

Advancing the Search for Neutrinoless Double-Beta Decay with LEGEND

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Zürich^{UZH}**





Large Enriched Germanium Experiment for Neutrinoless double beta Decay

LEGEND

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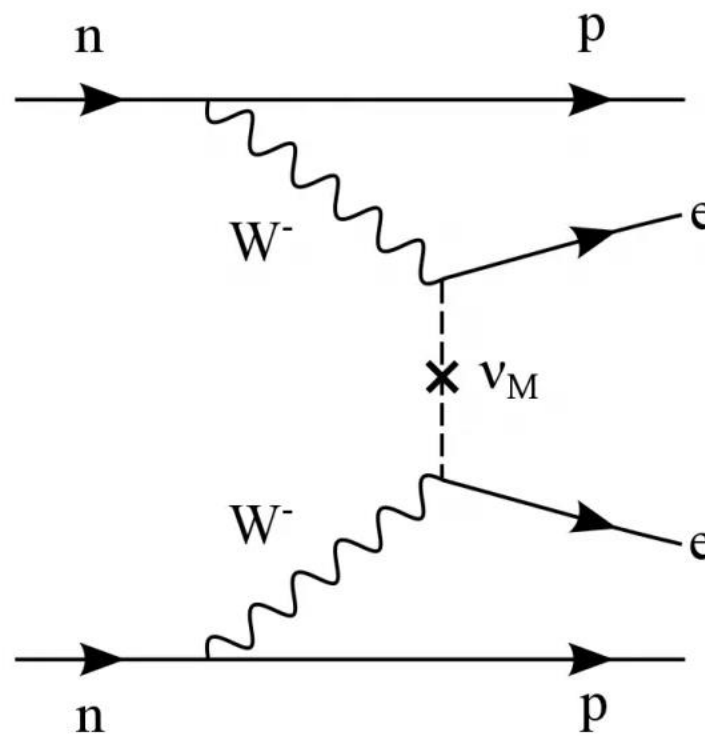
58 institutions across 13 countries are collaboratively advancing a phased experimental program of LEGEND

LEGEND

Large Enriched Germanium Experiment for Neutrinoless double beta Decay

1. Neutrinoless double beta decay ($0\nu\beta\beta$)

- ◆ create matter without antimatter
- ◆ lepton number violation
- ◆ currently not observed



LEGEND

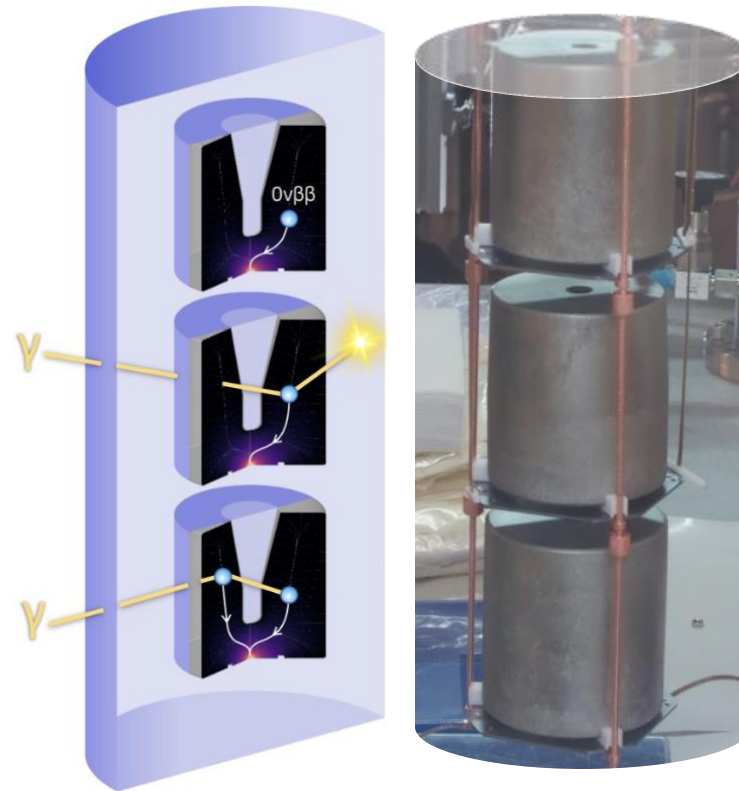
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2. Enriched germanium detectors

- ◆ excellent energy resolution
- ◆ topological discrimination
- ◆ leading material for $0\nu\beta\beta$ searches



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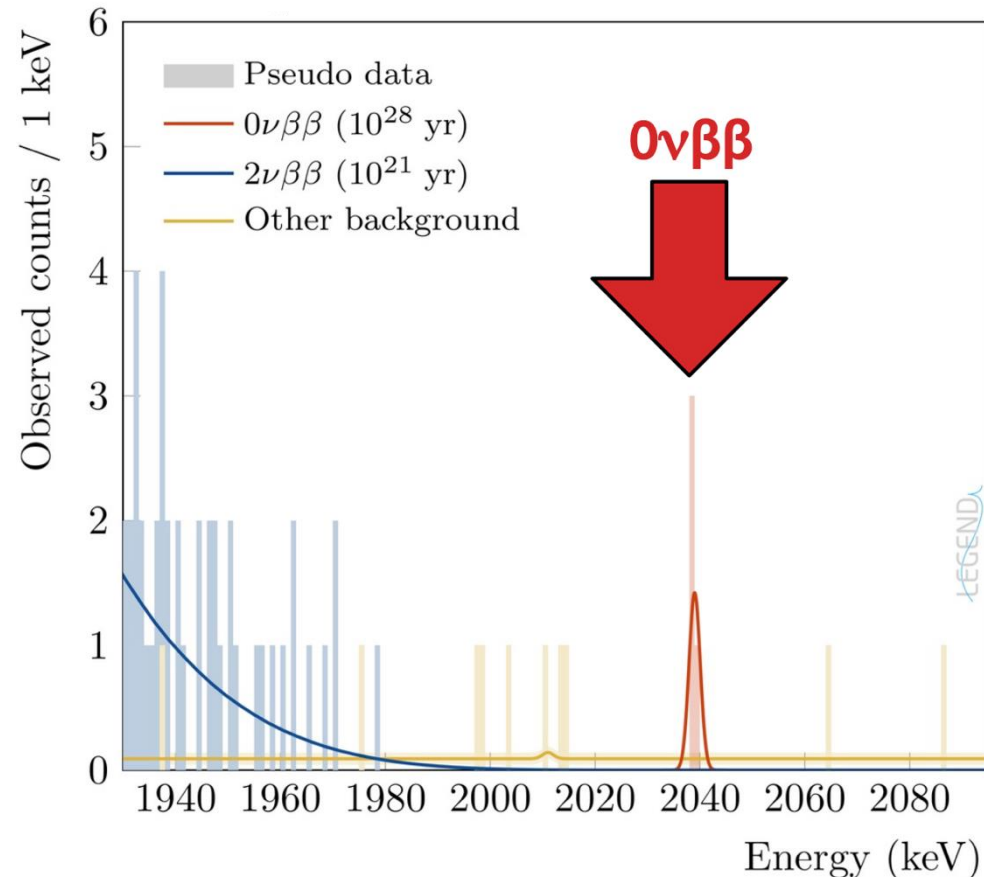
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3. The LEGEND experiment

- ◆ indeed large – 1000 kg of germanium
- ◆ optimized for $0\nu\beta\beta$ discovery
- ◆ or push the lower limit on decay half-life to 10^{28} yr

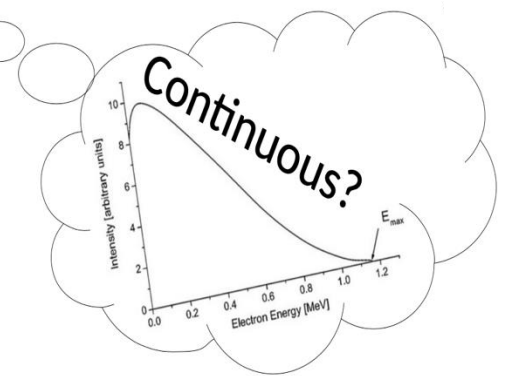
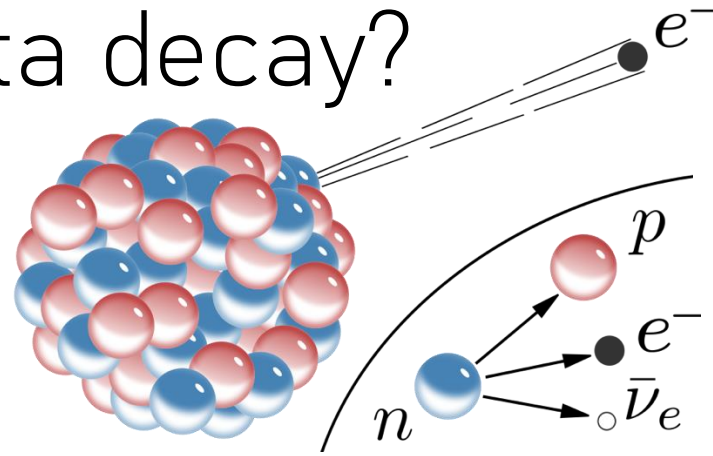
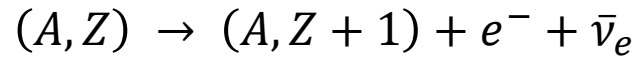


But let's start from the beginning...



What is double beta decay?

- β -decay in the Standard Model:

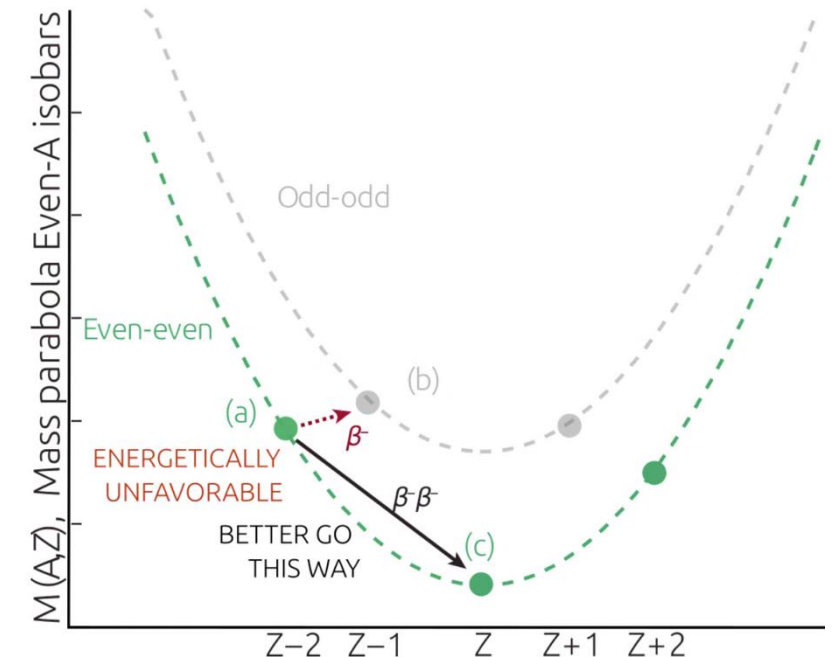


- when β -decay from even-even (a) to odd-odd (b) atoms isn't energy-efficient, $\beta\beta$ -decay occurs, resulting in:



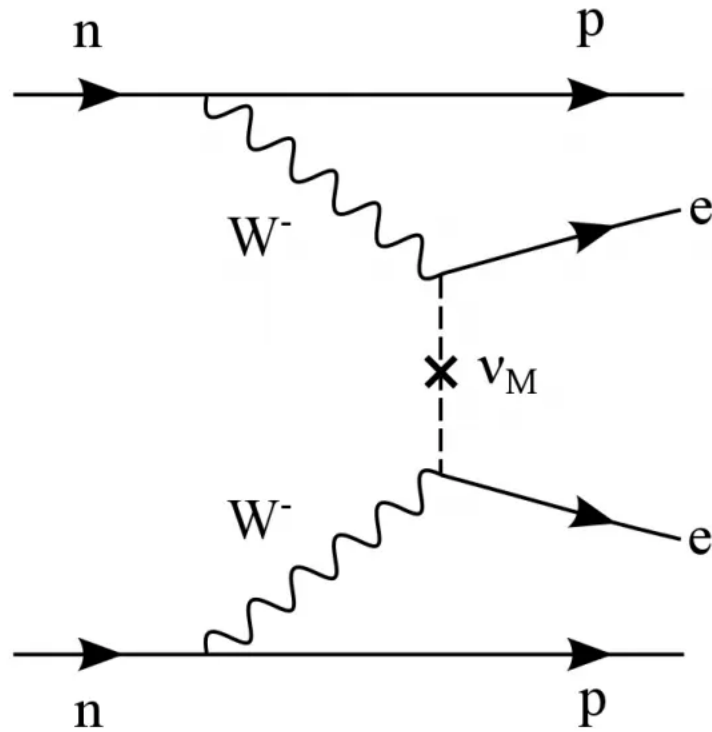
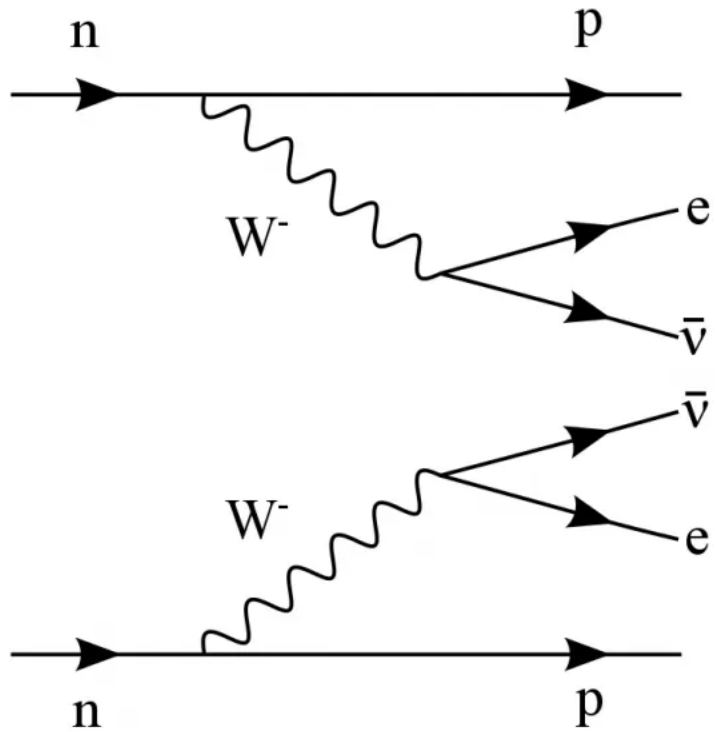
Isotopes like ⁴⁸Ca, ⁷⁶Ge, ¹⁰⁰Mo, ¹³⁰Te, ¹³⁶Xe can undergo $\beta\beta$ -decay

This rare process was first observed by S. Elliot et al, in 1987, marking the longest decay lifetime ($T_{1/2} > 10^{20}$ yr)* then.

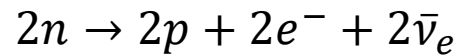


*This record is now surpassed by other isotopes' $\beta\beta$ -decay and the double electron capture of ¹²⁴Xe (Nature 568, 532-535, 2019)

Neutrinoless Double Beta Decay



Two neutrino double beta decay ($2\nu\beta\beta$) Neutrinoless double beta decay ($0\nu\beta\beta$)

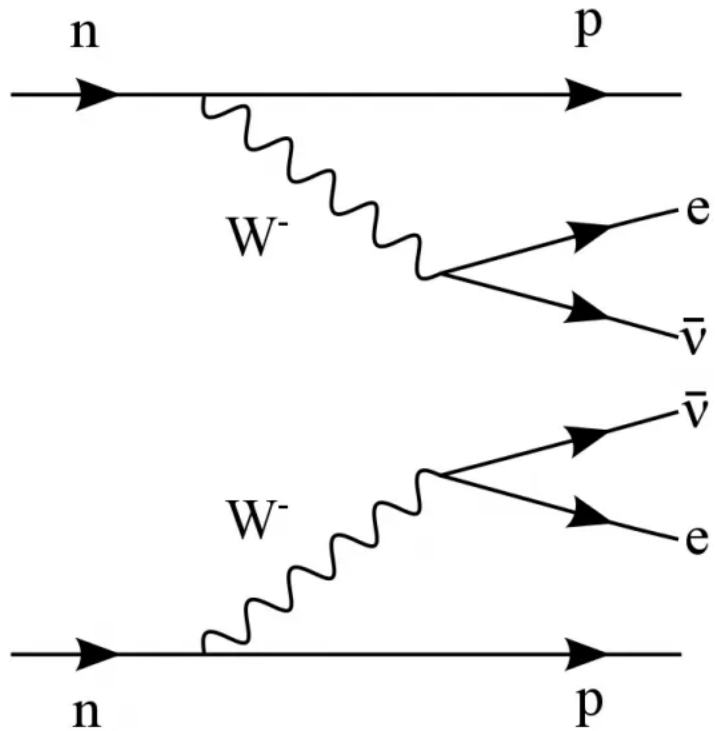


(in a nucleus)

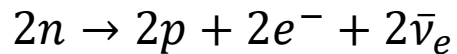


(in a nucleus)

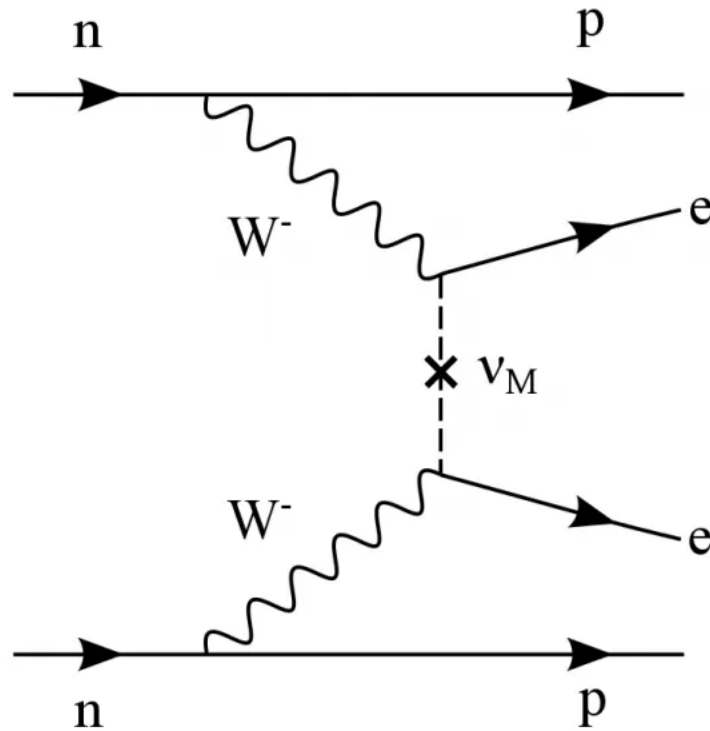
Neutrinoless Double Beta Decay



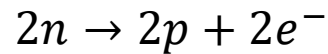
Two neutrino double beta decay ($2\nu\beta\beta$)



(in a nucleus)



Neutrinoless double beta decay ($0\nu\beta\beta$)



(in a nucleus)

No neutrinos are emitted, under the hypothesis of light neutrino exchange

Charge conjugate spinor:

$$\psi^C = C\bar{\psi}^T$$

Majorana field:

$$\psi = \psi^C$$

$$\psi = \psi_L + \psi_L^C$$

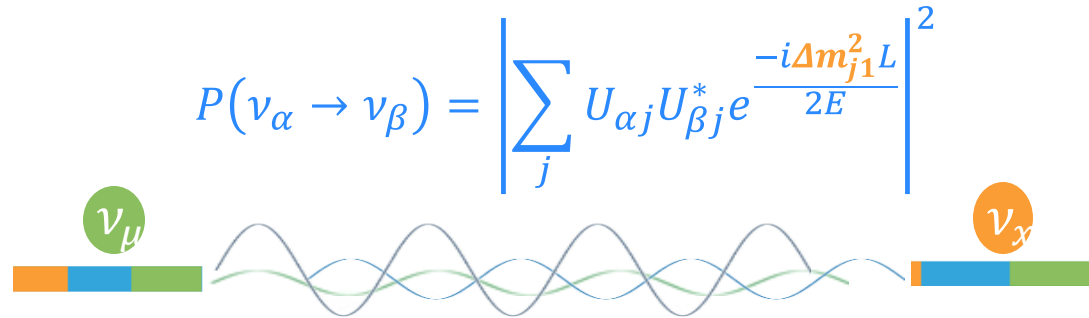


The neutron decays under emission of a right-handed 'anti-neutrino' ν_L^C

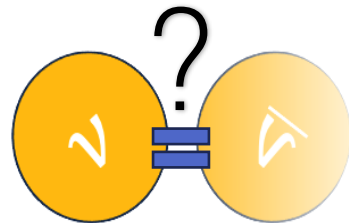
- the ν_L^C must be absorbed at the second vertex as left-handed 'neutrino' ν_L
- for the decay to happen neutrinos and anti-neutrinos must be identical, thus Majorana particles

Neutrino mass problem

Standard Model posits massless neutrinos, yet **flavour oscillations suggest mass**:



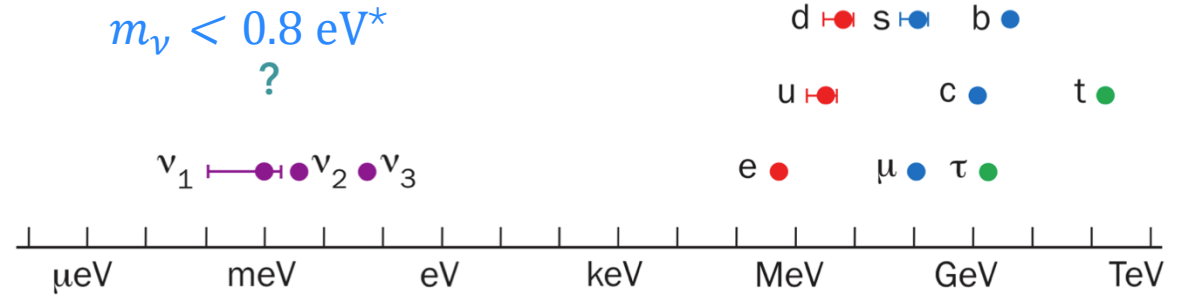
Could neutrinos be their own antiparticle and have a Majorana mass?



Neutrinos are chargeless fermions → may possess a Majorana mass, potentially yielding small masses via the 'see-saw' mechanism

What is the origin of small neutrino masses?

$$m_\nu < 0.8 \text{ eV}^*$$



Dirac mass lagrangian:

$$-\mathcal{L}_D = m_D \bar{\nu}_L \nu_R + h.c.$$

+ Majorana mass lagrangian:

$$-\mathcal{L}_{M+D} = m_D \bar{\nu}_L \nu_R + \frac{1}{2} M \bar{\nu}_R^C \nu_R + h.c.$$

$M \gg m_D \rightarrow$ Light (ν) & heavy (N) states

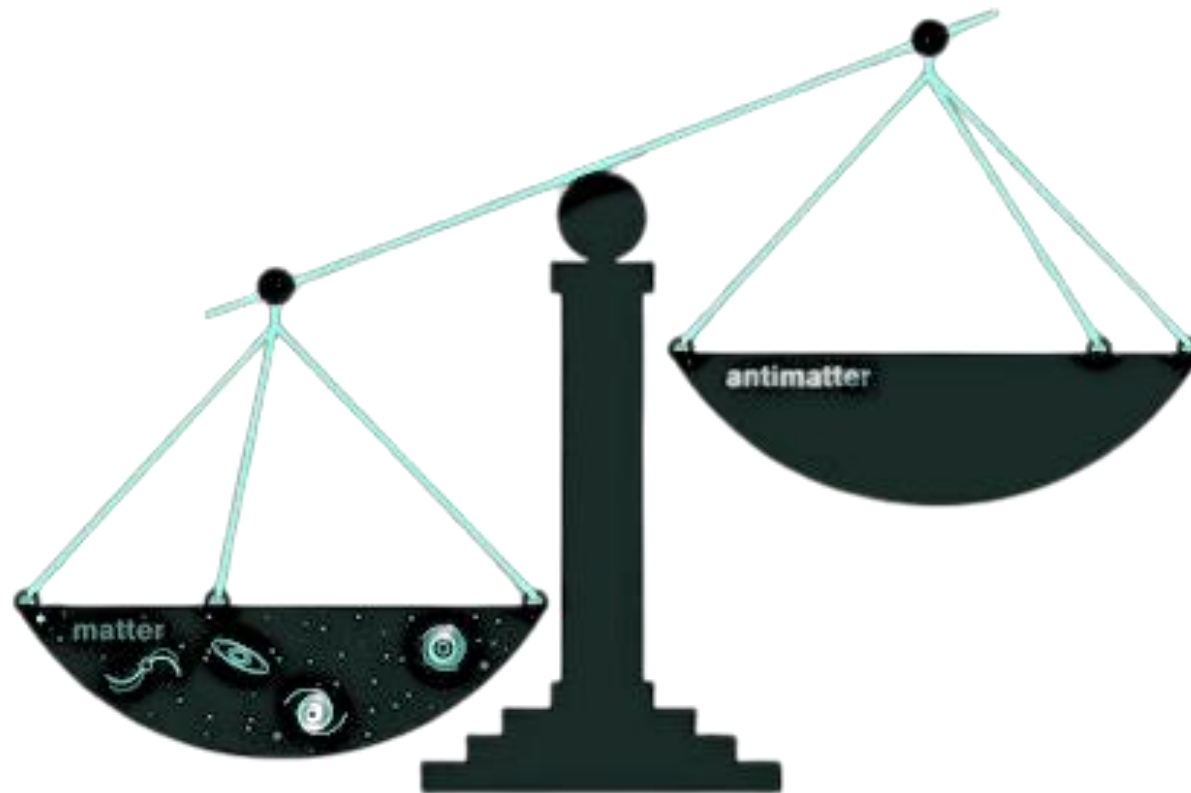
$$m_\nu \approx \frac{m_D^2}{M}, \quad m_N \approx M$$



*Nat. Phys. 18 (2022) 160166

Matter-antimatter asymmetry in the Universe

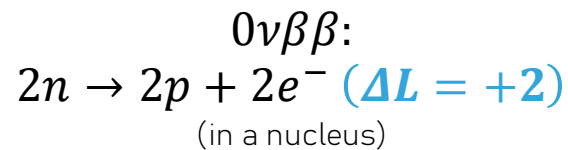
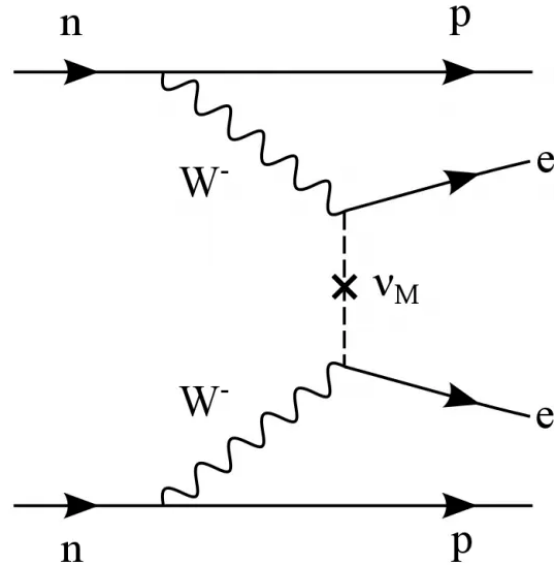
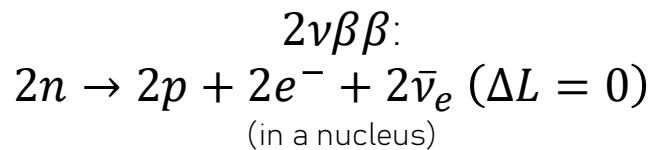
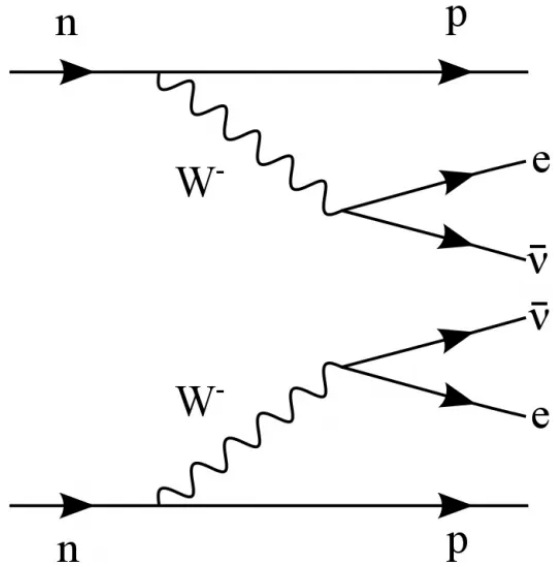
- ◆ The Big Bang should have created equal amounts of matter and antimatter.
- ◆ So why is there far more matter than antimatter in the universe?



Could Majorana neutrinos
explain this?

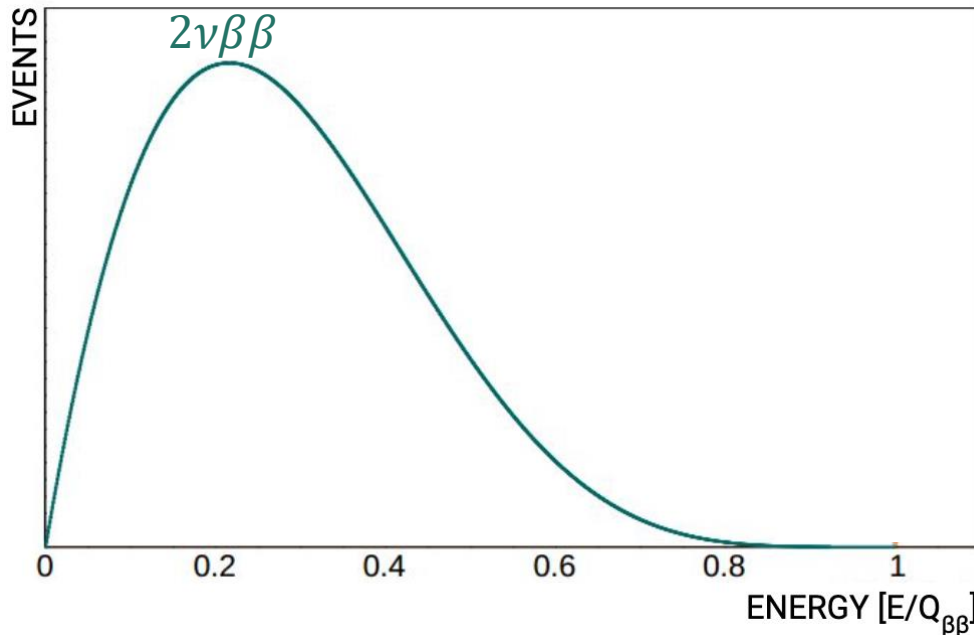
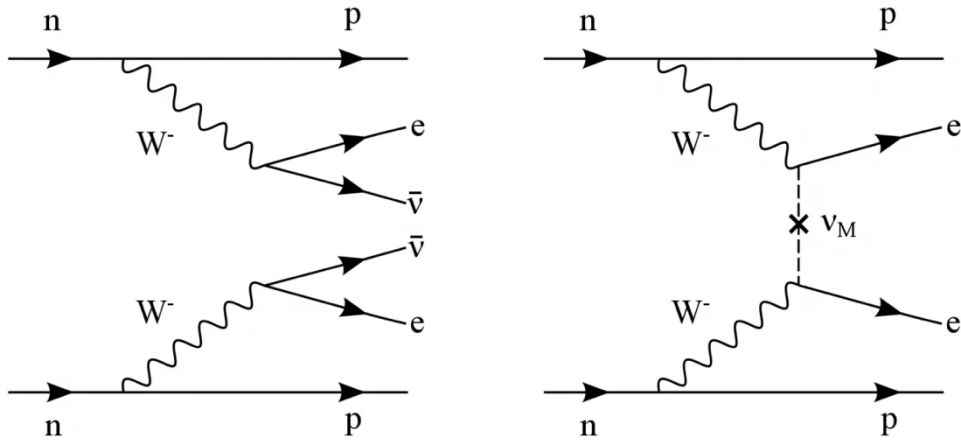


Neutrinoless Double Beta Decay



- ◆ Violation of lepton number conservation could explain the matter-antimatter asymmetry of the universe (provided that all Sakharov conditions are fulfilled).
- ◆ $0\nu\beta\beta$ -decay: the most sensitive probe for L-violation

Neutrinoless Double Beta Decay



- ◆ In $0\nu\beta\beta$, virtual light ($\lesssim 10$ MeV) Majorana neutrinos are exchanged*, resulting in no neutrino emission.
- ◆ The electrons emitted in the $0\nu\beta\beta$ decay take the full energy of the decay and produce a peak at $Q_{\beta\beta}$, the endpoint of the $2\nu\beta\beta$ -decay spectrum
- ◆ The decay signature is a **peak** at its Q-value:

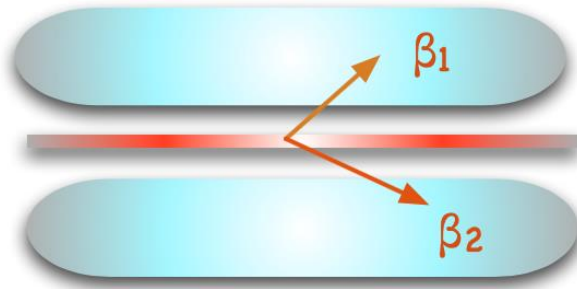
$$Q = E_{e1} + E_{e2} - 2m_e$$

*There are other mechanisms that could mediate the $0\nu\beta\beta$ process. Here only the light neutrino exchange is discussed

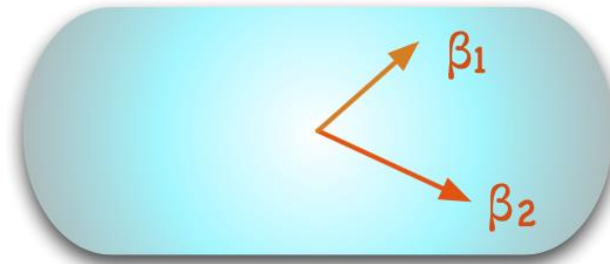
How to measure Neutrinoless Double Beta Decay?

- ◆ We need: source of the decay and something to detect it

Source \neq Detector



Source = detector

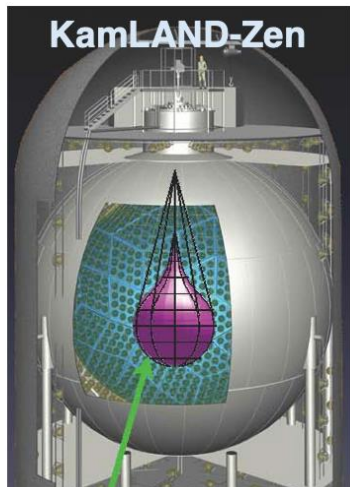
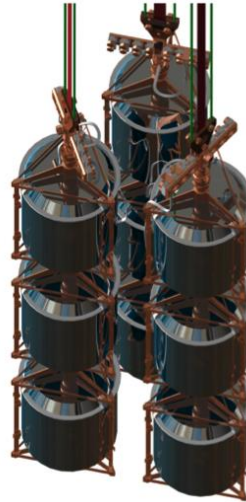
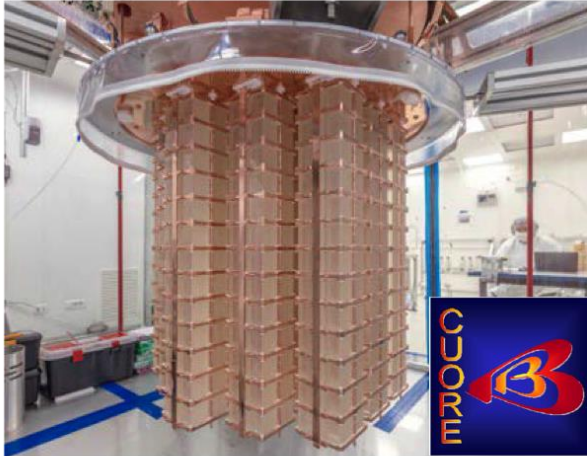


How to measure Neutrinoless Double Beta Decay?

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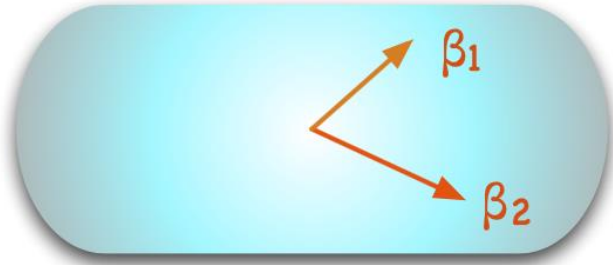
◆ Main experimental challenges:

- Energy resolution: ultimate background from $2\nu\beta\beta$ -decay
- cosmic rays and cosmogenic activation
- radioactivity of detector materials (^{238}U , ^{232}Th , ^{40}K , ^{60}Co , etc.)
- anthropogenic (e.g., ^{137}Cs , $^{110\text{m}}\text{Ag}$)
- neutrinos (e.g., ^8B from the sun)

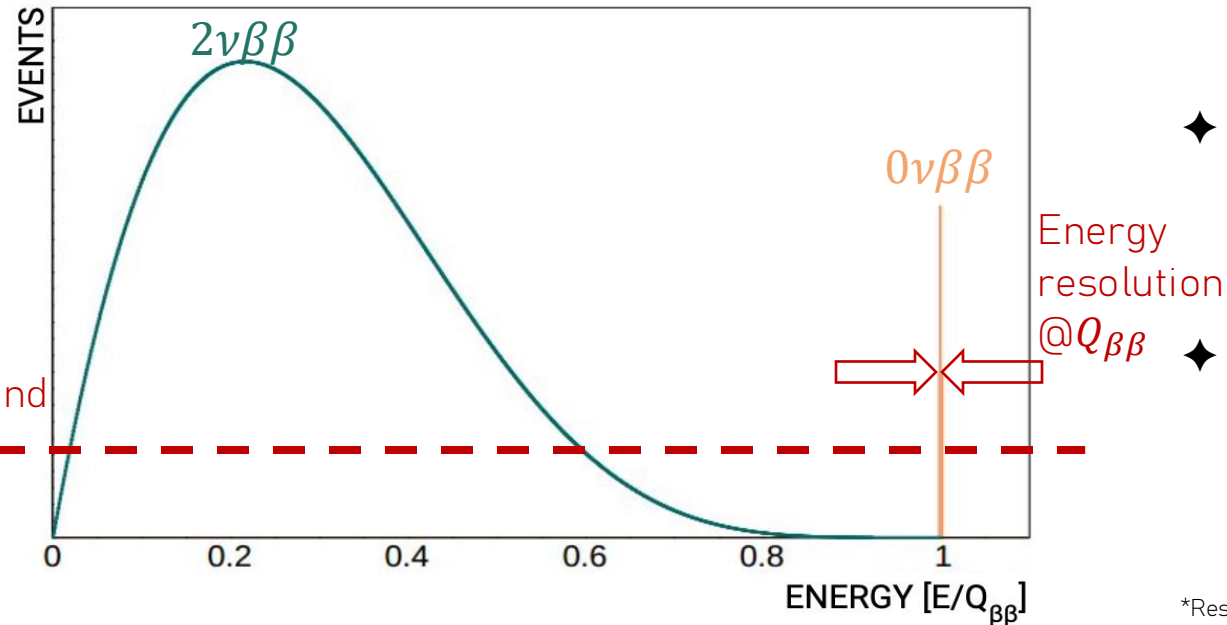


How to measure Neutrinoless Double Beta Decay?

Source = detector



$\beta\beta$ -decay sources: ^{48}Ca , ^{76}Ge , ^{100}Mo , ^{130}Te , ^{136}Xe , ...



◆ To ensure high sensitivity to this rare process, we need:

- Large exposure
 - Abundance (a)
 - Mass (M), time (t)
- High detection efficiency (ε)
- High energy resolution (ΔE)
- Low background index (BI)

◆ Measurement of the decay half-life:

$$T_{1/2}^{0\nu} \propto a\varepsilon \sqrt{\frac{Mt}{BI\Delta E}}$$

◆ High purity germanium detectors present high detection efficiency, the best energy resolution and lowest background index in the field*

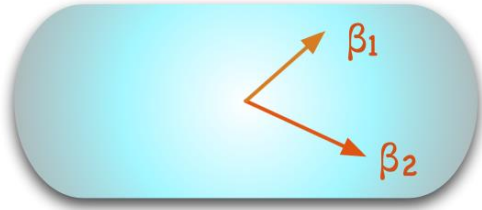
*Resolution of $\sim 0.1\%$ FWHM at $Q_{\beta\beta}$. BI of 5.2×10^{-4} counts/(keV·kg·yr) [GERDA Coll. PRL, 125:25202, 2020]

High Purity Germanium (HPGe) Detectors

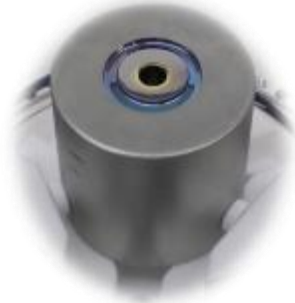


3600 m water equivalent
 Muon flux reduced of a factor 10^6

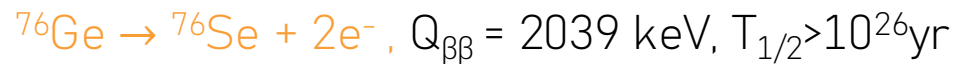
Source = detector



HPGe enriched in ^{76}Ge



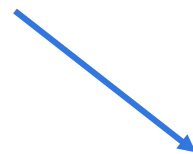
- ◆ Enrichment up to 92%
- ◆ Resolution of ~ 2.5 keV (FWHM at $Q_{\beta\beta}$)
- ◆ Low ^{232}Th - and ^{238}U -chain internal contamination
- ◆ Well-understood flat background and no known peak near $Q_{\beta\beta}$.
- ◆ Pulse shape discrimination (PSD)
- ◆ Lowest background among $0\nu\beta\beta$ experiments



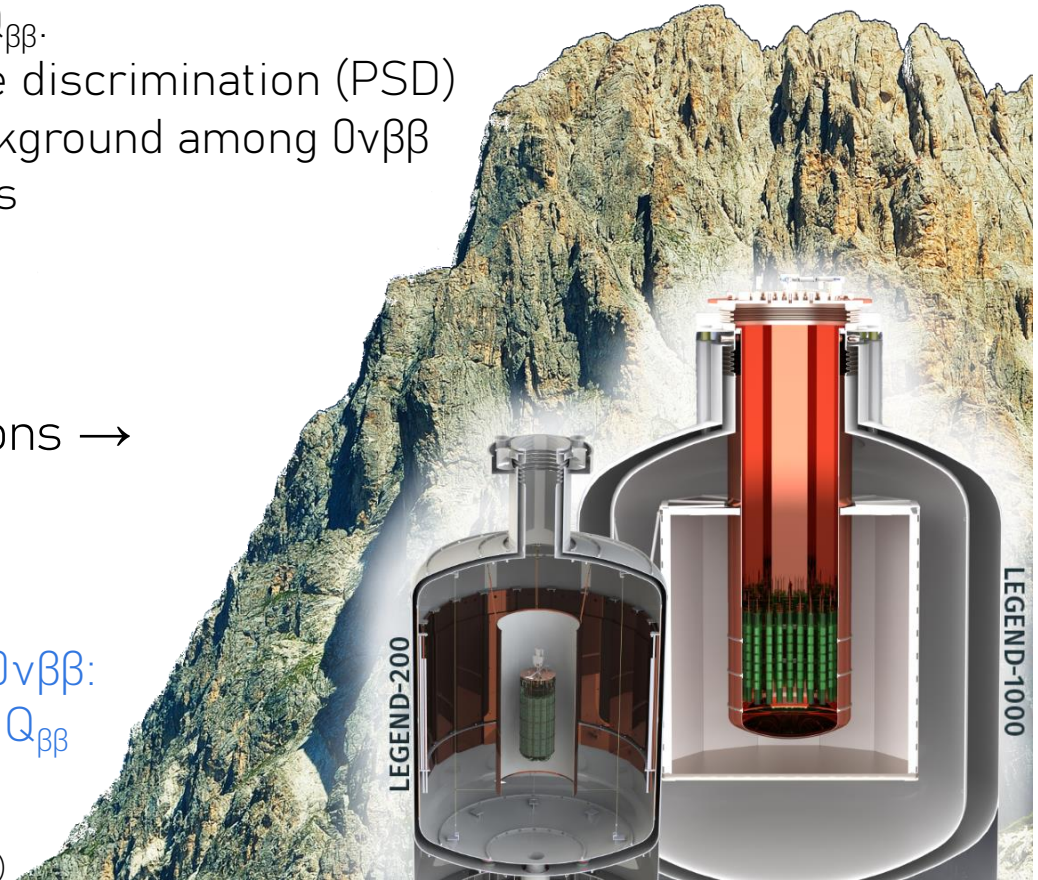
GERDA + MAJORANA DEMONSTRATOR + new institutions →



Lowest background index for $0\nu\beta\beta$:
 $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)



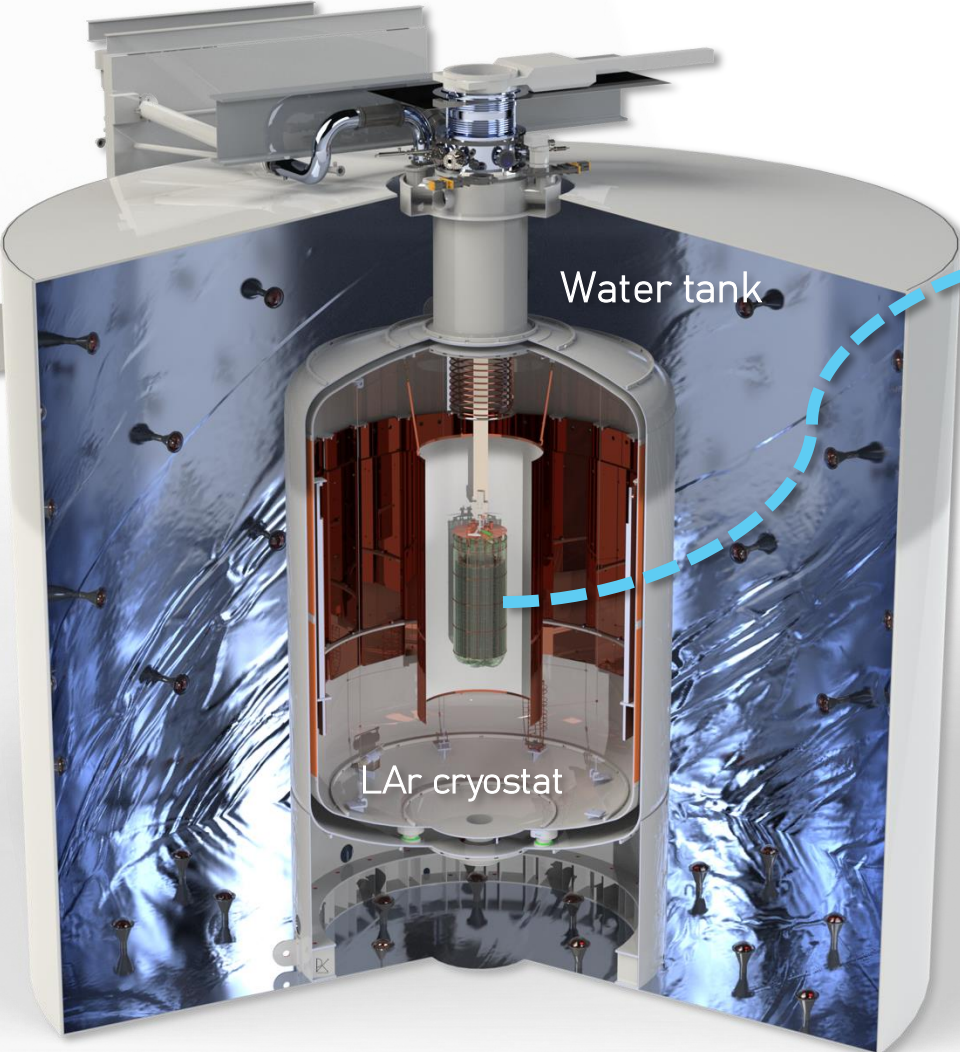
Best energy resolution for $0\nu\beta\beta$:
 2.52 ± 0.08 keV (FWHM) at $Q_{\beta\beta}$



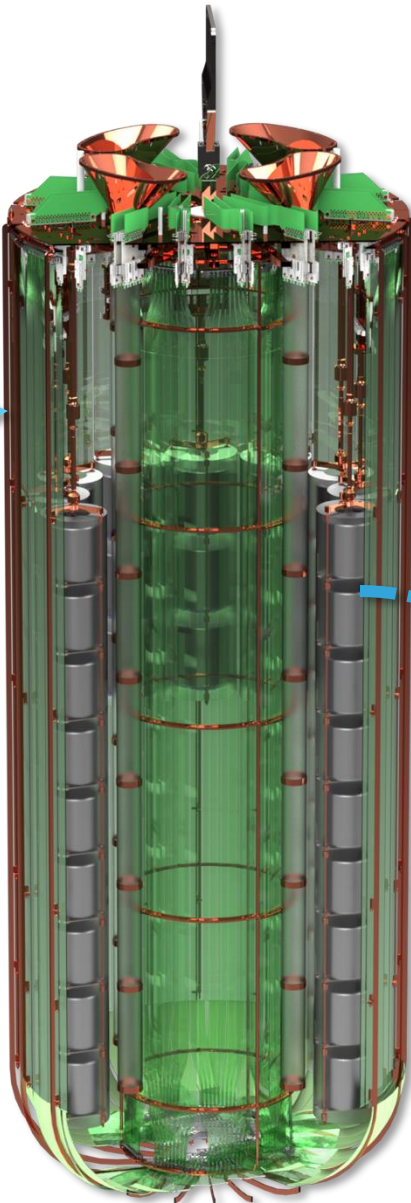
Ref.: GERDA Collab., PRL 125, 252502 (2020)

Ref.: MAJORANA Collab., PRL130, 062501 (2023)

LEGEND-200

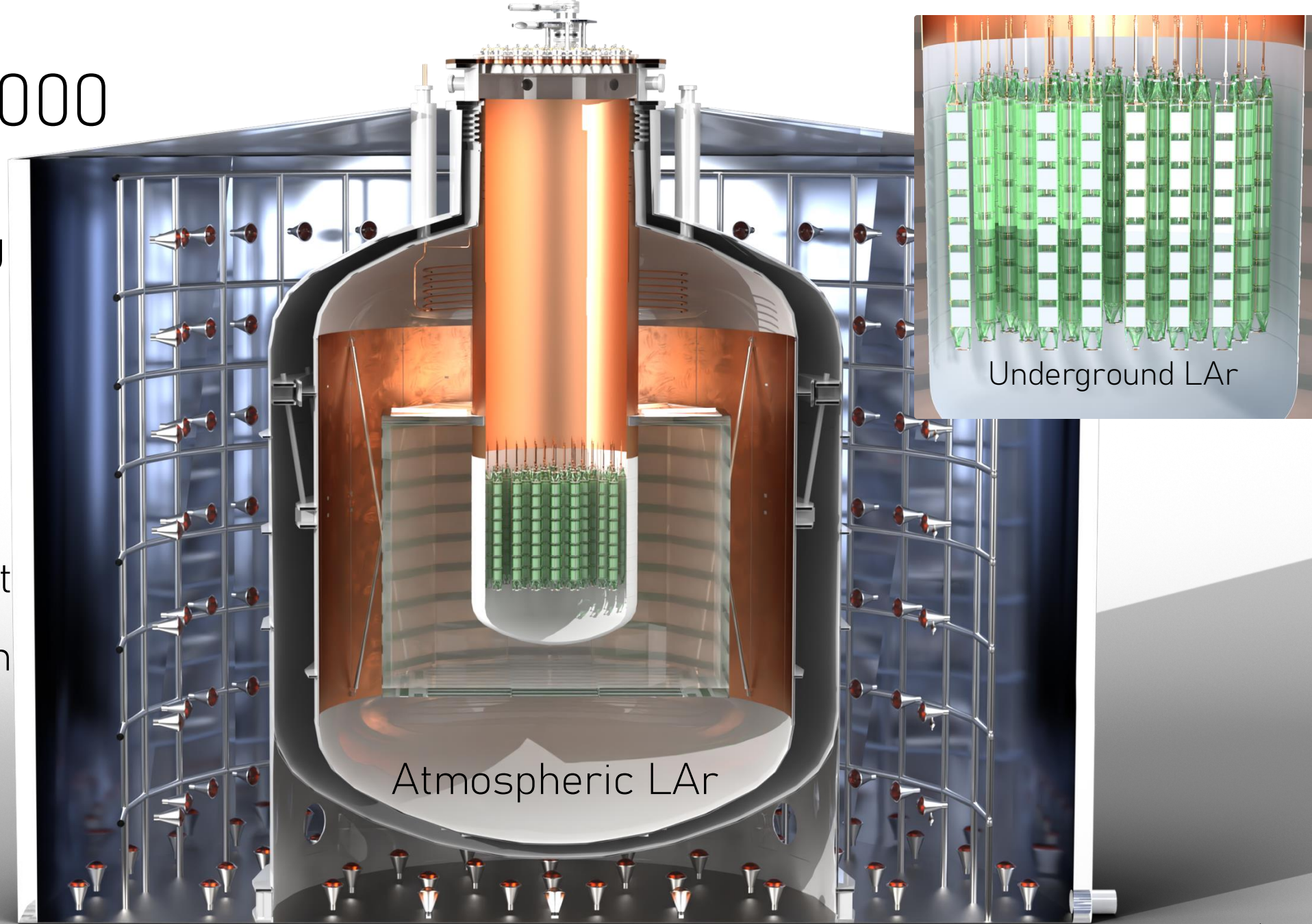


90 tons of LAr
200 kg of enriched Ge

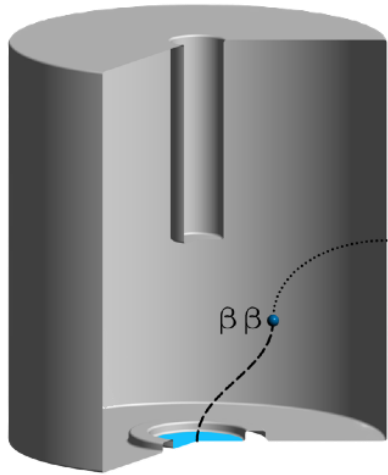


LEGEND-1000

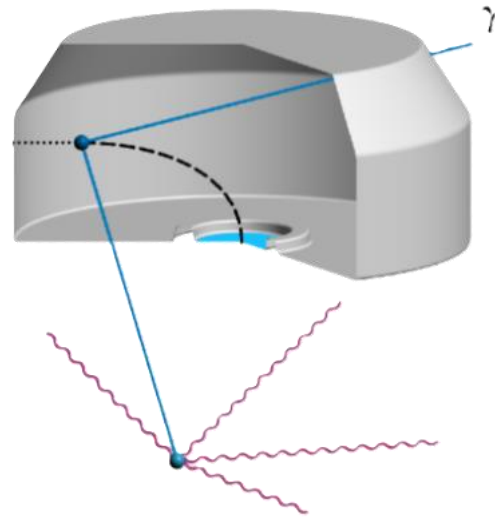
336 detectors of 3 kg
avg. mass each,
totaling
1000 kg of Ge- all
planned to use the
Inverted Coaxial Point
Contact (ICPC) design
exclusively



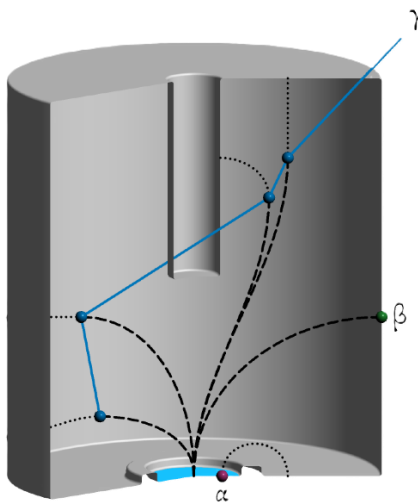
HPGe detectors event topology



Single Site Event (SSE)

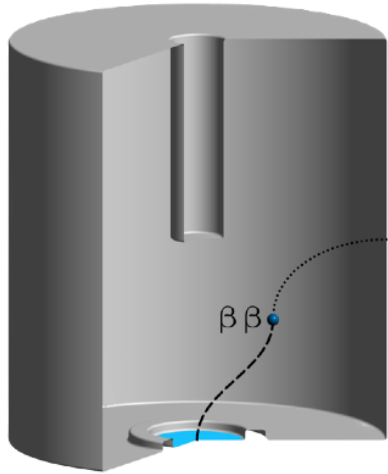


Liquid Ar coincidence

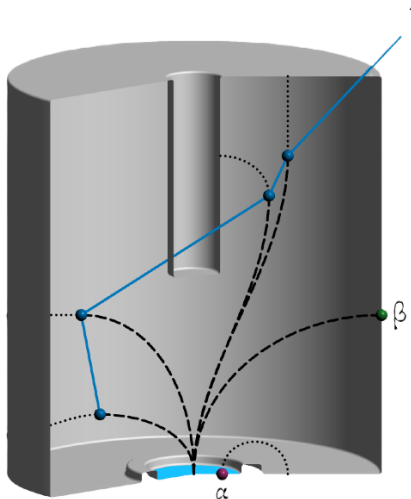


Multi Site Event (MSE)

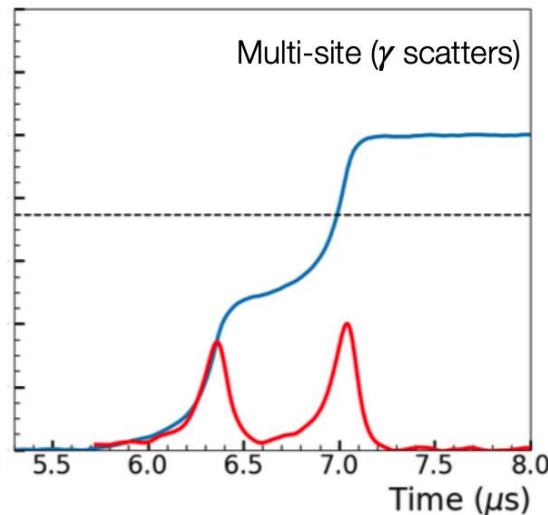
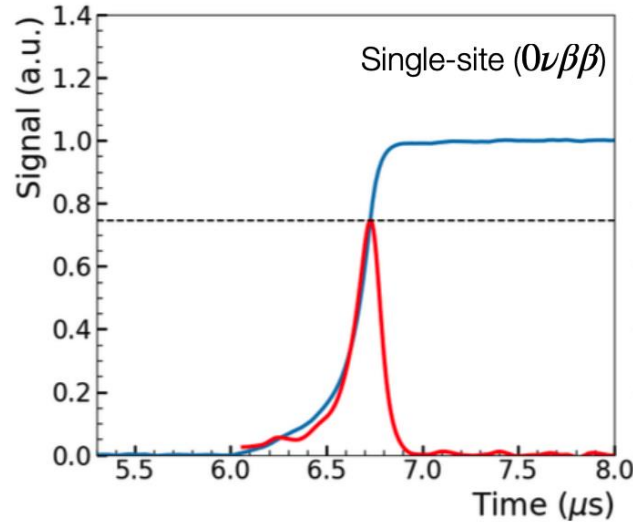
HPGe detectors event topology



Single Site Event (SSE)



Multi Site Event (MSE)



◆ Pulse-shape discrimination (PSD) differentiates single- and multi-site events via unique charge and current profiles:

◆ Single-Site Events (SSE): Energy deposited in a localized volume (e.g., $(0\nu)\beta\beta$ signal)

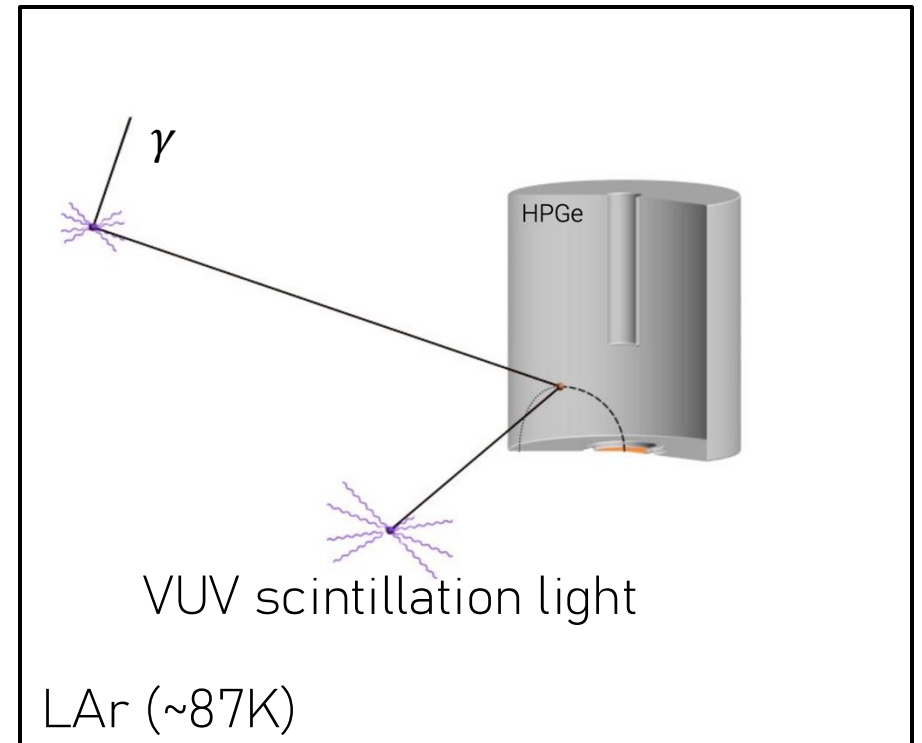
◆ Multi-Site Events (MSE): Energy deposited across multiple interaction points (e.g., γ -ray backgrounds)

HPGe detectors operate in liquid argon (LAr)

- ◆ Liquid Argon:
 - ◆ serves as a coolant, passive and active shield
 - ◆ scintillates in response to background events

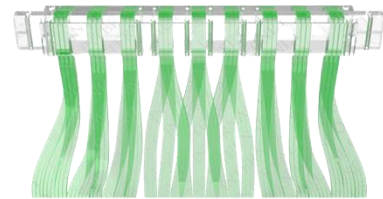
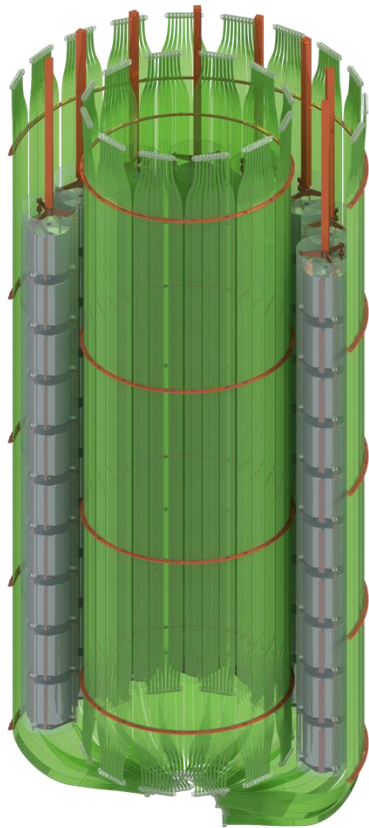
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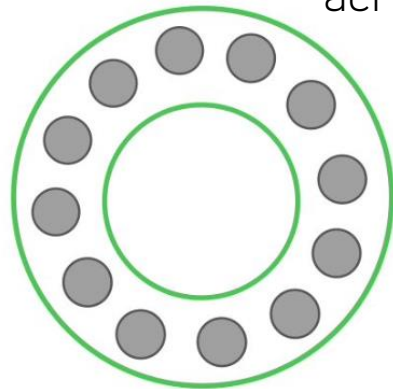


HPGe detectors operate in liquid argon (LAr)

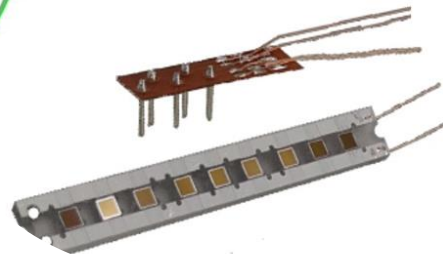
- To collect the LAr scintillation light, wavelength-shifting (WLS) fibres surround the HPGe detector array.



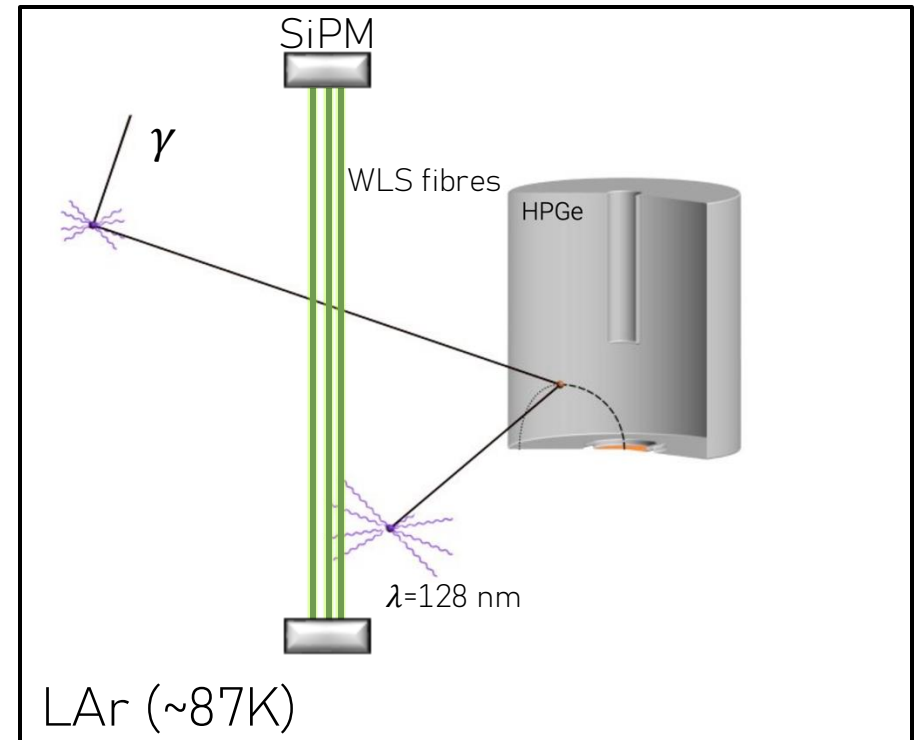
acrylic fiber coupling



Top view

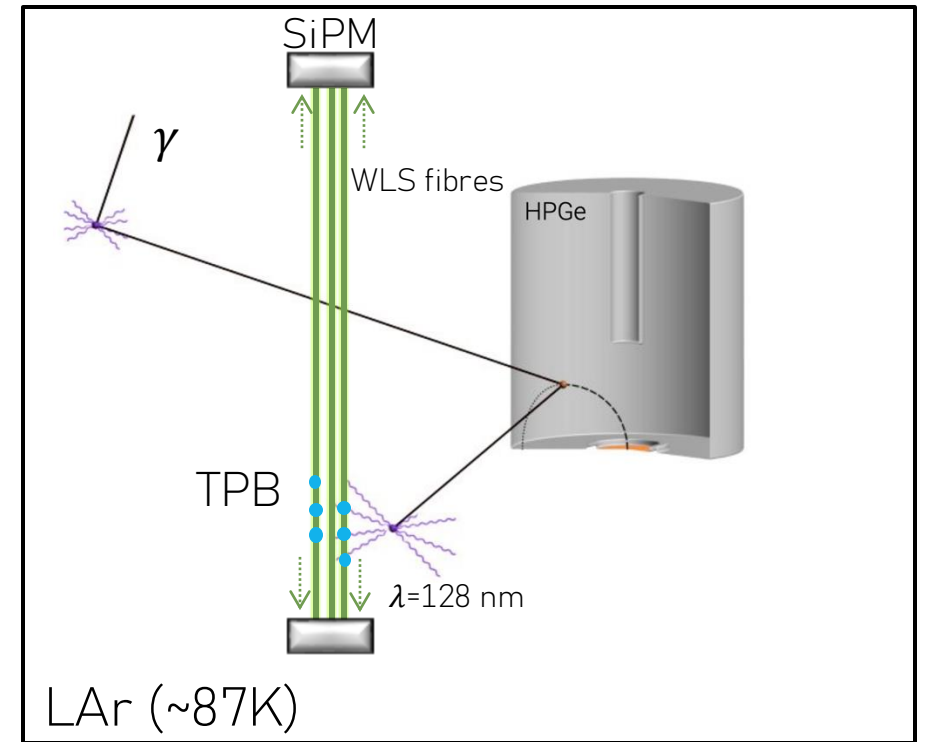
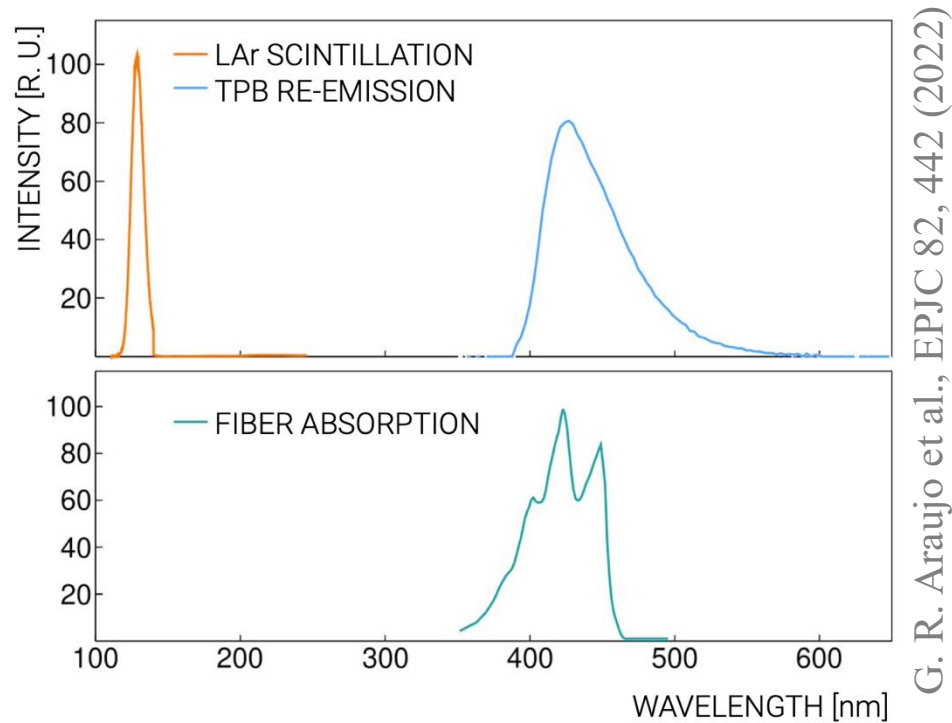


KETEK PM33100T
3x3 mm



HPGe detectors operate in liquid argon (LAr)

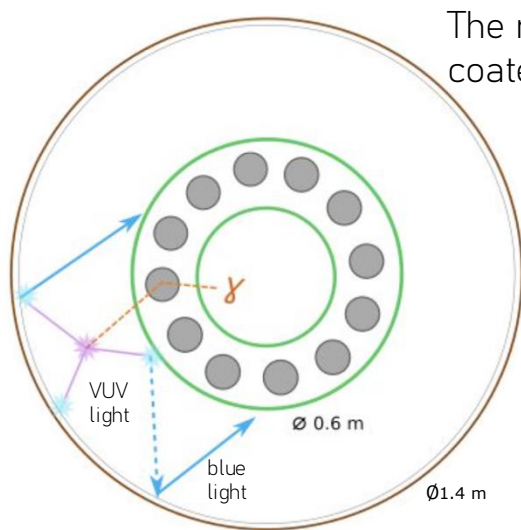
- LAr scintillation light peaks at 128 nm
- Tetraphenyl butadiene (TPB) shifts this light to blue wavelength.



- Blue light can be collected by the fibres and guided to SiPMs

HPGe detectors operate in liquid argon (LAr)

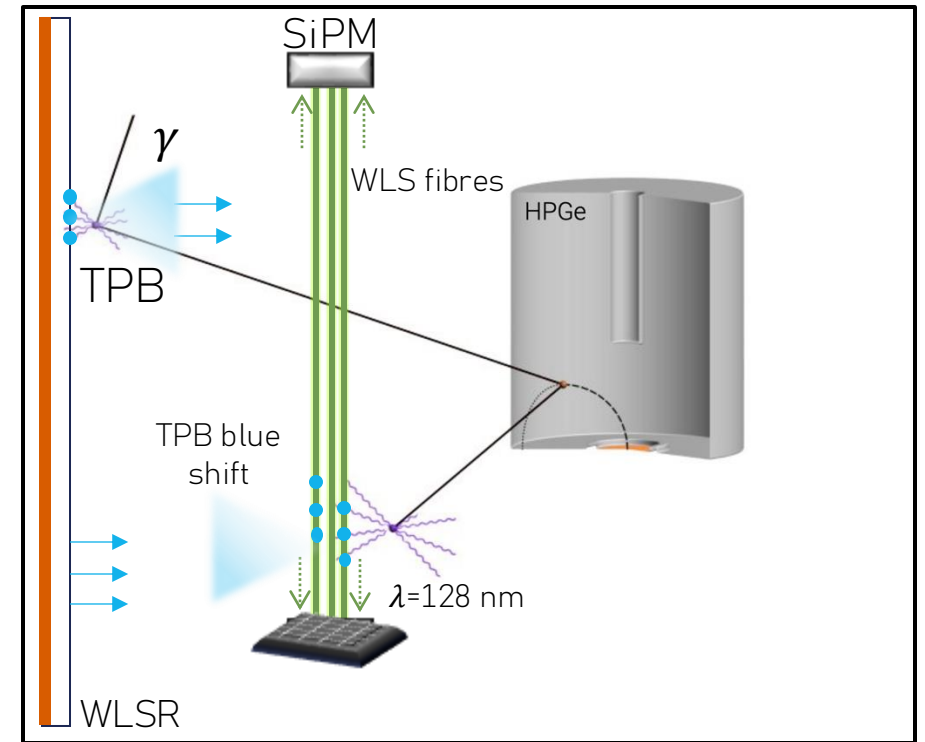
- To increase light collection efficiency, wavelength-shifting materials surround the fibres



The reflector is also coated with TPB

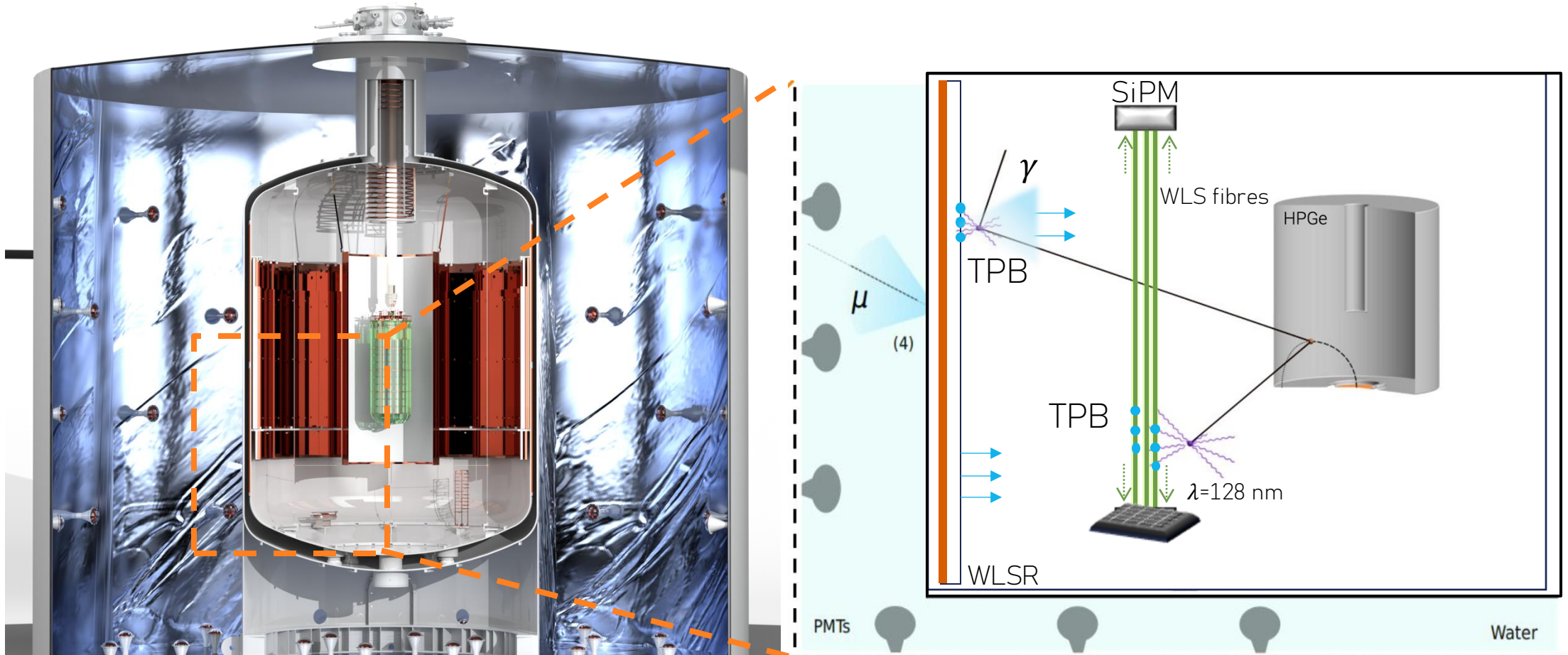
WLSR schematic cross-section

Image credit: G. Araujo



- WLS-reflector (WLSR) aid in identifying distant γ -scatters and recapturing uncollected light from the fibres.

Muon veto instrumentation

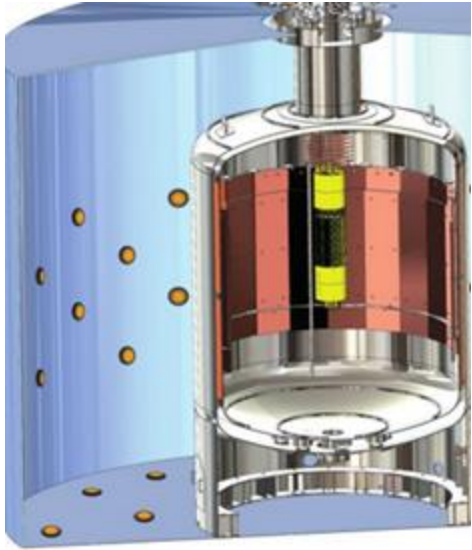


The experiment is located underground at the Laboratori Nazionali del Gran Sasso (LNGS), Italy

Photomultiplier Tube (PMT) instrumented water tank: A detector for Cherenkov light from muons

Image credit: G. Araujo

LEGEND-200 Timeline



Construction phase: Utilizing GERDA's infrastructure, integrating detectors from GERDA and MJD + new Inverted Coaxial detectors



2022-2023

Results with 61 kg·yr exposure

Data taking with 142 kg HPGe detectors

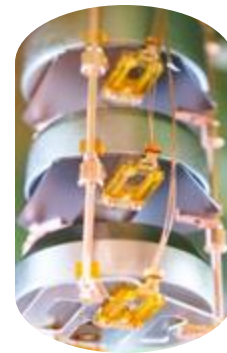
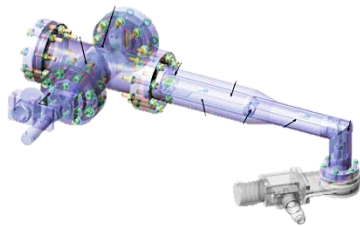
Spring 2025



~ 2029

2020-2022

Commissioning: 03/2023-02/2024
HPGe Detectors, LAr, and Calibration Systems.



Restarting data taking with additional 35 kg of HPGe detectors

Reach target sensitivity of $T_{1/2} > 10^{27}$ years

Construction and commissioning



Image credit: M. Willers

- First test of new technologies (HPGe electronics, PEN plates) and detectors in GERDA infrastructure
- Detector holders, made of polyethylene naphthalate (PEN), shift VUV light

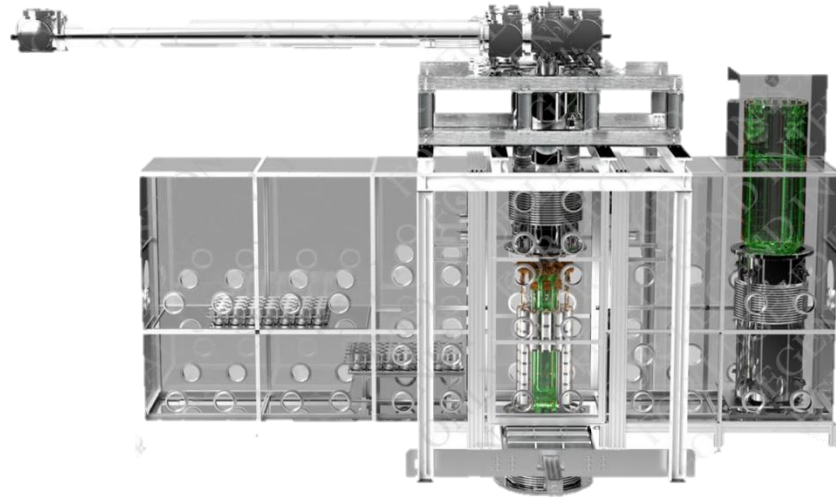


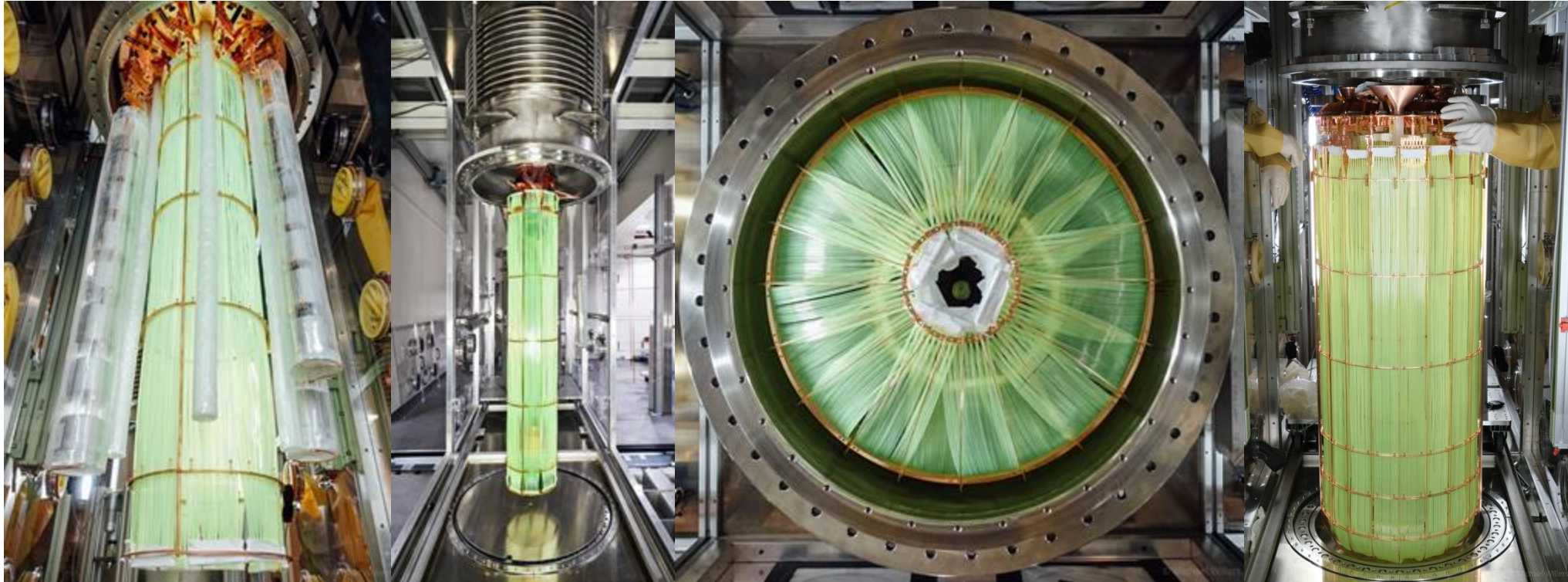
Image credit: P. Krause



Image credit: E. Sacchetti

- New lock, mechanics, wiring, and glove box installed (with water tank and cryostat repurposed from GERDA) to house the expanded LEGEND-200 detector array and additional channels.

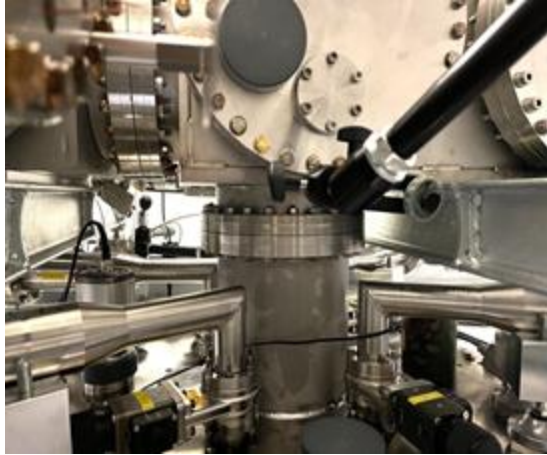
Liquid Argon Instrumentation



Images credit: E. Sacchetti and M. Willers

- LAr instrumentation hardware and readout electronics have been successfully constructed and commissioned.
- A milestone during the 60 kg campaign: inaugural operation of 60 kg of HPGe within the LAr instrumentation. final optimization of hardware and execution of specific calibration runs.
- 142 kg installation: installation of all available HPGe detectors and full setup of the LAr instrumentation

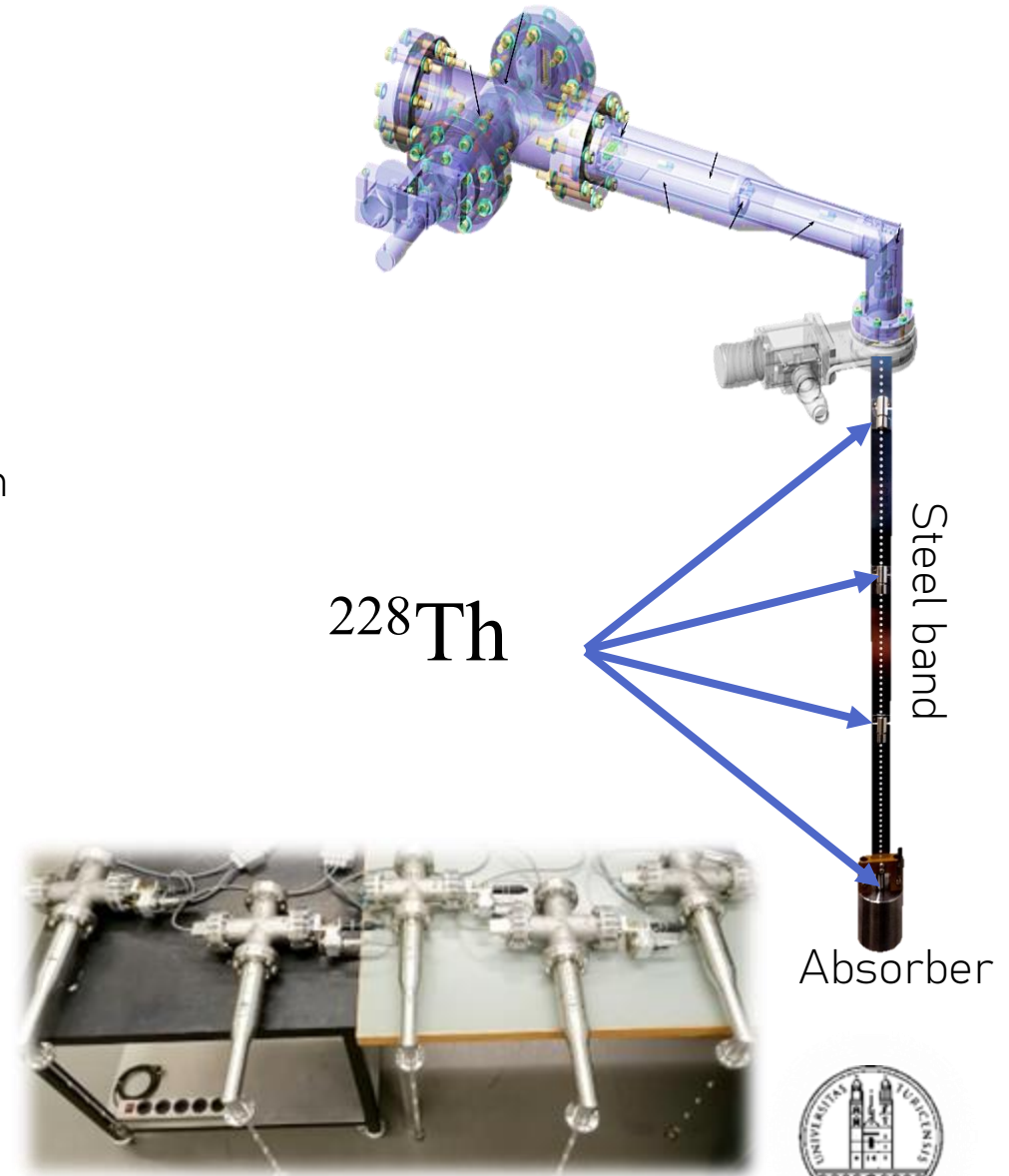
Calibration System



Images credit: M. Willers

- Calibration system is installed on the top of the cryostat.
- It precisely positions the ^{228}Th sources close to the HPGe detectors for weekly calibration runs.
- The sources are attached to a steel band, which is guided through a funnel to reach the correct calibration location.
- The systems were built and tested at UZH. The calibration sources were characterized prior to installation*.

*L. Baudis et al., JINST 18, P02001 (2023)

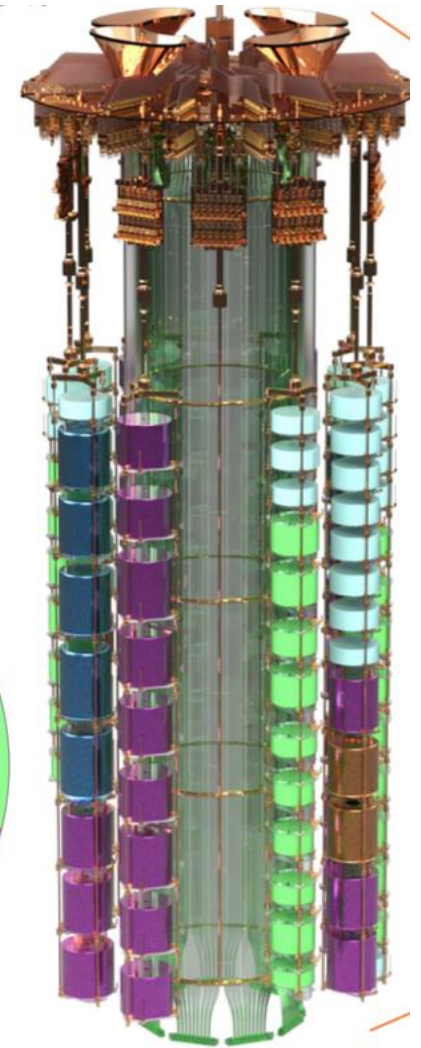
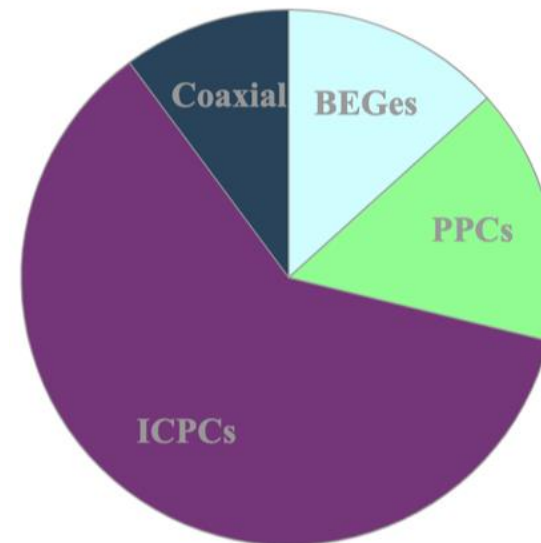
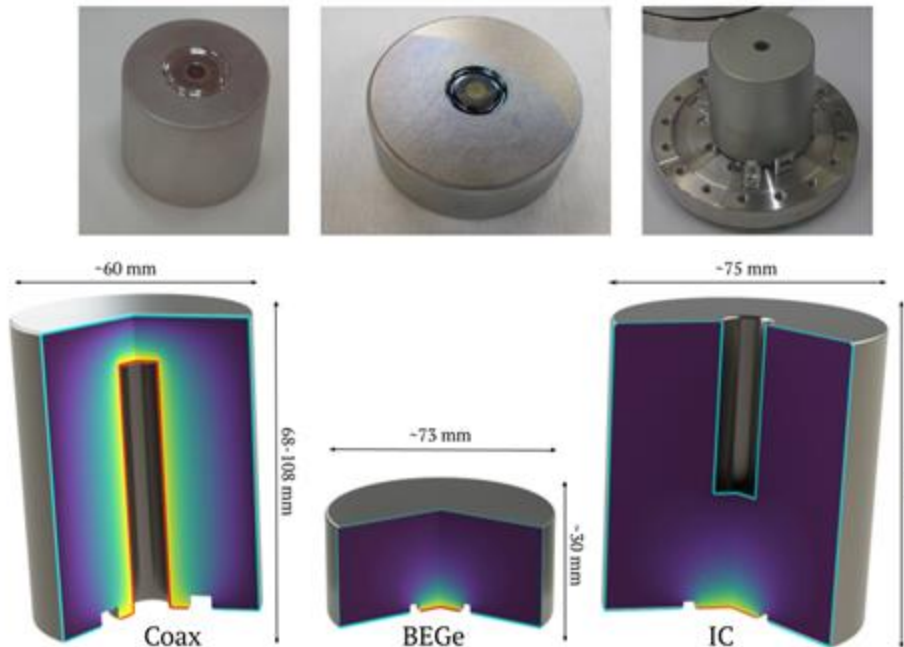


Status of LEGEND-200

- A total of 101 detectors, weighing around 142 kg, have been installed.
- 130 kg operational (12 kg OFF due to hardware issues)
- First results with 48.3 kg·yr exposure (presented at Neutrino 2024), updated with 61 kg·yr exposure (APS 2025)

Data is categorized into two subsets:

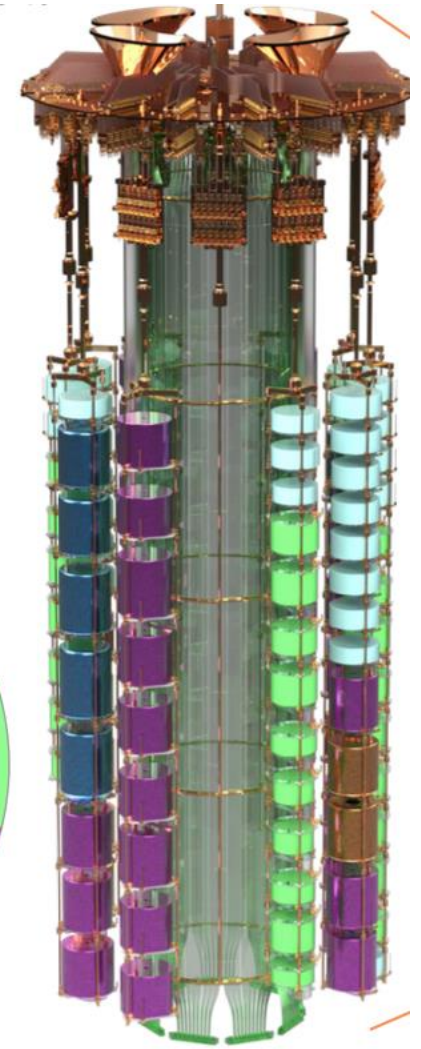
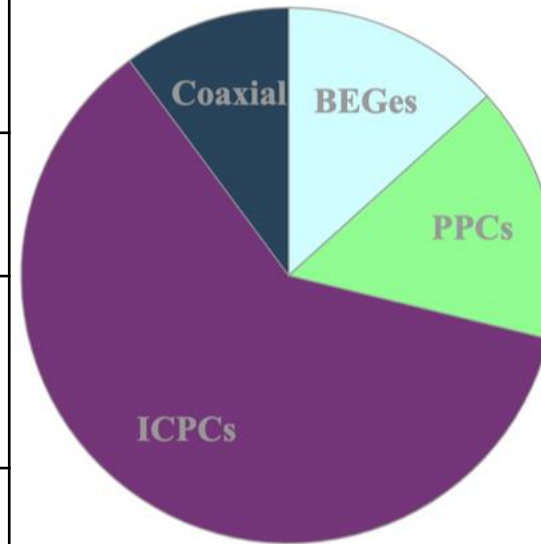
- **Golden dataset:** Detectors with stable energy and PSD performance
- **Silver dataset:** Detectors with known limitations (e.g., higher background or unstable PSD)



Status of LEGEND-200

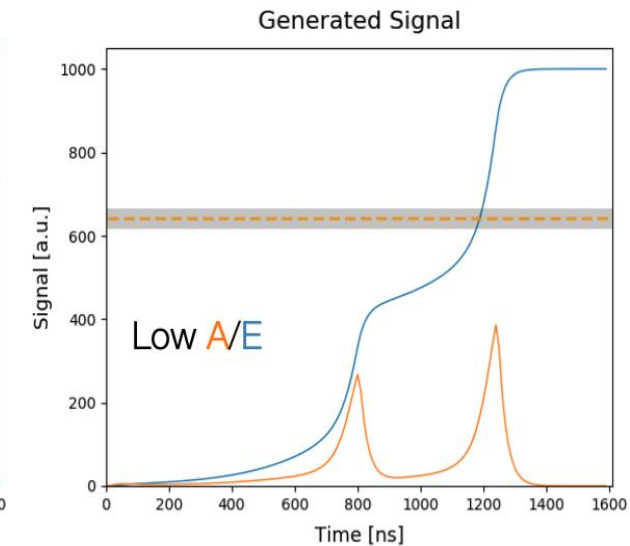
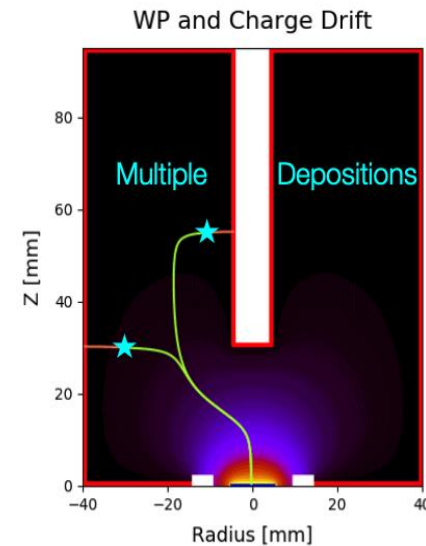
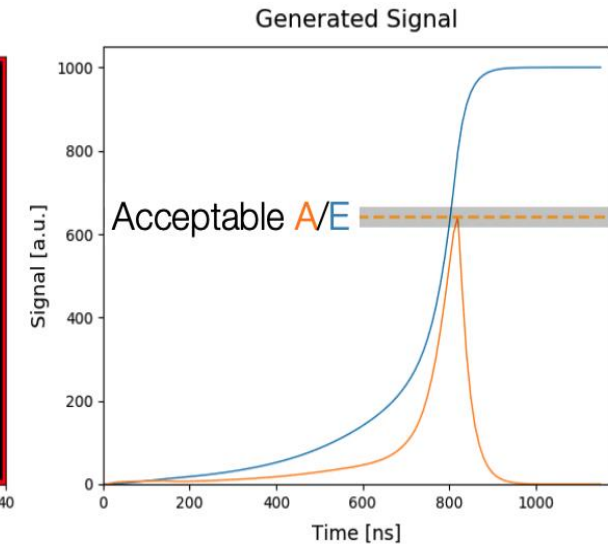
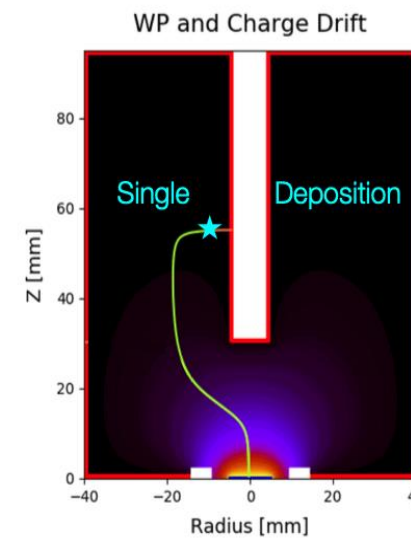
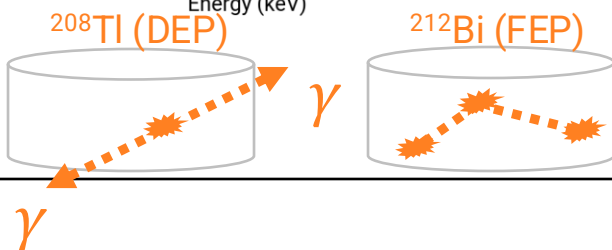
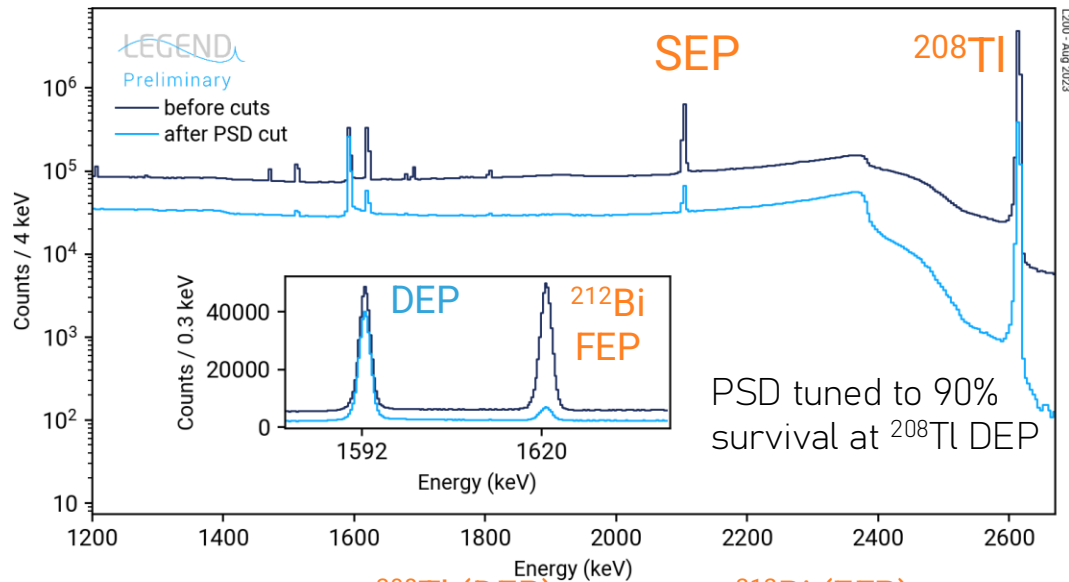
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	Name	Advantage	Mass
PPC	p-type Point Contact	Efficient discrimination of low-energy background events	Varies
BEGe	Broad Energy Germanium	Excellent energy resolution (~ 2 keV FWHM at $Q_{\beta\beta}$)	~ 0.7 kg
ICPC	Inverted Coaxial Point Contact	Increased surface-to-volume ratio, reducing background	1 – 4 kg
COAX	Semi-Coaxial	Robust design, but lower energy resolution and PSD performance	~ 2 kg

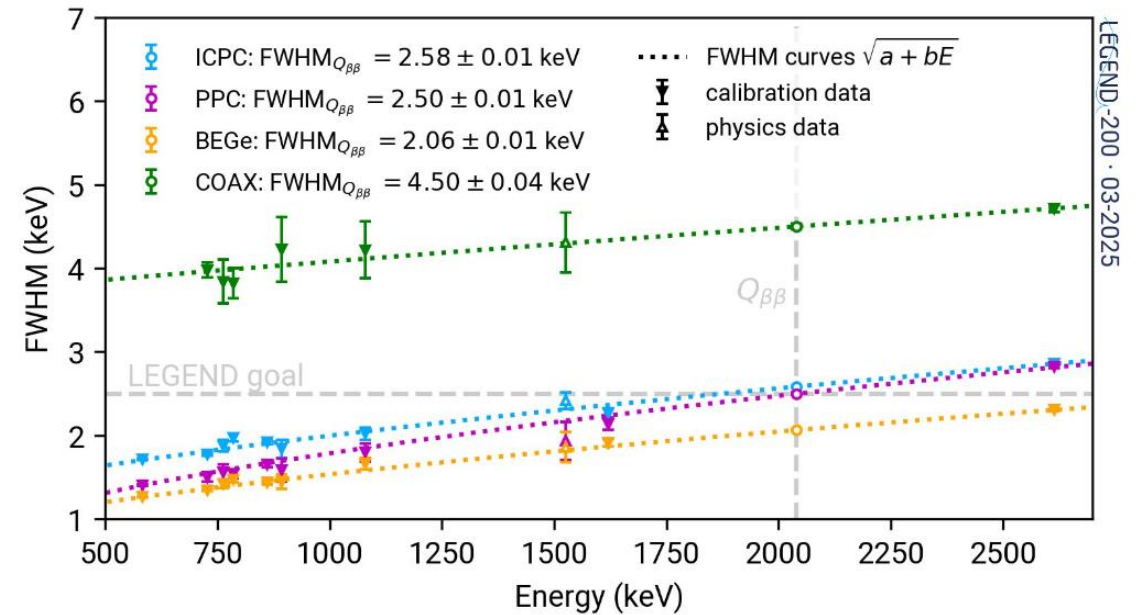
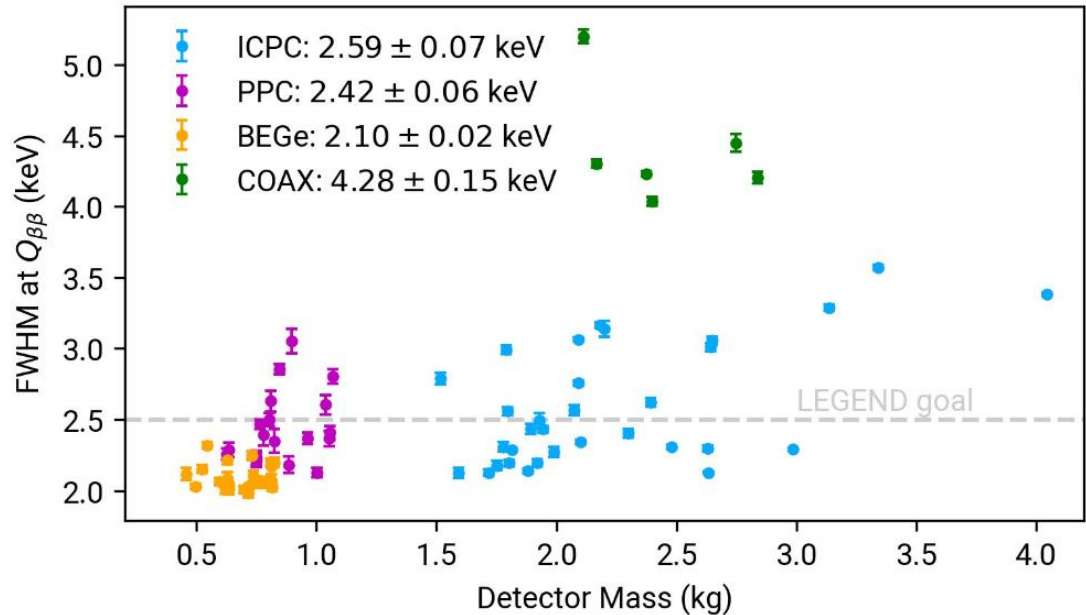


Pulse Shape Discrimination (PSD)

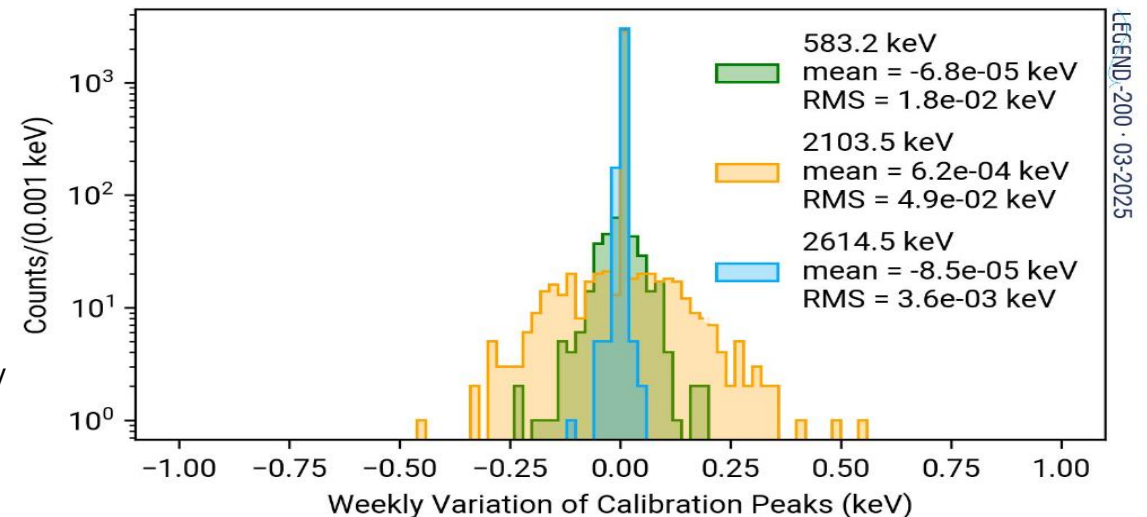
- ◆ Compare event **Energy** from waveform with the derivative **Amplitude (A/E)**
- ◆ Single-site γ events ($0\nu\beta\beta$, DEP): a narrow **A/E** parameter range
- ◆ Calibrate with ^{228}Th calibration spectrum



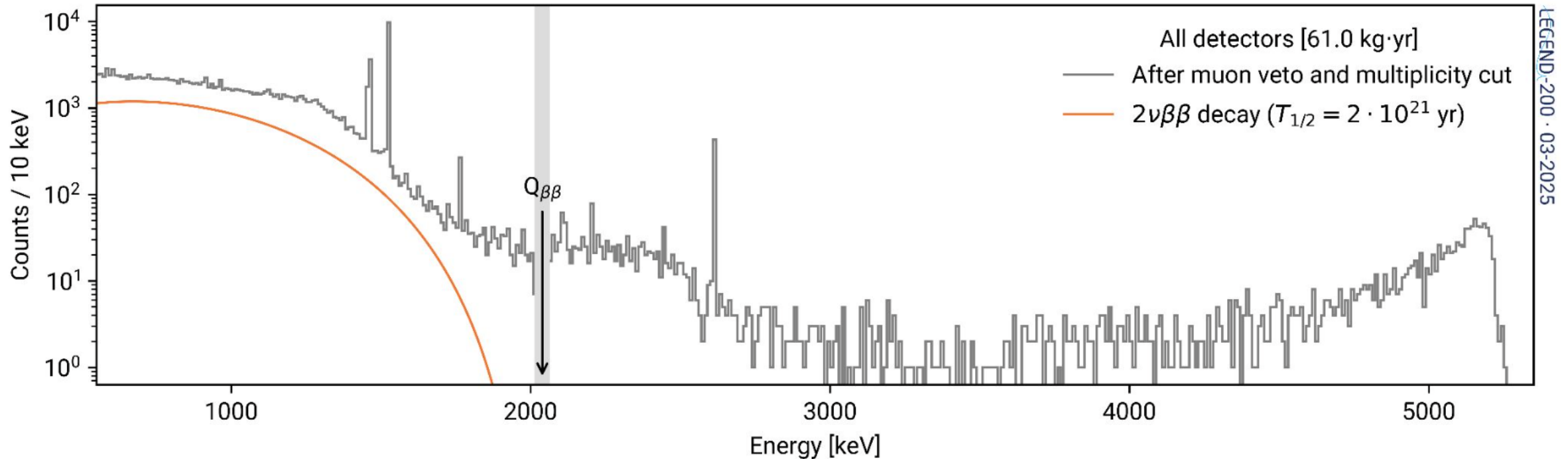
LEGEND-200: energy resolution and stability



- Energy scale evaluated via weekly ^{228}Th calibrations between physics runs
- Most detectors meet the LEGEND energy resolution goal (0.12% at $Q_{\beta\beta}$)
- Stable energy scale observed across calibrations
- Data partitioned based on the stability of both energy and PSD observables to ensure optimal cut performance throughout the dataset



LEGEND-200: background spectrum

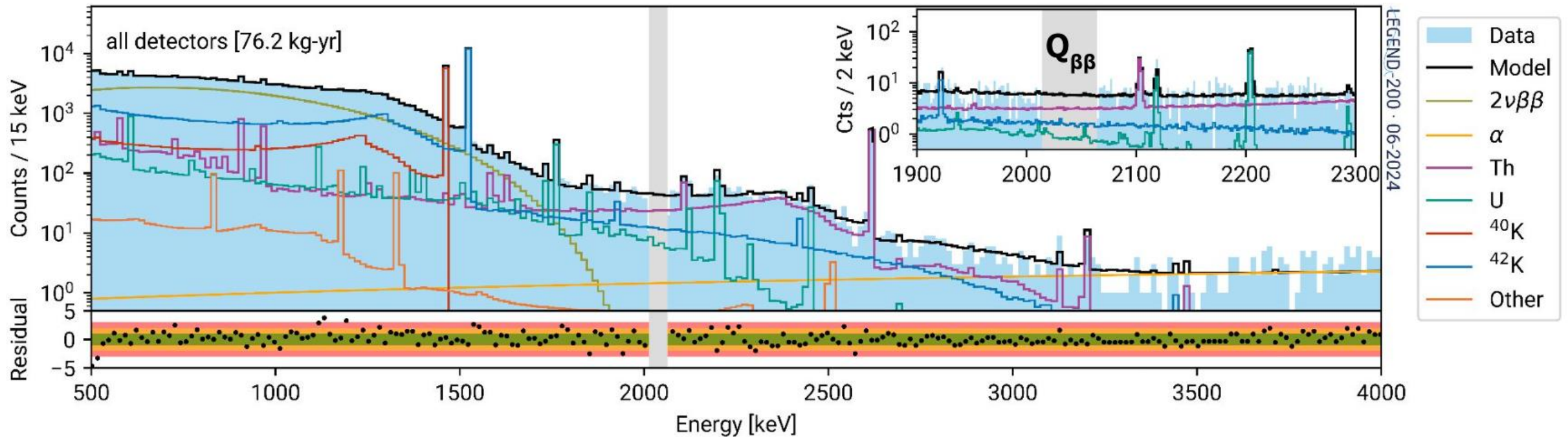


Blinded analysis at $Q_{\beta\beta} \pm 25$ keV

Spectrum after:

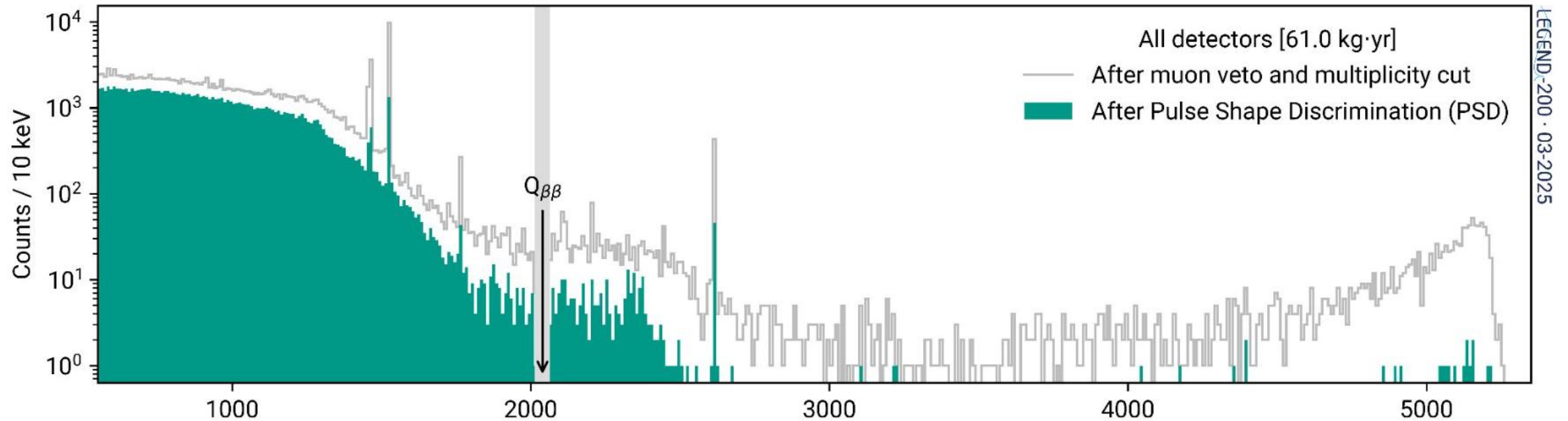
- data cleaning → 95-99% survival after removal of unphysical events
- muon veto → 2 events removed at $Q_{\beta\beta}$
- multiplicity cut (Ge-anticoincidence) → 26% events removed at $Q_{\beta\beta}$

LEGEND-200: background model

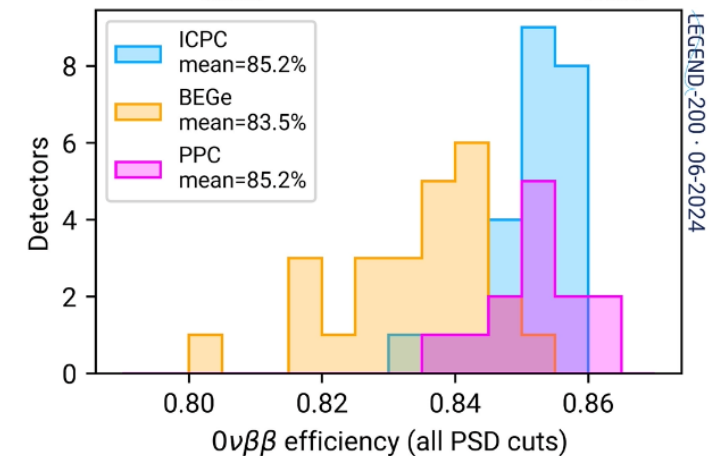


- No unexpected background components (^{238}U and ^{232}Th decay chains, γ -lines from ^{40}K and ^{42}K)
- Spectral shape reproduced well by Bayesian background model
- Higher ^{228}Th background compared to expectation (screening campaign currently ongoing to identify sources)
- Effective suppression of this excess by active LAr and PSD cuts
- Flat background in the region of interest for the $0\nu\beta\beta$ -decay analysis

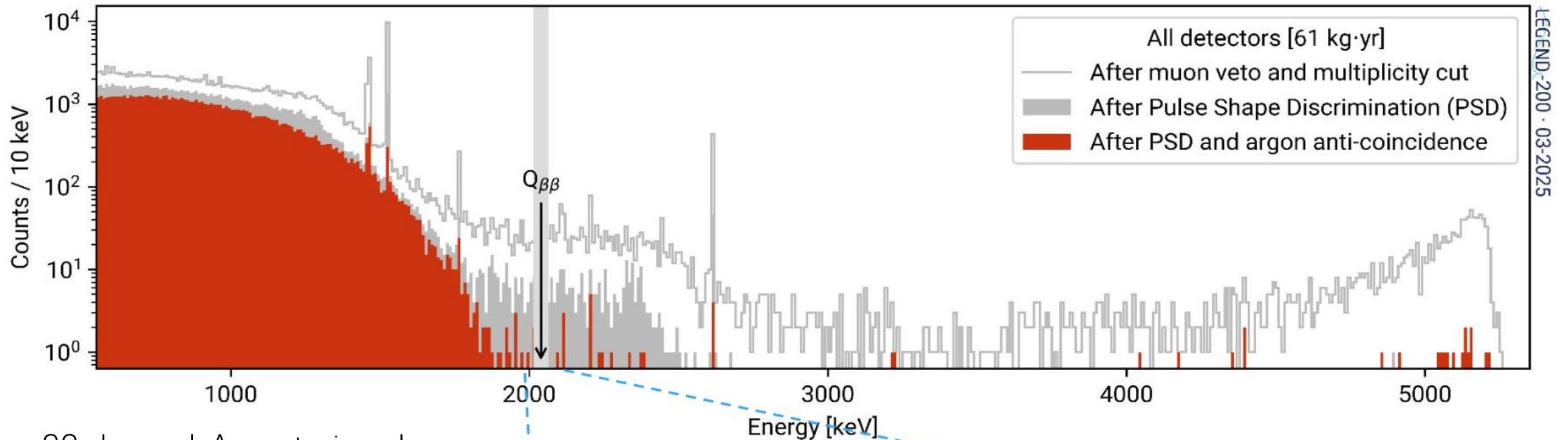
LEGEND-200: background spectrum after PSD



- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- $0\nu\beta\beta$ decay survival fraction of 85%

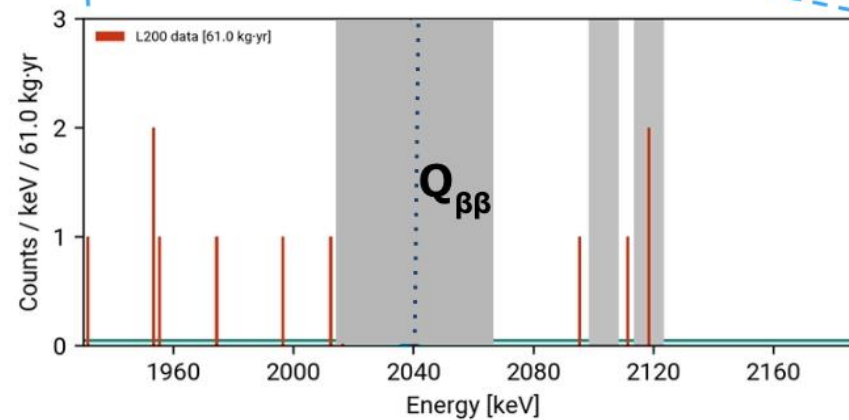


LEGEND-200: background spectrum after cuts



LEGEND-200 · 03-2025

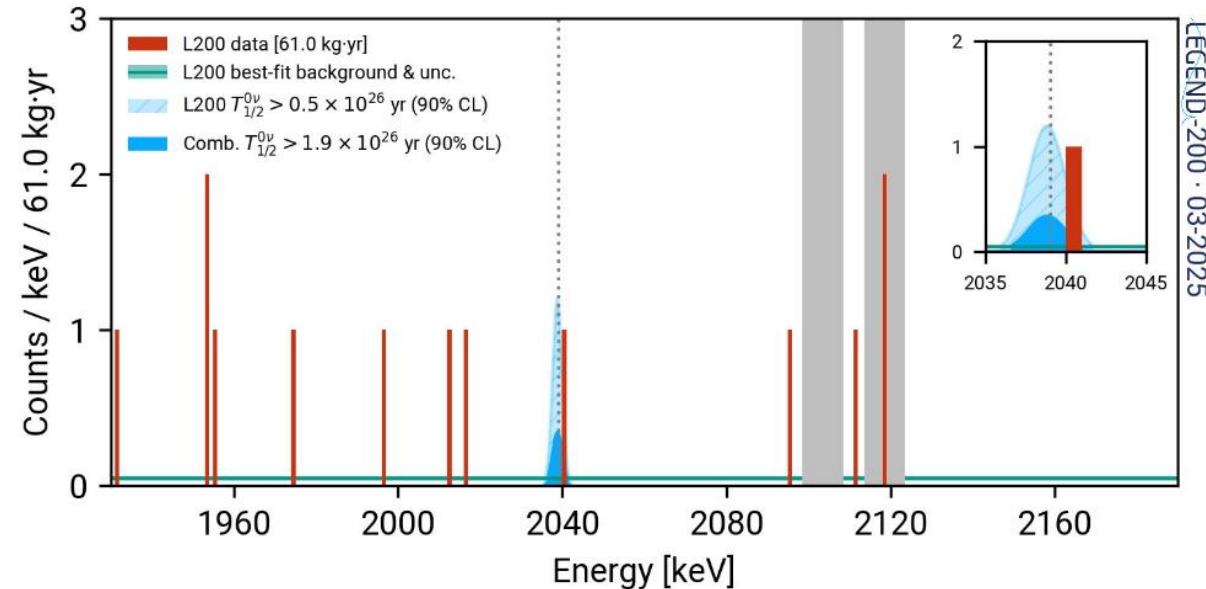
- $\beta\beta$ decay LAr cut signal acceptance $\sim 93\%$ (^{42}K) events
- Strong anti-correlation of LAr & PSD cuts
- Very pure $2\nu\beta\beta$ distribution



- Analysis window:
 - $E = (1930 - 2190 \text{ keV})$
- Excluded γ -lines:
 - ^{208}Tl at $(2104 \pm 5) \text{ keV}$
 - ^{214}Bi at $(2119 \pm 5) \text{ keV}$

LEGEND-200: unblinded results

- 11 events surviving after cuts
- background indices
 - $BI_{\text{gold}} = 5.4_{-2.0}^{+2.7} \times 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
 - $BI_{\text{silver}} = 13_{-5.4}^{+8.0} \times 10^{-4} \text{ cts}/(\text{keV} \cdot \text{kg} \cdot \text{yr})$
- Silver dataset (13 kg yr): primarily coaxial detectors with worse background rejection

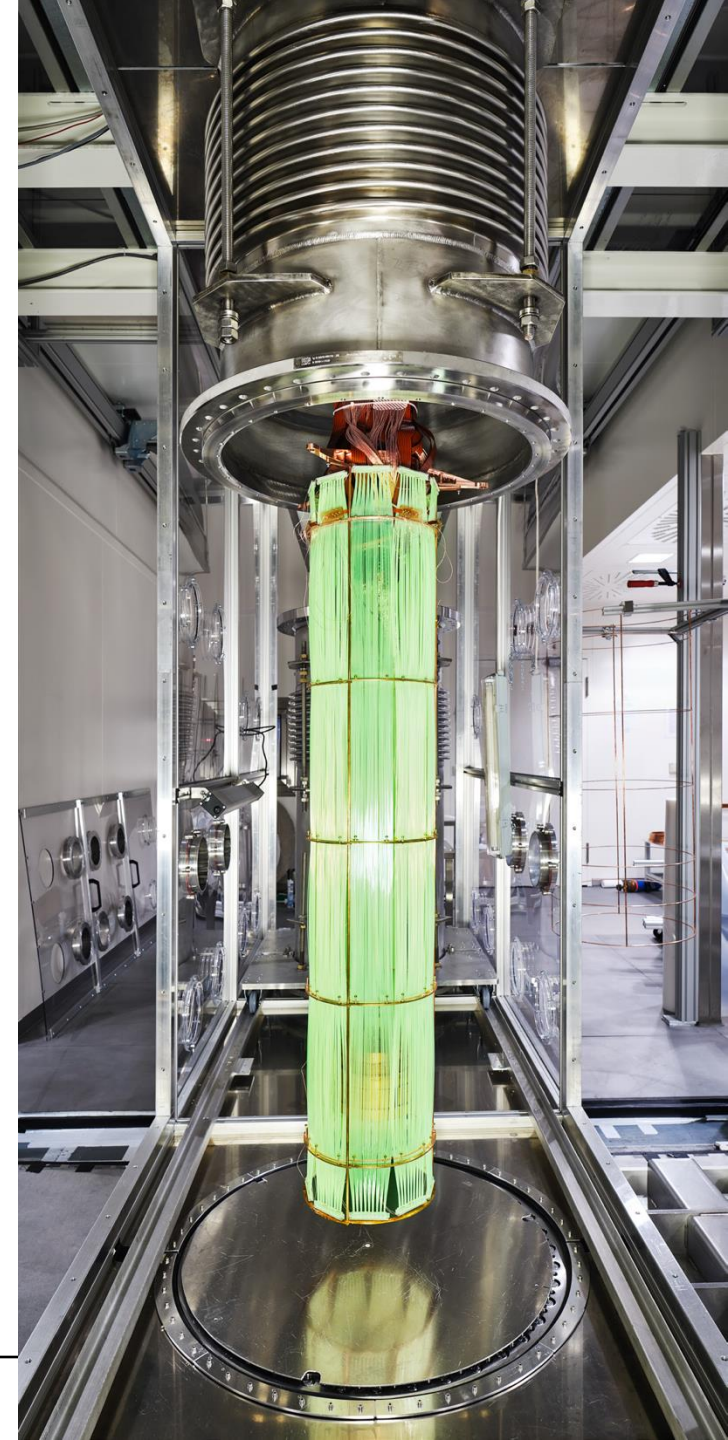


Combined fit GERDA + MJD + LEGEND-200

- frequentist and Bayesian statistical analysis → **no evidence of $0\nu\beta\beta$ signal**
- Lower limit $T_{1/2} > 1.9 \times 10^{26} \text{ yr}$ @ 90% CL → $m_{\beta\beta} < 70\text{-}200 \text{ meV}$
- Median sensitivity $2.8 \times 10^{26} \text{ yr}$ @ 90% CL
- world-leading sensitivity, one event at 1.3σ from $Q_{\beta\beta}$ weakens observed limit

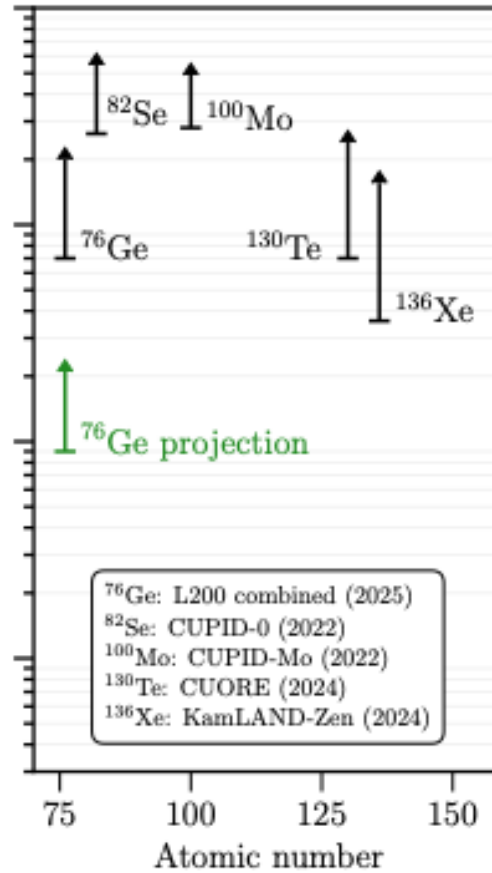
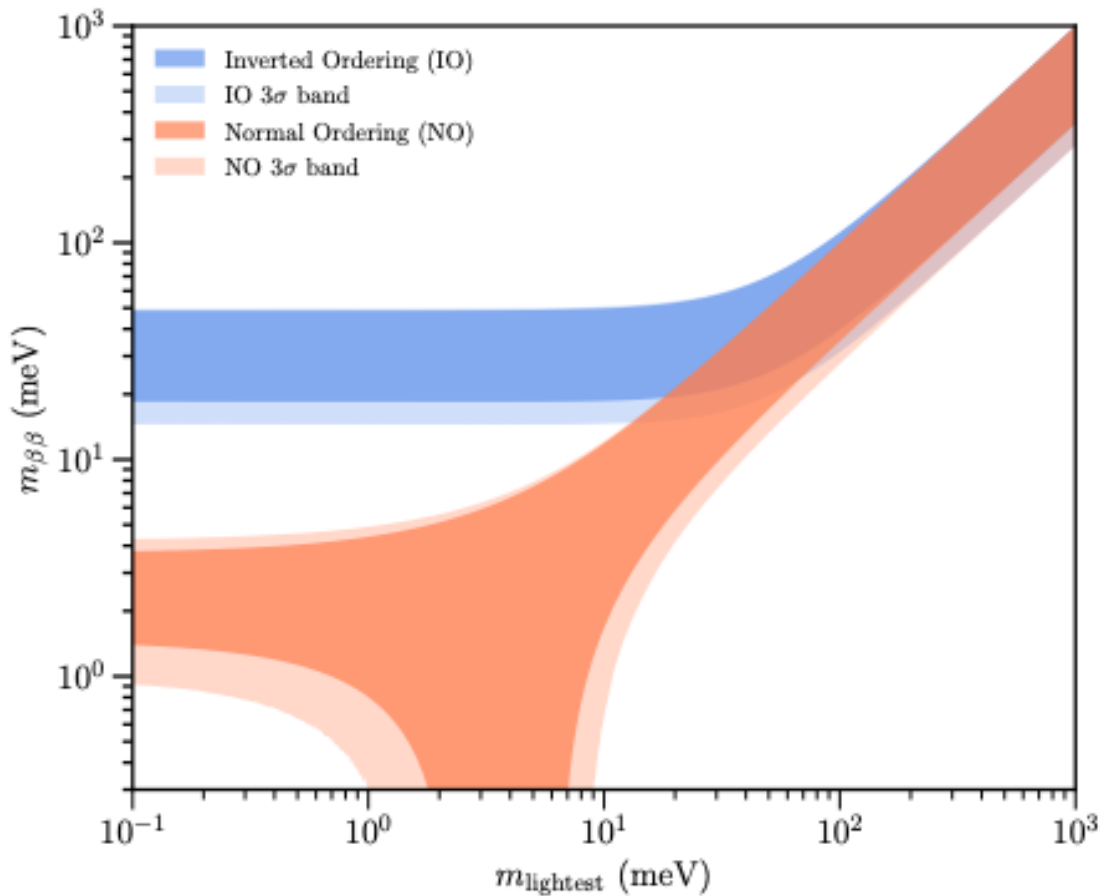
LEGEND-200: Summary

- ◆ GERDA infrastructure successfully upgraded for LEGEND-200
- ◆ First 142 kg of HPGe detectors installed (Oct 2022)
- ◆ Good performance from detectors & LAr instrumentation
- ◆ First LEGEND-200 results (61 kg·yr exposure):
- ◆ LAr veto + PSD: strong background suppression in ROI
- ◆ Combined with GERDA + MJD:
 - New half-life limit: 1.9×10^{26} yr
 - World-leading sensitivity: 2.8×10^{26} yr
- ◆ What's next:
 - ◆ 35 kg of new HPGe detectors being installed — data-taking resumes soon!
 - ◆ LEGEND-200 can also serve as a test-bed for new designs for LEGEND-1000



The future of the $0\nu\beta\beta$ -decay search

The neutrino mass ordering can be probed by $0\nu\beta\beta$ -decay searches if neutrinos are Majorana particles*



Completed:

^{76}Ge : GERDA: $T_{1/2} \geq 1.8 \times 10^{26}$ yr (90% C.L.),
 $|m_{\beta\beta}| \leq 79\text{-}180$ meV

^{136}Xe : KamLAND-Zen: $T_{1/2} \geq 3.8 \times 10^{26}$ yr
 (90% C.L.), $|m_{\beta\beta}| \leq 28\text{-}122$ meV (current
 best limits: [S. Abe et al.,
 arXiv:2406.11438](https://arxiv.org/abs/2406.11438))

New:

^{76}Ge : GERDA+MJD+LEGEND-200:
 $T_{1/2} \geq 1.9 \times 10^{26}$ yr (90% C.L.),
 $|m_{\beta\beta}| \leq 70\text{-}200$ meV

Planned:

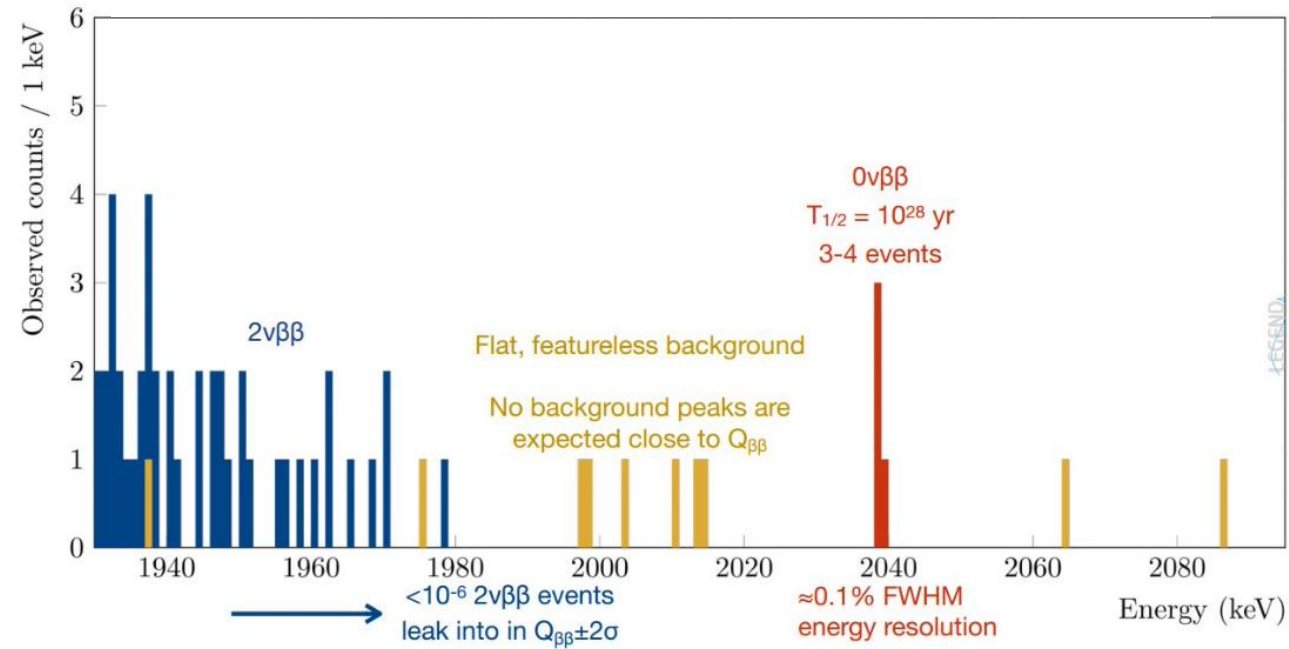
^{76}Ge : LEGEND-1000**: $T_{1/2} \geq 10^{28}$ yr
 (99.7% C.L.), $|m_{\beta\beta}| \leq 10\text{-}20$ meV

*and if the decay mechanism is of light neutrino exchange

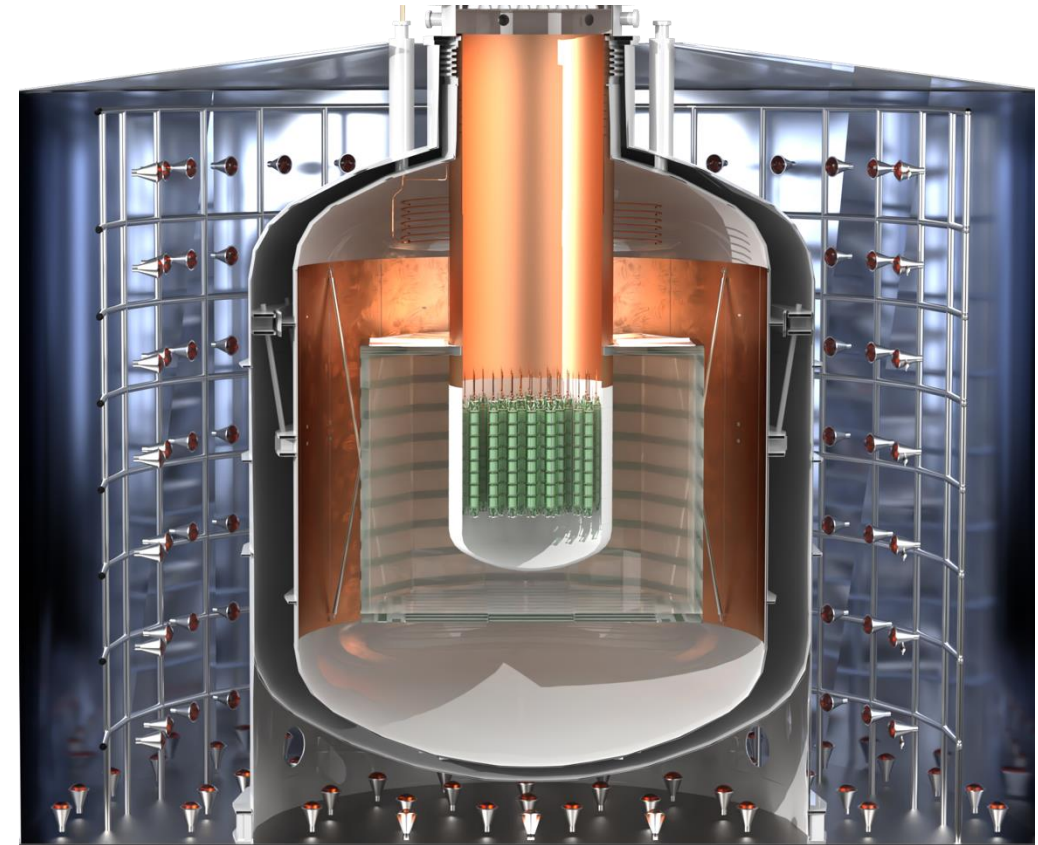
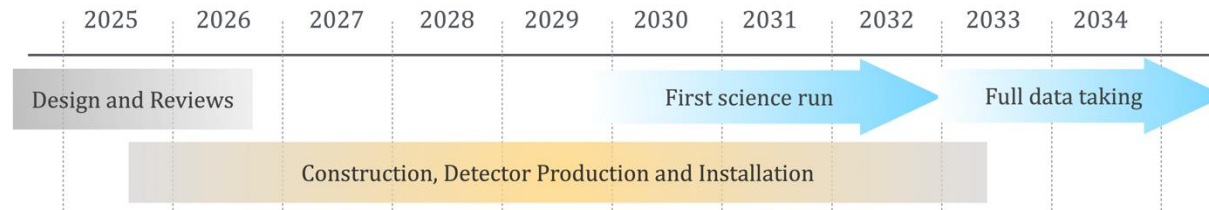
**For 10 yr exposure and BI of $\sim 1 \times 10^{-5}$ cts / (keV kg yr)

LEGEND-1000

- Designed for an unambiguous discovery and a quasi-background-free $0\nu\beta\beta$ search.
- Simulated LEGEND-1000 example spectrum for $T_{1/2} = 10^{28}$ yr, BI $<10^{-5}$ cts/keV kg yr, after cuts from 10 yr of data.



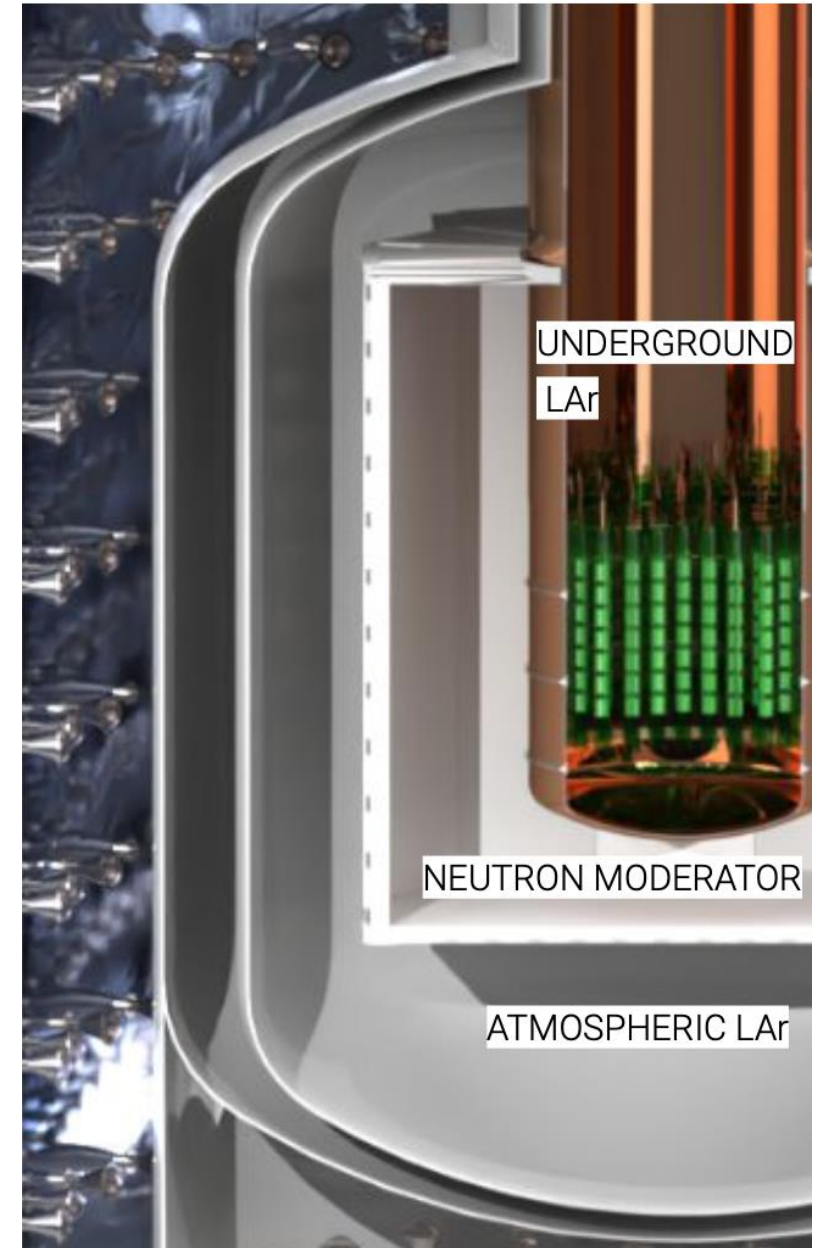
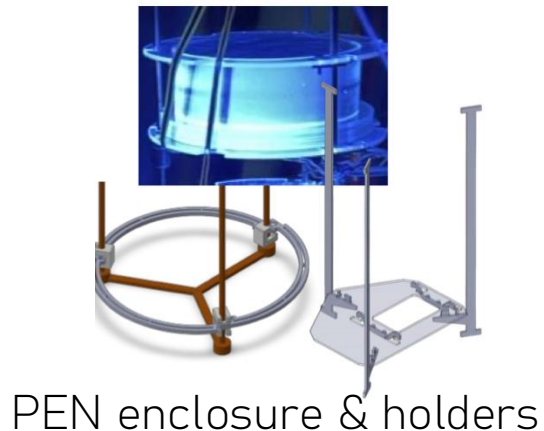
- 336 detectors, each with 3 kg average mass, amounting to a total of 1000 kg of HPGe.
- Planned at LNGS, with staged commissioning in 2030.
- Data taking for 10 years, aiming for a discovery sensitivity of $T_{1/2} > 10^{28}$ yr (99.7% C.L.)



Improvements in LEGEND-1000

 LEGEND-1000 target BI: $\sim 10^{-5}$ cts/ (keV kg yr):

- LEGEND-1000 background improved by $\sim 20\times$ over L-200 primarily by ^{42}K background reduction (^{42}K originates from cosmogenic ^{42}Ar decay)
- Large ICPC detectors immersed in underground LAr
- Neutrino moderator instrumented with WLS light guides
- Xe-doped atmospheric LAr
- PEN materials used for scintillating and radiopure detector support materials



Summary

- ◆ We don't really understand why there's more matter than antimatter.
- ◆ Majorana neutrinos could solve this mystery.
- ◆ To discover them, we must search for $0\nu\beta\beta$ -decay by building large low-background detectors.
- ◆ ^{76}Ge is a clear leading choice for a ton-scale search: **experiments are optimised for an unambiguous discovery of $0\nu\beta\beta$ -decay.**
- ◆ The LEGEND program builds on these successes for a low-risk path to exploring half-lives beyond 10^{28} :
 - ◆ LEGEND-200 data taking is about to re-start.
 - ◆ LEGEND-1000 pre-conceptual design available, with R&D and conceptual design development under way.

