Modeling Background Rejection in LEGEND with the LAr Instrumentation

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The LEGEND project in the quest for 0νββ

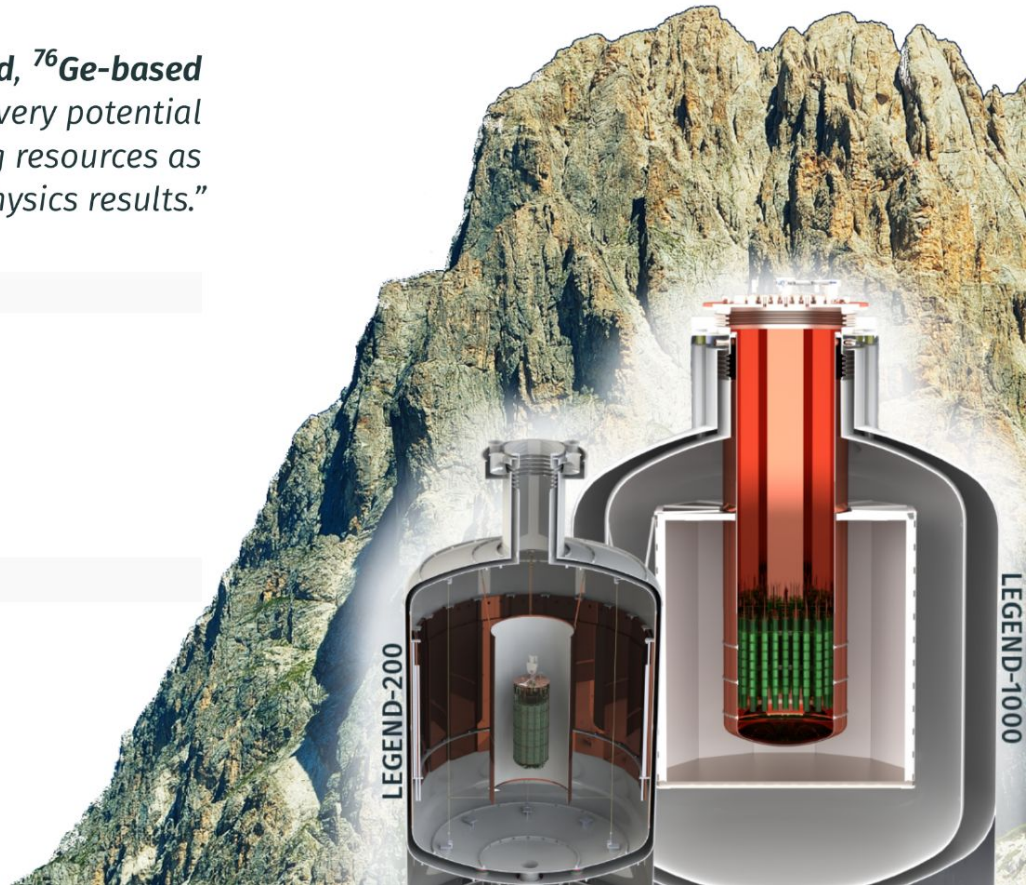
*"The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results."*

LEGEND-200

- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Operating with 140 kg of ^{enr}Ge
- $B \sim \mathbf{2 \cdot 10^{-4}}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > \mathbf{10^{27}}$ **yr**

LEGEND-1000 arXiv 2107.11462

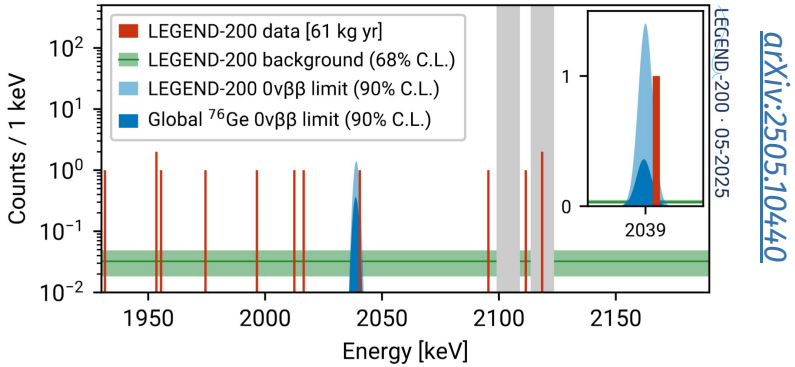
- **1 ton** of ^{enr}Ge (×10 yr), awaiting funding
- $B < \mathbf{10^{-5}}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > \mathbf{10^{28}}$ **yr**
- Cover full $m_{\beta\beta}$ inverted ordering region



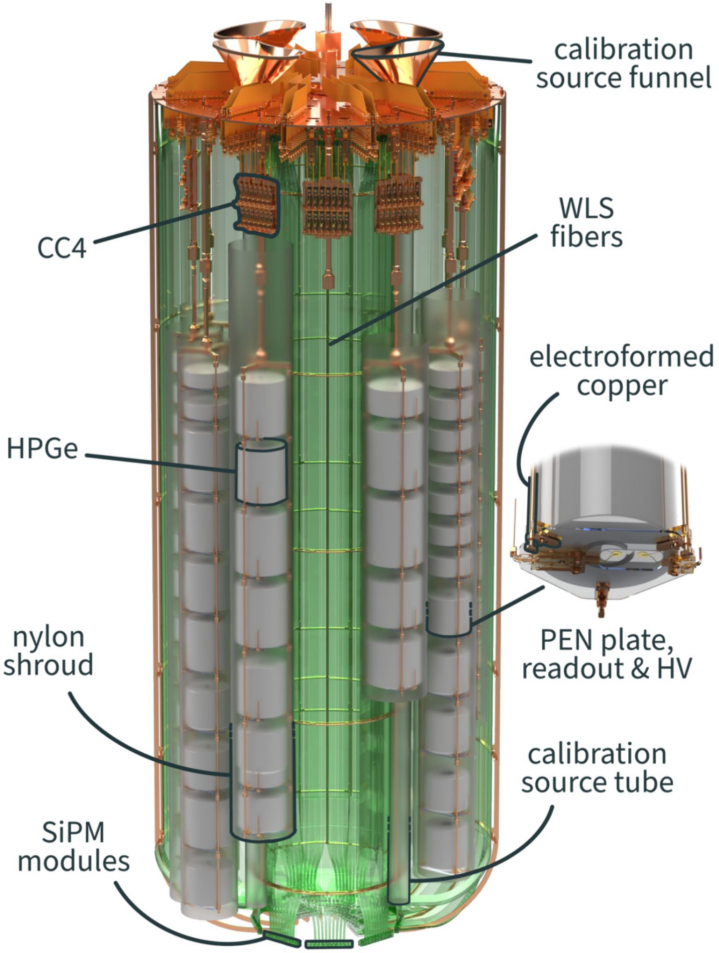
Status of LEGEND-200

- 0νββ results from the first **142 kg** deployment recently accepted by PRL!
- Current best ^{76}Ge constraints:

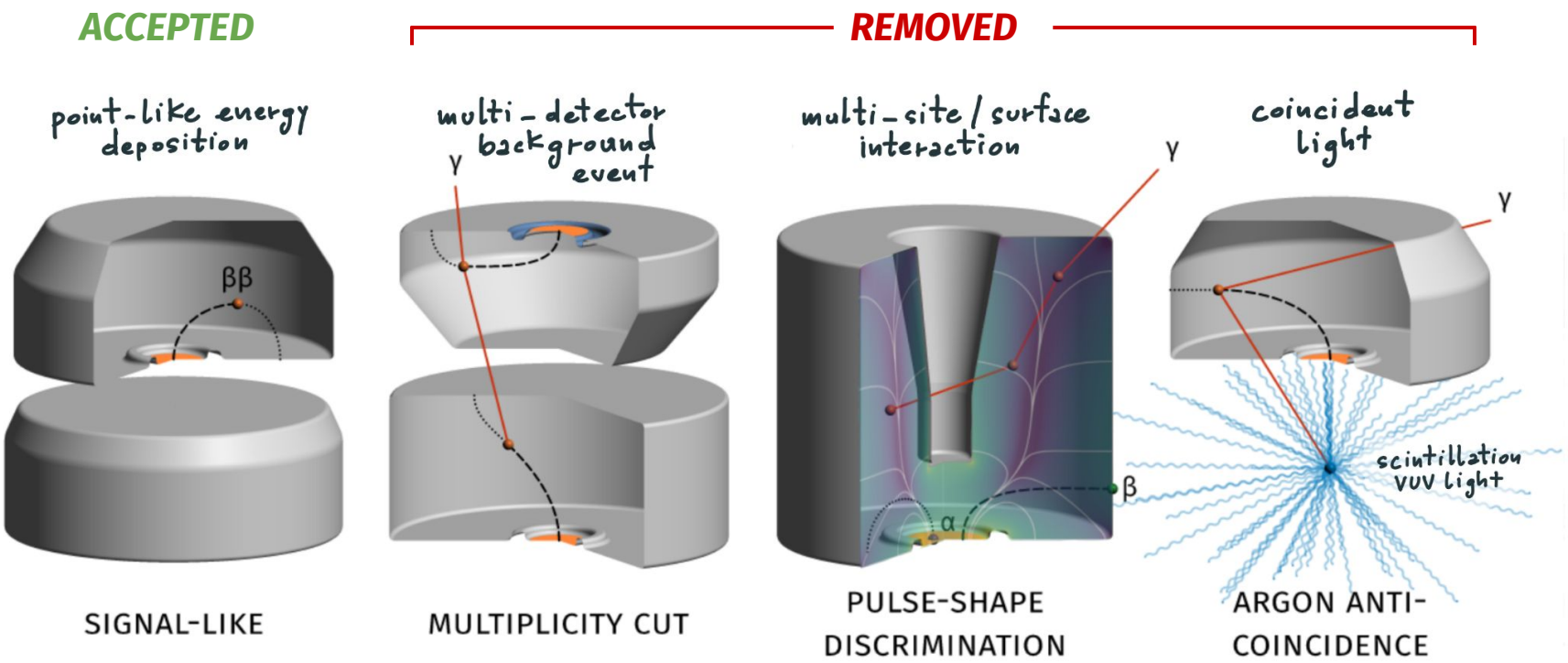
  [limit] 1.9×10^{26} yr // **[sensitivity] 2.8×10^{26} yr**
- Recently resumed data taking with cleaner array



arXiv:2505.10440

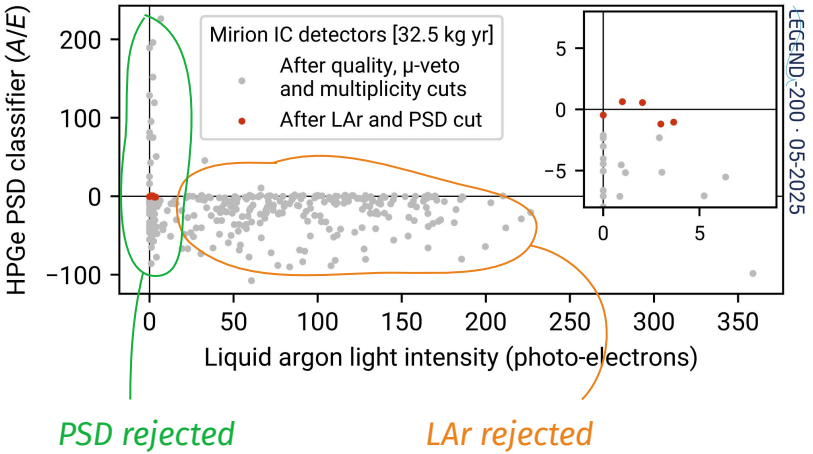


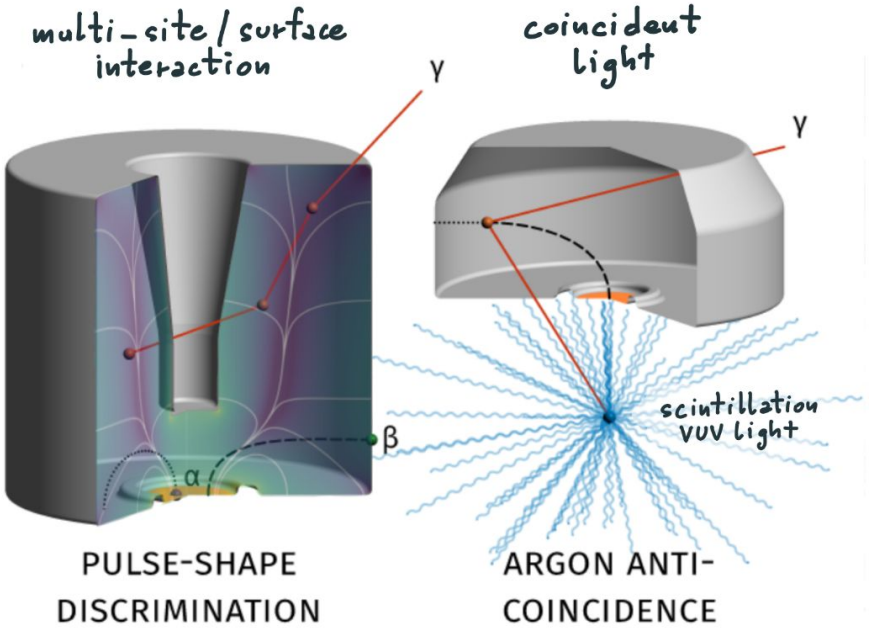
Signal and background signatures in LEGEND



Signal and background signatures in LEGEND

*Strong **complementarity** of the two cuts!*





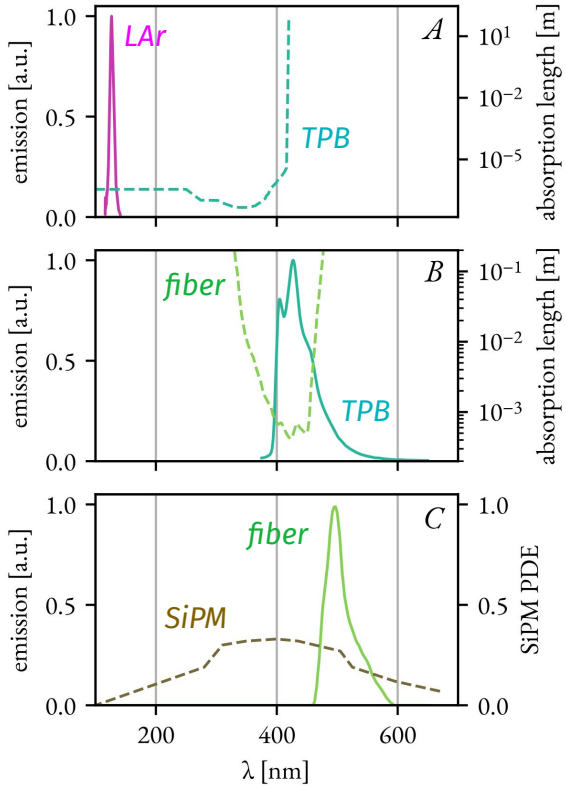
The LEGEND light detection principle

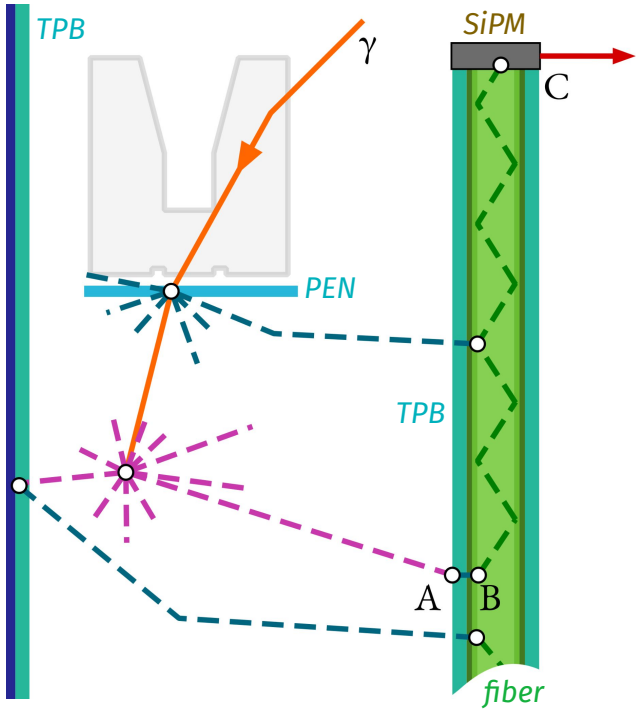
Scintillation light

WL-shifted / reflected

guided by **fibers**

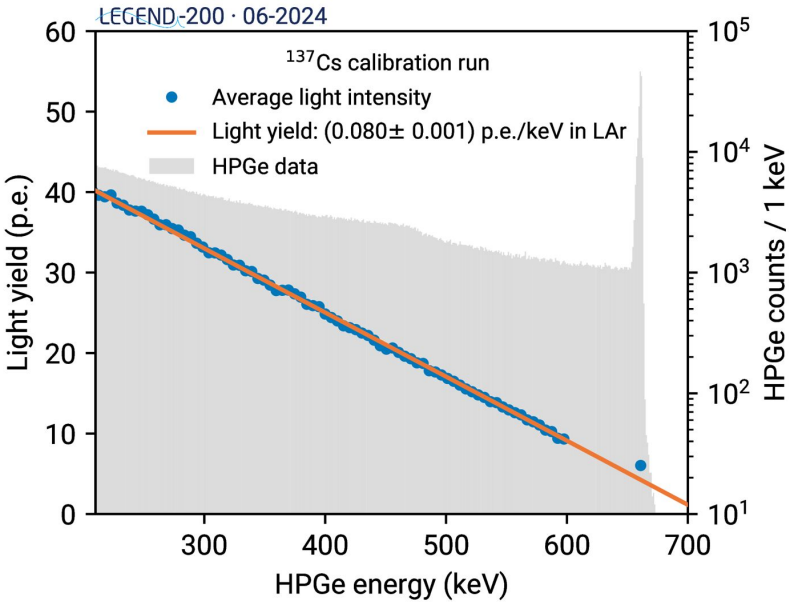
collected by **SiPMs**



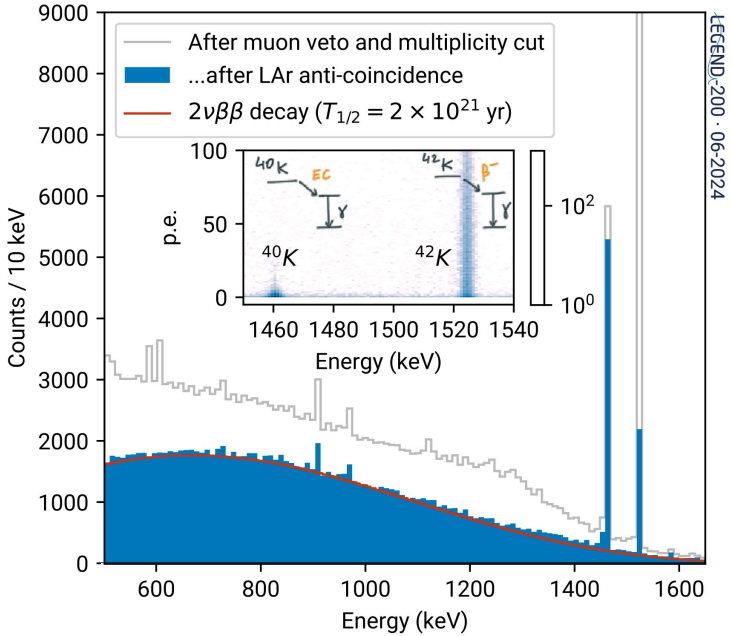


In-situ performance

System **response** with a ^{137}Cs source:
0.08 photoelectrons / keV



Clean 2νββ spectrum
surviving the LAr cut



Motivation for optical modeling of LEGEND

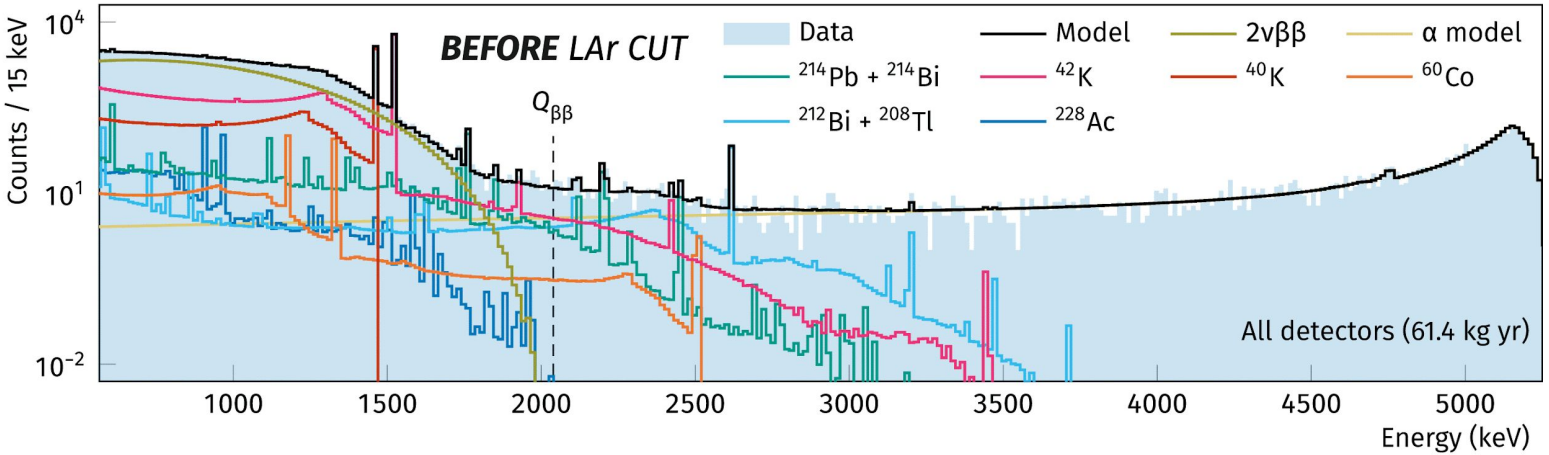
Identification and **modeling** of LEGEND **background** sources is key:

- hardware & analysis **mitigation** strategies
- boost **sensitivity** of 0νββ / BSM program

LEGEND-200 is a test bench for LEGEND-1000!

See next talk by R. Deckert!

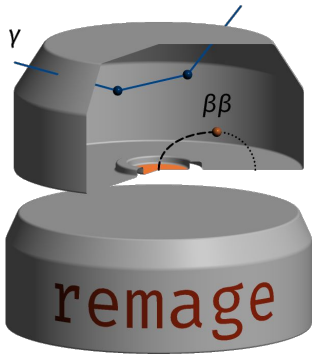
From the GERDA background model



remage — a modern simulation framework for low-background experiments

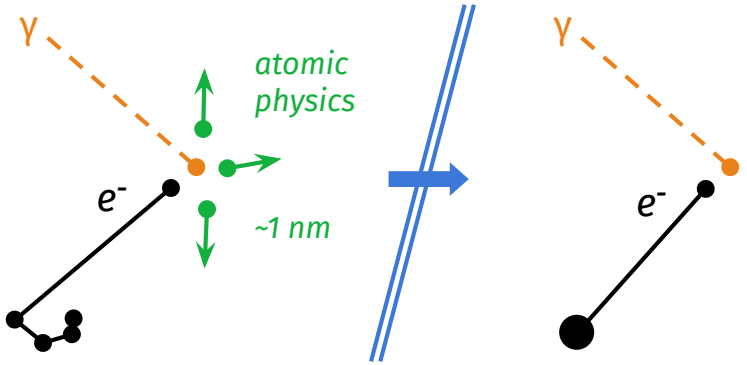
Implements **simulation patterns typical in low background experiments**

- Extended **HDF5** output for flexible output analysis
  - user can choose their favorite library
- **Multithreading** (via Geant4)
- **One executable**
  - easy to install: no user code/compilation required
- Modern software development practices, fully **open source**
- Continuously updated unit tests and **validation suite**
- Documentation pages
- Currently used in LEGEND and HPGe screening facilities



New users and contributors welcome!

remage — a modern simulation framework for low-background experiments

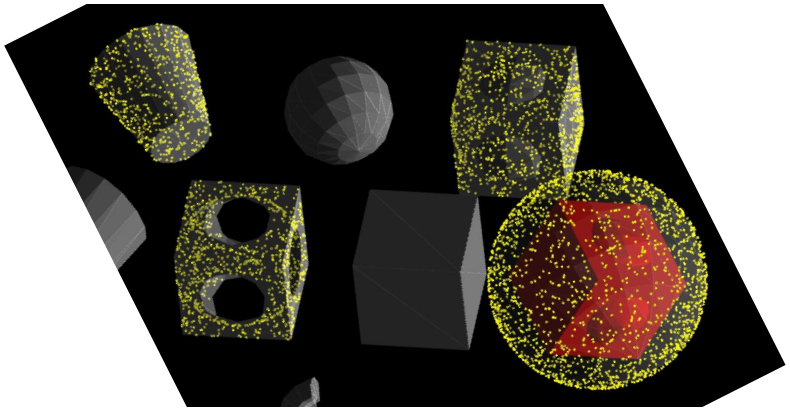


Advanced clustering of Geant4 steps:

- Actual detector time/space resolution
- Faster simulation if I/O limited!
- Smaller output files

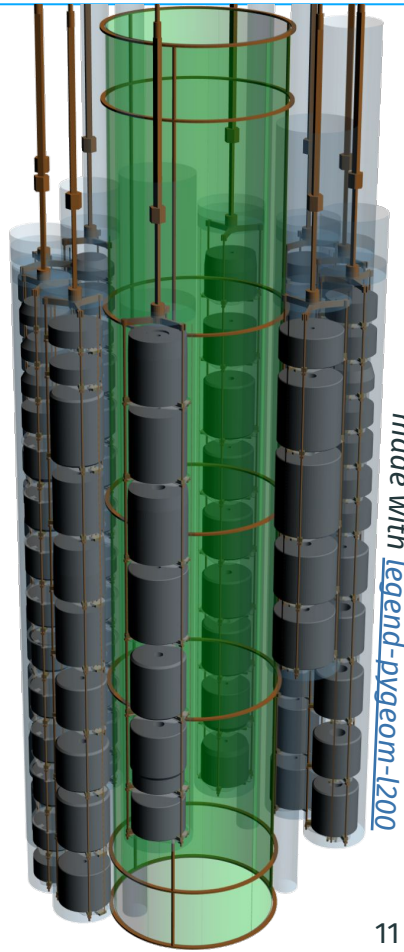
Advanced vertex confinement tools

- key for radiogenic background simulations
- Sampling from complex bulk/surface
- Sampling from intersections/unions



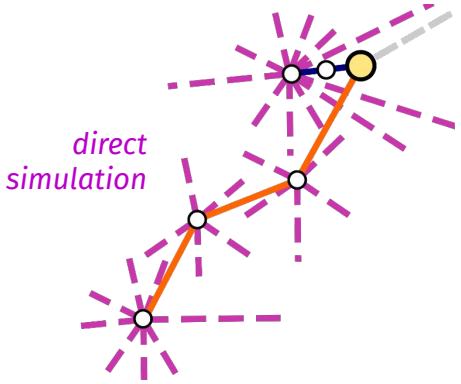
Experimental geometries for `remage`

- `remage` does **not** implement geometries or related tooling
- Geometry supplied by user as GDML files
  - keep `remage` lightweight
  - give users flexibility
- *pyg4ometry* is a great choice
  - constructive geometry **in Python** -> faster coding, modularization
  - replicates Geant4 API, exports GDML/FLUKA
  - supports manipulation CAD models
  - built-in high-quality interactive visualization
- Many features added in the LEGEND pygeom ecosystem
  - registration of sensitive volumes in the geometry
  - advanced visualization (e.g. simulation output)



Simulation of optical photons

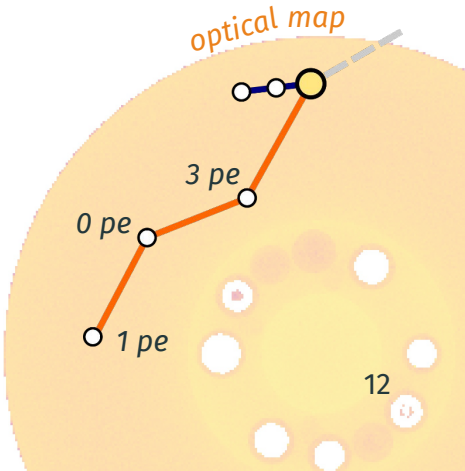
- Challenging, prohibitively **CPU intensive**
- No good GPU tooling on the market (yet)



Two **mitigation** strategies:

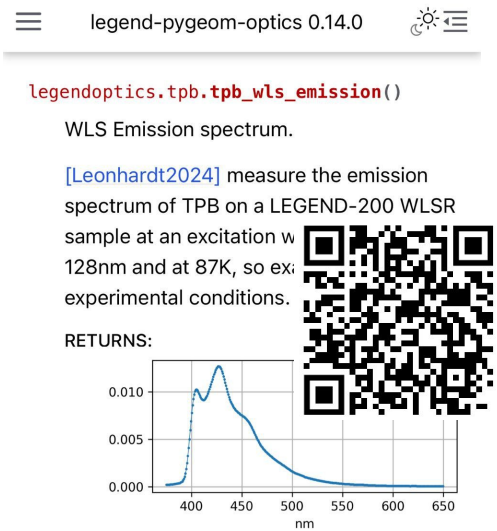
- Geant4 **stacking action tricks** in remage
  - only simulate optics if HPGe is hit
- **Optical maps** in reboost
  - pre-compute photoelectron detection probability in the scintillator
  - apply to simulated (no optics) scintillator hits

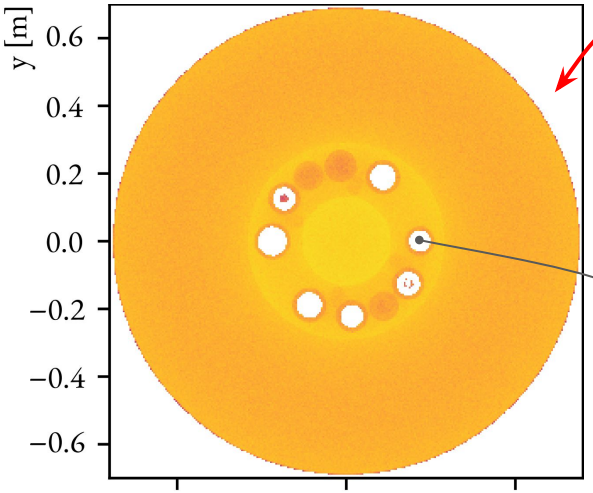
...while keeping an eye on GPU developments (Celeritas, Opticks...)

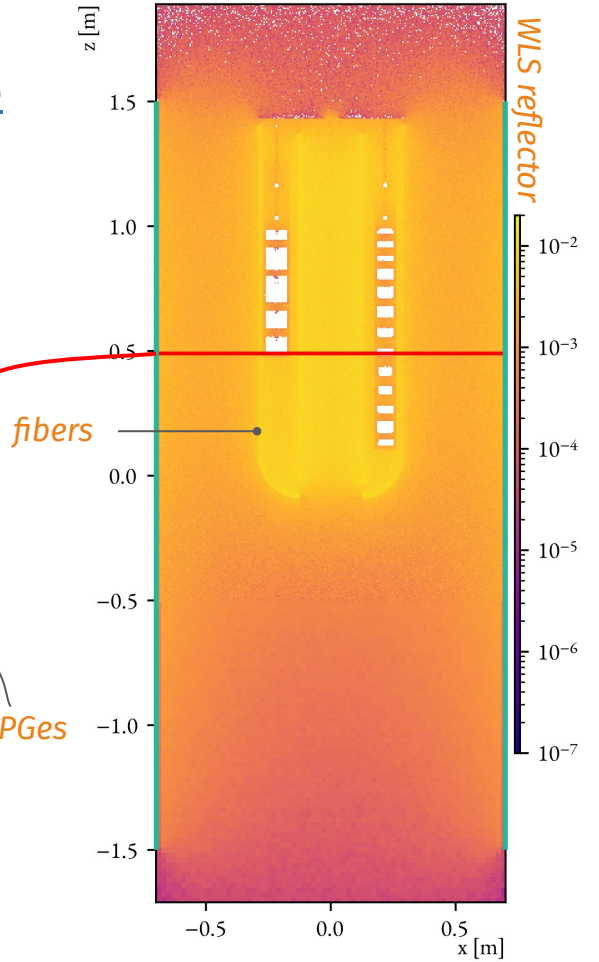


The LEGEND-200 optical map

- LEGEND optical properties stored in a dedicated package
  - with an online browser!
- The response is **complex**
  - notable difference with “monolithic” noble liquid detectors

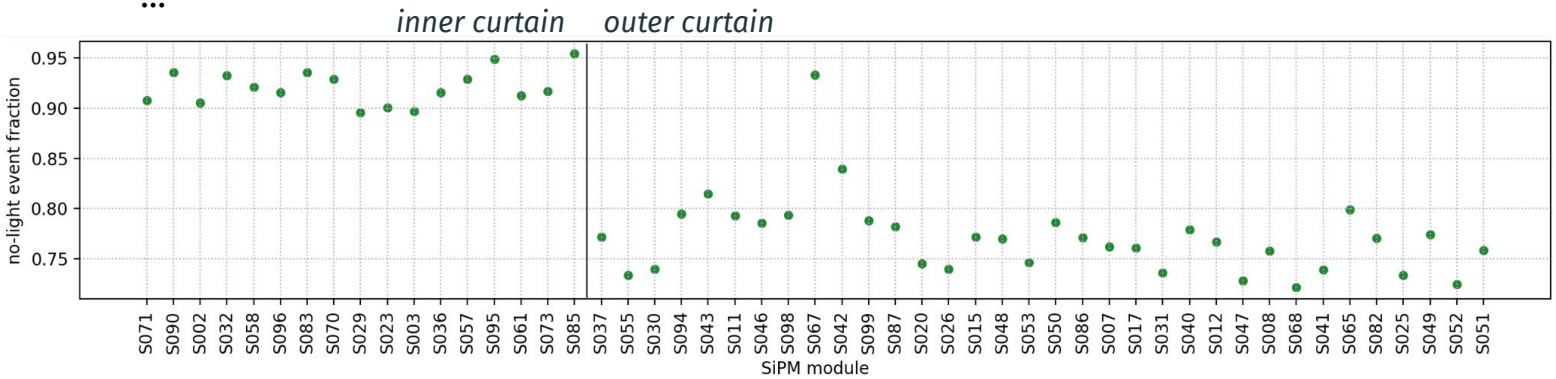






[WIP] Validating and tuning the model

- Some optical properties are **poorly known**:
  - e.g. liquid argon light yield / attenuation, SiPM detection efficiency...
- Our Monte Carlo model can be parametrized by:
  - $\{\epsilon_i\}$ **photon detection efficiency for each SiPM** channel
  - **global efficiency** (lower light yield and other effects)
  - LAr attenuation length
  - ...

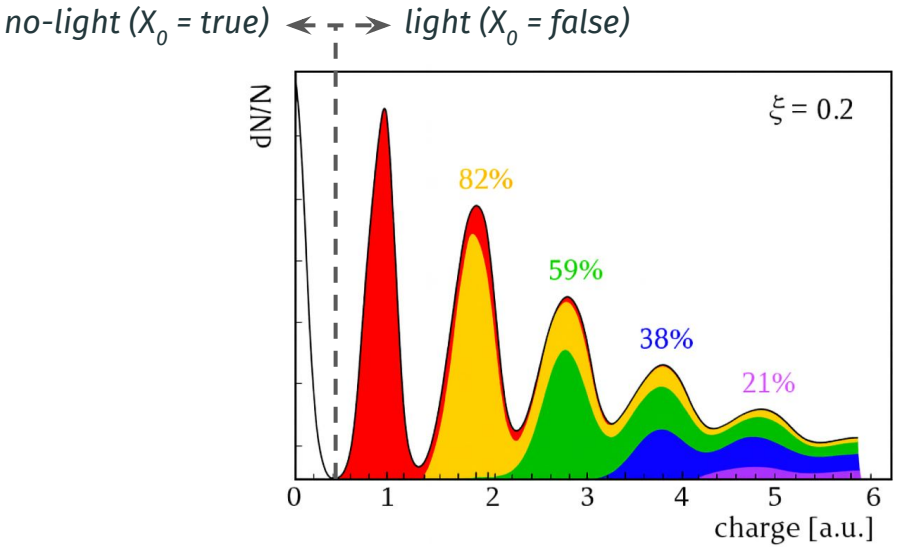


Can be partly constrained with measurements of light sources in LEGEND-200!

[WIP] Validating and tuning the model

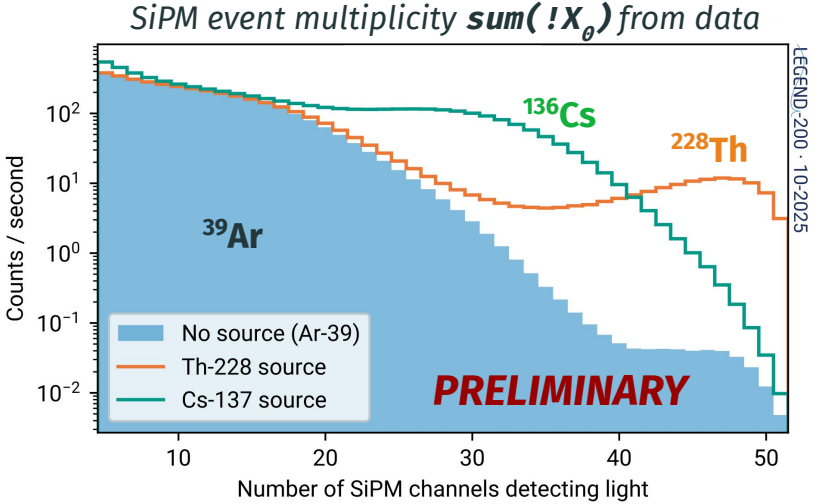
- LEGEND-200 **SiPM model** (optical x-talk, afterpulsing…) **not well known**
  - can't compare number of photoelectrons in data and simulation
- More robust (and LEGEND-relevant) observable: **presence of any light** (boolean)
  - already employed in GERDA

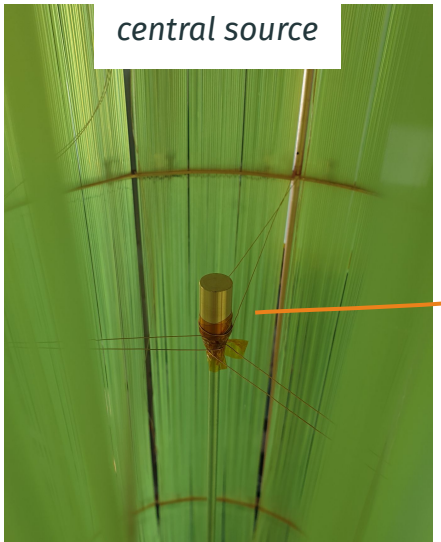
```
X0 = {
  true if Npe > 0
  else false
}
```

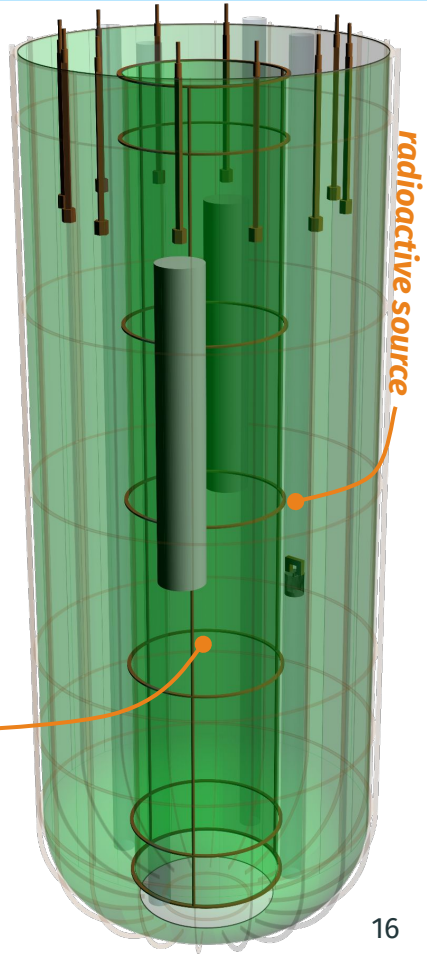


[WIP] Special characterization runs in LEGEND-200

- ^{137}**Cs** and ^{228}**Th** sources deployed **without HPGe array**
- Simplified **"Monolithic" LAr detector**
  - no optical complexity of the array!
- **Several source positions** help breaking degeneracies

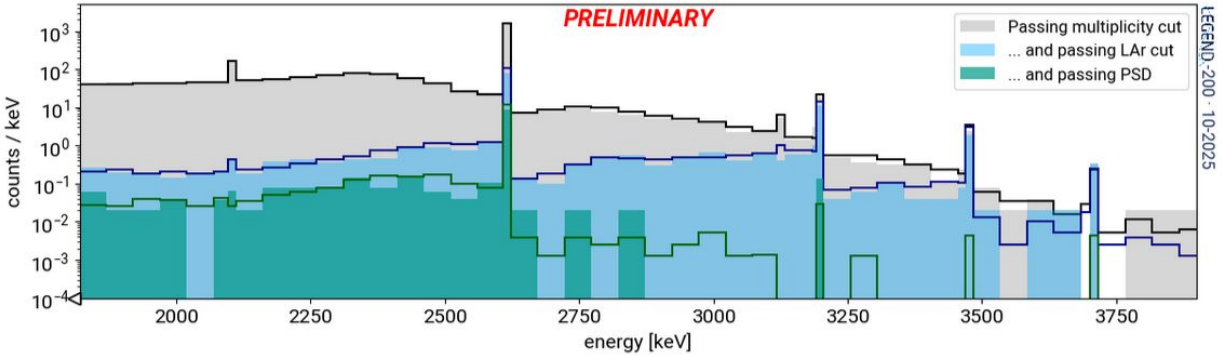


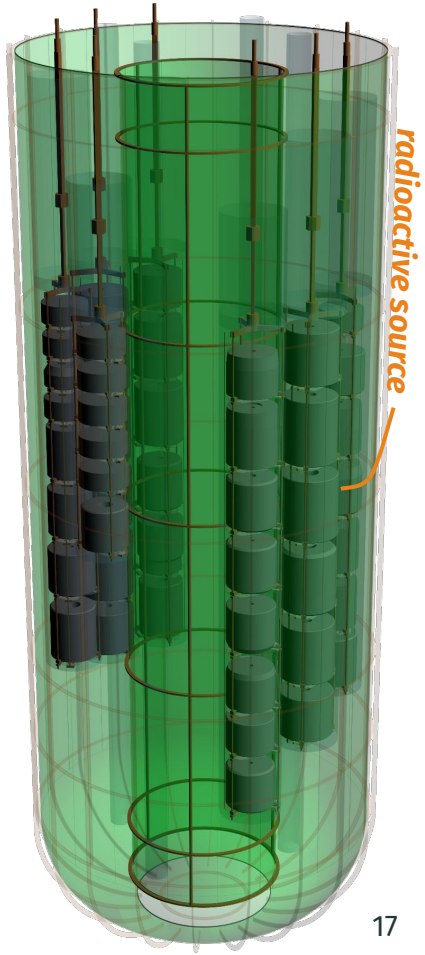




[WIP] Special characterization runs in LEGEND-200

- ^{228}**Th** measurement **with HPGe array**
  - used to quantify optical impact of the array
- **Tagging events with HPGe** is a powerful tool to select interesting LAr interaction topologies
- Spectrum of **events that survive the LAr veto** condition **well described** by the untuned model



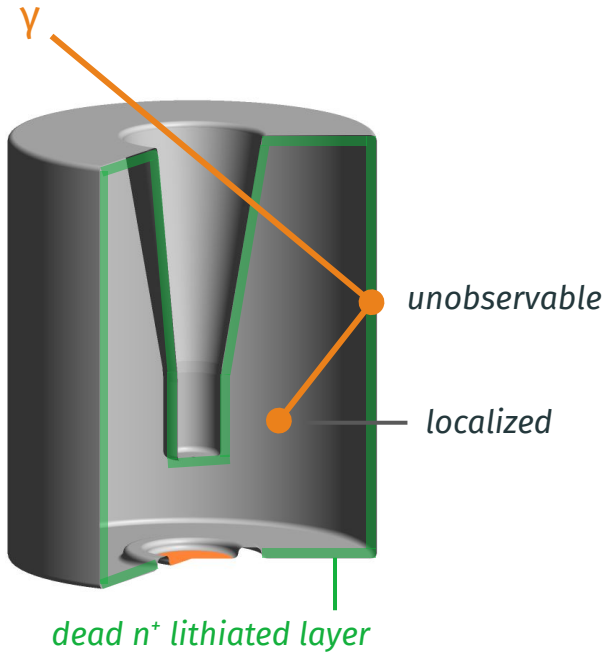


Bonus: γ-induced events surviving the LAr and PSD cuts

- **“dead layer events”** have:
  - some energy in the dead region of the HPGe
  - no energy in scintillators → passes LAr cut
  - localized bulk interaction → passes PSD cut
- Further mitigation possible in LEGEND-1000?
  - Optimization problem: n^+ shields from surface β

New **high-statistics ^{228}Th** and **^{226}Ra** data recently taken!

- validate/tune optical and PSD models
- study Th/U background signatures
- study interplay between LAr and PSD cuts



Summary

- LEGEND-200 will be sensitive to unprobed 0νββ signal strengths
- …and pave the way to LEGEND-1000

- A **predictive model of the background** (including rejection by the optical instrumentation) is key to reach the desired sensitivity and keep improving
- We are on a good track towards this ambitious goal through
  - a novel simulation framework (**remage**)
  - a series of **dedicated *in-situ* measurements**

Stay tuned!