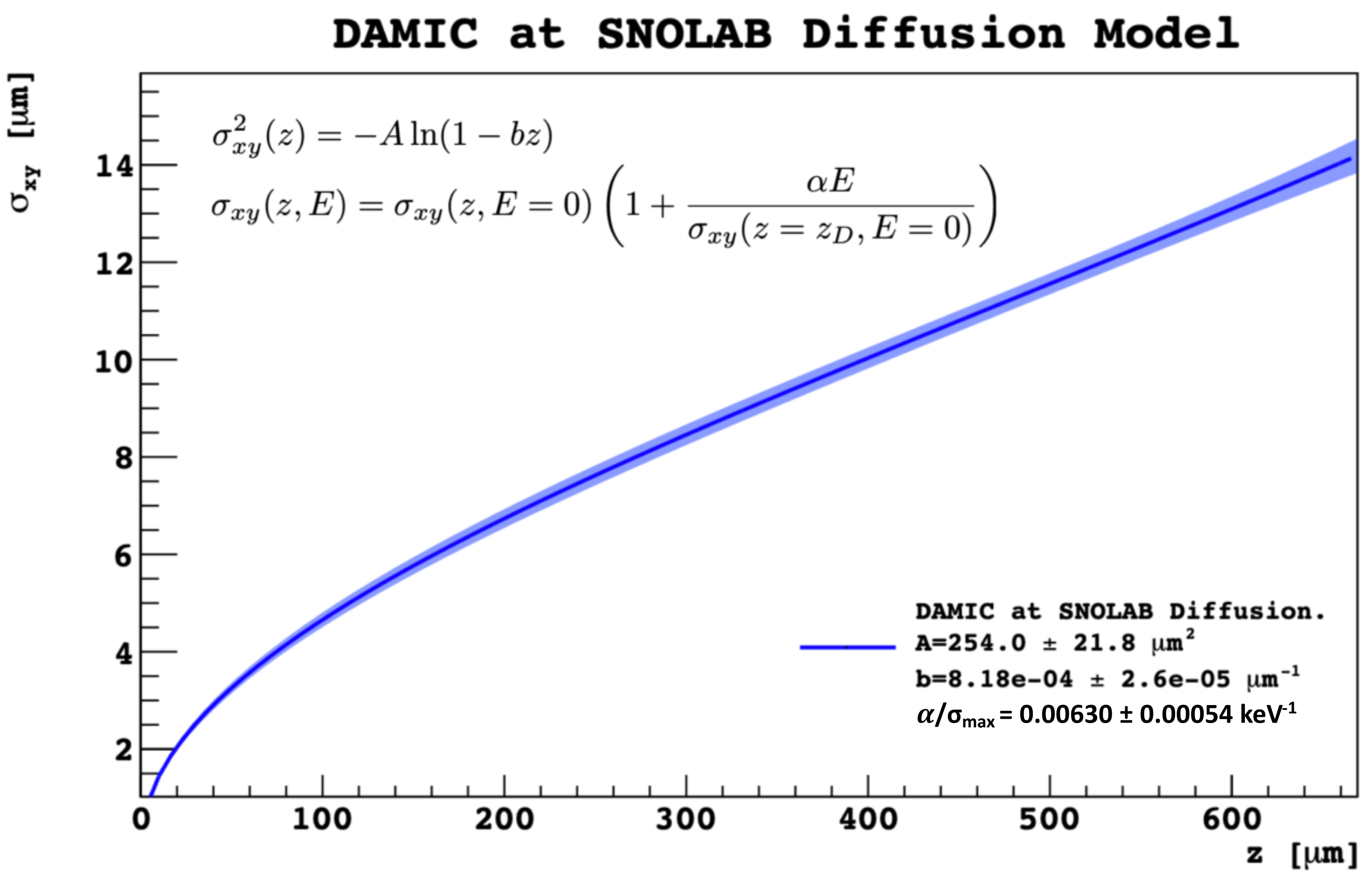
- Silicon band-gap: 1.2 eV
- Mean energy/e⁻: 3.8 eV

- As charges drift across the CCD, they experience lateral thermal motion (diffusion) proportional to vertical distance traveled (depth)
- Above 1 keV, the event profile can identify the progenitor…

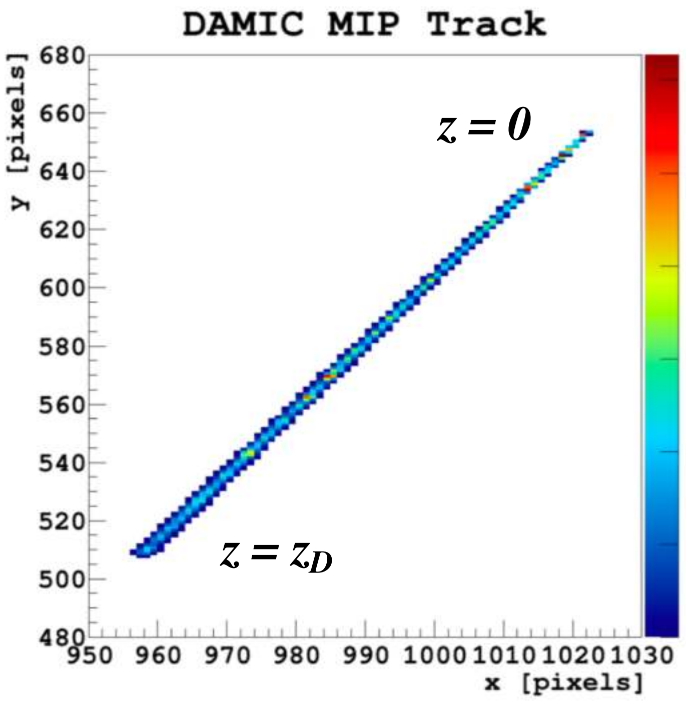
1. **Tight deposition:**
   - **nuclear recoil**
   - **low-E electron recoil**
2. Elongated track:
   - high-E electron recoil
   - muon
3. Large blob:
   - alpha decay



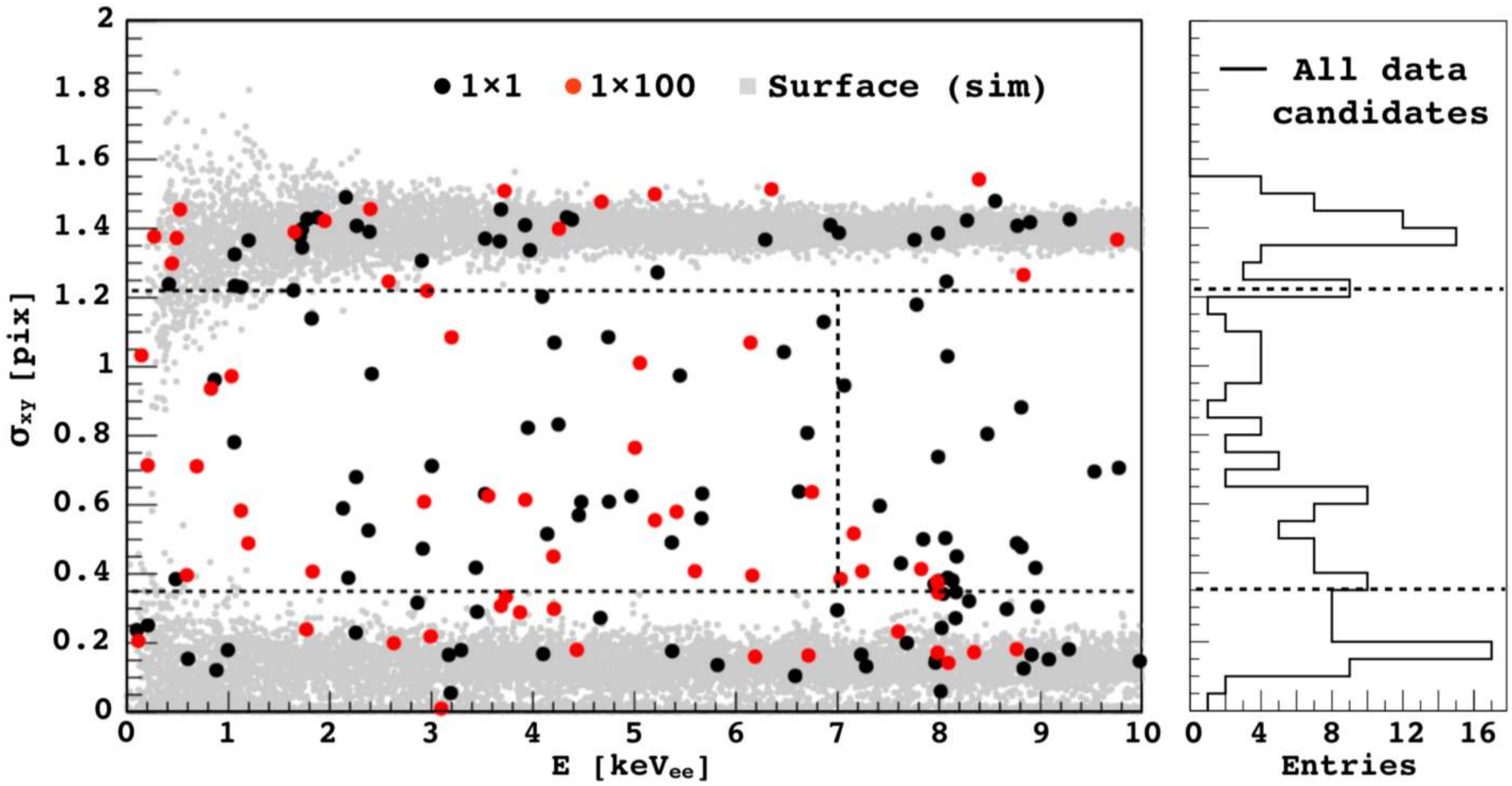
Modeling Diffusion



- Muons give an excellent calibration for the depth-dependence of sigma



DAMIC WIMP Results (2016)



A. Aguilar-Arevalo et al. Phys. Rev. D 94, 082006 (2016)

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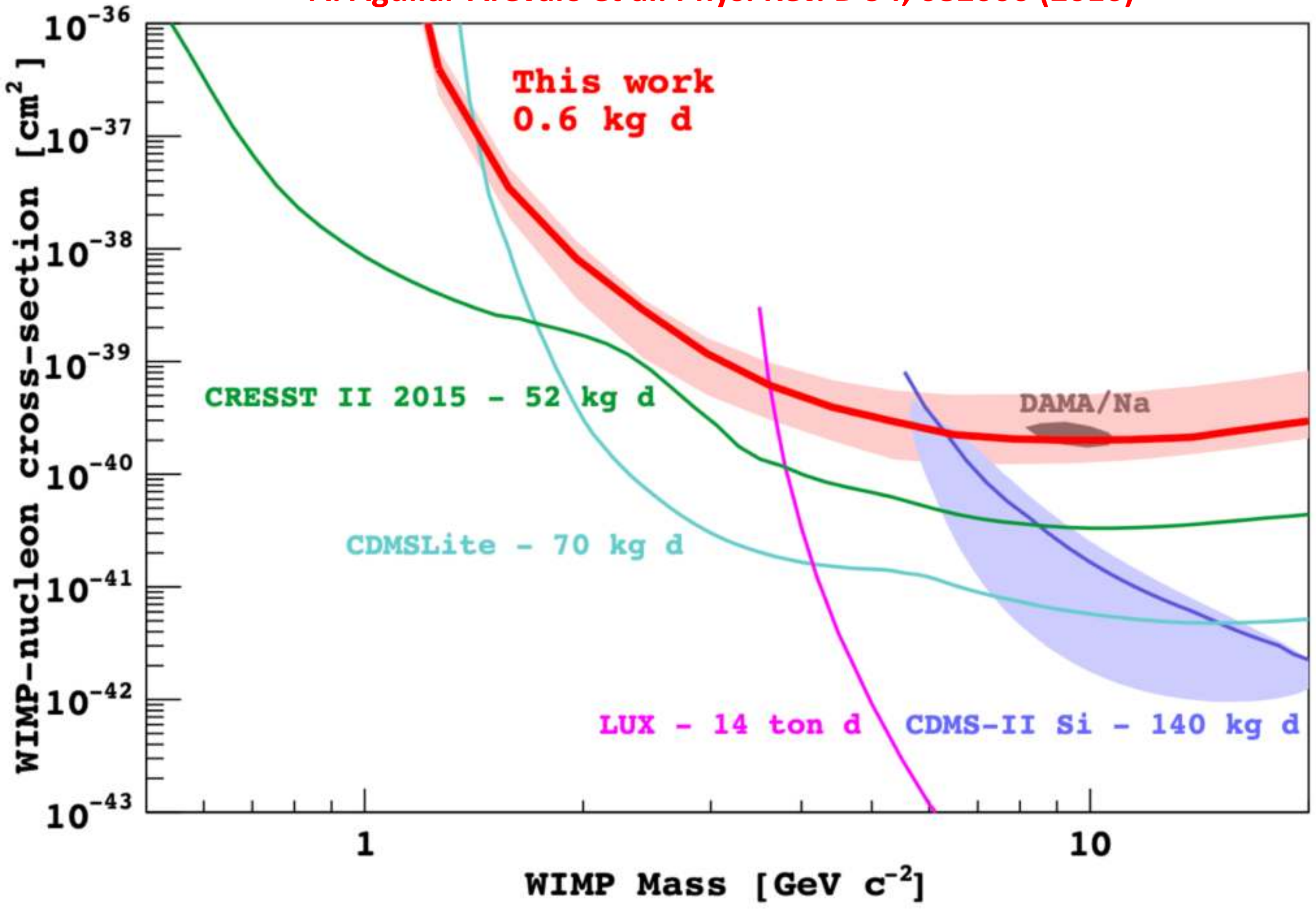
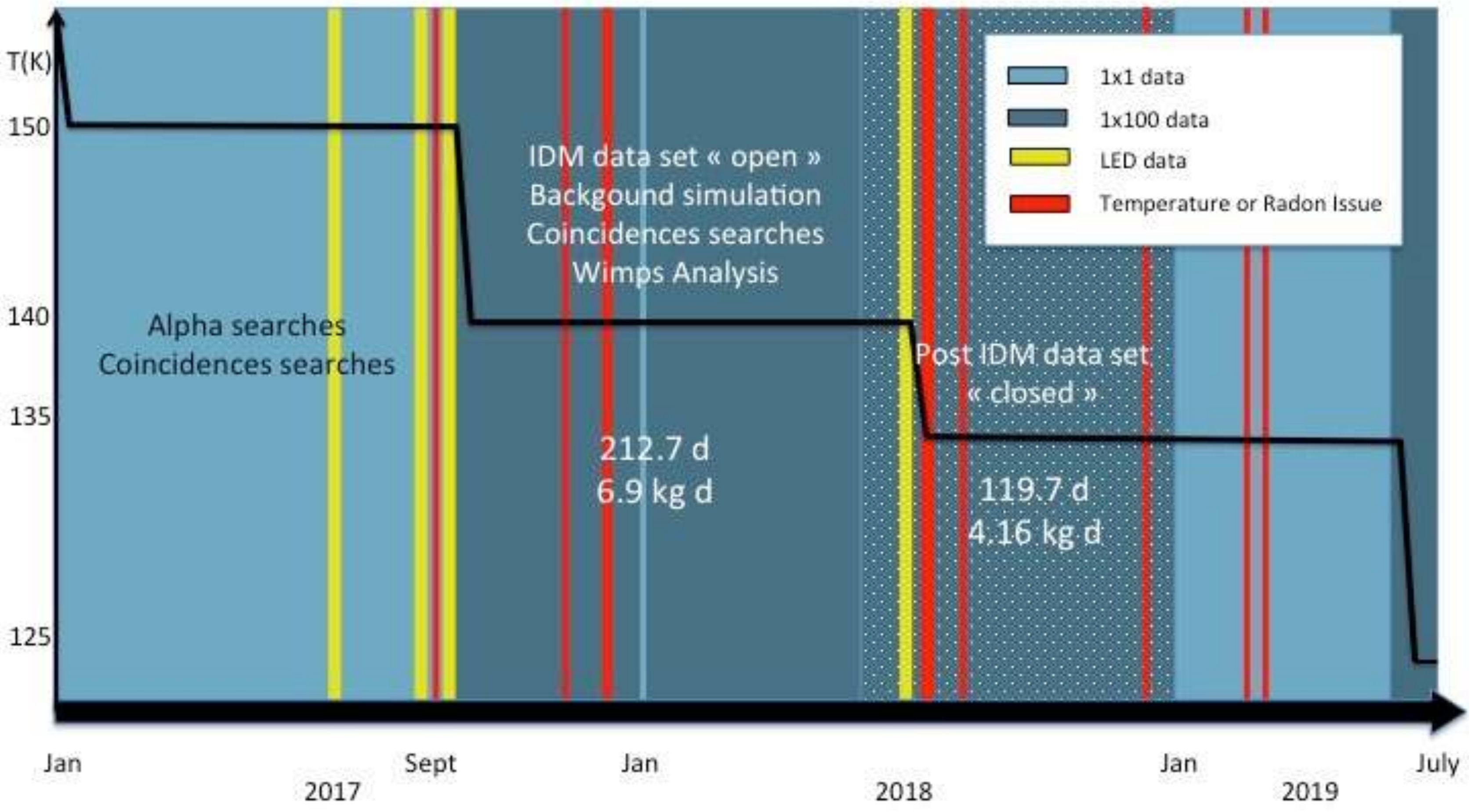


- Prototype detector deployed at SNOLAB with 8Mpix (2.9g) silicon CCDs during 2015
- Successfully demonstrated the ability of a low threshold CCD array to search for dark matter

DAMIC at SNOLAB Upgrade

- The prototype run of DAMIC at SNOLAB never held more than 9g of CCDs with a fiducialized background rate of ~15 counts/kg/day/keV (dru)
- The DAMIC at SNOLAB upgrade (presented here) contains:
  - (x7) 16 Mpix (6.0g) active CCDs (total mass = 42 g)
  - >300 days of cumulative exposure
  - Significantly lower backgrounds due to addition of ancient lead shield (fiducialized background rate of ~4 dru)
  - **One CCD (Extension 1) held in an EF copper module and surrounded by lead bricks (fiducialized background rate of ~2 dru)**

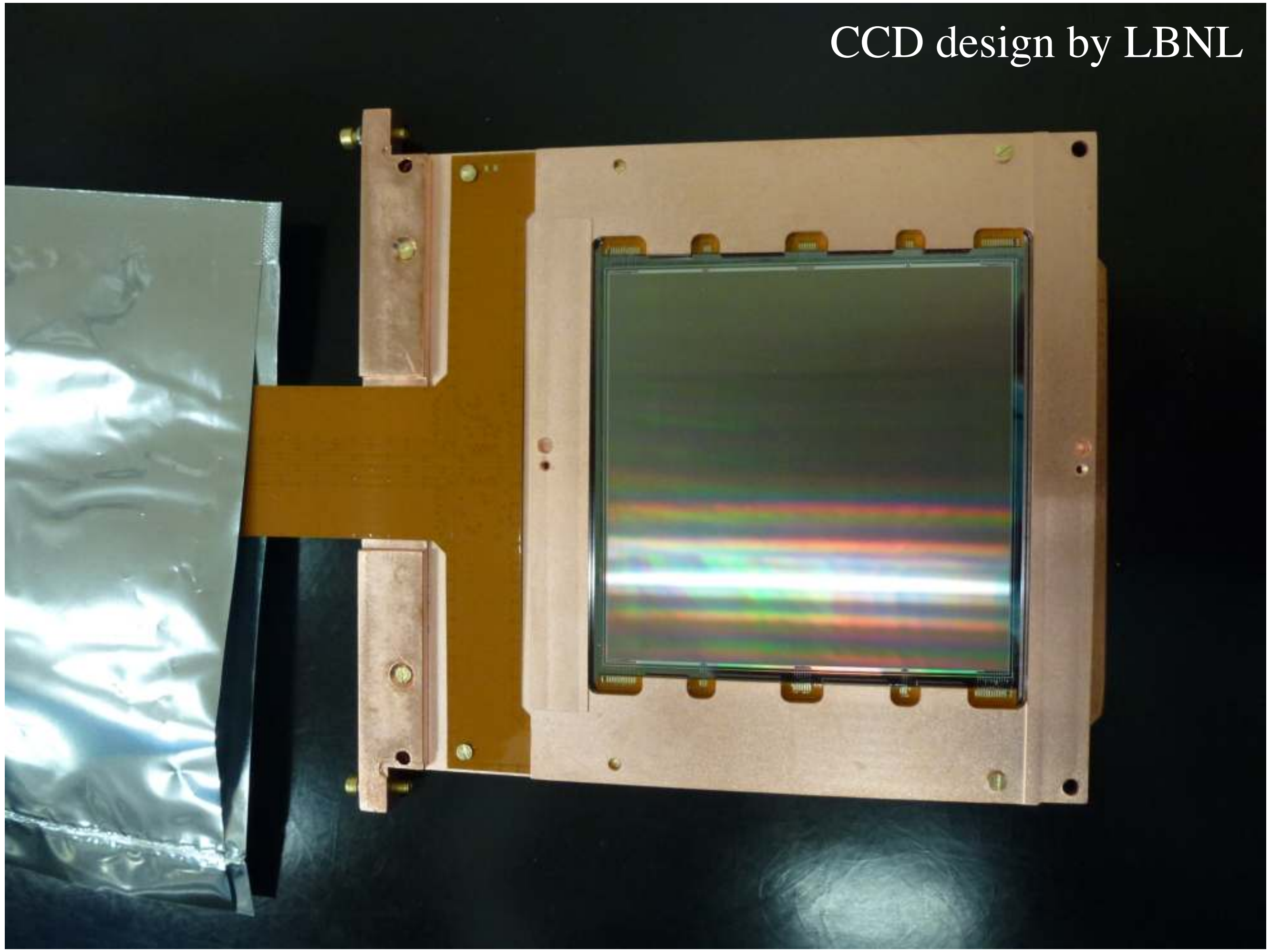
DAMIC at SNOLAB Upgrade



DAMIC at SNOLAB CCDs

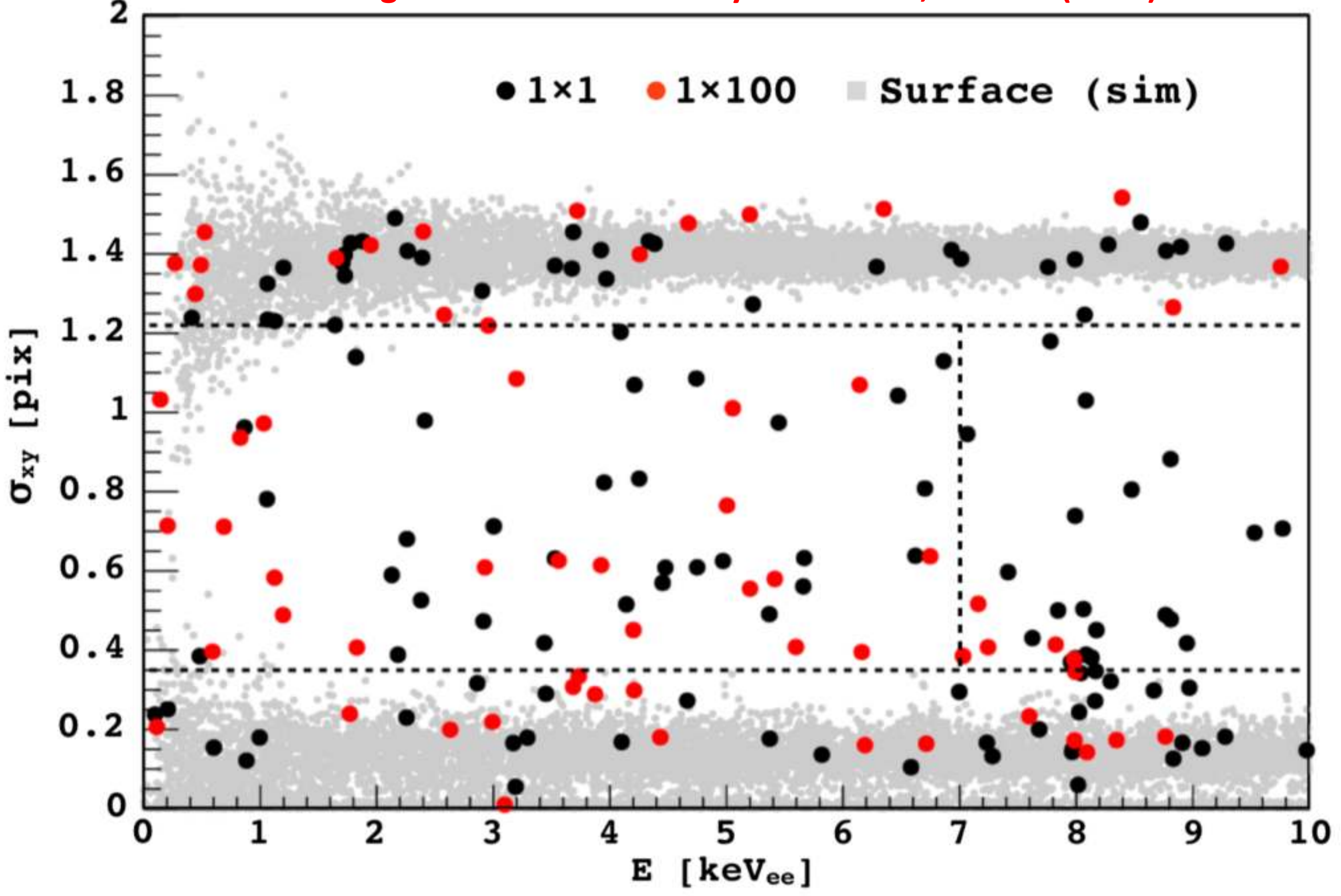
- 4000x4000 pixels (6x6 cm^2)
- Pixel size 15x15 $microns^2$
- Thickness ~675 microns
- Cooled to 140 K
- One Kapton cable per CCD

- Dominant intrinsic background expected to be tritium production from direct activation of the silicon wafers prior to production



Next: Updated Nuclear Recoil Search

A. Aguilar-Arevalo et al. Phys. Rev. D 94, 082006 (2016)



- In the 2016 result, a fiducial cut (in ***σ***) was used to isolate the "bulk" of the detector
- At lower energies, the difference between bulk and surface is less clear
- **We're going to need a background model!**

Build-a-Background-Model

1. **Categorize detector backgrounds (ER: $\boldsymbol{\gamma}/\boldsymbol{\beta}$)**
   - Assumption: neutron, muon, alpha –induced backgrounds are subdominant

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   - Maximum: above 6 keV_{ee}, mostly sensitive to heavier DM (M_χ > 10 GeV)

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   - Ext1 is sandwiched between two ancient lead bricks and has ~half the background

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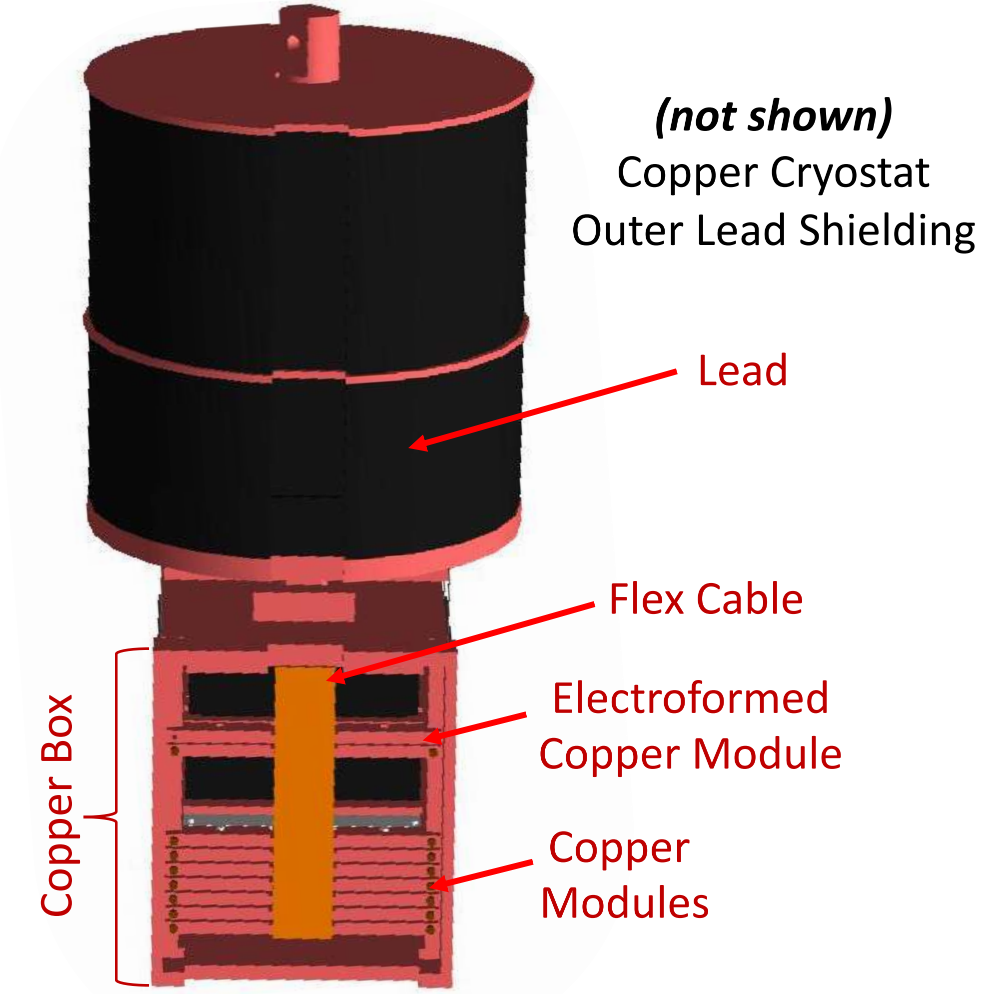
4. **Set aside some amount of data as a check (Ext1)**
   - Ext1 is sandwiched between two ancient lead bricks and has ~half the background
5. **Perform a fit against data (6 – 20 keV_{ee})**
   - Assumption: no DM sensitivity in this mass range
   - Maximum: want to include full tritium spectrum (endpoint 18.6 keV_{ee})

GEANT4 Geometry

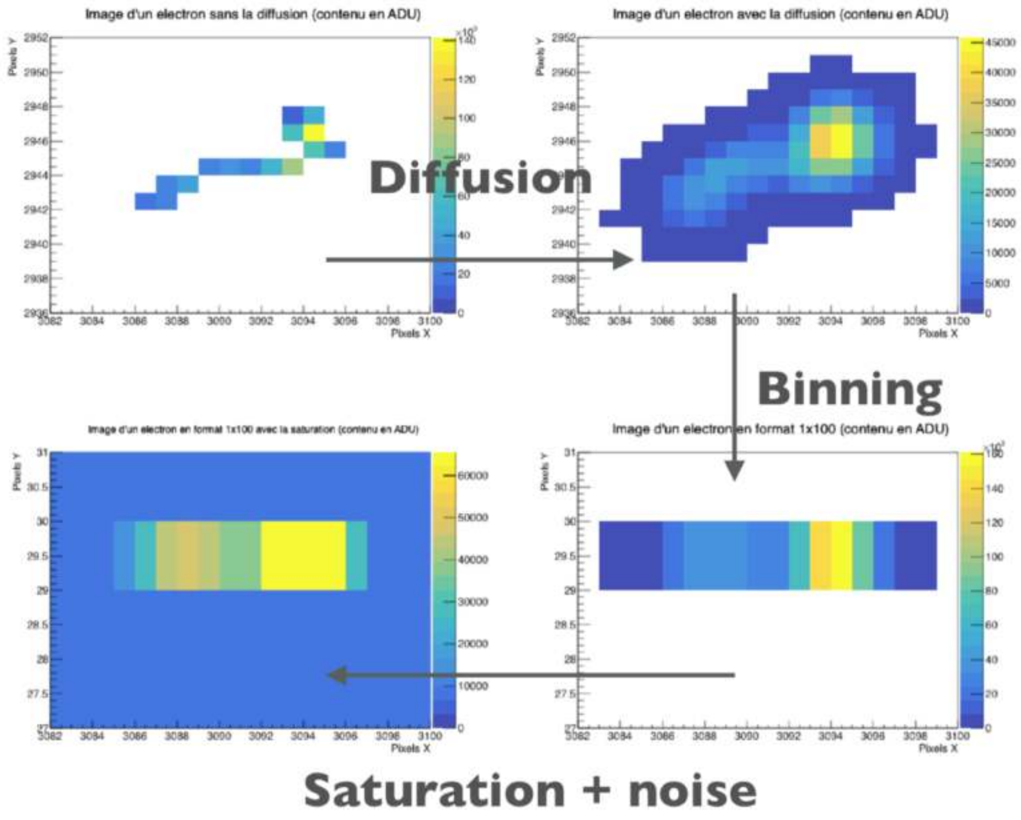


Decay Chains Simulated

Parent Chain	Isoptopes Considered	Simulation ID	Comments
U238	Pa234	234a91z	
	Th234	234a90z	
Ra226	Pb214	214a82z	
	Bi214	214a83z	
Pb210	Pb210	210a82z	(surface and bulk)
	Bi210	210a83z	
Th232	Ac228	228a89z	
	Ra228	228a88z	
	Pb212	212a82z	
	Bi212	212a83z	0.64 BR
	Tl208	208a81z	0.36 BR
K40	K40	40a19z	
Activation	Co56	56a27z	(copper/flex/screws)
	Co57	57a27z	
	Co58	58a27z	
	Co60	60a27z	
	Fe59	59a26z	
	Mn54	54a25z	
	Sc46	46a21z	
Si32	Si32	32a14z	(silicon only)
	P32	32a15z	
H3 (Tritium)	H3	3a1z	(silicon only)
Na22	Na22	22a11z	(silicon only)

Processing Simulation Output

- Each isotope is individually simulated for each detector volume with the energy and position of each deposition recorded.
- We then apply our diffusion model to the energy depositions and pixelate on our 15x15 micron CCDs
- …rebin these pixels according to our 1x100 readout
- …and apply saturation and noise



Material Assays

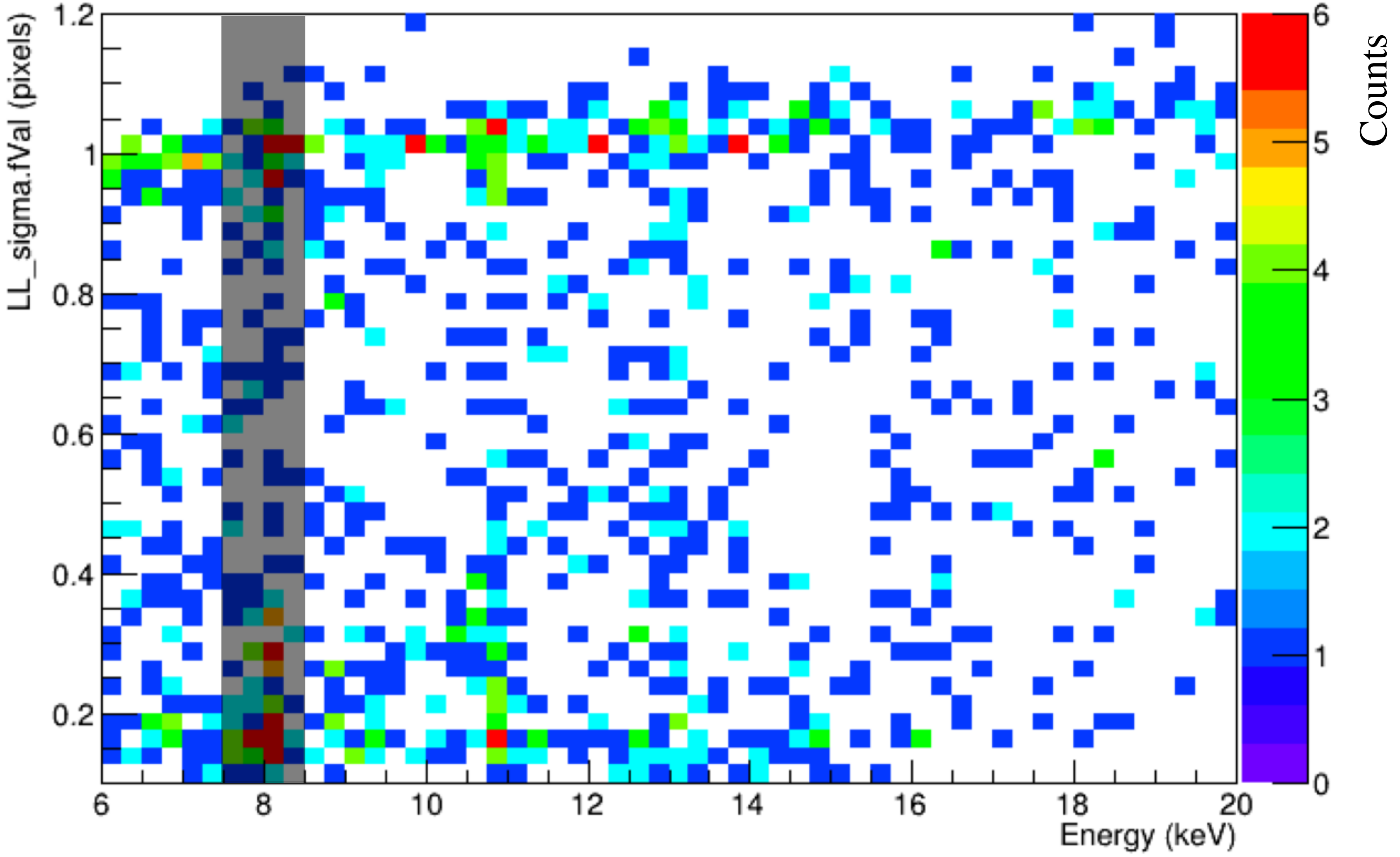
Part	U-238	Ra-226	Pb-210	Th-232	K-40
CCD	<0.53	<0.43	<33*	<0.4	<0.04
Kapton cable	5000 ± 420	420 ± 490	420*	280 ± 40	2480 ± 170
Copper	<10.7	<11.2	2350 ± 720	<3.5	<2.7
Module Screws	1400 ± 3800	<138	$2350 \pm 720^{\dagger}$	200 ± 140	2400 ± 1300
Ancient lead shield	<2.0	<22.5	$2850^{\ddagger}$	$0.2^{\ddagger}$	<0.5
Outer lead shield	<1.1	<17.6	1560000 ± 430000	<0.4	<19

(all activities above in decays/kg/day)

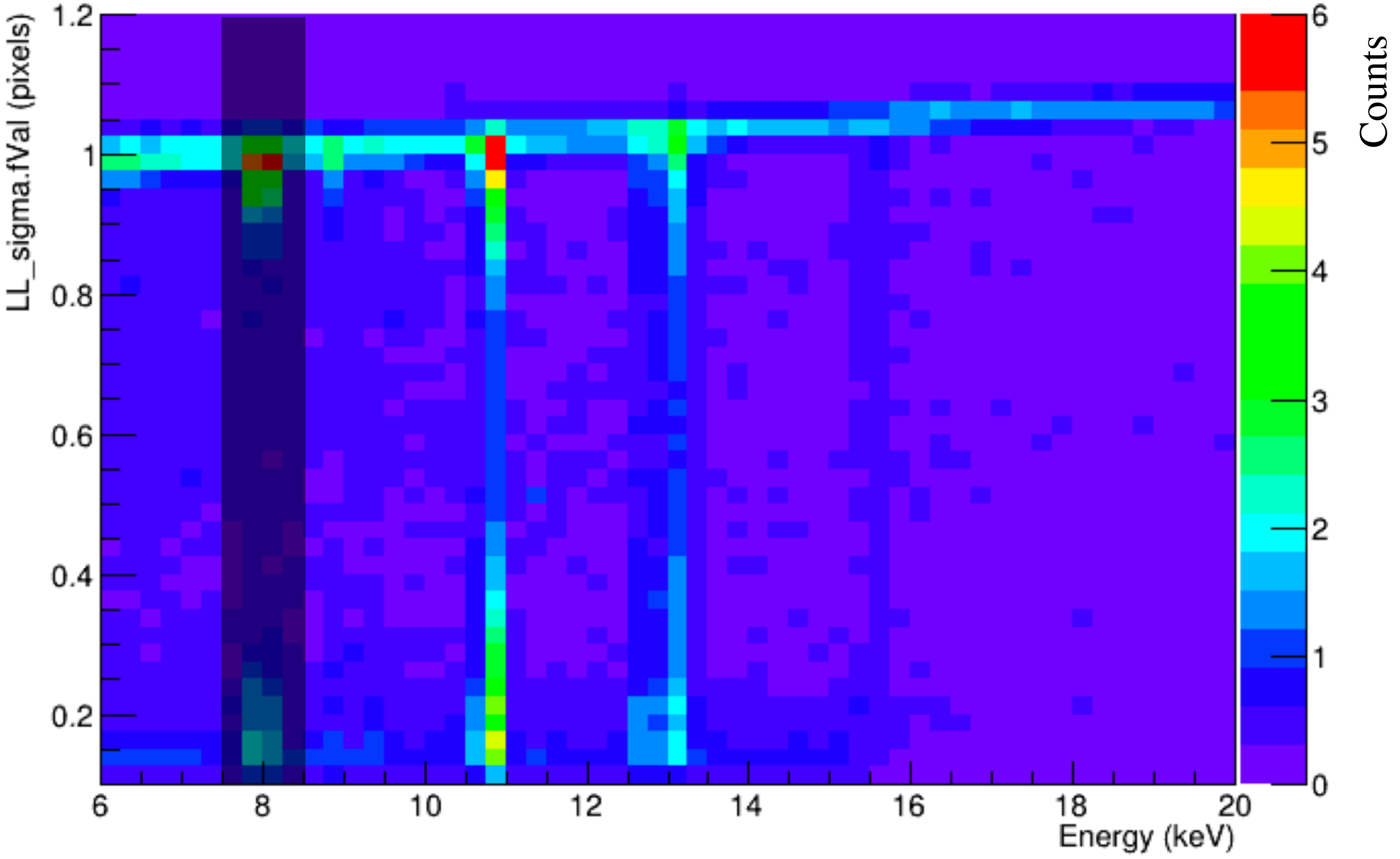
- We assayed all components near the CCDs to the level at which each is simulated to contribute 1 dru
- The CCD activities actually come from a direct analysis of our data, which puts far stronger constraints than the assays which we have performed thus-far

A. Aguilar-Arevalo et al, JINST 10 (2015) P08014 [arXiv:1506.02562]

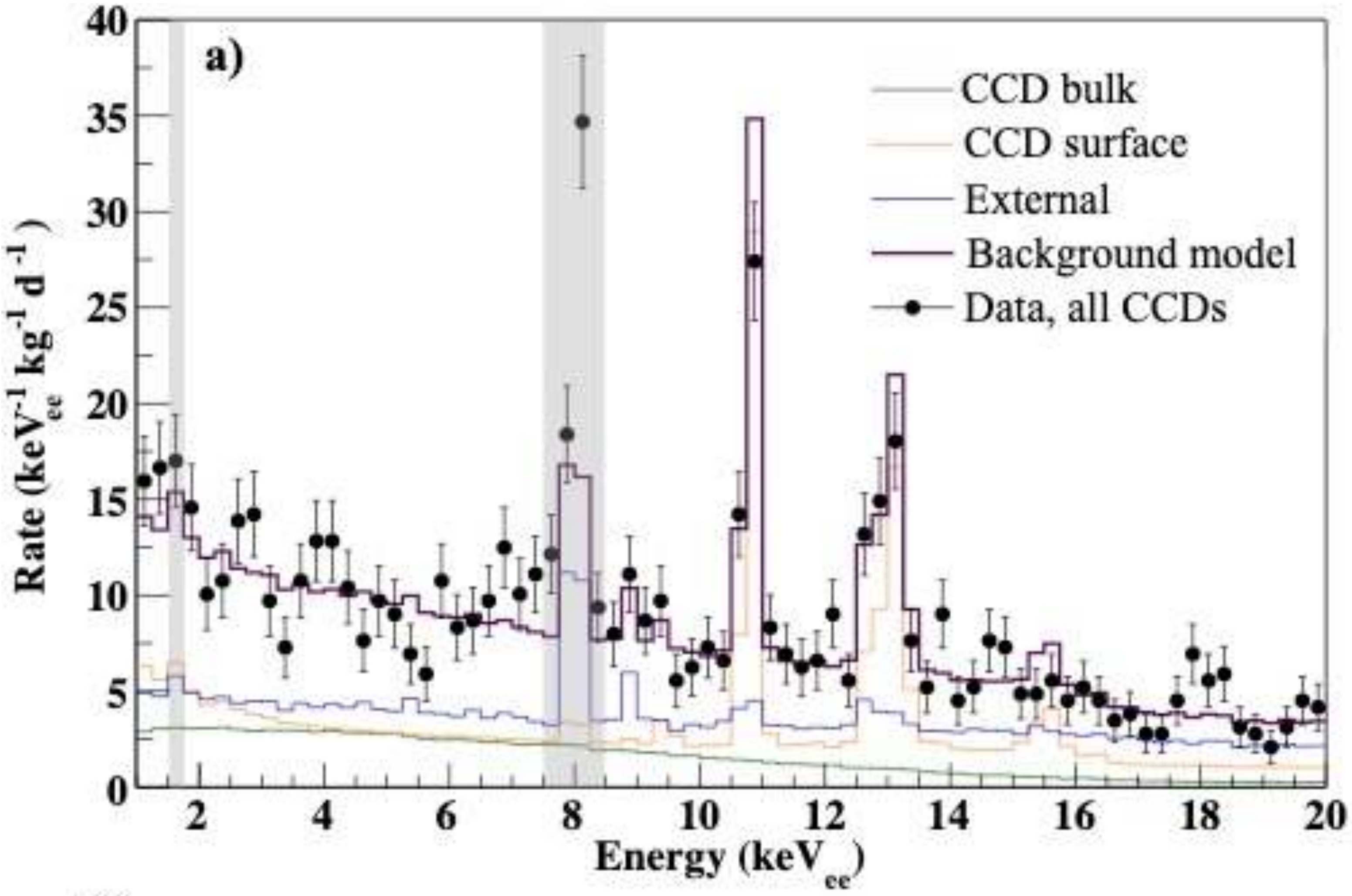
Fitting Against Data



Simulation Best Fit

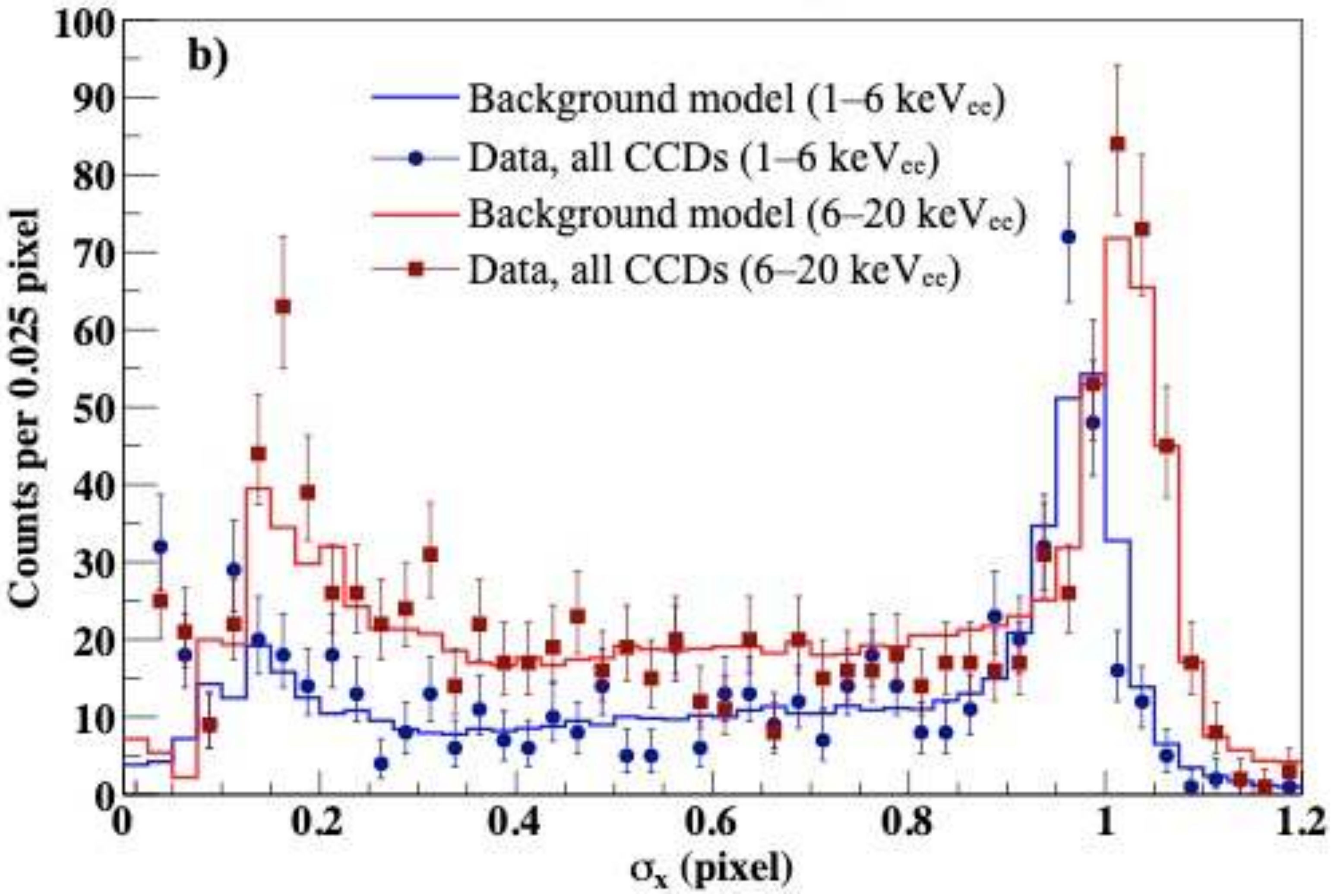


Energy Projection



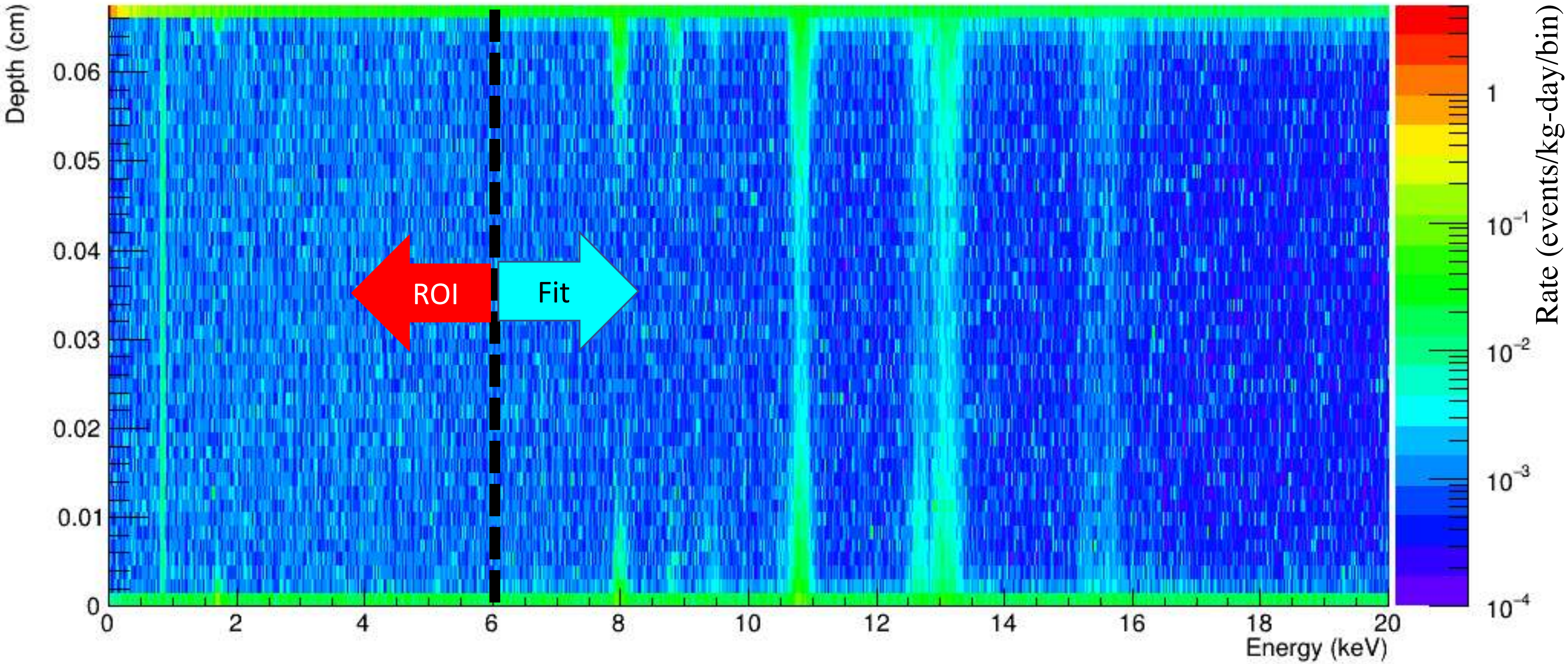
A. Aguilar-Arevalo et al. [arXiv:2007.15622] (2020)

Sigma Projection



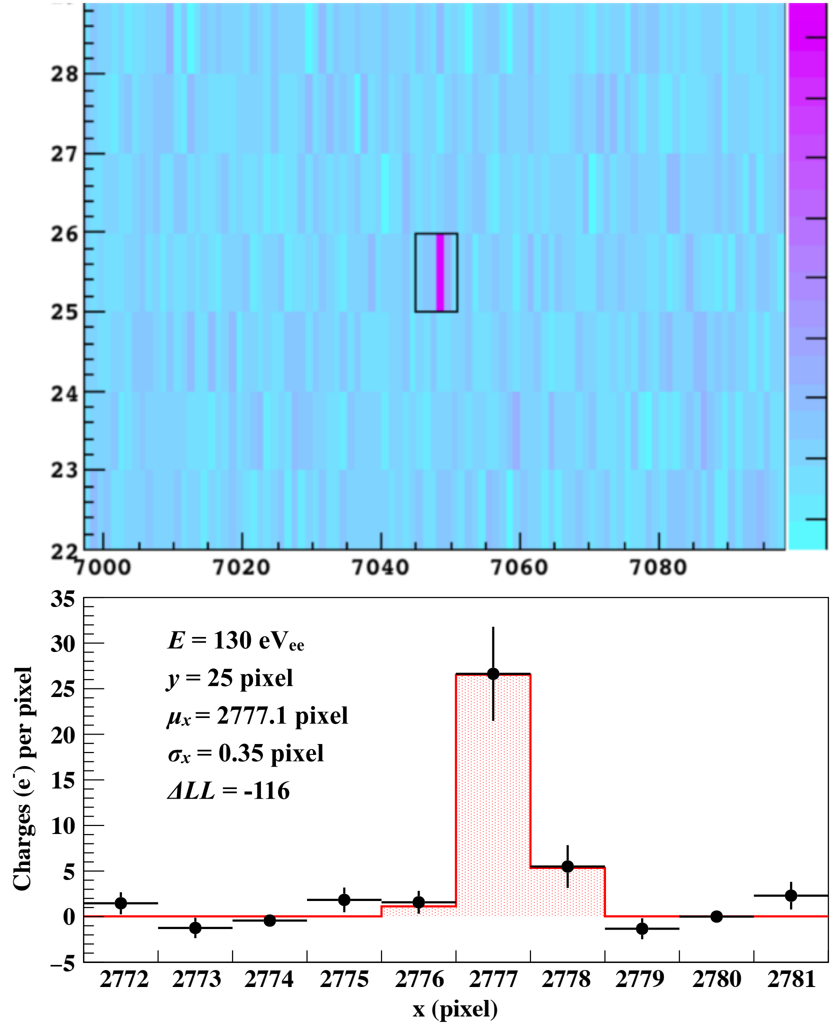
A. Aguilar-Arevalo et al. [arXiv:2007.15622] (2020)

Output (simulated variables)



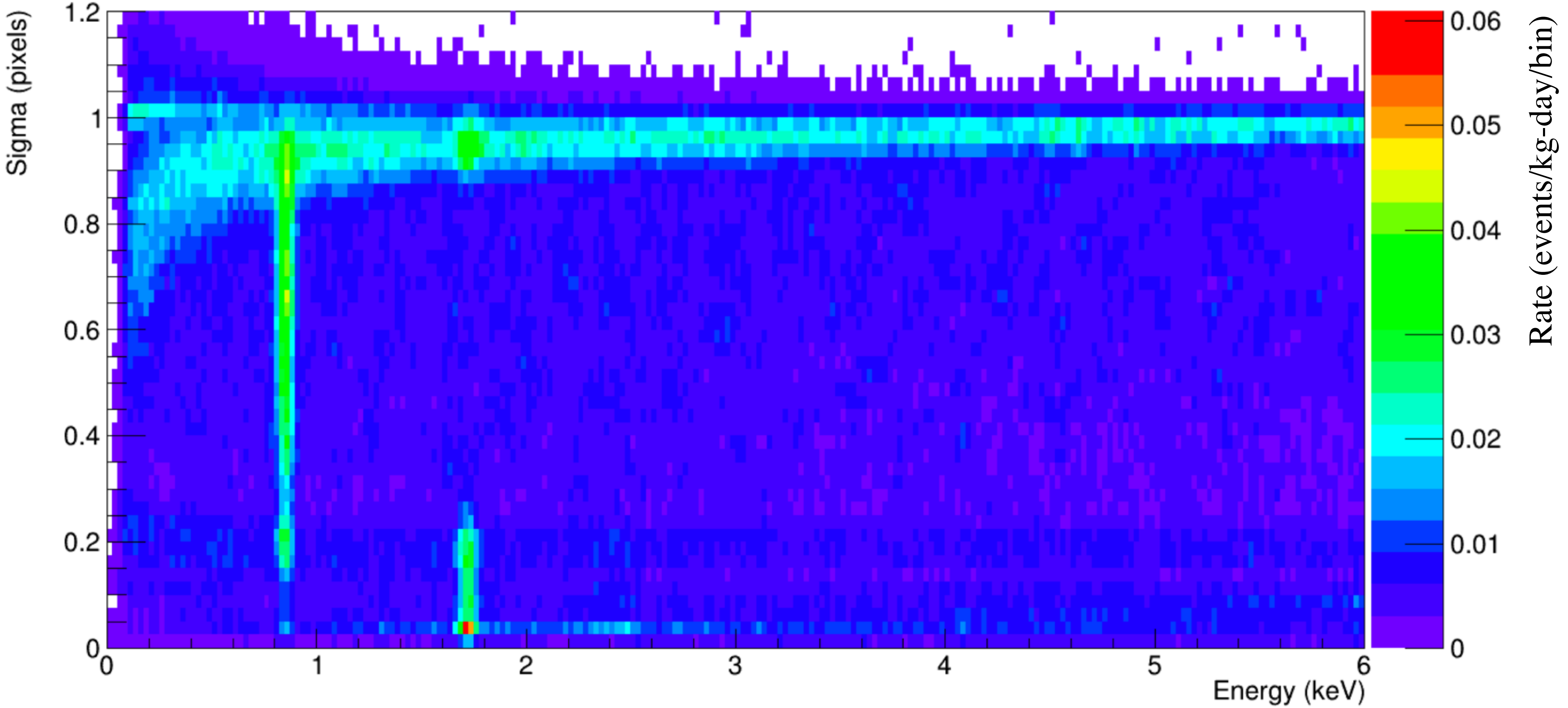
Producing Reconstructed Coordinates

- So we have a background model in terms of simulated (true) variables
- We need a way to translate these variables into reconstructed variables to compare against data down to our 50 eVee threshold
- Procedure:
  1. Randomly sample the background model
  2. Apply diffusion model to translate depth into a pixel spread
  3. Paste this diffused pixel spread on a blank (zero exposure) image to account for readout noise
  4. Run same clustering algorithm on these fake images as the data

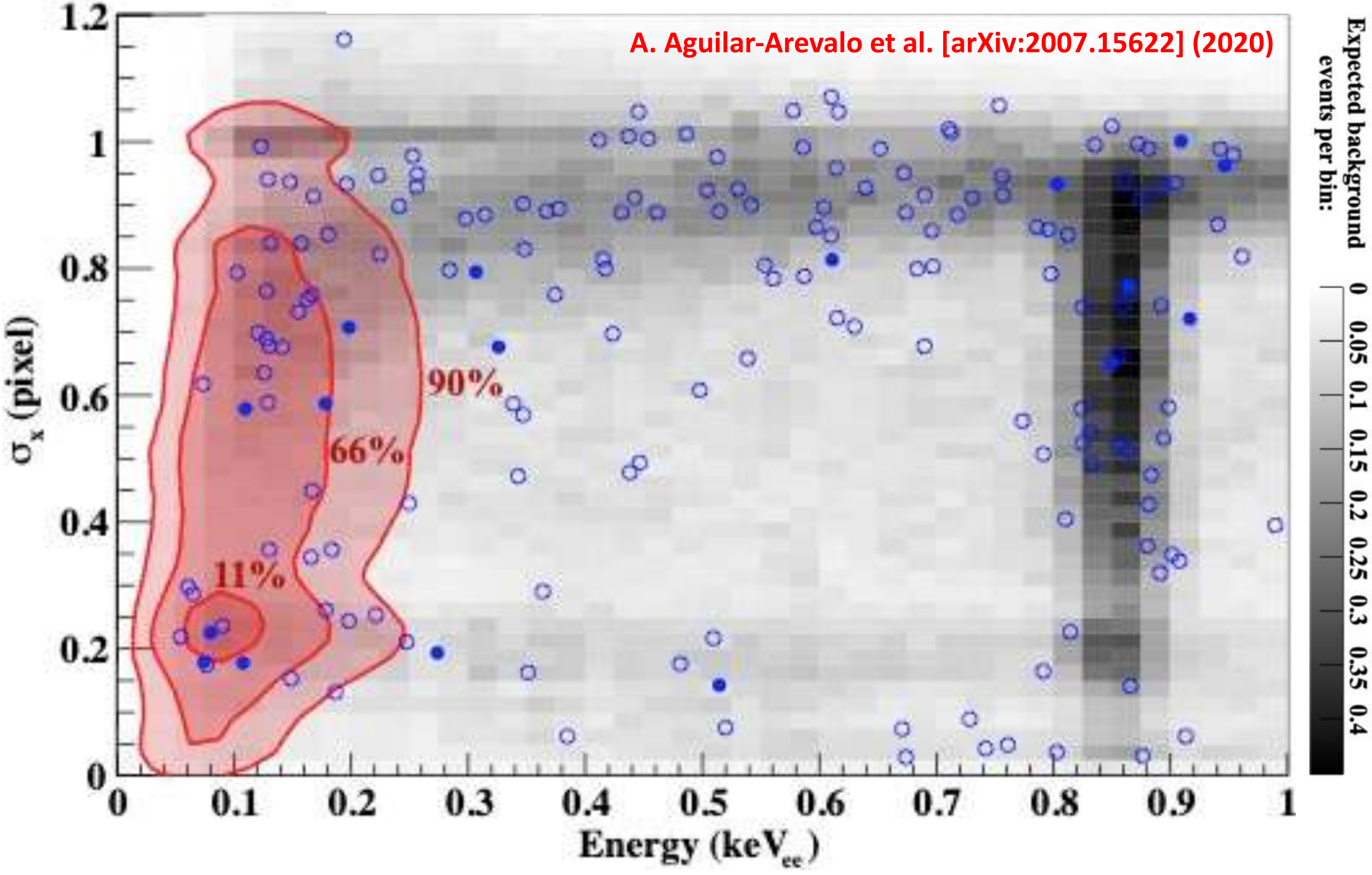


A. Aguilar-Arevalo et al. [arXiv:2007.15622] (2020)

Background Model

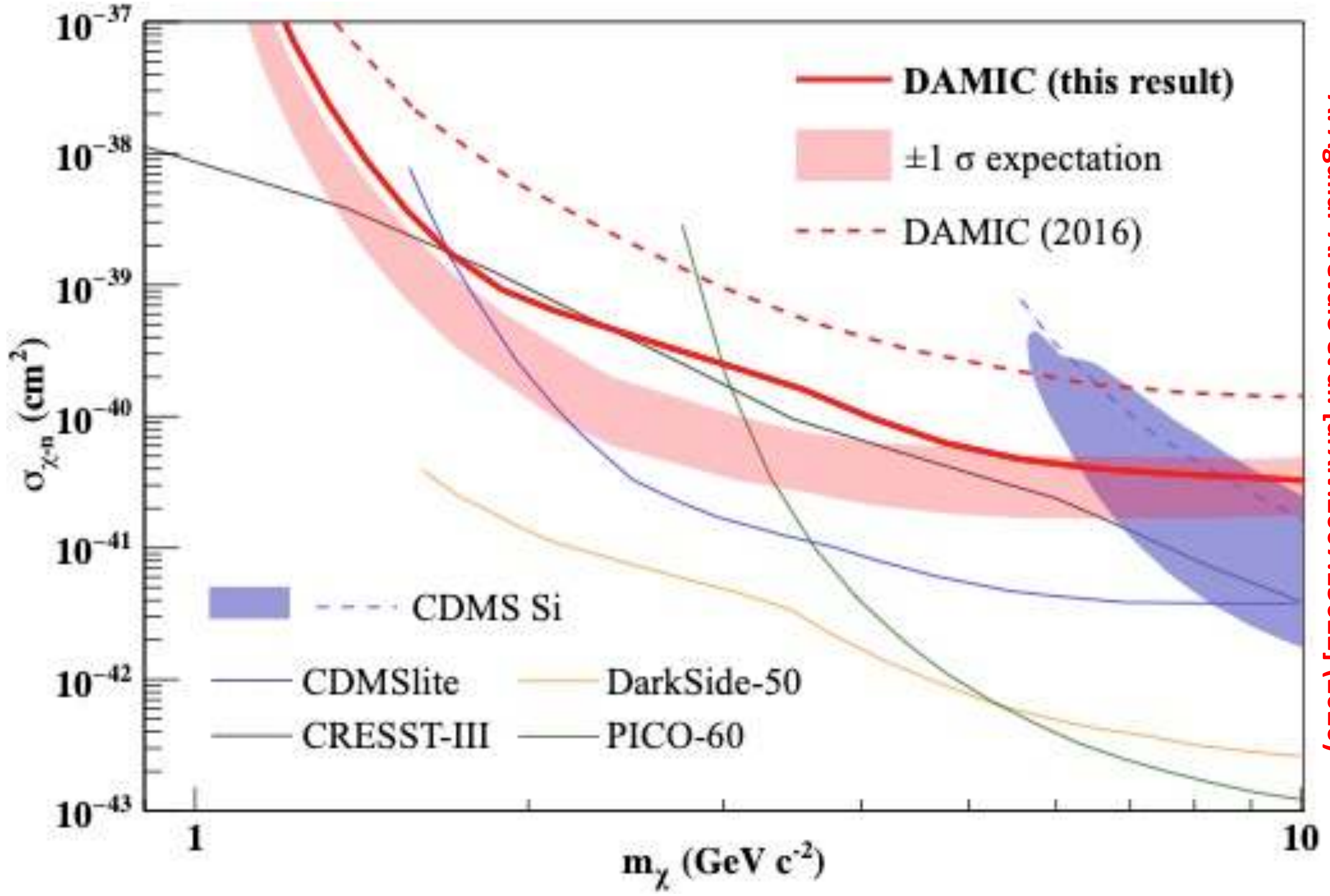


Results



- We observe an excess of bulk events at low energies
- **We do not report this bulk excess as a WIMP signal**
- Need better validation of the background model in this energy range

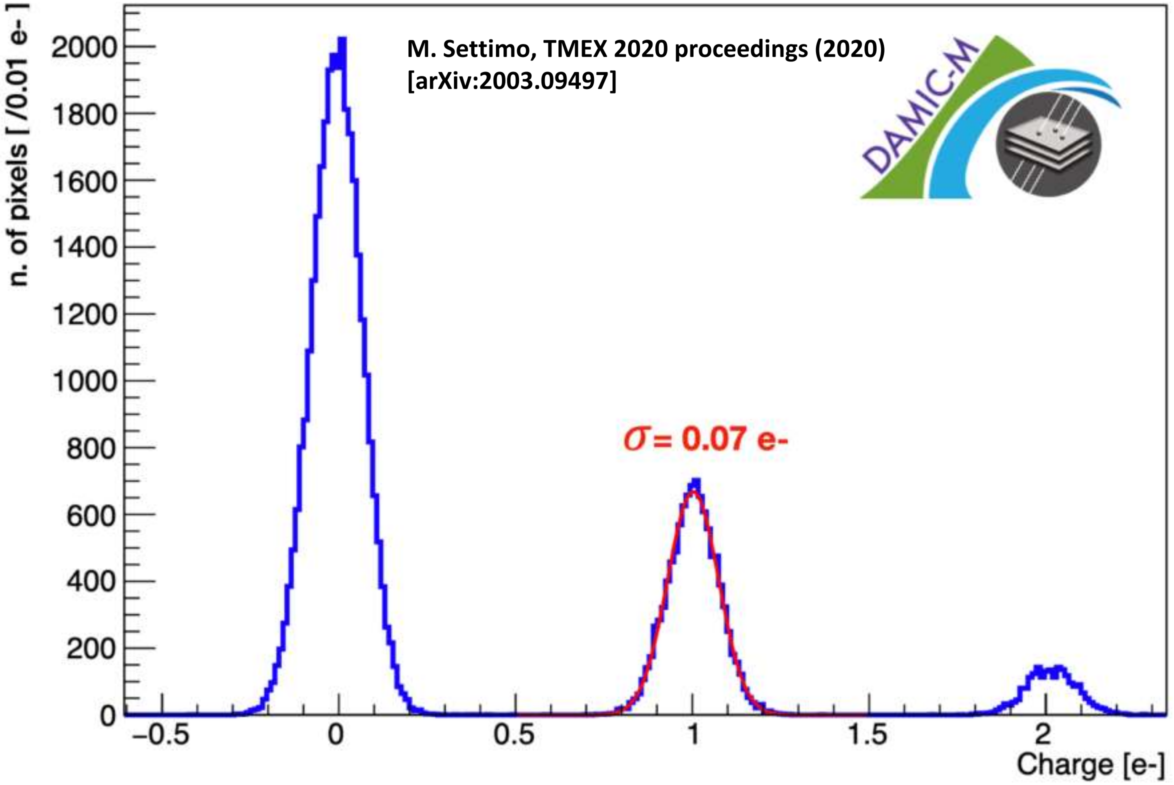
Results – WIMP Limits



A. Aguilar-Arevalo et al. [arXiv:2007.15622] (2020)

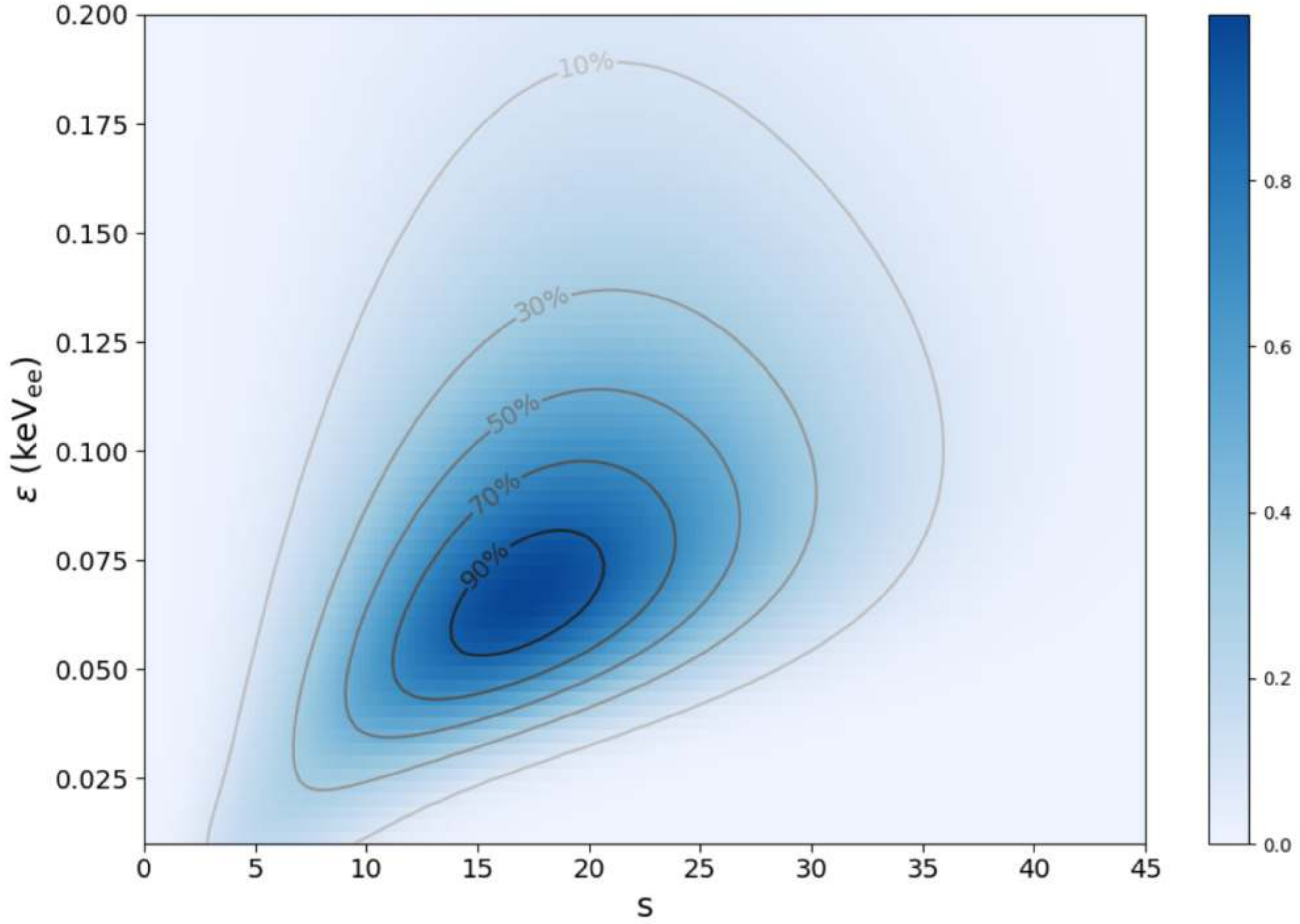
DAMIC Phase 1 Complete!

- DAMIC at SNOLAB is the first CCD dark matter array
- We have improved the limits by a factor of ~10 and excluded a significant fraction of the CDMS-II Si allowed region
- Inevitably, we were going to have a few surprises along the way
- … and we learned a lot about how low background CCDs work!
- Skipper CCDs are the future



Next Steps: Verify

- Ongoing upgrade to the SNOLAB detector will install Skipper CCDs
- …another measurement with lower threshold in the same background environment
    - If this is a threshold effect, it should go away
    - If it is a missing component in the background model, we will have many more events to study



How do we interpret the excess?

Possibilities:

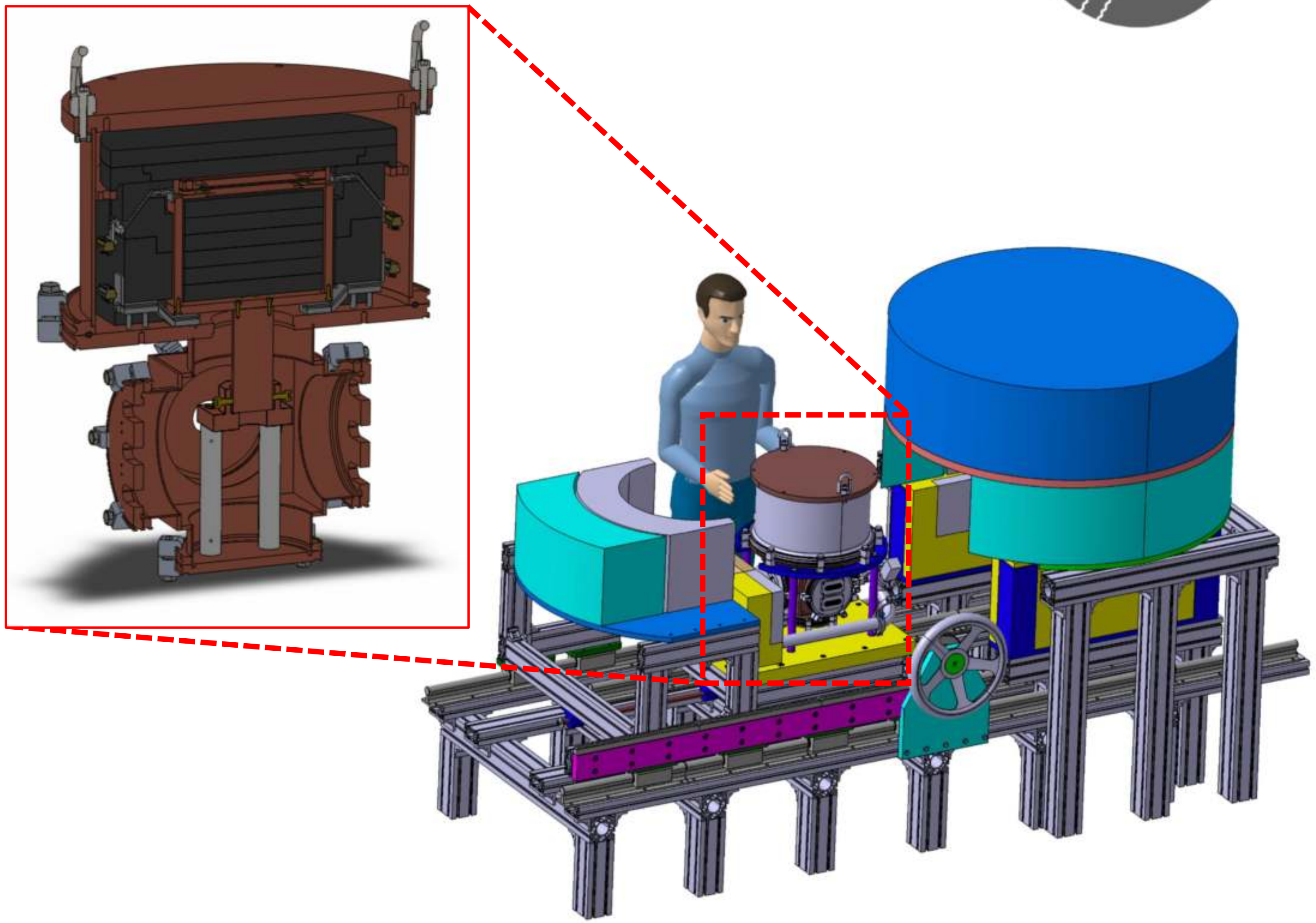
1. We are missing a bulk component in our background model
2. We are missing a front component in our background model
3. We are incorrectly modeling detector threshold effects
4. We are missing a front detector effect
5. **We are observing interesting new silicon physics**
6. **We are observing some type of dark matter interaction**

Background Model (items 1–4)

New Physics (items 5–6)

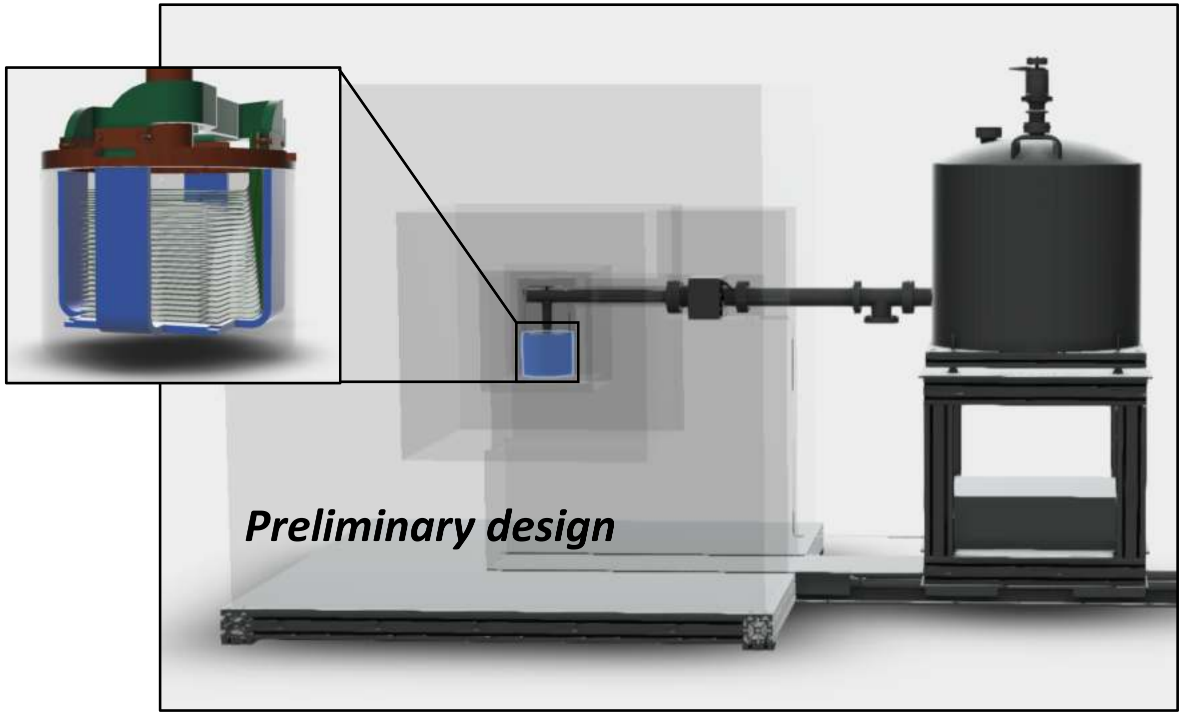
Looking to the Future – DAMIC-M

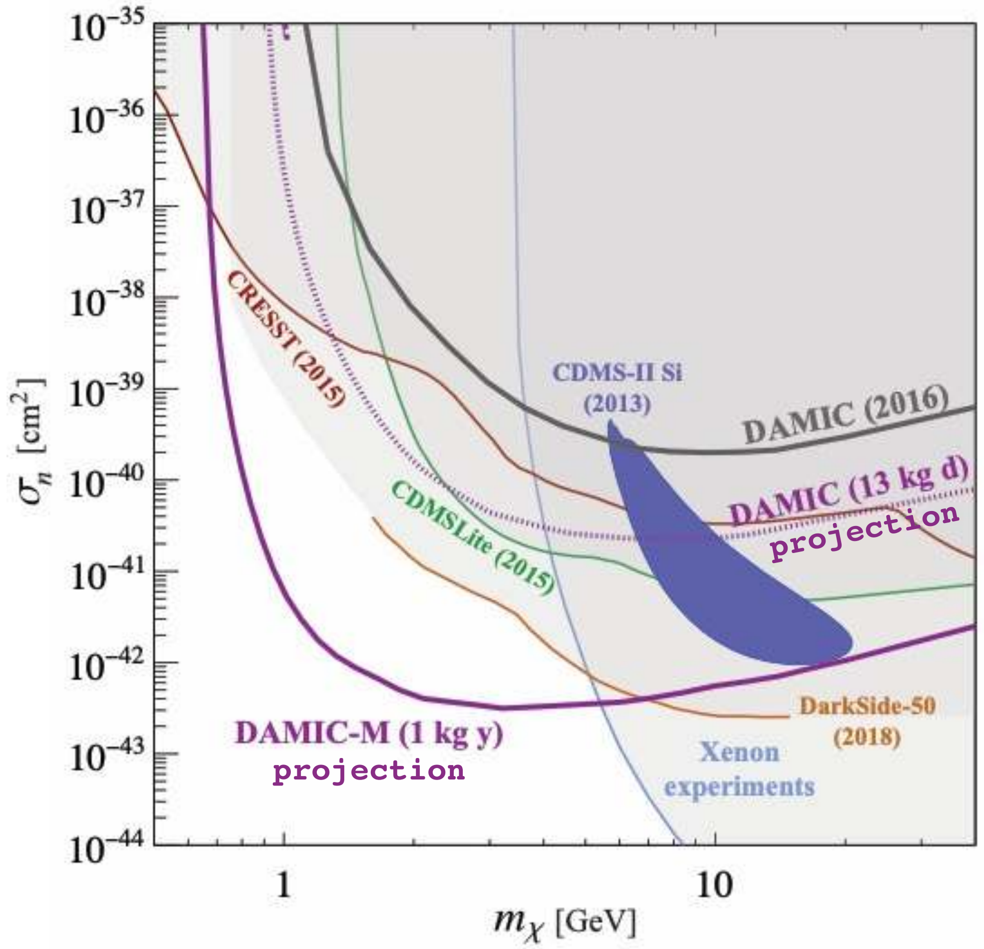
- Prototype DAMIC-M “low background chamber” will test this background model
- 25g of low background Skipper CCDs
- 2 (+4) cm of ancient (low background) lead on all sides of CCD
- Goal: 1 dru and 2e- threshold
- **Results in 2021**



Looking to the Future – DAMIC-M

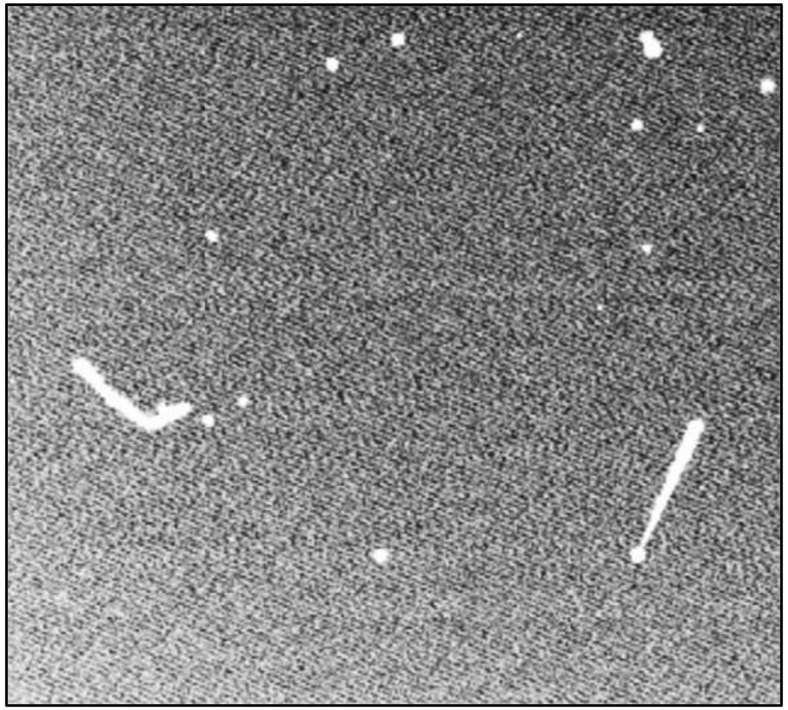
- The DAMIC-M detector (DAMIC at Modane) will achieve background-free exposure of 1 kg-year above a threshold of 2e$^-$ using Skipper CCDs



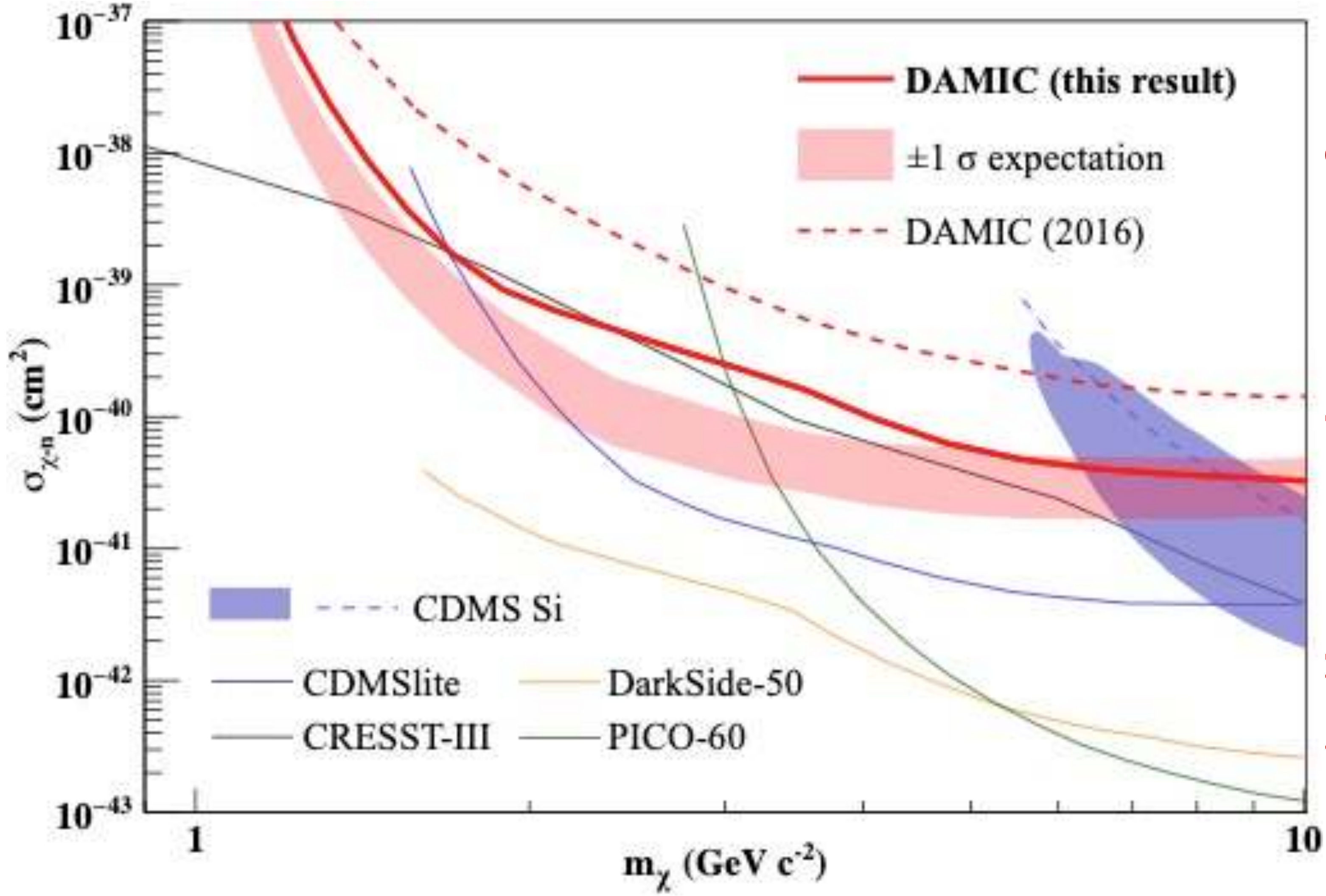


Conclusions

- DAMIC at SNOLAB continues to produce new, interesting results:
  - **NR Limits:** *submitted to PRL (2020) [arXiv:2007.15622]*
  - **ER Limits:** *PRL 123, 181802 (2019) [arXiv:1907.12628]*
- DAMIC-M will improve on this with lower backgrounds, single electron resolution, and much larger exposure
  - LBC (2021)
  - Full detector (installation 2023)
- OSCURA will push the limits of the CCD technology to 10 kg of silicon, single-electron threshold, 0.01 dru detector
  - DoE BRN funded R&D experiment merging the efforts of all US scientists work on DAMIC at SNOLAB, DAMIC-M, and SENSEI



Thank you

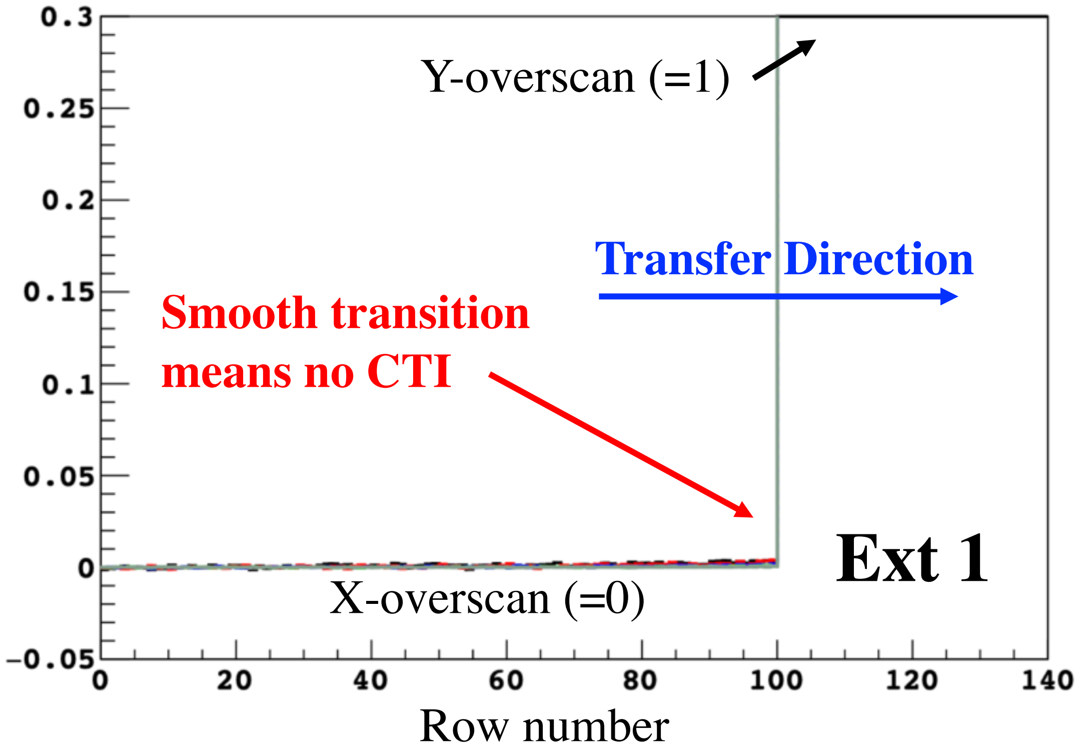


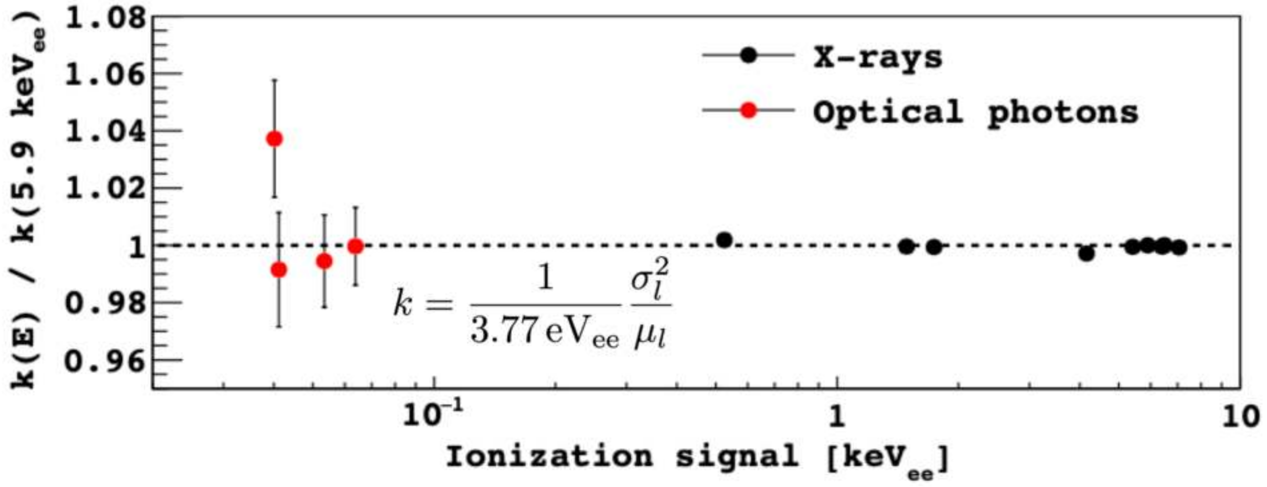
A. Aguilar-Arevalo et al. [arXiv:2007.15622] (2020)

Extra Slides

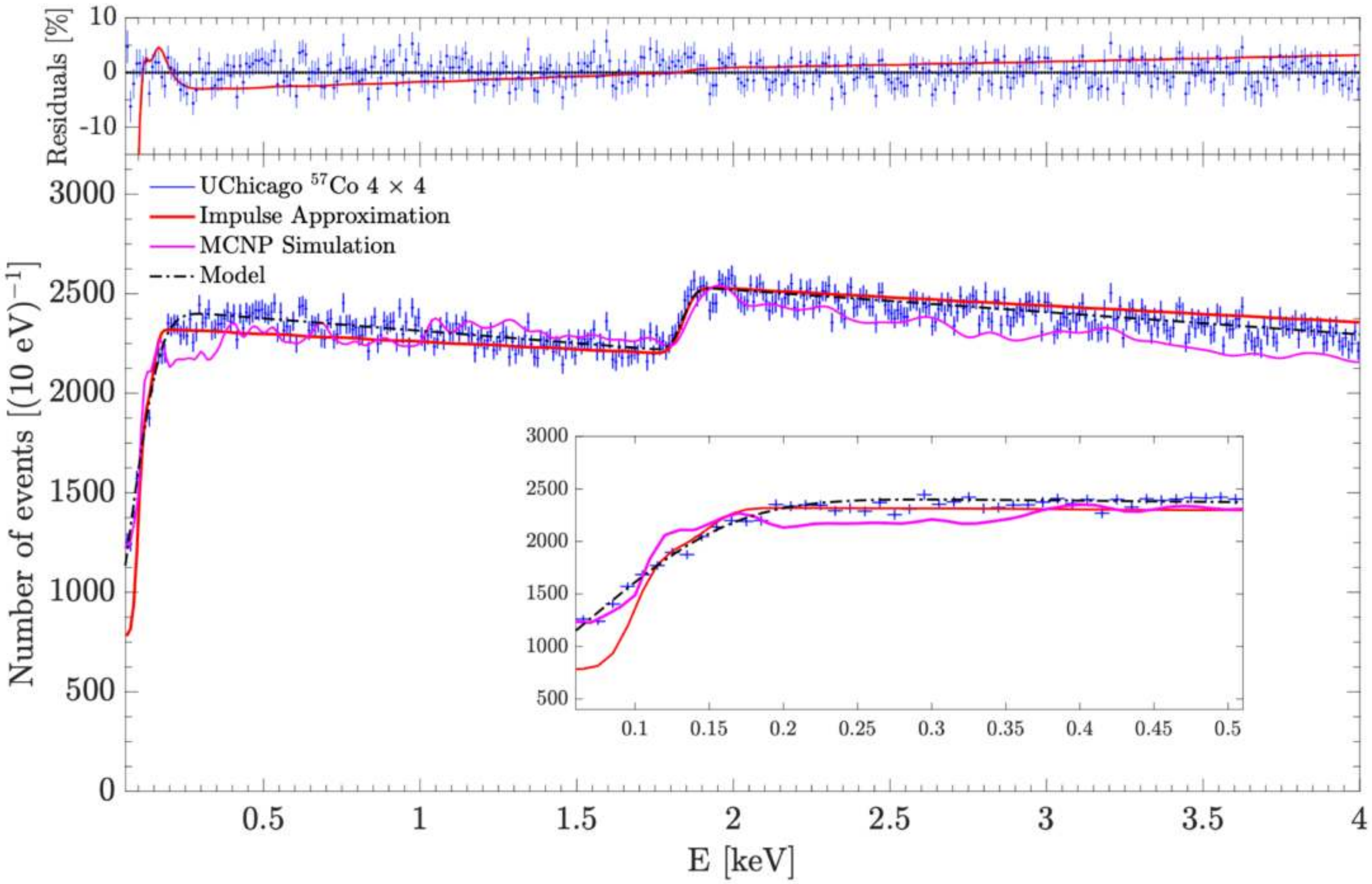
Energy Calibration

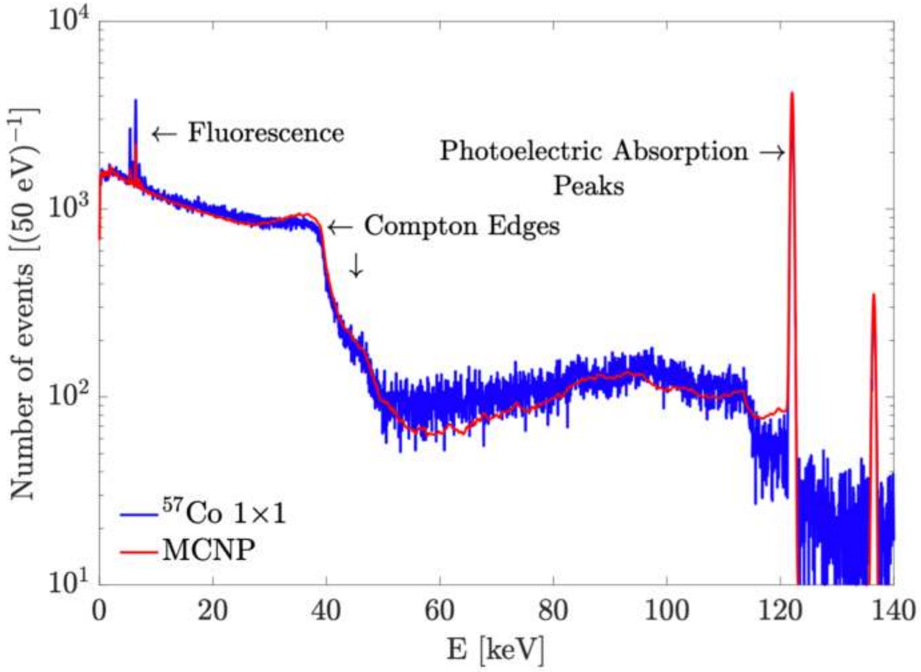
- Charge Transfer inefficiencies in the serial register are much less than 1% per 4000 transfers – the serial register length (right)
  - ➢ No expected energy distortion of the cluster in x
- Optical photon calibrations were done in situ for all CCDs at SNOLAB (below)





Compton Scattering

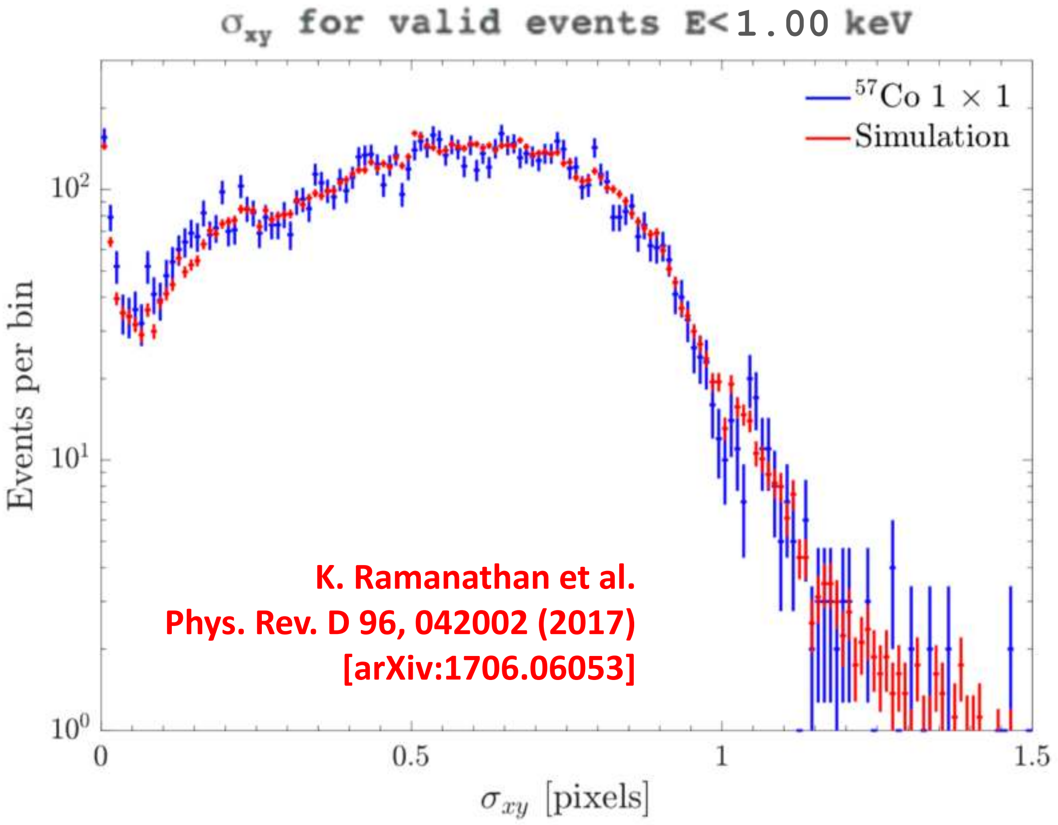




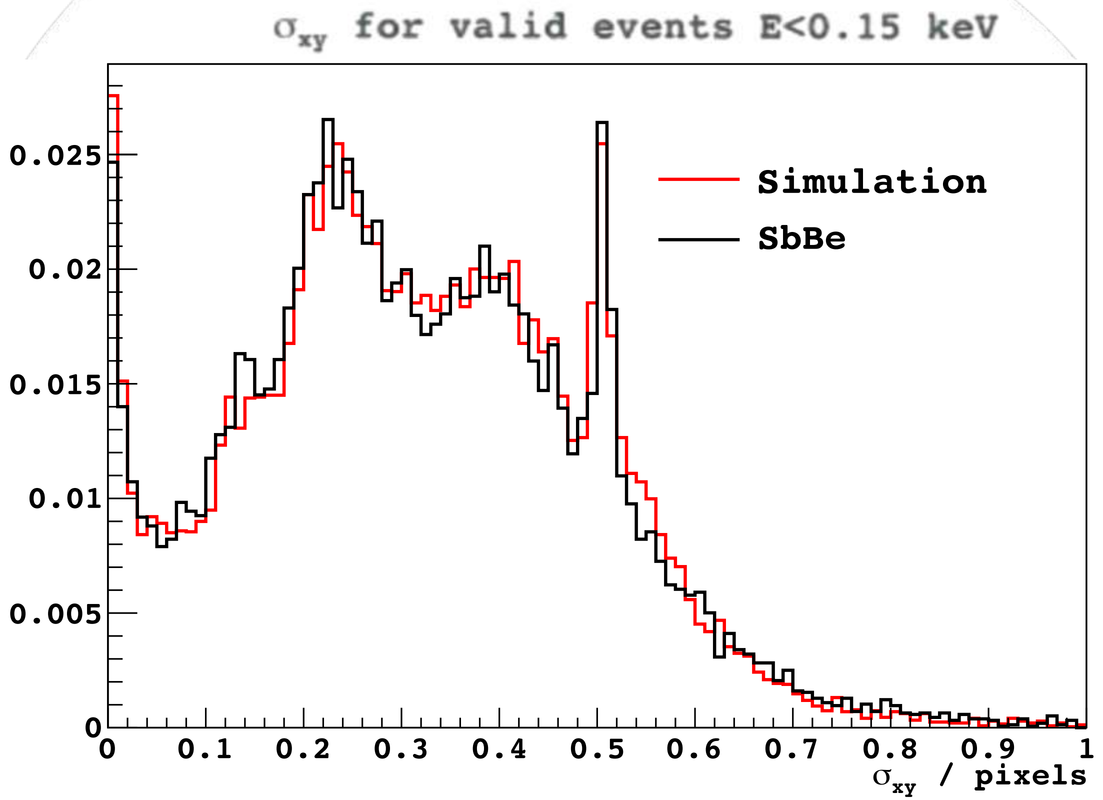
K. Ramanathan, et al. PRD 96, 042002 (2017) [arXiv:1706.06053]

Low-Energy Sigma Validation

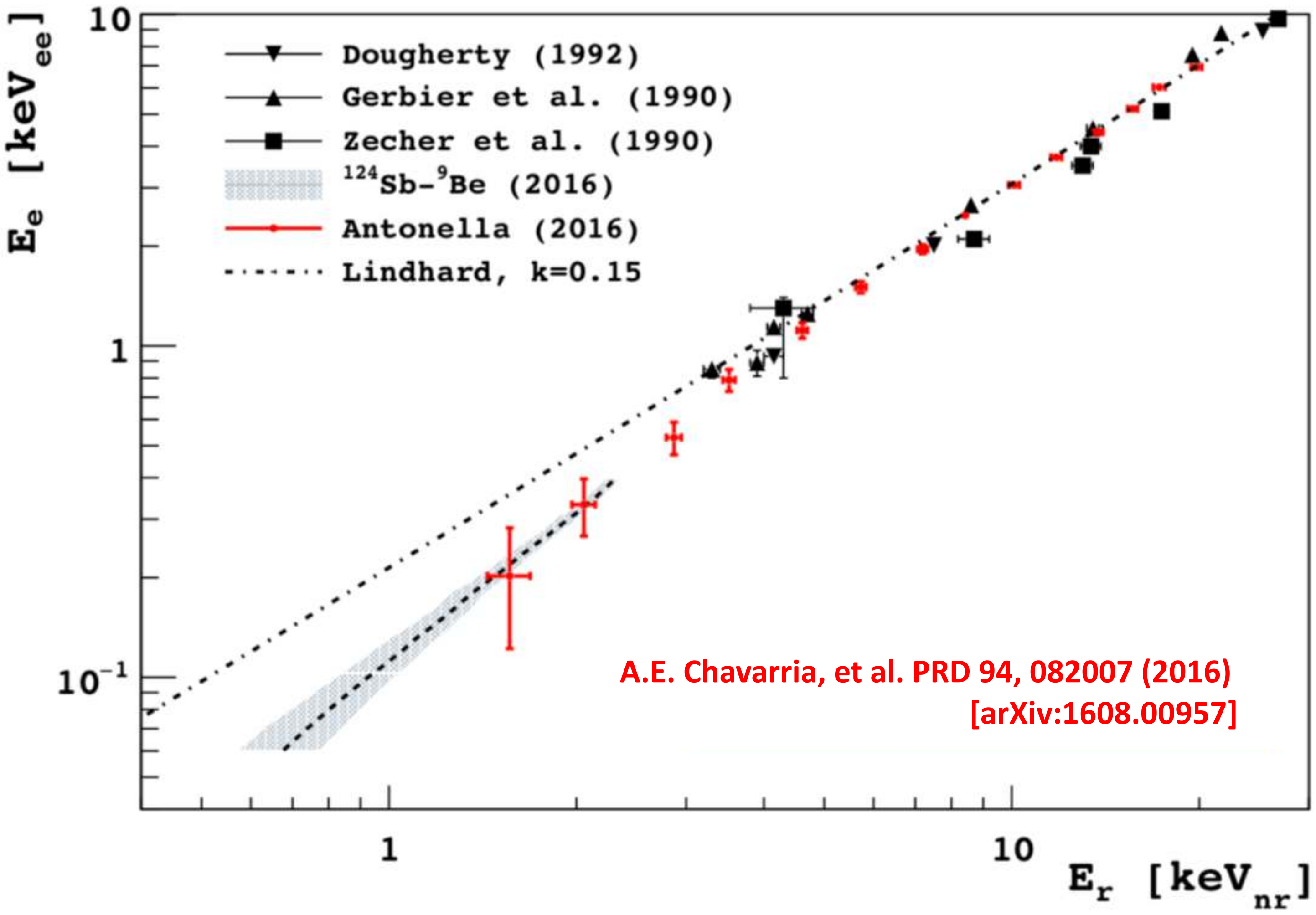
Gammas



Neutrons



Ionization Efficiency

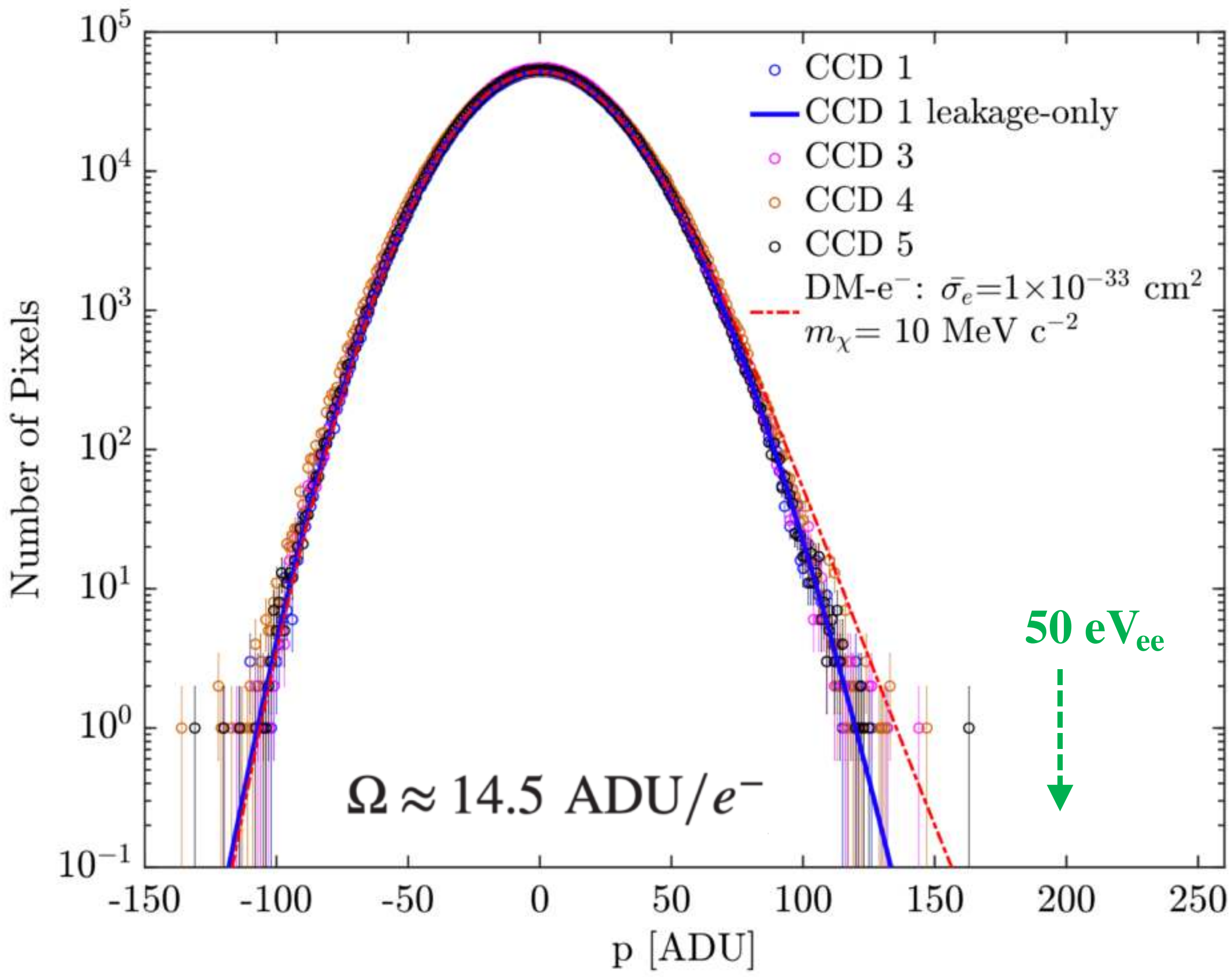


- Calibration using SbBe source with very low energy neutrons (< 24 keV)
- Ionization efficiency calibrated down to 60 eV_{ee}!!!

Dark Current

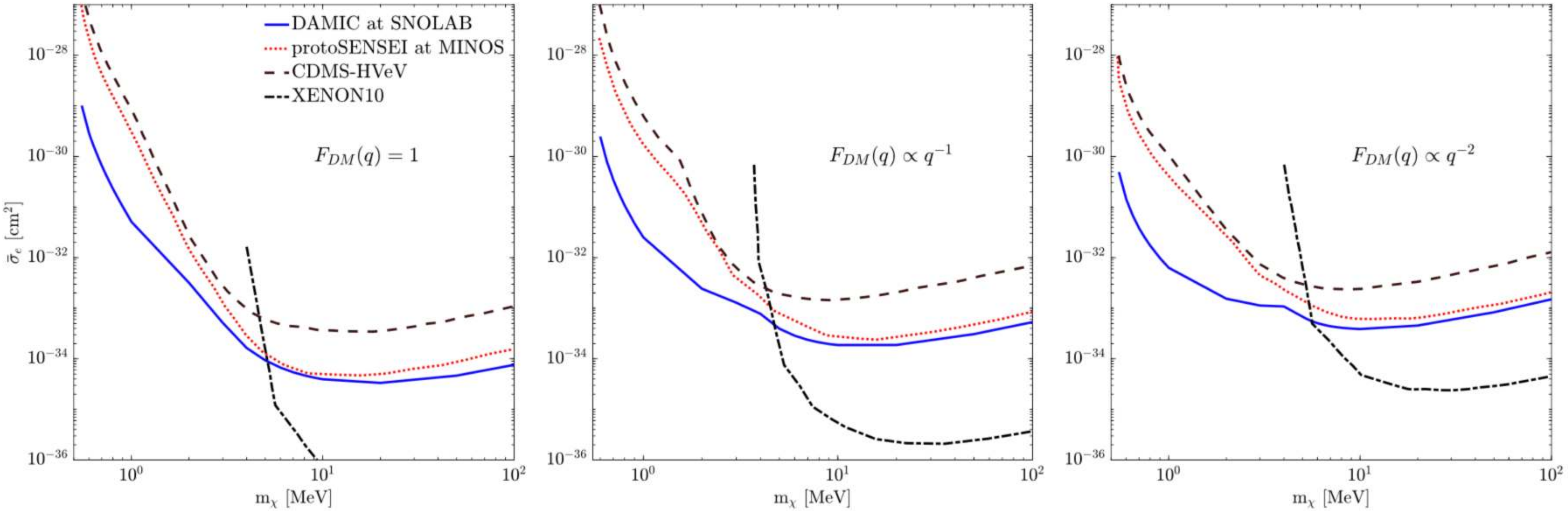
- DAMIC at SNOLAB has reported the lowest published dark current of any silicon experiment: 2 x 10^{-22} A cm^{-2}

CCD No.	σ_{pix} $[e^-]$	λ_d $[e^-\ mm^{-2}\ img^{-1}]$	μ_0 $[e^-]$	$\lambda = \lambda_{tot} - \lambda_d$ $[e^-\ mm^{-2}\ d^{-1}]$
1	1.628(1)	8.2(2)	–0.185(3)	2.8(2)
3	1.572(1)	7.8(2)	–0.160(4)	1.7(2)
4	1.594(1)	10.0(2)	–0.219(4)	1.0(2)
5	1.621(1)	8.5(2)	–0.183(4)	2.0(2)



A. Aguilar-Arevalo et al. PRL 123, 181802 (2019) [arXiv:1907.12628]

Electron Recoil Limits

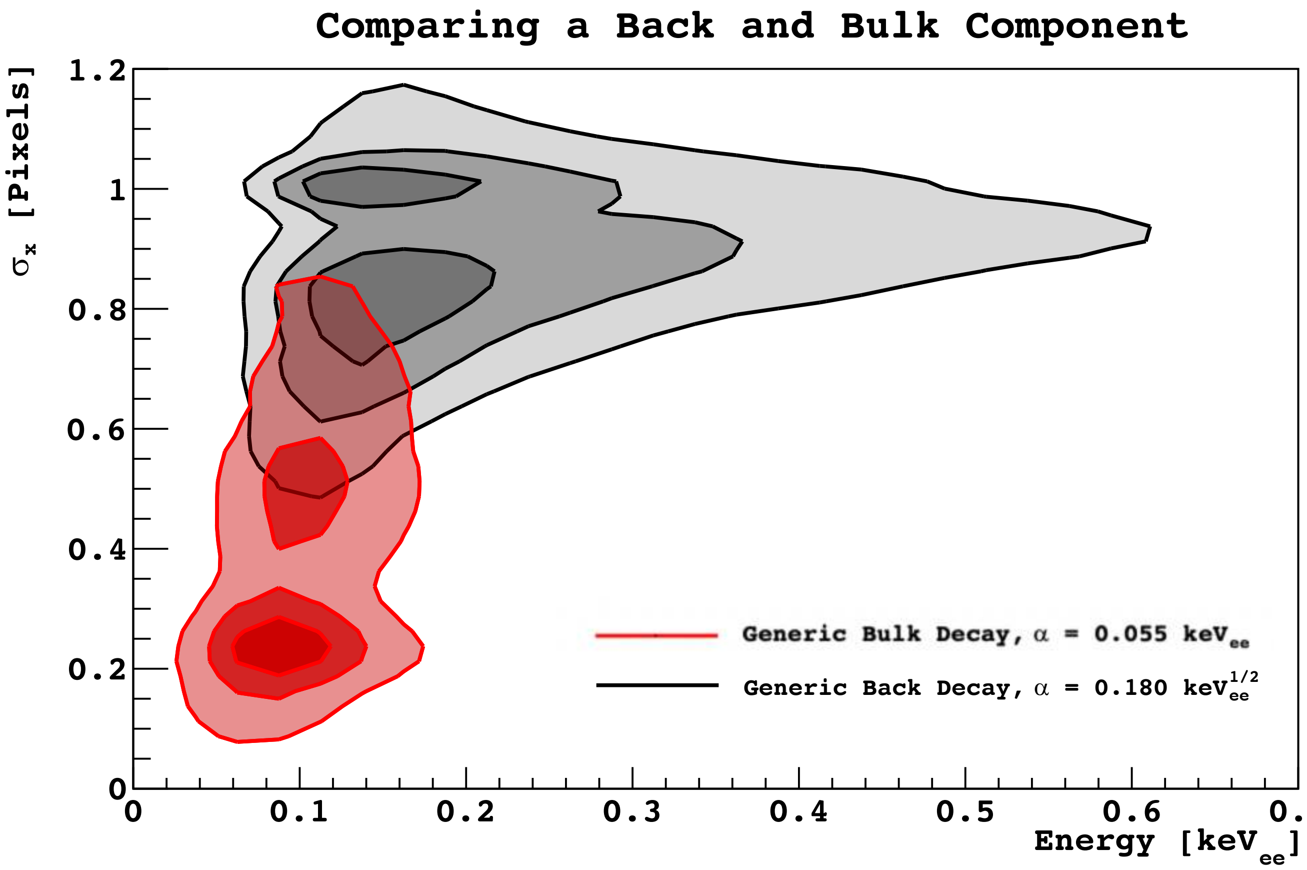


A. Aguilar-Arevalo et al. PRL 123, 181802 (2019) [arXiv:1907.12628]

…see Sho Uemura's talk from March 27 for new results from SENSEI

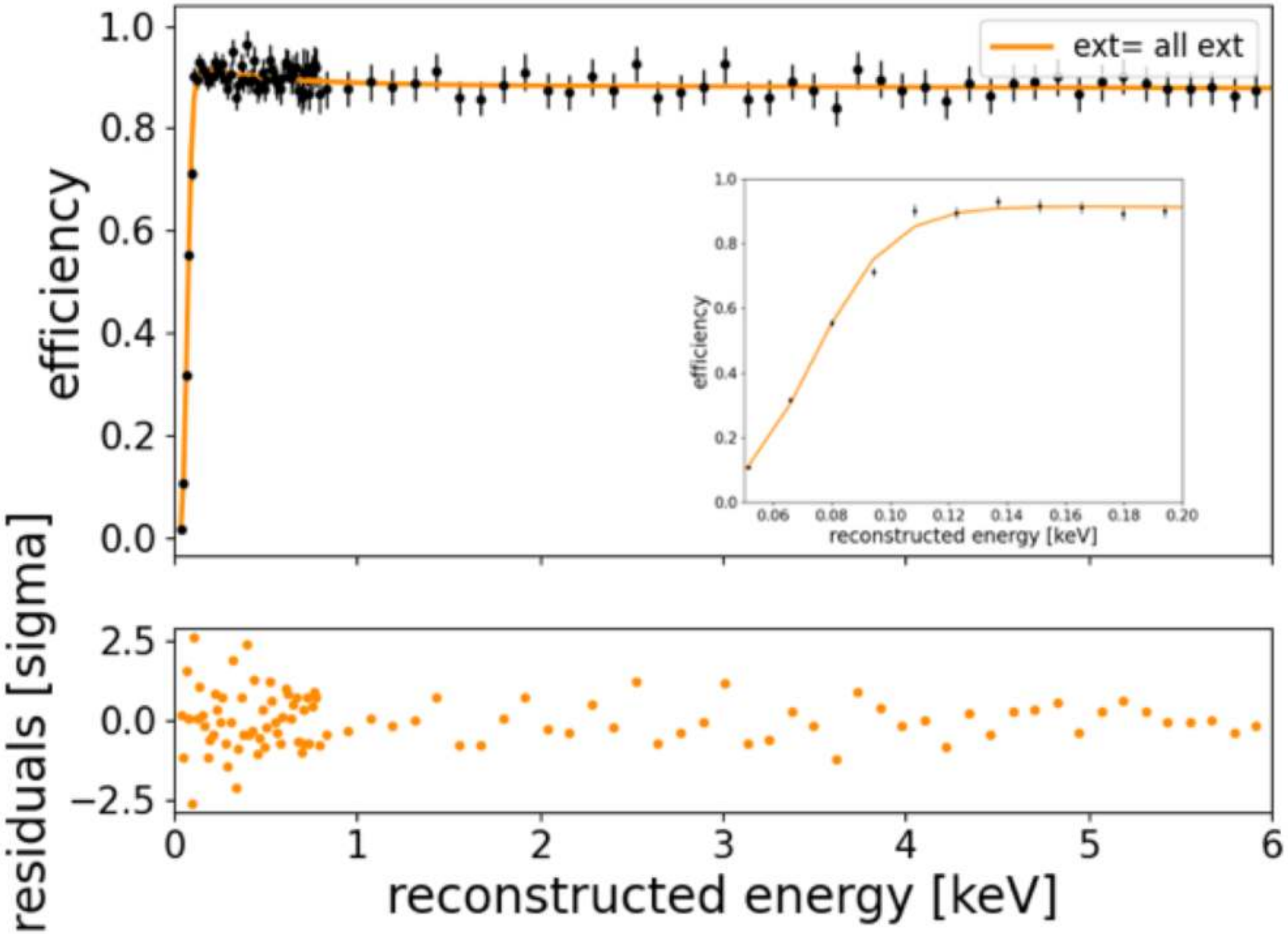
Systematic Uncertainties – Back

- **Our dominant background model uncertainty can be parameterized by a backside exponential**
- A back-side exponential rise is non-degenerate with a signal excess
- Consider this a free parameter in the WIMP analysis to account for the systematic uncertainty of the ^{210}Pb location and PCC
- **No need for a fiducial cut!**



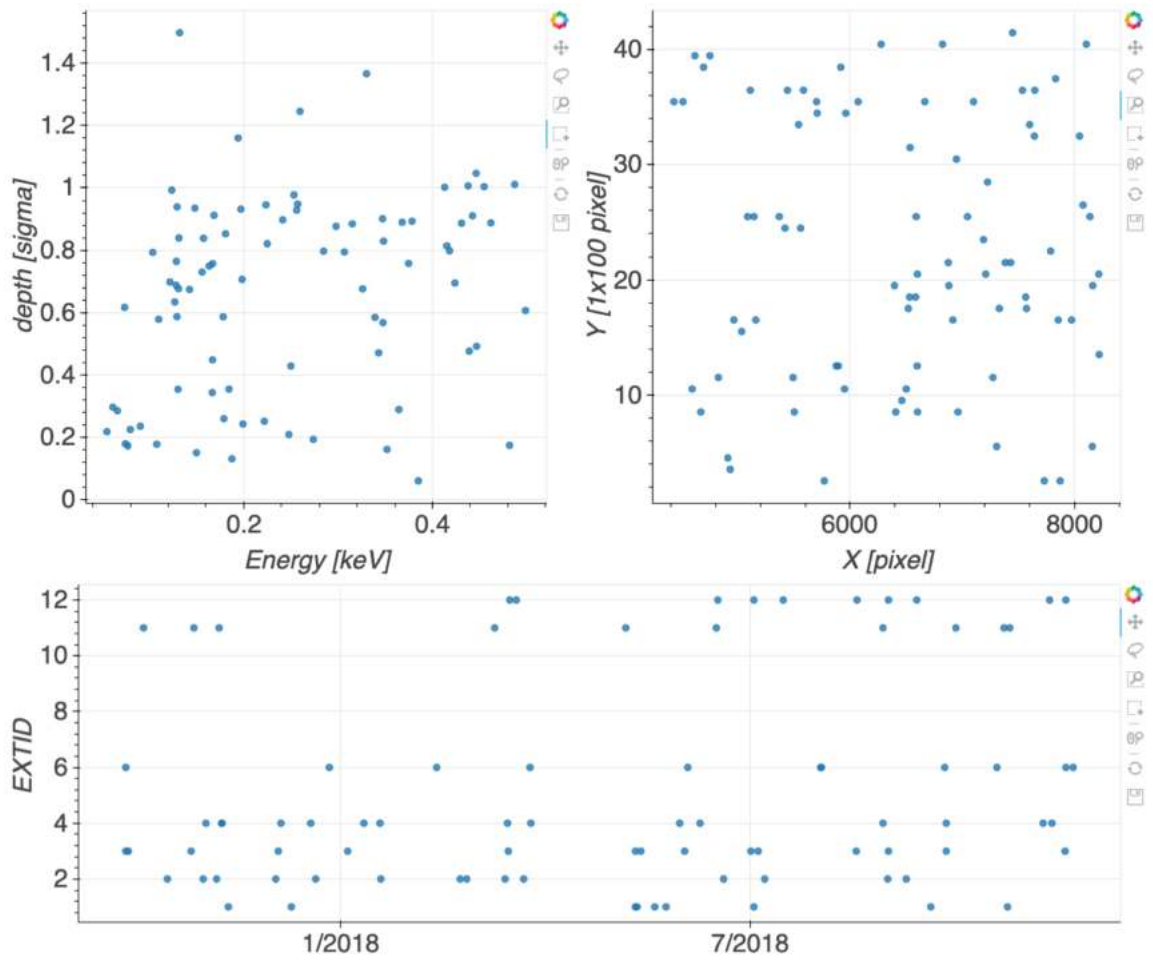
Quality Cuts and Efficiencies

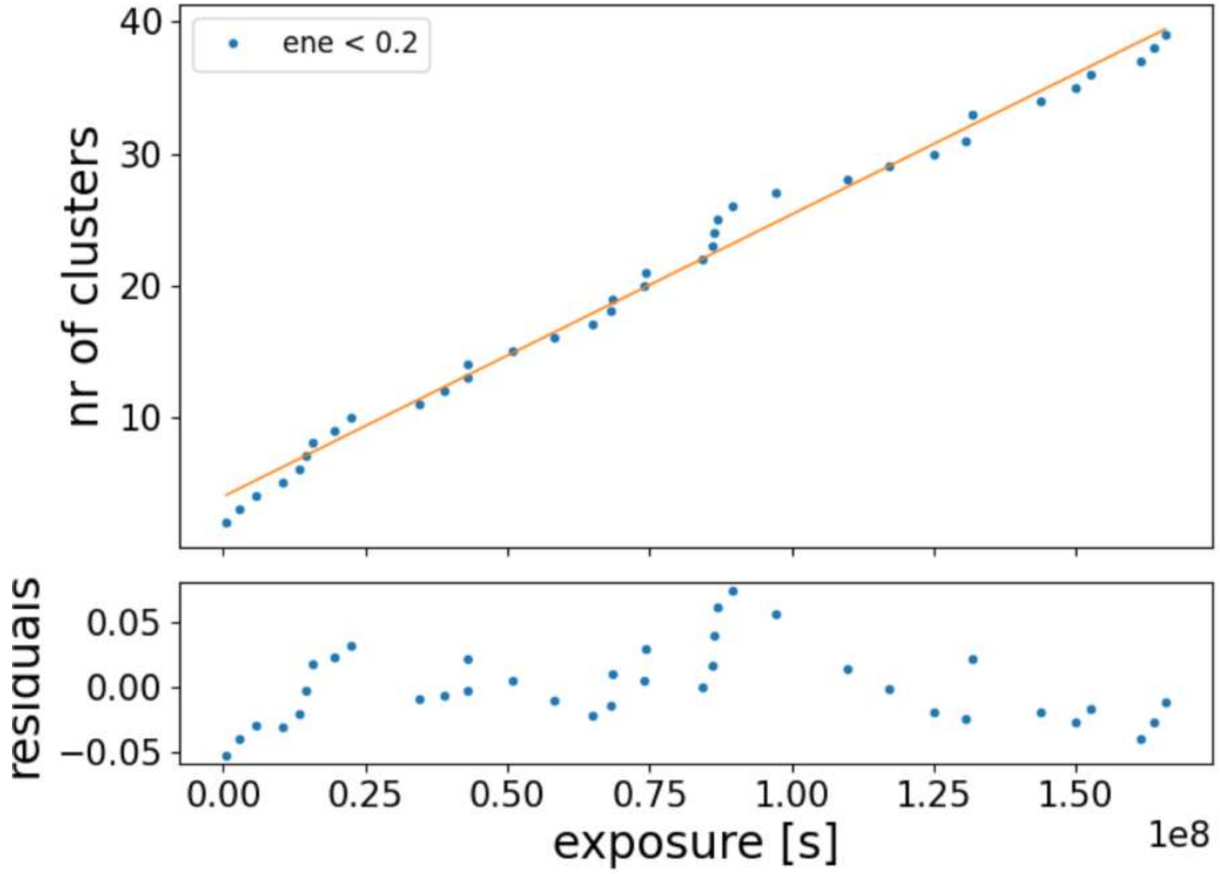
- Mask "hot" regions of the CCD which contain higher dark current (remove ~16% mass) or high-E depositions
- Scan over the image and perform a likelihood ratio test of Gaussian vs. flat to find event clusters
- This clustering algorithm has been characterized to have nearly full efficiency down to approximately 100 eV_{ee}



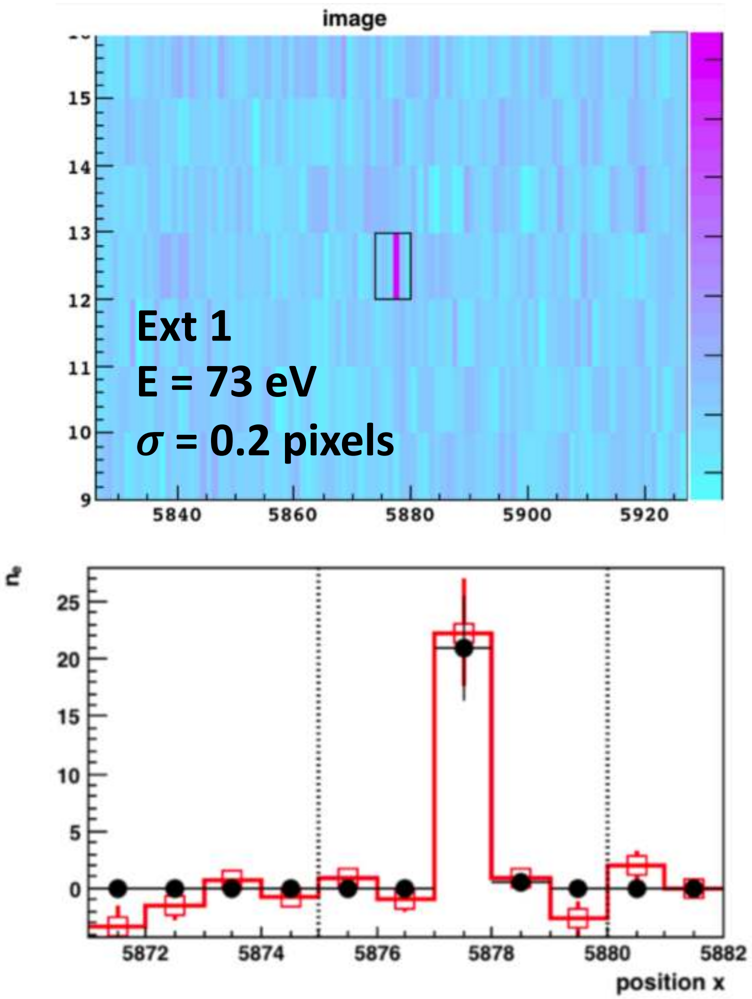
Low Energy Event Distribution

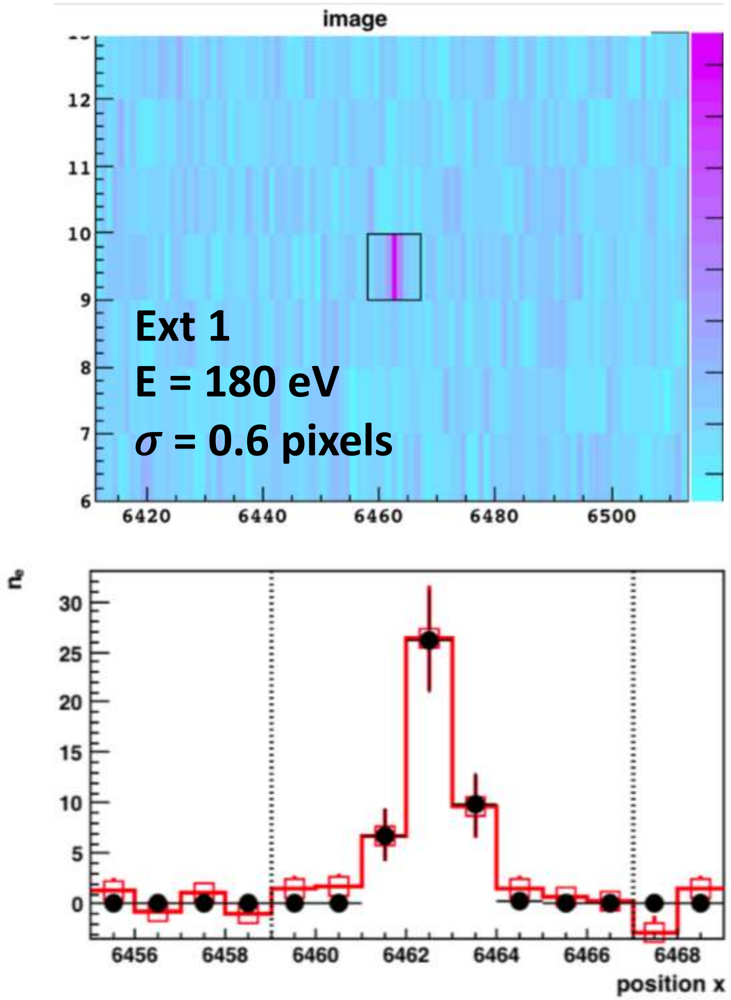
ene < 0.5





Event Gallery





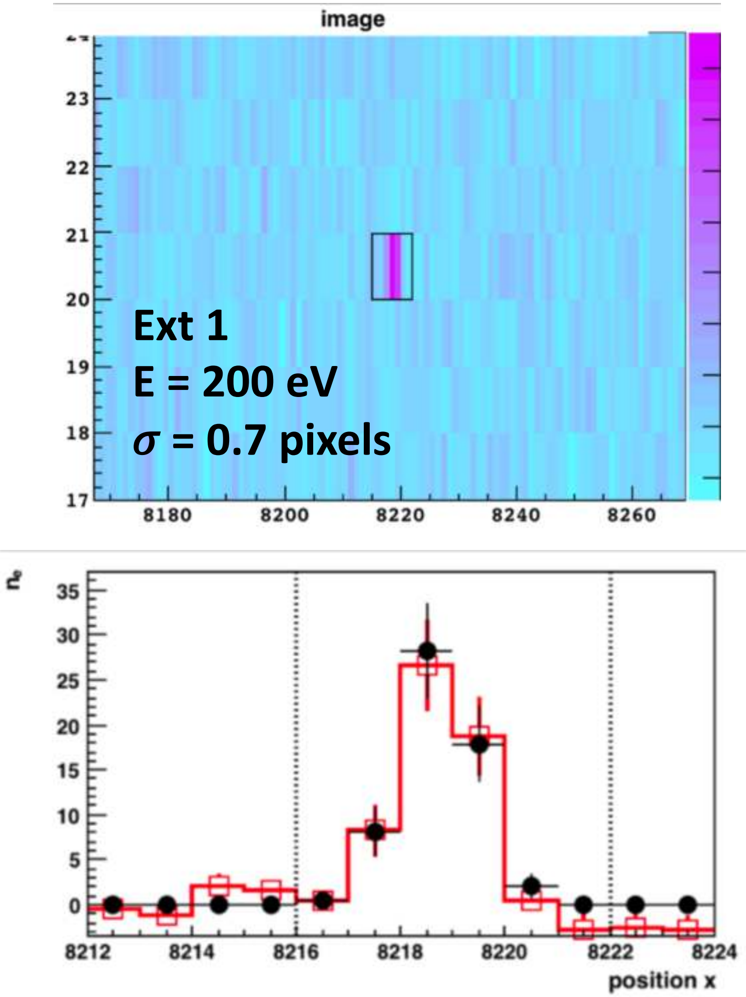
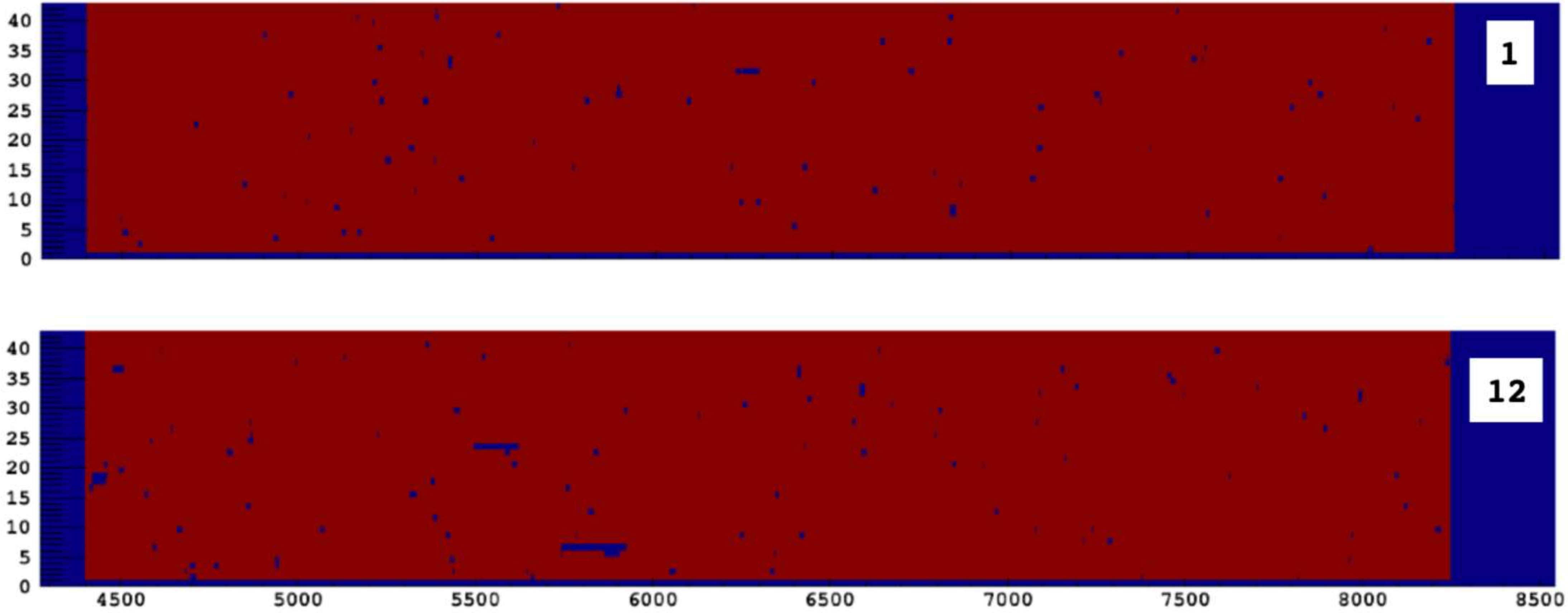


Image Mask

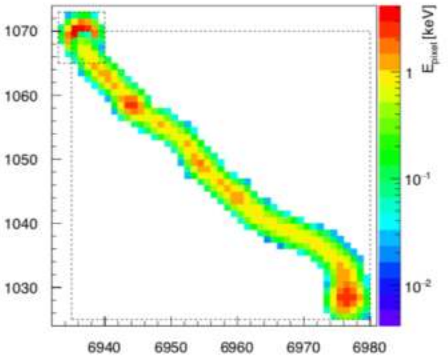

40
35
30
25
20
15
10
5
0
1
12
4500
5000
5500
6000
6500
7000
7500
8000
8500

Coincidence Analysis

Bulk Contamination		
$^{32}Si \rightarrow {}^{32}P$	Q = 224.5 keV	$t_{1/2}$ = 150 y
$^{32}P \rightarrow {}^{32}S$	Q = 1710 keV	$t_{1/2}$ = 14.3 d

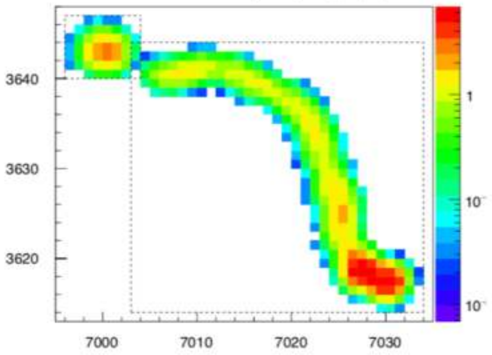
Surface Contamination		
$^{210}Pb \rightarrow {}^{210}Bi$	Q = 63.5 keV	$t_{1/2}$ = 22.3 y
$^{210}Bi \rightarrow {}^{210}Po$	Q = 1161 keV	$t_{1/2}$ = 5.01 d
$^{210}Po \rightarrow {}^{206}Po$	Q = 5407 keV	$t_{1/2}$ = 138 d

^{32}Si β_1-β_2



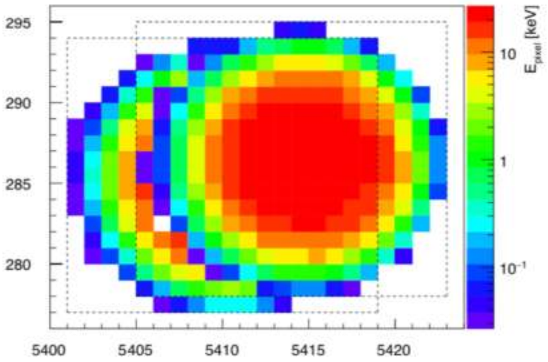
- $E_{\beta 1}$ = 110 keV
- $E_{\beta 2}$ = 361 keV
- Δt = 11.7 d

^{210}Pb β_1-β_2



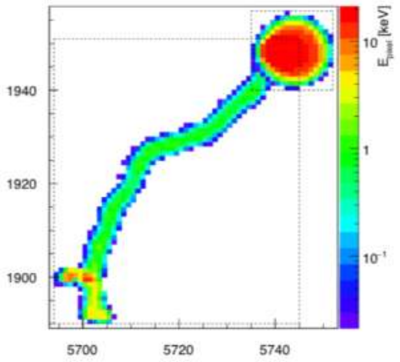
- $E_{\beta 1}$ = 57 keV
- $E_{\beta 2}$ = 376 keV
- Δt = 1.4 d

α-α



- $E_{\alpha 1}$ = 4.3 MeV
- $E_{\alpha 2}$ = 3.8 MeV
- Δt = 5.2 d

^{210}Pb β_1-α



- $E_{\beta 1}$ = 717 keV
- E_{α} = 3.62 MeV
- Δt = 32.3 d

…see upcoming publication or A. Aguilar-Arevalo et al, JINST 10 (2015) P08014 [arXiv:1506.02562] for details