Active Volume Characterisation of Germanium Detectors for LEGEND-200

NBIA Summer School on Neutrinos: Here, There and Everywhere
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For the LEGEND collaboration

Introduction

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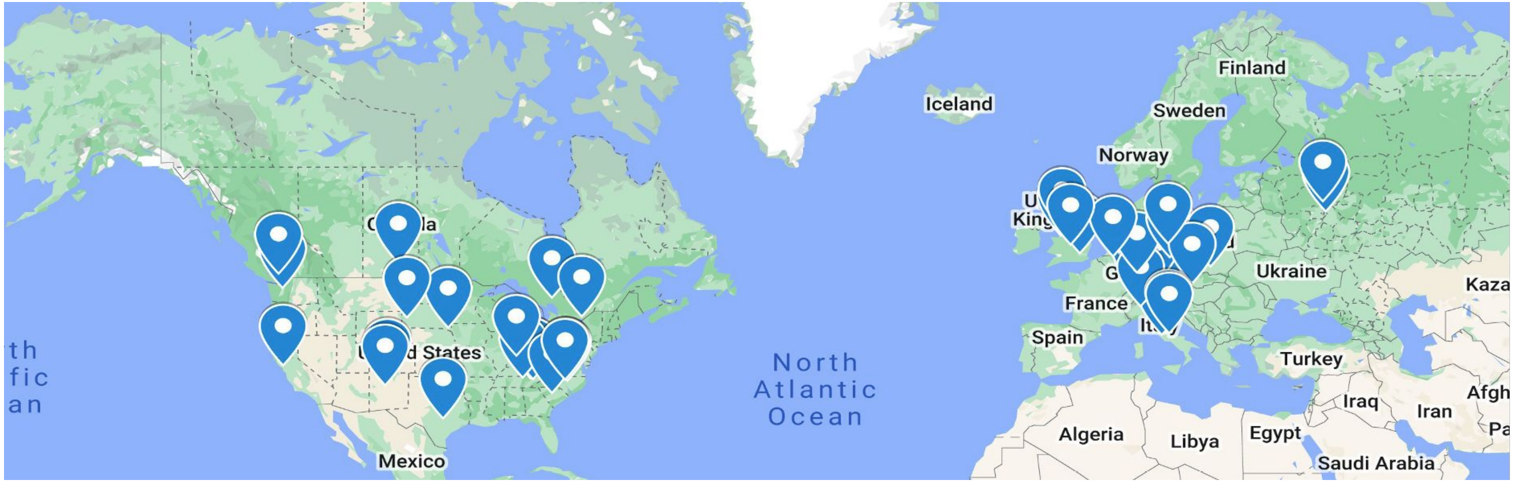
LEGEND = The Large Enriched Germanium Experiment for Neutrinoless double beta Decay

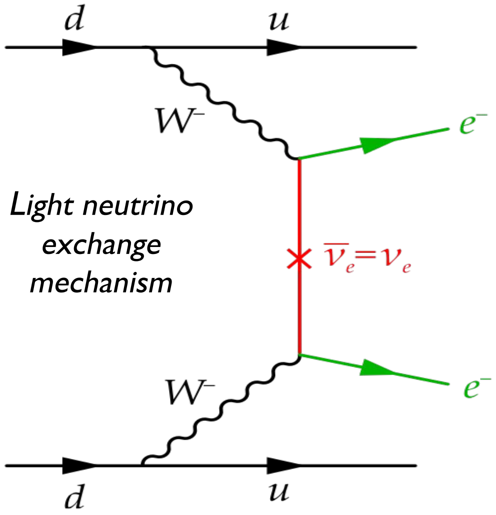


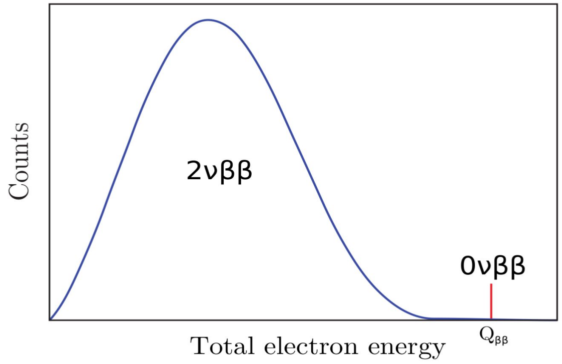
LEGEND Mission:
"Develop a two-phased ^{76}Ge based neutrinoless double beta decay experimental program with discovery potential at a half-life beyond 10^{28} yrs."

The LEGEND collaboration:
- 260 members
- 47 institutions, 11 countries

Neutrinoless Double Beta Decay

- **Neutrinoless double beta** ($0\nu\beta\beta$) **decay** = a hypothetical nuclear transition
- **Detection would:**
  - Prove neutrinos are Majorana in nature
  - Lepton-Number-Violating (LNV) process → matter-antimatter asymmetry
  - Probe the absolute neutrino mass scale and neutrino mass ordering
- Search in certain even-even **isotopes**: e.g. ^{76}Ge, ^{82}Se, ^{136}Xe, ^{100}Mo, ^{130}Te
- **Experimental signature:** single delta peak at Q-value (2039 keV for ^{76}Ge)





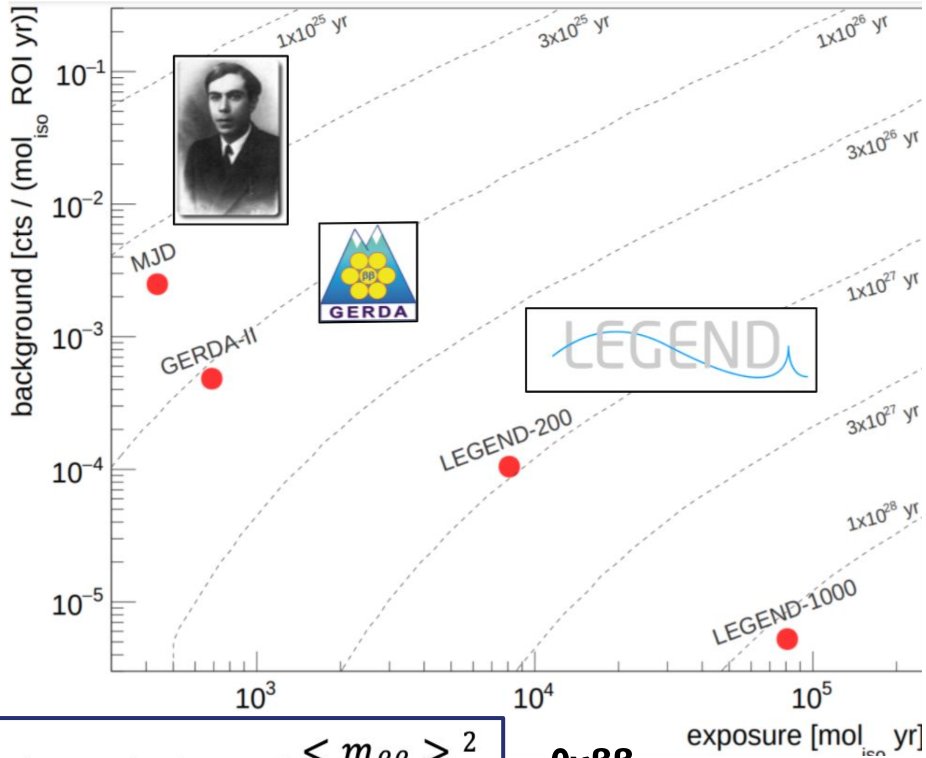
LEGEND: Phases

L-200

- 200 kg ^{enr}Ge
- Half-life ($T_{1/2}$) sensitivity: 10^{27} yrs
- Effective majorana mass ($m_{\beta\beta}$) sensitivity: 30-70 meV

L-1000

- 1000 kg ^{enr}Ge
- $T_{1/2}$ sensitivity: beyond 10^{28} yrs
- $m_{\beta\beta}$ sensitivity: 9-21 meV (fully covers IO region)



$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{m_e^2}$$

0νββ half-life

LEGEND-200

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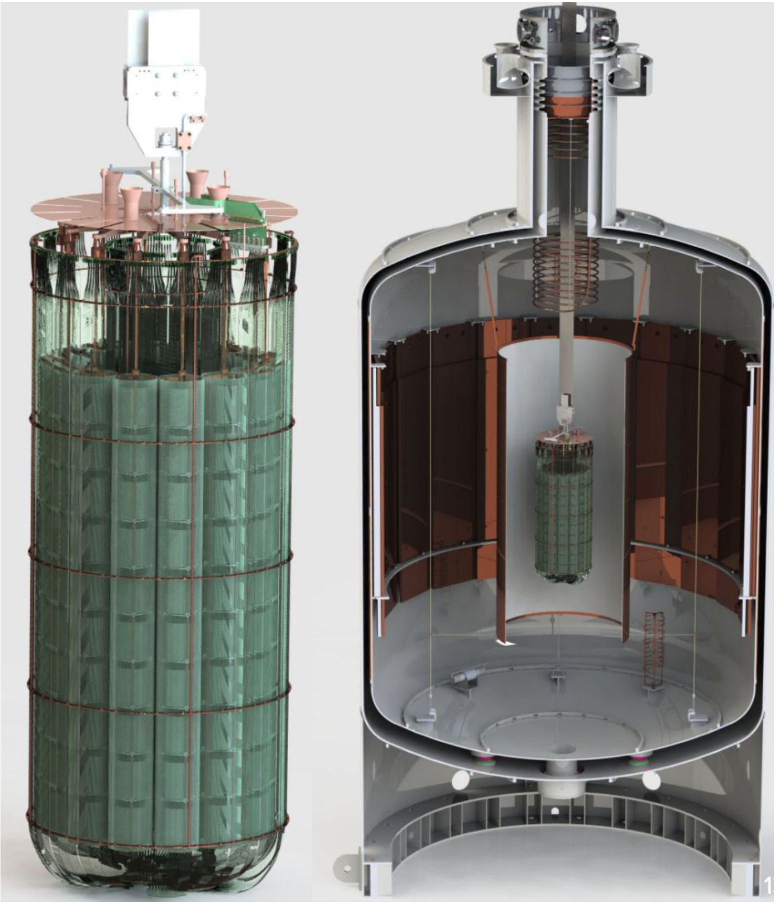

- **L-200 Experimental Design:**
  - Builds on existing infrastructure and electronics of parent GERDA and Majorana Demonstrator experiments
  - Deep underground at LNGS, Italy
  - Germanium detectors: source = detector
  - Liquid argon scintillation light detectors: active veto
  - 5 years of data taking for a 1 ton.yr exposure
  - Background index target of $2x10^{-4}$ cts/(keV.kg.yr)
- **L-200 Status:** now commissioning!

LEGEND-200: Commissioning

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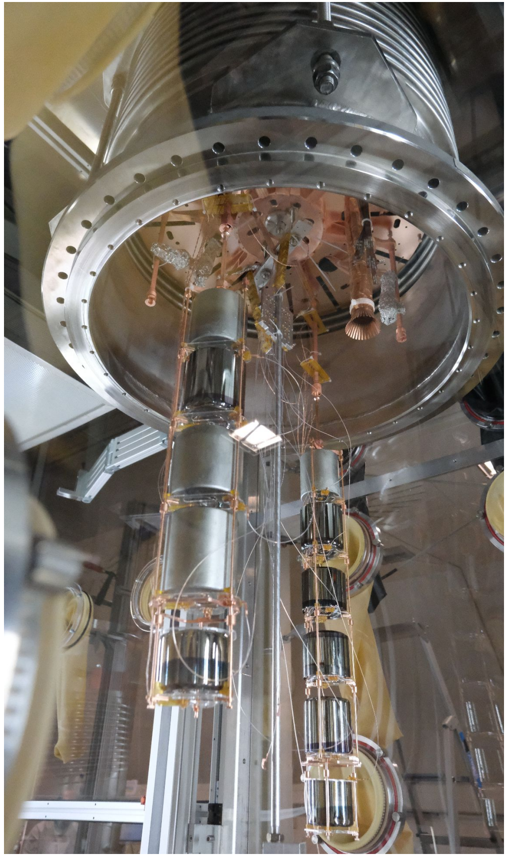
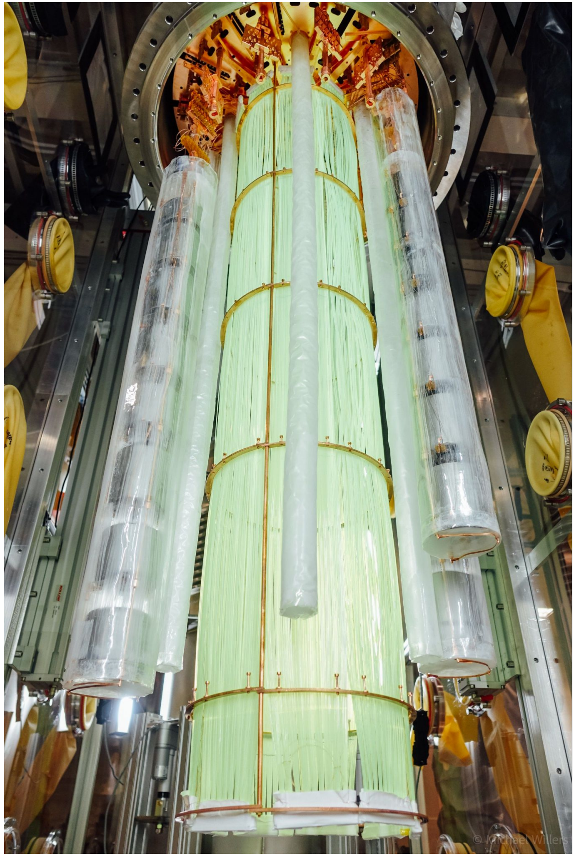




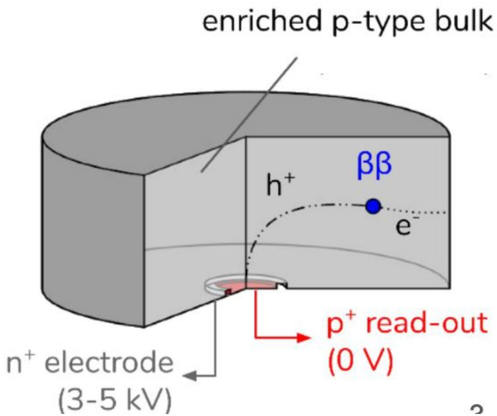
Germanium Detectors

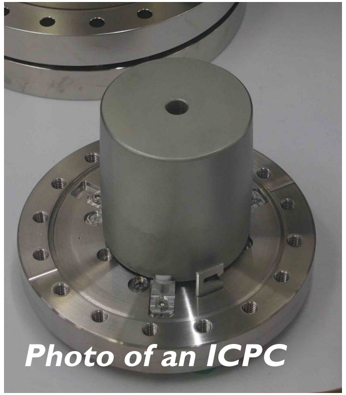
High Purity Germanium (HPGe) Detectors:

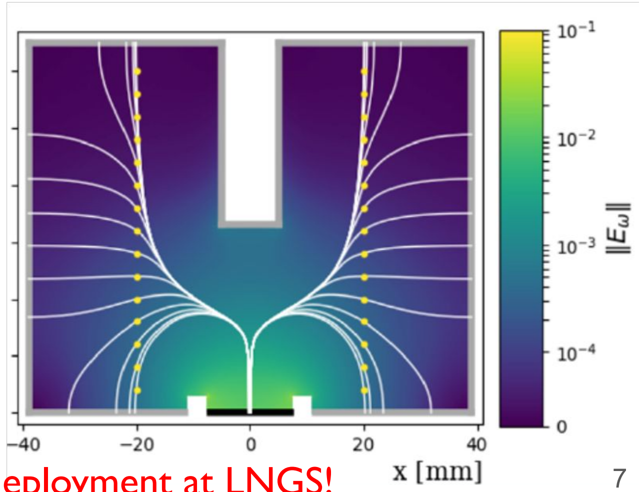
- Semiconductor detectors
- Enriched detectors: 92% of detector material is ^{76}Ge
- High spatial and superior energy resolution
- ~100 individual detectors for L-200 of 3 key geometries: PPCs, BEGe, ICPCs

Inverted Coaxial Point Contact (ICPC) Detectors:

- New design with unique geometry
- Large detector mass (up to ~4 kg)
- Strong signal-background Pulse Shape Discrimination (PSD) power







All detectors must be thoroughly characterised before deployment at LNGS!

Active Volume of Germanium Detectors

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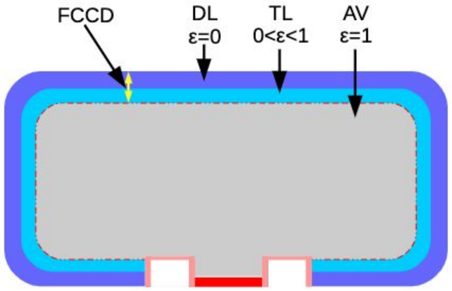
HPGe detectors have a dead layer:

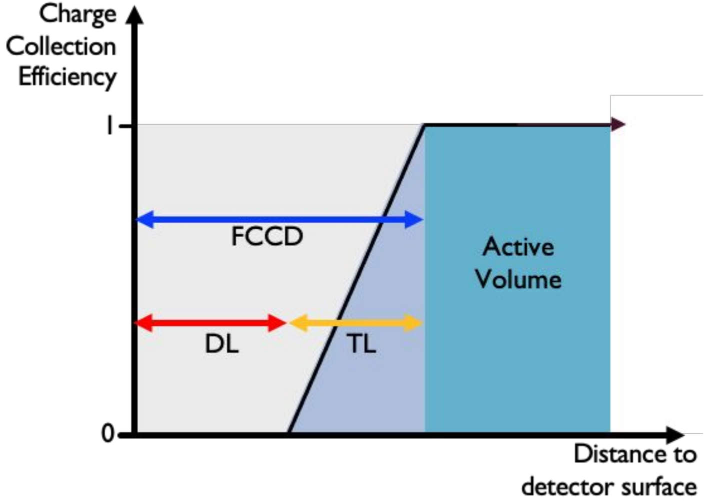
- Dead Layer (DL) = region of no charge collection on surface of semiconductor detectors. A conductive layer, created by Lithium diffusion.
- Transition Layer (TL) = partial charge collection
- Full Charge Collection Depth (FCCD) = TL + DL
    - *NB: TL is ignored at first order such that FCCD=DL*

The DL, and hence active volume, determination is important because:

- The 0νββ half-life is a function of active mass
- Degraded events could mimic 0νββ signature

We estimate the DL empirically by comparing characterisation data of detectors exposed to known radioactive sources with MC simulations





Detector Characterisation for L-200

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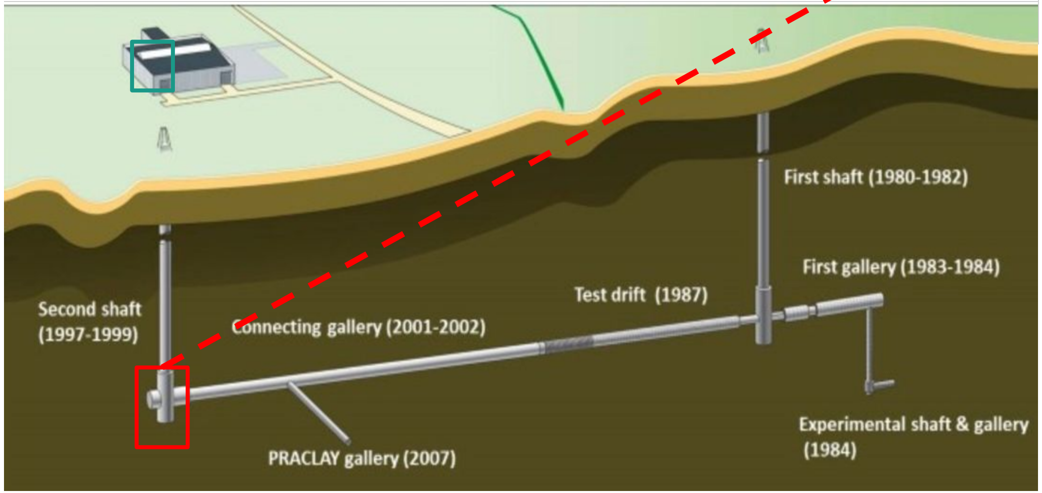
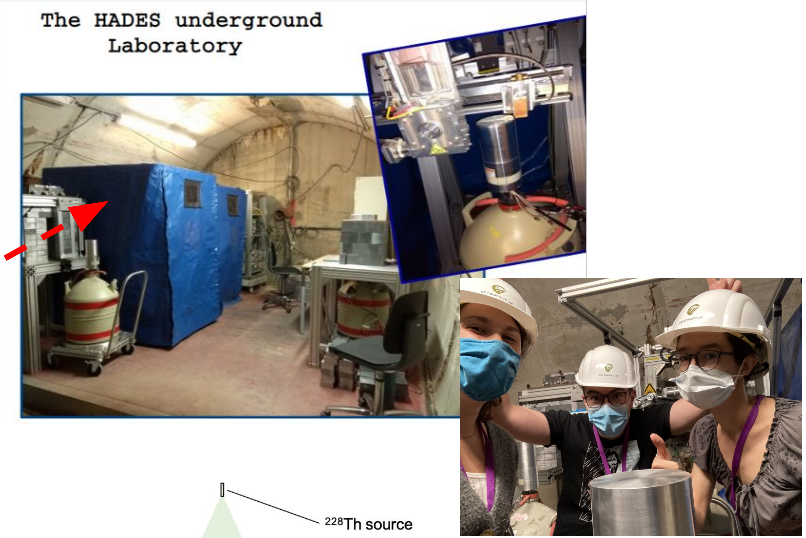
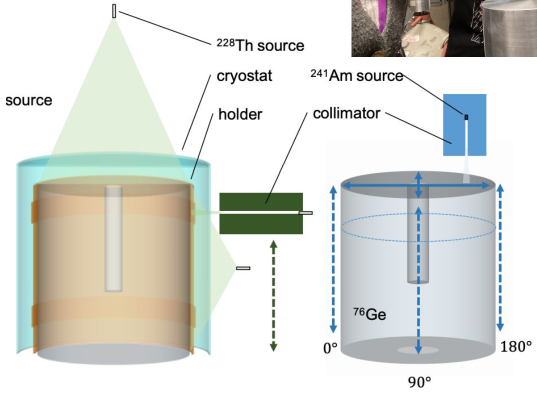
- Data taking at HADES underground lab (Mol, Belgium)
- Detectors are exposed to different radioactive sources
- This is ongoing work as new detectors arrive.
- ~30 LEGEND ICPCs have been characterised at HADES so far.







Active Volume Characterisation

Simulations:

GEANT-4 MC simulations of detector, test stand and radioactive source [https://github.com/legend-exp/g4simple]

DL Post Processing:

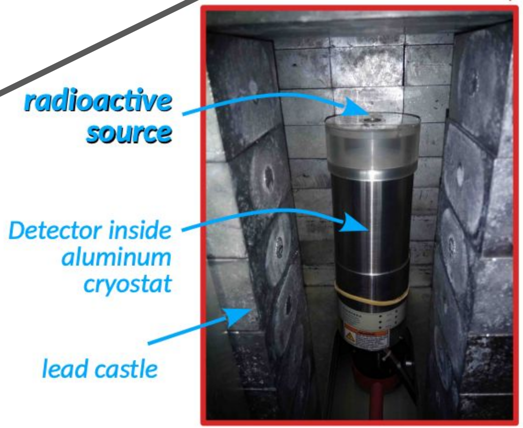
Position based weighting and removal of energy deposits to simulate different FCCD values

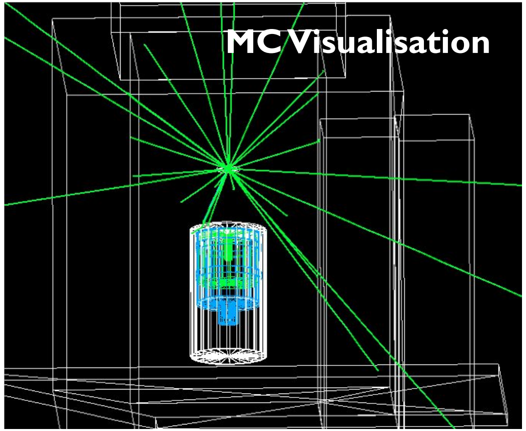
Analysis:

Compare post-processed MC of varying FCCDs with the data by constructing an FCCD sensitive observable: a gamma line count ratio → infer best fit FCCD

Data:

Detectors exposed to ^{133}Ba (low energy spectrum→ FCCD sensitive)



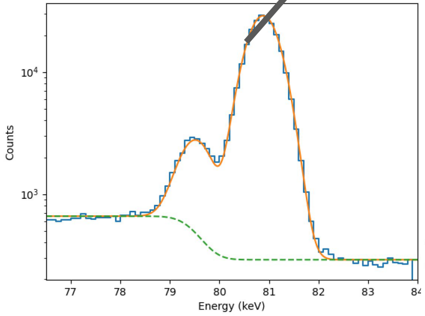


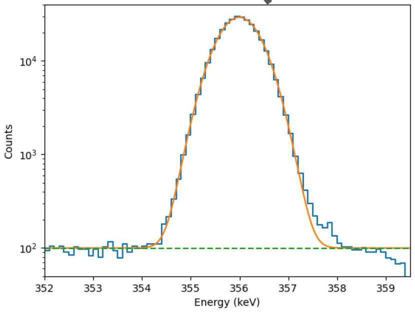
Active Volume Characterisation: FCCD

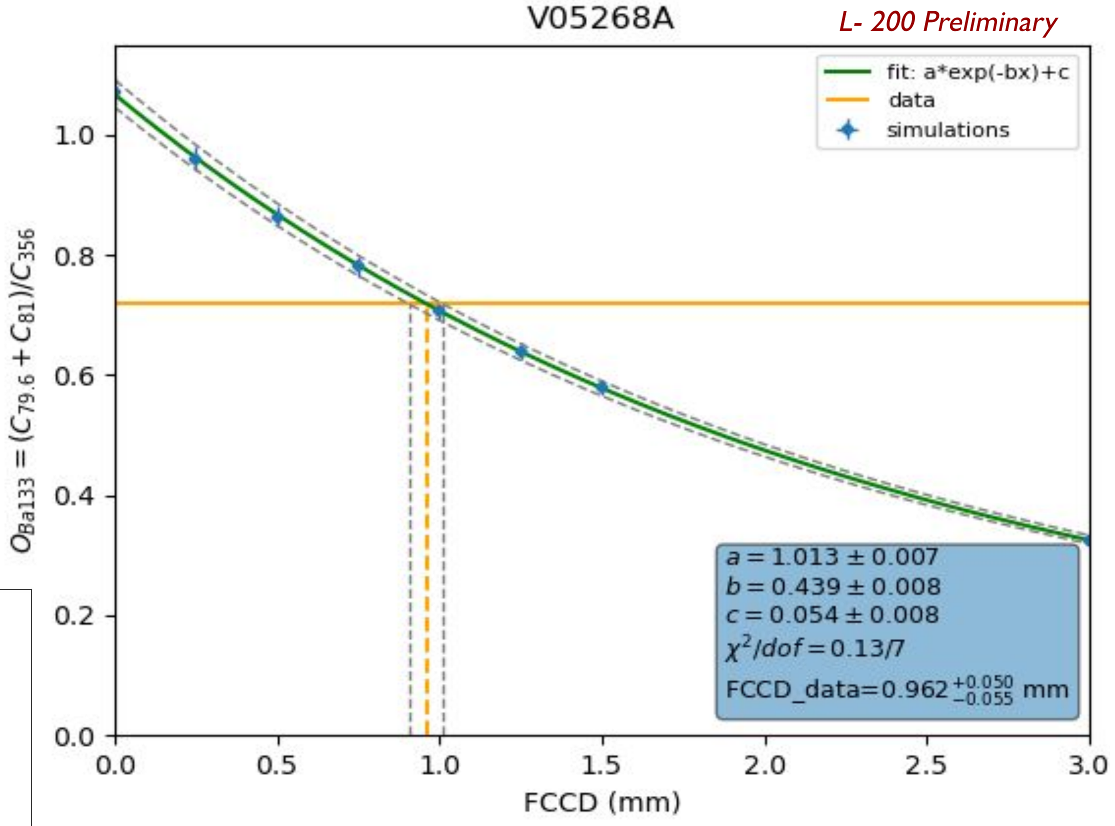
FCCD sensitive observable for ^{133}Ba:

- Fit and integrate the counts, C, in the 81/79 and 356 keV gamma lines
- Compute for each post-processed MC and data

$$O_{133\text{Ba}} = \frac{C_{79.6\,\text{keV}} + C_{81.0\,\text{keV}}}{C_{356.0\,\text{keV}}}$$

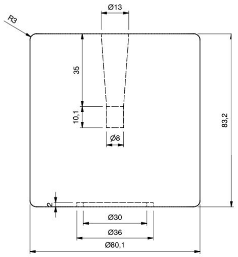


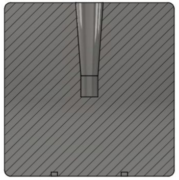




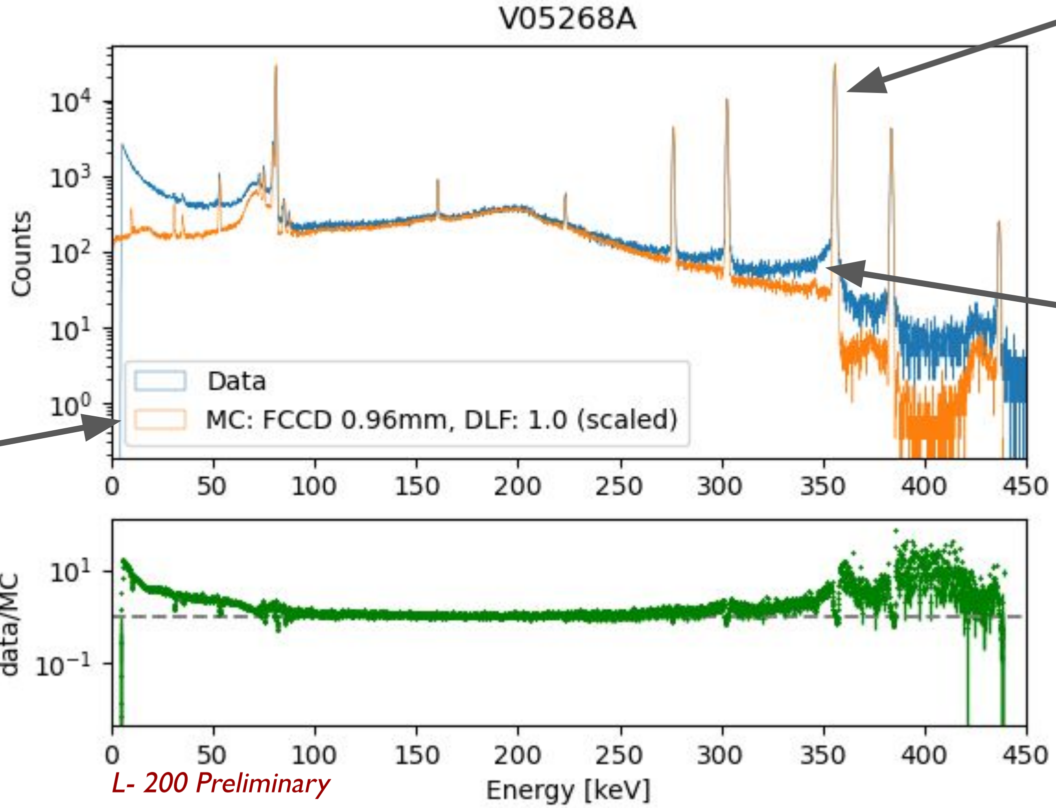
Active Volume Characterisation: FCCD

- **Data-MC Comparisons for ^{133}Ba energy spectrum:**





Li thickness: 0,91mm
Weight: 2298g



Full energy peaks well matched

Best fit FCCD

Discrepancies between data and MC due to current lack of Transition Layer → next step!

Exemplar plot for an ICPC detector with:

FCCD $=0.96^{+0.05}_{-0.06}mm$

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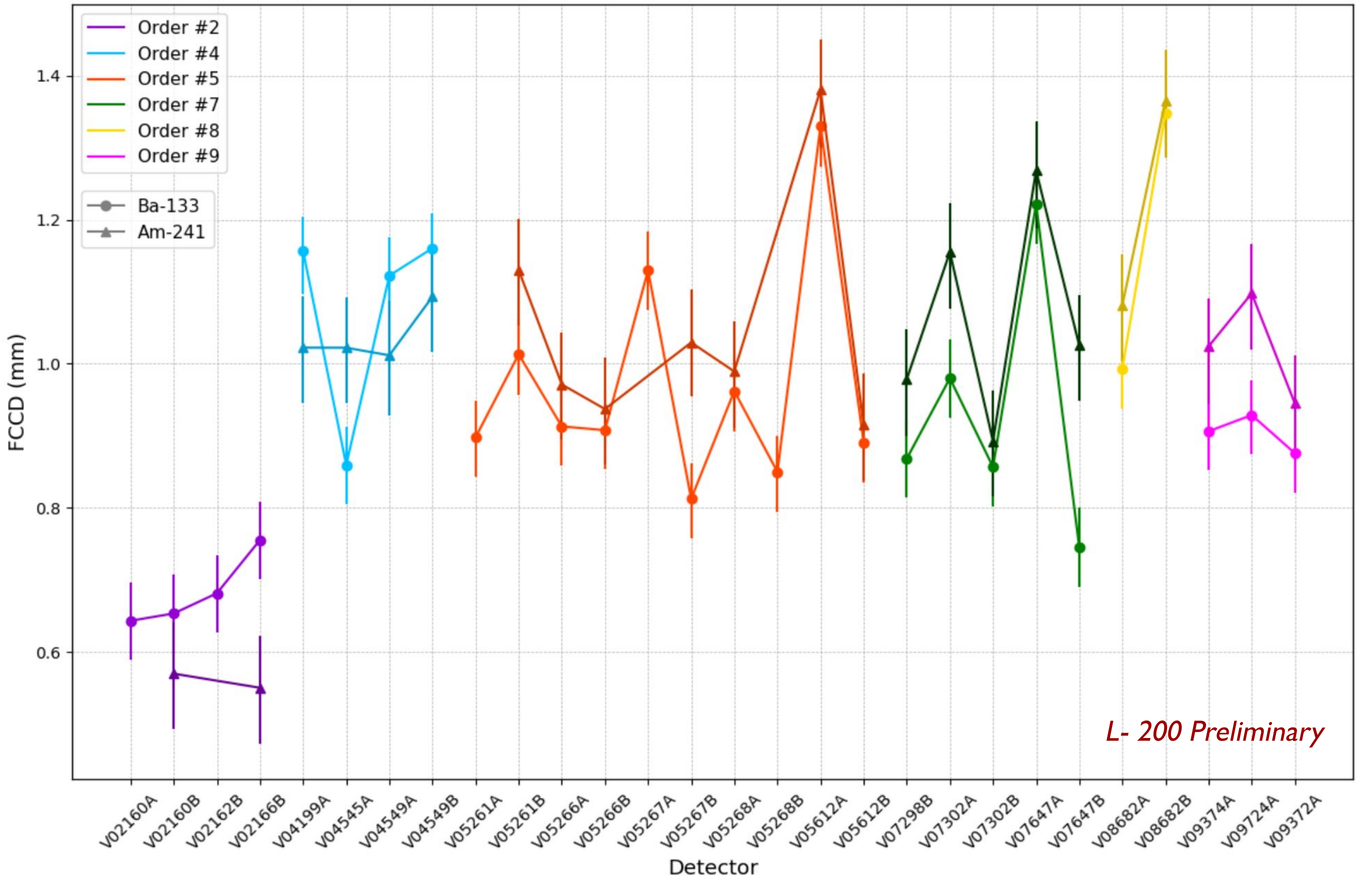
Active Volume Characterisation: FCCD



Process is repeated for all ICPC detectors:

- Automatisation implemented to allow for rapid characterisation of new detectors
- Similar process repeated for different radioactive sources: e.g. ^{241}Am

Active Volume Characterisation: TL

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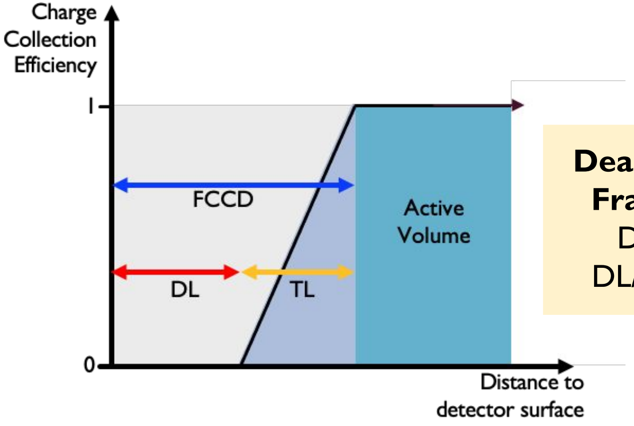
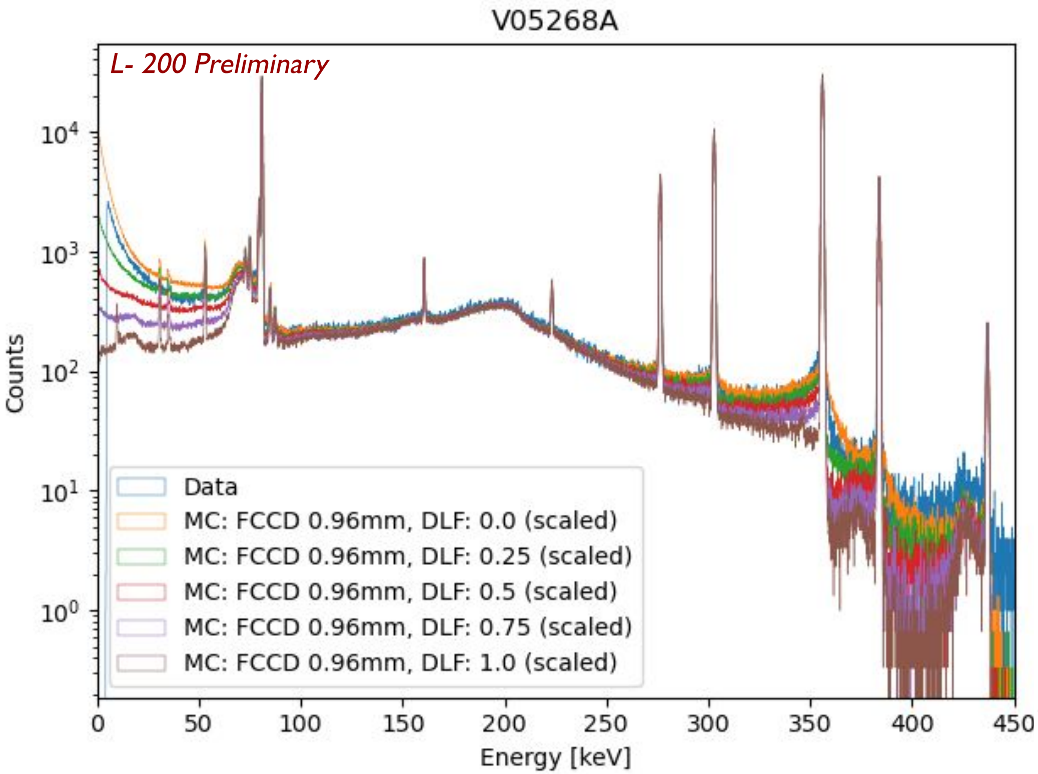
- **Next steps:** explore **Transition Layer** profiles for the best fit FCCDs to improve data/MC agreement
- Linear TL only is shown here, but can also try more complex profiles: e.g. sigmoidal



Dead Layer Fraction:
DLF = DL/FCCD

By eye, we can observe the effect on the spectra of varying the dead layer fraction.



Summary

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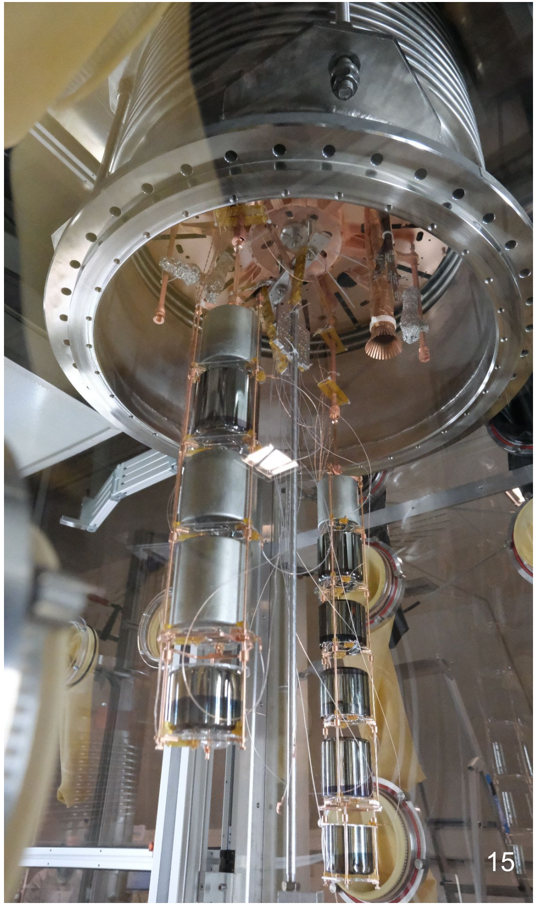
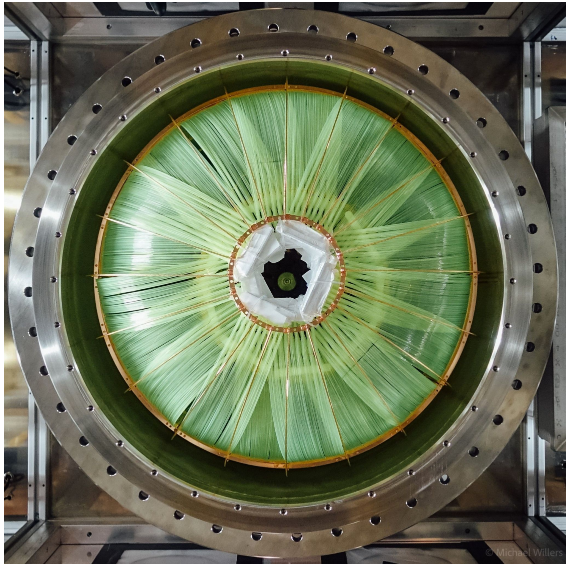
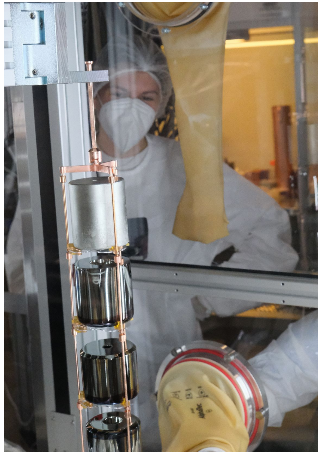
- LEGEND will search for $0\nu\beta\beta$ decay in ^{76}Ge via 2 phases
- L-200 is now commissioning, ramping up to ~200 kg of HPGe detectors
- Ahead of physics data taking, HPGe detectors must be characterised - this is ongoing work in underground laboratories such as HADES
- The Active Volume of the HPGe detectors is determined
  - Dead layer modelled
  - Next step: model the transition layer for all detectors



2 HPGe detector strings in the glove box, ready to be deployed, L-200 clean room

Thanks for listening, any questions?





Back Up: Half Life Sensitivity

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

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

Back Up: Neutrino Mass

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$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} U_{ei}^2 m_i$$