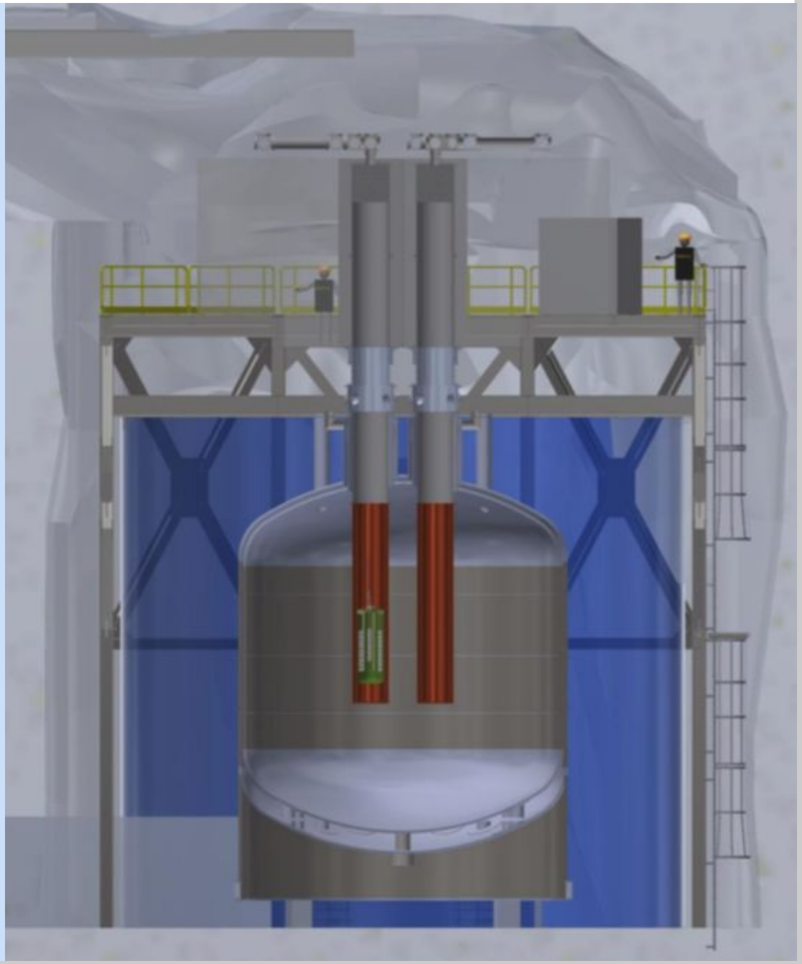
Detector characterization for LEGEND-200 experiment

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



Valentina Biancacci

26.07.2021

EPS-HEP 2021

Collaborators:
Abigail Alexander, Yoann Kermaidic

MCCXXII

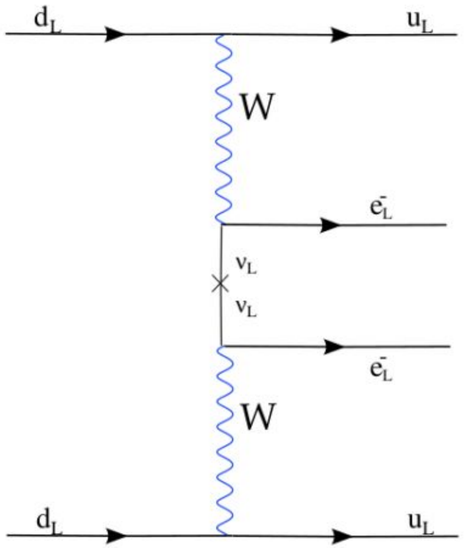
INFN

Double beta-decay without neutrinos

The neutrinoless double beta (0νββ) decay is a hypothetical nuclear transition.

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$

For the standard interpretations, 0νββ can be mediated by the exchange of two massive Majorana neutrinos.

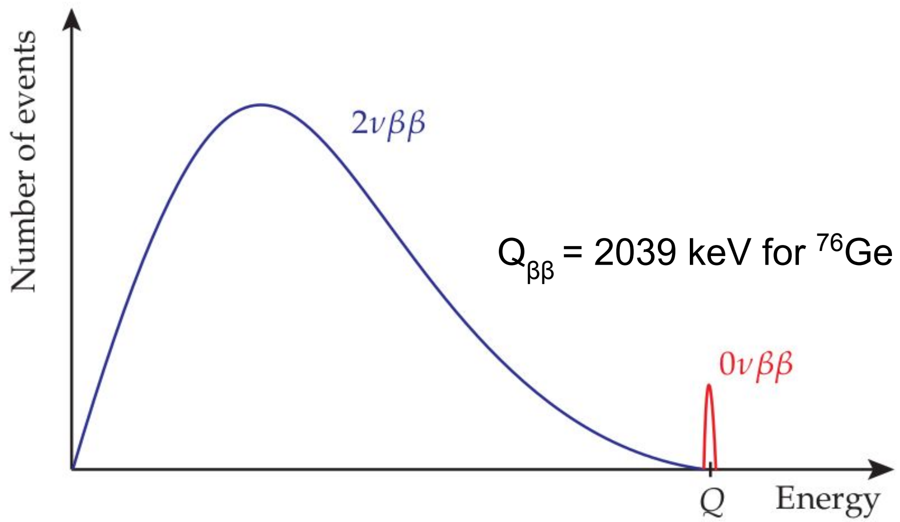


$$\frac{1}{T^{0\nu}_{1/2}} = |M^{0\nu}|^2 G^{0\nu}(Q, Z) \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

nuclear matrix element

phase space factor

$$\langle m_{\beta\beta}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$ effective neutrino mass



Motivation for 0νββ decay searches

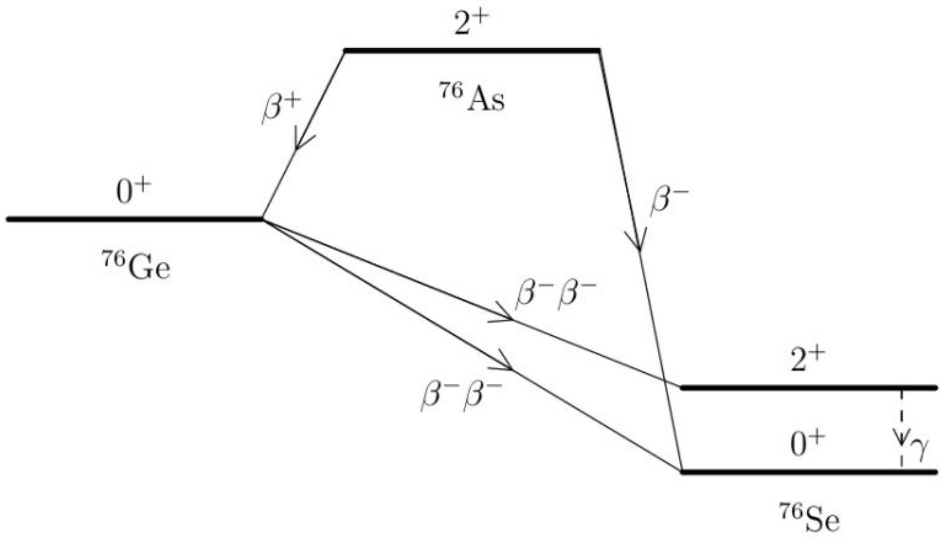
- Establish **lepton number violation** (LNV) → ΔL=2
- Only way to determine **if neutrino is its own antiparticle** ($\nu = \bar{\nu}$)
- Important to understand the **origin of the neutrino mass**
- Probe the a**bsolute neutrino mass scale** and **neutrino mass ordering**
- Provide important **input to cosmology**

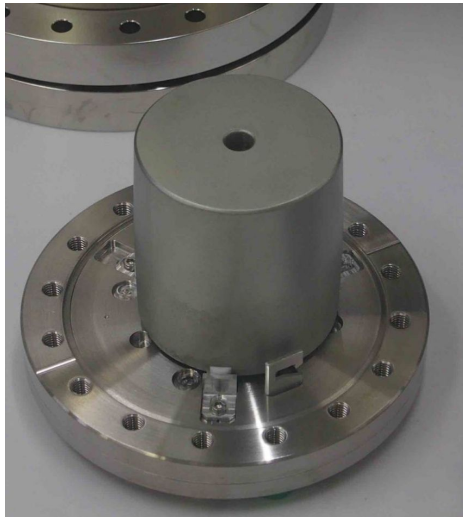
Searching in ^{76}Ge

Why using Germanium?

Advantage
- High efficiency → Source=Detector
- Small intrinsic BI = high purity Ge
- Excellent ΔE
- Well-established technology

Disadvantages
- Small Q-value
- Small $G^{0\nu}(Q, Z)$
- Small abundance 0νββ of isotope



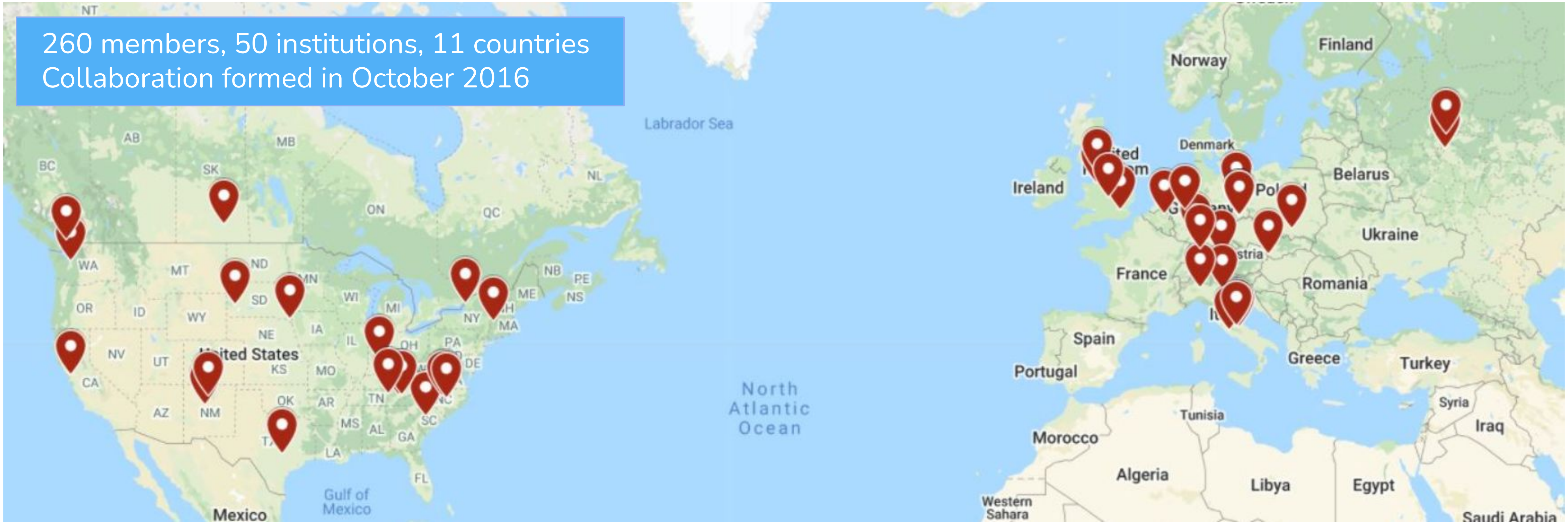


HPGe detector

LEGEND collaboration

LEGEND = **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless Double-Beta **D**ecay

260 members, 50 institutions, 11 countries
Collaboration formed in October 2016



LEGEND mission:

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

LEGEND experiment

First Stage (**LEGEND-200**):

- Upgrade of the existing infrastructure of GERDA experiment
- Reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- ~200 kg of detector mass: 35 kg from GERDA + 30 kg from MJD + 140 kg which are new.

Further Stage (**LEGEND-1000**):

- 1000 kg detector mass (staged)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- To reach beyond 10^{28} yrs half-life discovery sensitivity
- Location to be defined (SNOLAB or LNGS)

L200 Goals

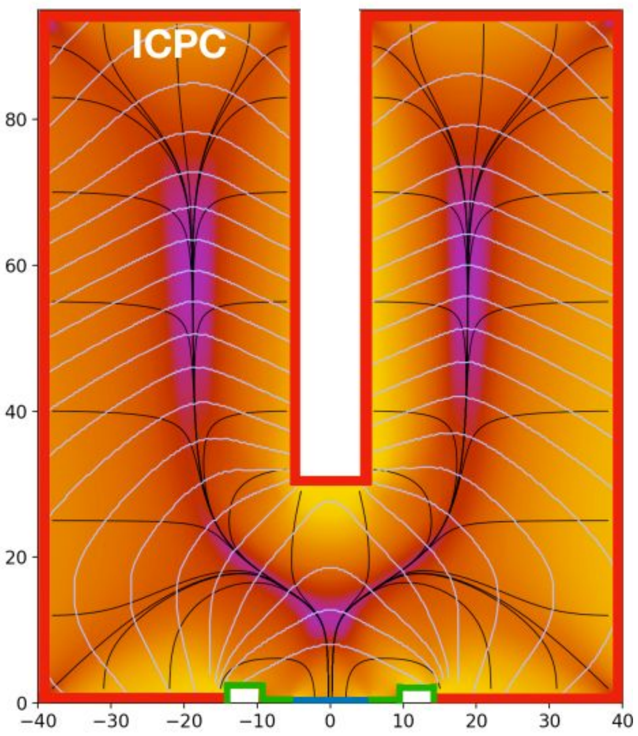
half life discovery sensitivity	10^{27} yrs
mass sensitivity	30-70 meV
background index	$2 \cdot 10^{-4}$ cts/(keV $\cdot$ kg $\cdot$ yr)

Michael Willers "The Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay" (presentation)
Luis Manzanillas "Usage of PEN as self-vetoing structural material in the LEGEND experiment" (poster)

HPGe detectors

Advantages of Inverted Coaxial Point Contact (ICPC) detectors:

- Enriched detectors, 92% of detector material is ^{76}Ge
- Excellent resolution and pulse shape discrimination
- Significantly larger w.r.t. BEGe or PPC (up to 3 kg)
- Less channels, less background
- Better surface to volume-ratio (30-40%)
- Production started early 2019
- About 60 detectors expected by fall 2021



n+ electrode
p+ electrode
passivation

Detector characterization

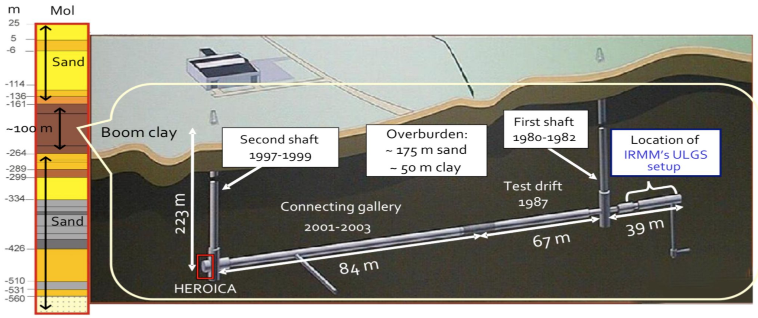
Why is the characterization so important?

- Determine the nominal bias voltage
- Probe the geometrical detector response
- Estimate the best achievable **energy resolution**
- Evaluate the **pulse shape discrimination (PSD)** performance
- Measure the **material enrichment**
- Estimate the **active volume** ←
- Determine the **total detector mass**

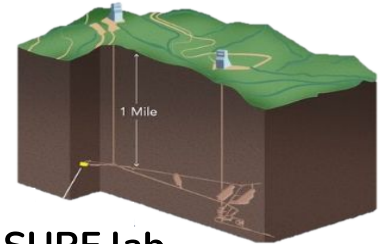
$$T^{0\nu}_{1/2} \propto \epsilon \cdot a \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

ϵ: detection efficiency
a: isotopic abundance
M: total detector mass
t: run time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Two underground characterization sites in Europe and US to reduce cosmic activation.

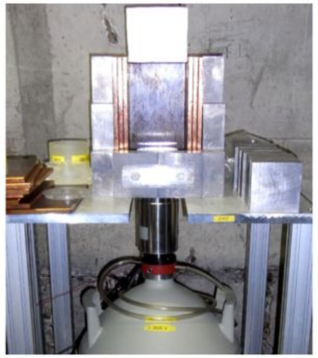


HADES lab

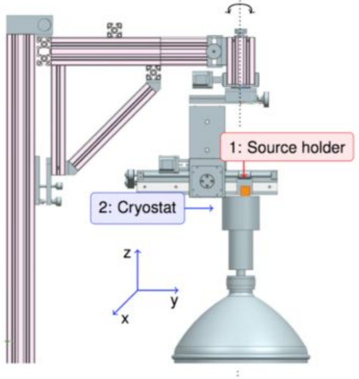


SURF lab

The detectors are exposed to different radioactive sources.



Static measurements: (^{232}Th, ^{60}Co, ^{133}Ba, ^{241}Am)

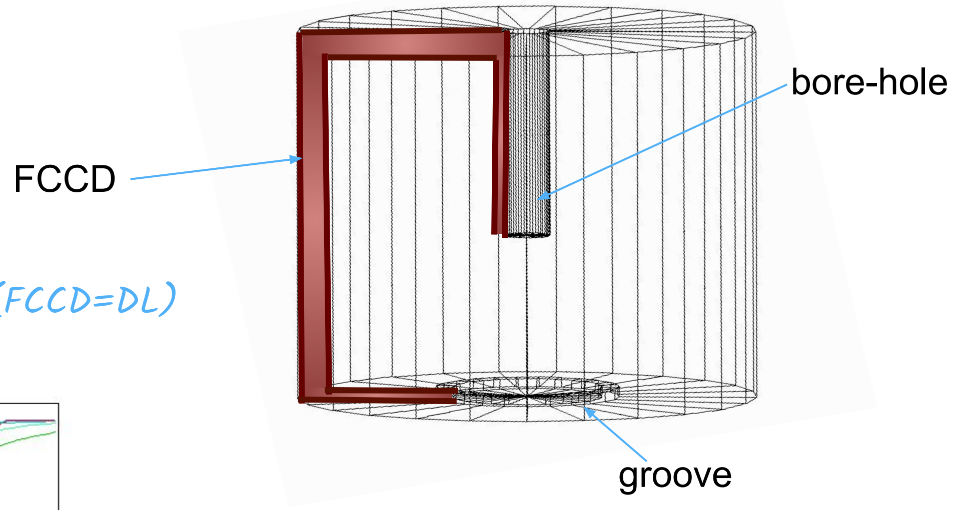


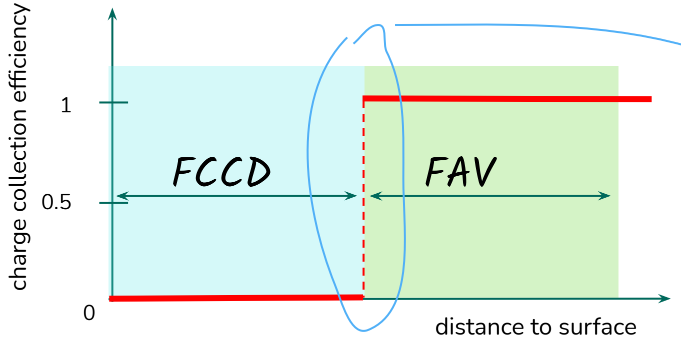
Surface scans: (collimated ^{241}Am)

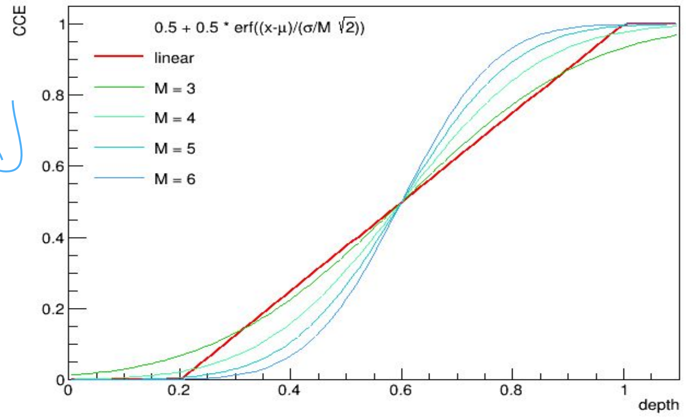
Active volume characterization

In addition to the fully active volume (FAV), around the surface there is the full charge collection depth (FCCD).
It consists of:

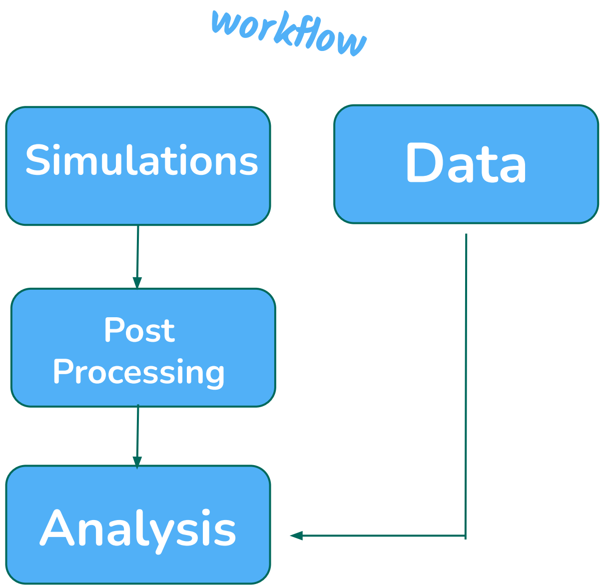
- dead layer (DL) = zero charge collection; *ignored at first order (FCCD=DL)*
- ~~transition layer (TL) = partial charge collection.~~







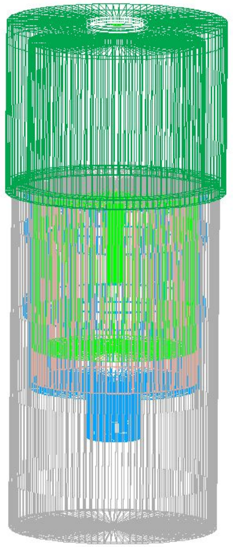
1. MC simulations are created through g4simple tool.
2. Starting from raw MC, generate subsequent spectra for different FCCD thicknesses.
3. Compare post-processed simulations and data by constructing a sensitive observable.

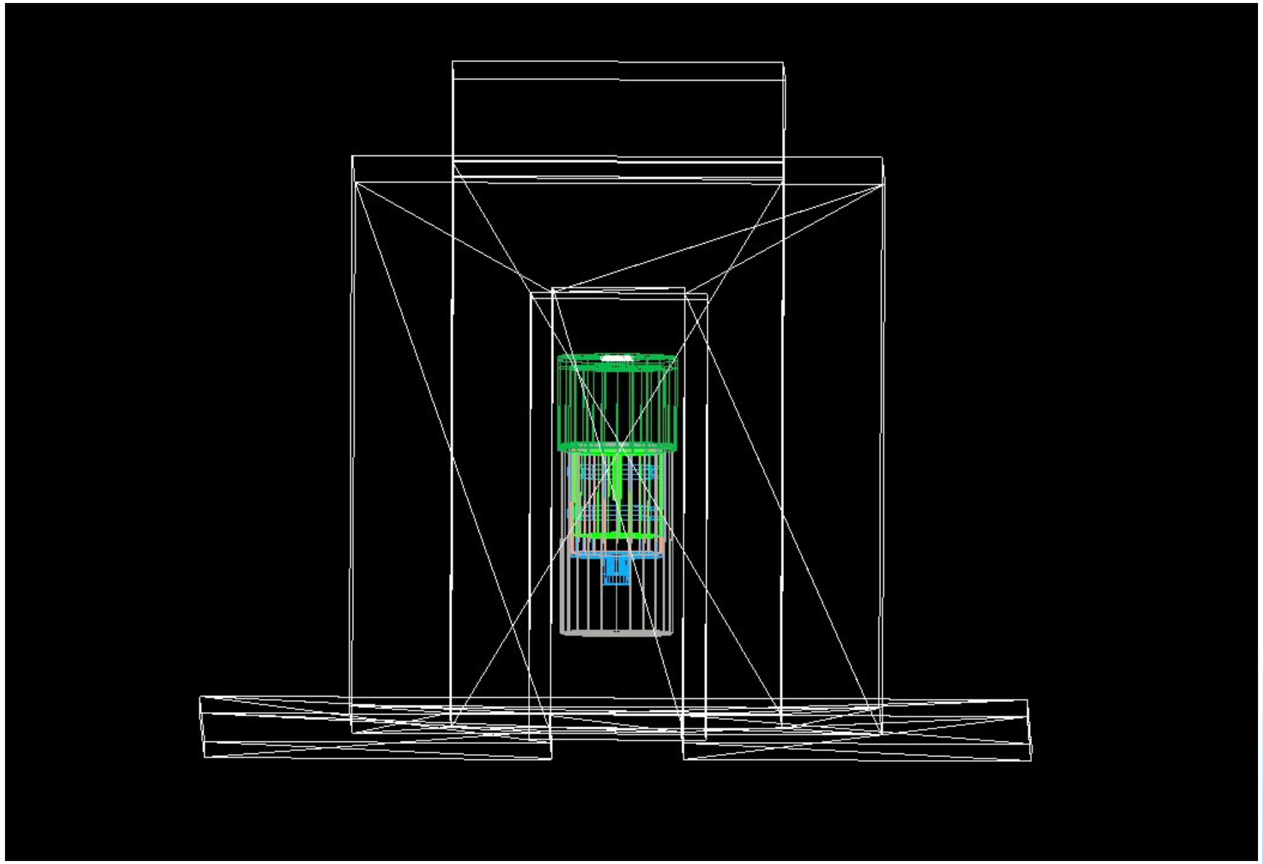


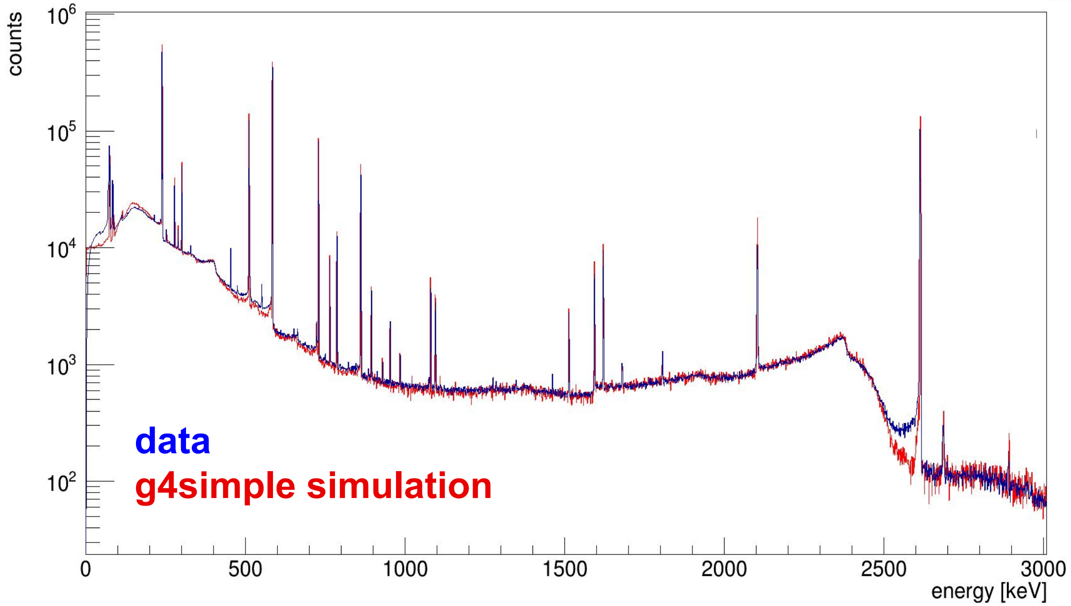
G4simple simulations

G4simple is a simple Geant4 simulation suite developed by the Legend collaboration.

- Lead **castle**
  - Aluminium alloy* **cryostat**
    - Enriched germanium **detector**
    - Aluminium alloy* **holder**
    - HD1000 **wrap**
  - Acrylic **source holder**
    - Acrylic/HD1000 **source**







^{228}Th source is used to validate the simulation comparing the resulted energy spectrum with the data.

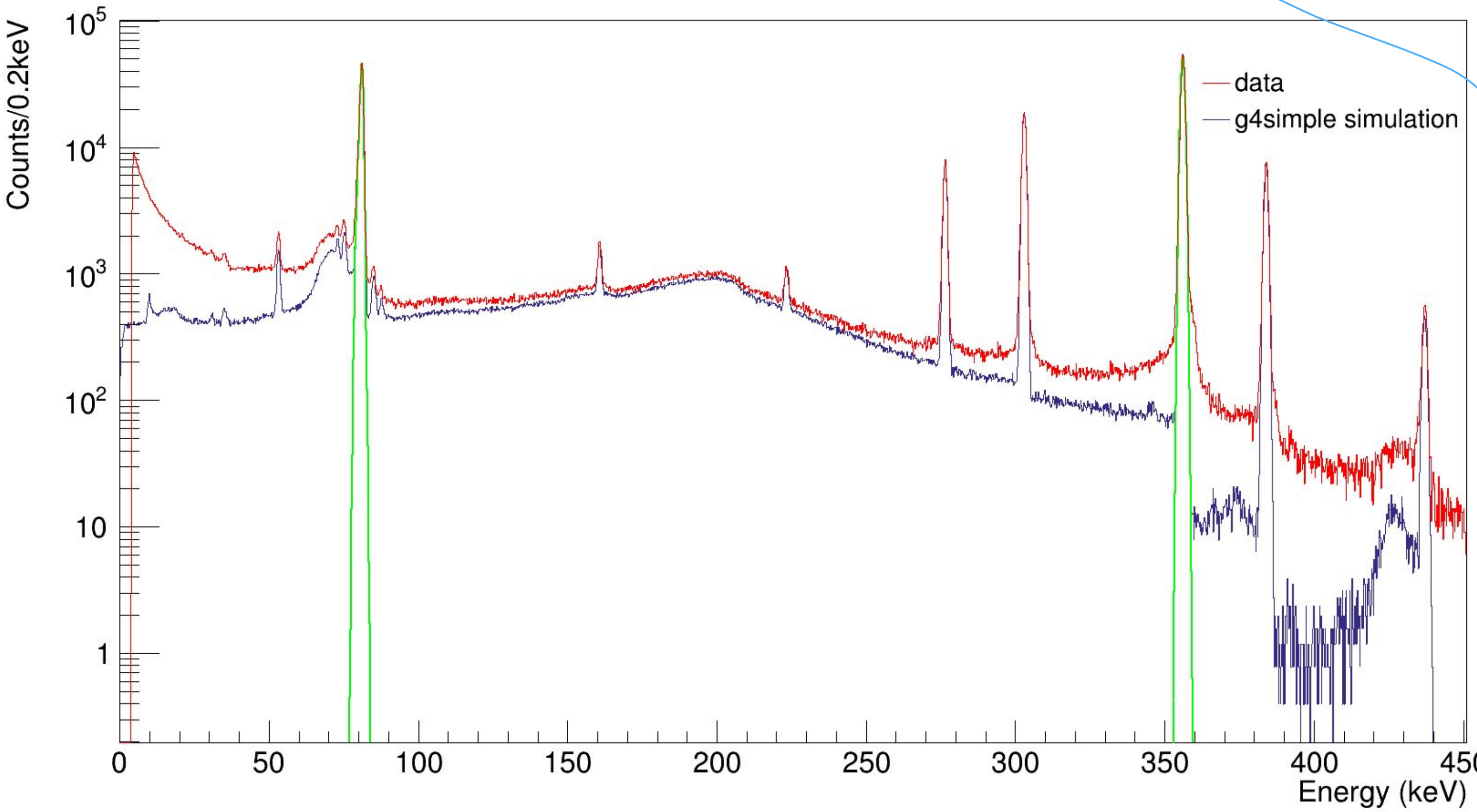
*EN AW-2011 Al Cu6BiPb

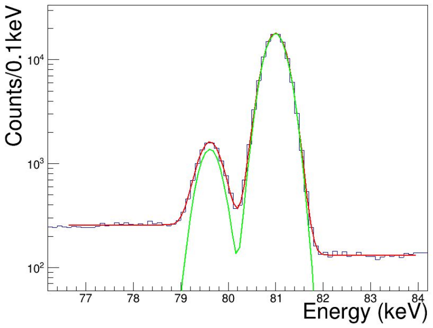
Analysis using ^{133}Ba source

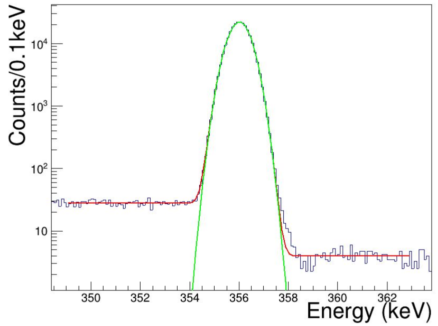
Compare data to post-processed MC simulations by the following FCCD sensitive observable:

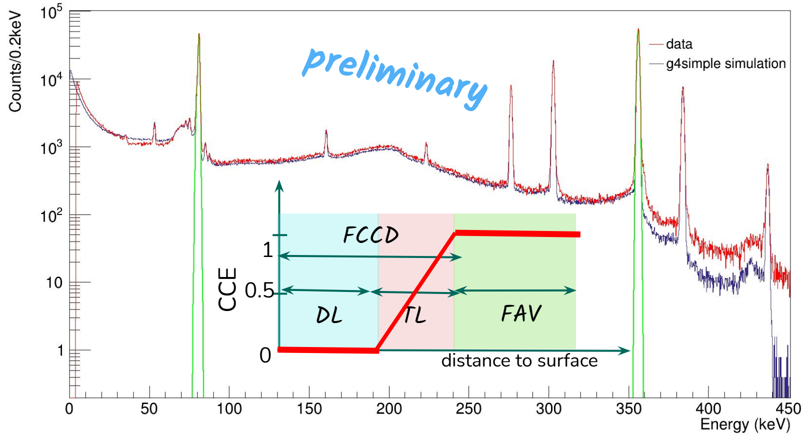
count ratio

$$R = \frac{I_{79.6keV} + I_{81keV}}{I_{356keV}}$$



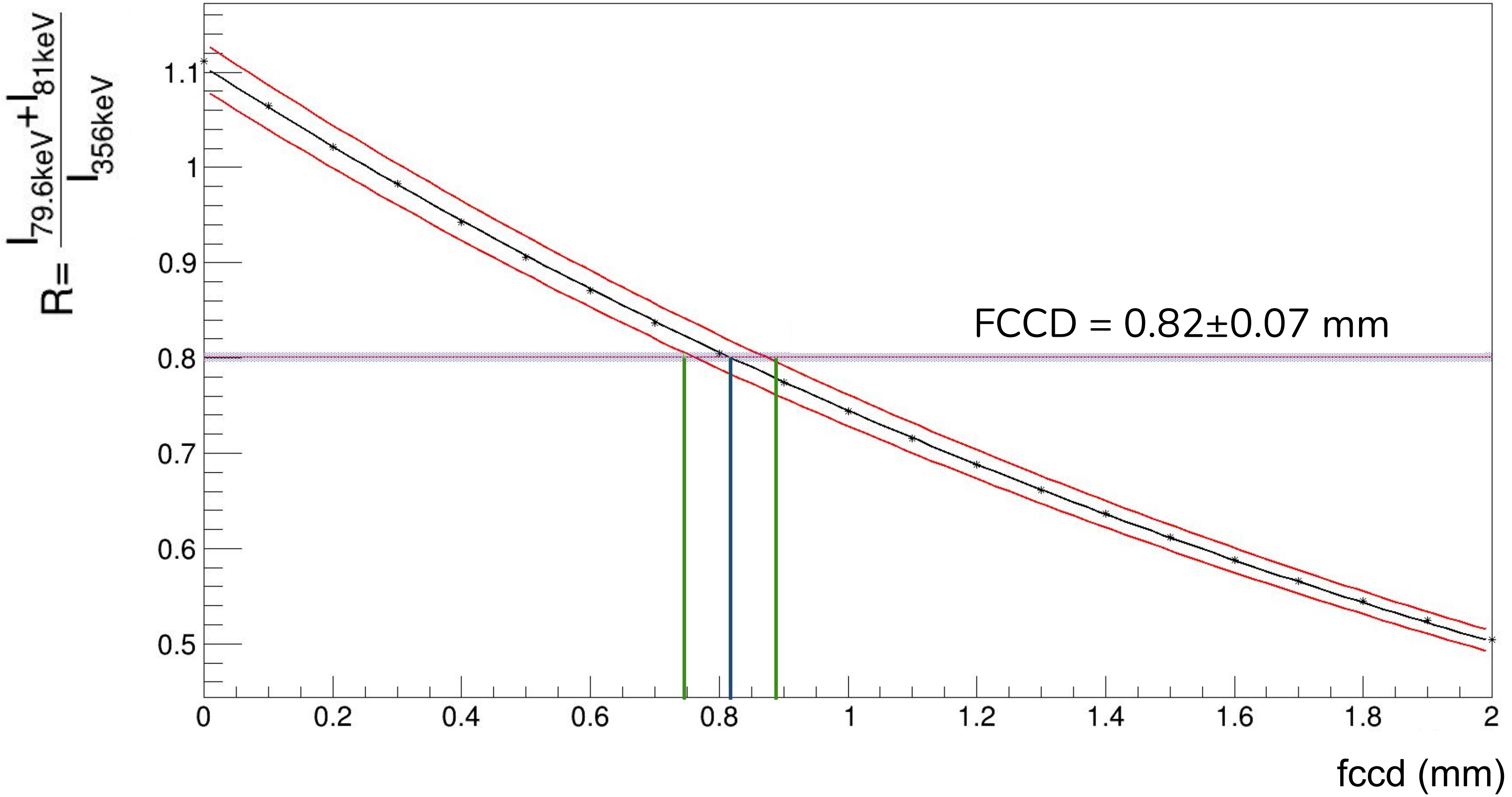






Analysis using ^{133}Ba source – results

Exemplar plot for the determination of the FCCD value of an ICPC detector.



work in progress!

- This process is repeated for all the detectors by automatisation.
- Other radioactive sources are used to compare the FAV results.

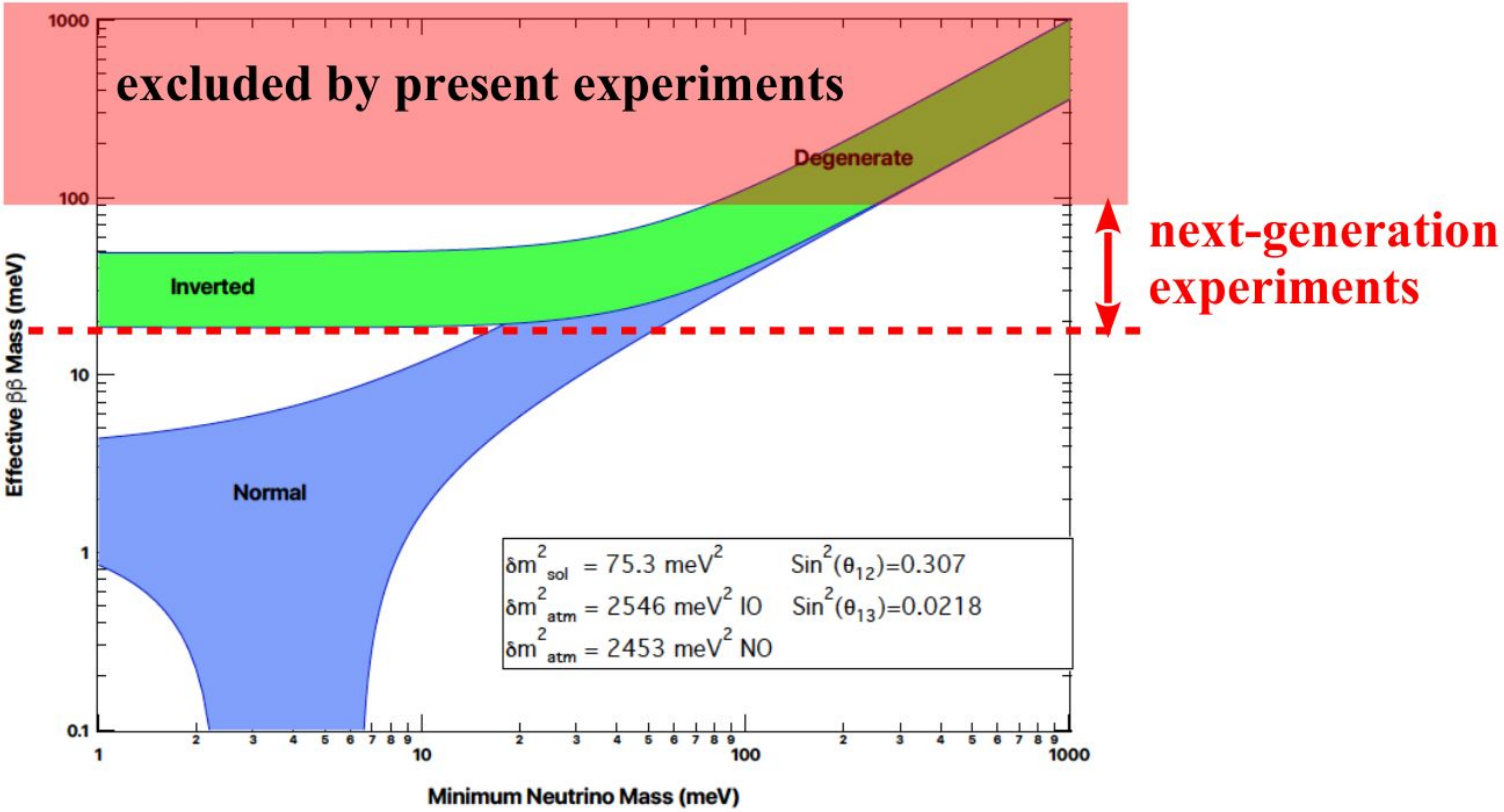
Conclusion

- **LEGEND** will search for $0\nu\beta\beta$ decay in ^{76}Ge via 2 stages.
- LEGEND-200 is going to start taking data at the end of this year with ~200kg of **HPGe detectors**.
- HPGe detectors must be characterised before being submerged in LAr cryostat.
- The **Active Volume** of the HPGe detectors is determined:
  - **Dead layer** modelled
  - **Transition layer** model (next step)

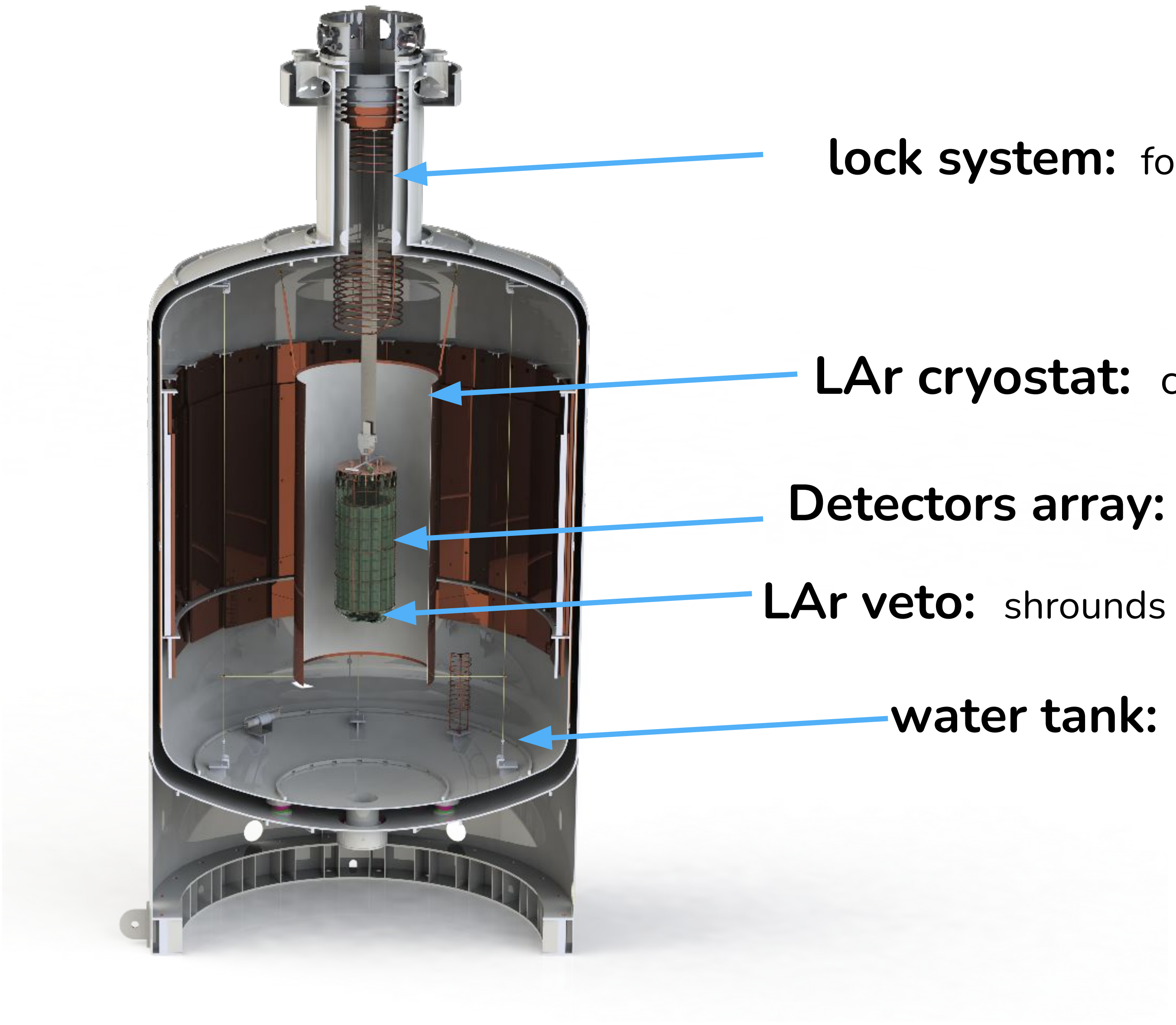
Backup

Results and goals

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$



General layout of LEGEND-200



lock system: for the deployment of the Ge detectors

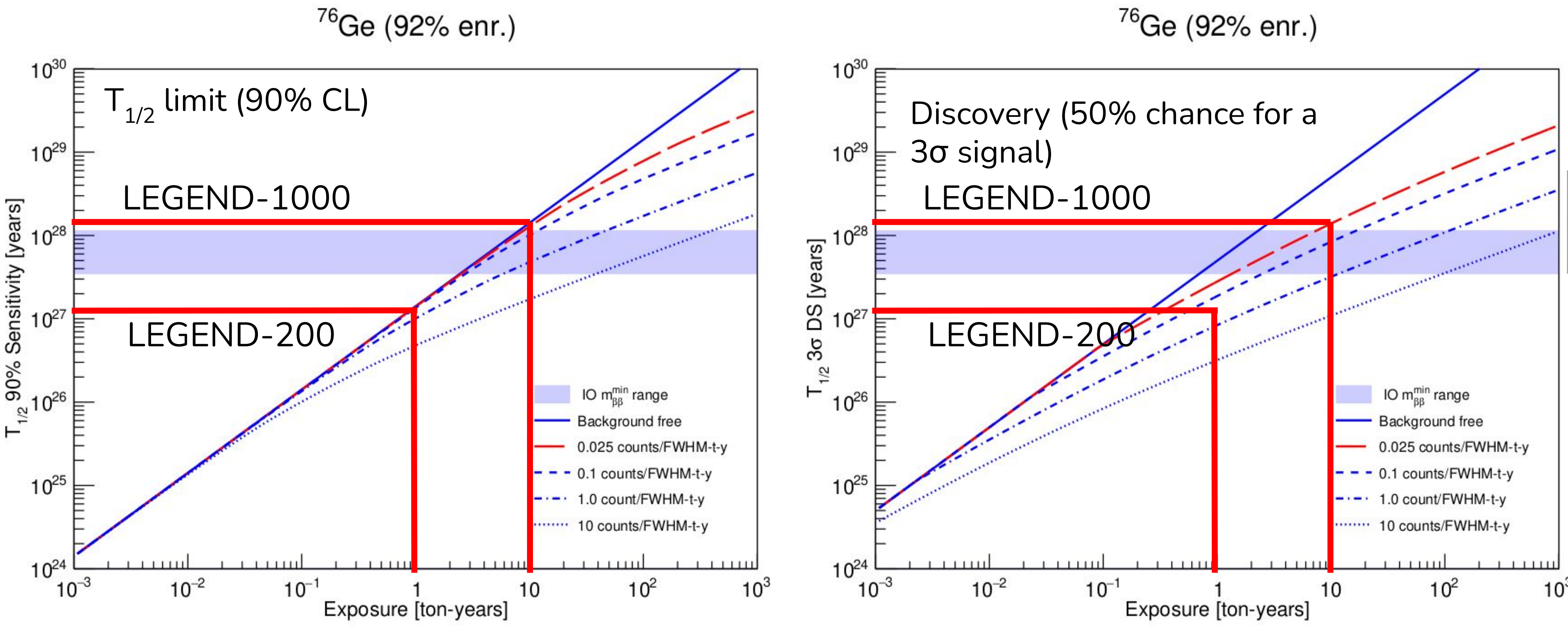
LAr cryostat: coolant shielding

Detectors array: string of naked enriched germanium detectors

LAr veto: shrounds with scintillating fibers for the detection of the light

water tank: neutron moderator/absorber muon Cherenkov veto

Discovery Sensitivity

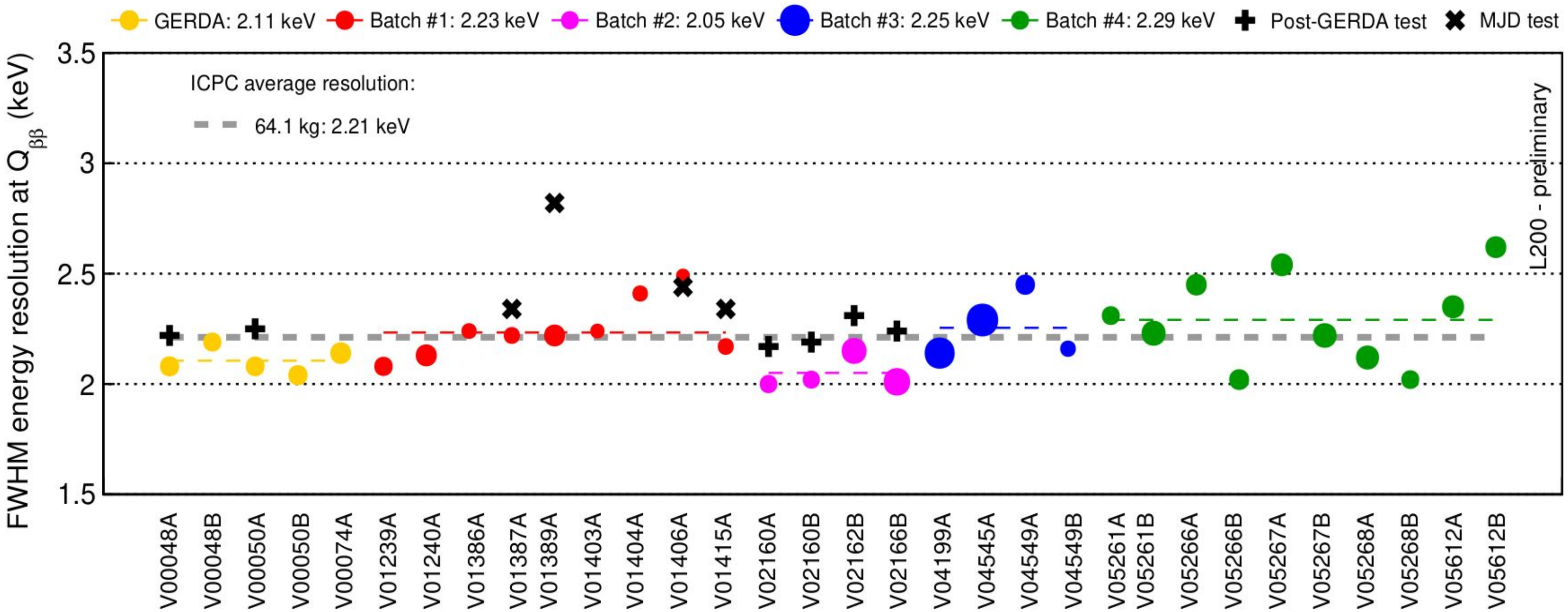


	Bkg Index cts/(FWHM·ton·yr)
LEGEND-200	0.6
LEGEND-1000	0.025

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot a \cdot M \cdot t & \text{without background} \\ \epsilon \cdot a \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} & \text{with background} \end{cases}$$

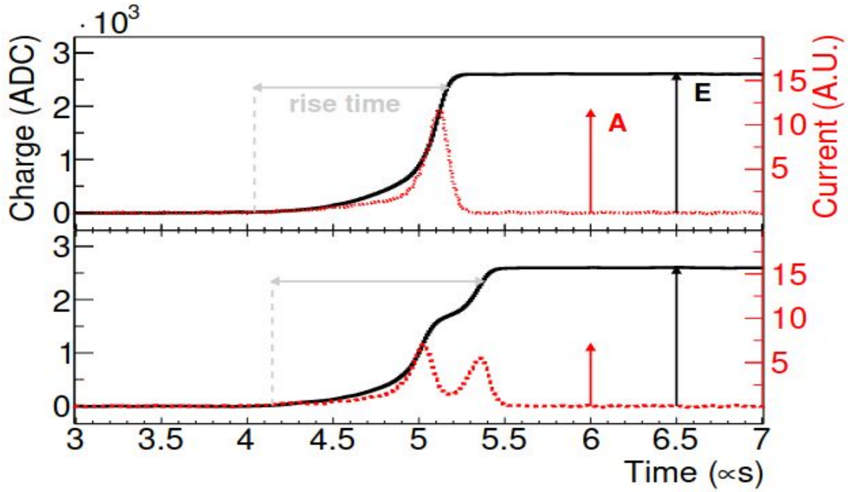
ϵ: detection efficiency
a: isotopic abundance
M: total detector mass
t: run time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Energy resolution and PSD performance



resolution

- No resolution degradation seen in ICPCs
- Well-understood peak shape, energy scale stability, and linearity (better than 0.1%) lead to improved confidence in results



pulse shape discrimination

- The multi-site events (bkg) can be rejected looking at pulse shapes
- Compton continuum γ background reduced (~50%)
- α and β events reduced (≥ 99%)