

PASSAGE OF THE YEAR

Low temperature data processing with OCTOPUS



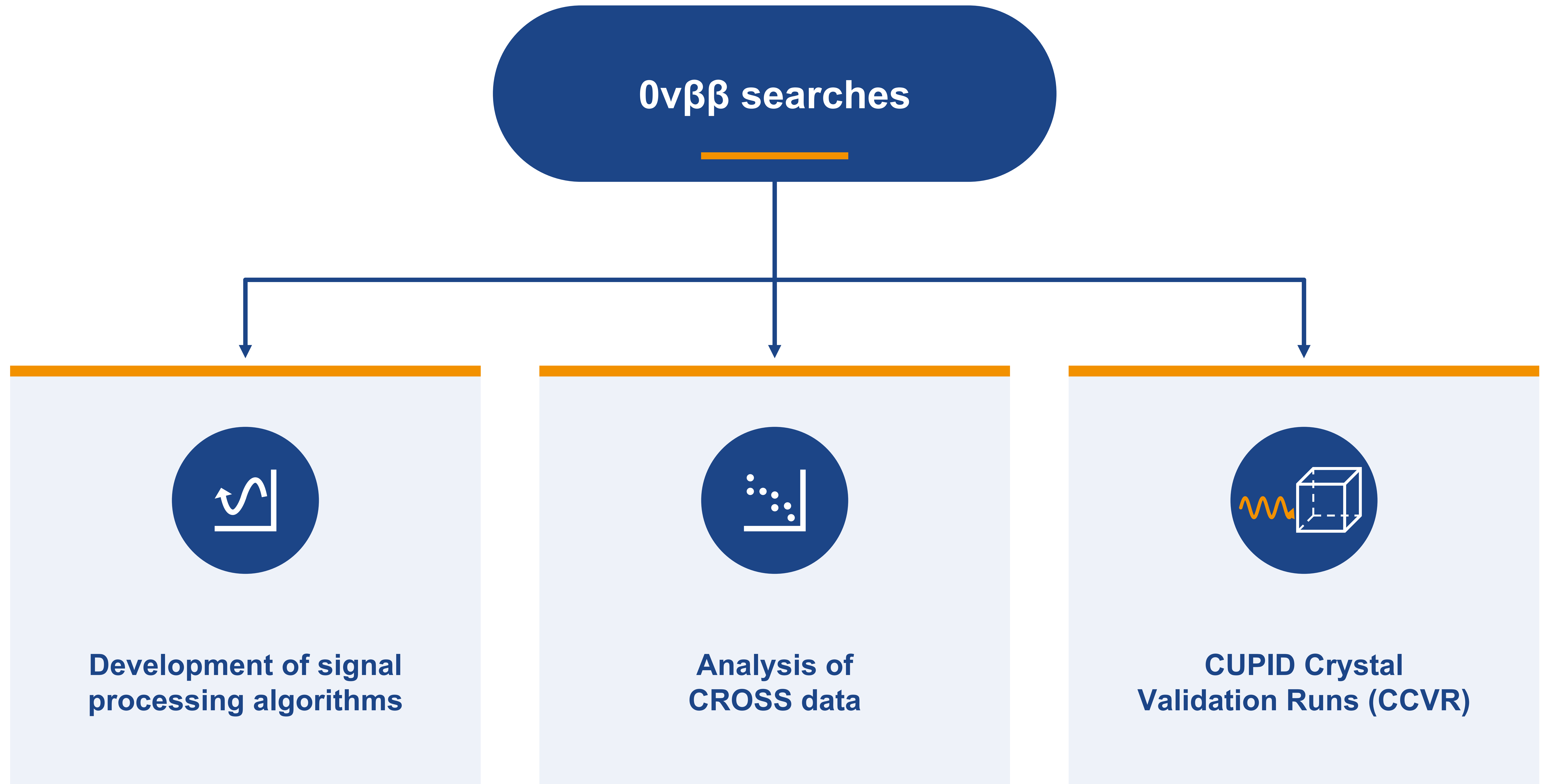
Leonardo Perna

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Advisor: Giovanni Benato



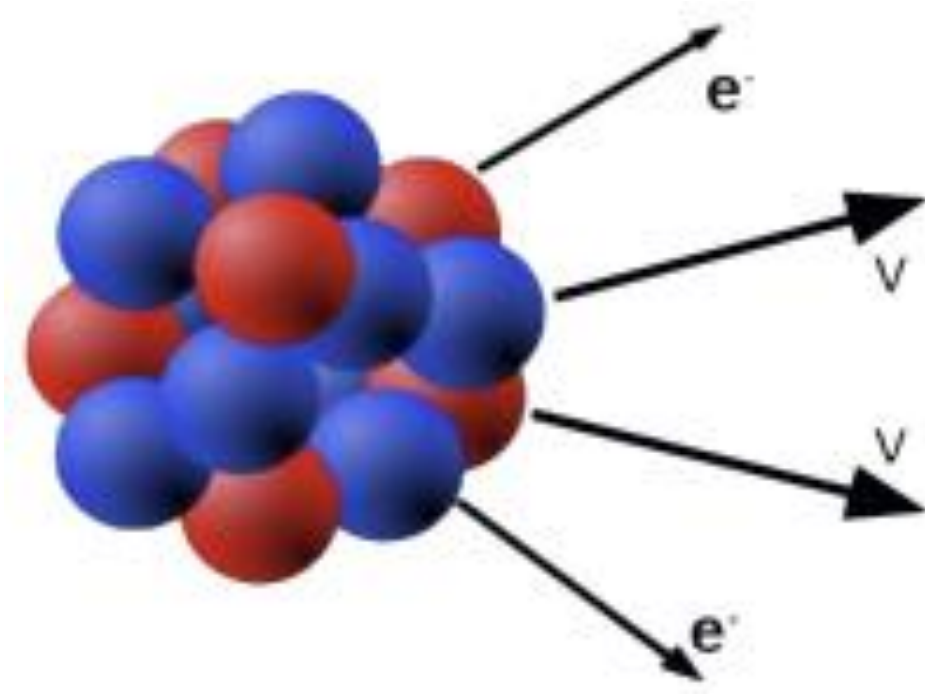
Overview



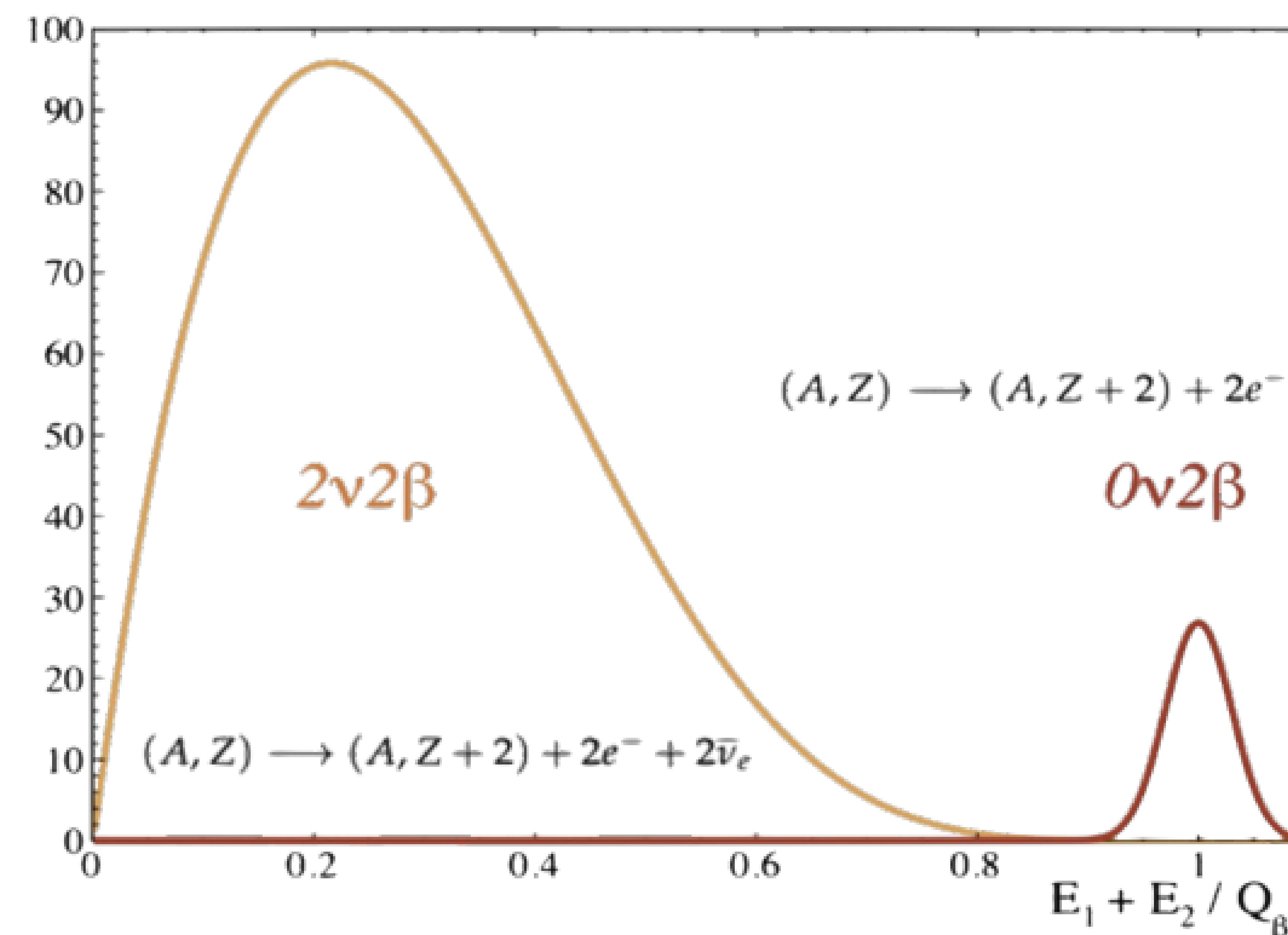
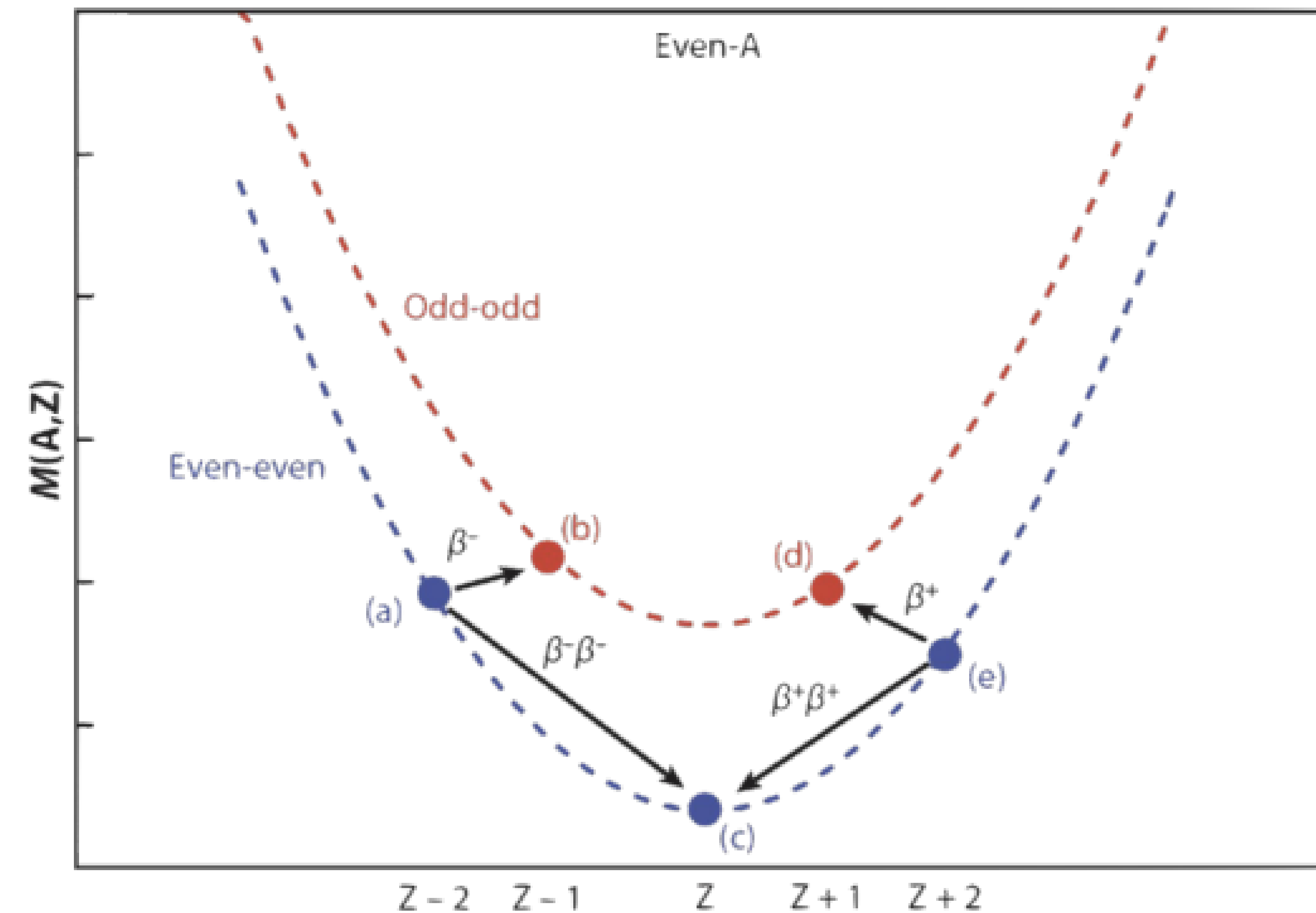
Double beta decay

Double beta decay: rare second-order weak process in which a nucleus undergoes two **simultaneous** beta decays

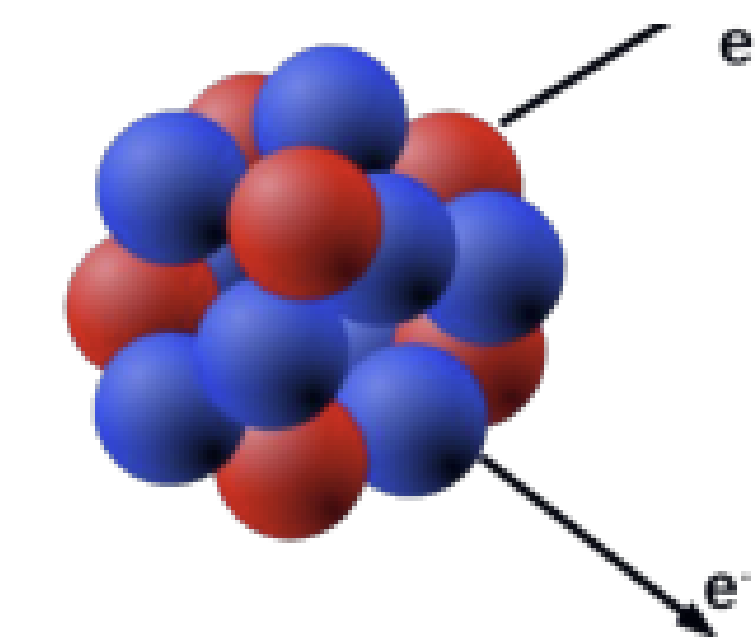
$2\nu\beta\beta$



- Allowed by the Standard Model for even-even nuclei ($\Delta L = 0$)
- First direct **observation** in 1987 in ^{82}Se
- Half-life $T_{1/2} \approx 10^{18} - 10^{24}$ yr
- Signature: **continuous spectrum** from 0 up to $Q_{\beta\beta}$



$0\nu\beta\beta$

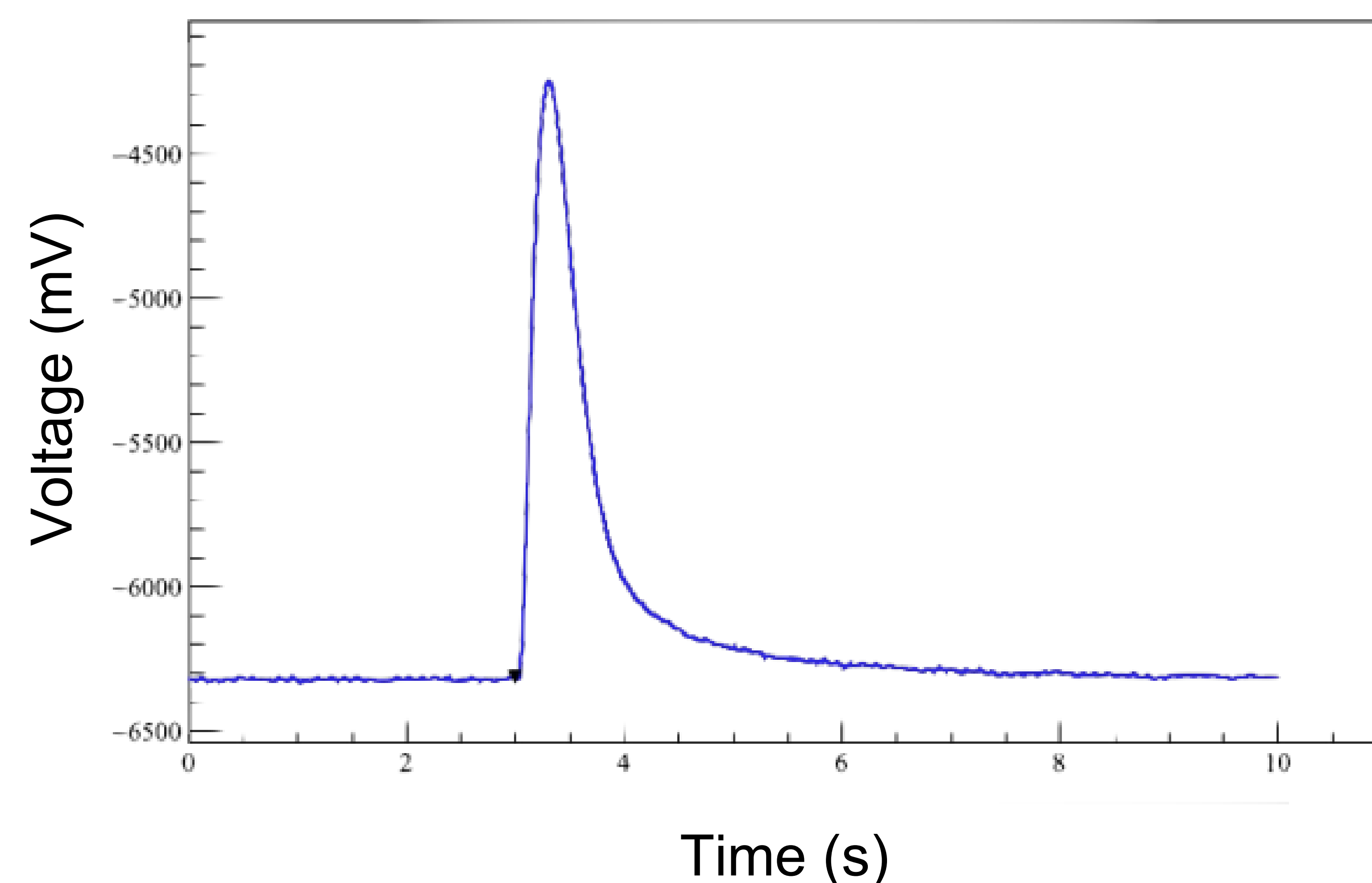
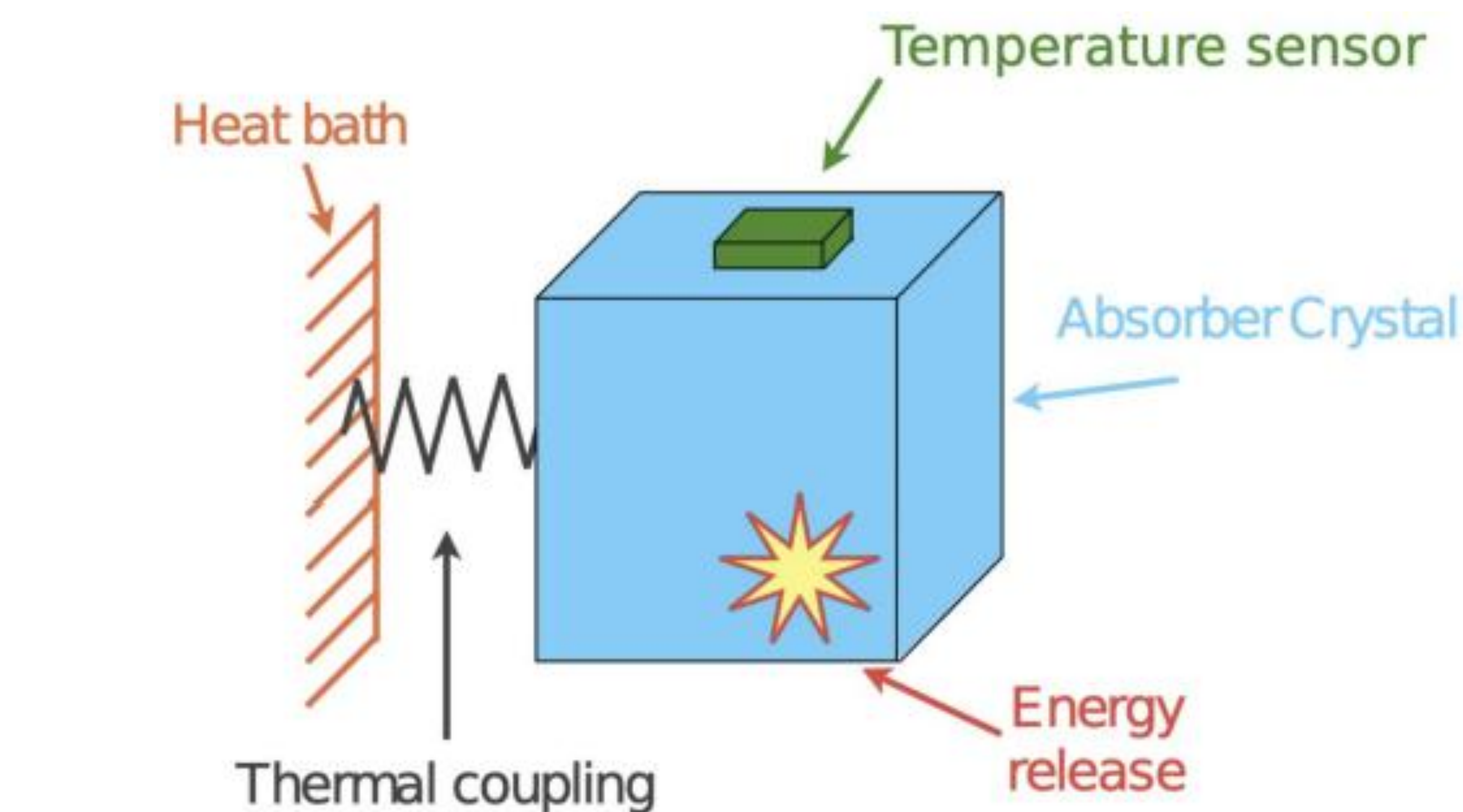


- **Violates** lepton number conservation ($\Delta L = 2$)
- **No experimental evidence** up to now
- Half-life $T_{1/2} > 10^{24} - 10^{26}$ yr
- Signature: **peak at $Q_{\beta\beta}$**
- Could play an important role in the **matter-antimatter asymmetry**

Cryogenic calorimeters

The energy deposited by particles is converted into **phonons**

→ Through a **sensor** (Ge-thermistor) the heating of the absorber is measured



- The absorber is operated at approximately **10 mK**
- **Slow** signal response (timescale of ~ 1 s)
- **Excellent** energy resolution (FWHM $\approx 0.1\%$) at $Q_{\beta\beta}$
- **$\beta\beta$ source** is **embedded** within the detector (high detection efficiency)
- Wide choice of absorber **materials**, allowing the use of different **$\beta\beta$ isotopes**
- **Scalable** technology (ton-scale experiment)

Purpose

- “Open-source” **C++** software that **reconstructs events** from cryogenic calorimeter data
- Serves both fast **R&D measurements** and **large-scale** campaigns: official software of **CROSS** and **CUPID**

Structure

- Pipeline split into **modules**, each running **one algorithm** and deriving from a common base class responsible for the interface to the input and output files
- Users chain modules in a **TOML** file (text file)

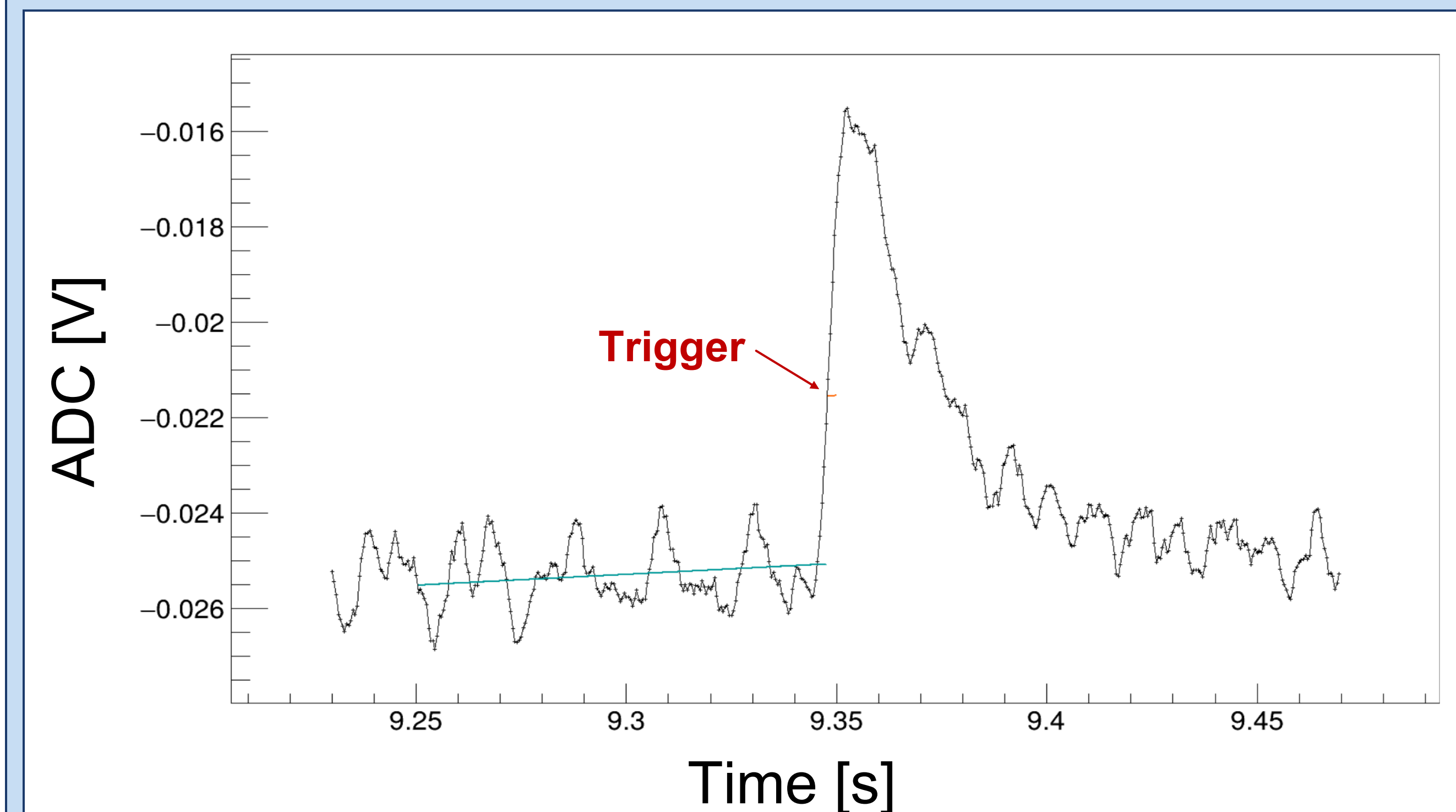
Technical details

- **C++20**, built with **CMake** on Linux and macOS; output in **ROOT** format
- Digital **trigger**, **optimum filter** amplitude, pulse-shape cuts and **energy calibration**

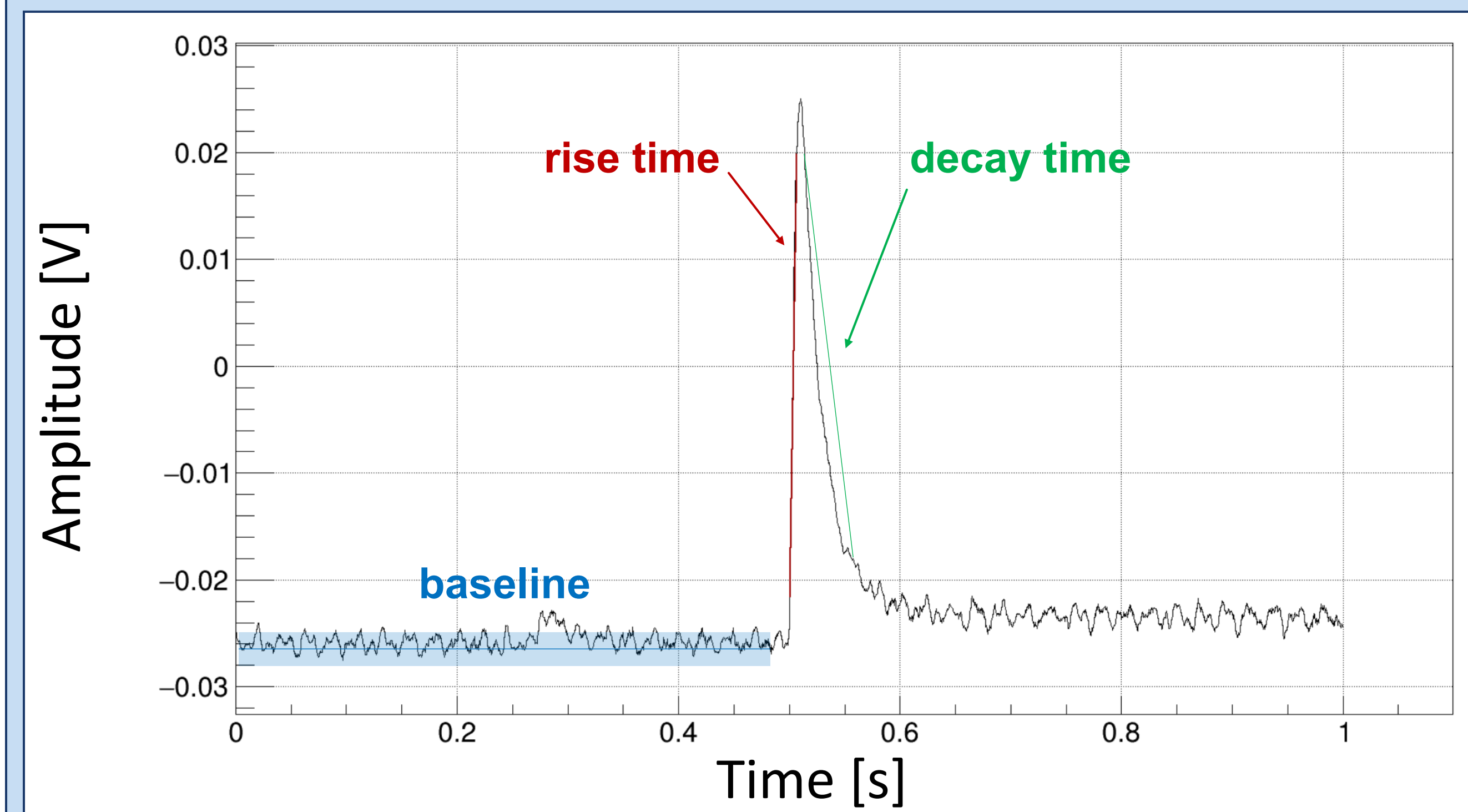
```
src
├── GUI
├── Legacy
├── Macros
├── analysis
│   ├── base
│   ├── deprecated
│   ├── driver
│   ├── modules
│   ├── CMakeLists.txt
│   └── update_modules.cmake
├── datahandlers
├── filters
├── main
├── octo
├── optimalfilter
├── toml
├── trigger
│   ├── base
│   ├── driver
│   ├── triggermodules
│   └── CMakeLists.txt
├── utils
└── CMakeLists.txt
```

Processing pipeline

Trigger and basic pulse parameters

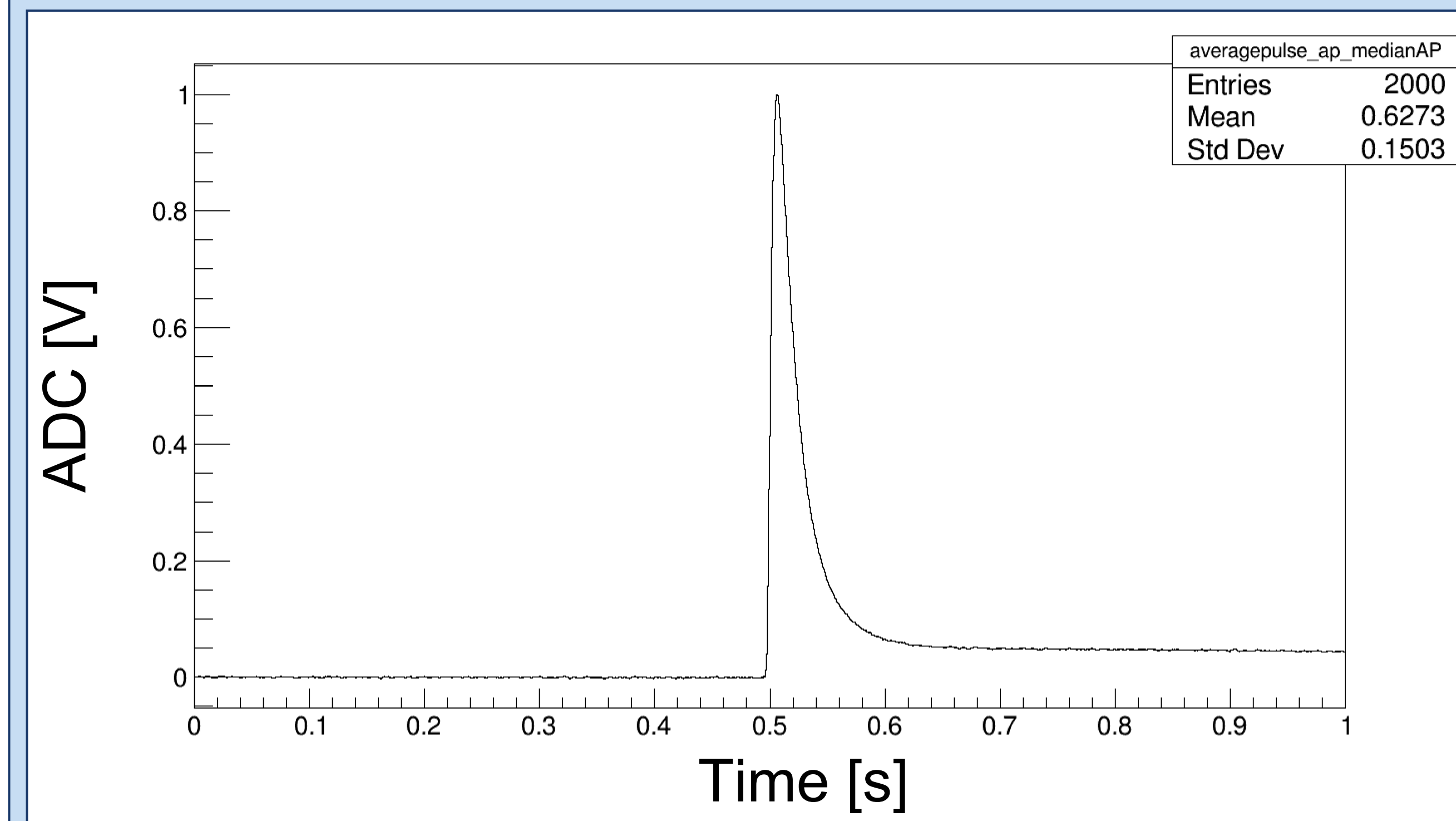


Linear interpolation trigger

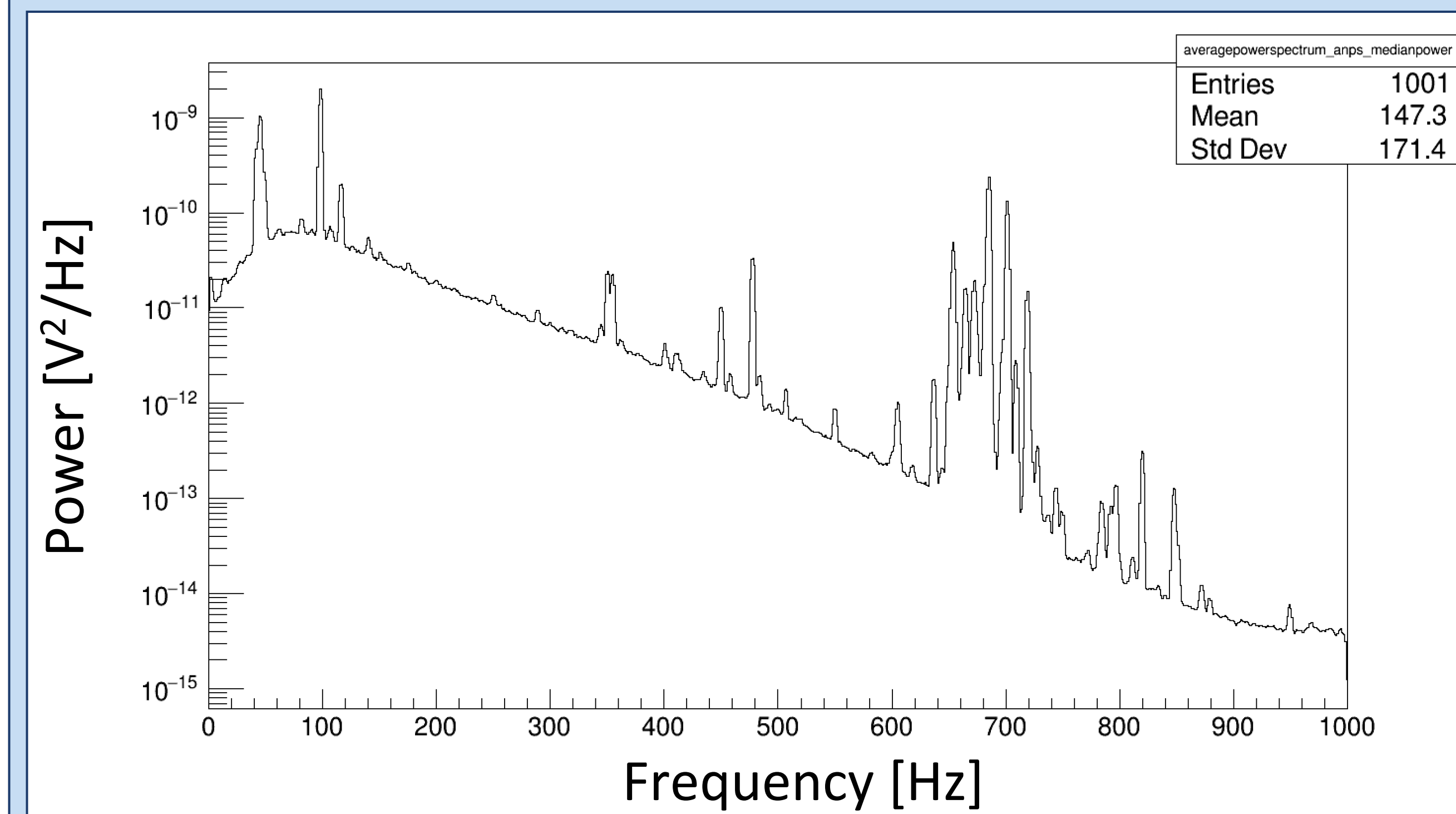


Baseline, rise time and decay time

Average Pulse (AP) and Average Noise Power Spectrum (ANPS)

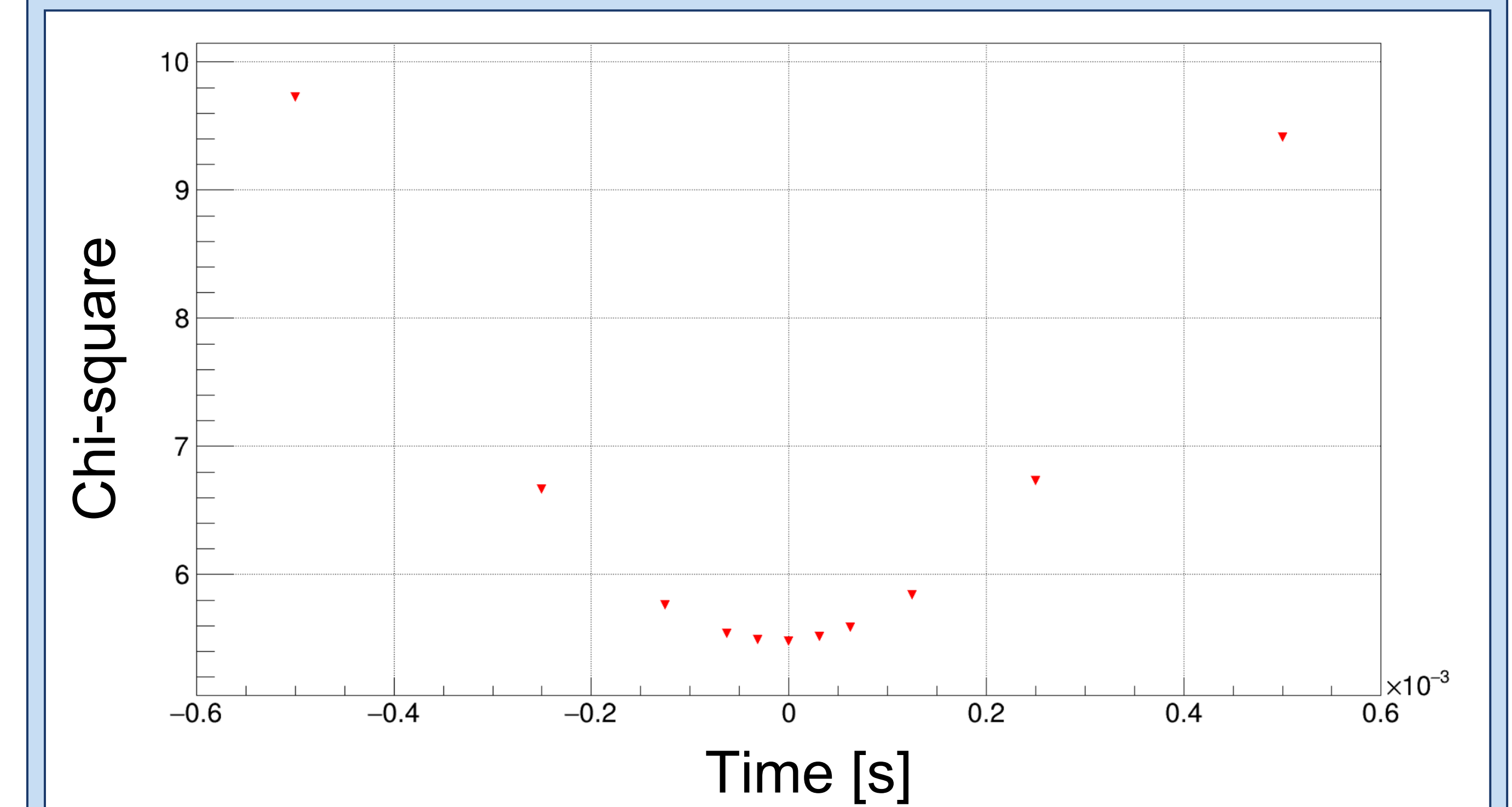


AP

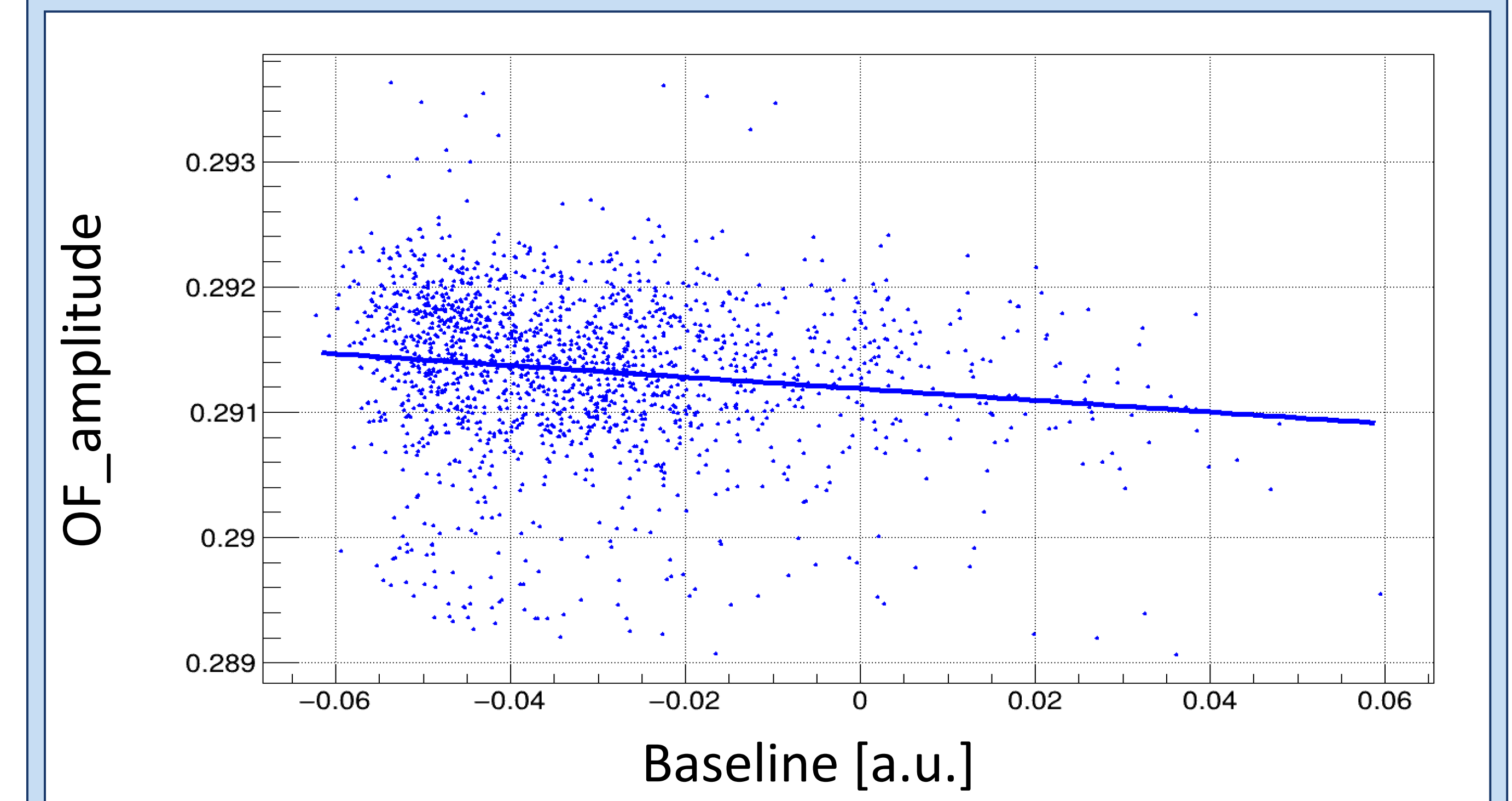


ANPS

Amplitude reconstruction with Optimum Filter (OF) and stabilization



OF χ^2 minimization



Stabilization

Optimum Filter amplitude

$$\chi^2 = \sum_f \text{Re} \left[\frac{S(f) - \mathbf{A} \bar{S}_f e^{-i\omega \delta t}}{N_F^2} \right] \quad \chi^2 \text{ minimized over } \delta t \rightarrow \text{best-fit amplitude } \mathbf{A}$$

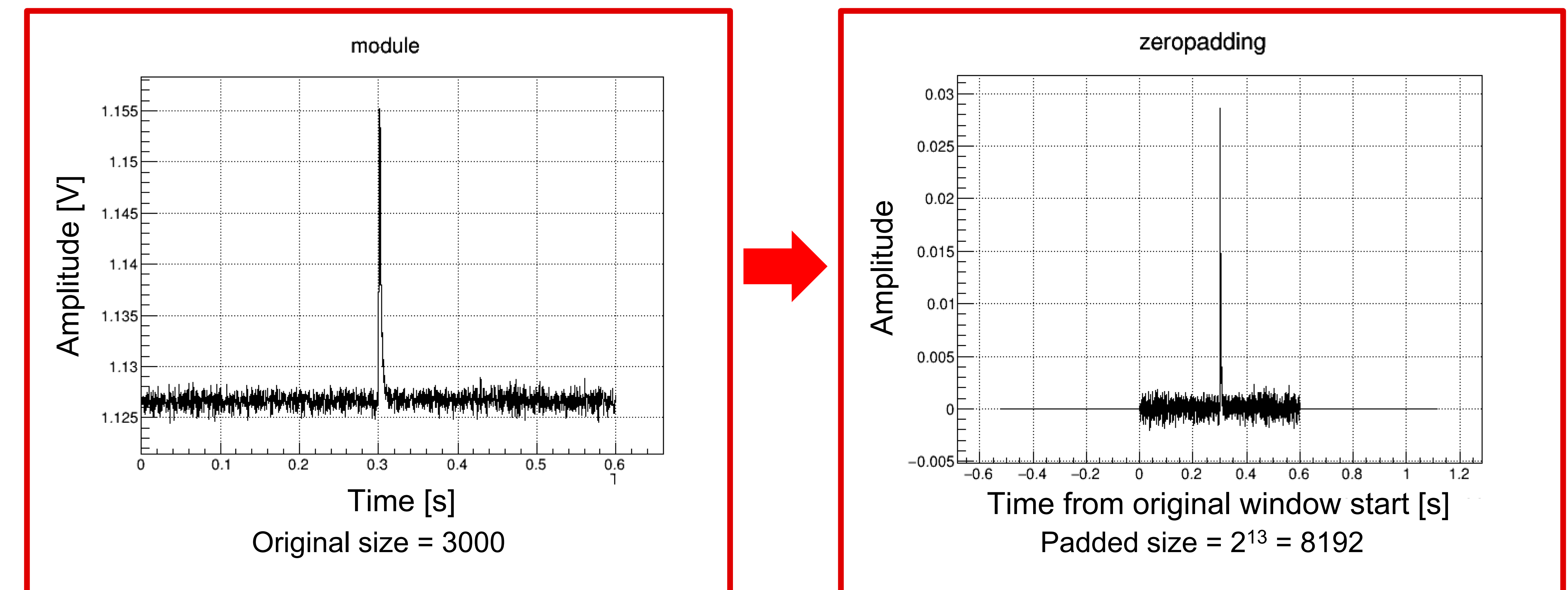
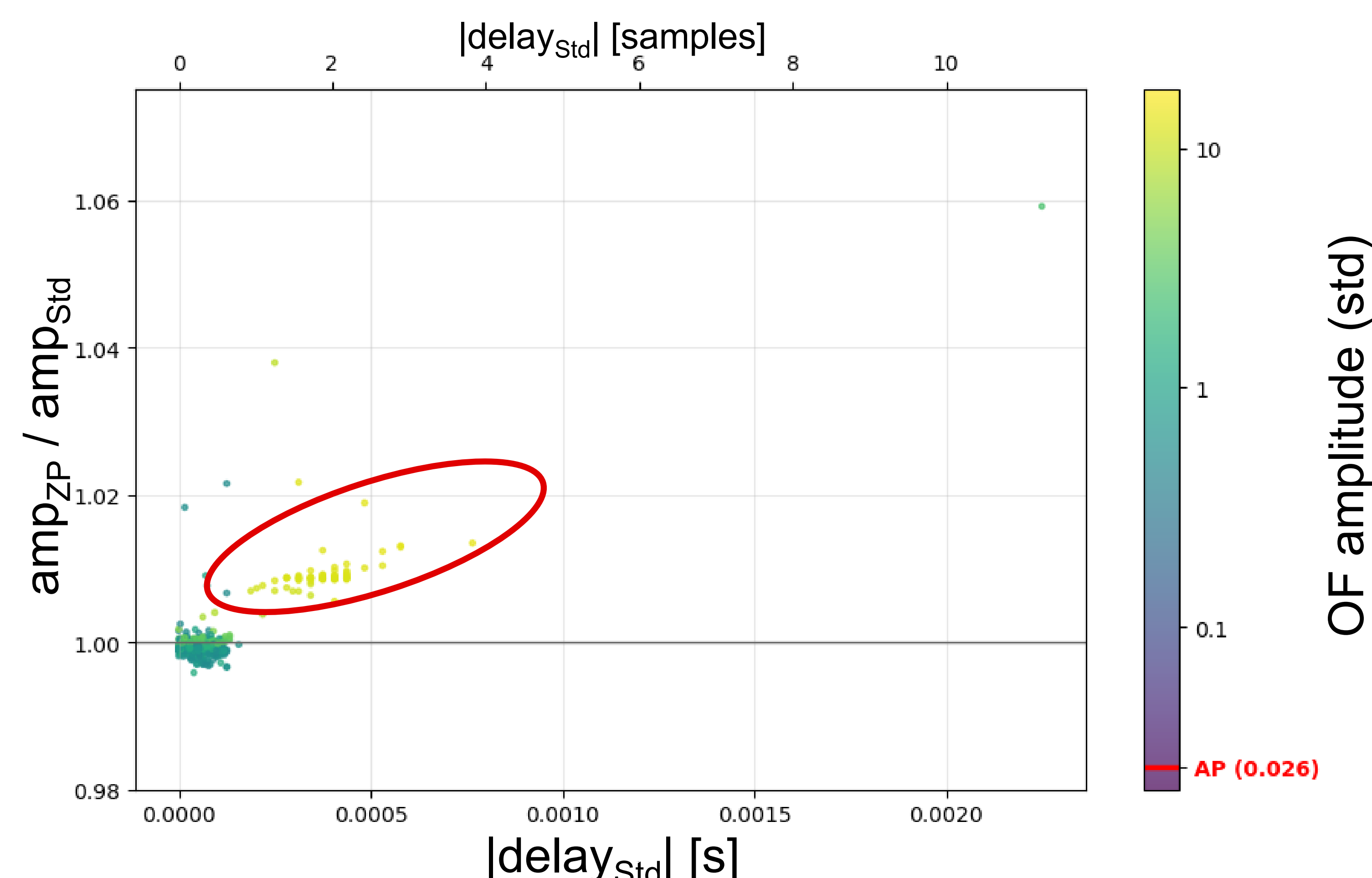
Task 1: Maintenance, development & debug

Newly implemented algorithms

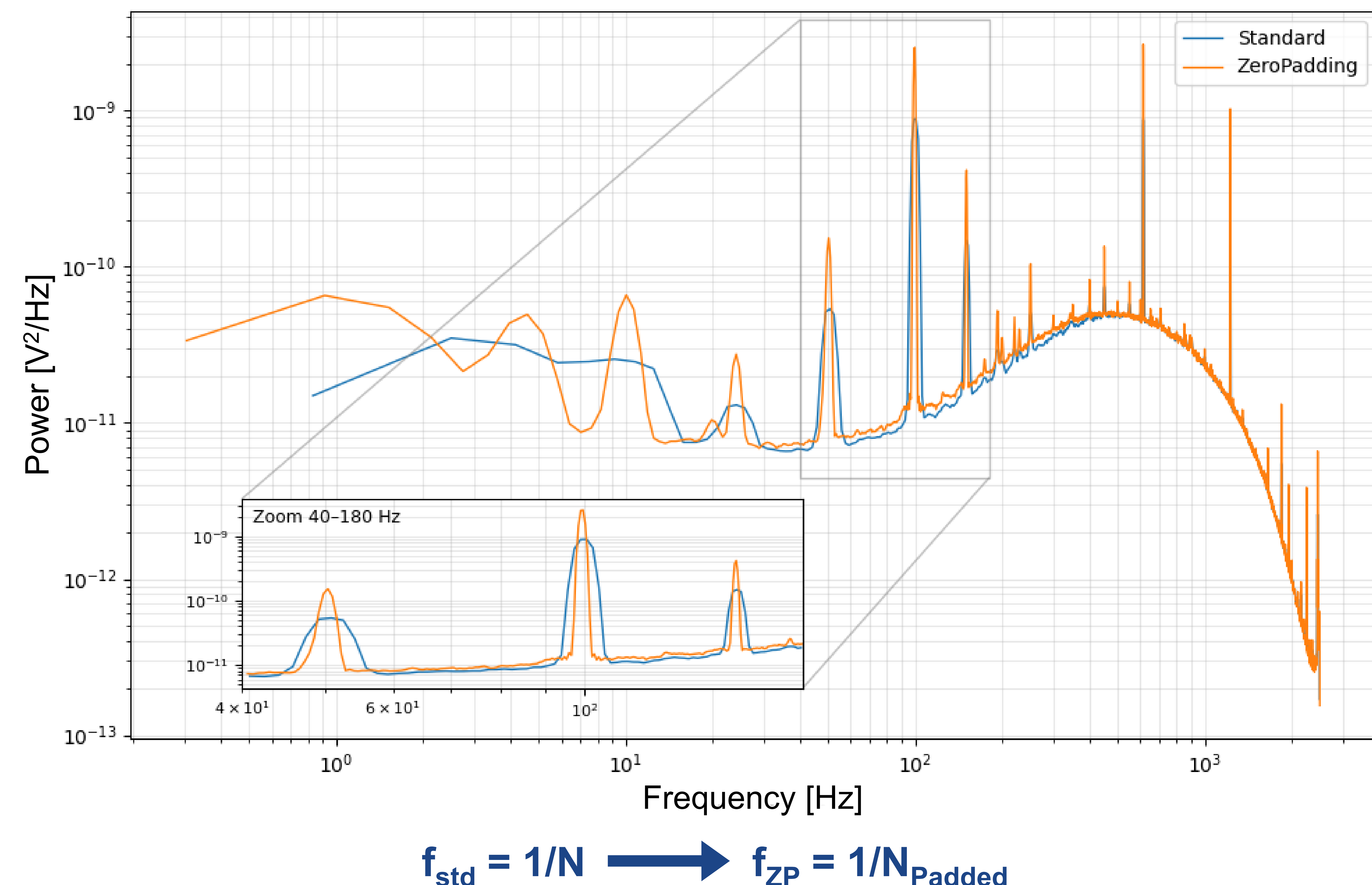
➤ Zero padding module:

- Padded length: smallest power of two (n_{clos}) greater than twice the waveform length ($N_{\text{pad}} = 2^{n_{\text{clos}}}$). Zeros added symmetrically on both sides
- Avoids DFT wrap-around artefacts in frequency-domain, critical for high-energy and non-recovering events
- The chosen length speeds up FFT algorithms
- Allows a more precise energy determination

**The larger the delay, the larger the padding correction:
without padding, the time shift ($e^{-i2\pi f t}$) wraps around
circularly**



Average power spectrum

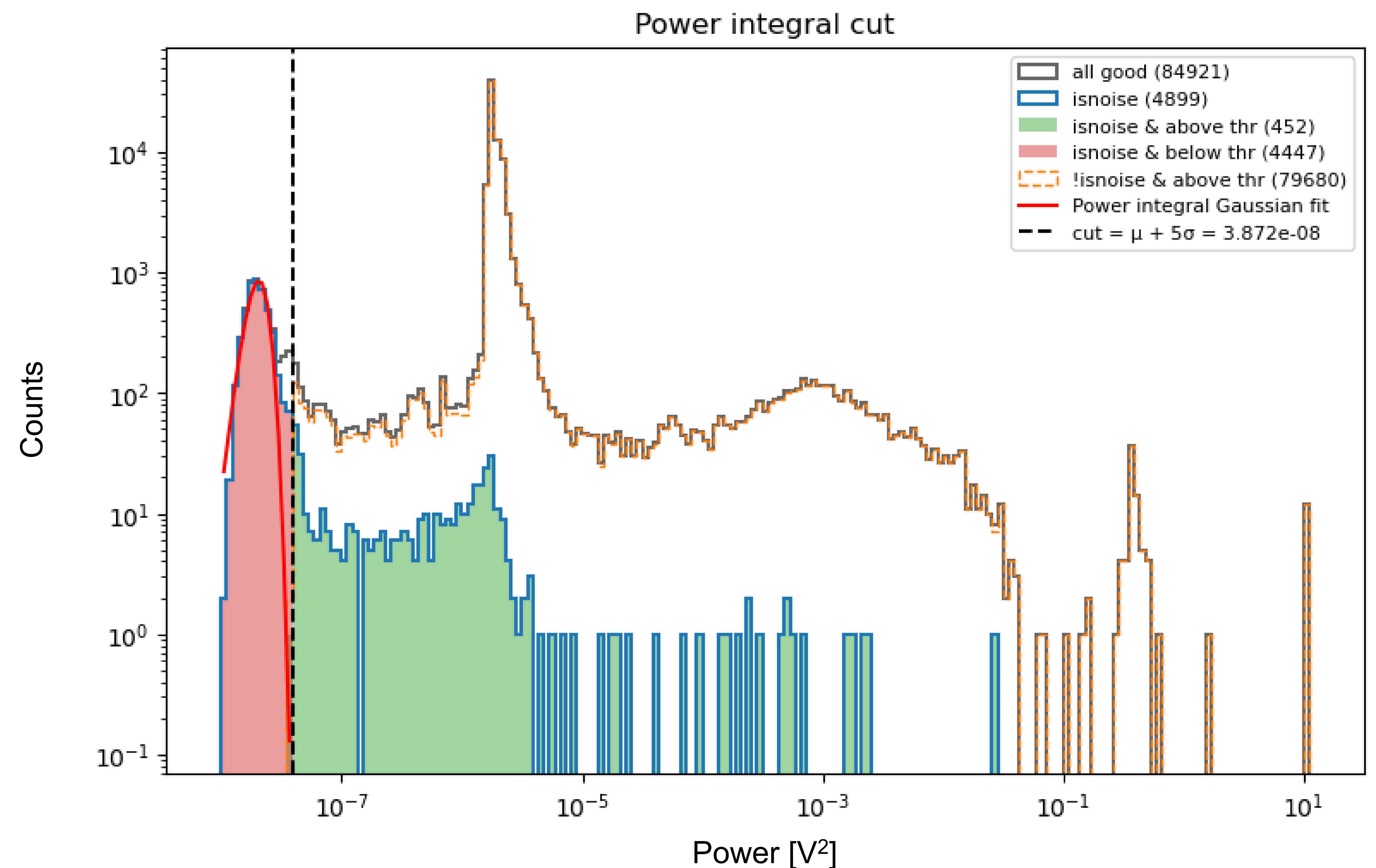
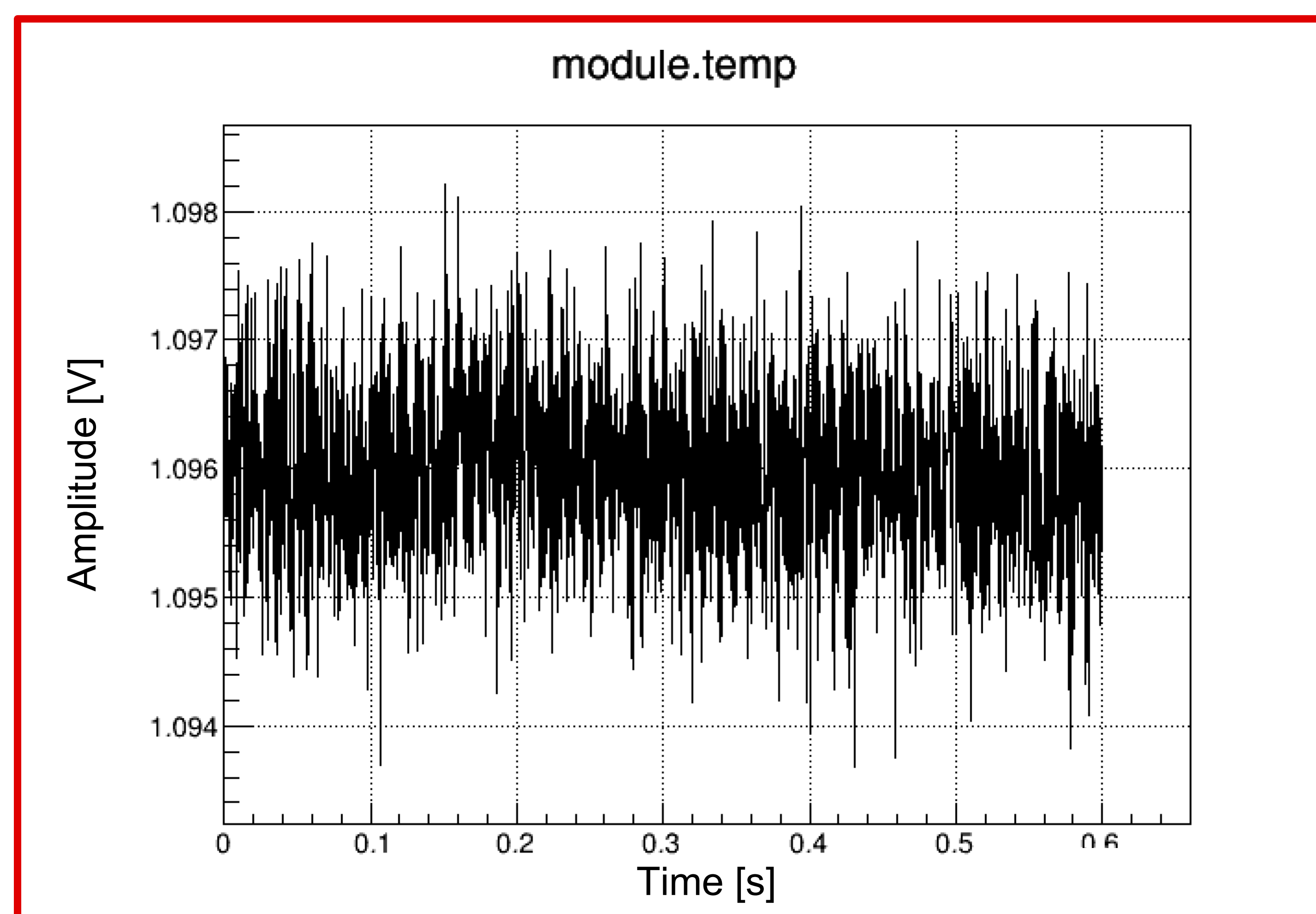


Task 1: Maintenance, development & debug

Newly implemented algorithms

- Zero padding module
- **Power Integral Noise rejection**
 - Motivation: $\text{Power} \propto A^2$, where A is the WF amplitude
 - Fitted power integral noise peak
 - Cutoff value set at $(\mu + 5\sigma)$ by default
 - Removes spurious triggers on the noise

**Signal event triggered on noise.
Rejected using the cut**



Task 1: Maintenance, development & debug

Newly implemented algorithms

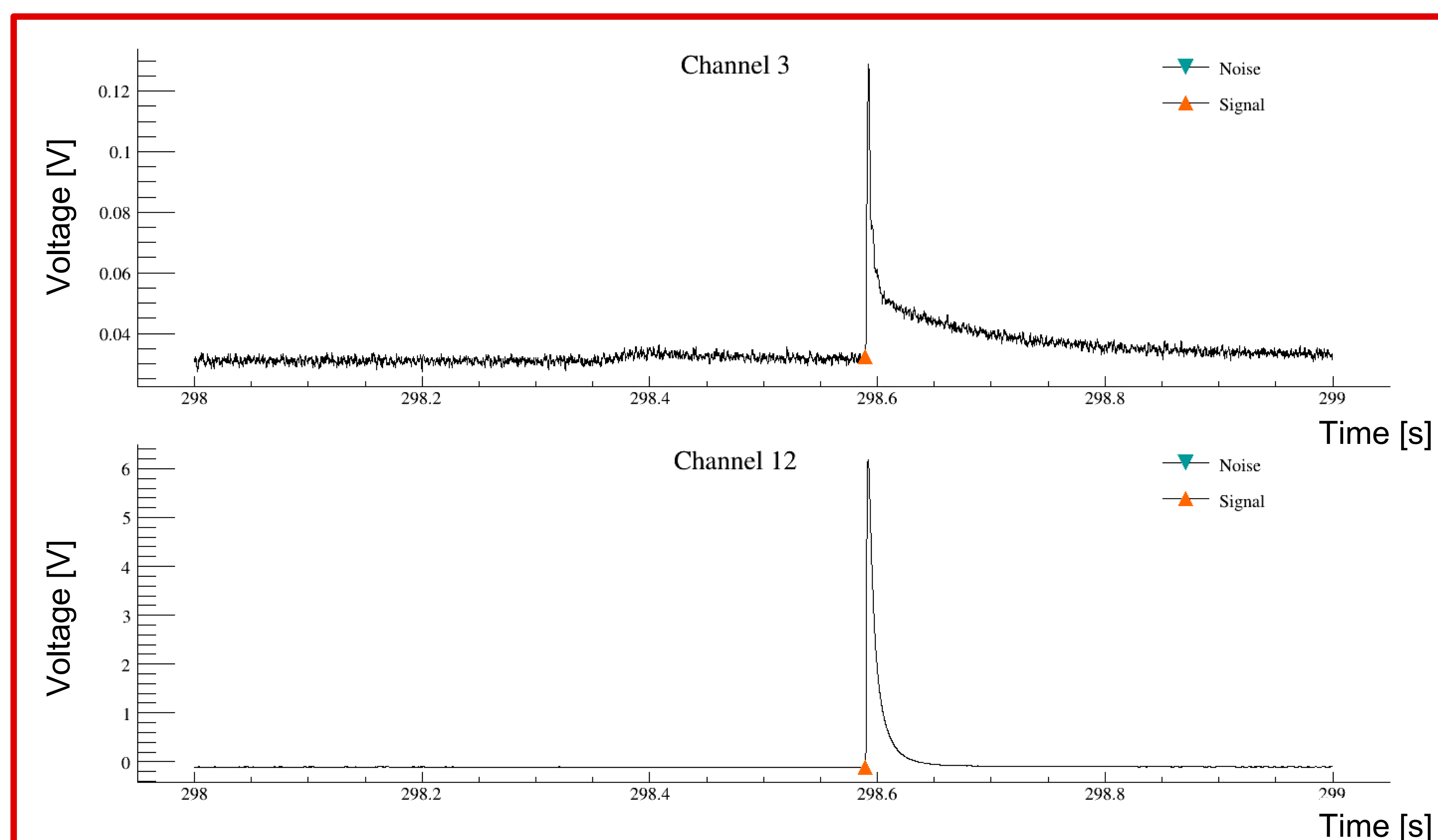
- Zero padding module
- Power Integral Noise rejection

Improved algorithms

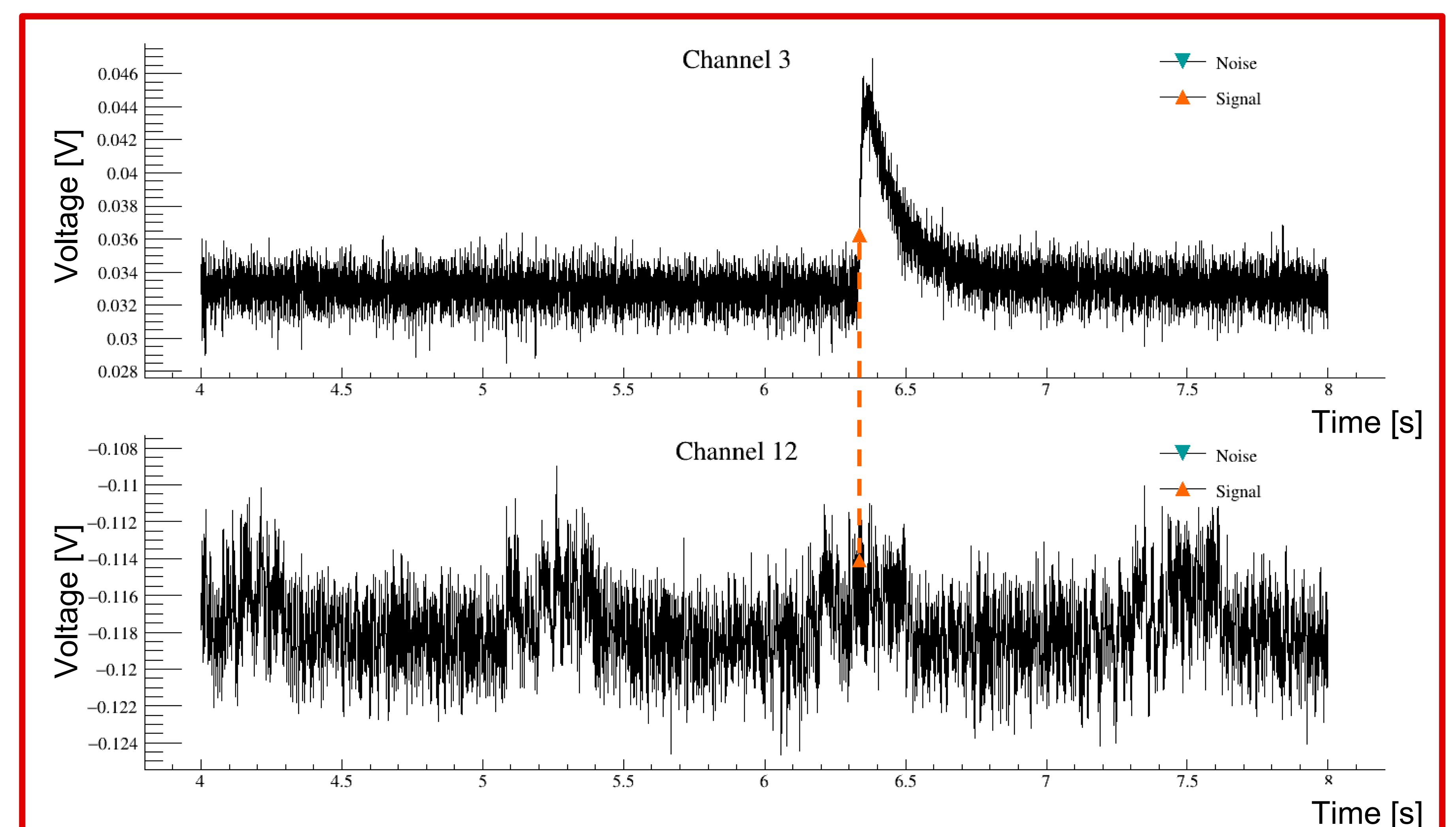
- **Trigger merger** →

Needed to propagate triggers and to flag in-coincidence events. Crucial for Particle IDentification (PID) and α background suppression. Changed logic to support detectors with different sampling frequencies during the CUPID Crystal Validation Run 5 monitoring.

Heat-Light Trigger coincidences



Trigger Propagation Heat → Light



Task 1: Maintenance, development & debug

Newly implemented algorithms

- Zero padding module
- Power Integral Noise rejection

Improved algorithms

- Trigger merger
- **And many others** →

Chi2 module → computes the Left and Right χ^2 on the waveform for Pulse Shape Discrimination (PSD) purposes; modified FFT to avoid crashes on flat FFTs; automatic runtime retrieval of plot names (TGraph, TH1D, TH2D) ...

Task 1: Maintenance, development & debug

Newly implemented algorithms

- Zero padding module
- Power Integral Noise rejection

Improved algorithms

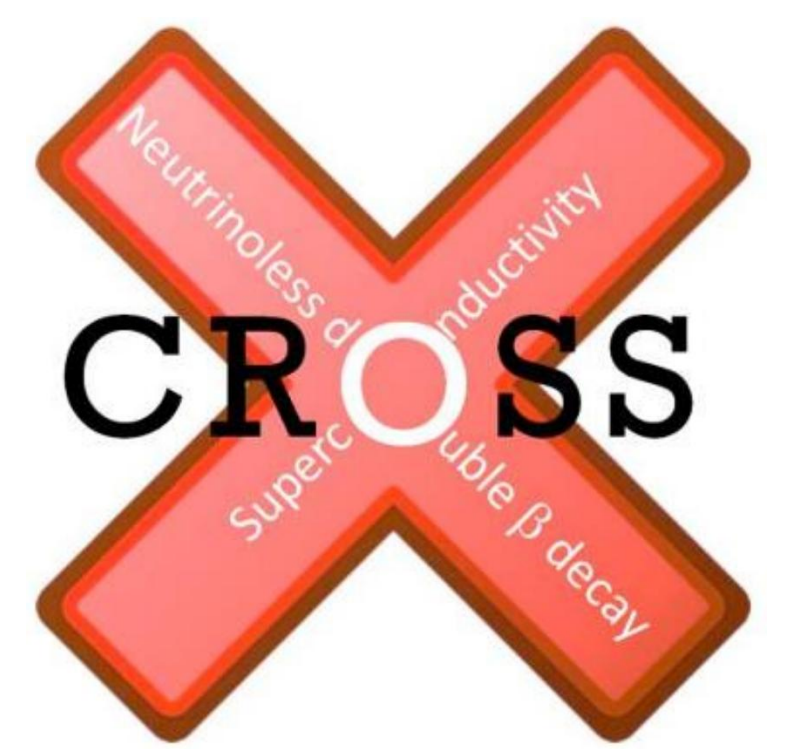
- Trigger merger
- And many others

Future algorithms

- **Mock data generator to compute software and experimental efficiencies**
- **Heat-light trigger propagation with time delay correction¹**

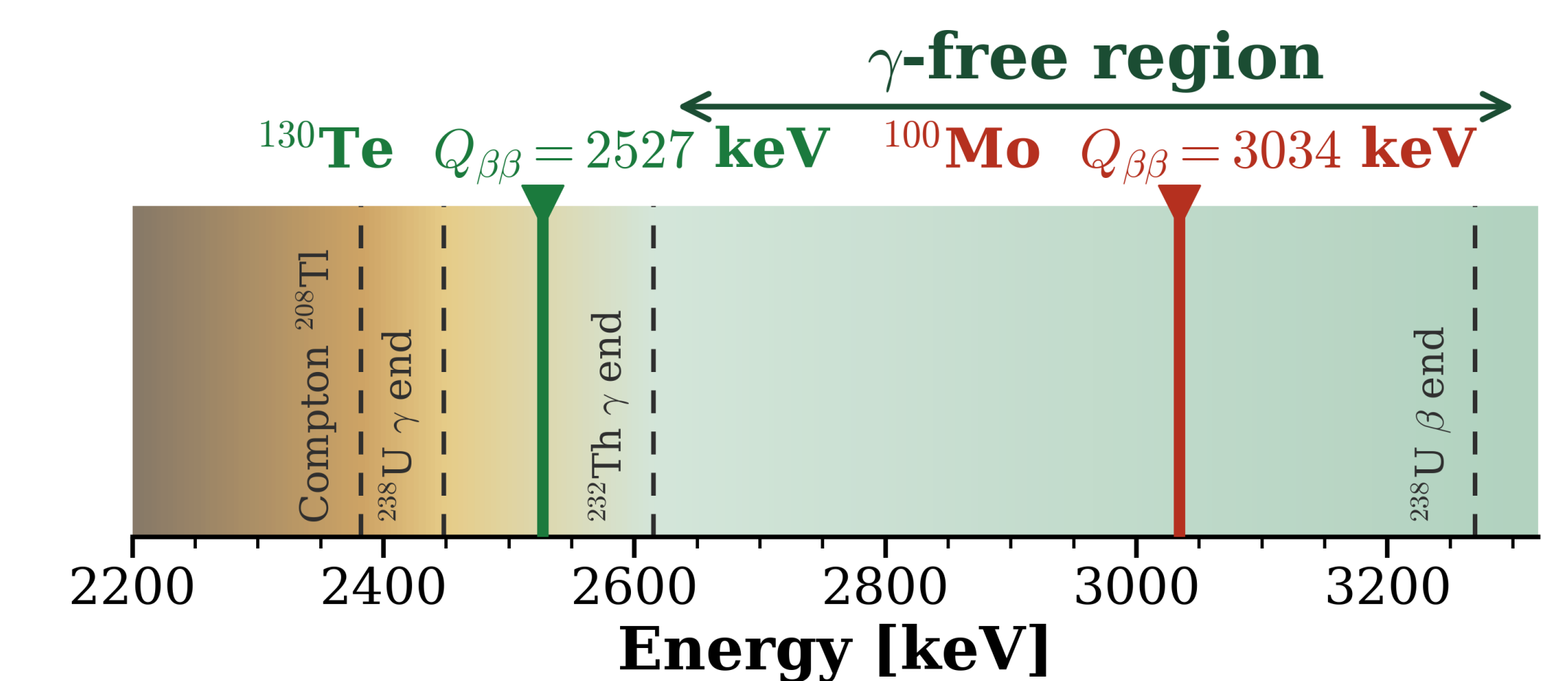
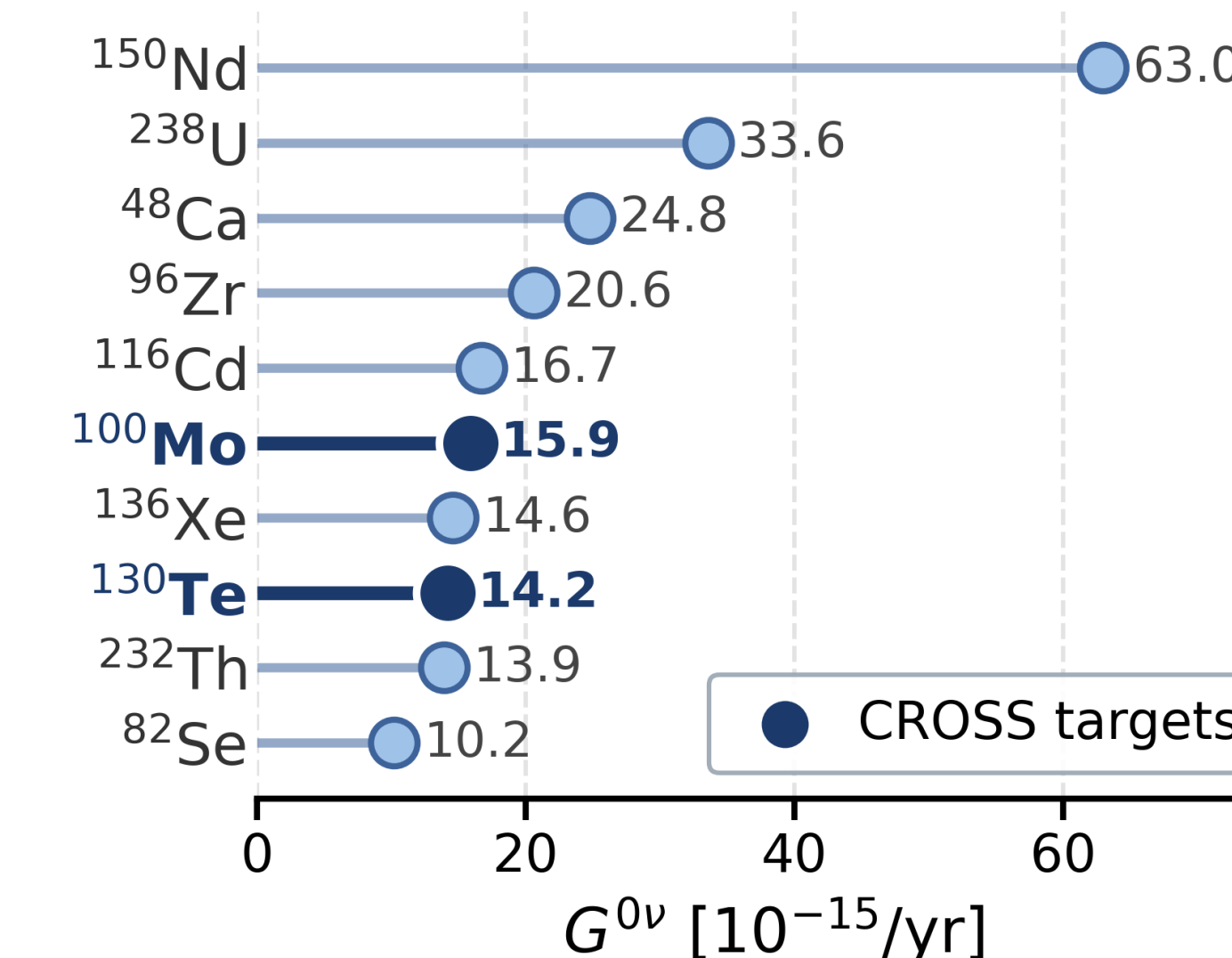
¹ G. Piperno, S. Pirro, M. Vignati, JINST 6 (2011) P10005, doi:10.1088/1748-0221/6/10/P10005

CROSS Experiment



Purpose

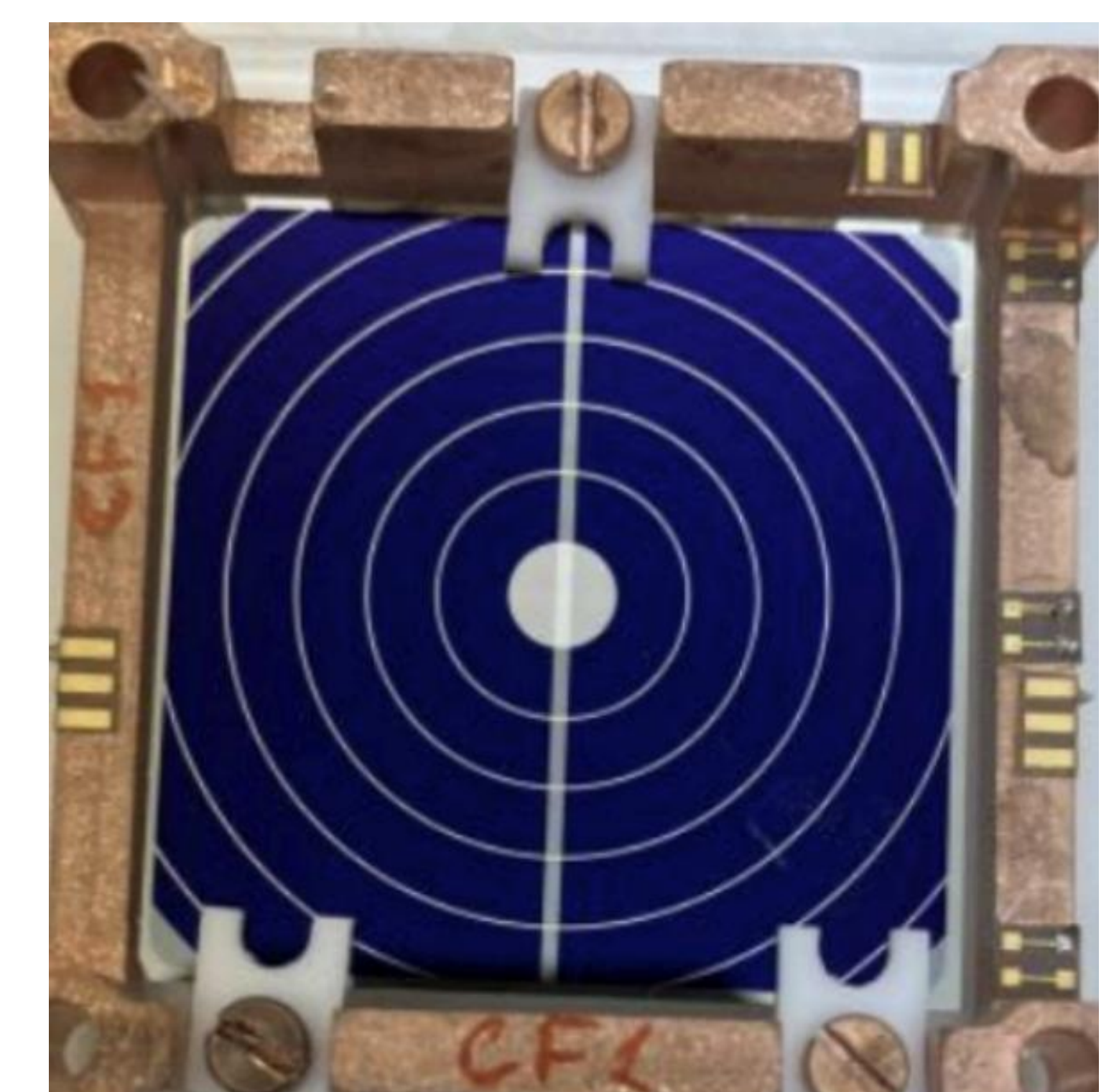
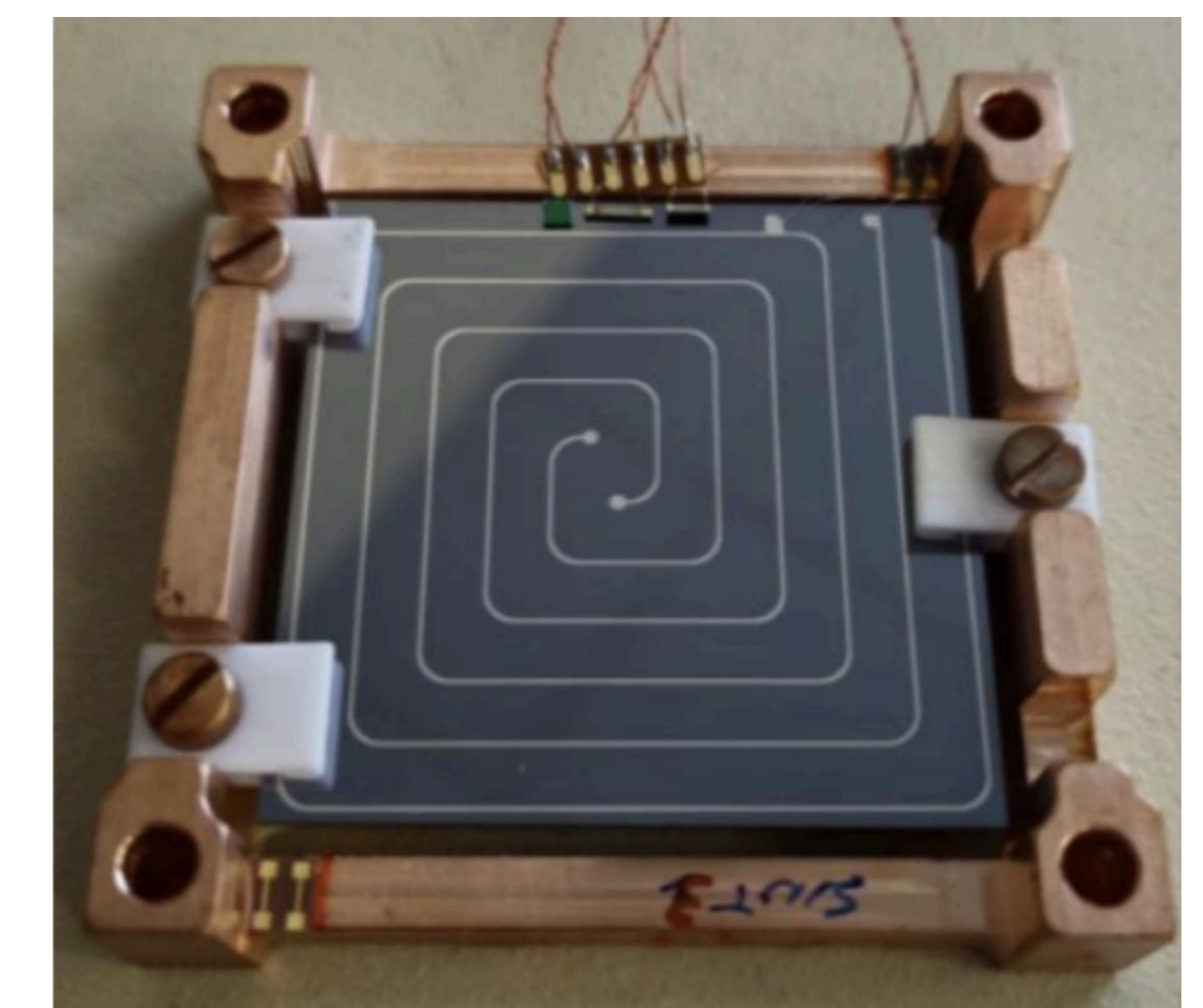
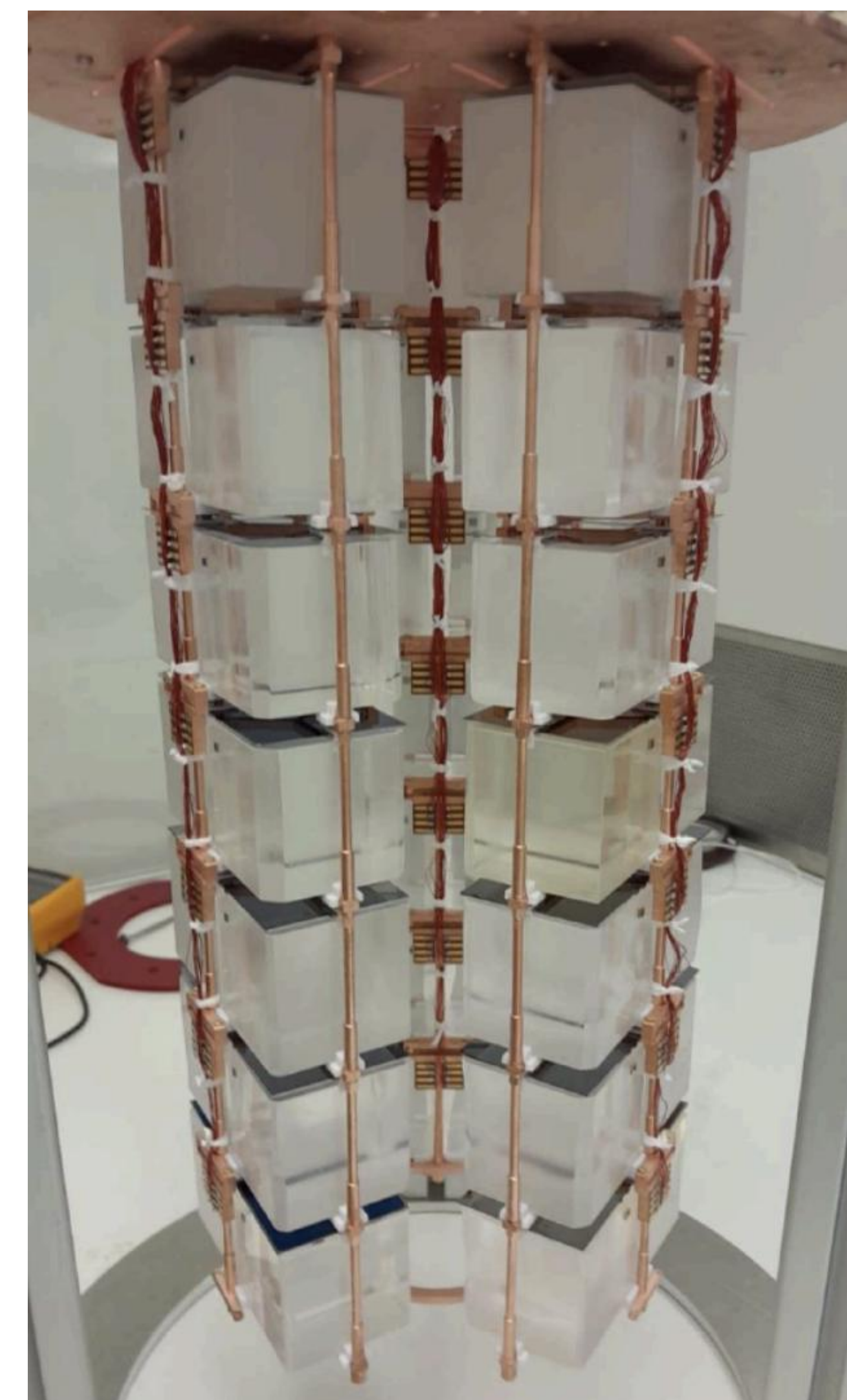
- Develop and test a bolometric technology to search for **neutrinoless double-beta decay**, using ^{100}Mo and ^{130}Te as target isotopes, embedded respectively in $\text{Li}_2^{100}\text{MoO}_4$ and $^{130}\text{TeO}_2$ crystals



$$\frac{1}{T_{1/2}^{0\nu}} = g_A^4 G^{0\nu}(Q_{\beta\beta}, Z) |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e} \right)^2$$

Experimental setup

- **42 modules** with **dual heat–light readout** (36 Li_2MoO_4 , 6 $^{130}\text{TeO}_2$ crystals)
- **Neutron Transmutation Doped-Ge thermistors** on crystals and wafers
- **Si-based resistive heater** glued on each crystal for **gain-stabilization pulses**
- **Ge/Si light detectors** ($45 \times 45 \text{ mm}^2$) with **Neganov-Trofimov-Luke signal amplification** *via* Al electrodes
- **Operational temperature 17-27 mK**

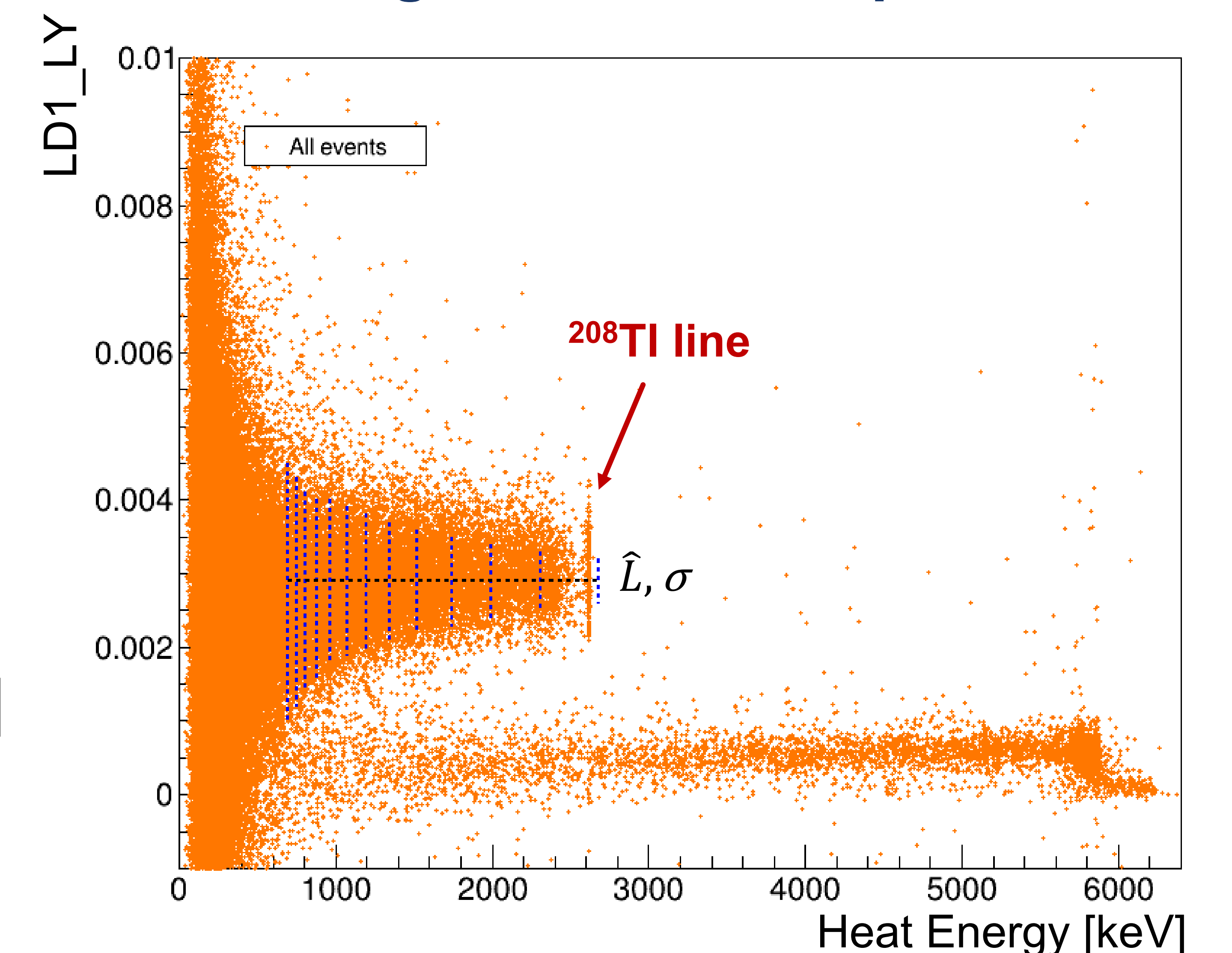


Task 2: CROSS analysis

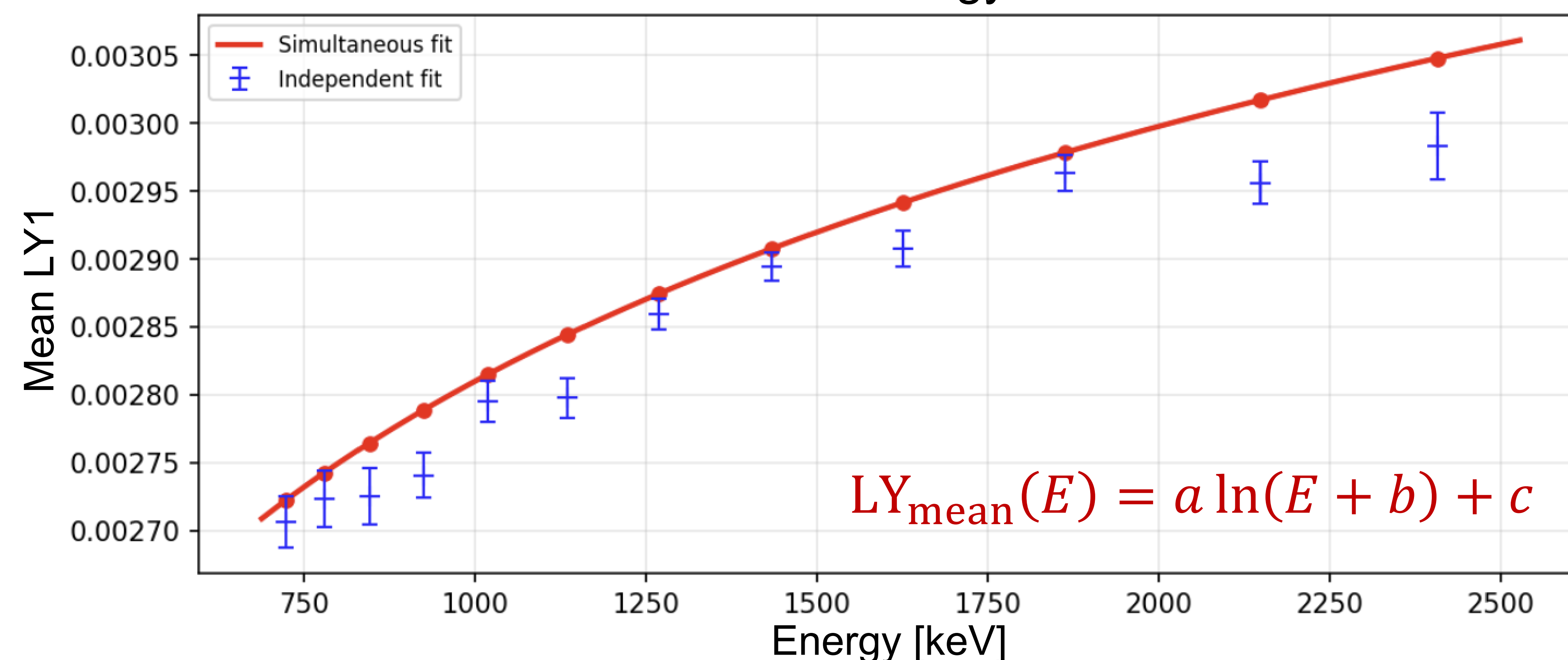


- Heat and light detector **data** are **reconstructed** using **OCTOPUS** software
- Light channels follow the **same reconstruction stream** as the heat channel. The trigger is **propagated from the heat channel** so weak pulses below the LD self-trigger threshold are not lost
- The light channels build a **PSD variable based on the Light Yield**: events are divided into **heat-energy intervals** and in each one mean and sigma of the LY distribution are extracted through **independent** and **simultaneous** fits

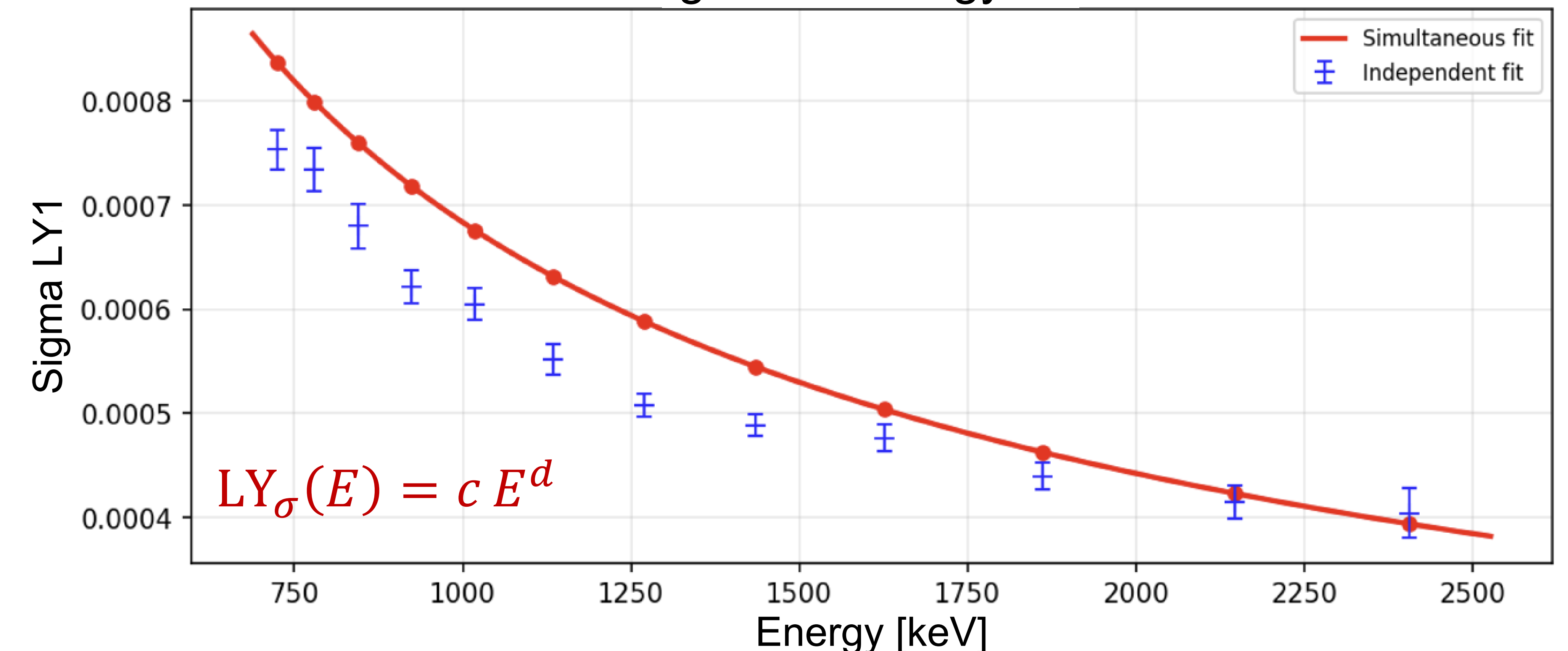
Light Yield scatterplot



LY1 — Mean vs Energy



LY1 — Sigma vs Energy



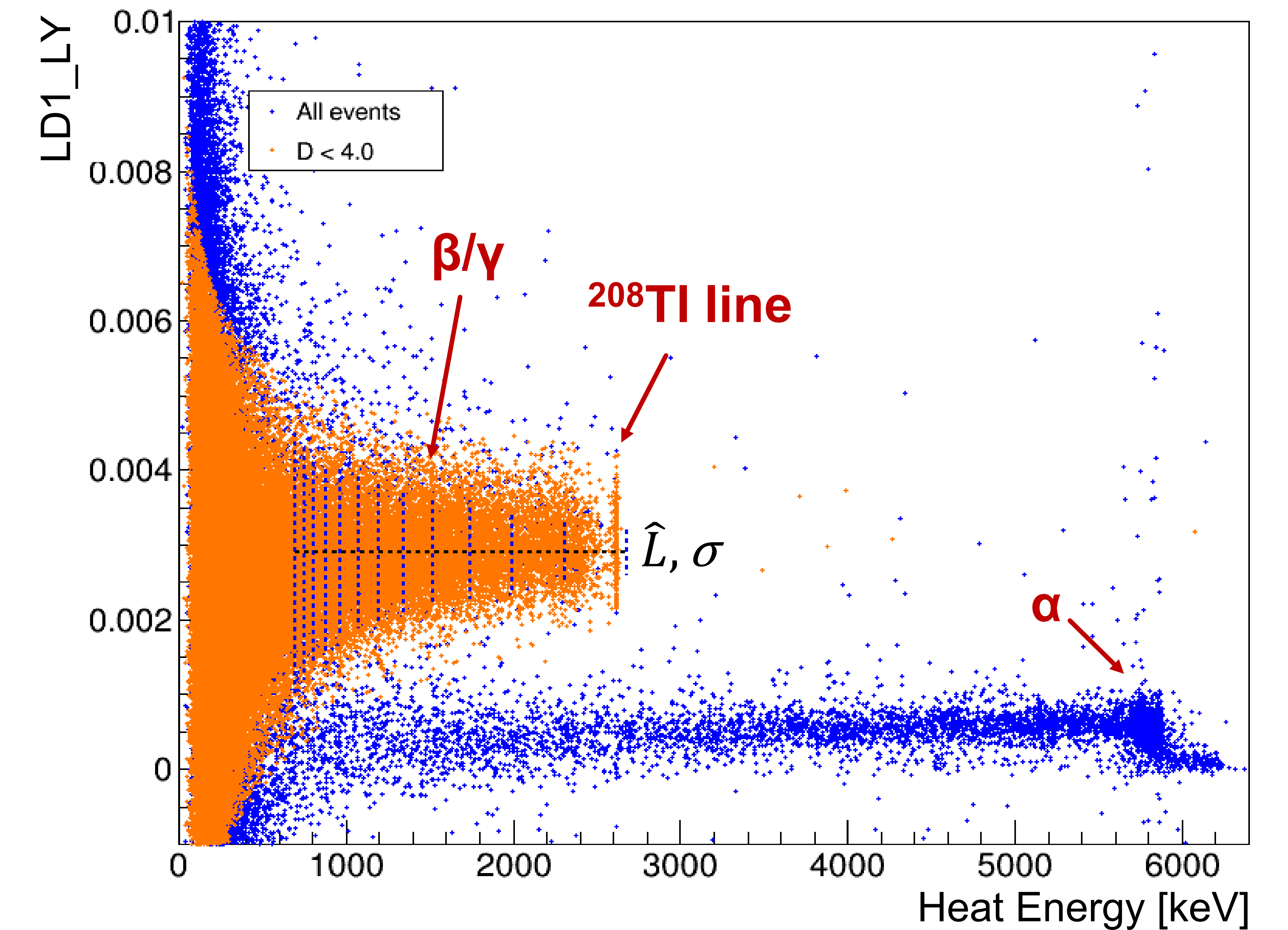
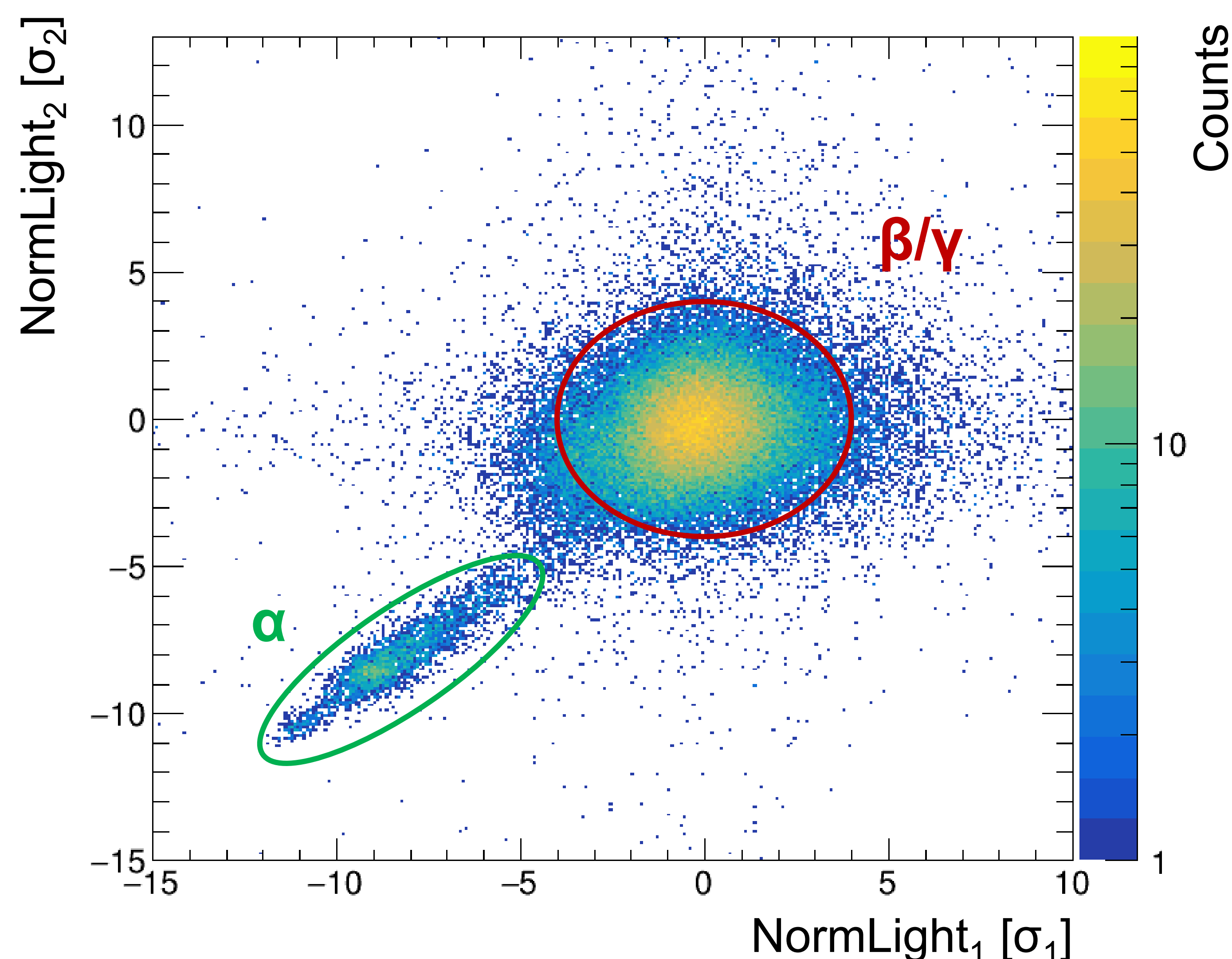
Task 2: CROSS analysis

α/β discrimination – normalized light distance

$$n_{c,s,d} = \frac{L_{c,s,d} - \hat{L}_{c,s,d}(E)}{\sigma(E)_{c,s,d}}$$

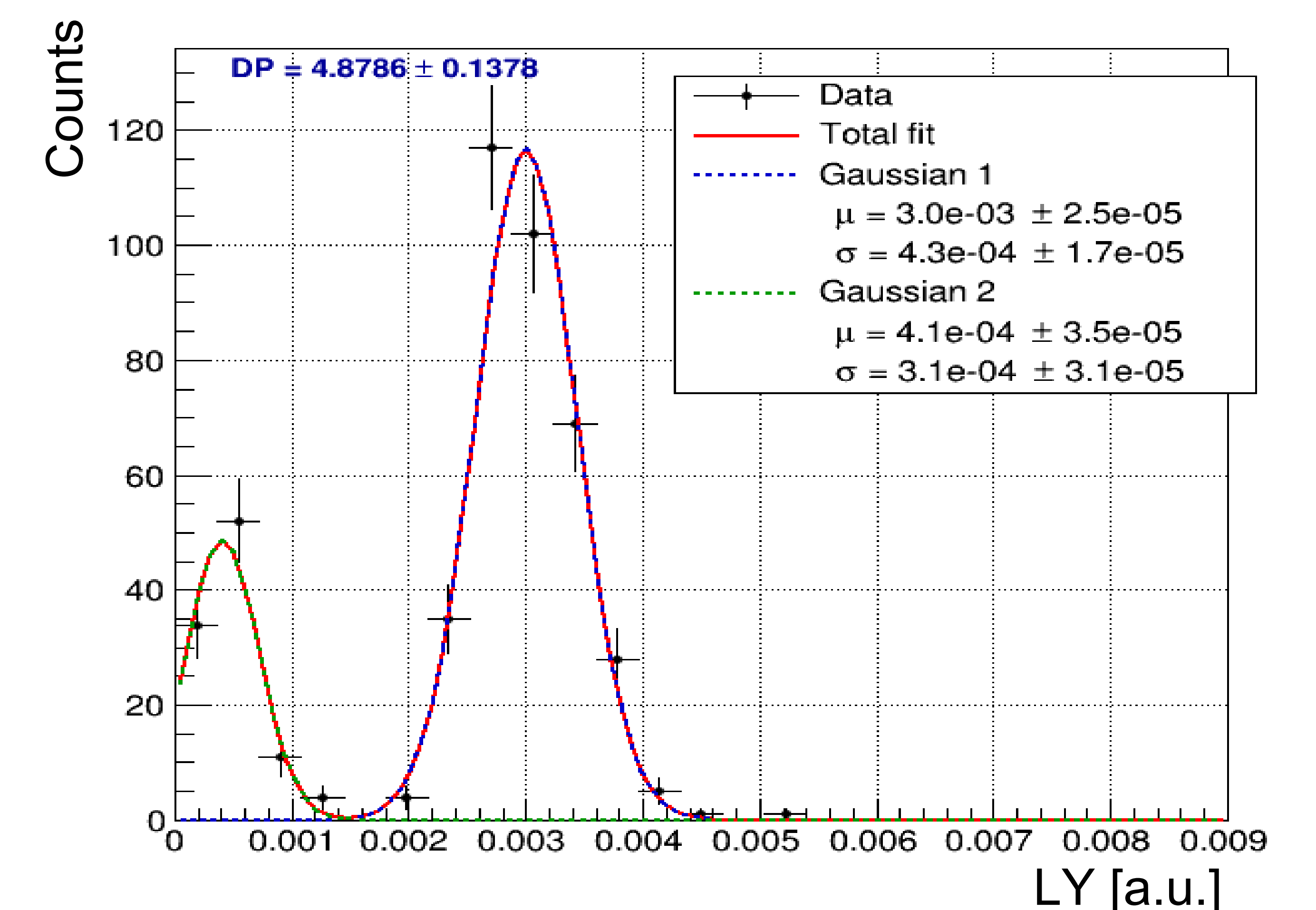
$$D = \sqrt{(n_{c,1}^2 + n_{c,2}^2)}$$

α background removed
with the cut: **$D < 4$**



Light Yield Discrimination Power
@ ^{208}TI peak (2614.5 ± 100 keV)

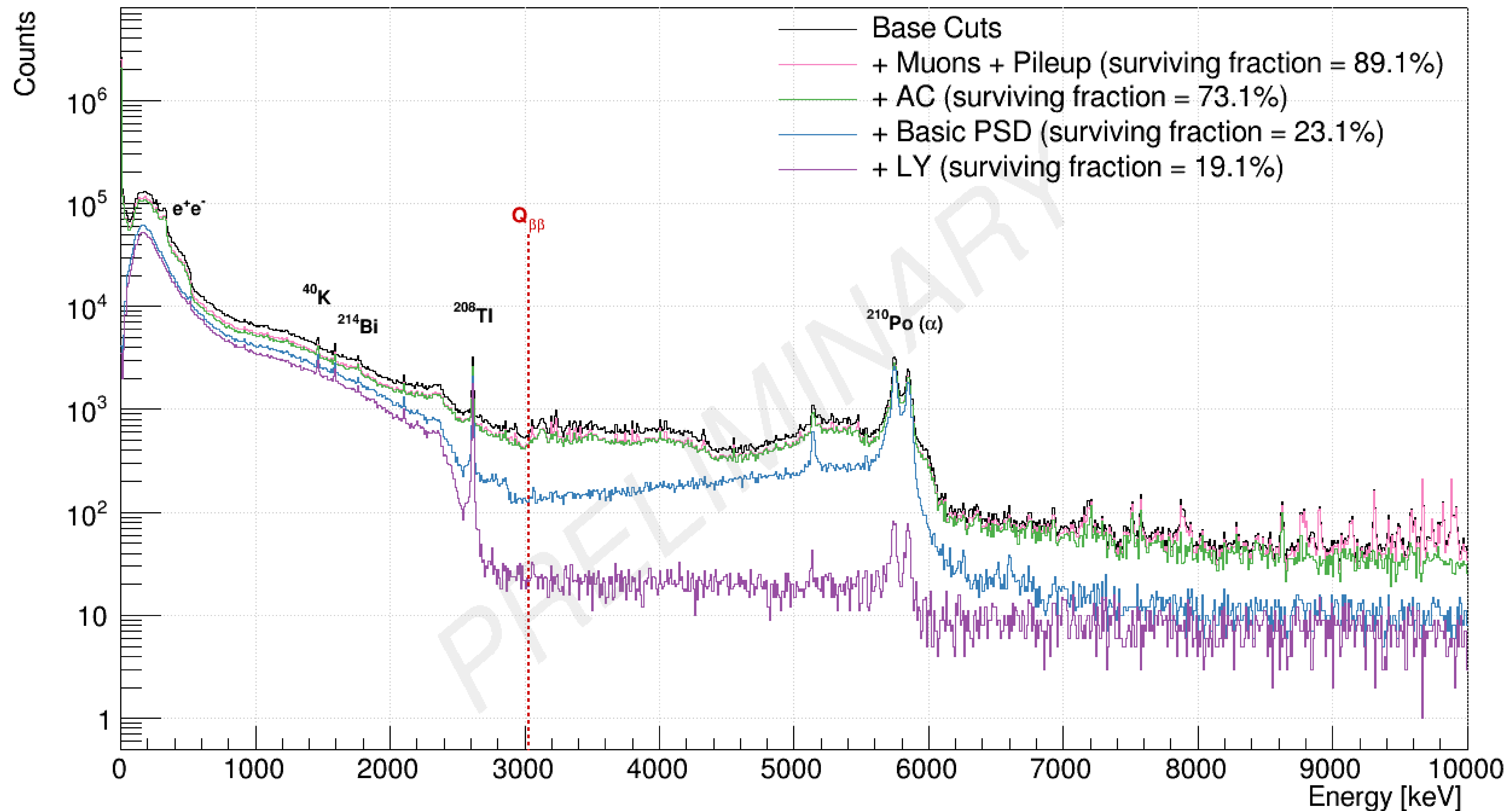
$$DP = \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$



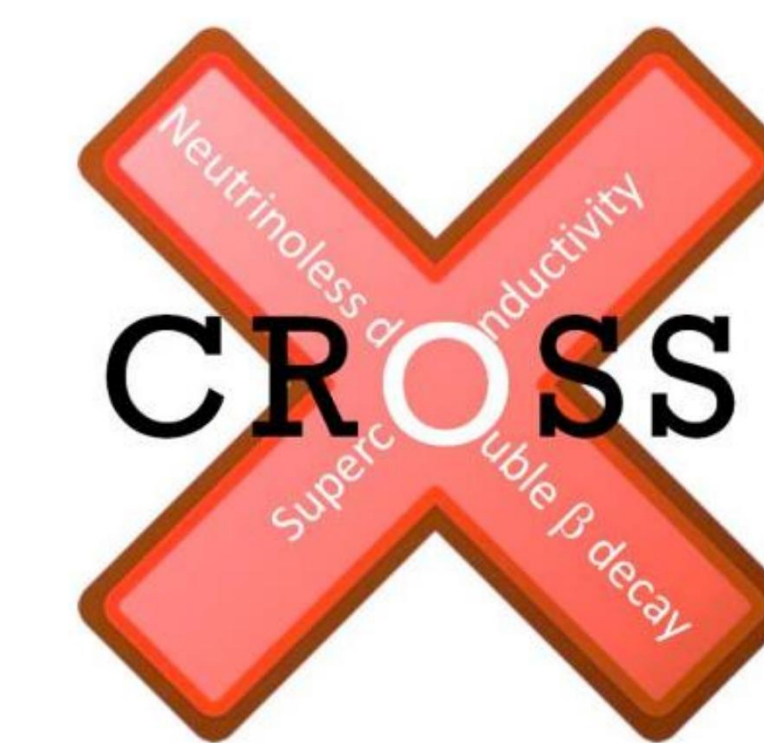
Task 2: CROSS analysis

It looks like the background rejection is not working

Calibrated spectrum of 36 $\text{Li}_2^{100}\text{MoO}_4$ crystals; 40 days of exposure

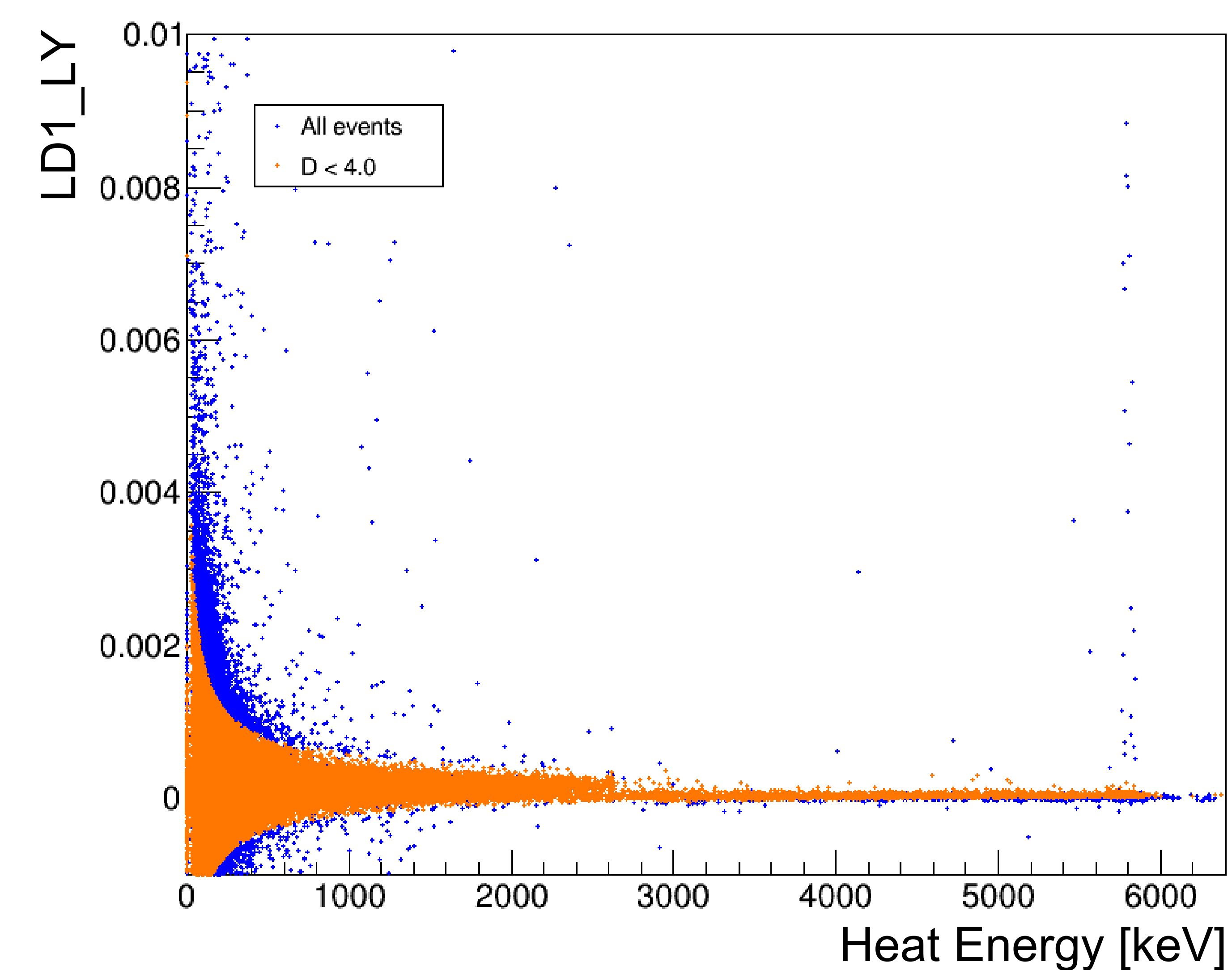


Task 2: CROSS analysis



It looks like the background rejection is not working **BUT**

Not properly working LD



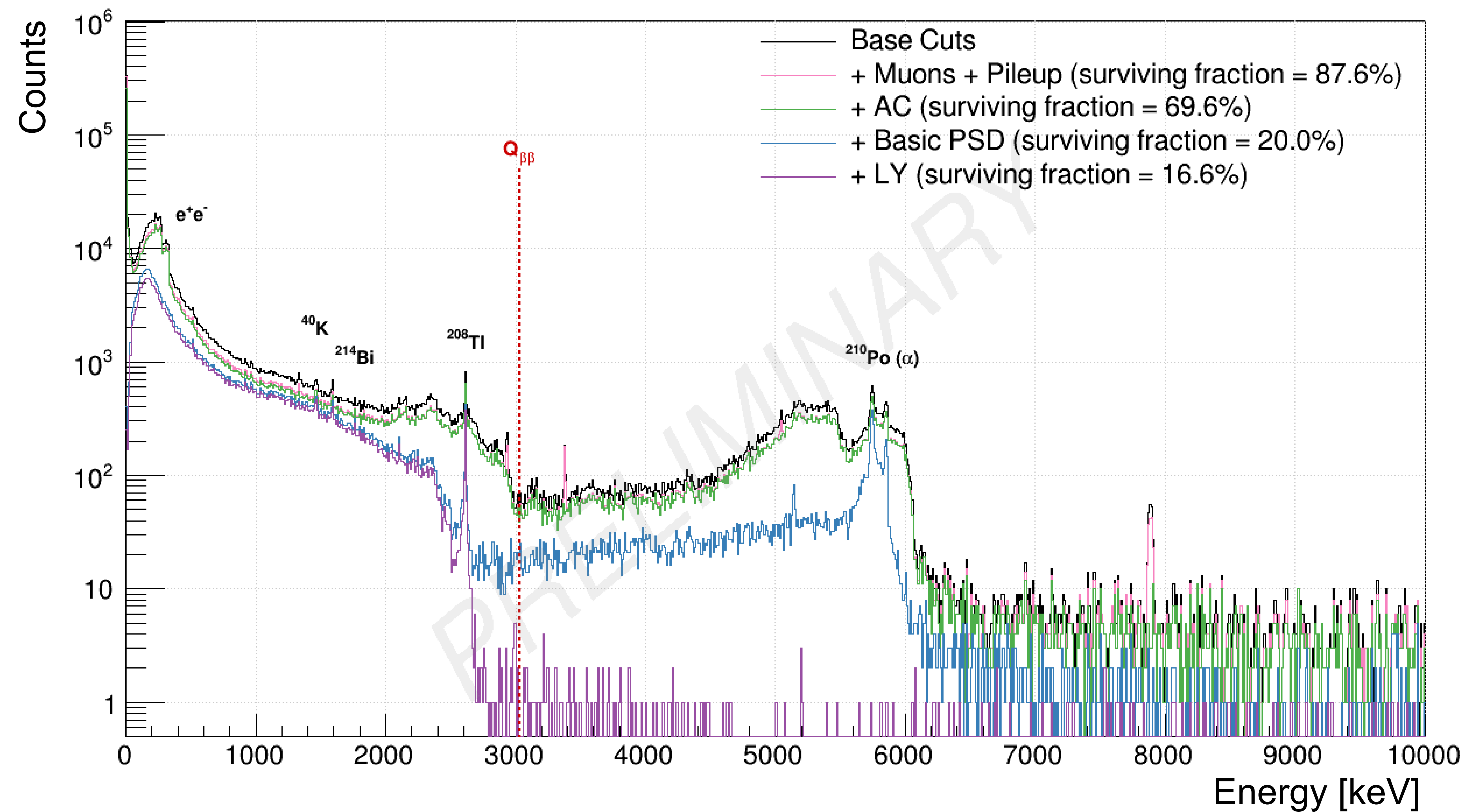
Task 2: CROSS analysis



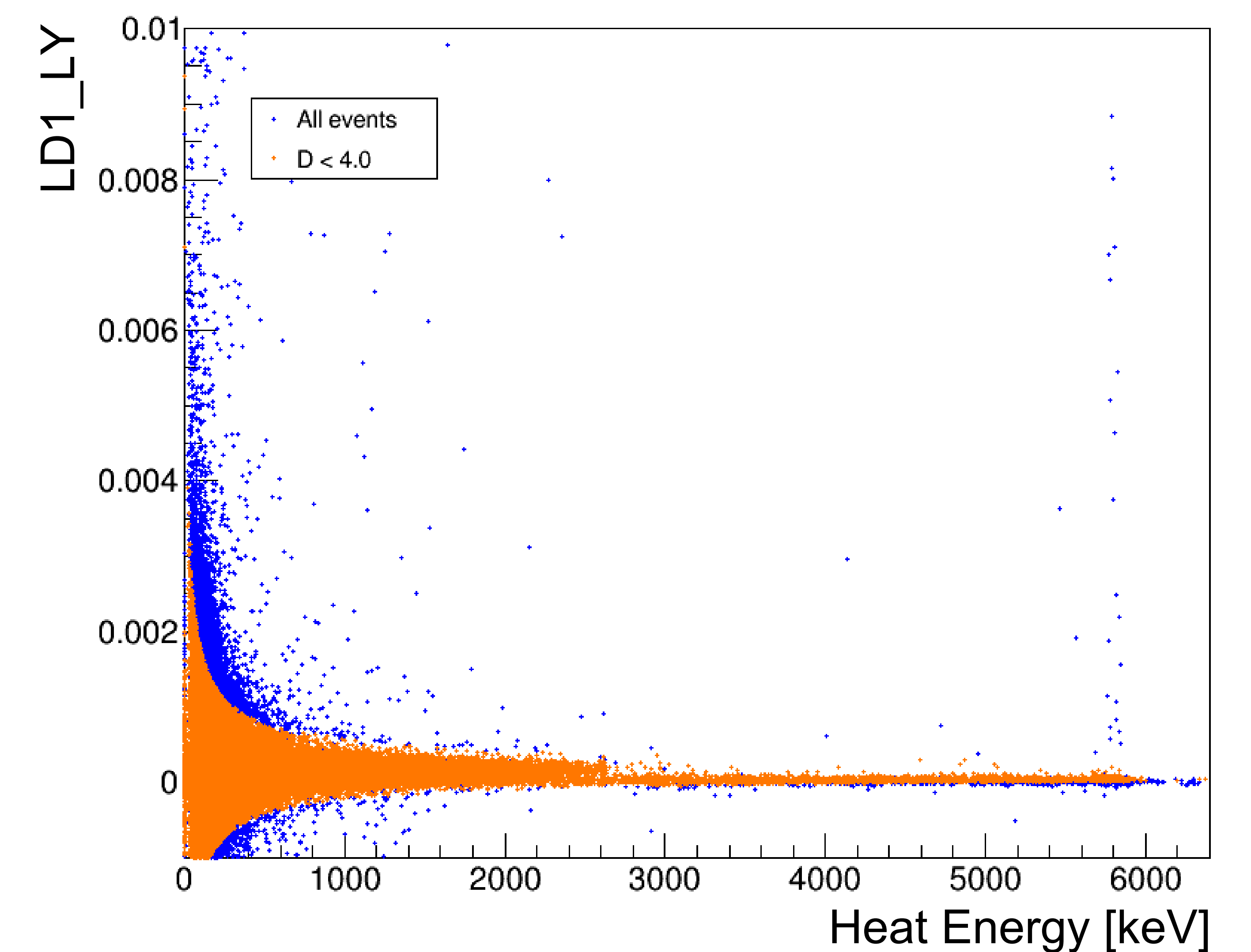
It looks like the background rejection is not working **BUT**



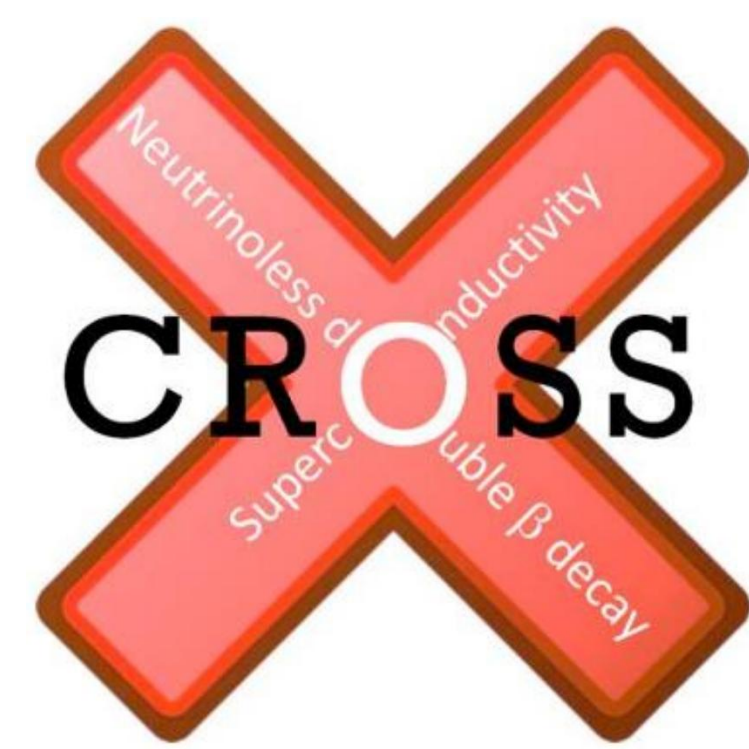
Calibrated spectrum of 5 $\text{Li}_2^{100}\text{MoO}_4$ crystals; 40 days of exposure



Not properly working LD

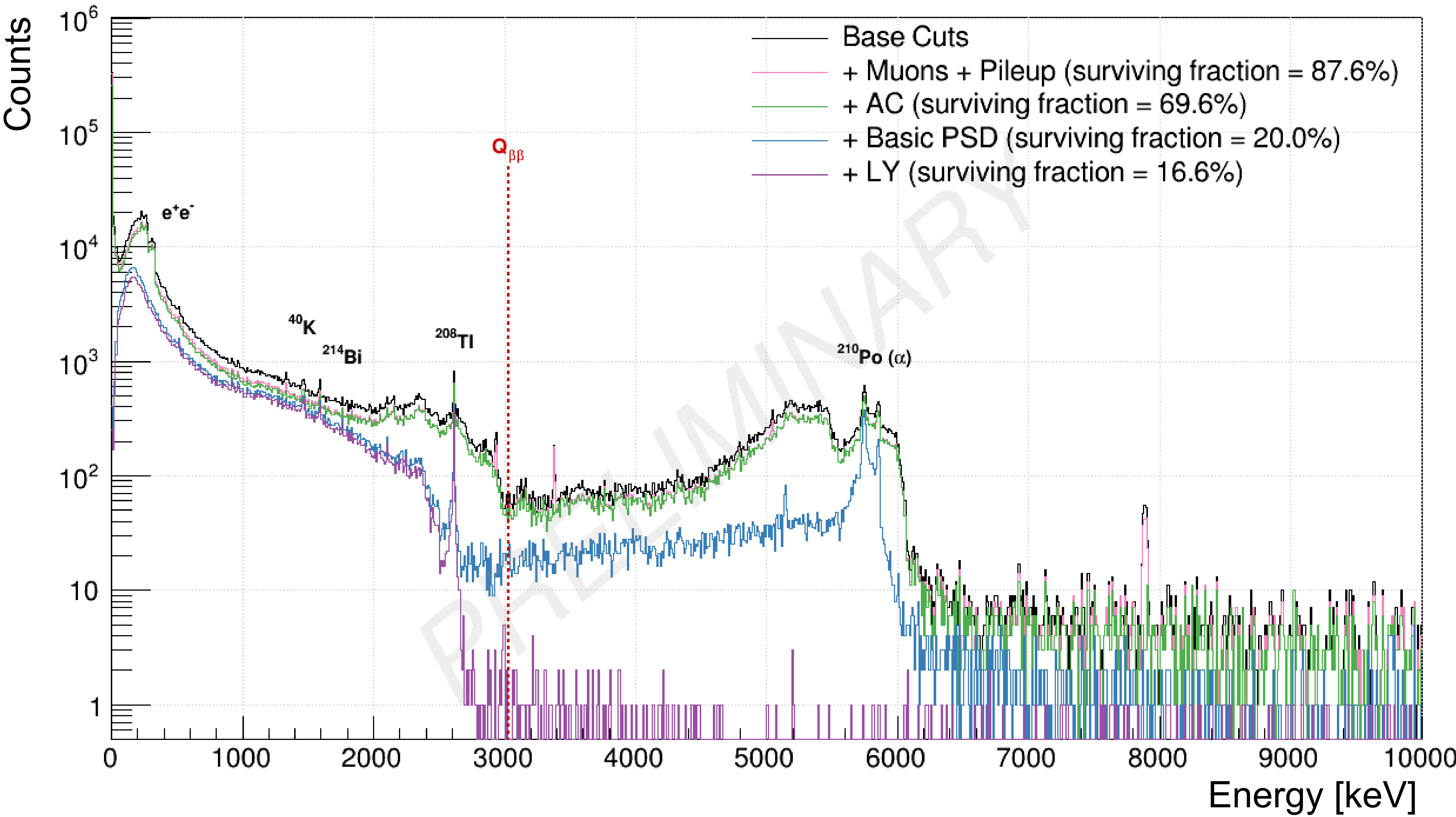


Task 2: CROSS analysis

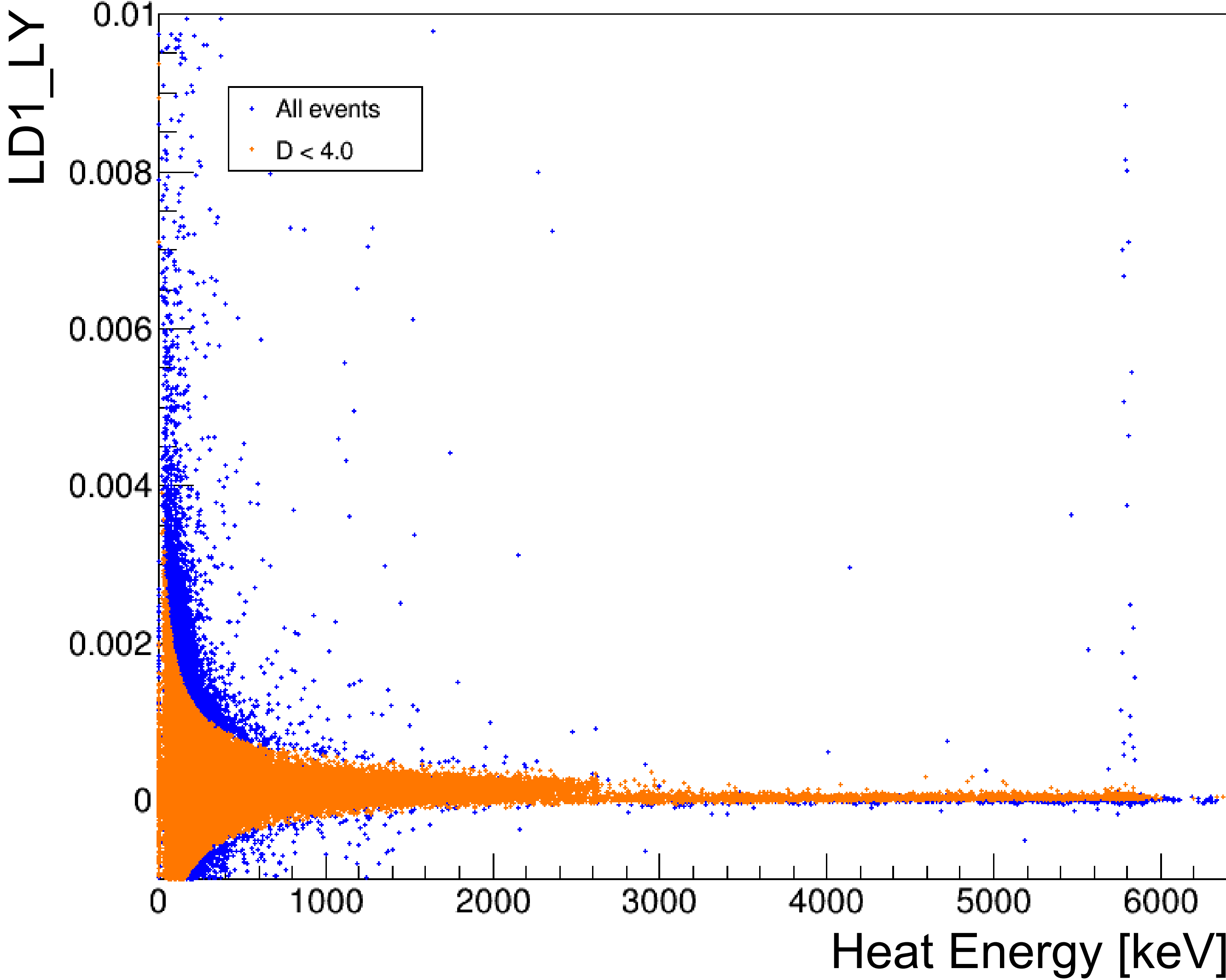


It looks like the background rejection is not working **BUT**

Calibrated spectrum of 5 $\text{Li}_2^{100}\text{MoO}_4$ crystals; 40 days of exposure



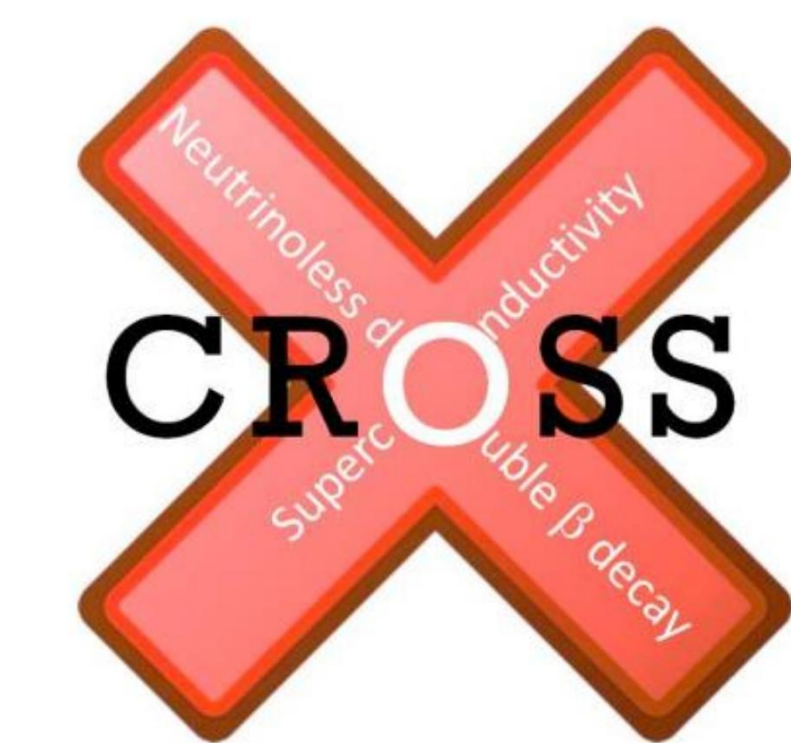
Not properly working LD



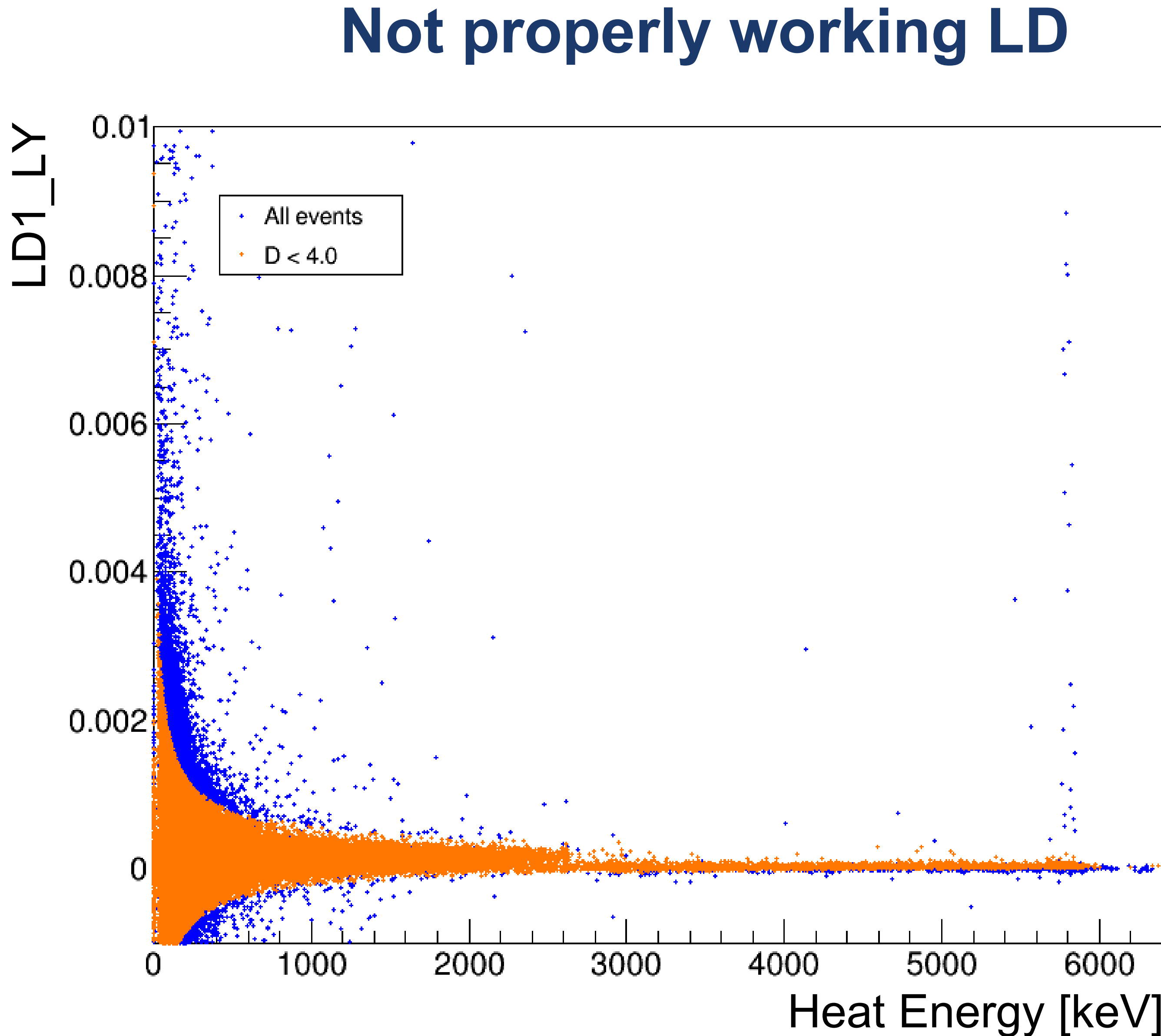
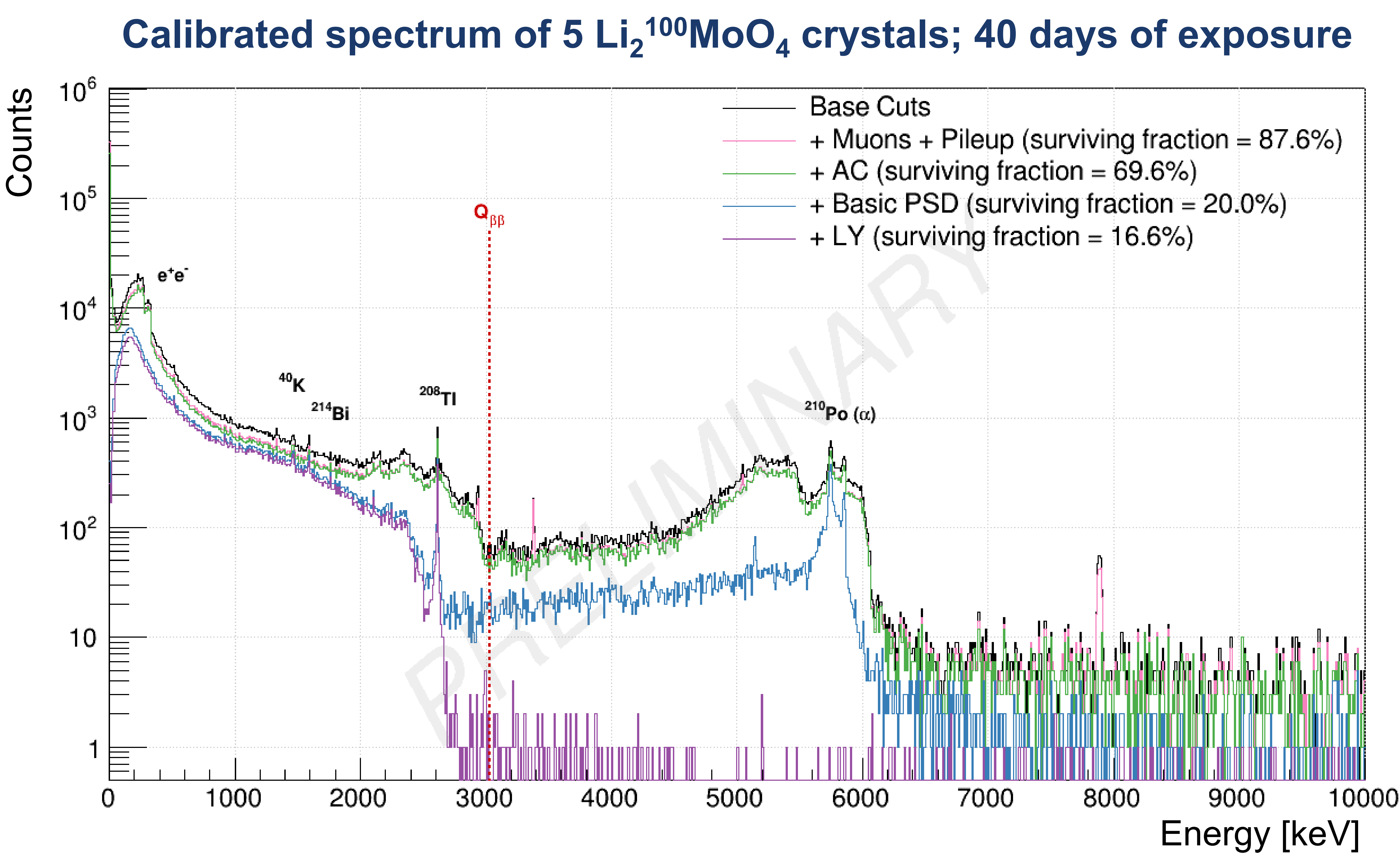
Some results

Quantity	Value
$\text{FWHM}_{\text{Tl}} (24/32 \text{ }^{100}\text{Mo}_{\text{enr}})$	$8.2 \pm 0.2 \text{ keV}$
$\text{FWHM}_{\text{baseline}} (24/32 \text{ }^{100}\text{Mo}_{\text{enr}})$	$\sim 3.2 \text{ keV}$
NTL_{gain}	$\sim 9 @ 80\text{V}$
$\text{FWHM}_{\text{baseline}} (\text{LD})$	$\sim 10 \text{ eV}$
$\text{DP} (30/36 \text{ LDs})$	4.4 ± 0.6

Task 2: CROSS analysis



It looks like the background rejection is not working **BUT**



What comes next?

- Re-process data with fine-tuned coincidence time window among crystals (3 ms now) to properly reject M2 events
- Re-process data with fine-tuned coincidence time window with the muon veto (2 ms now)
- Address the leftover contamination in the ROI
- Test alpha stabilization to correct gain due to temperature drifts
- Continue with different data set
- Planned contamination and efficiency measurements

Some results

Quantity	Value
$\text{FWHM}_{\text{Tl}} (24/32 \text{ } ^{100}\text{Mo}_{\text{enr}})$	$8.2 \pm 0.2 \text{ keV}$
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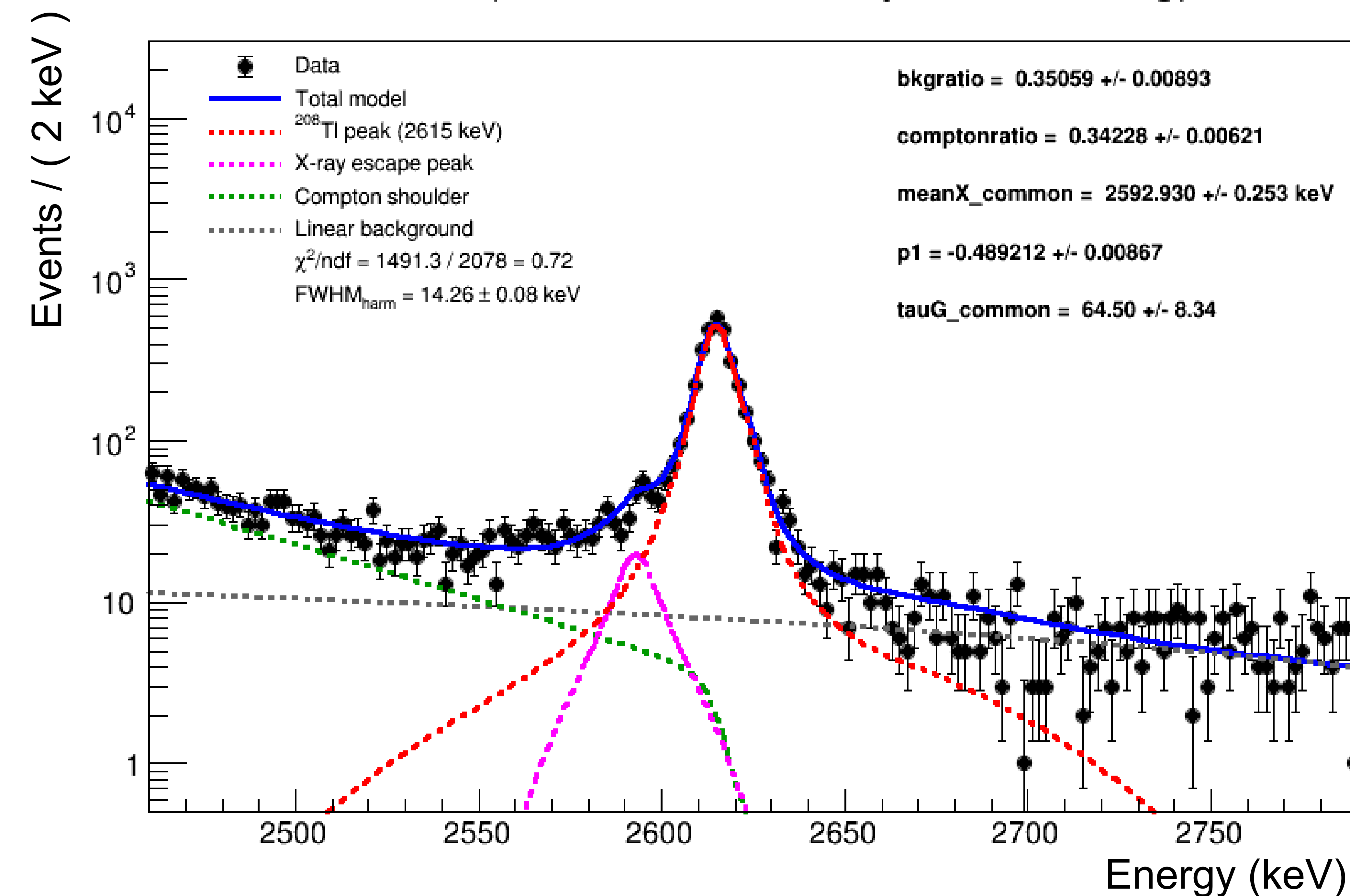
Task 2: CROSS analysis

Detector response model @²⁰⁸Tl γ line

- Set up the **simultaneous fit procedure** (channel by channel) using an **unbinned likelihood approach**
- **Model per channel** (fit window [2460–2790] keV)
 - $\lambda_c(E) = N_c [G + r_C C + r_B B] + N_c^X G_X$
 - $G(\mu, \sigma)$: Gaussian [²⁰⁸Tl peak];
 $G_X(\mu_X, \sigma)$: Gaussian [K^α X-ray];
 C : multi-Compton step; B : linear background
- **Extended likelihood** over all channels
 - $v_c = N_c (1 + r_C + r_B) + N_c^X$
 - $-\ln L = \sum_c [v_c - \sum_{k \in c} \ln \lambda_c(E_k)]$
- **Free parameters**
 - Per channel: $\mu_c, \sigma_c, N_c, N_c^X$
 - Shared: $r_C, \tau, r_B, p_1, \mu_X$

Background Run

2615 keV (c_allch_allruns_xray_commonBkg)

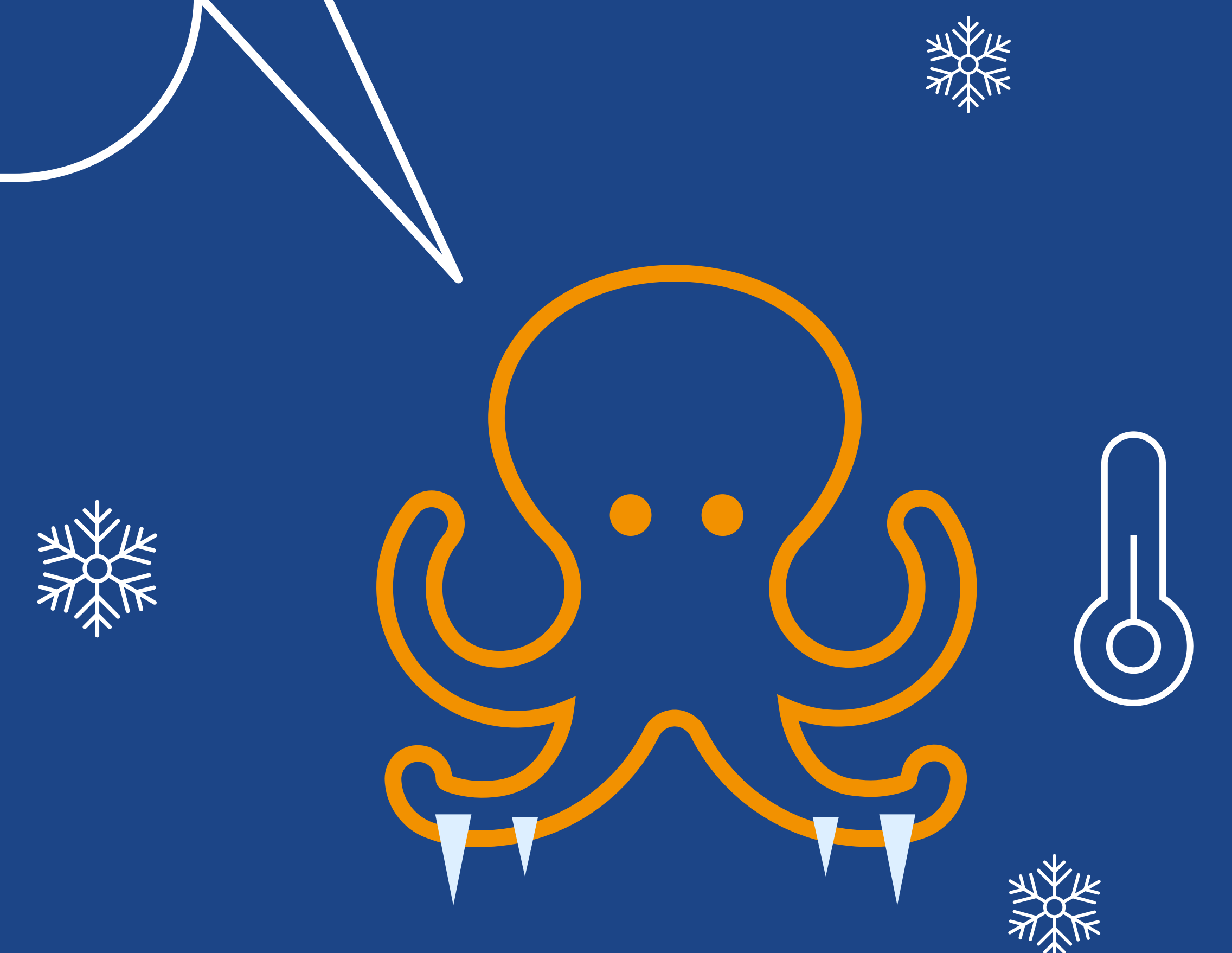


- **Software** and **analysis** are being developed **in parallel**, driven by the needs of each measurement (as experienced during the online monitoring of CCVR5). This work is **pushing OCTOPUS** to be **reliable** for **processing long-exposure data** (e.g. **CUORE Upgrade with Particle Identification** experiment)
- What have we learned from the **CROSS** R&D?
 - **Alpha rejection** procedure is **reliable and stable** (**although several LDs are not** 😞)
 - **Fine-tuning** of **processing parameters** is needed
 - A detailed study of the **leftover contamination in the ROI** is needed
- Validation of OCTOPUS
 - **Planned results comparison** between CCVR5 data processed with **DIANA** (CUORE software) and **OCTOPUS**
 - **Re-processing 3 ton-year exposure CUORE data** (long-term plan)
- What comes next
 - **Search** for $^{100}\text{Mo } 2\nu\beta\beta$ decay to ^{100}Ru excited states
 - **Background model**

Conferences, schools and planned papers

Conferences & workshops	Schools	Planned papers
● 7-9 Oct 2026 · LNGS CUORE Collaboration Meeting ● 20-24 Sep 2026 · York, UK Low Radioactivity Techniques Contributed poster ● 4-8 May 2026 · LNGS Joint CUORE/CUPID Collaboration Meeting ● 21-24 Oct 2025 · LNGS CUPID Collaboration Meeting ● 1-2 Jul 2025 · Nijmegen, NL PTOLEMY International Workshop	● 11-22 Oct 2026 · Bertinoro, IT Efficient Scientific Computing School ● 27-31 Jul 2026 · Prague, CZ XIII International GEANT4 School ● 12-17 Oct 2025 · Bertinoro, IT Scientific Communication in Astronomy ● 7-11 Jul 2025 · Copenhagen, DK Neutrinos: Here, There & Everywhere	● OCTOPUS paper ● CROSS detector performance ● CCVR paper ● PTOLEMY sensitivity paper In preparation, side project

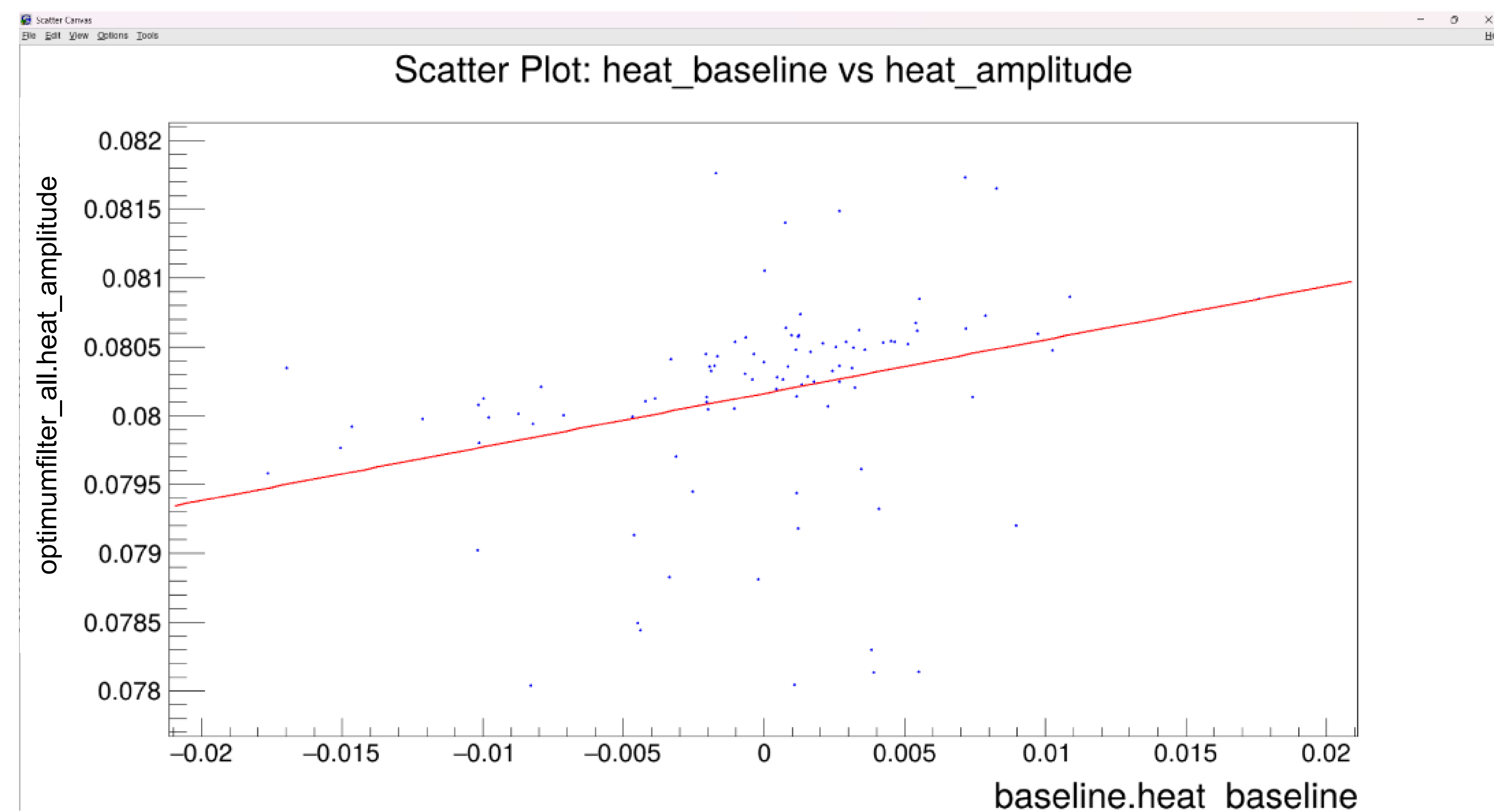
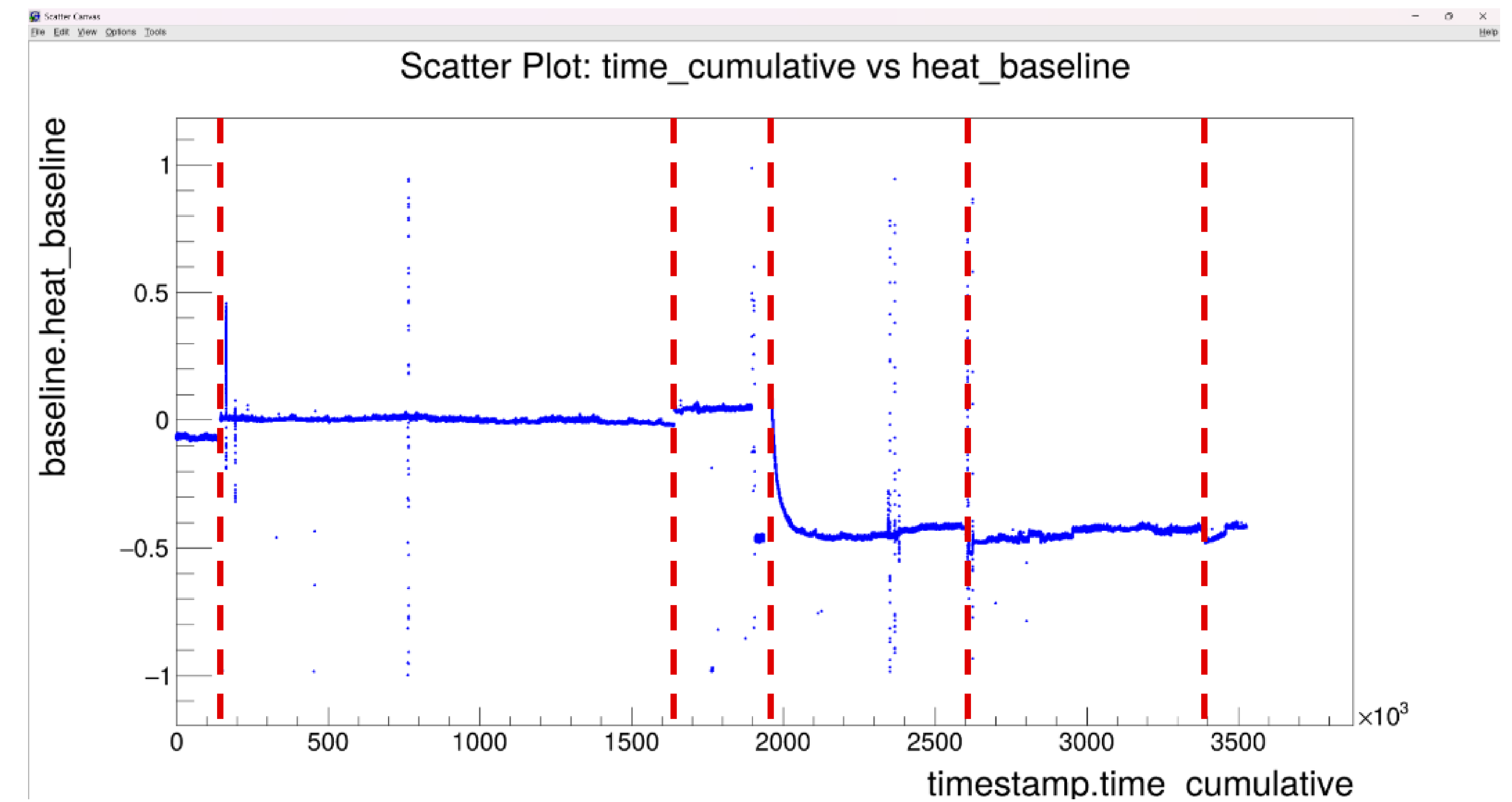
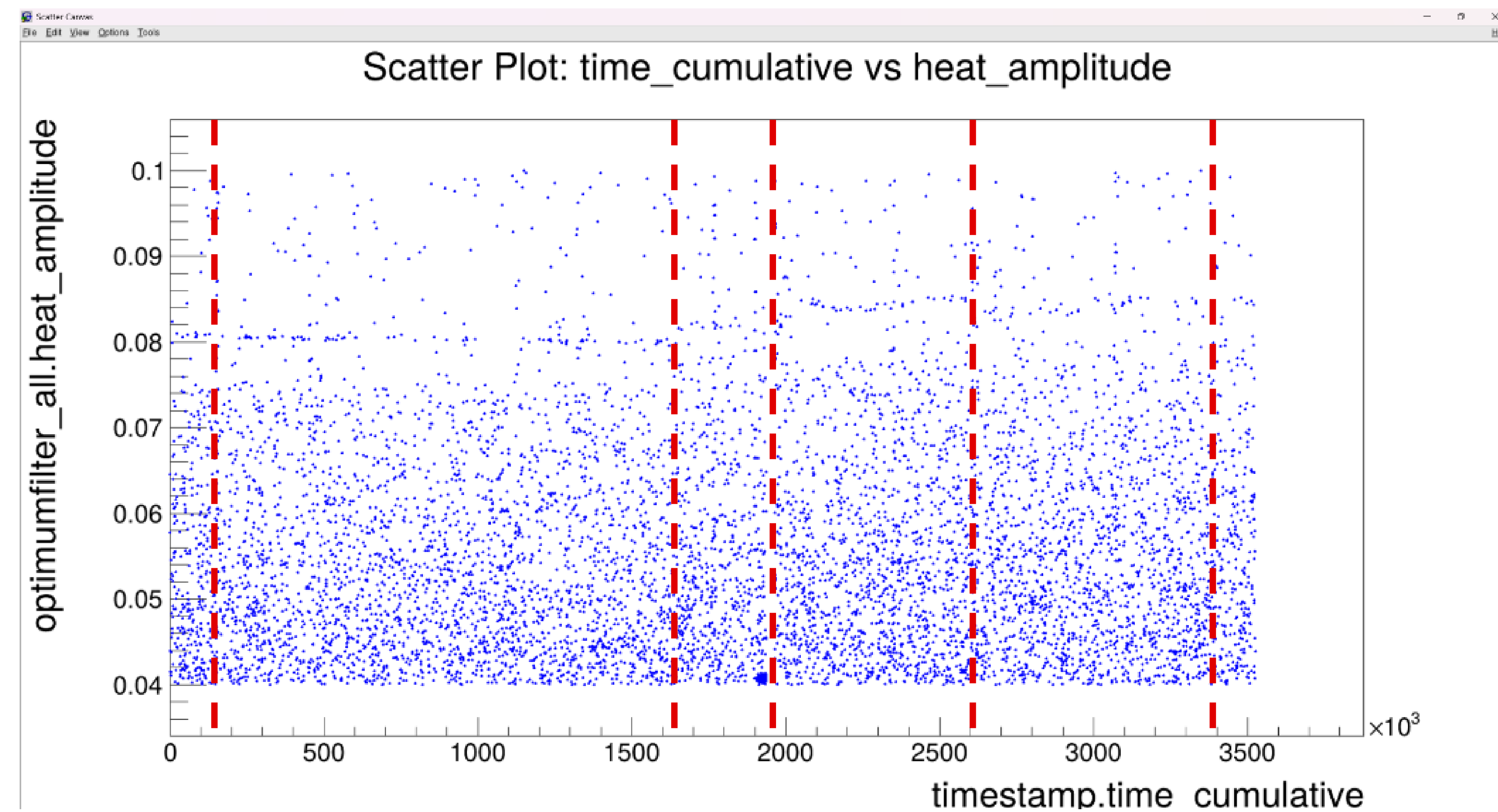
Thank you
for your attention



Backup slides

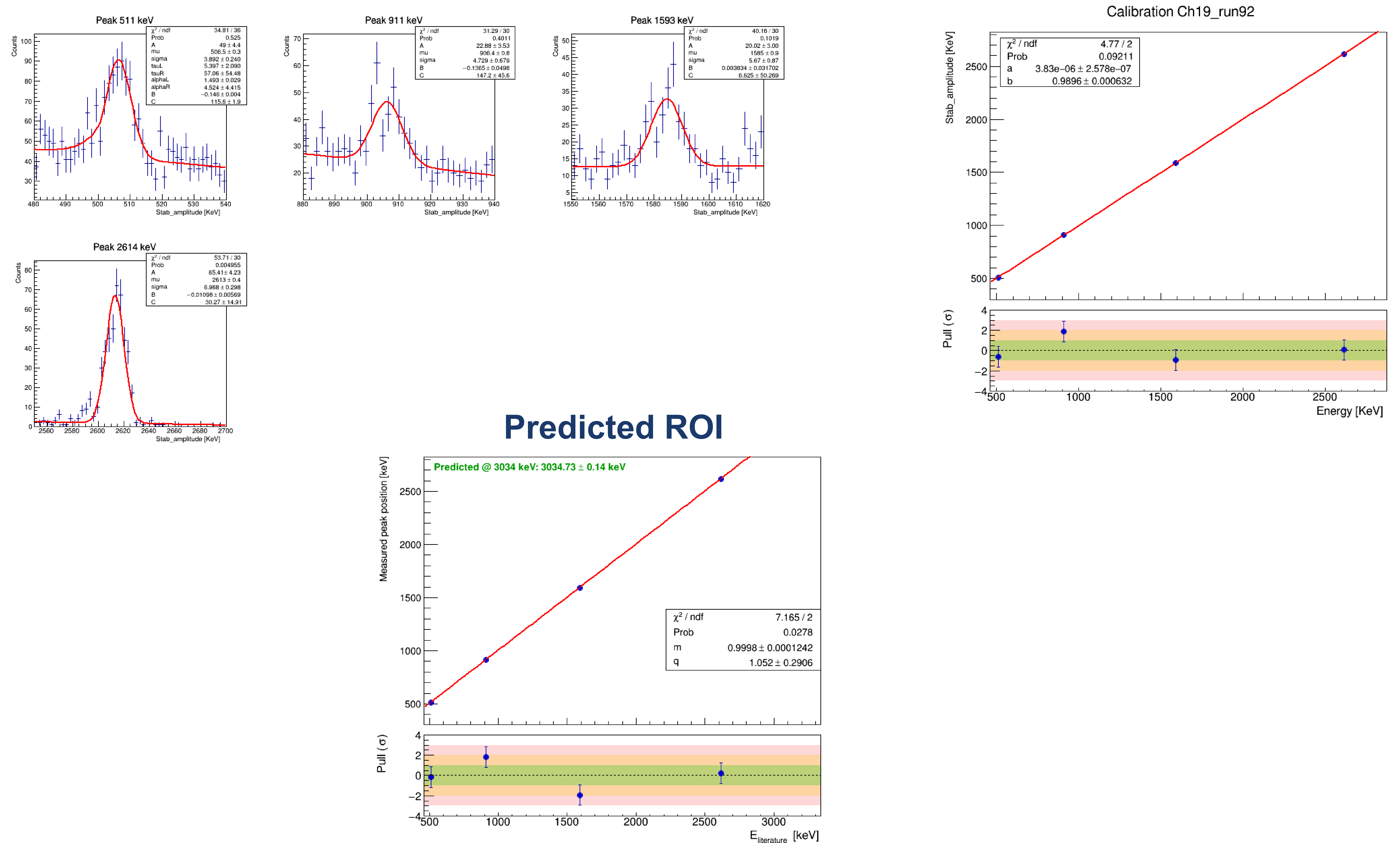
Stabilization and calibration

Stabilization on TI



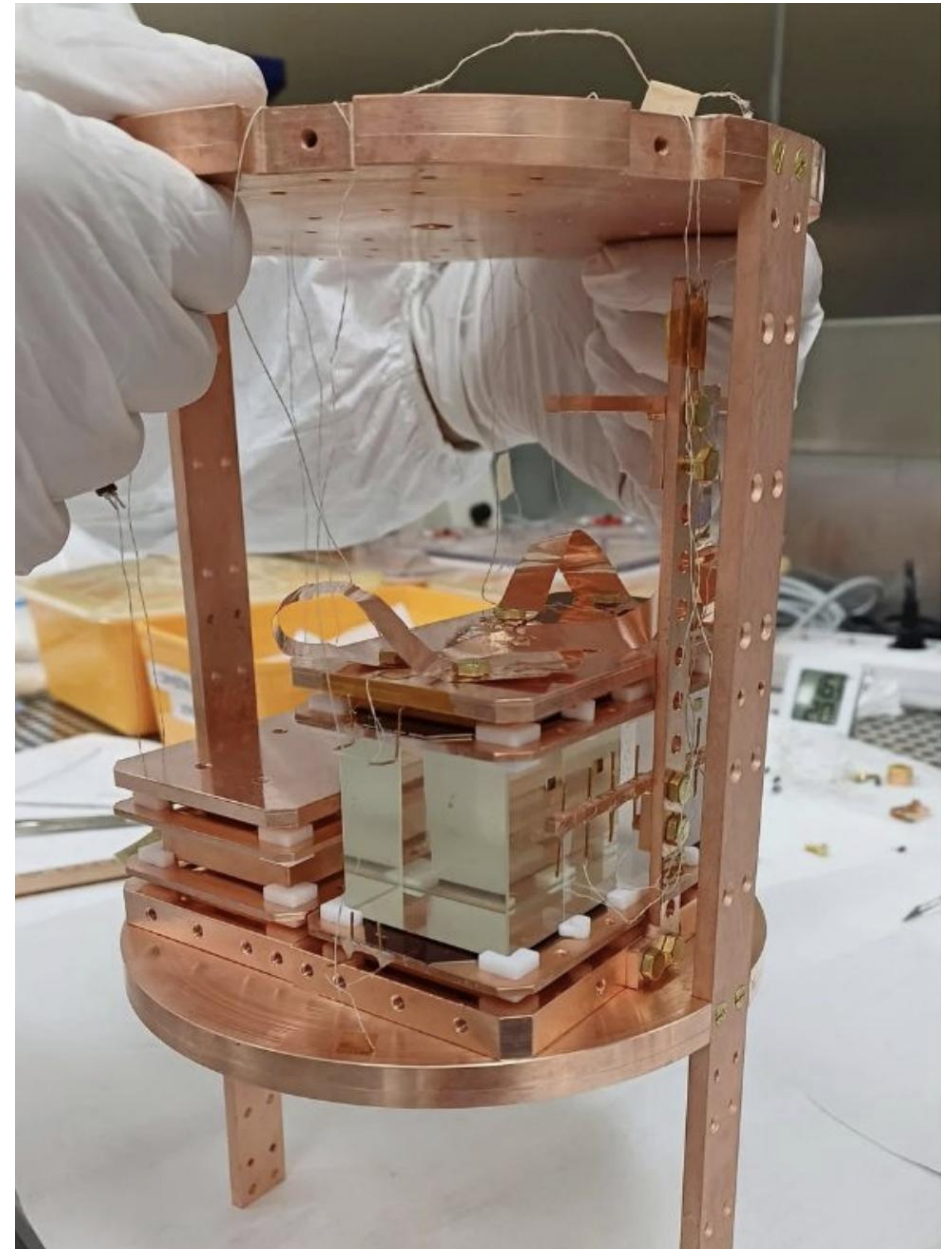
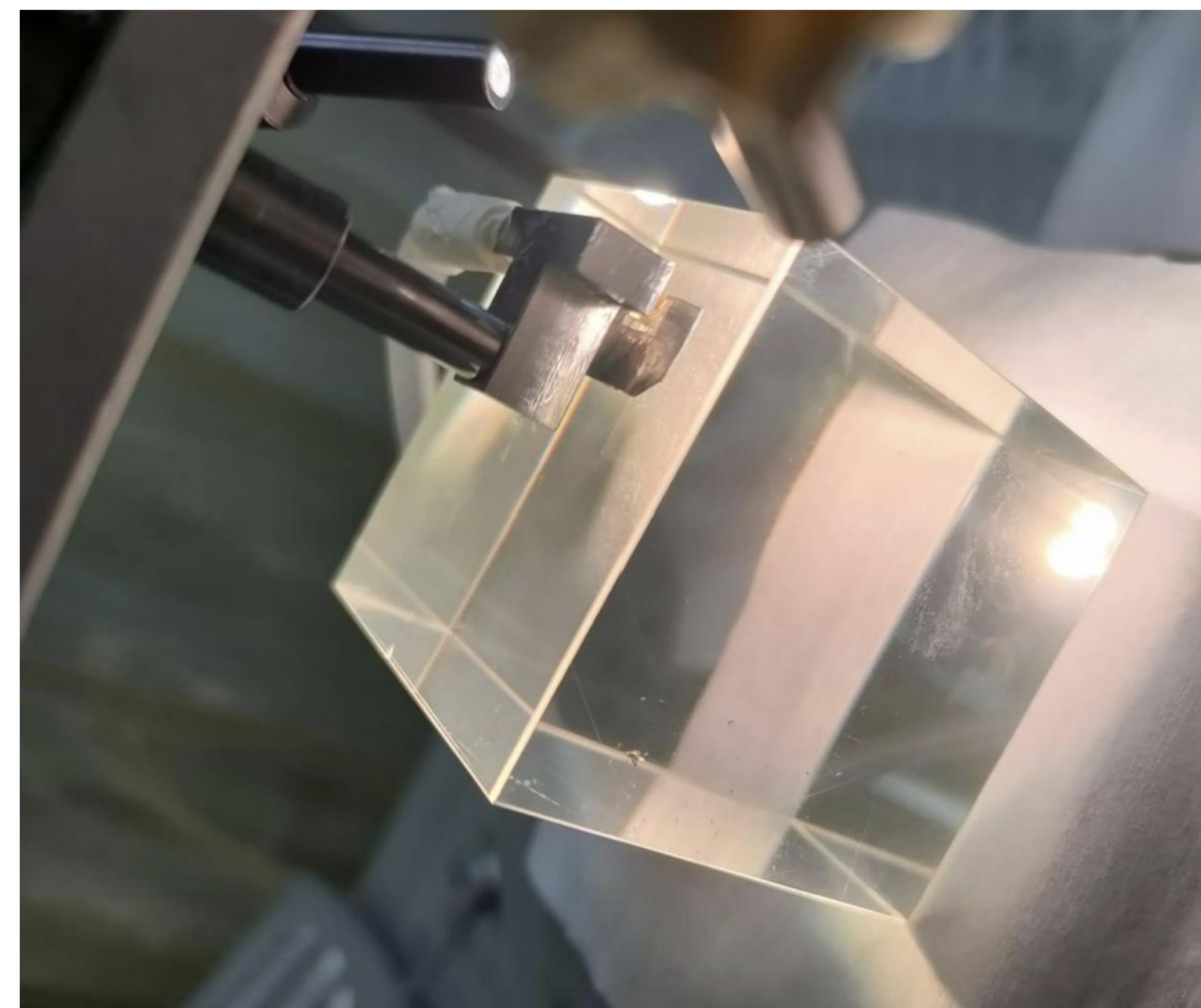
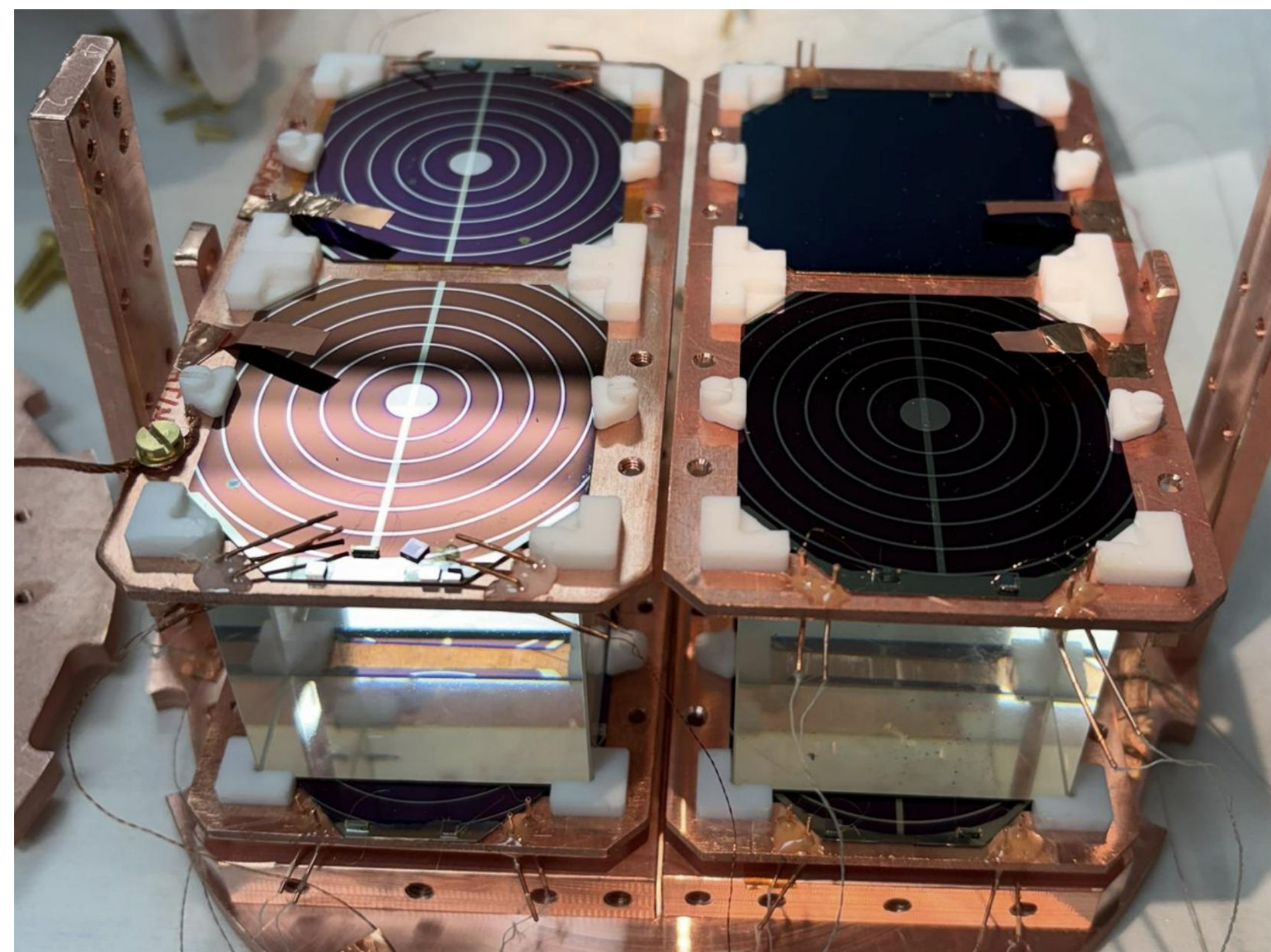
Stabilization and calibration

Calibration



CUPID Crystal Validation Run 5

- **Cryogenic runs** performed with **LMO + LD** setup that **replicates** the **CUPID** modules
- **4 LMOs**, each **instrumented with one NTD** and **two Germanium LDs with Neganov-Luke amplification**
- **Standard facility: low-background wet cryostat at LNGS Hall C**
- **Goal: assess crystal internal contamination, LMOs optical performance and LD performance**



A side project: PTOLEMY neutrino mass sensitivity

Using the **PTOLEMY theory group**'s code, I generated **spectra** for the different **$^3\text{He}^+$ –graphene interaction regimes** (sudden, semi-sudden, adiabatic), including **Gaussian smearing** from the finite **energy resolution**.

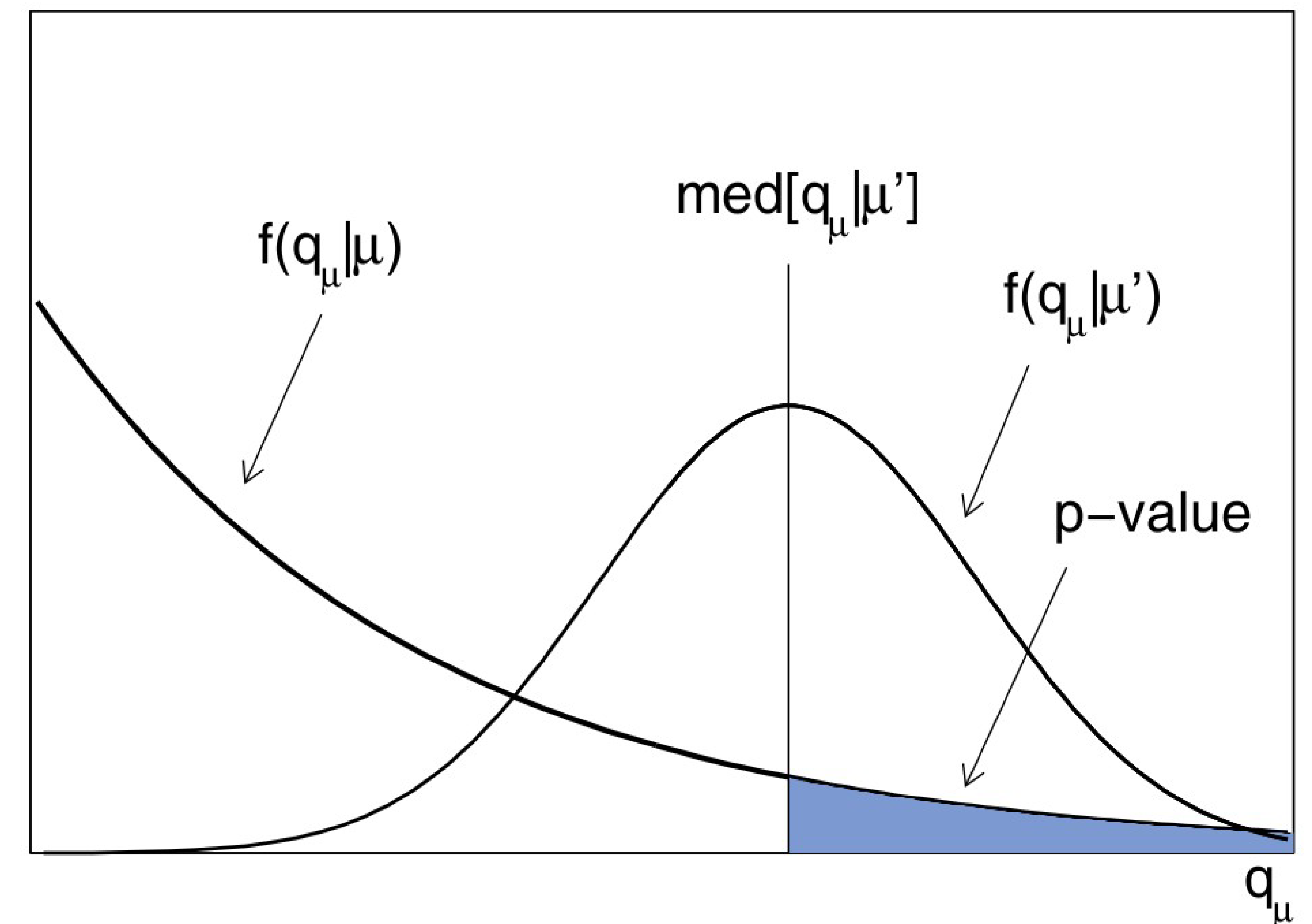
I consider the **profile likelihood** as the **test statistic**:

$$q_\mu = -2 \ln \left(\frac{L(\mu)}{L(\hat{\mu})} \right)$$

$$q_\mu \sim \chi_1^2, \text{ if } \mu = \mu_{true}$$

$$q_\mu = -2 \log \left(\frac{L(S_{\sigma,m} | \text{data}_0)}{L(S_{\sigma,0} | \text{data}_0)} \right) \rightarrow \text{Exclusion sensitivity}$$

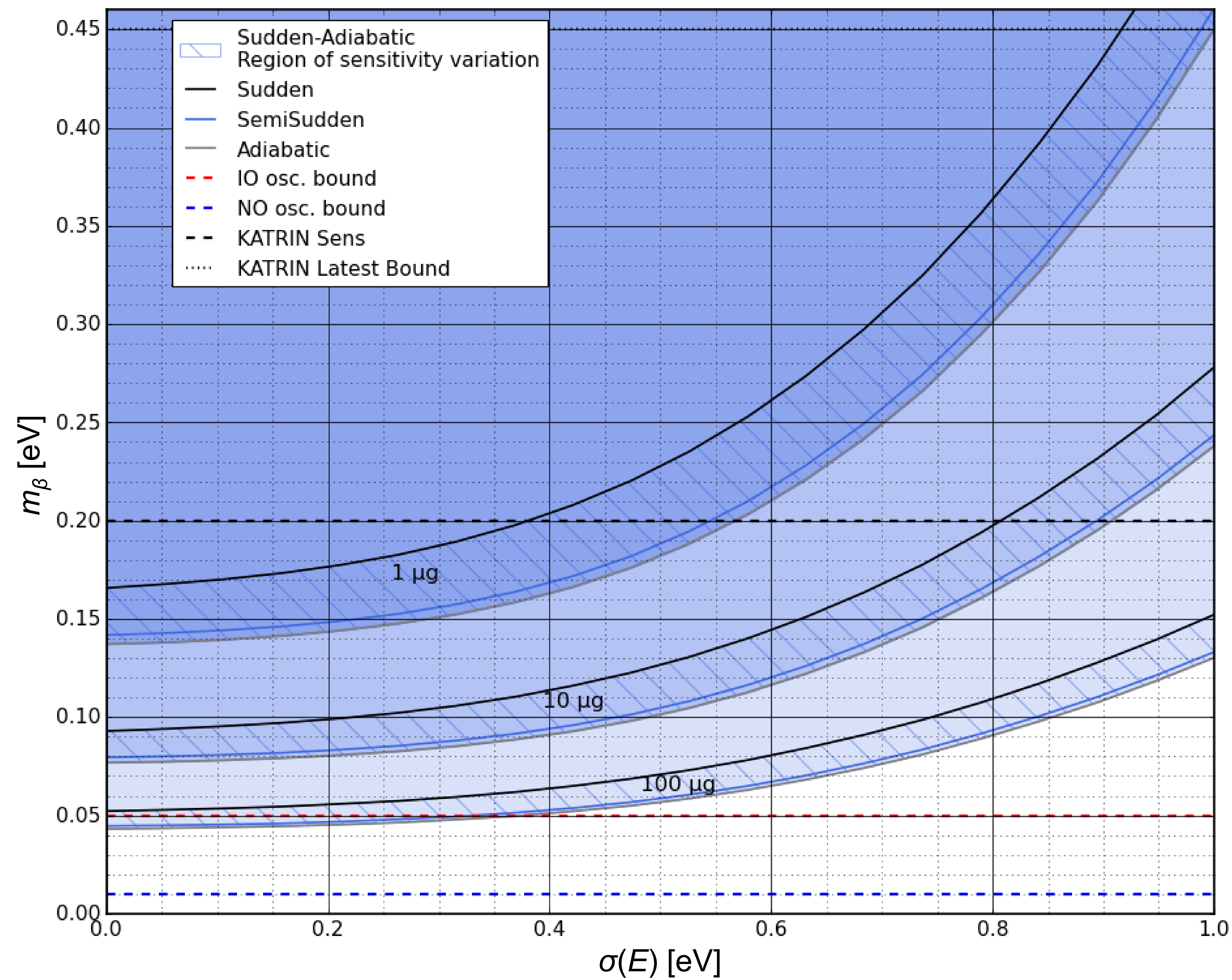
$$q_\mu = -2 \log \left(\frac{L(S_{\sigma,0} | \text{data}_m)}{L(S_{\sigma,m} | \text{data}_m)} \right) \rightarrow \text{Discovery sensitivity}$$



[Cowan et al., EPJC 71 (2011) 1554]

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PTOLEMY Exclusion Sensitivity (3y - 50% eff) - PL



PTOLEMY Discovery Sensitivity (3y - 50% eff) - PL

