Radioassays for the LEGEND ^{76}Ge 0νββ search

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on behalf of the LEGEND collaboration

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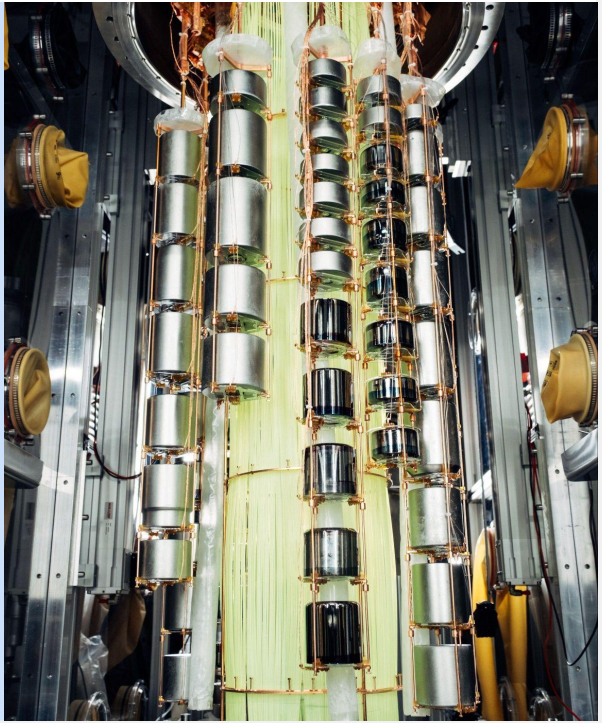
4 Oct. 2024

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

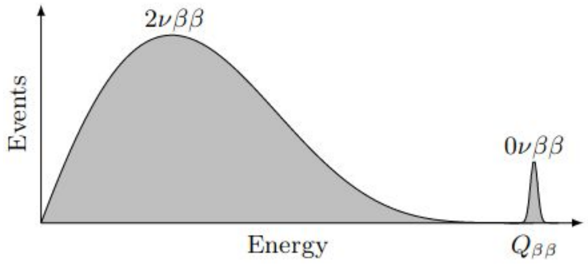


LEGEND

- **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless ββ **D**ecay
- ~0.1% FWHM resolution at **$Q_{\beta\beta}$= 2039 keV**
- Nearly background-free search with uniform background
    - LEGEND-200 background goal:

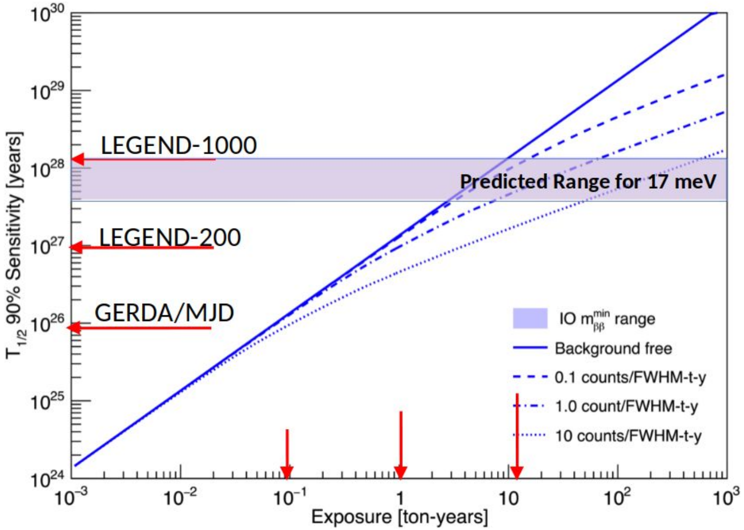
      2×10^{-4} cts/(keV·kg·yr)
- First physics deployment in 2023
- Future LEGEND-1000 experiment aims to cover inverted mass ordering

M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023).

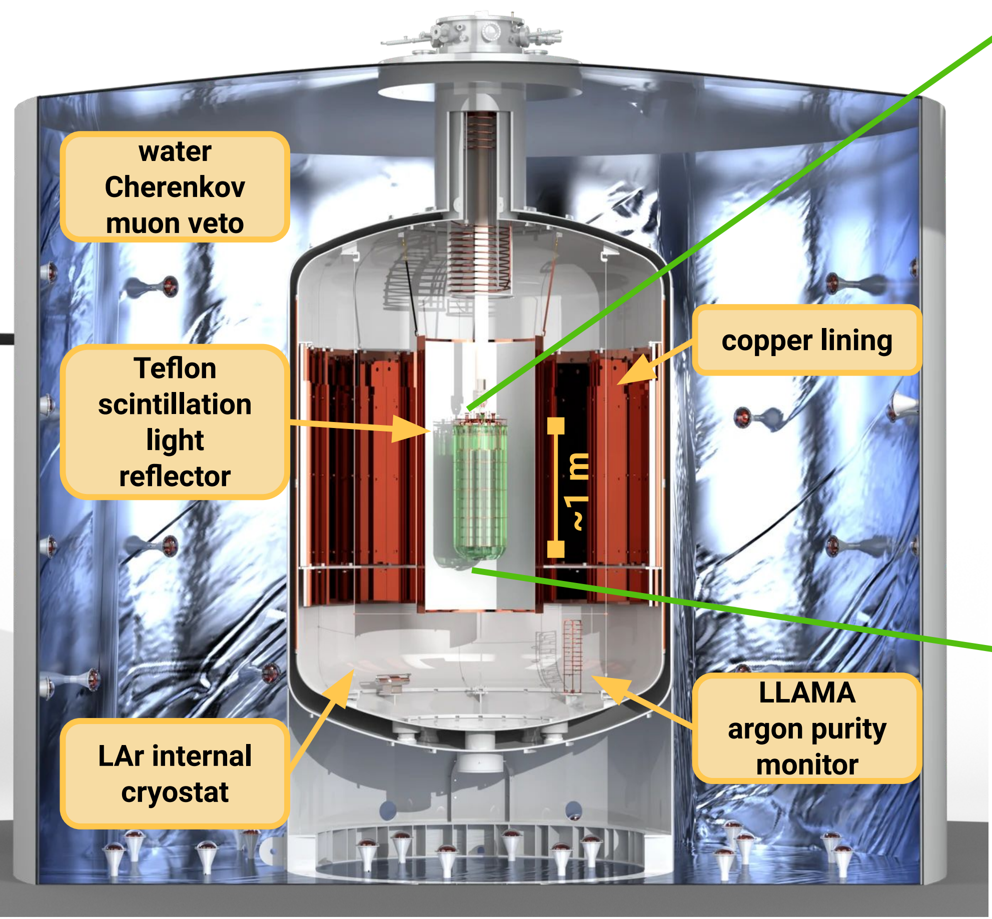


2039 keV

^{76}Ge (88% enr.)



LEGEND-200 - 200 kg of ^{76}Ge enriched detectors



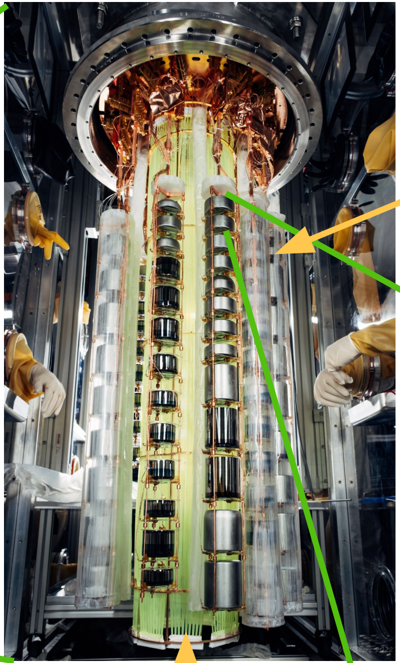
water Cherenkov muon veto

Teflon scintillation light reflector

LAr internal cryostat

copper lining

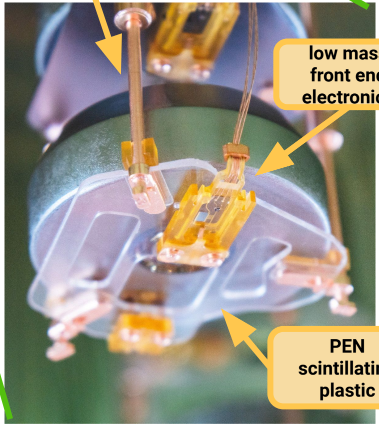
LLAMA argon purity monitor



latest deployment: 142 kg of ~90% ^{76}Ge enriched detectors

TPB-coated nylon casings to reduce ^{42}K ion drift

wavelength shifting fibers coupled to SiPM readouts to detect LAr scintillation (outer barrel not pictured)



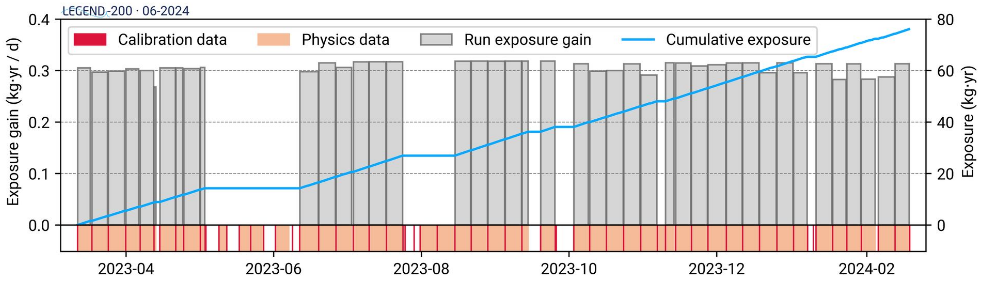
underground electroformed copper

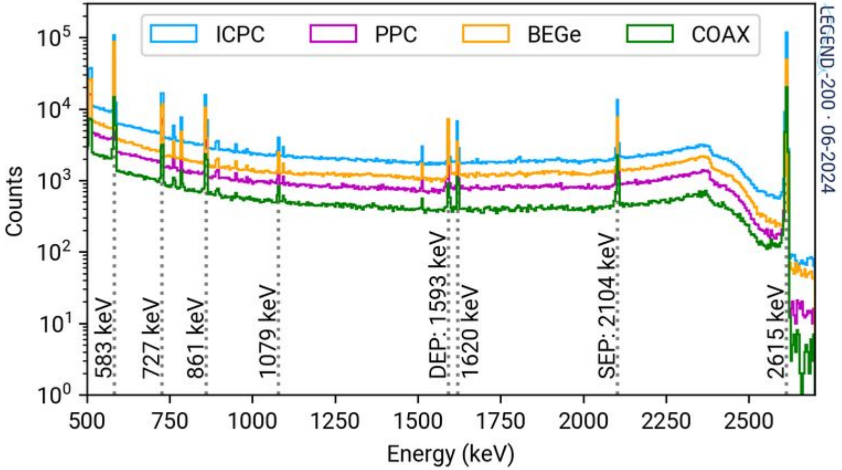
low mass front end electronics

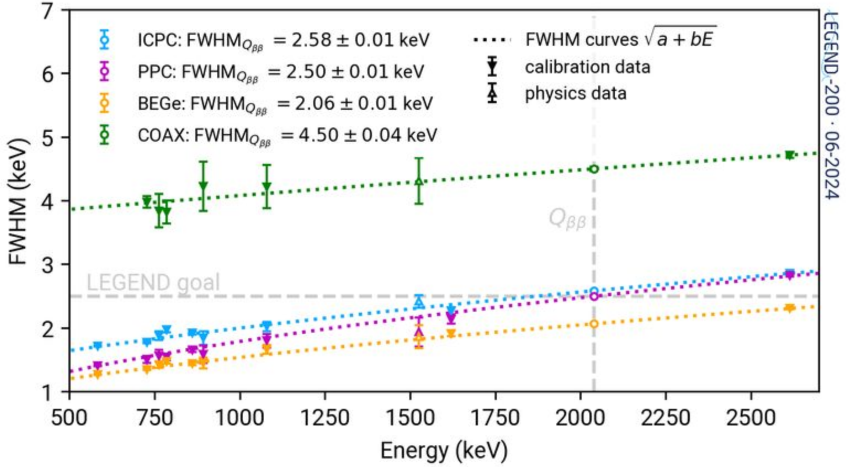
PEN scintillating plastic

First ~year of data-taking since March 2023

- Energy resolution of ~0.1% FWHM at $Q_{\beta\beta}$.
- Weekly calibrations with ^{228}Th source.
- **First unblinding June 2024!**
- **ICPC detectors meeting performance requirements for L1000.**



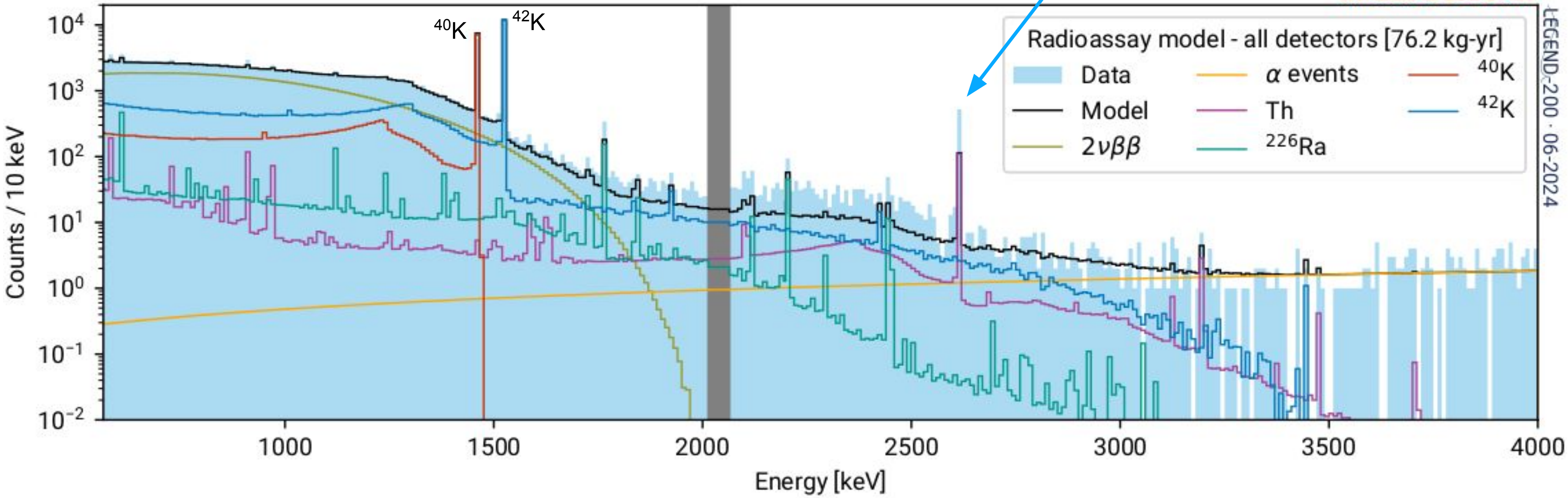




Data before analysis cuts

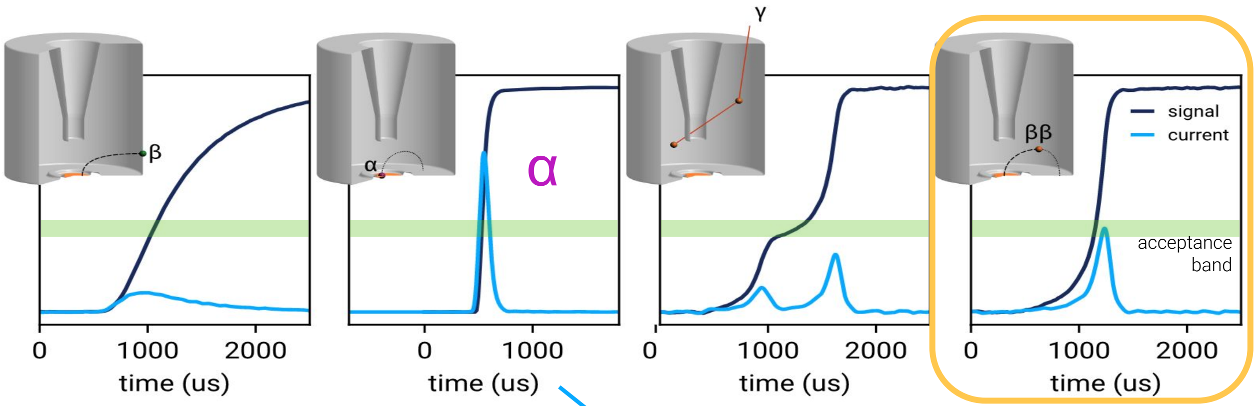
- Radioassays underpredict observed backgrounds (particularly ^{232}Th chain).
    - Campaign of radioassays currently underway to identify possible sources.
- Background is well suppressed by analysis cuts, however.

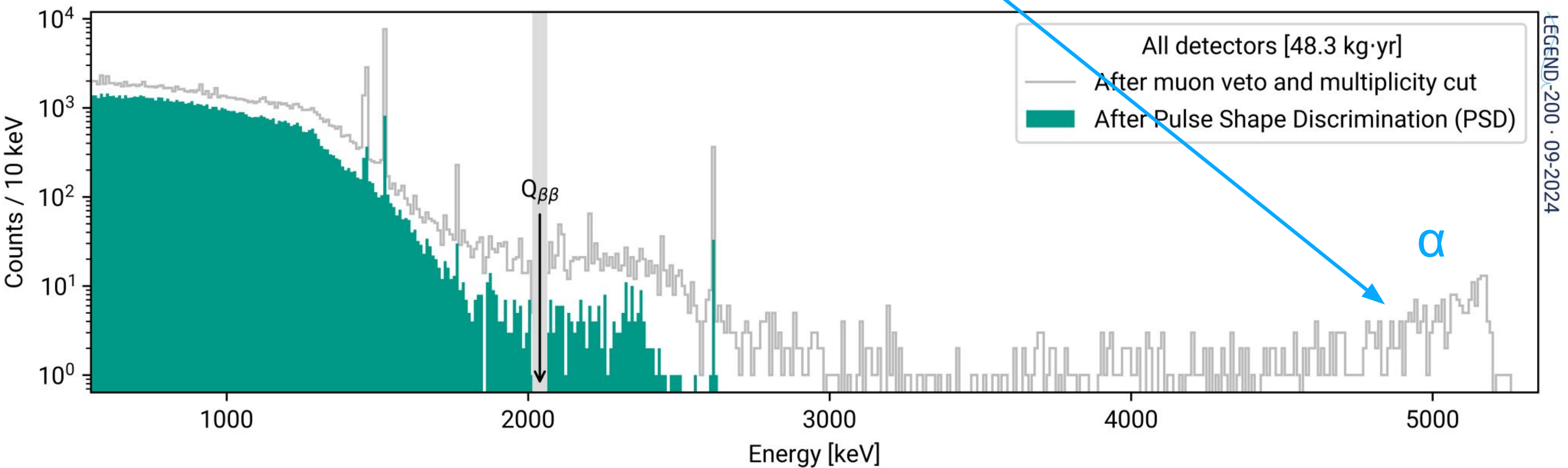
See next talk by Toby Dixon on background modeling!



Pulse shape discrimination (PSD)

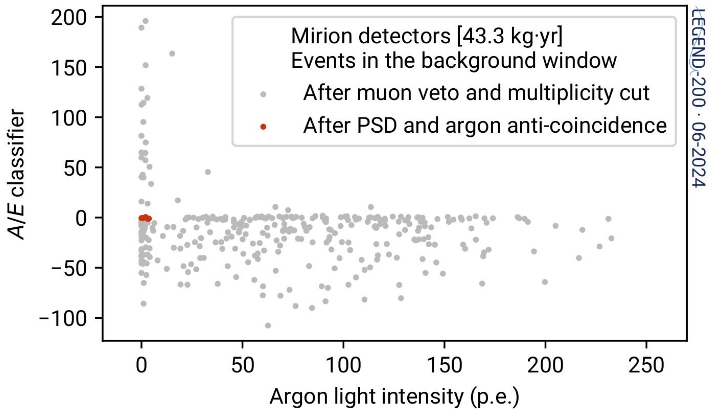
- A/E classifier
  [max(current) / energy]
- Strongly suppresses α, β backgrounds
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$



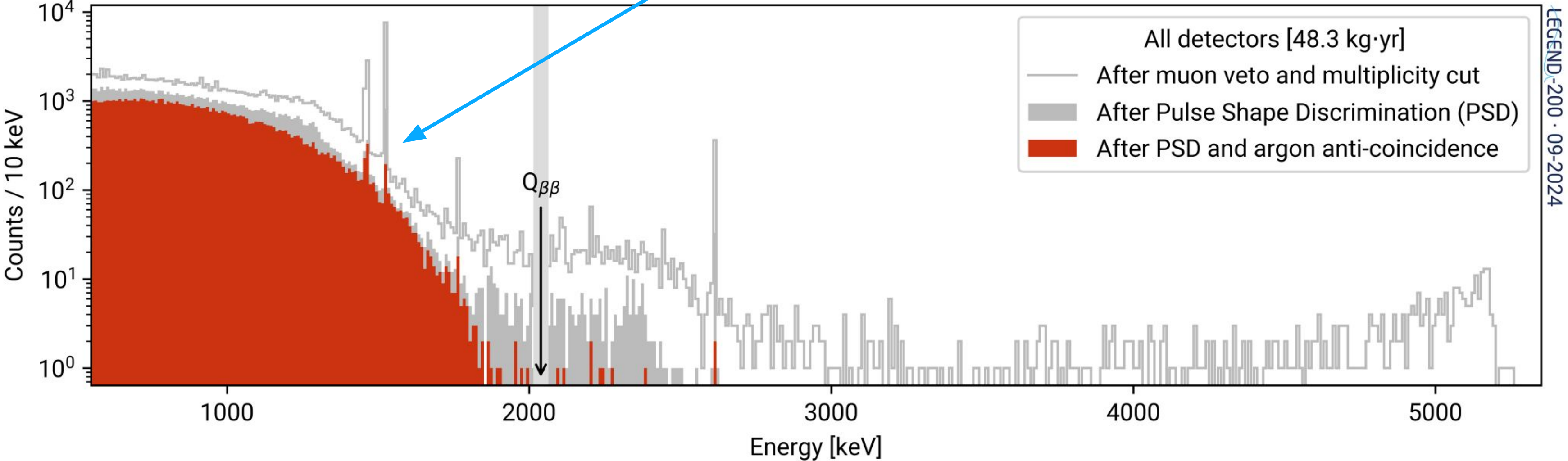


Liquid argon anti-coincidence

- Improved light yield compared to GERDA (×3).
- LAr veto and PSD cuts are largely anti-correlated.
- Combination of cuts suppresses nearly all backgrounds.



particularly effective at removing ^{42}K β-decays

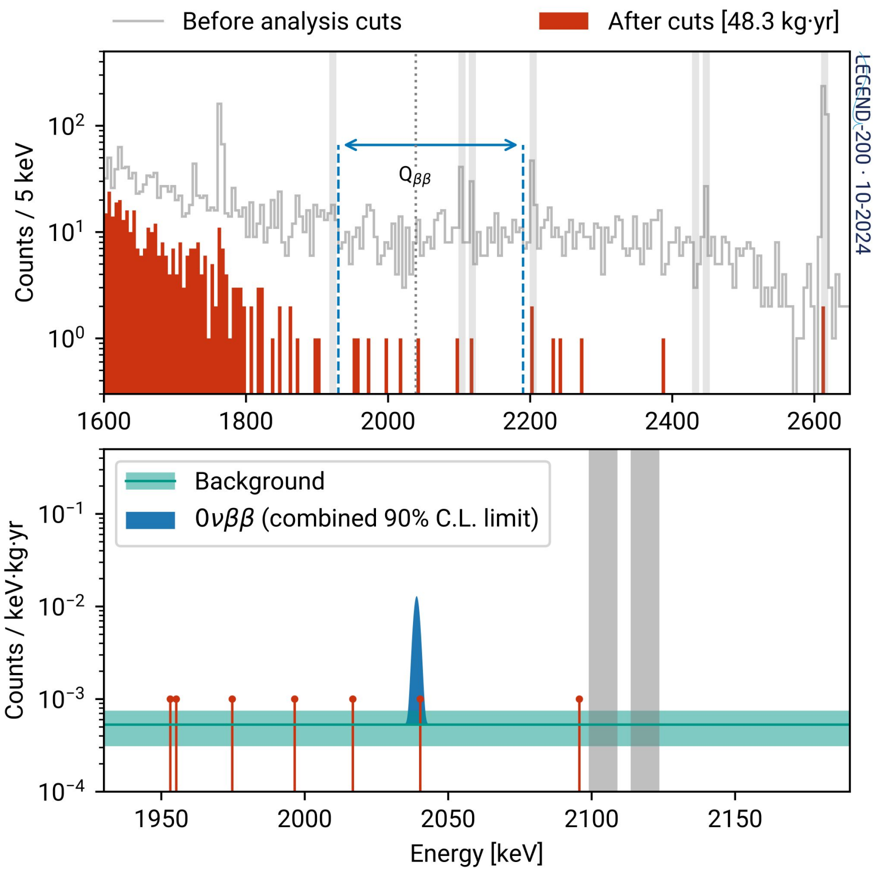


First unblinding

- **Unblinded 48.3 kg·yr** of exposure.
- **7 events after cuts** (including 2 events in blinded region)
  - background of $5.3 \pm 2.2 \times 10^{-4}$ cts/(keV·kg·yr)
- Observed limit **$T_{1/2} > 0.5 \times 10^{26}$ years** (90% CL)
- One event near $Q_{\beta\beta}$ (E = 2040.3 keV) weakens observed limit compared to expected sensitivity. Consistent with background at p = 0.08.

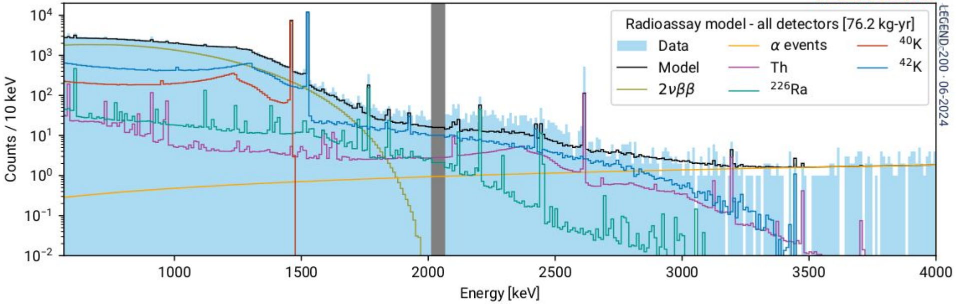
GERDA, MAJORANA, and LEGEND combined result (90% CL)

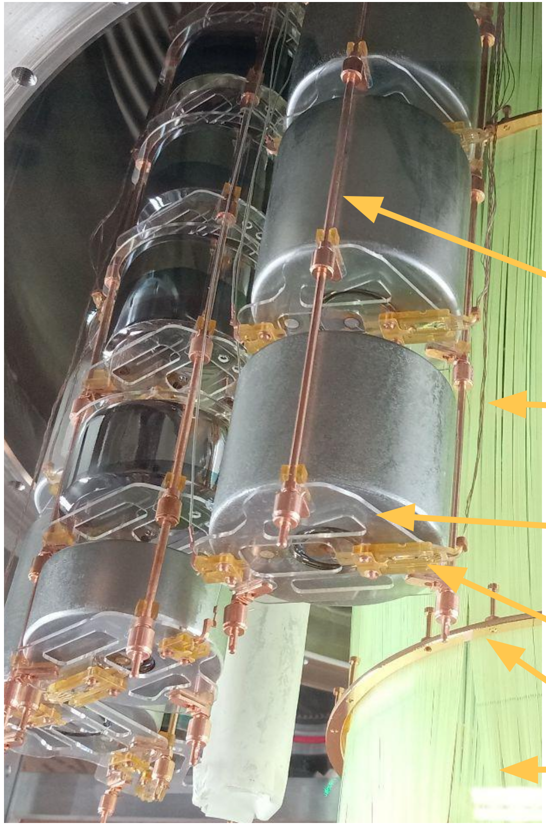
	Observed	Sensitivity
$T_{1/2}$	**$> 1.9 \times 10^{26}$ yr**	2.8×10^{26} yr



Low background materials for LEGEND

- Both ICP-MS and gamma assays for *most* materials with gamma assays preferred.
- Evidence that secular equilibrium is broken for at least some components
- Only some isotopes relevant background for LEGEND
- From nearby materials:
    - ^{238}U chain: ^{214}Pb, ^{214}Bi
    - ^{232}Th chain: ^{228}Ac, ^{212}Bi, ^{208}Tl
- Other major sources:
    - Rn chain alphas on sensitive detector surfaces
    - ^{42}K (from ^{42}Ar)





Michael Willers / LEGEND Collaboration

front end electronics

underground electroformed copper

Axon' picocoax cables

PEN scintillating plastic

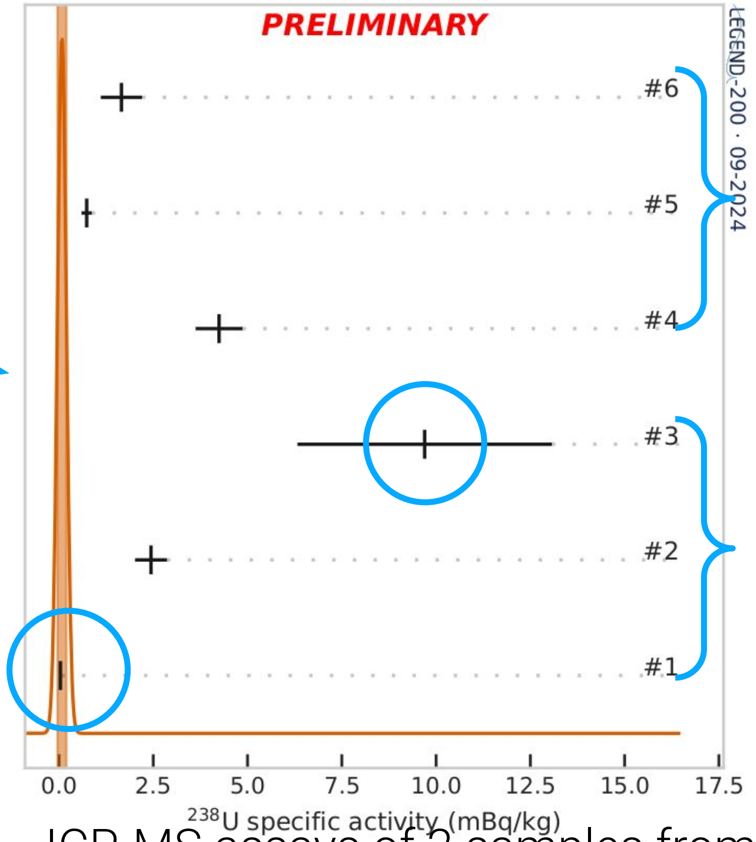
Ultem

NOSV copper

BCF-91A fibers w/ TPB coating

Assay statistical interpretation

- Some ICP-MS assays have showed “inconsistent” results →
- How to treat these assays to find total expected activity?
- Conventional weighted average gives result that is not “common sense”
- Can we throw out the outlier assay results? How to correctly handle them?
- We developed a more agnostic averaging technique that better estimates the total activity and uncertainty.



replicates of sample A

replicates of sample B

ICP-MS assays of 2 samples from L200 high voltage cables

Statistical averaging model

- Take two simple models for contamination and assays

A. Activity is homogeneously distributed, and there is one true activity among parts.

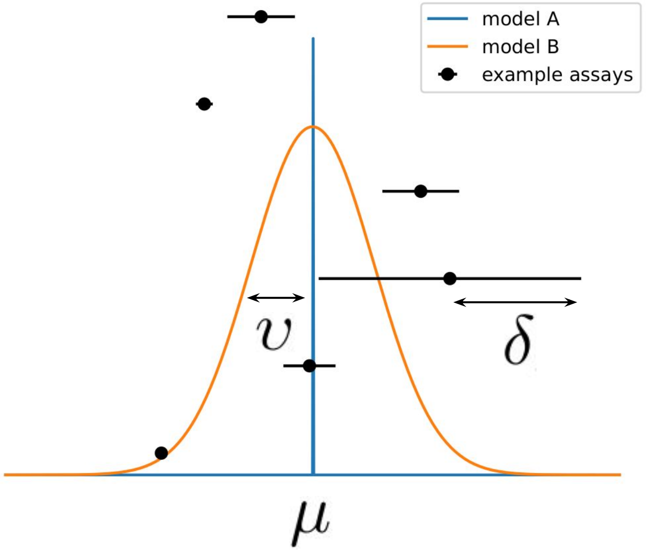
- Variation in assays is due to statistical and systematic uncertainties. Results that disagree widely are due to unaccounted-for systematic uncertainties.
- Weighted average with Birge ratio inflation should work well but fails when uncertainties vary by large factors.

arXiv:2408.06786 (MAJORANA DEMONSTRATOR)

- Extension of this model: independent batches of components are considered to have separate activities.

B. Activity is *not* homogeneous, and there is some (Gaussian) distribution of activities among parts .

- Variation in assays is due to statistical and systematic uncertainties, but also due to inherent part-to-part or sample-to-sample variation.
- Large variations well-handled under this model.



Approximation for “simplicity”

- In our approximation, we take a weighted average of the assays, where the uncertainty is inflated by a constant factor approximating the part-to-part variation υ

\# assays

assay uncertainty

$$\hat{\mu} = \left(\sum_{i=1}^{N_A} \frac{x_i}{\upsilon^2 + \delta_i^2}\right) \cdot \left(\sum_{i=1}^{N_A} \frac{1}{\upsilon^2 + \delta_i^2}\right)^{-1}$$

$$\delta_{\hat{\mu}} = \left(\sum_{i=1}^{N_A} \frac{1}{\upsilon^2 + \delta_i^2}\right)^{-\frac{1}{2}}$$

$$\upsilon^2 \approx \max\left(0, \frac{\sum_{i=1}^{N_A}(x_i - \bar{\mu})^2}{N_A - 1.5} - \frac{1}{N_A}\sum_{i=1}^{N_A}\delta_i^2\right)$$

- Conventional weighted average with Birge ratio uncertainty inflation scales the uncertainties by a multiplicative factor instead.

c.f. arXiv:2408.06786 (MAJORANA DEMONSTRATOR)

\# parts

average activity uncertainty

$$\eta \approx N(\hat{\mu} \pm \delta_{\hat{\mu}}) \pm \sqrt{N}\upsilon$$

predicted total activity

average activity

part-to-part variation

or more explicitly

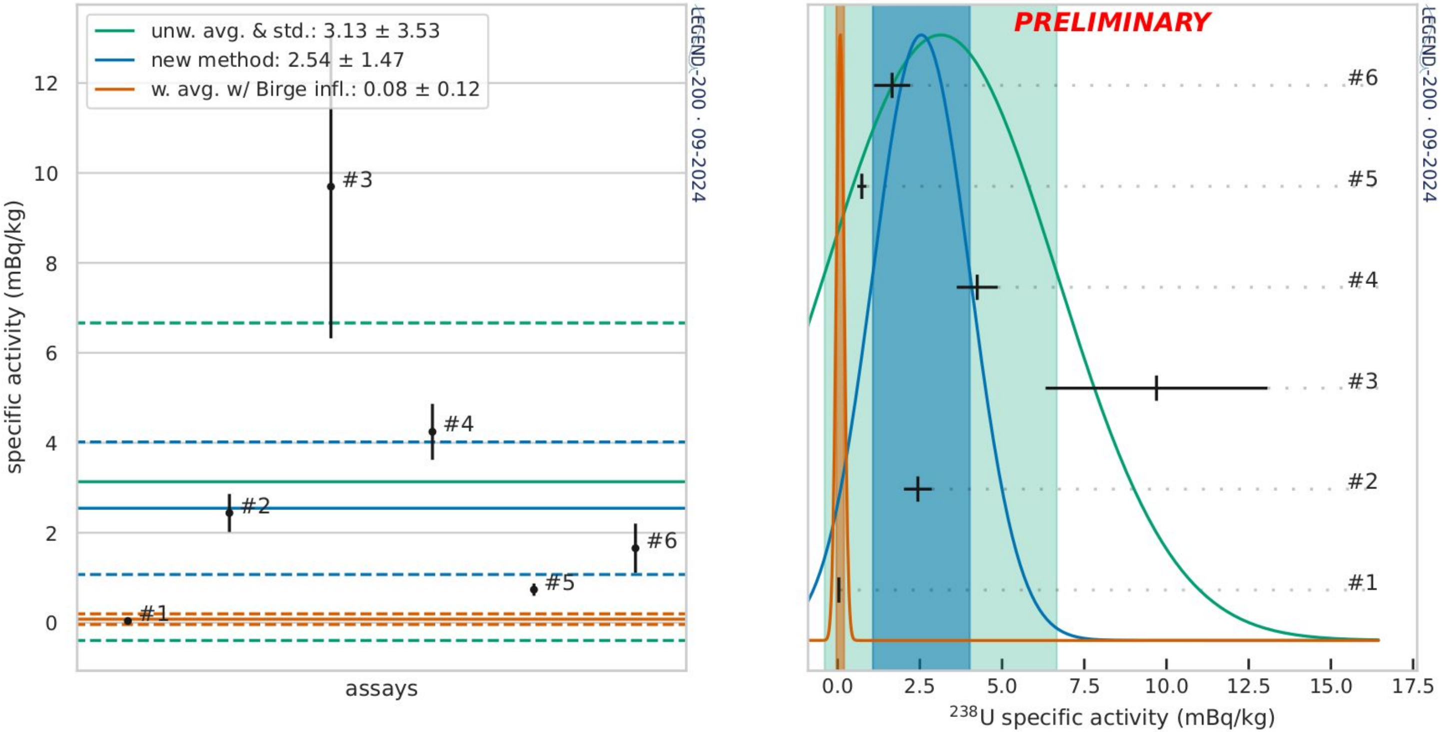
$$\eta \approx N\mu \pm \frac{N}{\sqrt{N_A}}\bar{\delta}_i \pm \frac{N}{\sqrt{N_A}}\upsilon \pm \sqrt{N}\upsilon$$

“extra” term typically does not meaningfully contribute

This model implies that more assays are required to estimate the part-to-part variance and reduce its impact on the uncertainty (~3-5 assays).

Application to our assays

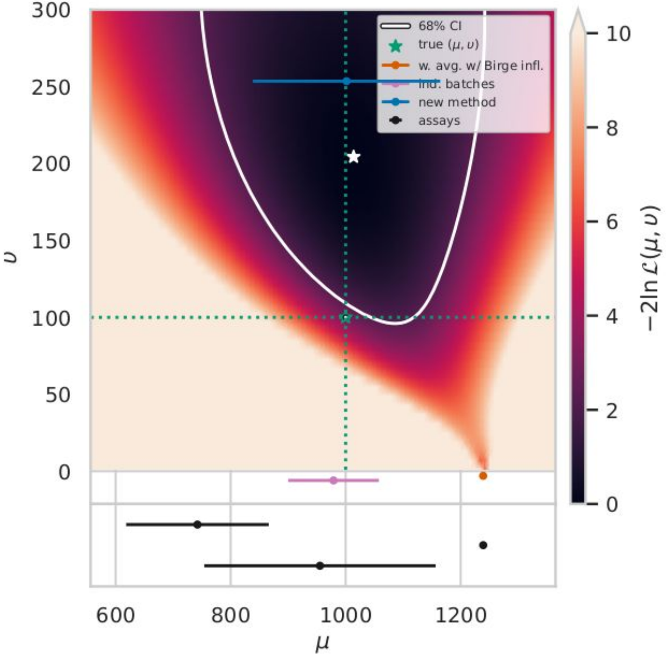
- New method gives a more reasonable activity and uncertainty.



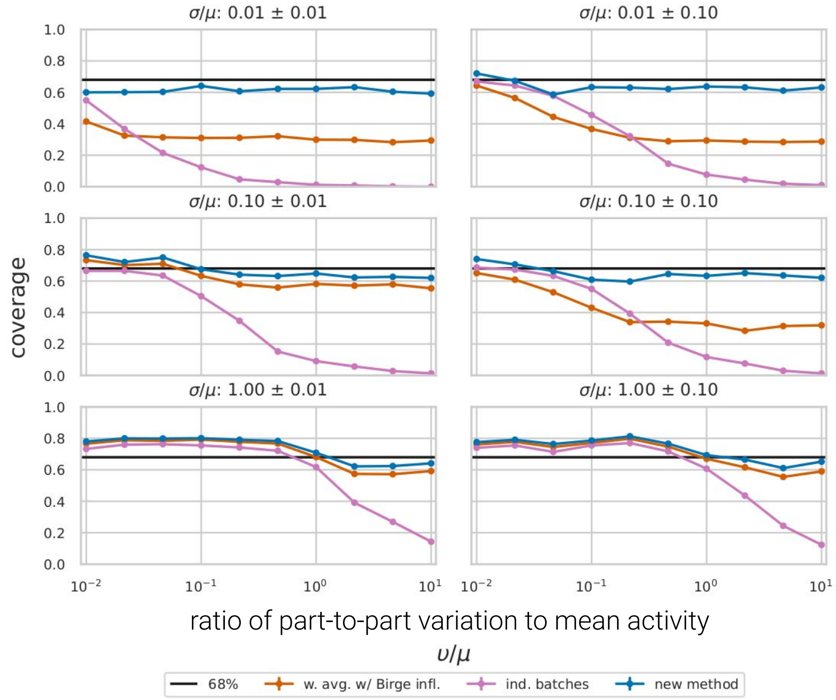
ICP-MS assays of 2 samples from L200 high voltage cables

New method gives better coverage

- Performing Monte Carlo simulations under a Gaussian distributed activity model, we find the new method gives better coverage.



ratio of assay resolution and variation to mean activity



ratio of part-to-part variation to mean activity

(a) $N = 100$ and $N_A = 3$

PEN plate assays

Y. Efremenko et al., J. Inst. **17**, P01010 (2022)

- Custom production of PEN materials using commercially available granulate. Assay performed at each stage during production process - raw materials, molding, and machining.
- Final parts are too low mass to have useful sensitivity.
- **Proper cleaning and handling of final parts is known to be essential to maintaining radiopurity**

See Thursday's talk by Andreas Leonhardt for more details!

	Raw TN-8065S GeMPI4 at LNGS	Discs GeMPI4 at LNGS	Discs OBELIX at LSM	L200 holders GeMPI3 at LNGS
μBq/kg	-	14.3 kg 68 days	5.2 kg 79 days	1.1 kg 68 days
^{228}Ra	< 150	92 ± 25	107 ± 38	< 460
^{228}Th	230 ± 50	32 ± 16	67 ± 18	< 480
^{226}Ra	250 ± 50	60 ± 15	76 ± 22	< 360
^{40}K	1.6 ± 0.4 Bq/kg	< 240	< 600	< 4100

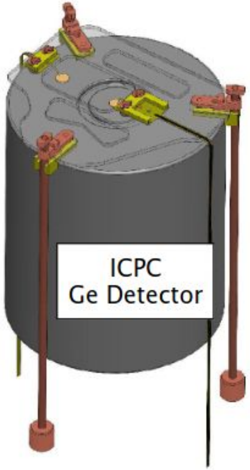
Identification of possible higher background

LEGEND-200 bkg. goal	observed bkg.	GERDA bkg.
2×10^{-4} cts/(keV·kg·yr)	$5.3 \pm 2.2 \times 10^{-4}$ cts/(keV·kg·yr)	$5.2 \pm 1.5 \times 10^{-4}$ cts/(keV·kg·yr)

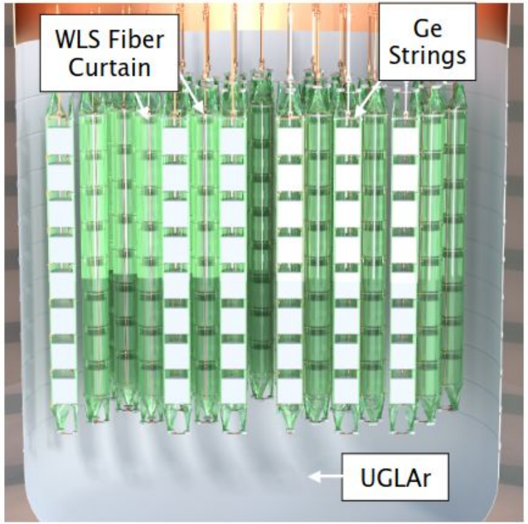
- At low stats, 2.8σ away from goal and consistent with previous GERDA background.
- Current background only reduces L200 sensitivity by ~20% with 1 ton·yr exposure - will achieve physics goal with present background, but want to gain experience and mitigate risks for L1000
- To identify possible background sources, in the past 6 months:
  1. Ran two special deployments with components removed for self-assaying
  2. Disassembled additional components for individual screenings
- **Likely source of higher than expected background identified.**
  - Secular equilibrium in ^{238}U chain seems broken in some components - found to have higher ^{226}Ra than ICP-MS results during construction implied.
- **Continuing assay campaign and re-evaluation of cleaning techniques while reassembling for further physics data taking.**

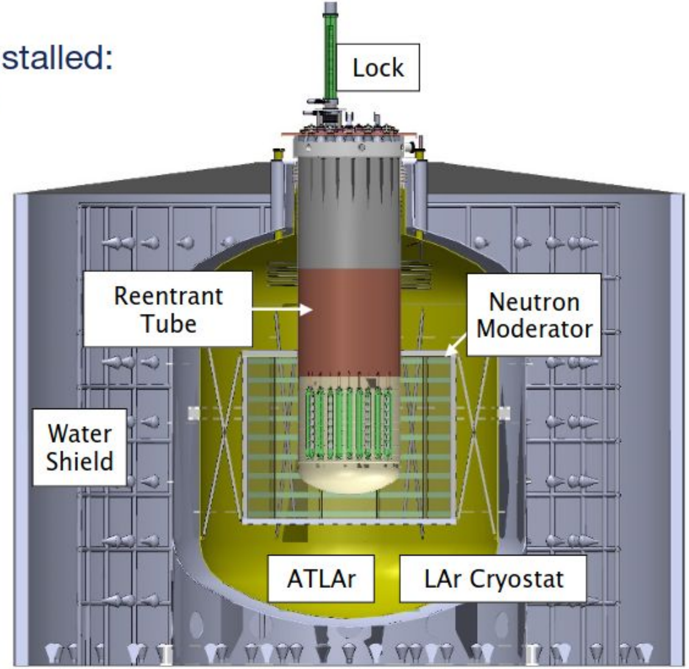
LEGEND-1000 - next generation experiment

336 detectors
3 kg avg. mass



Detector strings can be individually installed:
Early data as detectors are produced





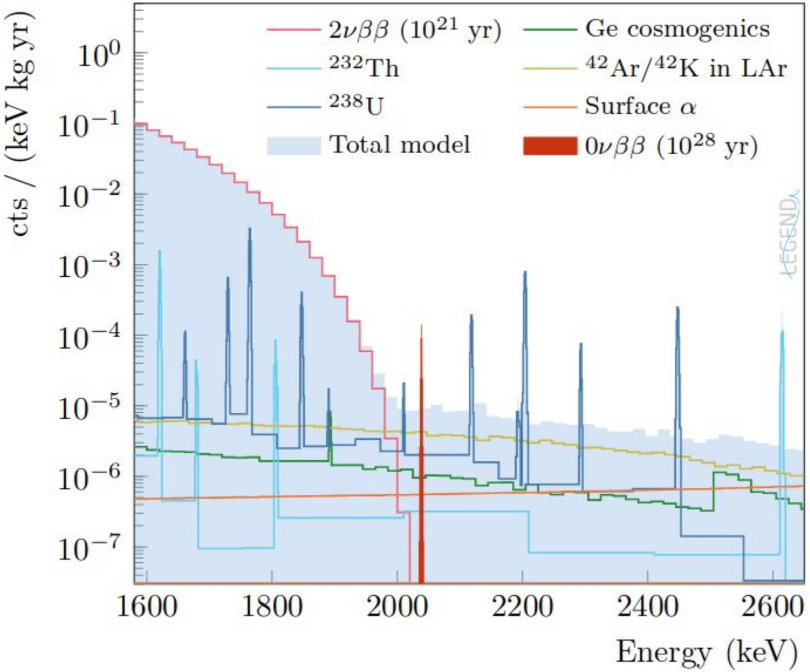
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar
ATLar: Atmospheric Liquid Ar

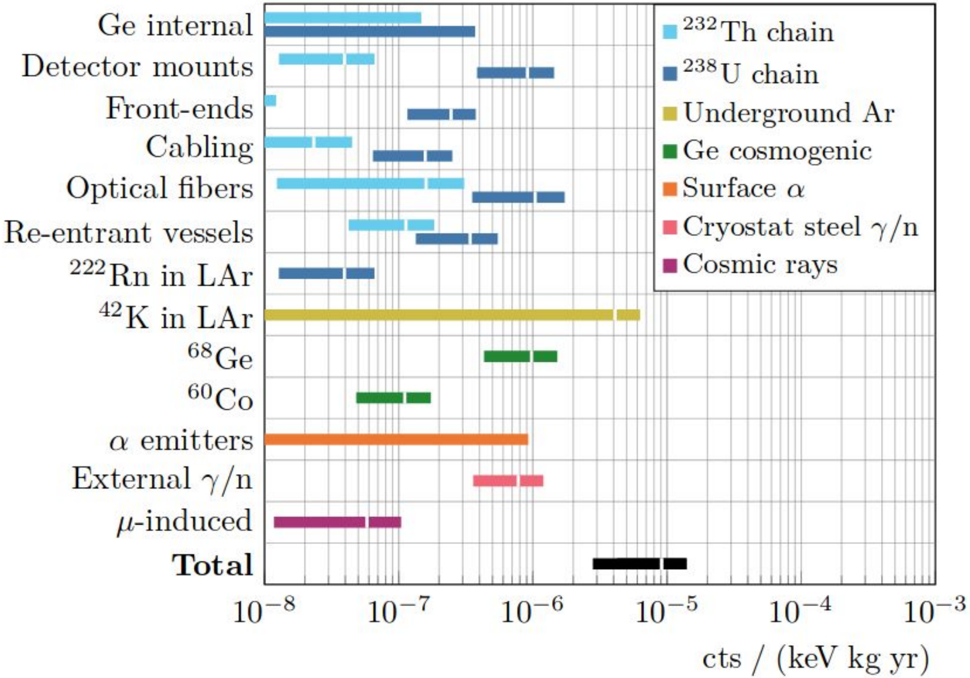
LEGEND-1000
Pre-Conceptual Design Report
arXiv:2107.11462

L1000: 0νββ discovery sensitivity > 10^{28} yr with background goal of 10^{-5} cts/(keV·kg·yr) and 10 ton·yr exp.

L1000 expected backgrounds

Pre-Conceptual design report





L1000 potential assay locations

ICP-MS assay		
Location	**238U sens. [ppt]**	**232Th sens. [ppt]**
LNGS/TUM	0.01 – 10	0.01 – 10
UCL	10	10
Comenius Univ.	0.1 – 10	0.1 – 10
ORNL	1	1

Gamma assay		
Location	**238U sens. [mBq/kg]**	**232Th sens. [mBq/kg]**
LNGS	0.1 – 0.01	0.1 – 0.01
GeRysy/LSC	0.01	0.01
Obelix/LSM	0.1	0.1
SNOLAB	0.1	0.1
Boulby	0.1	0.1
HADES	0.1 – 0.05	0.1 – 0.05

- Additionally, several locations (Jagiellonian Univ., UCL, SNOLAB) can provide radon emanation and surface screening assays for particular L1000 components and to validate cleaning procedures.

Conclusions

- LEGEND-200 recent unblinding and combination with MAJORANA and GERDA sets new limit on ^{76}Ge 0νββ decay half-life.

GERDA, MAJORANA, and LEGEND combined result (90% CL)

	Observed	Sensitivity
$T_{1/2}$	**$> 1.9 \times 10^{26}$ yr**	2.8×10^{26} yr

- New assay averaging technique improves statistical properties of assay predictions, is more agnostic to outliers, and informs future assaying strategy.
- Due to modular design of L200, identification of higher activity components has been investigated and will be mitigated quickly - a great test bed for future L1000 design.
- **Exciting prospects for the future of L200 and L1000!**

LEGEND Collaboration

CIEMAT
Comenius Univ.
Czech Tech. Univ. Prague and IEAP
Daresbury Lab.
Duke Univ. and TUNL
Gran Sasso Science Inst.
Indiana Univ. Bloomington
Inst. Nucl. Res. Rus. Acad. Sci.
Jagiellonian Univ.
Joint Inst. for Nucl. Res.
Joint Res. Centre Geel
Lab. Naz. Gran Sasso
Lancaster Univ.
Leibniz Inst. for Crystal Growth
Leibniz Inst. for Polymer Research
Los Alamos Natl. Lab.
Max Planck Inst. for Nucl. Phy.
Max Planck Inst. for Physics
Natl. Res. Center Kurchatov Inst.
Natl. Res. Nucl. Univ. MEPhI
North Carolina State Univ.
Oak Ridge Natl. Lab.
Polytech. Univ. of Milan
Princeton Univ.
Queen's Univ.
Roma Tre Univ. and INFN
Simon Fraser Univ.
SNOLAB
South Dakota Mines
Tech. Univ. Dresden
Tech. Univ. Munich
Tennessee Tech. Univ.
Univ. of California and LBNL
Univ. College London
Univ. of L'Aquila and INFN
Univ. of Cagliari and INFN
Univ. of California San Diego
Univ. of Houston
Univ. of Liverpool
Univ. of Milan and INFN
Univ. of Milano Bicocca and INFN
Univ. of New Mexico
Univ. of North Carolina at Chapel Hill
Univ. of Padova and INFN
Univ. of Regina
Univ. of South Carolina
Univ. of South Dakota
Univ. of Tennessee
Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and CENPA
Univ. of Zurich
Williams College

LEGEND detector geometries

- L1000 will use exclusively ICPCs
    - large mass ($\gtrsim$ 3.5 kg) with energy resolution of 2.5 keV FWHM @ $Q_{\beta\beta}$