# Modelling of HPGe Detectors

For LEGEND Experiment & Low-Background Research

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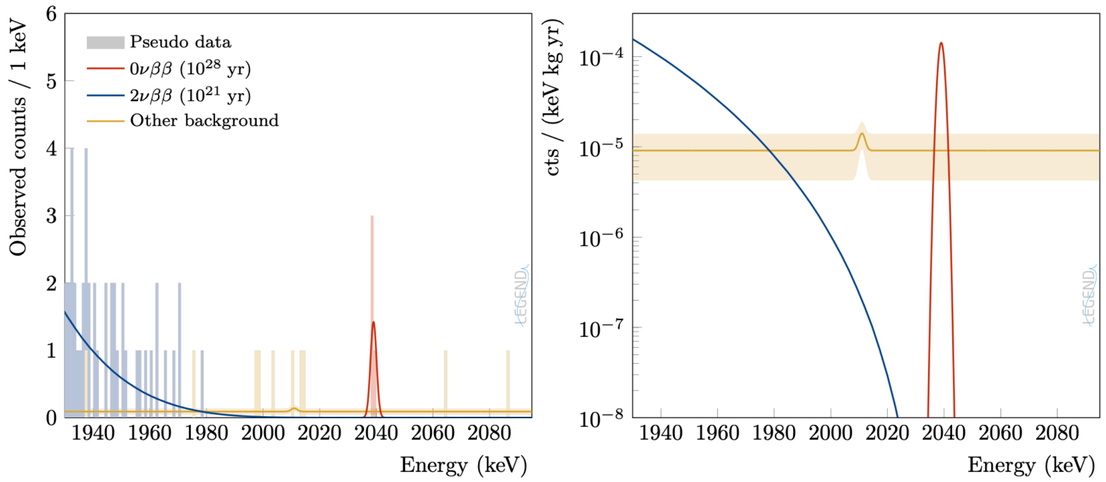
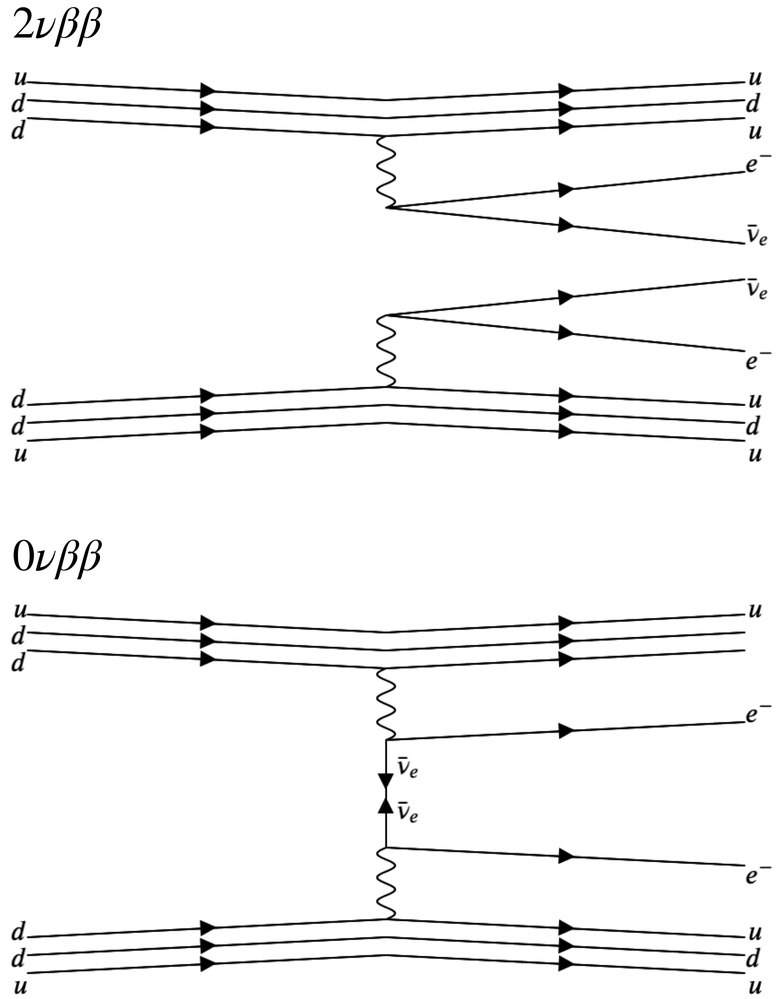
# Outline

- Brief introduction of $0\nu\beta\beta$
- LEGEND experiment & HPGe detectors
- Motivation: why is modelling important?
- *remage*: an improved simulation framework for LEGEND
- Conclusion & Future plan

# Neutrinoless Double Beta Decay

- $2\nu\beta\beta\ (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}$
  - Allowed in SM
- $0\nu\beta\beta\ (A, Z) \rightarrow (A, Z+2) + 2e^-$
  - violating lepton number conservation by 2 units
  - Beyond SM



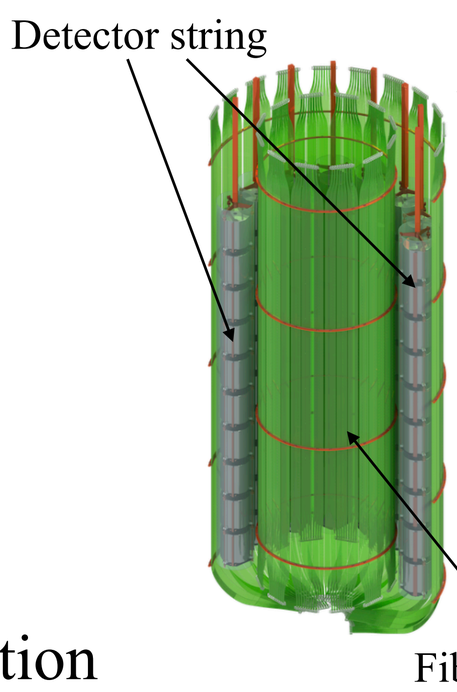
# LEGEND

**L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrino-less $\beta\beta$ **D**ecay

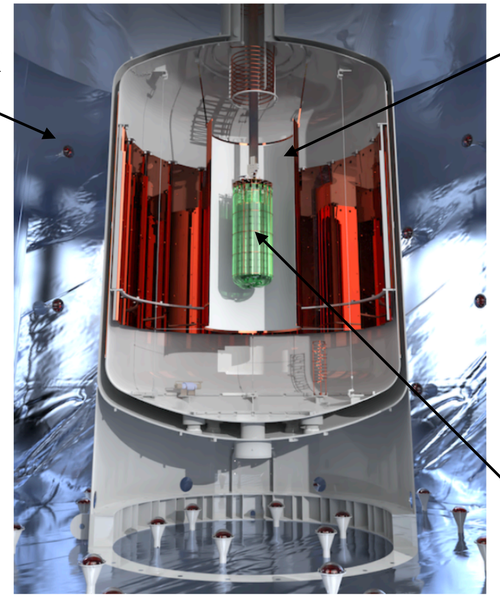
# LEGEND

## Experimental Design

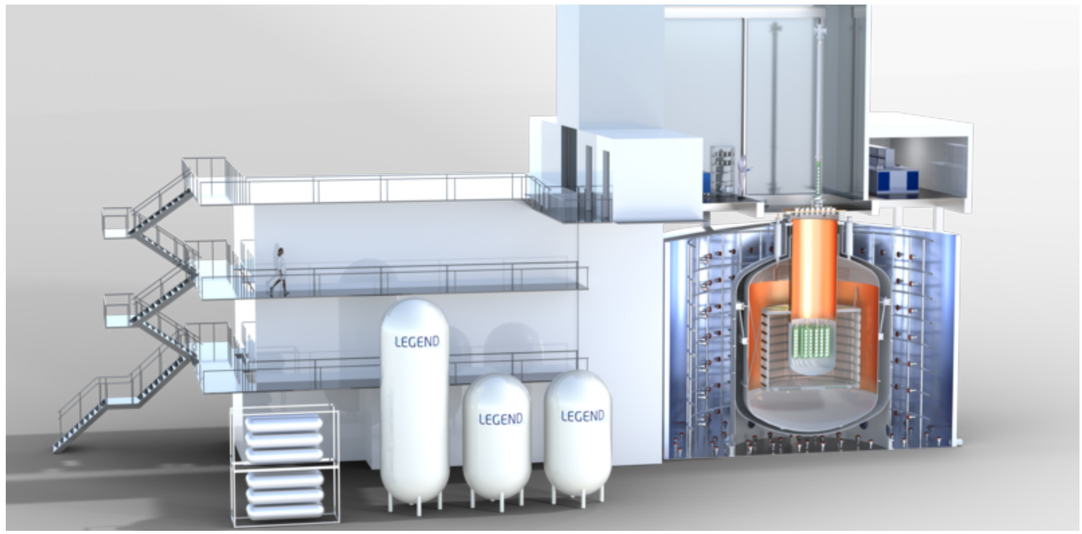
- LEGEND-200:
  - 200 kg HPGe (PPC, BEGe, ICPC)
  - $T_{1/2}^{0\nu} = 10^{27}$yr in five years of operation
  - Data taking since summer 2022
- LEGEND-1000:
  - Around 400 ICPCs (>2.5 kg each)
  - 1000 kg active mass
  - $T_{1/2}^{0\nu} = 10^{28}$yr after 10 years of data taking




LEGEND-200

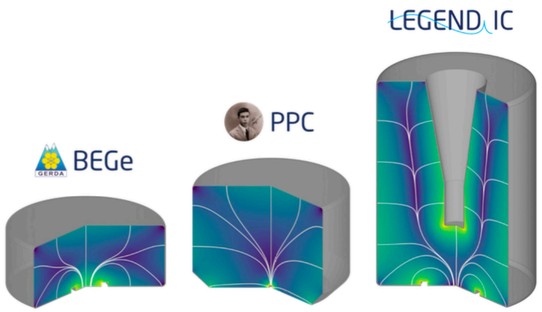



LEGEND-1000



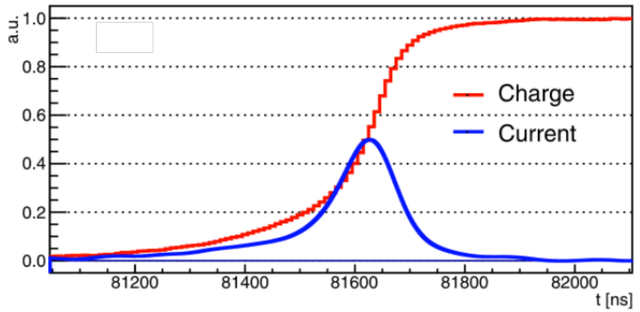
# LEGEND

## HPGe Detector

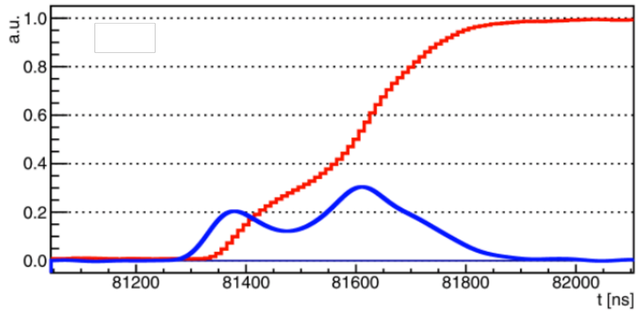


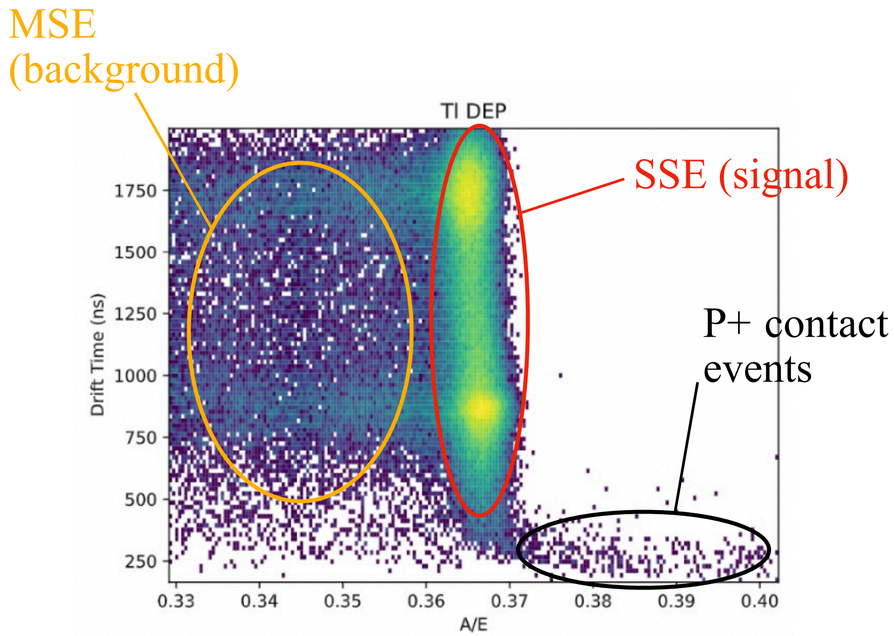

- PPC & BEGe:
  - Maximum mass limited to ~1 kg;
- IC (inverted-coaxial):
  - Lower depletion voltage required;
  - Significantly larger (2-3 kg).
- Point-like contact: pulse-shape analysis;
- Pulse shape analysis — **A**mplitude / **E**nergy cut.

Single-sited event (SSE)



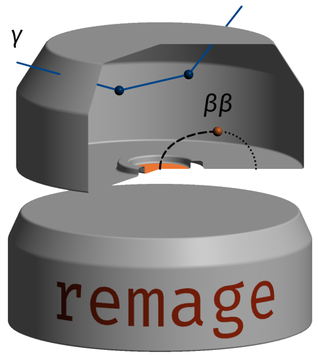

Multi-sited event (MSE)




A/E map for Tl-208 double escape peak from LEGEND-200 calibration data

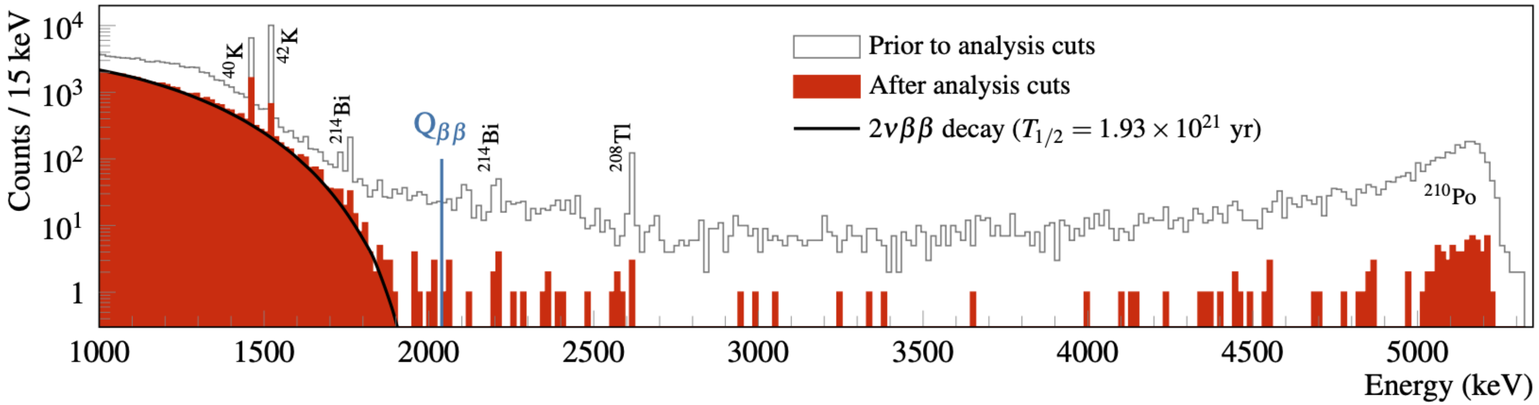
# *remage*




Improved Modelling & Simulation Framework

# Motivation

## Importance of solid simulation



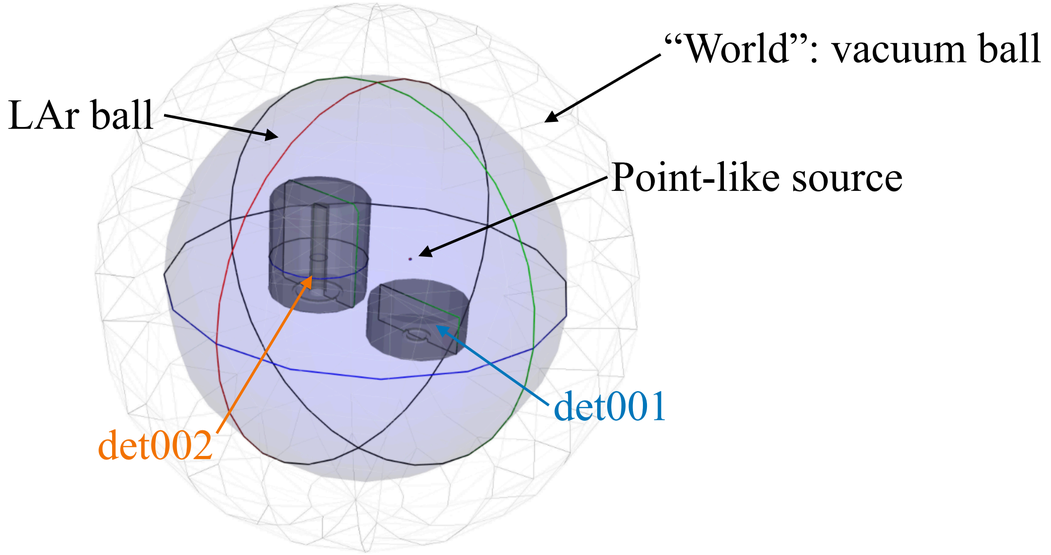

- Background after analysis cuts: long-lived isotopes ($^{238}$U, $^{232}$Th, $^{40}$K, etc.)
- Robust simulation is required for material background modelling
- *remage* — an efficient & user-friendly framework:
  - Detector efficiency simulation for better quantifying of background rejection;
  - Radioassay of materials at Boulby HPGe screening station (UCL group goal).

# *remage*

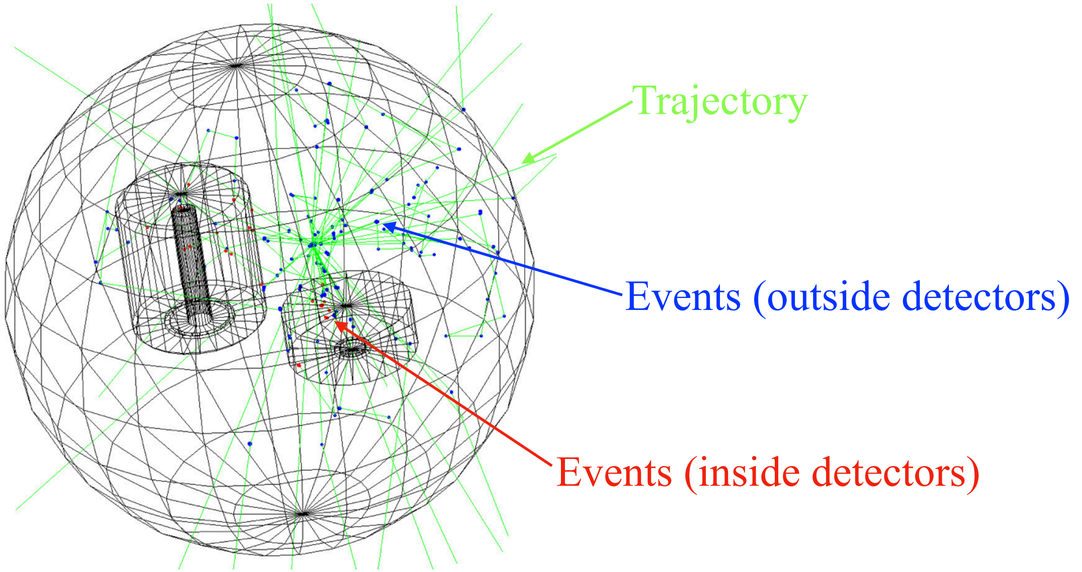
## Simulation Chain

- Pyg4ometry:
  - Python package for geometry creation & visualisation
- *remage*:
  - Geant4-based framework for efficient particle physics simulation
  - Simulate multiple detectors and view outputs separately

**Geometry visualisation**




**Viewing energy deposition**



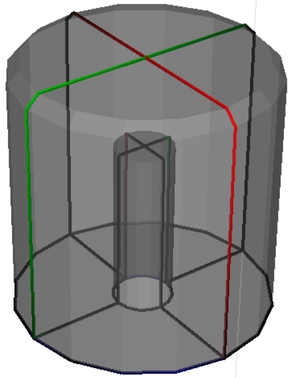
# *remage*

## Key Concepts & Advantages

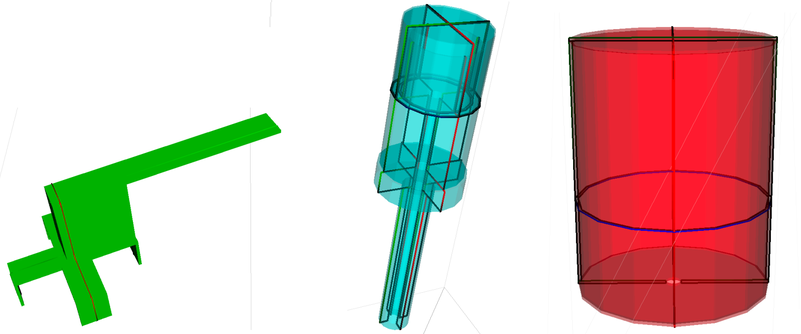
- *remage* GitHub page: https://github.com/legend-exp/remage
- Experimental geometry built with pyg4ometry: https://github.com/g4edge/pyg4ometry
- Modern principles of open science / software development
- Continuous validation
- Optimised support for radiogenic and optical physics
- Easy-to-analyse HDF5 simulation output

# Remage Validation

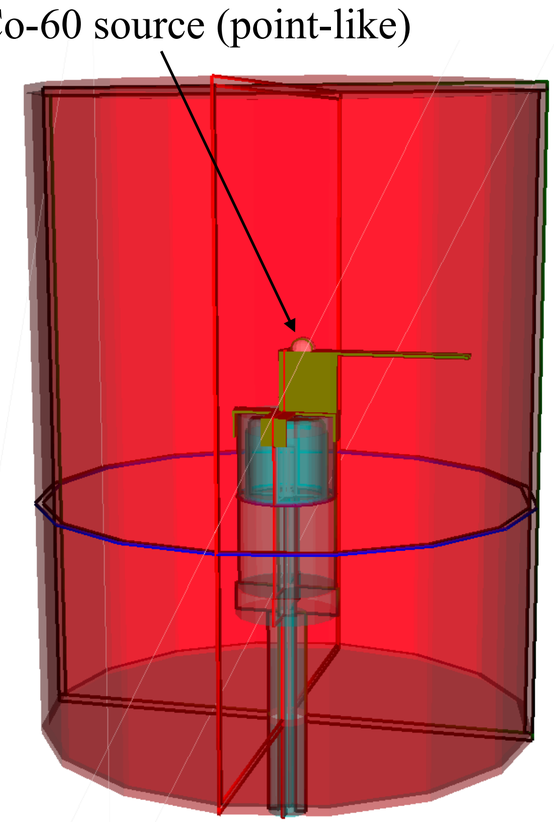
Validation work at UCL as part of a more comprehensive effort



HPGe detector:
Coaxial & p-type;
Diameter = 60.9 mm,
Height = 62.0 mm,
Volume = 176.8 $cm^3$



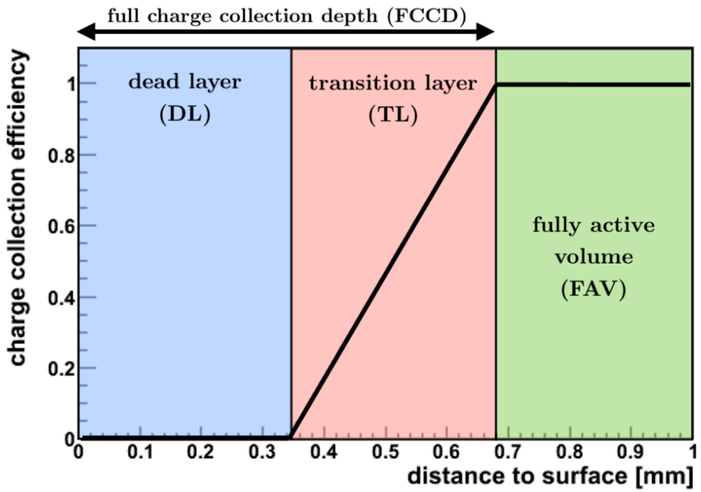
Nylon source holder Al housing Copper shield

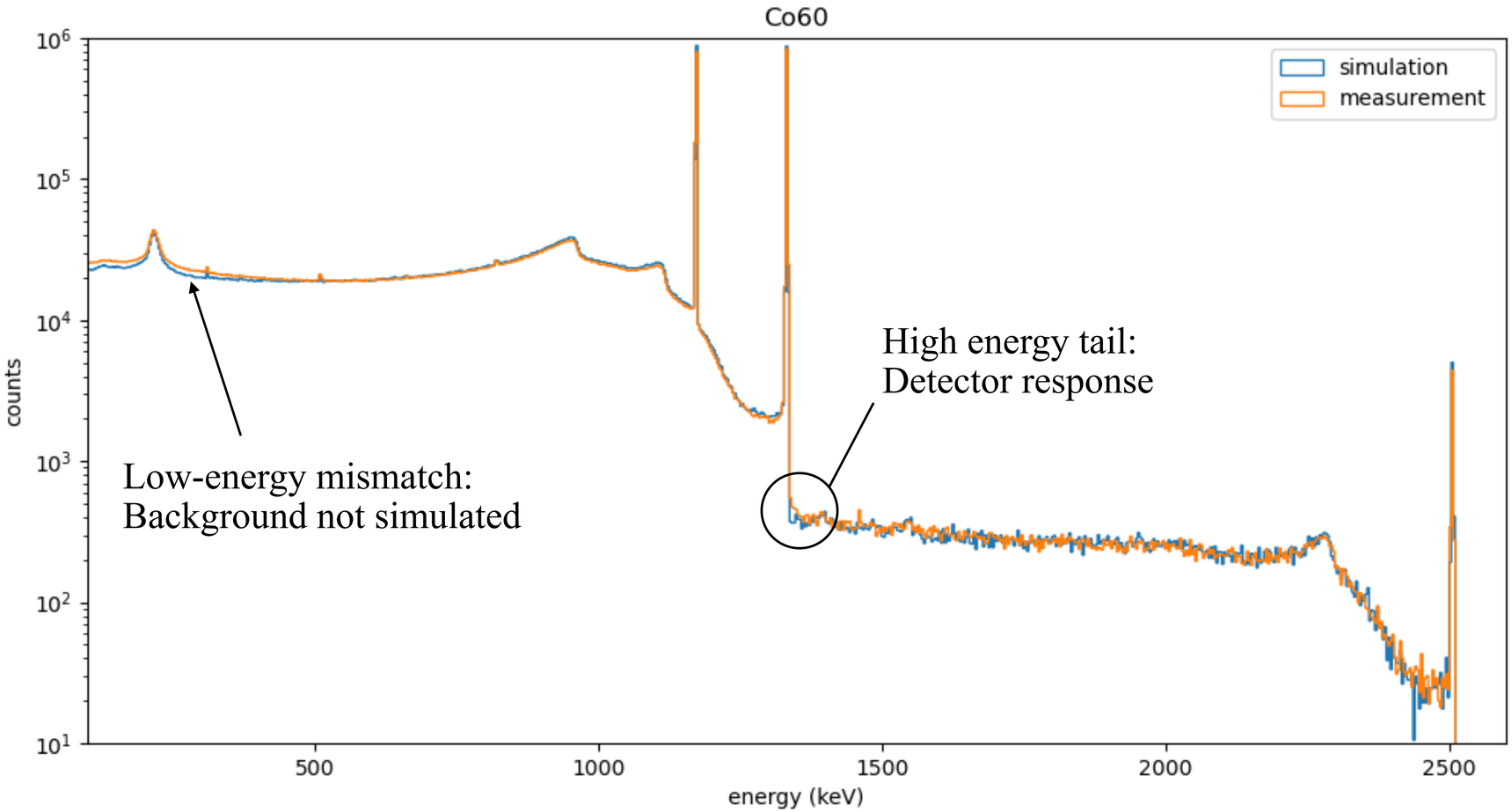



# Remage Validation

## Spectra Comparison

- A linear dead layer (DL) model is applied;
- Validation work is still in progress.



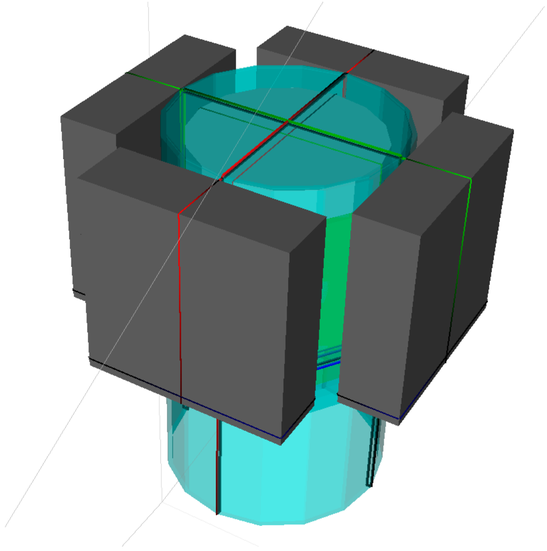
# Validation

## Efficiency Curve Comparison with BUGS

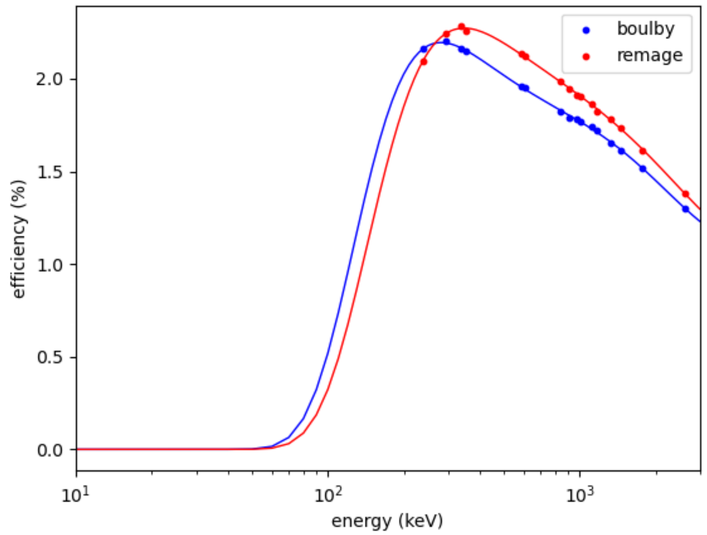
- Material samples from L-200 & L-1000 are sent to Boulby underground laboratory for radiation screening (**B**oulby **U**nderground **G**ermanium **S**uite, BUGS).
- Mismatch between *remage* & Boulby curves is due to different DL models.


UCL group Boulby tour!

Sample on detector



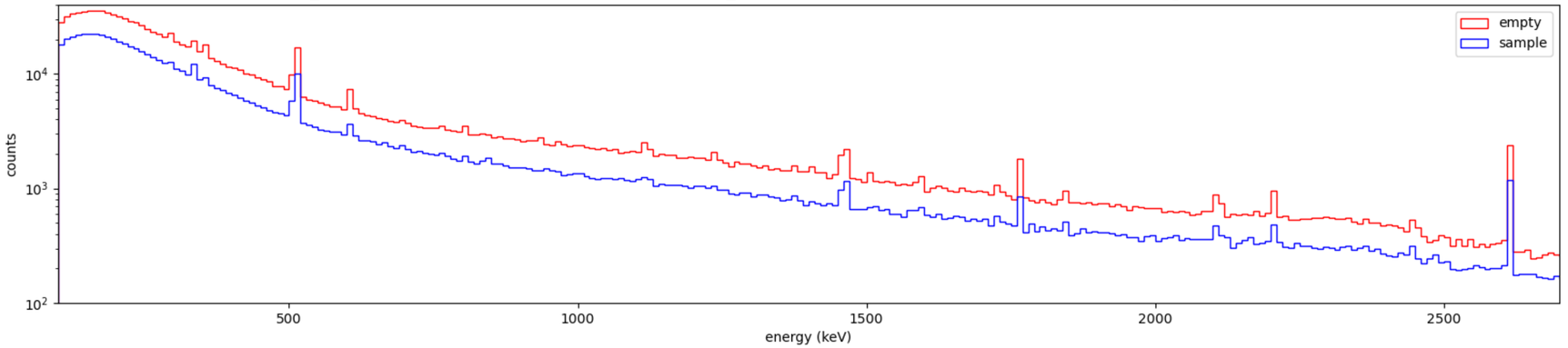
*remage* simulation geometry



# Application

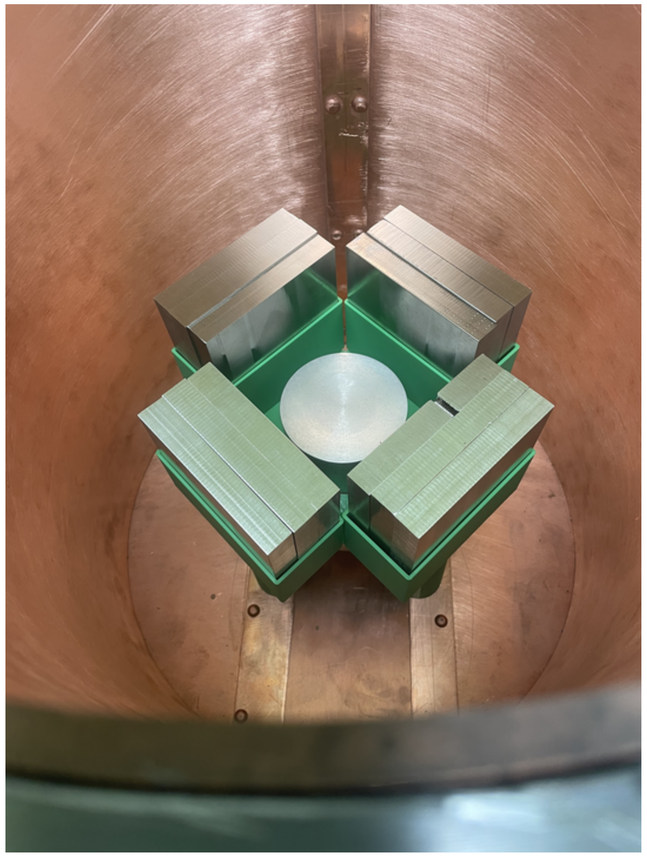
## Activity Upper Limit

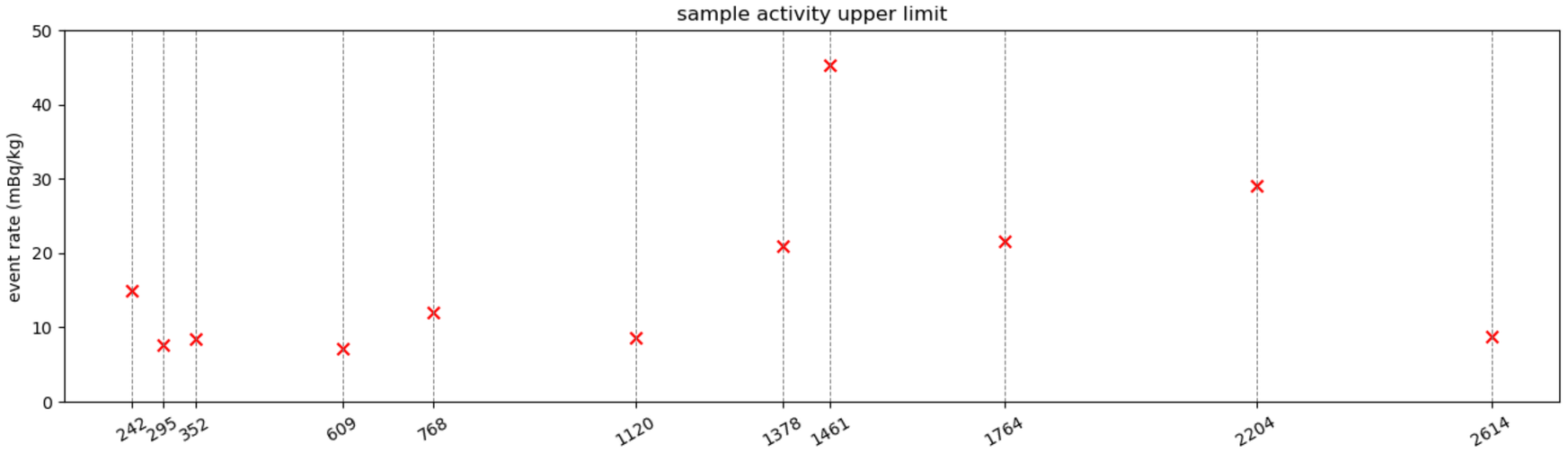
Spectra with & without samples, taken at UCL lab (overground)




- A pre-screening is operated overground (at UCL) before sending samples to Boulby for test.
- Data taken with steel sample (from L-200) are lower due to shielding and self-shielding effects.

Steel sample mass: 15 kg



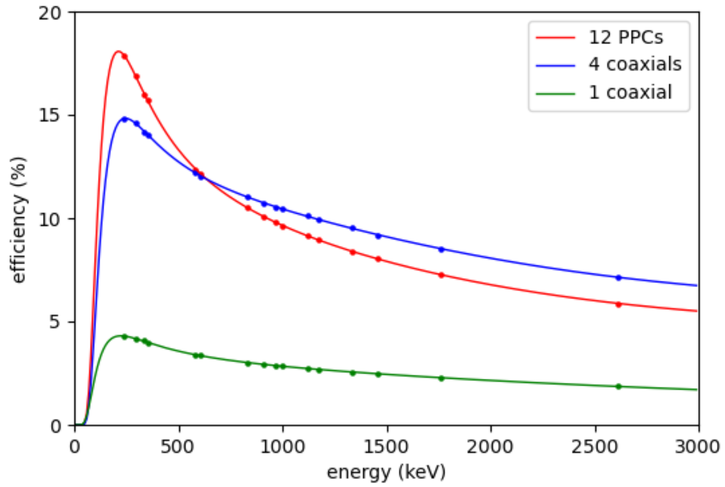


# Application

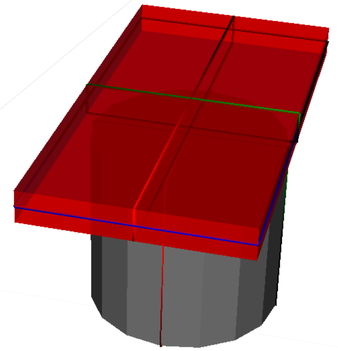
## Screening Station

- Large screening station: higher efficiency, shorter time, lower cost
- HPGe alignment: ~12 PPCs (small) or ~4 Coaxials (new, large)
- ~10% efficiency across whole energy range

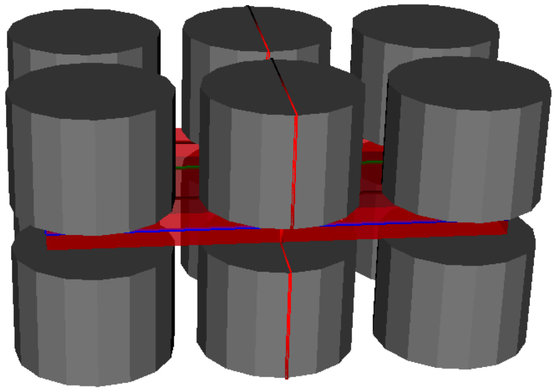
Sample (source):
Copper, x = 200 mm, y = 100 mm, z = 15 mm



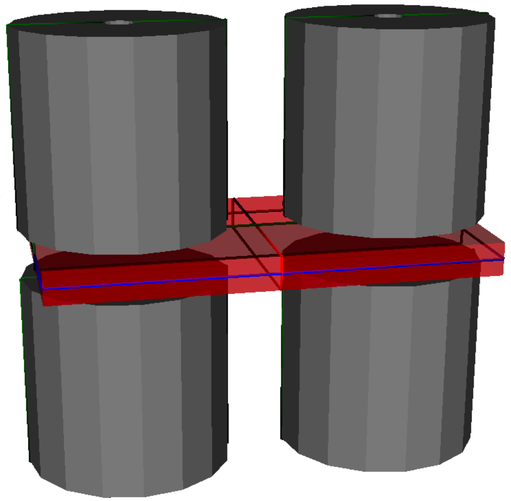

Single coaxial



12 PPCs:
r = 35 mm, h = 40 mm



4 coaxials:
Crystal: r = 46.5 mm, h = 89 mm
Borehole: r = 7 mm, d = 65 mm



# Conclusion

- Accurate material modelling and simulation remain essential for background rejection in LEGEND and related low-background experiments.
- *remage*, a user-friendly Geant4-based simulation framework, has been developed to support LEGEND's background modelling and material screening efforts.
- It has been validated with experimental data and is still under validation. Meanwhile, remage can be applied for LEGEND-200 and LEGEND-1000.

# Outlook

- Further validation study, implementation of more advanced dead layer modelling and detailed shielding geometries.
- Expanding focus beyond efficiency calculations to include background suppression in screening studies.
- Continued validation with experimental benchmarks and application to other low-background physics experiments.

# Other LEGEND-related Talks / Posters

- **Alberto Garfagnini** – Talk: Search for 0nbb in $^{76}$Ge with the LEGEND experiment at Gran Sasso
- **Christoph Vogl** – Talk: $^{42}$K mitigation studies in $^{42}$Ar-spiked liquid argon for LEGEND
- **Tobias Sterr** – Poster: Status of the development of the water tank neutron tagger of LEGEND-1000
- **Raoul Cesarano** – Poster: Background rejection by Pulse Shape Discrimination in the LEGEND experiment