

Search for the Majorana Nature of Neutrino with the LEGEND Experiment

LEGEND

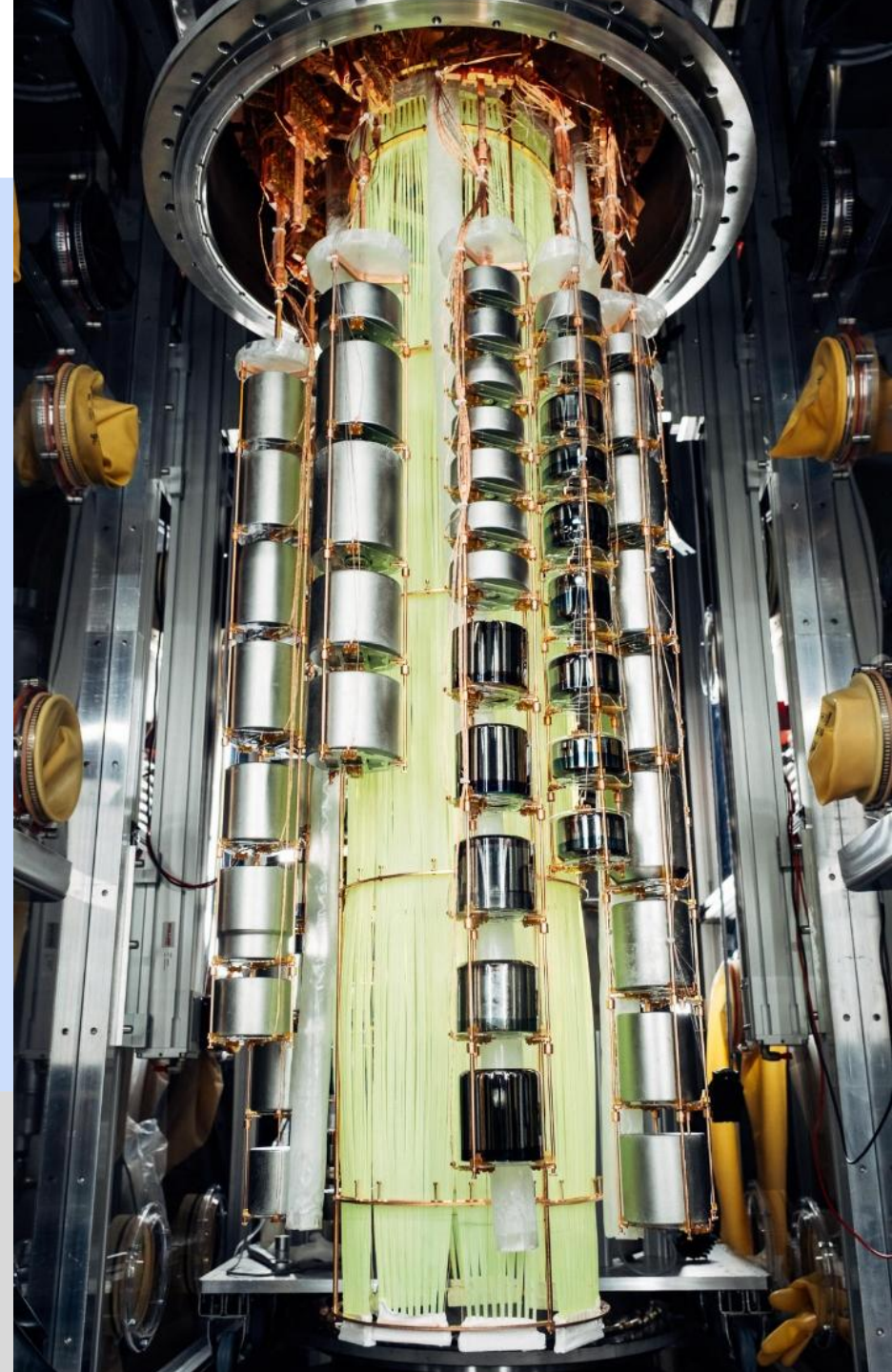
Alex Biondi

on behalf of the LEGEND Collaboration

23 June 2026

PASCOS2026

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay



JAGIELLONIAN UNIVERSITY
IN KRAKÓW

Neutrinoless double beta decay

Motivation

Standard Model process

$2\nu\beta\beta: (A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$
 Lepton number conserved: $\Delta L = 0$

Beyond Standard Model process

$0\nu\beta\beta: (A,Z) \rightarrow (A,Z+2) + 2e^-$
 Lepton number violated: $\Delta L = 2$

Majorana ν

Is neutrino its own antiparticle?

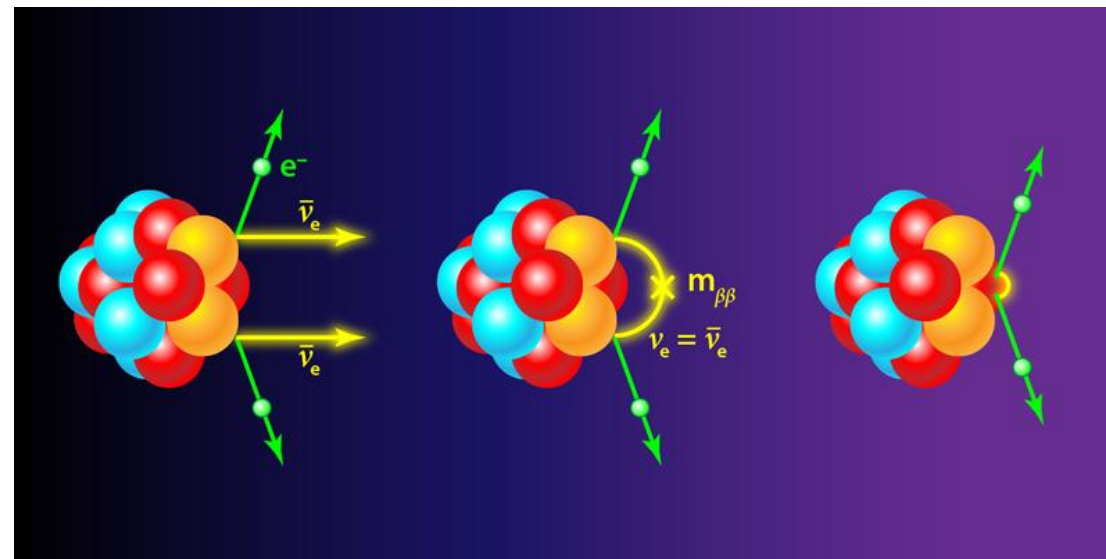
$\Delta L = 2$

Is lepton number conserved?

$m_{\beta\beta}$

What is neutrino's absolute mass scale?

Observation of $0\nu\beta\beta$ decay would establish that neutrinos are Majorana particles and prove lepton-number violation



$$\left[T_{1/2}^{0\nu} \right]^{-1} = G^{0\nu} |M^{0\nu}|^2 \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

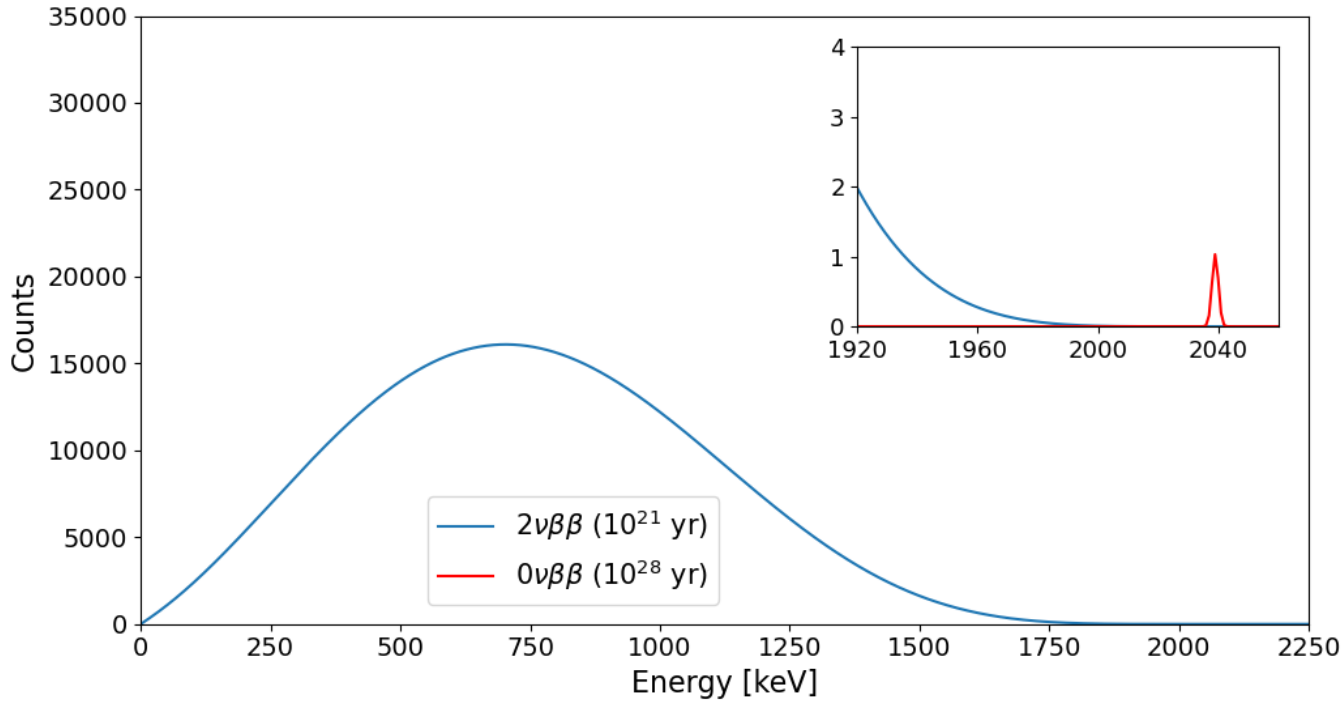
$$\langle m_{\beta\beta} \rangle = \left| \sum_i m_i U_{ei}^2 \right|$$

$0\nu\beta\beta$ decay search in ^{76}Ge



- $2\nu\beta\beta$ decay already observed in ^{76}Ge (not only!)
- Is ^{76}Ge capable of $0\nu\beta\beta$ decay ?
- Relatively high $Q_{\beta\beta}$ and no known gamma lines in the vicinity
- **HPGe detectors**: well-established technology
- High detection efficiency (**source = detector**)
- **Excellent energy resolution**
- **Low intrinsic background**

2039 $Q_{\beta\beta}$ [keV] **~2.5 keV** FWHM at $Q_{\beta\beta}$ **source** = detector



The LEGEND Collaboration



~ 300 Researchers

60 Institutions



LEGEND-200

Mass	up to 200 kg
Exposure goal	1 t · yr
Background goal	$< 2 \times 10^{-4}$ cts/(keV · kg · yr)
Half-life goal	$> 10^{27}$ yr

LEGEND-1000

Mass	up to 1000 kg
Exposure goal	10 t · yr
Background goal	$< 10^{-5}$ cts/(keV · kg · yr)
Half-life goal	$> 10^{28}$ yr

GERDA infrastructure at LNGS

LEGEND-200 is located in the Hall-A of LNGS and reuses the GERDA infrastructure

Enriched Ge detectors

Detectors used in LEGEND are enriched in ^{76}Ge to 86% - 92%

Liquid Argon active veto

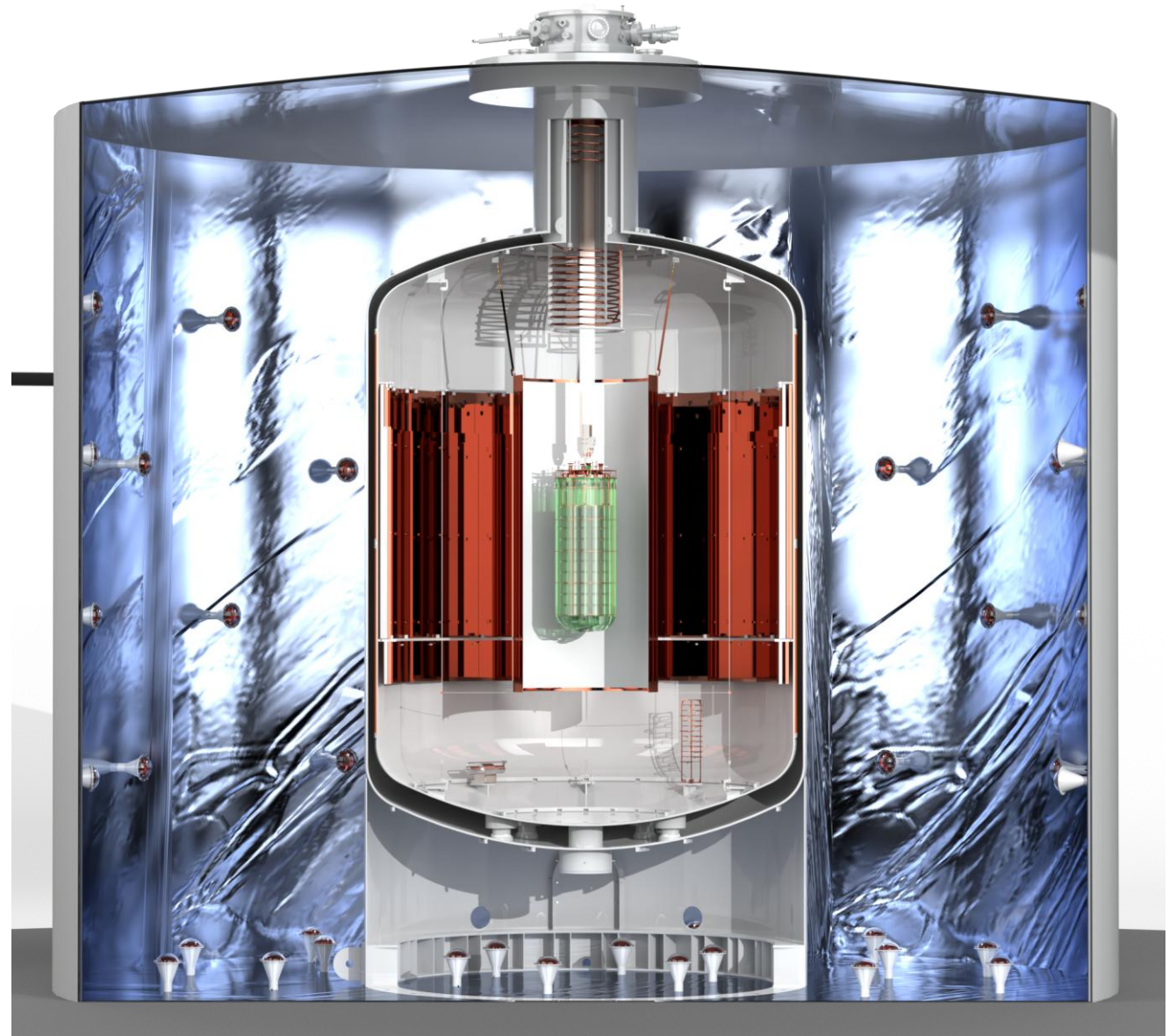
Two concentric curtains of WLS fibres surround the detectors and guide the light of Ar scintillation to SiPMs

Instrumented water tank

Water tank is equipped with 66 PMTs to identify muons and reject muon-induced background

Current status

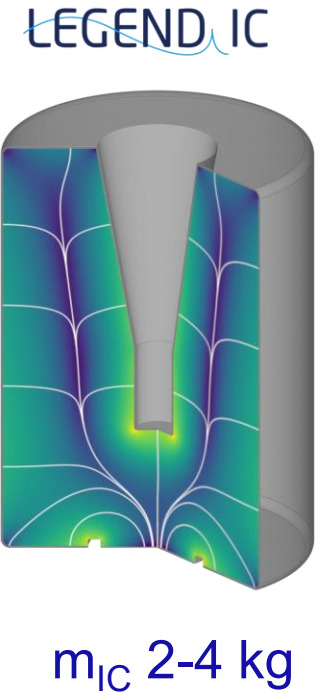
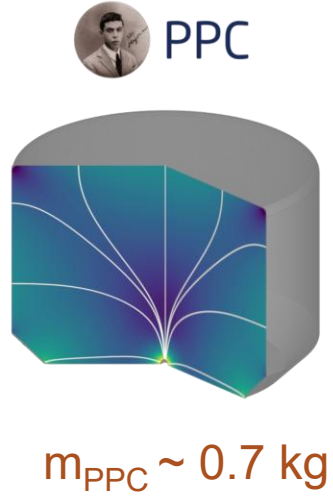
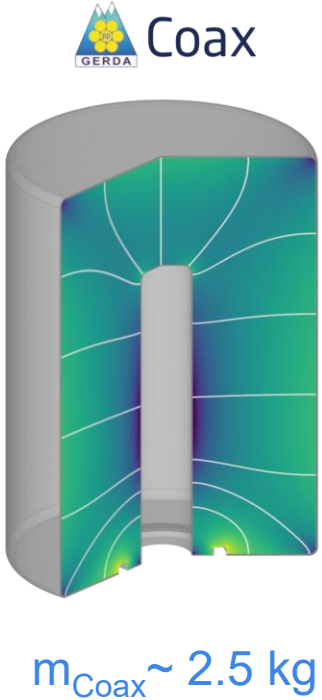
Taking data since March 2023; First results published in [Phys. Rev. Lett. 136, 022701](#) based on the unblinding of 61 kg · yr exposure



First deployment

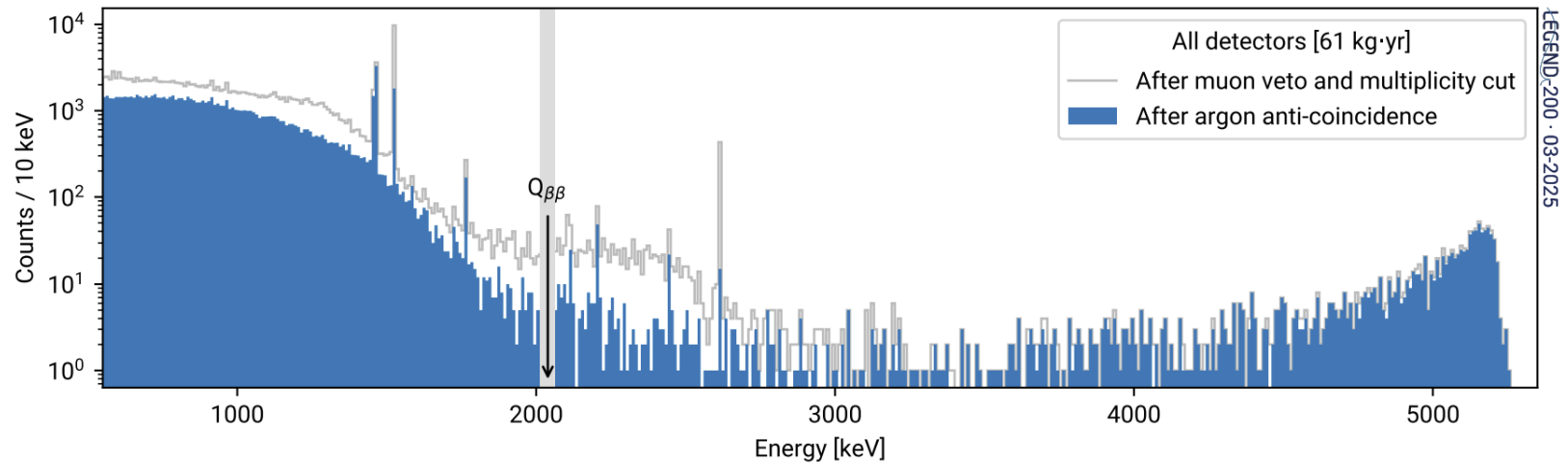
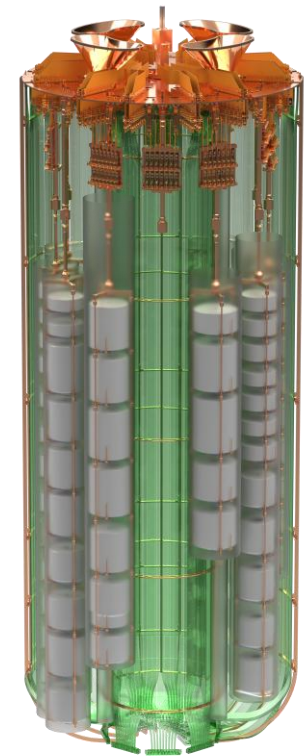
- 14.7 kg Semi-Coaxial (GERDA)
- 19.0 kg BEGe (GERDA)
- 22.1 kg PPC (MAJORANA DEMONSTRATOR)
- 86.7 kg IC (LEGEND)

Total of 142 kg of HPGe detectors installed; 130 kg operational



Liquid argon veto

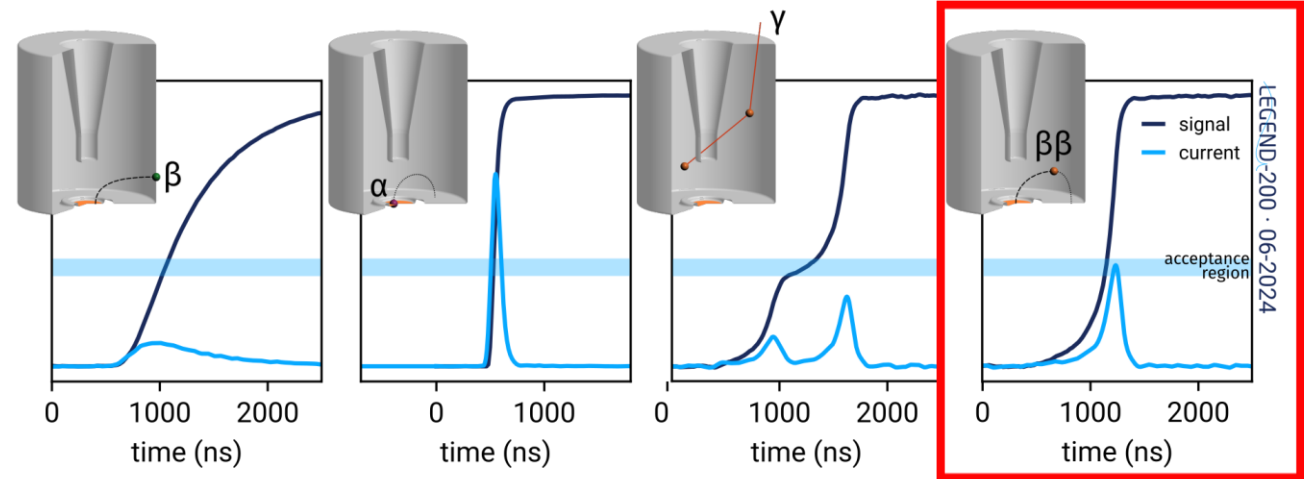
- LAr serves as **cooling medium**, **passive shield** and **active veto**
- Commercial argon 5.5 purified in the liquid phase with a **custom purification system**
- **Triplet lifetime** monitored to verify **argon purity**
- Two concentric curtains of **WLS fibres** surround the detectors strings and guide scintillation light to **SiPM**
- Events with a **coincidence** between Ge and LAr **are rejected**
- **Particularly effective on Compton events**



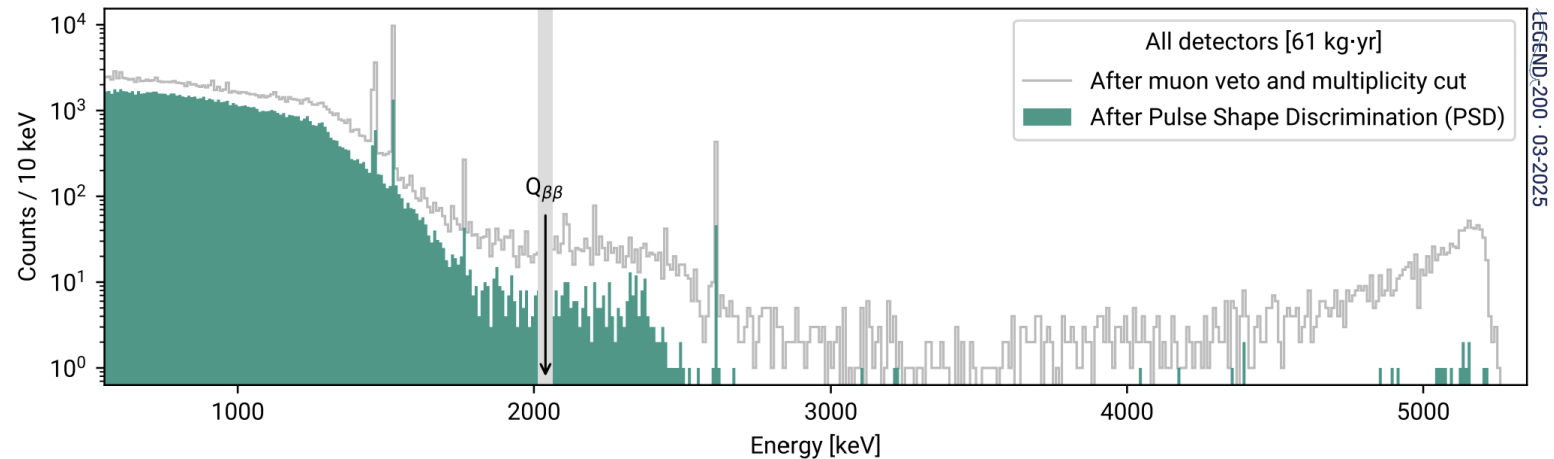
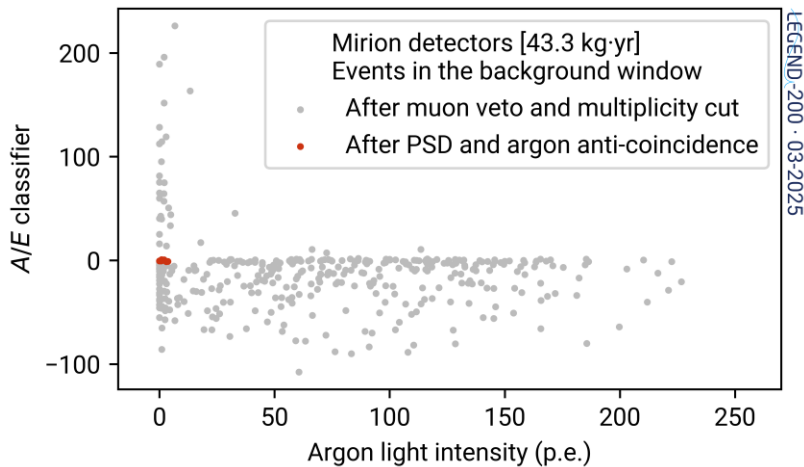
LEGEND-200 · 03-2025

Pulse shape discrimination

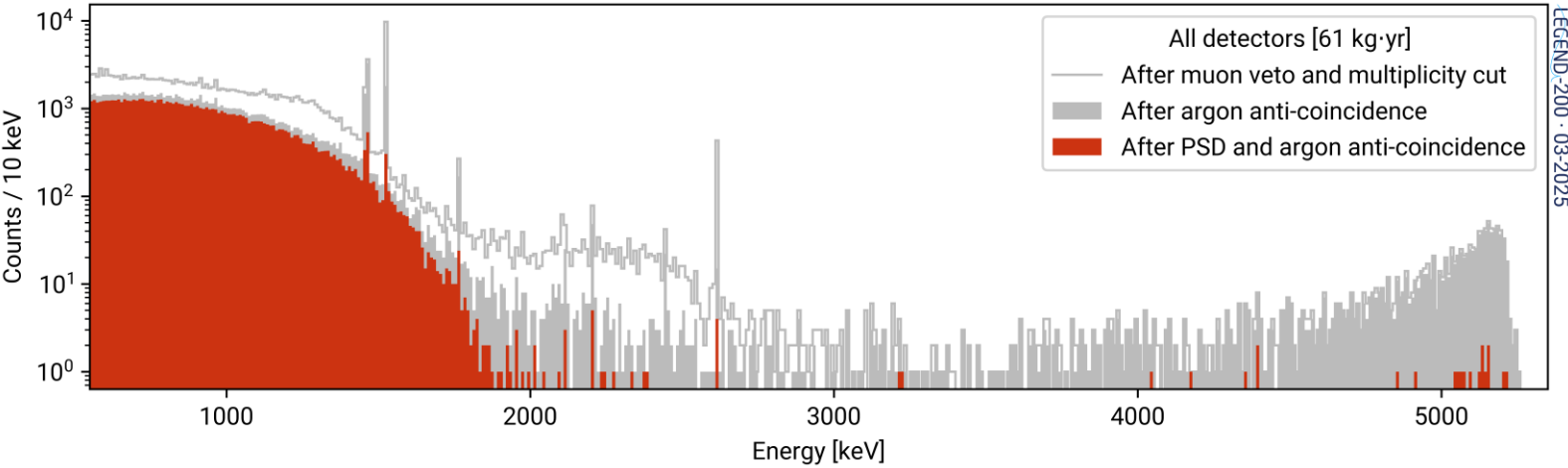
- $0\nu\beta\beta$ events generate two electrons which deposit their full energy in $< 1 \text{ mm}^3$ of Ge (**single-site event**)
- **A/E classifier** based on the ratio between the **maximum amplitude** of the current pulse and the **energy**
- **Very effective against multi-site events**



Key point
PSD and LAr veto provide complementary cuts



LEGEND-200 performance in the first physics data



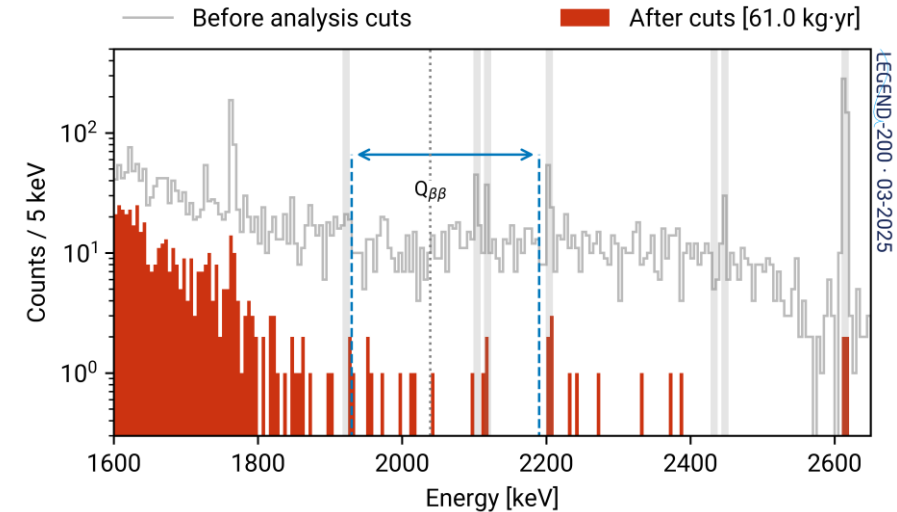
LEGEND-200 · 03-2025

61
kg · yr $0\nu\beta\beta$ data

~ 2.5 keV
FWHM at $Q_{\beta\beta}$

11
events in ROI after cuts

5×10^{-4}
cts/(keV · kg · yr)



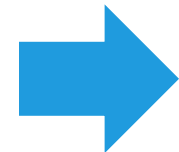
LEGEND-200 · 03-2025

GERDA
127 kg · yr

LEGEND-200
61 · yr

MAJORANA DEMONSTRATOR
65 kg · yr

Combined fit



Median sensitivity: 2.8×10^{26} yr

$T_{1/2}^{0\nu} > 1.9 \times 10^{26}$ yr

90% C.L. frequentist lower limit

$m_{\beta\beta} < 70\text{--}200$ meV

Conclusion

No evidence of $0\nu\beta\beta$ decay found!

Forensic campaign and second deployment

Problem

- **Unpredicted background** of ^{228}Th / ^{228}U in physics data
- Secular equilibrium broken, ICP-MS not predictive

Upgrade

- **New screening campaign** with gamma spectrometers
- **Re-cleaning of the components** closer to the detectors and re-evaluation of cleaning techniques
- **HPGe detectors with worse performance removed**
- **New deployment of IC detectors**

After Upgrade

- Data taking ongoing
- ^{228}Th and ^{228}U lines **strongly reduced**

First deployment

- 14.7 kg Semi-Coaxial (GERDA)
- 19.0 kg BEGe (GERDA)
- 22.1 kg PPC (MAJORANA DEMONSTRATOR)
- 86.7 kg IC (LEGEND)

Total of 142 kg of HPGe detectors installed; **130 kg operational**

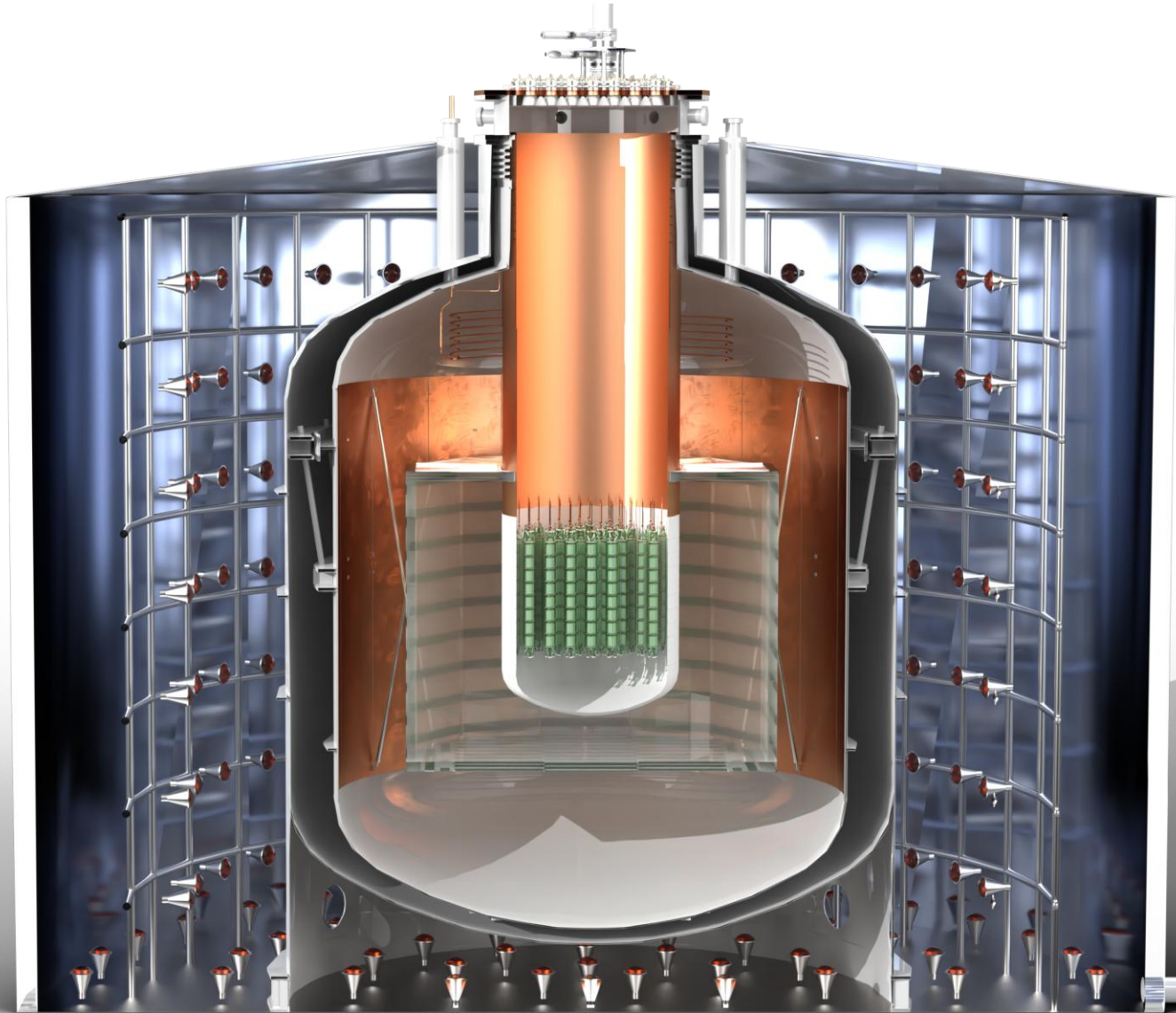


Second deployment

- 7.9 kg BEGe (GERDA)
- 129.7 kg IC (LEGEND)

Total of **137.6 kg of HPGe detectors installed**





Mass Capacity

Up to 200 kg → up to 1000 kg enriched Ge

New infrastructure

LEGEND-1000 will be located in a new infrastructure in Hall-C at LNGS

IC detectors

IC detectors only. Installed in several independent strings

Underground argon

Re-entrant tube filled with ~ 30 t of UAr to reduce $^{42}\text{Ar}/^{42}\text{K}$ background

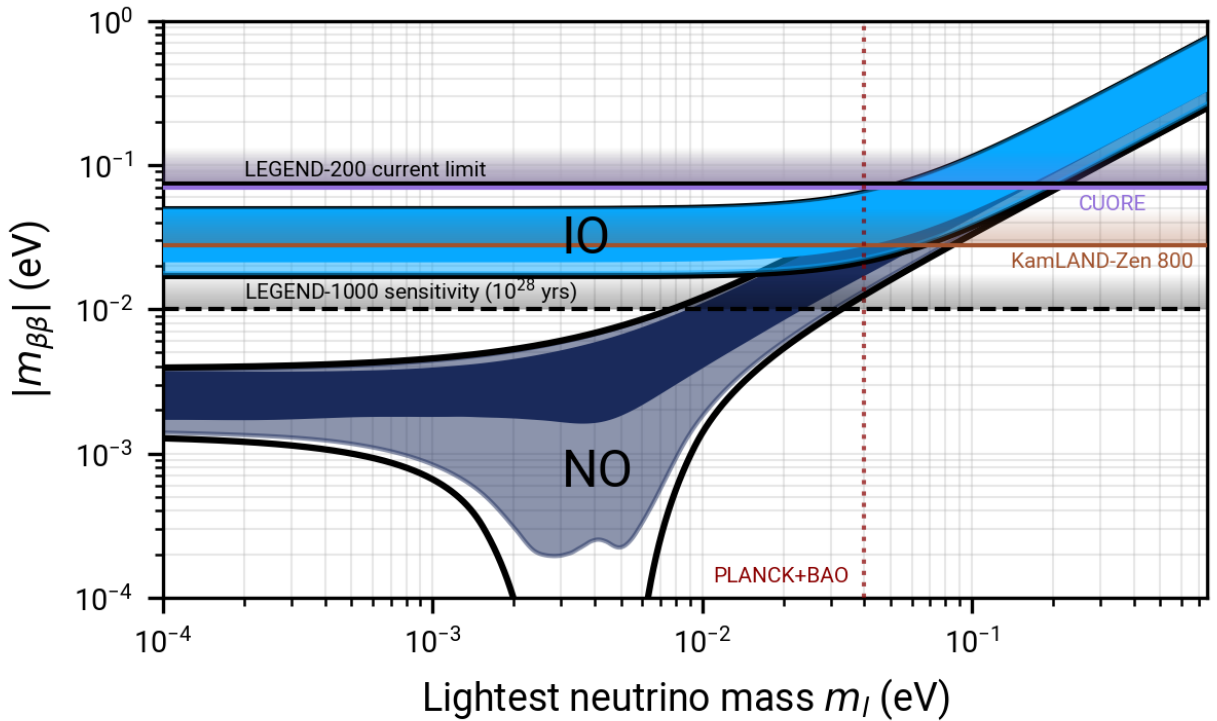
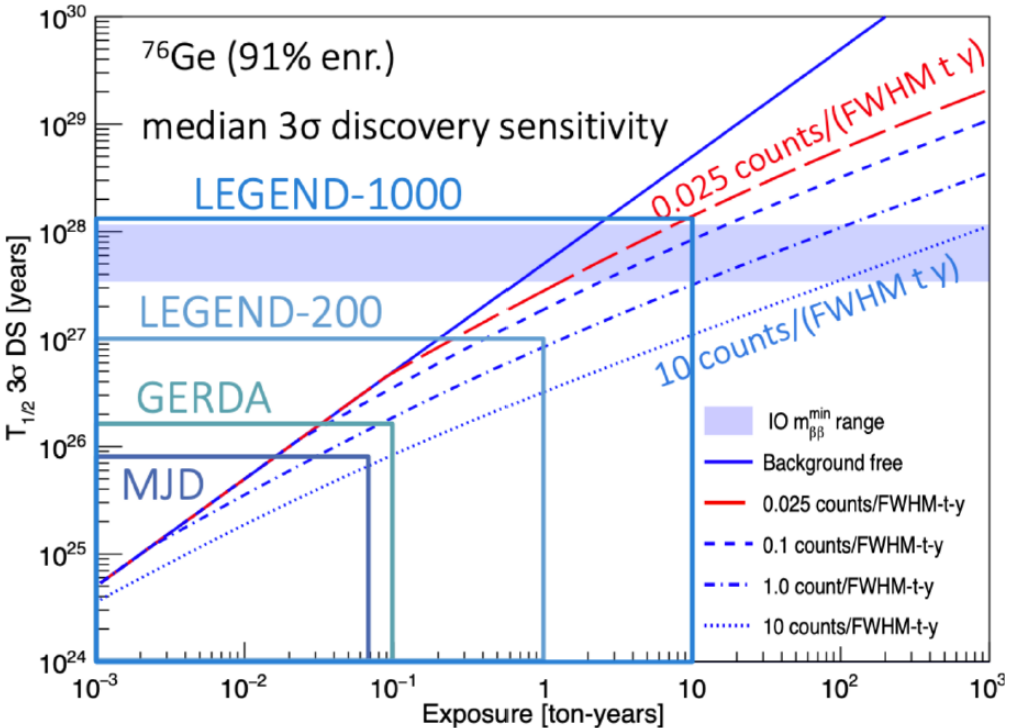
Purification system

Cryostat filled with ~ 180 t of AtAr purified with a new custom purification system

Cosmogenic mitigation

Instrumented moderator around the cryostat

LEGEND-1000 projected sensitivity and status



Discovery sensitivity
 $T_{1/2}^{0\nu} \approx 1.3 \times 10^{28}$ yr

Effective mass reach
 $m_{\beta\beta} \approx 9\text{--}21$ meV

Background goal
 $<10^{-5}$ cts/(keV · kg · yr) \approx
 0.03 cts/(FWHM · t · yr)

Exposure goal
 10 t · yr

Status of LEGEND-1000
 Currently under design, simulations ongoing, partially funded by several agencies (Italy, Germany, Switzerland, Poland, US), other proposals under evaluation (US DOE, US NSF, German BMFTR) or in preparation

Physics Goal: cover the inverted ordering region

Physics motivation

A discovery of $0\nu\beta\beta$ decay would demonstrate lepton-number violation and establish the Majorana nature of neutrinos

LEGEND-200 first result

LEGEND-200 has published its first results, setting a limit on half-life of $0\nu\beta\beta$ decay in ^{76}Ge of 1.9×10^{26} yr. After the update, data taking is ongoing to collect exposure.

LEGEND-1000 outlook

LEGEND-1000 will scale up the mass and further reduce the background to reach a discovery sensitivity beyond 10^{28} yr and cover the inverted mass hierarchy

Acknowledgment

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Thank you!