Characterisation of Germanium Detectors for LEGEND-200

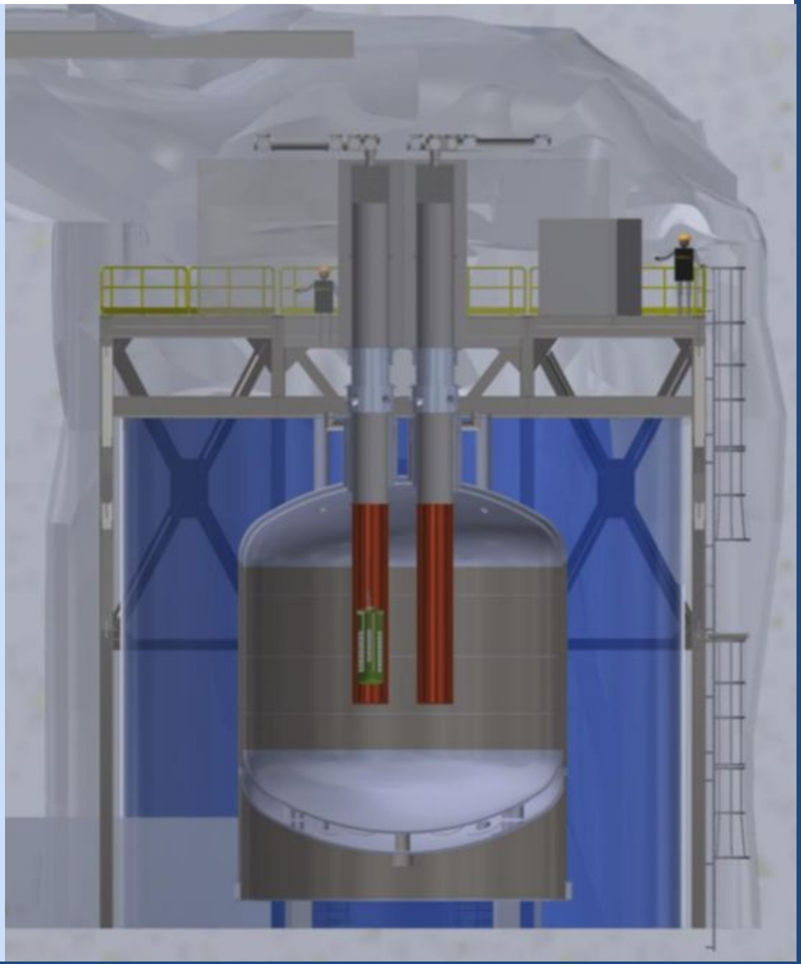
LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Abigail Alexander* on behalf of LEGEND
*University College London

25.06.2021

ANIMMA Conference 2021



Email: abigail.alexander.19@ucl.ac.uk

Collaborators: Matteo Agostini, Valentina Biancacci, Yoann Kermaidic, David Waters

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:

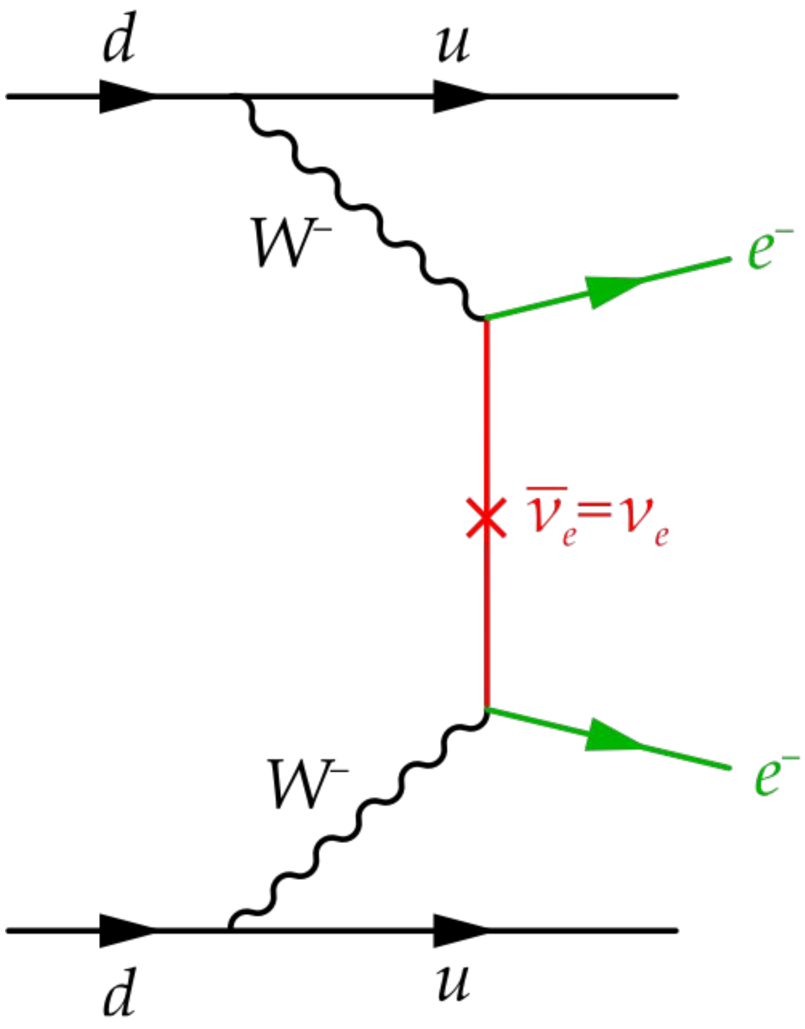
- 260 members
- 50 institutions, 11 countries

Neutrinoless Double Beta Decay

- **Neutrinoless double beta (0νββ) decay**
  = a hypothetical nuclear transition

- **Detection would:**
  - Prove neutrinos are Majorana in nature
  - Show a Lepton-Number-Violating (LNV) process → matter-antimatter asymmetry
  - Probe the absolute neutrino mass scale and neutrino mass ordering

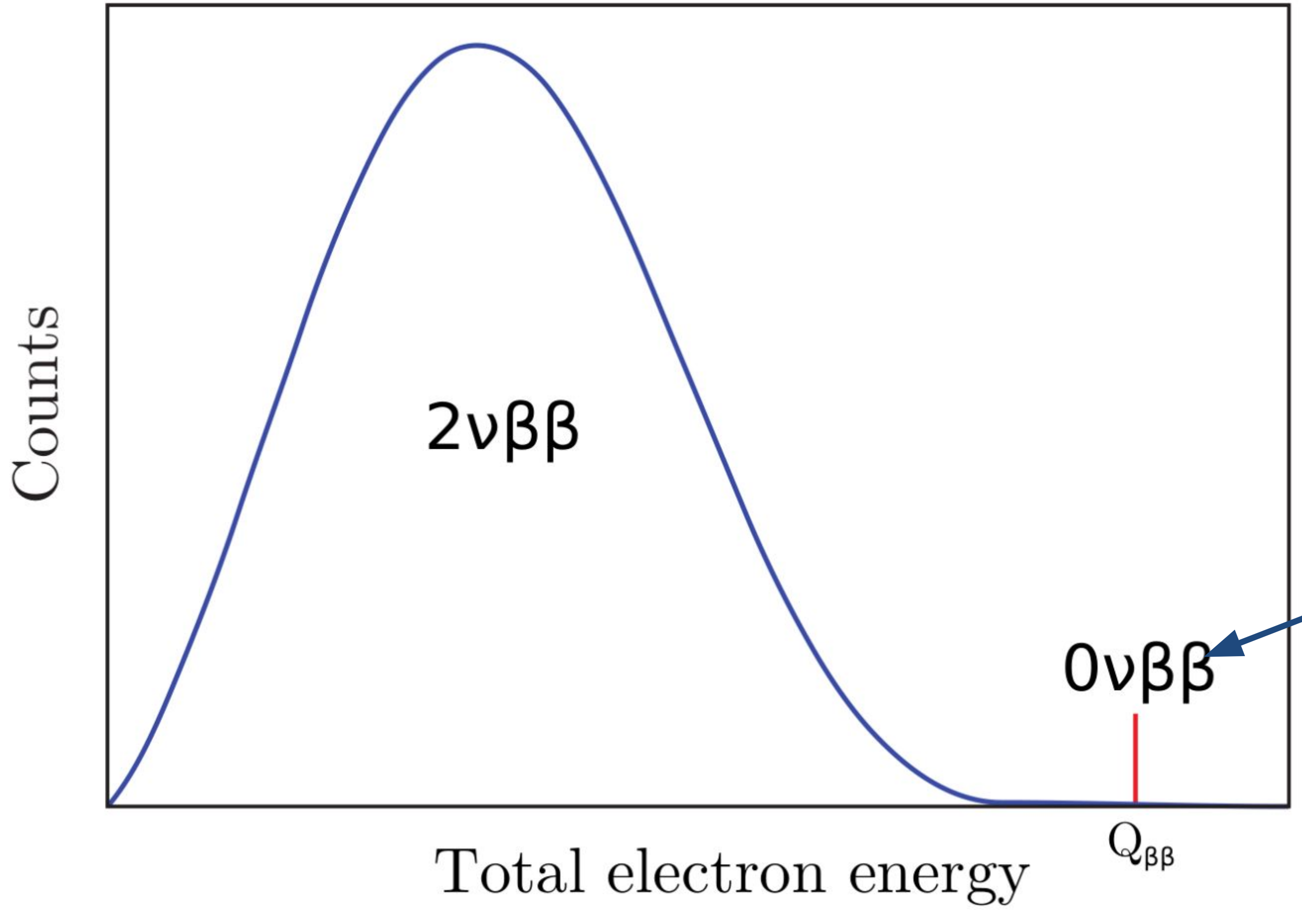
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{m_e^2}$$



Light neutrino exchange mechanism

Neutrinoless Double Beta Decay

- **0νββ Experimental Signature**:



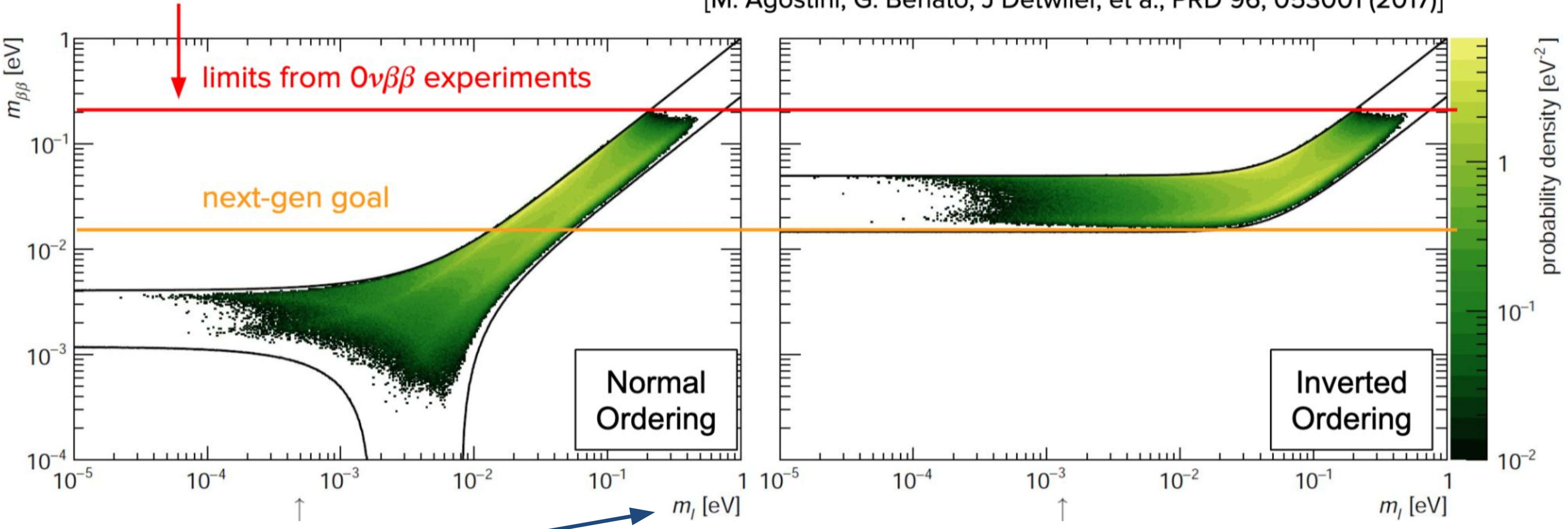
$Q_{\beta\beta}$ for ^{76}Ge = 2039 keV

Neutrinoless Double Beta Decay

Effective Majorana Neutrino Mass:

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

[M. Agostini, G. Benato, J Detwiler, et a., PRD 96, 053001 (2017)]



Lightest neutrino mass eigenstate

LEGEND-200

- **LEGEND phases**:

L200		L1000
- 200 kg ^{enr}Ge - 10^{27} yrs half-life sensitivity	→	- 1000 kg ^{enr}Ge - beyond 10^{28} yrs half-life sensitivity

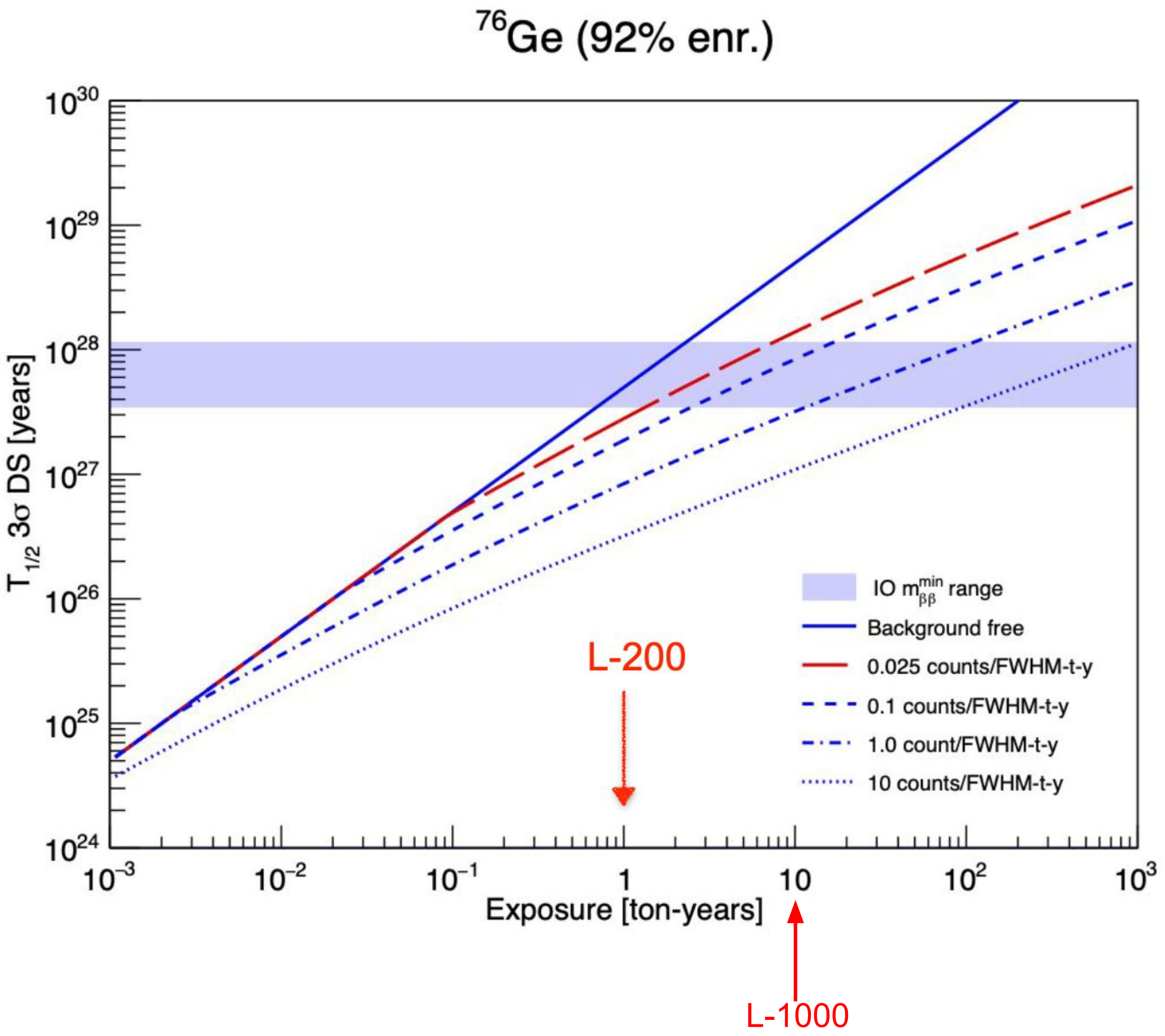
- **L200 Experimental Design**
  - Builds on existing infrastructure and electronics of parent GERDA and Majorana Demonstrator experiments
  - Deep underground at LNGS, Italy
  - Germanium detectors: source = detector
  - Liquid argon scintillation light detectors - active veto
  - 5 years of data taking for a 1 ton.yr exposure

LEGEND-200

- **L200 Status:** currently under construction at LNGS, due to start commissioning in Autumn 2021

- **L200 Targets:**
  - Half life sensitivity: 10^{27} yrs
  - Effective Majorana neutrino mass sensitivity: 30-70 meV
  - Background free regime:
    - Background index of 2×10^{-4} cts/(keV.kg.yr)

Discovery Sensitivity



Background Limited

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

Background Free

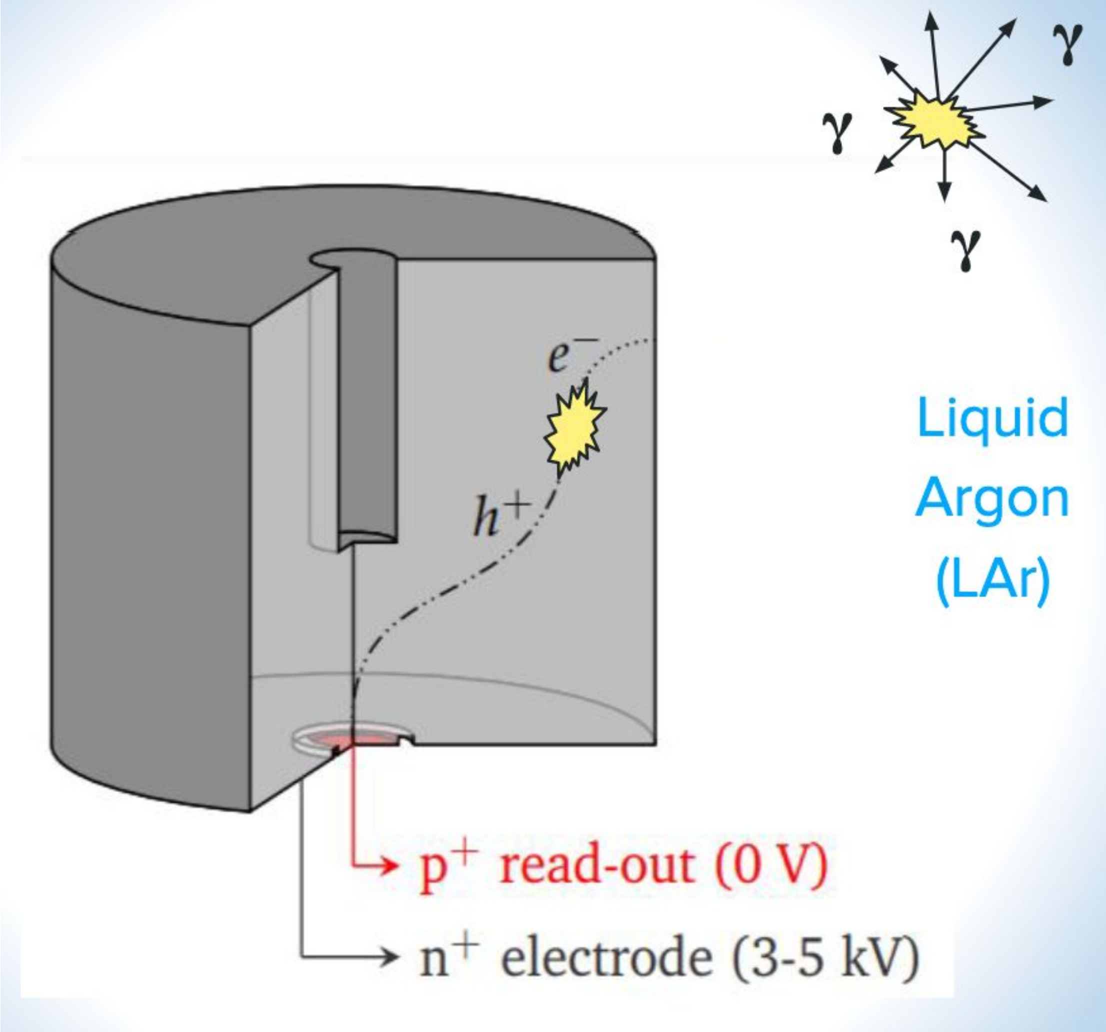
$$T^{0\nu}_{1/2} \propto M.t$$

Half life sensitivity

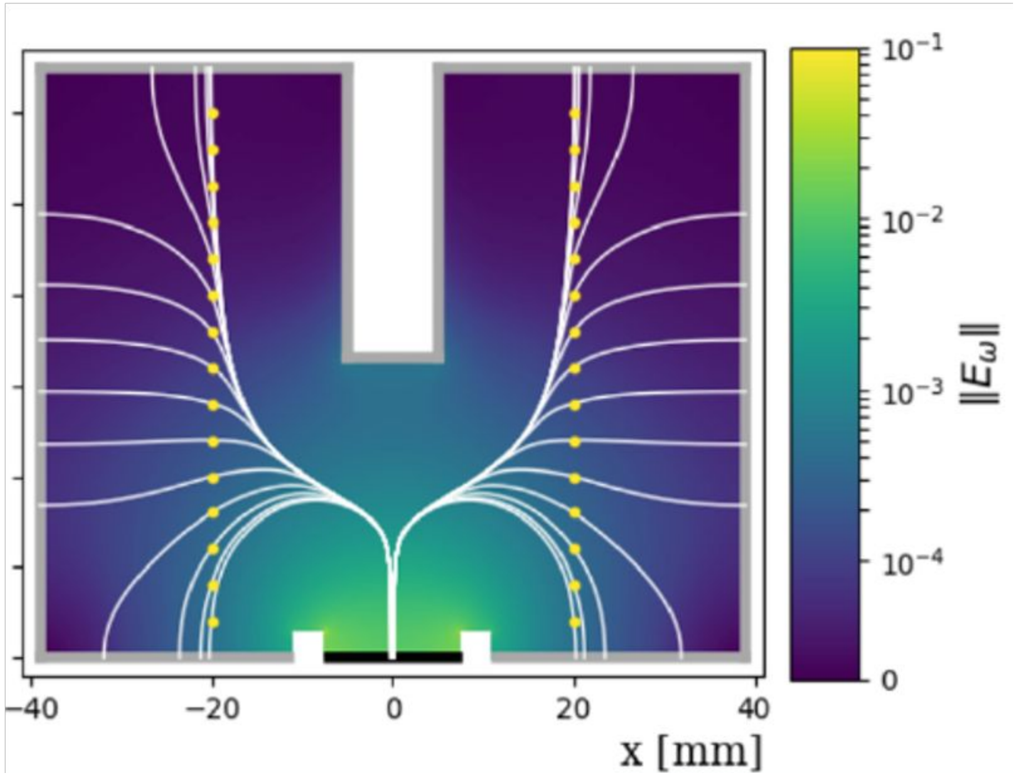
M = active mass, t = time, b = background index, ΔE = energy resolution

Germanium Detectors

- **High Purity Germanium (HPGe) Detectors:**
  - Semiconductor detectors
  - Enriched detectors: 92% of detector material is ^{76}Ge
  - High spatial and superior energy resolution

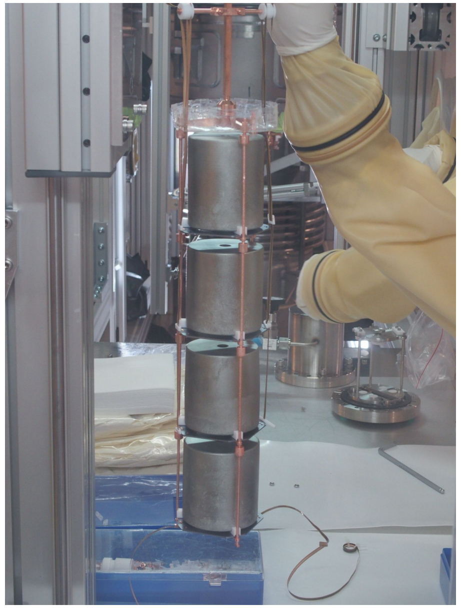


Germanium Detectors



- **Inverted Coaxial Point Contact (ICPC) Detectors:**
  - New design HPGe detectors
  - Unique geometry
  - Large detector mass (up to 3 kg)
  - Strong Pulse Shape Discrimination (PSD) power

All detectors must be thoroughly characterised before deployment at LNGS!



Detector Characterisation

- **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 - proportional to total active detector mass

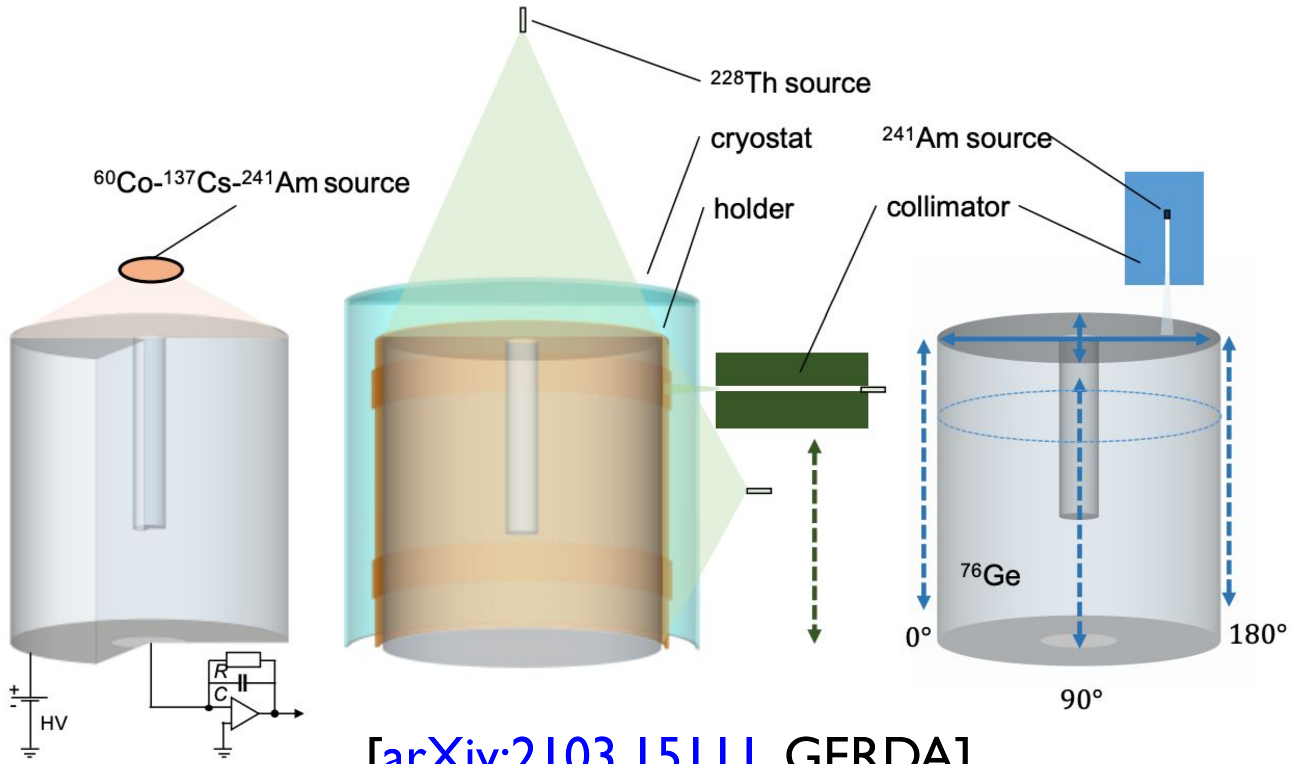
$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M.t}{b.\Delta E}}$$

Half life sensitivity for an experiment with backgrounds

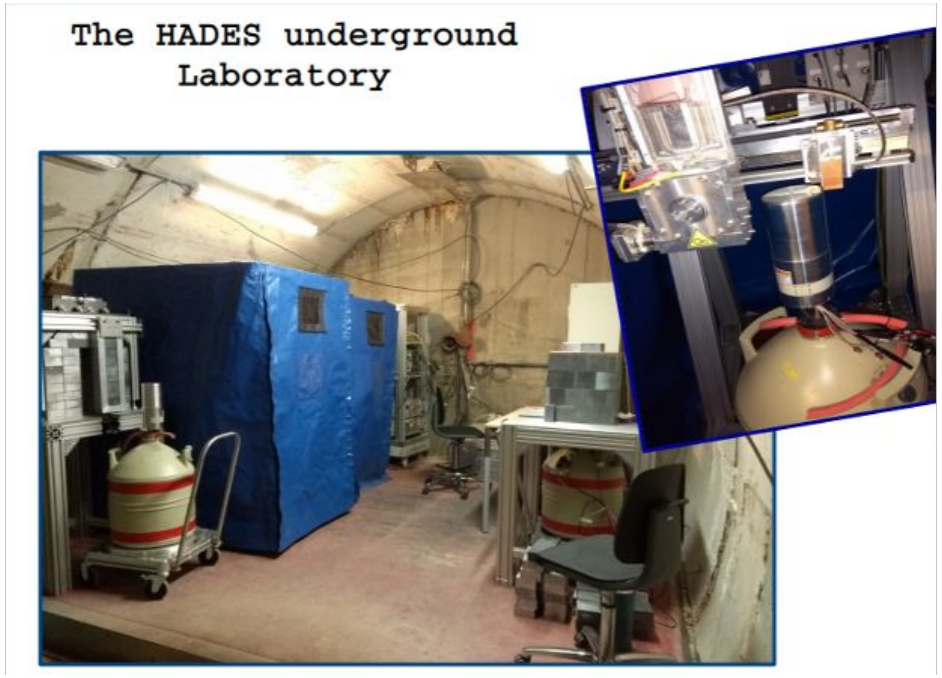
M = active mass, t = time, b = background index, ΔE = energy resolution

Detector Characterisation

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

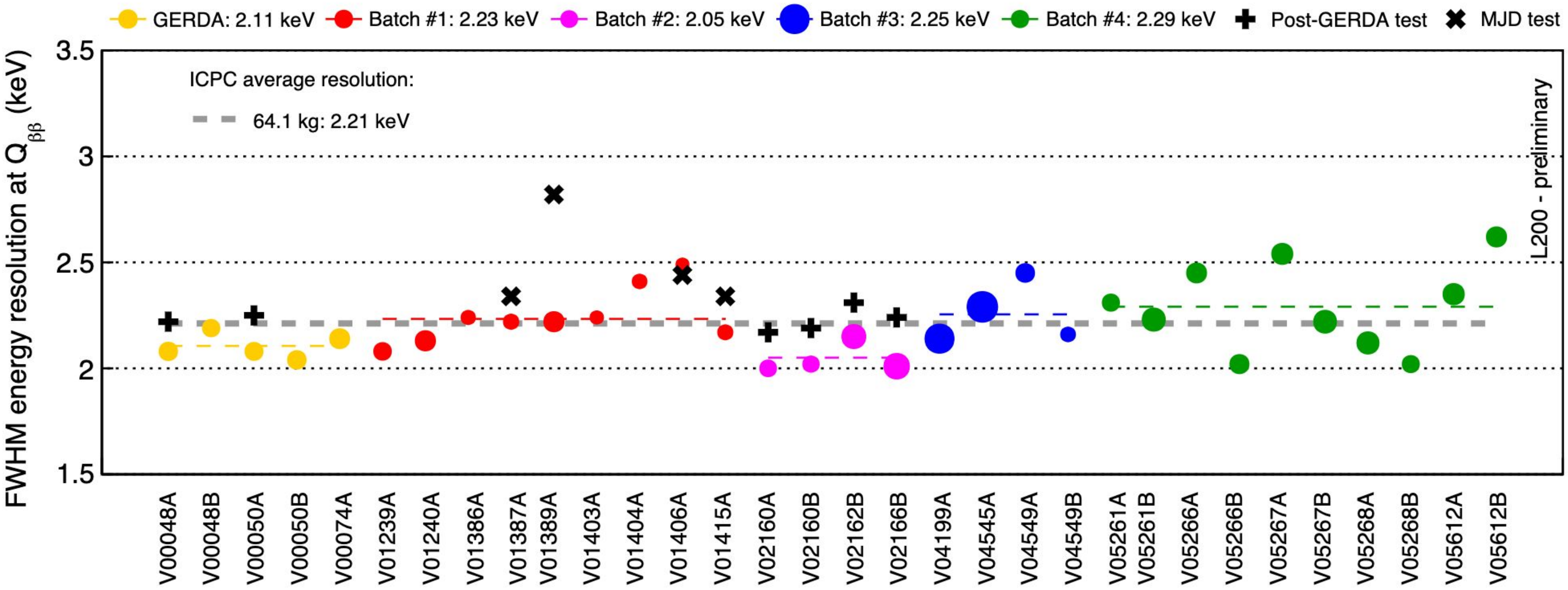


[arXiv:2103.15111, GERDA]



This is ongoing work as new detectors arrive

Energy Resolution



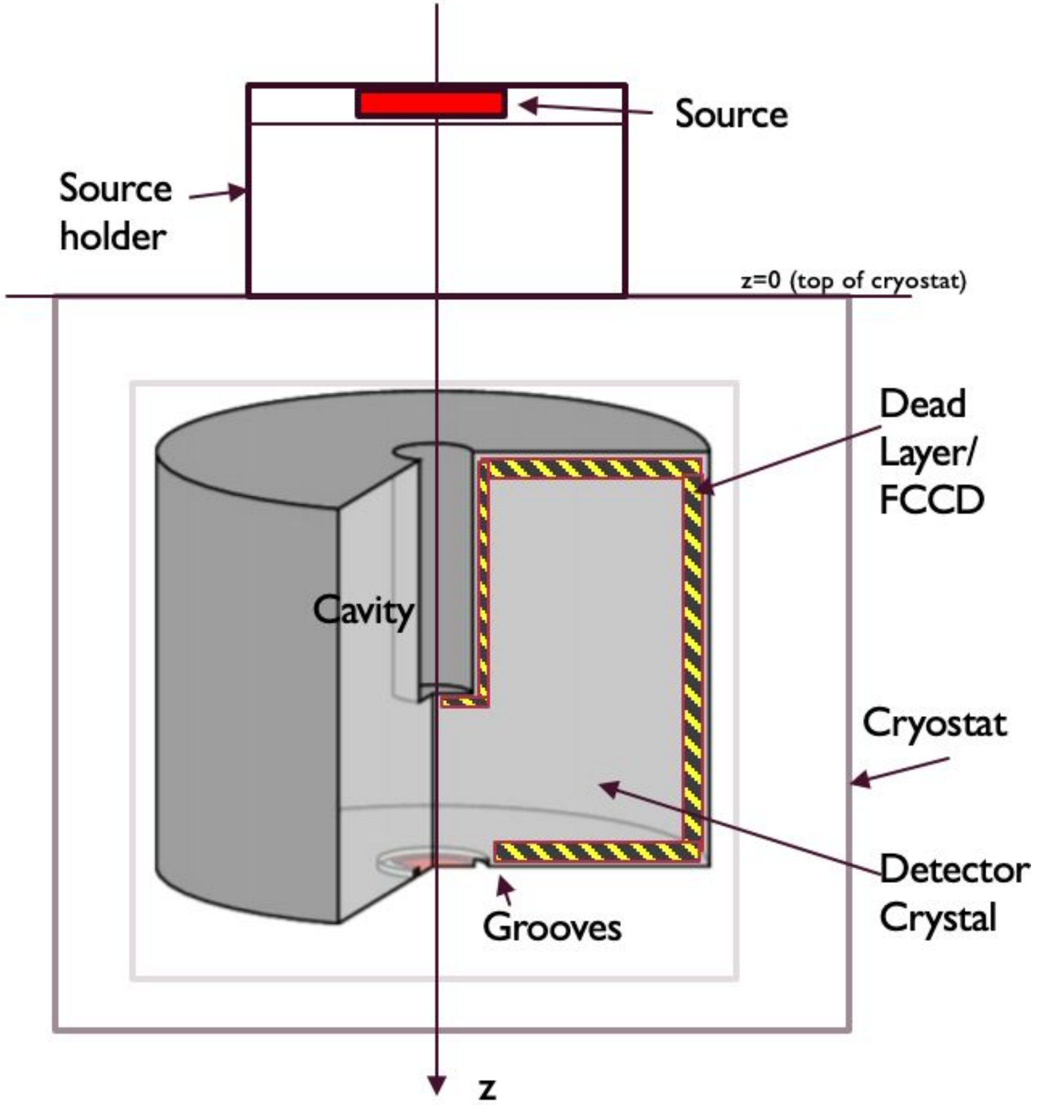
L200 target energy resolution is 2.5 keV or 0.12% of $Q_{\beta\beta}$

Current average energy resolution, 2.21 keV, exceeds target!

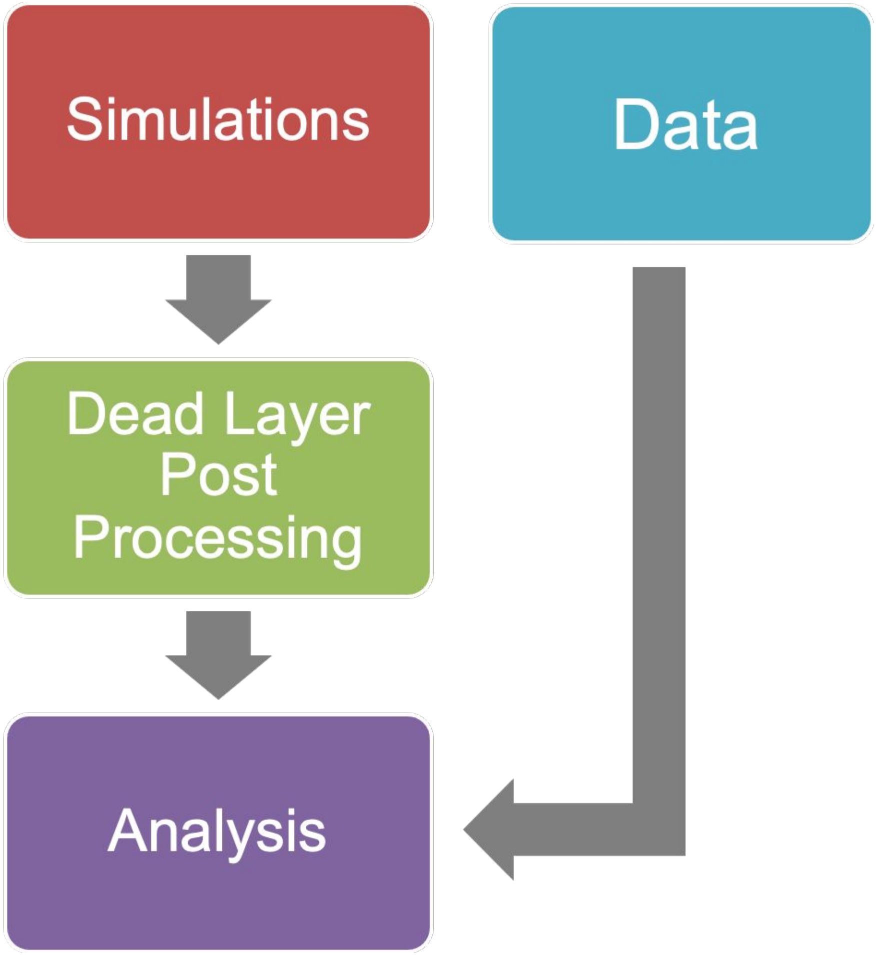
Active Volume Characterisation

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

- **Determination of detector active volume is important for LEGEND because:**
  - 0νββ half-life directly proportional to active mass
  - Degraded events could mimic 0νββ signature



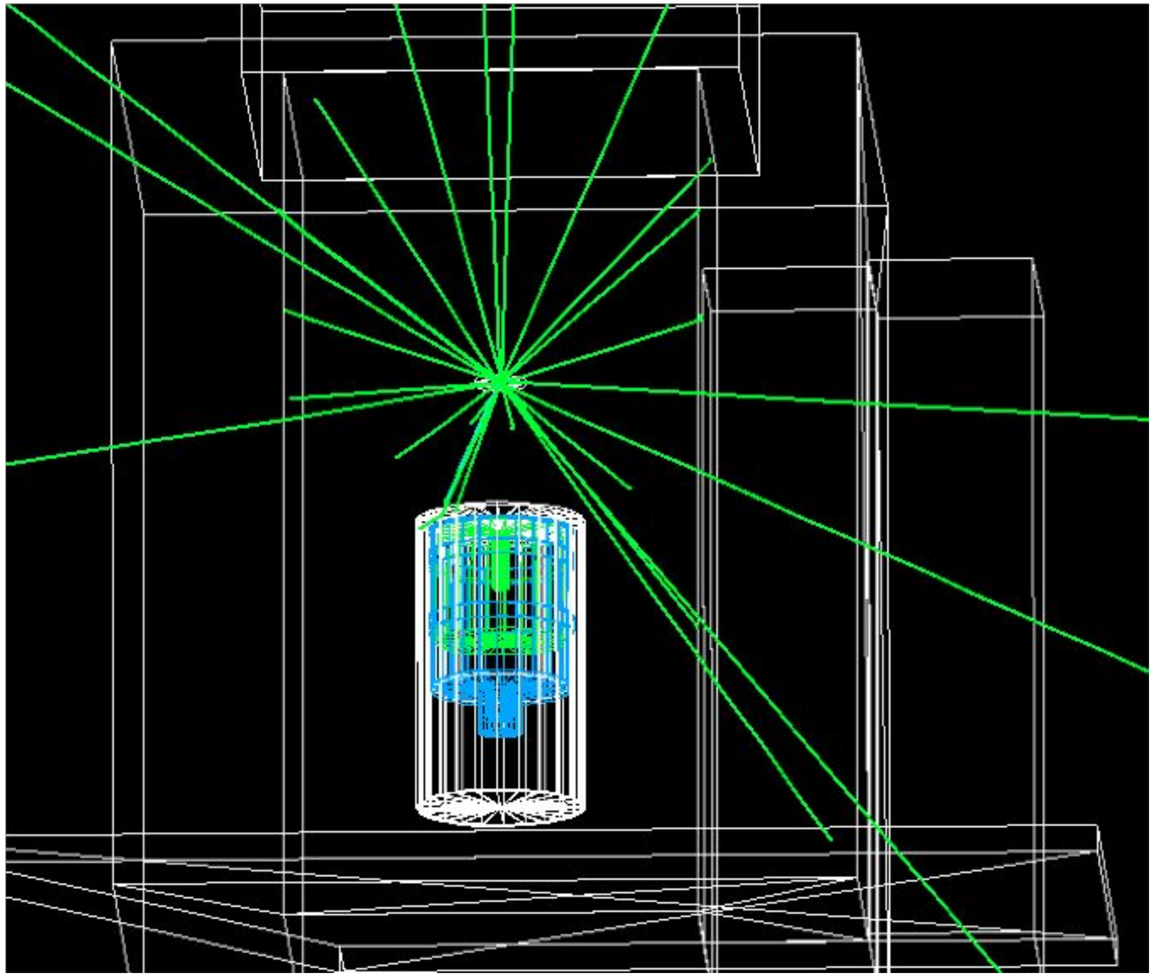
Active Volume Characterisation

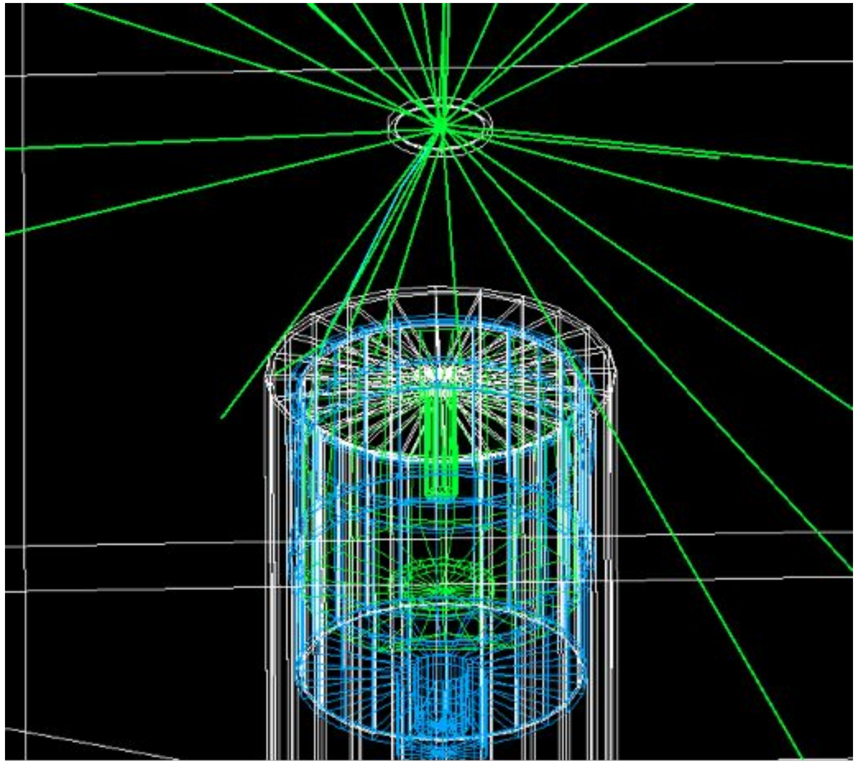


- **Aim:** Determine the active volume of the detectors by comparing HADES characterisation data with simulations
  - Detectors exposed to ^{133}Ba (low energy spectrum→ FCCD sensitive)
- **Simulations:** *GEANT-4 based* MC simulations [https://github.com/legend-exp/g4simple]
- **Post Processing:** starting 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

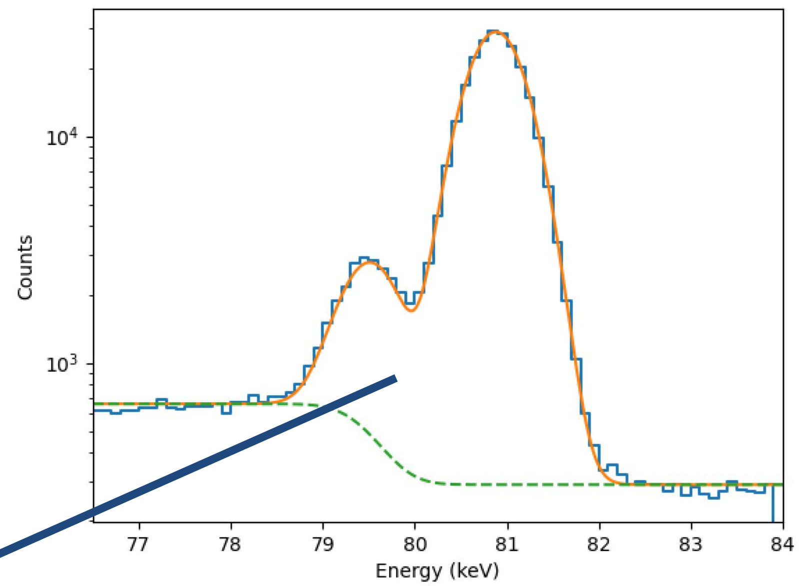
- MC visualisation





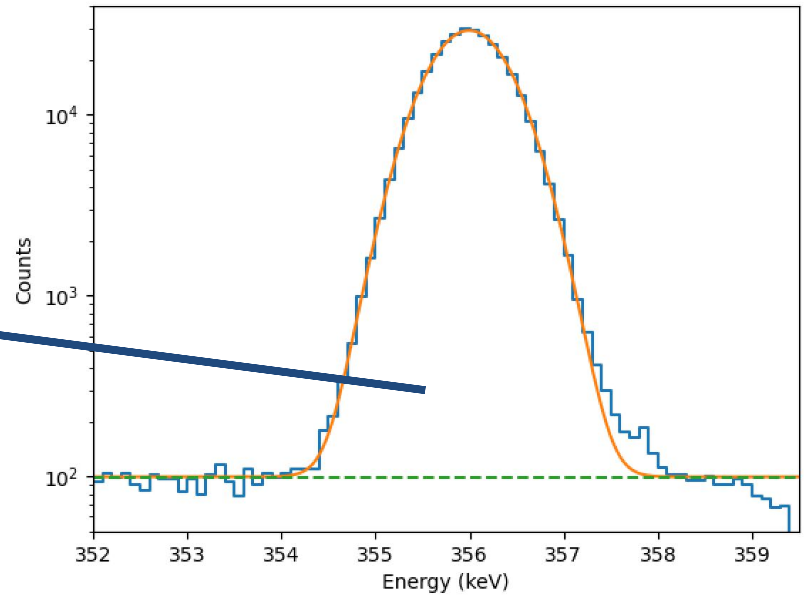
Active Volume Characterisation

- **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



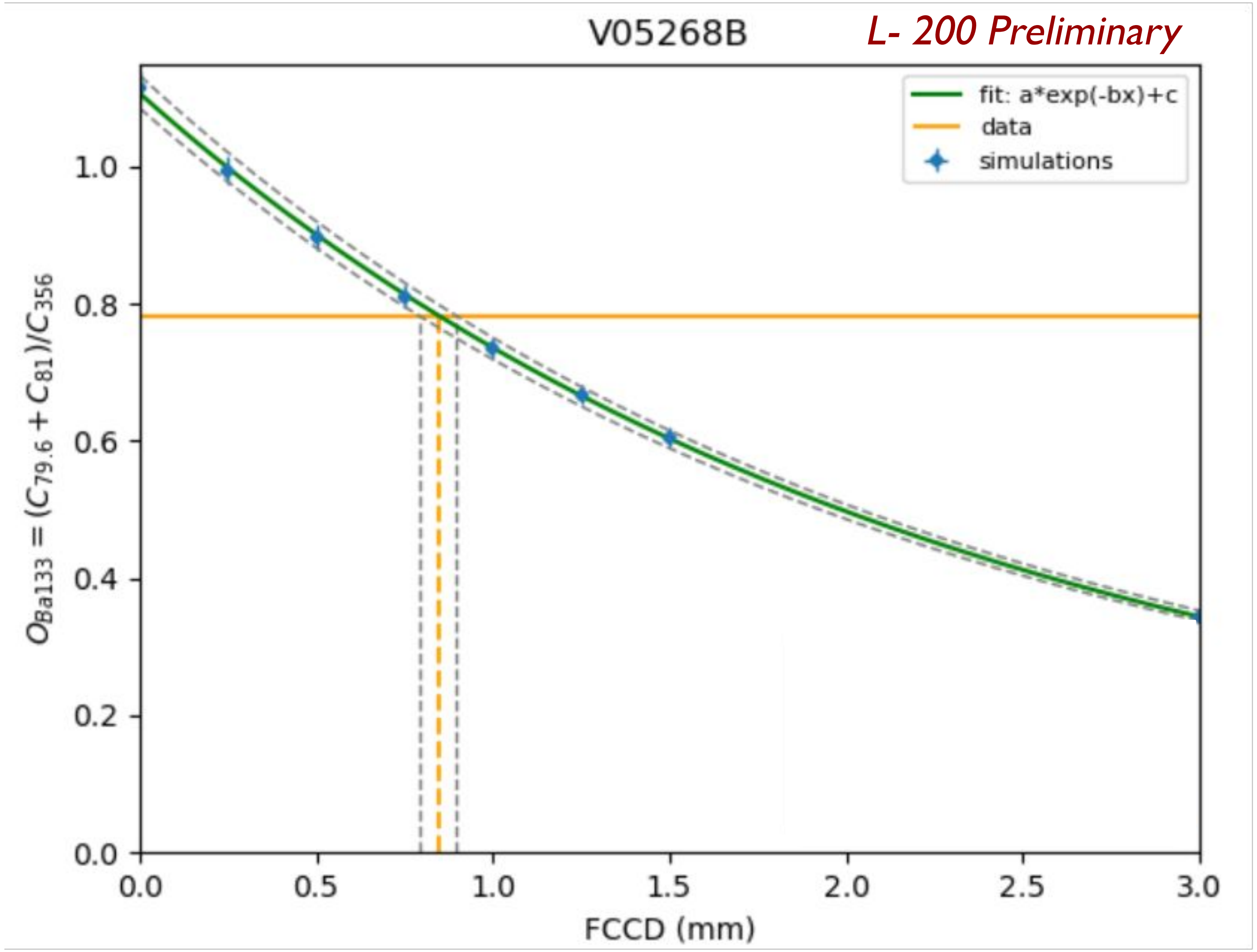
$$O_{^{133}Ba} = \frac{C_{79.6keV} + C_{81.0keV}}{C_{356.0keV}}$$

FCCD sensitive observable



Active Volume Characterisation

- FCCD determination:



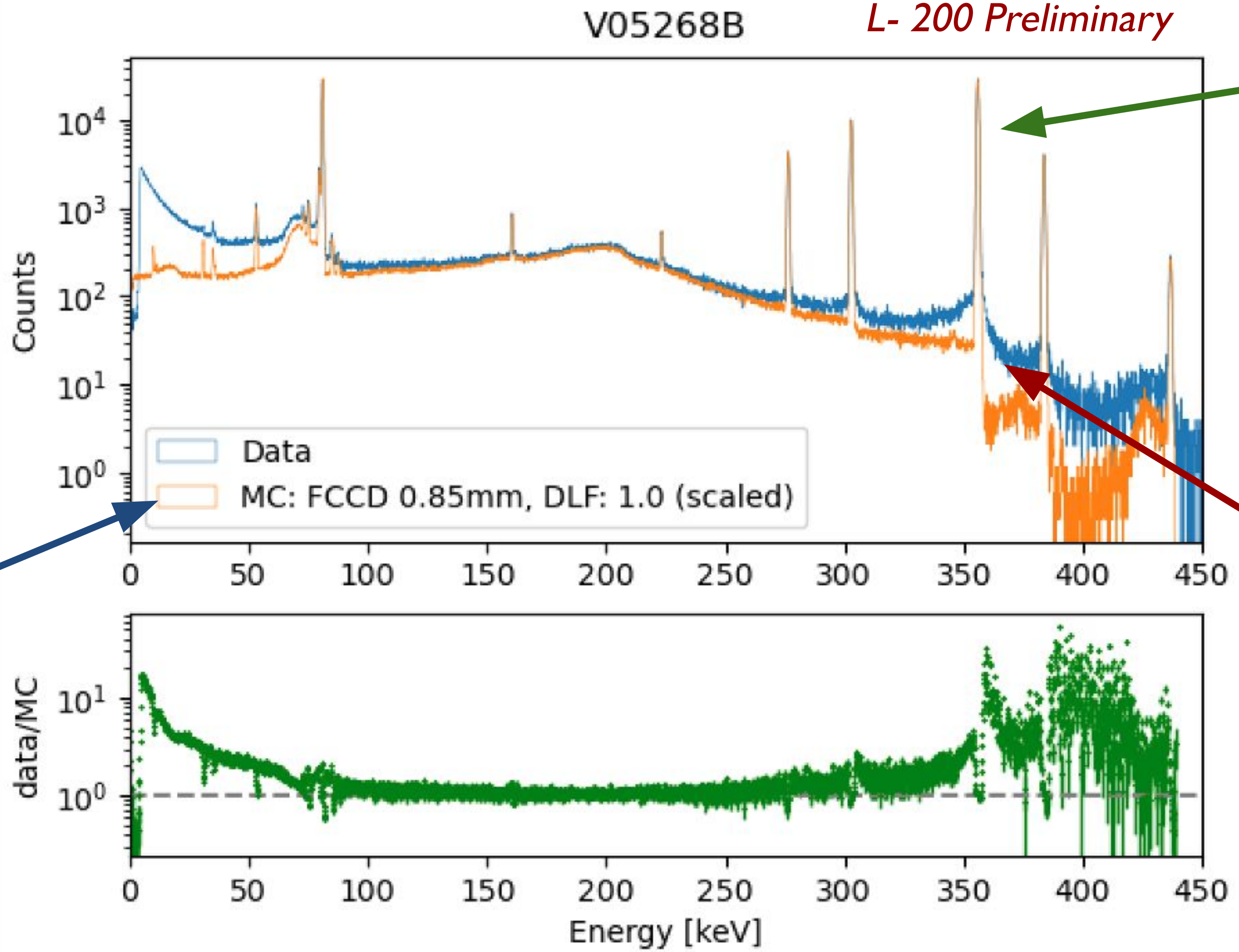
Exemplar plot for an IC detector with:

$$FCCD = 0.85^{+0.05}_{-0.06} mm$$

Active Volume Characterisation

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

L- 200 Preliminary



Full energy peaks well matched

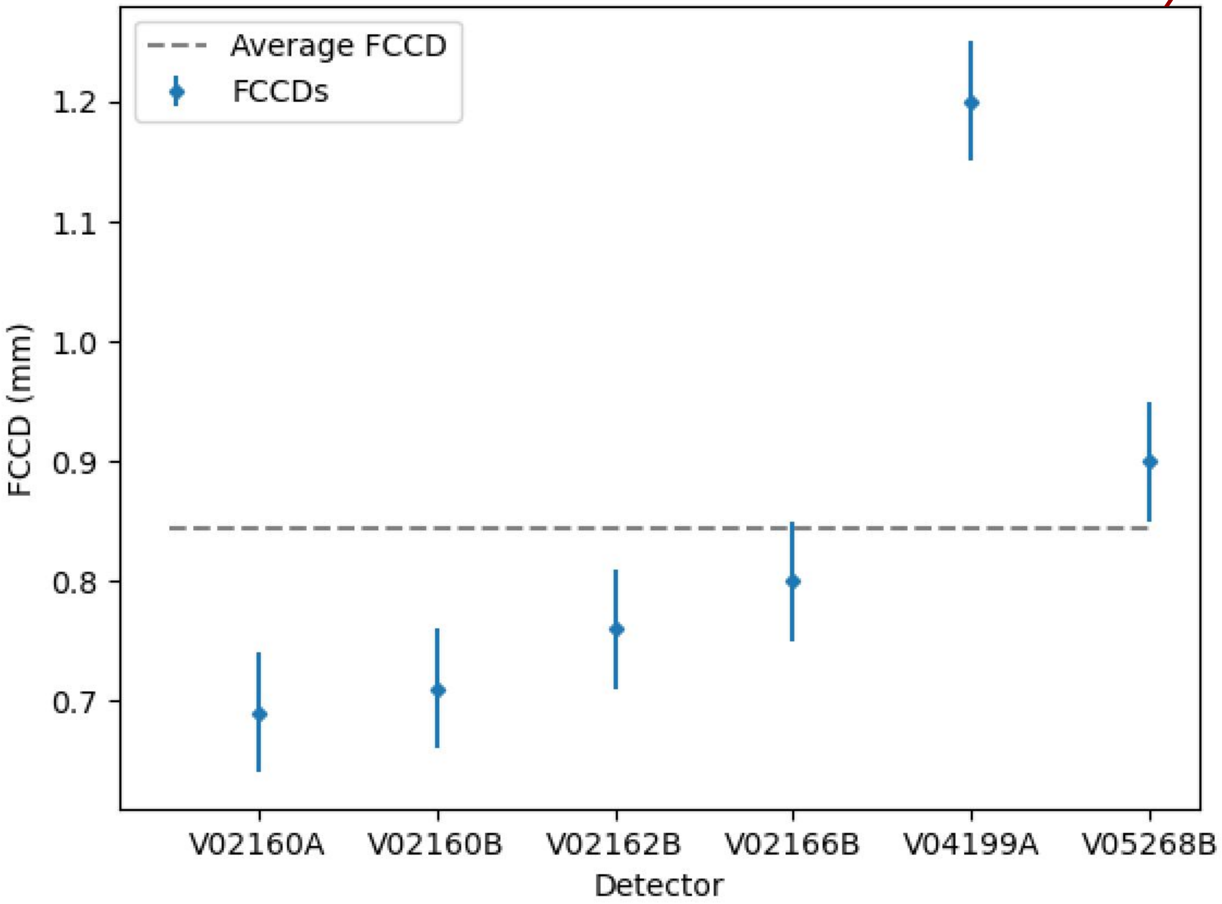
Best fit FCCD

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

Active Volume Characterisation

- **Process is repeated for all detectors:**
  - Automatisation implemented to allow for rapid characterisation of new detectors
  - This is ongoing work
- **Next steps**:
  - Transition layer modelling
  - Repeat and compare with different radioactive sources, e.g. ^{241}Am

L- 200 Preliminary



Summary

- LEGEND will search for 0νββ decay in ^{76}Ge via 2 phases
- L200 is due to start taking data later this year with ~200 kg of HPGe detectors
- Ahead of commissioning, HPGe detectors must be characterised - this is ongoing work in underground laboratories such as HADES (and SURF)
- The energy resolution of the HPGe detectors is determined
  - Average resolution exceeds L200 target
- The Active Volume of the HPGe detectors is determined
  - Dead layer modelled
  - Next step: model the transition layer

Seattle - Dec. 2019