LEGEND at NTU

The Large Enriched Germanium Experiment for Neutrinoless double beta Decay

Department of Physics
National Taiwan University

Pin-Jung Chiu 邱品融
pin-jung.chiu@phys.ntu.edu.tw

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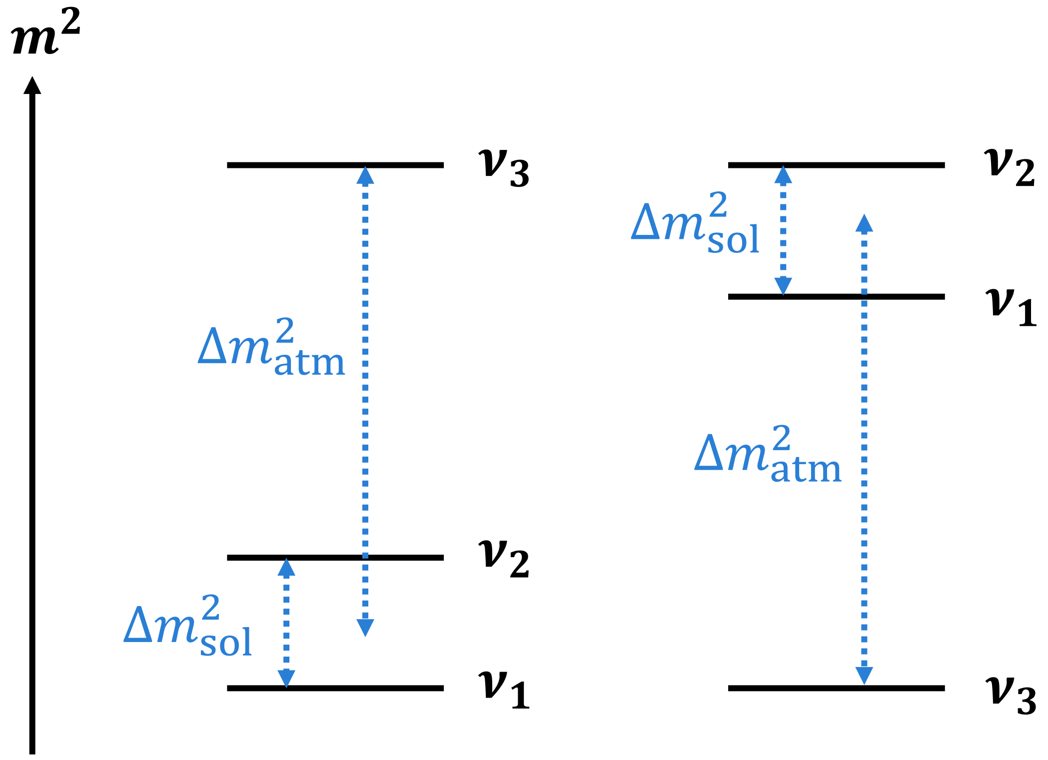
National Museum of Natural Science, Taichung

Open questions in neutrino physics

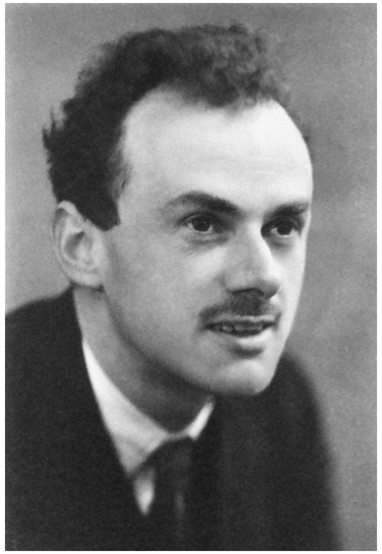
- **Neutrino mass ordering and absolute scale**



Normal Ordering | **Inverted Ordering**

- **Nature**

Observed: ν_{L} and $\overline{\nu_{\mathrm{R}}}$



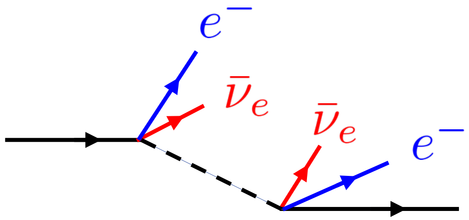
Dirac mechanism $\nu \neq \bar{\nu}$

Majorana mechanism $\nu = \bar{\nu}$

Neutrinoless double beta decay

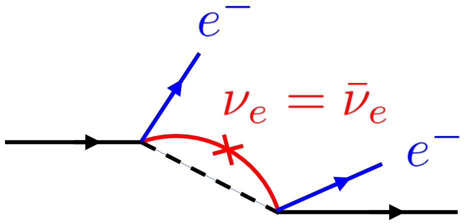
- **Two neutrino double beta decay 2νββ**
  - Standard-Model-allowed process
  - Nature provides 35 isotopes, e.g., ^{76}Ge, ^{100}Mo, ^{136}Xe

$$2n \longrightarrow 2p^+ + 2e^- + 2\bar{\nu}_e$$



- **Neutrinoless double beta decay 0νββ**
  - Hypothetical process

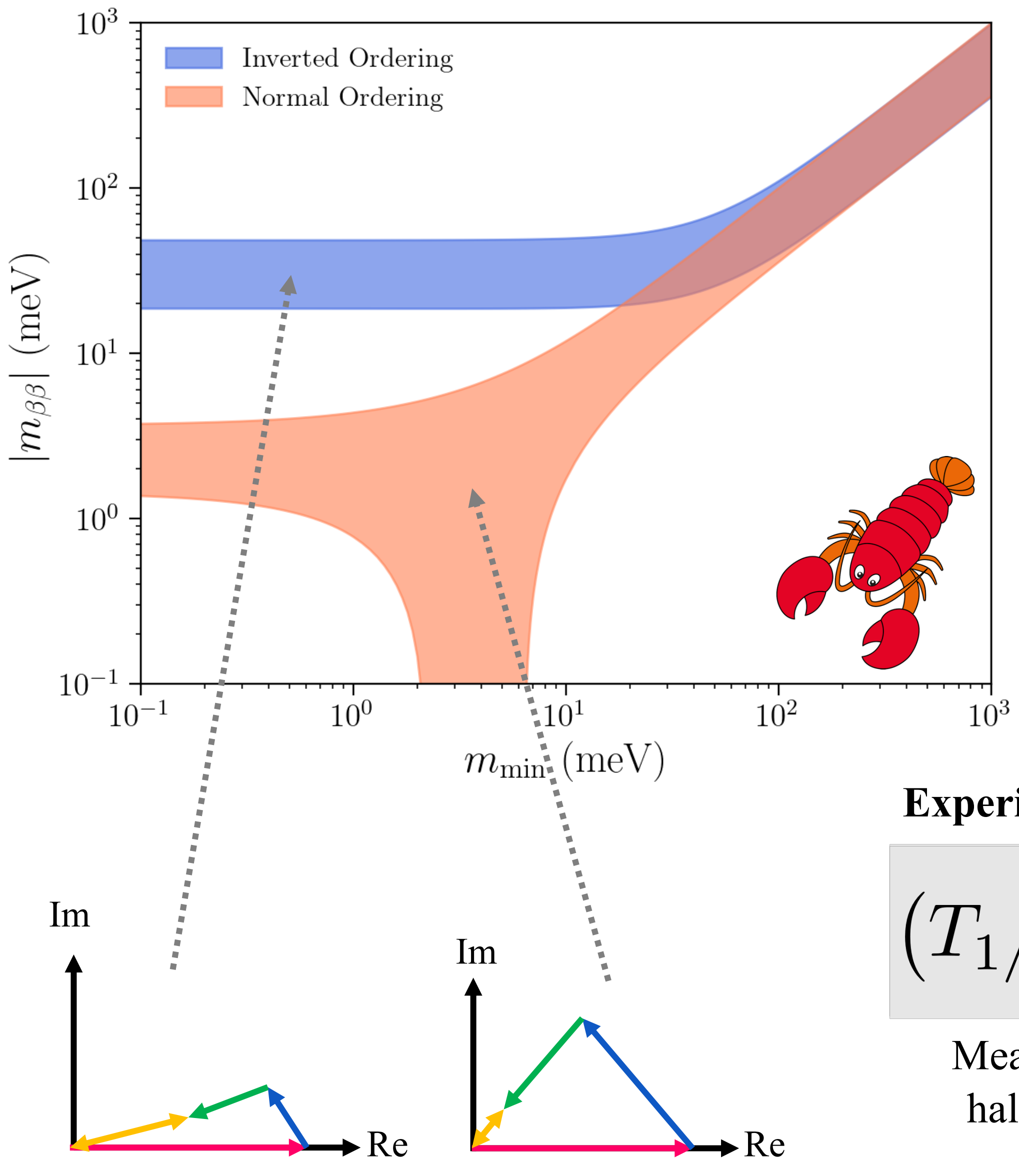
$$2n \longrightarrow 2p^+ + 2e^-$$



If observed:

- Majorana nature of ν: $\nu = \bar{\nu}$
- Lepton number violation: $\Delta L = 2$

Effective Majorana neutrino mass



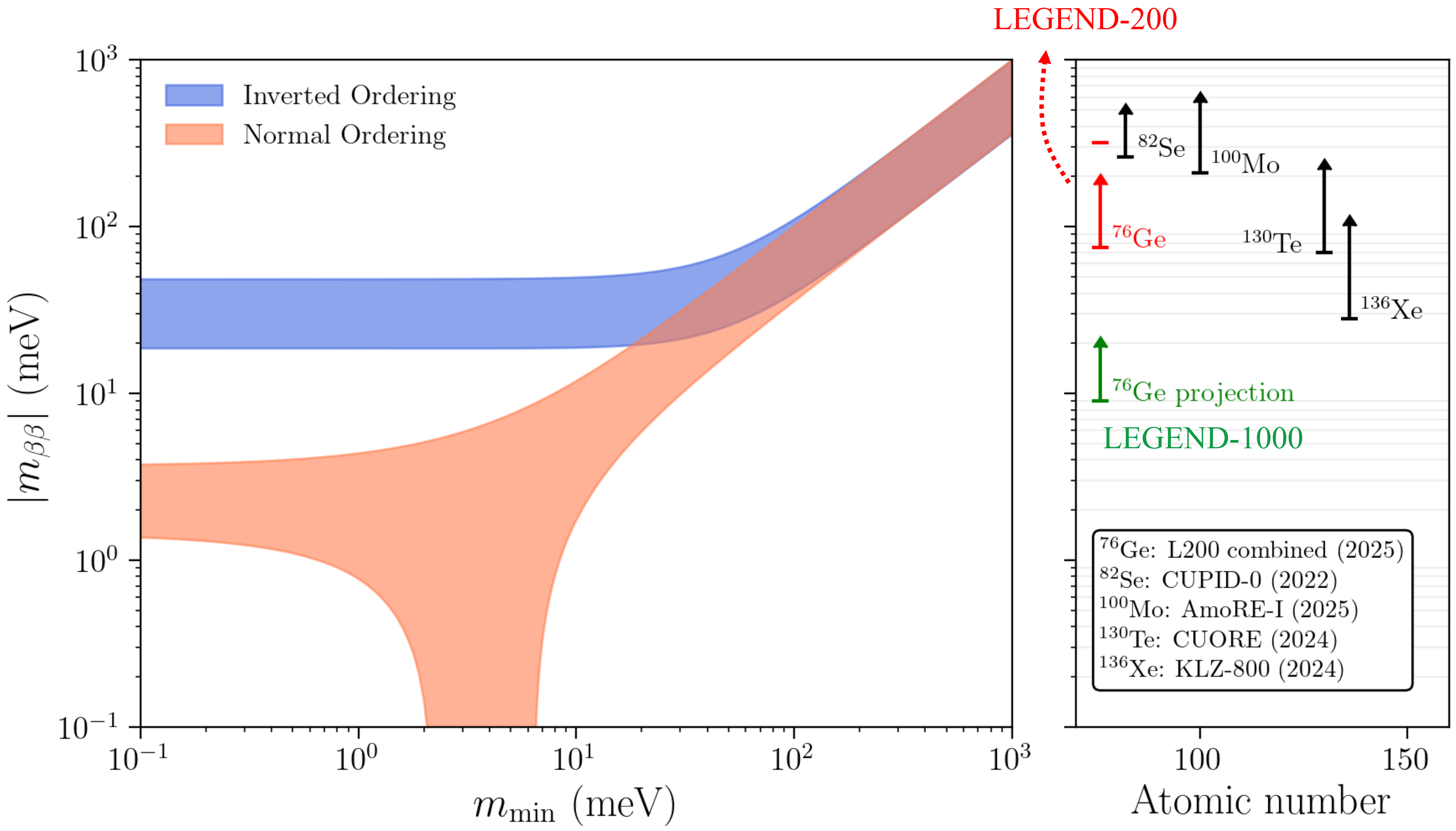
$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right|$$
$$= \left| m_1 \left| U_{e1} \right|^2 + m_2 \left| U_{e2} \right|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 \left| U_{e3} \right|^2 e^{-i(\alpha_1 + 2\delta)} \right|$$

α_1, α_2: Majorana phases

δ: Dirac phase

Experiment		Atomic phys.				Nuclear phys.		Particle phys.
$\left(T_{1/2}\right)^{-1}$	$=$	$G\left(Q_{\beta\beta}, Z\right)$	$\cdot$	${g_A}^4$	$\cdot$	$\left\|M_{\text{nucl}}\right\|^2$	$\cdot$	${m_{\beta\beta}}^2$
Measured half-life		Phase space factor		Axial coupling		Nuclear matrix elements		Effective Majorana neutrino mass

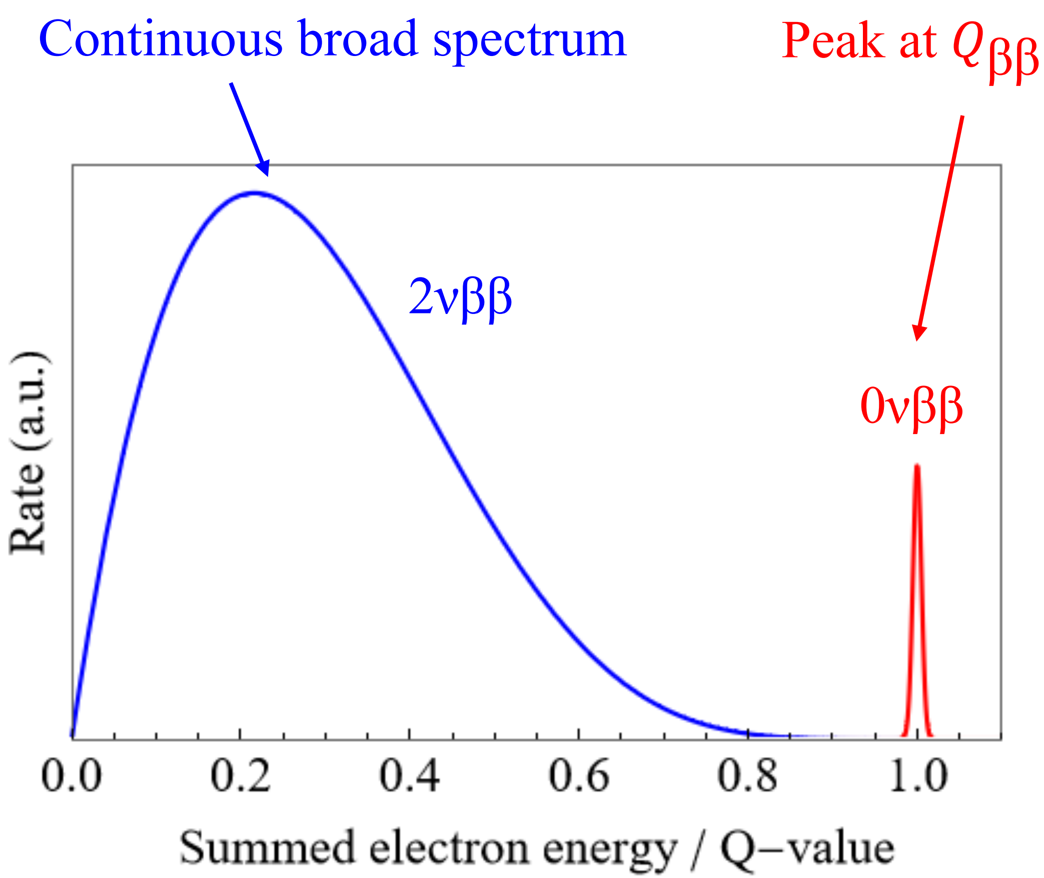
Where the community is standing



Experimental detection approach

$$2n \longrightarrow 2p^+ + 2e^- + 2\bar{\nu}_e$$

Measure the summed energy of the two emitted electrons

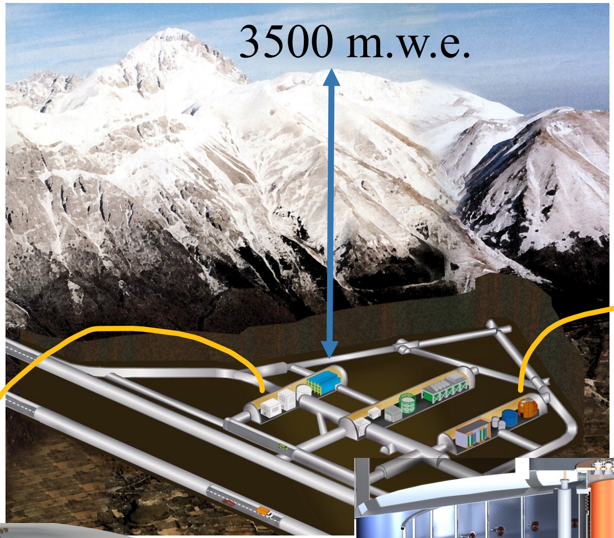


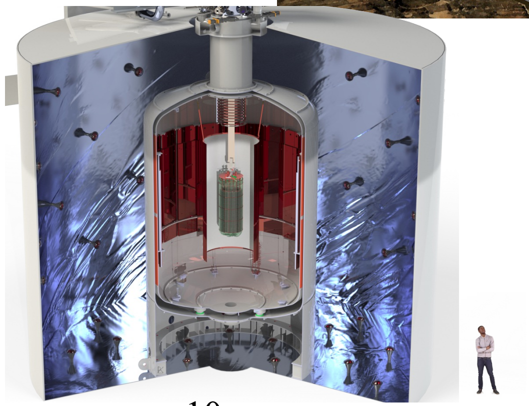
The LEGEND project

Phase I: LEGEND-200

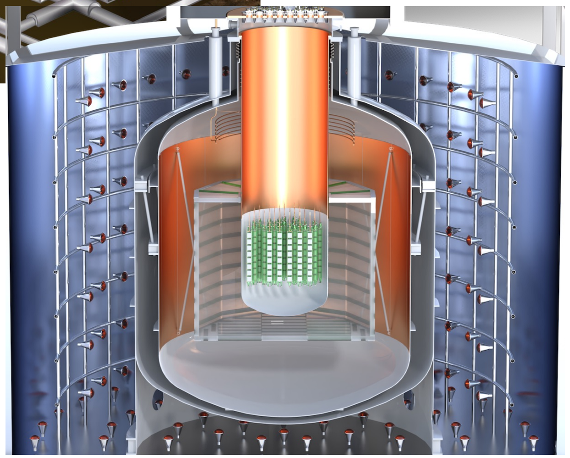
- Up to 200 kg of Ge detectors in modified existing GERDA infrastructure
- Taking physics data since 2023. Will continue until 1 t · yr of exposure is reached
- BI goal: 2×10^{-4} counts/(keV·kg·yr)
- $T_{1/2} > 10^{27}$ yr

Laboratori Nazionali del Gran Sasso, Italy





10 m



12 m

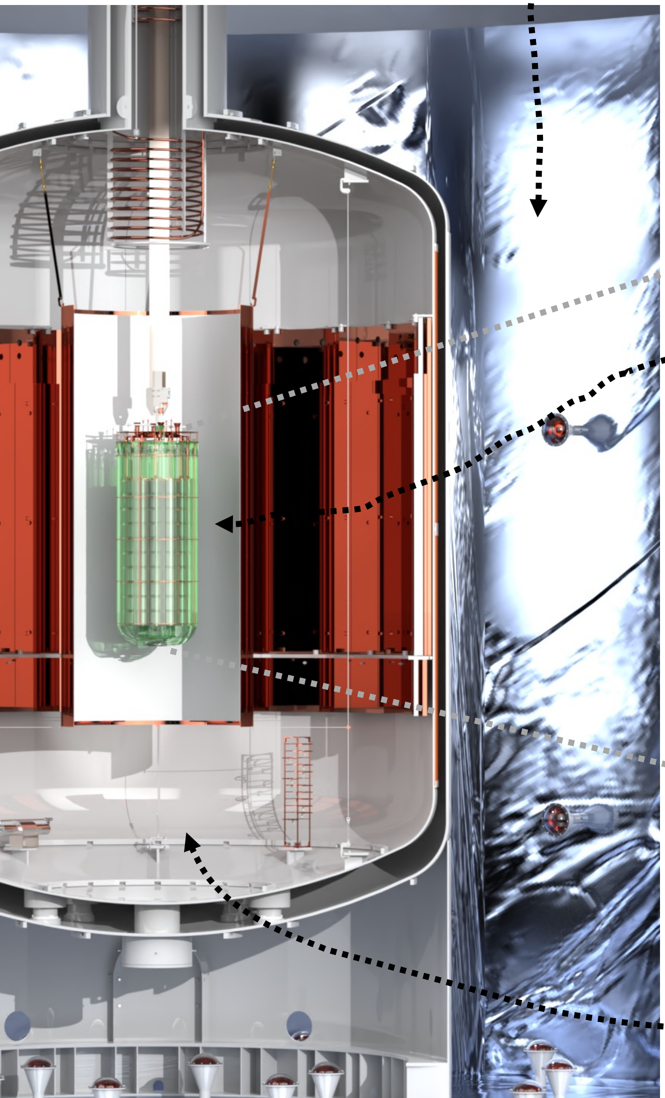
Phase II: LEGEND-1000

- 1000 kg of Ge detectors
- 10 t · yr of exposure
- BI goal: 1×10^{-5} counts/(keV·kg·yr)
- $T_{1/2} > 10^{28}$ yr
- $m_{\beta\beta}$ would cover full $m_{\beta\beta}$ inverted ordering regime

Ref.: LEGEND-1000 Preconceptual Design Report

LEGEND-200 at LNGS

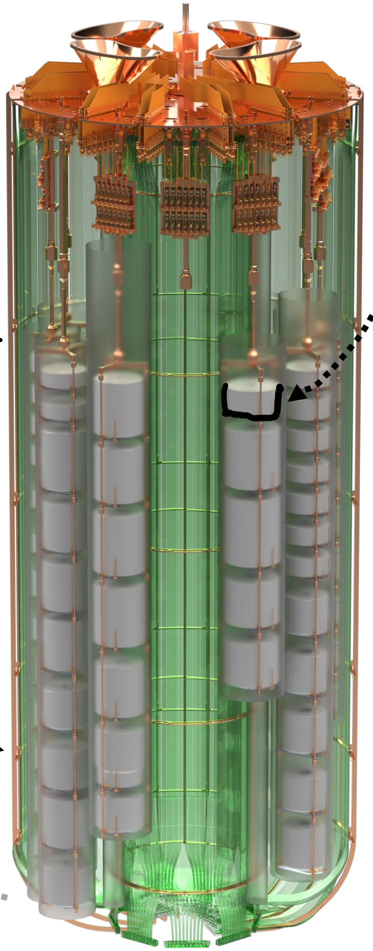
Water tank with PMTs for muon veto (Φ = 10 m, H = 9 m)



Detector array with max. 12 detector strings

Wavelength-shifting reflector

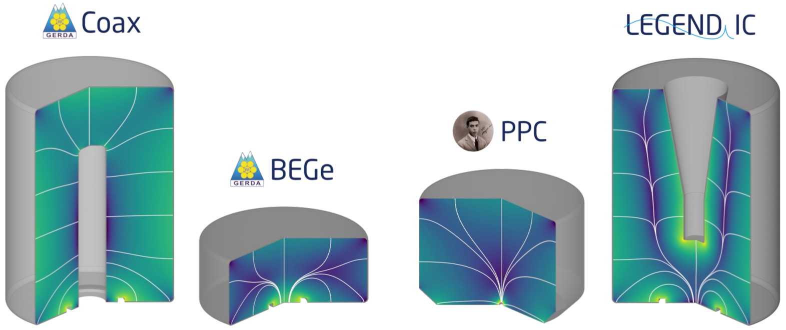
Inner and outer fiber barrels with silicon photomultiplier (SiPM) readouts at top and bottom

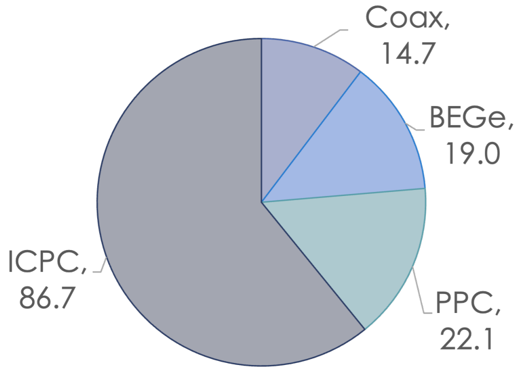


LAr cryostat cryostat (Φ = 4.2 m, H = 6 m)

Detector unit

Four detector types



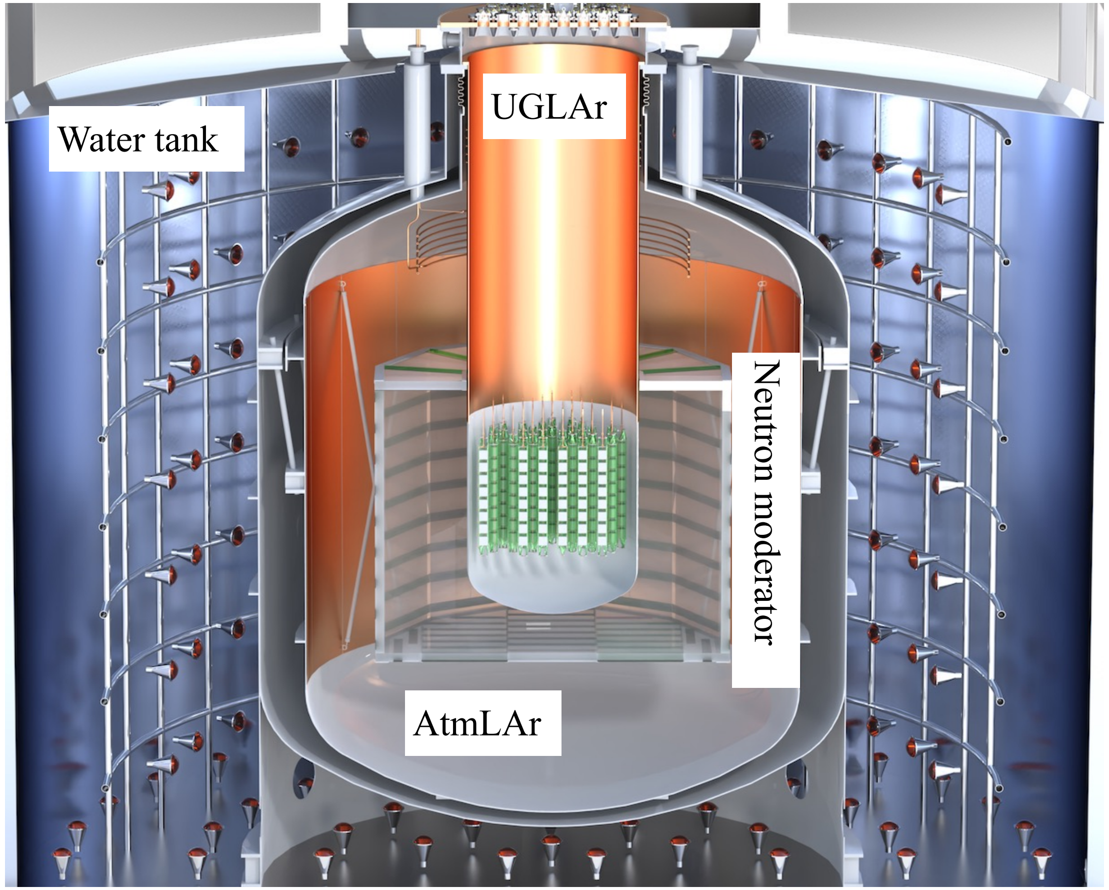


Baseline design of LEGEND-1000

- Background reductions: Requires 20x improvement in background index
  - Radiopure underground argon (UGLAr): direct mitigation of ^{42}K (from ^{42}Ar) background
  - Underground electroformed copper (EFCu)
  - Neutron moderator in LAr
  - Neutron shielding materials around Ge detectors

- ICPC detectors:
  - Increasing mass reduces surface to volume ratio
  - ^{76}Ge enrichment up to 92%

- LAr veto:
  - Optimal wavelength-shifting material combinations (shifter + reflector) required given larger surfaces

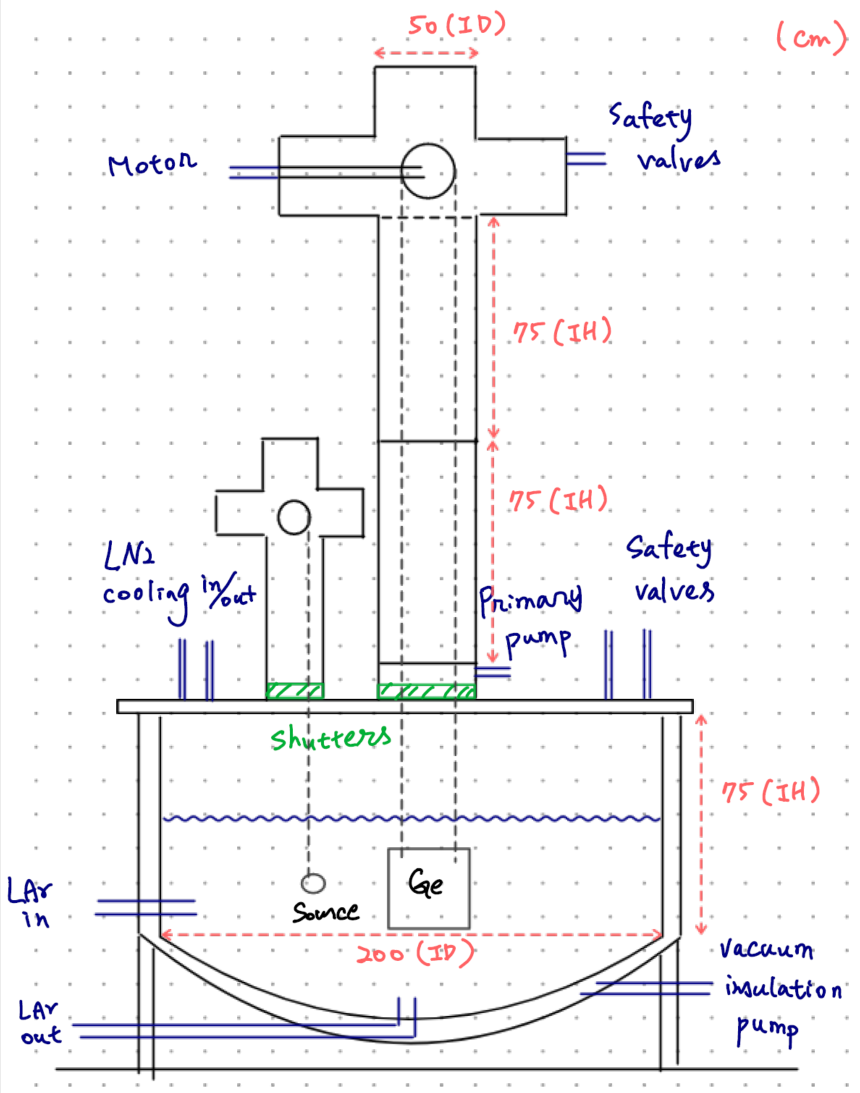


Ref.: LEGEND Collab., arXiv:2107.11462

Design and construction of the LAr facility at NTU

Preliminary

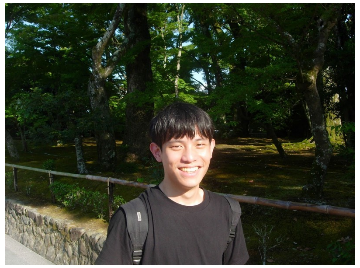
- We are preparing to build a LAr facility at NTU
  - Study next-generation wavelength-shifting materials
  - Investigate HPGe detector properties in LAr environment

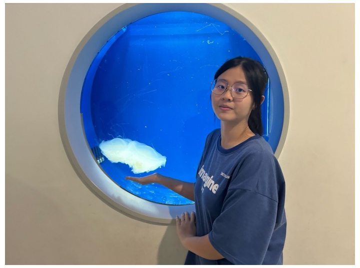


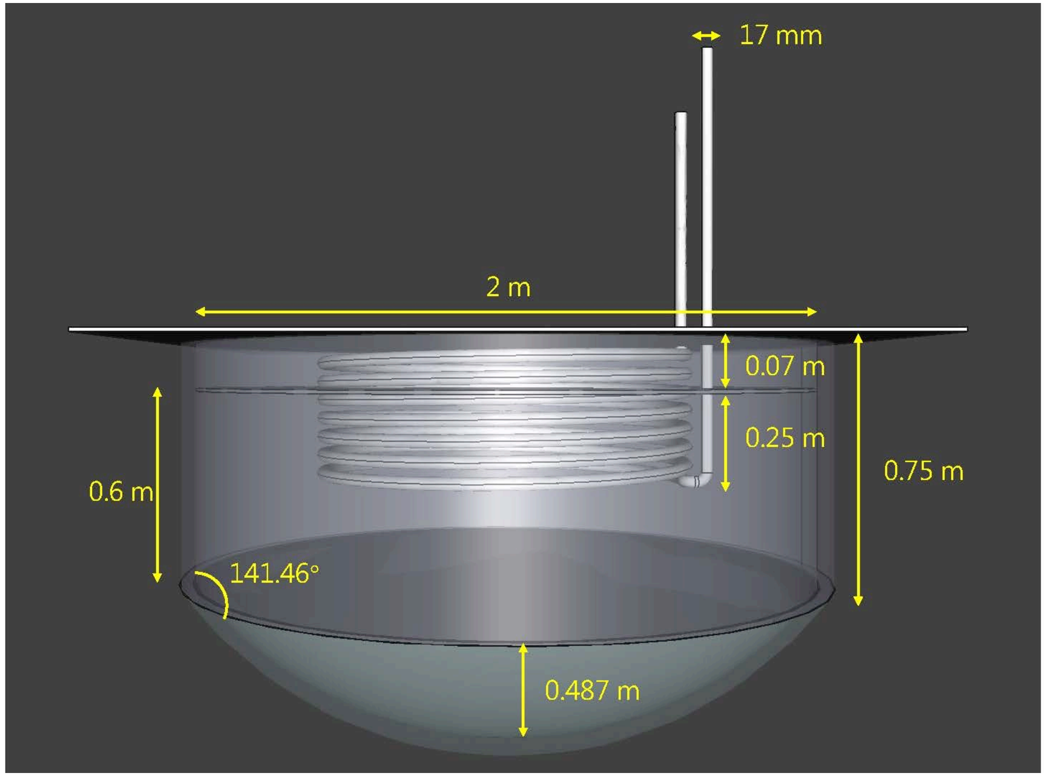
Stainless steel cryostat and top flange

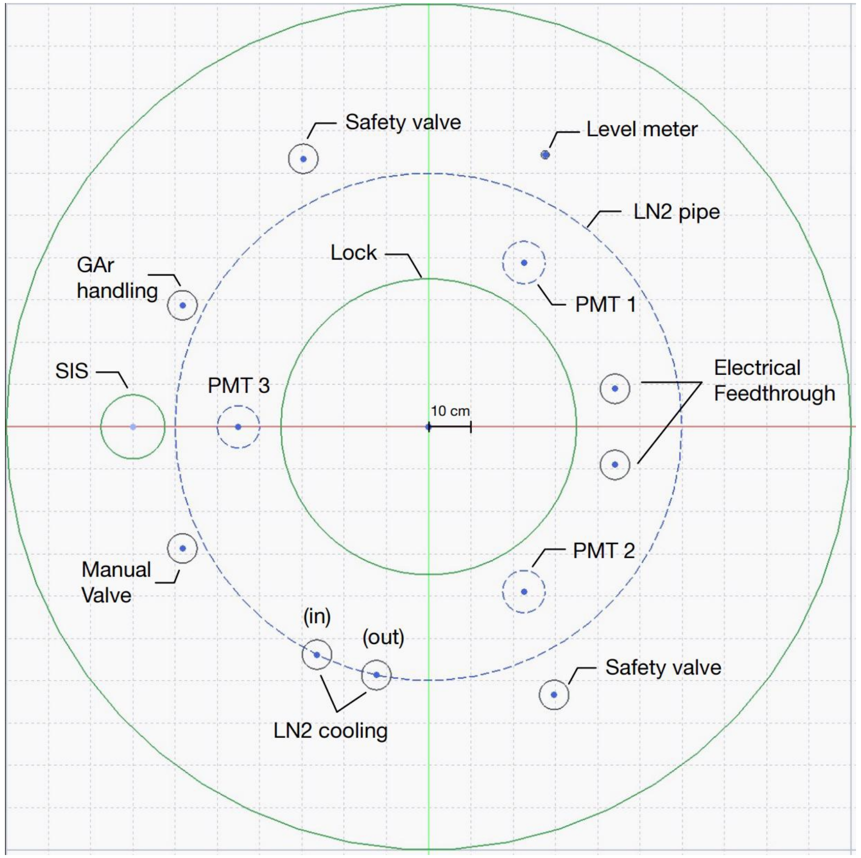
See poster from Yu-Hua Huang

- Stainless steel cryostat with a diameter of 2 m and a height of > 1 m
- Double layer with a vacuum gap in between to ensure thermal insulation
- During stable condition, filled with LAr and kept at 87 K









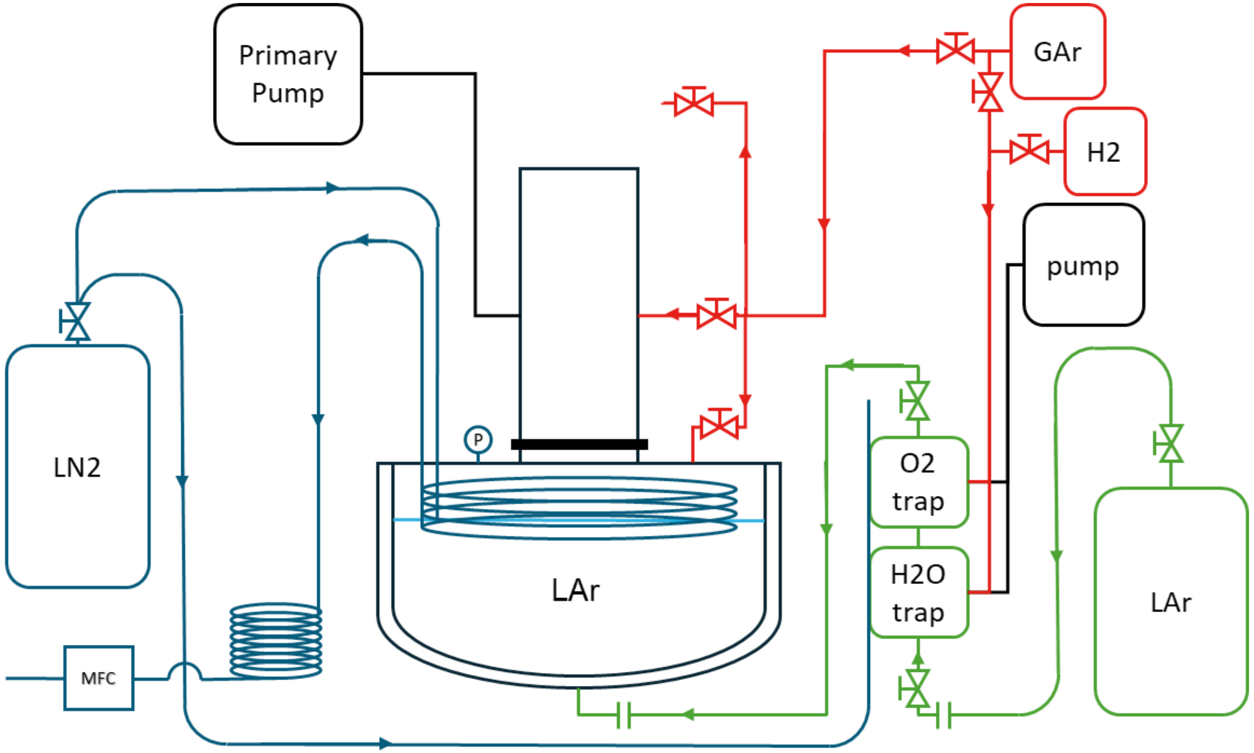
Pin-Jung Chiu | TIDC 2025 | 2026.01.06.

Piping and LAr purification system

See poster from Chia-Yen Wang

- Piping systems is responsible for
  - Vacuum pumping
  - GAr flushing
  - LAr filling/draining
  - LN_2 cooling of the cryostat controlled by a mass flow controller with PID mechanism

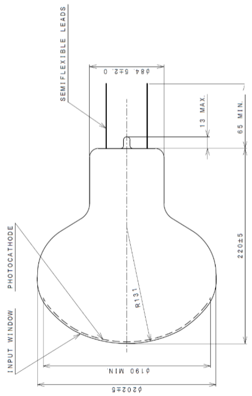
- Purification system is used to purify LAr before being filled into the cryostat



Other projects related to the NTU LAr test stand

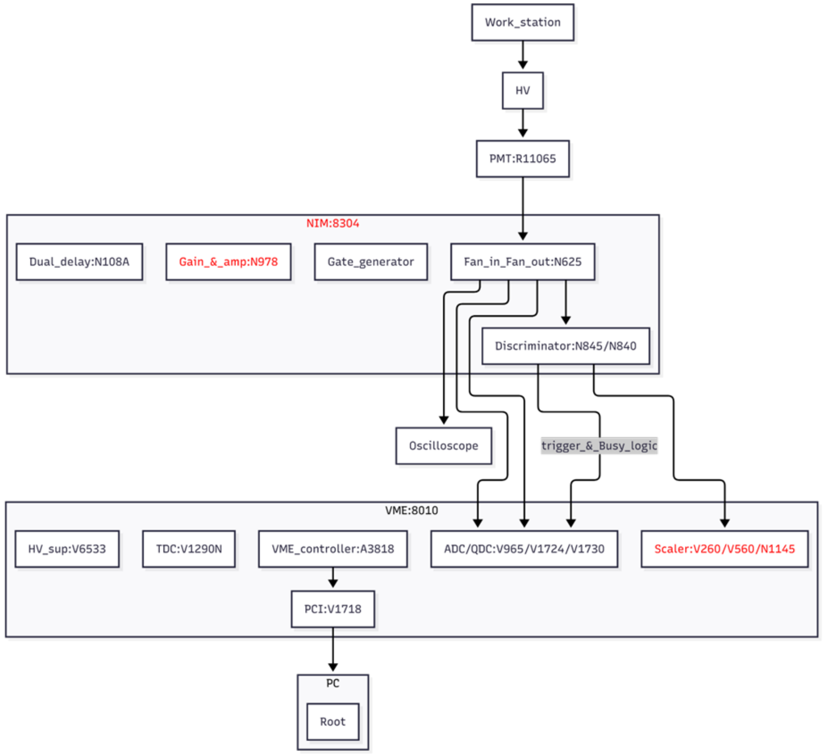
- Characterize photomultiplier tubes to be installed in the NTU LAr facility for LAr scintillation light detection

Ref. Hamamatsu



- Build a DAQ system to read out LAr and Ge signals

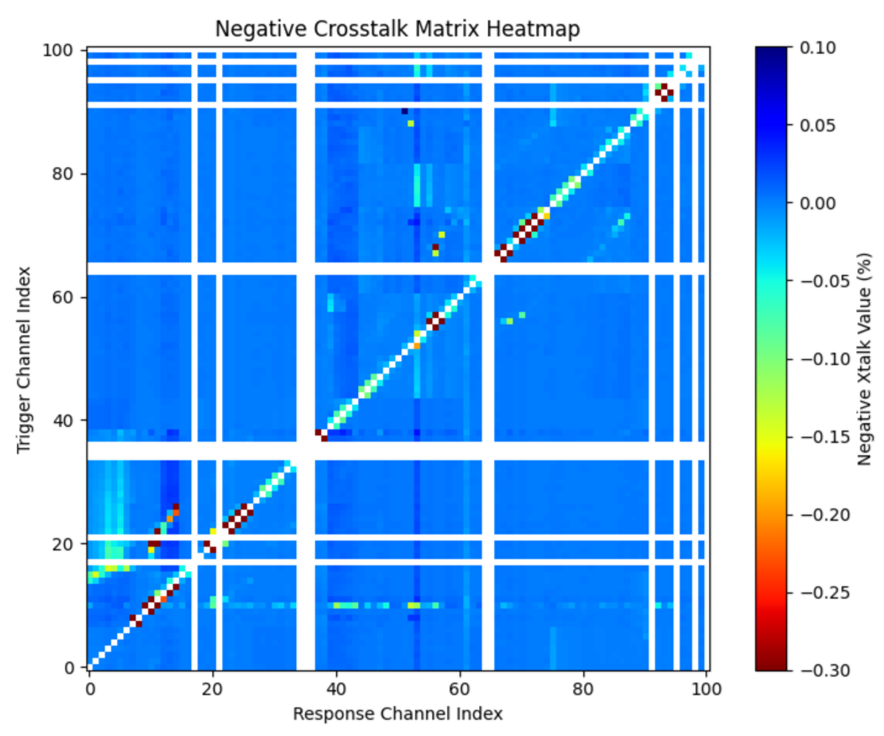
- Construct a simulation framework for the LAr facility

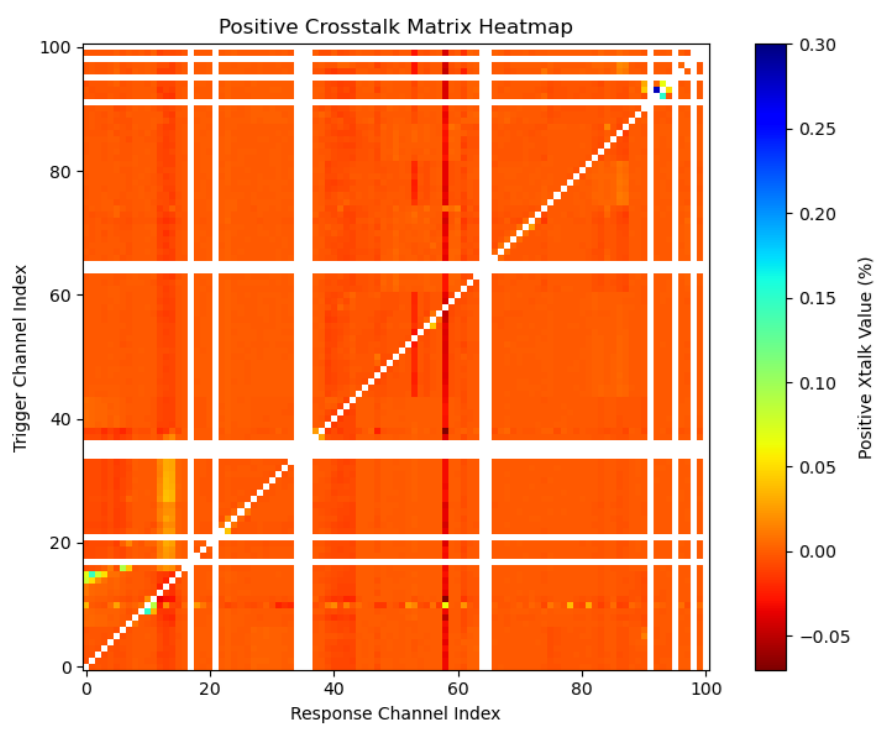


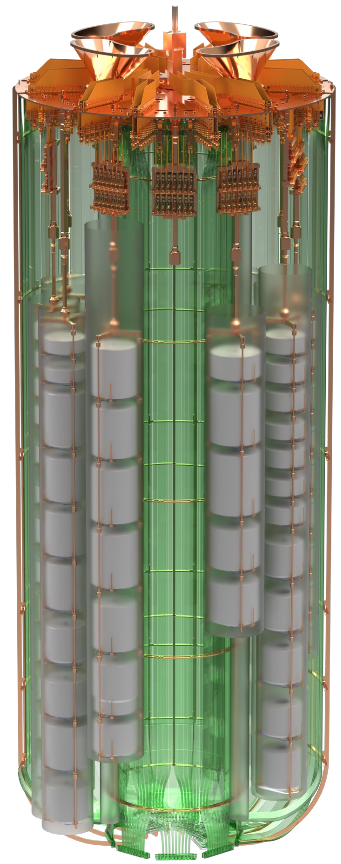
HPGe-detector cross-talk study

See poster from Hung-Wei Liu

- In LEGEND-200, around 100 detectors were installed
- We observed cross-talks among near-by detectors
- With dedicated data, we studied the cross-talks between each detector pair and constructed a cross-talk matrix for future data correction

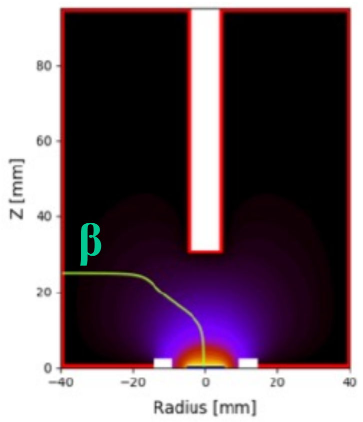




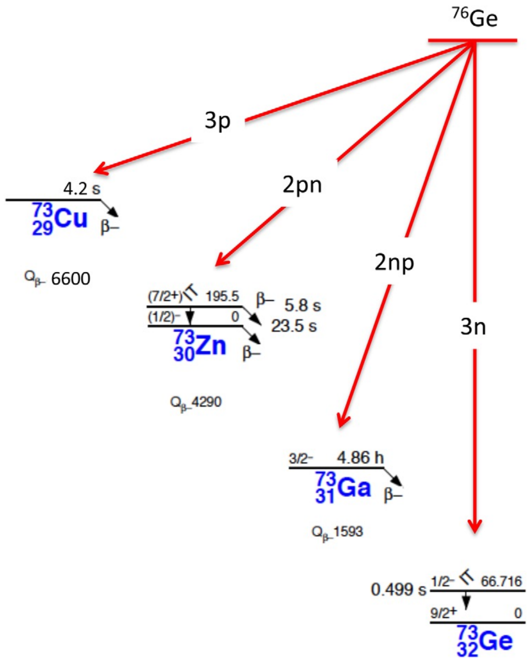


Other analysis and simulation projects in LEGEND

- Investigate Ge detector N+-surface events
  - Understand the charge drift in the transition layer between the dead layer and the bulk
  - Implement a simulation model to describe events close to N+ surface of Ge detectors
  - Validate a semi-heuristic model with data → data selection



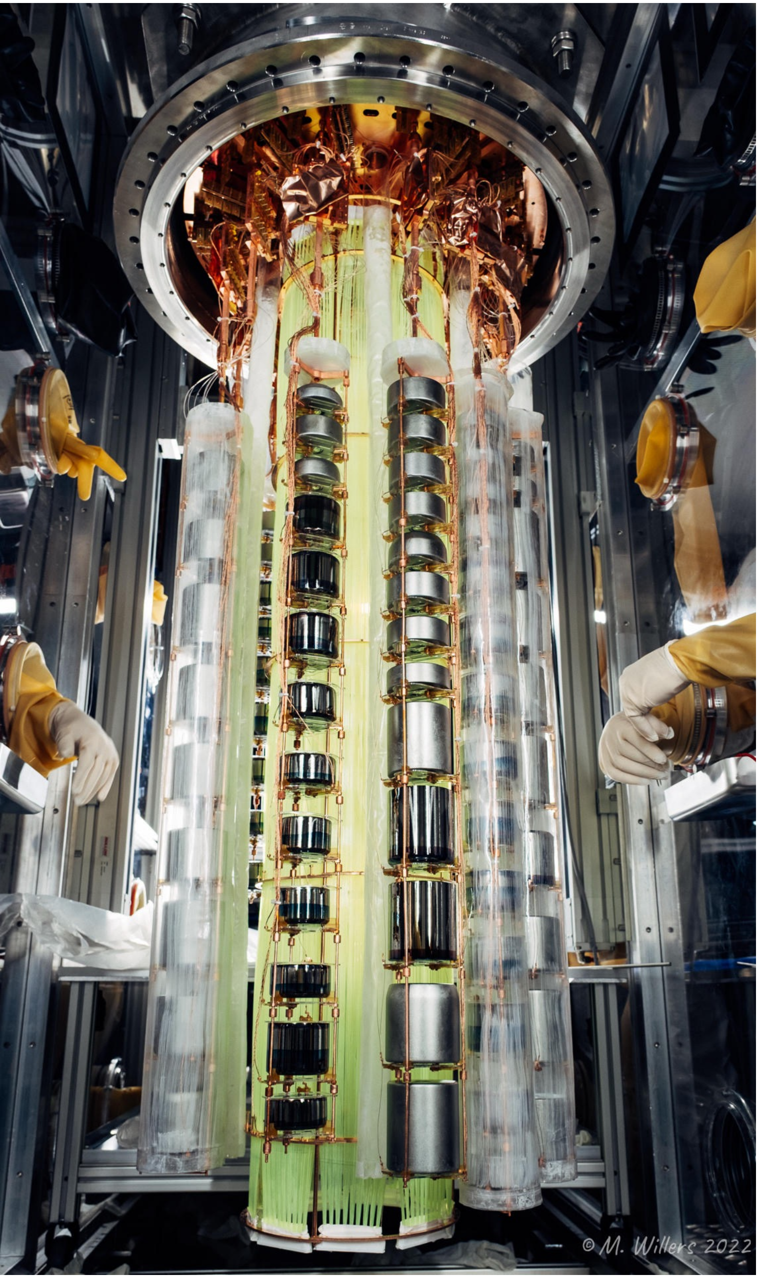
- Search for tri-nucleon decay in ^{76}Ge
  - E.g., $^{76}\mathrm{Ge} \rightarrow ^{73}\mathrm{Cu} + e^{+} + \pi^{+} + \pi^{+} \rightarrow ^{73}\mathrm{Zn} \rightarrow ^{73}\mathrm{Ga} \rightarrow ^{73}\mathrm{Ge}$
  - Search for events in temporal coincidence fulfilling certain energy constraints



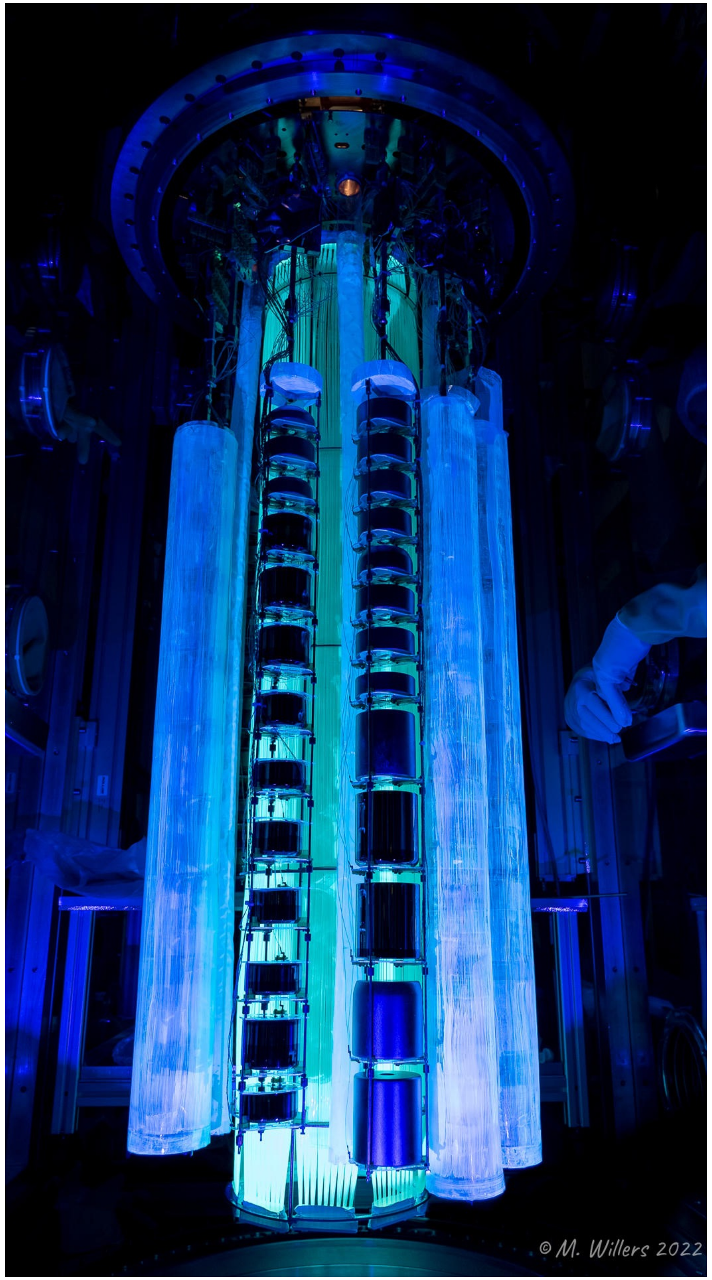
Ref.: S.I. Alvis et al., PRD 99, 072004 (2019)

Summary

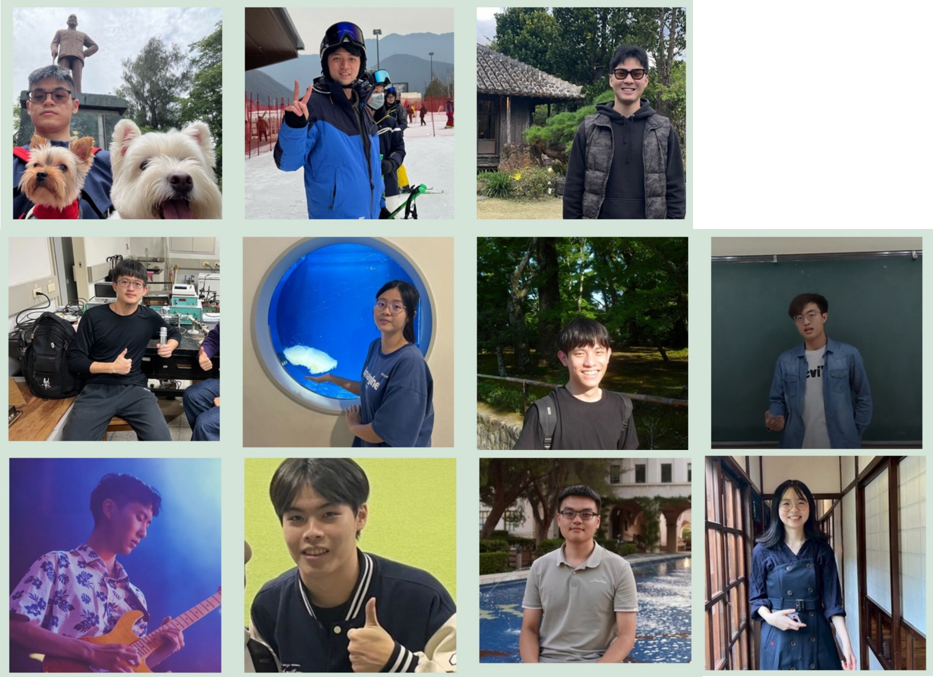
Credit: M. Willers



- LEGEND is a world-leading experiment searching for 0νββ
- If 0νββ is observed, it would be the first evidence of lepton-number violation and would prove the Majorana nature of neutrinos
- At NTU, we contribute to all aspects of LEGEND including hardware R&D, physics simulation, and data analysis
- The design and construction of a liquid argon facility at NTU is underway dedicating to next-generation wavelength shifting materials and high-purity germanium detector studies



Acknowledgement



https://pin-jung-chiu.phys.ntu.edu.tw/

https://legend-exp.org/

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Ministry of Education
Republic of China (Taiwan)

YUSHAN
FELLOW PROGRAM
MINISTRY OF EDUCATION, TAIWAN

NSTC

Thank you

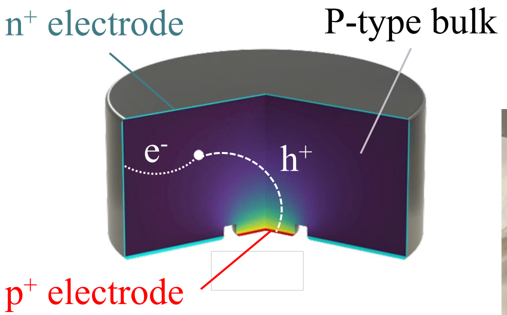
Backup slides

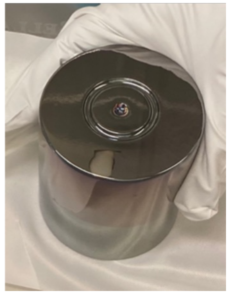
Advantages of using germanium detectors enriched in ^{76}Ge

2.52 keV (FWHM) at $Q_{\beta\beta}$ from the MAJORANA DEMONSTRATOR

Best energy resolution of any ββ detector

Commercial semiconductor detectors





Made from high-purity germanium (HPGe) materials

No measurable internal background

Excellent detection efficiency

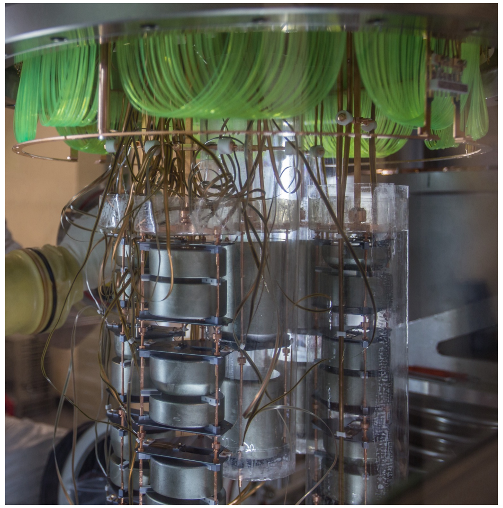
Source = Detector

~100% in the active volume

High enrichment level

Enrichment in ^{76}Ge isotope > 90% is possible

^{76}Ge-based 0νββ experiments

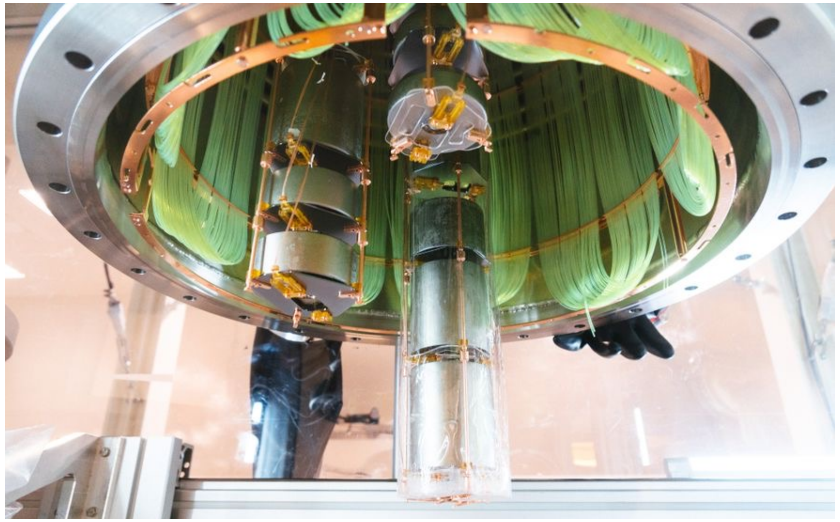


Credit: GERDA Collab.

LNGS, Italy

Credit: MAJORANA Collab.

SURF, US



LNGS, Italy

GERDA + MAJORANA DEMONSTRATOR (MJD) + new institutes → LEGEND

Lowest background level for 0νββ:
Mean background in ($Q_{\beta\beta}$±2σ) is 0.3 counts
(with 103.7 kg·yr of exposure)

Best energy resolution for 0νββ:
2.52 keV (FWHM) at $Q_{\beta\beta}$
(with 64.5 kg·yr of exposure)

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

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

0νββ decay half-life $T_{1/2}$

- Half-life sensitivity

$$T_{1/2} \propto f\,\epsilon\,\sqrt{\frac{Mt}{B\sigma_{\mathrm{E}}}}$$

f: isotope enrichment fraction

ϵ: Detection efficiency

M: Isotope mass

t: Measurement time

} Mt: exposure

B: Background index = counts / [energy-range · mass · time], e.g., counts / (keV·kg·yr)

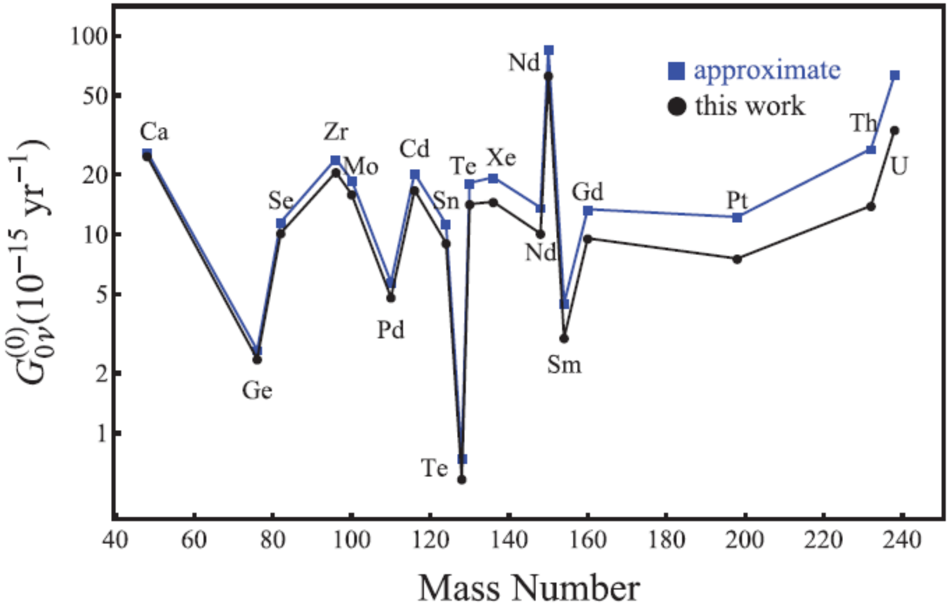
σ_{E}: Energy resolution at the decay Q-value ($Q_{\beta\beta}$)

Decay half-life vs. effective Majorana neutrino mass

Experiment	Atomic phys.		Nuclear phys.	Particle phys.

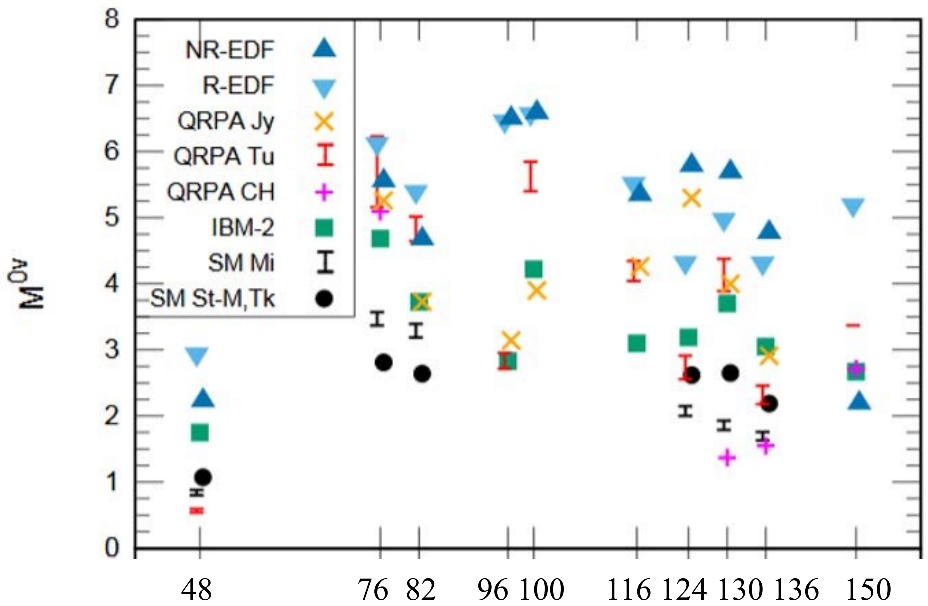
$$\left(T_{1/2}\right)^{-1} = G\left(Q_{\beta\beta}, Z\right) \cdot {g_A}^4 \cdot \left|M_{\text{nucl}}\right|^2 \cdot {m_{\beta\beta}}^2$$

Measured half-life	Phase space factor	Axial coupling	Nuclear matrix elements	Effective Majorana neutrino mass



Ref.: J. Kotila and F. Iachello, PRC 85, 034316 (2012)

$g_A = 1.27$



Ref.: J. Engel and J. Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

Various detection concepts

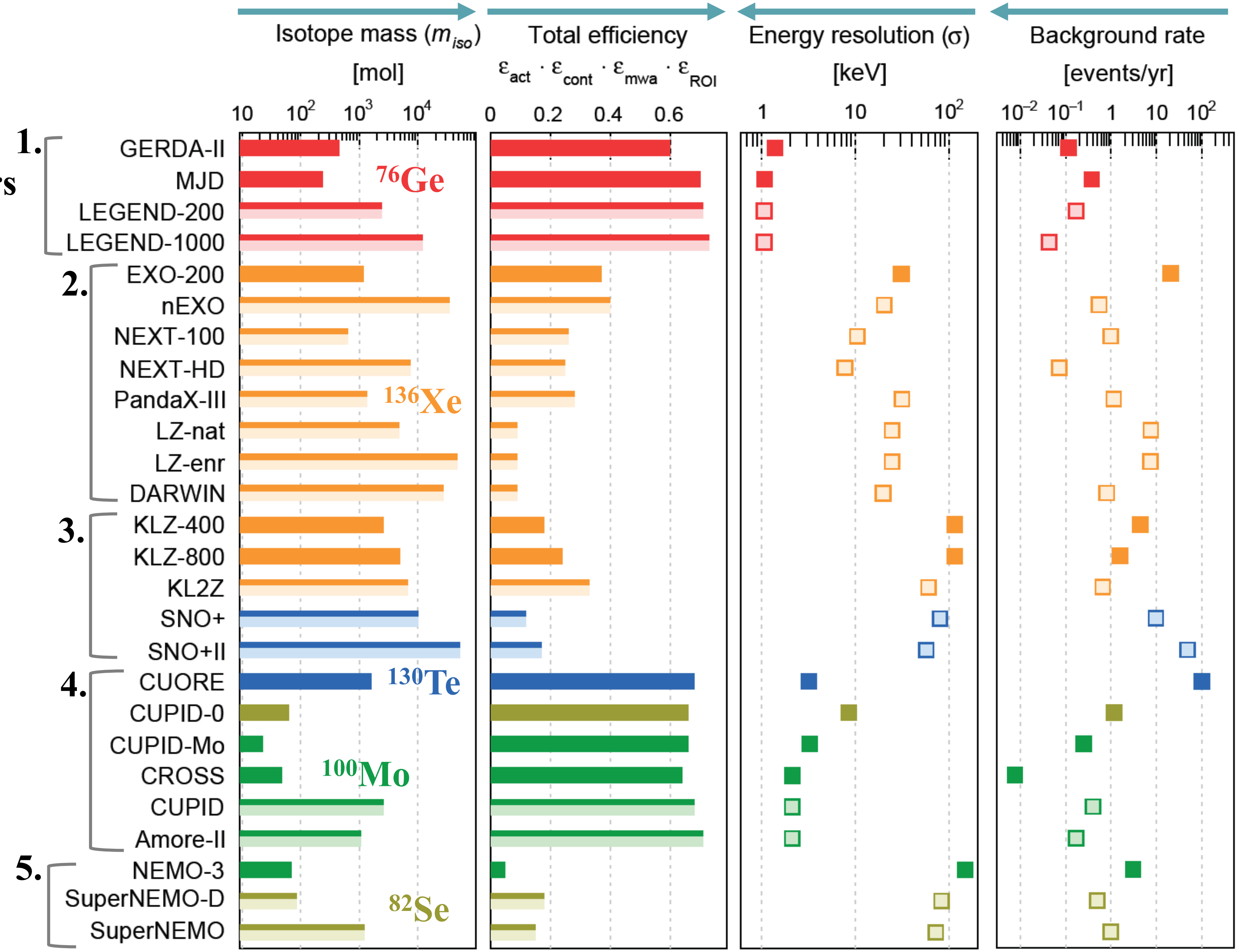
1. **High-purity germanium detectors**
   energy resolution, efficiency, background

2. **Xenon time projection chambers**
   isotope mass, particle tracking

3. **Large liquid scintillators**
   isotope mass

4. **Cryogenic calorimeters**
   energy resolution, efficiency, granularity

5. **Tracking calorimeters**
   particle tracking



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

Recently best limits

Ordered by $T_{1/2}$ limit

Isotope	Experiment	$T_{1/2}$ limit	Detector type	$m_{\beta\beta}$ (meV)	Exposure (kg yr)
^{136}Xe [1]	KamLAND-Zen-800	3.8×10^{26}	Liquid scintillator, 745 kg of enriched Xe (91% ^{136}Xe / 9% ^{134}Xe)	28–122	2097
^{130}Te [2]	CUORE	3.8×10^{25}	Cryogenic calorimeter, 742 kg of TeO_2 crystals (206 kg ^{130}Te)	70–240	567.0 ^{130}Te (= 2039.0 TeO_2)
^{76}Ge [3]	LEGEND-200 (+GERDA+MAJORANA)	1.9×10^{26}	High-purity germanium detectors, 142.5 kg (LEGEND)	75–200	61+127.2+64.5
^{100}Mo [4]	AmoRE-I	2.9×10^{24}	Cryogenic calorimeter, 6.2 kg of crystals ($Li_2{}^{100}MoO_4$ and $^{48depl}Ca^{100}MoO_4$)	210–610	3.89 ^{100}Mo (=8.02 total)
^{82}Se [5]	CUPID-0	4.6×10^{24}	Scintillating bolometers, 9.65 kg of $Zn^{82}Se$ crystals (5.13 kg of ^{82}Se)	263–545	8.82 ^{82}Se (= 16.59 ZnSe)

Refs.:

[1] KamLAND-Zen Collab., arXiv:2406.11438 [hep-ex] (2024)

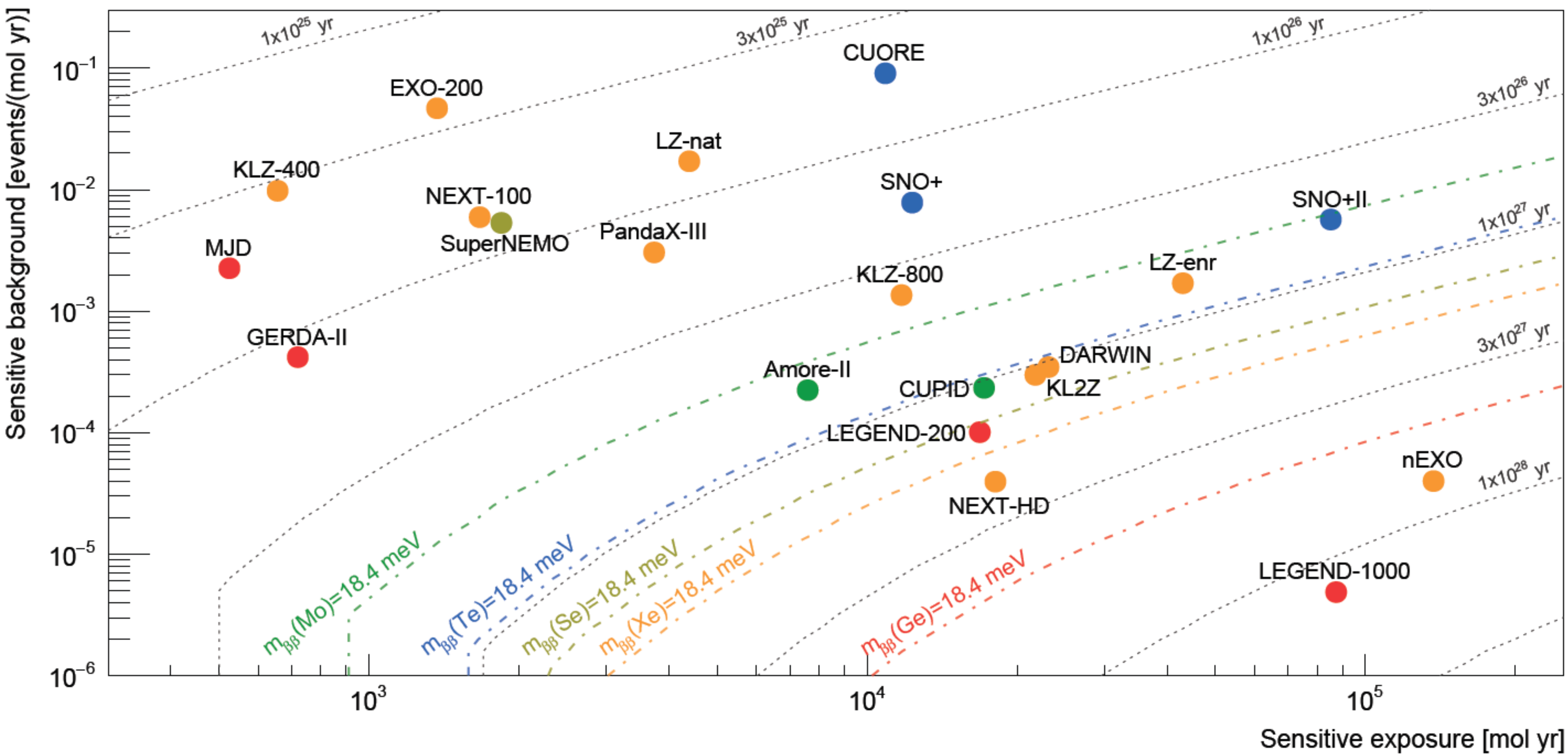
[2] CUORE Collab., arXiv:2404.04453 [nucl-ex] (2024)

[3] LEGEND Collab., arXiv:2505.10440 [hep-ex] (2025)

[4] AMoRE Collaboration, PRL 134, 082501 (2025)

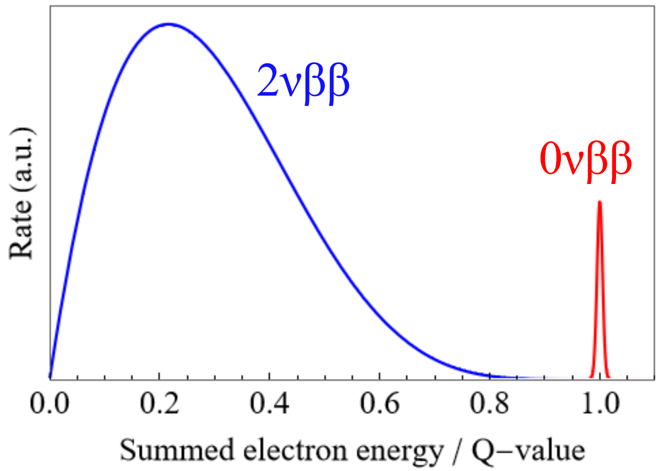
[5] O. Azzolini *et. al.,* PRL 129, 111801 (2022)

Sensitivity overview



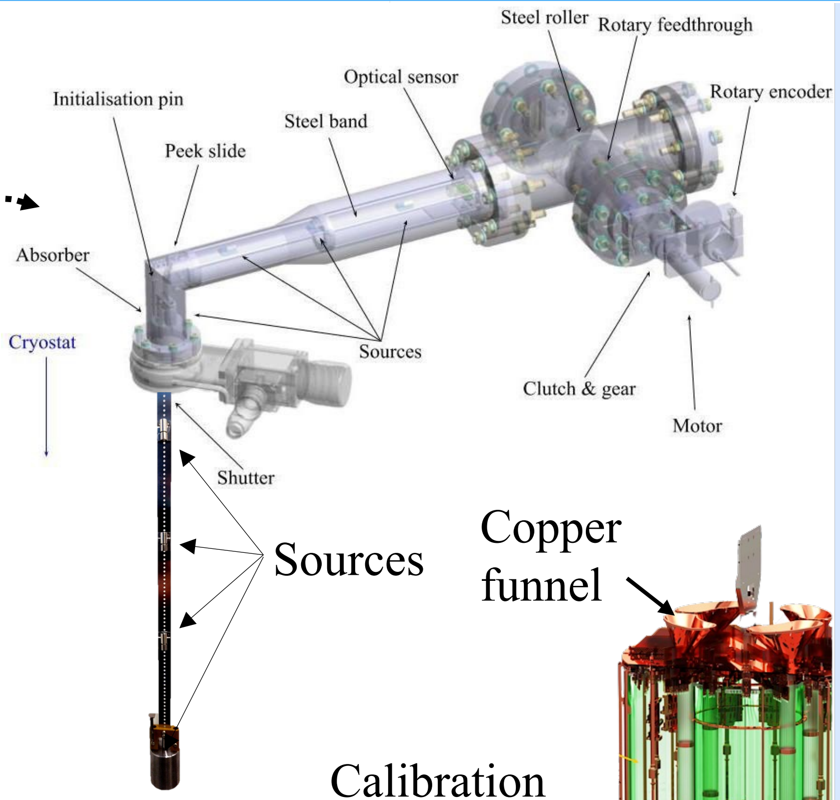
Ref.: M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

Energy calibration of HPGe Detectors



Calibration source insertion systems

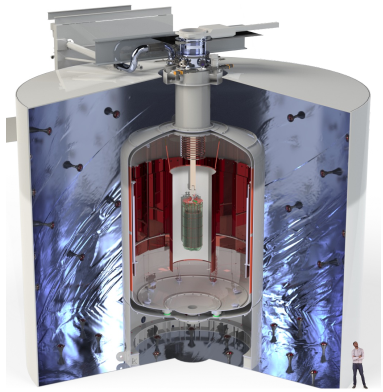
- Large-distance vertical movements of ~ 9 m
- Precision of 1 mm
- Reliability over the experimental duration

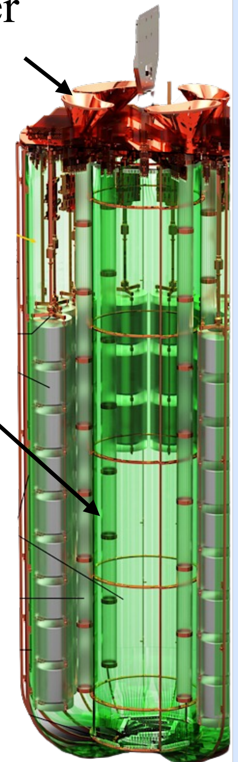


Precise identification of 0νββ requires:

- Stable energy scale
- Excellent energy resolution

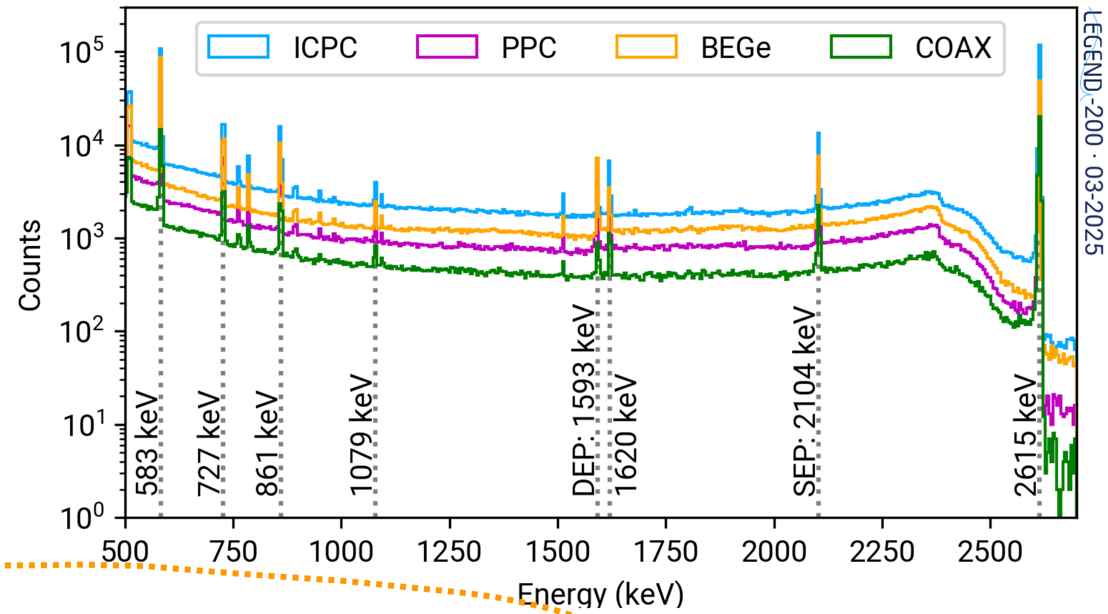
→ Monitored with **weekly calibrations** using ^{228}Th sources

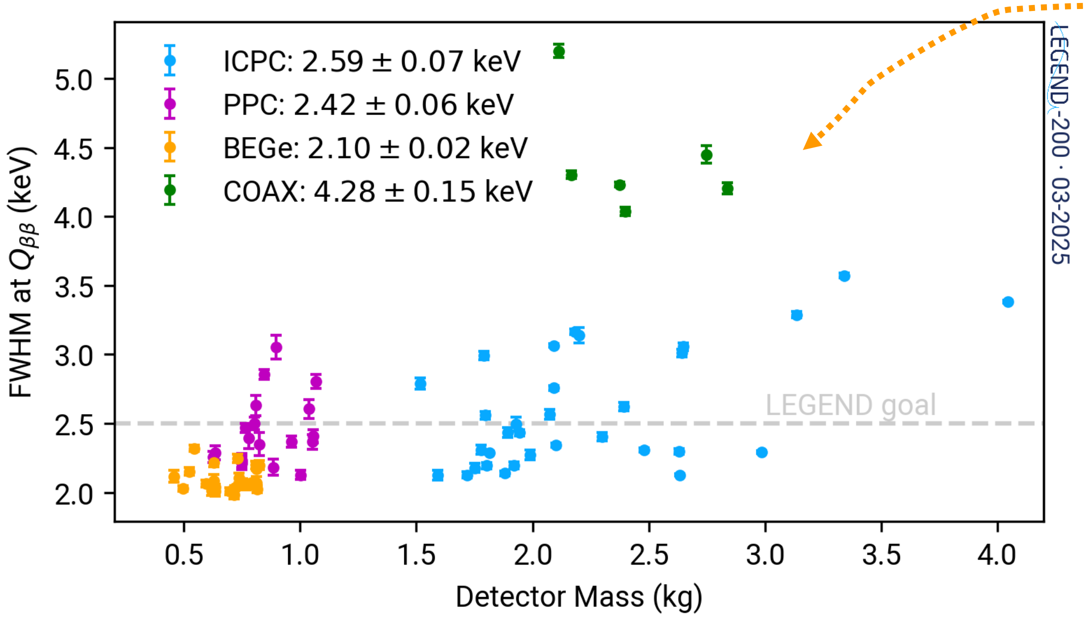


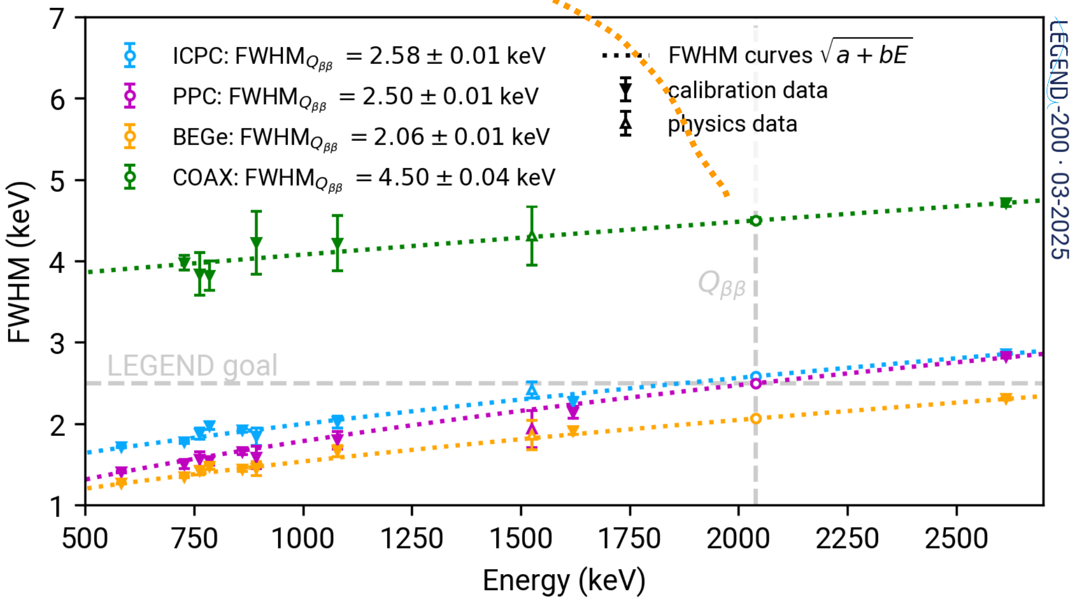


Energy scale and resolution

- Stable energy scale up to 2.6 MeV
- Energy resolution (FWHM) ~ 0.1% at $Q_{\beta\beta}$
  - 2.1– 4.3 keV for different detector types
  - Independent of detector mass

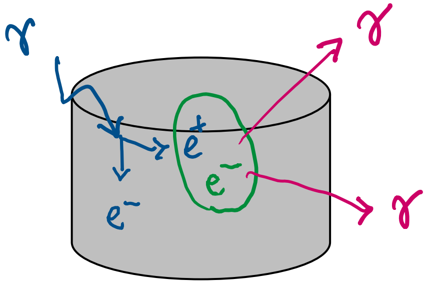




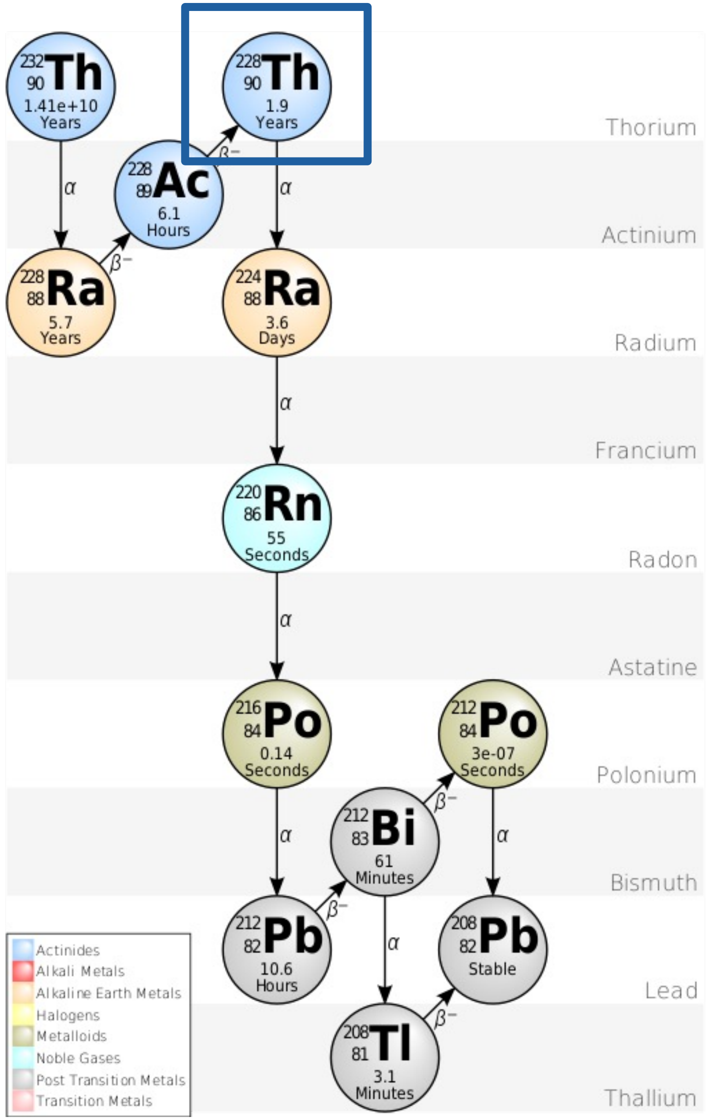


Why do we use ^{228}Th sources?

- ^{228}Th undergoes multiple α and β decays
- High statistics monoenergetic x and γ rays from < 100 keV up to 2.6 MeV are available
- The double-escape peak (DEP) of ^{208}Tl at 1592.5 keV is useful to train the PSD technique



Credit: Wikipedia



Potential backgrounds from ^{228}Th sources

Nevertheless…

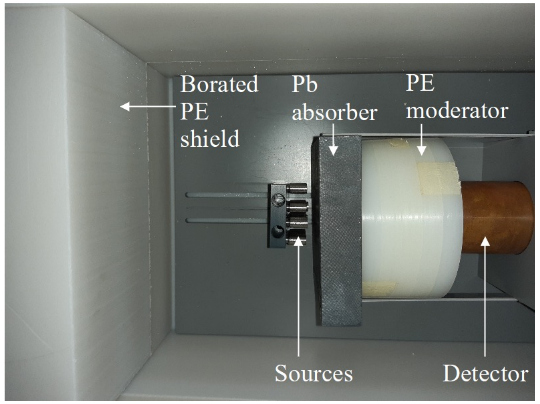
- ^{228}Th emits α with energies in the range of 5.2 – 8.8 MeV
  → yields neutron fluxes via (α, n) reaction
- Parasitic neutrons can
  - activate ^{76}Ge, producing ^{77}Ge (half-life 11.3 h) and ^{77m}Ge (half-life 53.7 s)
    → β decays with Q values > 2 MeV
  - be captured by surrounding materials, producing high energetic γ rays

→ Characterize neutron emission rate of ^{228}Th source

Neutron rate measurement

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

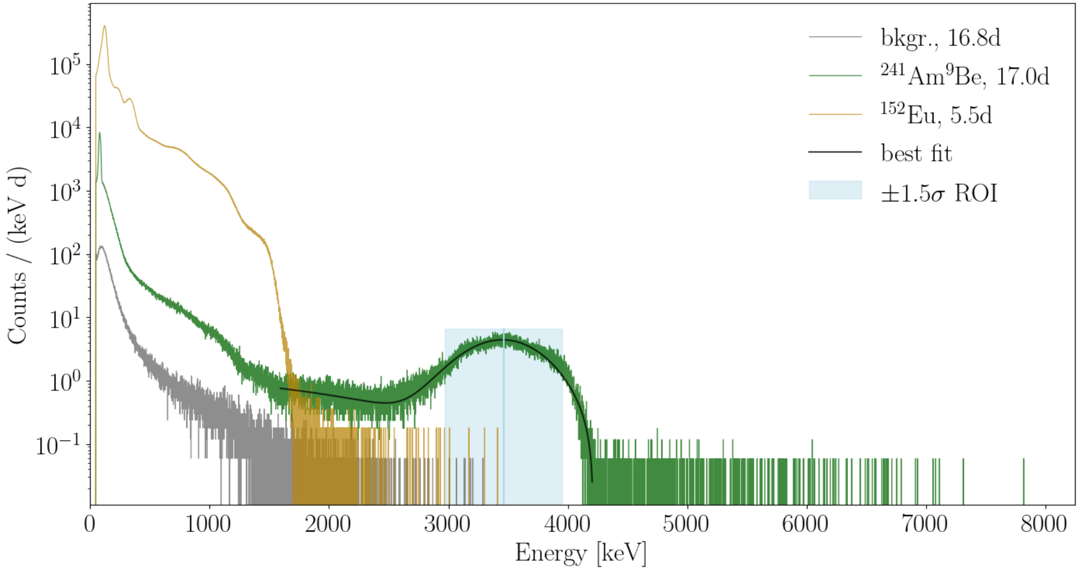
Low background environment underground at LNGS

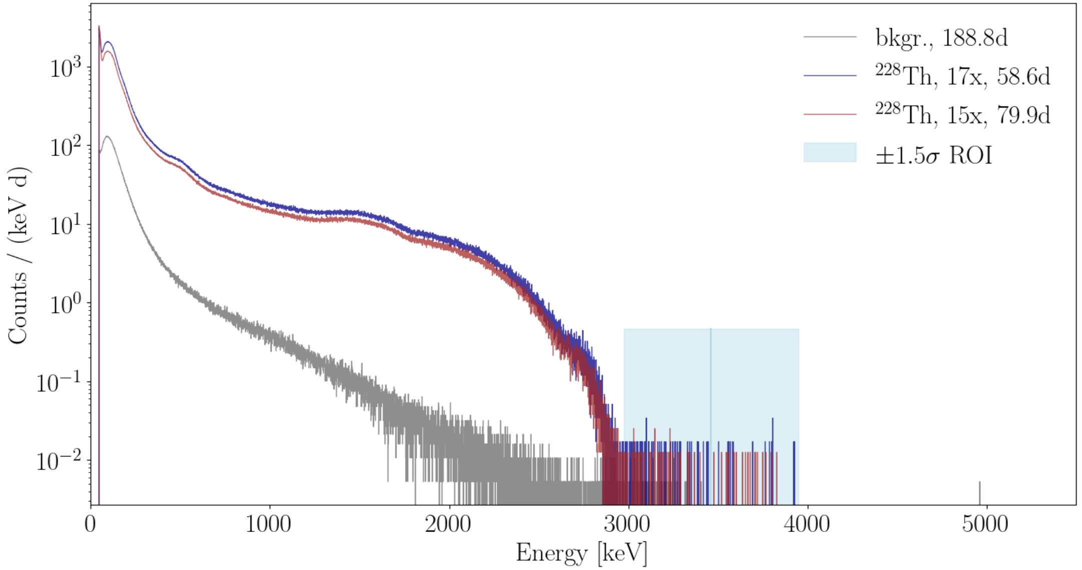


Calibration-induced background:
$\mathcal{O}(10^{-7})$ events/(keV kg yr)
after background reductions cuts
→ three orders of magnitude lower than the L200 background goal

^{152}Eu γ source for energy calibration
^{241}Am^{9}Be n source for efficiency determination (activity 160(4) n/s in 2013)

Combined neutron flux is
$\psi = (4.27 \pm 0.60_{stat} \pm 0.92_{sys}) \times 10^{-4}$ n/(kBq s)

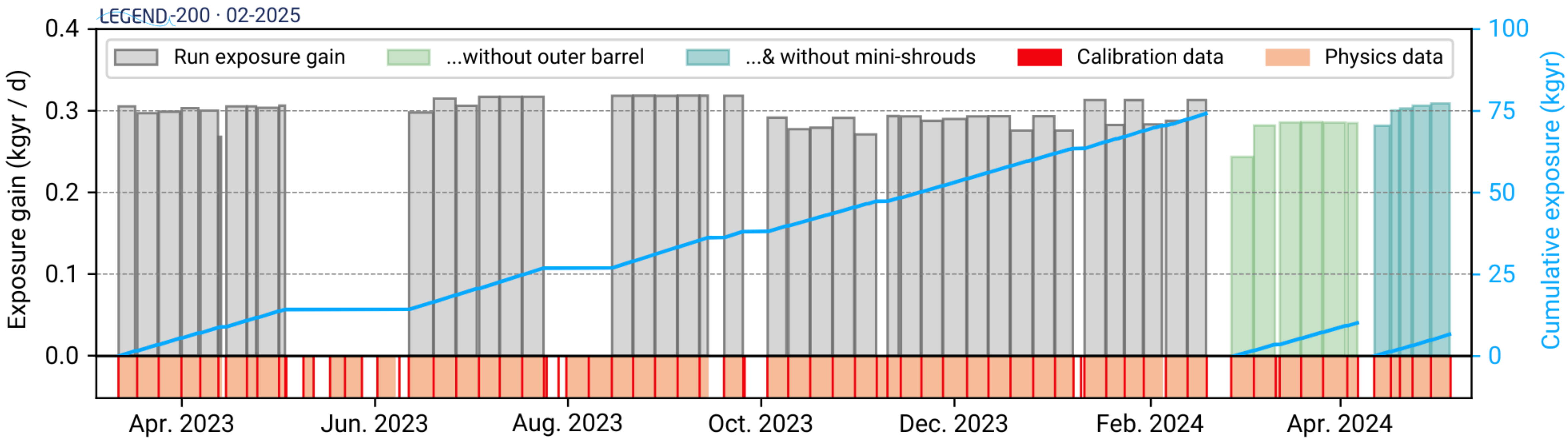




New LEGEND-200 results

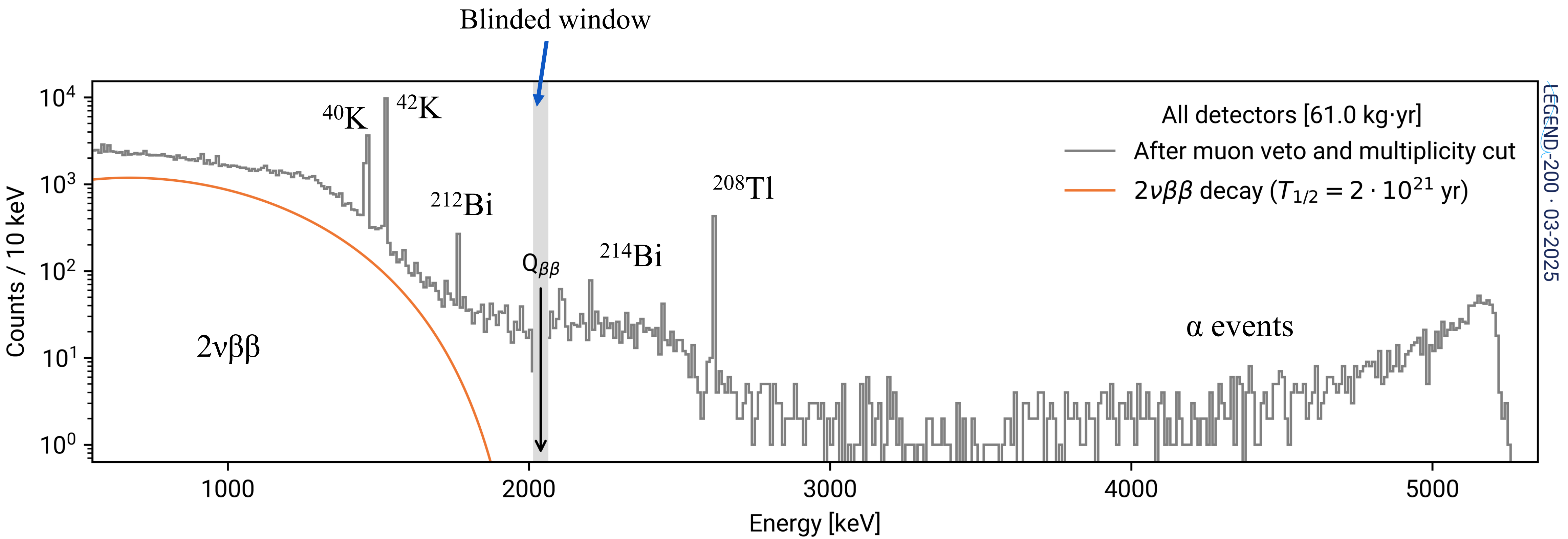
Ref.: LEGEND Collab.,
arXiv:2505.10440 [hep-ex] (2025)

- Exposure accumulated over one year (spring 2023 – spring 2024)
- Taken with 130 kg operating detectors out of 142 kg detectors installed in Oct. 2022
- Usable physics data summing up to 61.0 kg yr
- 50 keV window **blinding** applied at $Q_{\beta\beta}$ (2039 ± 25 keV)



Data after muon veto and multiplicity cut

- 50 keV window blinding applied at $Q_{\beta\beta}$ (2039 ± 25 keV)
- At $Q_{\beta\beta}$, 95–99% survival of physical events after data cleaning

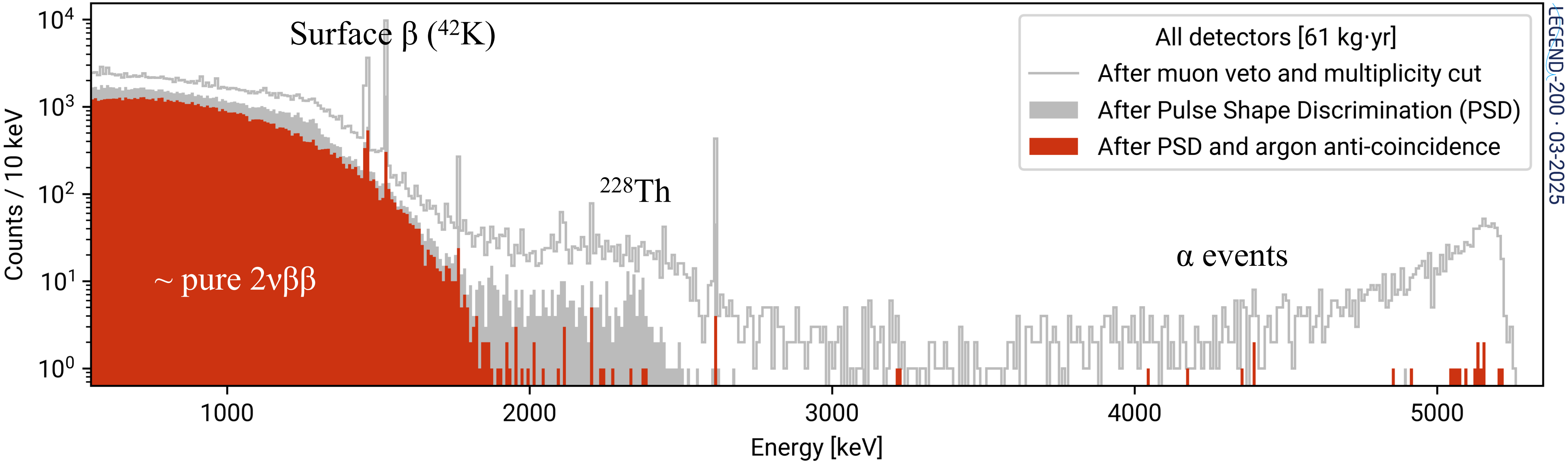


Data after analysis cuts

- Data cleaning (muon veto and multiplicity cut)
  - At $Q_{\beta\beta}$, 95–99% survival of physical events after data cleaning

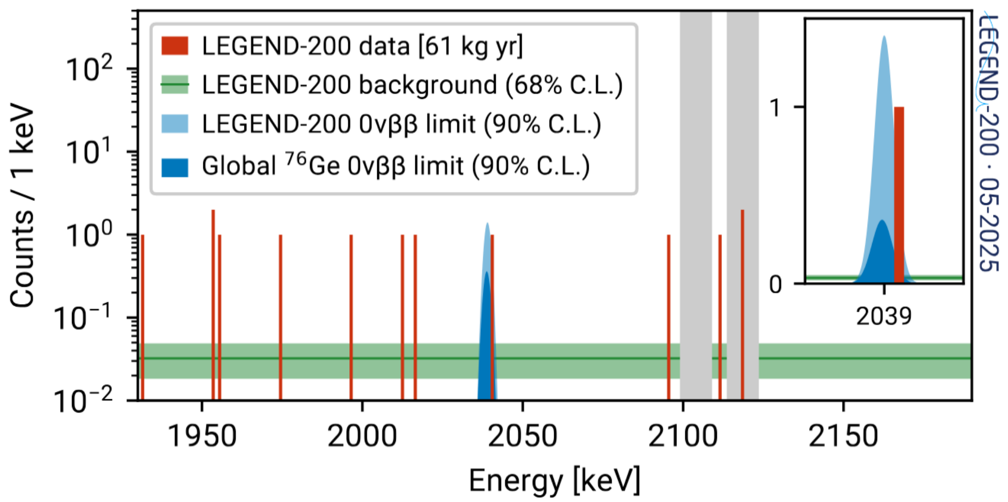
- PSD
  - Strong suppression of surface α and β (^{42}K) events
  - ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$

- + LAr
  - Pure 2νββ distribution



Data in the region of interest

- 11 events after cuts **after unblinding**
- Background indices
  - BI 1 (12.7 kg yr) = $1.3^{+0.8}_{-0.5}$ cts / (keV ton yr) (detectors with worse background level: Coax & 5 IC detectors)
  - BI 2 (48.3 kg yr) = $0.5^{+0.3}_{-0.2}$ cts / (keV ton yr) (rest of the detectors)
- L200 observed limit $T^{0\nu}_{1/2} > 0.5\times10^{26}$ yr (90% CL)
- One event at an energy 1.3σ from the expected $Q_{\beta\beta}$ signal location weakens observed limit compared to exclusion sensitivity of 1.0×10^{26} yr



ROI = 1930–2190 keV

GERDA, MAJORANA, and LEGEND ^{76}Ge combined result

	Observed (90% CL)	Sensitivity (90% CL)
$T^{0\nu}_{1/2}$	$> 1.9\times10^{26}$ yr	2.8×10^{26} yr

^{76}Ge limits on Majorana mass $m_{\beta\beta}$

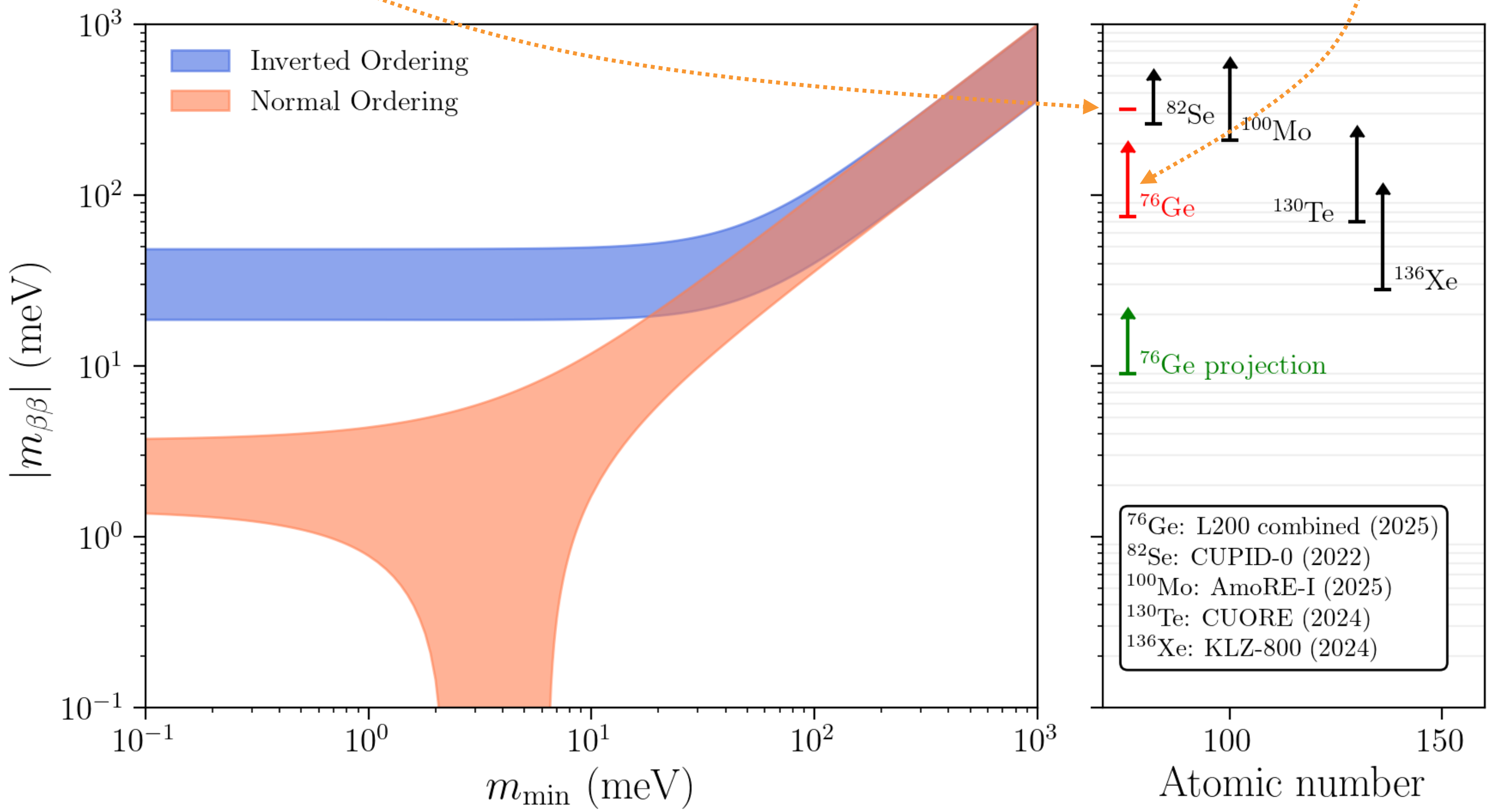
$$\left(T_{1/2}\right)^{-1} = G\left(Q_{\beta\beta}, Z\right) \cdot {g_A}^4 \cdot \left|M_{\rm nucl}\right|^2 \cdot {m_{\beta\beta}}^2$$

Uncertainty quantified NME: $2.6^{+1.28}_{-1.36}$

$m_{\beta\beta} < 320$ meV (Bayesian 90% CI)

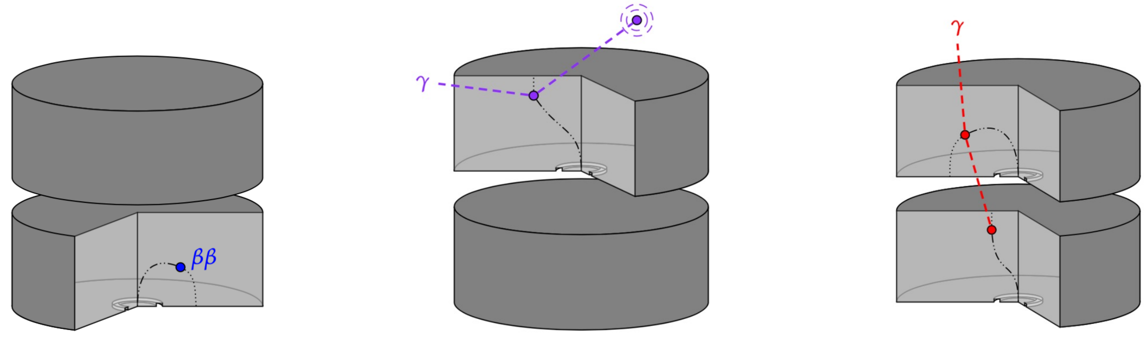
Phenomenological NME: $2.35 - 6.34$

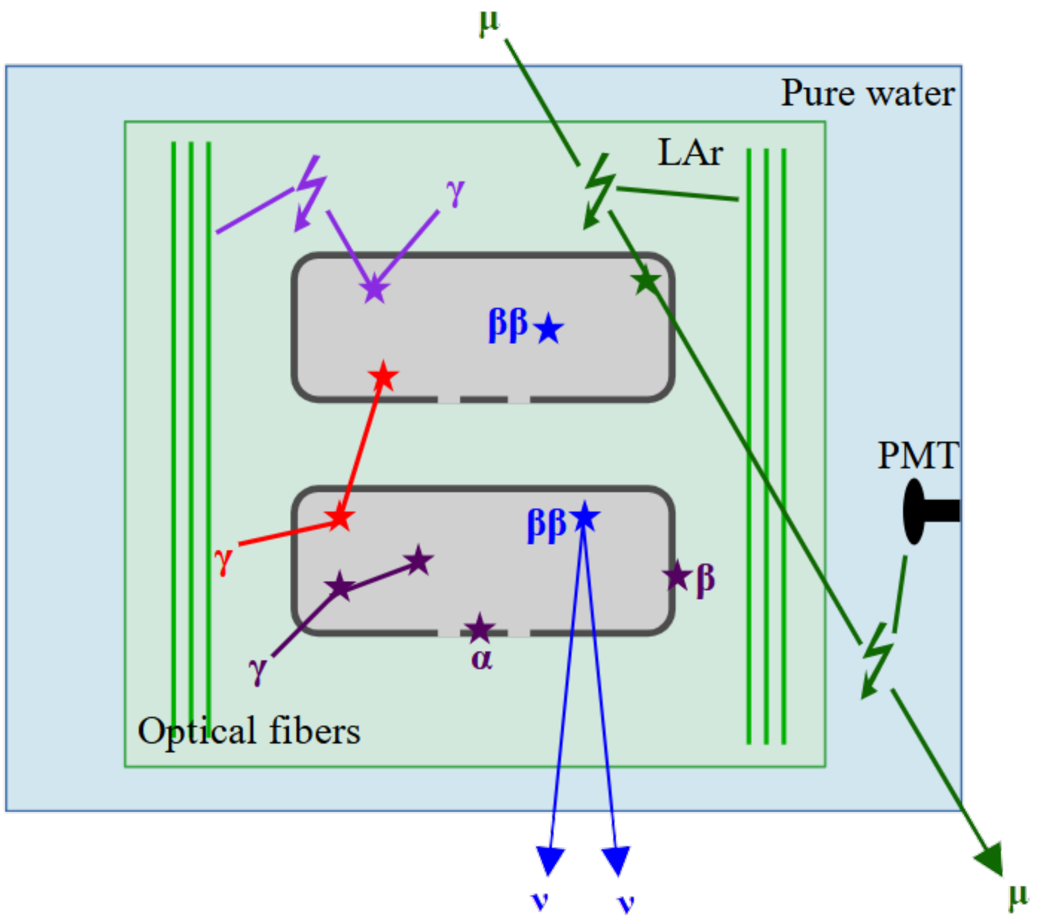
$m_{\beta\beta} < 75 - 200$ meV (90% CI)



Background mitigation

- ββ decay signal: localized energy deposition ~ $\mathcal{O}$ (1 mm)
  → Single-site event (SSE)
- μ: water Cherenkov → muon veto
- γ with MeV energies: multiple energy depositions ~ $\mathcal{O}$ (1 cm)
  - Anti-coincidence from multiple detectors → multiplicity
  - Multi-site event (MSE) in a single detector
    → pulse shape discrimination (PSD)
  - LAr veto (anti-coincidence)
- Surface α and β: PSD



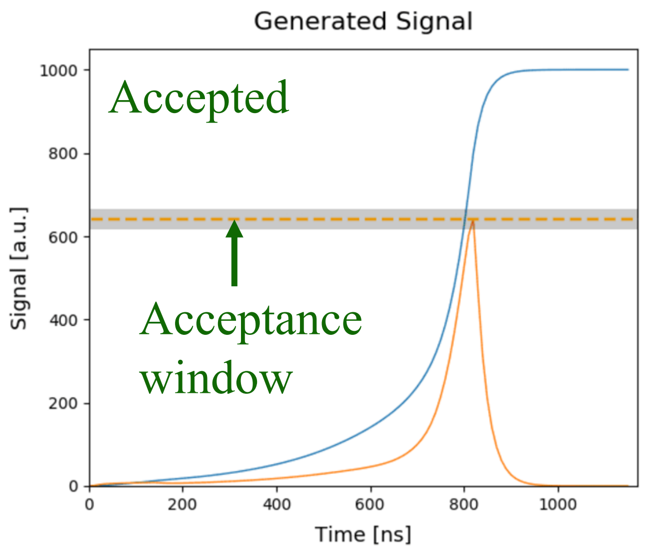


Pulse shape discrimination (PSD)

- Pulse shape classifier: A/E = max (current) / energy
- Monitored with weekly ^{228}Th calibrations

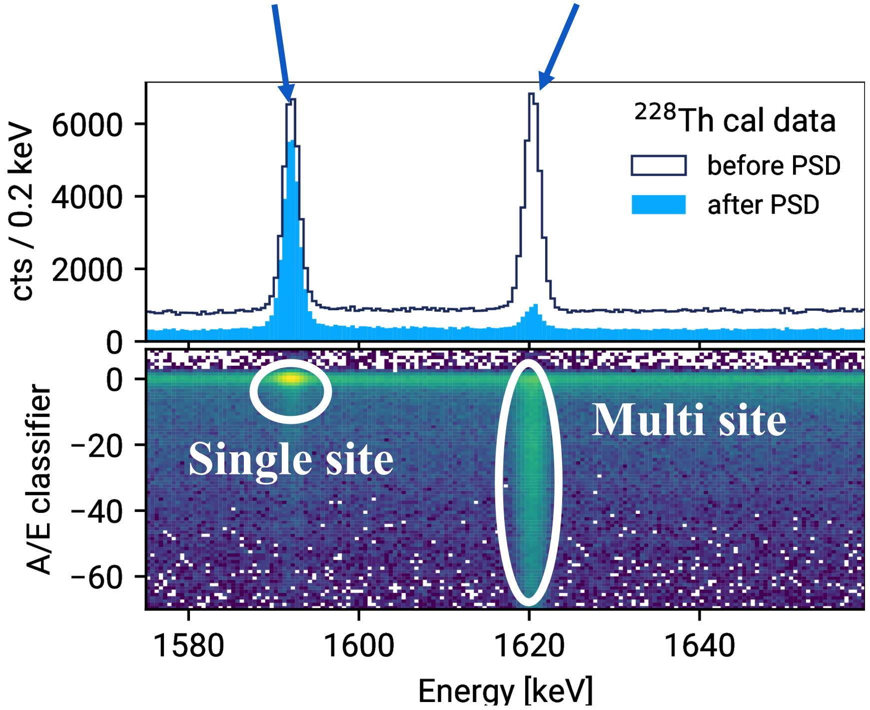
Signal-like

Charge signal
Current signal

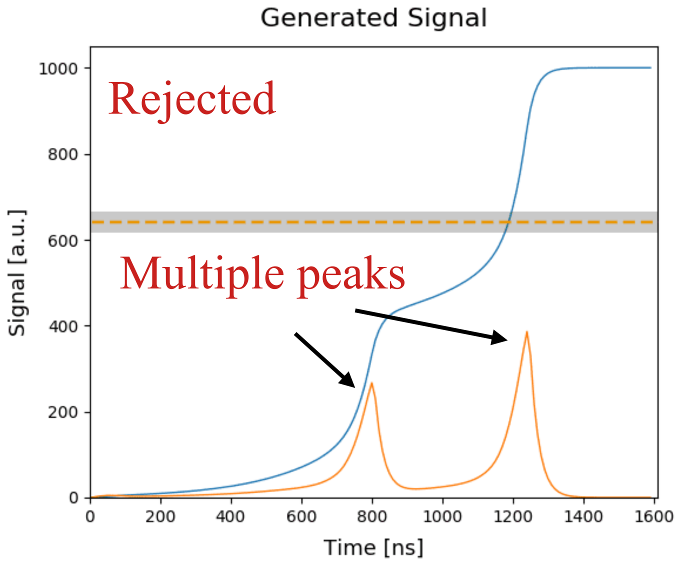


^{208}Tl double escape peak

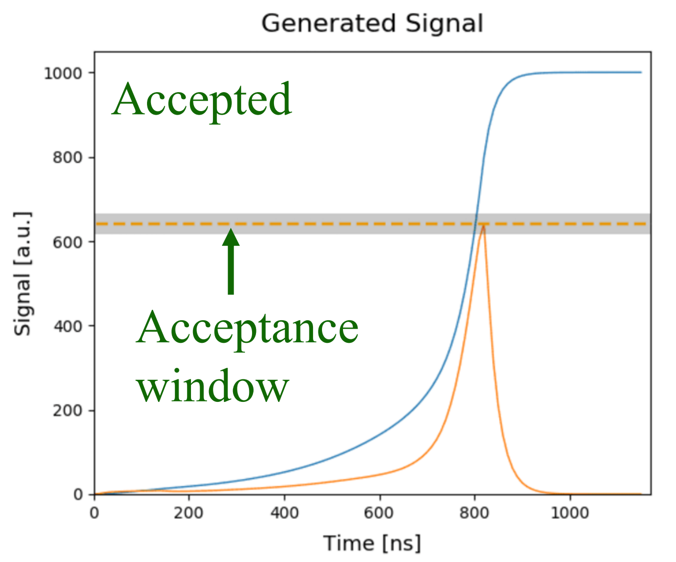
^{212}Bi full energy peak

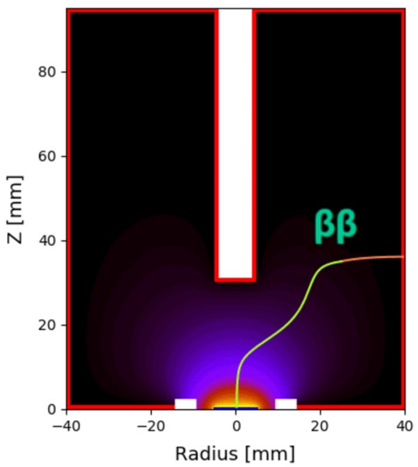


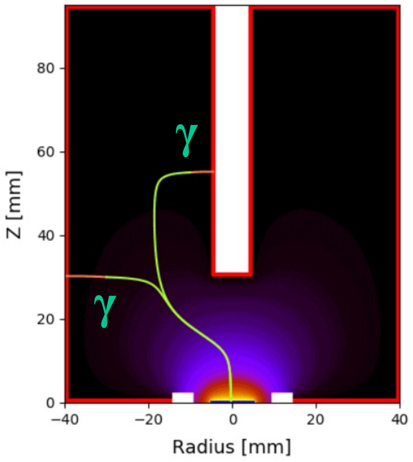
Background-like

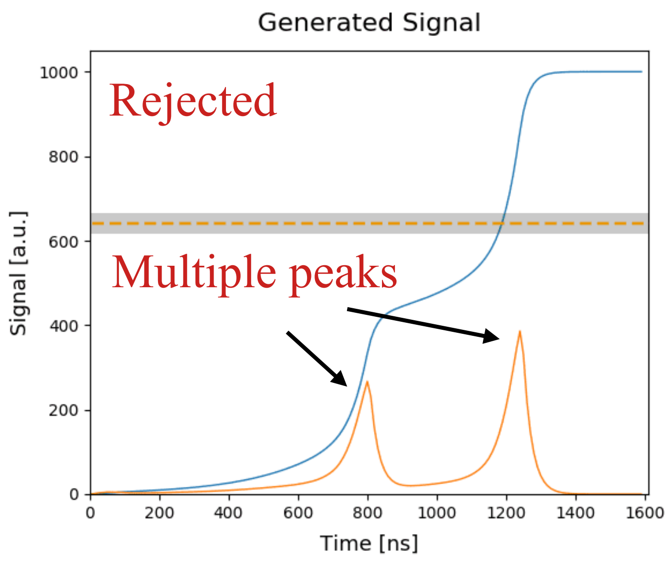


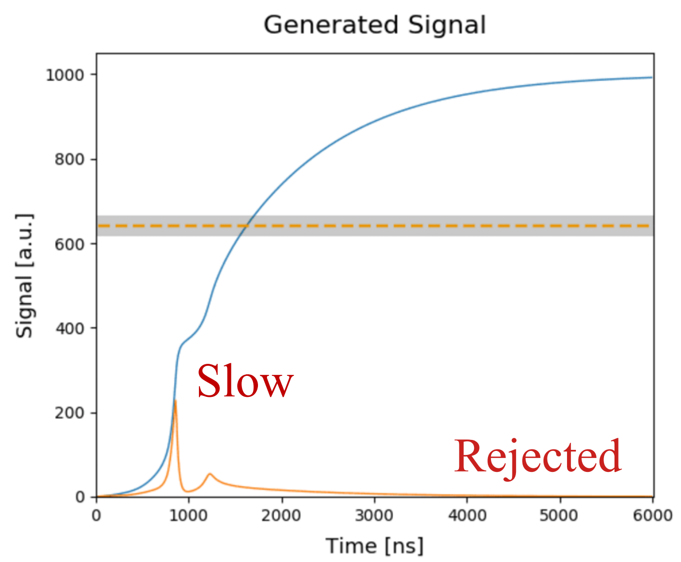
Pulse shape discrimination (PSD)

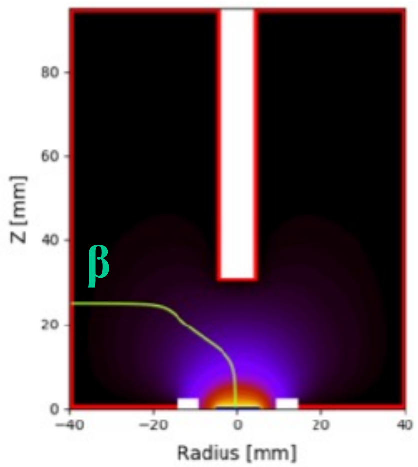




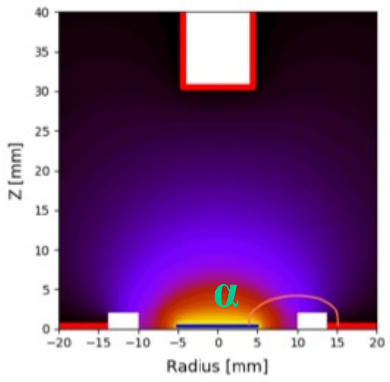


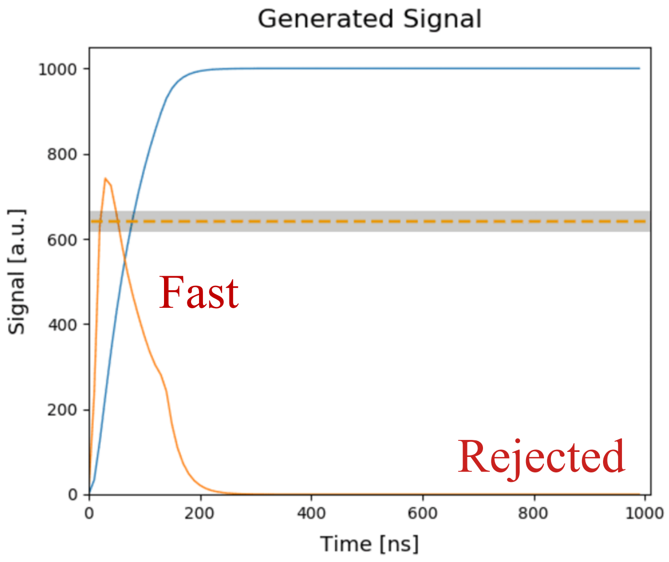






Charge signal
Current signal

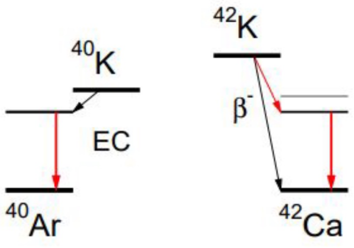




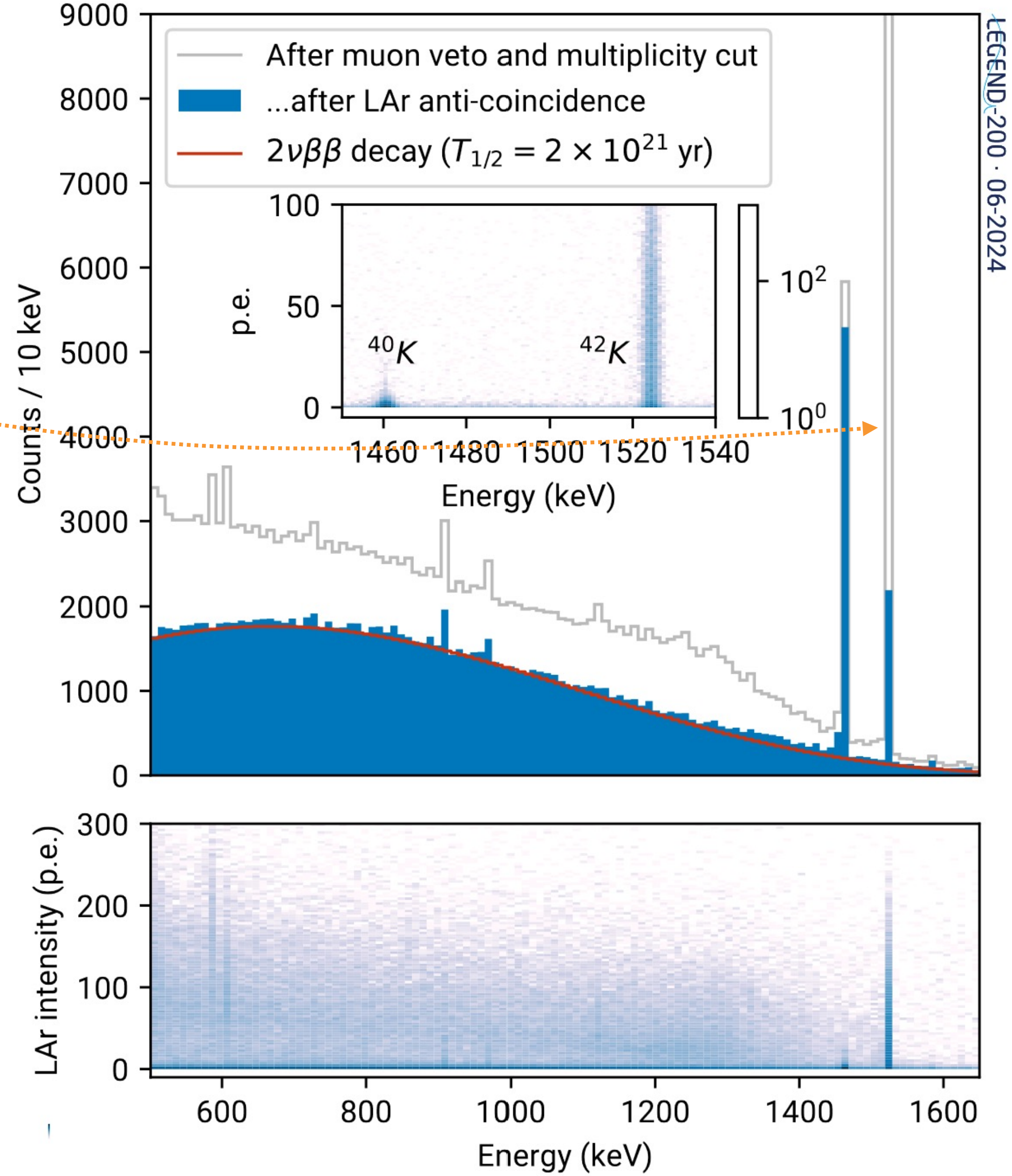
LAr anti-coincidence

- Characterized with special calibration runs
  - 1 photoelectron / 10 keV

- Strong suppression of background above 2νββ, e.g., from ^{42}K



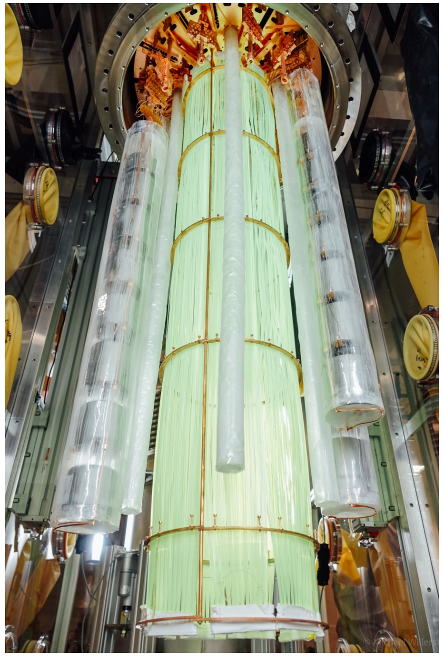
Credit: K. v. Sturm

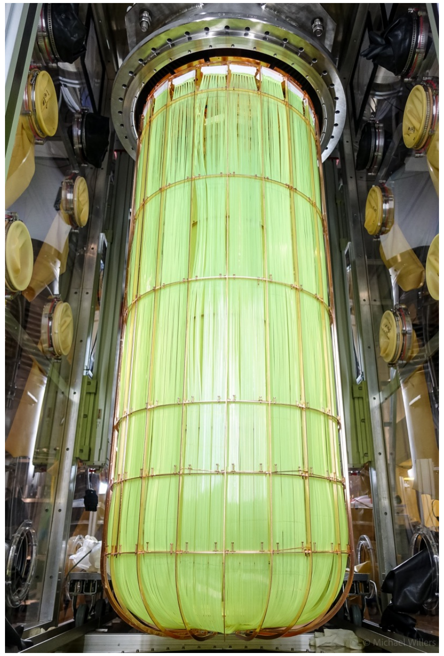


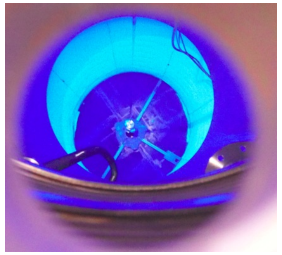
LAr veto systems

Inner (left) and outer (right) fiber barrels:

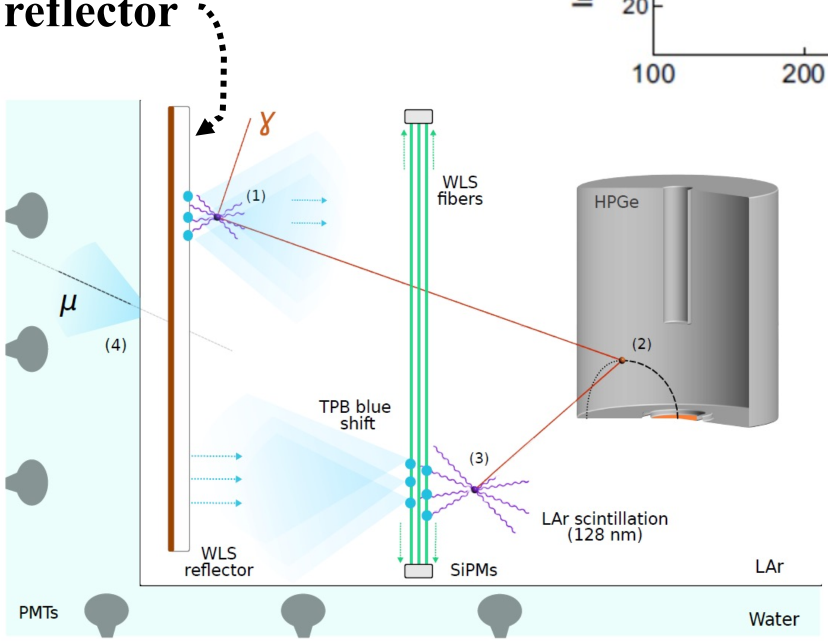
Wavelength-shifting fibers connected to SiPMs consisting 18 (inner) and 40 (outer) readout channels



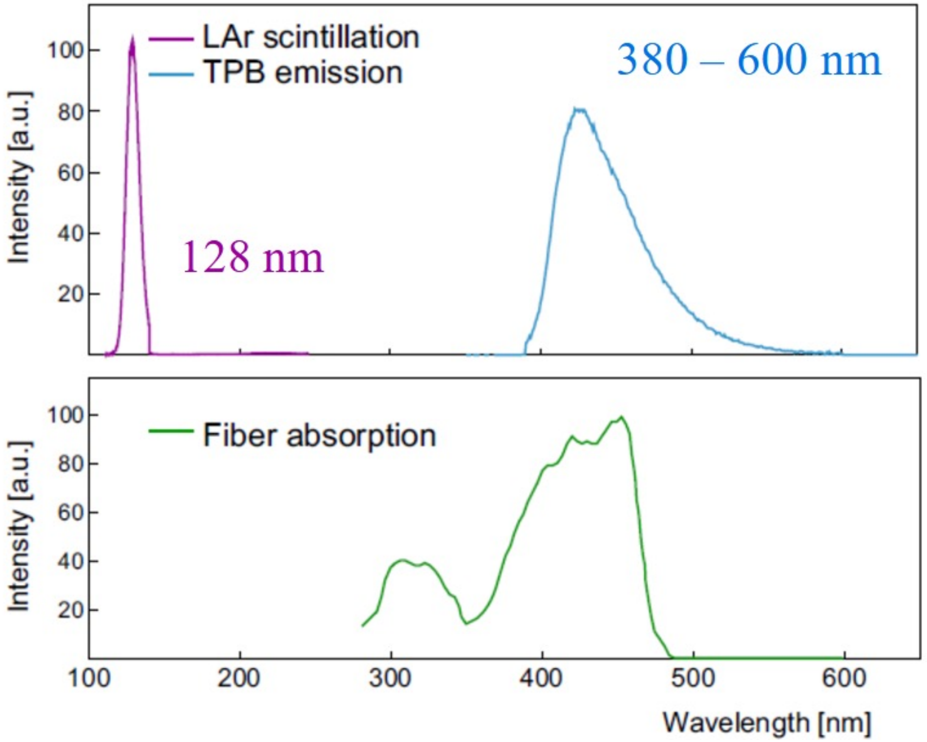




Wavelength-shifting reflector

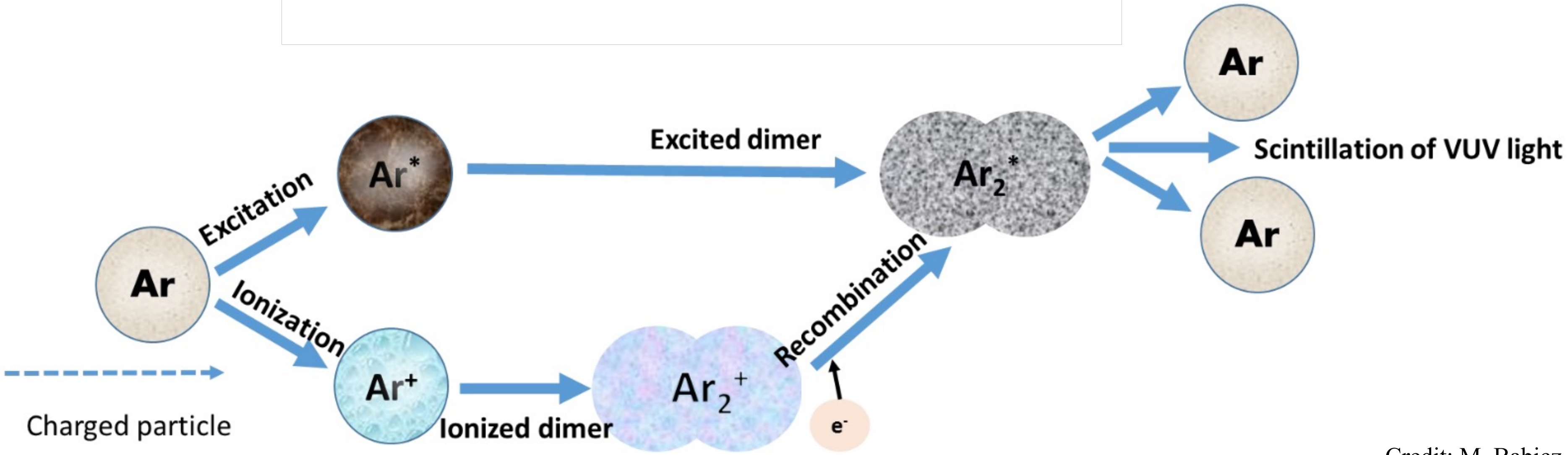


Credit: G. R. Araujo



Ref.: G. R. Araujo et al., EPJC 82, 442 (2022)

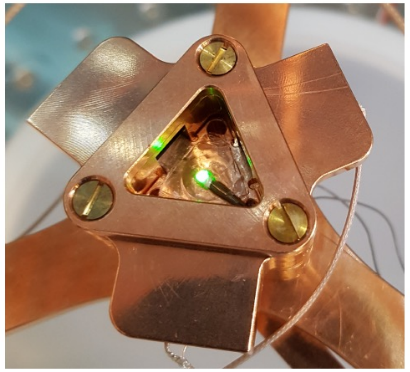
Ar scintillation

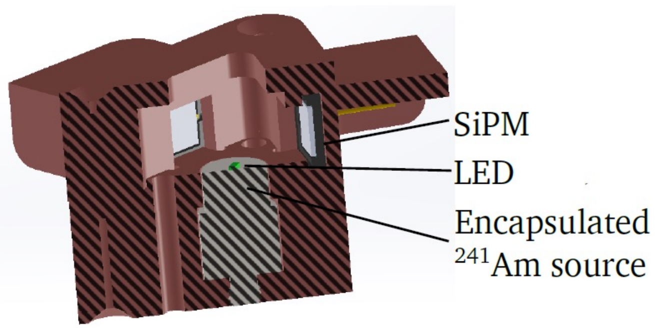


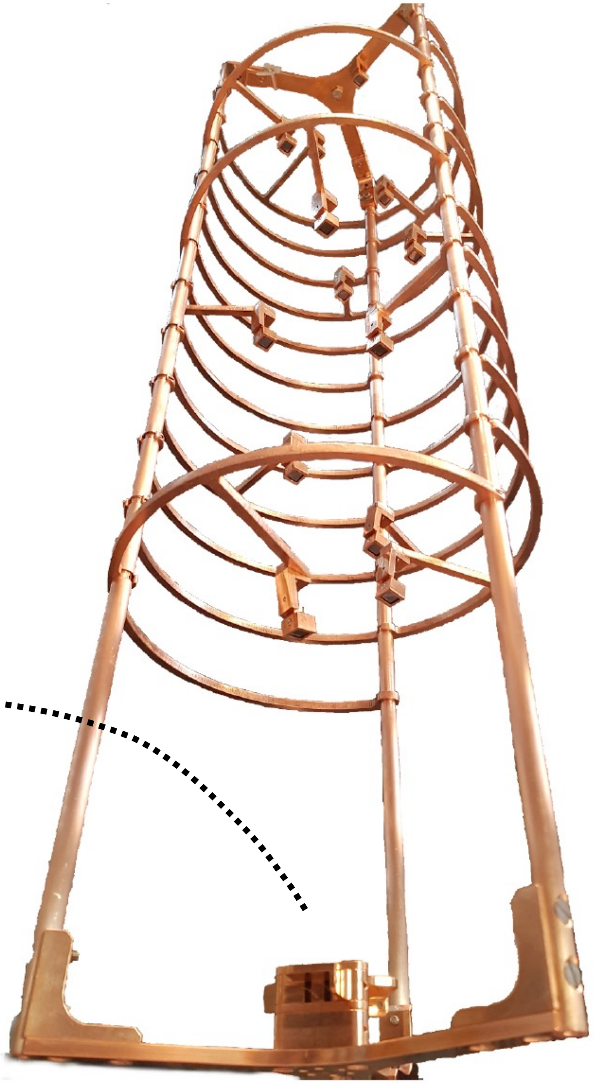
Credit: M. Babicz

LLAMA

LEGEND Liquid Argon Monitoring Apparatus



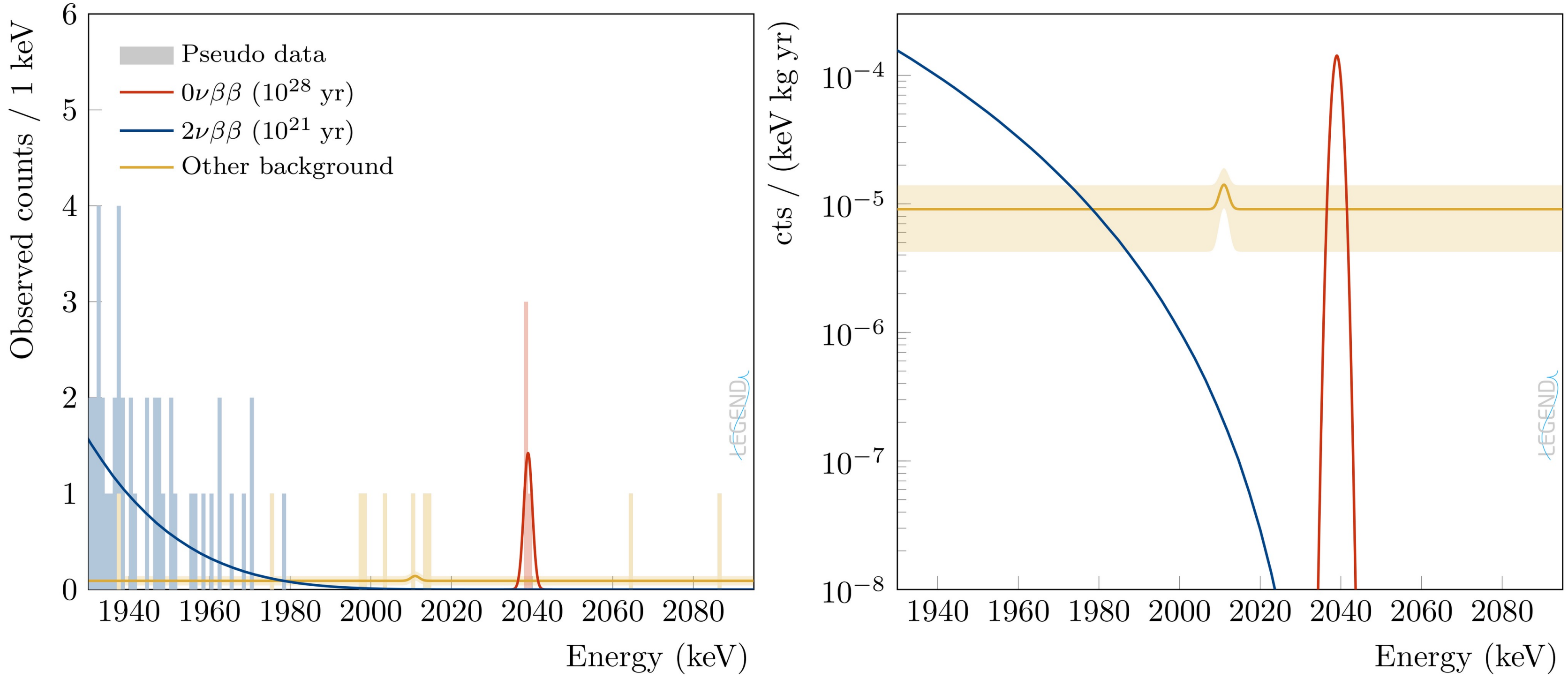




Discovery sensitivity

Our background goal:
1×10^{-5} counts / (keV kg yr) → < 1 count in 10 years of measurement
→ “Quasi background free”

Monte-Carlo pseudo-dataset of L-1000 (λ = 10 t yr) after analysis cuts



No background peak expected around $Q_{\beta\beta}$

Planned staged commissioning ~ 2030