Background Controls for the DAMIC-M Dark Matter Search

Daniel Baxter

Topics in Astroparticle and Underground Physics

September 9, 2019

THE UNIVERSITY OF CHICAGO

Background Model for DAMIC Detectors

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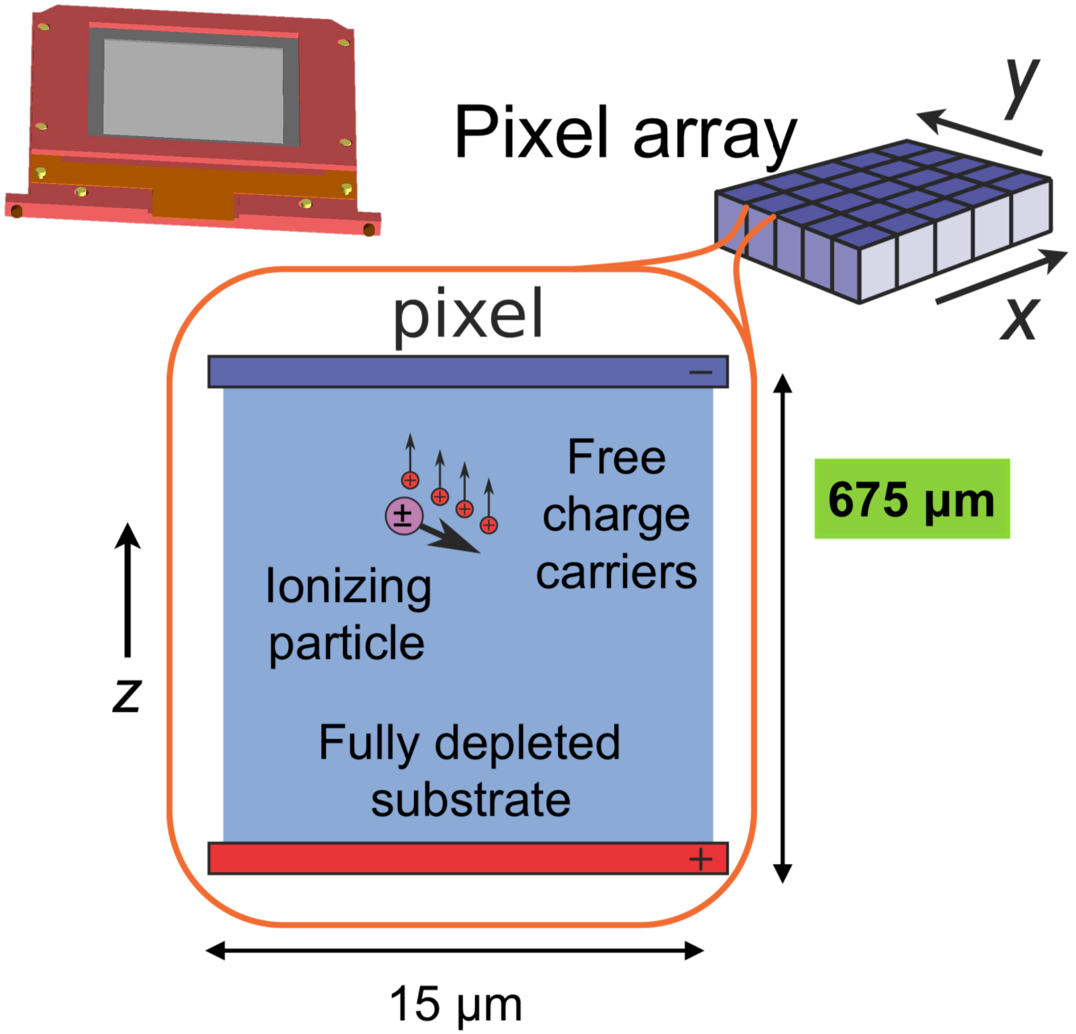
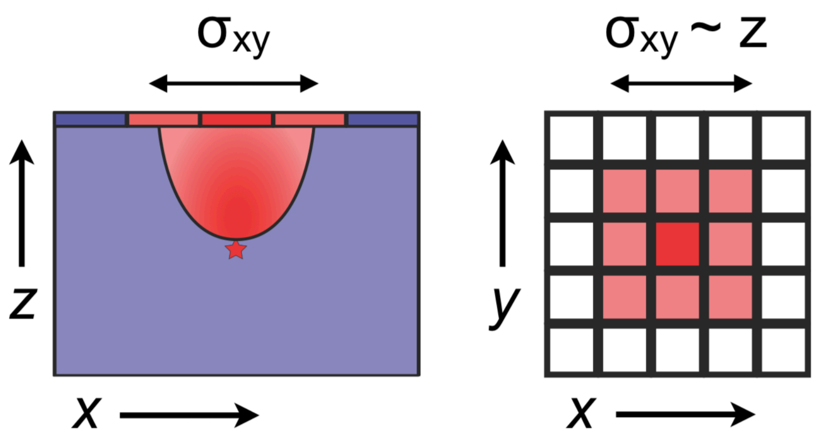
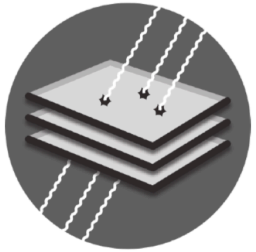
CCD Introduction



- 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 read-out time

CCD Introduction

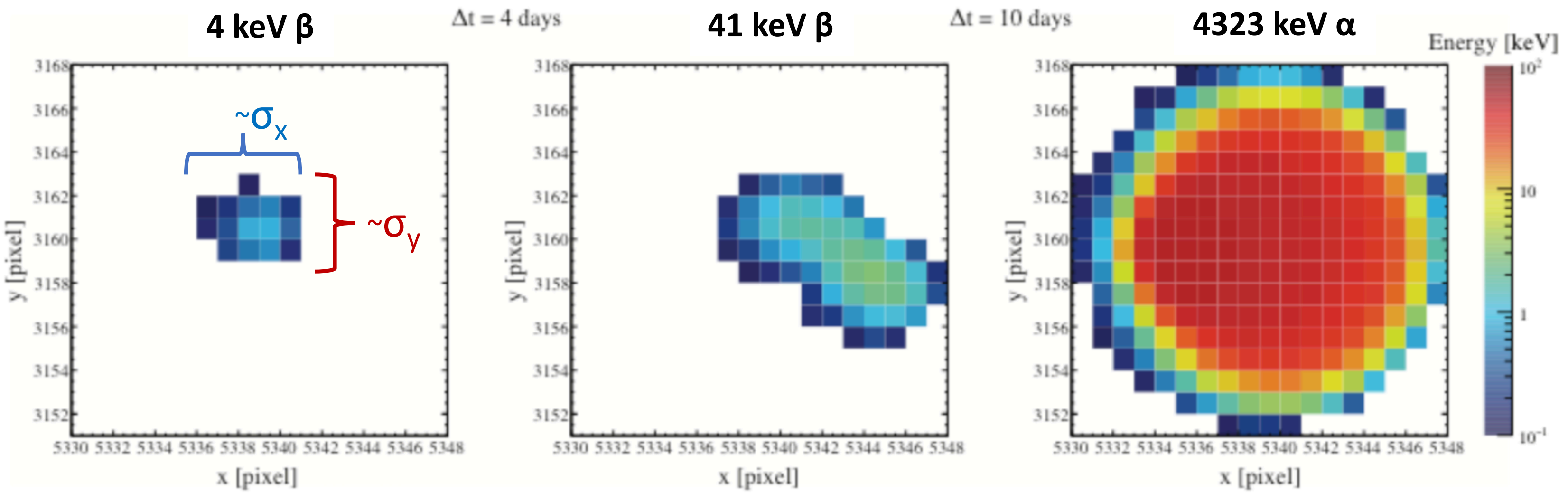




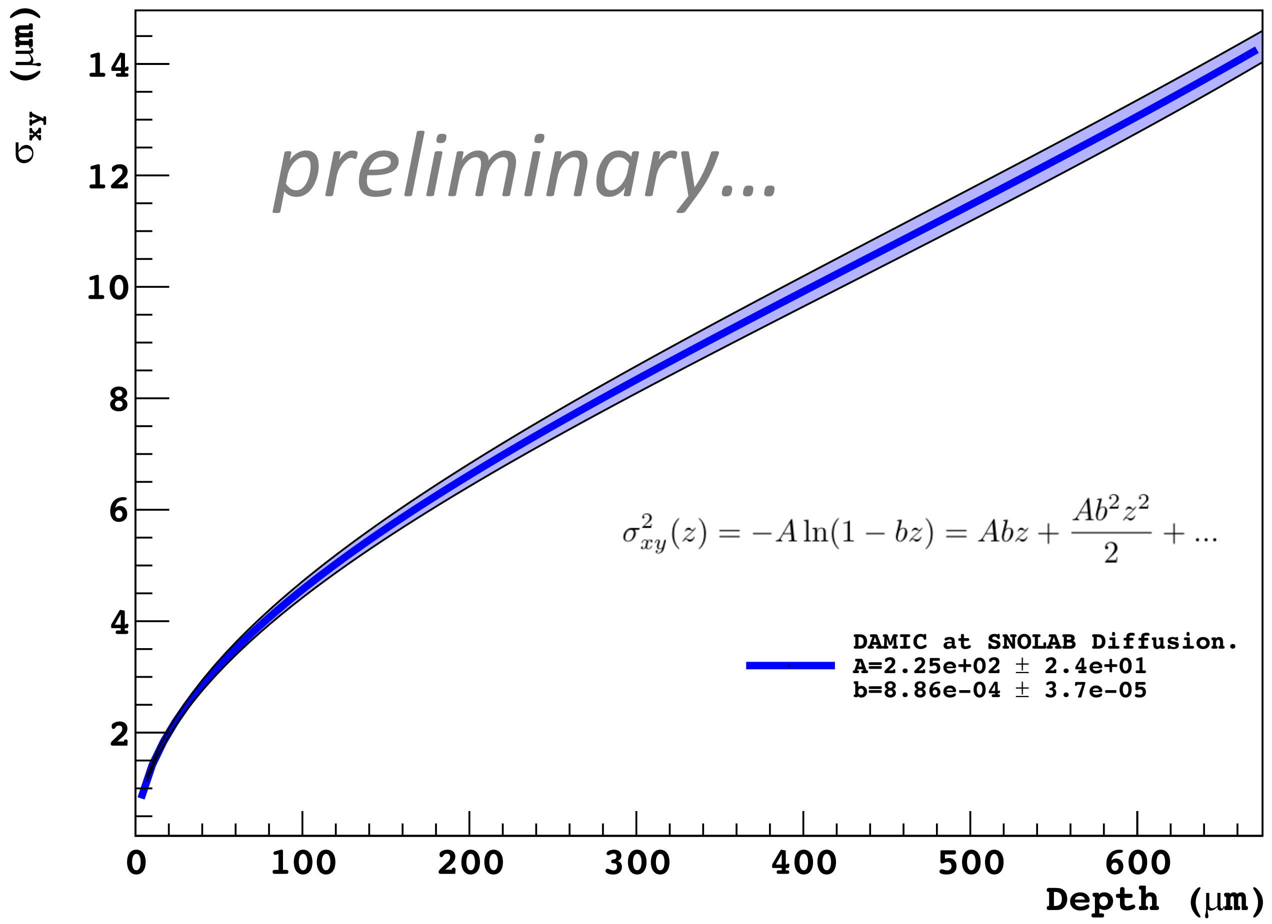
- Silicon band-gap: 1.2 eV
- Mean energy/e⁻: 3.8 eV

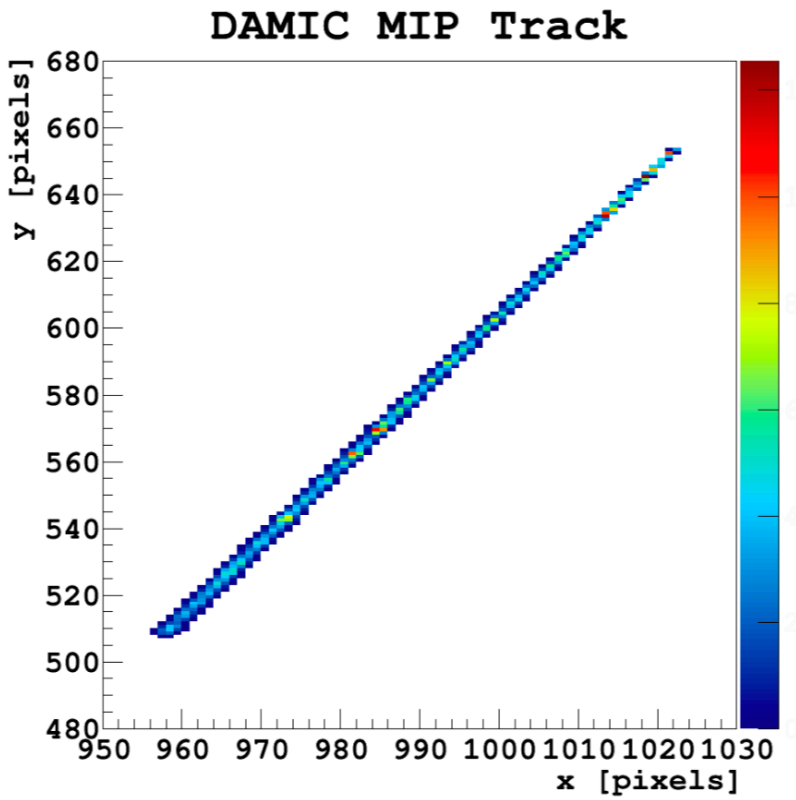
- As charges drift across the CCD, they experience lateral thermal motion (diffusion) proportional to vertical distance traveled (depth)
- Above 1 keV, the event profile can identify the progenitor…

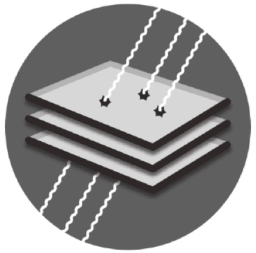
1. **Tight deposition:**
   - **nuclear recoil**
   - **low-E electron recoil**
2. Elongated track:
   - high-E electron recoil
   - muon
3. Large blob:
   - alpha decay



Modeling Diffusion



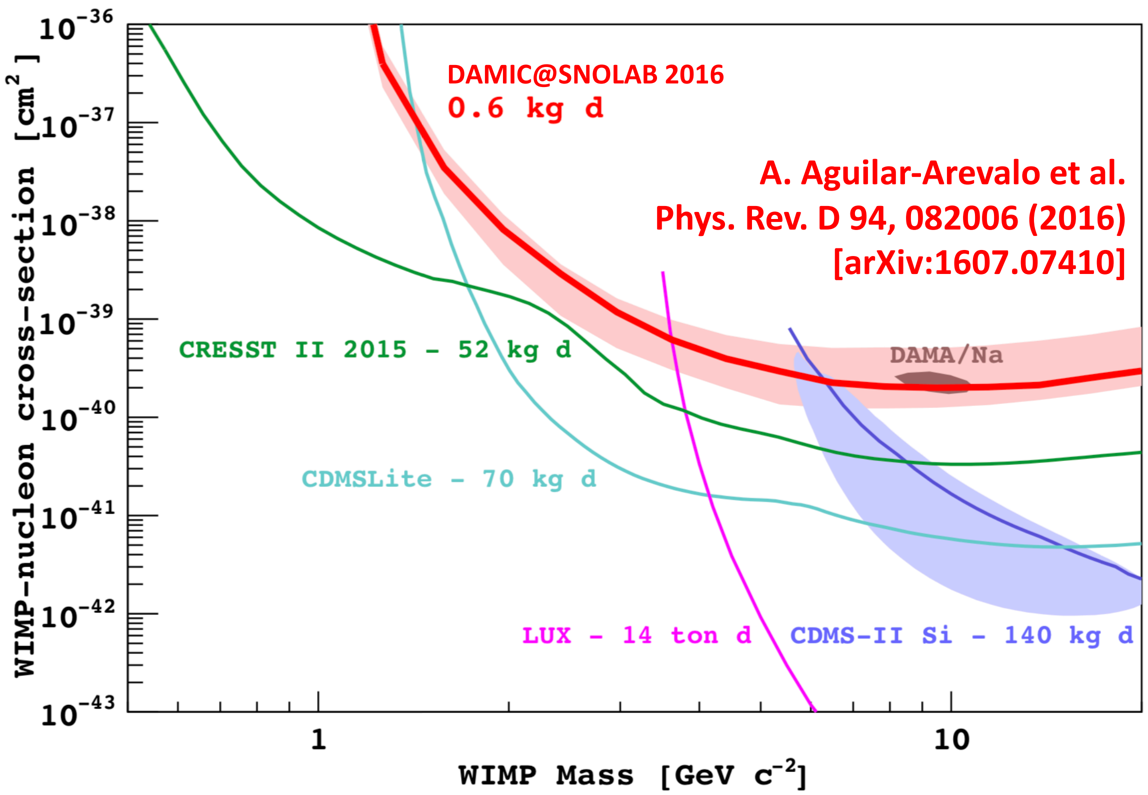


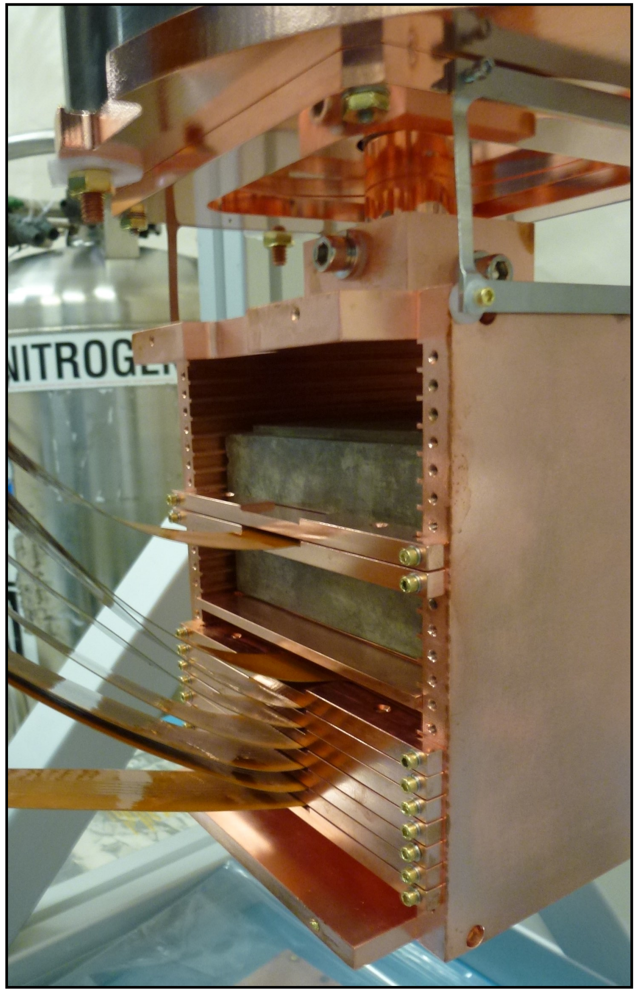


- We calibrate depth (diffusion) using events at the back of the CCD and muons passing through

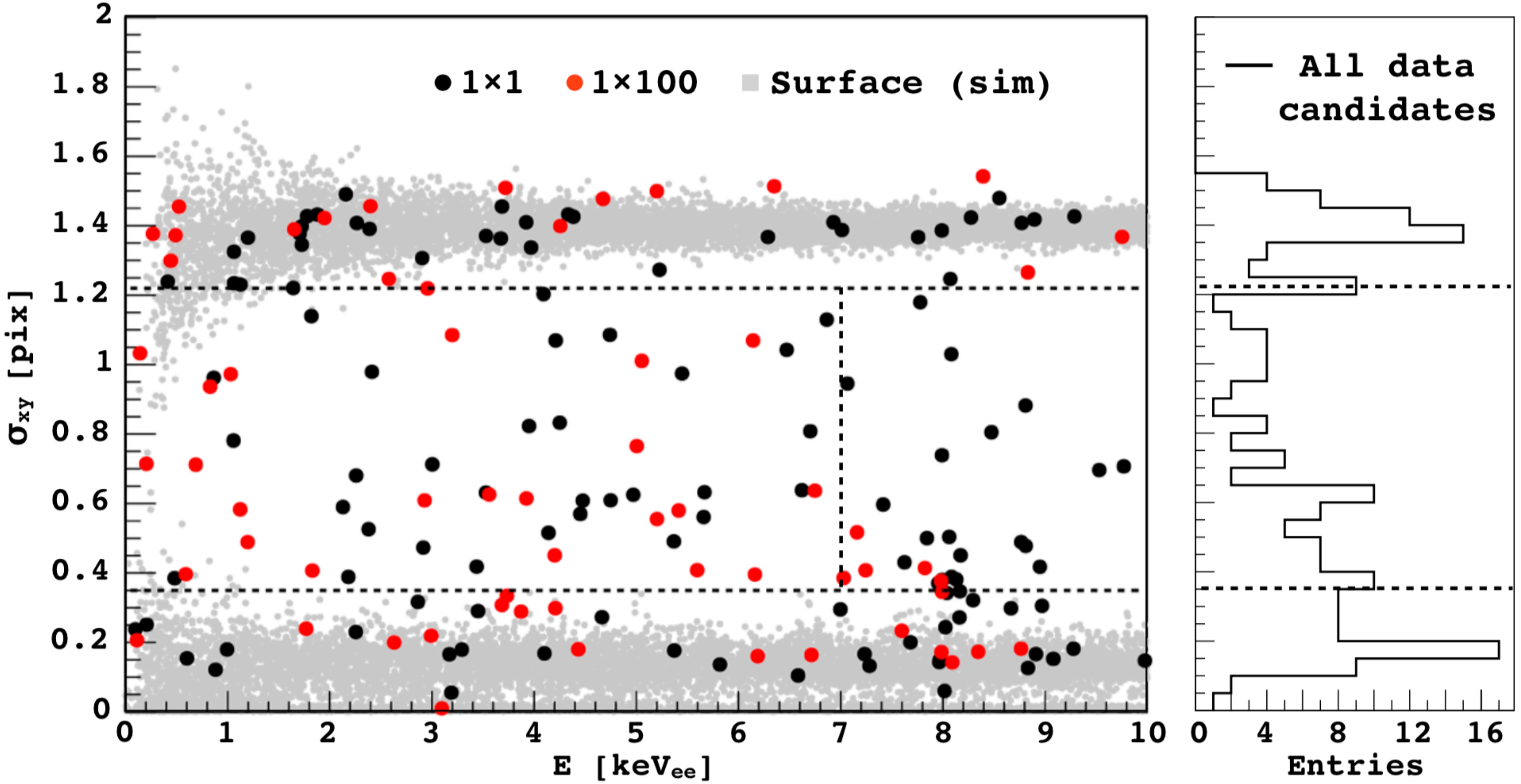
Previous Limits from DAMIC at SNOLAB

- Limits set in 2016 after commissioning…



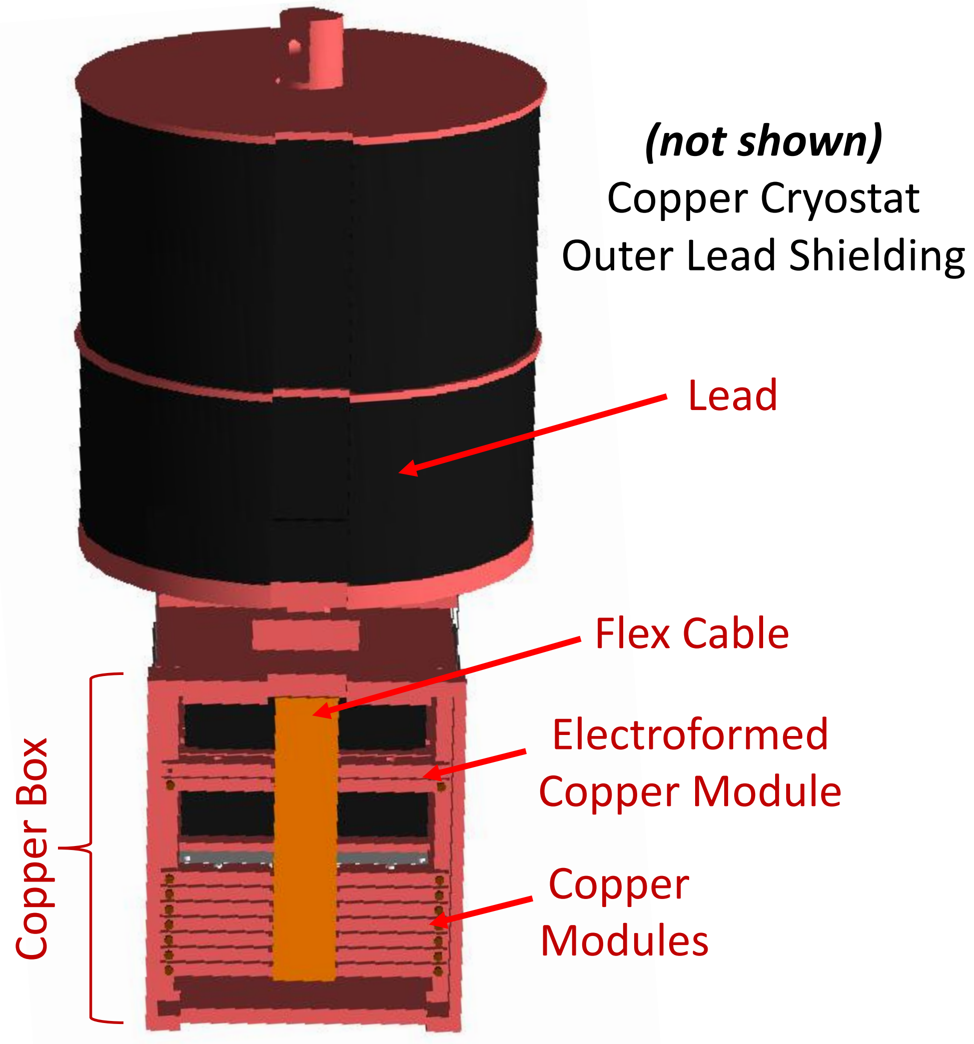


DAMIC at SNOLAB Fiducial Cut (2016)



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

GEANT4 Geometry



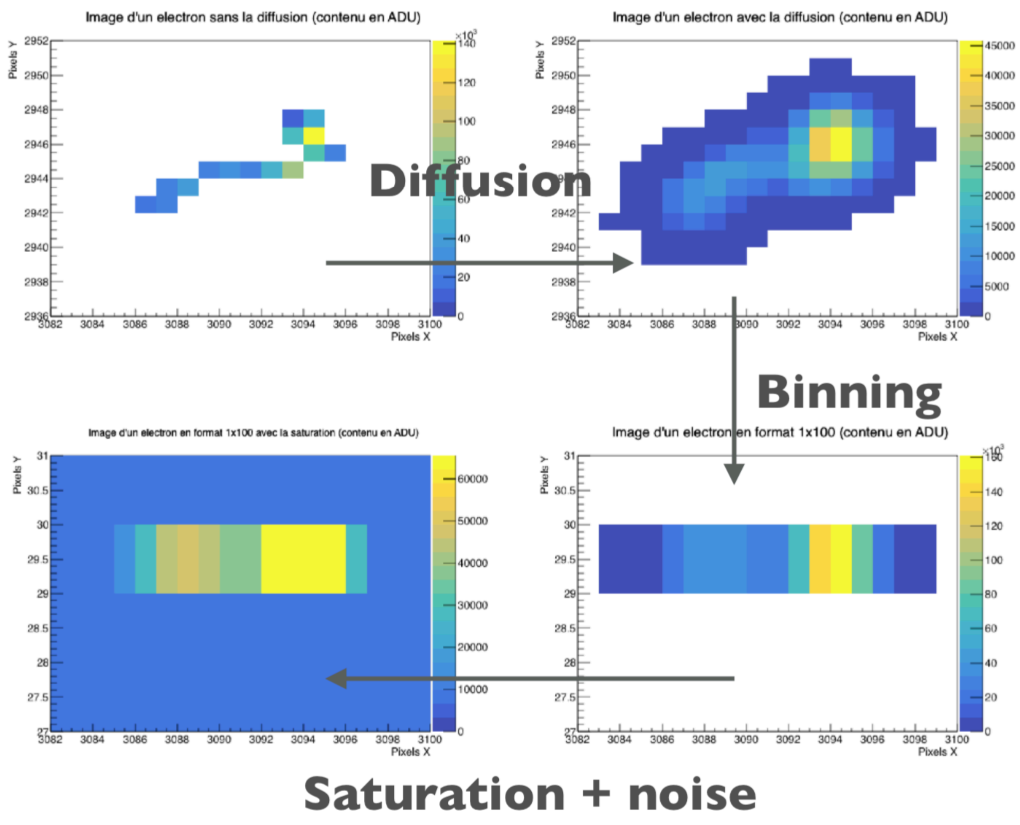
Decay Chains Simulated

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)

Simulations in GEANT4

Part	U-238	Ra-226	Pb-210	Th-232	K-40
CCD	<0.53	<0.43	<33	<0.4	<0.04
Kapton cable	5013.8 ± 423.4	420 ± 490	420 ± 490*	276.5 ± 42.0	2475.4 ± 172.8
Copper	<10.7	<10.7*	2350 ± 720	<3.5	<2.7
Module Screws	1400 ± 3800	<138	2350 ± 720	200 ± 140	2400 ± 1300
Ancient lead shield	<10.7	<25.9	2850 ± 285*	<2.8	<0.5
Outer lead shield	<1.1	<13*	1560000 ± 430000	<0.4	<19

- We assay each component to determine its activity in decays/kg/day (above)
- We simulate the various isotopes in our detector and group them by decay chain (see previous slide)
- We constrain the amount of each to assays of that component



Constraints from Event Coincidence

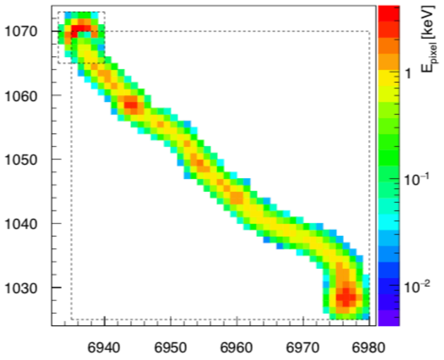
Bulk Contamination

$^{32}Si \rightarrow {}^{32}P$	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

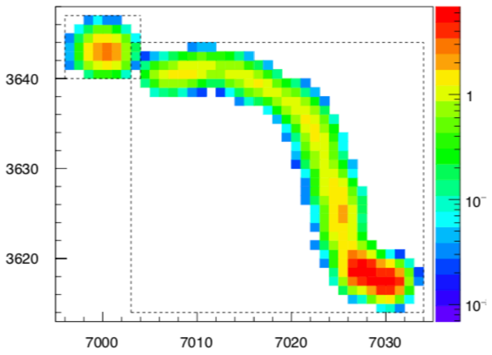
$^{210}Pb \rightarrow {}^{210}Bi$	Q = 63.5 keV	$t_{1/2}$ = 22.3 y
$^{210}Bi \rightarrow {}^{210}Po$	Q = 1161 keV	$t_{1/2}$ = 5.01 d
$^{210}Po \rightarrow {}^{206}Po$	Q = 5407 keV	$t_{1/2}$ = 138 d

^{32}Si β_1-β_2



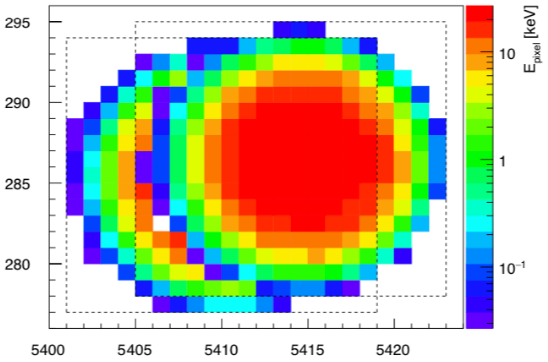
- $E_{\beta1}$ = 110 keV
- $E_{\beta2}$ = 361 keV
- Δt = 11.7 d

^{210}Pb β_1-β_2



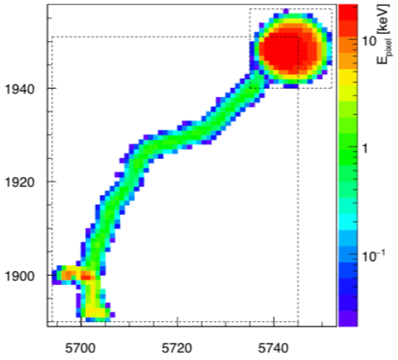
- $E_{\beta1}$ = 57 keV
- $E_{\beta2}$ = 376 keV
- Δt = 1.4 d

α-α



- $E_{\alpha1}$ = 4.3 MeV
- $E_{\alpha2}$ = 3.8 MeV
- Δt = 5.2 d

^{210}Pb β_1-α



- $E_{\beta1}$ = 717 keV
- E_{α} = 3.62 MeV
- Δt = 32.3 d

see A. Matalon presentation at LRT 2019 or A. Aguilar-Arevalo et al, JINST 10 (2015) P08014 [arXiv:1506.02562] for details

Fitting to Data

- Perform a 2D template **likelihood** fit in energy-sigma space
- Assume the probability of measuring ***k*** events given an expectation ***v*** from the ***i*** th energy bin and ***j*** th sigma bin is described by a Poisson distribution:

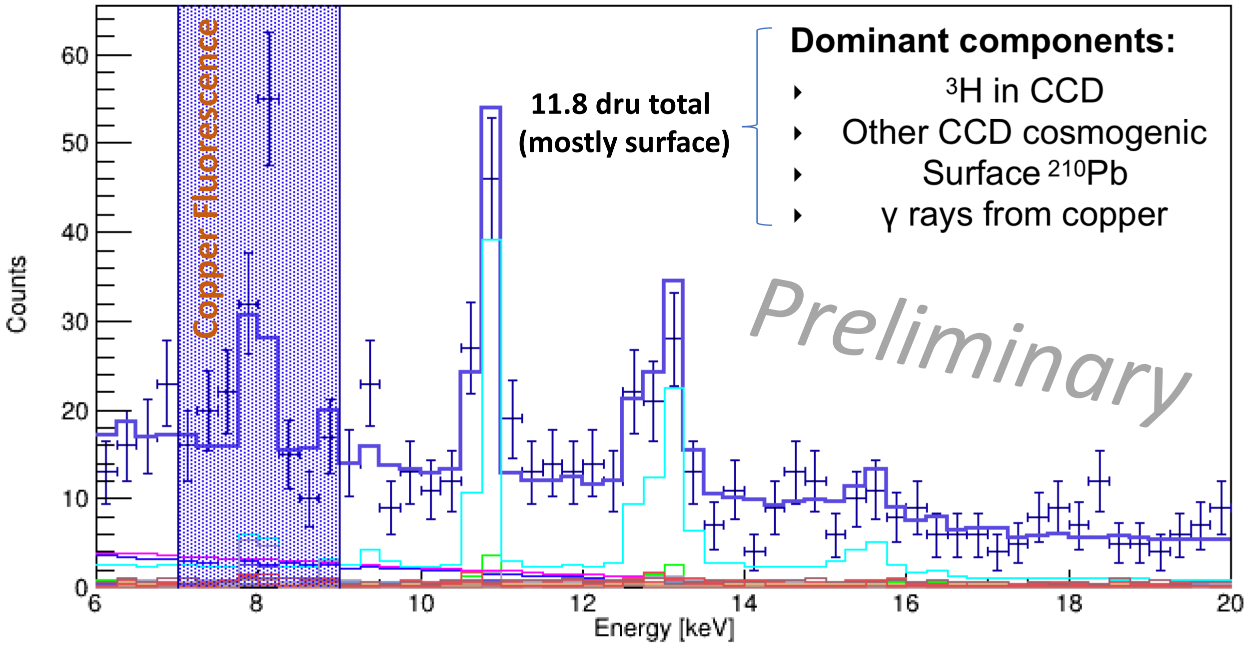
$$P(k_{ij}|\nu_{ij}) = \frac{e^{-\nu_{ij}}\nu_{ij}^{k_{ij}}}{k_{ij}!} \qquad \nu_{ij} = \sum_l C_l \nu_{ijl}$$

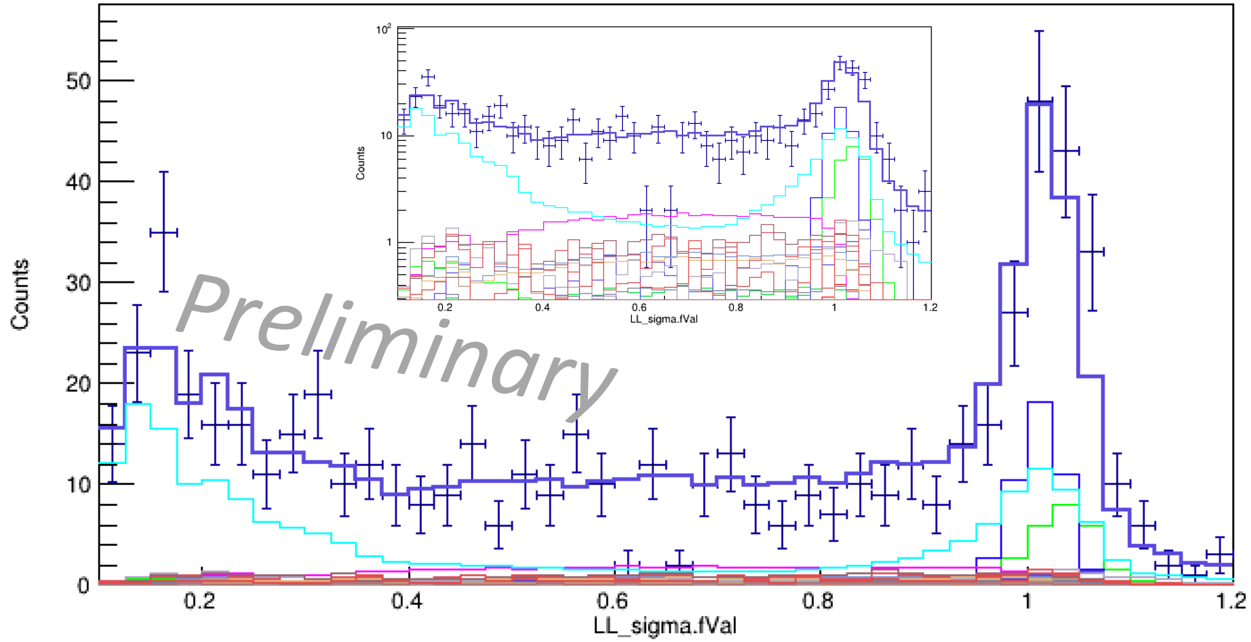
- Assign each template ***l*** a fit parameter C_l that scales it up or down and constrain these fit parameters according to material assays using a Gaussian constraint for each ***n*** measured activity constraint

$$LL = \sum_i \sum_j \left(k_{ij}\log(\nu_{ij}) - \nu_{ij} - \log(k_{ij}!)\right) - \sum_n \left(\frac{(N_n^o - N_n)^2}{2\sigma_n^2}\right)$$

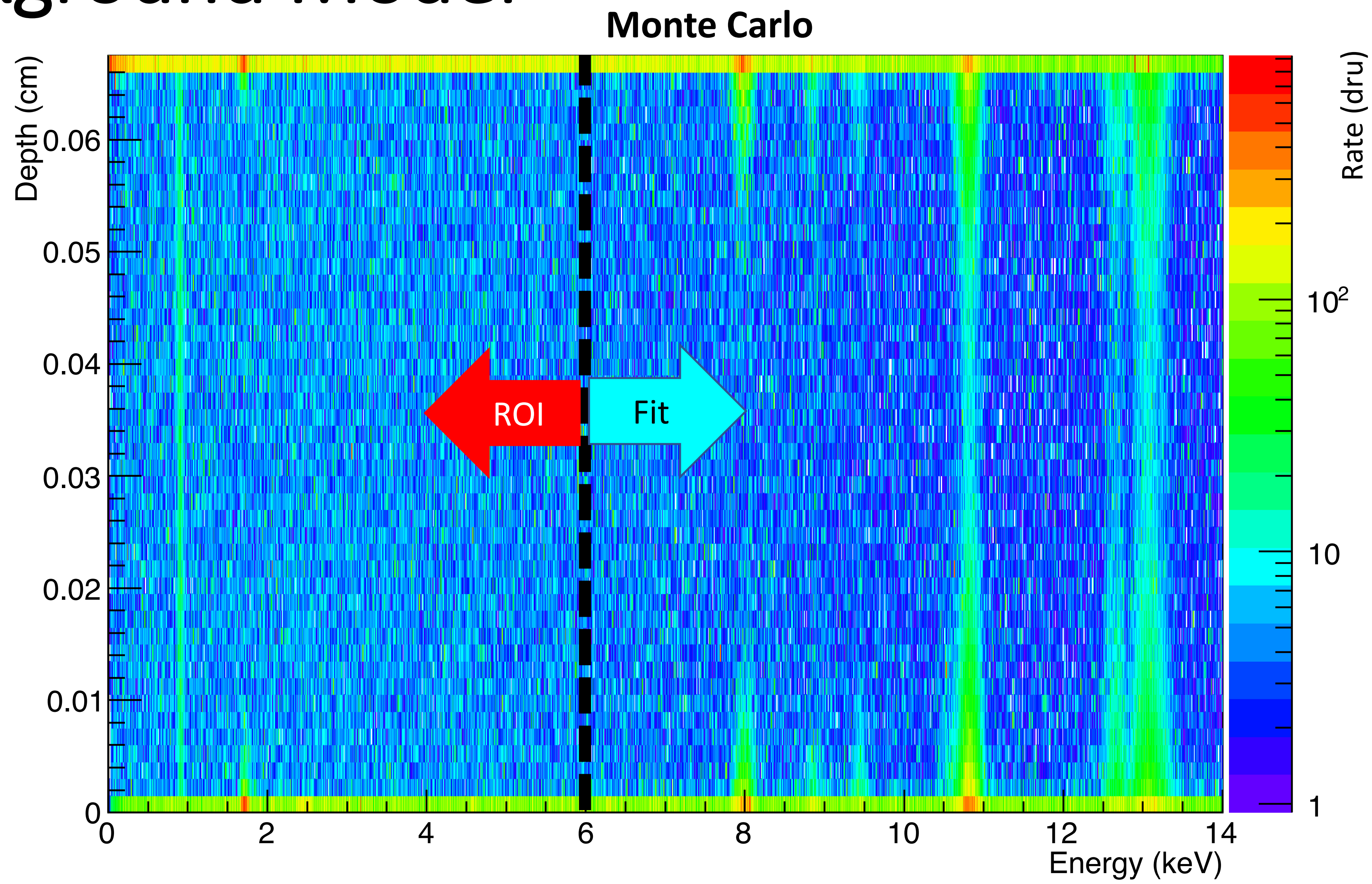
Fit Results

- This gives us 53 templates in energy-sigma for each detector part and decay chain
- …which we fit against the data above 6 keV
  - This implicitly assumes that we have no DM signal above 6 keV (DM mass > 10 GeV)
  - Each component is allowed to float within the uncertainty of the respective assay (or float freely down to zero if constrained by an upper bound)
- We use the fit above 6 keV to give us a background model for our WIMP ROI (0.05-6 keV)…



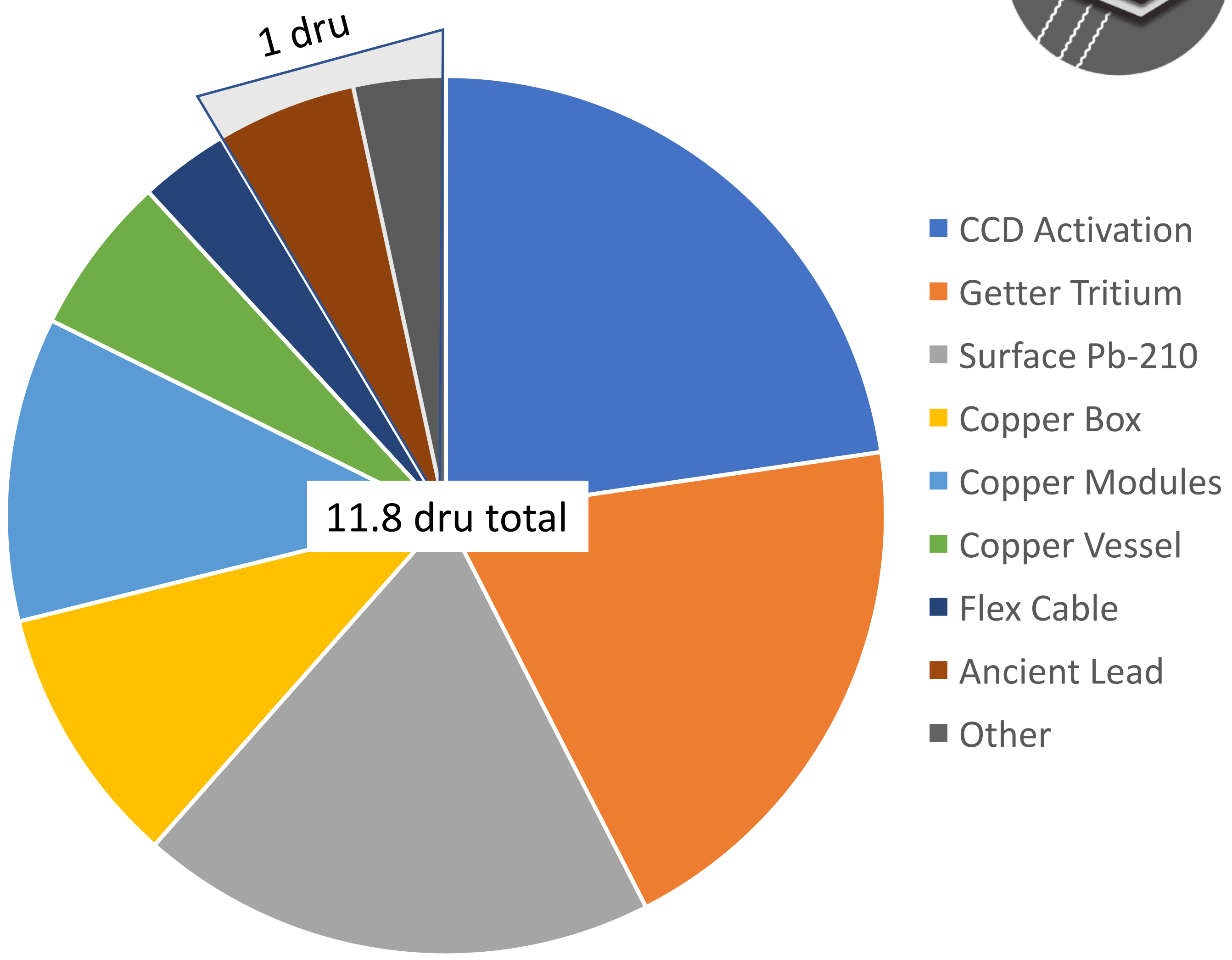


Background Model



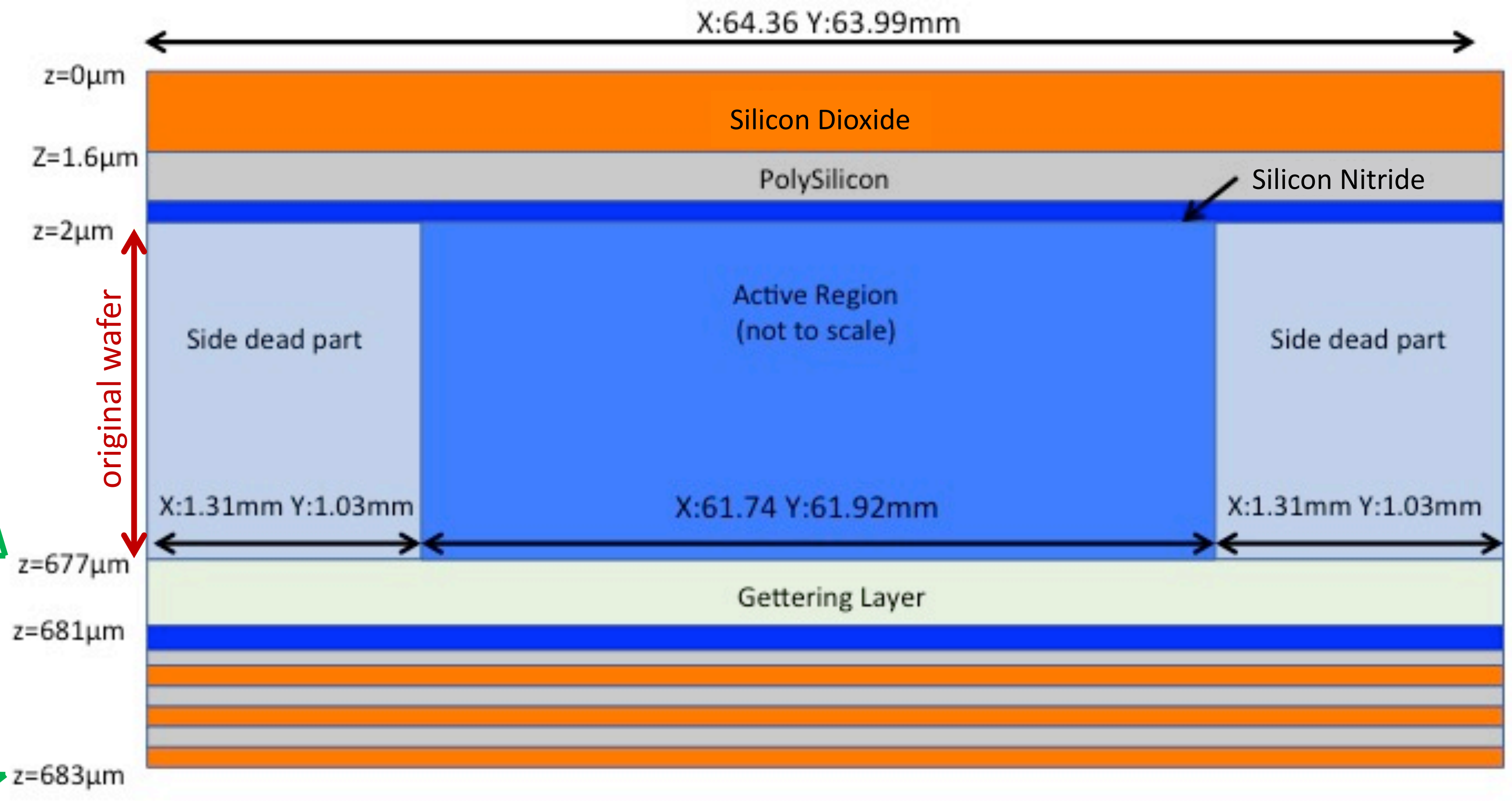
Result: Composition

- 20% of background comes from ^3H production from silicon activation
- 20% of background comes from tritium in the getter
- 20% of background comes from ^{210}Pb
- 20% of background comes from OFC copper
- …remaining 20% comes from a mixed bag of detector materials (mostly kapton cabling)



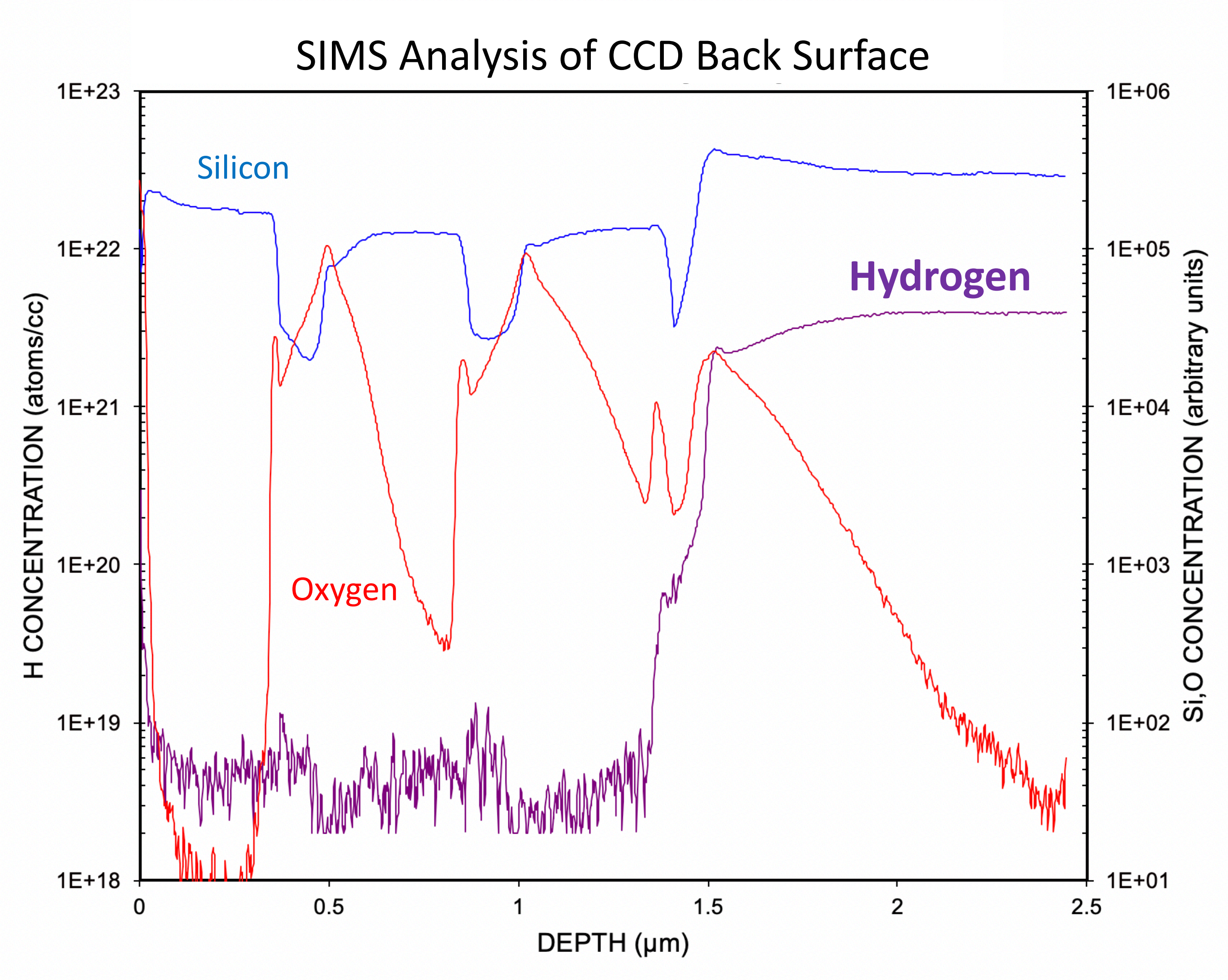
Checking the Result: Tritium

In-situ doped polysilicon	~4 μm
Silicon nitride	0.1 μm
P-doped polysilicon	0.4 μm
Silicon dioxide	0.3 μm
P-doped polysilicon	0.4 μm
Silicon dioxide	0.3 μm
P-doped polysilicon	0.4 μm
Silicon dioxide	★ 0.3 μm
TOTAL	**~6 μm**



★ Layer removed on the next slide

Checking the Result: Tritium

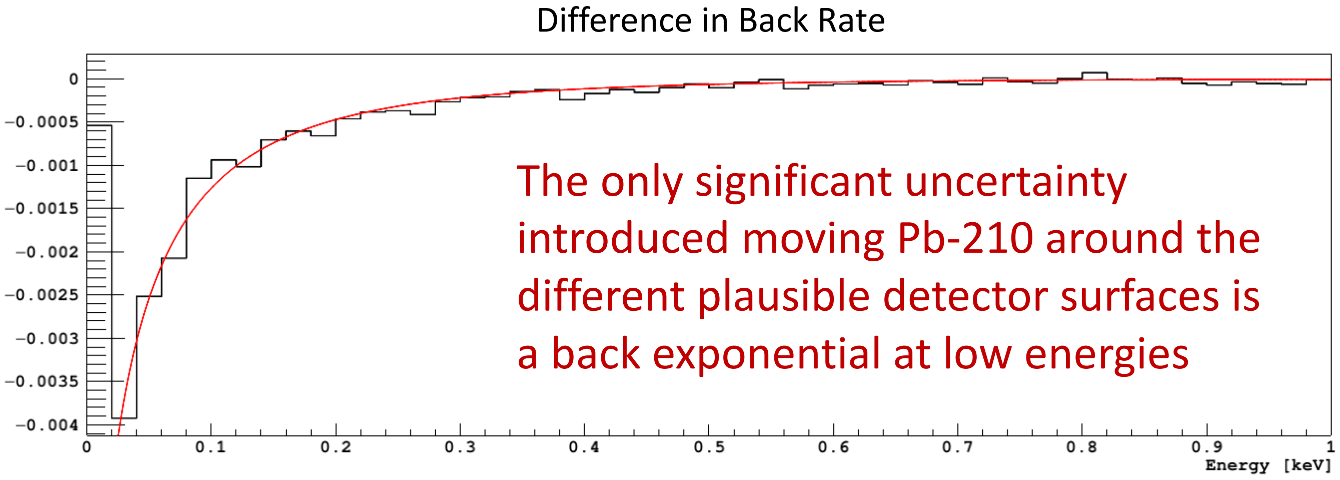


- **We find 4 x10^{21} H/cm^3 in the backside getter layer!**
- If we assume tritium fraction in water (1 x10^{-18} ^{3}H/H)…
- …we calculate
  - **3 x10^5 decays/kg/day**
- The DAMIC@SNOLAB analysis gives
  - **1.3 ± 0.3 x10^5 decays/kg/day** ***(preliminary)***
- **Completely independent measurement!**

Systematic Uncertainty: Pb-210

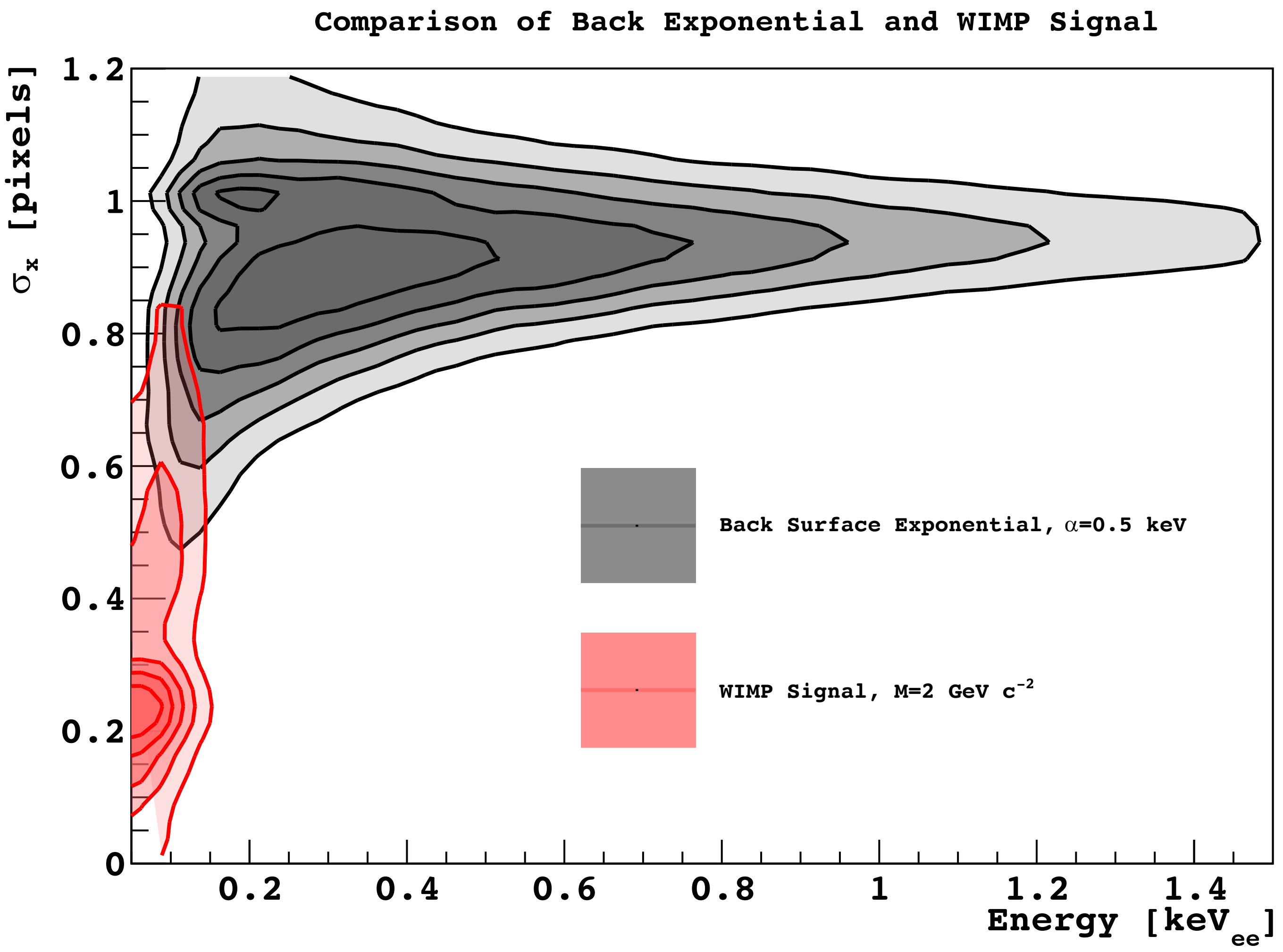
- We know there is a significant surface Pb-210 component to our background…
- **…but we don't know which surface.**
- The fit prefers to put Pb-210 on the back of the active region
  - This corresponds to the back of what was the silicon wafer

Location	Bulk	Front	Back	Wafer	External
Preferred?	No	No	No	**Yes**	**Yes**

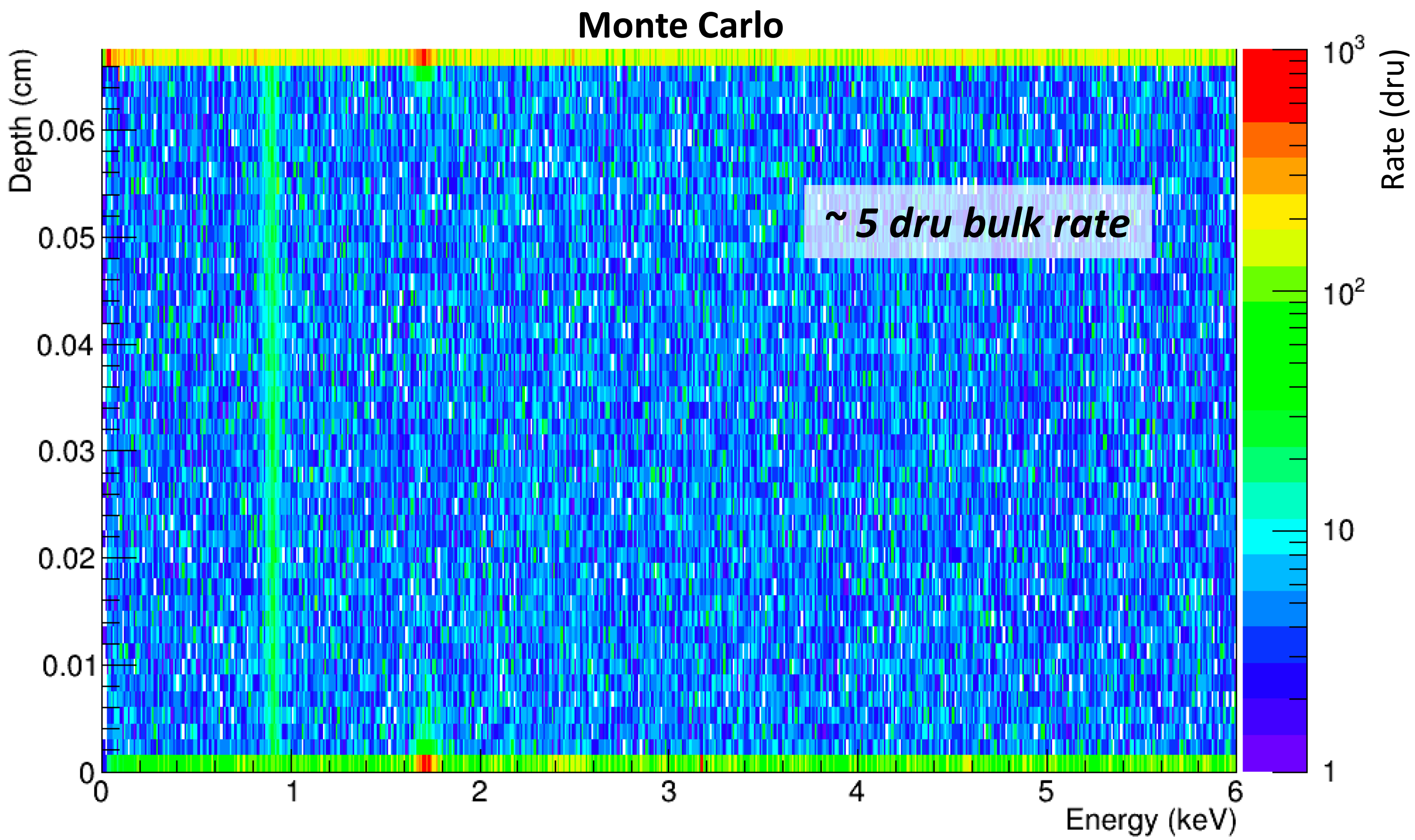


Systematic Uncertainty: Pb-210

- A back-side exponential rise is non-degenerate with a WIMP signal
  - Solution: Consider this a free parameter in the WIMP analysis to account for the systematic uncertainty of the ^{210}Pb location
- For DAMIC-M, this component must be removed…
  - Criteria: < 0.5 nBq/cm^2 on the wafer
- No need for a fiducial cut!

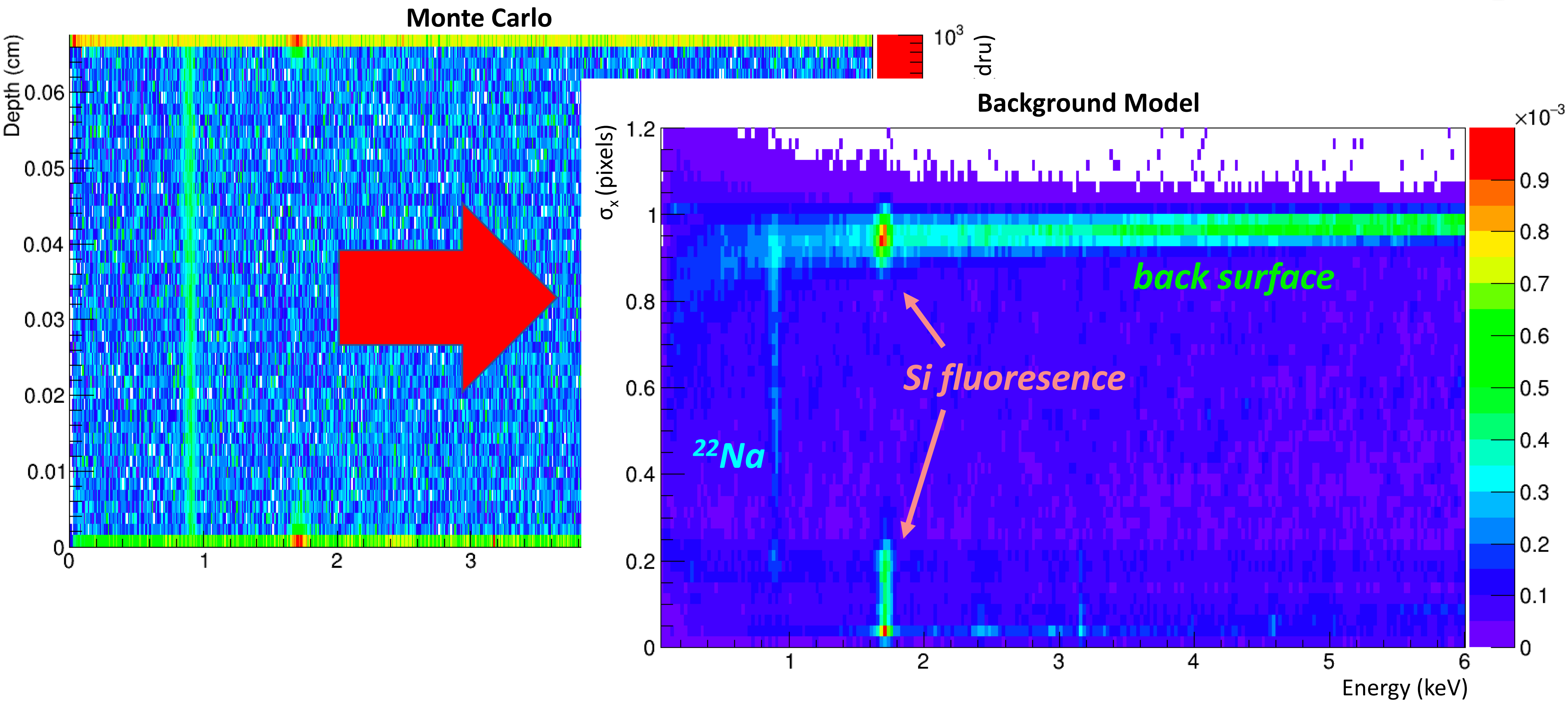


DAMIC at SNOLAB Background Model



- We randomly sample our background model (in E-z)…
- …apply our diffusion model to fake events…
- …paste onto blank images to account for read-out noise…
- …run the same clustering algorithm that is used on the data to account for efficiencies…
- …and output a background model in observed variables energy-sigma

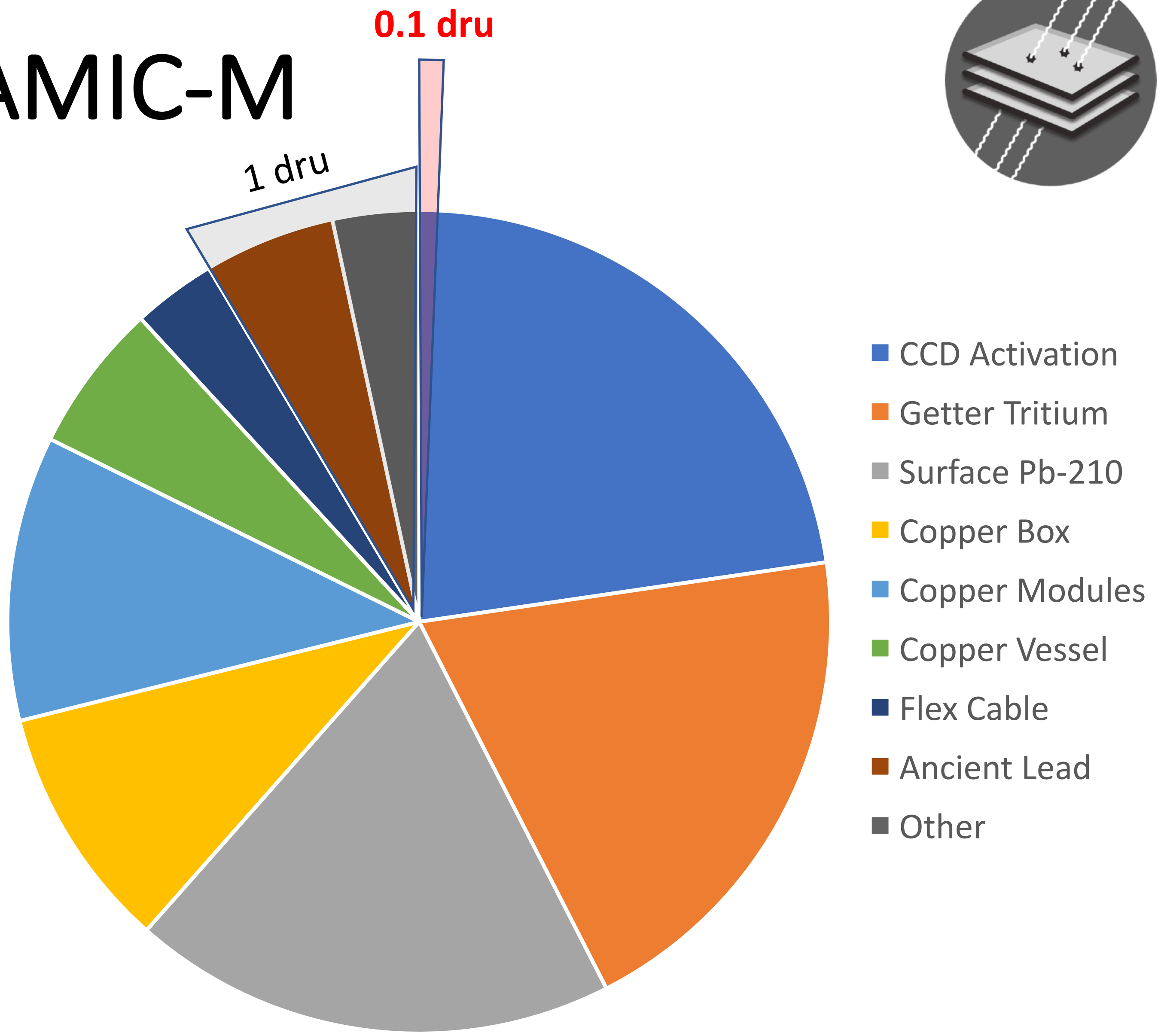
DAMIC at SNOLAB Background Model



Looking forward: DAMIC-M

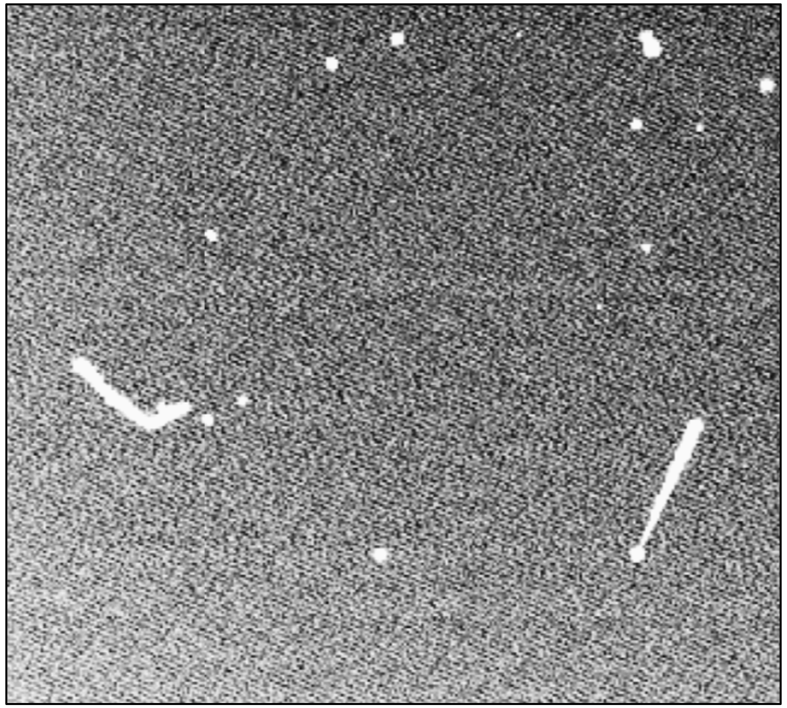
- **Tritium** – will shield silicon to eliminate activation backgrounds and remove getter hydrogen
- **Pb-210** – will properly clean all surfaces and control exposure to radon
- **Copper** – will electroform all components near CCD and shield from activation
- **Cable** – extensive research ongoing into clean cable and connector options
- **Other (< 1 dru)** – need to better measure component activities (ongoing)

- Removes **ALL** *known* backgrounds that we expect to contribute > 1 dru
- Working now to better understand the contributions down to 0.1 dru



Conclusions

- DAMIC at SNOLAB continues to produce excellent physics
  - **see talk by Alvaro Chavarria**
  - Paper on dark matter electron coupling: arXiv:1907.12628
  - *Expect paper on DM-nucleon coupling soon…*
- DAMIC-M will improve on this by orders of magnitude due to lower backgrounds, single electron resolution, and much larger exposure
  - **see talk by Paolo Privitera**



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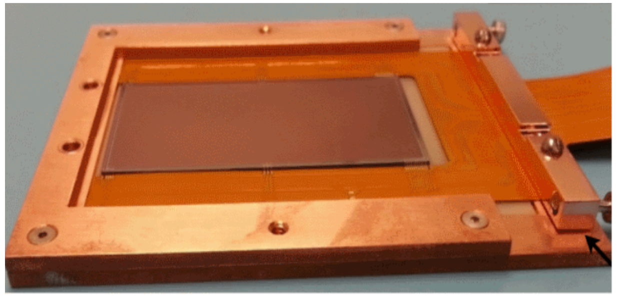
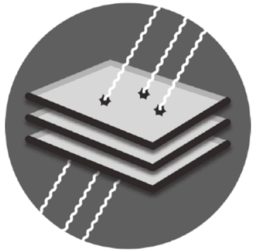
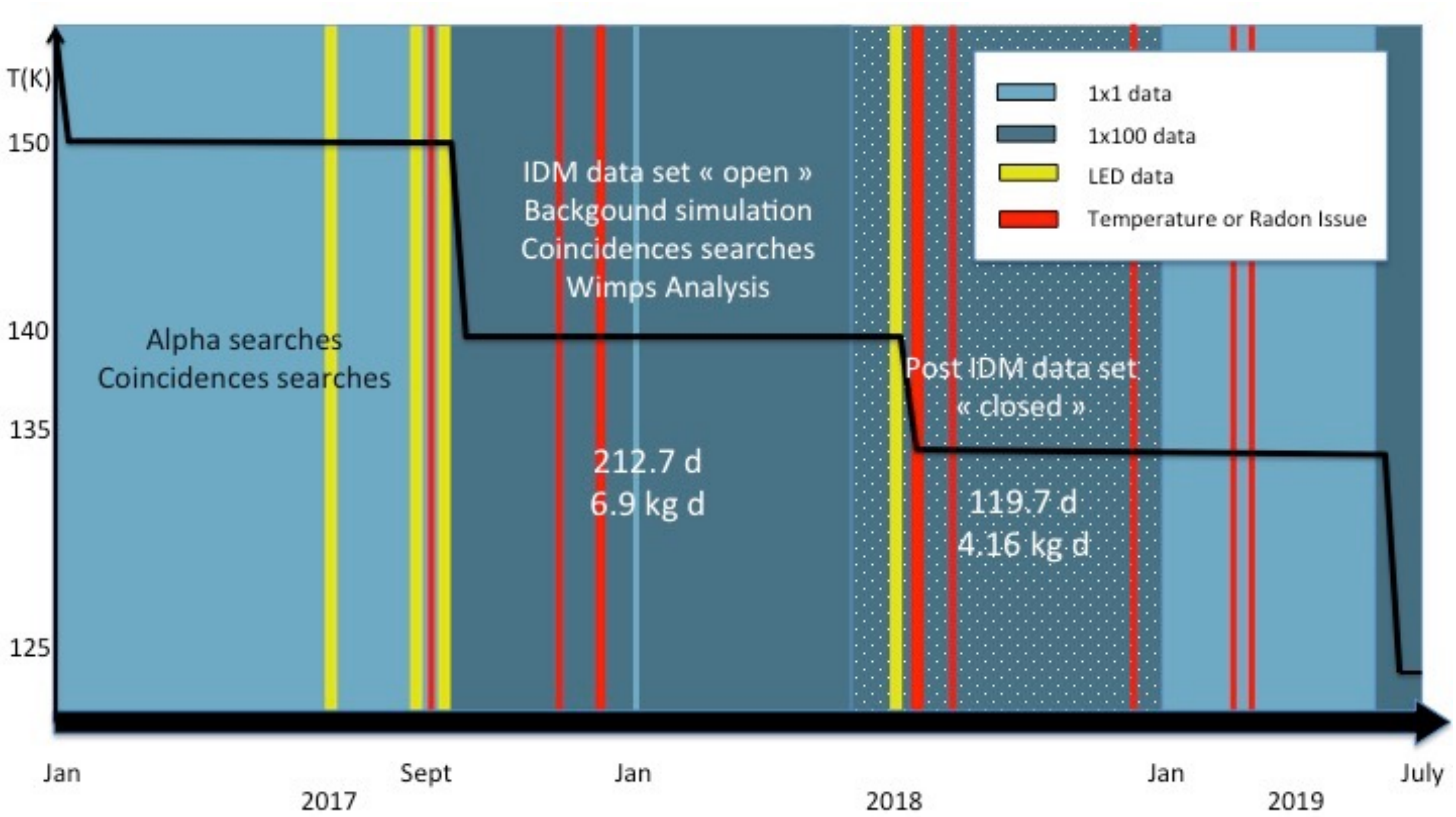
DAMIC Collaboration

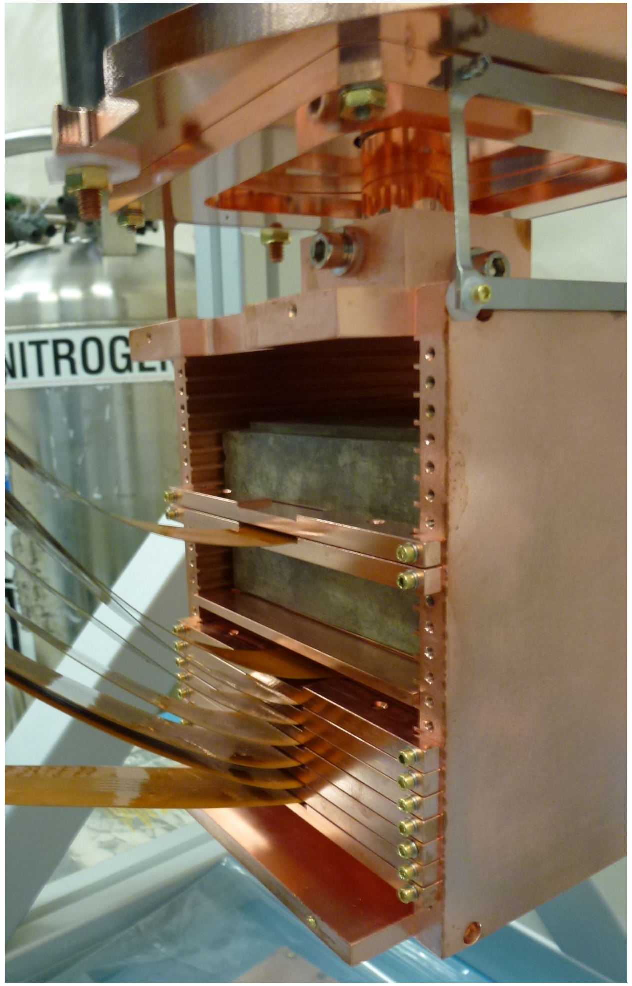
Extra Slides

DAMIC at SNOLAB



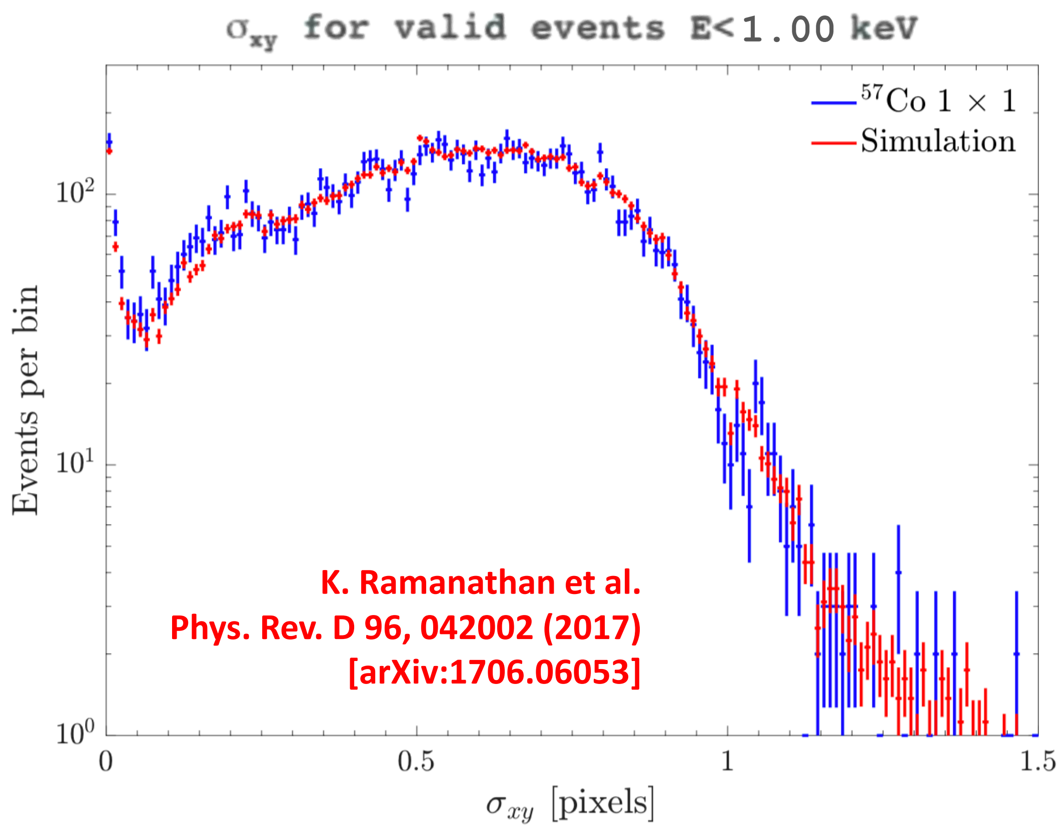




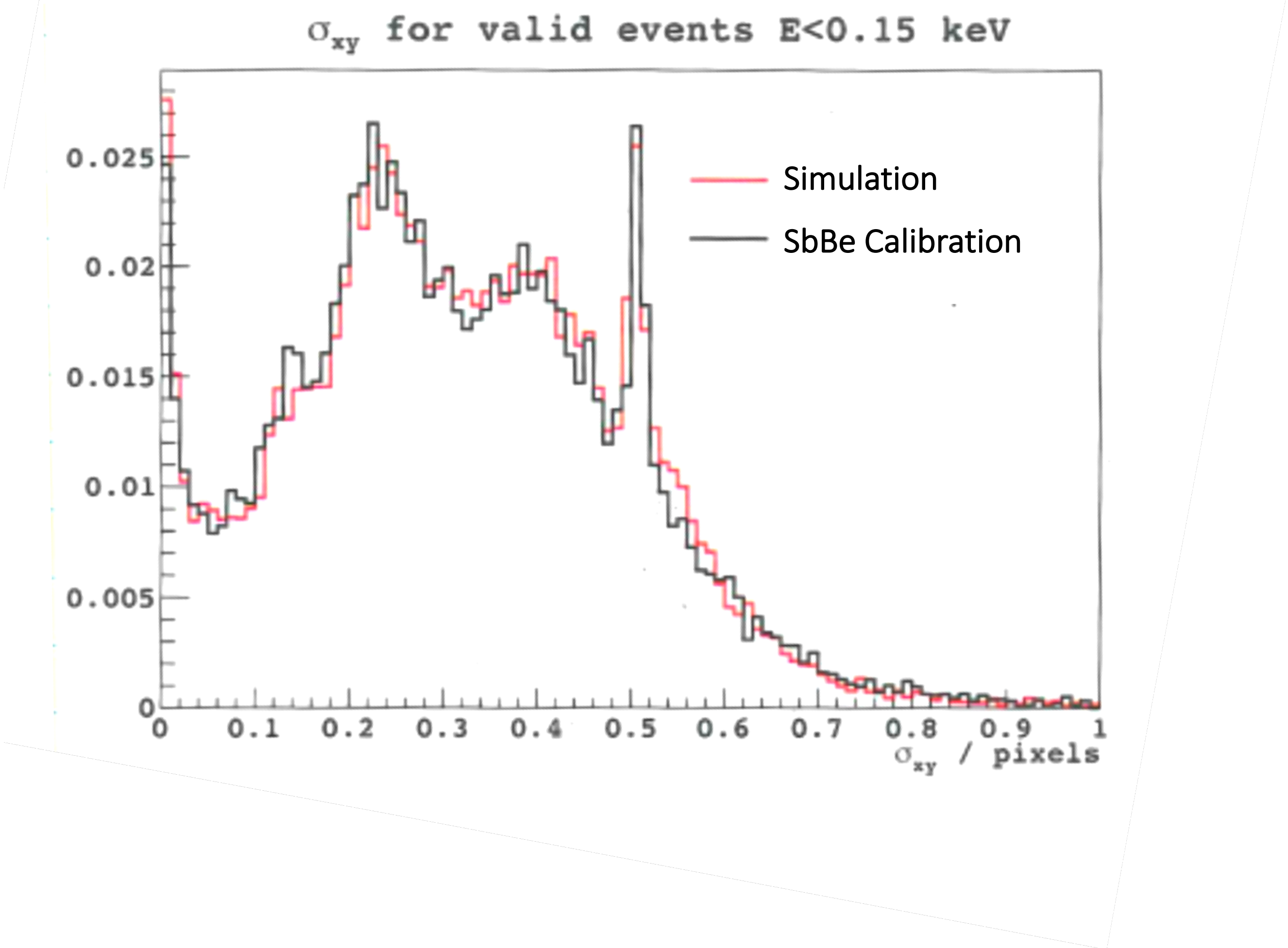


Low-Energy Sigma Validation

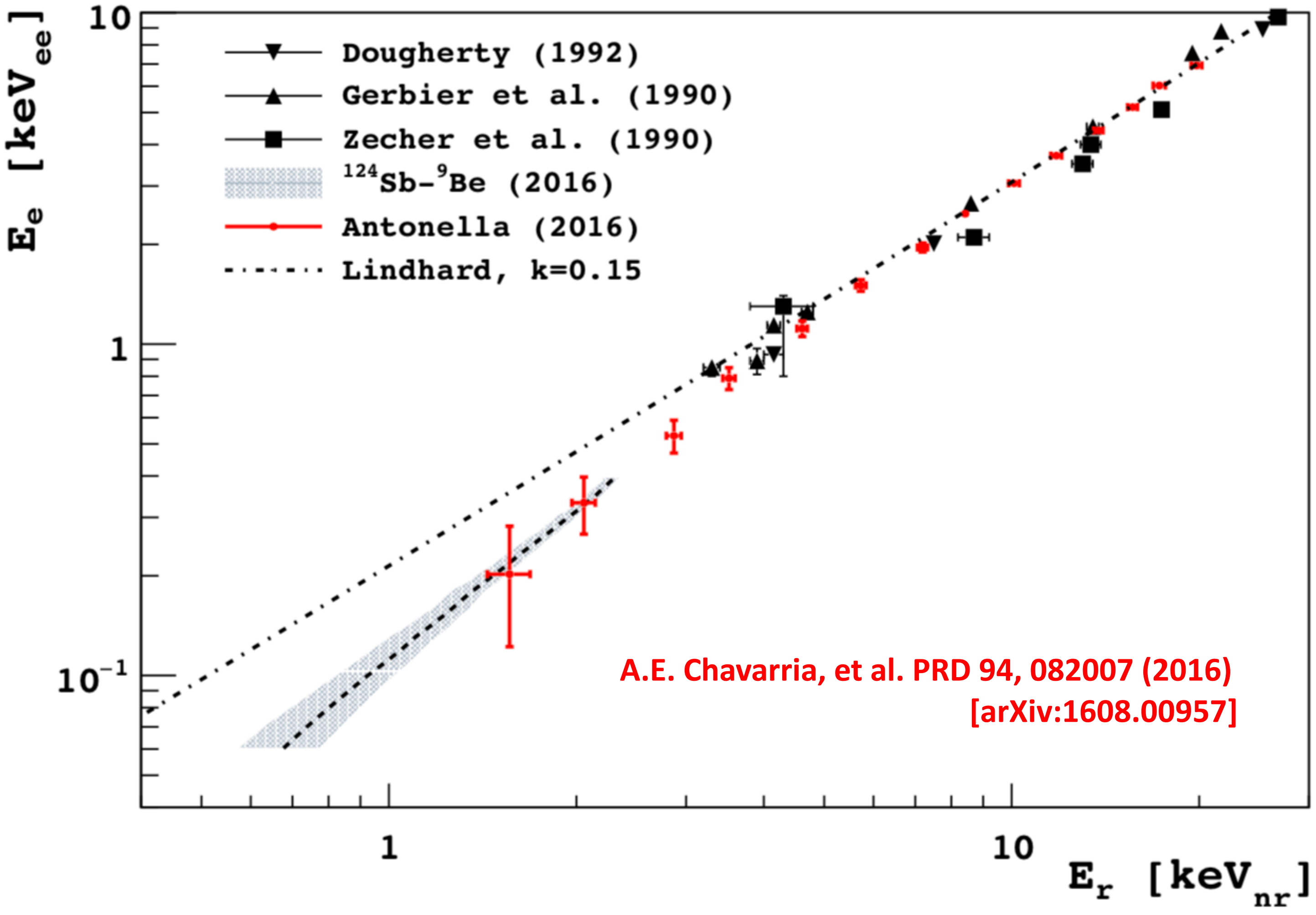
Gammas



Neutrons



Ionization Efficiency



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

Ionization Model