Characterization of low energy ionization signals from Compton scattering in a CCD Dark Matter detector

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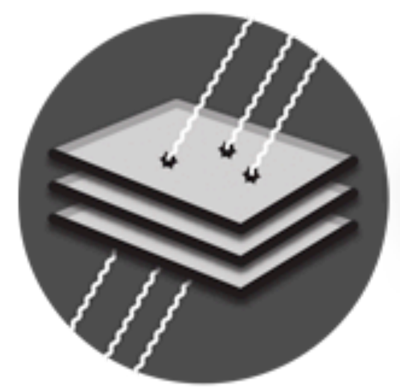
(Accepted PRD)



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Motivation

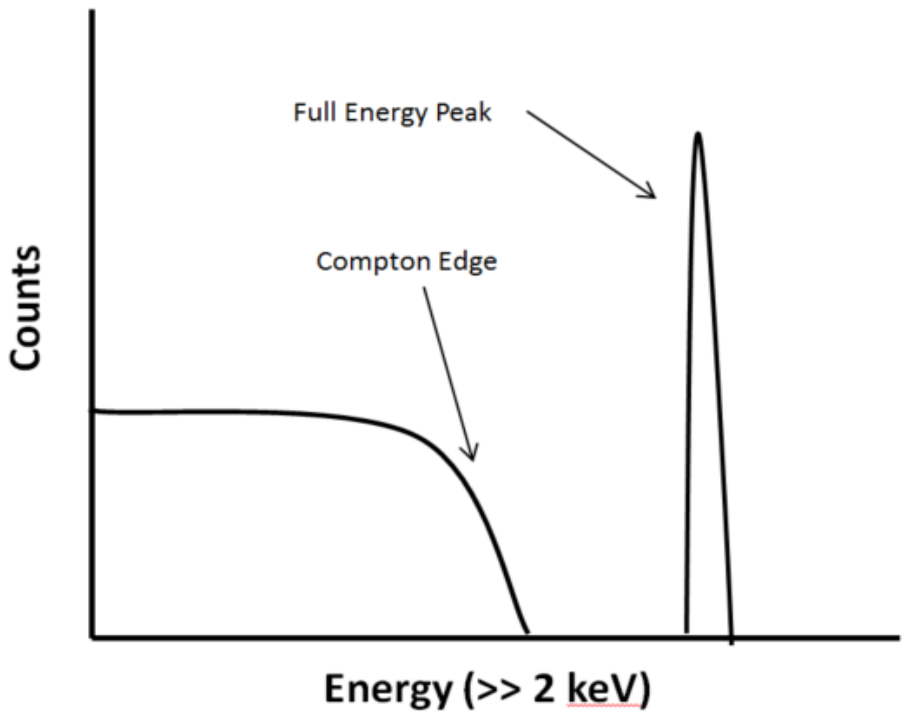
- Solid state ionization detectors are integral component of next-generation dark matter searches due to their very low noise and the small band gap of semiconductor targets.
- However in this low energy search regime (2-1000e-) dominant background from environmental radiation are low-energy electron recoils due to small-angle **Compton Scattering** of external gammas.
- Flux is orders of magnitude higher than fast neutrons – the usual consideration for external source of signals
- Irreducible Electron Recoil background → any potential Dark Matter **can only be identified by energy spectrum**.

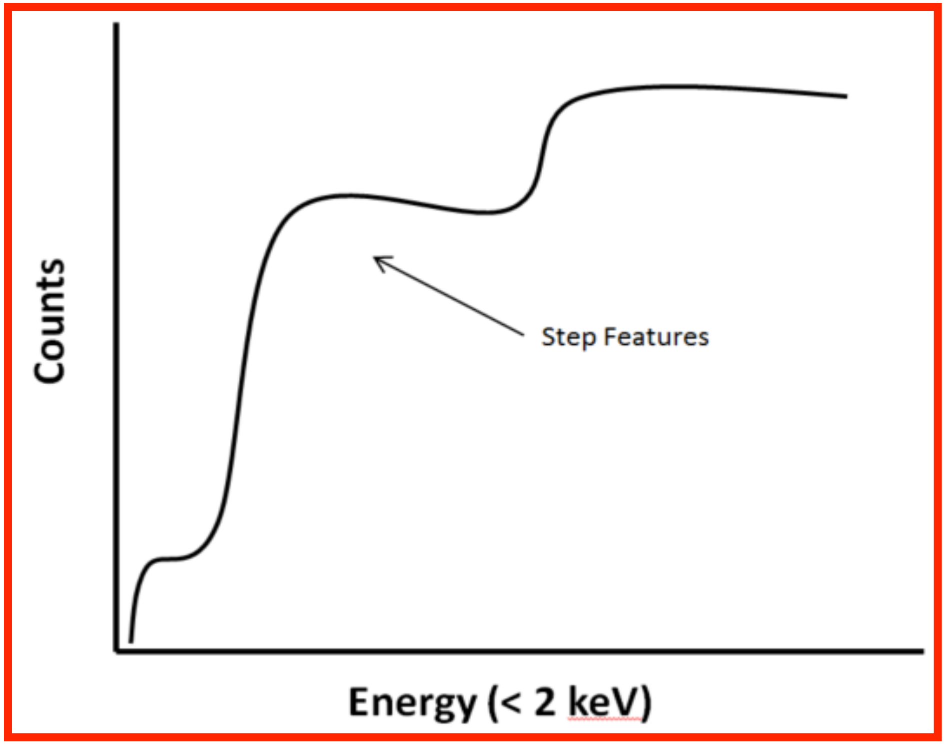
→ Need complete understanding of low-energy spectral features.

→ Expose UChicago Silicon CCD detector to gamma source

Motivation II

- Expose to γ-ray source
  - Compton features + ?

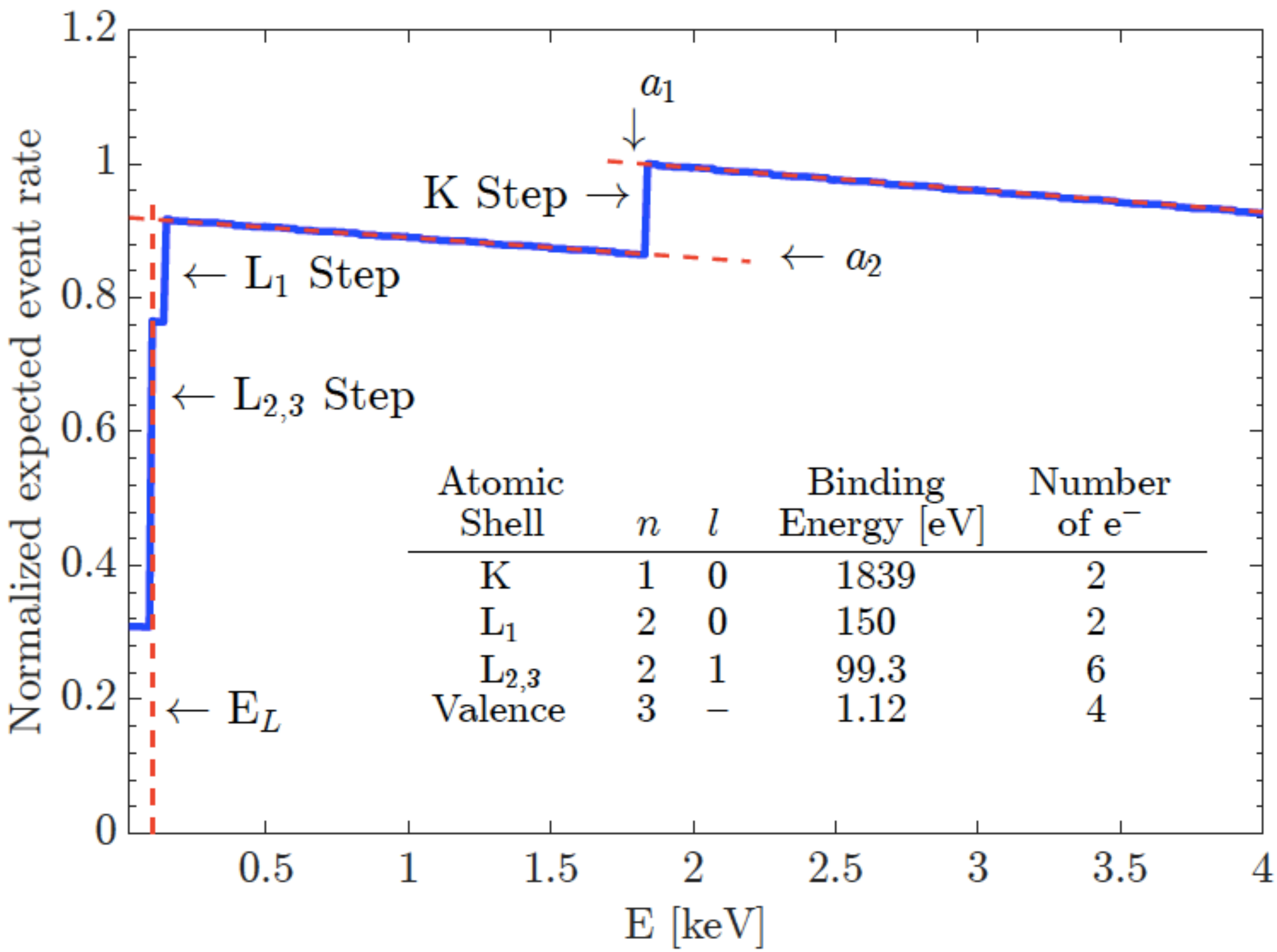




Modeling

- Generically scattering cross-section given by textbook Klein-Nishina. However dealing with bound electrons.
  - Expect effectively flat spectrum (with these added steps)
- **Impulse Approximation**: Each atomic shell treated independently. Bound electrons are modeled as free with constrained momentum distribution derived from bound-state wave function.
  - Ribberfors 1982 (https://doi.org/10.1103/PhysRevA.26.3325)
  - Valid in our region of interest with low energy and momentum transfers
- Useful since we can obtain differential cross section expressions per atomic electron with quantum numbers n, l

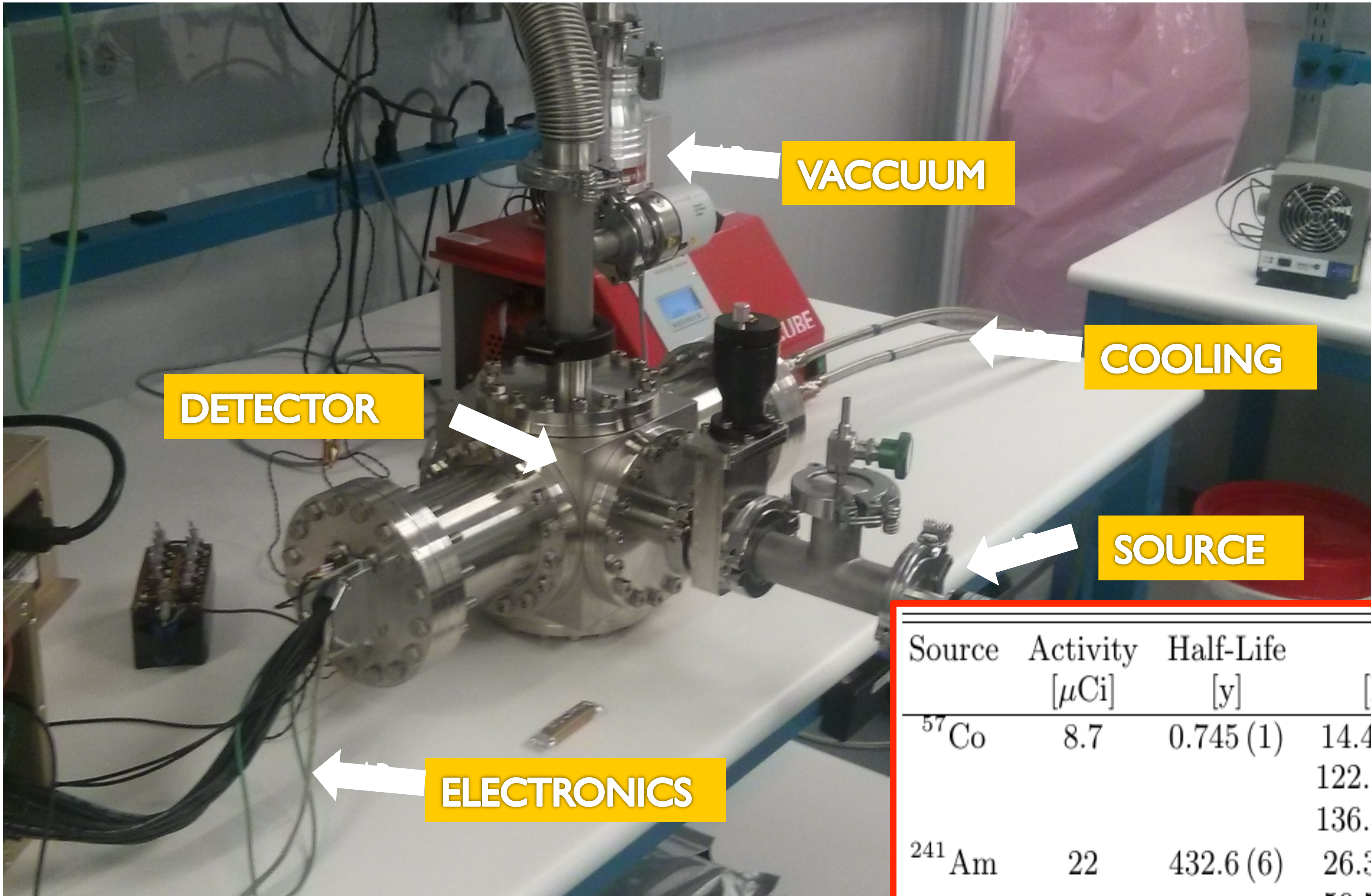
Expected Spectrum



Atomic Shell	n	l	Binding Energy [eV]	Number of e^-
K	1	0	1839	2
L_1	2	0	150	2
$L_{2,3}$	2	1	99.3	6
Valence	3	–	1.12	4

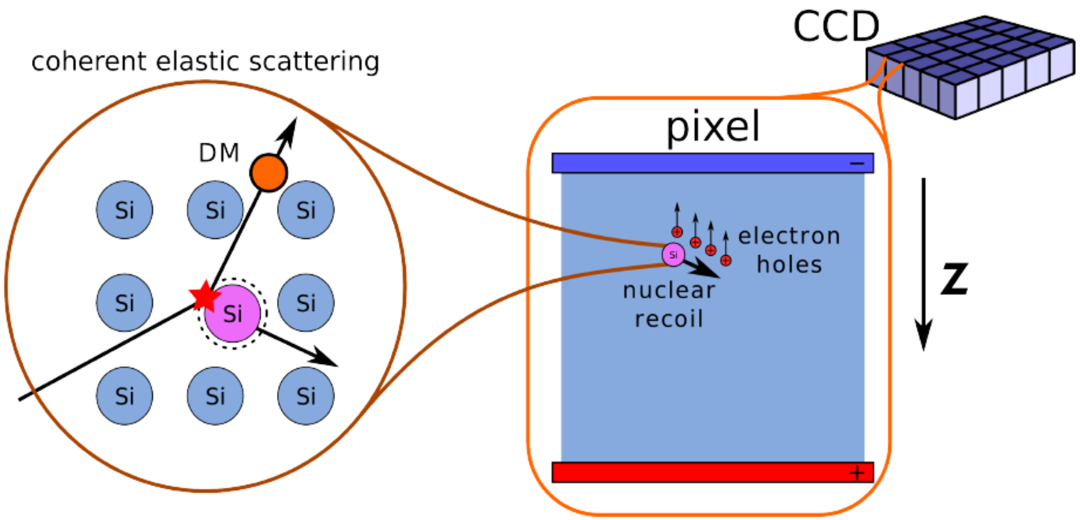
- **Silicon Target**
- Visible Step features
  - Binding Energies
- Provide linear parameterization (since in aggregate an unknown spectrum can be fit with straight lines…)

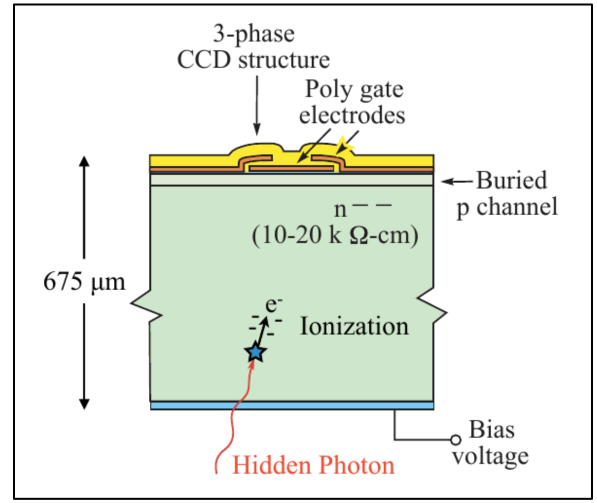
Testbed (UChicago)



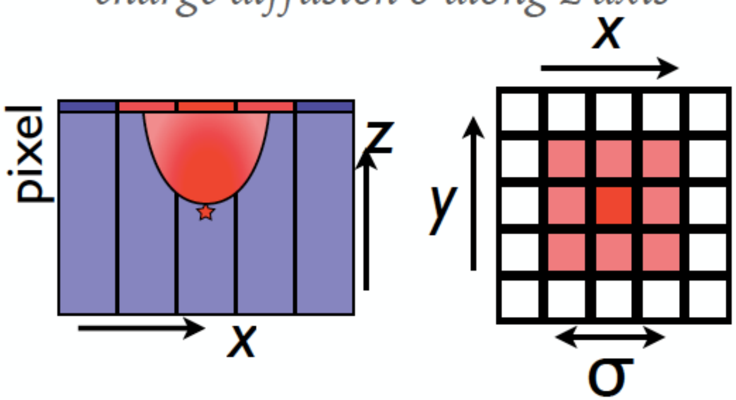
Source	Activity [μCi]	Half-Life [y]	E_γ [keV]
^{57}Co	8.7	0.745 (1)	14.4130 (3)
			122.0607 (1)
			136.4736 (3)
^{241}Am	22	432.6 (6)	26.3446 (2)
			59.5409 (1)

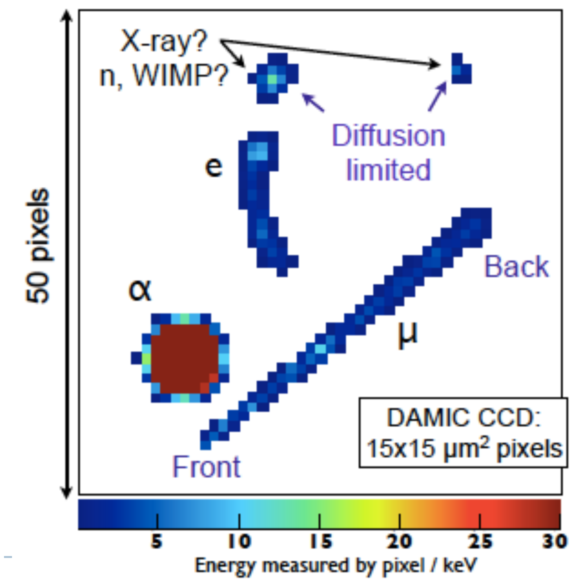
Detection Principle



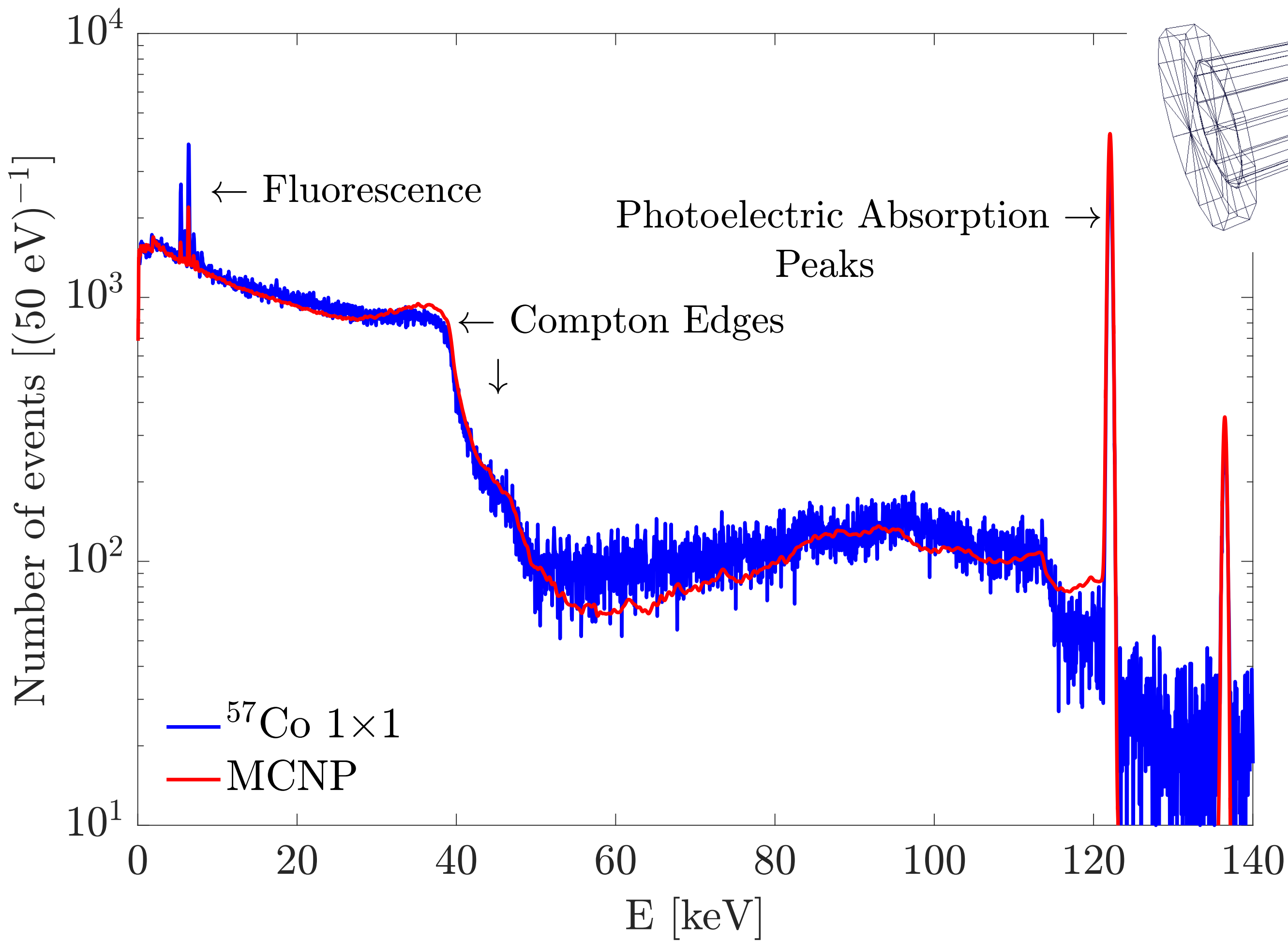


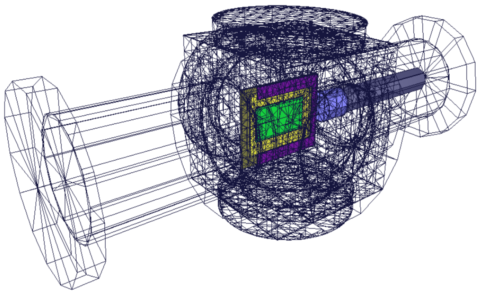
charge diffusion σ along z axis



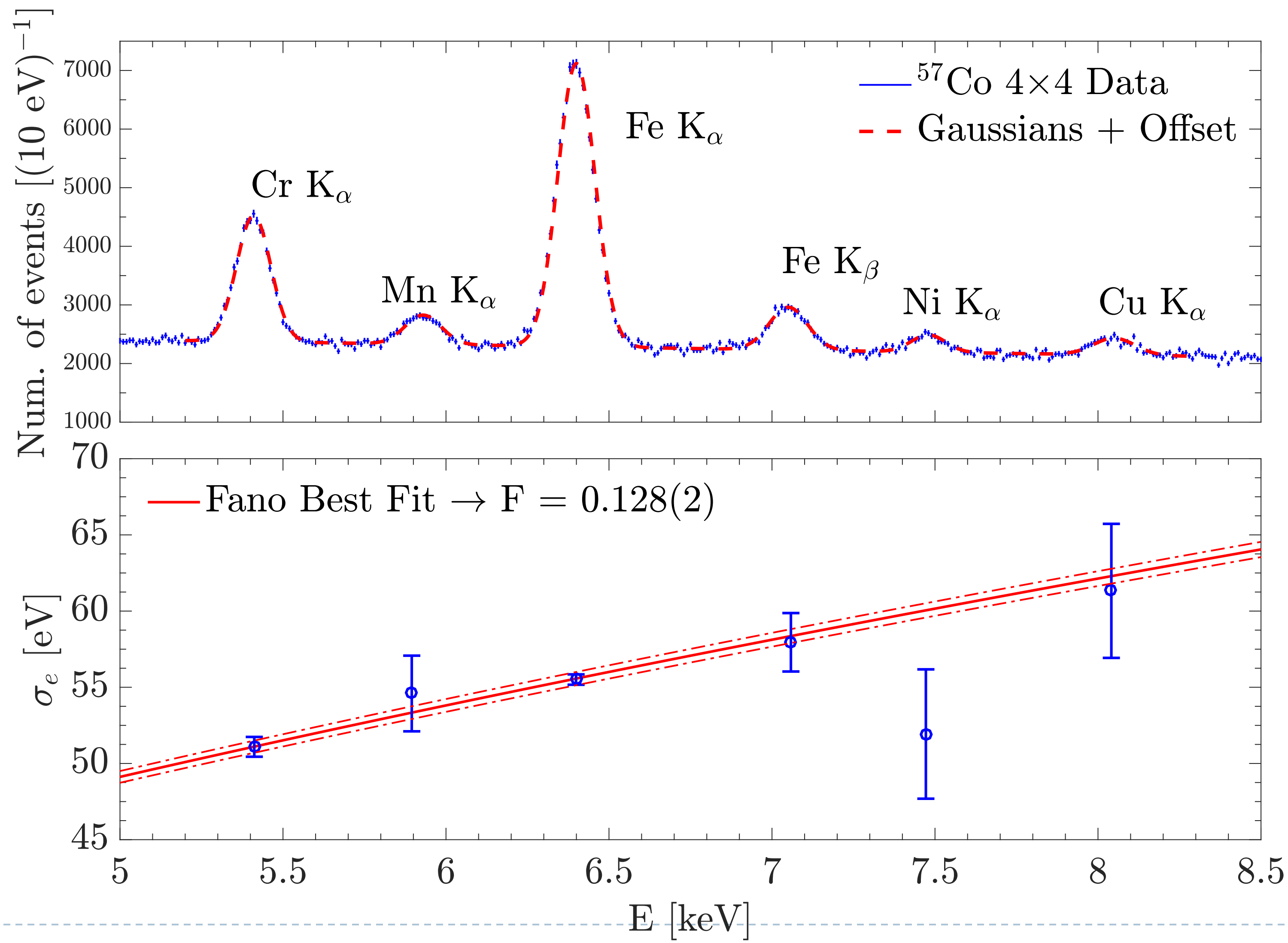


1x1 Data & MCNP Simulation Model

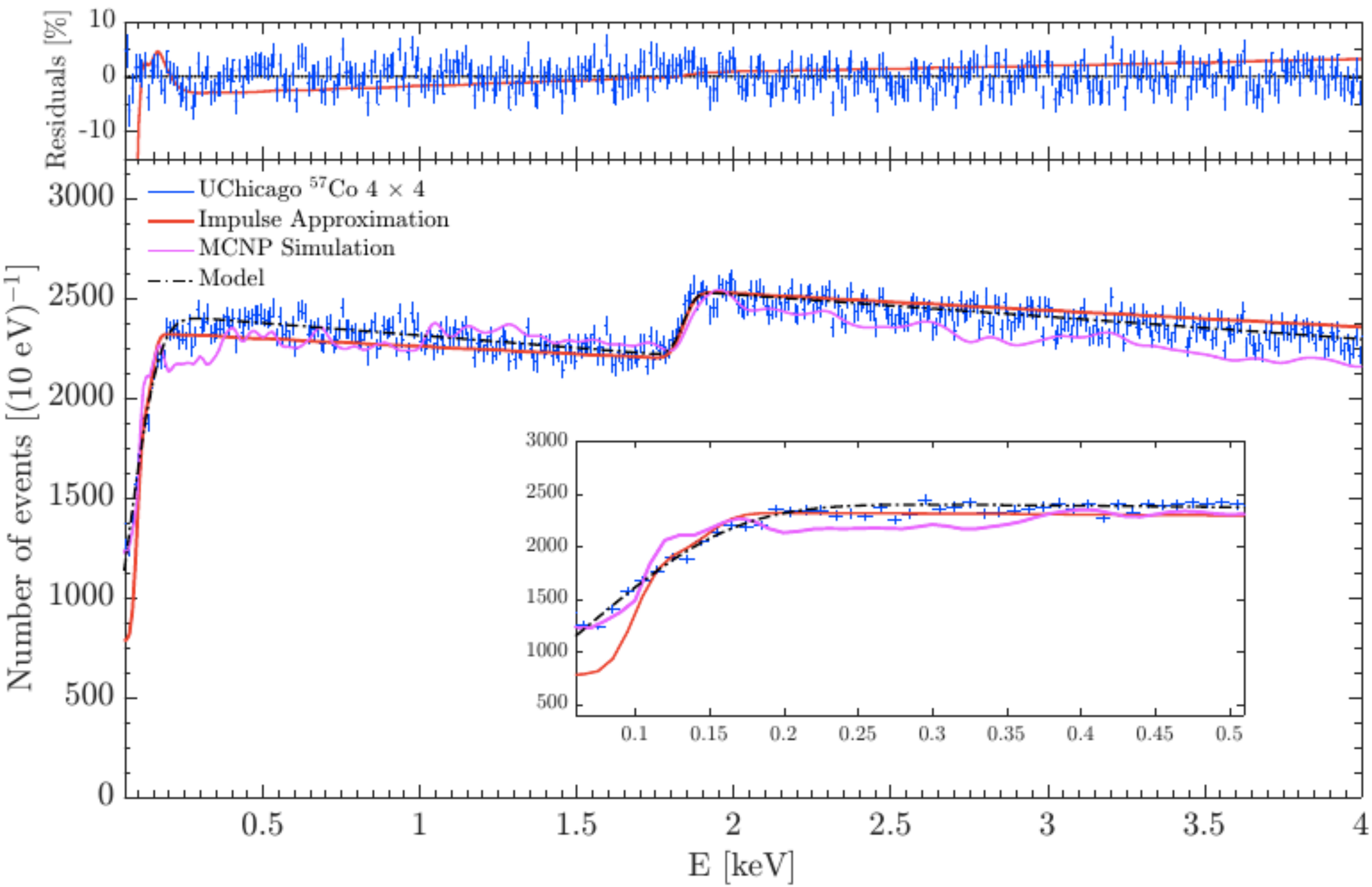




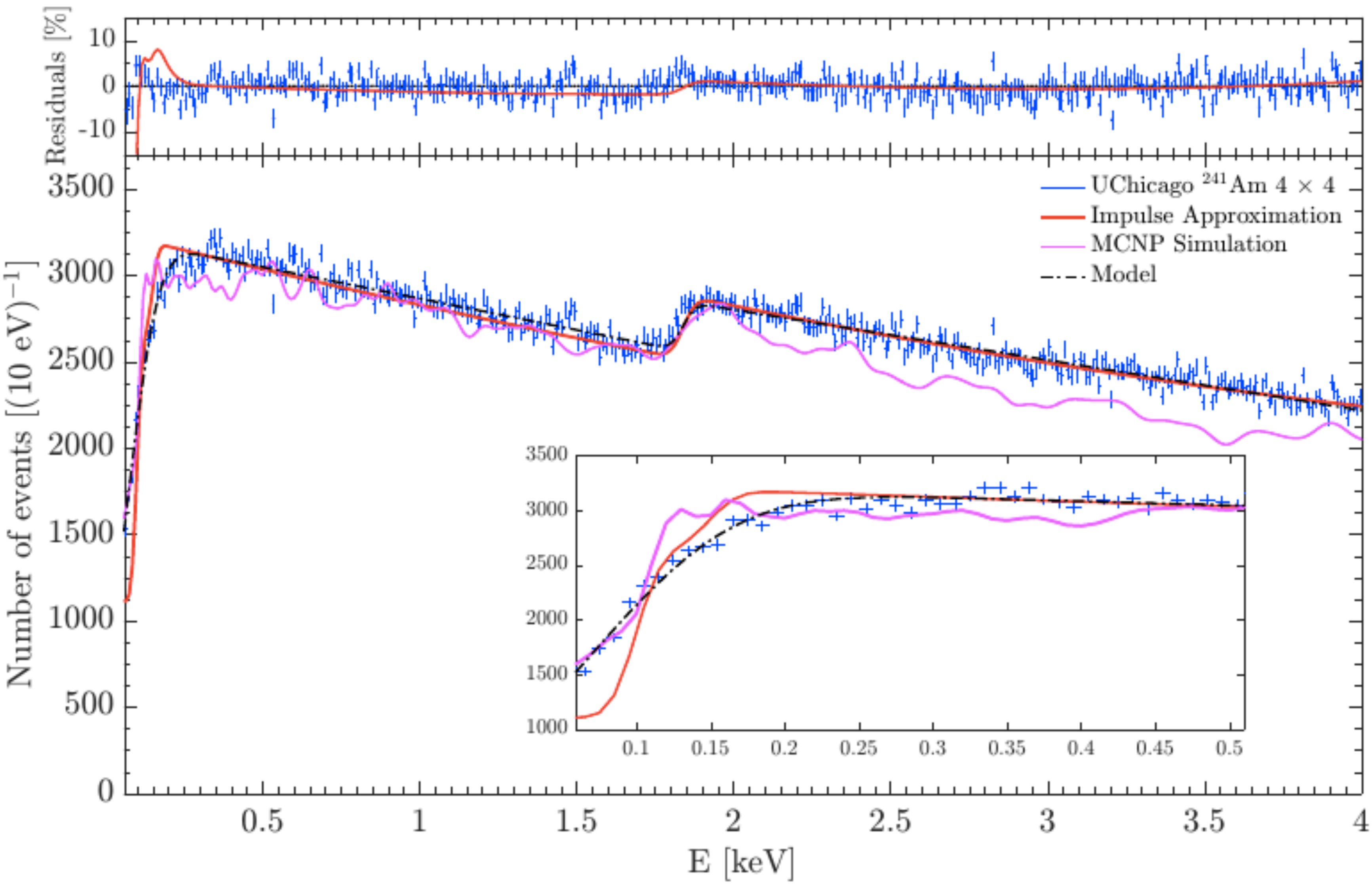
Fano Factor (@ 130 K)



Results - Cobalt



Results - Americium



L-Step

- Fano model should be valid
  - External modeling of all low-energy electrons emitted in Auger cascade (RELAX atomic relaxation spectra code)
- Calibration with Oxygen fluorescence x-rays → 21 eV resolution at E_g = 525 eV
- Interpret decreased resolution as coming from softened L step in electron spectrum

→ Assumption that each atomic shell can be treated as independent does not hold? Many-body effects?

Model

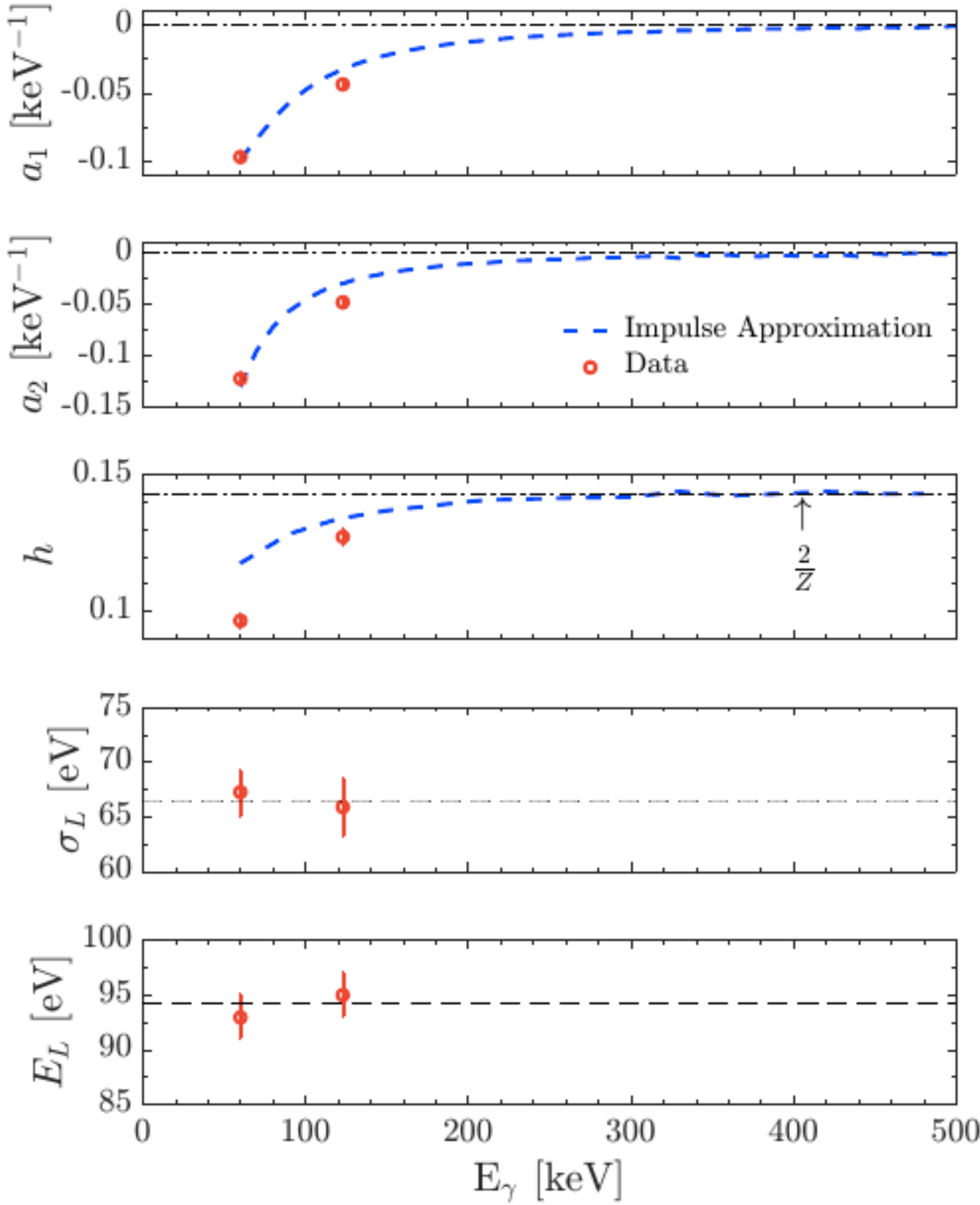
- From 0.5-4 keV
- Initial 3 parameter model with fixed step heights discarded
- 6 parameter model
  - → 2 slopes
  - → K step height
  - → L step location and resolution (σ_L)
  - → Normalization

$$f(E) = A \times \begin{cases} a_1(E - E_K) + 1 & E \geq E_K \equiv E_{10} \\ a_2(E - E_K) + b_2 & E_L \leq E < E_K \\ b_3 & E < E_L, \end{cases}$$

$$b_3 = \frac{Z - 10}{Z - 2}[b_2 + a_2(E_L - E_K)],$$

Model II

- 6 parameter model
  - → 2 slopes
  - → K step height
  - → L step location and resolution
  - → Normalization
- Able to model fit in <4 keV range to within 5% without accurate background knowledge
- Flattens out at high γ energies



Takeaway

Primary

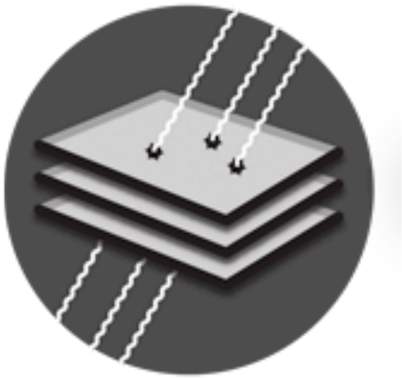
- Report, for first time, spectral Compton features associated with the atomic structure of the target.
- Characterize the spectrum of low-energy ionization signals from electrons Compton scattered by radiogenic γ-rays, vital for future DM searches
- Validate applicability of simple linear model

Secondary

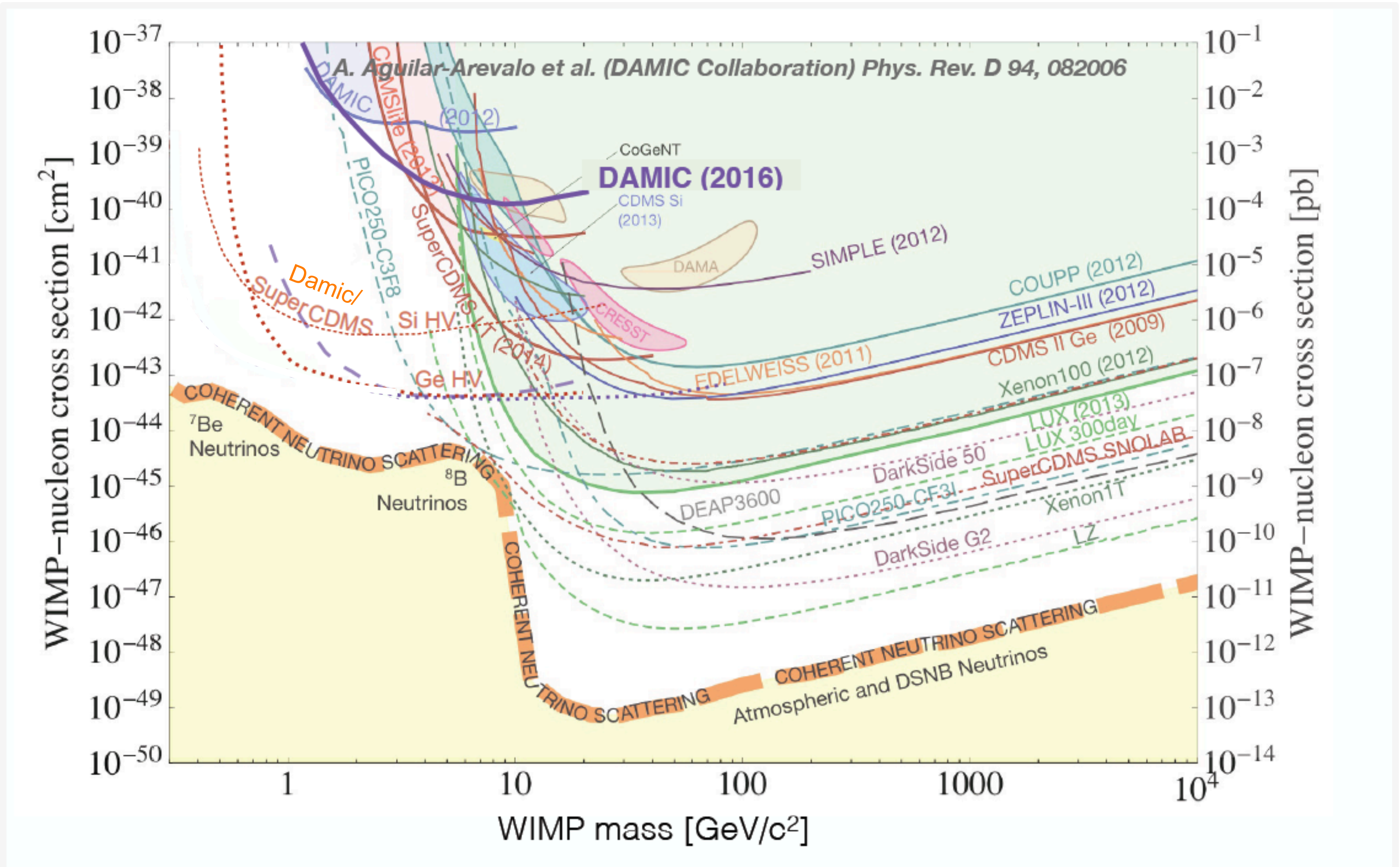
- Demonstrate again CCD resolution down to ~60 eV
- Measure Fano Factor @ operating temperature

Remains an open question as to what happens at low energies?

Questions?



Exclusion Plot



Impulse Approximation

$$\left.\frac{d\sigma}{dE}\right|_{nl} = C \int_{-1}^{1} \frac{(1-\delta)(1+\cos^2\theta)+\delta^2}{|\vec{q}|} J_{nl}(p_z)\, d\cos\theta$$

$$p_z = \frac{(E_\gamma/c)(1-\delta)(1-\cos\theta)-\delta mc}{|\vec{q}|}$$

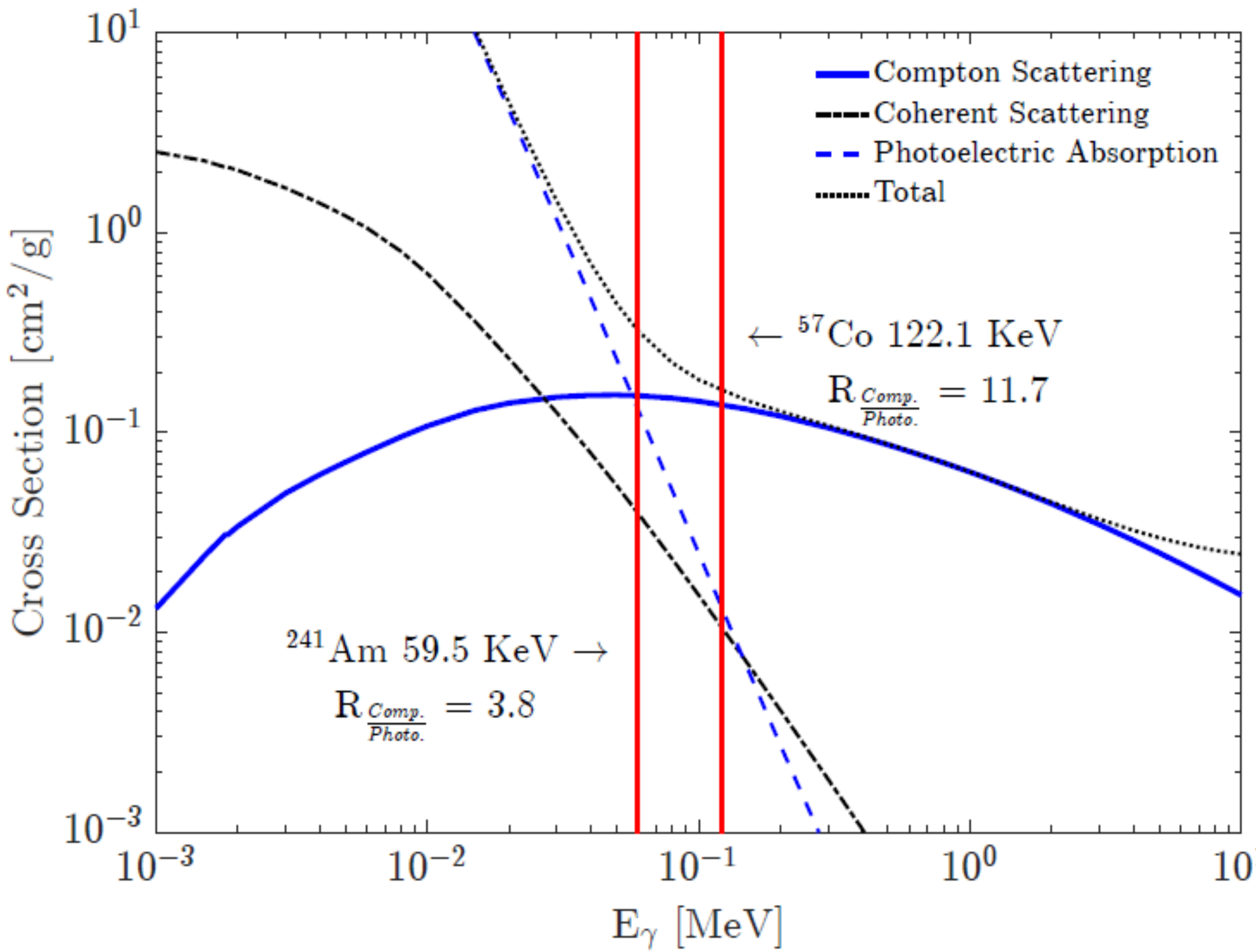
$$|\vec{q}| = \sqrt{2(1-\delta)(1-\cos\theta)+\delta^2}.$$

Projection of electron momentum on scattering vector

Expression valid only for $E > E_{nl}$, the target electron's binding energy. Otherwise it's 0 as the min. energy photon can lose is that required to free the target electron

$J_{nl}(p_z)$ are the Compton profile functions, which encode the momentum distribution of the target electron and is taken from tabulated data. Further the integral can only be evaluated numerically.

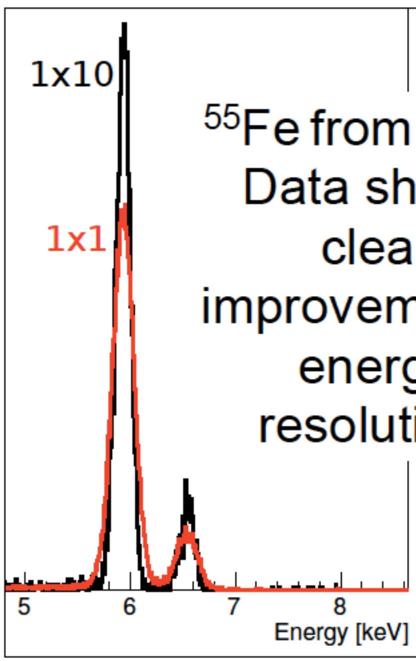
Source Selection



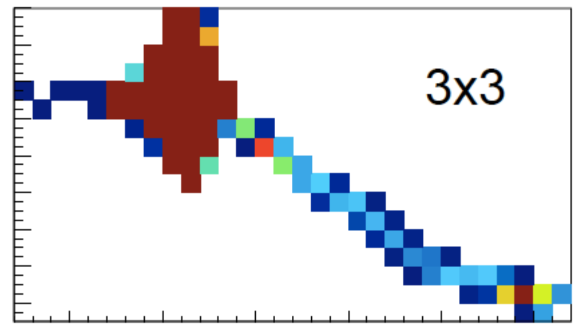
Binning

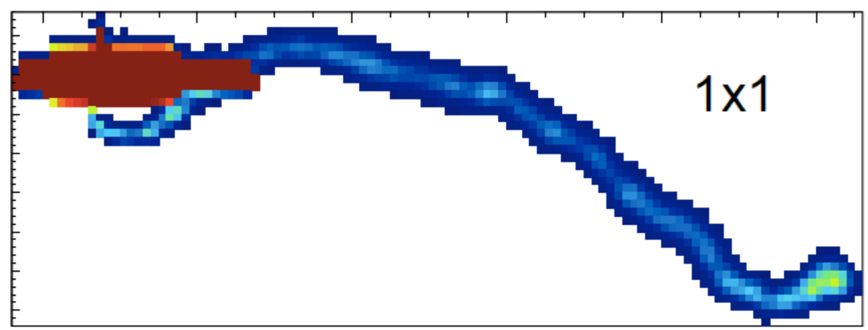
- Hardware adding of neighboring pixels at serial register
  - e.g. 1x100 → 100 rows (y) transferred into serial register before clocking in x (column) direction

→ Fewer pixels but same noise per pixel



Loss of x, y and z information





Dataset

- Cobalt dataset taken early 2016, Americium early 2017
- Single 4k x 2k CCD (2.2 g mass)
- Analysis conducted using 4x4 data (1x1 used for validation)

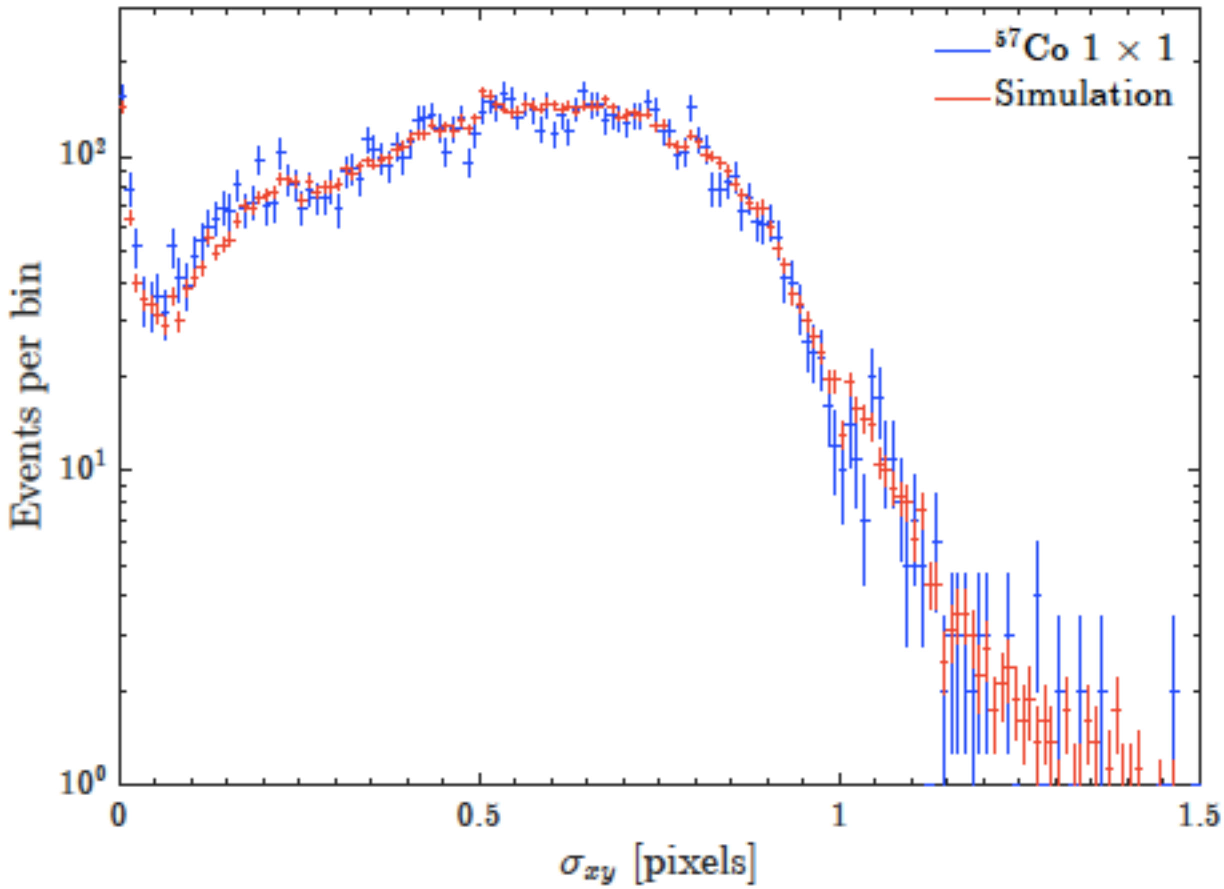
Binning	Source	N images	V_{sub} [V]	Event density [keV^{-1}]
1×1	^{57}Co	1981	45	3.5×10^4
	Background	1235	45	4.3×10^3
	^{241}Am	971	45	4.7×10^4
	Background	2062	45	2.4×10^3
4×4	^{57}Co	1981	127	2.5×10^5
	Background	10276	127	2.6×10^2
	^{241}Am	9828	127	2.5×10^5
	Background	2062	127	1.1×10^3

Image Processing

- Pedestal (DC offset) subtraction → Pixel values centered at 0 with noise σ_{pix}
- Mask "hot" pixels & lattice defects (~10% removed)
- Energy calibration done with fluorescence & P.E peaks
  - Linearity previously demonstrated using this setup
- 1x1 datasets
  - Clustering done by 11x11 moving window maximizing difference in log-likelihood between 2 hypotheses: 2D Gaussian+Noise or just Noise.
- 4x4 datasets
  - Clusters identified as ionization events with contiguous pixels > 4 σ_{pix}

1x1 Diffusion Modeling

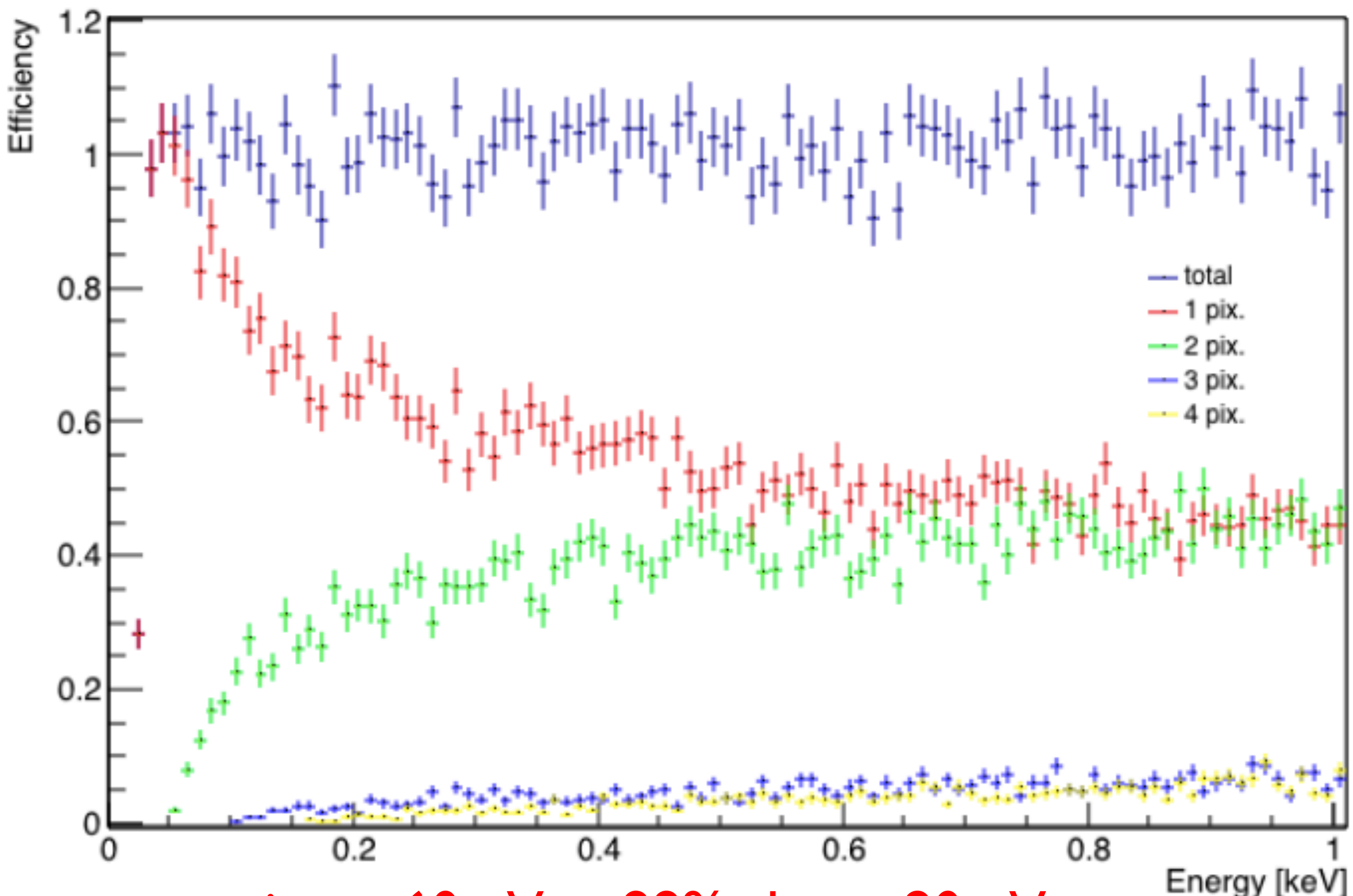
- Simulated events with uniform energy distribution between 0-1 keV and uniform spatial distribution, using diffusion parameters tuned at high energies, and compared to data.



Verifies that recorded spatial distribution is consistent with the signal from Compton scattering, with negligible contamination from surface events.

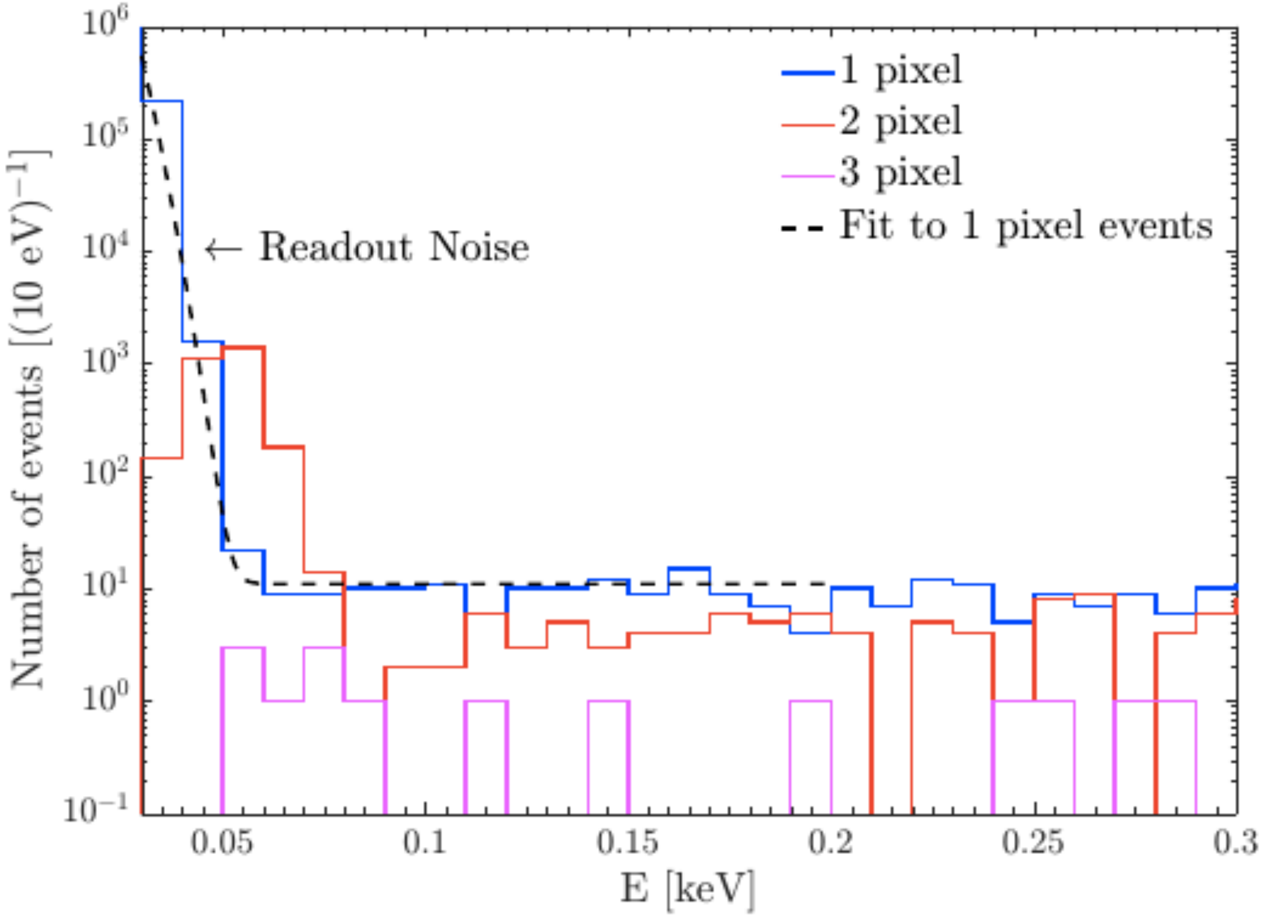
Efficiency

- Based on simulation, able to construct detector efficiency curves



90%+ efficient at energies > 60 eV; > 99% above 80 eV

Pixel Cuts



- Energy threshold chosen to exclude readout noise.
- Negligible single pixel readout noise > 60 eV, but present for 2+ pixels until 80 eV.

Consider only single pixel events between 60-80 eV

"Sensei"

- Repeat measurement in near future
- Non destructive "skipper" readout R&D project.
- Perform N uncorrelated measurements for ~1/Sqrt(N) noise reduction

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