

The LEGEND Program to Search for Neutrinoless Double Beta Decay

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on behalf of the LEGEND collaboration

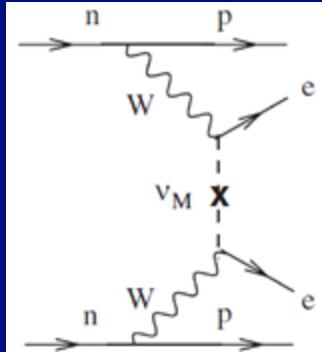
European Nuclear Physics Conference
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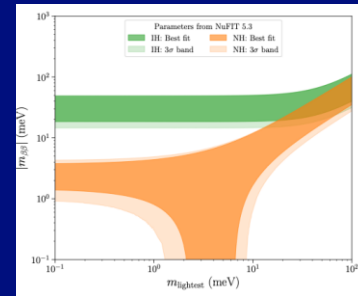
LEGEND-200 Results



Moving Forward



Summary/ Conclusion



Introduction/Overview

Open Questions about Neutrinos

- Nearly 100 years after Pauli's "desperate remedy" of the neutrino we still have open questions about this little neutral particle:
 1. Mass hierarchy – Inverted/Normal?
 2. Absolute mass
 3. Is the neutrino its own antiparticle?

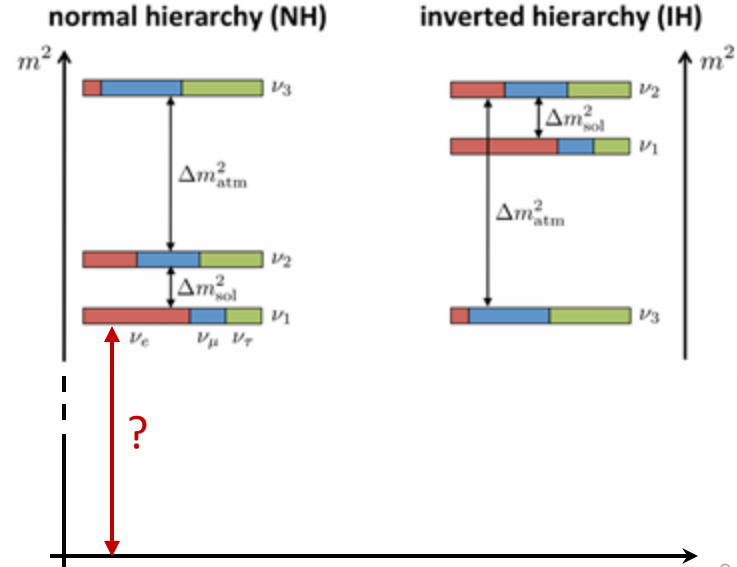
Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,
Wie der Ueberbringer dieser Zellen, den ich huldvollst



Open Questions about Neutrinos



- Nearly 100 years after Pauli's "desperate remedy" of the neutrino we still have open questions about this little neutral particle:
 1. Mass hierarchy – Inverted/Normal?
 2. Absolute mass
 3. Is the neutrino its own antiparticle?

Neutrinoless Double Beta Decay can directly probe question 3 and inform 1 and 2

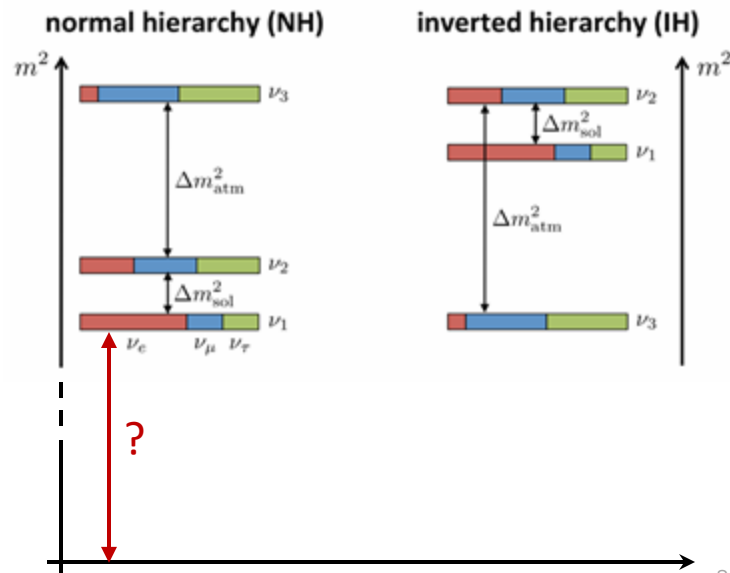
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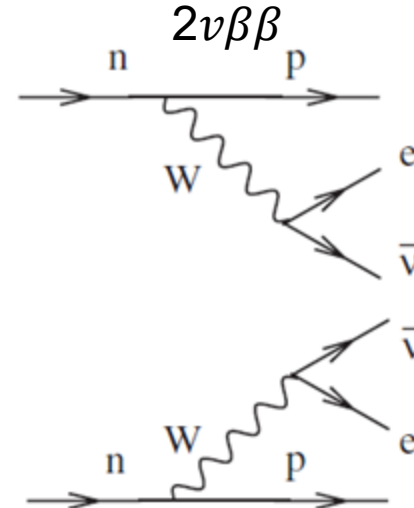
Double Beta Decays

LEGEND

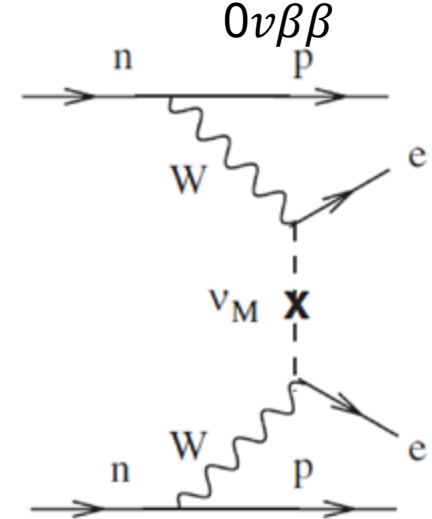
- Comes in two types: $2\nu\beta\beta$ and $0\nu\beta\beta$
- $0\nu\beta\beta$ would be definitive evidence that neutrinos are Majorana fermions
- Rate Given by:

$$[T_{\frac{1}{2}}^{0\nu}]^{-1} = G_{0\nu}^{(0)} |M'_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

- All experiments measure: $[T_{\frac{1}{2}}^{0\nu}]^{-1}$
- $\langle m_{\beta\beta} \rangle$ contains the neutrino mass information
- $|M'_{0\nu}|^2$ contains all the nuclear physics



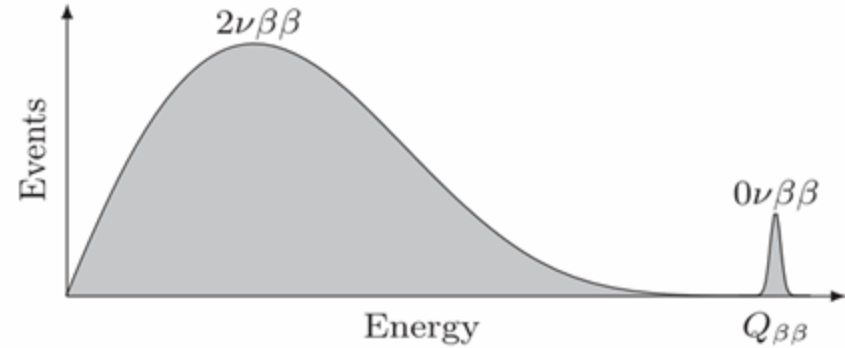
Rare Process:
 $T_{\frac{1}{2}}^{2\nu} \in [10^{18}-10^{24}]$ years
 Observed in 11 isotopes



Super Rare Process:
 $T_{\frac{1}{2}}^{0\nu} > 10^{25}$ years
 Beyond the Standard Model!

How to find $0\nu\beta\beta$

- $0\nu\beta\beta$ is a tiny signal compared to background and the $2\nu\beta\beta$ signal
- Experiments need to increase the signal rate by increasing the:
 - Exposure ($M \cdot t$)
 - Detector Efficiency (ϵ)
 - Natural Signal Rate (f)
- Background rate determined by:
 - Background Index (BI)
 - Detector energy resolution (ΔE)



$$\text{Bg limited} \quad T_{1/2}^{0\nu} \propto \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

$$\text{Bg-free} \quad T_{1/2}^{0\nu} \propto \epsilon \cdot f \cdot M \cdot t$$

ϵ : Efficiency

f : Isotopic abundance

M : Mass

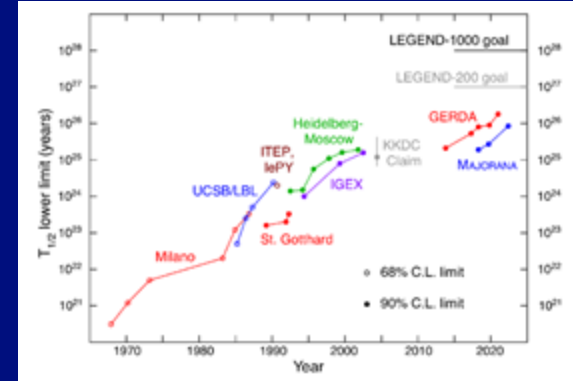
t : Time

BI : Background Index

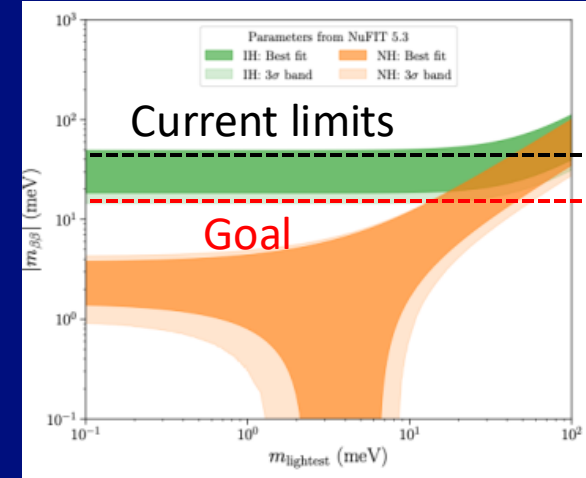
ΔE : Energy Resolution

Current State of the Field

- Over 50 years we have advanced nearly 6 orders of magnitude in sensitivity
- Goal is now to probe the inverted hierarchy with the next generation of experiments – in our case LEGEND-1000



Isotope	Experiment	Paper	Half Life Limit (10^{25} yrs)	$m_{\beta\beta}$ limit (meV)
Xe-136	KamLAND-Zen	https://arxiv.org/abs/2406.11438	38	28-122
Ge-76	LEGEND-200 + GERDA + MJD	https://arxiv.org/abs/2505.10440	19	75-200
Te-130	CUORE	https://arxiv.org/abs/2404.04453	3.8	70-240



The LEGEND Experimental Program



LEGEND-200

- 200 kg of $^{\text{enr}}\text{Ge}$ detectors
- Running since 2023
- Goals:
 - 1 tonne-yr of exposure
 - Background: $2 * 10^{-4}$ cts/keV * kg * yr
 - $T_{\frac{1}{2}}^{0\nu} > 10^{27}$ years ($m_{\beta\beta} \sim 30\text{--}70$ meV)

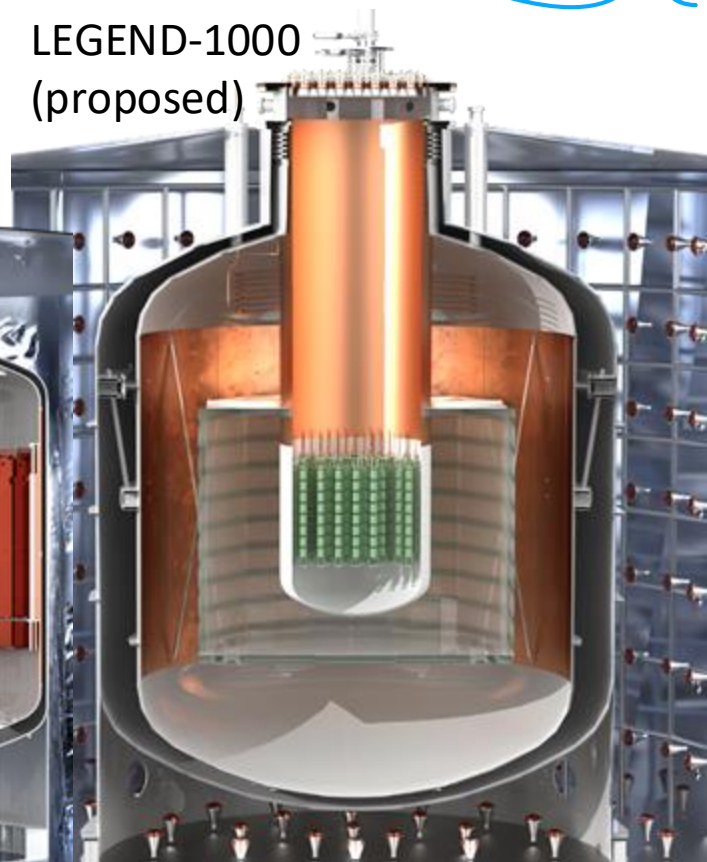
LEGEND-1000

- 1000 kg of $^{\text{enr}}\text{Ge}$ detectors
- To be installed at LNGS
- Goals:
 - 10 tonne-yr of exposure
 - Background: 10^{-5} cts/keV * kg * yr
 - $T_{\frac{1}{2}}^{0\nu} > 10^{28}$ years ($m_{\beta\beta} \sim 10\text{--}20$ meV)

LEGEND-200 (currently operating)



LEGEND-1000 (proposed)

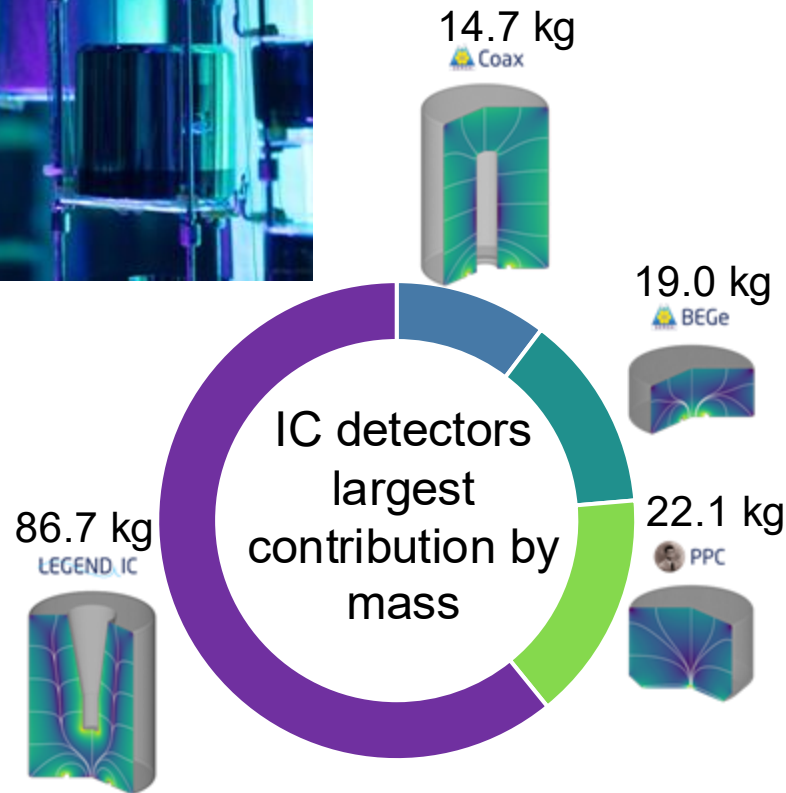


LEGEND-200 Experiment

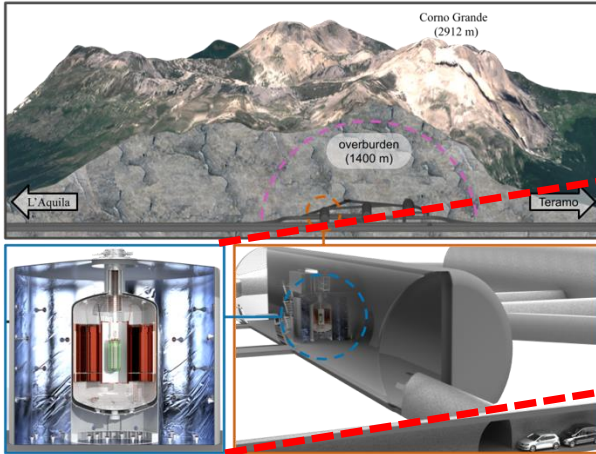
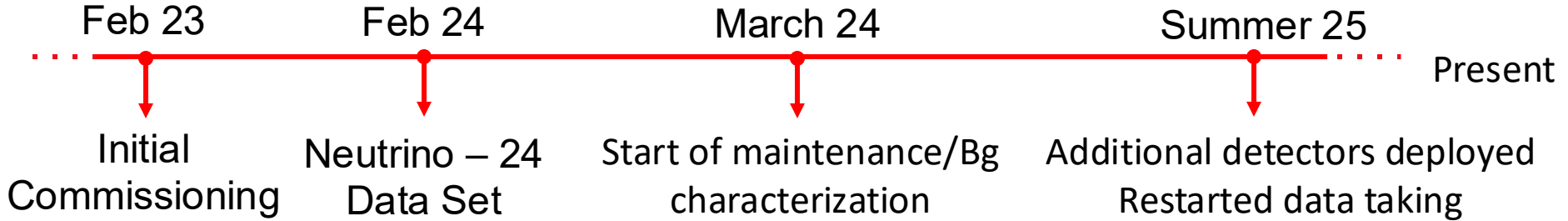
LEGEND-200 Germanium Detectors



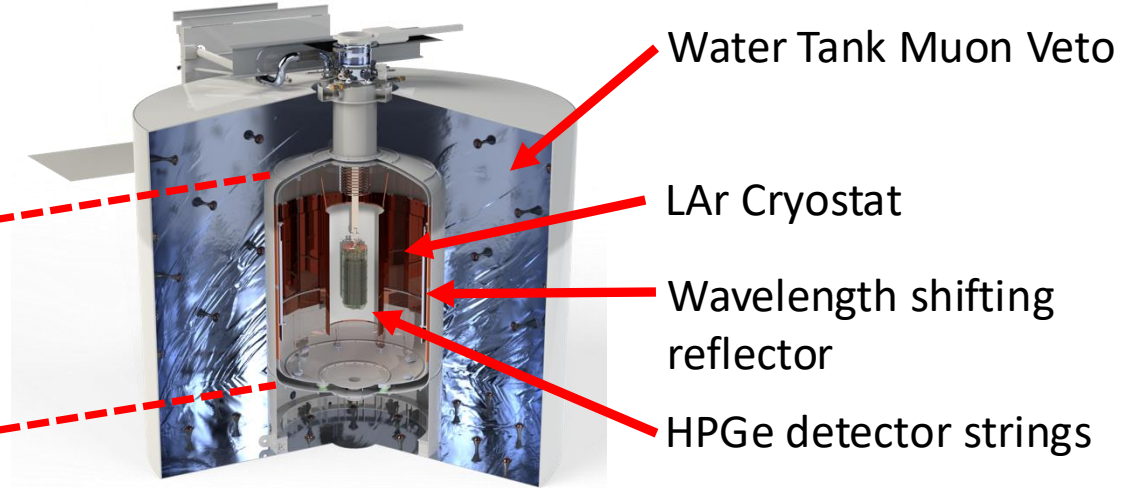
- LEGEND-200 has deployed HPGe detectors for use in a source = detector configuration
- HPGe have a proven track record:
 - Good resolution (0.12% FWHM @ $Q_{\beta\beta}$)
 - Low background counts (10^{-4} cts/keV * kg * yr)
- For Neutrino result (<https://arxiv.org/abs/2508.18573>)
 - 130 kg detectors deployed
 - 101 detectors in 10 strings
 - 61 kg * yr total exposure
- Present campaign – Summer 2025
 - Detectors redeployed
 - Additional IC detectors installed
 - 137.2 kg of detectors deployed across 60 detectors



LEGEND-200 Experiment

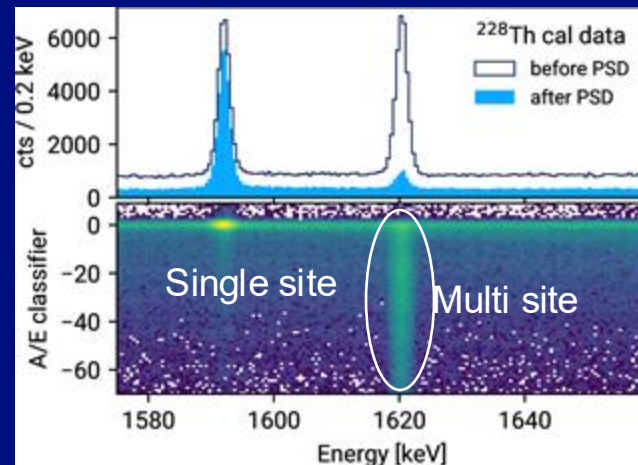


Running at LNGS

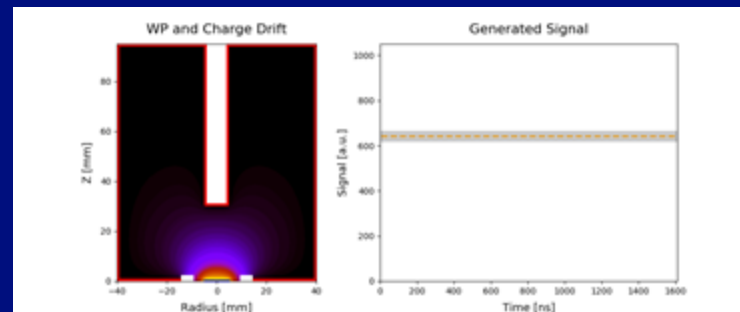
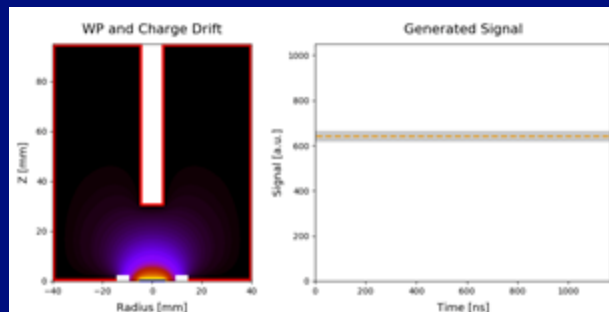


LEGEND-200 Background Rejection (Pulse Shape Discrimination)

- LEGEND-200 uses a combination of PSD cuts to cut background events
 - $A/E = \max(\text{current})/\text{energy}$
 - Late Charge (LQ) surface event cut
- PSD observables - Monitored with weekly Th-228 calibration runs



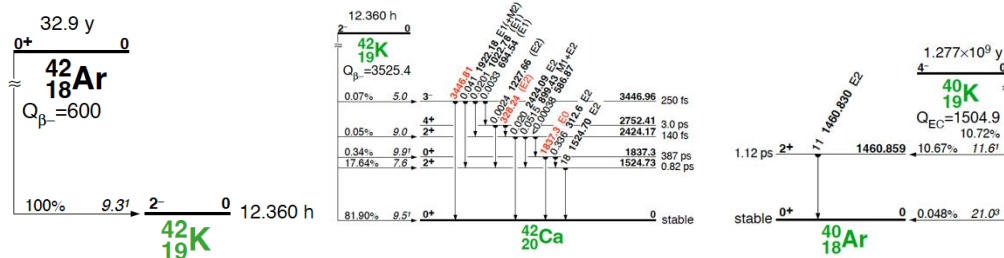
- Charge waveform
- Current (Smoothed derivative of charge waveform)



LEGEND-200 Background Rejection (Liquid Argon Instrumentation)

LEGEND

- LAr serves as coolant/active shield
- LAr helps with U/Th backgrounds
- High light yield configuration with inner/outer barrels
- Stability of argon properties monitored through the Liquid Argon Monitoring Apparatus.



Outer barrel
40 channels



Inner barrel
18 channels

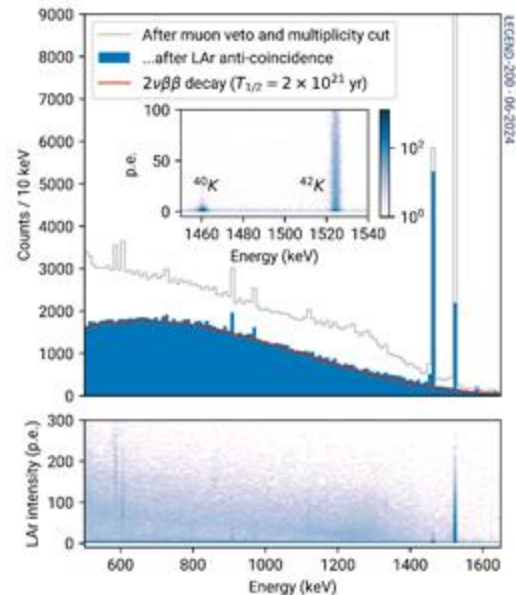
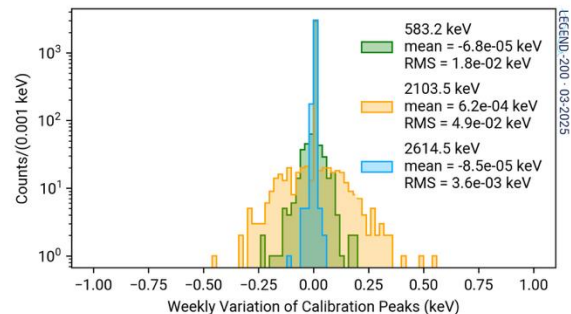
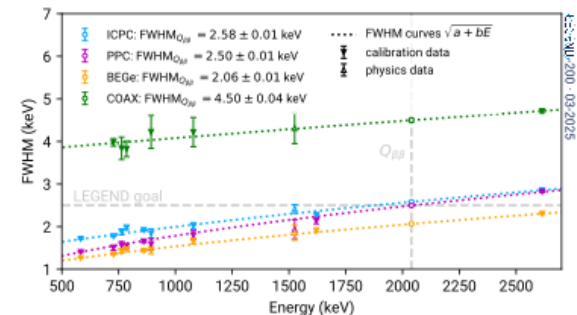
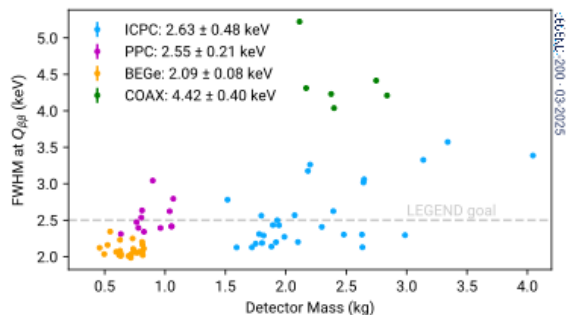


Photo credits Mike Willers

LEGEND-200 Energy Resolution And Stability



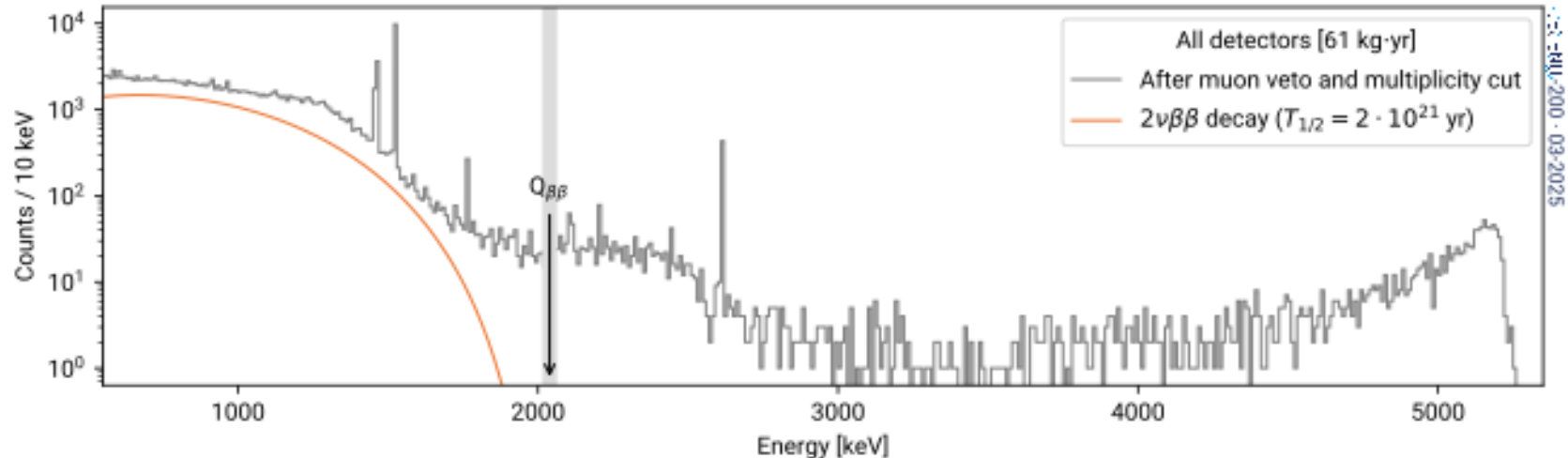
- LEGEND detectors are meeting energy resolution goals (0.12% @ $Q_{\beta\beta}$)
- Energy scale stable over the course of weekly Th-228 calibration runs
- Energy observables used to create data partitions to filter out best data taking runs
- $2\nu\beta\beta$ not an issue due to resolution



LEGEND-200 Results

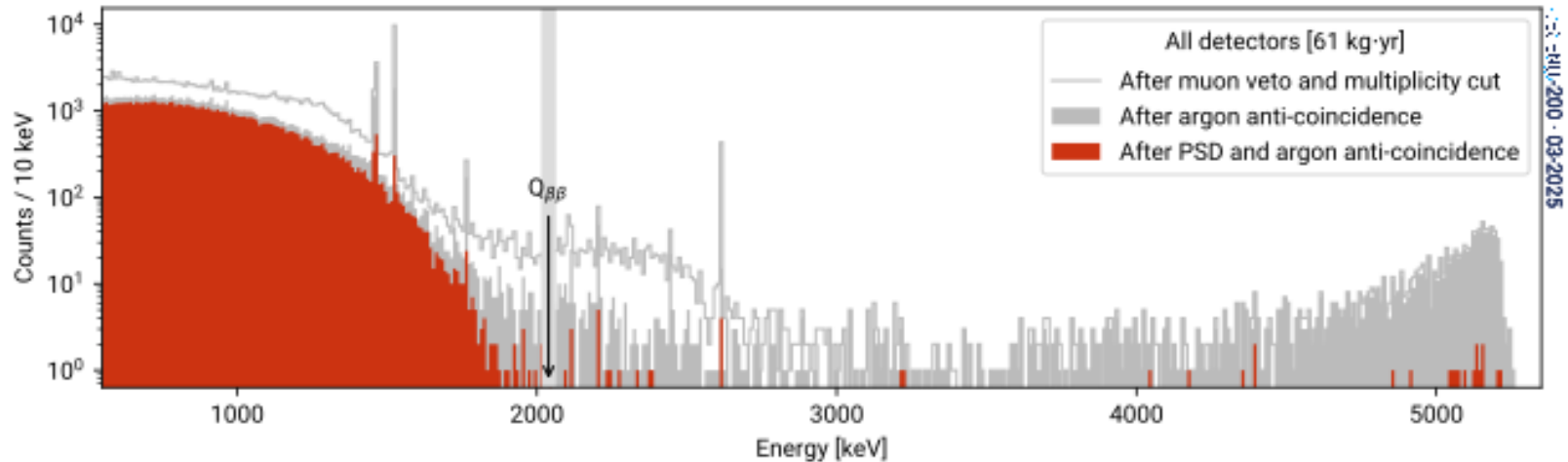
LEGEND-200 Spectrum

- $0\nu\beta\beta$ blinded analysis performed with a 50 keV blinded window around $Q_{\beta\beta}$
- Spectrum after:
 - Data cleaning: 95-99% survival fraction
 - Muon veto: 2 events removed
 - Ge-anticoincidence cuts (Multiplicity cut): 26% of events removed at $Q_{\beta\beta}$



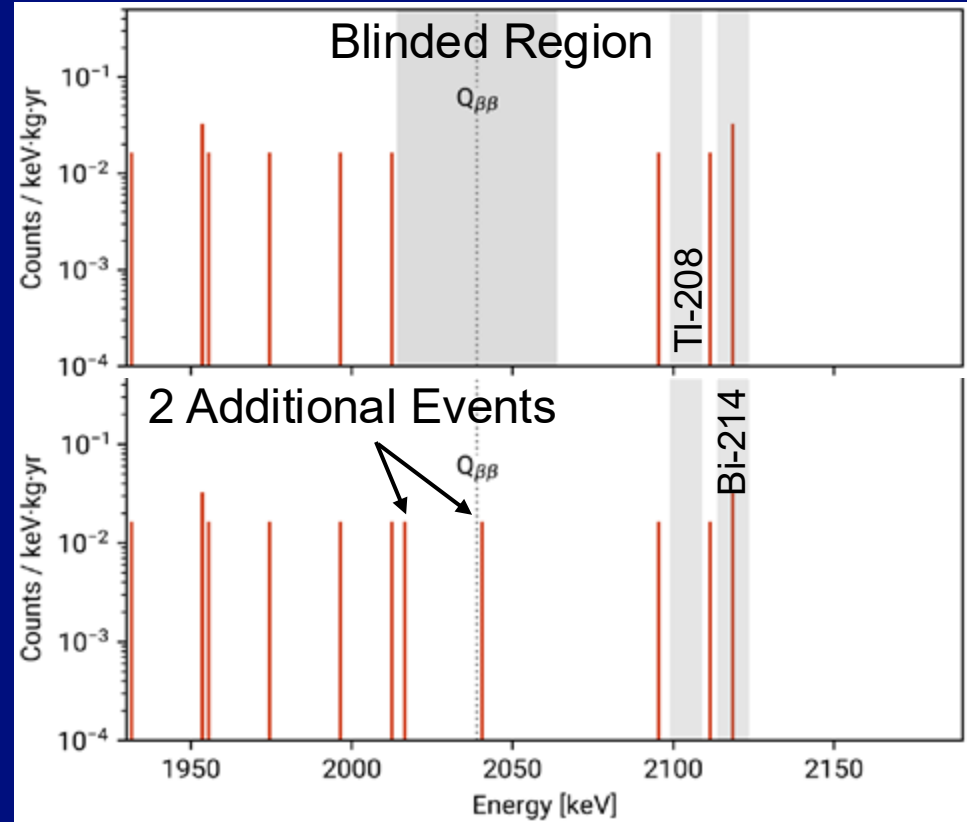
Spectrum after PSD and LAr Cuts

- Cuts applied: data cleaning + muon veto + multiplicity cut + PSD
- LAr anti-coincidence:
 - PSD and LAr cuts complement each other
 - Strong suppression of remaining Compton background
 - Largest remaining background signal: $2\nu\beta\beta$



LEGEND-200 Results – Blinding

- LEGEND-200 performed a blinded search using a 50 keV blinding window and a 1930-2190 keV Bg estimation window
- Collected two data sets:
 - Golden (48 kg * yr) - ν 24 dataset
 $BI_{golden} = 5.4_{-2.0}^{+2.7} \times 10^{-4} \text{cts/keV} \cdot \text{kg} \cdot \text{yr}$
 - Comparable to GERDA
 - Sliver (13 kg * yr): mainly Coax
 $BI_{sliver} = 13.0_{-5.4}^{+8.0} \times 10^{-4} \text{cts/keV} \cdot \text{kg} \cdot \text{yr}$

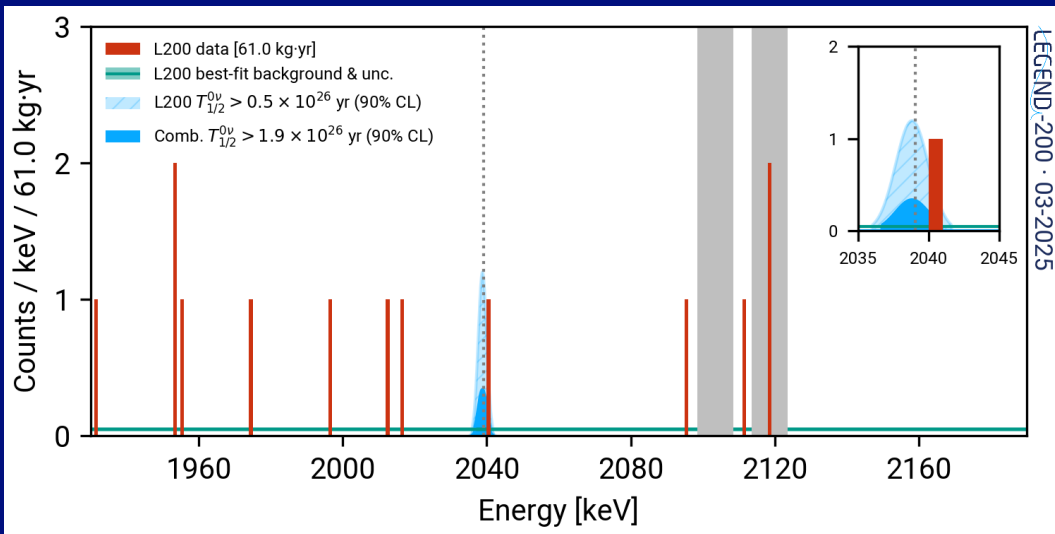


LEGEND-200 Results



- Combined GERDA+MJD+LEGEND-200 analysis
- Single event near $Q_{\beta\beta}$ weakens limit
- Results:

Parameter	Value (90% CL)
Observed	$T_{\frac{1}{2}}^{0\nu\beta\beta} > 1.9 \times 10^{26} \text{ yr}$
Sensitivity	$T_{\frac{1}{2}}^{0\nu\beta\beta} > 2.8 \times 10^{26} \text{ yr}$
Mass	$m_{\beta\beta} < 75 - 200^* \text{ meV}$



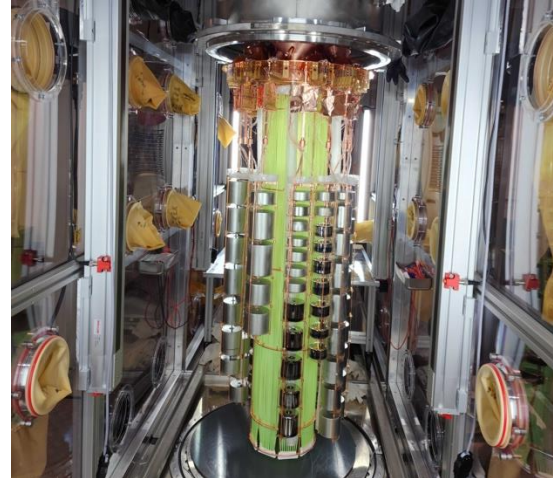
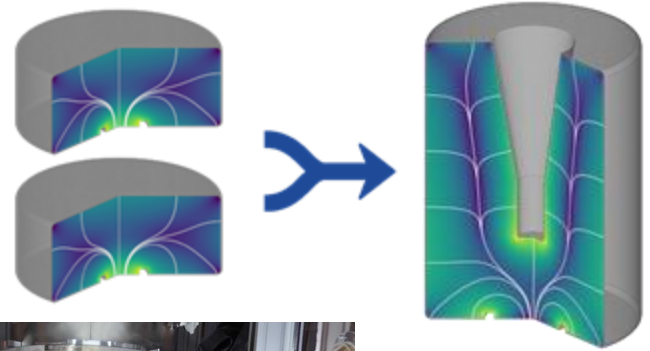
World Leading Sensitivity

Paper(<https://arxiv.org/abs/2508.18573>) currently under review at PRL

Moving Forward/Summary

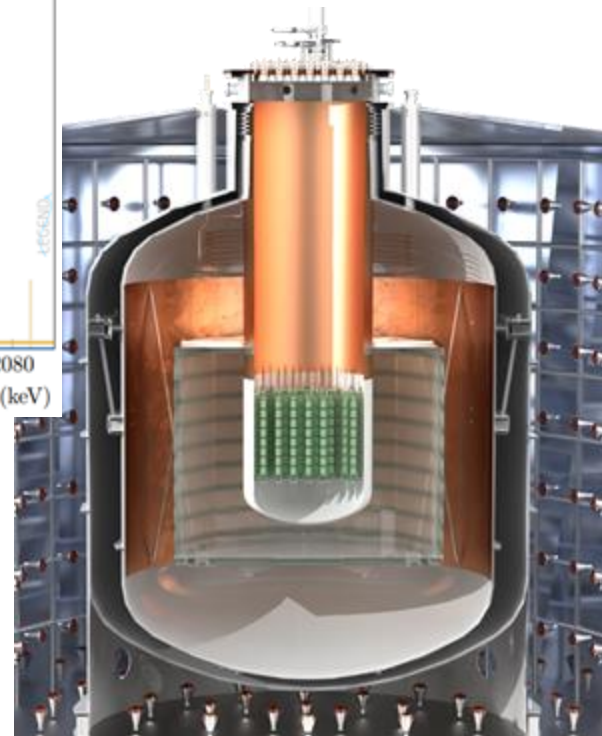
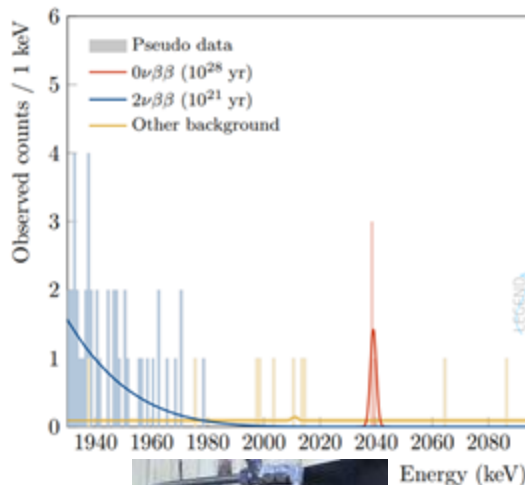
Immediate Plans

- Melt smaller detectors into larger ICPC detector to further sensitivity reach
- Radio-assay campaign to verify radiopurity of components
- Based on previous experience – reevaluate cleaning procedures
- Late Aug. 25 – Started data taking with new deployment

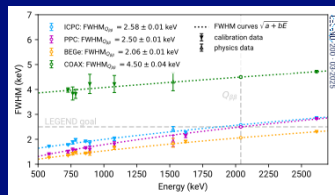
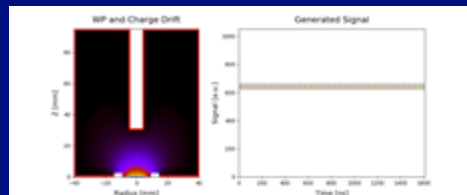


LEGEND-1000

- LEGEND-1000 is the upgraded version of LEGEND-200 capable of sensitivity well beyond LEGEND-200 incorporating several innovations
- Goal is to reduce backgrounds from LEGEND-200 by a factor of 20 using a variety of techniques
- R&D campaign is well underway
- Funding for design and infrastructure of LEGEND-1000 has already started



Summary/Conclusion



- LEGEND program has shown excellent performance in resolution/stability/BI/PSD together with LAr veto
- Latest Results:
 - Combined limit (90% CL): $T_{\frac{1}{2}}^{0\nu\beta\beta} > 1.9 \times 10^{26} \text{ yr}$
 - Sensitivity limit (90% CL): $T_{\frac{1}{2}}^{0\nu\beta\beta} > 2.8 \times 10^{26} \text{ yr}$
- Restarted data taking in Aug. 2025 with 137 kg of HPGe
- LEGEND-1000 preparations well underway

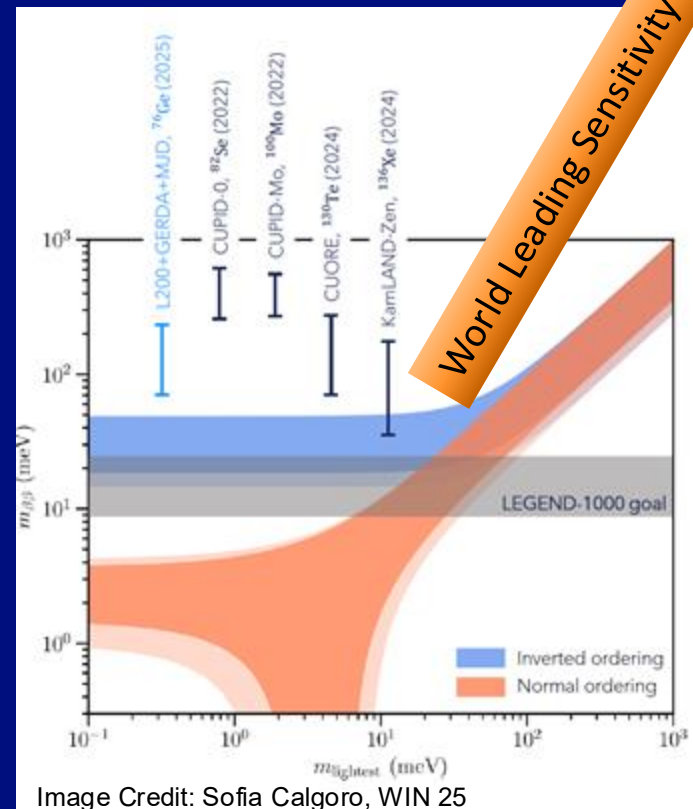
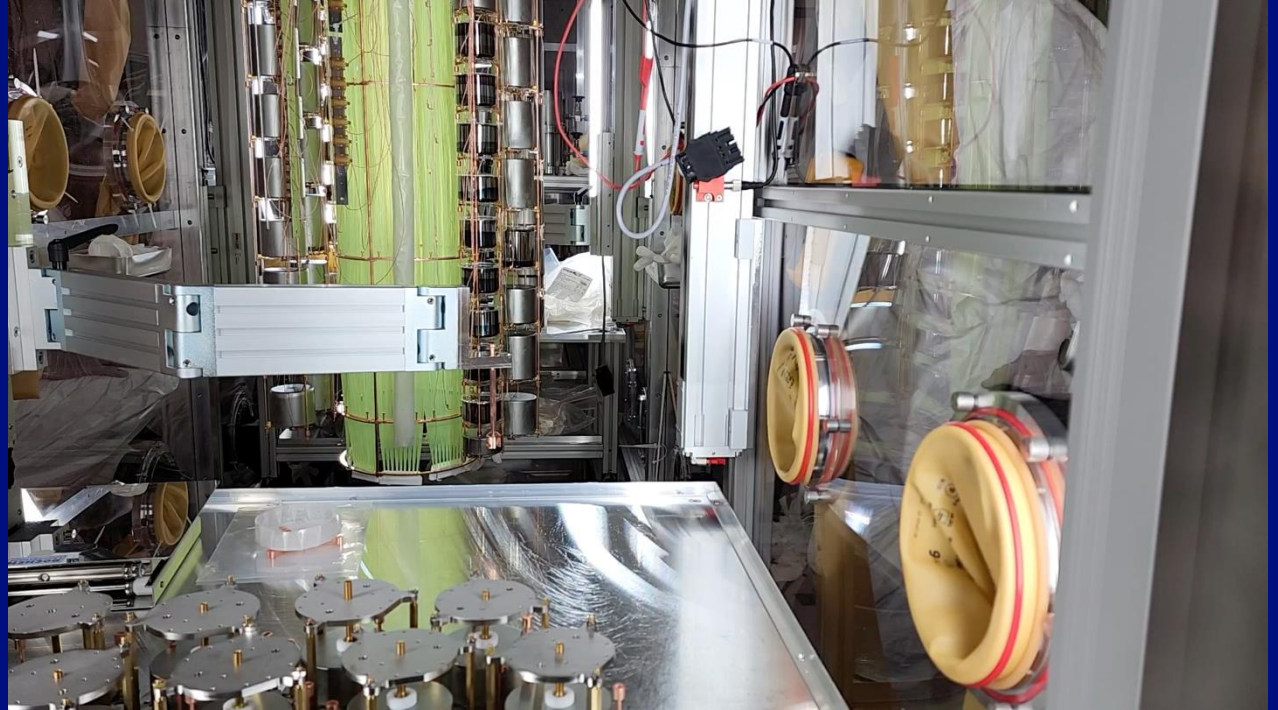


Image Credit: Sofia Calgoro, WIN 25

**Thank you for
your attention!**



Backup

LEGEND

LEGEND-200 Background Model



- Bayesian background using full dataset + extra 10.2 kg * yr of dedicated runs
- No unexpected background components
- Radioassays underpredicted U and Th contributions before cuts
 - Data cuts highly effective at removing excess events
 - Screening campaign + re-evaluation of cleaning techniques ongoing
 - Ge-anticoincidence cuts (Multiplicity cut): 26% of events removed at $Q_{\beta\beta}$

