Exercises on LEGEND-200 Energy reconstruction and calibration

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GGI School Theory Meets Experiments: Neutrinoless double beta decay
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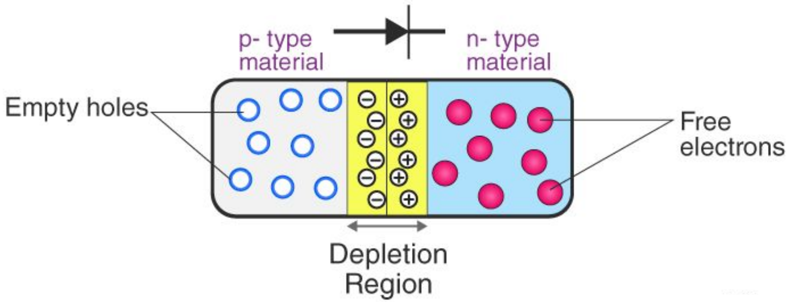
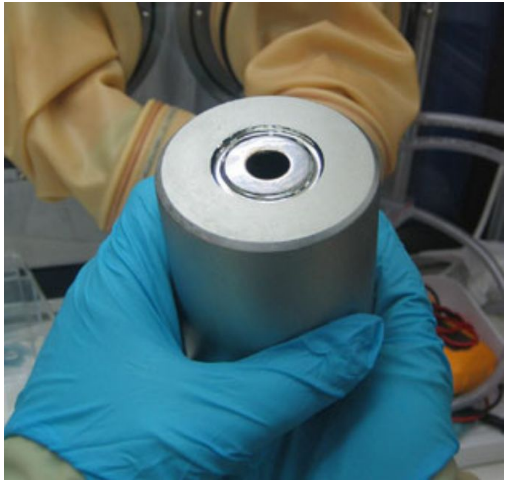
HPGe detectors

- ionization detector (excellent energy resolution, gamma spectroscopy)
- impurity concentration ~10^{-13} atoms/Ge
- the detector work with a **p-n junction** with **n-type (with ^{3}Li)** and **p-type (with ^{5}B)** regions
- the **depletion region** is the active region of the detector; with **Reverse Bias** is extended to the entire volume (high voltage ~kV)
- particles entering the active region release energy, producing:

$$N = E / \eta \quad \rightarrow \quad Q = E\,e / \eta$$

in Ge η = 2.96 eV, with E = 1 MeV, we have
N = 3 x 10^5 (Q = 54 fC)



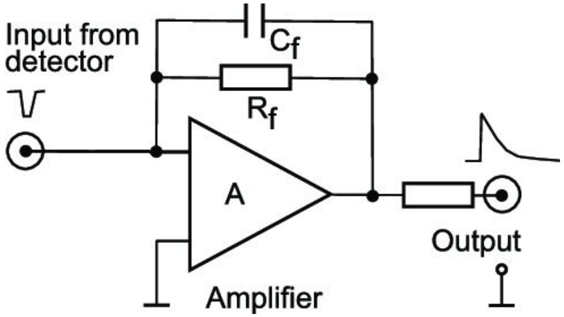


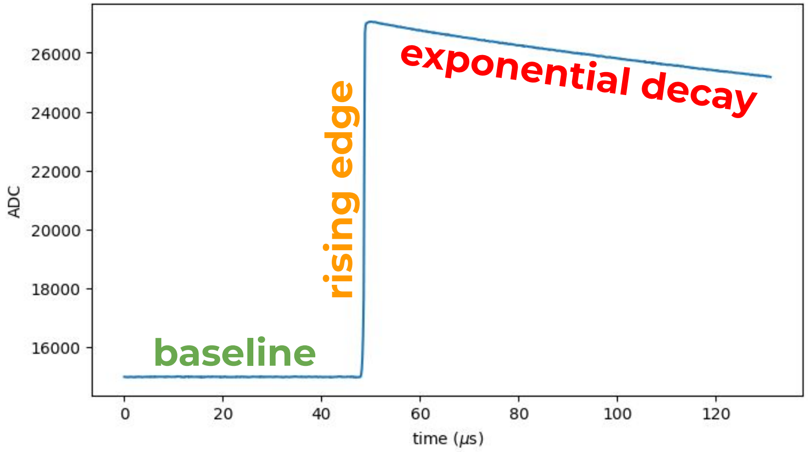
HPGe detectors read-out

- HPGe detector signals are read-out by a **charge sensitive preamplifier** that generate a **voltage output signal** with amplitude proportional to **input charge**
- **feedback capacitor C_F** integrate the charge and generate a fast signal
- **feedback resistor R_F** restore voltage to initial value; exponential decay with $\tau = C_F R_F$

$$V(t) = Q / C_F \exp(-t / \tau)$$

with C_F = 0.4 pF and Q = 54 fC → V_{MAX} = 135 mV





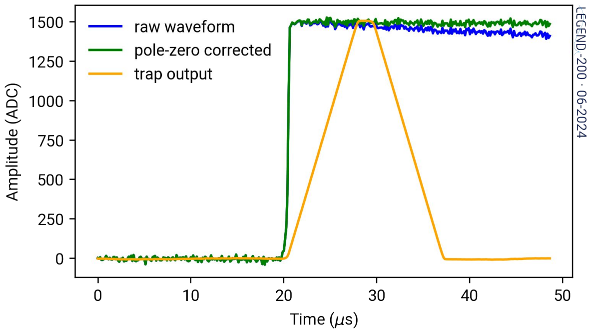
- the preamplifier output is then digitized with **Analog-to-Digital Converter (ADC)**
- main ADC specifications are **bit resolution** and **sampling rate** (in L-200: 14 bits and 62.5 MHz sampling)
- typical L-200 signal: **fast signal rise** (~40-200 ns) and **exponential decay** with τ = 400 μs (R_F = 1 GΩ and C_F = 0.4 pF)

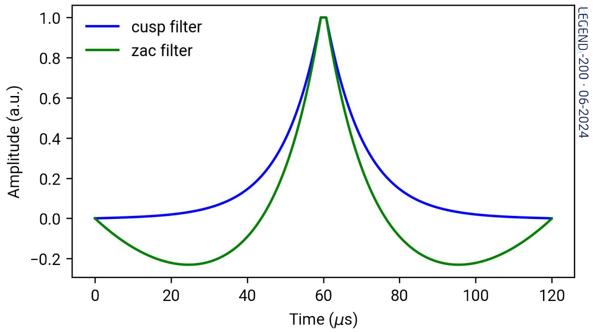
Energy Reconstruction for HPGe detectors

- **digital signal processing (DSP)** is needed to properly extract the energy released in the detector, there are many DSP techniques
- basic processing, e.g. **moving average** (replace each point with the average of a subset of data points within a defined window)
- filtering by performing a discrete convolution (**x[n]** input signal, **h[*n*]** filter, **y[n]** filtered signal)

$$\mathbf{y[n] = (x*h)[n] = \sum_k x[k] \cdot h[n-k]}$$

- commonly used filter are **trapezoidal** and **cusp**, several methods exists, also methods to build optimum filters (for more details about DSP: EPJC 75, 255 2015, EPJC 83, 149 2023)





Proposed Tasks and Provided Material

Task 1: Energy Calibration
Task 2: Calculation of Energy Resolution at $Q_{\beta\beta}$
Task 3: Process Waveforms and Find Best Shaping Filter

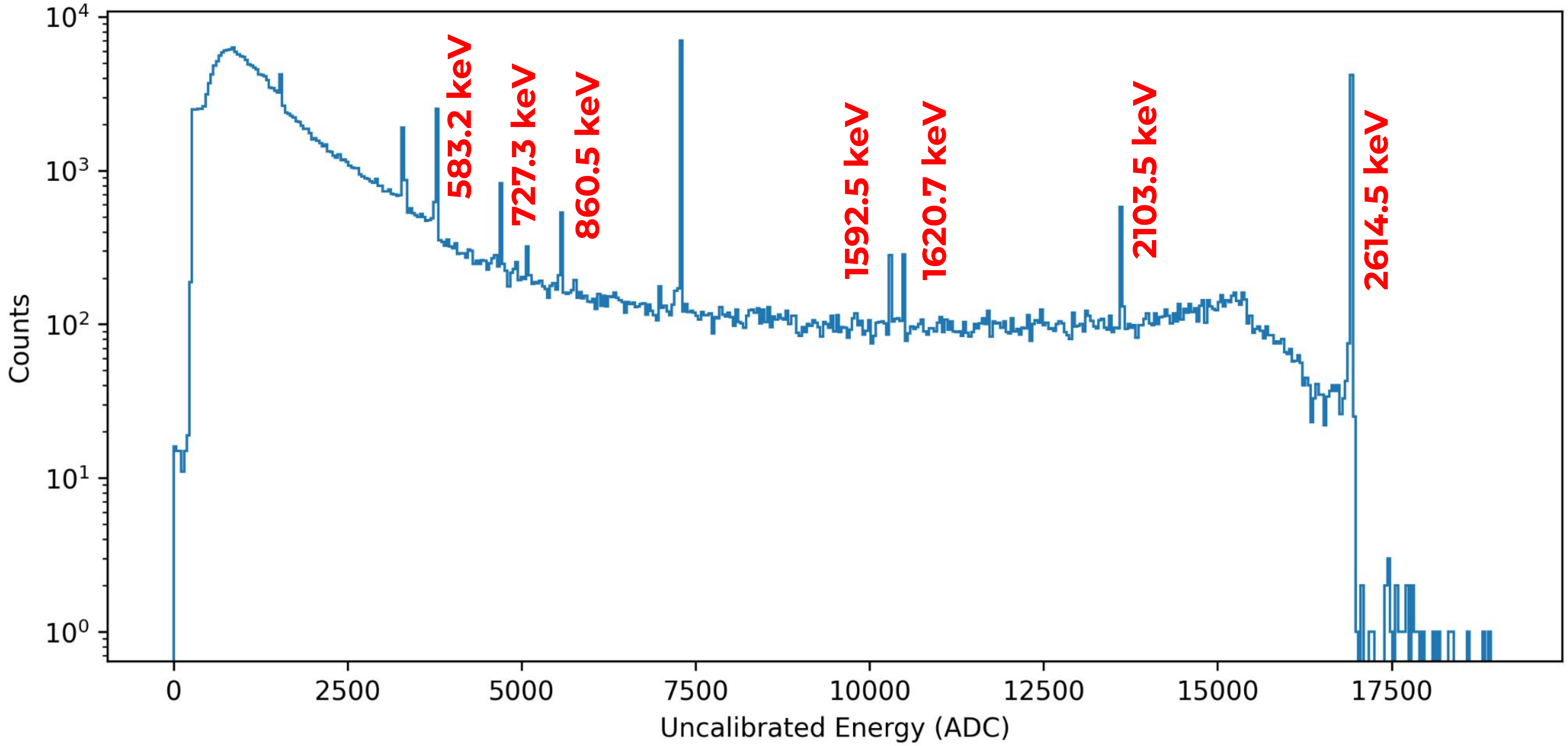
Material:

- jupyter notebook with tutorial ("legend200-exercises-part1.ipynb")
- **data in LH5 format** for two LEGEND-200 detectors (BEGe named B00032B and ICPC named V02160A):
  - **tier1** data with raw waveform (~1 GB/detector), link to download
  - **tier2** data with uncalibrated energy (~ MB) in the shared folder

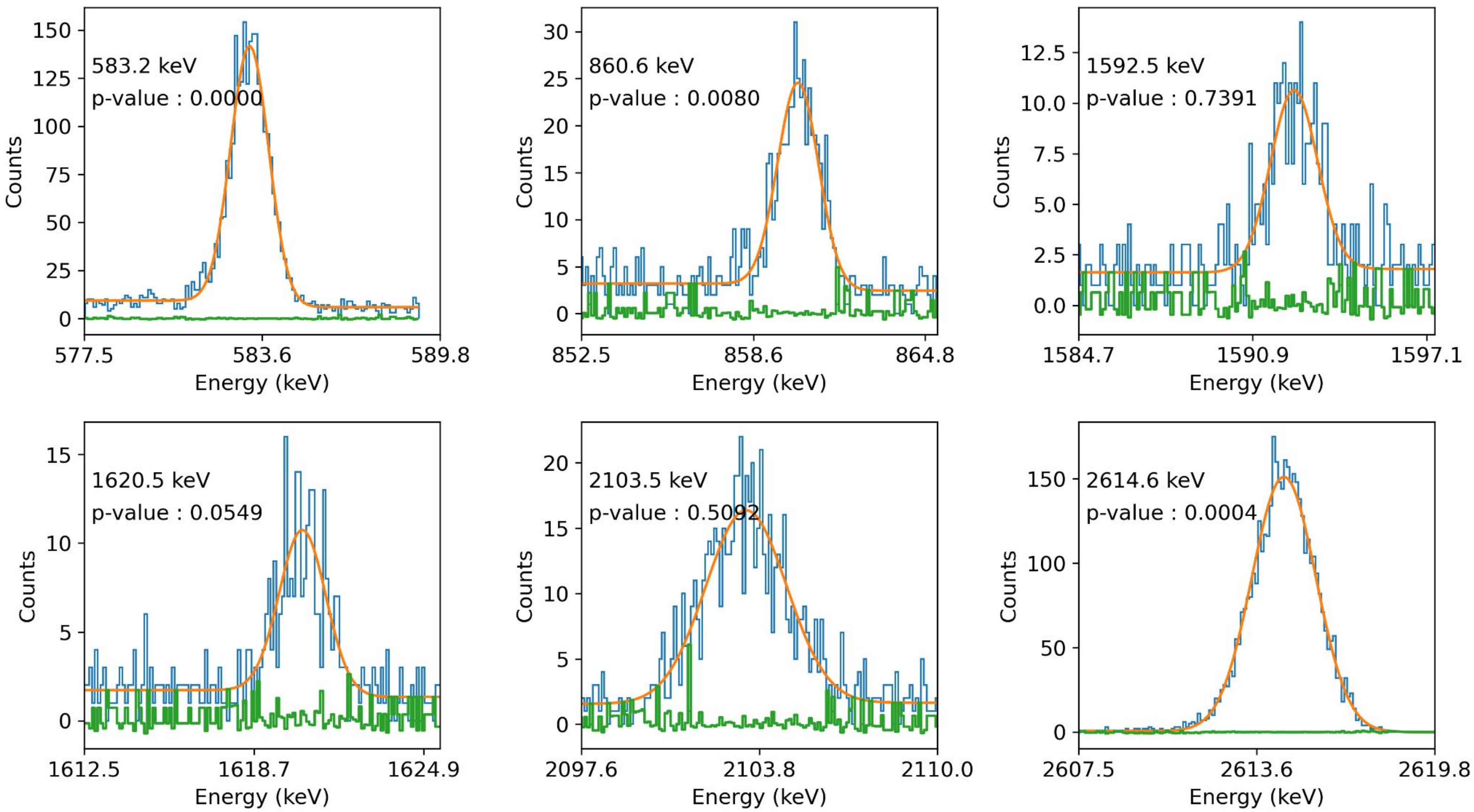
TASK 1
Energy calibration

1. Produce uncalibrated ^{228}Th spectrum
2. Find ^{228}Th peaks and calculate the position
3. Calibration curve and produce calibrated spectrum

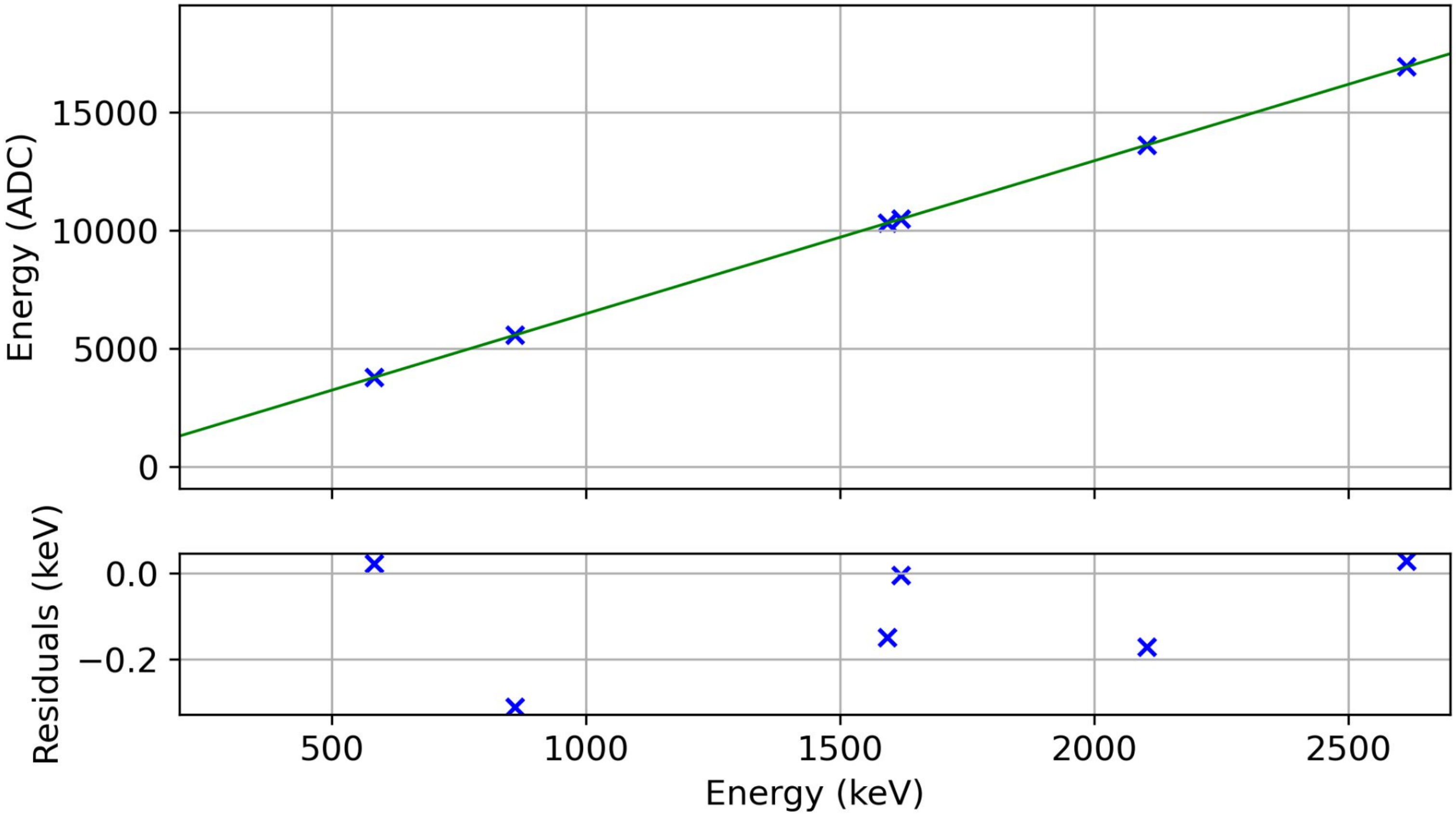
Uncalibrated ^{228}Th spectrum



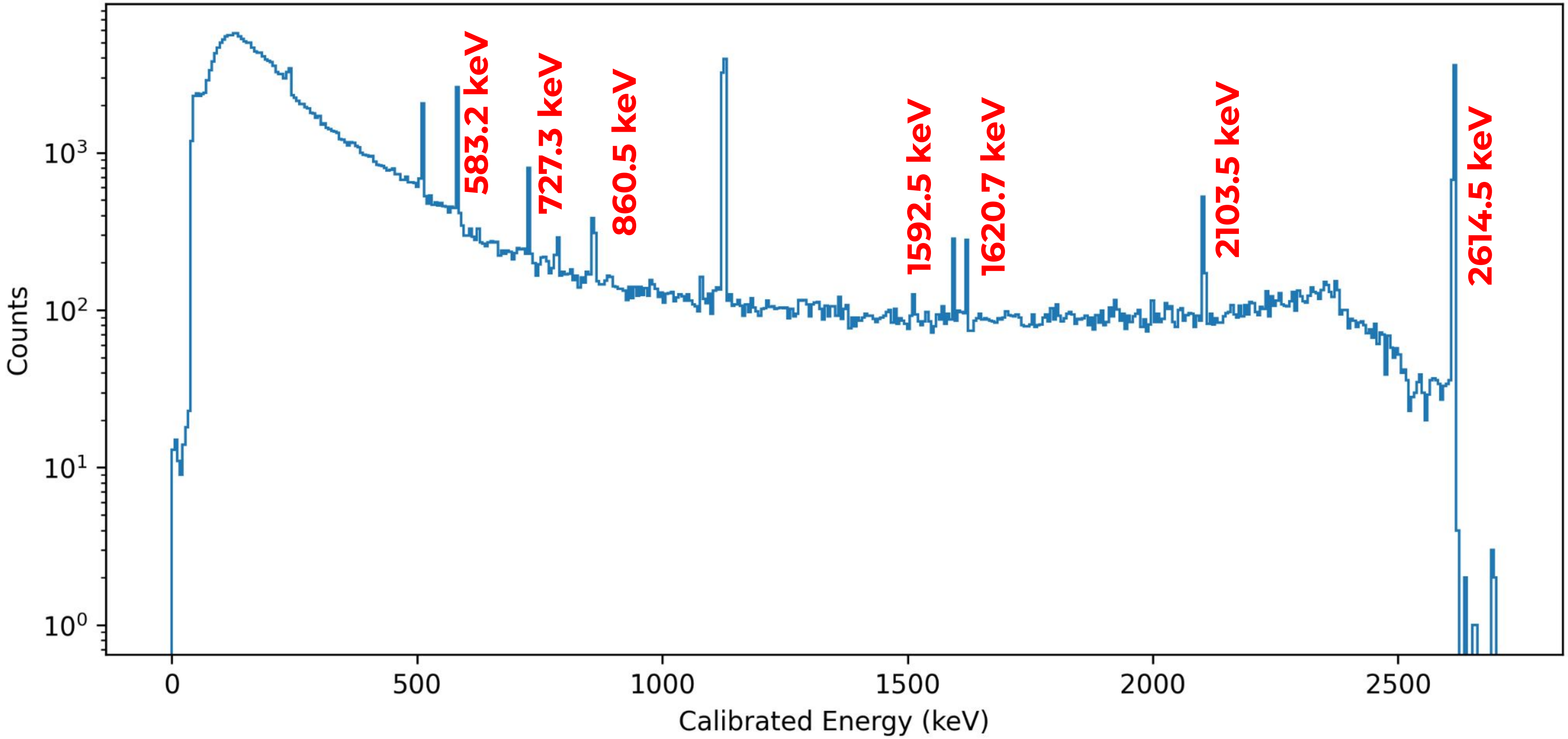
^{228}Th calibration peaks



Calibration Curve



Calibrated ^{228}Th spectrum



TASK 2
Calculate Energy Resolution at $Q_{\beta\beta}$

1. Fit ^{228}Th peaks on calibrated spectrum
2. Calculate the FWHM of each peak
3. Fit the results with the resolution curve and find the FWHM at $Q_{\beta\beta}$

HPGe detectors energy resolution

$$\Delta E^2 = \Delta E^2_{el} + \eta\, F\, E + c\, \cancel{E^2}$$

electronic noise
(not energy dependent)
0.7 - 1.2 keV

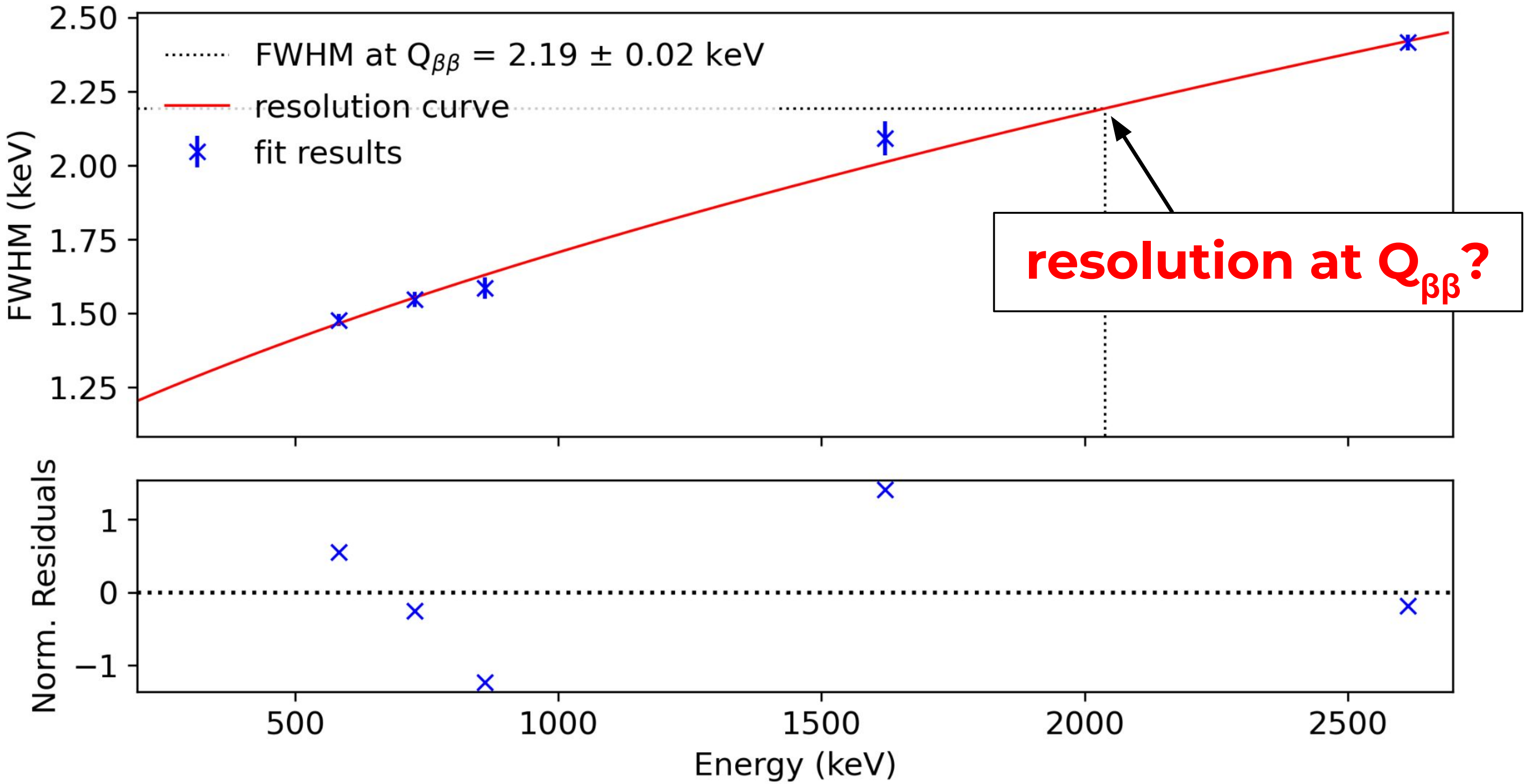
fluctuation of e^--h^+ pairs number in charge production process
(F = 0.11-0.15 Fano factor, η = 2.96 eV)

detector charge collection
(negligible for fully depleted detectors)

$$\mathrm{FWHM} = \sqrt{(\mathrm{FWHM}^2_{el} + 2.355\, \eta\, F\, E)}$$

function to fit the FWHM vs energy

Resolution Curve $Q_{\beta\beta}$ = 2039 keV



TASK 3
Process Waveforms and Find Best Shaping Filter

1. Open raw waveforms
2. Apply a filter and calculate uncalibrated energies
3. Find the best shaping time by optimizing the FWHM of 2614.5 keV peak

Process Waveforms and Optimization

1. convolve the raw waveform with a filter (can be done by using pygama)
2. select the events of the peak at 2614.5 keV
3. optimization loop for the shaping parameter (between 1 and 25 μs)
4. select the shaping time that is giving the best resolution at the 2614.5 keV peak