

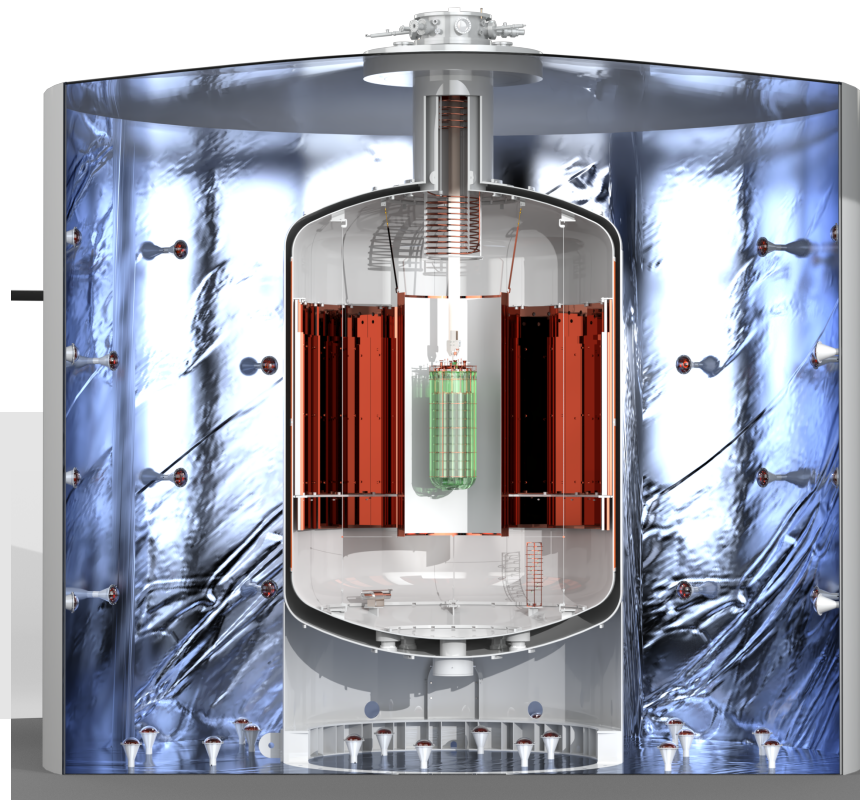
Status and prospects of the **LEGEND** experiment towards $0\nu\beta\beta$ decay

Carmen Romo-Luque (LANL),
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on behalf of the **LEGEND** Collaboration

Neutrino 2026 - June 24th 2026

LA-UR-26-24973

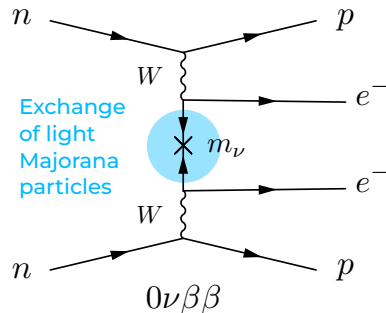
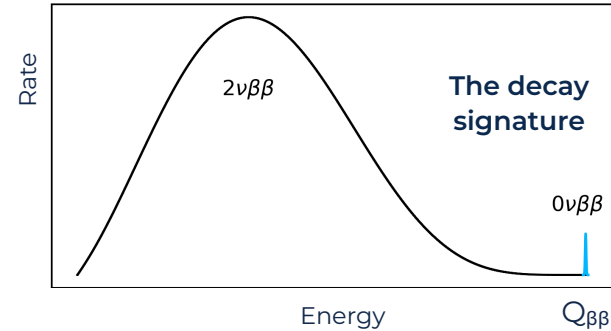


- **Neutrinoless double beta decay** ($0\nu\beta\beta$) is a hypothetical nuclear transition where no neutrinos would be emitted.



- Only possible if neutrinos are **Majorana** particles.
- **$0\nu\beta\beta$ vs $2\nu\beta\beta$** : violates lepton number by 2 units and electrons would carry the full available energy.
- If observed, could provide insights about underlying physics and its connection to the **matter-antimatter asymmetry** observed in the universe.

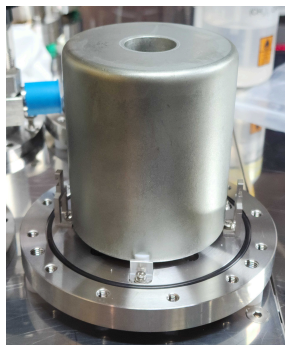
Energy released during the decay process



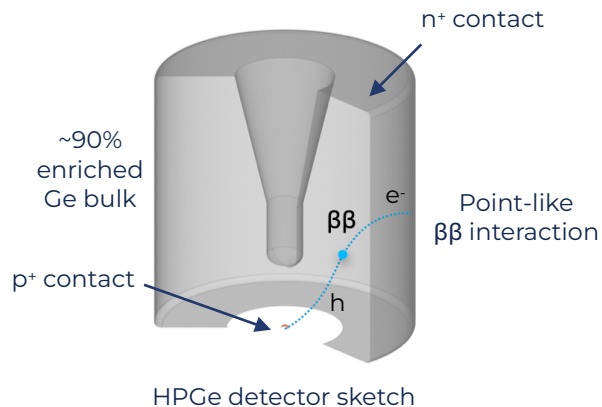
An experiment looking for $0\nu\beta\beta$:

- Low background level
- Good energy resolution
- Large exposure
- Large $Q_{\beta\beta}$

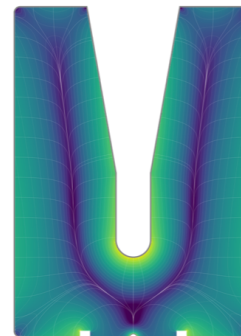
Germanium technology: excellent for $0\nu\beta\beta$ searches



HPGe detector on transport baseplate



HPGe detector sketch



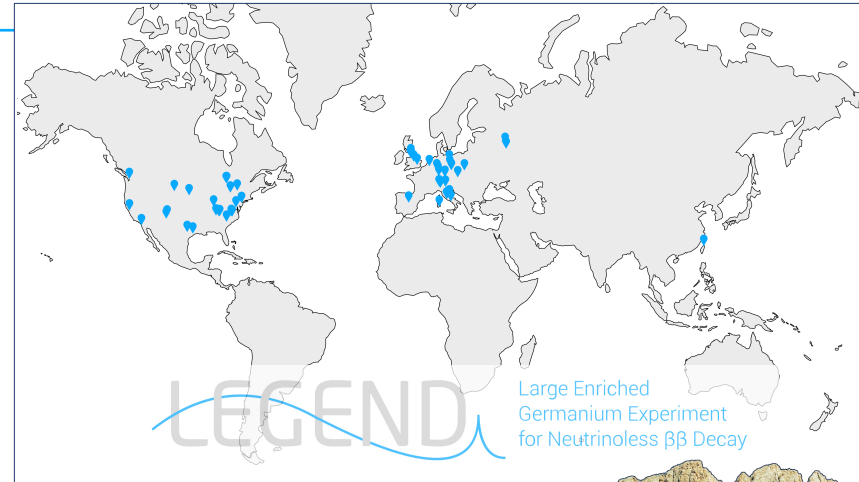
Electric field

High-Purity Germanium (HPGe) detectors enriched in ^{76}Ge

- † Source and detector are the same material: high efficiency.
- † **Enrichment** (~90%) \rightarrow high purity: low intrinsic background.
- † Ge crystal: outstanding energy resolution (**$\sim 0.1\%$ FWHM at $Q_{\beta\beta}$**).
- † Topological discrimination based on the nature of particles (**pulse shape analysis - PSD**).

LEGEND

- Collaboration formed in 2016.
- **Today:** ~350 researchers from about ~60 institutions from around the world.
- Combines the technological expertise and experience from the predecessor experiments:
 - ✦ **GERDA:** lowest background in ROI. Poster - J. Chapman
 - ✦ **MAJORANA DEMONSTRATOR:** best energy resolution.
- LEGEND aims to improve the **half-life discovery sensitivity for ^{76}Ge $0\nu\beta\beta$ by two orders of magnitude.**



• LEGEND-200

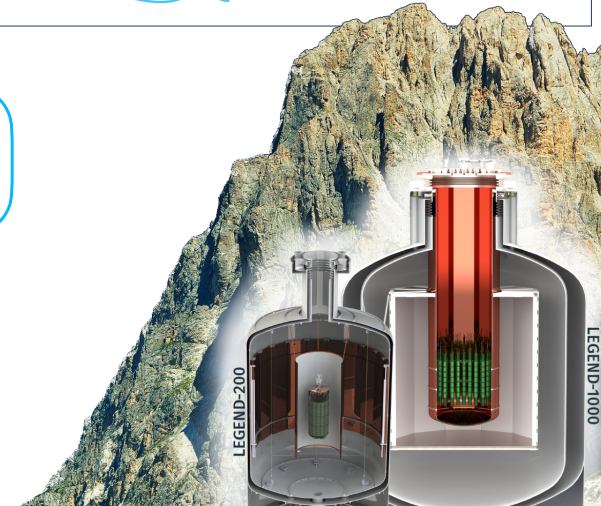
Present

- Running since 2023 in the upgraded GERDA infrastructure at LNGS.
- Up to 200 kg of 90%-enriched HPGe detectors.
- BI goal: $\sim 2 \times 10^{-4}$ cts/(keV kg yr) $\rightarrow T_{1/2} > 10^{27}$ yr.

• LEGEND-1000

Future

- 1 tonne 90%-enriched HPGe detectors deployed at LNGS.
- BI goal: $< 2 \times 10^{-5}$ cts/(keV kg yr) $\rightarrow T_{1/2} > 10^{28}$ yr.
- Start data taking in early 2030's.

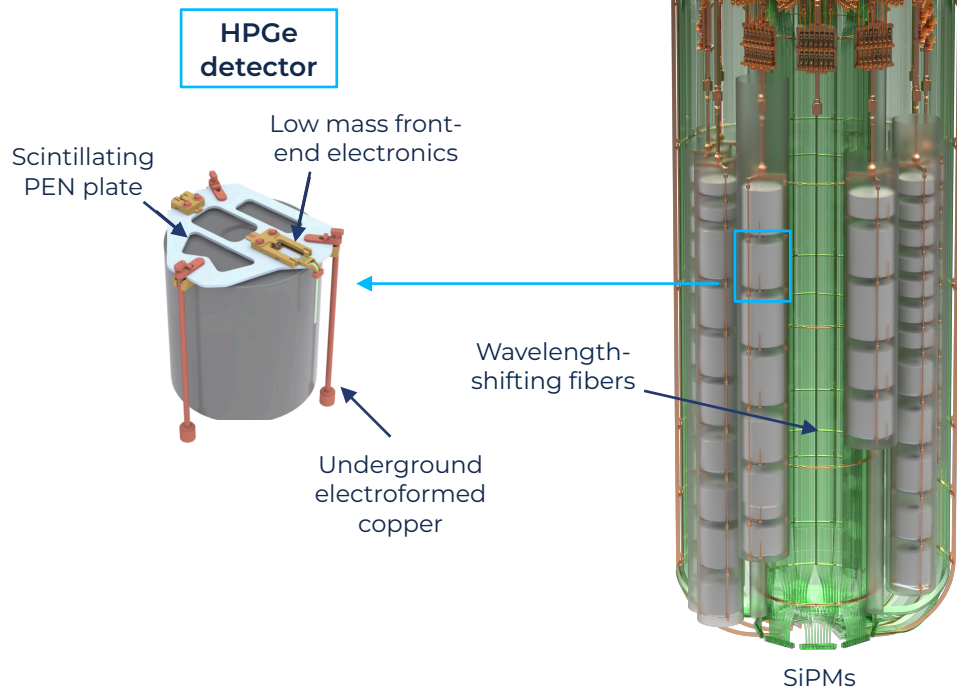


LEGEND-200 Experimental Overview

LEGEND is designed to minimize backgrounds and efficiently suppress them employing a layered active shield system.

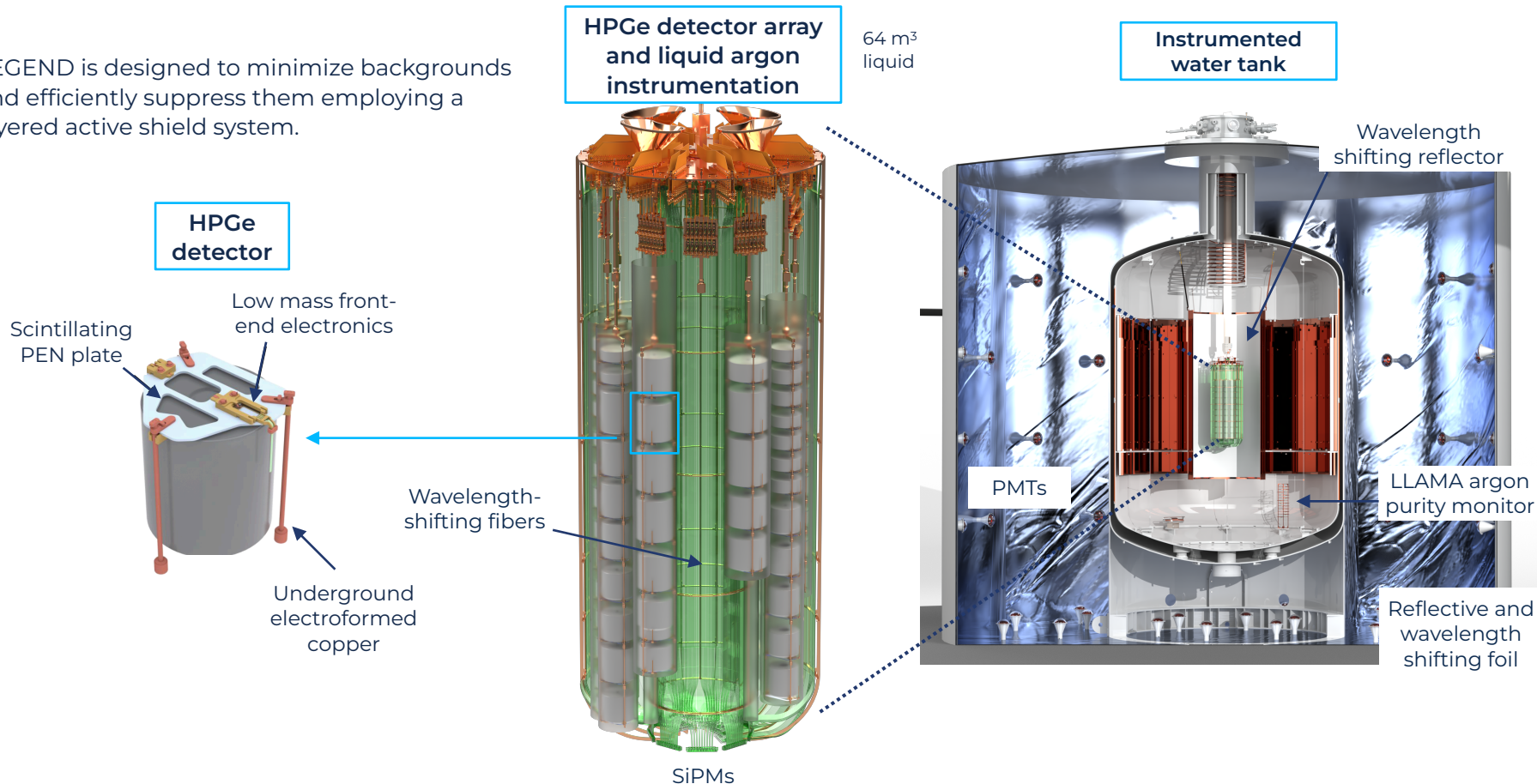
HPGe detector array and liquid argon instrumentation

64 m³ liquid



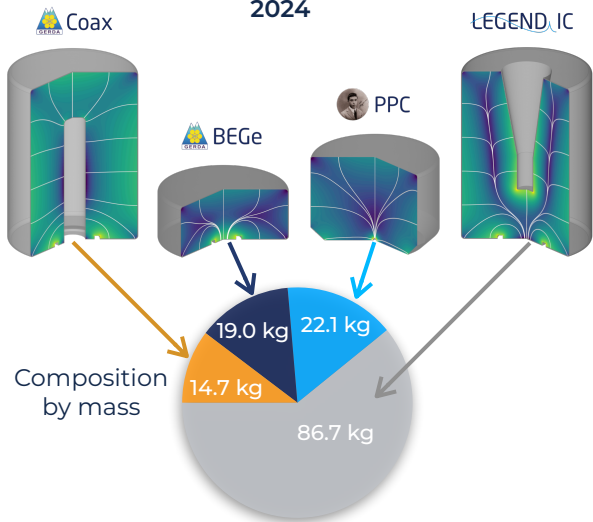
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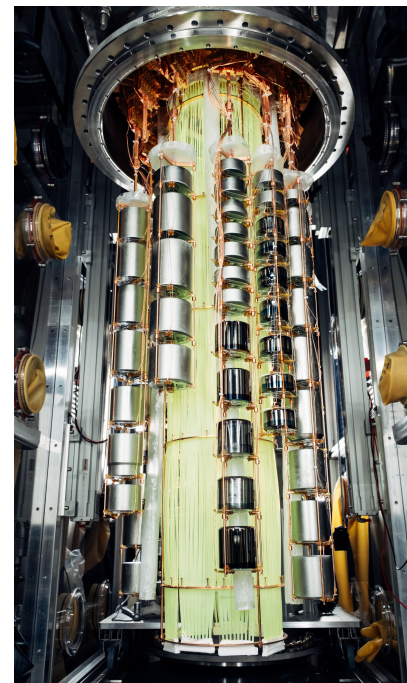
Hardware status until 2024



First data unblinding in June 2024 (shown at Neutrino '24)

Second unblinding in Feb 2025 with Coax and set of IC

- **142 kg of HPGe** were installed in October 2022. 130 kg operational.
- First physics data taking from March 2023 to February 2024 with **61 kg yr exposure**.



L200 Ge strings and inner LAr barrel

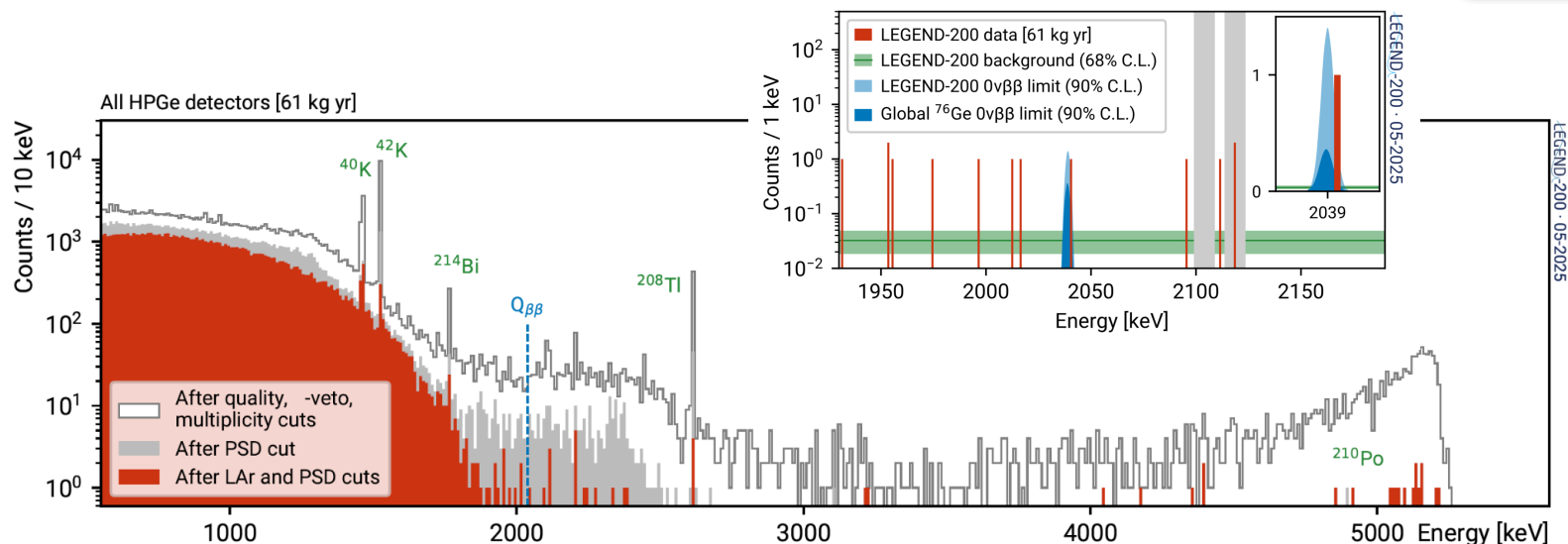
- Data taking from March 2023 to February 2024: **61 kg yr exposure**.
- **11 events** surviving in the BI region after cuts, including 1 event near $Q_{\beta\beta}$.
- **Background index:** $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts / (keV kg yr) in the “golden dataset” (48 kg yr).
- **GERDA + MJD + LEGEND-200 combined:** Exclusion sensitivity: 2.8×10^{26} yr.
 $T_{1/2}(0\nu\beta\beta) > 1.9 \times 10^{26}$ yr (90% CL).
- Full beginning to end **secondary analysis stack** in full agreement with the primary analysis.

Poster - G. Duran

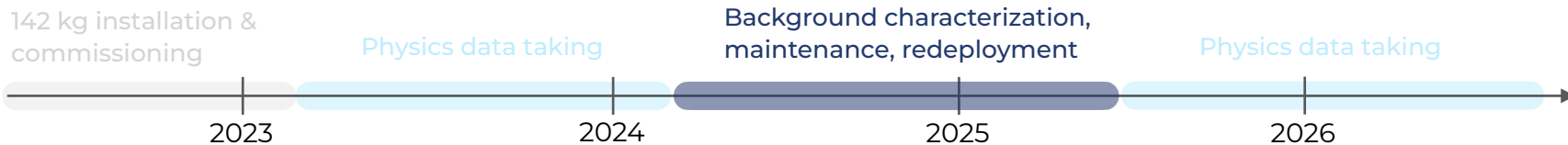
Poster - I. Guinn

Poster - G. Marshall

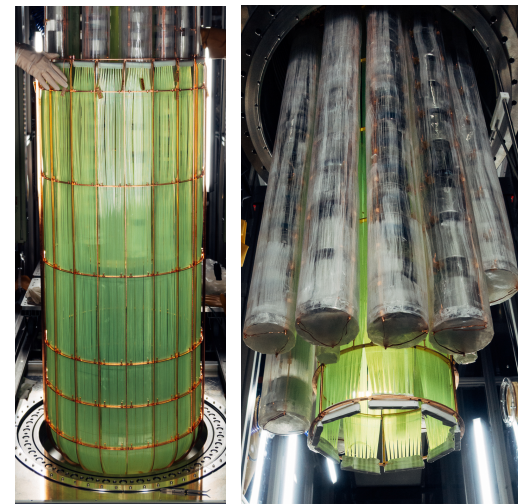
Poster - A. Gieb



Background Investigations and Redeployment



- Final BI **~2.5 higher** than predicted \rightarrow **elevated U (^{214}Bi)/Th (^{208}Tl)** levels before cuts.
- **Forensic campaign:**
 - ✦ Special runs: **outer fiber barrel** and **nylon mini-shrouds** removed.
 - ✦ Array dismantled and all components sent for **assay**.
 - ✦ Results from assays: elevated U (^{214}Bi)/Th (^{208}Tl) in some components: hypothesized **surface contamination**, BI dominated by U (^{214}Bi).



Ultem γ assay

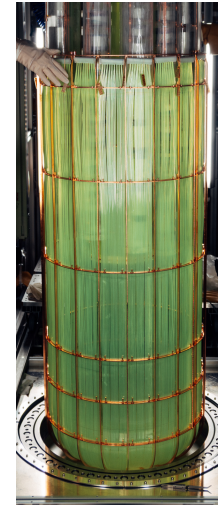
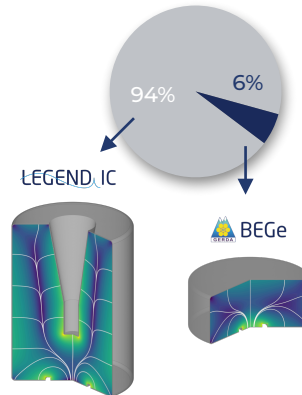


Cu pins Rn emanation assay

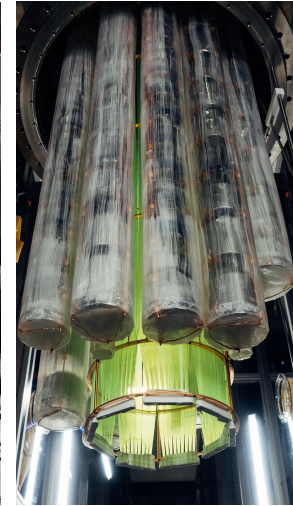
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- **2025 redeployment:**
 - ✦ Change of paradigm: **most** of L200 HPGe detectors **large-mass IC-detectors** (L1000-type).
 - ✦ Conversion of Coax, PPC, BEGe and underperforming detectors **to IC** meeting L1000 mass requirements.
 - ✦ All components re-etched/leached.
 - ✦ Total of **138 kg Ge** detectors deployed in July 2025. ICs and BEGes arranged in 9 strings.

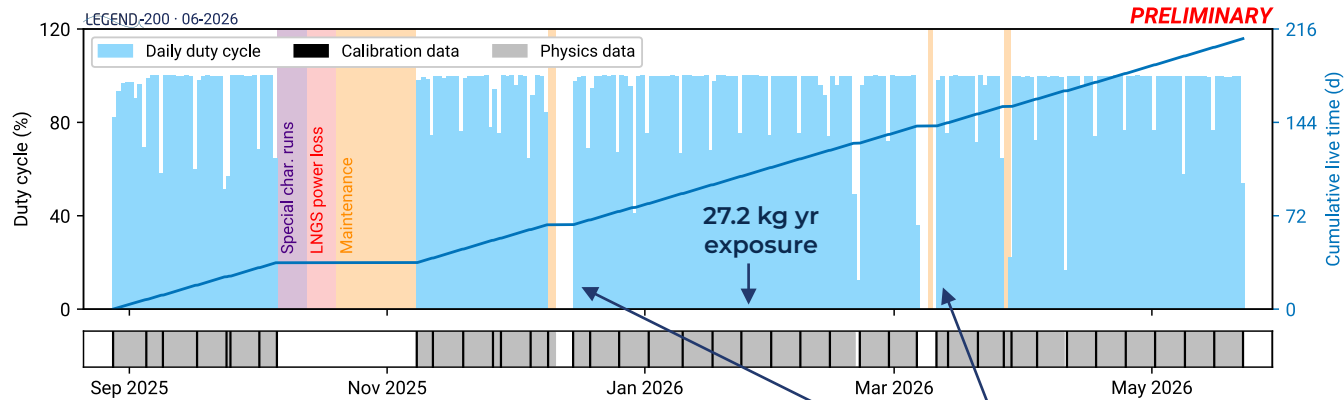
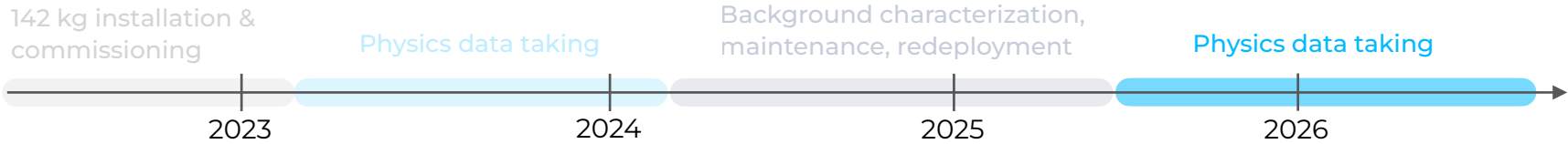


Outer barrel



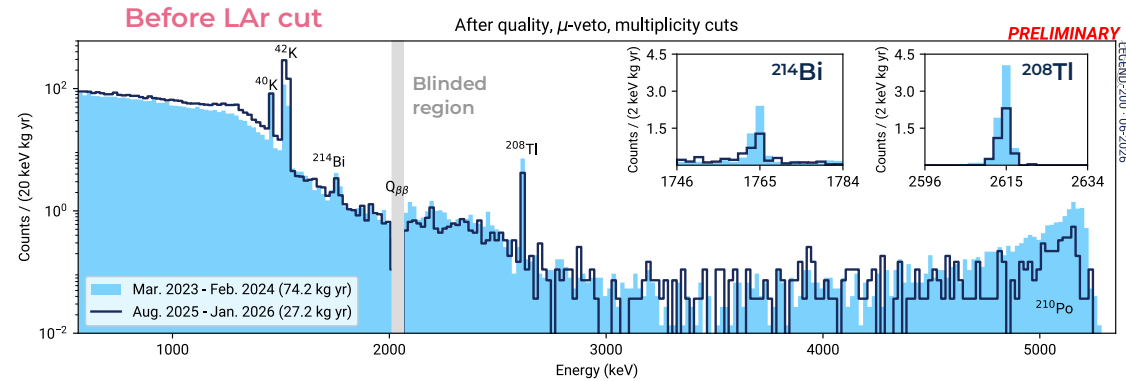
Nylon mini-shrouds

Redeployment Operations and Performance



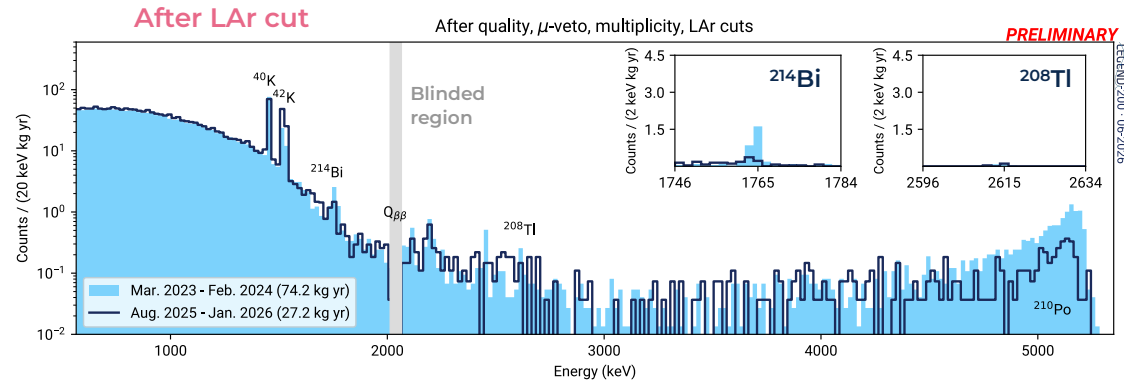
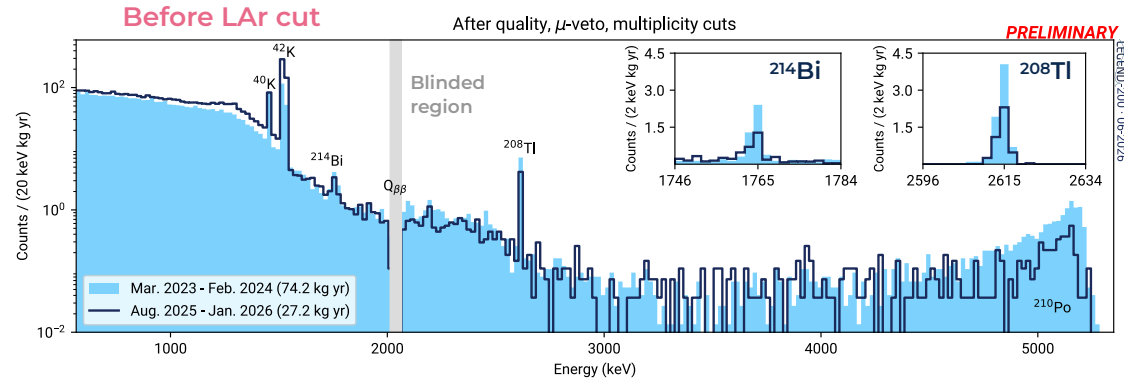
- Currently **taking stable physics data** since Fall 2025.
- Downtimes for special calibrations and maintenance.
- **Duty cycle:** 95% (70%) without/with downtimes.
- Data validated and shown here up to end of Jan 2026: **27.2 kg yr exposure** (no PSD consideration).

- ^{214}Bi (U)/ ^{208}Tl (Th) reduced by $\sim x2$ before cuts relative to the first-year results.



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- After LAr cut:
 - $x5$ overall reduction of ^{214}Bi 1764 keV gamma-line!
 - ^{208}Tl \sim **eliminated** at current statistics.

- ➔ Effectiveness of etching and leaching.
- ➔ Key input to L1000 background model.
- ➔ Expected to improve on L200 physics searches.



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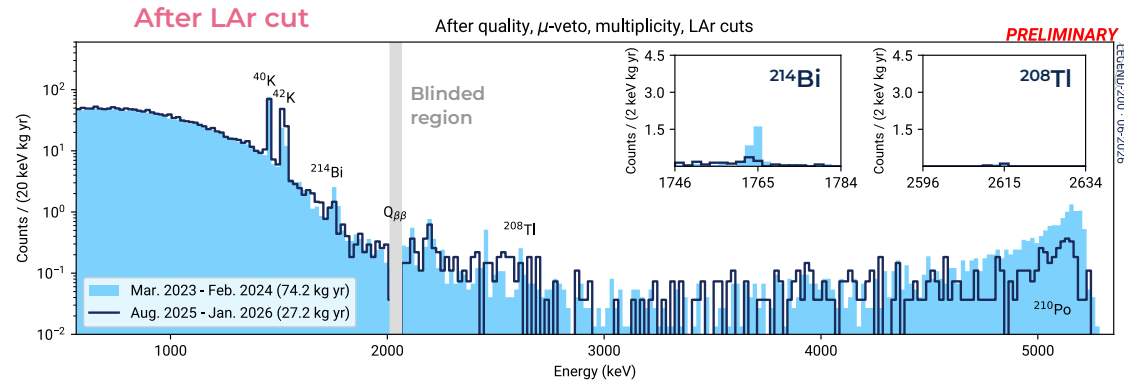
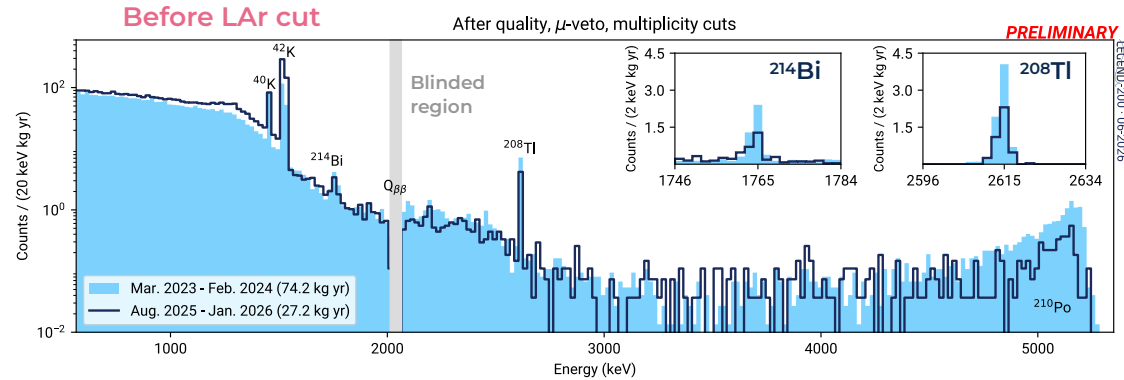
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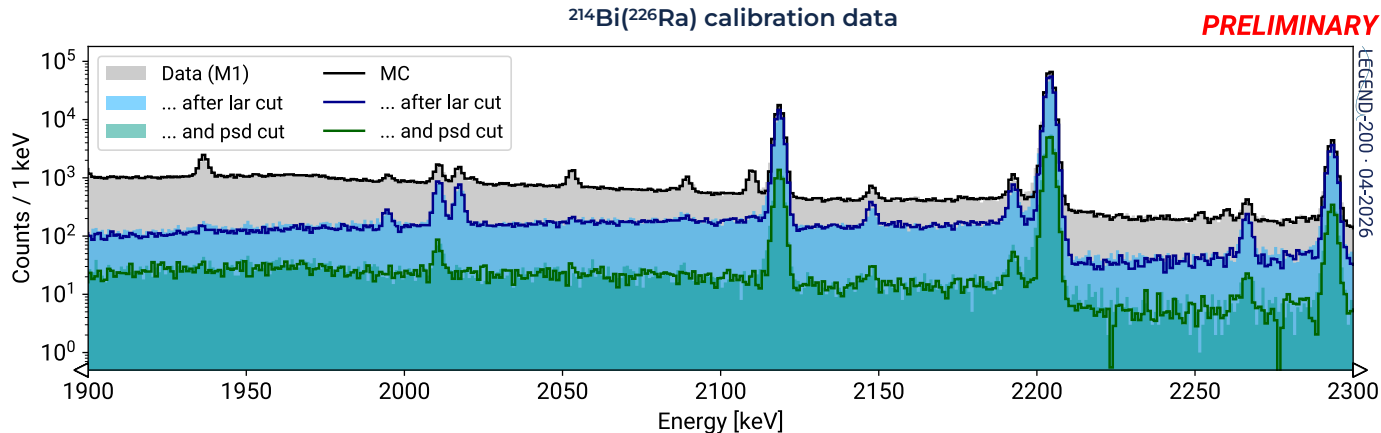
- After LAr + PSD cuts: remaining backgrounds seem to be dominated by ^{42}K surface events.

- Work in progress: optimize analysis methods to reject ^{42}K surface events.
- ^{42}K expected to be mitigated in L1000 with **underground-sourced argon** (UAR).



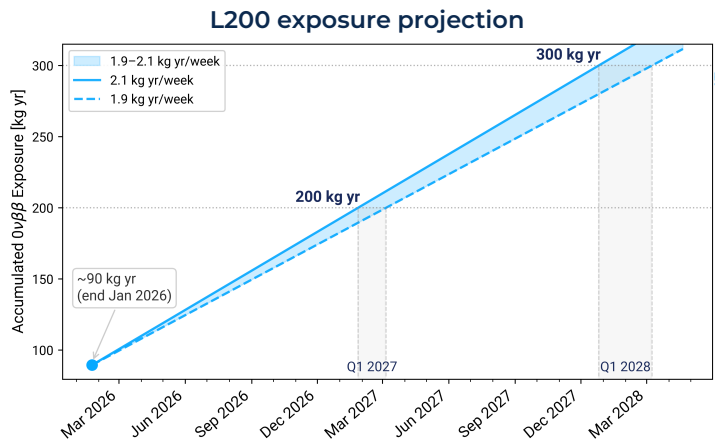
- Goal: **refine and validate as-built MC models** of the active background rejection (PSD and LAr).
- **Special runs:**
 - ✦ LAr instrumentation only.
 - ✦ Weak ^{228}Th source data.
 - ✦ ^{226}Ra source data.
- Background reduction well described by Monte-Carlo simulations.
- Further modeling underway.

Poster - G. Saleh



- **Current data taking**

- ✦ Continue running to **maximize exposure** in the current experimental configuration while expanding the physics program.



Poster - A. Mazumdar

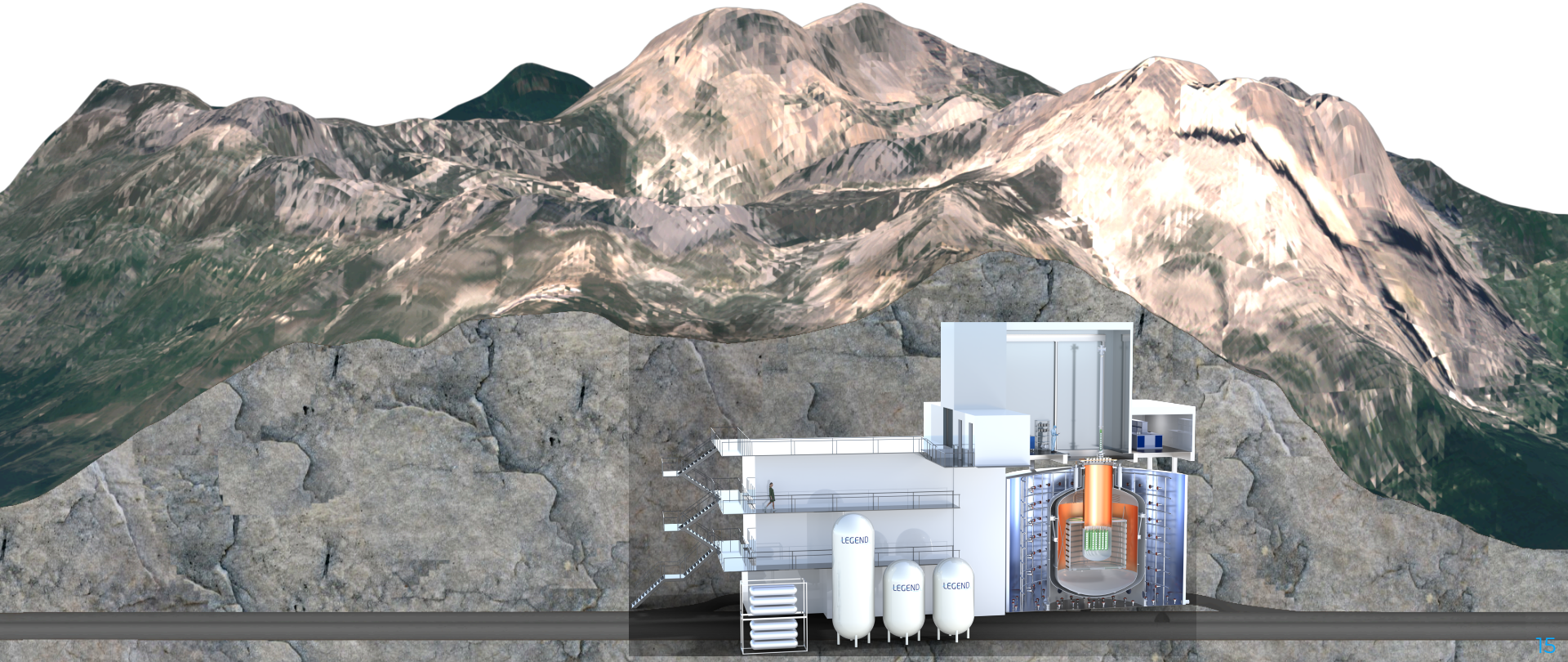
(including all cuts!)

- **Next deployment**

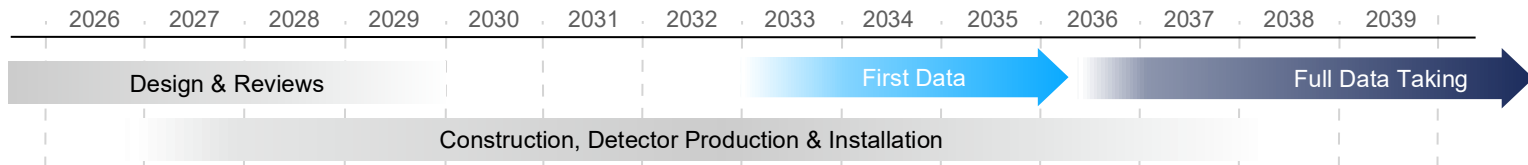
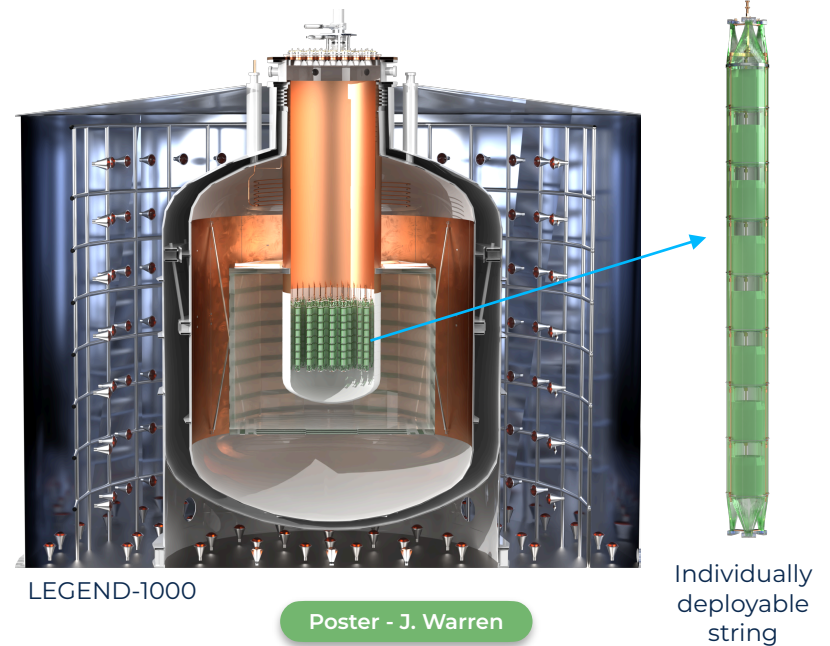
- ✦ Detector production ongoing (~20 kg).
- ✦ Planned for 2028 with a total of **~160 kg Ge detectors**.
- ✦ **Ongoing R&D** for deployment: PEN films to replace nylon mini shrouds, redesigned PEN baseplates and electronics improvements for noise mitigation.
- ✦ Continue operation until L1000 commissioning and demonstration of BI lower than L200's.

Poster - A. Leonhardt

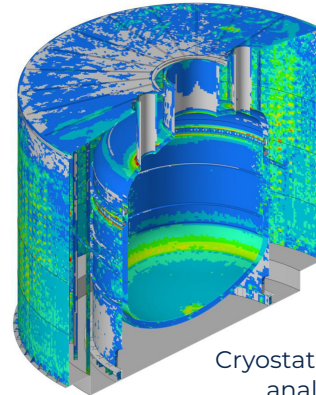
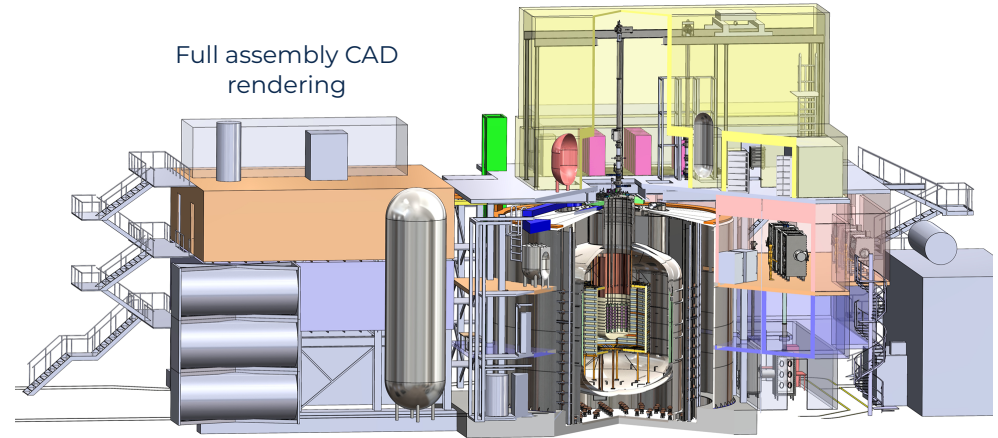
LEGEND-1000



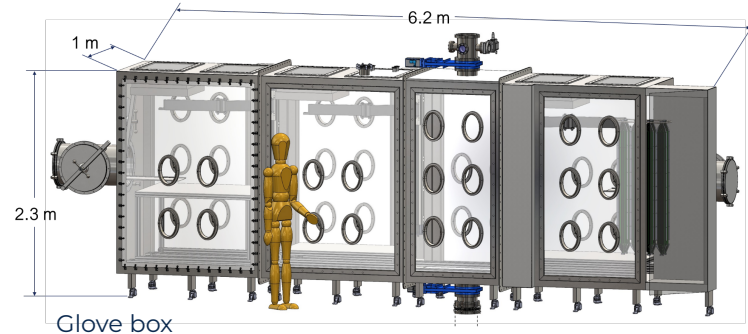
- Tonne scale experiment with large **background reduction compared to L200** to reach $0\nu\beta\beta$ discovery sensitivity $> 10^{28}$ yr, BI goal of 10^{-5} cts/(keV kg yr) and 10 t yr exposure.
- Key **improvements**:
 - All larger-mass **IC detectors** (~ 3 kg).
 - Inner volume of **UAR**: removes $^{42}\text{Ar}/^{42}\text{K}$ backgrounds.
 - **Single-string modules**, individually deployable.
 - **ASIC-based** readout electronics.
 - New **atmospheric argon instrumentation** (neutron moderator + light detection modules).
- LEGEND-1000 **funding**:
 - **US**: NSF (final design phase MREFC) & DOE (CD-1 review).
 - **Europe**: MPG and DFG support; German FIS National Research Infrastructure process (decision July 2026); INFN flagship project; contributions from Switzerland and Poland; UK roadmap pending.
- LEGEND-1000 **schedule**:



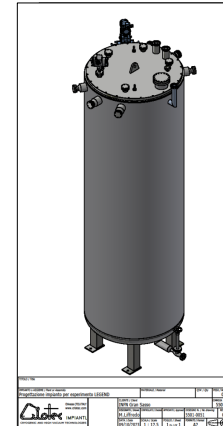
- BOREXINO **dismantling** and **site preparation** are about to start at LNGS. Installation plan developed.
- **Cryostat** and **water tank** design in advance state.
 - ✦ Cryostat steel is purchased and assayed.
 - ✦ New P&ID developed for Ar handling.
- **UAr procurement** to follow DarkSide extraction.
 - ✦ Plant under commissioning in Colorado. Transport tank design ready for internal review, then tender.



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- **Ge procurement and enrichment**
 - ✦ Discussion with commercial suppliers ongoing.
- **Reentrant tube.** Welding / burst tests underway.
- **Deployment systems: lock** (test apparatus under construction) and other system designs maturing: **LEGENDArY** cryostat, **glove box**, **calibration** systems...

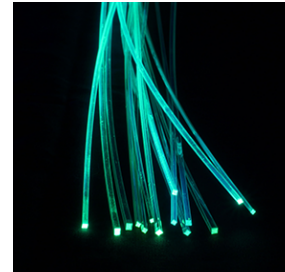


Lock sealing mechanism testing



LEGENDArY cryostat design

- **Inner Ar instrumentation**
 - ✦ Prototyping and thermal / mechanical tests ongoing.
 - ✦ SiPM evaluation and scintillation fibers R&D.
- **Outer Ar instrumentation**
 - ✦ Design optimization and simulation studies.
 - ✦ SiPM characterization and assay.
 - ✦ Prototype currently testing at LEGENDArYno.
- **Water tank instrumentation** optimization underway.



Inner Ar fibers being characterized

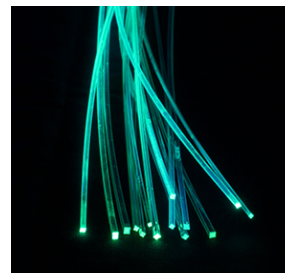
Poster - M. Harańczyk

Poster - T. Sterr



Test deployment in LEGENDArYno at LNGS

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 - ✦ Prototype currently testing at LEGENDArYno.
- **Water tank instrumentation** optimization underway.
- **ASIC development**
 - ✦ Two parallel designs with extensive prototyping and testing.
 - ✦ Integration with flex cables and low-background cabling development.
- **Readout integration** test stand: construction of initial stage ongoing.



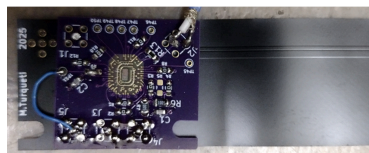
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Poster - M. Harańczyk

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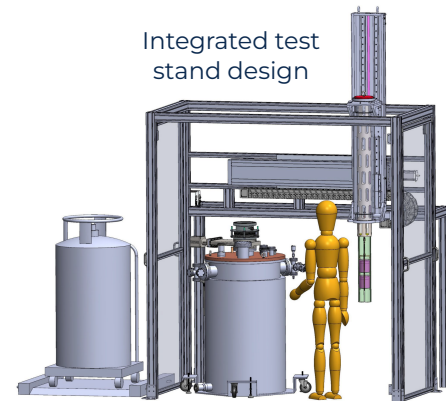
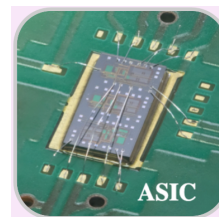


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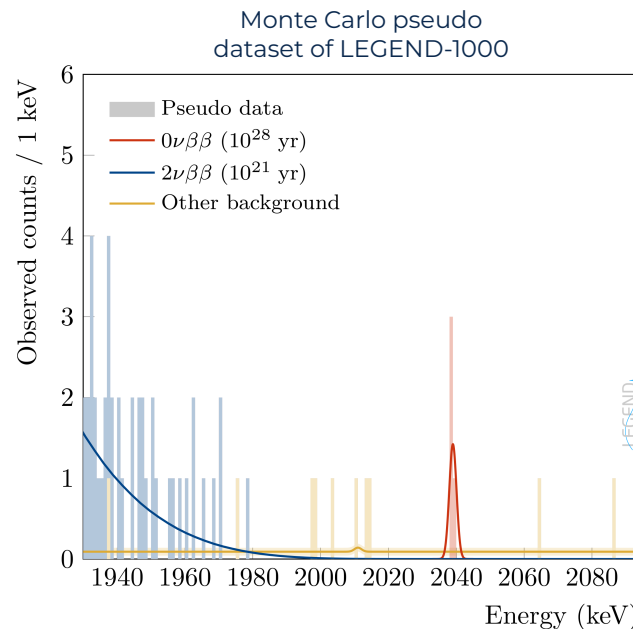
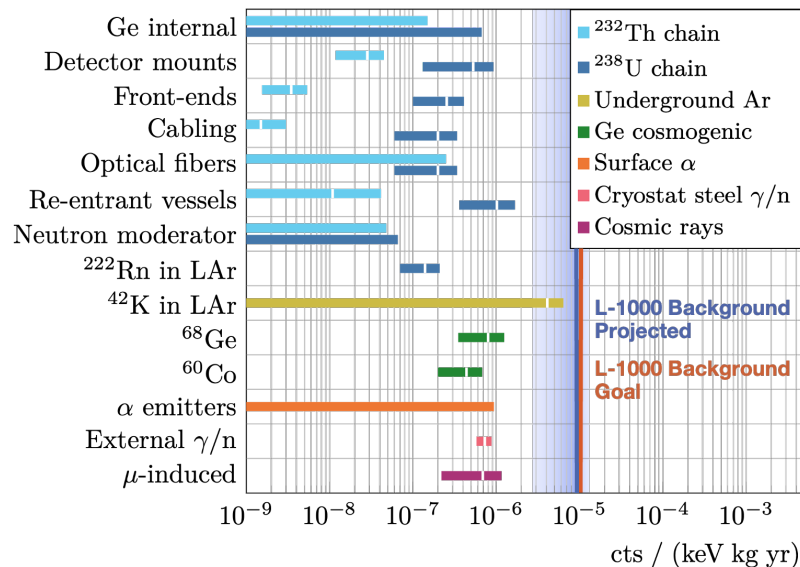
ASIC on a flex cable

LUIGI ASIC test



Integrated test stand design

- Ultra-low background + excellent energy resolution \rightarrow **quasi-background-free search**.
- UAr, plus improvements in material purity and handling, leads to required background reduction.
- **Dominant contributions** from:
 - ✦ U/Th in the reentrant vessel.
 - ✦ Conservative estimate of residual ^{42}K in the UAr.



- **LEGEND-200**

- ✦ Following initial results and a period of maintenance and background investigations, L200 is taking stable physics data with 138 kg of Ge detectors.
- ✦ Significant reduction and understanding of key background contributions.

- **LEGEND-1000**

- ✦ Strong momentum for a tonne-scale search for neutrinoless double-beta decay.
- ✦ Major technical developments and preparations are advancing toward construction.



G. Duran

Study of the Energy Dependence of the LEGEND-200 Pulse Shape Discrimination Parameters using ^{56}Co

A. Gieb

LEGEND Analysis with a Julia-Based Software Stack

I. Guinn

First Results of LEGEND's Search for Neutrinoless Double-Beta Decay in ^{76}Ge

M. Harańczyk

Design and R&D of the Outer LAr Instrumentation for Cosmogenic Background Mitigation in LEGEND-1000

A. Leonhardt

Optically Active Poly(ethylene naphthalate) for Liquid Noble Gas Neutrino Detectors

G. Marshall

Template Based Method for SiPM DSP in LEGEND-200

A. Mazumdar

Beyond $0\nu\beta\beta$: LEGEND-200's Sensitivity to Fractionally Charged Particles

G. Saleh

Signal and Background Pulse Shape Modelling for the LEGEND Experiment

T. Sterr

LEGEND-1000 Water Instrumentation and Neutron Tagger

J. Warren

LEGEND-1000 Progress and Status

J. Chapman

Characterizing Inverted Coaxial Detectors' Low-Energy Performance in the MAJORANA DEMONSTRATOR