Characterisation of Germanium Detectors for LEGEND-200

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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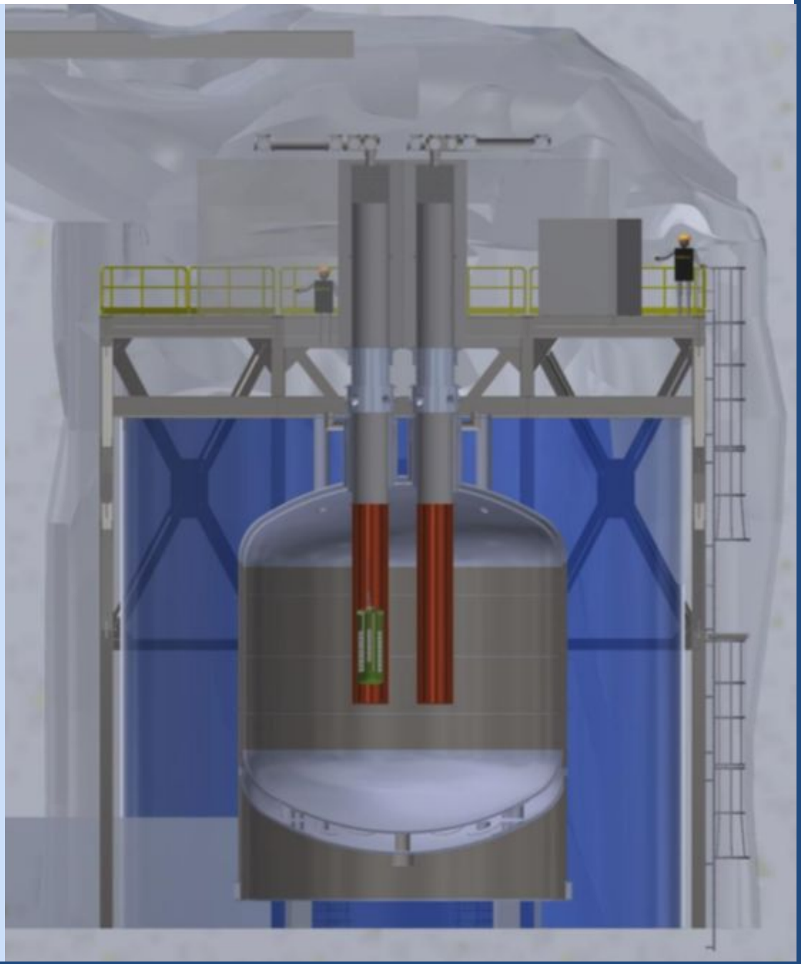

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Introduction

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

LEGEND Mission:

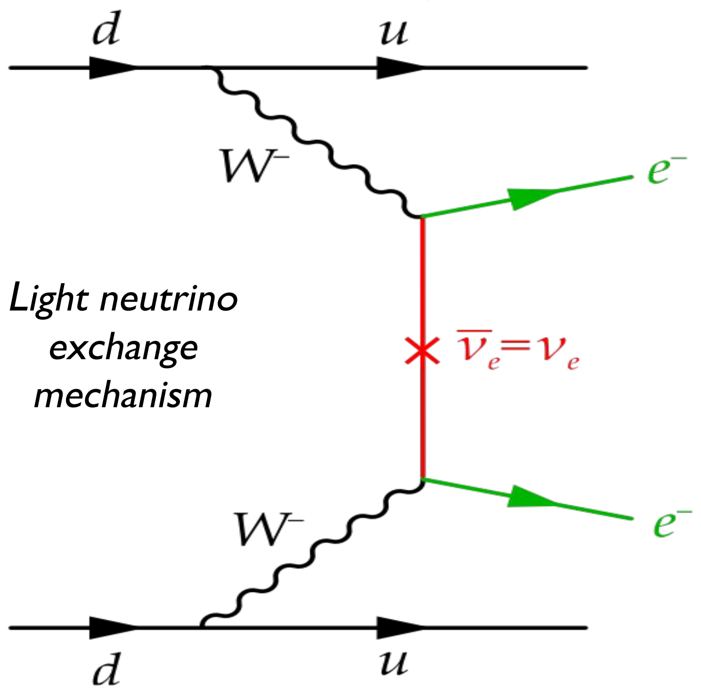
"Develop a two-phased ^{76}Ge based neutrinoless double beta decay experimental program with discovery potential at a half-life beyond 10^{28} yrs."

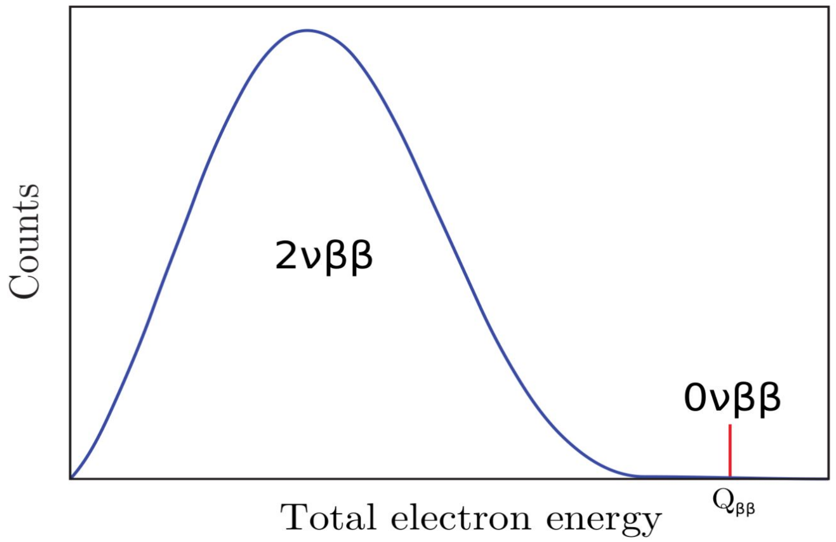
The LEGEND collaboration:

- 260 members
- 47 institutions, 11 countries

Neutrinoless Double Beta Decay

- **Neutrinoless double beta** (0νββ) **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)



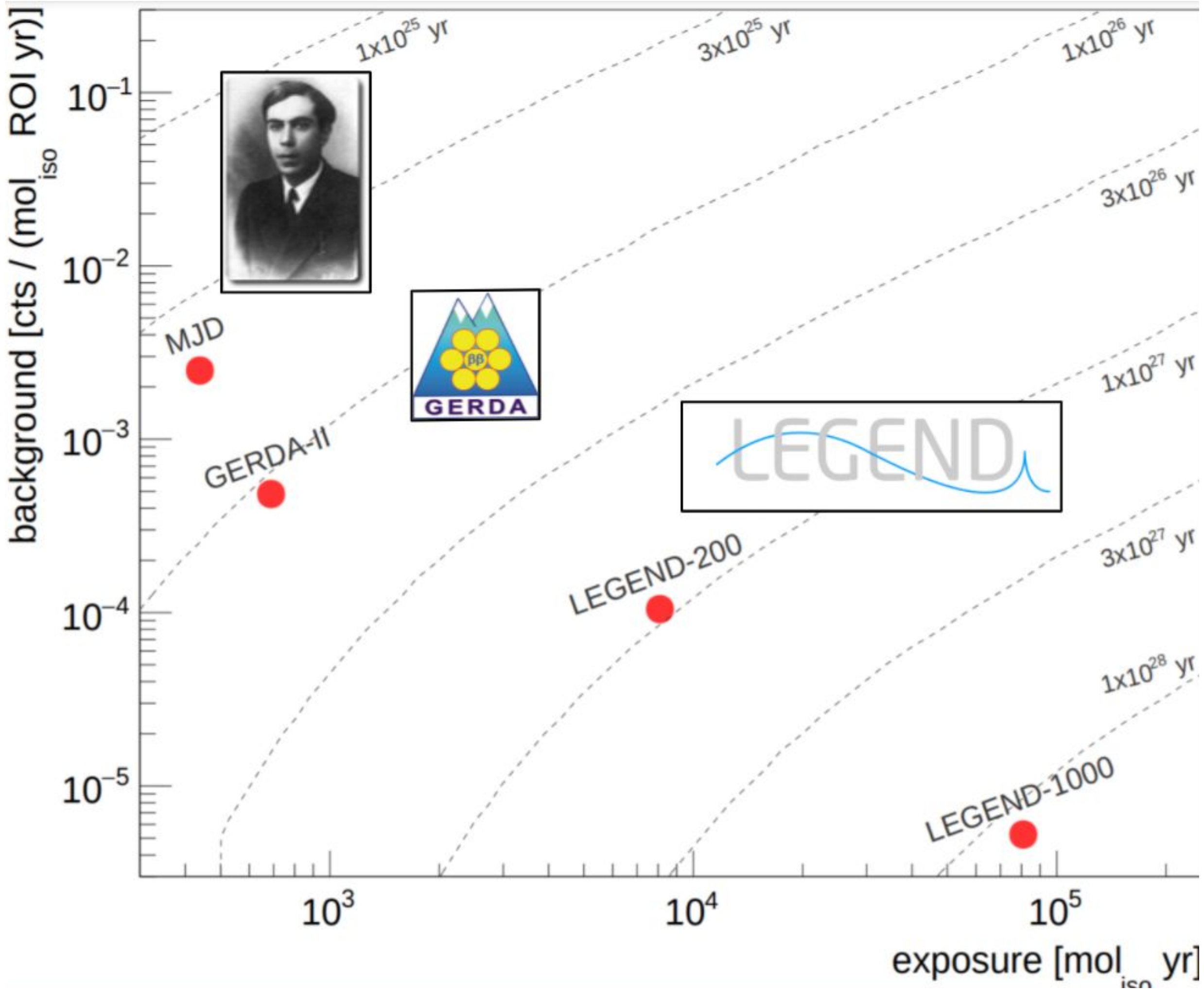


LEGEND

- **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)



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

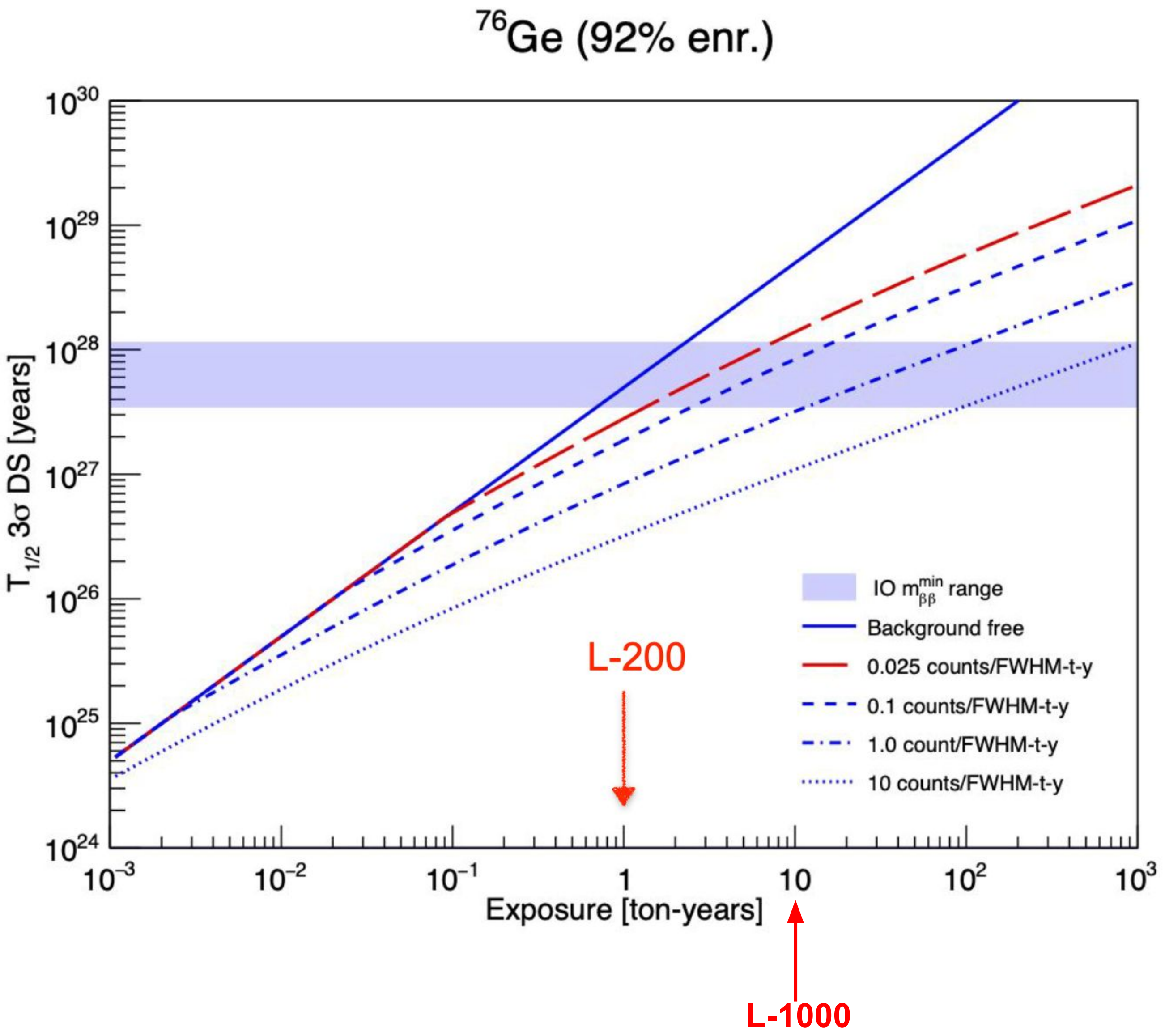
0νββ half-life

LEGEND-200

- **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 0.5 cts/(FWHM.ton.yr)

- **L-200 Status:** now commissioning!

Discovery Sensitivity



Background Limited

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M.t}{b.\Delta E}}$$

Background Free

$$T^{0\nu}_{1/2} \propto M.t$$

Half life sensitivity

M = active mass, t = time, b = background index, ΔE = energy resolution

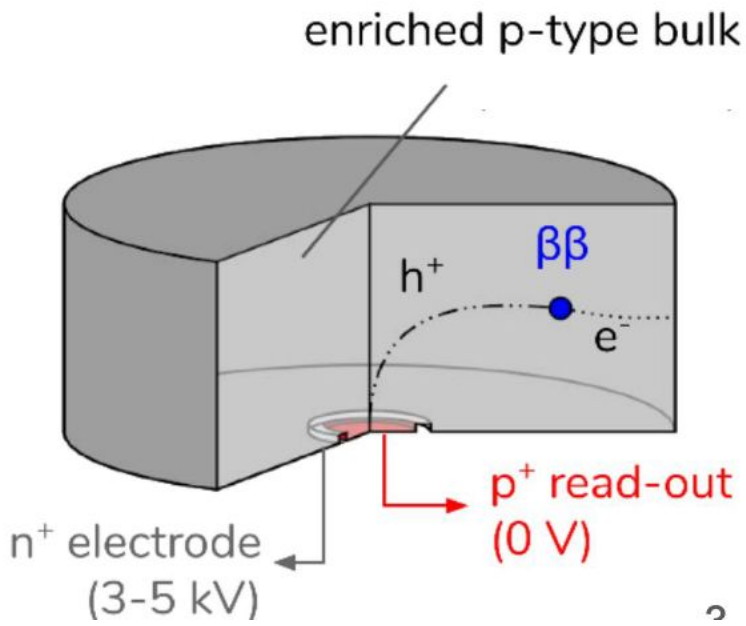
Germanium Detectors

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, <u>ICPCs</u>

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



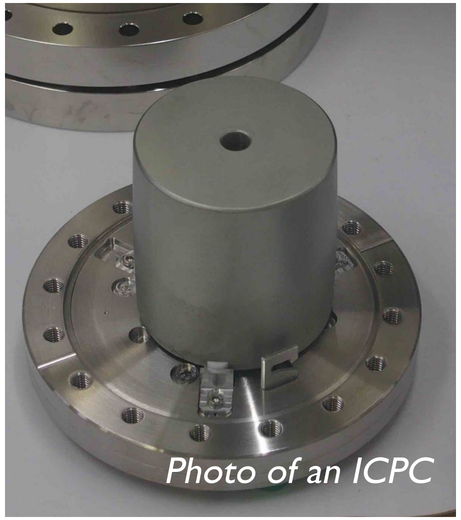
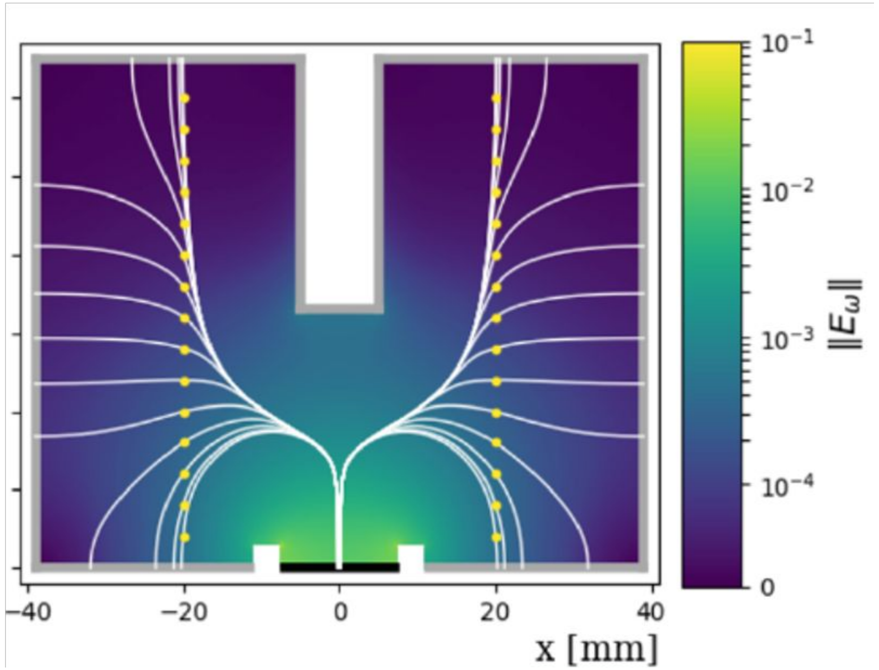


Photo of an ICPC



Detector Characterisation

All detectors must be thoroughly characterised before deployment at LNGS!

- **Characterisation Tasks:**
  - Operational voltage
  - Pulse Shape Discrimination (PSD) performance
  - Energy resolution
  - Active volume determination

- **Why:**
  - Low background requires good energy resolution and background rejection from PSD
  - The 0νββ signal strength/half life sensitivity is proportional to the total active detector mass

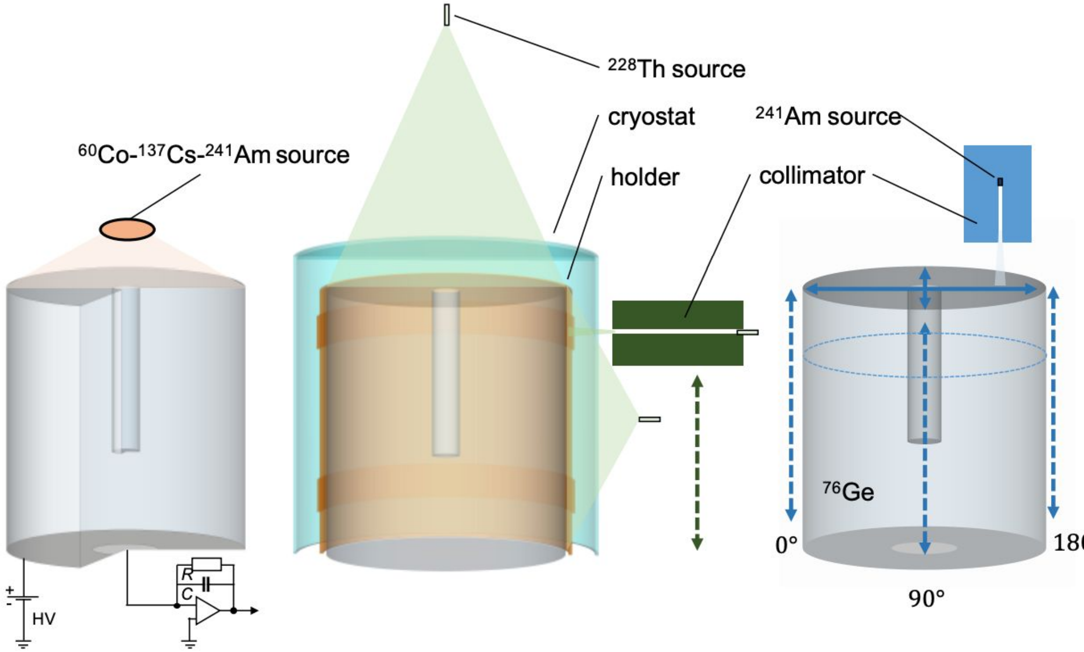
$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M.t}{b.\Delta E}}$$

Half life sensitivity for an experiment with backgrounds

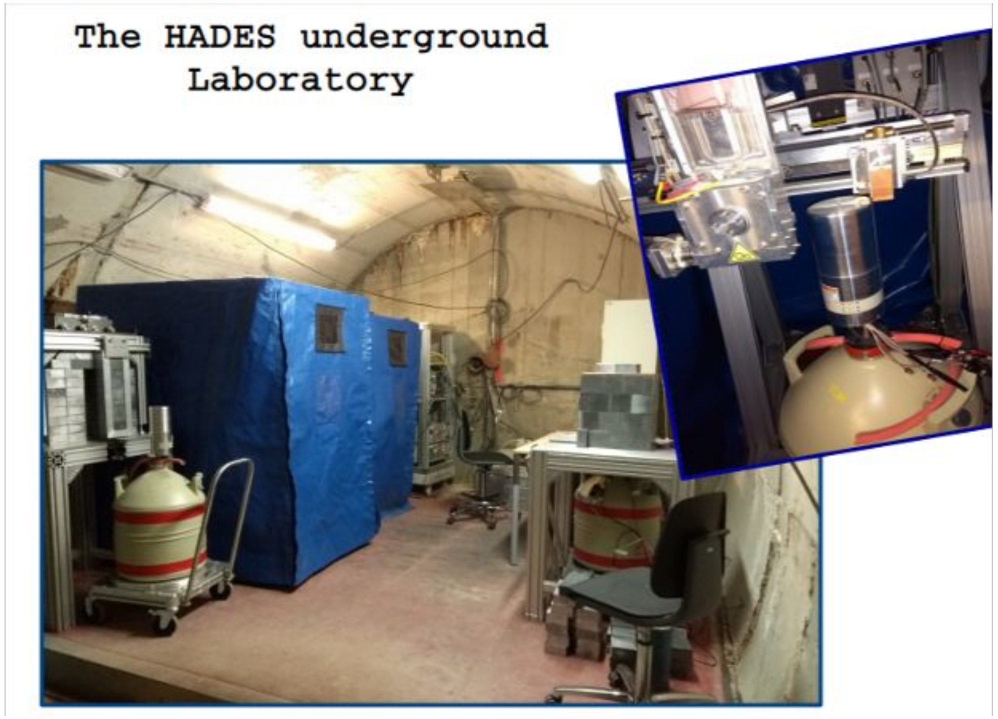
M = active mass, t = time, b = background index, ΔE = energy resolution

Detector Characterisation

- Data taking at HADES underground lab, Belgium
- Detectors are exposed to different radioactive sources



[arXiv:2103.15111, GERDA]

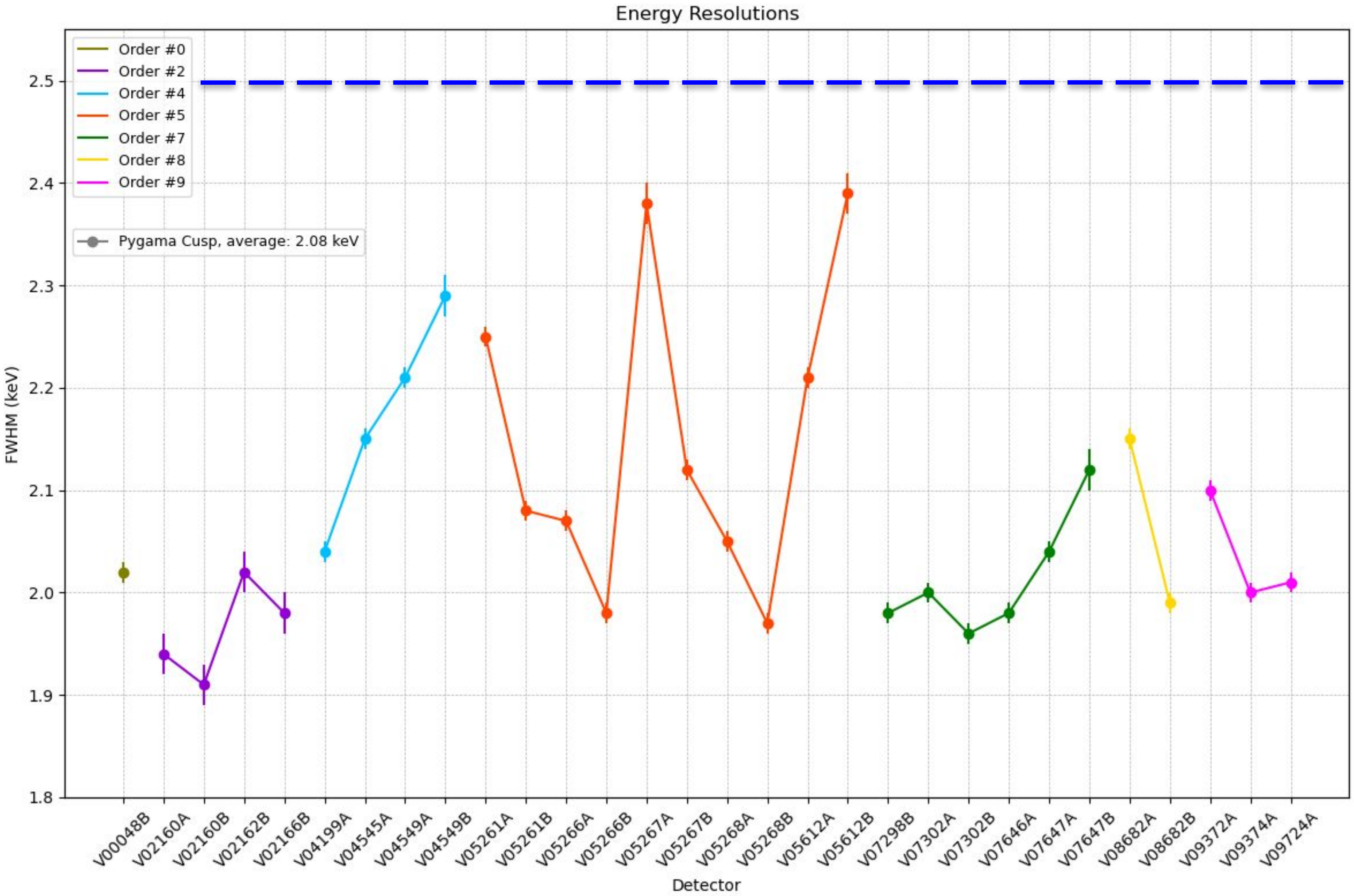


- This is ongoing work as new detectors arrive.
- ~30 LEGEND ICPCs have been characterised at HADES so far.

Energy Resolution

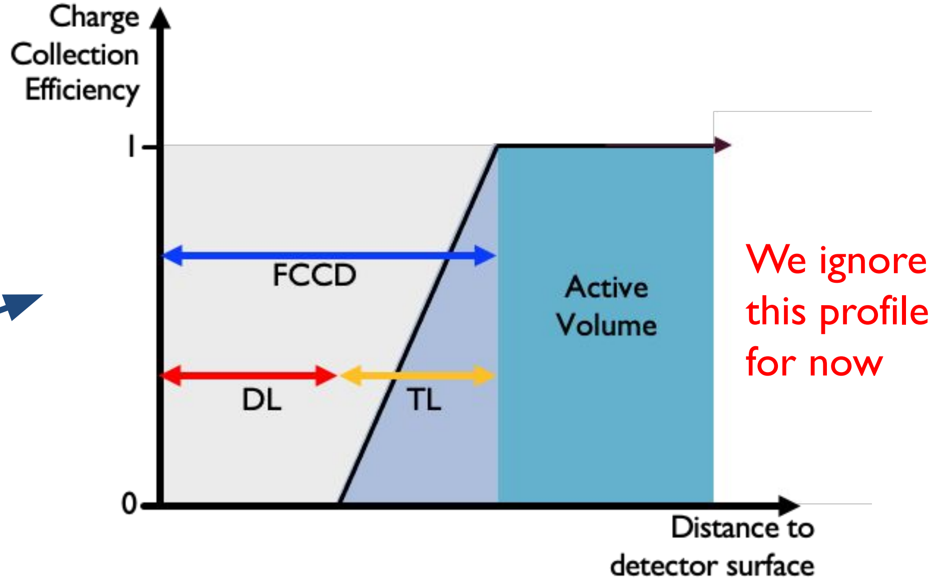
L200 target energy resolution is 2.5 keV or 0.12% of $Q_{\beta\beta}$

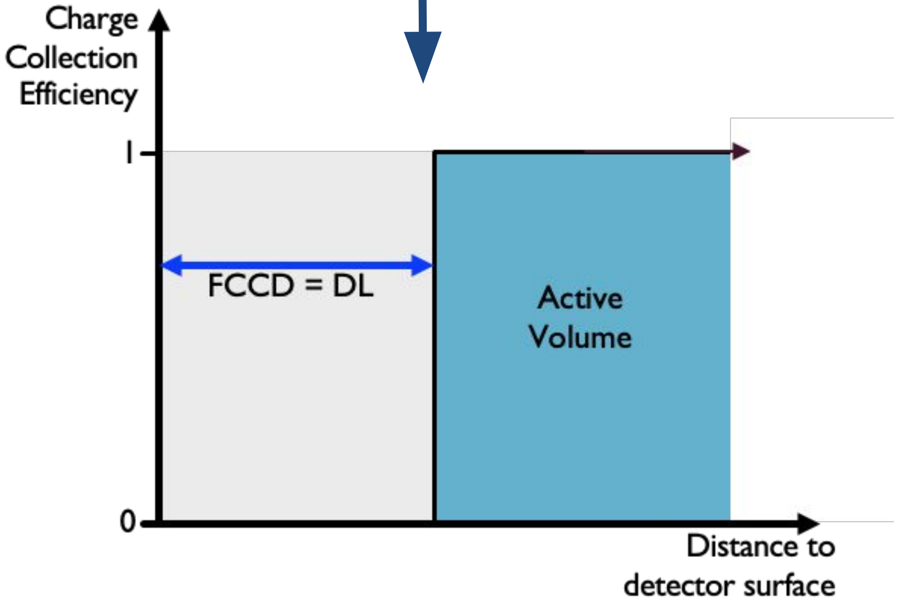
Current average energy resolution, 2.08 keV, exceeds target!



Active Volume Characterisation

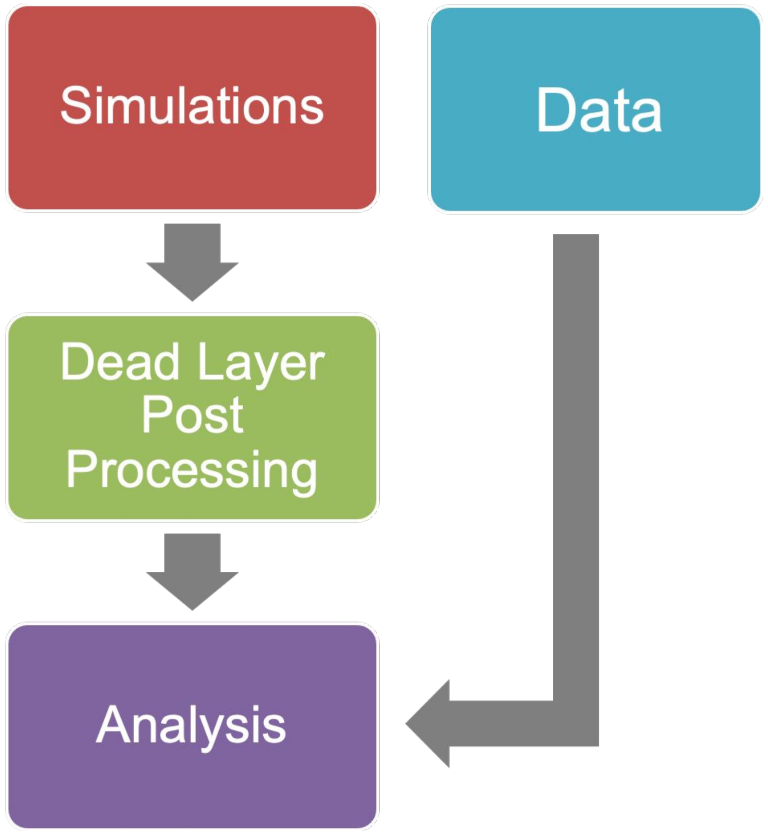
- **Dead Layer** = region of no charge collection on surface of semiconductor detectors. A conductive layer, created by Lithium diffusion.
- **Transition Layer** = partial charge collection
- **Full Charge Collection Depth (FCCD)** = Transition Layer + Dead Layer
    - NB: the TL is ignored currently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





- **Determination of detector active volume is important for LEGEND because:**
    - The $0\nu\beta\beta$ half-life is a function of active mass
    - Degraded events could mimic $0\nu\beta\beta$ signature

Active Volume Characterisation

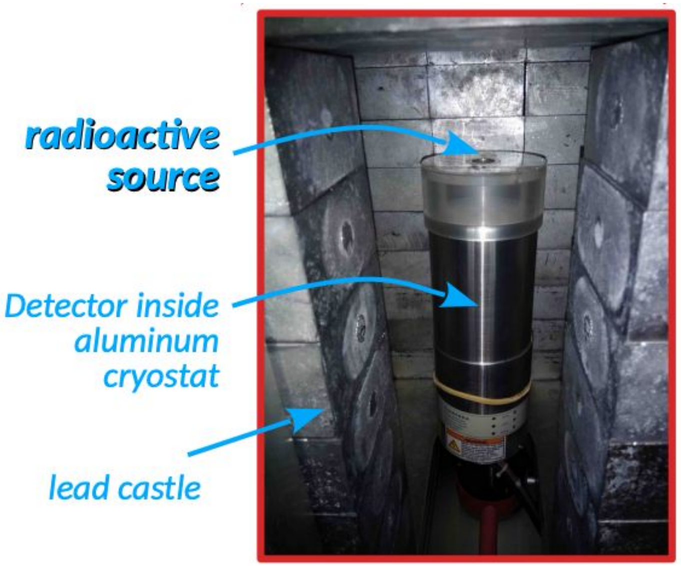


Workflow

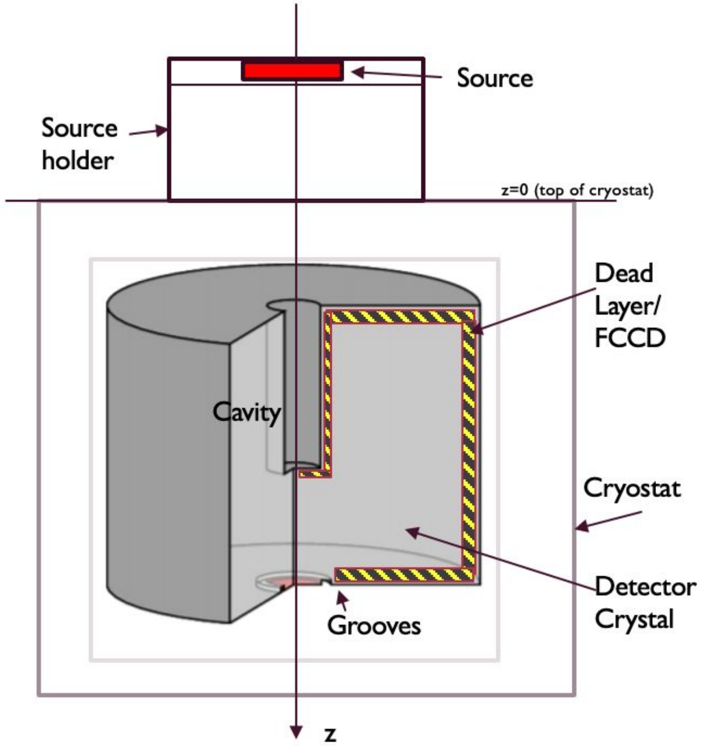
- **Aim:** Determine the FCCD (and active volume) of the detectors by comparing HADES characterisation data with simulations
- **Data:** Detectors exposed to ^{133}Ba (low energy spectrum→ FCCD sensitive).
- **Simulations:** *GEANT-4 based* MC simulations [https://github.com/legend-exp/g4simple]
- **Post Processing:** starting from raw MC, generate subsequent spectra for different FCCD values through the systematic removal and weighting of energy depositions based on position

Active Volume Characterisation

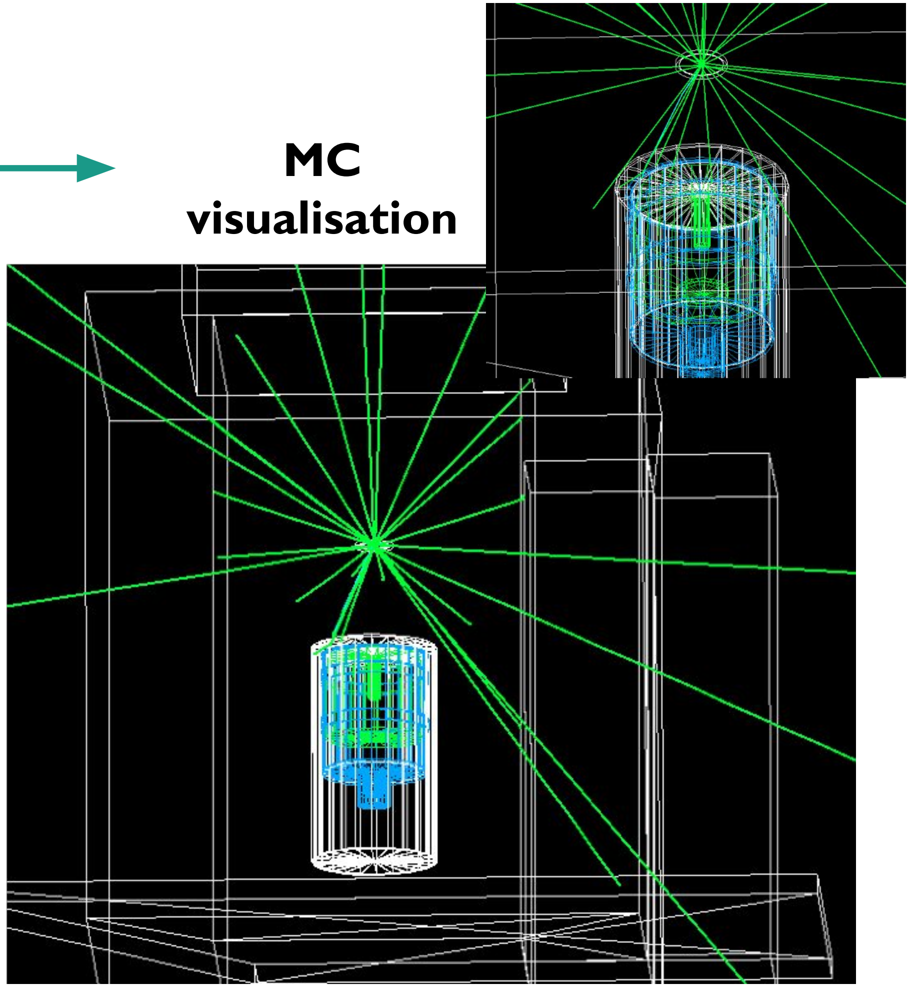
- From experiment to simulation:



Experimental setup at HADES:
uncollimated flood ^{133}Ba source in "top" position

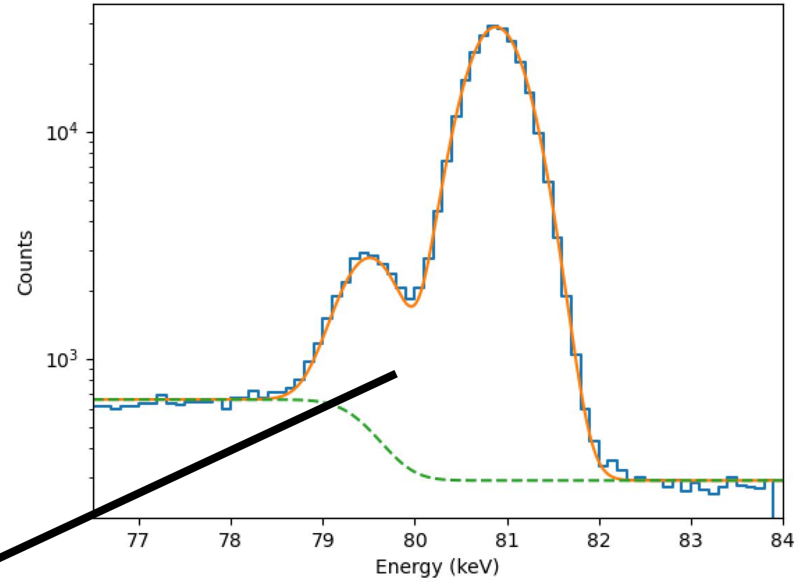


MC visualisation



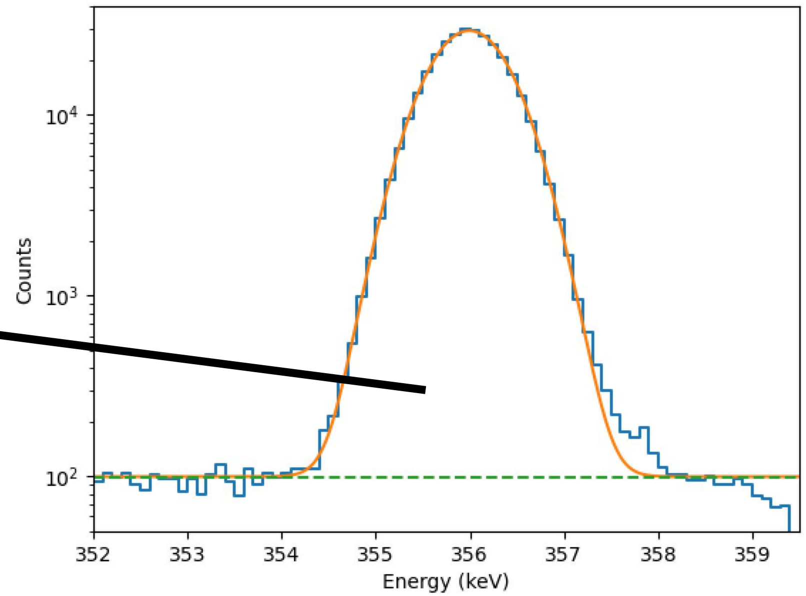
Active Volume Characterisation: FCCD

- **Analysis:** compare post-processed simulations and data by constructing an FCCD sensitive observable
    - Gamma line counting - fit and integrate the counts (C) in 81/79 and 356 keV gamma peaks
    - Observable is a count ratio and is computed for the data and each post-processed simulation



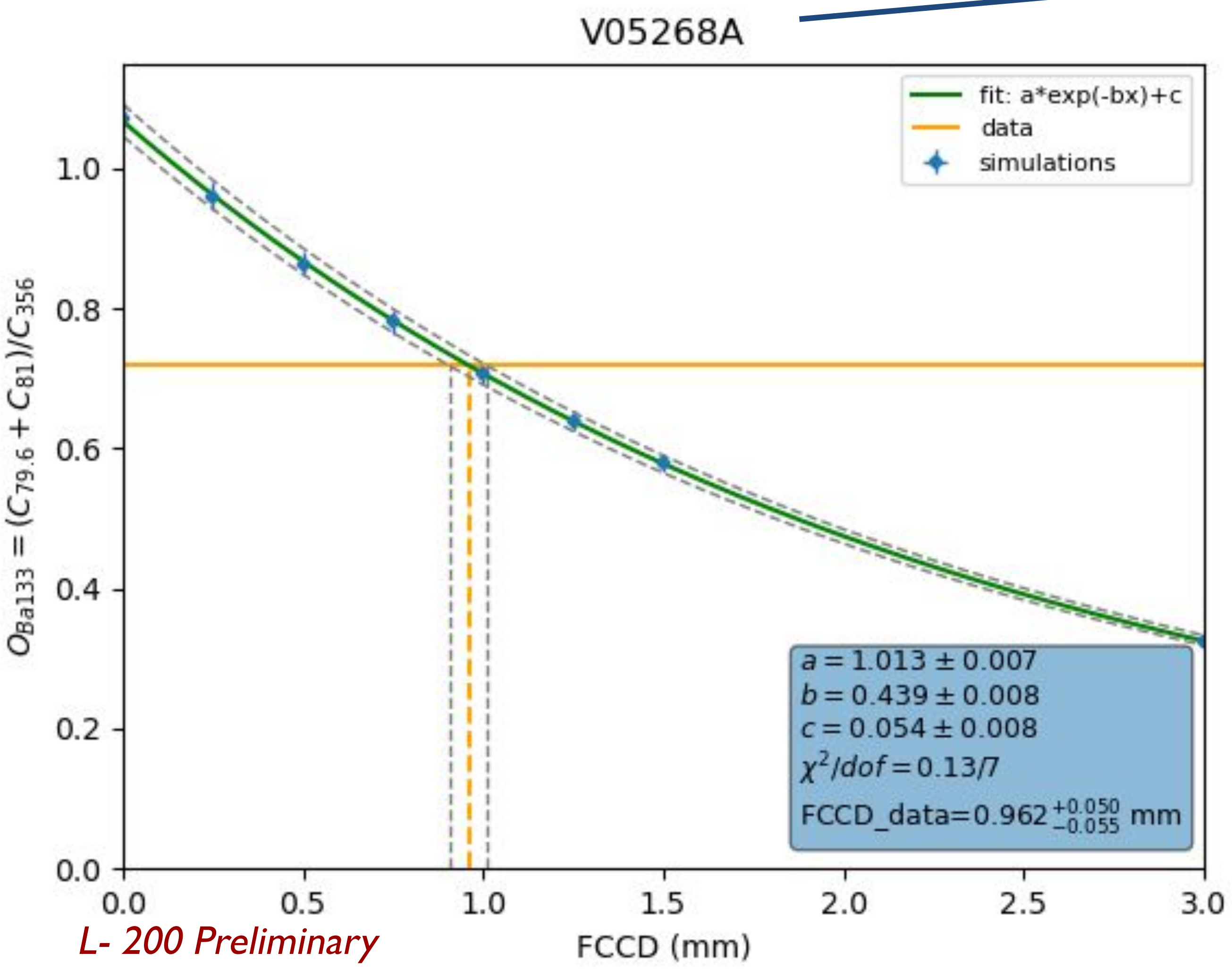
$$O_{133\mathrm{Ba}} = \frac{C_{79.6\,\mathrm{keV}} + C_{81.0\,\mathrm{keV}}}{C_{356.0\,\mathrm{keV}}}$$

FCCD sensitive observable for ^{133}Ba

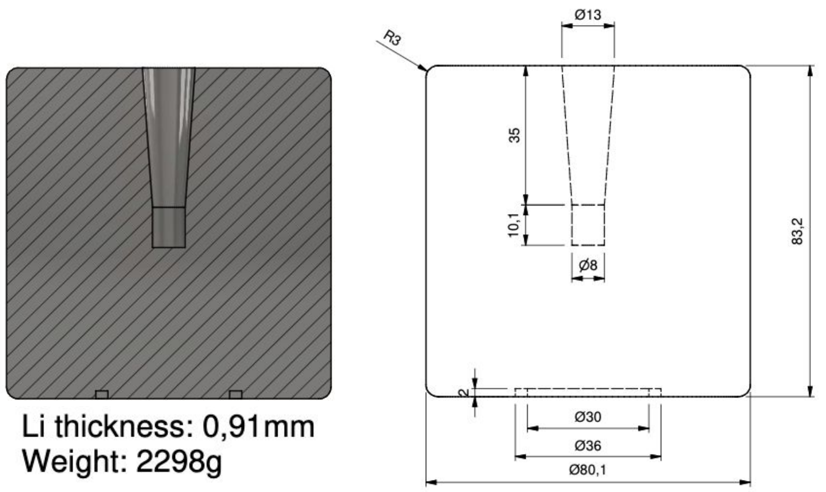


Active Volume Characterisation: FCCD

- **FCCD estimation:**



L- 200 Preliminary

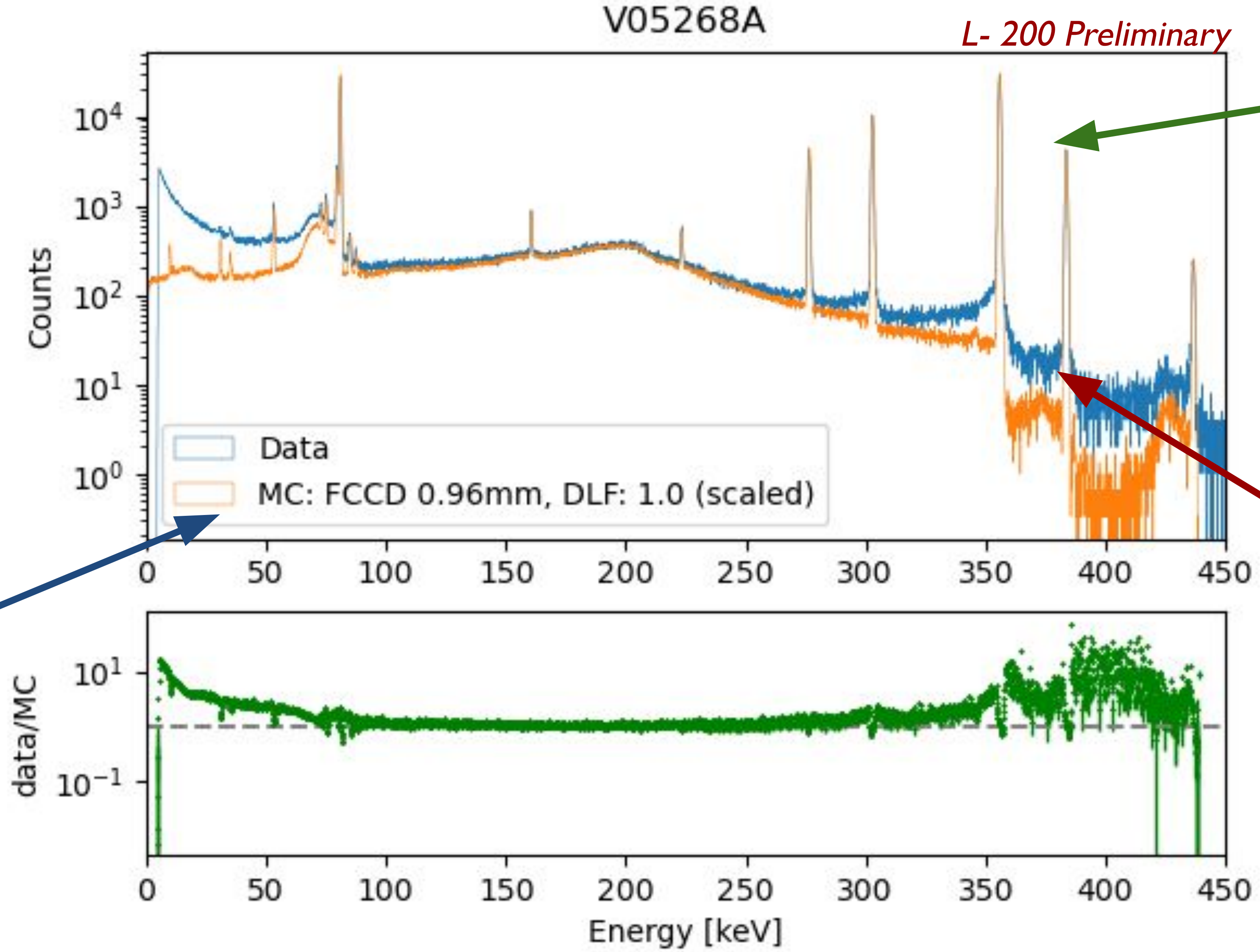


Exemplar plot for an ICPC detector with:

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

Active Volume Characterisation: FCCD

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



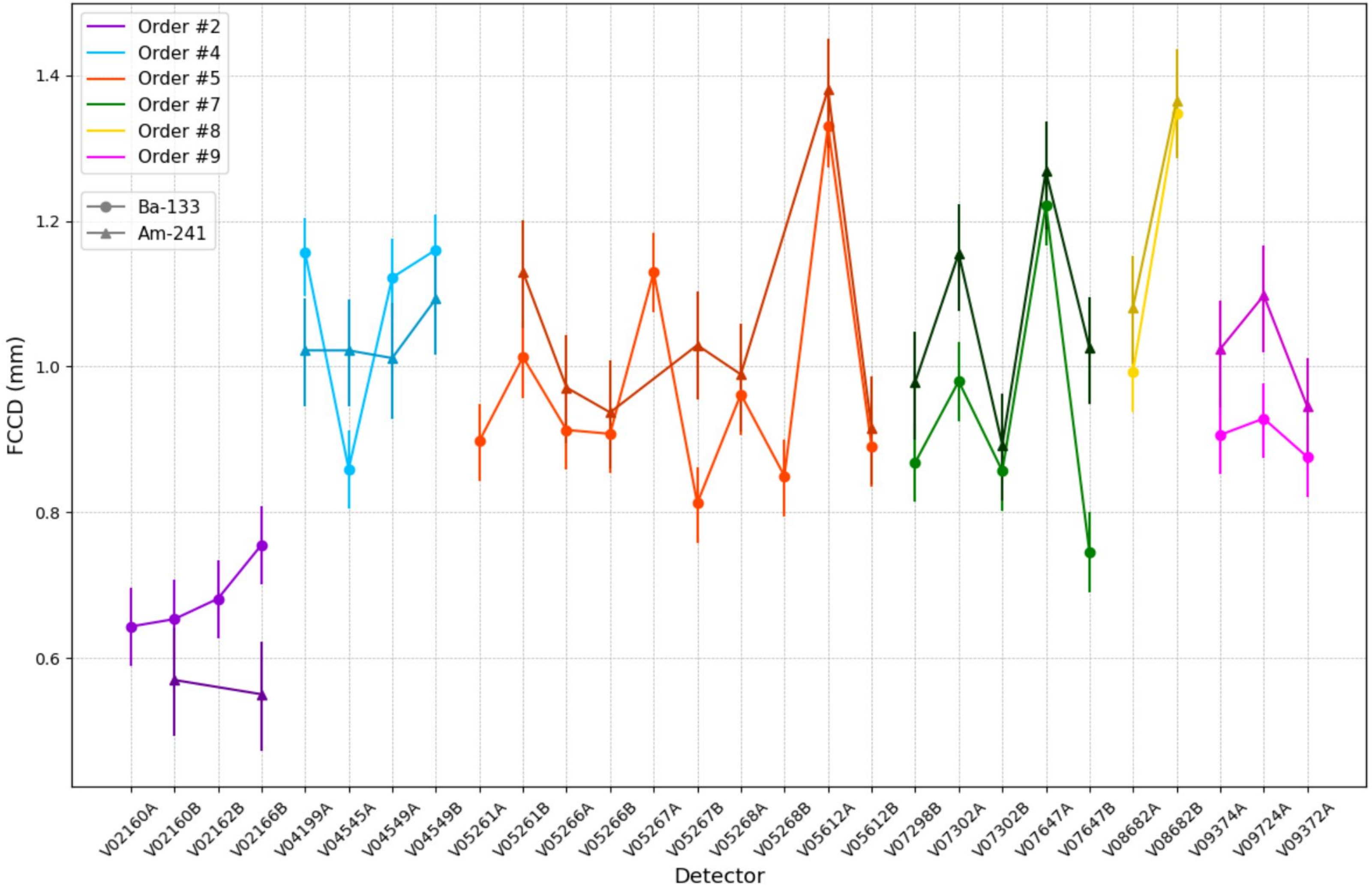
Full energy peaks well matched

Best fit FCCD

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

Active Volume Characterisation: FCCD

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



L- 200
Preliminary

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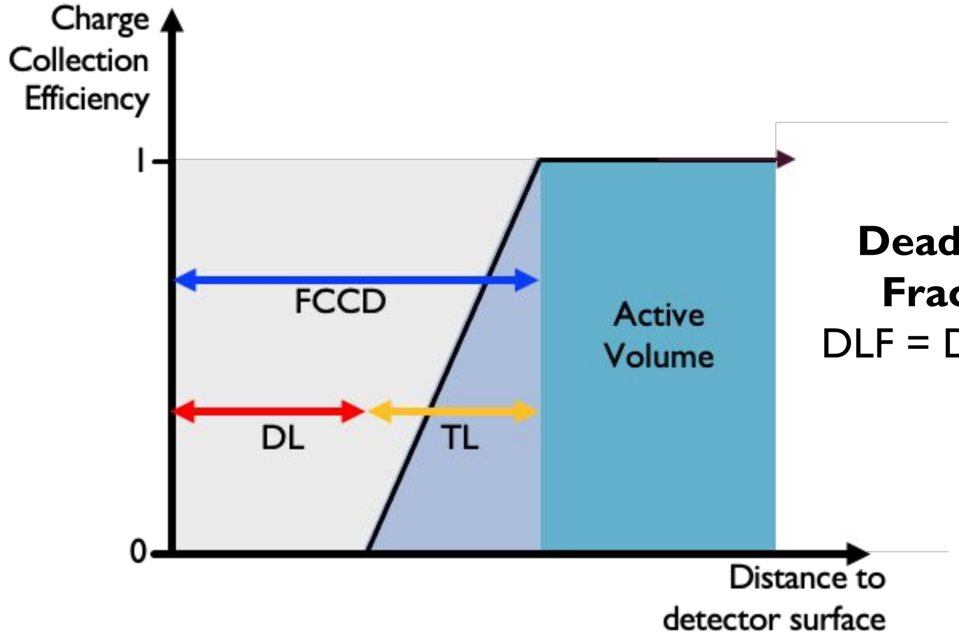
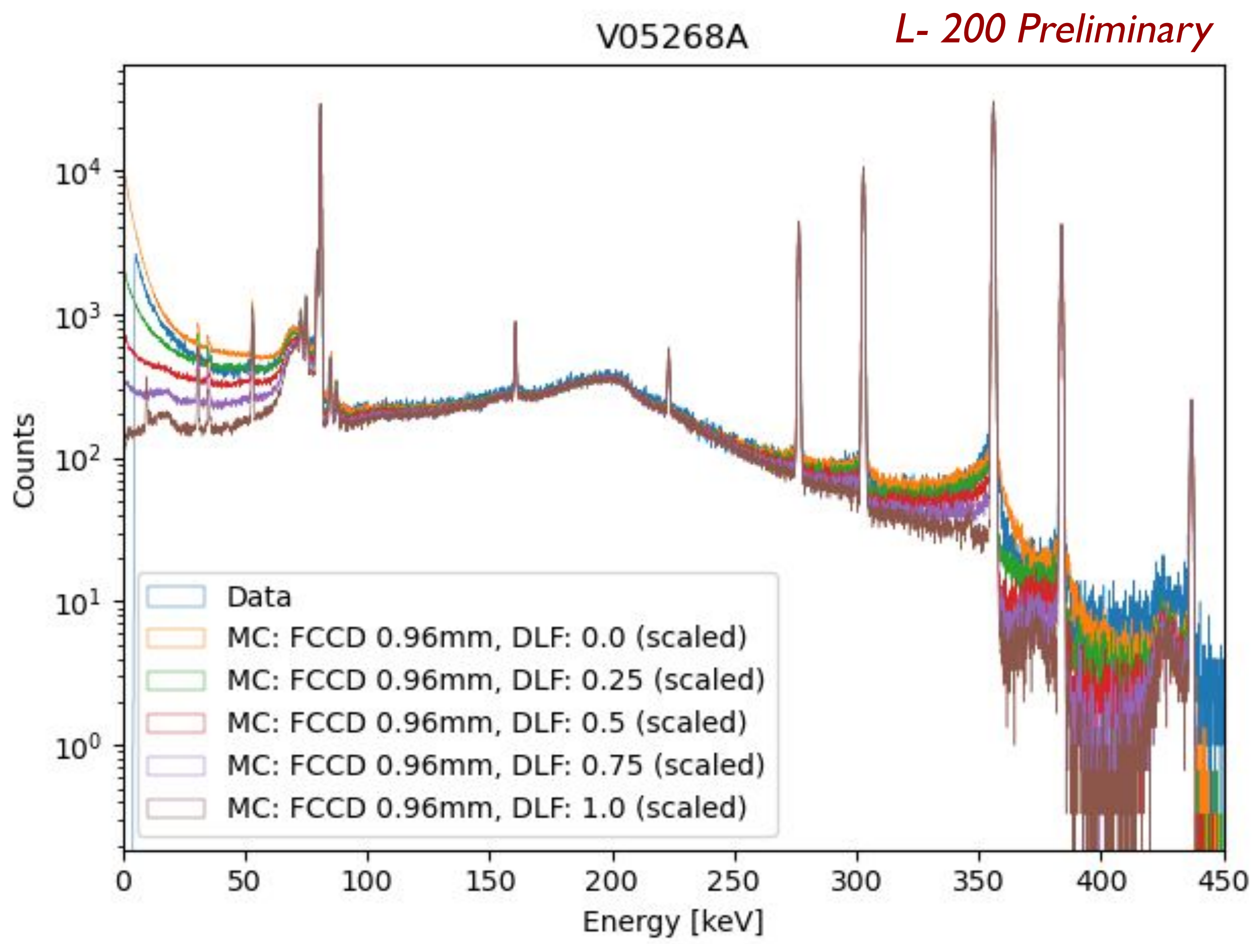
Active Volume Characterisation: Transition Layer

- **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



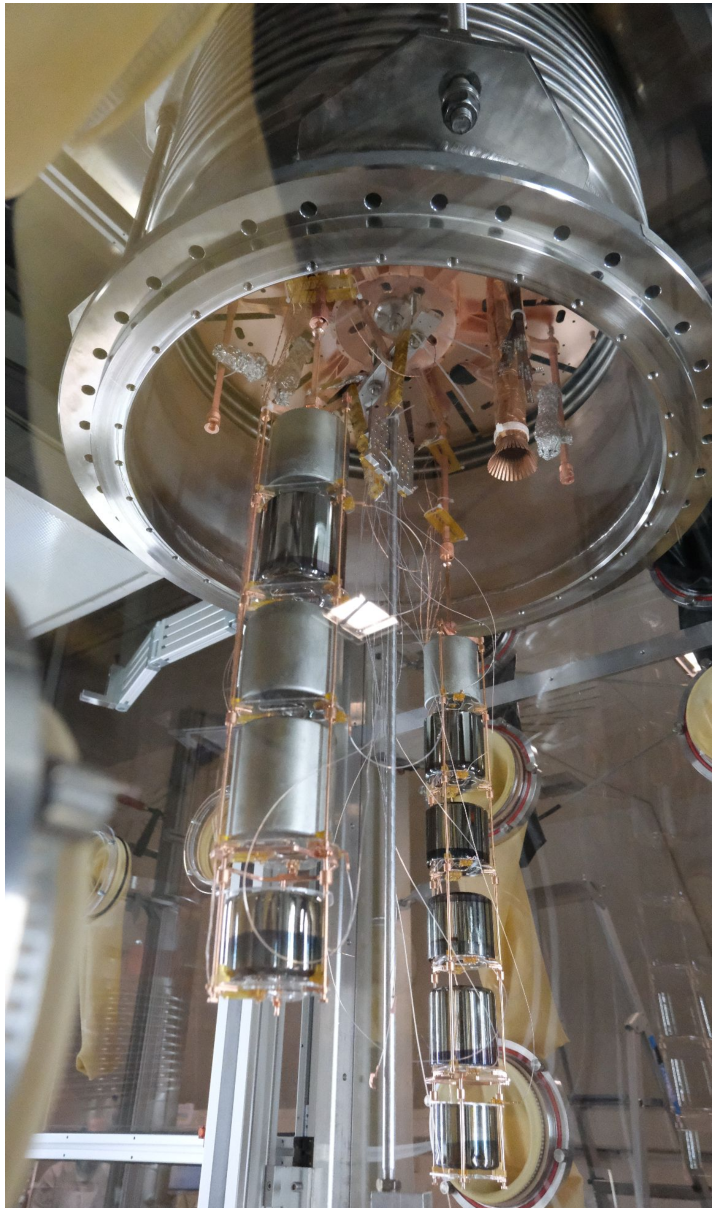
Dead Layer Fraction:
DLF = DL/FCCD

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



Summary

- LEGEND will search for 0νββ 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 energy resolution of the HPGe detectors is determined
  - Average resolution exceeds L-200 target
- The Active Volume of the HPGe detectors is determined
  - Dead layer modelled
  - Next step: model the transition layer for all detectors



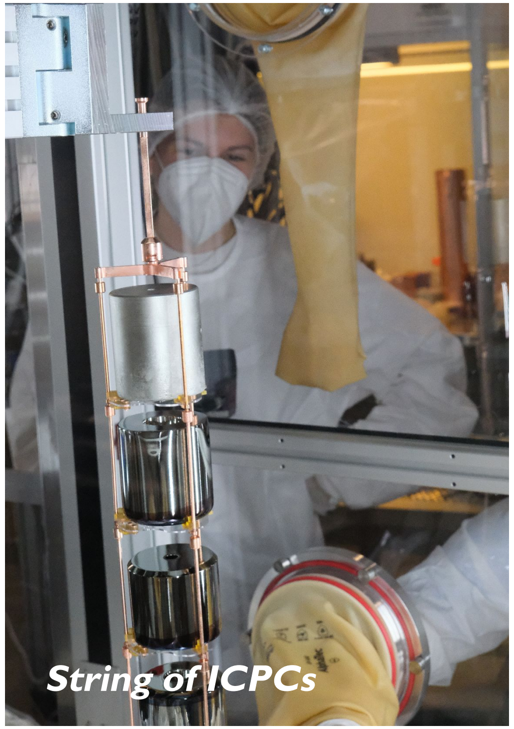
2 HPGe detector strings in the glove box, ready to be deployed, L-200 clean room

Summary


L-200 Lock, Clean Room


L-200, LNGS
LVD
GERDA


LAr veto: 3 Fibre modules
on outer barrel, in the lock


String of ICPCs


Hiking in Campo Imperatore, Gran Sasso


LEGENDary hikers


L'Aquila