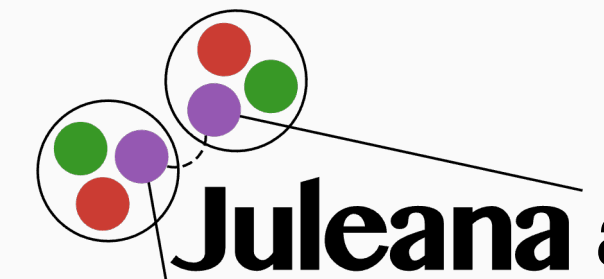
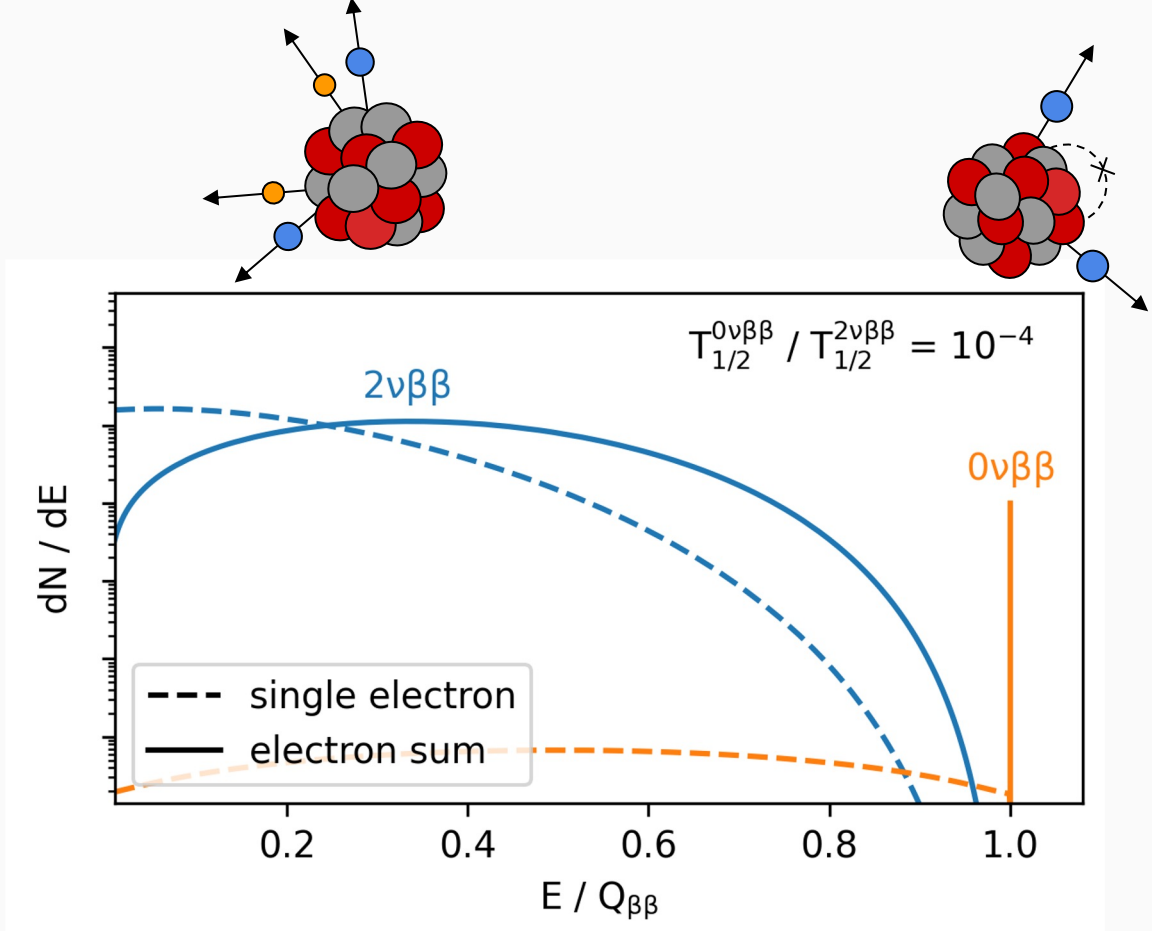




## Introduction

$0\nu\beta\beta$  decay is BSM process

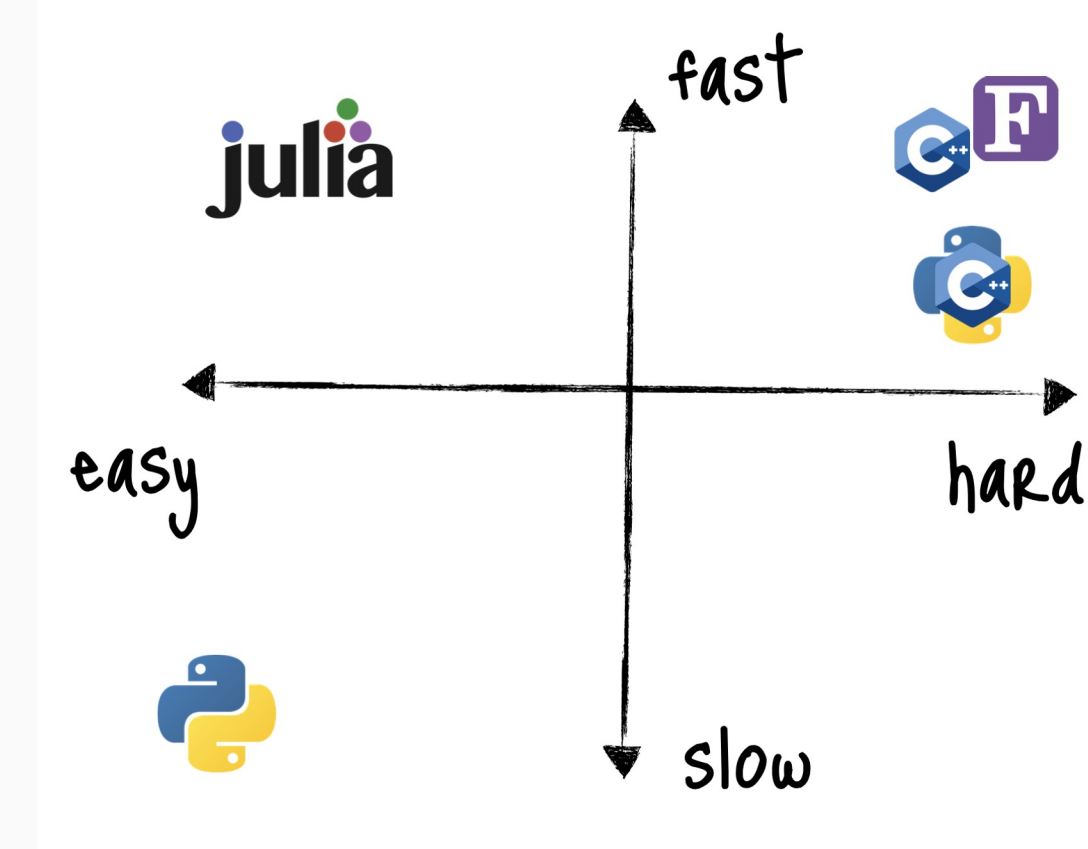
- **Lepton number violation**
  - **Majorana nature** of neutrinos
  - Determine effective Majorana mass
- Signature:
- Unaccompanied emission of two electrons
  - Mono-energetic peak in energy spectrum



## Juleana analysis framework [3]

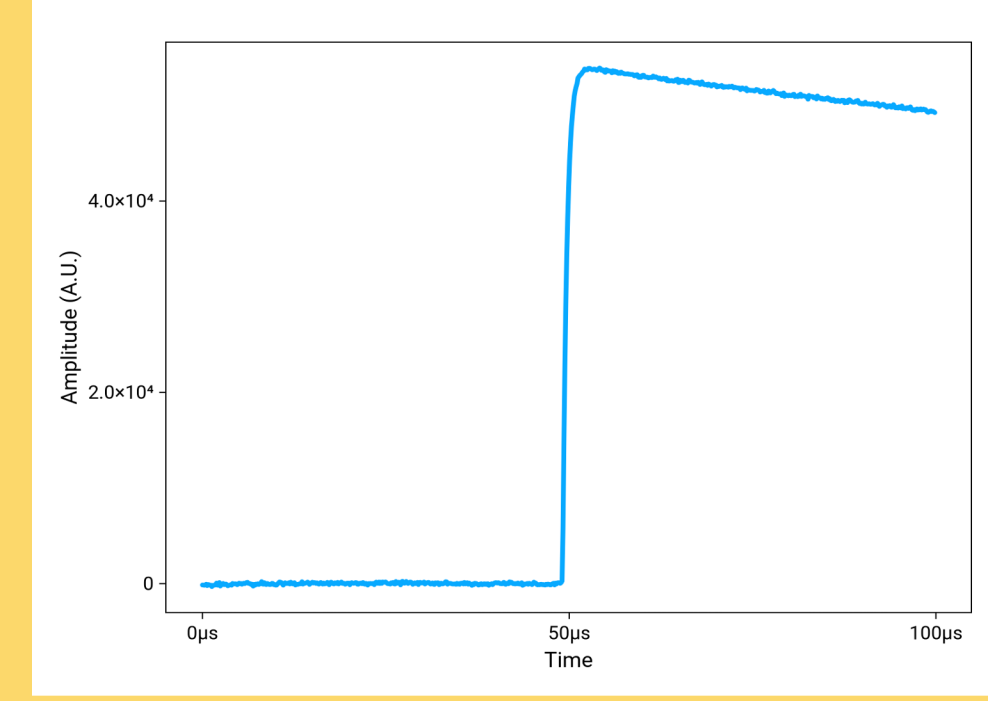
Two independent software stacks:

- Main software stack Pygama in Python
  - Secondary software stack in Julia
- Offline analysis of full digitized raw waveforms  
Julia: near-C performance, intuitive syntax, rich scientific ecosystem  
Extended with open-source, LEGEND-specific packages



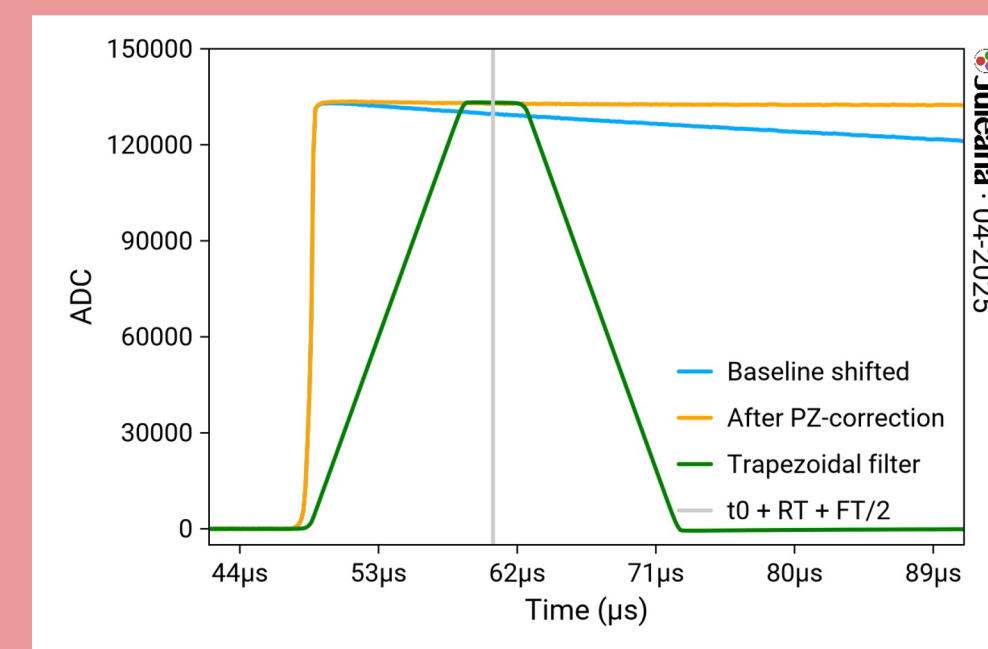
## HPGe Detector signals

- ~60 HPGe Detectors (~130 kg total mass)
- Integrated charge signal proportional to deposited energy
- Tail from front end electronics
- Non-signal like events rejected by quality cuts



## Digital signal processing

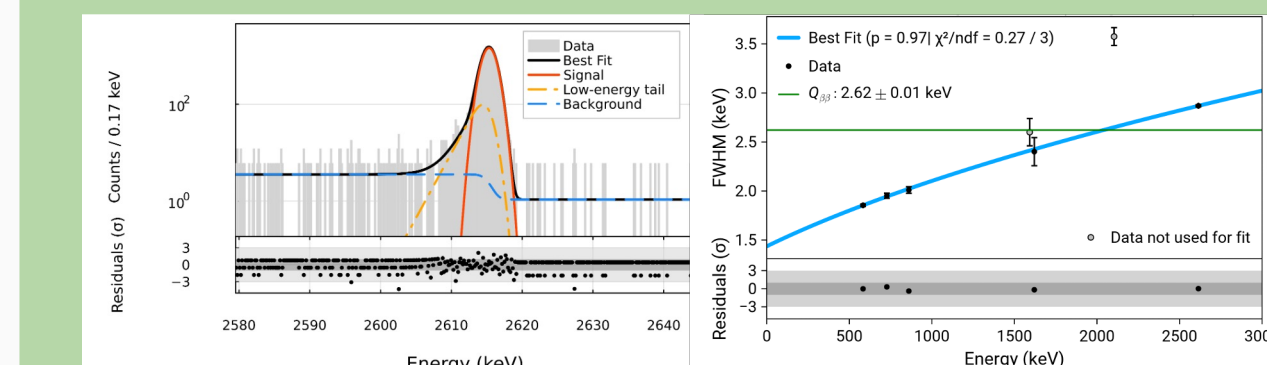
- Customizable sequence of waveform operations to extract analysis parameters
- Optimization for ideal filter settings
- Custom GPU-accelerated routines



Waveform parameters  
e.g. energy, time information, pulse shape parameters

## Energy calibration

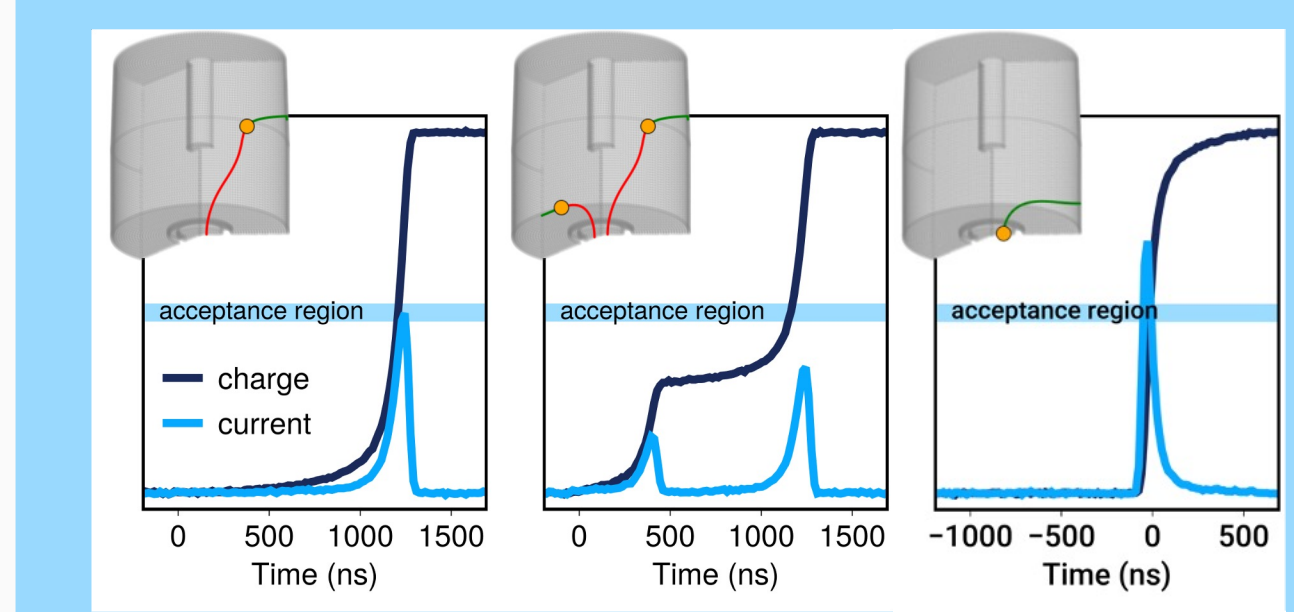
- Weekly  $^{228}\text{Th}$  calibrations
- Fit of  $^{228}\text{Th}$   $\gamma$ -ray peaks to determine energy scale and resolution
- Correction for charge trapping along the drift path



Calibrated energy spectrum

## Pulse Shape Discrimination

- Background rejection by pulse shape differences (by e.g. A/E)
- Distinguish multisite and surface from bulk events



Background discrimination flags

## The LEGEND experiment

- Enriched HPGe detectors submerged in instrumented LAr
- Two phases:

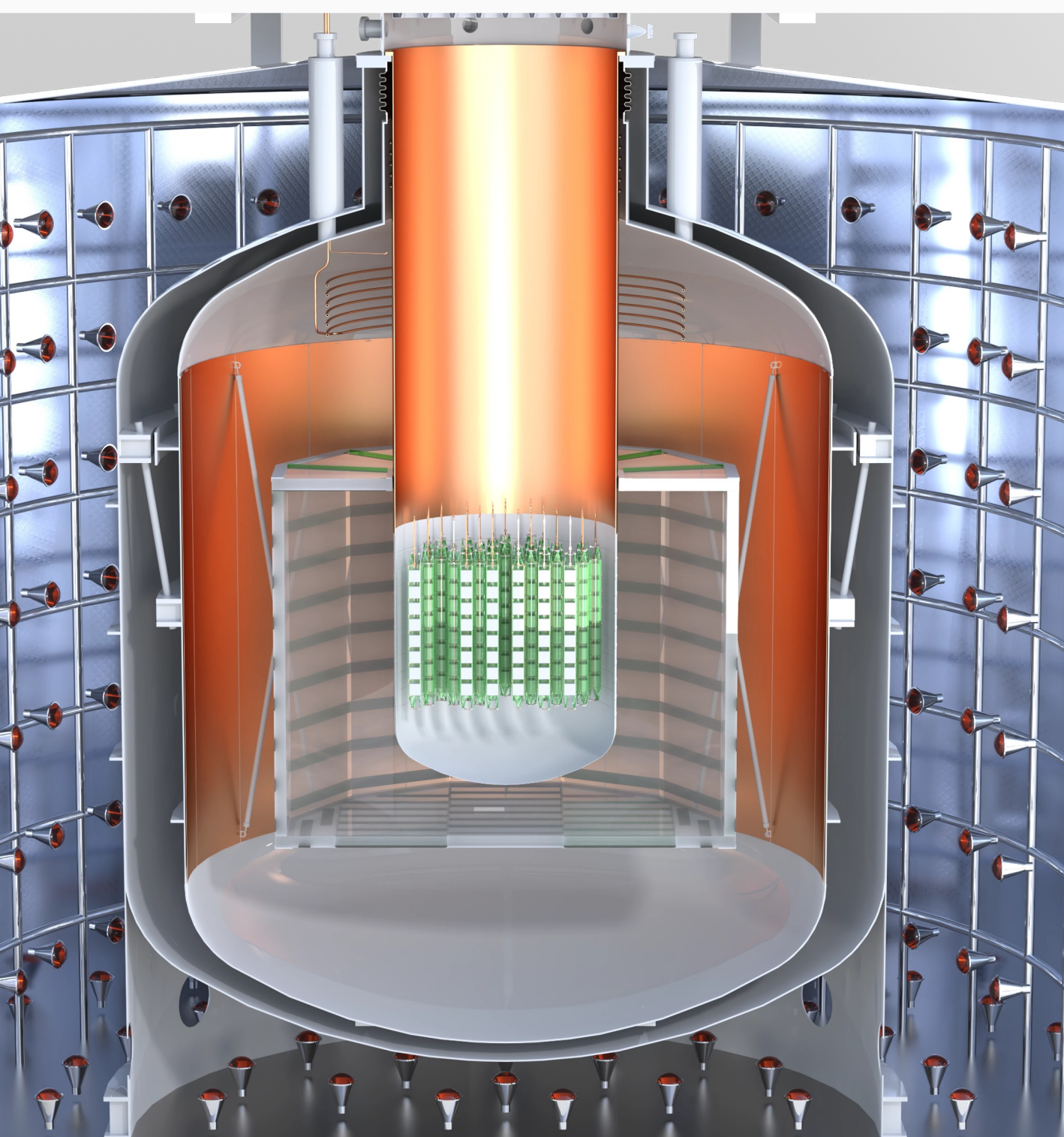
### LEGEND - 200

- Currently taking physics data at LNGS
- First result, world leading constraint
- $T_{1/2}(^{76}\text{Ge}) > 1.9 \cdot 10^{26} \text{ yr}$  (90% C.L.) [1]

Published in PRL

### LEGEND - 1000

- New infrastructure in preparation at LNGS
- Improved background, underground sourced argon, more detector mass
- Discovery sensitivity [2]:  
 $T_{1/2} > 1.3 \cdot 10^{28} \text{ yr}$  ( $3\sigma$ )



## HPGe detectors

Semiconductor detectors enriched in  $^{76}\text{Ge}$

- High Isotope enrichment of >90 %
- High purity -> no intrinsic background
- Excellent energy resolution of 0.1% (FWHM) at  $Q_{\beta\beta}$  (2039 keV)
- Detector = source -> high efficiency
- High stopping power -> background rejection by event topology



## Liquid Argon Instrumentation

- LAr scintillates after energy deposition
- Light is collected by WLS fibers and guided to SiPMs



## Water Cherenkov Veto

- 53 PMTs located in the water tank
- Identification of Cherenkov light to detect cosmic muons



## SiPM processing

- Photoelectron (p.e.) peak identification
- Calibration with first peak fixed to 1 p.e.
- Classical classifier based on p.e. threshold
- ML classifier incorporating position information
- $^{40}\text{K}/^{42}\text{K}$   $\gamma$  lines used as efficiency proxy

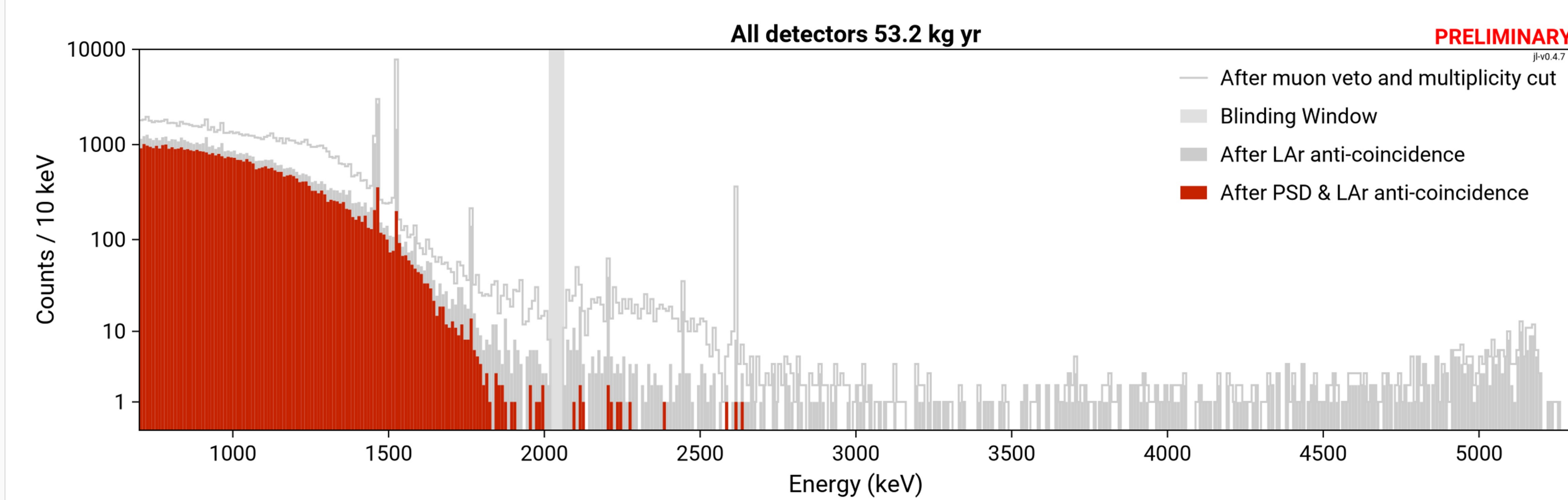
## PMT processing

- LED calibration runs
- Identification of first p.e. peak; calibrated to 1 p.e.
- Threshold based on p.e. sum and multiplicity

Anti coincidence flags

## Event building

- Combine the information of all detector systems into the final energy spectrum



Juleana - 06-2025

## Event building

### LEGEND Institutions

Centre for Energy, Environmental and Technological Research  
Comenius Univ.  
Czech Technical Univ. in Prague and IEAP  
Daresbury Laboratory  
Duke Univ. and Triangle Universities Nuclear Laboratory  
Gran Sasso Science Institute  
Hochschule RheinMain  
Indiana Univ. Bloomington  
INFN - Sezione di Napoli  
Institute for Nuclear Research Russian Academy of Sciences  
Jagiellonian Univ.  
Joint Institute for Nuclear Research  
Joint Research Centre Geel  
Laboratori Nazionali del Gran Sasso

Laboratori Nazionali di Frascati  
Lancaster Univ.  
Leibniz Institute for Crystal Growth  
Leibniz Institute for Polymer Research  
Los Alamos National Laboratory  
MPI for Nuclear Physics  
MPI for Physics  
National Research Centre "Kurchatov Institute"  
National Research Nuclear Univ. MEPhI  
National Taiwan University (NTU)  
North Carolina State Univ.  
Oak Ridge National Laboratory  
Polytechnical Univ. of Milan  
Princeton Univ.

Roma Tre Univ. and INFN  
South Dakota School of Mines and Technology  
Technical Univ. of Dresden  
Leibniz Institute for Particle and Heavy Ion Physics  
Tennessee Technological Univ.  
Univ. of California and Lawrence Berkeley National Laboratory  
Univ. College London  
Univ. of L'Aquila and INFN  
Univ. of Cagliari and INFN  
Univ. of California San Diego  
Univ. of Houston  
Univ. of Liverpool  
Univ. of Milan and INFN

Univ. of Milano Bicocca and INFN  
Univ. of New Mexico  
North Carolina at Chapel Hill  
Univ. of Padova and INFN  
Univ. of South Carolina  
Univ. of South Dakota  
Univ. of Tennessee, Knoxville  
Univ. of Texas at Austin  
Univ. of Tuebingen  
Univ. of Warwick  
Univ. of Washington and Center for Experimental Nuclear Physics and Astrophysics  
Univ. of Zurich  
Williams College



[1] H. Acharya et al. (LEGEND Collaboration), First Results on the Search for Lepton Number Violating Neutrinoless Double- $\beta$  Decay with the LEGEND-200 Experiment, Phys. Rev. Lett. 136, 022701 (2026).  
[2] LEGEND Collaboration, LEGEND-1000 Preconceptual Design Report, arXiv:2107.11462 (2021).  
[3] LEGEND Internal Note, F. Henkes et al (2026).