Juleana

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

How to analyze a full experiment in Julia

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Oliver Schulz – Max-Planck Institute for Physics

MAX-PLANCK-INSTITUT FÜR PHYSIK

What happens in this talk

1. Introduction to LEGEND and 0νββ-decay physics
2. What is the JuLeAna Software Stack?
3. Features and highlights in the application to LEGEND data
4. Summary & Outlook

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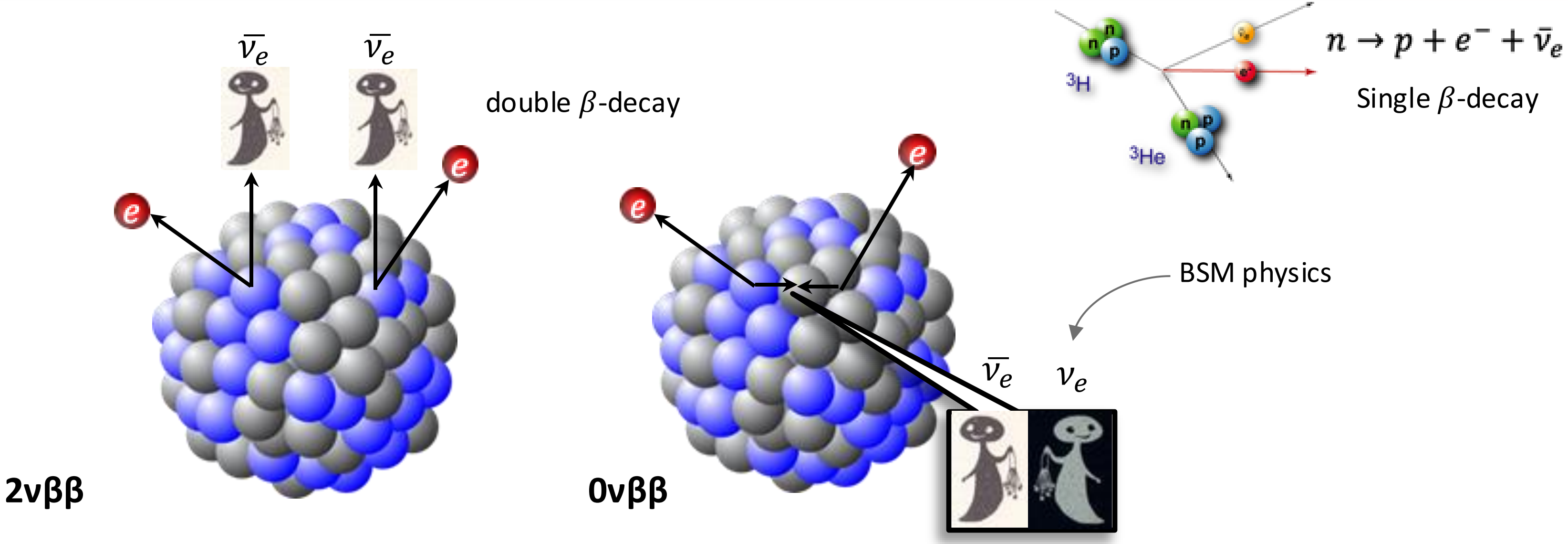
Neutrinoless double beta decay

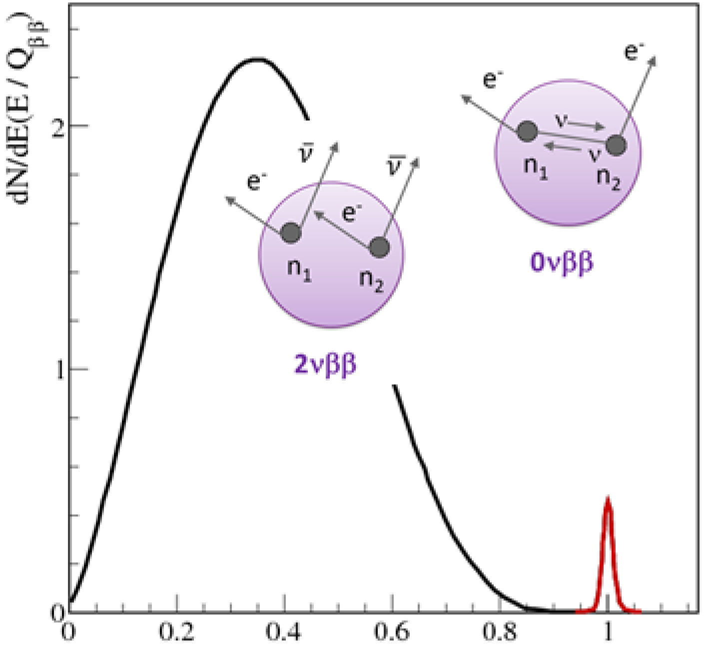


- 2νββ: simultaneous decay of two neutrons in a nucleus (observed e.g. in ^{76}Ge)
- 0νββ: process in which two particles are created without balancing anti-particles

  → Lepton-Number Violation by 2 orders

  → Could possibly explain matter-antimatter asymmetry in the early universe

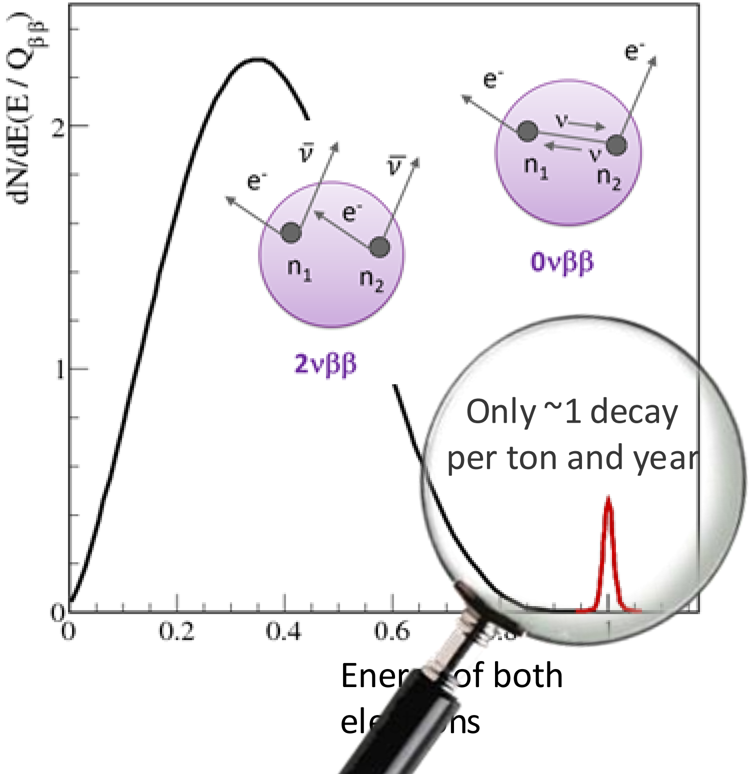
The signature



Energy of both electrons

- 2νββ: continuous energy spectrum
- 0νββ: peak at the Q-value
- For ^{76}Ge: Q = 2.039 MeV

The challenge



- 2νββ: continuous energy spectrum
- 0νββ: peak at the Q-value
- For ^{76}Ge: $Q_{\beta\beta}$ = 2.039 MeV

Key requirements:

- Large exposure (tonne-scale)
- Excellent energy resolution (~ 1% @ $Q_{\beta\beta}$)
- Low background (< 1 cts/year/t/ROI)

The LEGEND Experiment

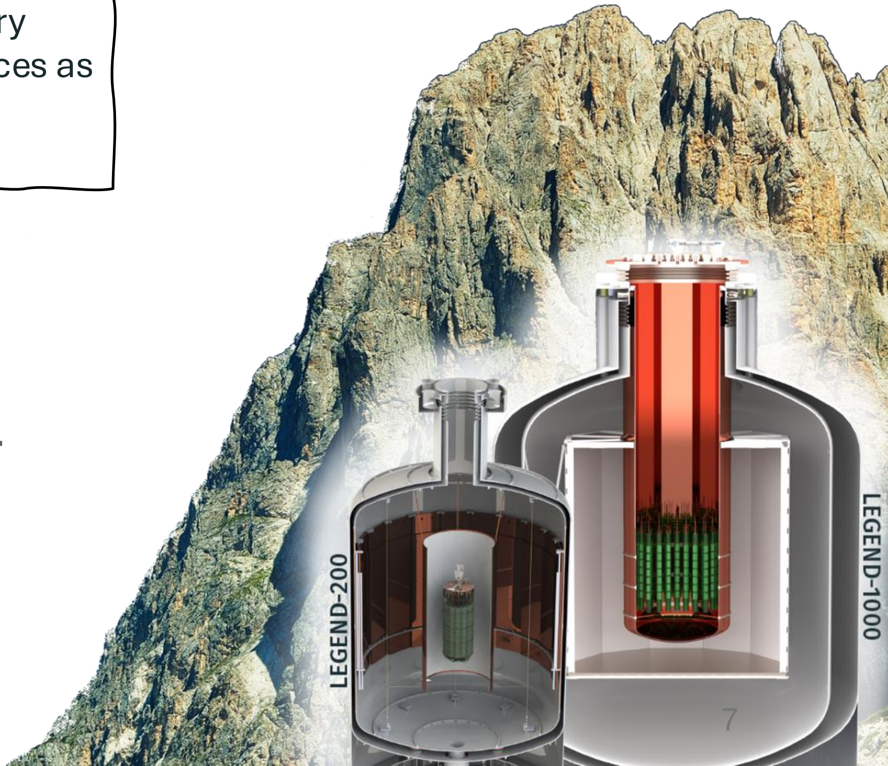
"The collaboration aims to develop a **phased, ^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28}yr**, using existing resources as appropriate to expedite physics results."

LEGEND-200

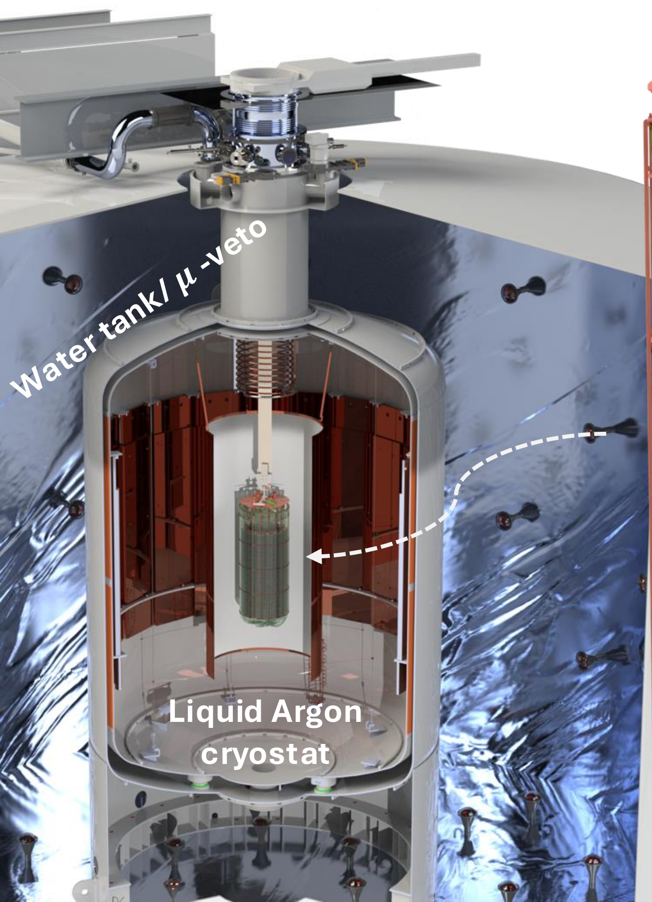
- **200kg** of ^{enr}Ge (x 5yr), in *GERDA cryostat*
- Physics data taking since March 2023
- B ~ **2 · 10^{-4}** cts / (keV · kg · yr) → $T^{0\nu}_{1/2} >$ **10^{27} yr**

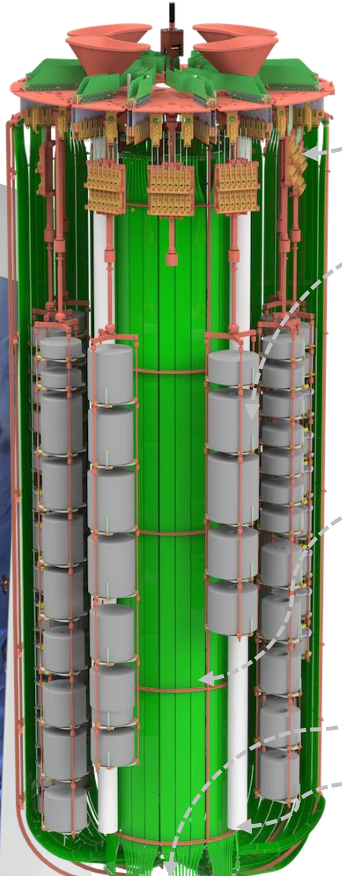
LEGEND-1000

- **1t** of ^{enr}Ge (x 10yr), pending funding
- B < **10^{-45}** cts / (keV · kg · yr) → $T^{0\nu}_{1/2} >$ **10^{28} yr**
- Fully cover $m_{\beta\beta}$ inverted ordering region



The LEGEND Experiment





HPGe readout electronics

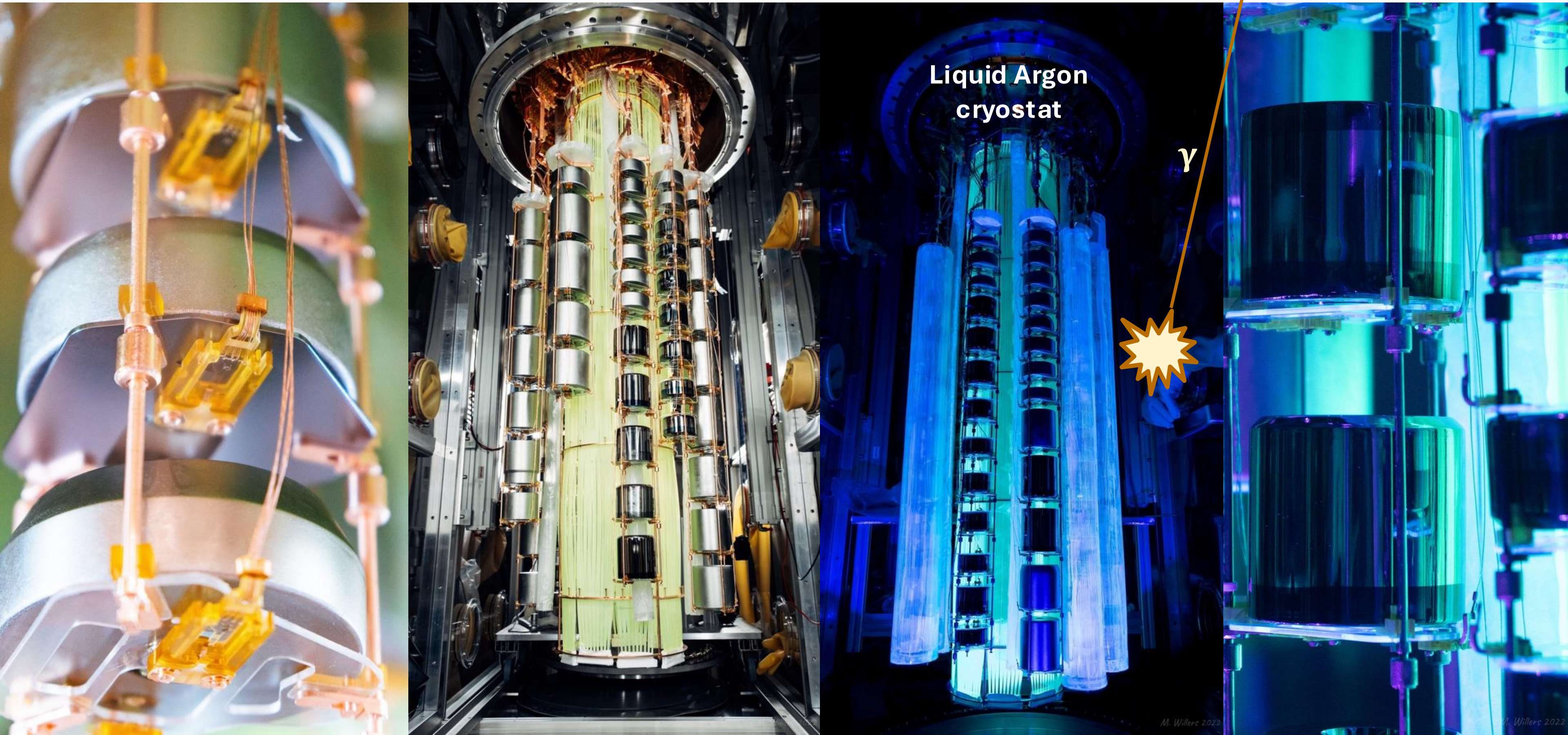
Larger mass (inverted coaxial) **HPGe detectors** with up to 4 kg

Liquid Argon instrumentation: inner & outer fiber barrels with silicon photomultiplier (SiPM) readout at top & bottom

Source funnels for ^{228}Th calibration sources

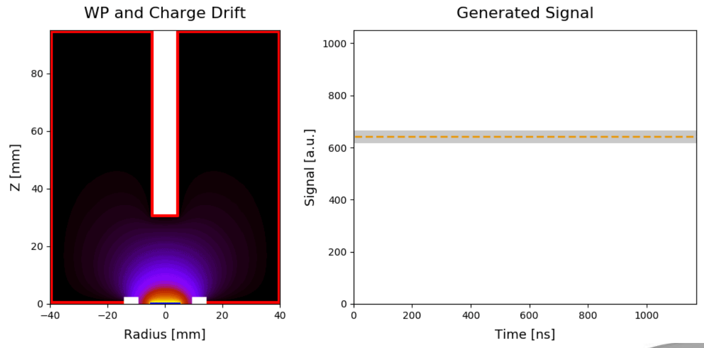
Detector mount: underground copper, optically active PEN plates and radiopure PEI

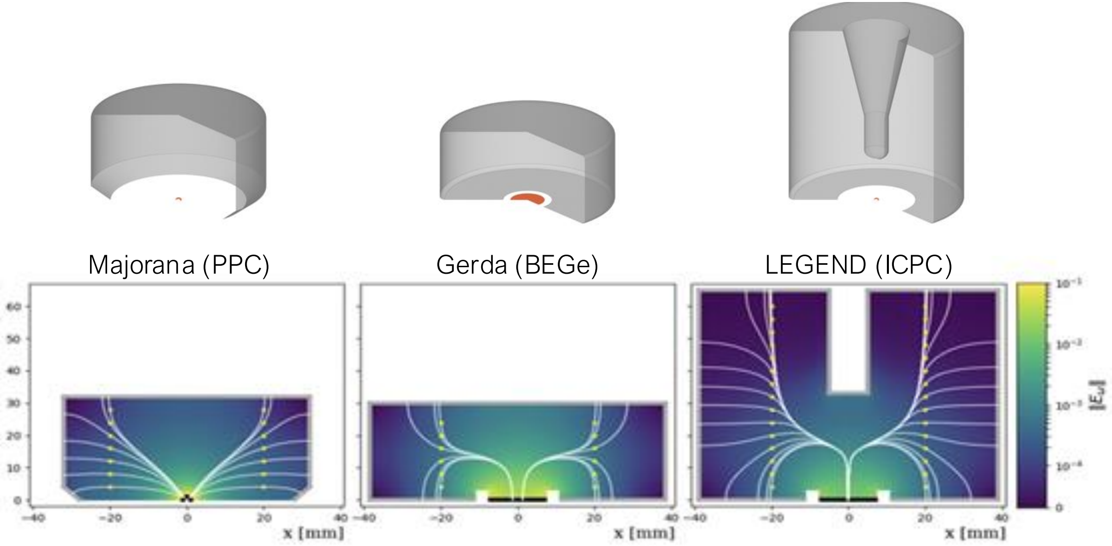
The LEGEND Experiment



HPGe Detectors

- **Detector = source** of ββ decay events
- **Isotope enrichment** from 7.7% to > 90 % possible
- Very good **energy resolution of $\mathcal{O}$ 0.1%** (FWHM) at 2039 keV (Qββ of 76Ge)
- High **density** & high **detection efficiency**

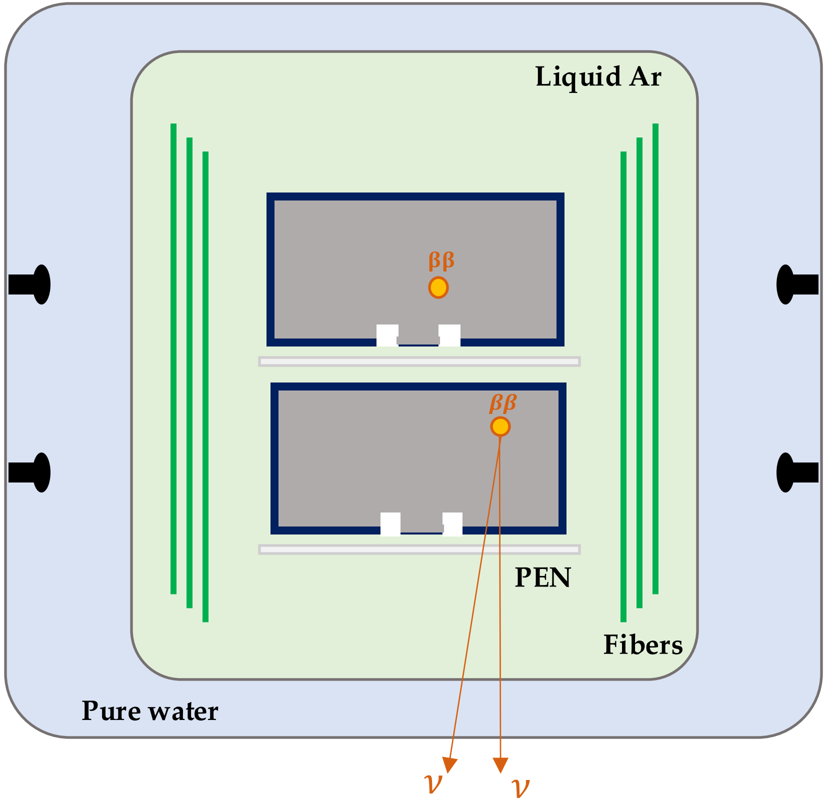




Background Reduction Strategy

MJD, GERDA, LEGEND

ββ decay signal: single-site event energy deposition in a ~1 mm^3 volume



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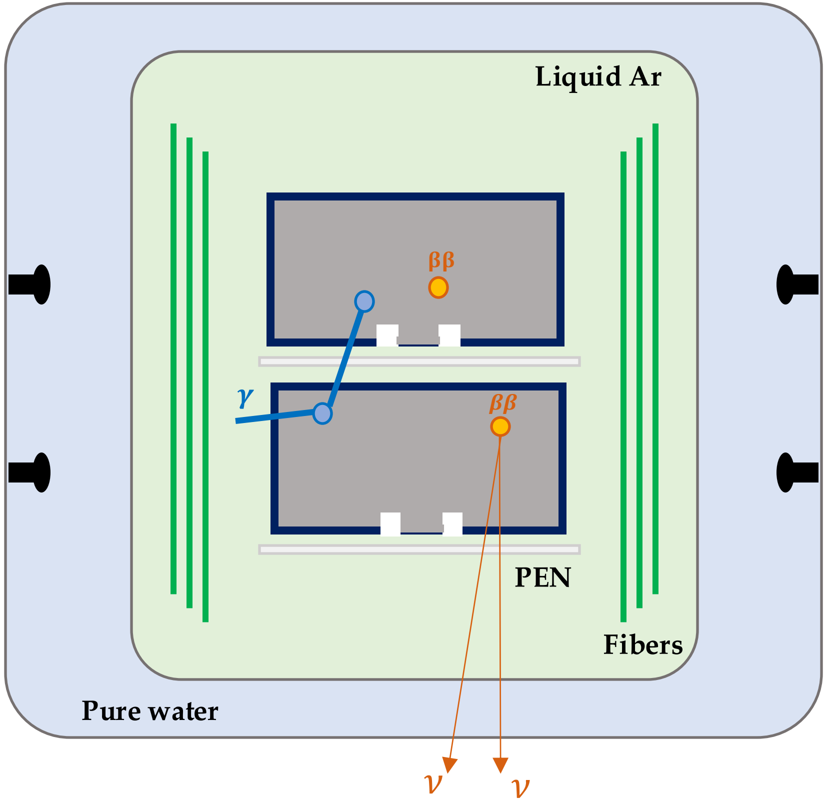

Ge detector anti-coincidence

MJD, GERDA, LEGEND

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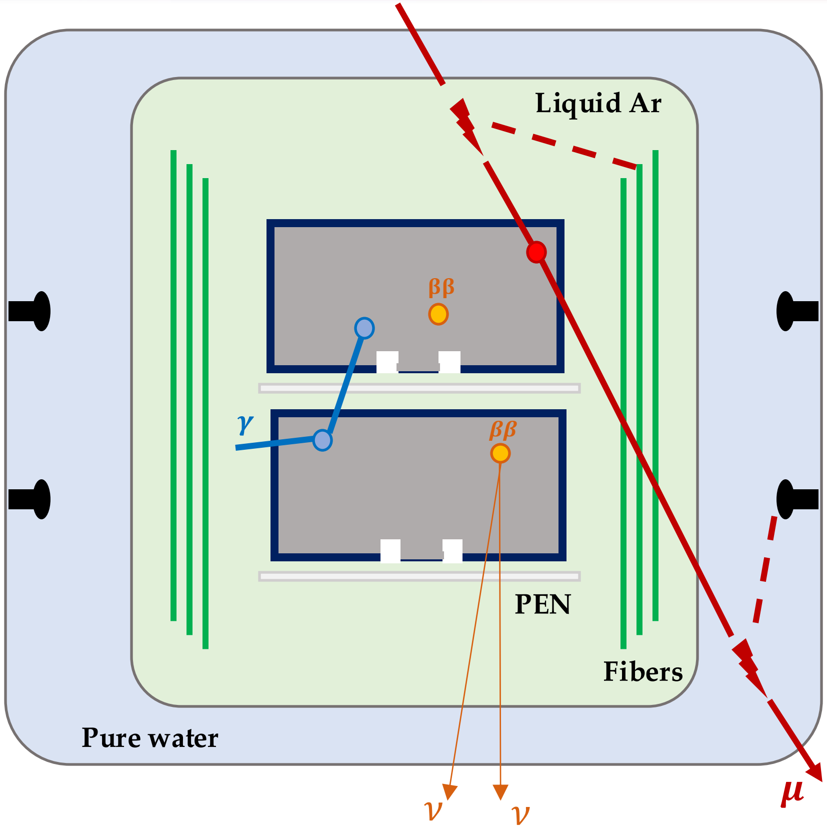
MJD, GERDA, LEGEND

Muon veto based on Cherenkov light and plastic scintillator



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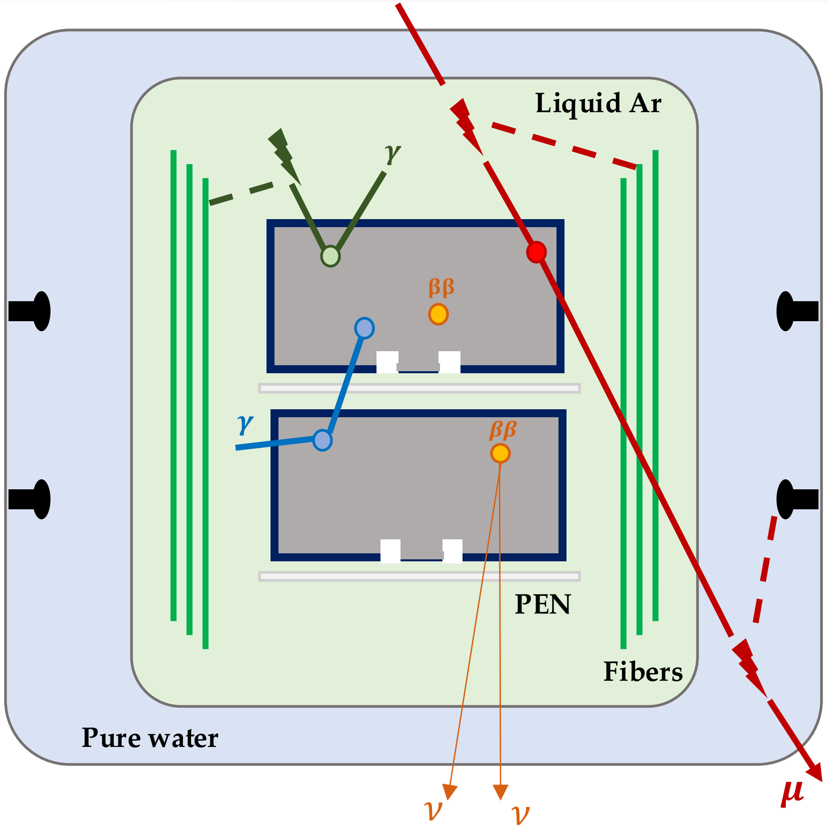

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MJD, GERDA, LEGEND

LAr veto based on Ar scintillation light read-out by fibers

GERDA, LEGEND

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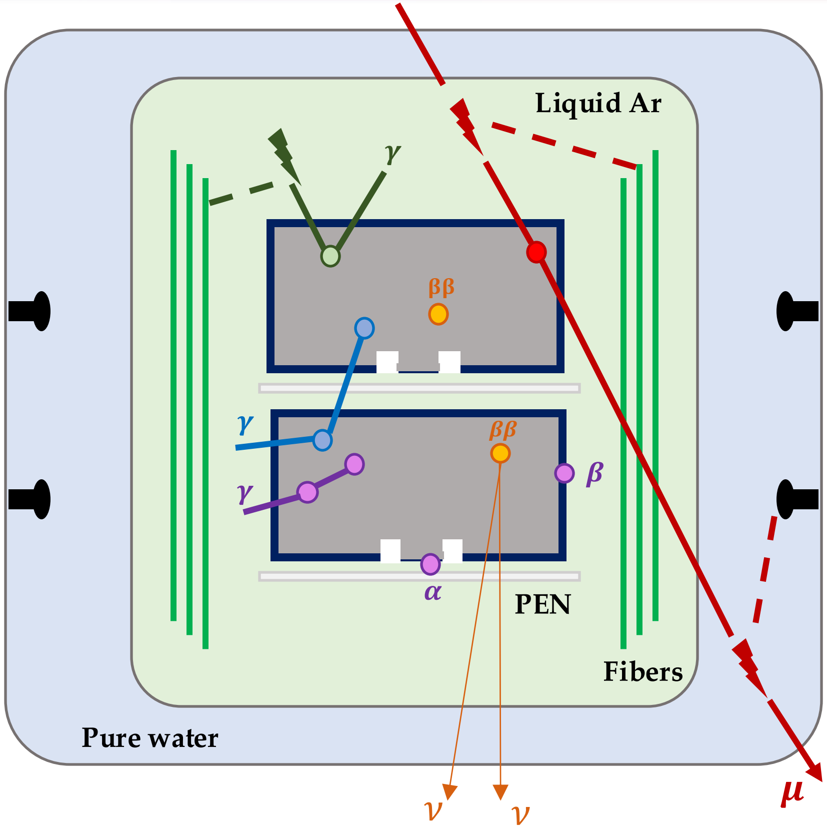
Pulse shape discrimination (PSD) for multi-site and surface events



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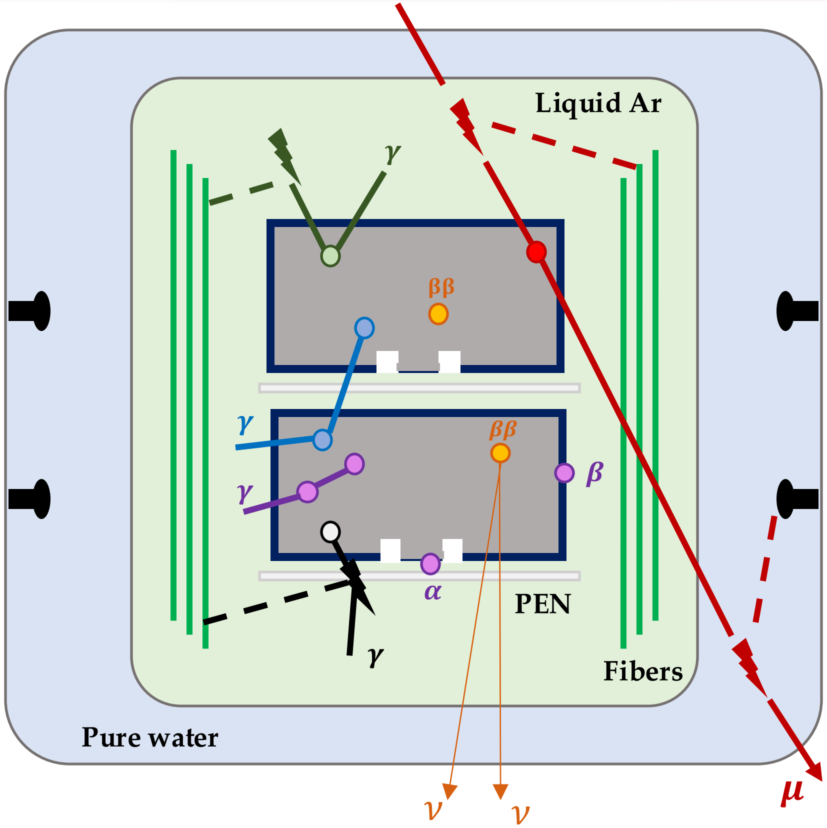

Ge detector anti-coincidence

MJD, GERDA, LEGEND

LAr veto based on Ar scintillation light read-out by fibers

GERDA, LEGEND

Scintillating PEN plate detector holders

LEGEND

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The juleana Software Stack

DataTier

sim → raw → dsp → hit → evt → ana

Offical julia-physics

- SolidStateDetectors.jl
- RadiationDetectorDSP.jl
- BAT.jl
- RadiationDetectorSignals.jl
- RadiationSpectra.jl

LEGEND Registry

- LegendDSP.jl
- LegendEventAnalysis.jl
- LegendVisu.jl
- LegendGeSim.jl
- LegendML.jl
- LegendSpecFit.jl
- LegendBSM.jl

IO: LegendHDF5IO.jl / LegendDataTypes.jl

Metadata & Pars: LegendDataManagement.jl

HPC Computing: ParallelProcessingTools.jl

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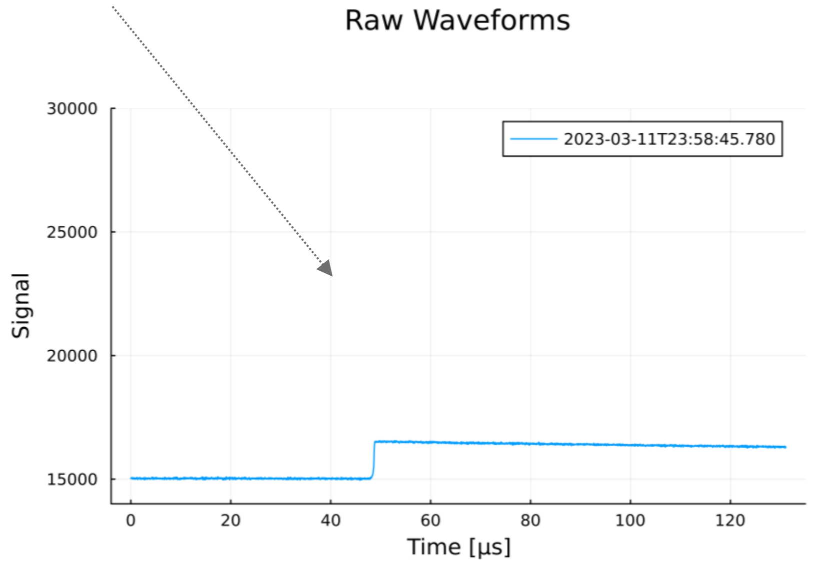
LEGEND Data

- All waveform data saved for offline processing
  - O(100) of HPGe channels
  - O(50) of SiPM channels
- *raw* tier based on HDF5
  - **Cal** runs ~1.1 TB
  - **Phy** runs ~700 GB

Custom plot recipes



- Read/Write IO into custom signal structs
- Fully connected to LegendDataManagement
- Possibility to read custom compression algorithms

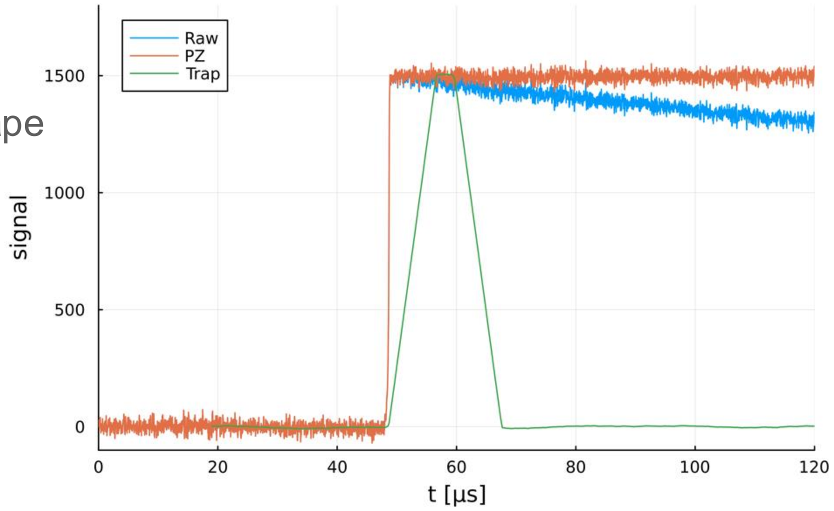
RadiationDetectorSignals.jl

LegendHDF5IO.jl / LegendDataTypes.jl

raw

Digital Signal Processing

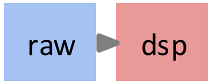
- First step in analysis chain → **DSP**
  - *Signal height* contains energy information
  - *Signal derivative* (“current”) contains Pulse Shape information
  - *Time points* contain drift information



- Filter and stats algorithm definitions
- Easy-to-extent API
- Filter optimization routine and DSP block definitions custom to LEGEND
- (Almost) fully runnable on GPUs

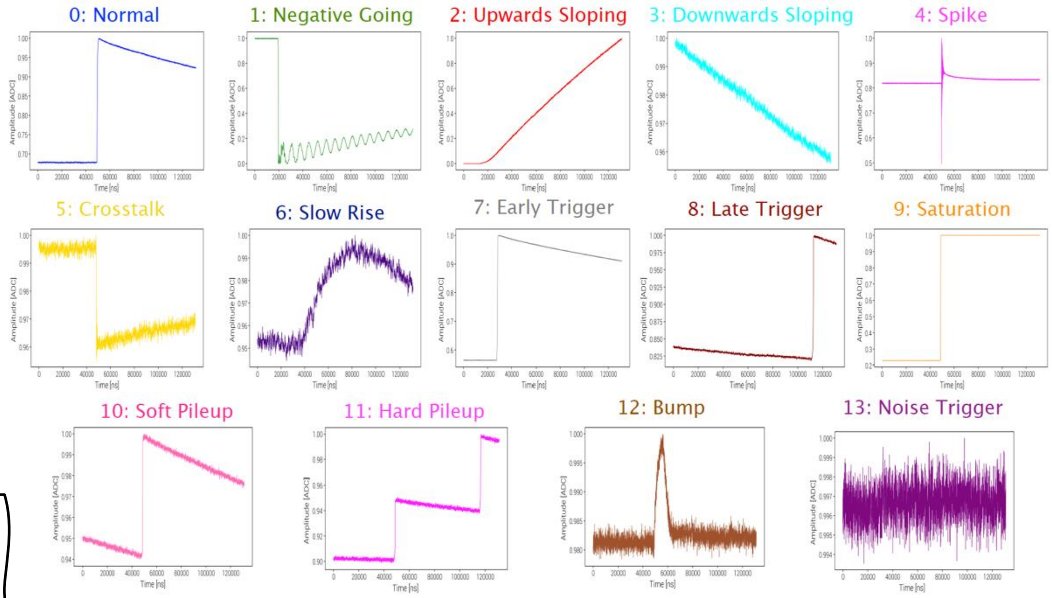
RadiationDetectorDSP.jl

LegendDSP.jl



Quality Cuts

- Quality cuts = Important step to identify non-physical events
- ML based quality cuts using Affinity Propagator



- *So far:* training process still in python
- Evaluation happens in Julia by exporting the models
- Julia implementation currently under active development

LegendML.jl

raw ▶ dsp ▶ hit

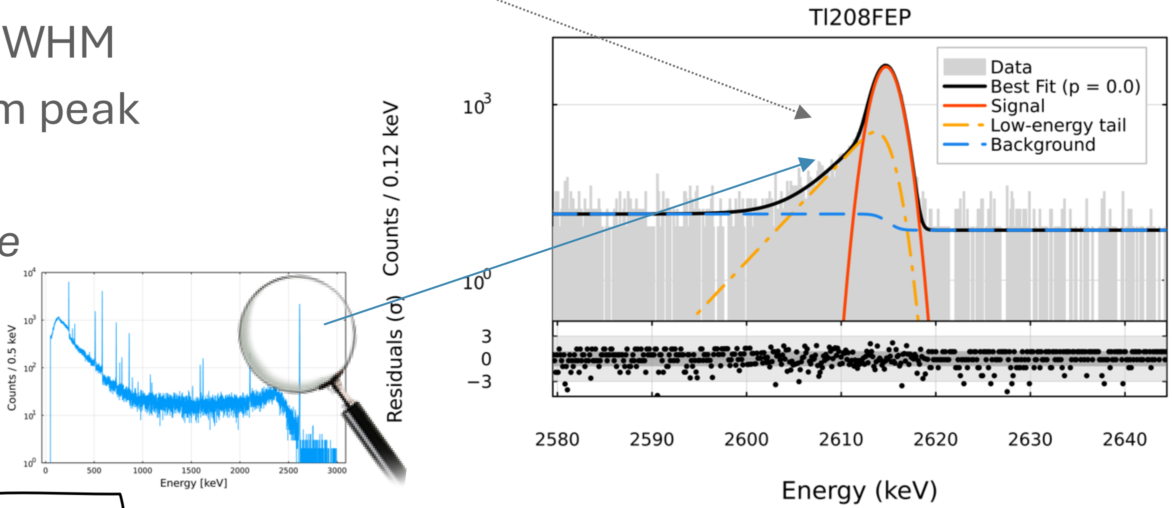
Energy Calibration

- Extract calibration curve + FWHM
- Each peak fitted with custom peak shape using

Bayesian Guided MLE technique

→ *s. Olivers in next session*

Custom plot recipes



- Auto calibration routines based on combination of *peak search* and *peak ratio matching*
- For spectral fitting customized MLE methods with selectable peak shape

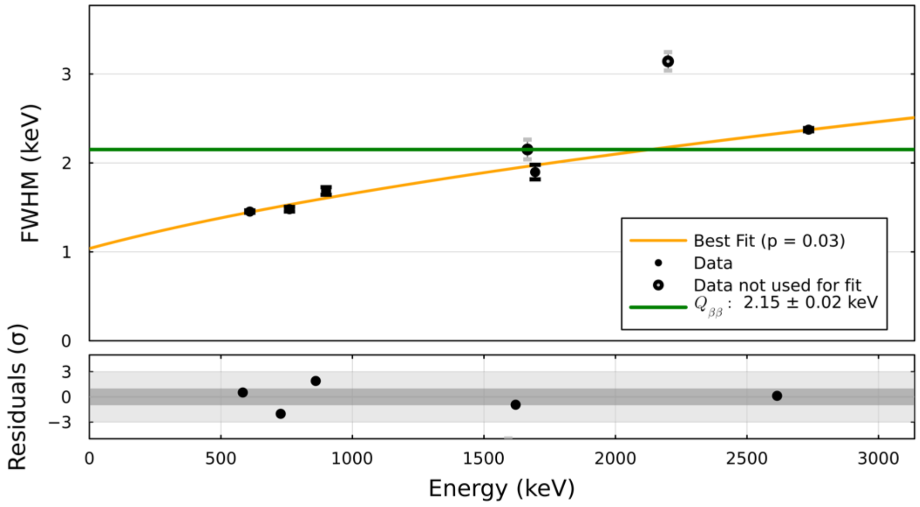
RadiationSpectra.jl

LegendSpecFit.jl

raw ▶ dsp ▶ hit

Energy Calibration

- *Energy Calibration:* Linear fit of peak positions against literature values
- *Peak FWHMs* to extrapolate resolutions at $Q_{\beta\beta}$



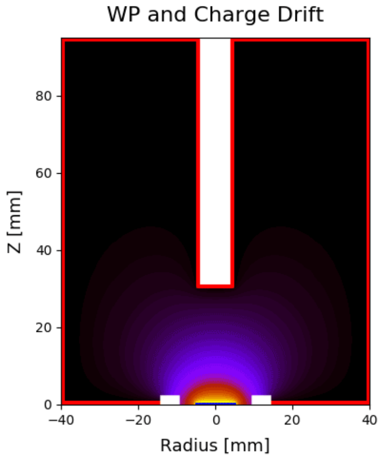
- Auto calibration routines based on combination of *peak search* and *peak ratio matching*
- For FWHM and calibration, custom χ^2-fitter with generic *PolynominamlFuncs* and uncertainty handling via *Measurements.jl*

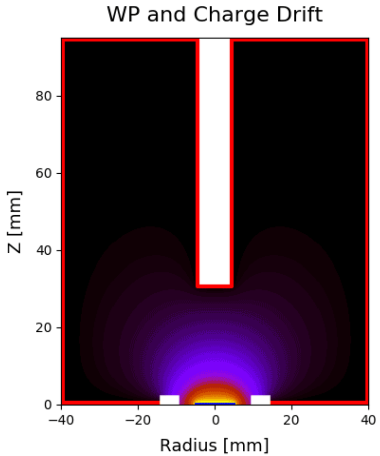
RadiationSpectra.jl

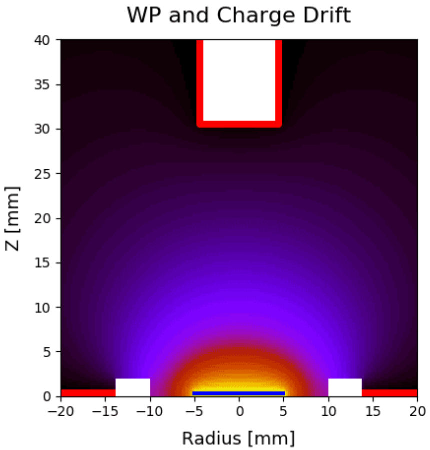
LegendSpecFit.jl

raw → dsp → hit

Pulse Shape Discrimination







Signal-Like event

- Localized

→ *Single-Site Event (SSE)*

- **A/E always similar**

Gamma background

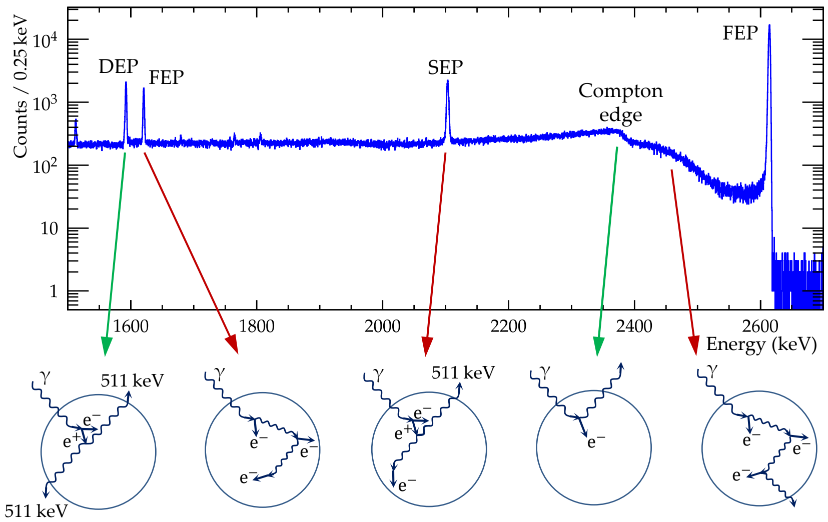
- Multiple Compton scatterings, pair production, …
- → *Multi-Site Event (MSE)*
- **A/E smaller than signal-like**

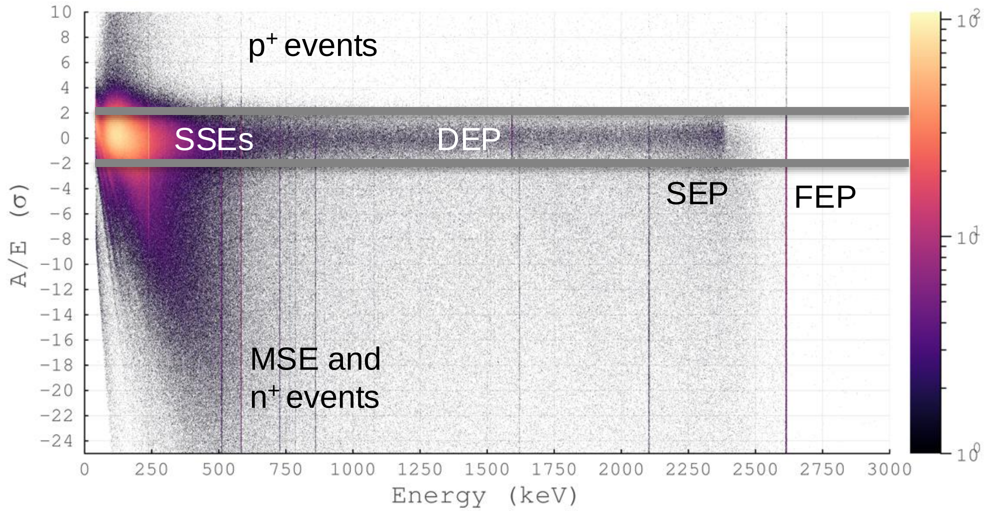
Surface α

- SSE, but short drift-time in large weighting potential but short drift-time in large weighting potential
- **A/E larger than signal-like**

Pulse Shape Discrimination

Double Escape Peak (DEP) as proxy for Single Site Events (SSE)





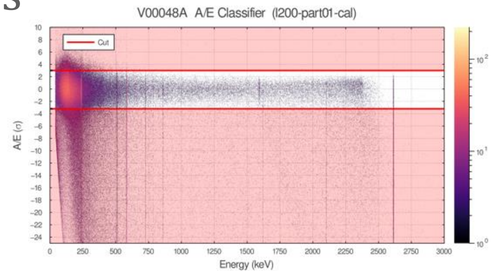
RadiationDetectorDSP.jl

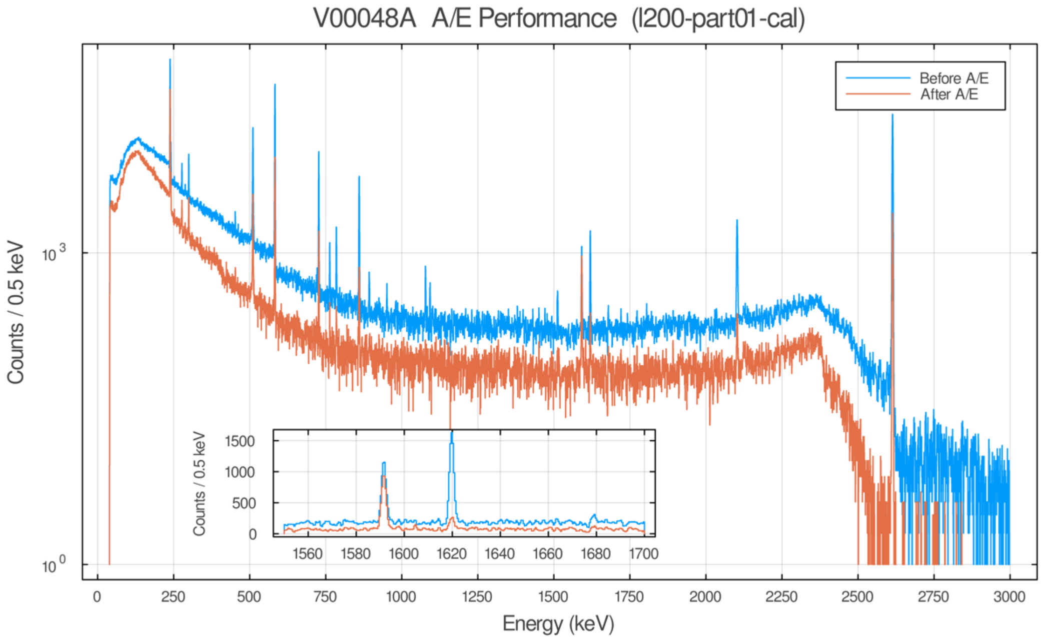
LegendDSP.jl

raw ▶ dsp ▶ hit

A/E Cut

- Low-sided cut to reduce Multi-Site Events (MSE)
- High-sided cut at 3.0 σ to suppress $\alpha's$





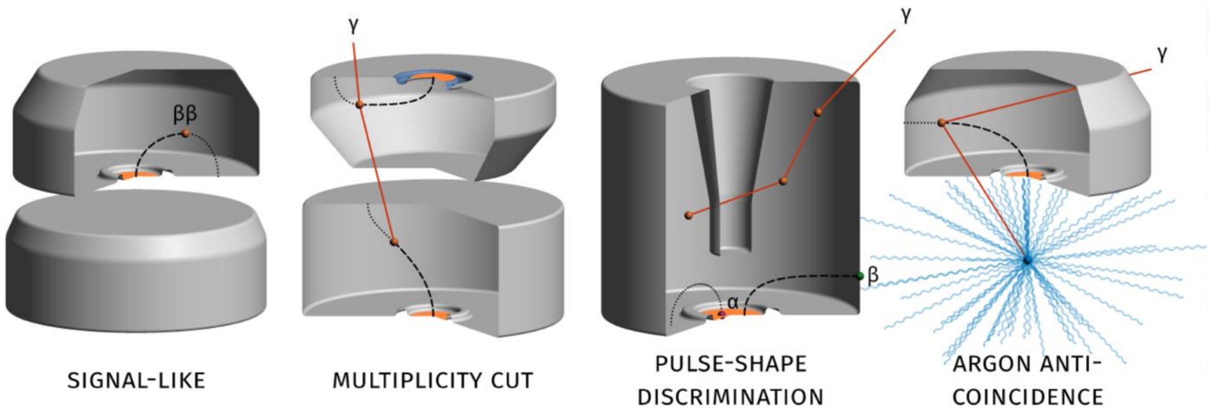
- Auto cut tuning routines based on a combination of energy calibration and fitting routines

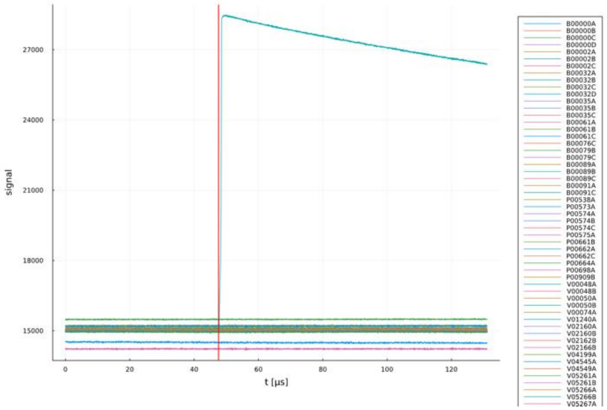
RadiationSpectra.jl

LegendSpecFit.jl

raw ▶ dsp ▶ hit

Event Building





- → Define Software trigger condition:
  - – Any{$Energy_{HPGe}$} > 25keV && waveform passes QC
- → Define physical event condition:
  - – All{$HPGe_{No\text{-}Trigger}$} == "Baseline-Only"
- → Define Lar cut condition:
  - – Sum{$Energy_{SiPM}$ in [t0 – 1µs, t0 + 5µs]} > 4 PE
- → Define Anti-Coincidence
  - – Number{$Trigger_{HPGe}$} == 1
- → Define PSD cut
  - – All{$HPGe_{Trigger}$} == Single-site events

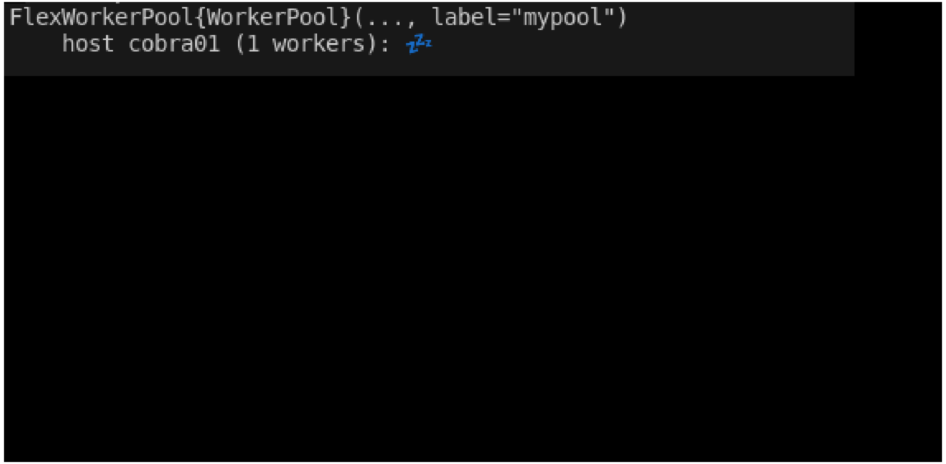
LegendEventAnalysis.jl

raw ▶ dsp ▶ hit ▶ evt

SLURM Cluster Computing

- Can scale cluster up and down repeatedly, even from interactive Julia session
- Timeout/retry mechanism, atomic file I/O with optional local caching, and more
- Best LH5 write performance achieved so far 1.2 TB in 70 seconds
- Ran up to 4000 multi-cpu worker processes in parallel
- Under development: better distributed progress and performance monitoring

Many long nights, but now we can … start with a single worker



All performed on MPCDF Munich HPC systems Cobra/Raven/Viper

ParallelProcessingTools.jl

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Poor little worker ... this will take a while ... let's invite some friends

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[ParallelProcessingTools.jl]

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We can add workers on the fly via SLURM, connect to a running Julia session

```
FlexWorkerPool{WorkerPool}(..., label="mypool")
    host co3004 (20 workers):
    host co3017 (20 workers):
    host co3343 (20 workers):
    host co3344 (20 workers):
    host co3497 (20 workers):
    host co3498 (20 workers):
    host co3502 (20 workers):
    host co3505 (20 workers):
    host co5059 (20 workers):
    host co5370 (20 workers):
    host co5417 (20 workers):
    host co5566 (20 workers):
    host co5582 (20 workers):
    host co5583 (20 workers):
    host co5591 (20 workers):
    host co5595 (20 workers):
```

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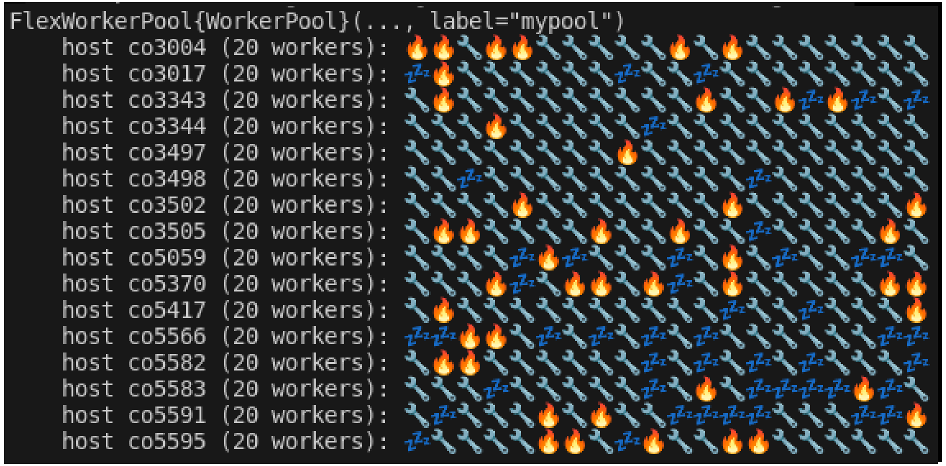
... and let them take over:



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When we're done, we can remove the SLURM workers (save some budget) and continue:

```
FlexWorkerPool{WorkerPool}(..., label="mypool")
   host cobra01 (1 workers): 💤
```

All performed on MPCDF Munich HPC systems Cobra/Raven/Viper

ParallelProcessingTools.jl

Altogether → Dataflow

Custom dataflow containing

- Processor based execution of individual runs or detectors
- Configuration via *JSON*
- Debug mode for *interactive* testing
- Can run on HPC, *local* notebook or single server natively
- Custom mini graph computing for dependencies
- *Markdown* based logging infrastructure
- *Pars* read and write with unit and error handling via *Unitful.jl* and *Measurements.jl*


```
"e_zac": {
    "fit": {
        "Tl208FEP": {
            "skew_width": {
                "val": 0.001274176632 43801,
                "err": 7.26620752178326e-5
            },
            "µ": {
                "unit": "keV",
                "val": 2616.0045498134514,
                "err": 0.20960014815095052
```

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Summary & Outlook

And of course we have T-shirts

- LEGEND features full Julia based Software Stack which can tackle all tiers
- Promising approach without any dependencies to other languages or tools
- In future → Try to release more and more tools and general purpose packages

FNSNF NSF INFN DFG

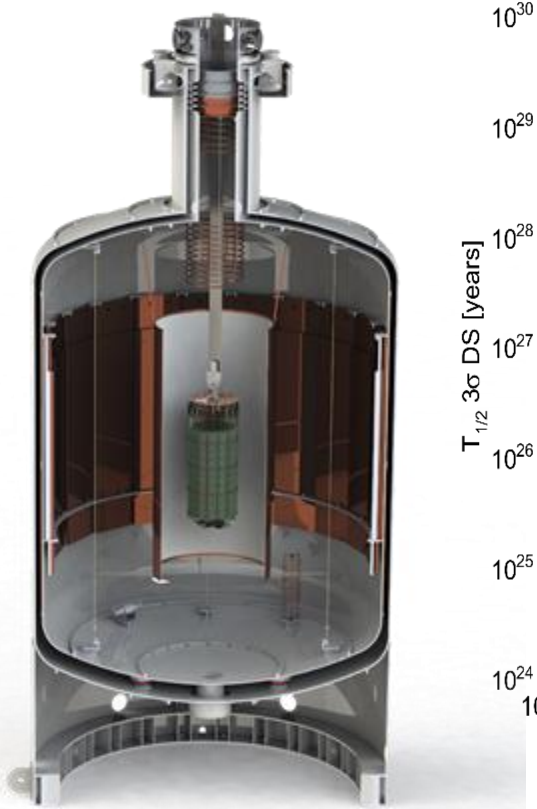
BACKUP

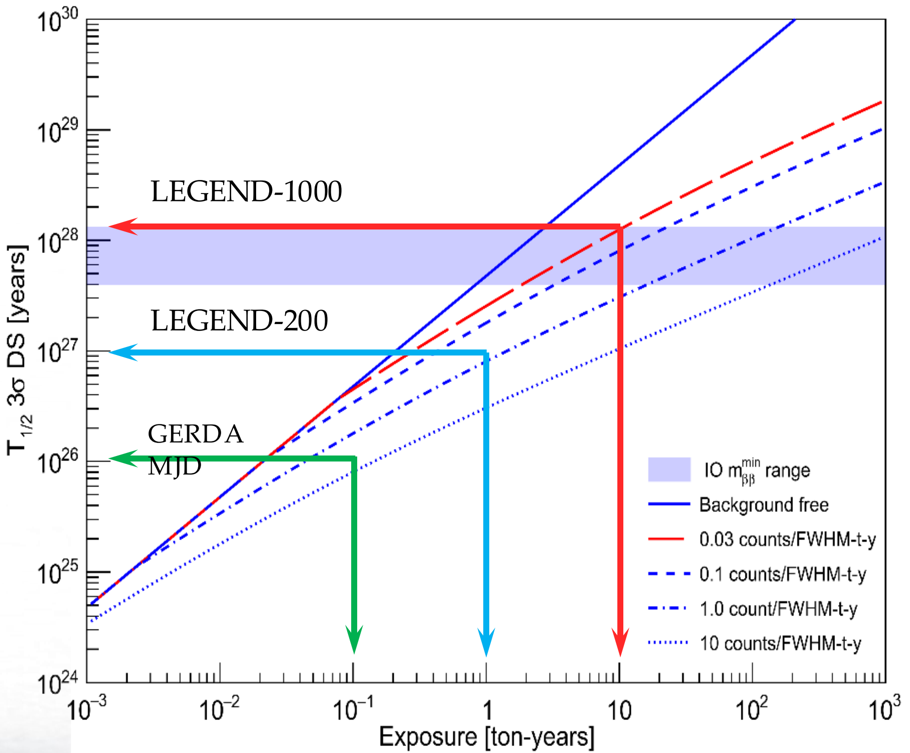
Role of Julia Software Stack

- *Primary* LEGEND software stack in Python, *alternative* in Julia
  - **Validation**: Independent code guards physics results against bugs in primary stack
  - **Experimentation**: Primary stack needs stable interface, alternative can use bleeding-edge technology and change/evolve more freely
  - **Future perspective**: Find out what's possible for LEGEND-1000
- Community-wide and LEGEND-specific open-source packages
- Custom dataflow and management routines for throughput cluster computing

raw ▶ dsp ▶ hit ▶ evt

LEGEND Experiment



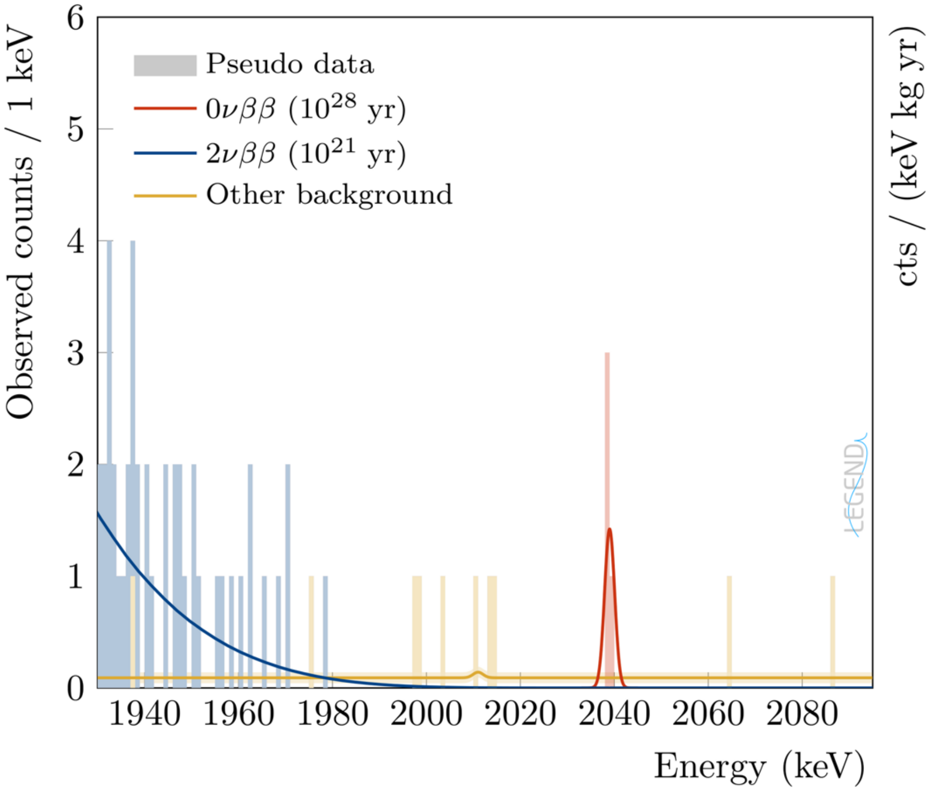


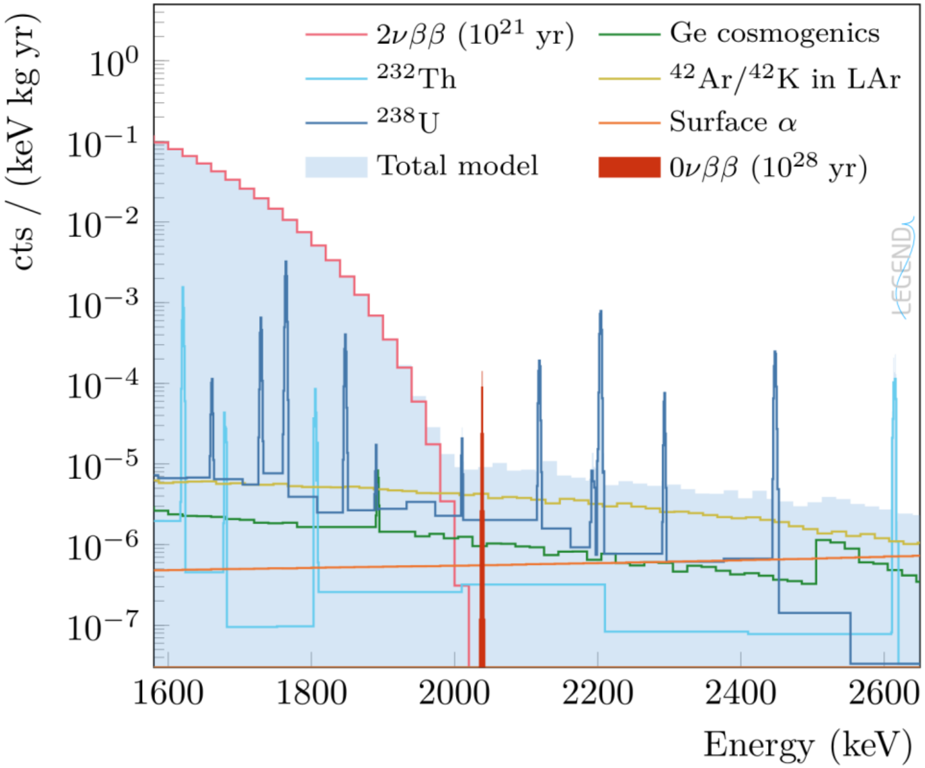
$$\langle m_{\beta\beta} \rangle \propto \frac{1}{g_A^2\, |M^{0\nu}|} \sqrt{\frac{1}{T_{1/2}^{0\nu}\, G^{0\nu}}}$$

$\langle m_{\beta\beta} \rangle$: Effective Majorana mass
$T_{1/2}^{0\nu}$: Decay half-life
$M^{0\nu}$: Nuclear matrix element
$G^{0\nu}$: Phase space factor

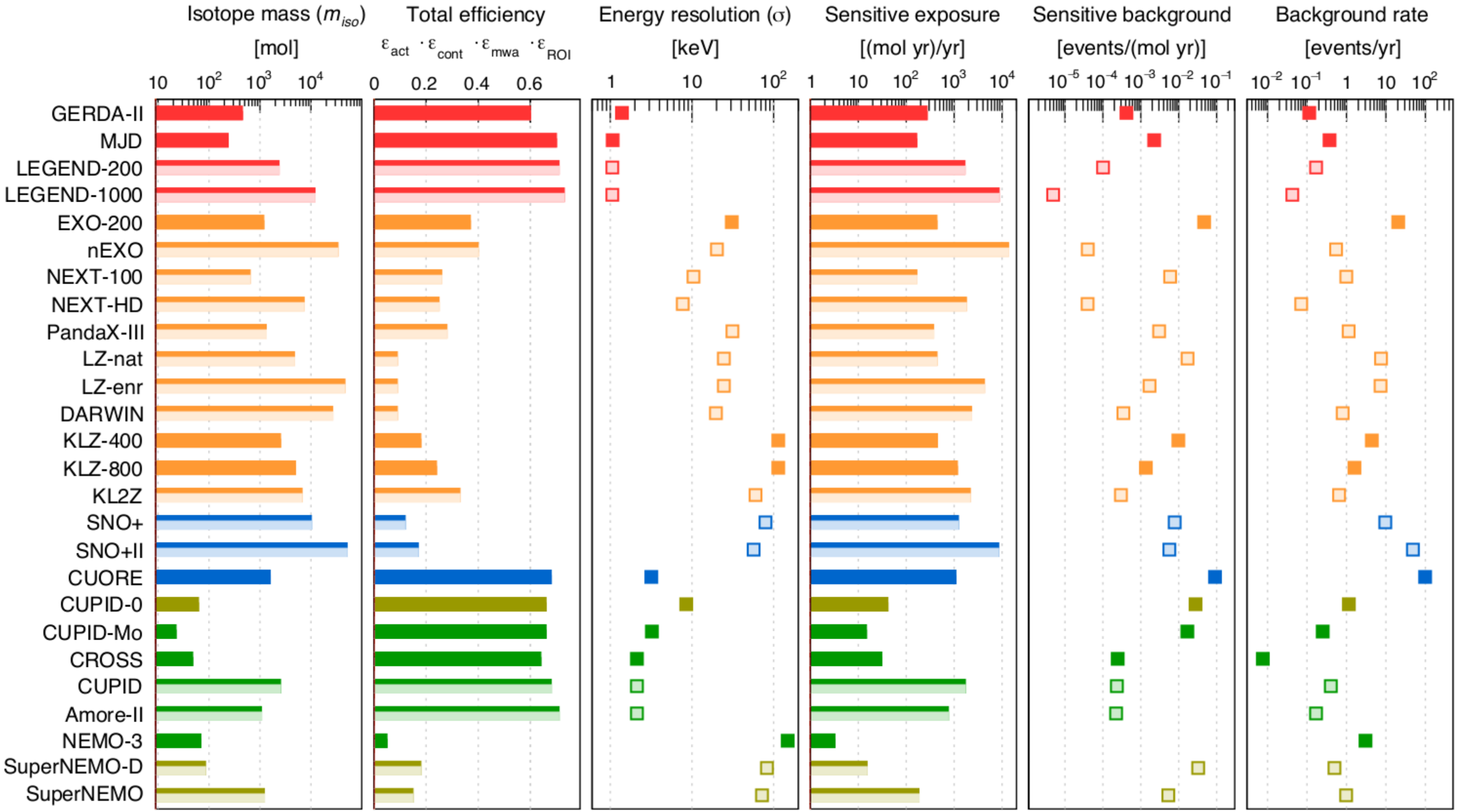
Goal is to cover inverted ordering with 3σ CL:
$T_{1/2}^{0\nu} > 10^{28}$ yr

LEGEND Experiment

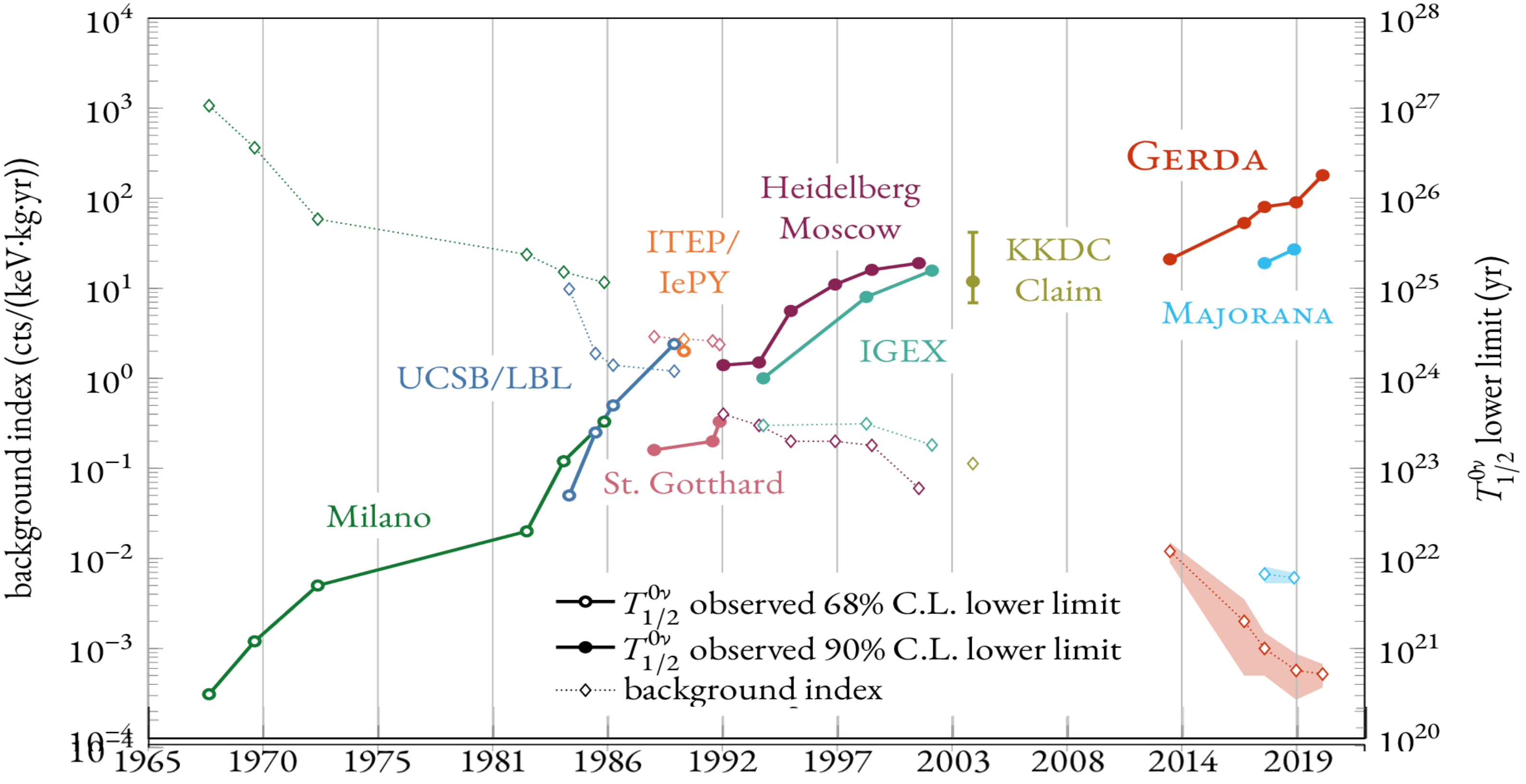




0νββ Decay Physics



LEGEND Experiment



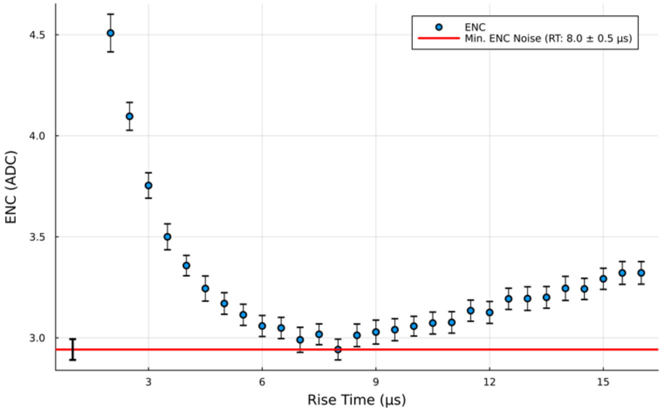
Filter Optimization

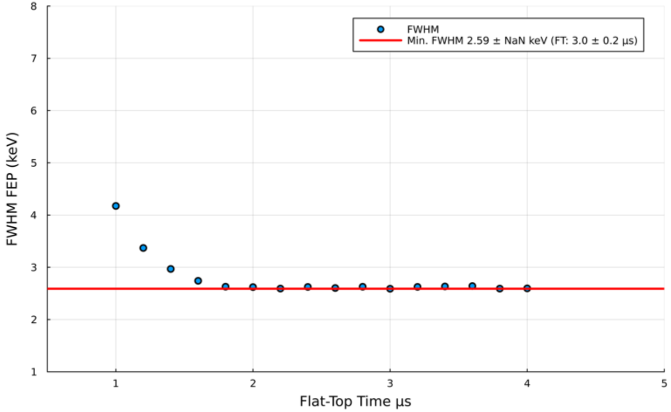
- To enhance performance

→ Filter parameter for energy and pulse shape

Two step process for energy filters:

1. Optimize *rise time* on baseline events
2. Optimize *flat-top time* by fitting peak shape

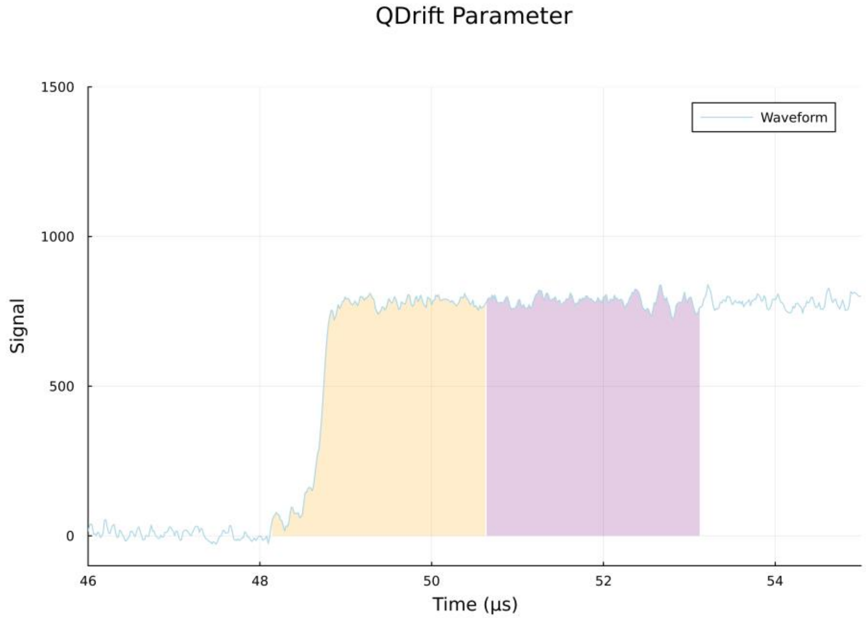




Charge Trapping Correction

- Trapping of charge from the initial charge cloud during drift
- Can be corrected via the correlation of the drift time weighted with the charge

QDrift = Area2 – Area1



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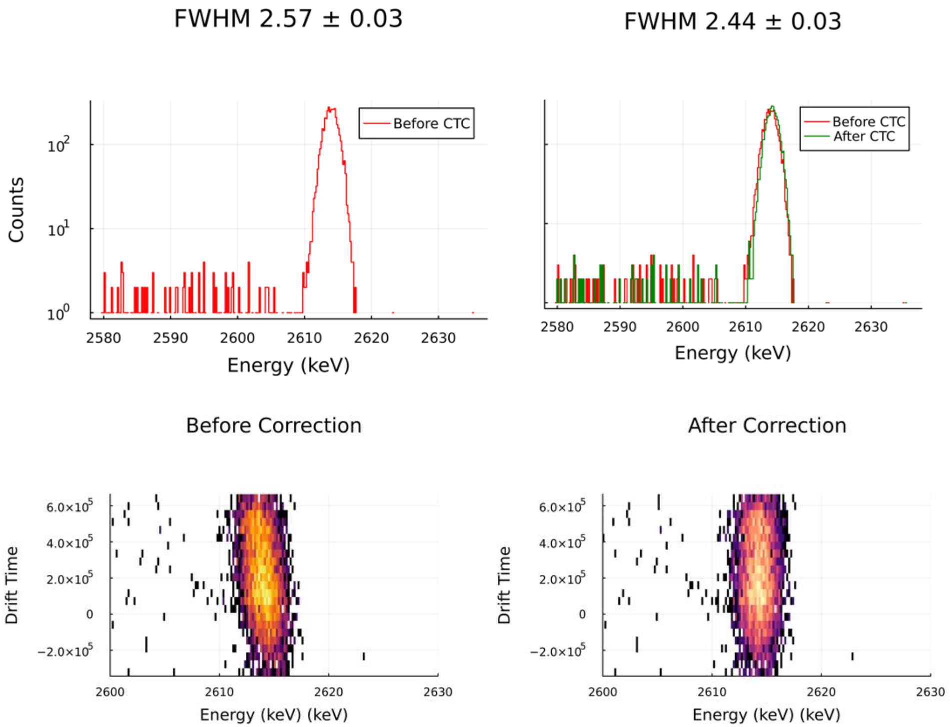
→ Corrected energy optimized by optimizing fct via *PeakHeight/FWHM*



raw → dsp → hit

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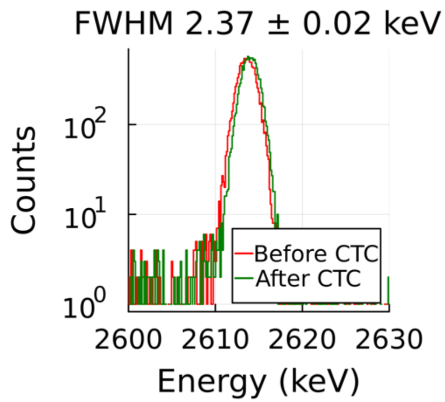
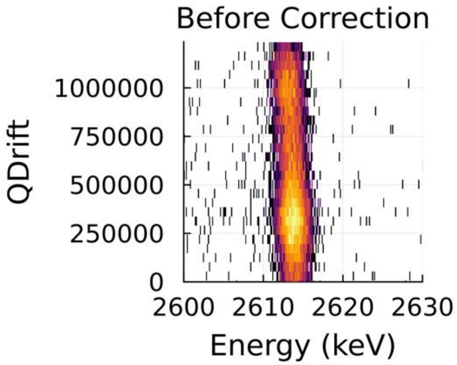
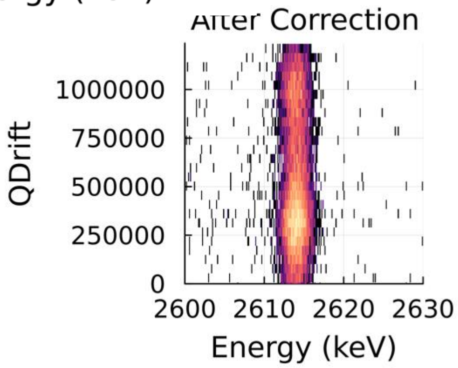


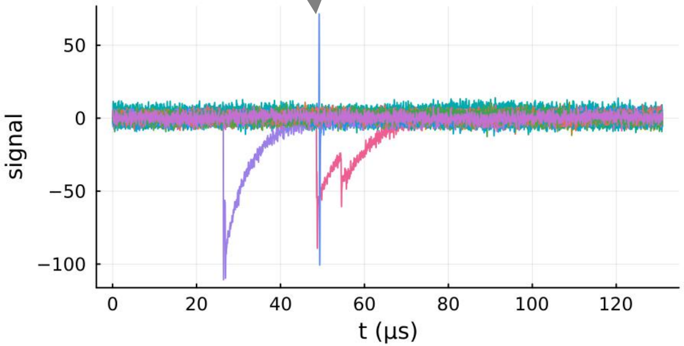


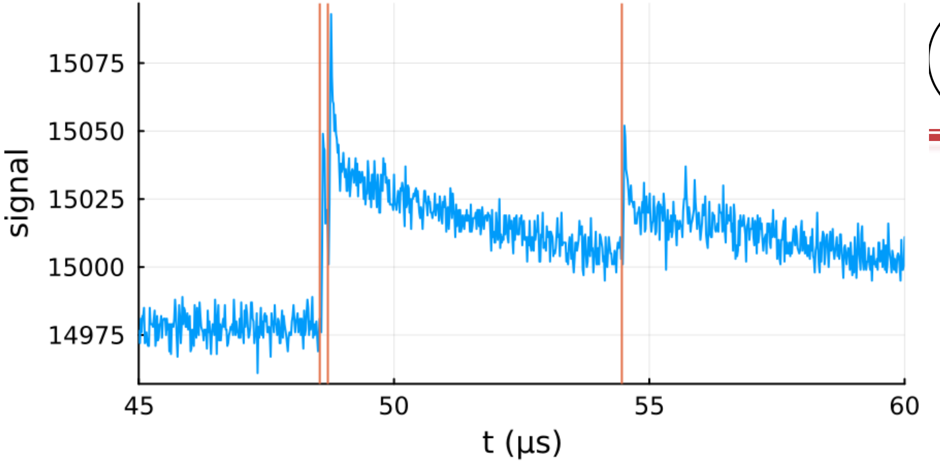


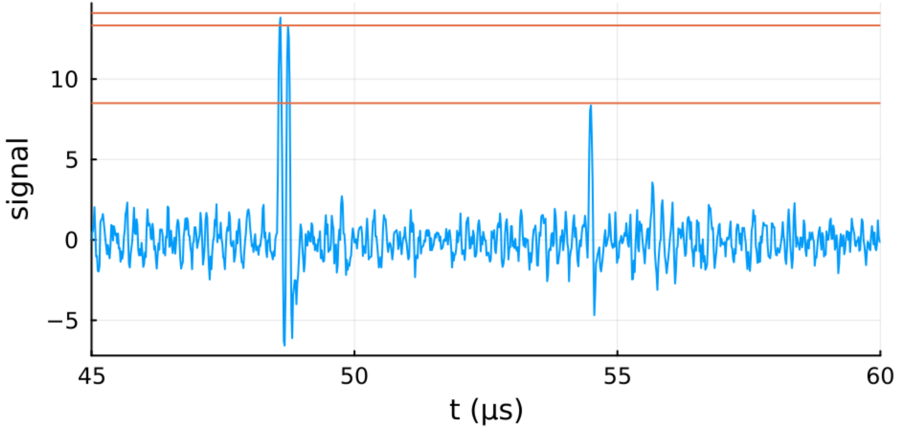
raw ▶ dsp ▶ hit

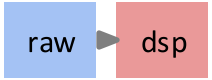
SiPMs

- Find peak positions that cross threshold
- Amplitudes of peak positions in filtered waveforms
- Discharges tagged by





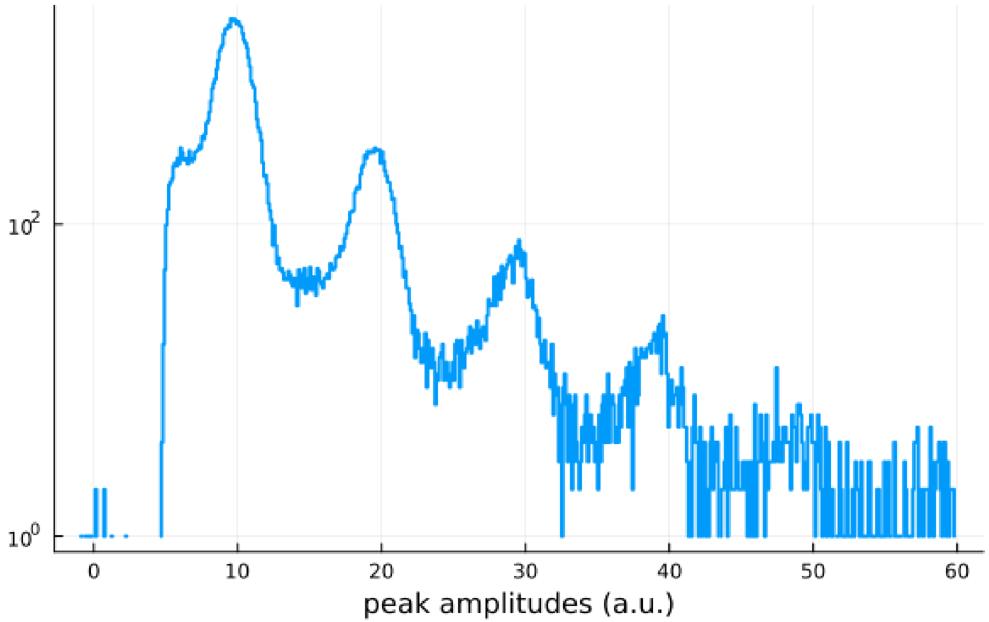




SiPMs

In *uncalibrated* histogram

- Find peaks “1 p.e.” and “2 p.e.” peak positions
- Linear calibration



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