Pulse Shape Analysis for Ultra-Low Background Gamma Spectroscopy

Application of LEGEND Analysis to BUGS

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Outline

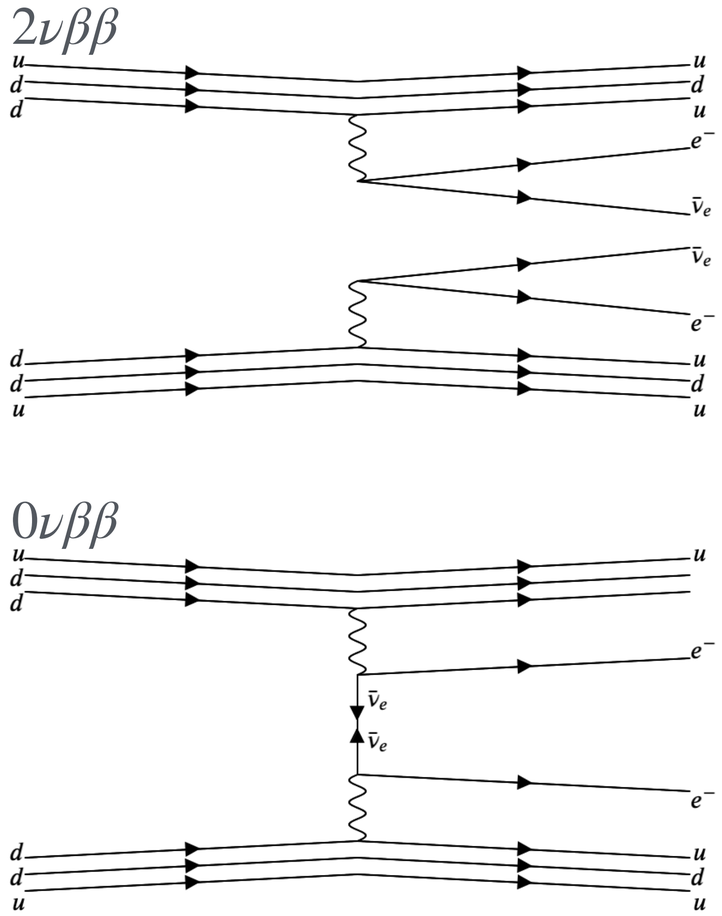
- Introduction
- Motivation
- Digital Signal Processing (DSP)
- Simulation Framework
- Conclusion & Outlook

Introduction

Neutrinoless ββ Decay

Lepton Number Violation & Majorana fermion

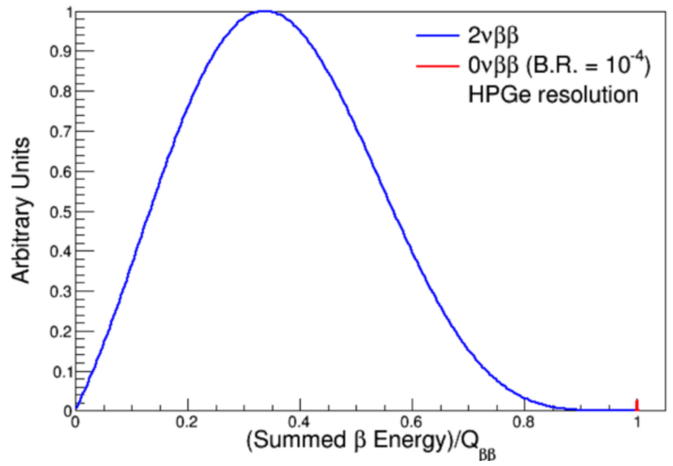
- ββ decay $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$ is the only allowed decay mode for nuclei which single β decay is forbidden.
- A Majorana fermion is a fermion that is its own antiparticle.
- Neutrinoless ββ decay $(A, Z) \rightarrow (A, Z+2) + 2e^-$ violates lepton number conservation by two units and would be arose from massive Majorana neutrinos.

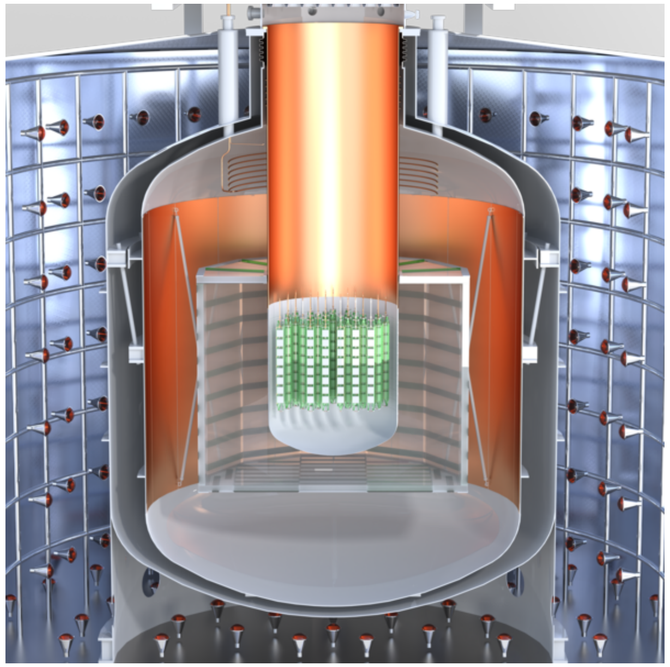


LEGEND Experiment

General Introduction

- **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay - LEGEND
- LEGEND uses High Purity Germanium (HPGe) detectors to detect 0νββ peak $Q_{\beta\beta}$ in spectrum.
- First physics results from LEGEND-200 has been published in 2025. doi.org/10.1103/25tk-nctn
- The next stage, LEGEND-1000, which will have an active mass of 1 ton, is under development.



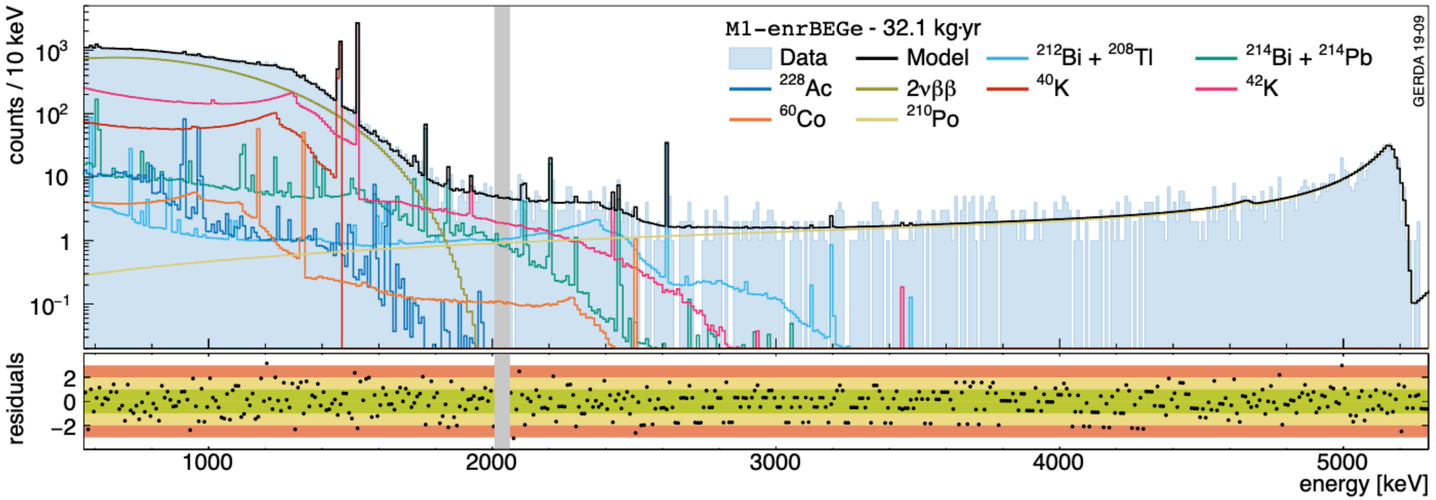


Challenge of LEGEND

Background Modelling & Reducing

- HPGe detectors contain no Th or U inside and LEGEND is located deep underground, so major background is from surrounding materials.

- Background modelling and reducing has been one of the main challenges for LEGEND and other underground experiments.



Motivation

Motivation

- Detection for rare events requires ultra-clean materials and a very good understanding of backgrounds.
- Boulby underground screening facility (BUGS) is among labs where samples are sent for measurement.
- Such materials are usually at the same or lower level of radioactivity compared to current BUGS sensitivity, so it is hard to identify the signal just from energy spectra.
- **Pulse shape discrimination** (PSD) from LEGEND might help push the sensitivity further and provide a better understanding of background location in BUGS.

Pulse Shape Discrimination

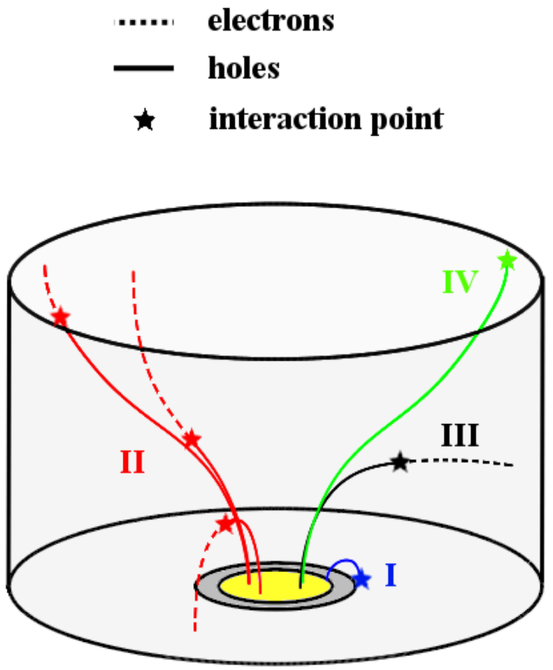
- LEGEND employs HPGe detectors with point-like p+ contact, which allow users to distinguish different types of events from waveforms:

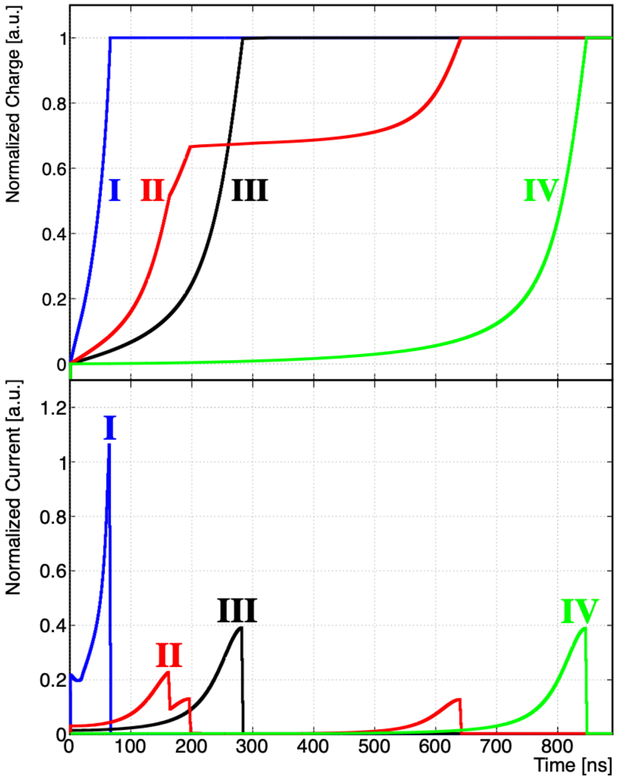
  I. p+ contact event

  II. Multi-sited event

  III. Single-sited event

  IV. Surface event





Digital Signal Processing

Waveform Collection

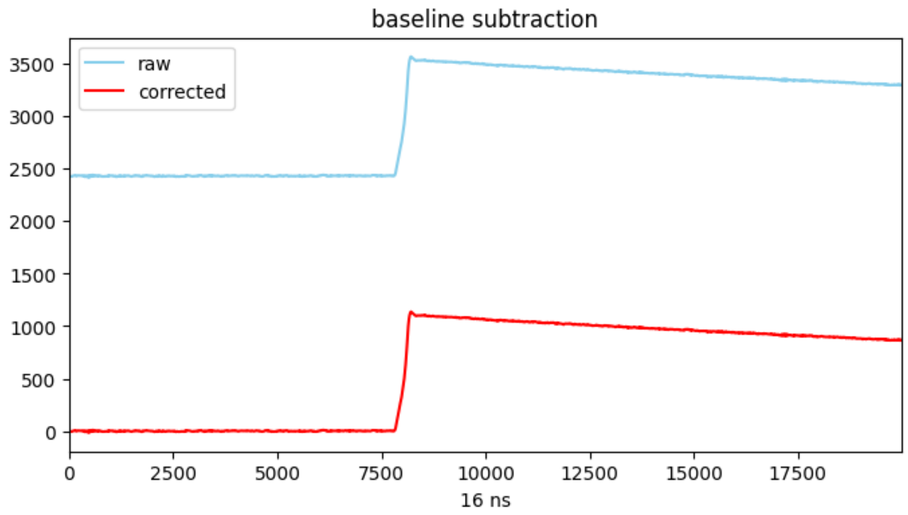
UCL Setup

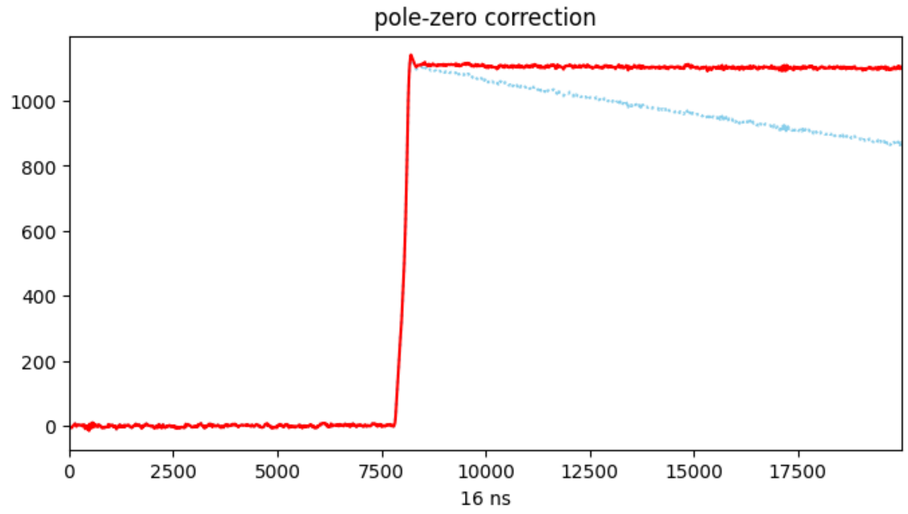
- Signals are collected with a CAEN digitiser.
- Two softwares are available for recording waveforms:
  - CAENScope — only for reading and storing waveforms;
  - CoMPASS — provides basic pulse shape analysis & stores both waveforms and spectrum.

Digital Signal Processing

Waveform Correction

- Baseline is measured with the pre-trigger part of waveform (4000 ns in our case) and subtracted through the waveform.
- The pole-zero correction for electronics response flattens the exponential decay tail with a decay time from config files.

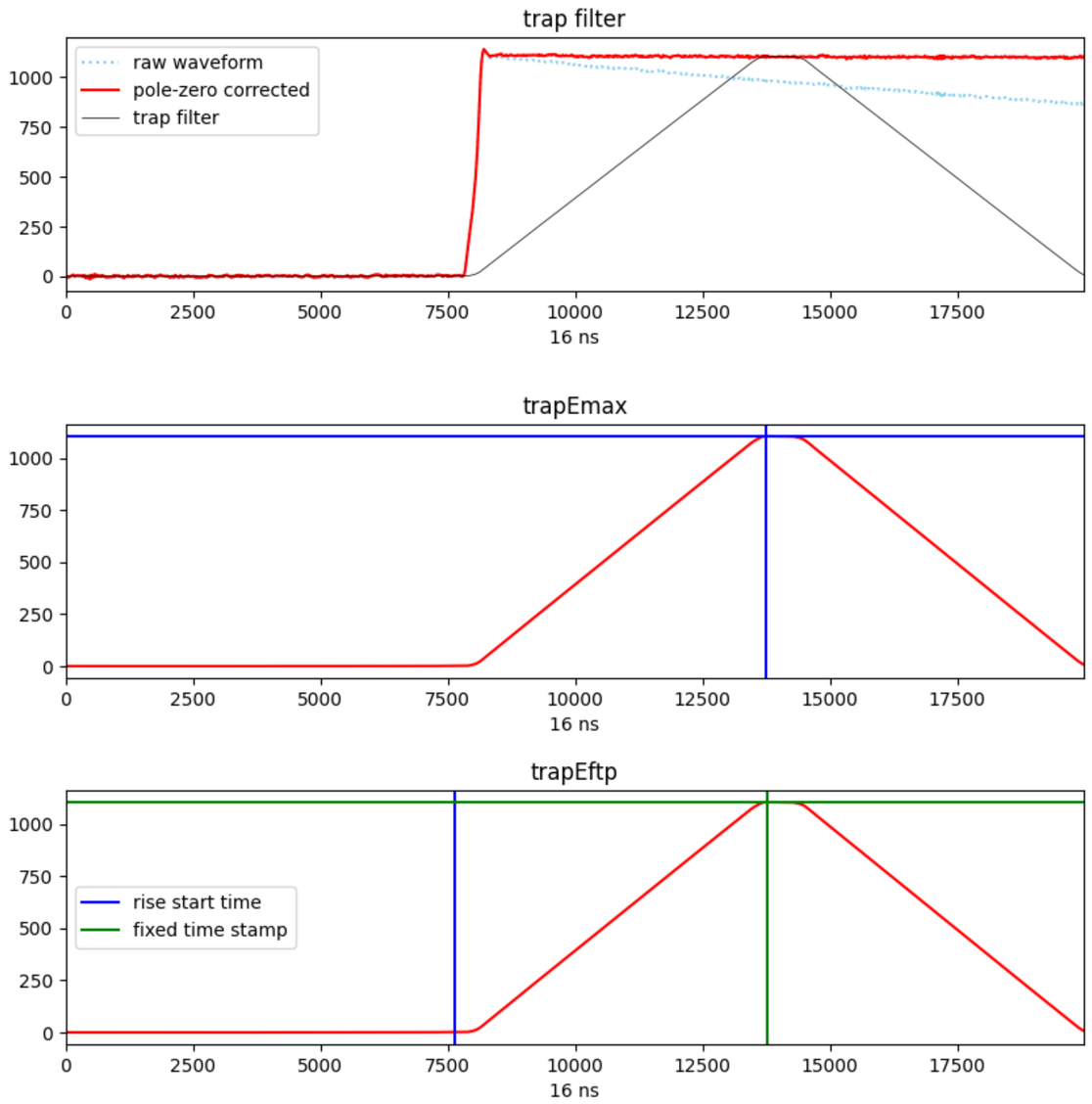




Digital Signal Processing

Energy Estimation

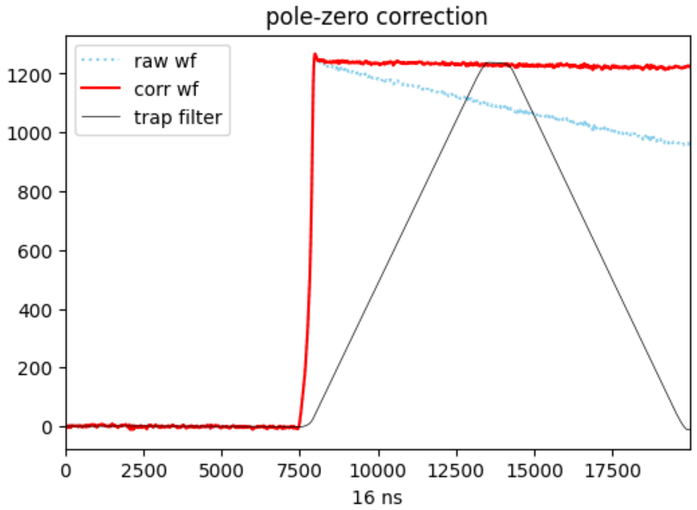
- Trapezoidal (trap) filter:
  - Rising & falling edge (integrate time): 5.6 μs
  - Flat top: 0.8 μs
- Uncalibrated energy is estimated as the maximum of trap filter (trapEmax) or the amplitude at a fixed time (trapEftp).

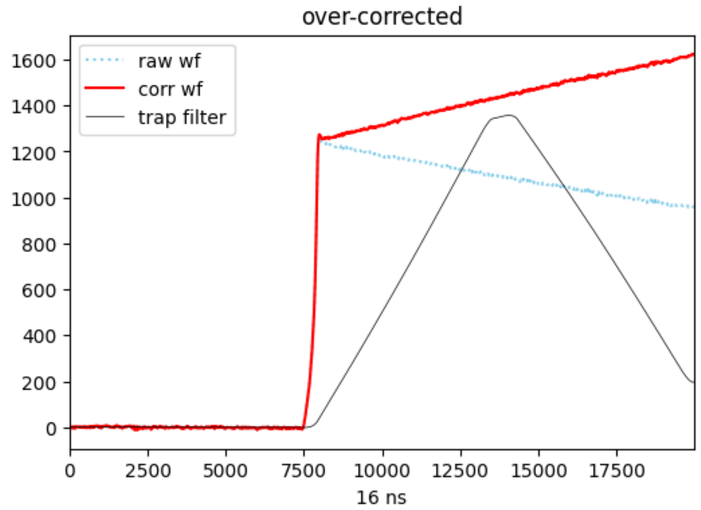


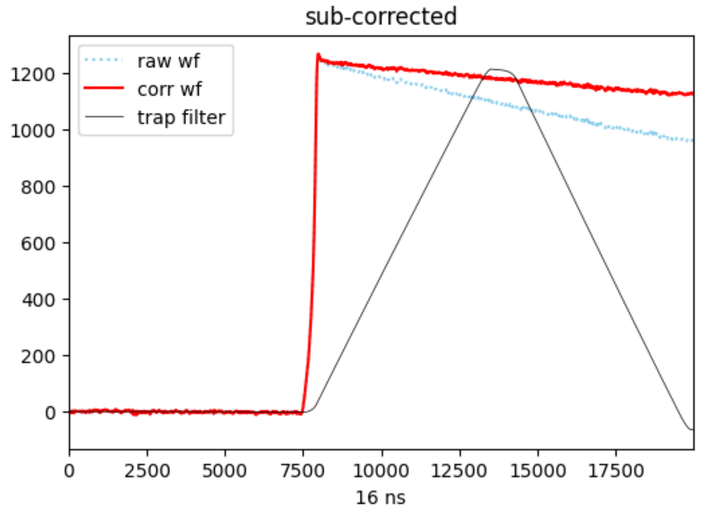
Digital Signal Processing

Pole-zero Correction & Trap Filter

- Pole-zero correction is essential for energy reconstruction.
- Trap filter rise time should be as long as possible to reduce noise effect; and flat time should be longer than waveform rising edge.



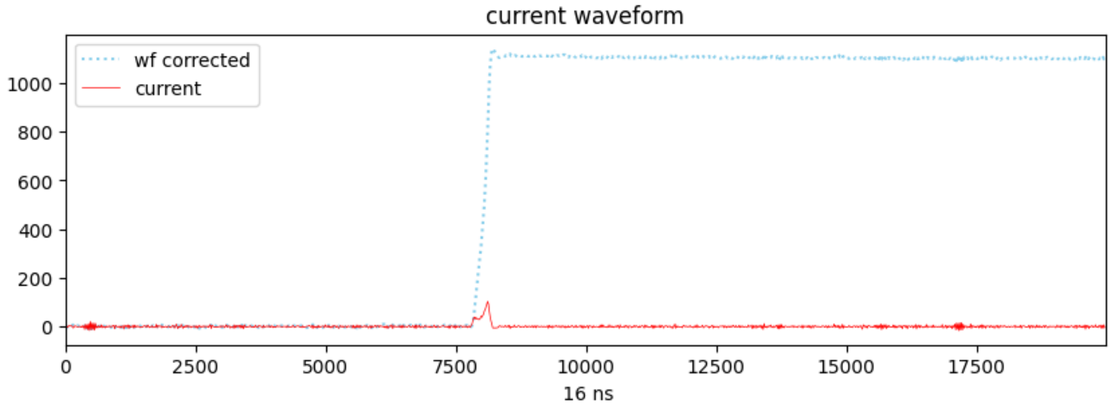


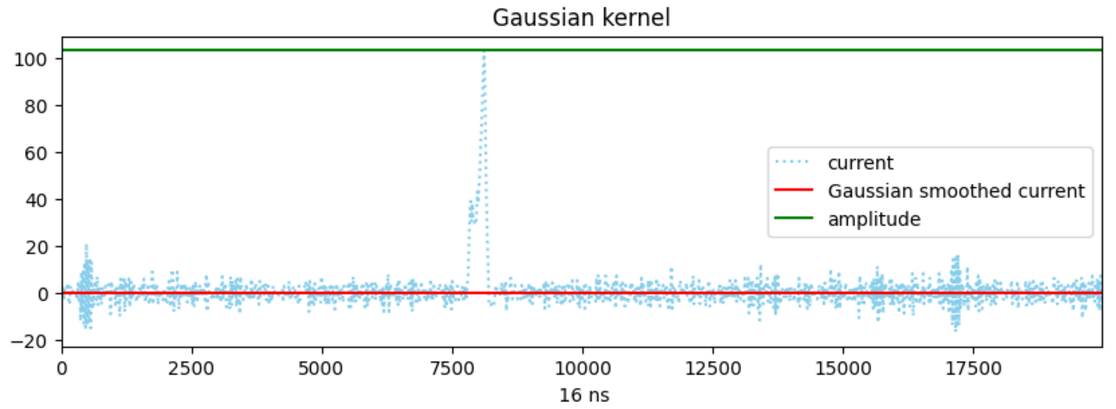


Digital Signal Processing

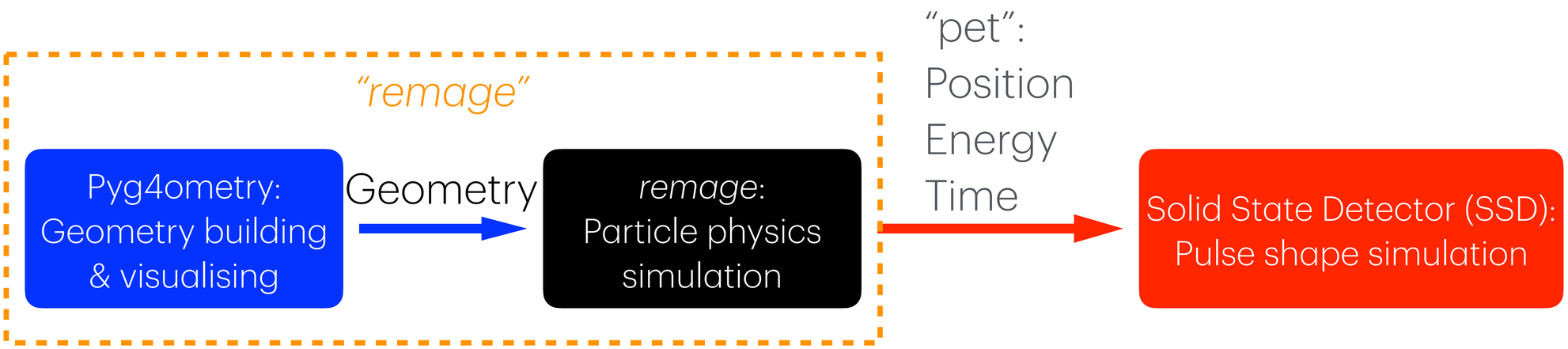
Current Measurement & AoE Analysis

- AoE (A/E) is a key parameter for pulse shape analysis, which is defined as **A**mplitude over **E**nergy:
  - A: maximum of current (differential of energy);
  - E: full waveform energy.





Simulation Framework



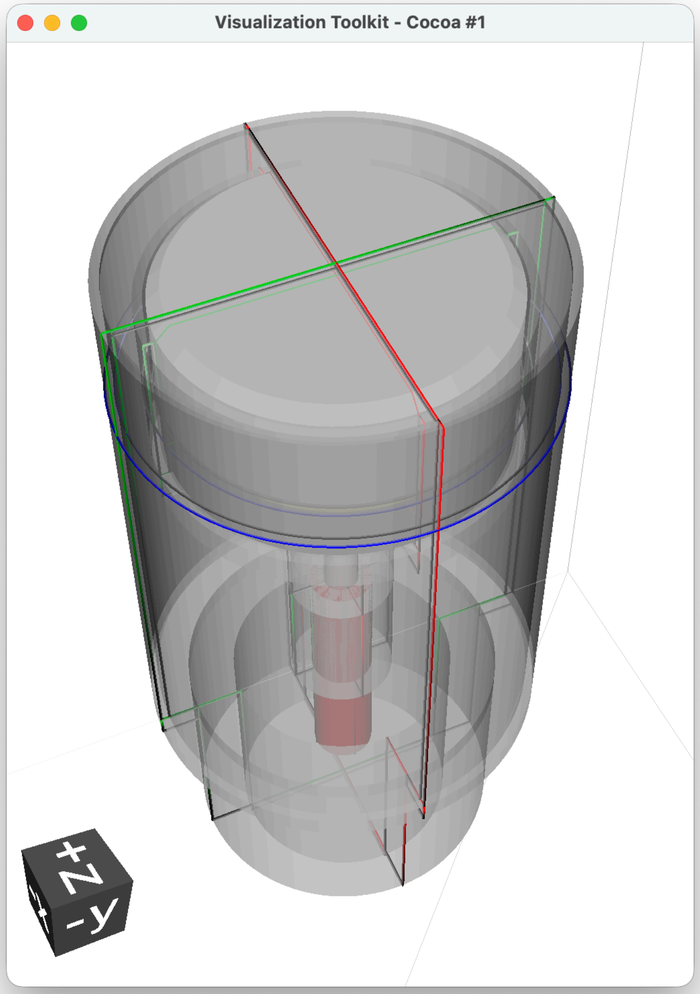
Why Need Simulation?

- Better understanding of physics.
  - Simulation allows us to view physical processes step-by-step and provides information beyond waveforms.
- Saving time.
  - It takes weeks, even months for a physical run in BUGS.

Pyg4ometry

User-friendly Geometry Building & Visualisation Tool

- https://github.com/g4edge/pyg4ometry
- Python package to create, load, write, and visualise solid geometry for particle tracking simulations
- Geometry building:
  1. Solid - describes shape only
  2. Logical volume - a solid (shape) plus a material
  3. Physical volume - a placement of a logical volume



remage

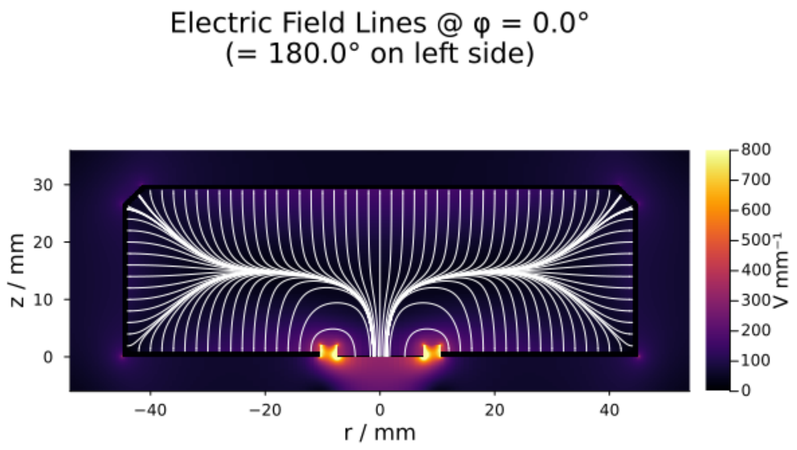
Particle Physics Process Simulation Software

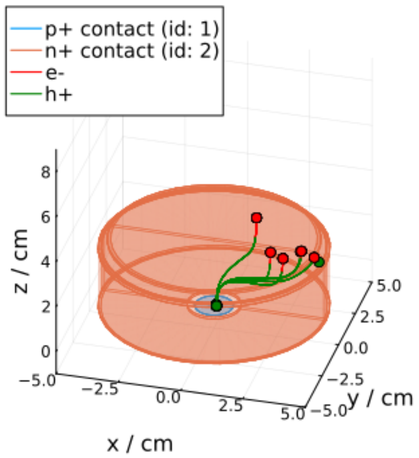
- https://github.com/legend-exp/remage
- Simulate particle interactions in an existing geometry by providing a configuration file using Geant4 macro commands
- Output properties:
  1. evtid: the index of the Geant4 event,
  2. particle: the PDG code of the particle,
  3. xloc, yloc, zloc: the global position,
  4. edep: the deposited energy.

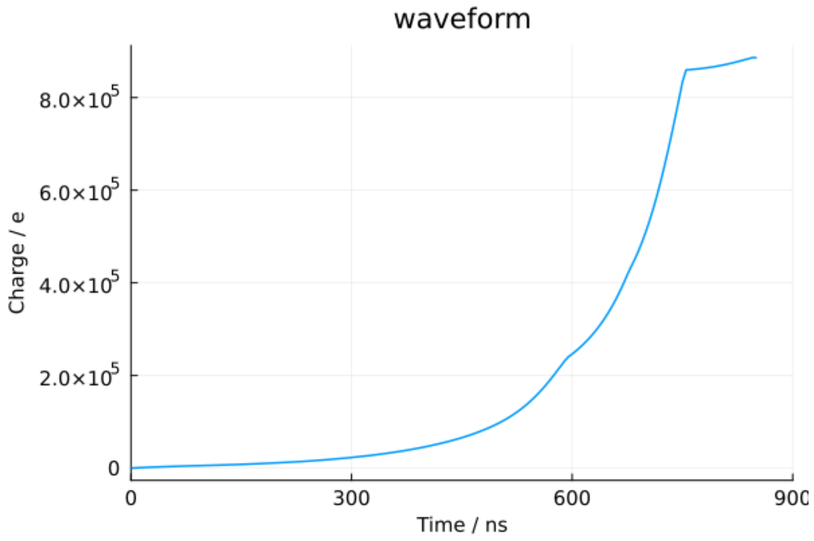
Solid State Detector (SSD)

Pulse Shape Simulation Software

- https://github.com/JuliaPhysics/SolidStateDetectors.jl
- A Julia package for fast 2D and 3D simulation of Solid State Detectors



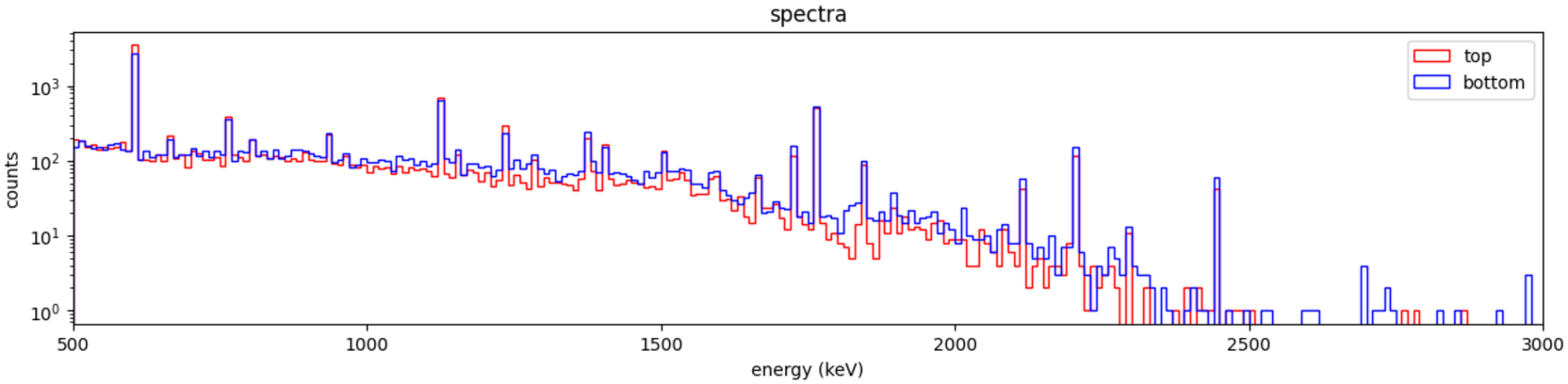


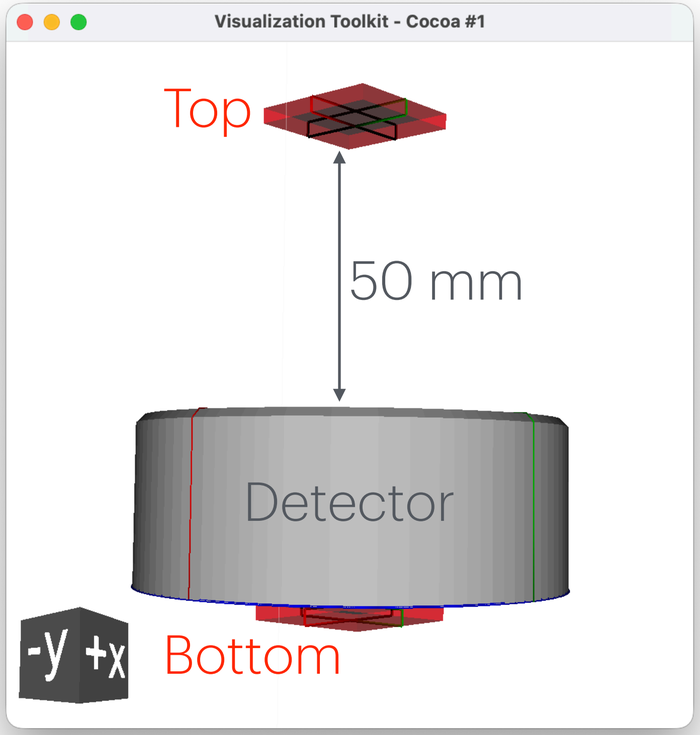


Viewing Simulation Results

Example: Bi-214 Source from Top and Bottom

- Bi-214 is a daughter from Rn-222 decay chain and is a commonly existing source of background.
- The major emission lines of Bi-214 are: 609 keV (~40%), 1120 keV (~15%), and 1764 keV (~15%).





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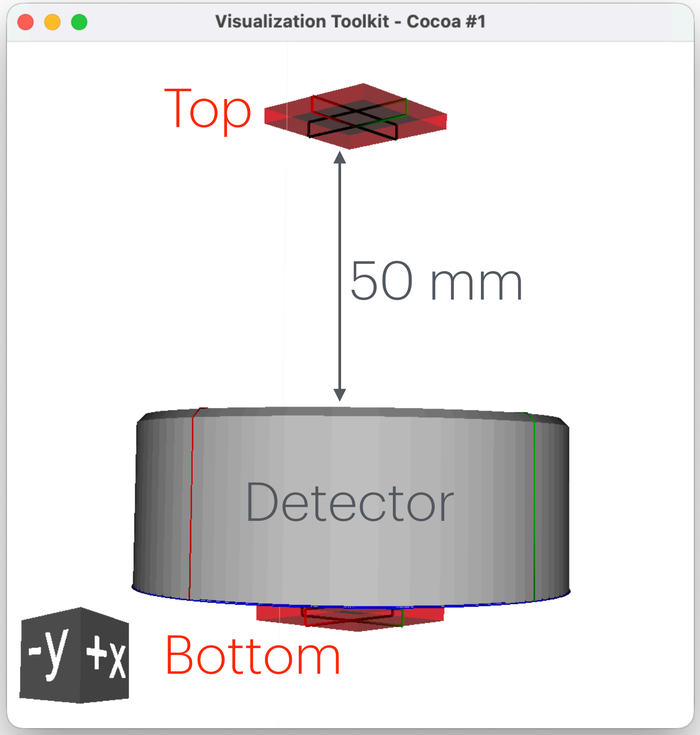

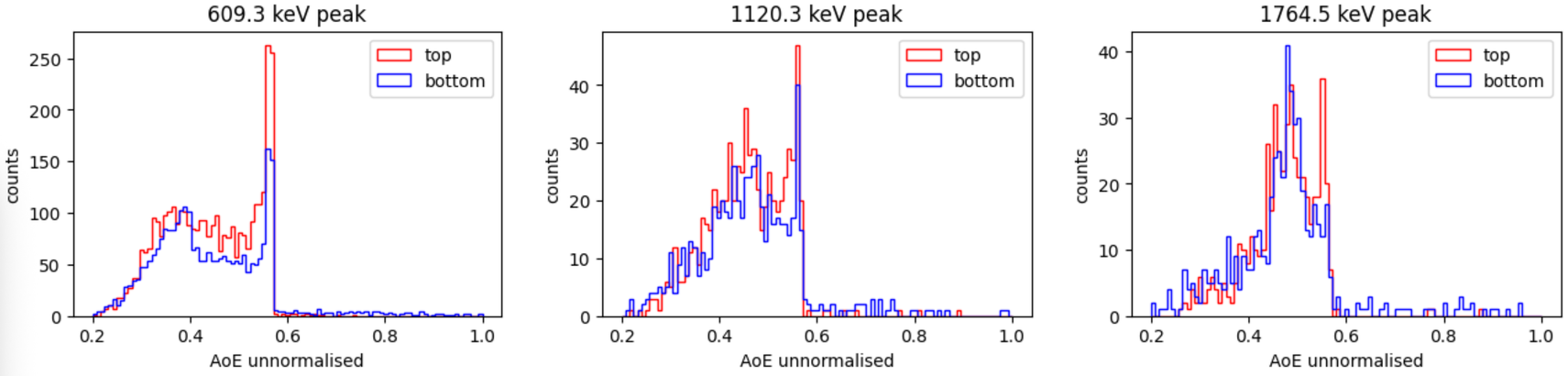

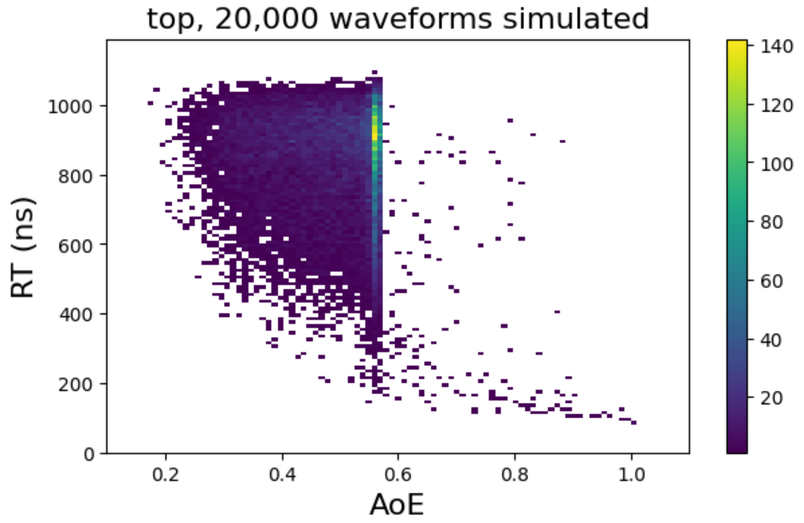

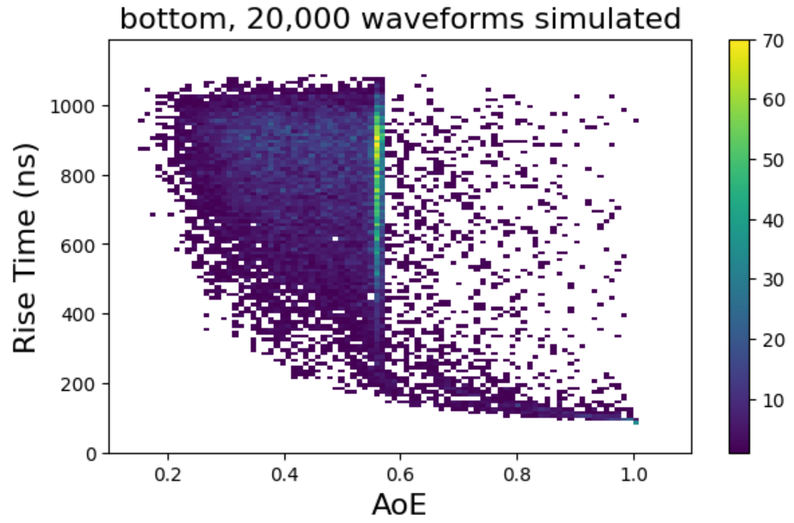

*Rise Time: time between 10% - 90% maximum height

Conclusion

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- LEGEND has developed pulse shape analysis for HPGe detectors with point-like contacts.
- Applying PSA to BUGS could help:
  - Improve signal-to-background ratio in screening;
  - Identify & reduce background.
- PSS is used to help understand waveform features from different sources.
- Multiple cuts will be applied based on simulation results and calibration data.

Outlook

- Carry out calibration and test on one of Boulby detectors, Chaloner, in April.
- Taking data from background & standard source during May & June.
- Data analysis and first-step output in summer 2026.