Exploiting Event Topologies in Liquid Argon Scintillation Signals for Background Identification in LEGEND-200

Rosanna Deckert | LIDINE 2025 | 23.10.2025

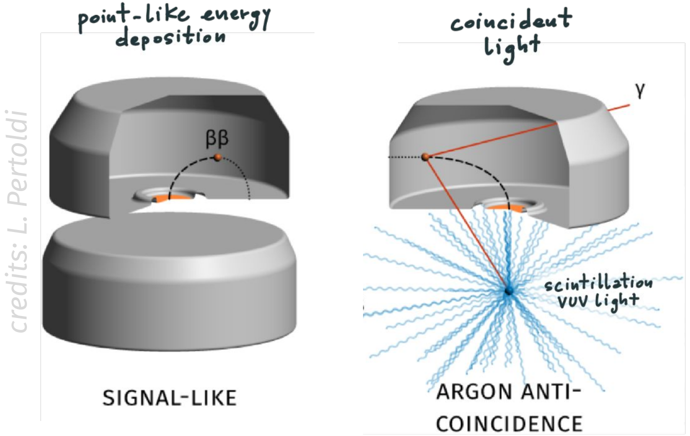
Background in LEGEND-200

First LEGEND-200 deployment (~2023–24) [doi:10.1103/25tk-nctn]

- Higher background before cuts than radioassay predicted

After argon anti-coincidence

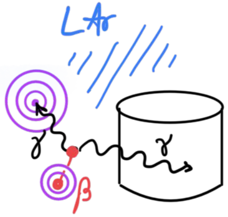
- ^{228}Th background almost fully suppressed
- ^{226}Ra background only partially suppressed

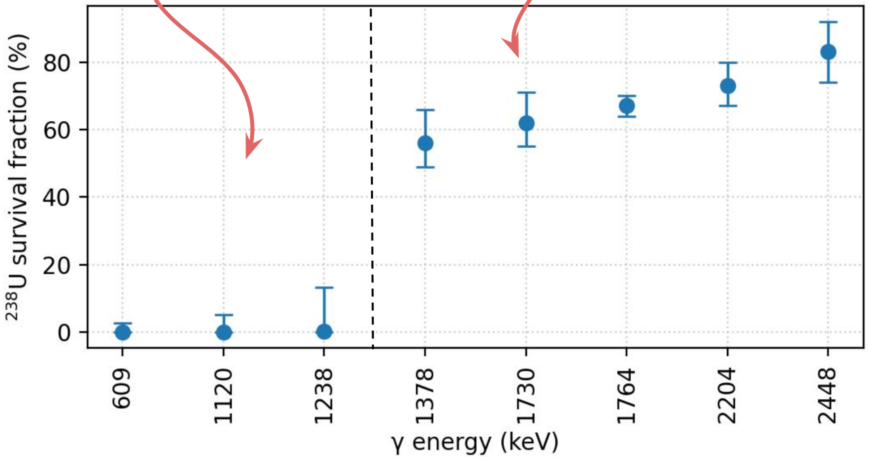


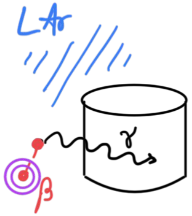
Background after argon anti-coincidence

^{214}Bi lines with **coincident γ's strongly suppressed**

Higher-energy ^{214}Bi lines **weakly suppressed (β-only)**







→ Points to a ^{214}Bi β decay location in the **bulk** of materials, or in a argon region of **low light detection probability**!

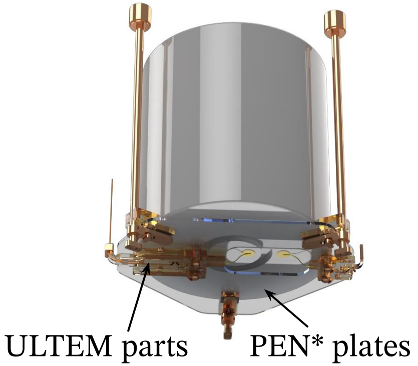
→ Concerning for **background after cuts** and **experiment sensitivity**!

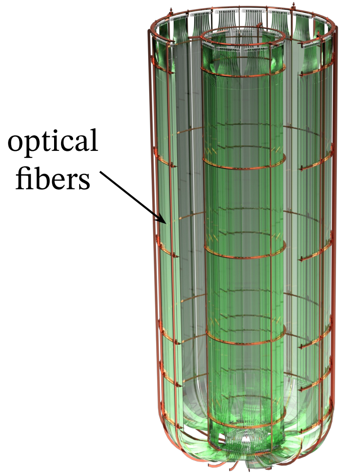
Location of ^{226}Ra background

Extensive efforts to understand the location of the ^{226}Ra contamination

- **γ screening of components** suggest main contributions from
  - **detector holder assembly**
  - **optical fibers**
- **Special data sets** (eg. removal of outer barrel)
  - confirm ^{226}Ra on fibers / outer barrel copper
  - γ-assay excludes significant contamination on copper structure

🔎 **Prompt and delayed coincident LAr signals can give valuable input!**



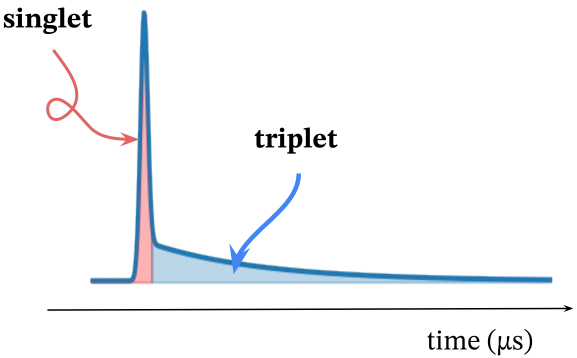


**Polyethylennaphthalat*

Particle discrimination

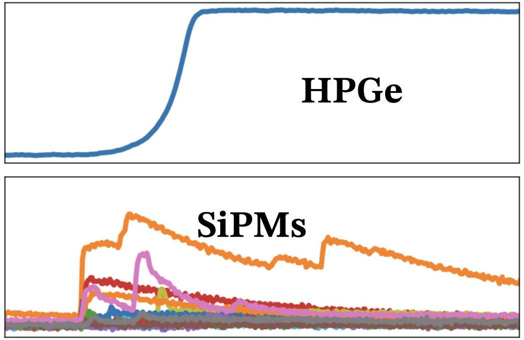
Argon scintillation time profile [**doi:**10.22323/1.441.0256]

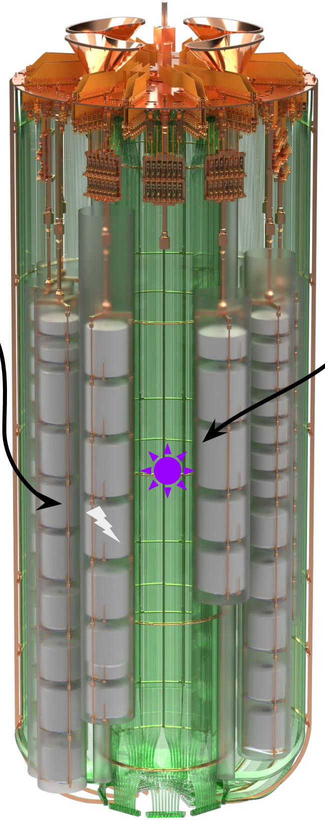
- **fast singlet + slow triplet** component
- **Singlet/triplet ratio** depends on particle type → separates **α vs. β/γ**
- Measured as singlet yield ratio = **fast light / total light**
  ("light" measured in photoelectrons, p.e.)
  - **α-like** singlet yield ratios ≈ 0.8
  - **β/γ-like** singlet yield ratios ≈ 0.3
- ***Other scintillators in LEGEND-200:*** **Fiber core & PEN plates** emit **fast light only** → singlet yield ratio ≈ 1 for all particles



Search for ^{214}BiPo coincidences

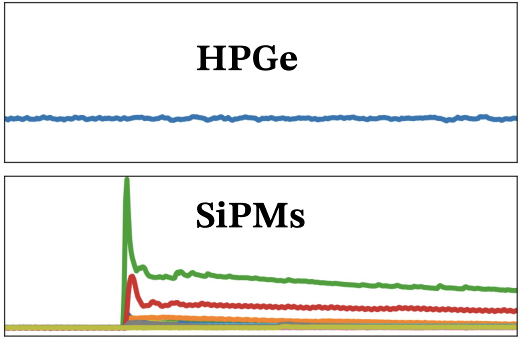
^{214}Bi decay γ in HPGe detector



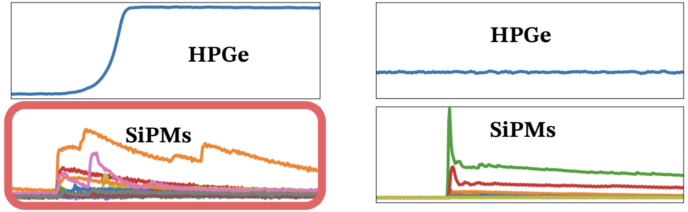


Time-delayed ^{214}Po α decay ($T_{1/2}$=164µs) in LAr detector system

… p.e. intensities and scintillation time structure can shed light on its **origin**!

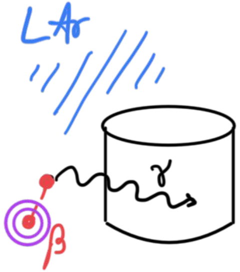


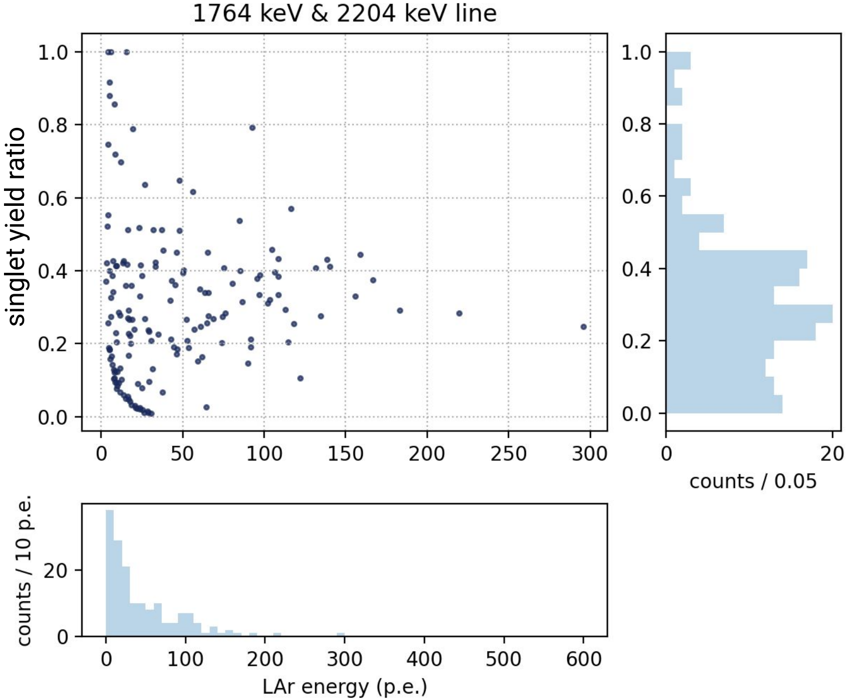
Prompt LAr coincidence



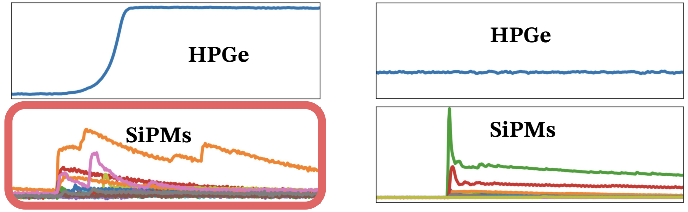
Higher energy ^{214}Bi lines

- directly populated by the β decay
- no coincident γ's from the cascade



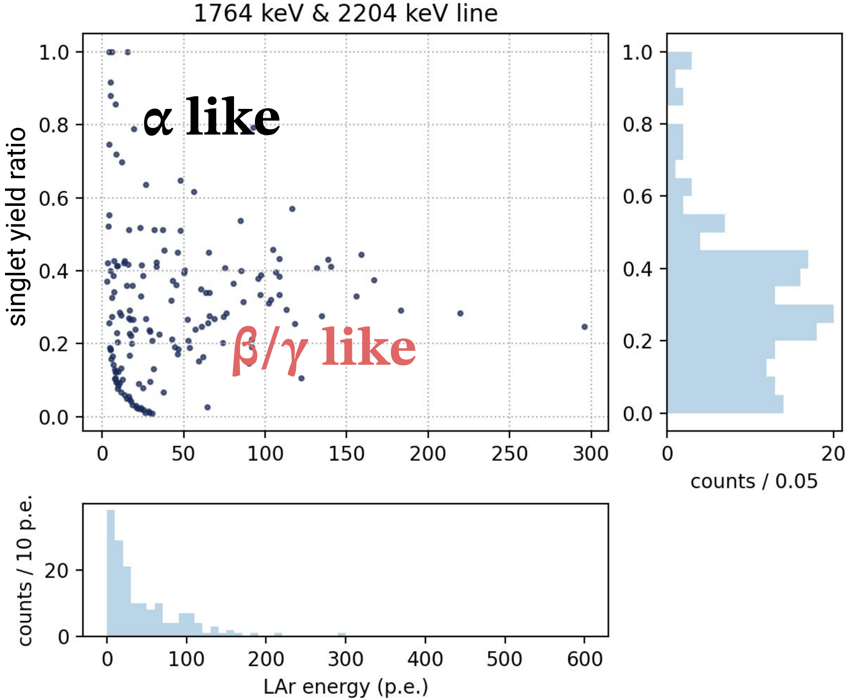


Prompt LAr coincidence

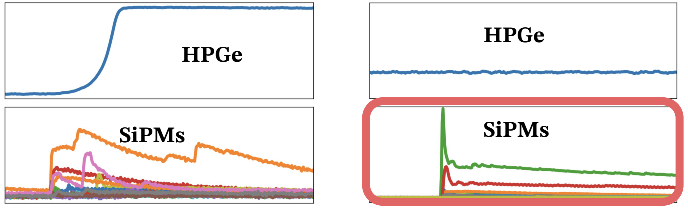


Bulk of distribution are “LAr-like” β’s!

- singlet yield ratios around 0.3
- 💡 the majority of the **^{214}Bi contamination that we suppress with the LAr veto** produces scintillation light in **argon** (and not in another scintillator)!



^{214}BiPo coincidences

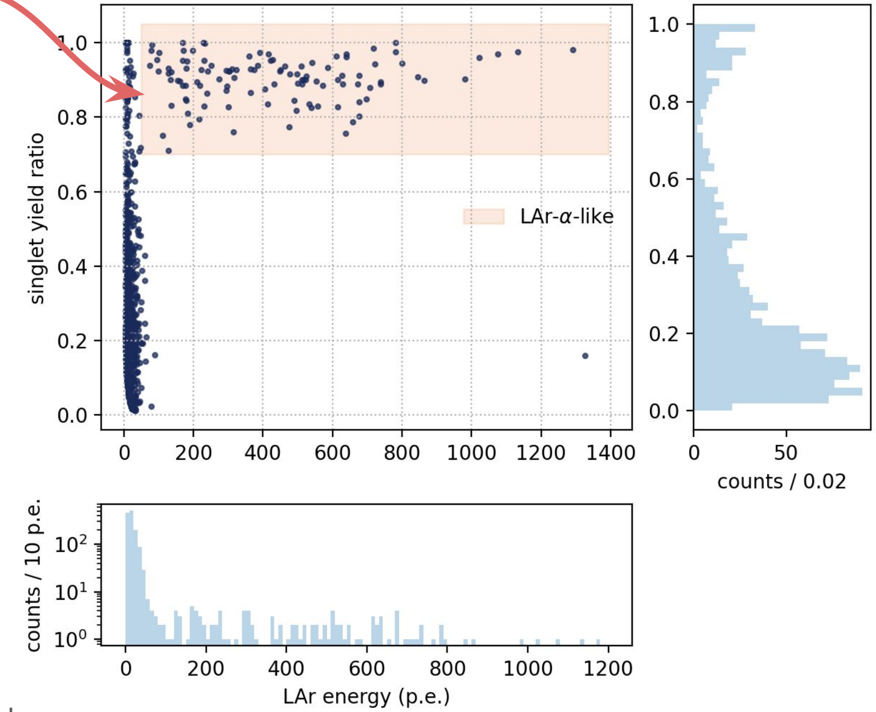


We find **delayed ^{214}Po α's** that are **"LAr-like"!**

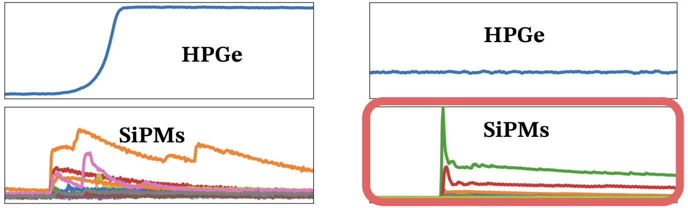
- high singlet yield ratios
- high p.e. intensities in a wide range

💡 indicates some **^{226}Ra contamination near surfaces** → α escapes to LAr!

💡 Partial energy loss of α's → points to **surface contamination**



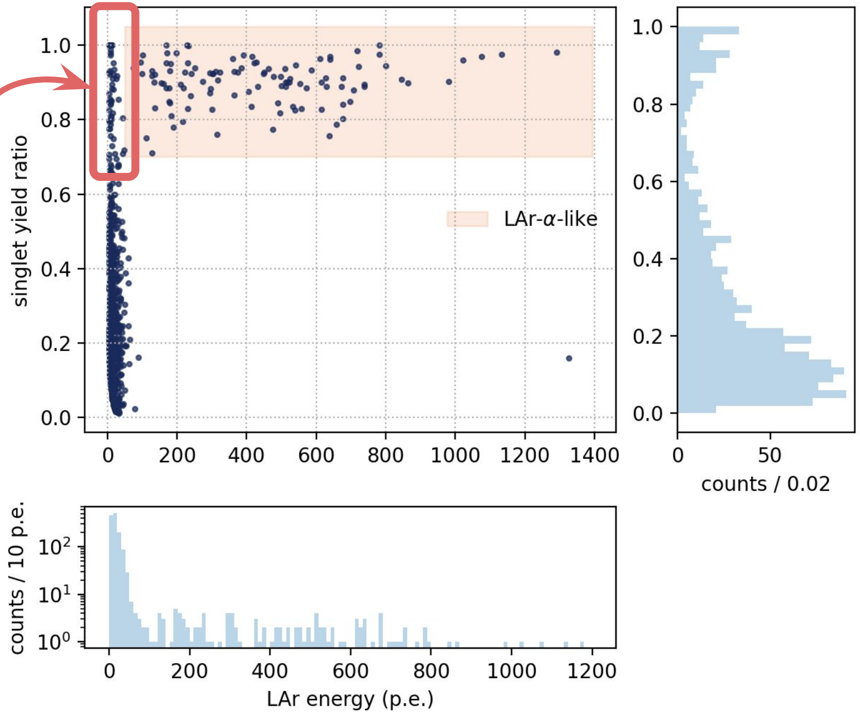
^{214}BiPo coincidences



No excess above random coincidences

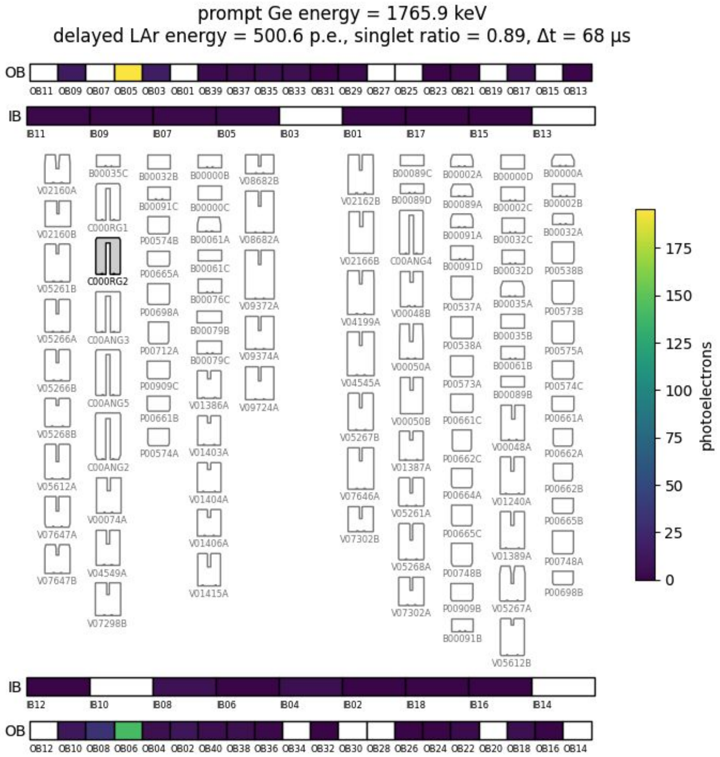
- low p.e. intensities (poor scintillators)
- high singlet yield ratios

💡 **No evidence of ^{214}Po α** scintillation light signals **from PEN or fiber core**



Location of detected photoelectrons

Light of ^{214}Po α's often seen in **mostly *one* fiber module** → Points to decays **on or near fiber modules**



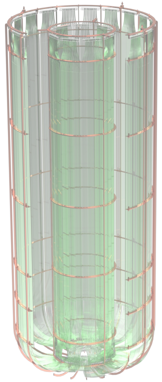
Location of ^{226}Ra background

Detector holder assembly

- ^{214}BiPo analysis: no prompt/delayed ***fast*** scintillation signals → **PEN *plates* disfavored**
- 🔎 separate screening of detector holder parts in progress

Optical fibers

- 💡 ^{214}BiPo analysis: no prompt/delayed ***fast*** scintillation signals → contamination most likely **not in fiber core**
- 🔎 **Simulation** of a fiber in LAr to study the observed prompt/delayed LAr signatures!



Location of ^{226}Ra background

Detector holder assembly

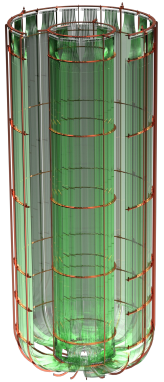
- ^{214}BiPo analysis: no prompt/delayed ***fast*** scintillation signals → **PEN *plates* disfavored**

🔎 separate screening of detector holder parts in progress

Optical fibers

💡 ^{214}BiPo analysis: no prompt/delayed ***fast*** scintillation signals → contamination most likely **not in fiber core**

🔎 **Simulation** of a fiber in LAr to study the observed prompt/delayed LAr signatures!



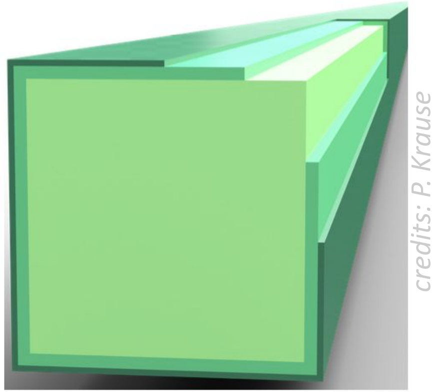
Calorimetric simulation of a single fiber

Fiber Geometry

- 1 mm polystyrene core (scintillating)
- two **PMMA cladding layers** (non-scintillating)

Simulations

- **^{214}Bi β's** → compare LAr survival of ^{214}Bi γ's
- **^{214}Po α's** → study ^{214}BiPo signatures

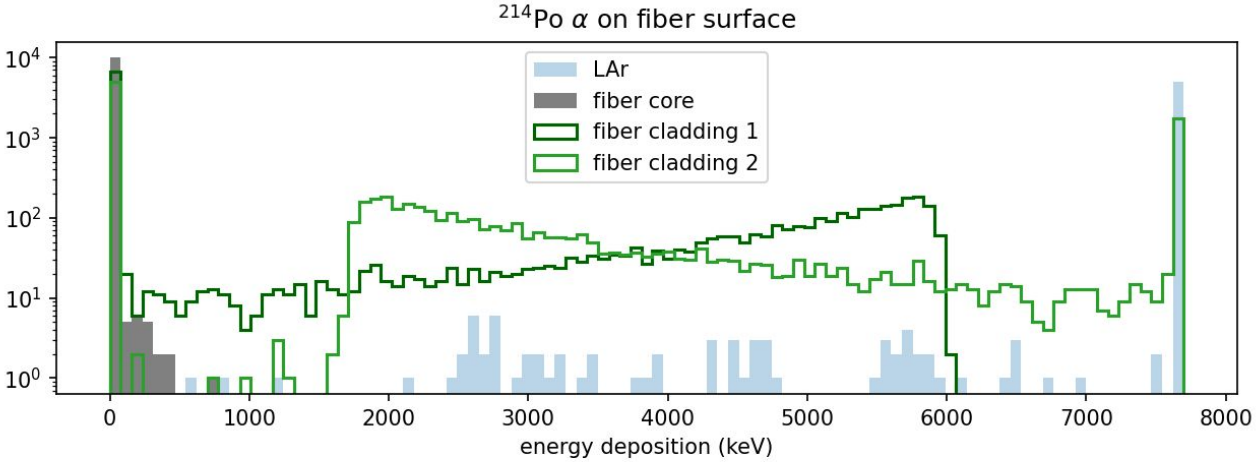


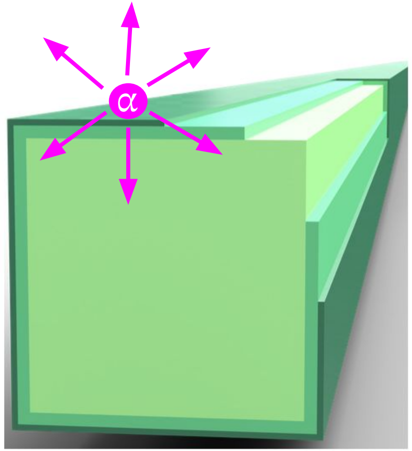
^{214}Po alphas on fiber surface

^{214}Po α's (7.8 MeV) starting on the surface of the *outer* cladding

- Only 0.2% reach the fiber core!

💡 A location of the Bi contamination on the **surface of the fibers** would **explain why we only see LAr-like α's in data**



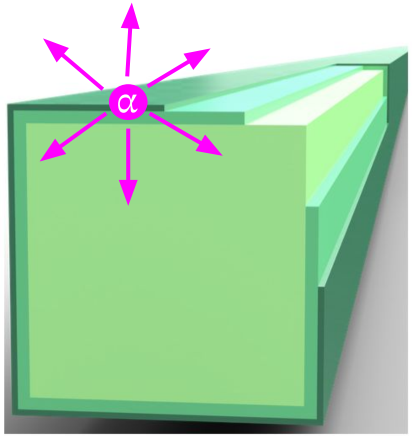


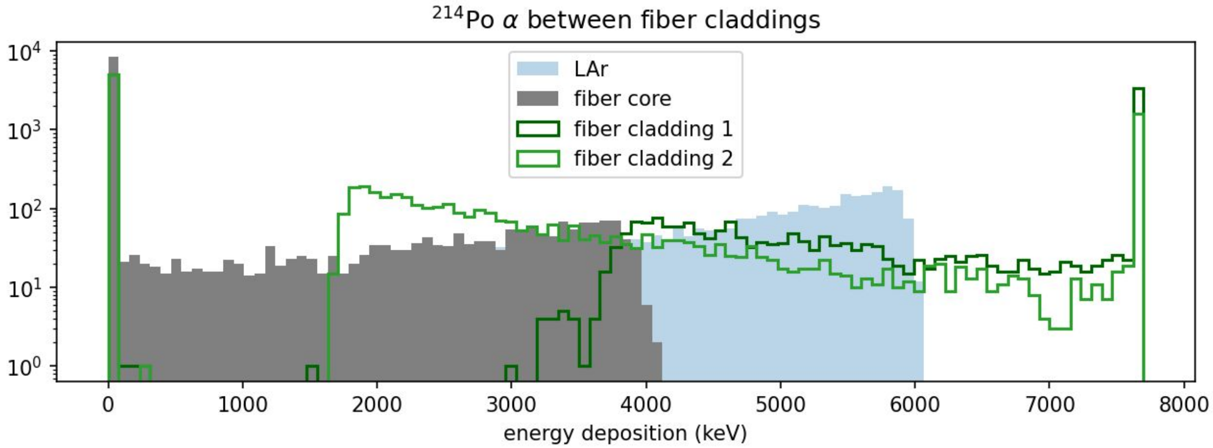
^{214}Po alphas below the fiber surface

^{214}Po α's (7.8 MeV) starting on the surface of the *inner* cladding, i.e. 21μm below the fiber surface

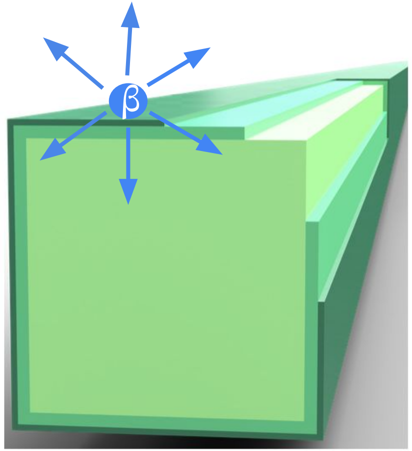
- **17%** reach the fiber core!

💡 **contamination more likely in the first few μm below the fiber surface**





^{214}Bi betas on fiber surface



Survival fraction of ^{214}Bi in the first few μm of the fibers…

- Survival fractions can only be *estimated* from calorimetric fiber simulation
- needs **modeling of light propagation** from origin to photodetectors

Only **optical simulations of the *full* LEGEND-200 setup** can model ^{214}Bi γ line survival fractions quantitatively!

Simulation of backgrounds in LEGEND-200

Simulations performed with ***remage***

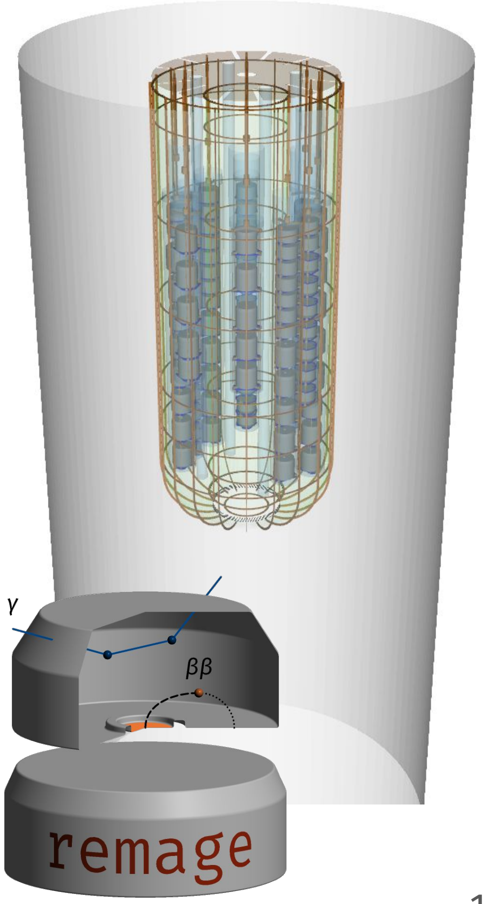
- LEGEND-200 **geometry fully implemented**
- Including optical properties

Simulate ^{214}Bi decays in...

- Outer cladding layer of **optical fibers**
- ULTEM parts from **detector holder assembly**

Post-processing:

- **model the argon anti-coincidence cut** *(validation with special calibration data in progress)*
- **visualize the topology of events** of interest (eg. passing the argon cut)



^{214}Bi survival fractions

Survival fractions (%)	1764 keV line
Outer fiber cladding	10.6 ± 0.3 %
ULTEM parts	79.1 ± 0.1 %
L200 data	**67 ± 3 %**

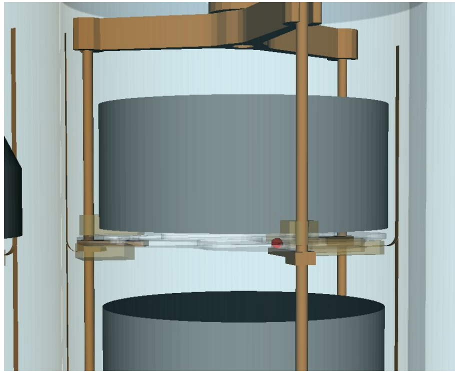
very **low survival** fraction from ^{214}Bi background in **fibers**

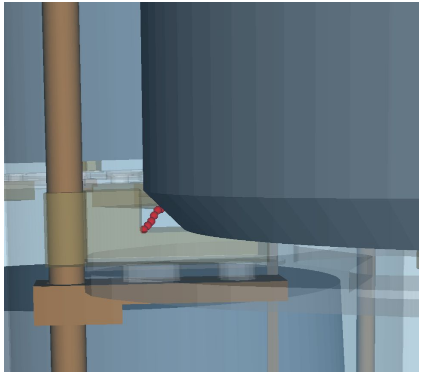
high survival fractions from ^{214}Bi background in the ULTEM parts → visualizing surviving events

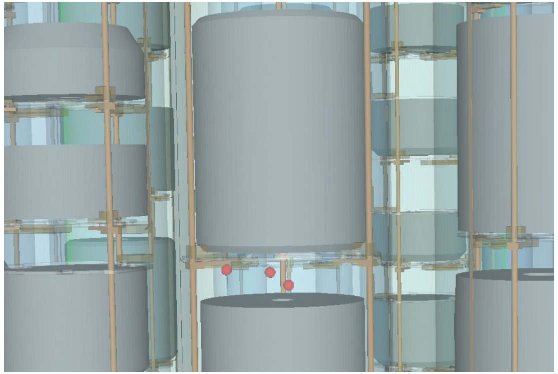
The survival fraction in data comes from multiple contributions!

^{214}Bi in ULTEM parts - Events surviving LAr veto

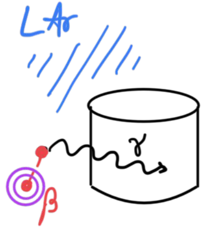
Energy depositions in regions of large “**shadowing**”







Summary of background study with argon signals



Key observations:

- **Weak LAr-suppression** of high energy ^{226}Ra γ lines
- γ assay measurements point to **optical fibers** and **detector holder components** as dominant sources

Insights from ^{214}BiPo analysis:

- "LAr-like" signals only
- No evidence for *fast* scintillation signals → **PEN plates and fiber core disfavored** as major origins
- Simulation of fiber in argon indicates background consistent with **activity in fiber claddings**, not core

L200 optical simulations:

- crucial to **interpret survival fractions** observed in data
- **Visualization** of events to gain intuition about signals from different background origins

Background reduction efforts & next steps

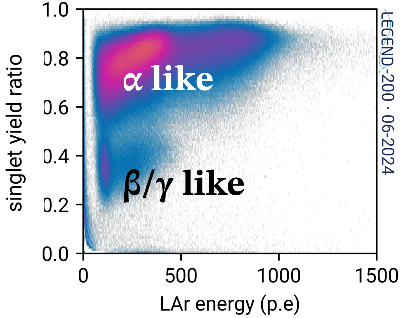
- Detector holder assembly parts **cleaned**
- **Fibers** can't be cleaned further but **low survival fraction after argon veto**
- 2nd LEGEND-200 deployment (this year): ~2 months of data. **Effectiveness of cleaning campaign promising, yet under study!**

→ ***LAr suppression*** *of γ lines &* ***event topology analysis of LAr signals*** *as powerful tools to understand background location*

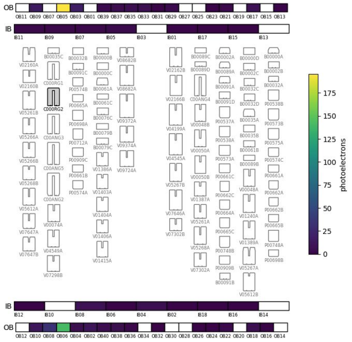
LAr signals ”toolbox”

LAr signals crucial for background rejection & identification!

Particle discrimination through singlet/triplet ratio



Light distribution across channels to study **event topologies**



Simulations crucial to interpret data