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Measurement of low-energy Compton and neutron scattering in Si CCDs for dark matter searches

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- Motivation,
- Experimental setup,
- Measurement of the Compton spectrum,
- Ongoing photoneutron measurement.

Motivation

- Provide precise detector calibration relevant for dark matter (DM) searches with the new generation of experiments featuring low energy thresholds.

- Two calibration measurements with a single-electron resolution (skipper) CCD down to E_{th} = 23 eV (~6 e^-):
  1) Compton scattering of γ-rays. Challenge for background models, because γs produce low-energy electrons in the bulk of the detector, vs surface events from low-energy β sources. In addition, understanding of scattering with e^- bound in semiconductors is relevant also for DM-e^- scattering.
  2) Neutrons elastically scattering off Si nuclei. Nuclear recoil ionization efficiency is relevant for the detection of WIMPs.

Talks by D. Norcini, A. Chavarria and D. Baxter (Excess workshop).

- Monte Carlo simulations and theoretical models have not been experimentally validated at such low energies.

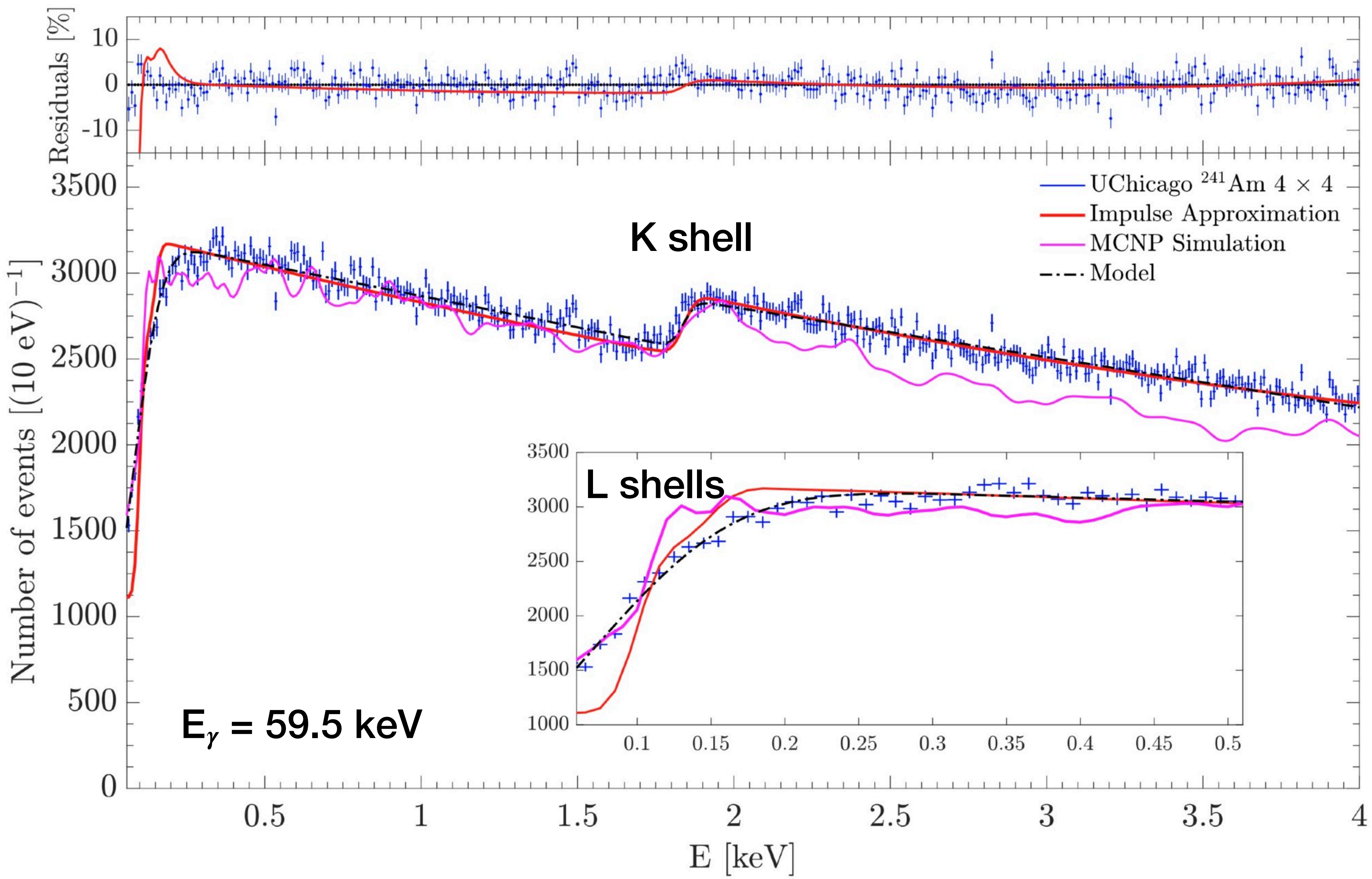
Previous measurements with a standard CCD:

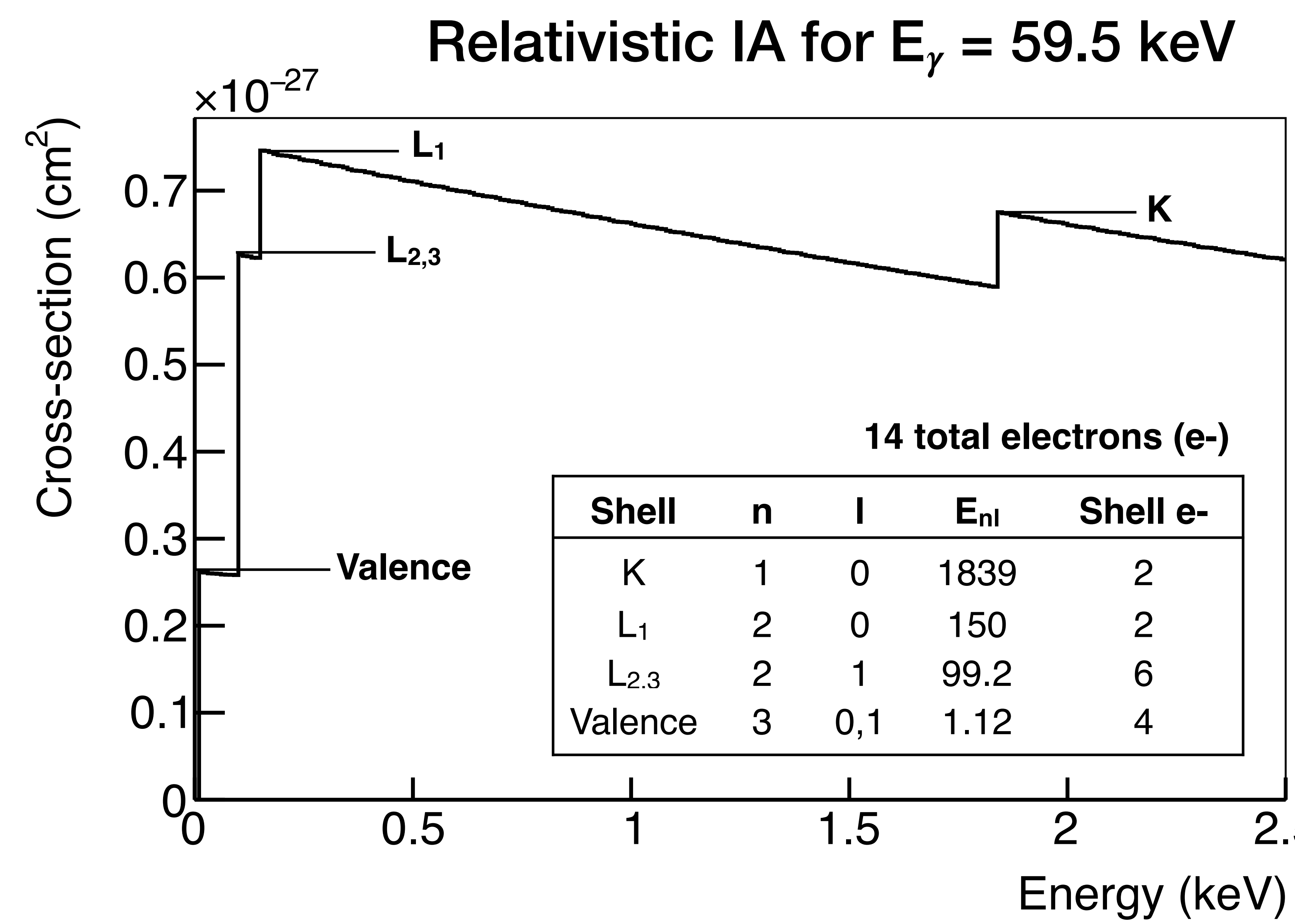
- Add 1) K. Ramanathan et al., Phys. Rev. D 96, 042002 (2017), observed a noticeable deviation from the prediction of the relativistic impulse approximation (RIA) model.

- Add 2) A. E. Chavarria et al., Phys. Rev. D 94, 082007 (2016), measured efficiency deviates from the extrapolation to low energies of the Lindhard model.

Previous Compton spectrum measurement

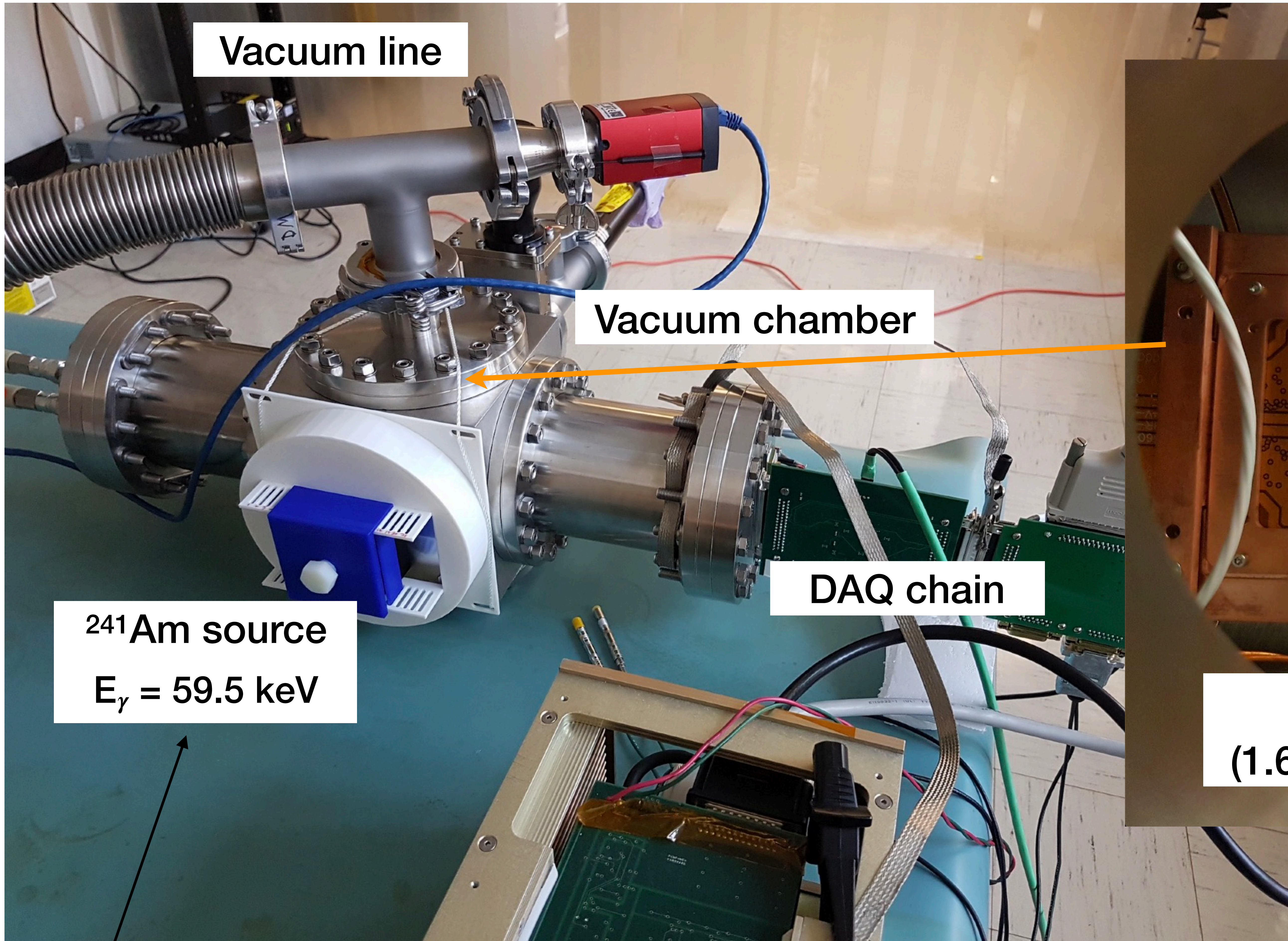
- K. Ramanathan et al., Phys. Rev. D 96, 042002 (2017)
- Significant differences between data and the predictions of Impulse Approximation (IA) and MCNP simulations. The spectrum shape softening around L-shell energies cannot be explained by experimental resolution.
- Plateau below $L_{2,3}$ shell (99 eV) was not observed, at the limit of experimental resolution (E_{th} = 60 eV).

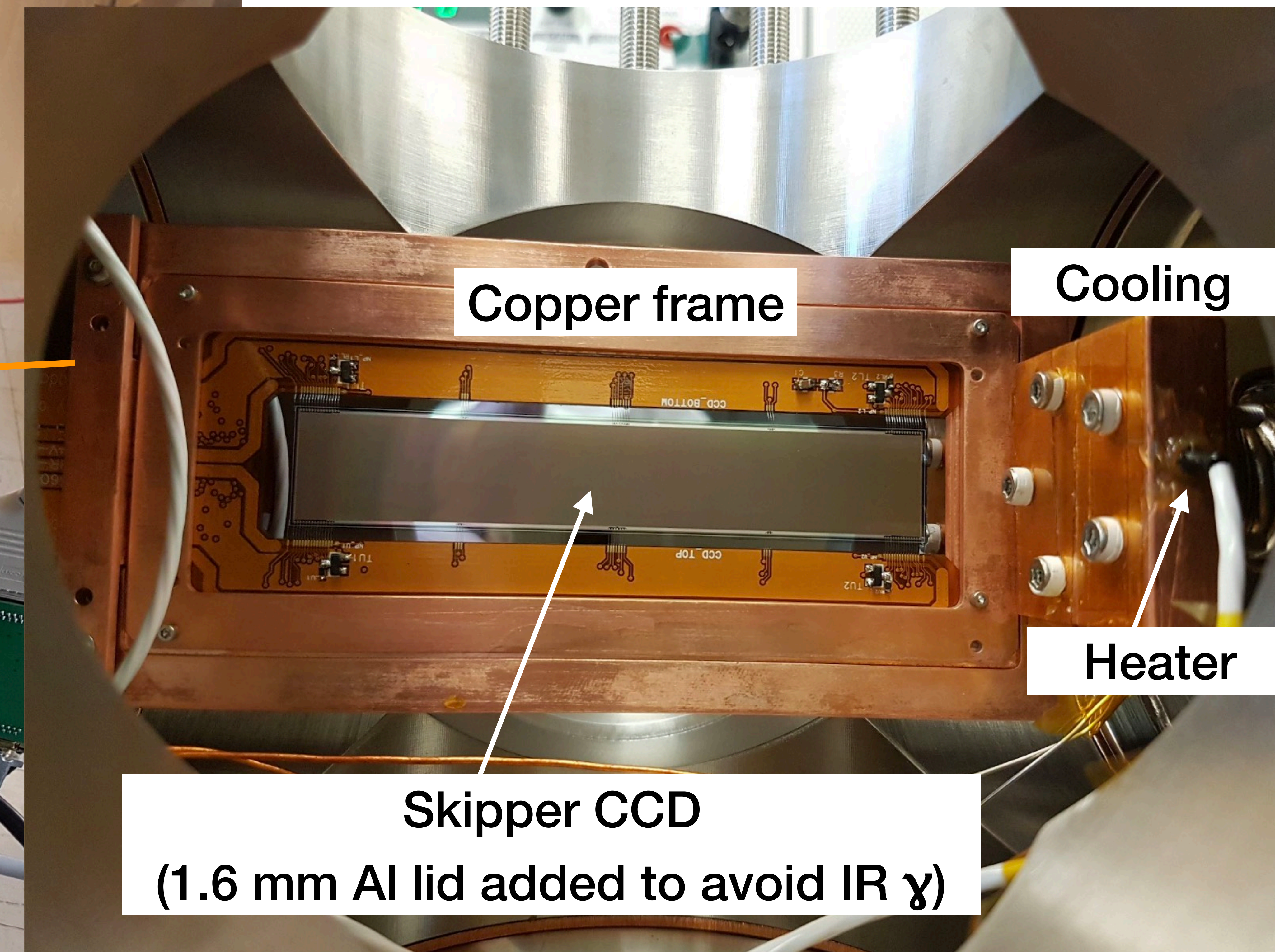




Shell	n	l	E_{nl}	Shell e-
K	1	0	1839	2
L_1	2	0	150	2
$L_{2.3}$	2	1	99.2	6
Valence	3	0,1	1.12	4

Experimental setup





Temperature ~130 K

13 mm Al blocks 10-35 keV lines => only E_γ = 59.5 keV line

$T_{1/2}$ = 432.2 years

Skipper CCD

Described by A. Chavarria and D. Norcini.

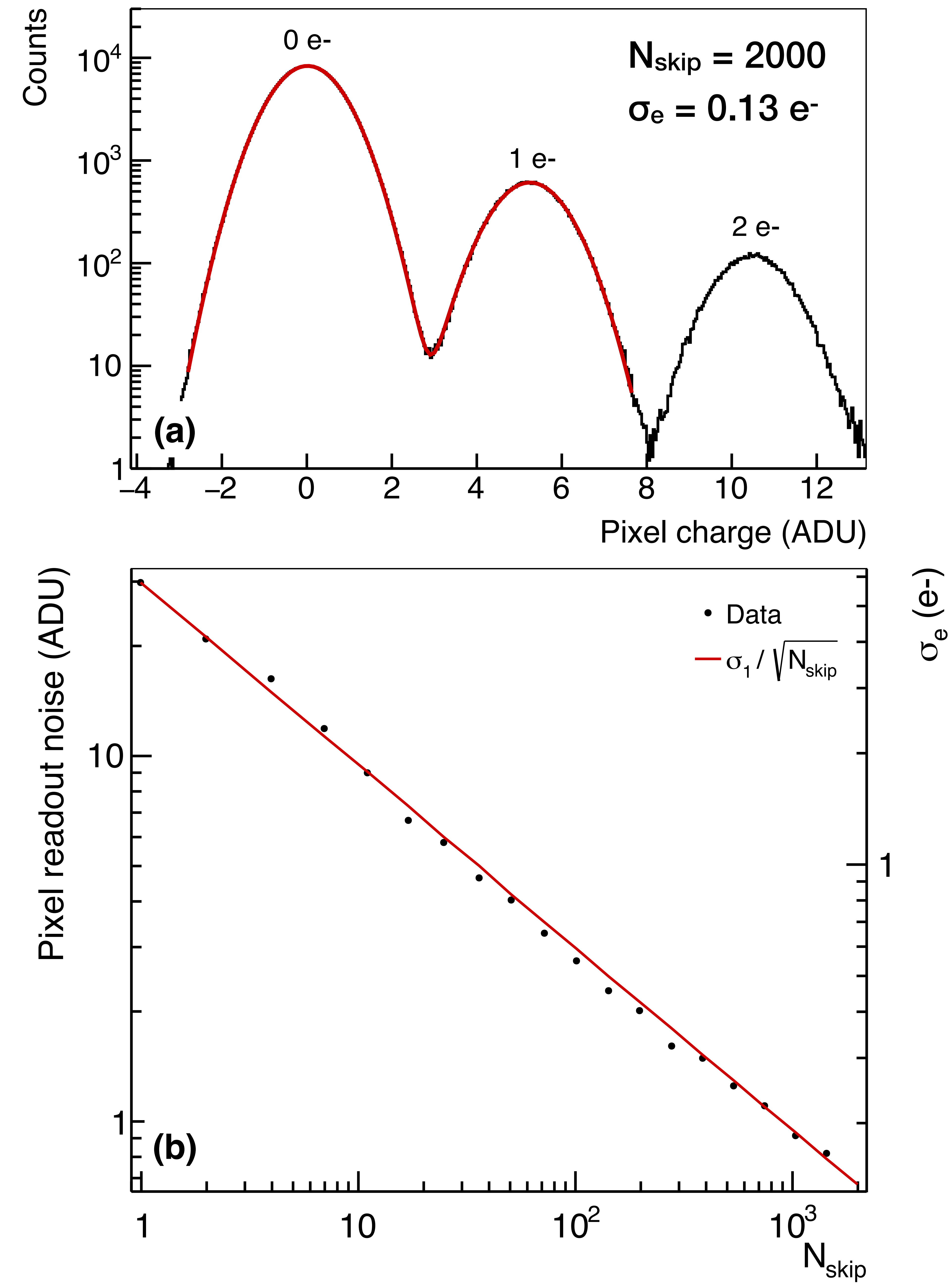
DAMIC-M prototype CCD:

- 1k × 6k pixels,
- 15 µm × 15 µm pixel size,
- 670 µm thick.

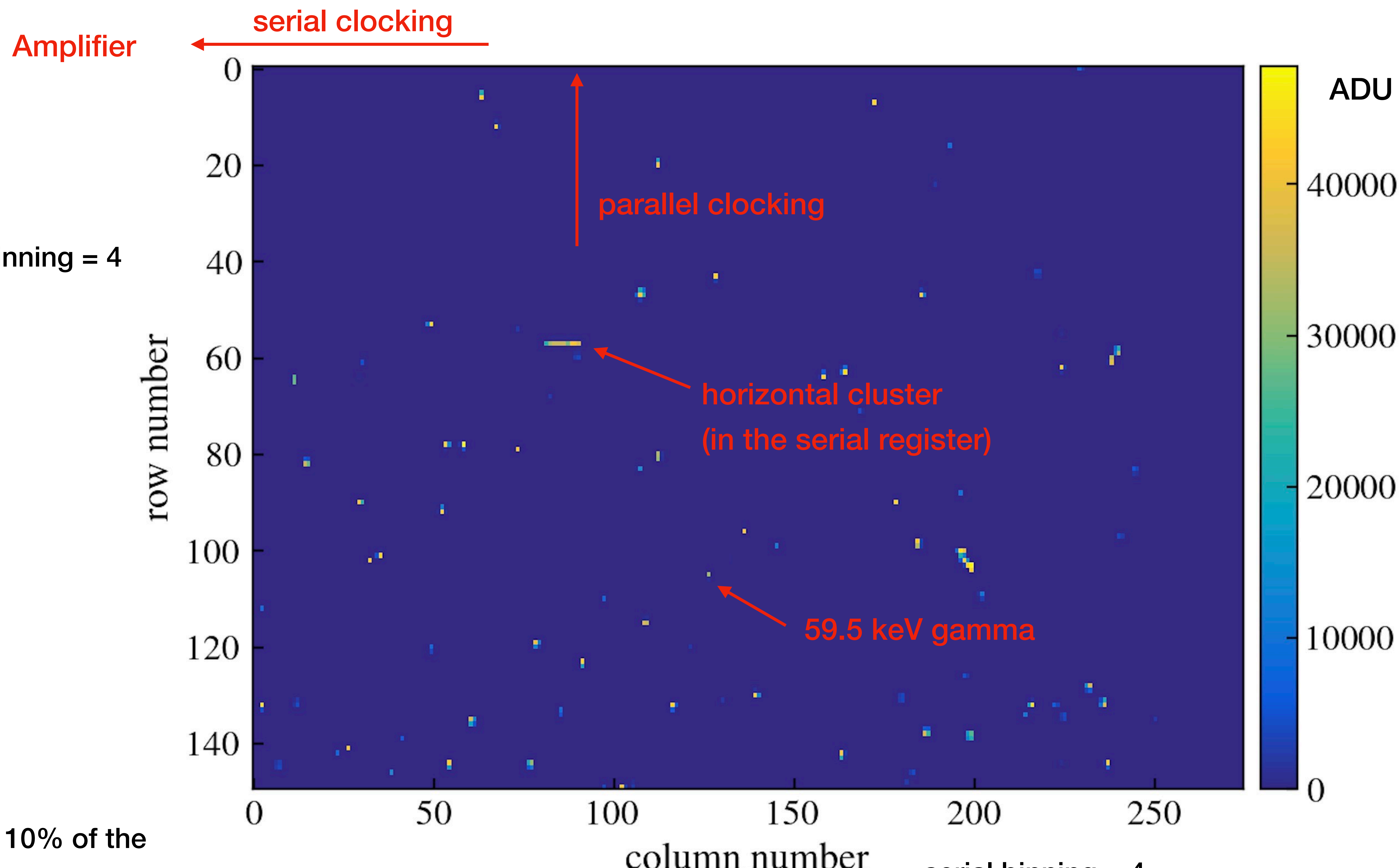
Multiple non-destructive charge measurements (skips) reduce the pixel readout noise by 1/sqrt(N_{skip}).

- Required number of skips to reach a given single e- resolution depends on noise of the system and CCD parameters (primarily the integration window).
- Readout time is much longer than in a standard CCD and is proportional to N_{skip}.

Optimization of CCD parameters is required.



CCD image with ^{241}Am source



parallel binning = 4

serial binning = 4

Image = 10% of the CCD active area

Data taking

To be considered while optimizing CCD parameters:

- High statistics for an accurate measurement at low energy ($>10^6$ events) within half a year,
- Avoid overlapping clusters from the ^{241}Am source which may distort the energy spectrum,
- Number of skips to improve single e^- resolution and lower the energy threshold. More skips leads to longer readout time.

Good data taking conditions achieved with binned images (4×4) and $N_{skip} = 64$ providing $\sigma_e = 0.73$ e^-. (Binning sums the charge of 4×4 pixels, columns × rows, before readout reducing the readout time by 16.)
This combination and further analysis lead to the energy threshold $E_{th} = 23$ eV (~6 e^-).

Data sets:

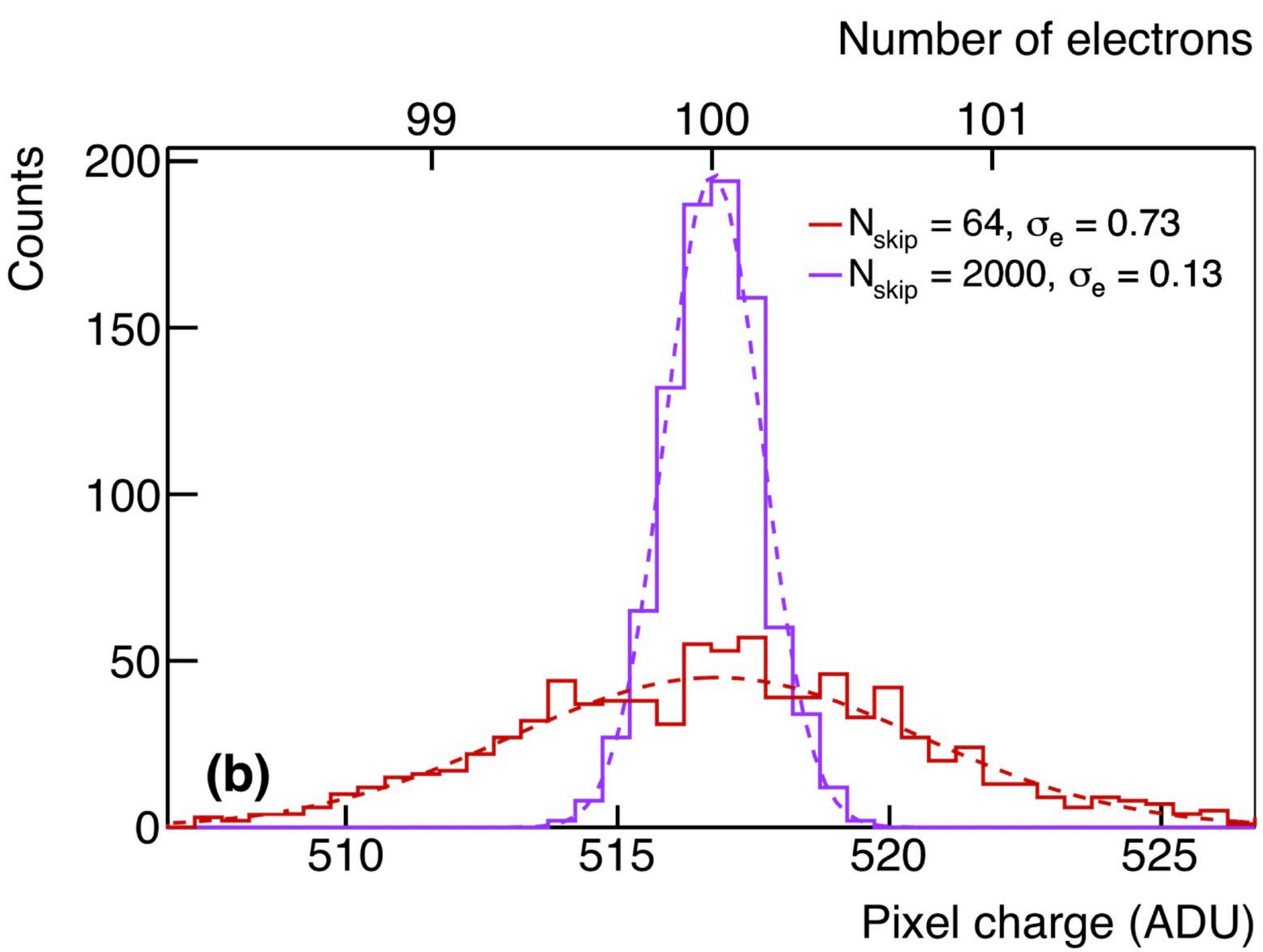
- Source ^{241}Am, total exposure 105.5 days,
- Background (no source), total exposure 48.1 days,
- Reading only the serial register with ^{241}Am (i.e. clocking only the charge in the serial register towards the CCD readout amplifier), total exposure 11.8 days. This is important for the correct background subtraction.

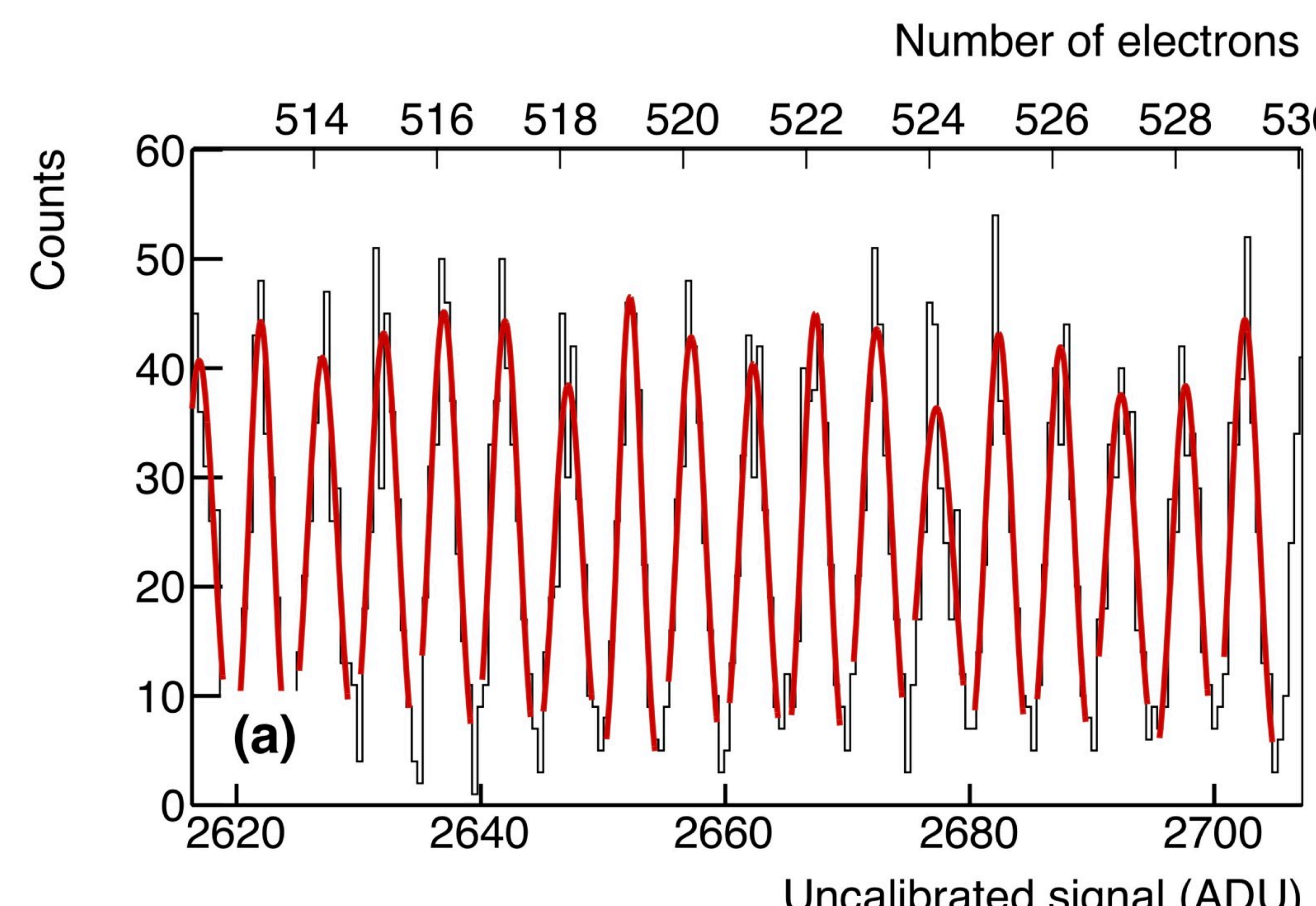
For monitoring and calibration we took periodically

- Full CCD images with no binning to check defects (faulty pixels) in the active area,
- Images with $N_{skip} = 2000$ ($\sigma_e = 0.13$ e^-) and 16×4 binning to check calibration and dark current. Precise calibration up to 550 e^- (~2.1 keV).

Calibration

- Single e^- resolution provides a powerful and simple way to calibrate the pixel charge (measured in ADU),
- We use high resolution data (N_{skip} = 2000) and calculate the charge (and also resolution) using only 64 of the 2000 skips with a Gaussian fit for each peak,
- Over 550 consecutive e^- peaks ($E \approx 2.1$ keV) are individually resolved with sufficient statistical precision,
- Our calibration and charge resolution are stable within few % up to the K shell energy and above for N_{skip} = 64.



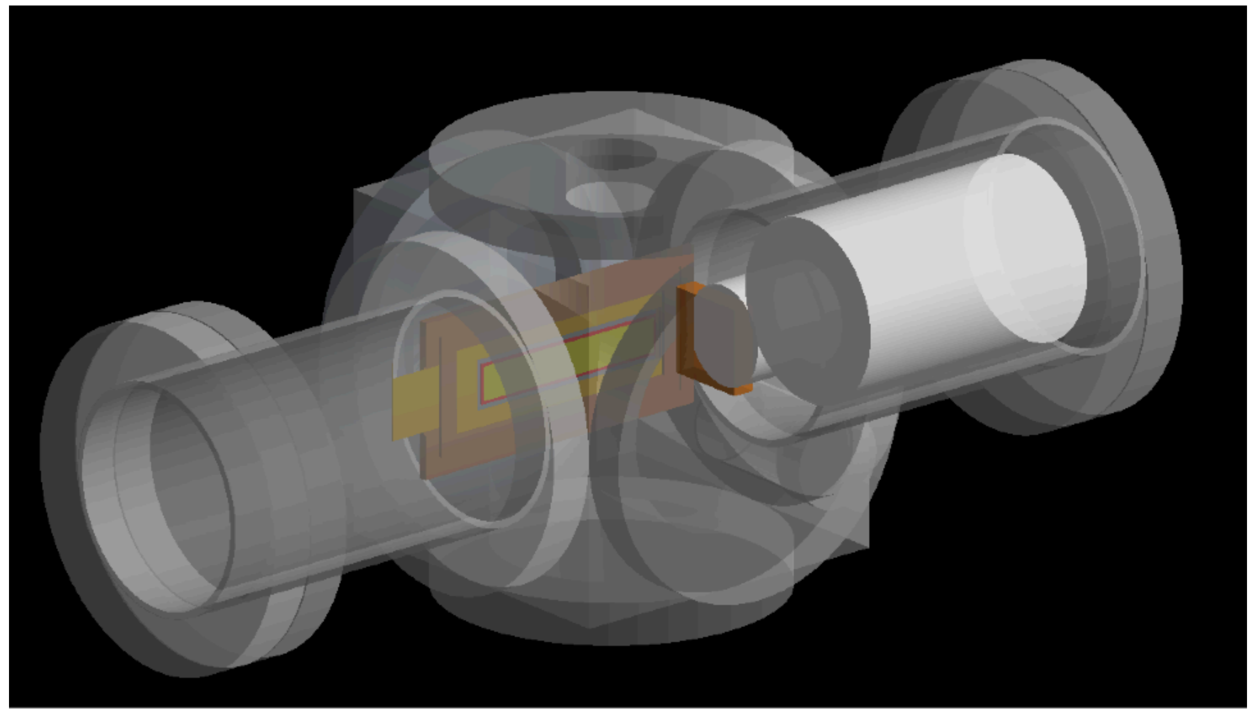


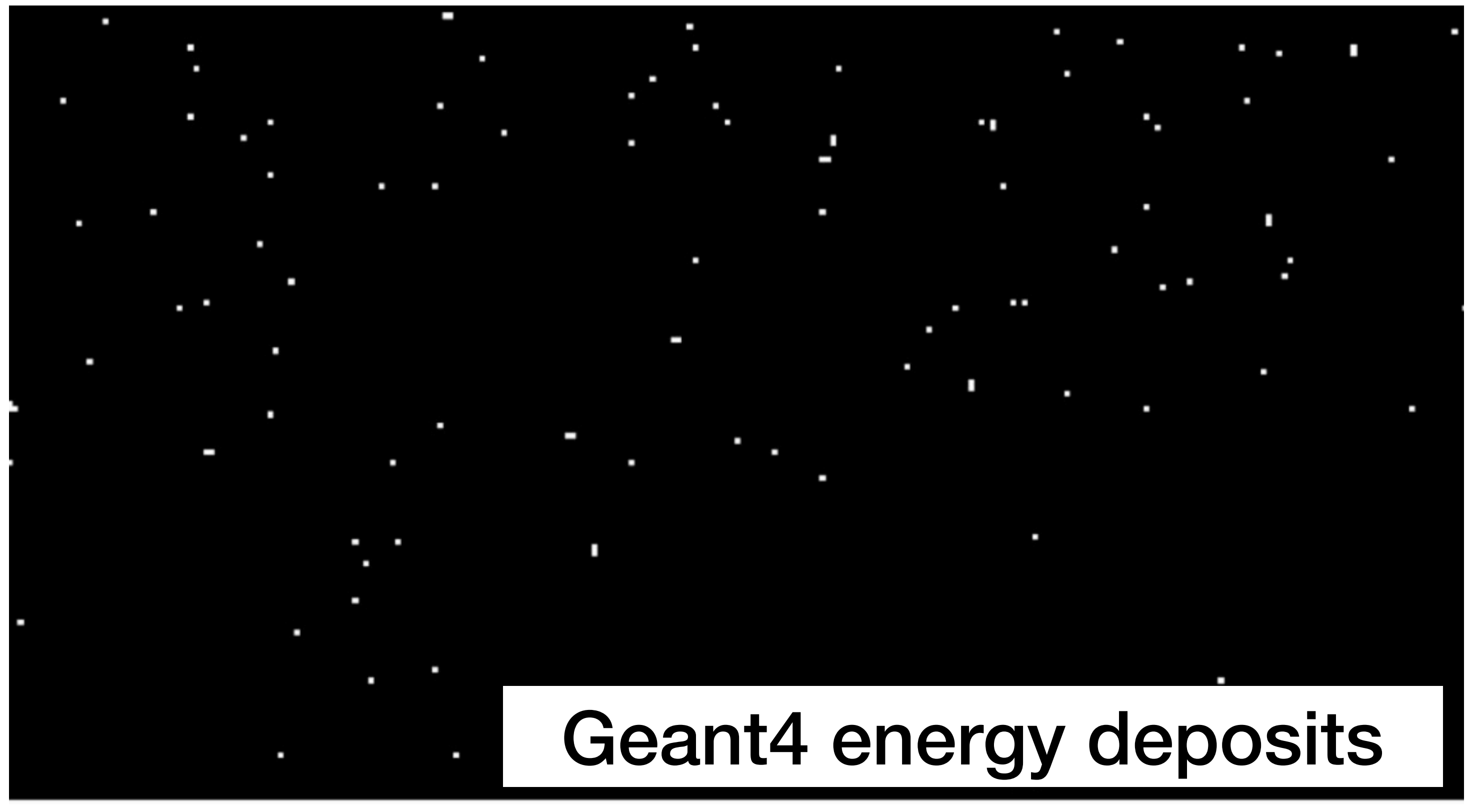
Simulations

A full simulation of the experiment was done with Geant4.

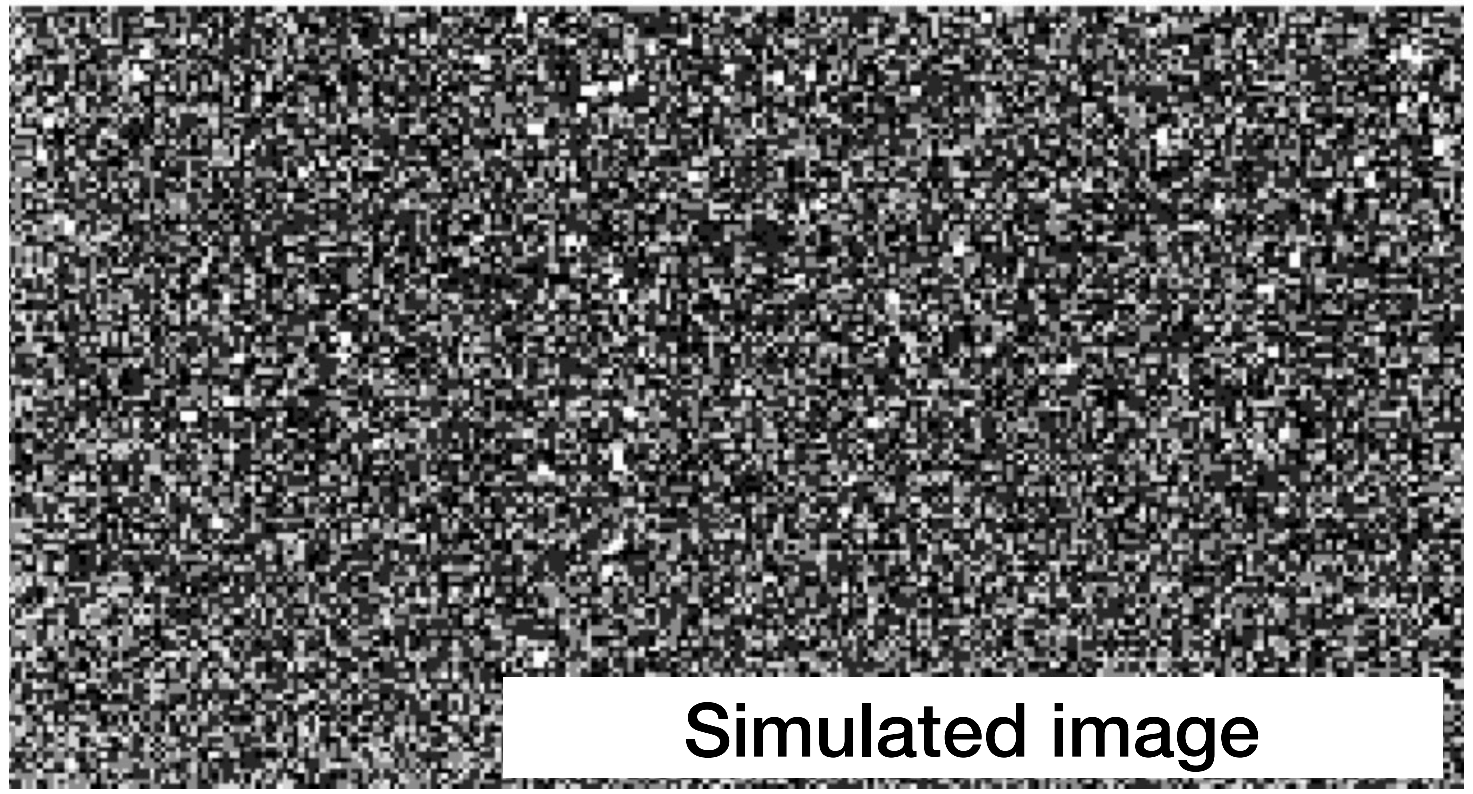
Realistic simulated images were constructed:

- G4 simulated energy deposited (E_{dep}) by γs in the CCD,
- The number of e^- is calculated by sampling electron-hole pair creation probabilities [K. Ramanathan and N. Kurinsky, PRD 102 (2020)] if E_{dep} < 50 eV or the average electron-hole pair creation energy (ϵ_{eh} = 3.74 eV/e^-) with Fano factor (F=0.128) for higher deposited energies,
- Electrons are diffused in the bulk Si of the CCD towards the pixel array (diffusion parameters as measured with cosmic ray muons),
- Charges are assigned to pixels in the array,
- Simulated ^{241}Am clusters are pasted onto images from the background data set to properly include the pixel readout noise, the dark current, and the presence of cosmic rays and other tracks.





Geant4 energy deposits



Simulated image

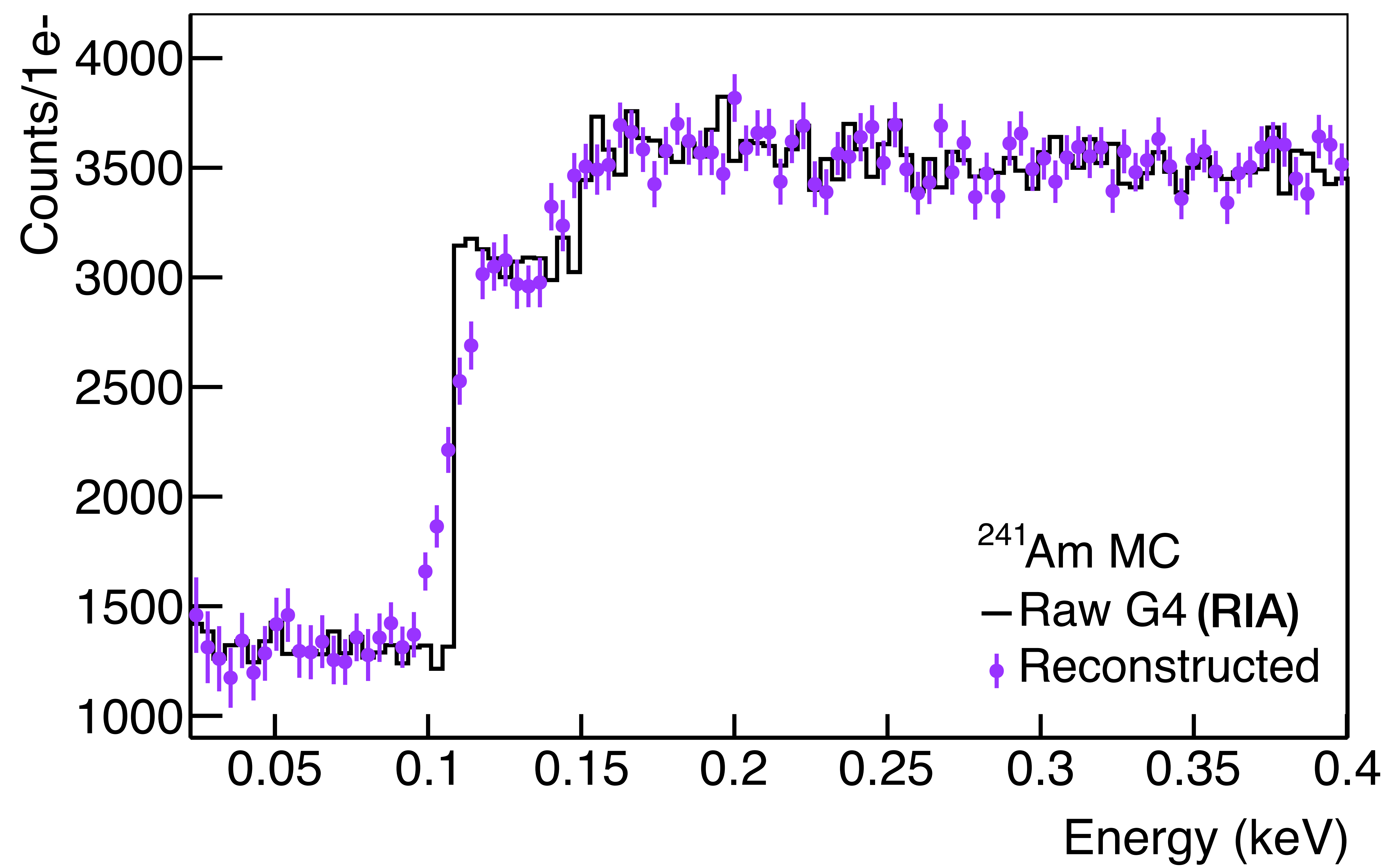
Simulations

The simulated images are then processed with the same cluster reconstruction and analysis chain as the data.

The reconstruction efficiency estimated from simulated images is 100% for energy deposits as low as 15 eV.

We accurately reconstruct the expected features at the lowest energy of the simulated Compton spectrum.

The smearing in the reconstructed spectrum comes from the Fano resolution and pixel readout noise.



Compton spectrum - K-shell

Our measured energy spectrum is in agreement with the RIA model above 0.5 keV.

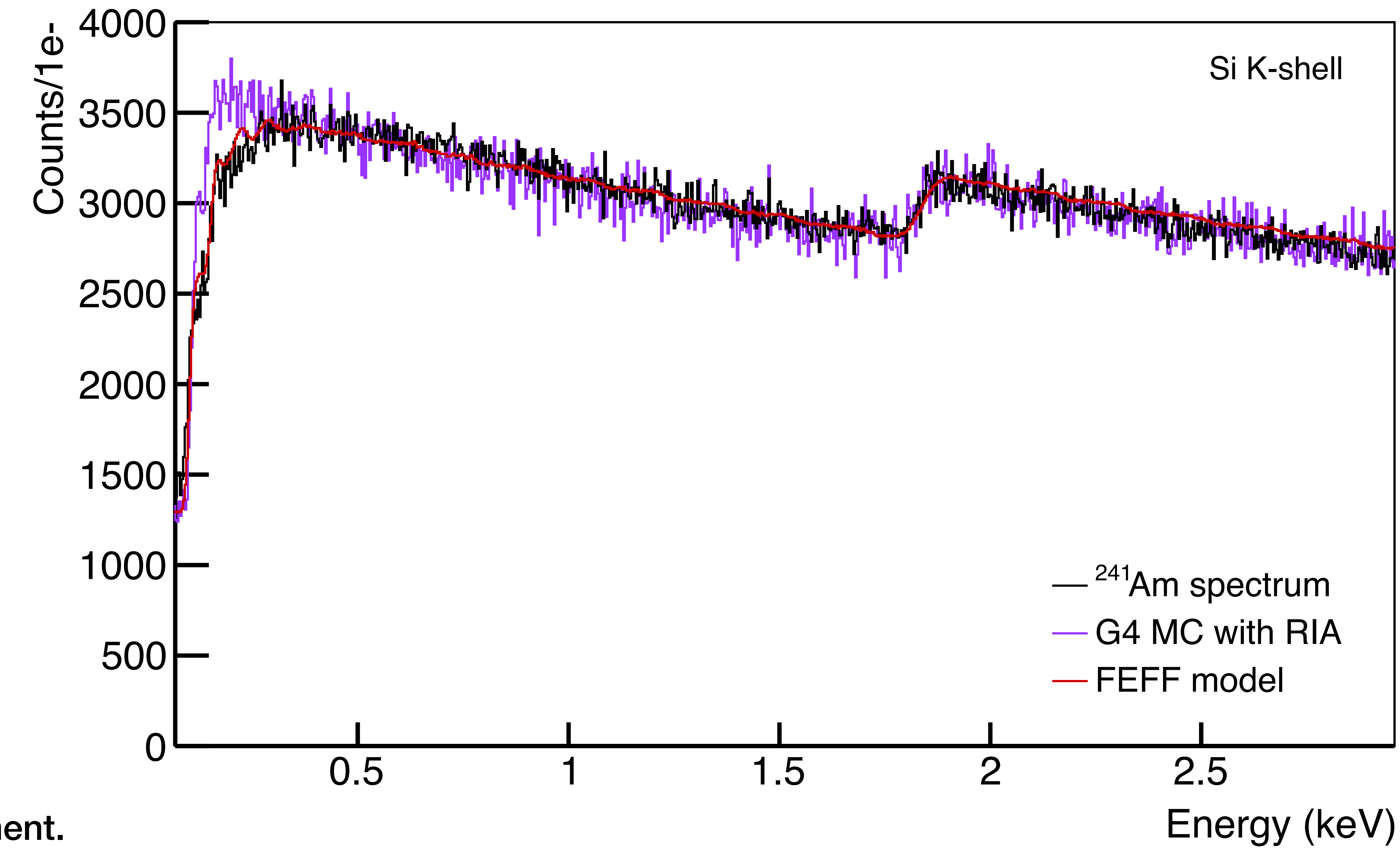
The K-shell transition step and slopes before and after the step are well reproduced.

K-shell step reconstruction:

E_K = 1839 eV and

ϵ_{eh} = 3.755 eV (agrees within 1% with 3.74 eV used in our reconstruction).

A softening of the spectrum below 0.5 keV is observed, confirming the previous measurement.



All spectra are shown in 1 e^- bins.

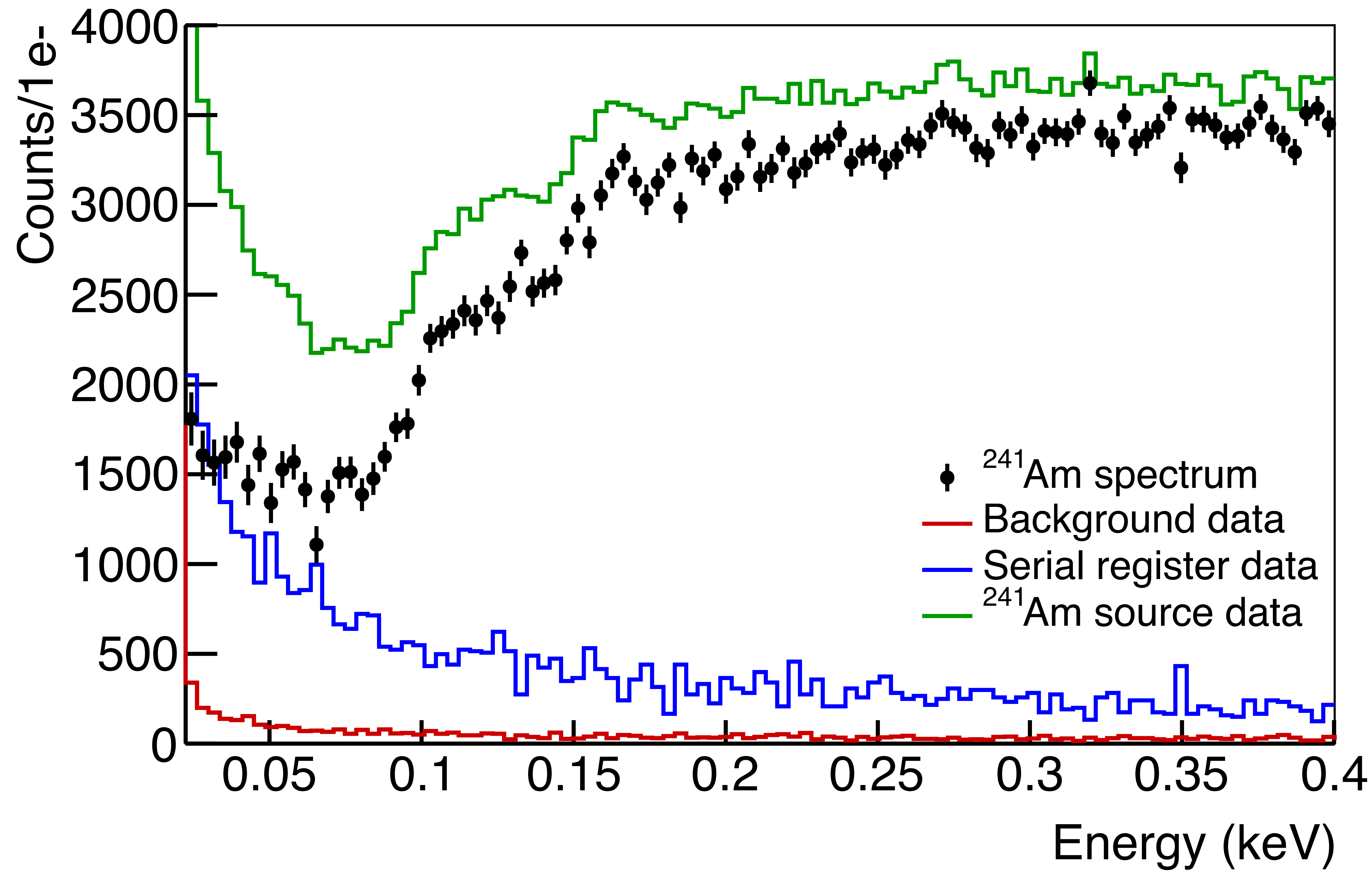
Compton spectrum - Background subtraction

Correct background subtraction is critical below 0.5 keV. The background data (i.e. no source) is just one component.

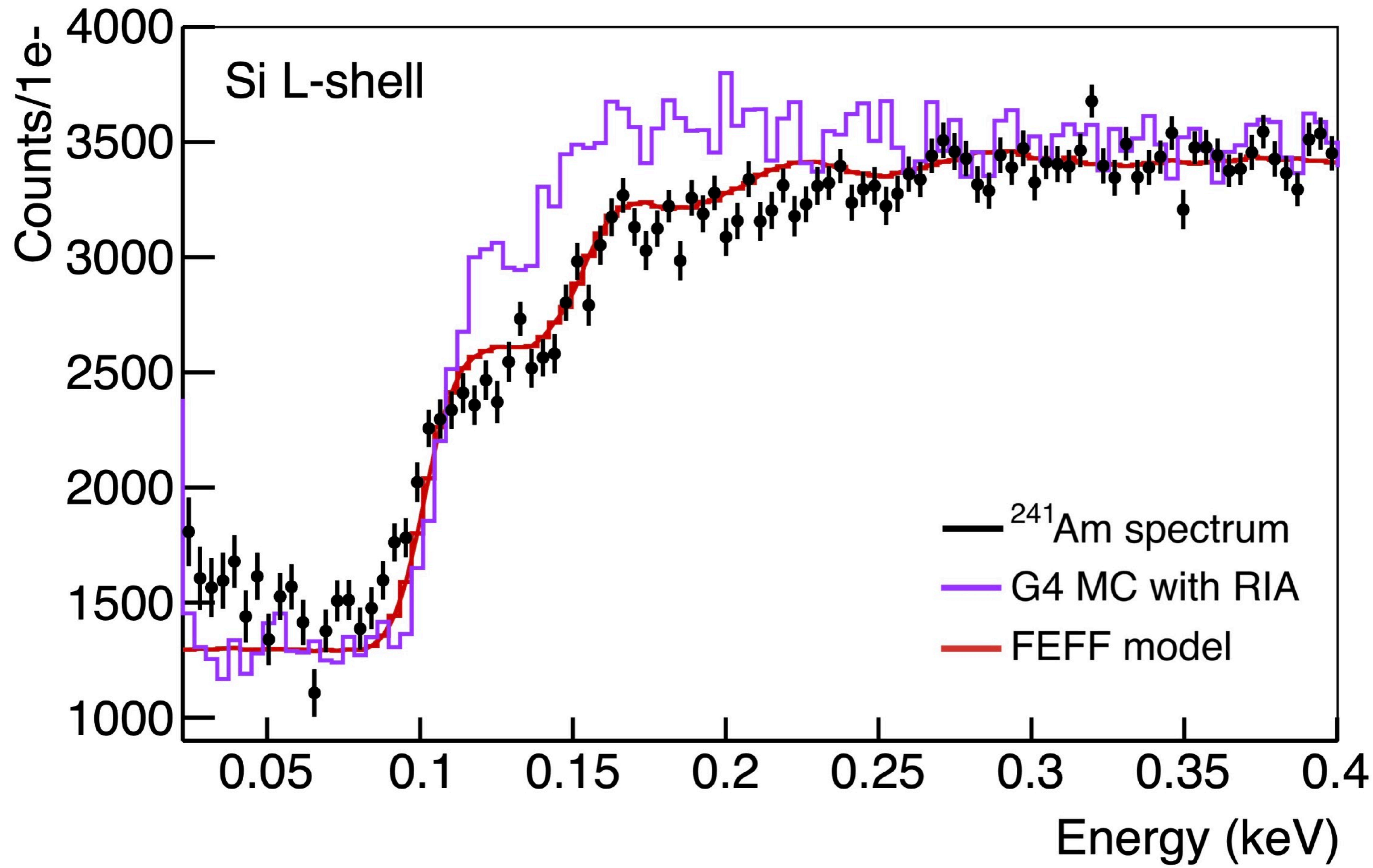
The dominant background source in low energies are so-called "horizontal clusters", i.e. particles hitting the serial register.

- These events are caused by cosmic rays and natural radiation depositing only partial energy in the serial register.
- In addition, the "horizontal clusters" contain only a few pixels and cannot be distinguished from real low energy gamma events.

We took dedicated data set (serial register data) to correctly subtract this contribution and reach the lowest energy threshold.



Compton spectrum - L-shell steps



- First detection of Compton scattering on valence electrons below 100 eV.
- Clearly identified features associated with the silicon L_1 (150 eV) and $L_{2,3}$ (99.2 eV) shells.
- RIA fails to reproduce the spectrum in the L-shell region and overestimate rates by up to 20%.
- The data are in better agreement with FEFF model (self-consistent calculations of local electronic structure and X-ray absorption spectra originally developed for X-ray absorption spectroscopy).

Paper submitted to Phys. Rev. D

arXiv:2207.00809

Precision measurement of Compton scattering in silicon with a skipper CCD for dark matter detection

D. Norcini,[1,*] N. Castelló-Mor,[2] D. Baxter,[1,†] N.J. Corso,[1] J. Cuevas-Zepeda,[1] C. De Dominicis,[3,1] A. Matalon,[1,4] S. Munagavalasa,[1] S. Paul,[1] P. Privitera,[1,4] K. Ramanathan,[1,‡] R. Smida,[1] R. Thomas,[1] R. Yajur,[1] A.E. Chavarria,[5] K. McGuire,[5] P. Mitra,[5] A. Piers,[5] M. Settimo,[3] J. Cortabitarte Gutiérrez,[2] J. Duarte-Campderros,[2] A. Lantero-Barreda,[2] A. Lopez-Virto,[2] I. Vila,[2] R. Vilar,[2] N. Avalos,[6] X. Bertou,[6] A. Dastgheibi-Fard,[7] O. Deligny,[8] E. Estrada,[6] N. Gadloa,[9] R. Gaïor,[4] T. Hossbach,[10] L. Khalil,[4] B. Kilminster,[9] I. Lawson,[11] S. Lee,[9] A. Letessier-Selvon,[4] P. Loaiza,[8] G. Papadopoulos,[4] P. Robmann,[9] M. Traina,[4] G. Warot,[7] and J-P. Zopounidis[4]

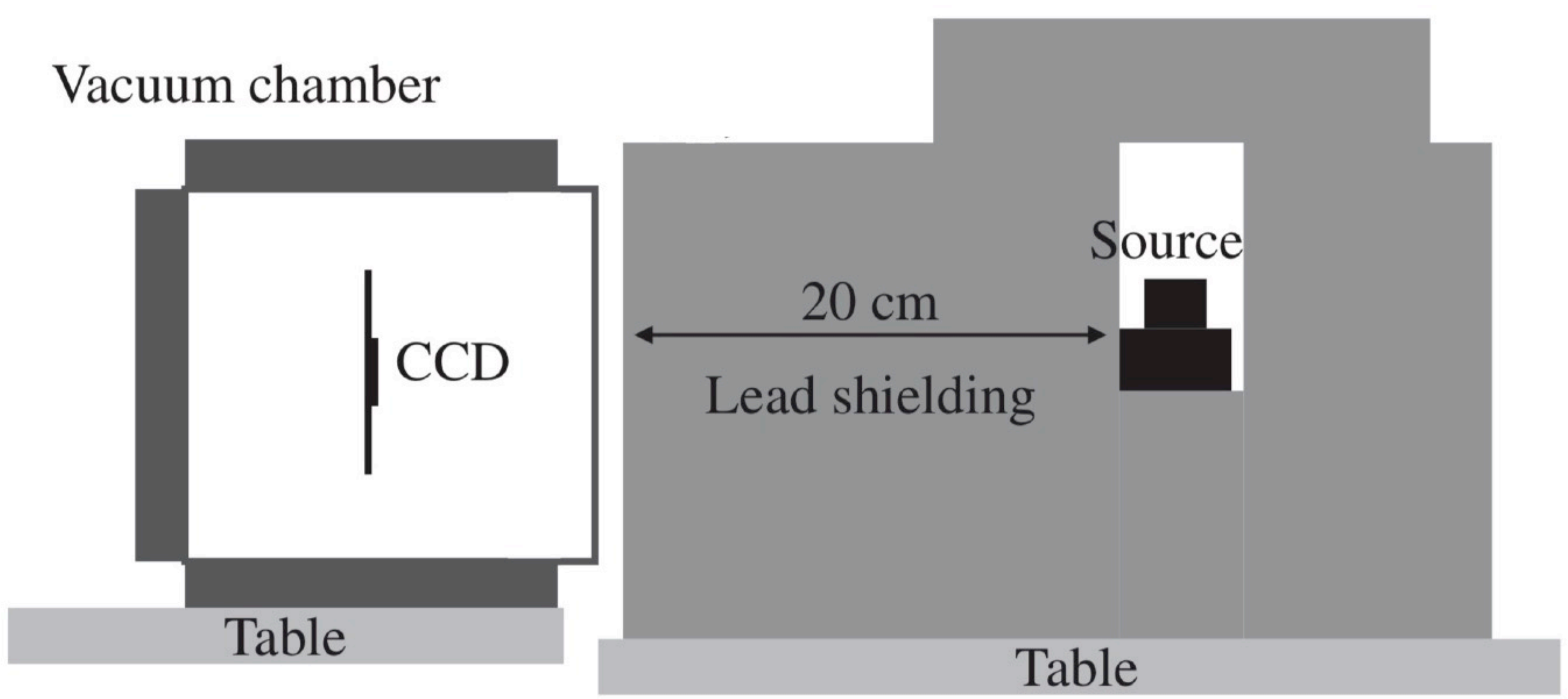
(DAMIC-M Collaboration)

Experiments aiming to directly detect dark matter through particle recoils can achieve energy thresholds of $\mathcal{O}(10\,\text{eV})$. In this regime, ionization signals from small-angle Compton scatters of environmental γ-rays constitute a significant background. Monte Carlo simulations used to build background models have not been experimentally validated at these low energies. We report a precision measurement of Compton scattering on silicon atomic shell electrons down to 23 eV. A skipper charge-coupled device (CCD) with single-electron resolution, developed for the DAMIC-M experiment, was exposed to a ^{241}Am γ-ray source over several months. Features associated with the silicon K, L_1, and $L_{2,3}$-shells are clearly identified, and scattering on valence electrons is detected for the first time below 100 eV. We find that the relativistic impulse approximation for Compton scattering, which is implemented in Monte Carlo simulations commonly used by direct detection experiments, does not reproduce the measured spectrum below 0.5 keV. The data are in better agreement with *ab initio* calculations originally developed for X-ray absorption spectroscopy.

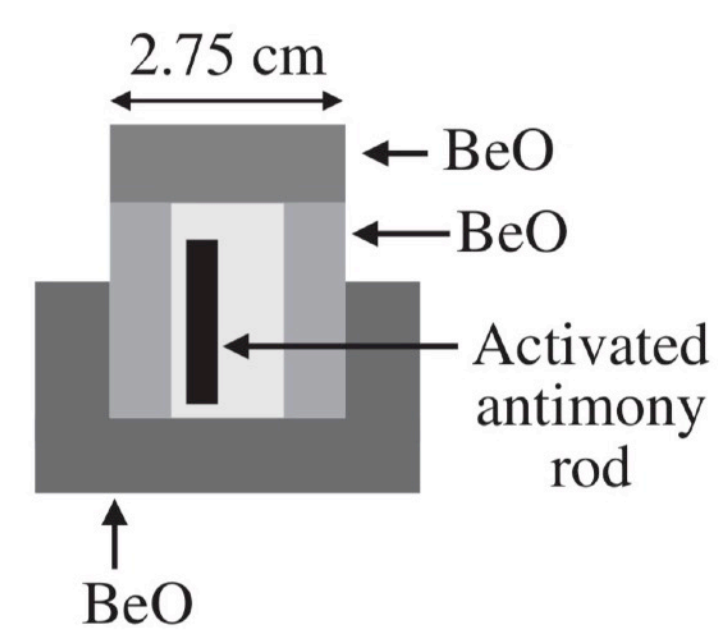
Photo-neutron measurement

- Ongoing measurement of nuclear recoil ionization efficiency in silicon,
- Similar setup as in the Compton measurement and Phys. Rev. D 94, 082007 (2016),
- Monochromatic 24 keV neutrons from ^{124}Sb-^{9}Be source ($T_{1/2}$ = 60.2 days), moderation in various materials before reaching the CCD.

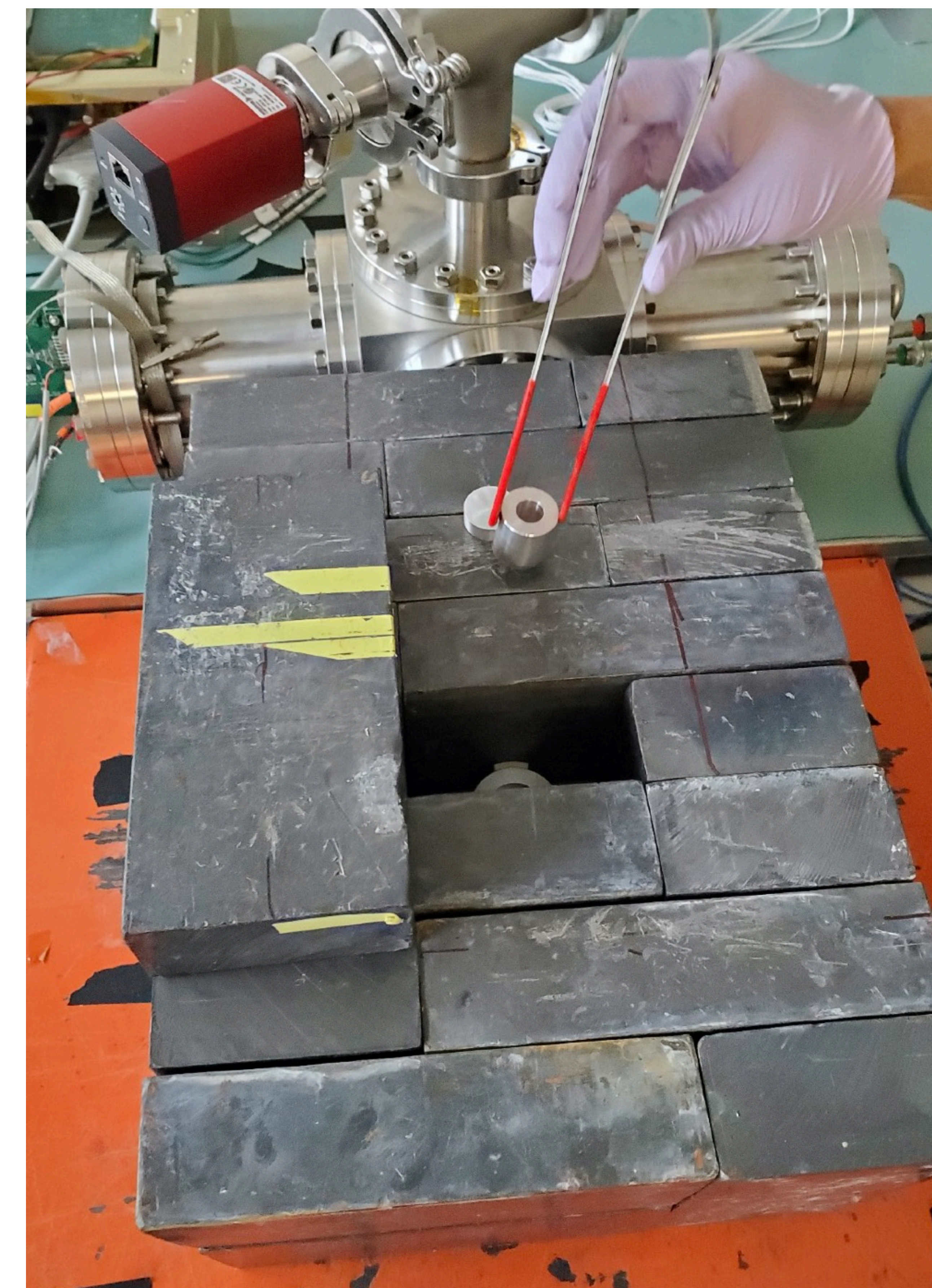
Cross section of setup



^{124}Sb-^{9}Be source detail



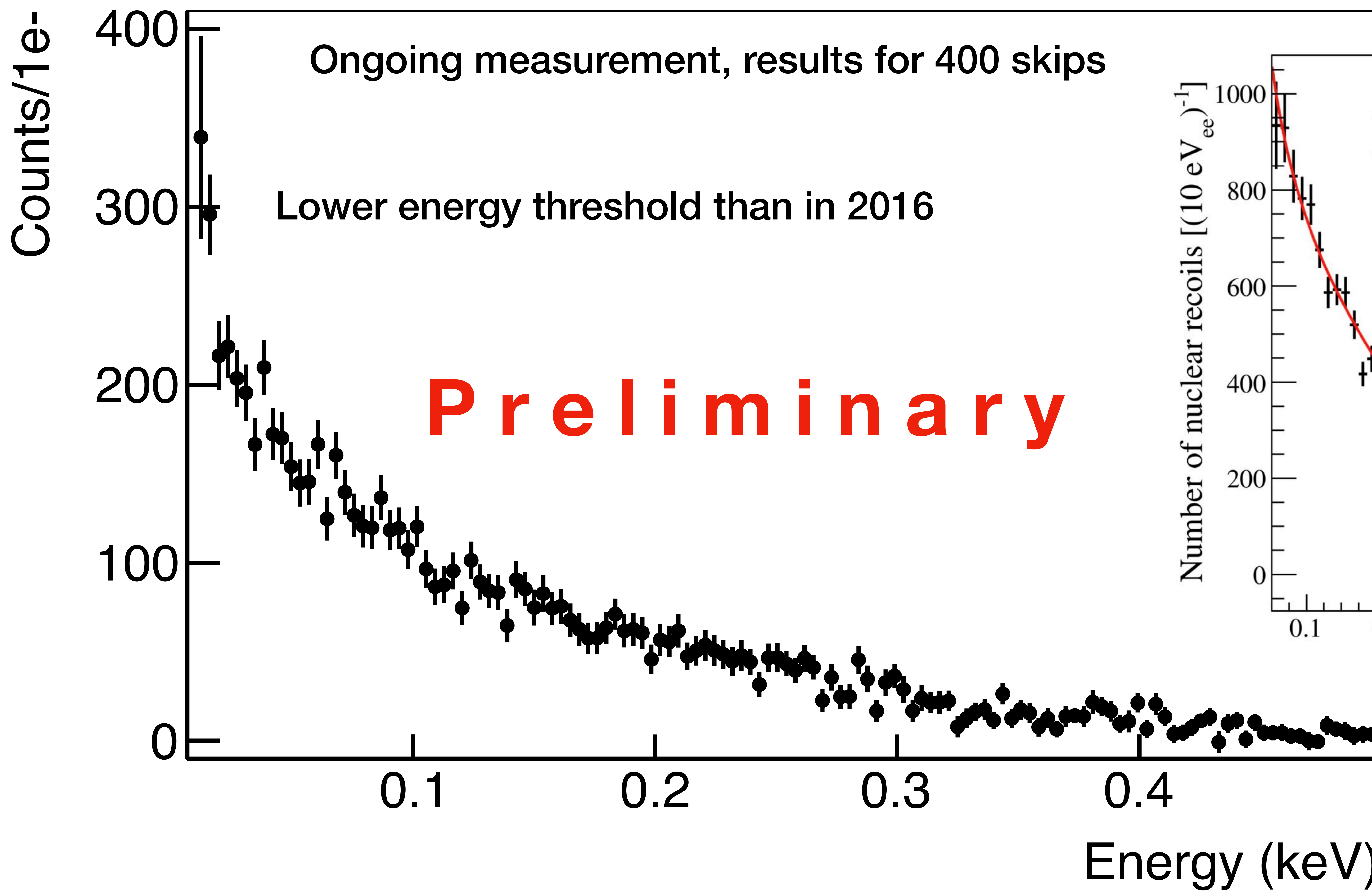
or Al in background runs



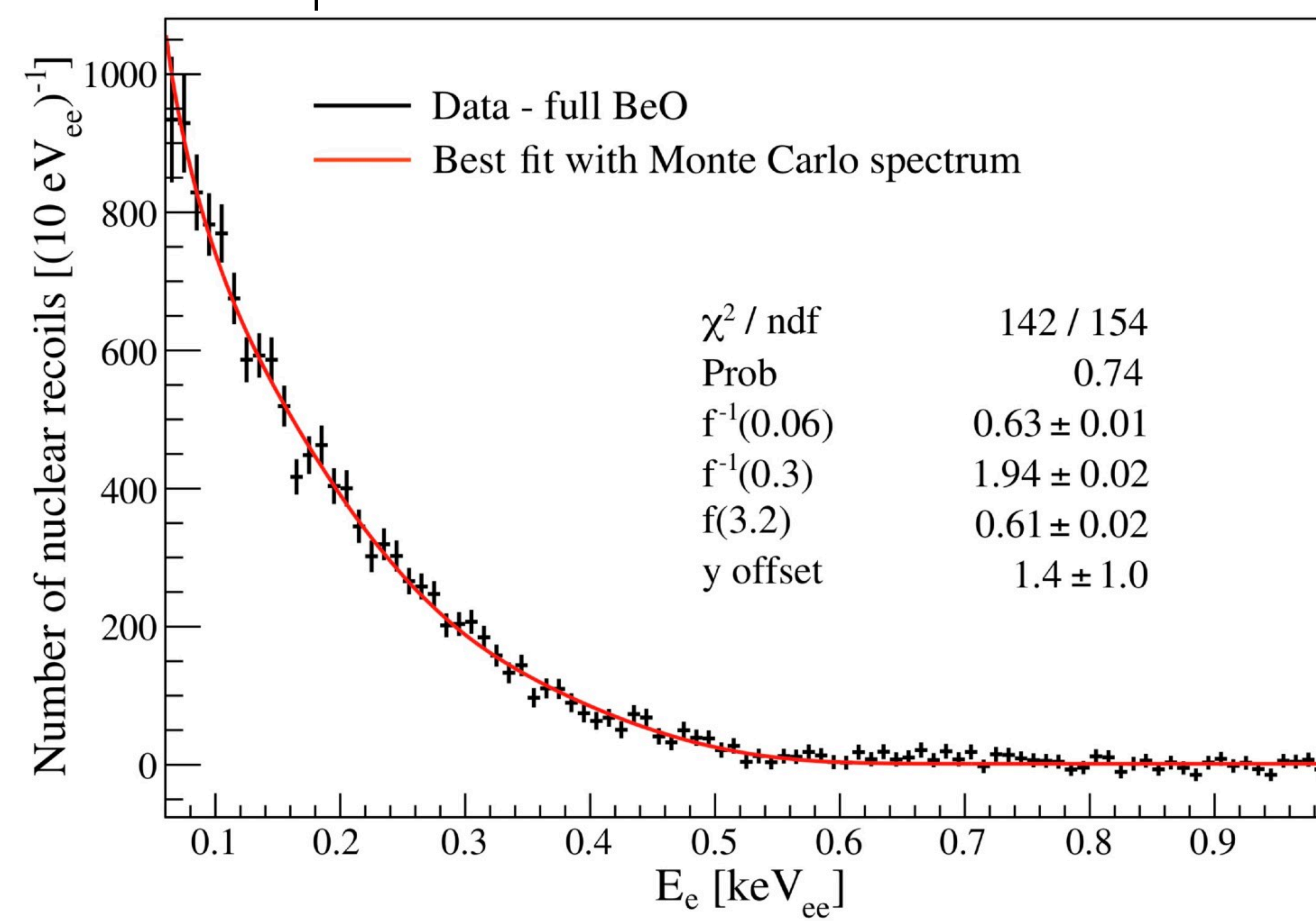
Setup in 2022

- Steps:
  1. Measure nuclear recoil and background spectra (we are here),
  2. Expected recoil spectrum from simulation (work in progress),
  3. Extraction of ionization efficiency.

Energy spectrum



Phys. Rev. D 94, 082007 (2016)

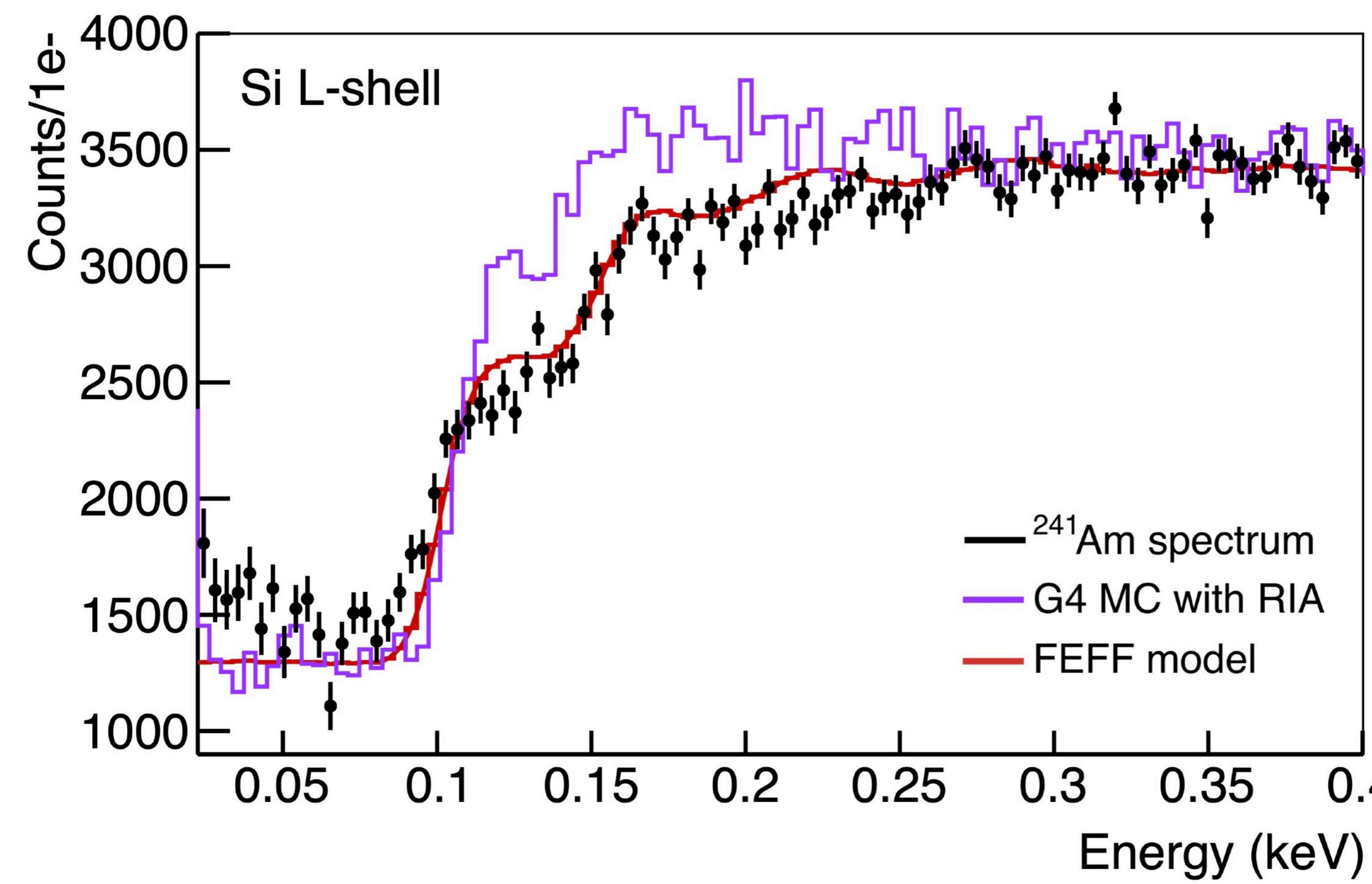


- Figure shows energy spectrum measured for 400 skips (σ_e = 0.30 e$^-$),
- Taking higher resolution data (i.e. 1600 skips with σ_e = 0.15 e$^-$) to explore the energy threshold region,
- The new spectrum has similar shape as published in 2016.

Conclusions

Precision measurement of the Compton-scattering energy spectrum in Si CCD down to 23 eV (~6 e^-):

- Significant improvement on previous results both in terms of resolution and threshold,
- Clearly identified L-shell steps and first detection of Compton scattering below 100 eV,
- The relativistic impulse approximation (RIA) for Compton scattering implemented in simulations commonly used by dark matter direct detection experiments does not reproduce the measured spectrum below 0.5 keV,
- The data are better described by the FEFF model.



Results are posted on arXiv:2207.00809.

- Measurement with other source (e.g. ^{57}Co) are under discussion.

Ongoing nuclear recoil ionization measurement with a photoneutron source with the same setup.

https://damic.uchicago.edu/

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