Results on Low-Mass WIMPs from a 11 kg d Target Exposure of DAMIC at SNOLAB

GDR DUPhy Plenary Meeting - LPNHE, Paris,
29 Nov-1 Dec 2021

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Outline:

1. DAMIC at SNOLAB
2. Background Rejection
3. Background Model
4. WIMP Search
5. Future Plans

DAMIC Collaboration

DAMIC AT SNOLAB

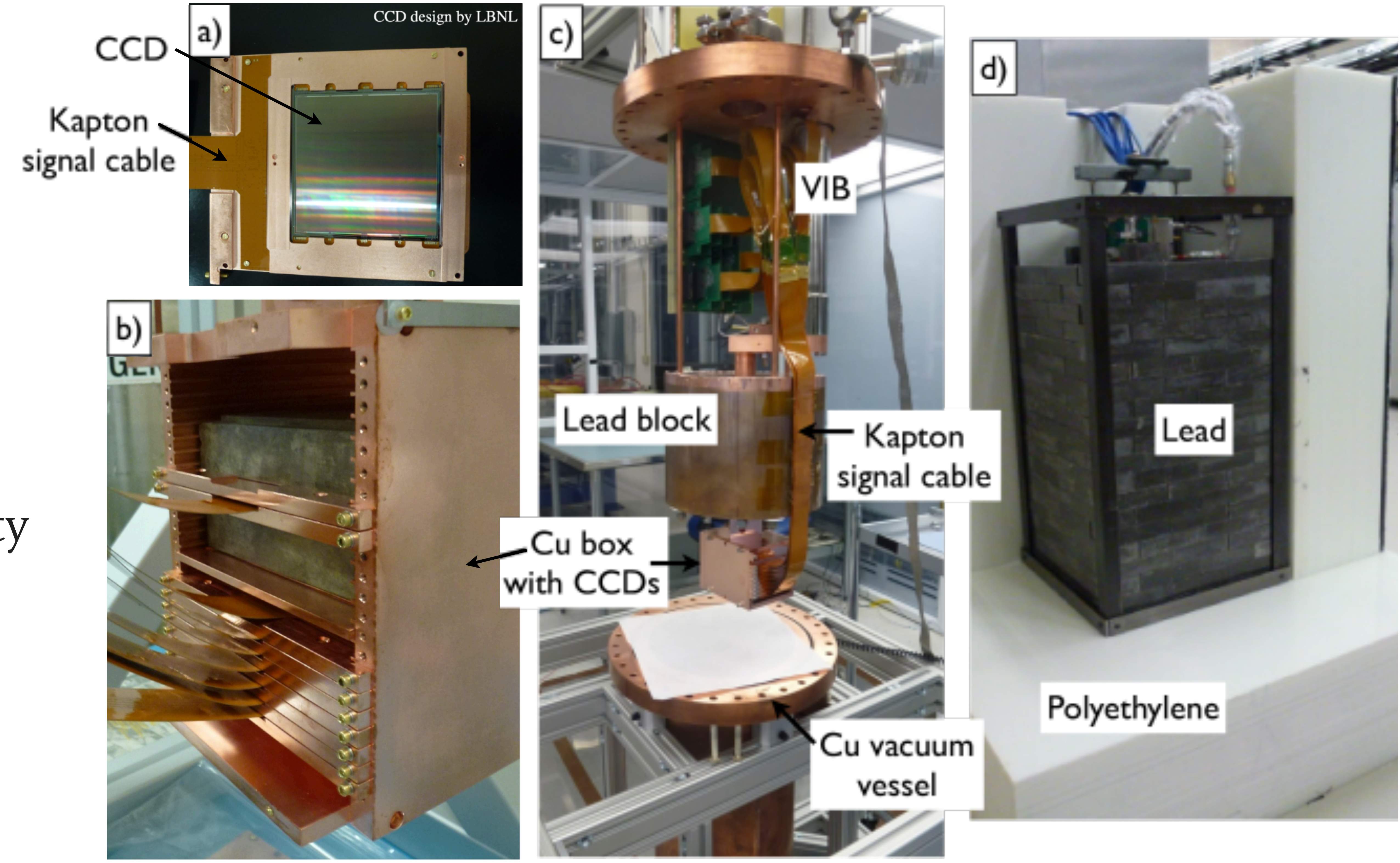
- **DArk Matter In CCDs** collaboration (since 2011)
- Setup beneath 2 km of granite **at SNOLAB** (Canada)
  (6 km water equivalent)

Charge-Coupled Devices

- Extremely low noise and dark current ⇒ sensitive to $\sim e^-$
- 3D track reconstruction and particle discrimination capability

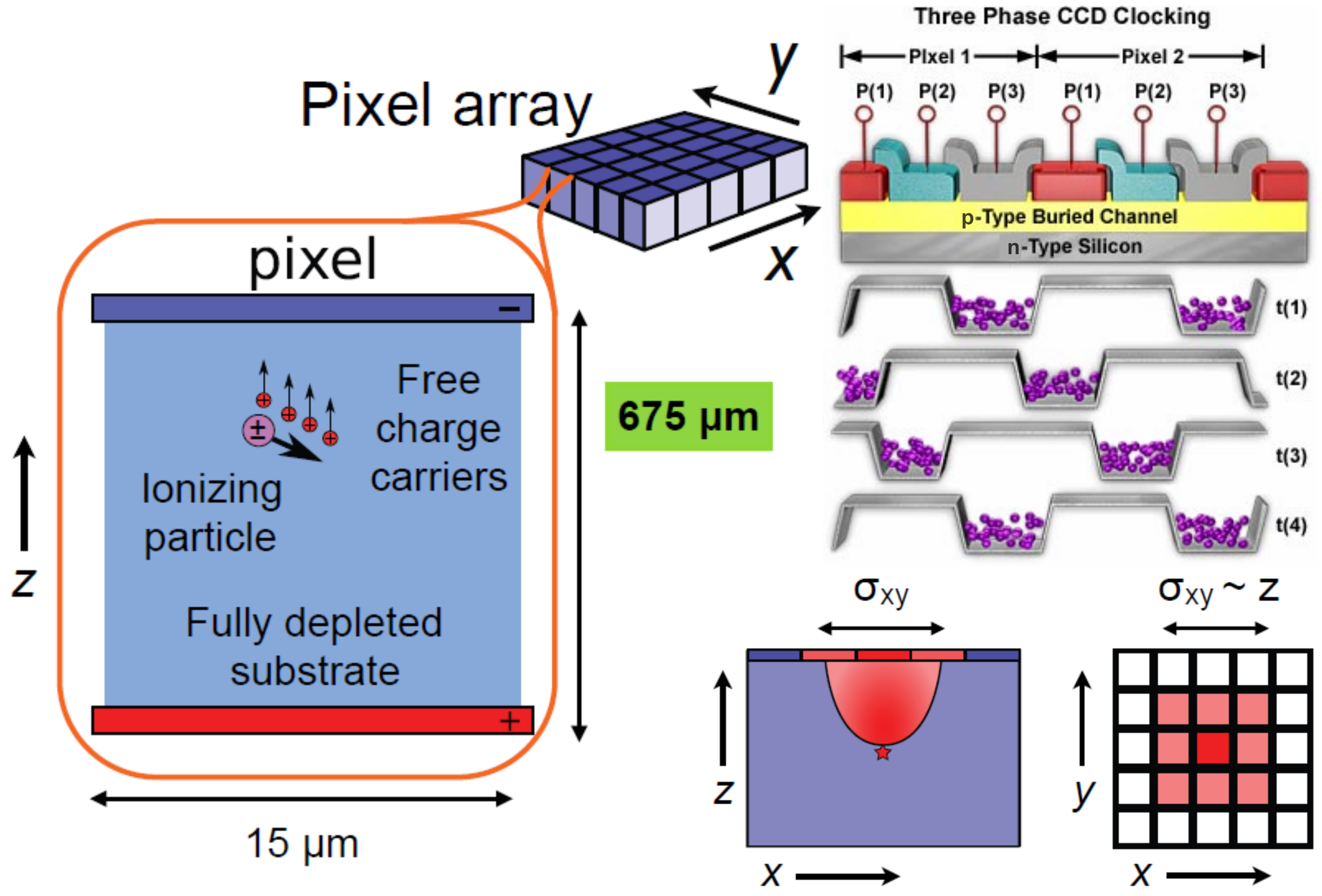
…for Dark Matter?

- Record thickness + several CCDs ⇒ massive target ($\sim$40 g)
  675 μm — 7 operational
- Different DM search options:
  - 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, buried channel structure
- Fully depleted (40 V substrate)
- High resistivity ~ 10 kΩ·cm
- Thickness: 675 μm

Performance:

- Charge transfer inefficiency < 10^{-6}
- Readout noise ~1.6 e^{-} (6 eV)
- Dark current < 10^{-3} e^{-}/pix/day

BACKGROUNDs AT DAMIC

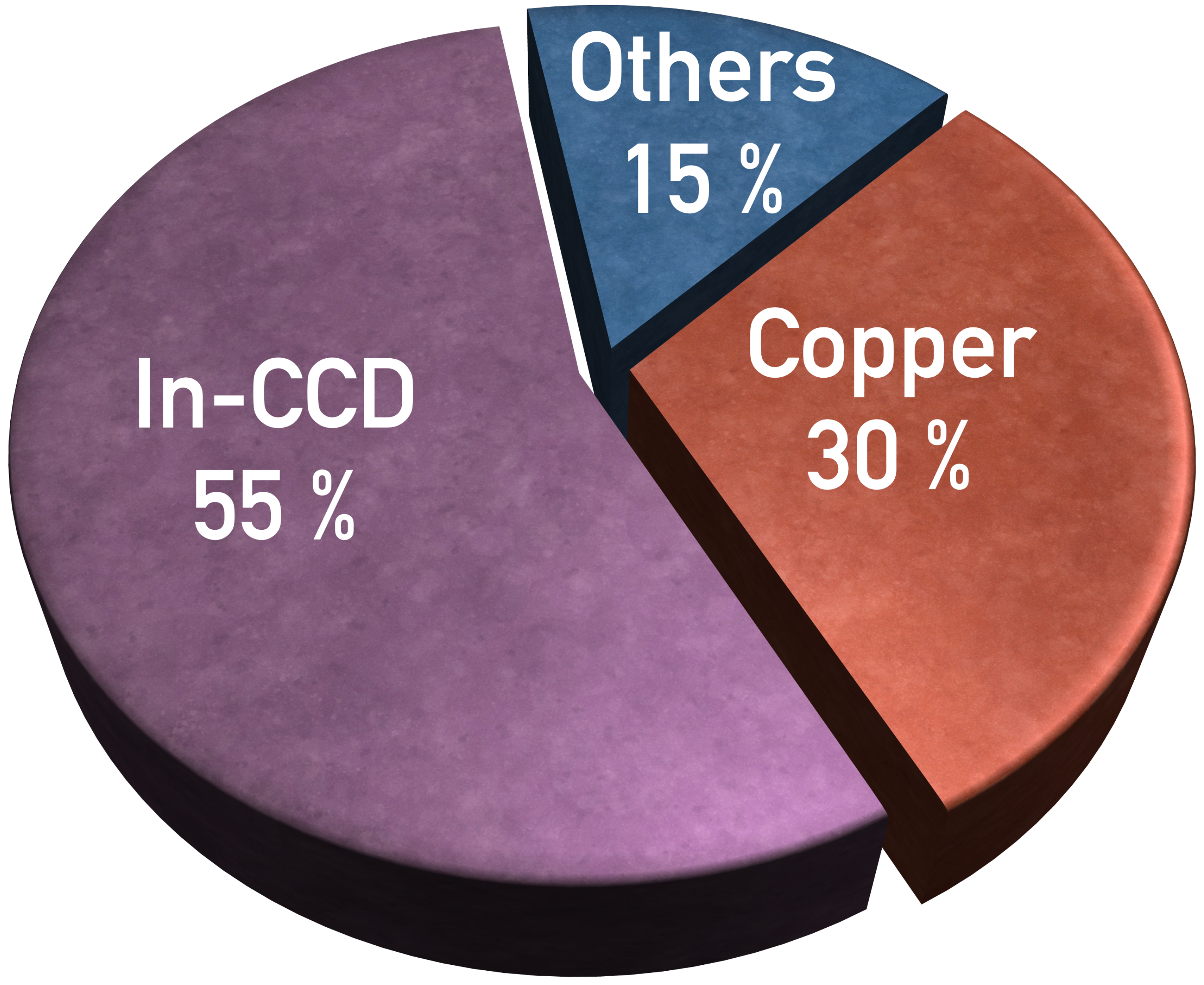
How we deal with backgrounds:

- Underground operation
- Material selection (assays)
- In situ shielding
- Discrimination and quantification of contaminants ⇒ bkg model

Background contributions:

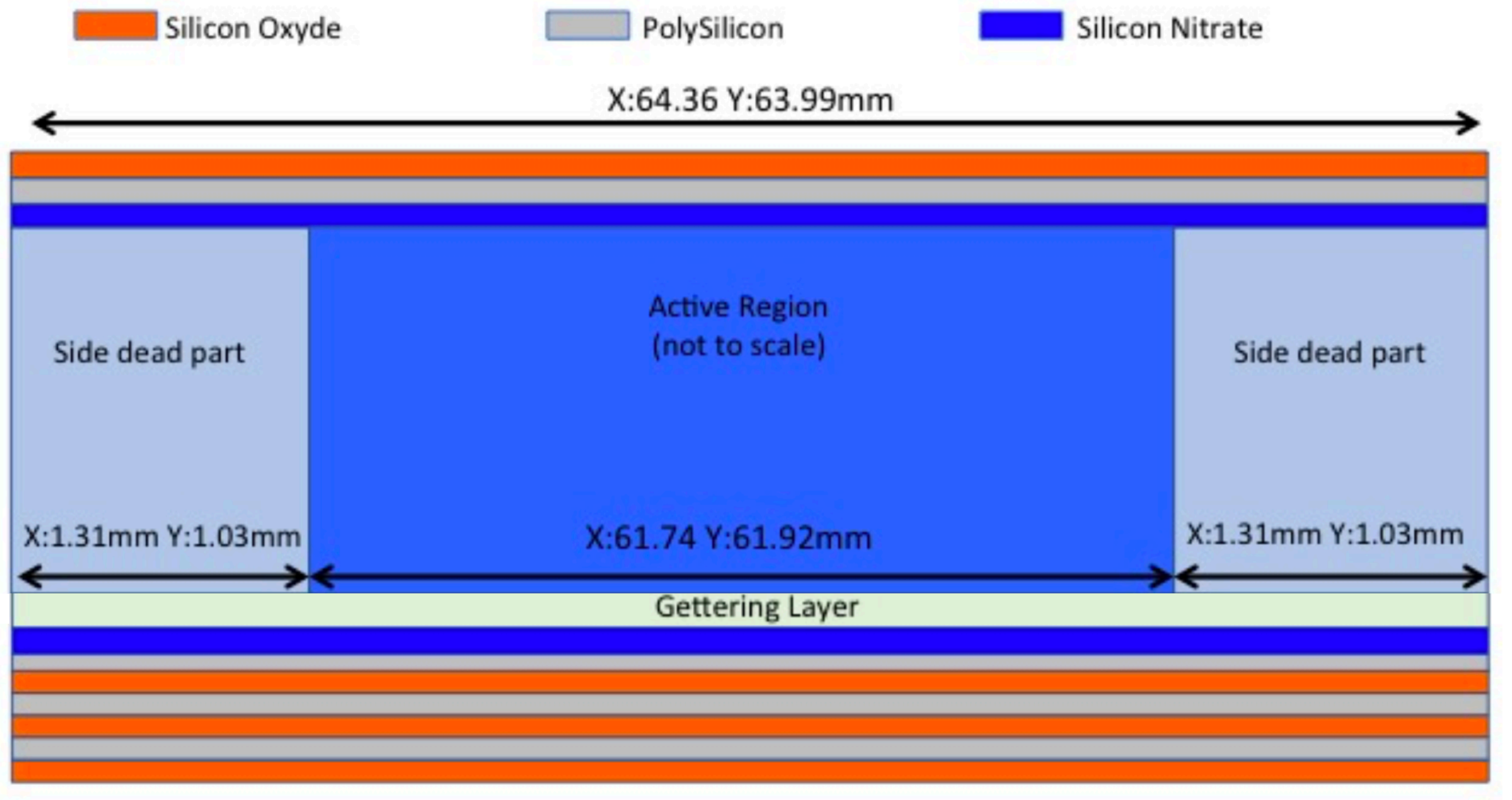
- ~ 55% in-CCD contaminants
- ~ 30% OFC Copper
- ~ 15% from various detector materials (lead shielding, flex cables, etc.)

~ 11.8 dru



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

IN-CCD CONTAMINANTS



Main Surface Contaminants

Deposition

Decay Sequence	$t_{1/2}$	Q-value
$^{210}\text{Pb} \longrightarrow {}^{210}\text{Bi} + \beta^- + \text{IC}/\gamma$	22.3 y	63.5 keV
$^{210}\text{Bi} \longrightarrow {}^{210}\text{Po} + \beta^-$	5.01 d	1.16 MeV

Main Bulk Contaminants

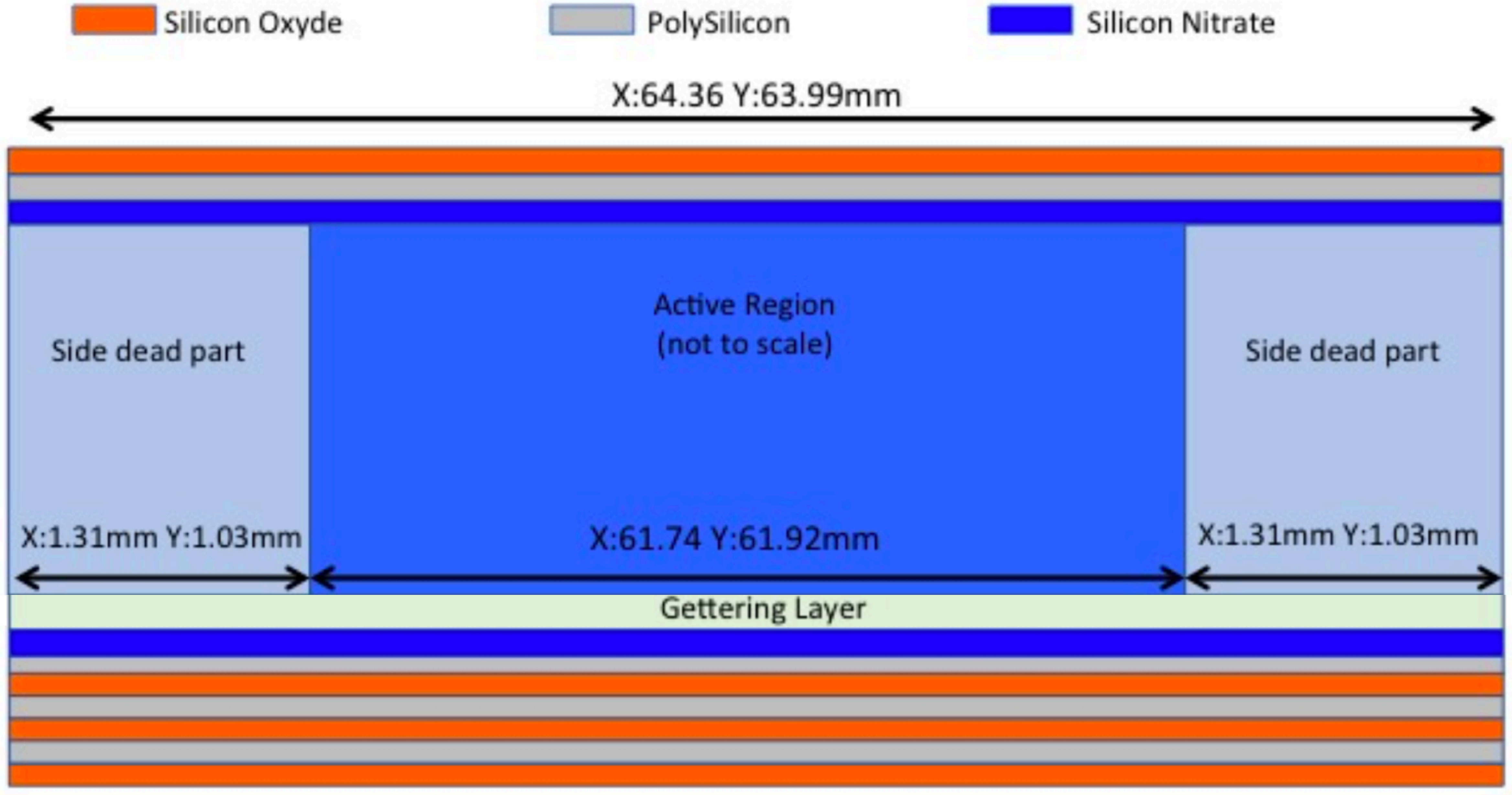
Natural abundance

Decay Sequence	$t_{1/2}$	Q-value
$^{32}\text{Si} \longrightarrow {}^{32}\text{P} + \beta^-$	150 y	225 keV
$^{32}\text{P} \longrightarrow {}^{32}\text{S}\,(\text{stable}) + \beta^-$	14.3 d	1.71 MeV

CCD activation

Decay	$t_{1/2}$	Q-value
$^{3}\text{H} \longrightarrow {}^{3}\text{He} + \beta^-$	12.3 y	18.6 keV

SPATIAL COINCIDENCE ANALYSIS



Main Surface Contaminants (Deposition)

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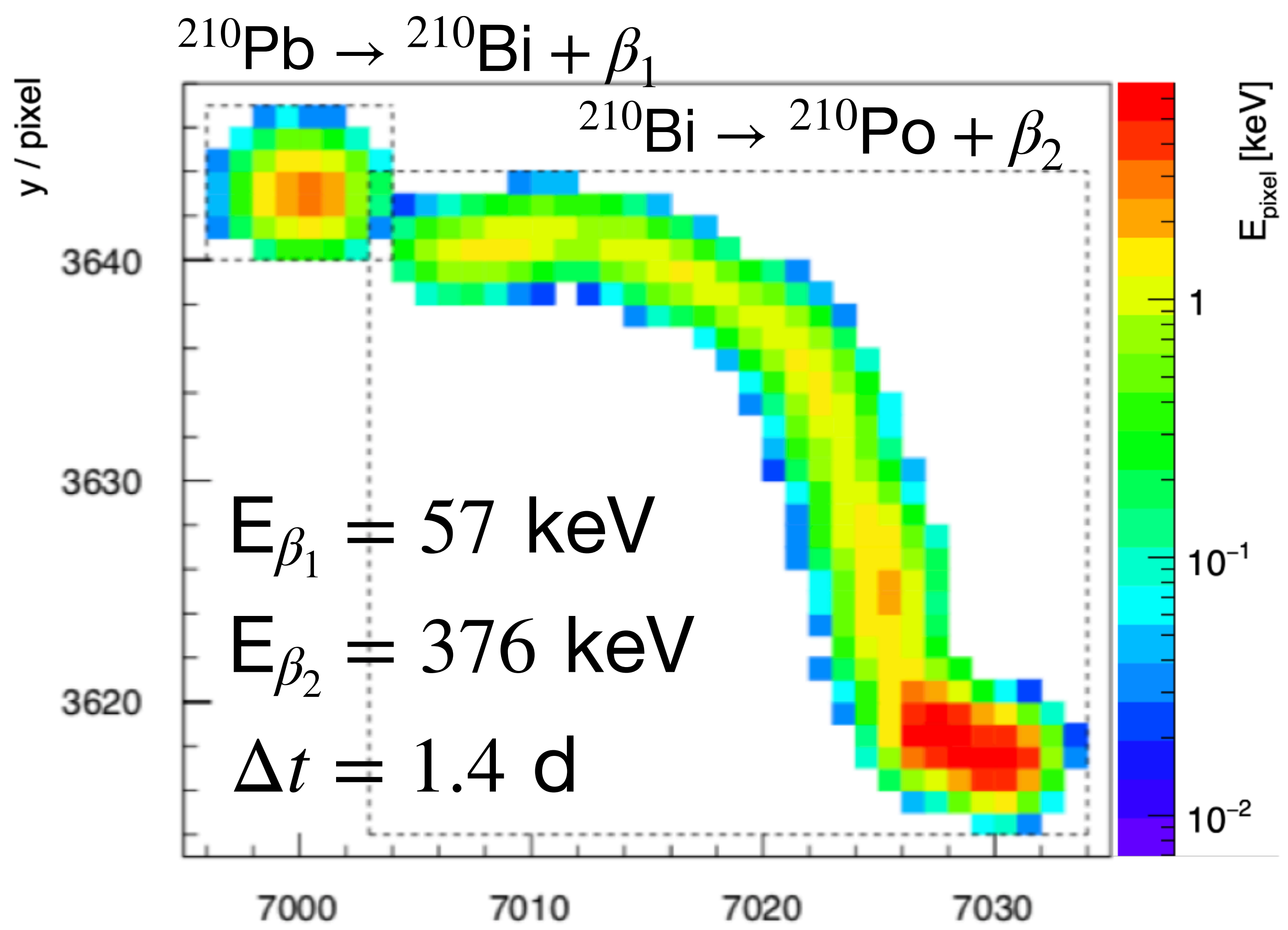
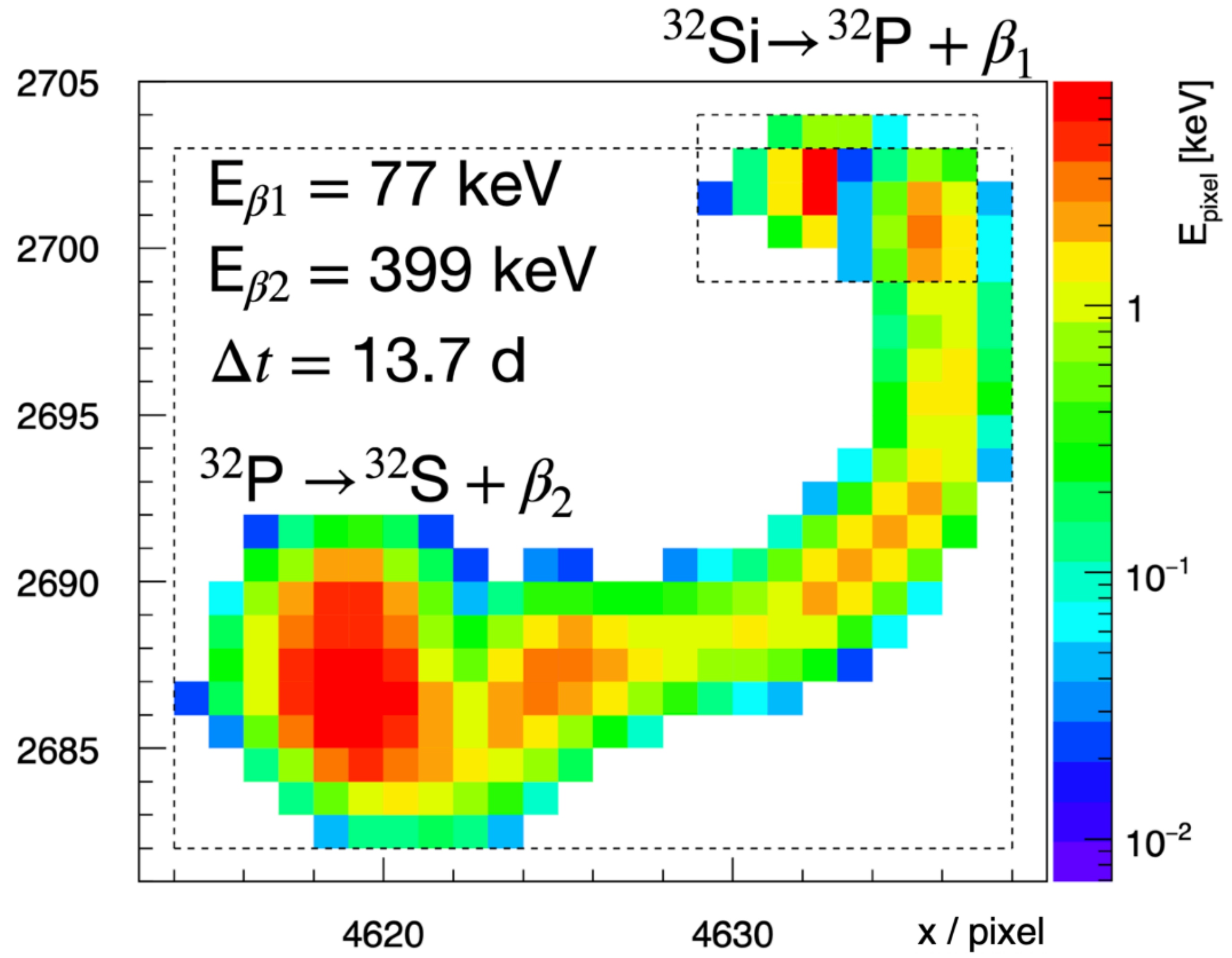




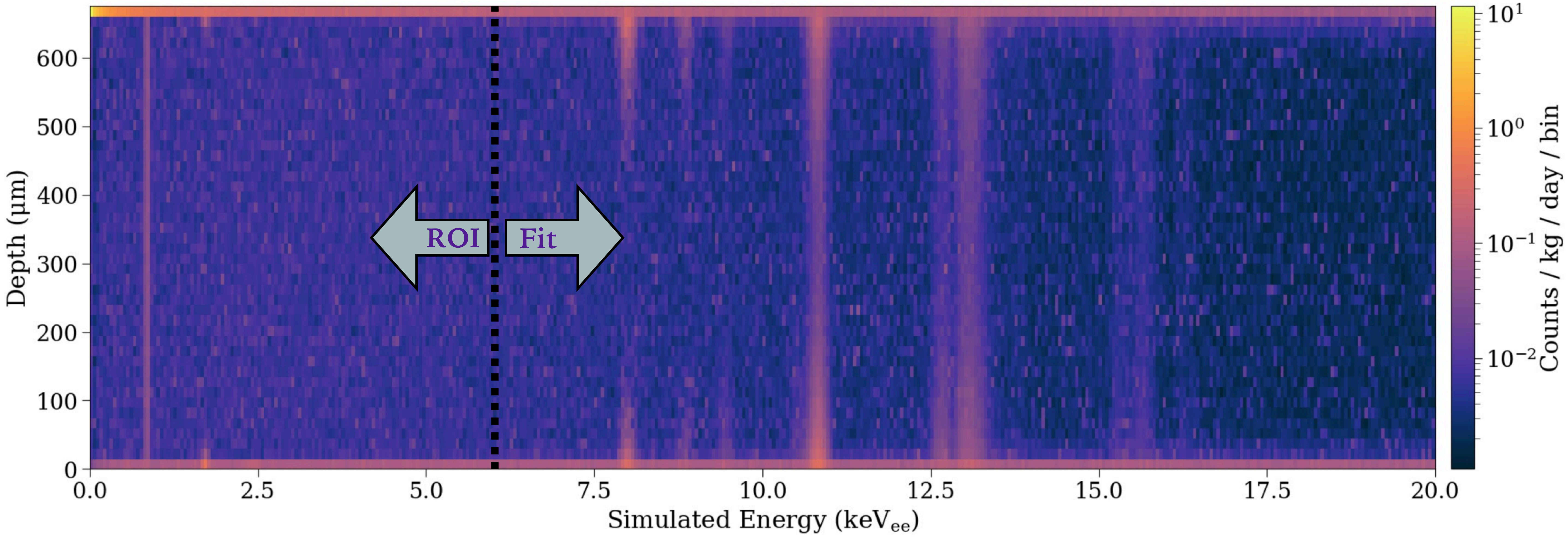
Limits on radioactive contaminants:

- ^{210}Pb: < 160 µBq/kg
- ^{32}Si: 140±30 µBq/kg
- ^{238}U: < 11 µBq/kg
- ^{232}Th: < 7.3 µBq/kg

BACKGROUND MODELING

Background model construction:

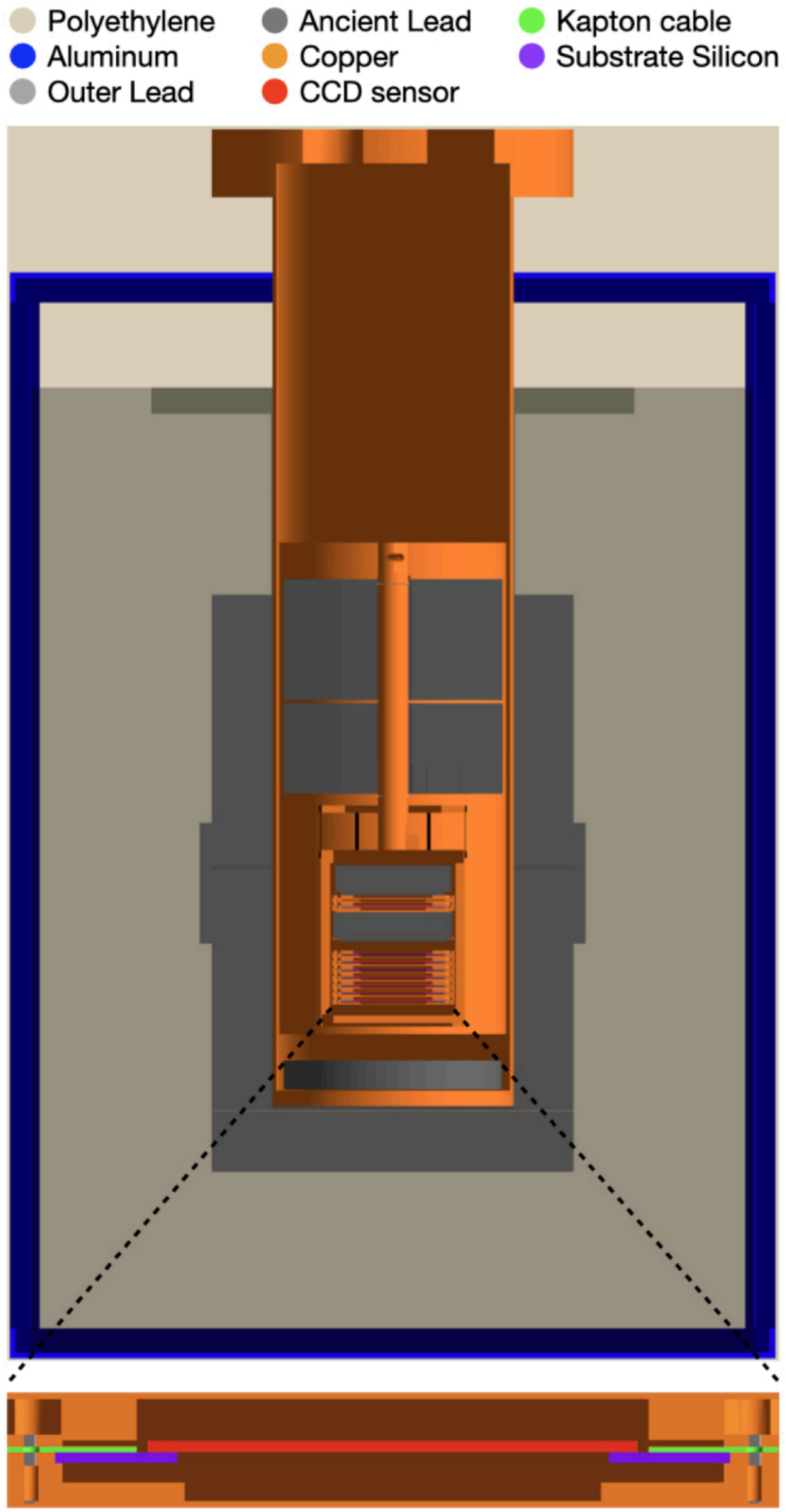
- **Decay** and **tracking** across detector geometry with Geant4
- **CCDs response simulation**: charge generation, (partial) collection/ transport, pixelation, binning and readout noise
- **Reconstruction** to **(E,σ_x)** space
- **Likelihood fit** to data in WIMP-safe region (6-20 keV) $\Longrightarrow$ extrapolate in ROI (0-6 keV)



BACKGROUND SIMULATIONS

Decay and tracking across detector geometry with Geant4

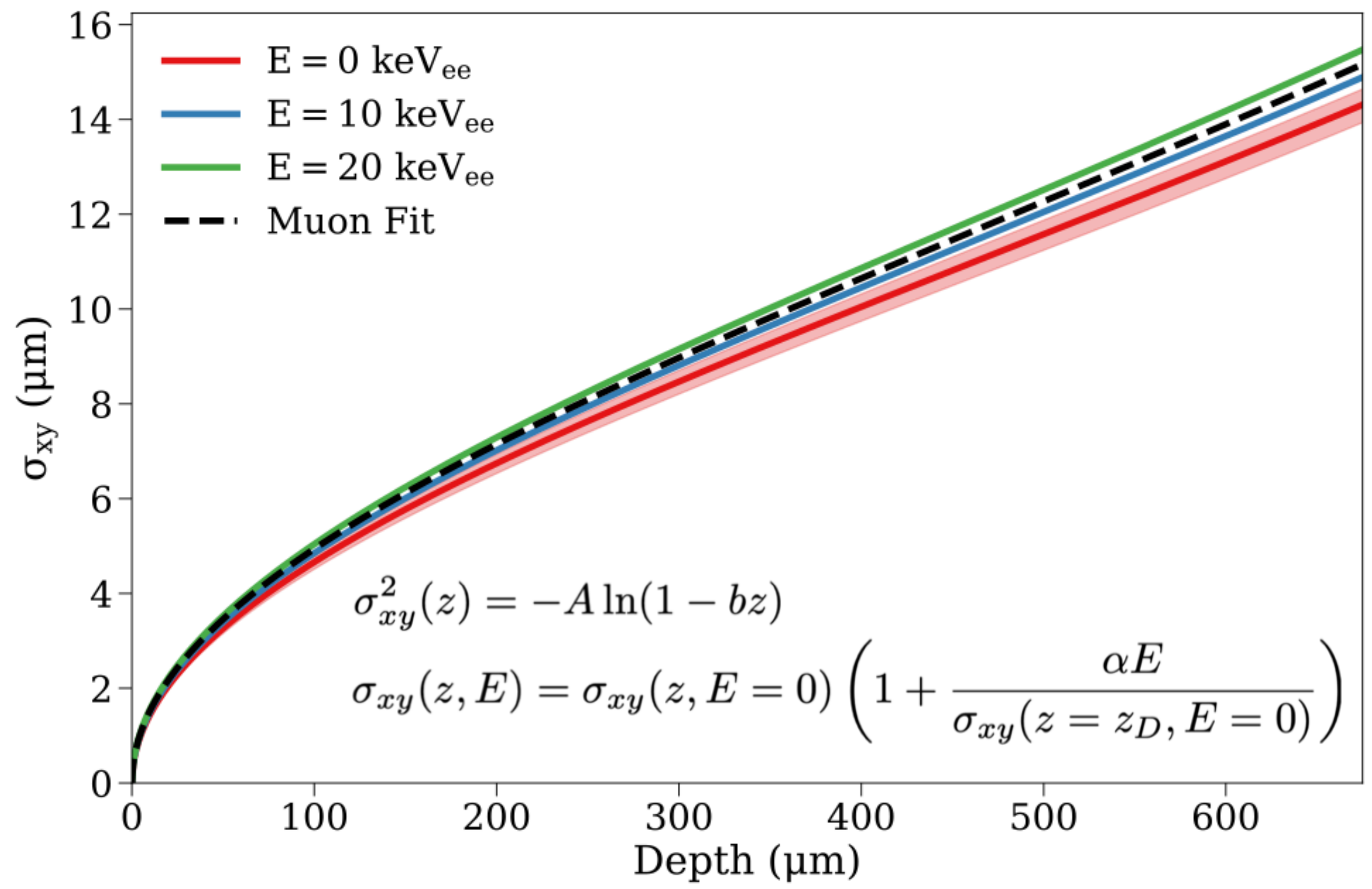
- **Livermore physics list:** low-energy electromagnetic interactions
  - Down to 10 eV for electrons, 100 eV for photons
- **Optimized range cuts** based on detector part
- **Simulated up to 500M decays for over 1000 isotope-volume** combinations
  - Prominent decay chains and material-specific isotopes simulated
    - ^{238}U, ^{232}Th and ^{40}K chains
    - Activation and naturally-occurring radioisotopes
  - ➡ Interaction energy and position information



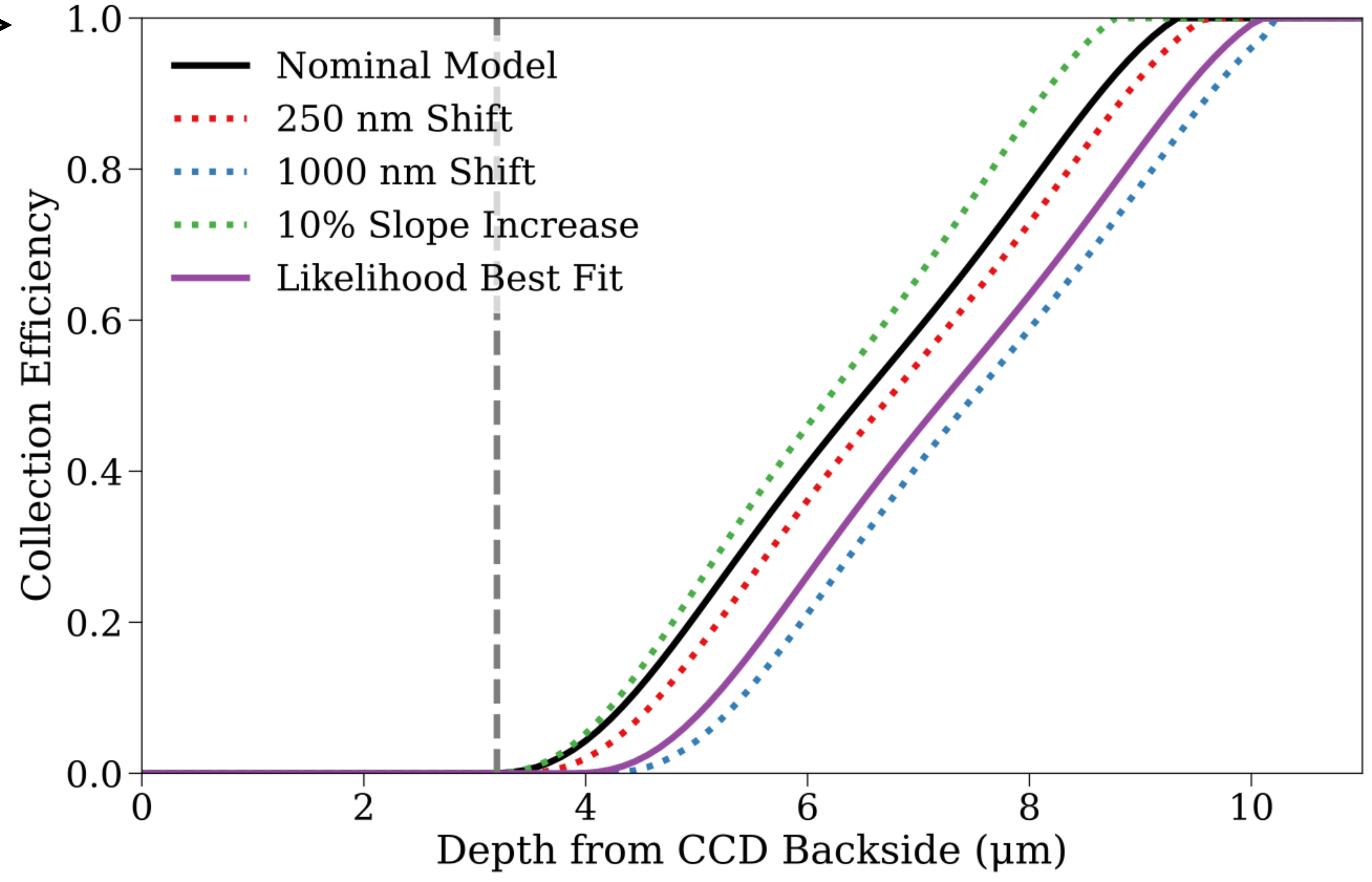
DETECTOR RESPONSE SIMULATION

Detector response simulation

- *Charge generated* assuming $\langle E_{e-h} \rangle = 3.8\ \mathrm{eV_{ee}}$
- *Diffusion* model calibrated on muon surface data



- *Charge collection efficiency* based on CCD *secondary ion mass spectrometry* (SIMS) measurements
  - Consistent with FNAL calibration
    arXiv:2007.04201



- *Pixelation, saturation, noise addition* and *binning*

$\Rightarrow$ **Reconstruction into (E,σ_x) distribution**

BACKGROUND TEMPLATE FITTING

Construction of Background Templates

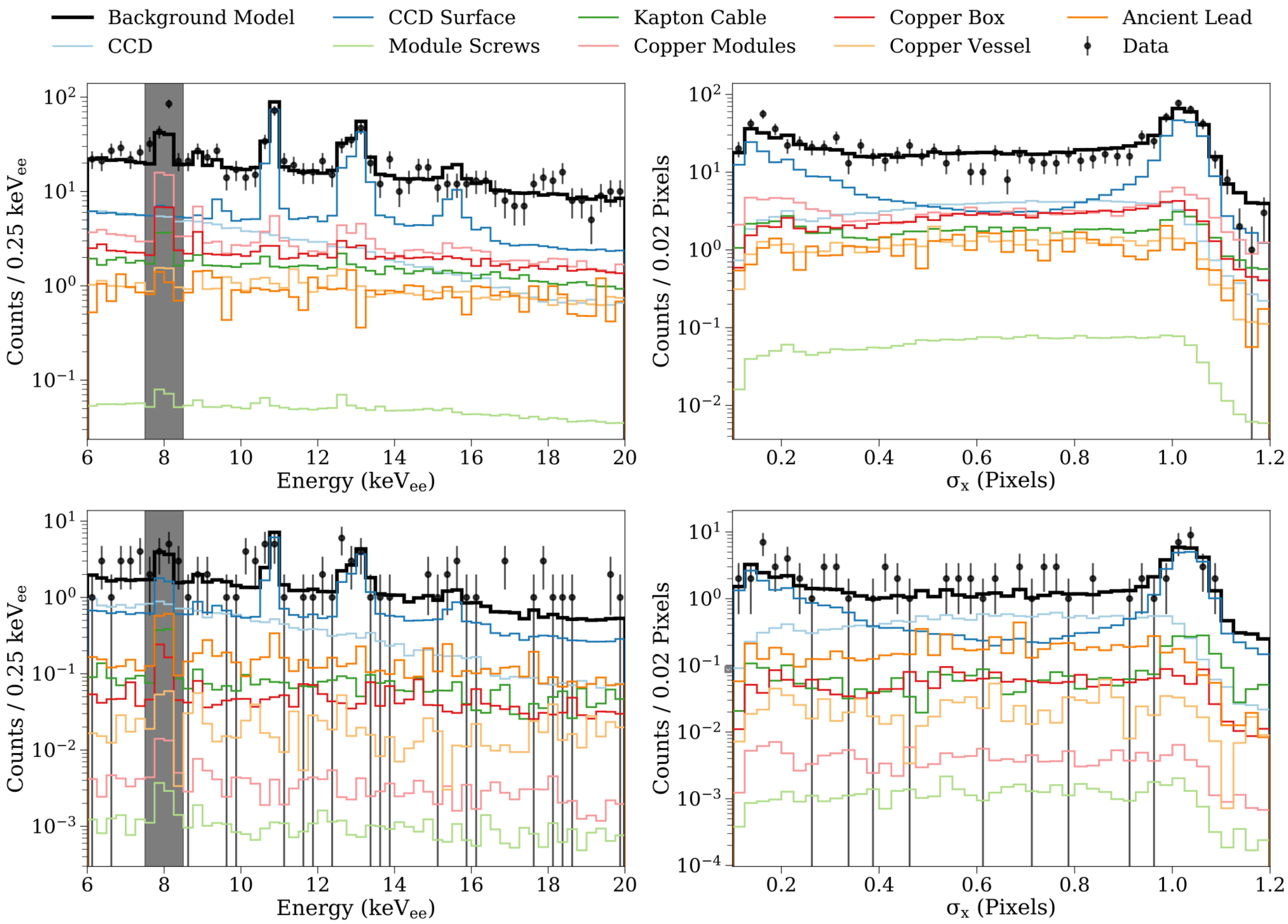
- Group in templates according to common materials and decay
- Construct number of expected events per bin, $\boldsymbol{\nu}_{\mathbf{ij}}$

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

- Compare it to the data bin content, $\boldsymbol{k}_{\mathbf{ij}}$, in a two-dimensional likelihood analysis

$$\ln \mathscr{L} = \sum_i \sum_j \left[k_{ij} \ln(\nu_{ij}) - \nu_{ij} - \ln(k_{ij}!)\right] - \sum_{n=0}^{N_{assays}} \frac{(C_n^0 - C_n)^2}{2\sigma_n^2}$$

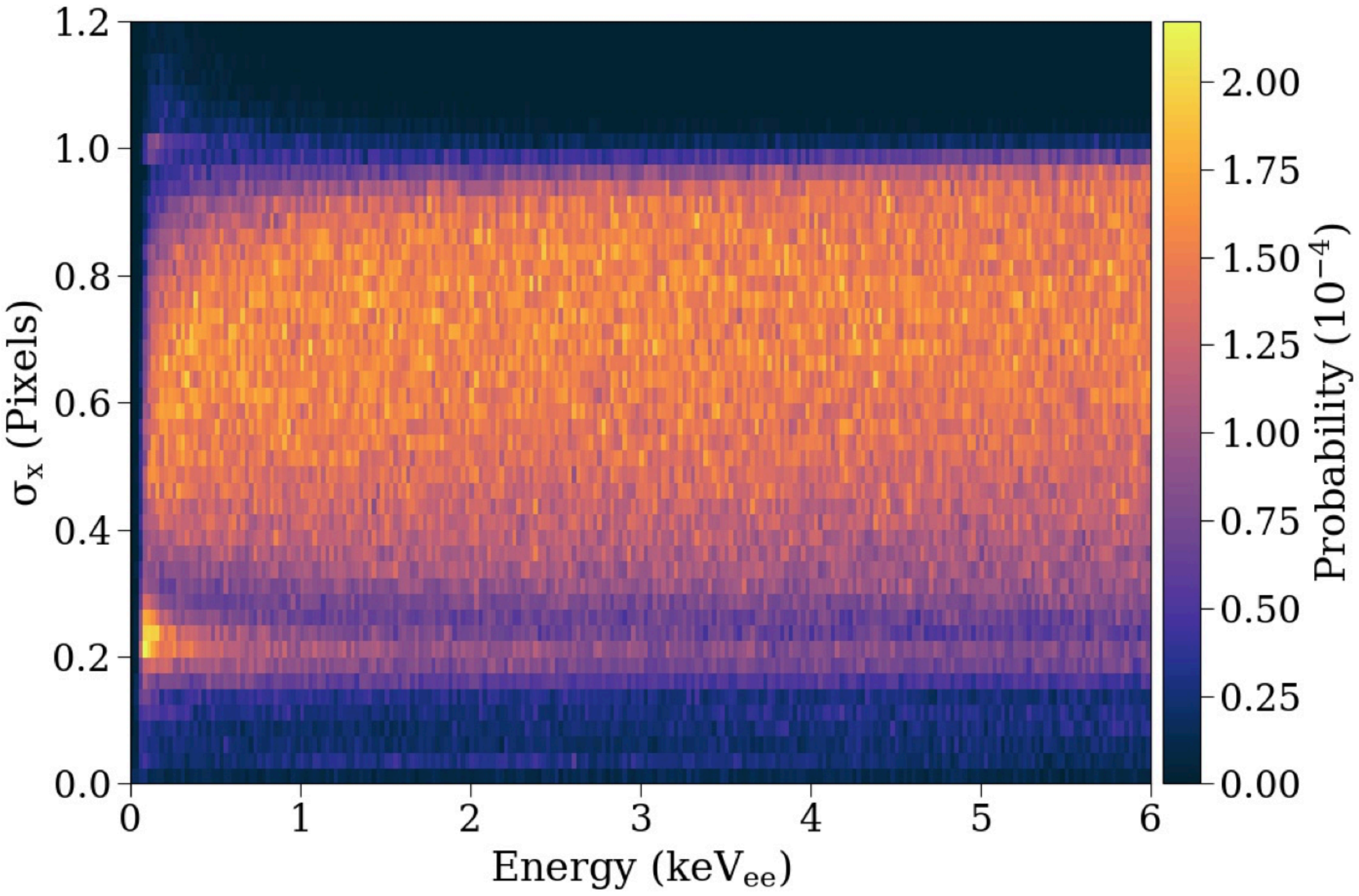
➡ Best-fit C_l's characterize bkg model



BACKGROUND EXTRAPOLATION

Background model extrapolation below 6 keV_{ee}

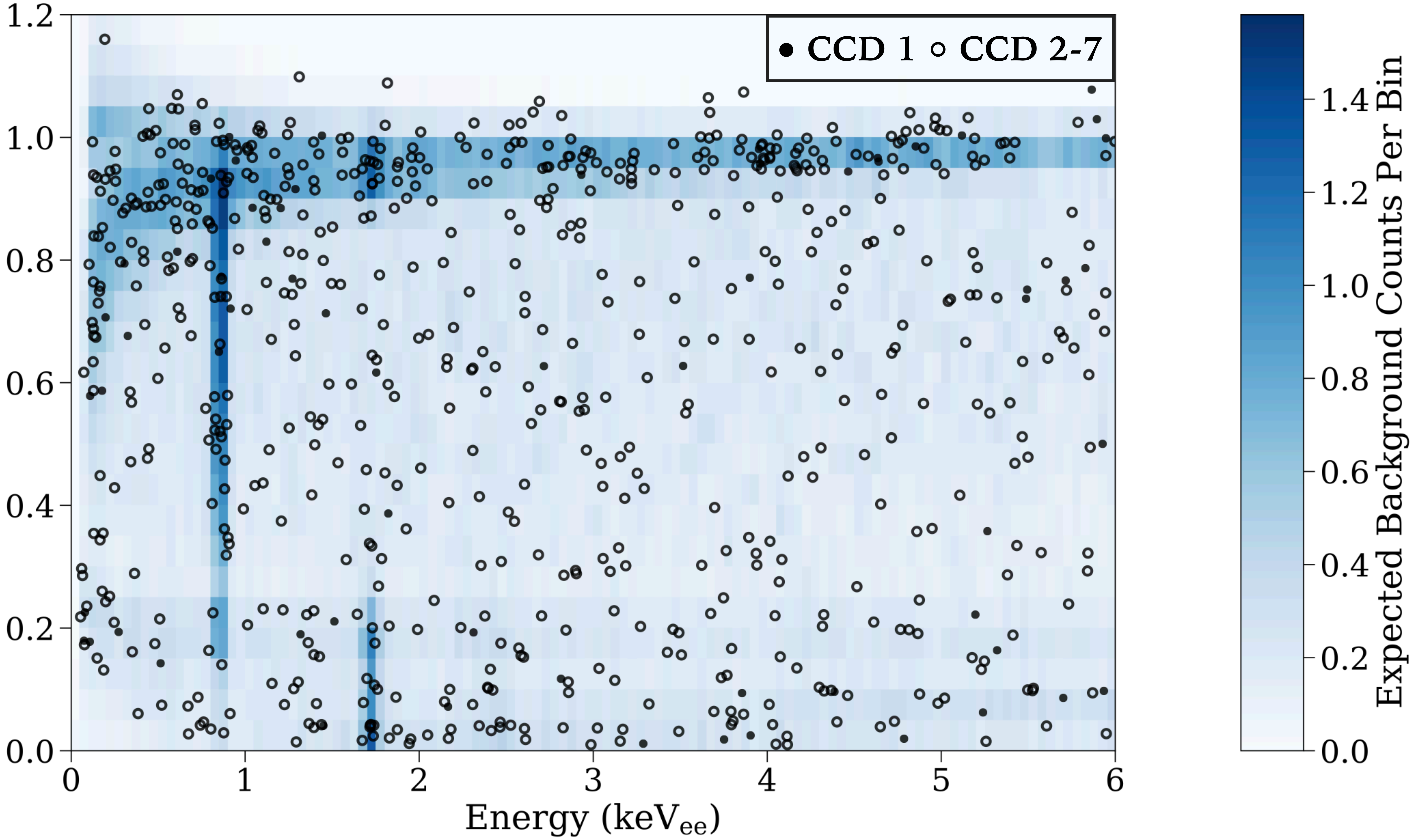
- Separate extrapolation for CCD1 and CCDs 2-7
- Single **(E,z)** template construction using simulation output and best-fit coefficients C_l
- Event sampling: ~200k events per CCD
- Detector response application
- Blank-image cluster paste
- Reconstruction to **(E,σ_x)** distribution by means of DAMIC *likelihood clustering*



LOW ENERGY ANALYSIS

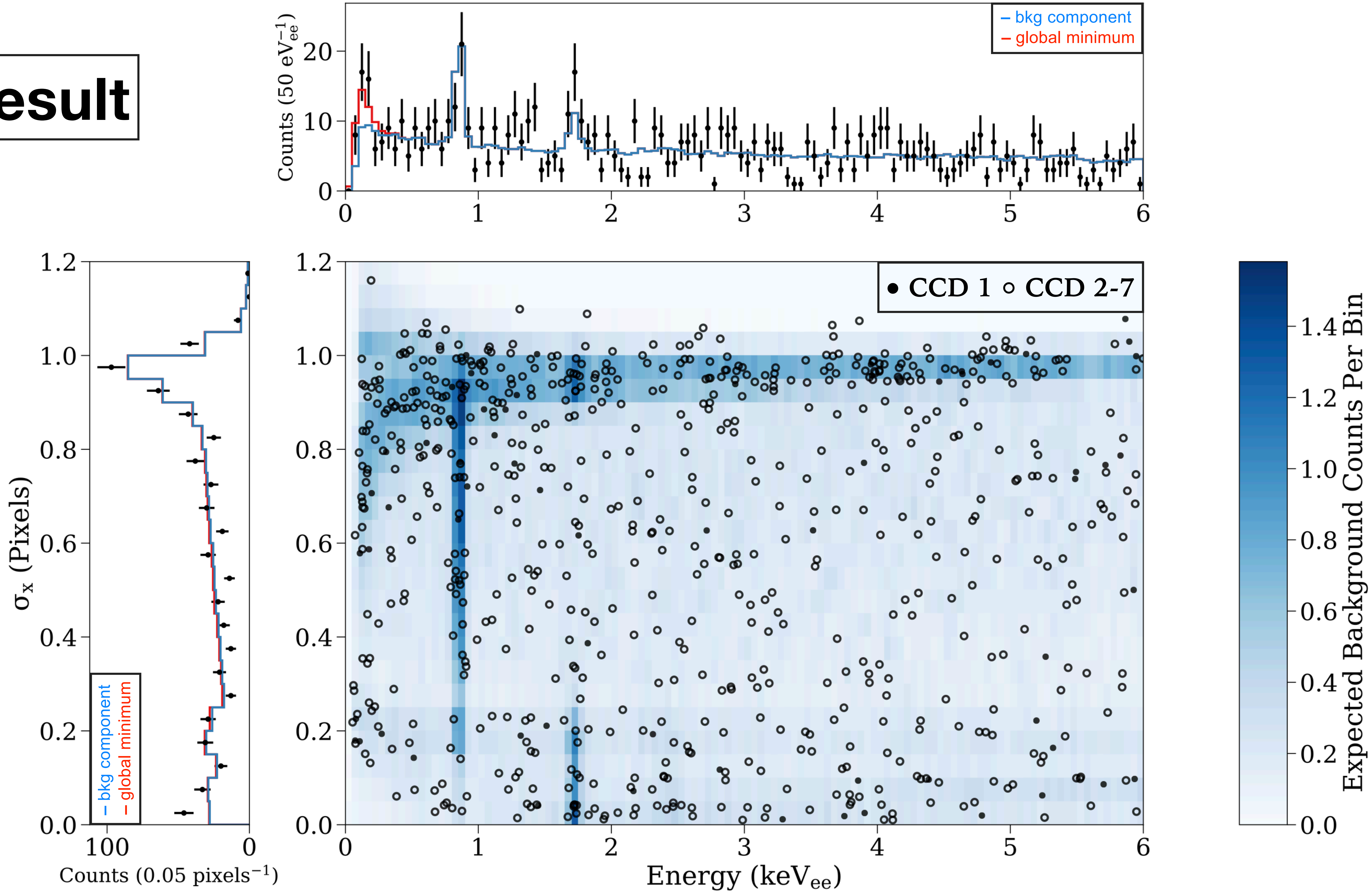
Profile likelihood ratio test on joint dataset. Extended likelihood function:

$$\ln \mathscr{L}(s, \epsilon, \vec{b}, \vec{c}) = \sum_{k}^{2} \left\{ -(\gamma_k s + b_k + c_k) + \sum_{i}^{N_k} \left[s\gamma_k f_s(E_i, \sigma_{x_i} | \epsilon) + b_k f_{b_k}(E_i, \sigma_{x_i}) + c_k f_c(E_i, \sigma_{x_i}) \right] + \frac{(b_k - b_k')^2}{2\sigma_{b_k}^2} \right\}$$

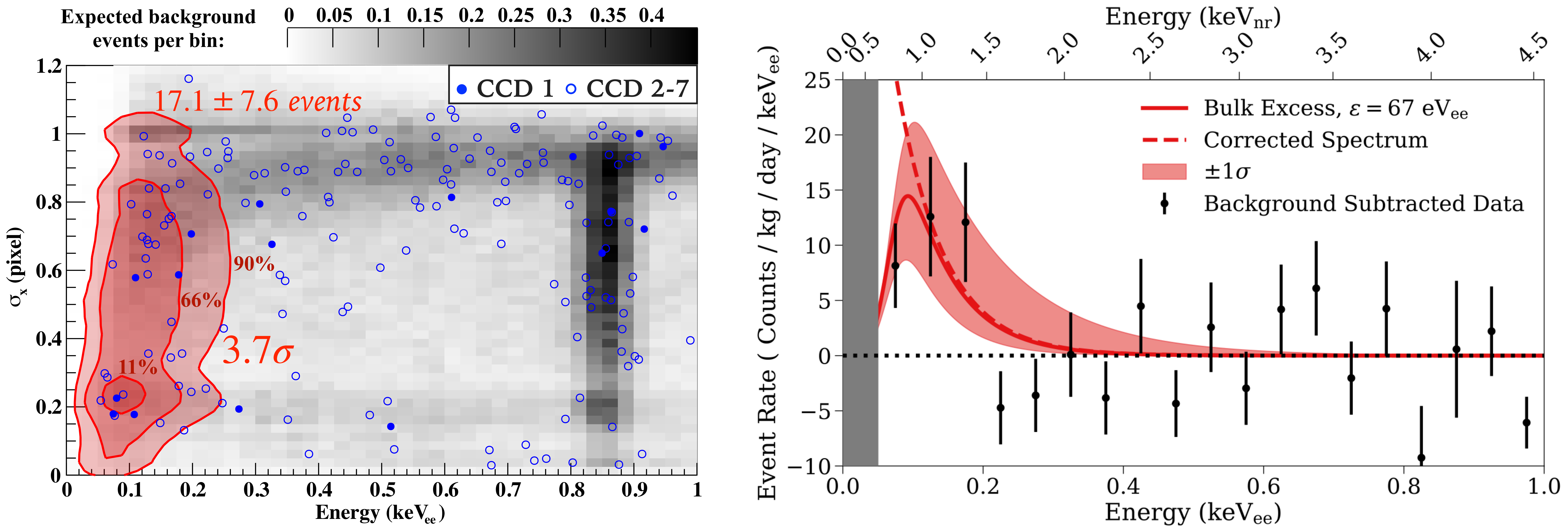


LOW ENERGY ANALYSIS

Fit result



NEAR-THRESHOLD EXCESS



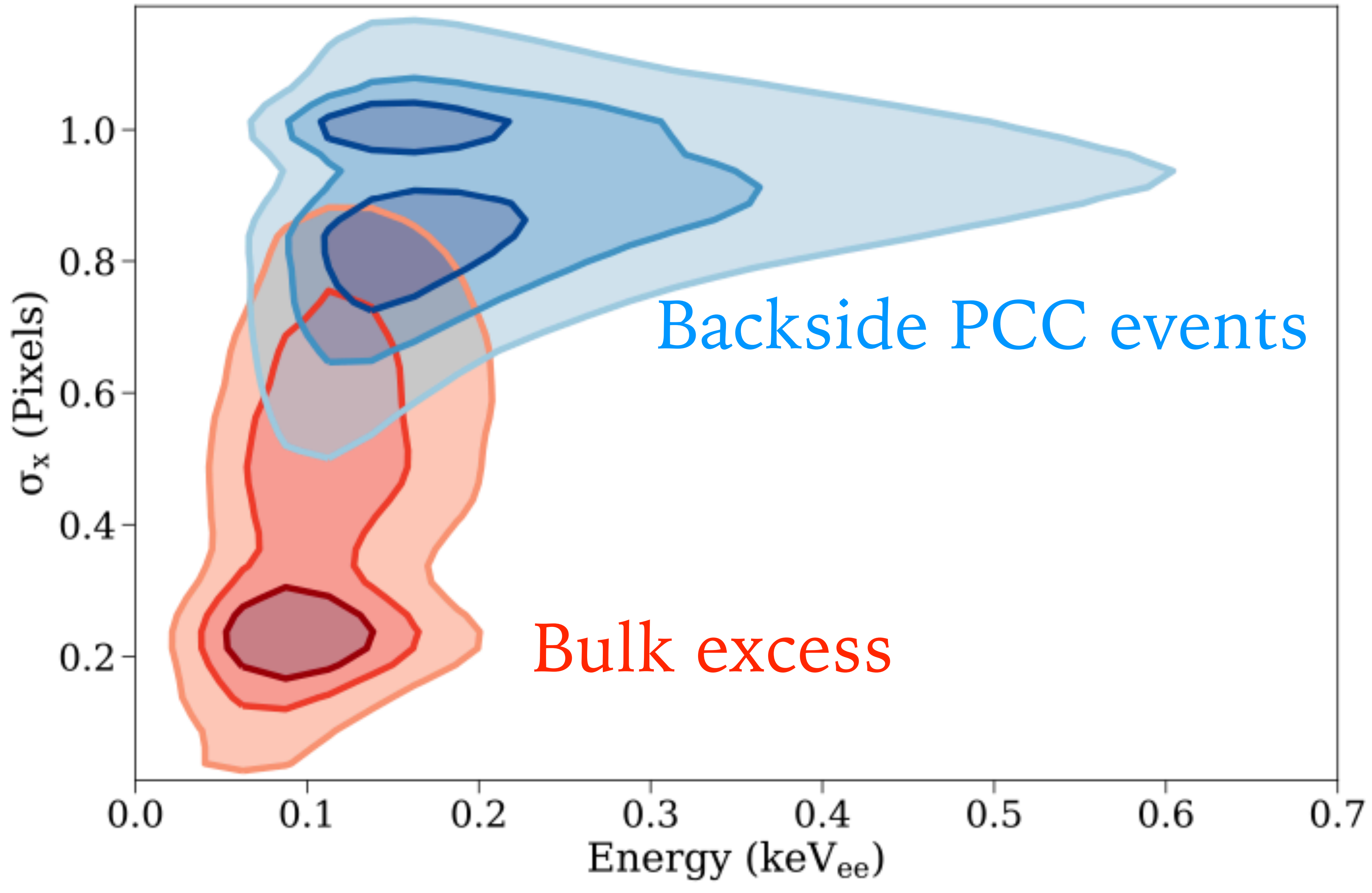
Most Plausible Interpretations of the Excess

- Missing front component in bkg model
- Unaccounted detector front-side effect

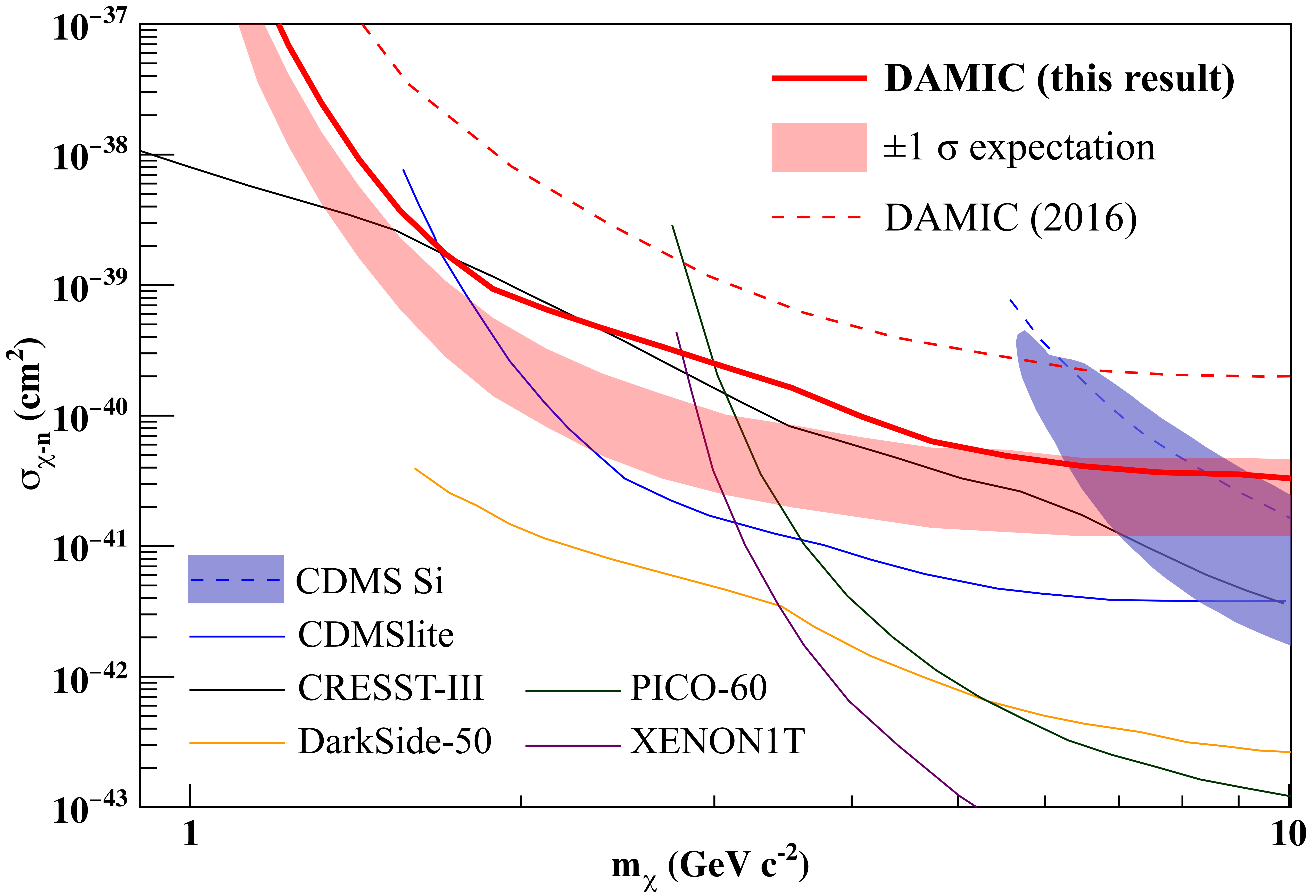
SYSTEMATIC CHECKS

Systematic Checks

- Fit above 200 eV_{ee} consistent with null hypothesis
- Fit to CCD1 and CCD2-7 data sets separately consistent with joint analysis
- 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)
- Parallel Markov Chain MC analysis



WIMP SEARCH LIMITS



SUMMARY & FUTURE PLANS

DAMIC at SNOLAB:

- WIMP Search paper published on PRL: Phys. Rev. Lett. **125**, 241803 arXiv:2007.15622

- Spatial coincidence analysis paper published on JINST: *JINST* 16 (2021) 06, P06019 arXiv:2011.12922

- Paper detailing background model construction submitted to PRD arXiv:2110.13133

- Upcoming setup upgrade to investigate excess: two DAMIC-M 6k×4k and four SENSEI 1k×6k skipper CCDs arXiv:2001.01476 arXiv:1706.00028

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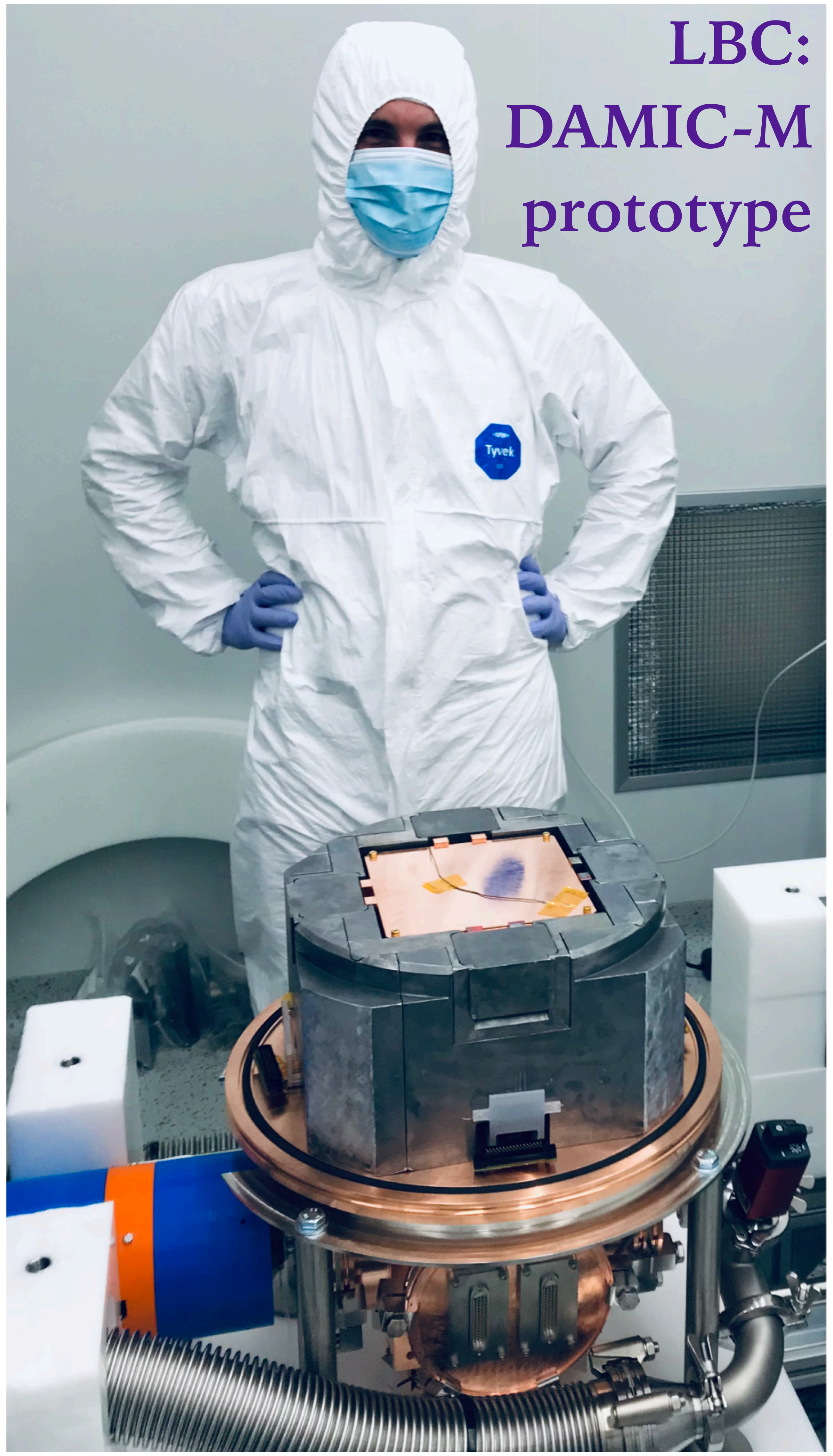
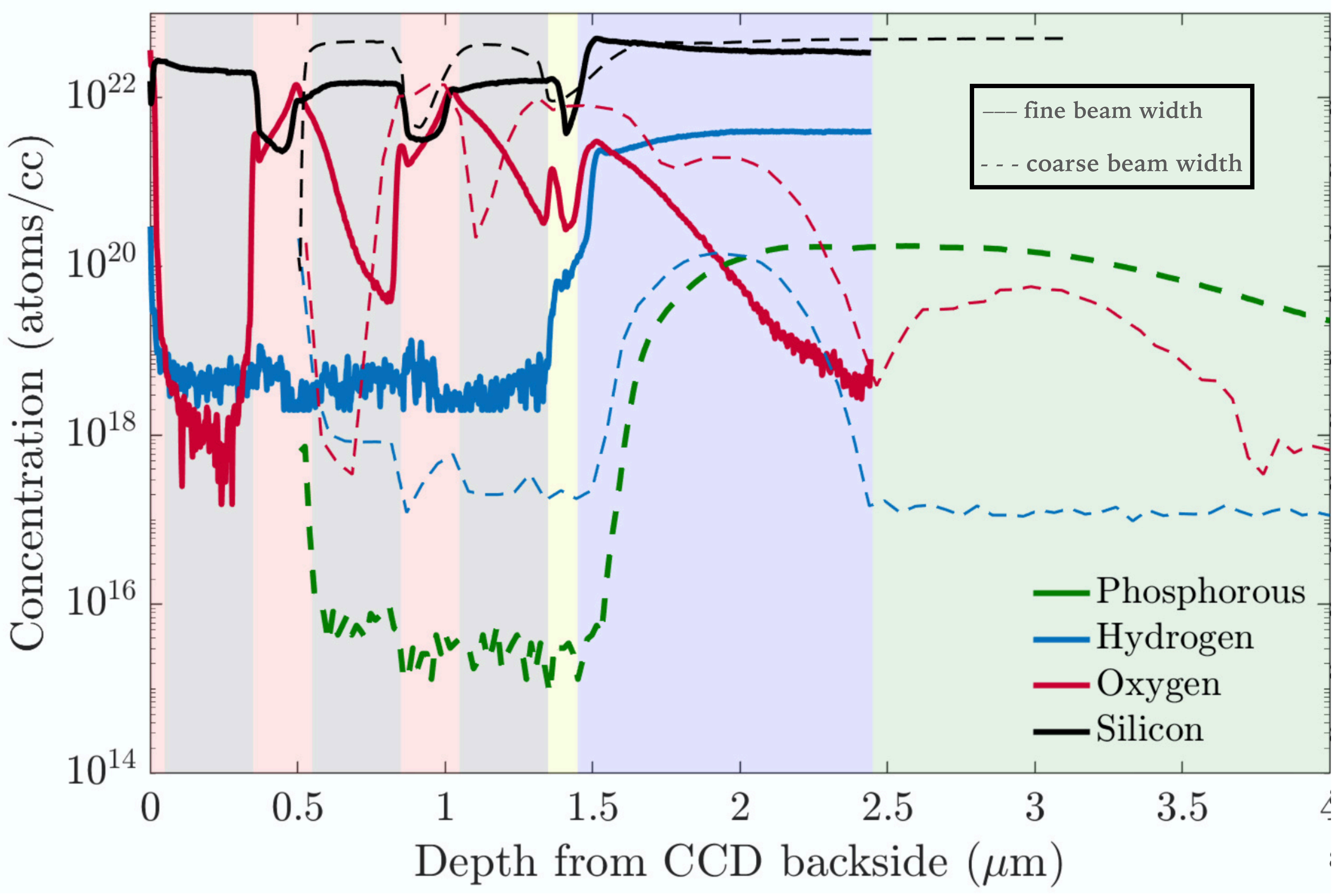
DAMIC at Modane:

- Kg-scale skipper CCD detector striving for 0.1 dru background rates
  - See contribution by Claudia De Dominicis: *Search for light Dark Matter with DAMIC-M*

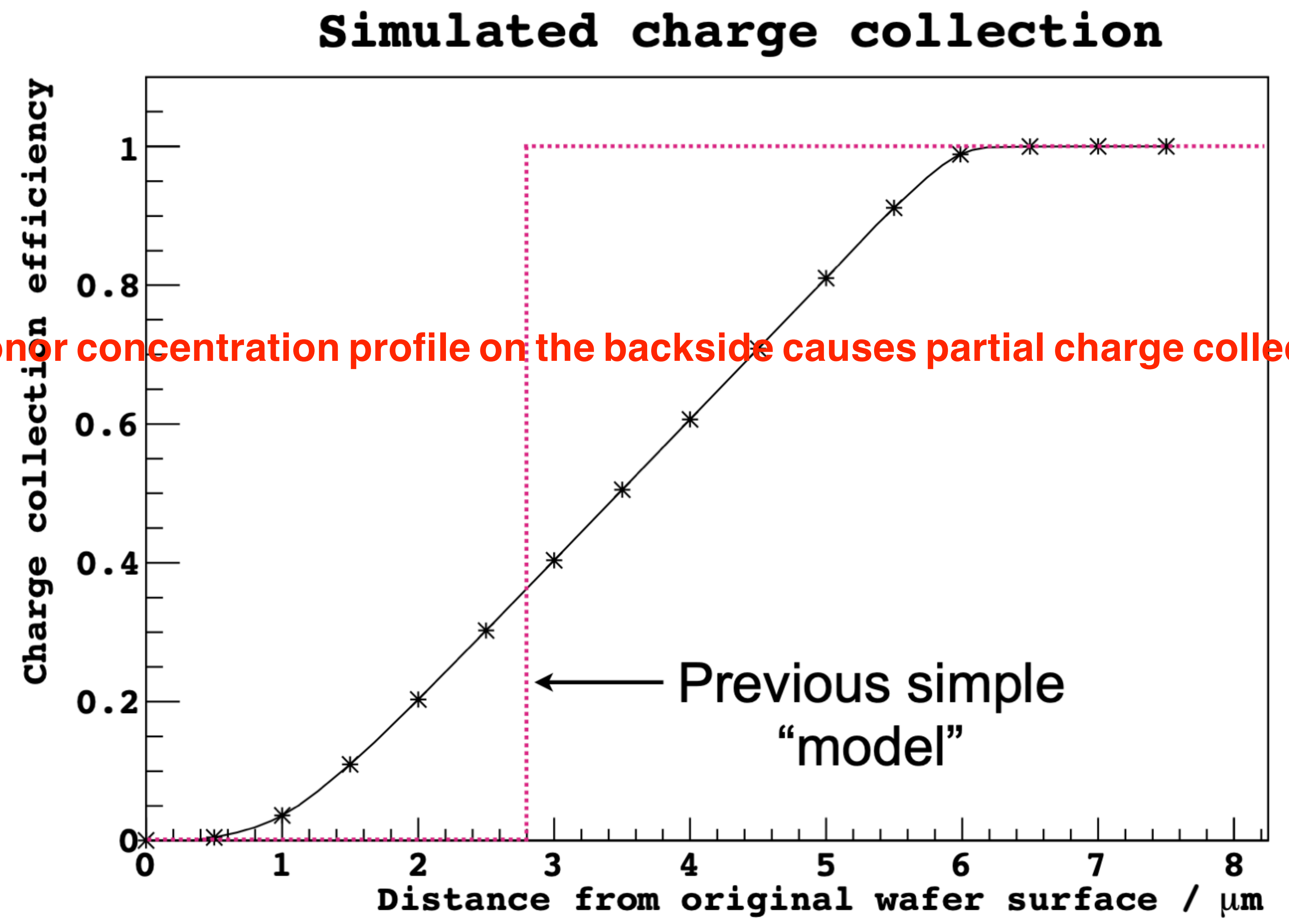


Thanks for your attention. It was a pleasure to tell you about us!

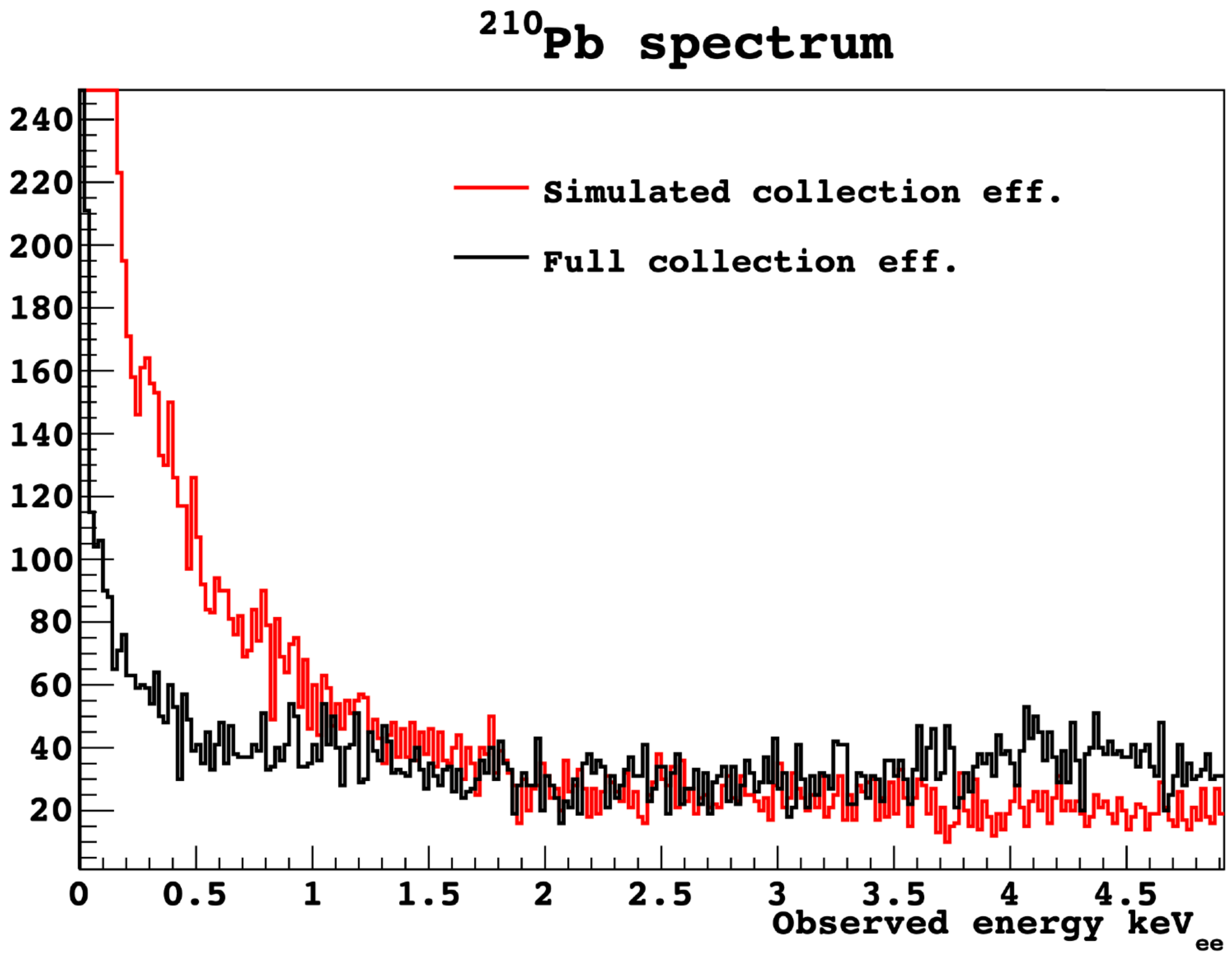
SENSOR BACKSIDE ANALYSIS



BACKSIDE ANALYSIS: PARTIAL CHARGE COLLECTION



Donor concentration profile on the backside causes partial charge collection



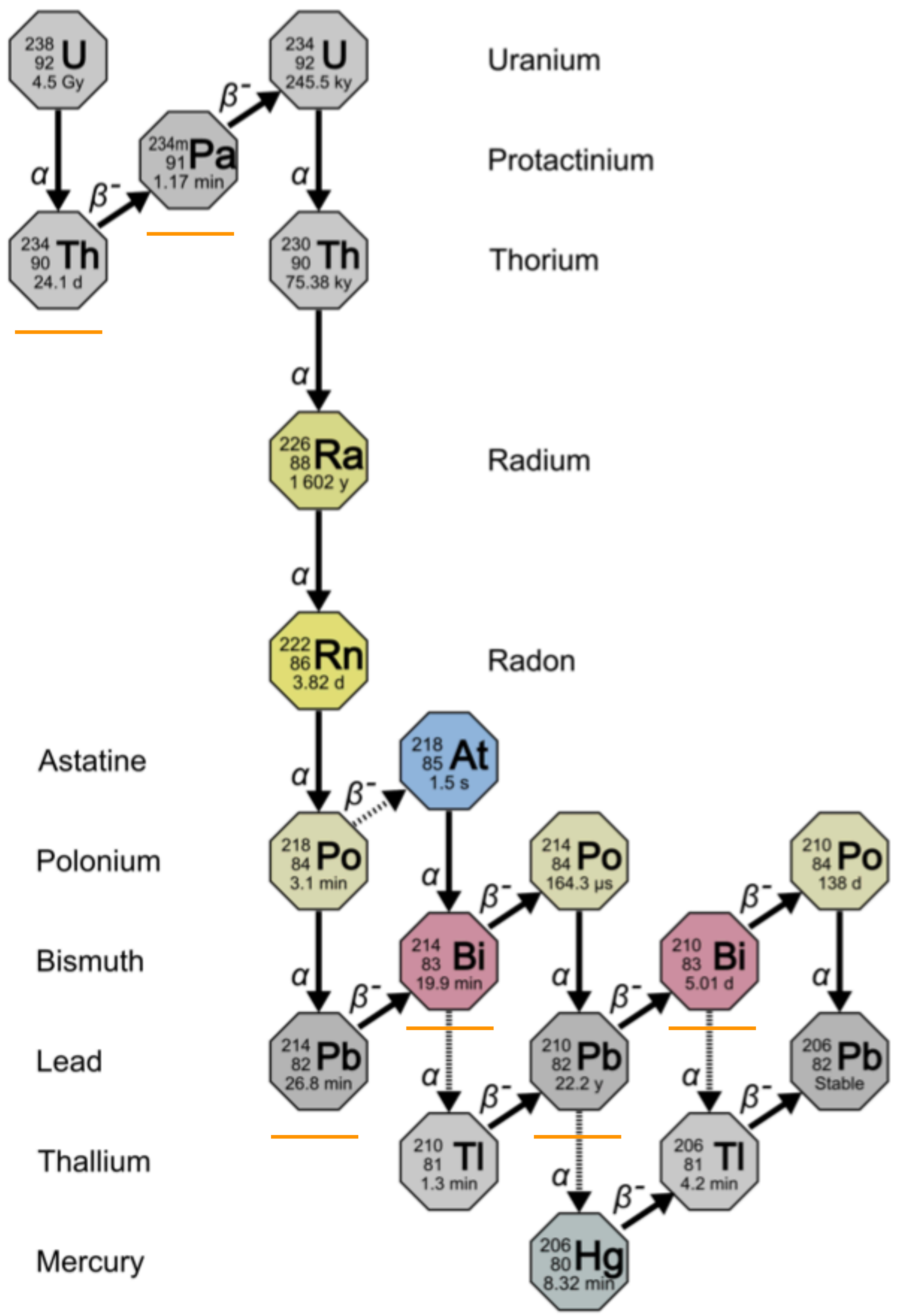
largest uncertainty in our response model → Incorporate it as systematic via back exponential in log-likelihood fit

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

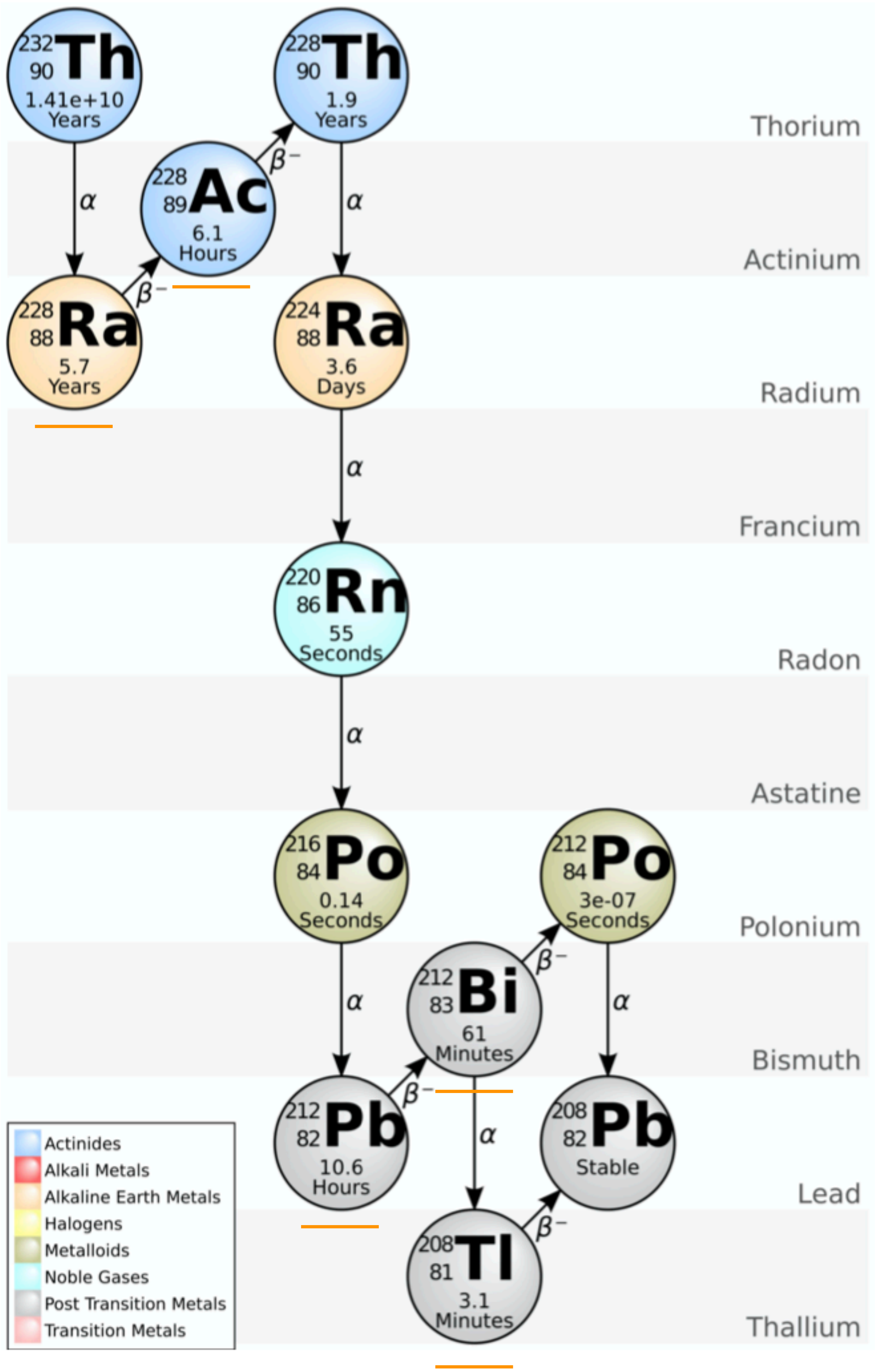
MAIN CONTAMINANTS

Parent Chain	Isoptopes Considered	Simulation ID	Comments
U238	Pa234	234a91z	
	Th234	234a90z	
Ra226	Pb214	214a82z	
	Bi214	214a83z	
Pb210	Pb210	210a82z	surface = Pb210front/Pb210back
	Bi210	210a83z	bulk = TotPb210
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)

MAIN CONTAMINANTS II



(b) Uranium Series decay chain



(c) Thorium Series decay chain

MAIN CONTAMINANTS III

Isotope	Half-life	Q_{Max}	Decay properties	Production
^{208}Tl	$3.058min$	$4999keV$	34γ lines: $12.4keV$ to $2614keV$	Coming from the ^{220}Rn chain
^{210}Pb	$22.23y$	$63.5keV$	Bismuth γ lines: $9.4keV$ to $16.3keV$	Coming from the ^{222}Rn chain
^{210}Bi	$5.011d$	$1161.2keV$	Only emission is the β	Coming from the ^{222}Rn chain - ^{210}Pb daughter
^{212}Pb	$10.64h$	$569.9keV$	Bismuth γ lines: $9.4keV$ to $16.3keV$	Coming from the ^{220}Rn chain
^{212}Bi	$60.54min$	$2252.1 - 6207.26keV$	64.07% β and 35.93% α	Coming from the ^{220}Rn chain
^{214}Pb	$26.916min$	$1019keV$	Bismuth γ lines: $9.4keV$ to $16.3keV$	Coming from the ^{222}Rn chain
^{214}Bi	$19.8min$	$3270keV$	High Energy $\gamma > 100keV$	Coming from the ^{222}Rn chain
^{228}Ra	$5.75y$	$45.8keV$	Actinium γ lines: $10.8keV$ to $19.2keV$	Coming from the ^{232}Th chain
^{228}Ac	$6.15h$	$2123.8keV$	High Energy $\gamma > 100keV$	Coming from the ^{232}ThLAAfi chain
^{234}Th	$24.10d$	$272keV$	Protactinium γ lines: $11.3keV$ to $112.6keV$	Coming from the ^{238}U chain
^{234m}Pa	$1.15min$	$2269keV$	High Energy $\gamma > 100keV$	Coming from the ^{238}U chain

Table 8: Table of the different radioactive isotopes simulated in the Uranium-Thorium-Actinium series

MAIN CONTAMINANTS IV

Isotope	Half-life	Q_{Max}	Decay properties	Production
^{56}Co	$77.236d$	$4566keV$	High Energy $\gamma > 100keV$	Produced in the copper by spallation
^{57}Co	$271.81d$	$836.2keV$	emission $122keV$ γ line	Produced in the copper by spallation
^{58}Co	$70.85d$	$2307.9keV$	emission $810keV$ γ line	Produced in the copper by spallation
^{60}Co	$5.2711y$	$2823.07keV$	emission $1.173MeV - 1.332MeV$ γ lines	Produced in the copper by spallation
^{59}Fe	$44.494d$	$1565keV$	emission $1.099-1.291MeV$ γ line	Produced in the copper by spallation
^{46}Sc	$83.787d$	$2366.5keV$	emission $0.889-1.120MeV$ γ line	Produced in the copper by spallation
^{87}Rb	$49.3410^{9}y$	$282.2keV$	Only emission is the β	Inside the copper and the epoxy
^{54}Mn	$312.19d$	$1377.2keV$	emission $834keV$ γ line	Produced in the copper by spallation
^{40}K	$1.210^{9}y$	$1311.07 - 1504.69keV$	emission $1460keV$ γ line	Inside the epoxy
^{137}Cs	$30.05y$	$1175.63keV$	High Energy $\gamma > 100keV$	Cosmogenic Isotope

Table 9: Table of the different radioactive isotopes present in copper and in epoxy

Isotope	Half-life	Q_{Max}	Decay properties	Production
^{32}Si	$130y - 320y$	$224.311keV$	Only emission is the β	Production by spallation on ^{40}Ar
^{32}P	$14.284d$	$1710.66keV$	Only emission is the β	Daughter of ^{32}Si
^{3}H	$12.312y$	$18.591keV$	Only emission is the β	Produced by spallation on Silicon
^{22}Na	$2.6029y$	$2843.02keV$	emission $511 - 1274keV$ γ line- Fluorescence-Auger from ^{22}Ne at $0.84keV$	Produced by spallation on Silicon

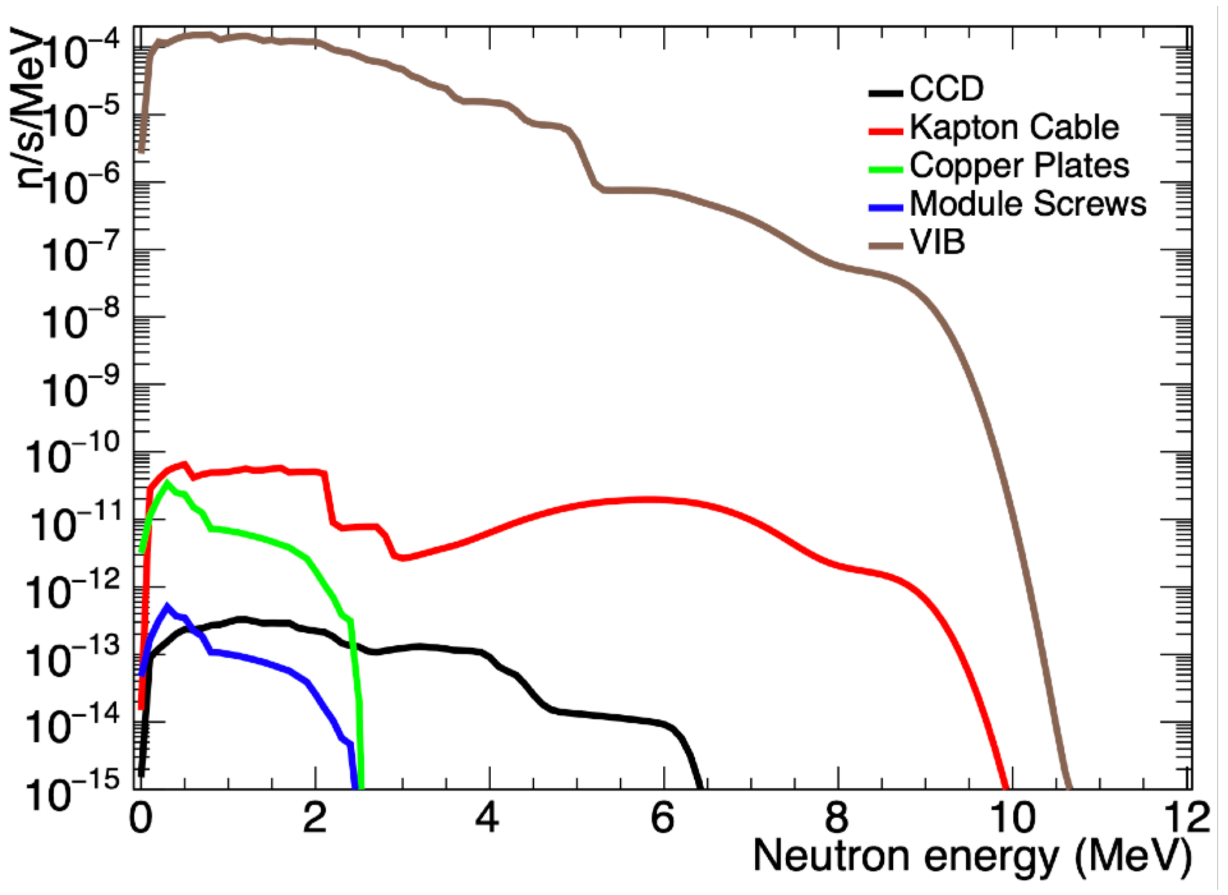
Table 10: Table of the different radioactive isotopes present in silicon

NEUTRONS IN DAMIC

Sources of neutrons for DAMIC:

- Cavern. Polyethylene and Pb attenuate flux: $0.5\ cm^{-2}\ d^{-1}$ ➡ $< 10^{-3}\ cm^{-2}\ d^{-1}$ ➡ $< 1\ d^{-1}$
- Production in Polyethylene and Pb: $< 1\ d^{-1}$
- Production in inner detector components: VIB dominates with $\sim 30\ d^{-1}$

Neutrons produced in inner components



⟶ *Geant4* ⟶ $N^{VIB}_{n^0\ recoils} < 1$ *over WS exposure (332.5 days)*

Neutrons nuclear recoils minor contribution to bkg model

BACKGROUND CONTROLS

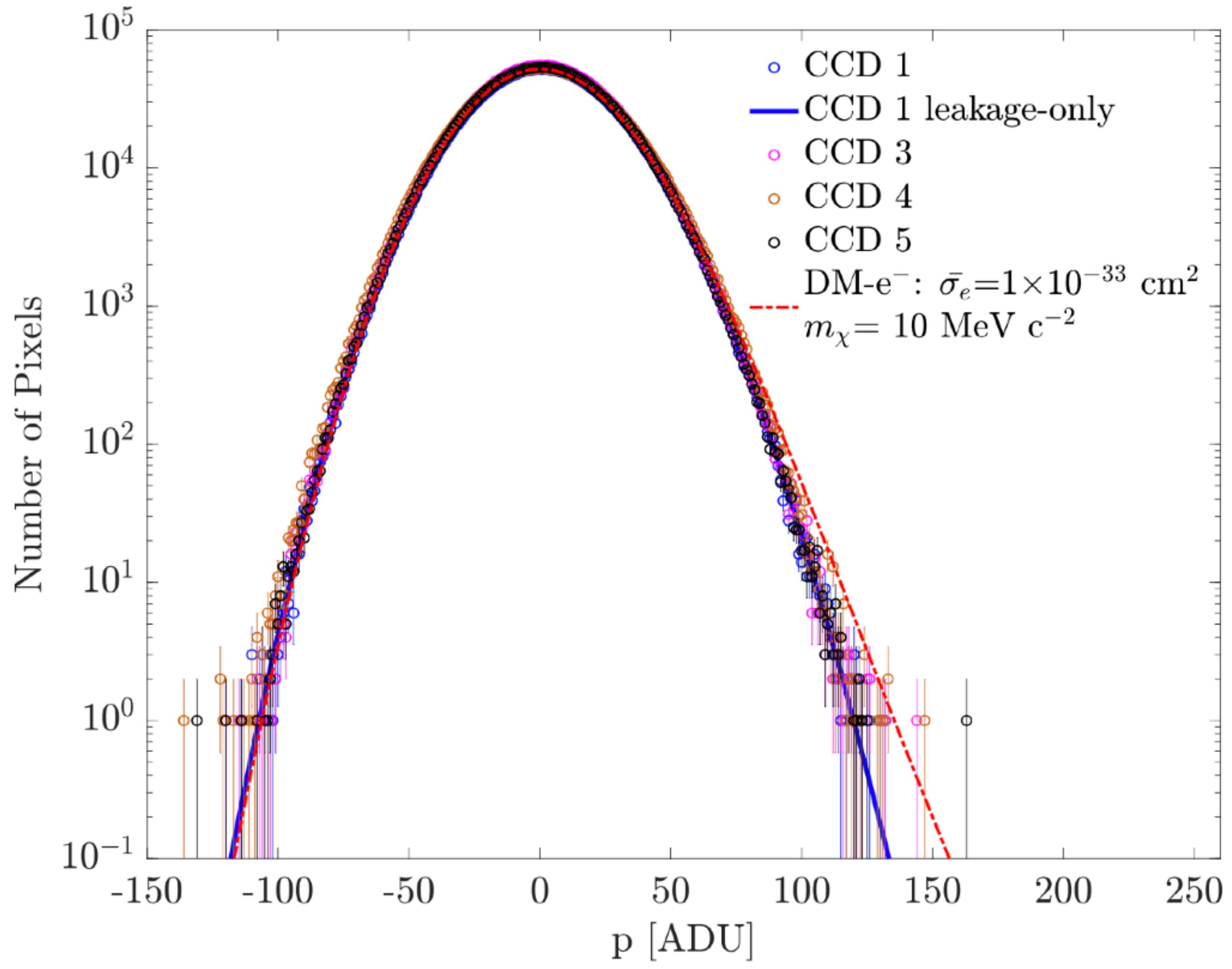
Lessons from DAMIC at SNOLAB:

- 55% in-CCD contaminants
  - ^{3}H from CCD activation + Surface ^{210}Pb from Rn deposition ☞ Improved storage/transportation protocols
  - Intrinsic ^{32}Si traces ☞ Rejection of radioactive chains through spatial coincidence
- 30% OFHC Copper
  - Cu activation and bulk ^{210}Pb contamination ☞ Use electroformed Cu with minimized activation time
- 15% mixed material contribution (lead shielding, flex cables, etc.)
  - About 2 dru
  - Design, material selection and fiducial cuts can all help: prototype low background chamber (LBC) will pave the way to achieve DAMIC-M desired low backgrounds

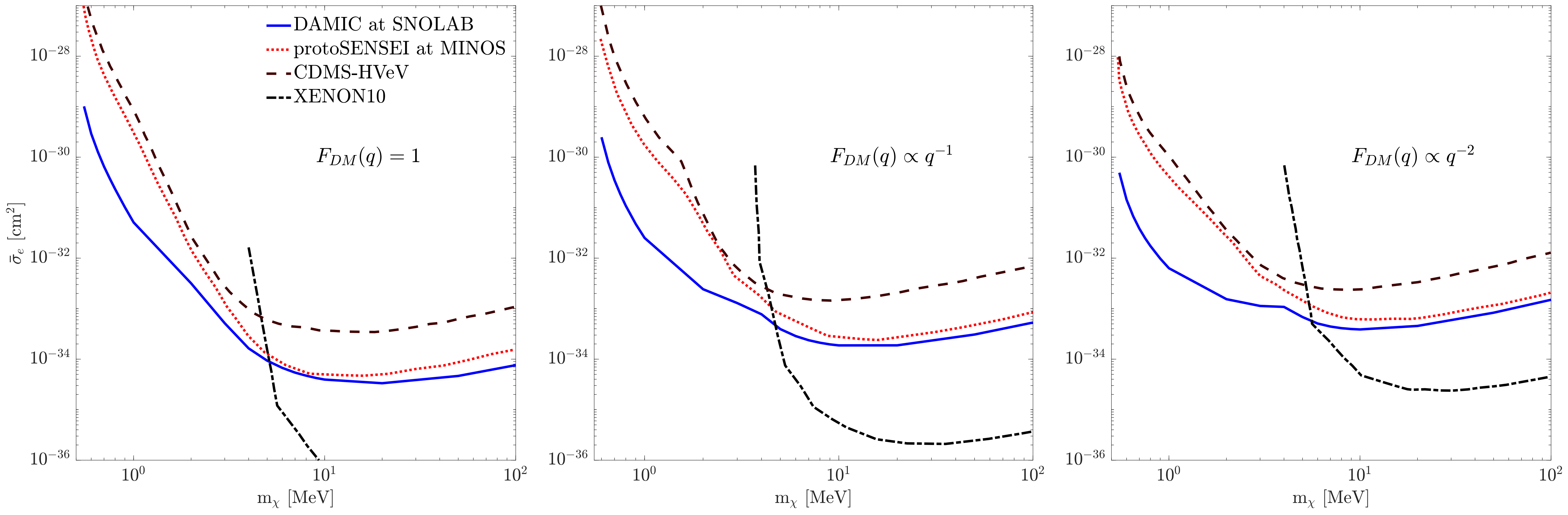
DAMIC HIDDEN–SECTOR SEARCH

How do we search for hidden-sector candidates?

- Characterize relevant noise: electronic noise and dark current
- Estimate expected hidden-sector particle(s) signal
- Include detector effects (diffusion, pixelation, etc.)
- Bulk excess search
- Limits in $(\sigma_e \, m_\chi)$ space $(\sigma_e \rightarrow \kappa$ for hidden photons)



90% C.L. upper limits on the DM-electron free scattering cross section



90% C.L. upper limits on the hidden-photon DM kinetic mixing parameter $\varkappa$