

Analysis of the backgrounds in the LEGEND-200 experiment

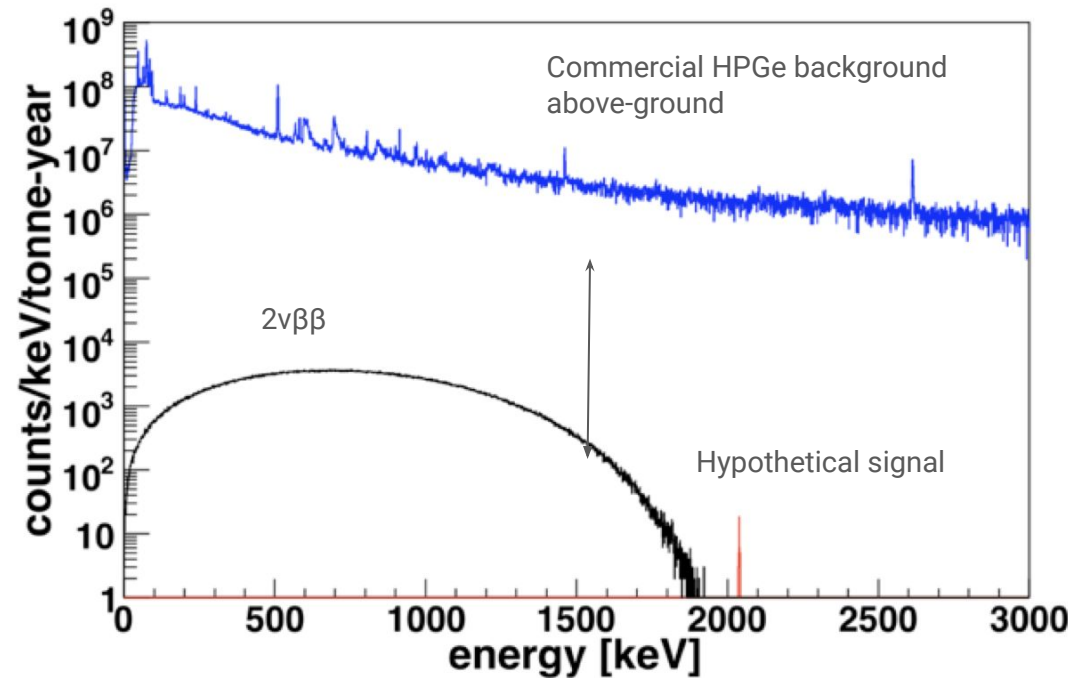
Toby Dixon^[1] on behalf of the LEGEND collaboration
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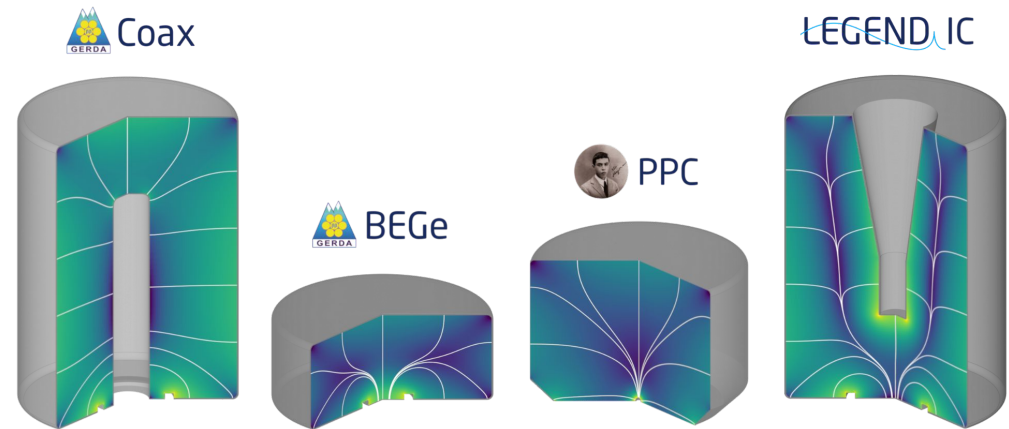
Neutrinoless double beta decay

- Neutrino oscillation experiments show **neutrinos have mass**
- Nature of this mass is still unknown
- Neutrinoless double beta decay ($0\nu\beta\beta$) probes the nature of neutrino mass
- Would lead to a **peak at the Q-value** of the decay



Very rare expected signal, control of background is critical and extremely challenging!

- **Large mass** (up to 4 kg)
Germanium diodes enriched in ^{76}Ge
- **High efficiency**
→ source == detector
- Excellent **energy resolution**
~2-3 keV FWHM at ^{76}Ge Q_{bb}
- Topological background rejection via **pulse shape discrimination**
- **Active background reduction** via operation in instrumented LAr



> 20 yr of development by the GERDA and MAJORANA collaborations

The LEGEND experiment



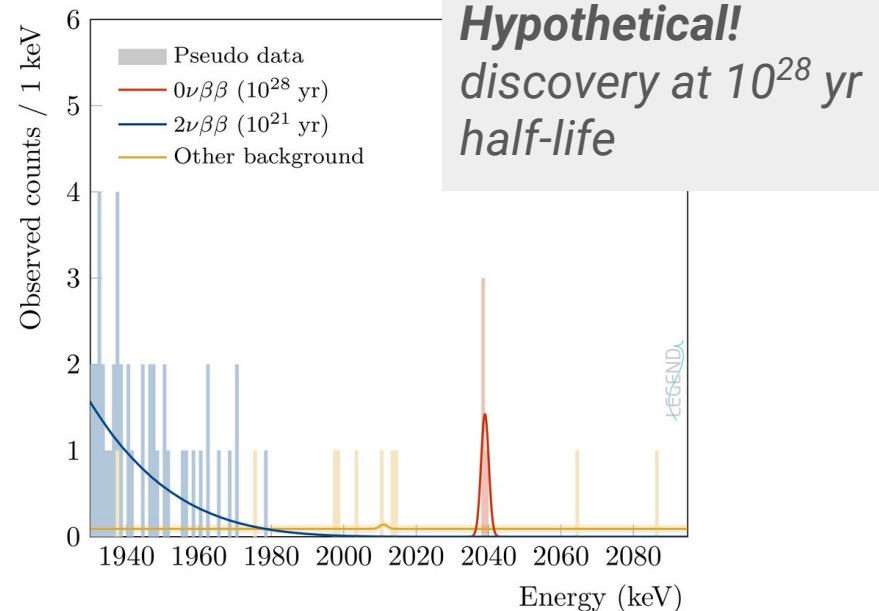
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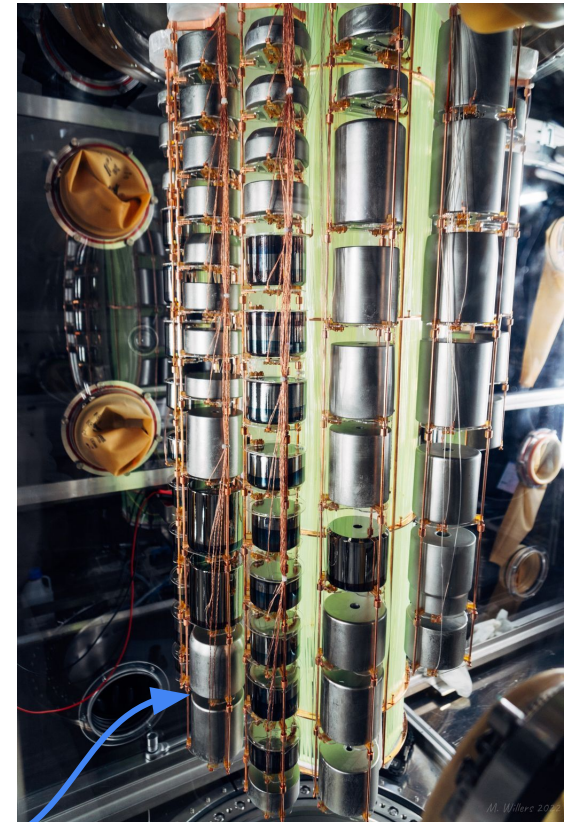
- Builds on the experience of **GERDA** and the **MAJORANA** demonstrator
- **LEGEND-200**
 - Currently operating at LNGS
- **LEGEND-1000**
 - Planned to operate at LNGS with ~ 1000 kg of ^{76}Ge

*“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.”*

Discovery focused, control of the backgrounds is critical so that a potential discovery would be convincing



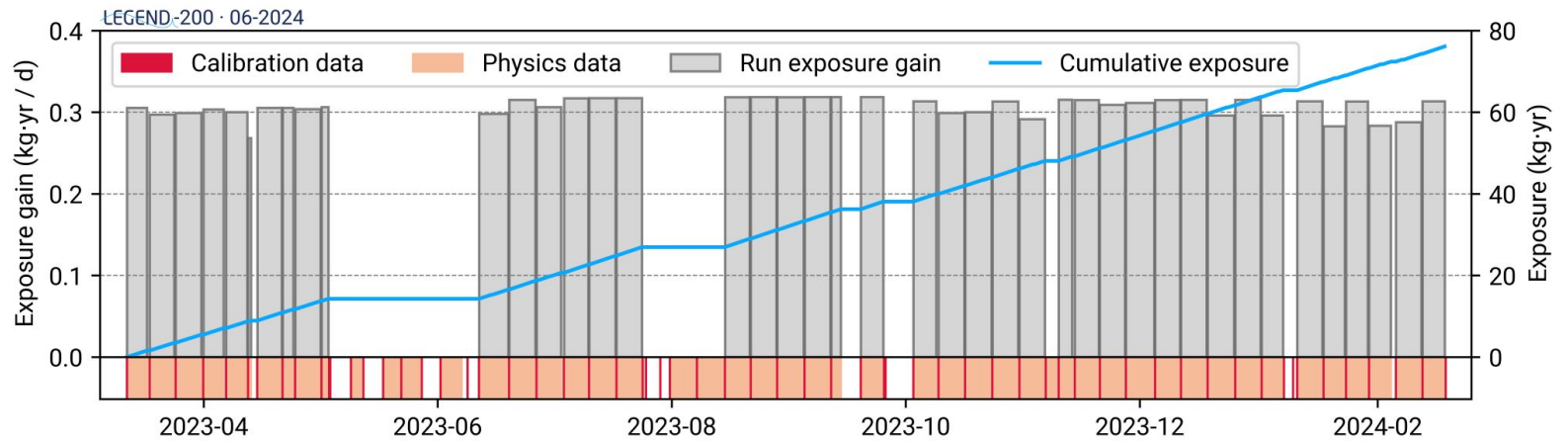
- First phase of the LEGEND program
- ~140 kg-yr of Germanium detectors operated in LAr at LNGS
- Detailed description of the various components of the experiment in Louis's talk
- First $0\nu\beta\beta$ physics search results shown at [\[Neutrino `24\]](#)
- Additional detector installation by the end of 2024
- Expected sensitivity of $\sim 10^{27}$ yr



HPGe detectors

L-200 data taking and analysis

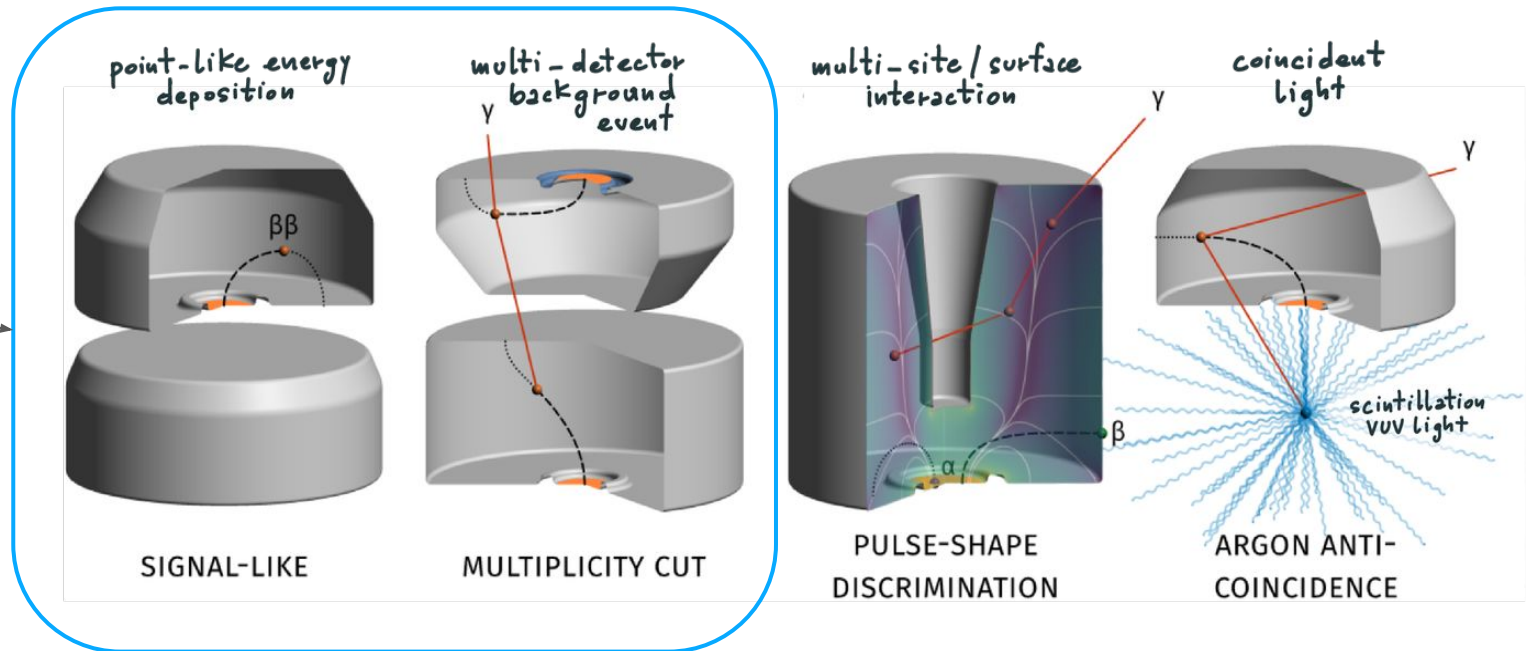
- First LEGEND-200 physics dataset based on ~1 year of data taking
- Exposure of 76.3 kg·yr of Ge collected
- Plus ~ 15 kg·yr of *special background runs*, more details later...



- Focus on modelling before LAr veto and PSD cuts
- Higher statistics of background like events to understand radioactive contaminants

However, cuts strongly suppress the background for the $0\nu\beta\beta$ decay search...

Focus for this talk



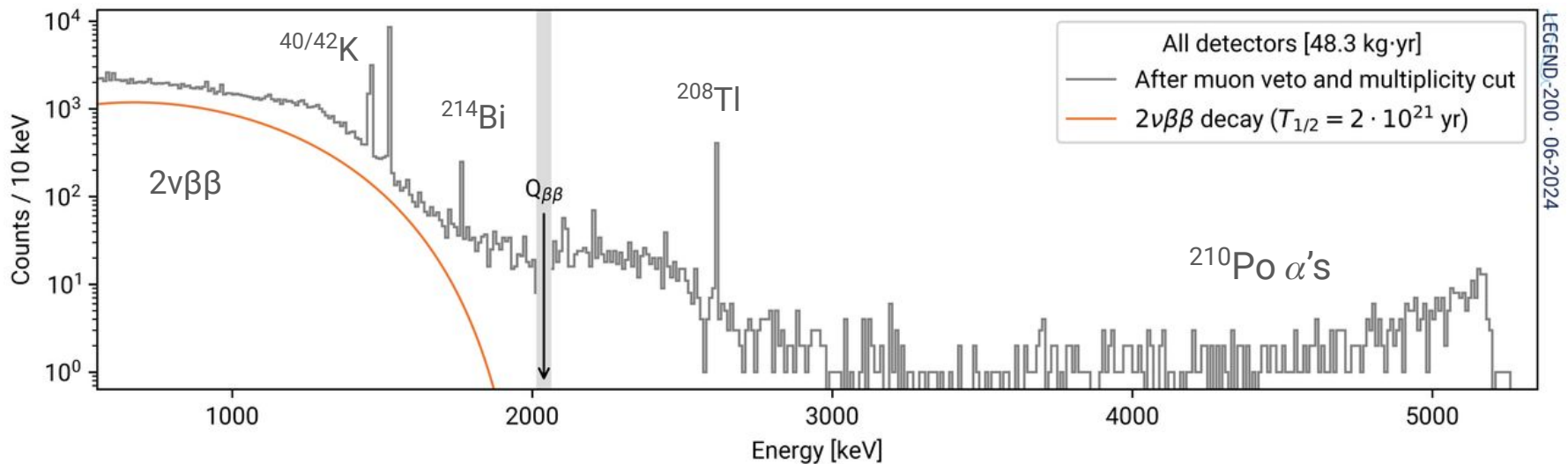
Expected background components

Focus for modelling data
before cuts



- **$2\nu\beta\beta$ decay**
 - Dominates spectrum below ~ 1.5 MeV
- **Natural radioactivity $^{232}\text{Th} + ^{238}\text{U}$ decay chains, ^{40}K**
 - Even μBq contaminations are relevant
 - Breaks in secular equilibrium can be important
- **^{42}Ar in LAr**
 - ^{42}K is charged and drifts in the fields of the Ge detectors
 - Very difficult to model the (inhomogeneous) spatial distribution

- **Cosmogenic activation**
 - Muons removed with water Cherenkov muon veto
 - Cosmogenically activated isotopes expected to be negligible for L-200
- **α particles on detector surface**



Special background runs - *in-situ* screening

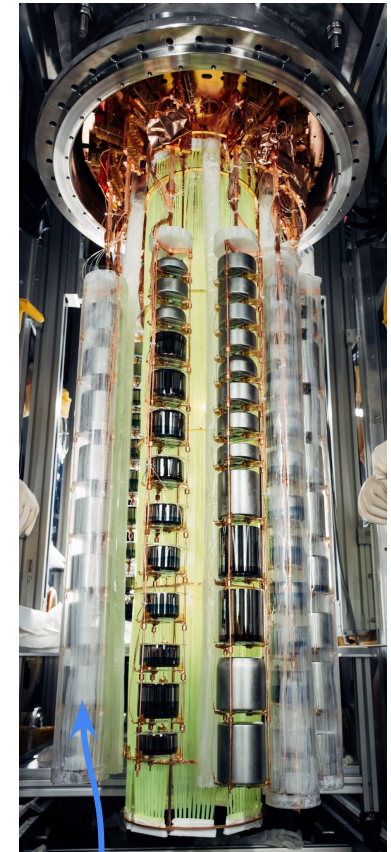
- Utilize LEGEND-200 as a screening station itself
- Took two *special background runs* where components of the experiment were removed
- Only ~1 week downtime for hardware interventions!

Analysis of this data provides a model independent constraint on their contribution to the observed background

LAr instrumentation



Nylon Mini Shrouds



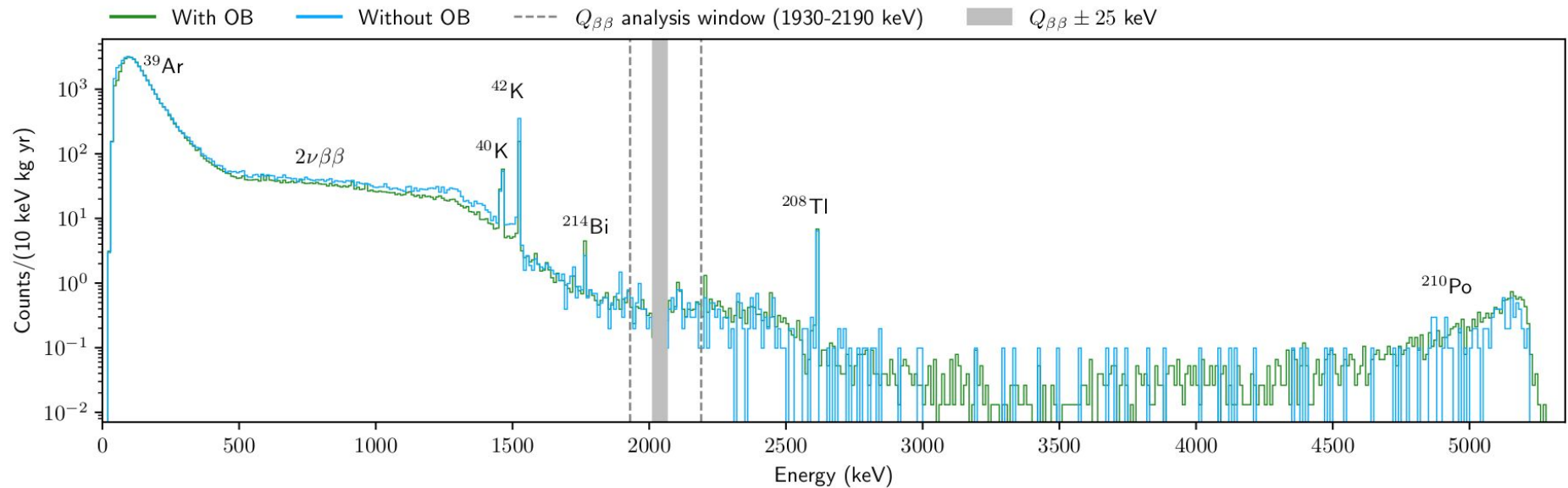
~ 1 week downtime



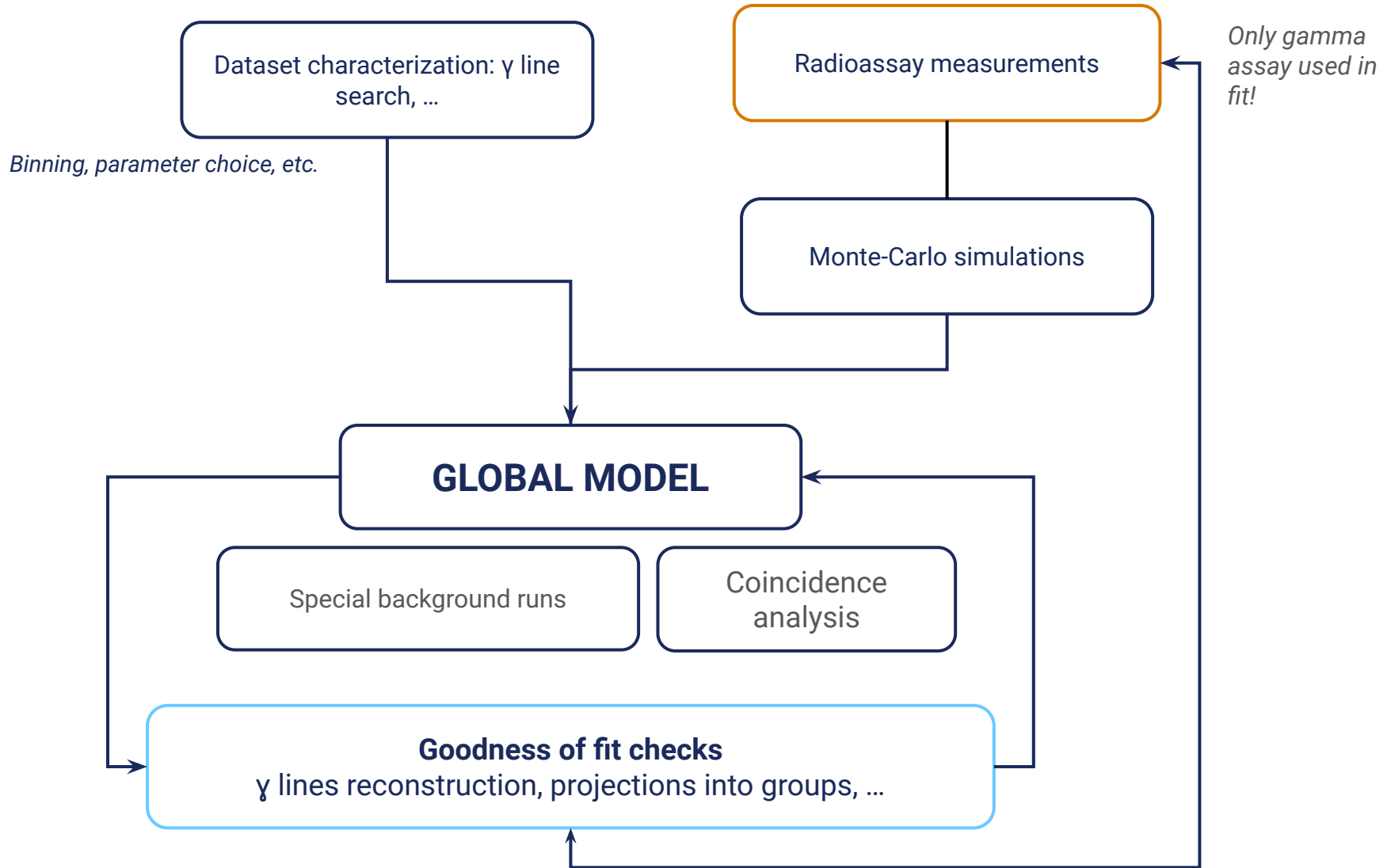
Special background runs results

- Show the results from the first background run removing LAr instrumentation outer fiber shrouds
- Differences between the count rate constrains the activities of the LAr instrumentation

Data is included into the 'global' background model fit

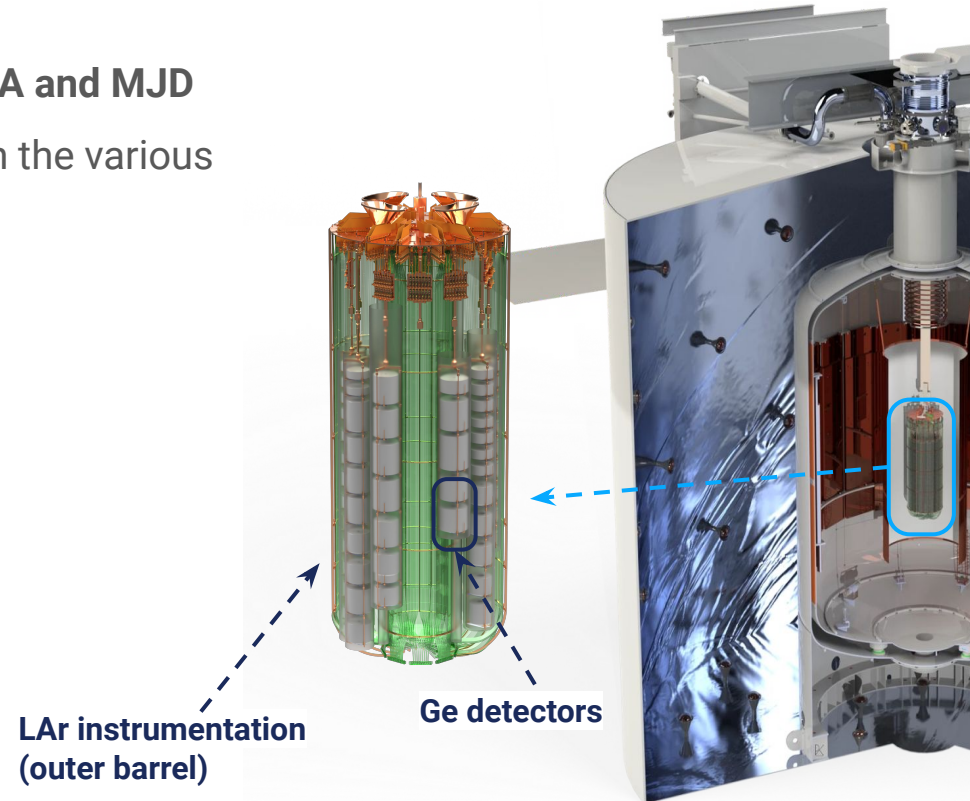


Background model workflow



Monte-Carlo simulations

- Detailed Geant4 model built of the *as built* L-200 experiment
- Based on **MaGe** software **validated by GERDA and MJD**
- Simulations performed of the radioactivity in the various components
- Detailed detector response model applied
 - Energy resolution/ threshold
 - HPGe dead layers
 - Detector usabilities over time
 - Coincidences and event multiplicity





Assay model

- Predictions from radioassay
- Gamma assay, ICP-MS etc.
- Samples from (truncated) Gaussian probability distributions of assay activities
- Uses this to build the expected contribution in each bin

Global model

- Bayesian binned MC template based likelihood fit to the data using BAT
- Informative priors only from γ assay
- Fully JSON configurable open source software [\[hmixfit-github\]](#)
- Allows us to easily include additional spectra into the fit

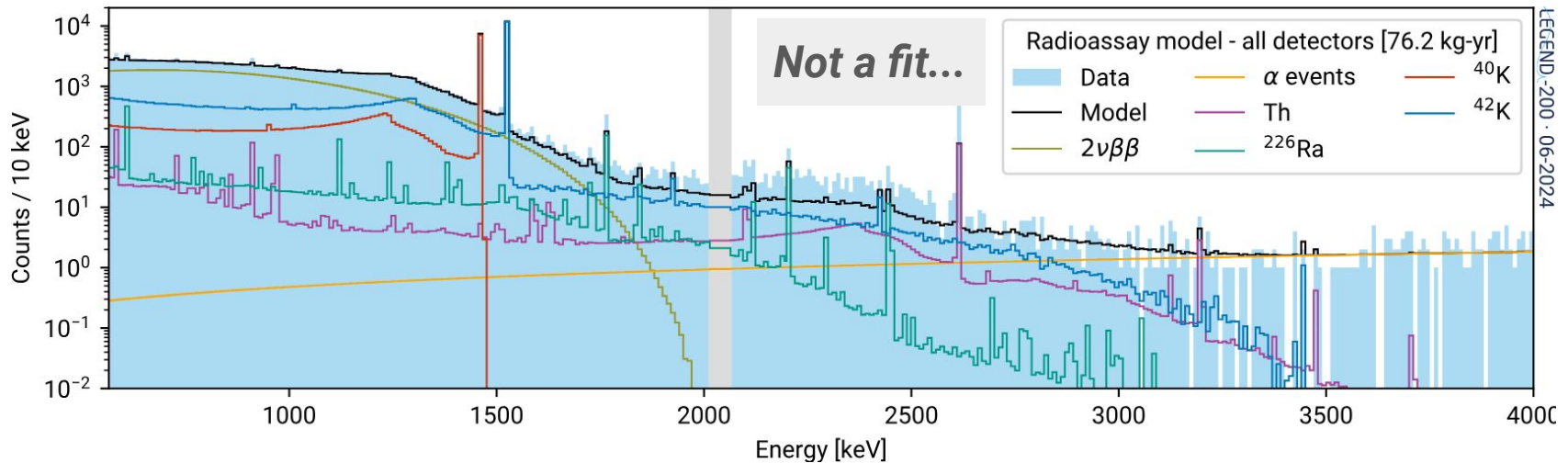
Data spectra

$$\mathcal{L}(\mathcal{D}) = p(\mathcal{D}|\vec{a}) = \prod_{h=1}^{N_h} \prod_{i=1}^N \prod_{j=1}^{M_i} \text{Pois}((n_{h,i,j} | \mu_{h,i,j}(\vec{a})).$$

Hardware configurations *Bins*

Predictions from radioassay

- Compare the predictions from assay described by Louis earlier to the L-200 data
- Simulations and material radioassay **underpredict ^{228}Th in physics data**
- Some sources have only ICP-MS measurements
 - Possible breaking of secular equilibrium in Th/ U chains
 - Systematics on assay values are hard to estimate...

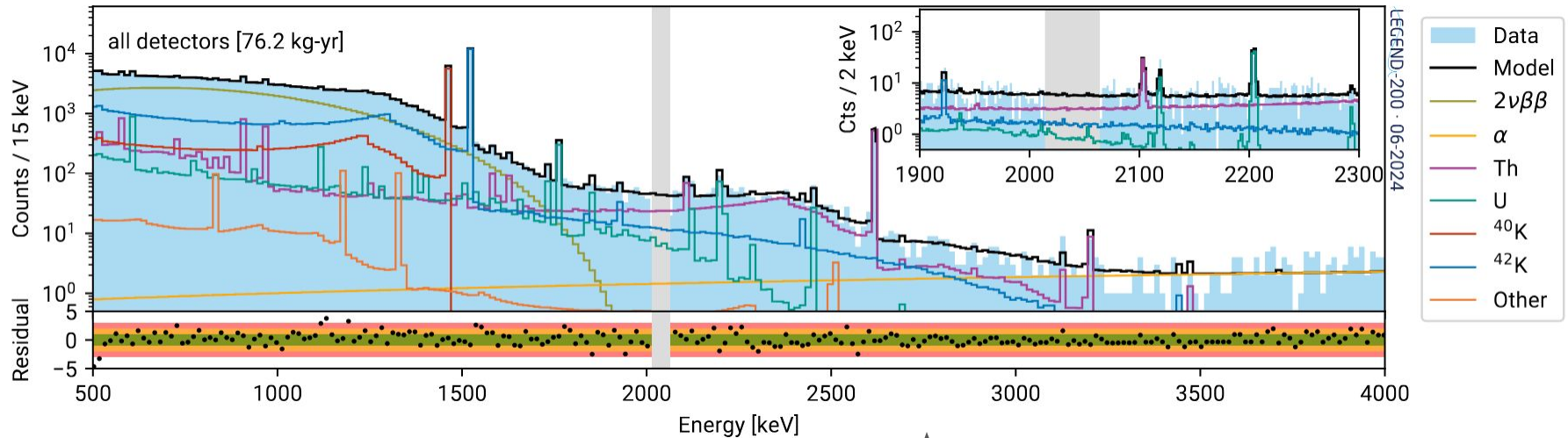


Background model before cuts

- Global background model reconstruction of all single detector data
- Results from the model provides useful information on the location of radioactive contamination

This is a fit...

Flat in the ROI...



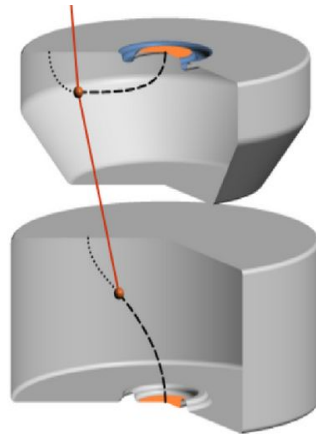
Model reproduces well the data!

Coincidence analysis

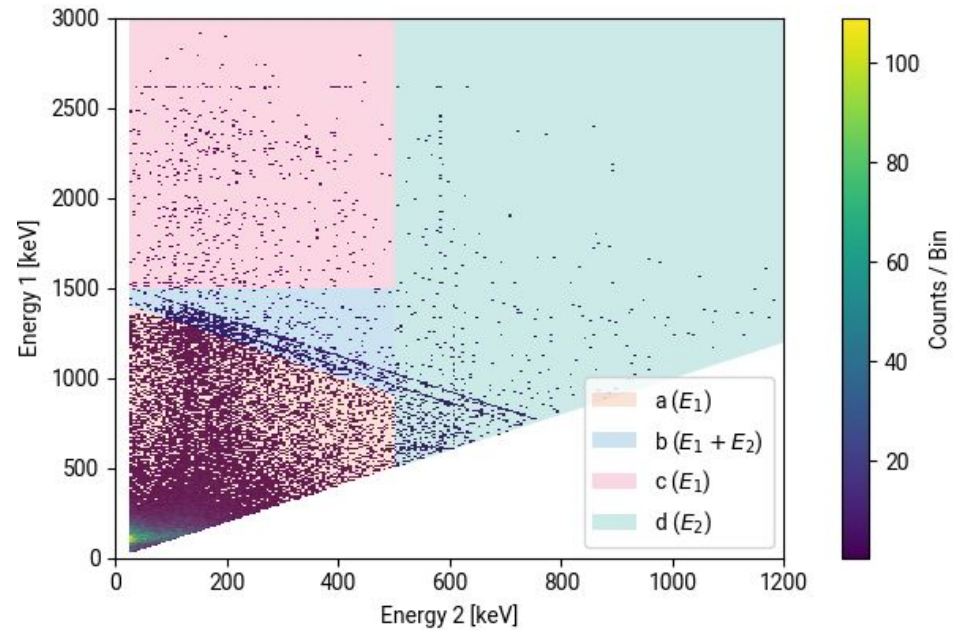
- Large amount of degeneracies in the fit
- Constrain activities close to the HPGe detectors by looking for coincidences between multiple detectors
 - → inherently 2D energy spectra
 - → more complicated analysis
- Division into **non-overlapping** groups
- 1D spectra for each included in the fit

Close sources

→ coincident events likely

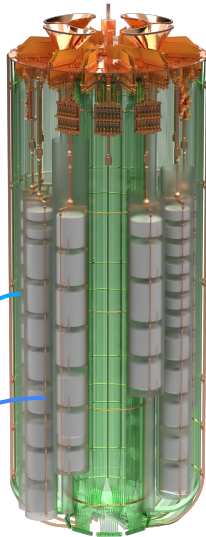


MULTIPLICITY CUT

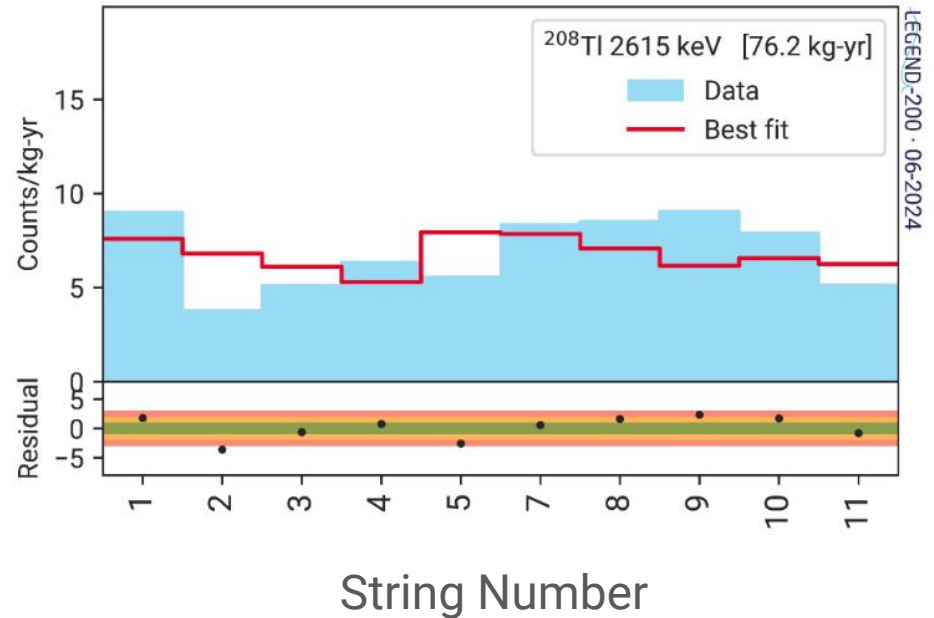


Model projections

- Search for non localised contamination
- *Project* the model onto different observables
 - Detector string
 - Detector
 - Vertical groupings



Detector Strings

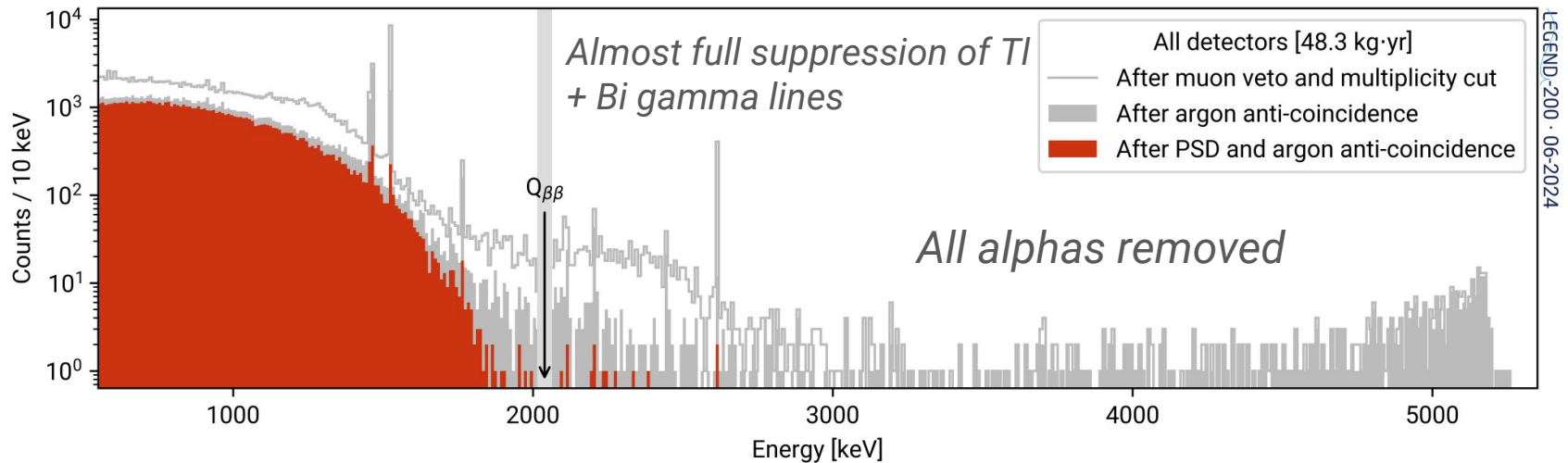


Example of the rate in the 2615 keV line by detector string

No hotspot or significant asymmetry observed in the data!

- But this is not the *background* for our $0\nu\beta\beta$ search!
- Our active background suppression is very effective
- Cuts efficiently suppress most of the background close to $Q_{\beta\beta}$

Background index at $Q_{bb} = (5.3 \pm 2.2) \times 10^{-4}$ cts/keV/kg/yr



Modelling of the effect of the cuts is more challenging but is in progress*

* building on experience from GERDA *Eur.Phys.J.C* 83 (2023) 4, 319

- Present a *consistent model* of the 1st year of L-200 data *before cuts*
- We are able to model well the available data!
- Includes data from novel *special background runs* representing an in-situ gamma assay measurement

LEGEND-200 is a versatile, “quick turnaround” experimental instrument. Enabling prompt investigation of issues and a swift return to data taking. A powerful test bench for LEGEND-1000!

- LEGEND-200 is currently in a hardware maintenance period
 - Installation of new HPGe detectors
 - Repair of SiPM modules
 - Additional HPGe screening



Thanks for the attention!

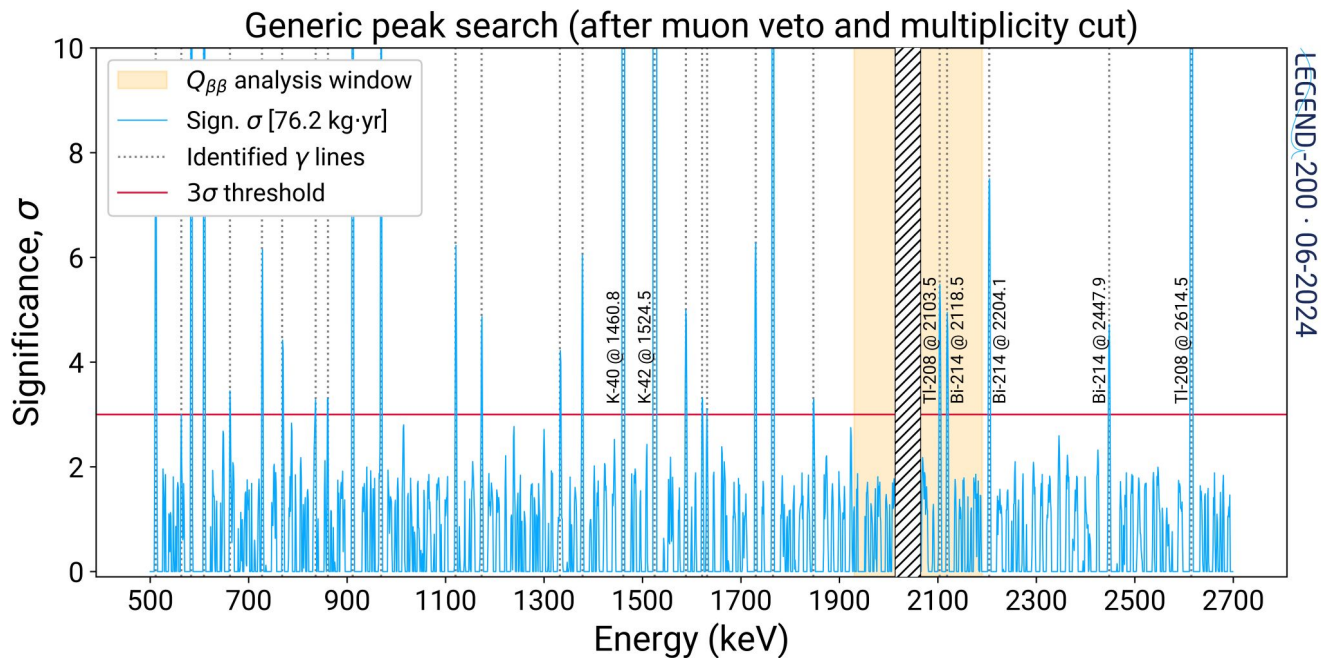


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Peak search

- Generic peak search performed over the entire spectrum
- Used to **identify features** to inform the background model
- Informs a **variable binning** algorithm where each gamma line is placed in a single bin



Shows γ 's from radioactivity from U, Th, $^{40/42}\text{K}$, ^{60}Co ,...