

Search for lepton number violating neutrinoless double beta decay

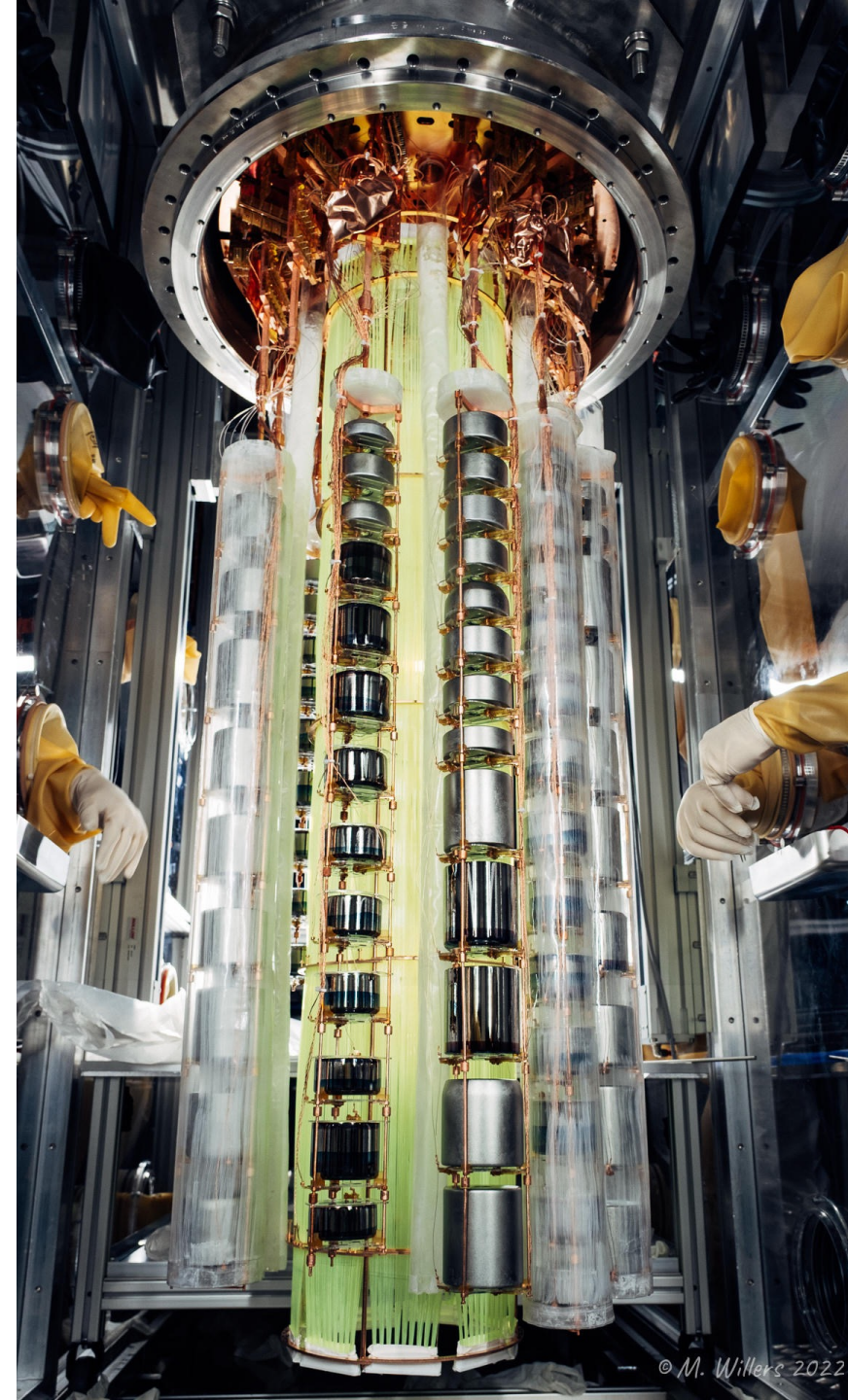
with 

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



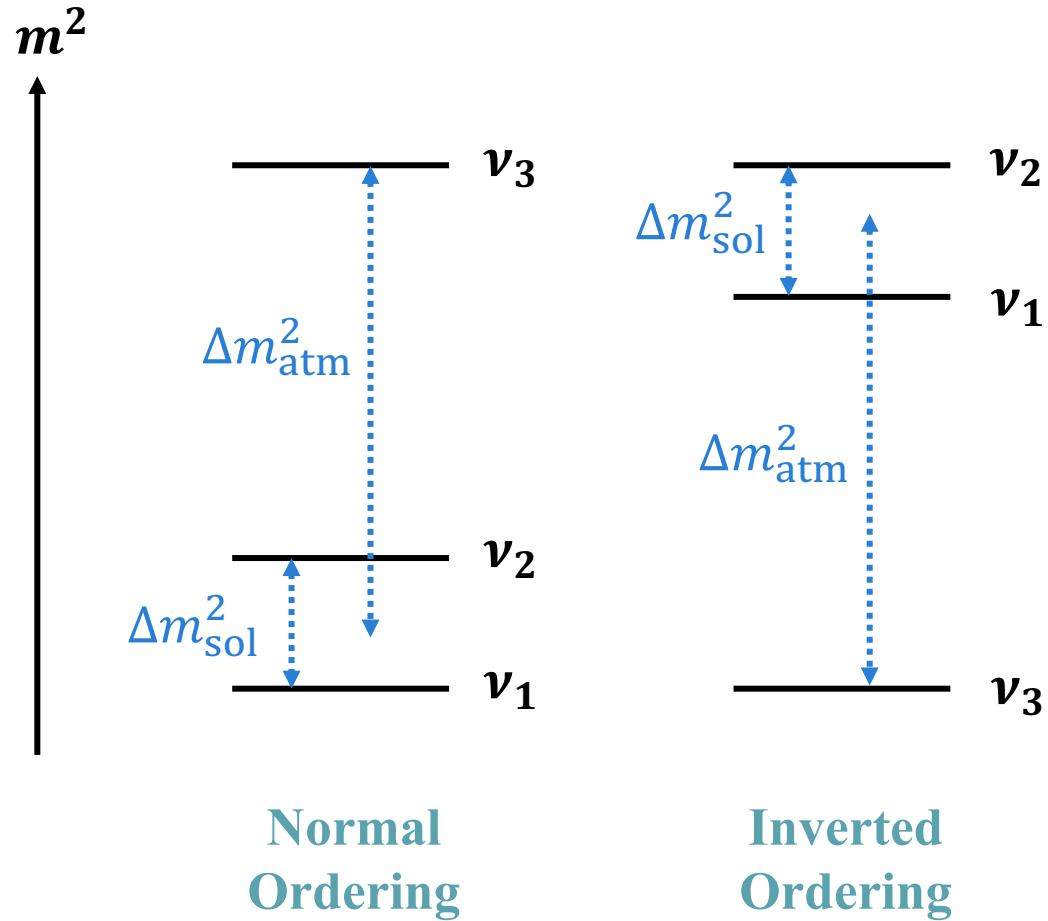
Department of Physics
National Taiwan University

November 28th, 2025, The ANPhA symposium on nuclear physics facilities in Asia
Institute of Physics, Academia Sinica, Taipei



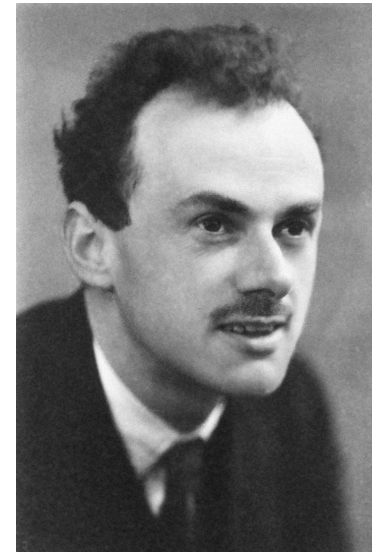
Open questions in neutrino physics

- Neutrino mass ordering and absolute scale



- Nature

Observed: ν_L and $\bar{\nu}_R$



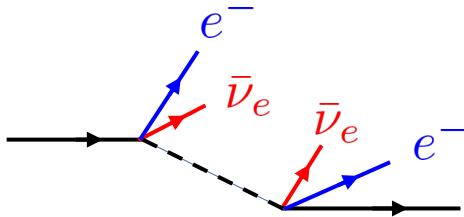
Dirac mechanism
 $\nu \neq \bar{\nu}$



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

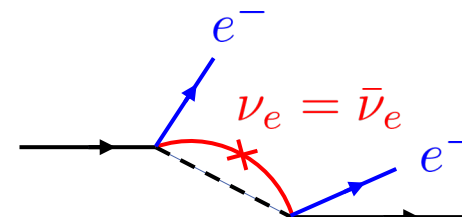
- **Two neutrino double beta decay $2\nu\beta\beta$**
 - Standard-Model-allowed process
 - Nature provides 35 isotopes, e.g., ^{76}Ge , ^{100}Mo , ^{136}Xe

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



- **Neutrinoless double beta decay $0\nu\beta\beta$**
 - Hypothetical process

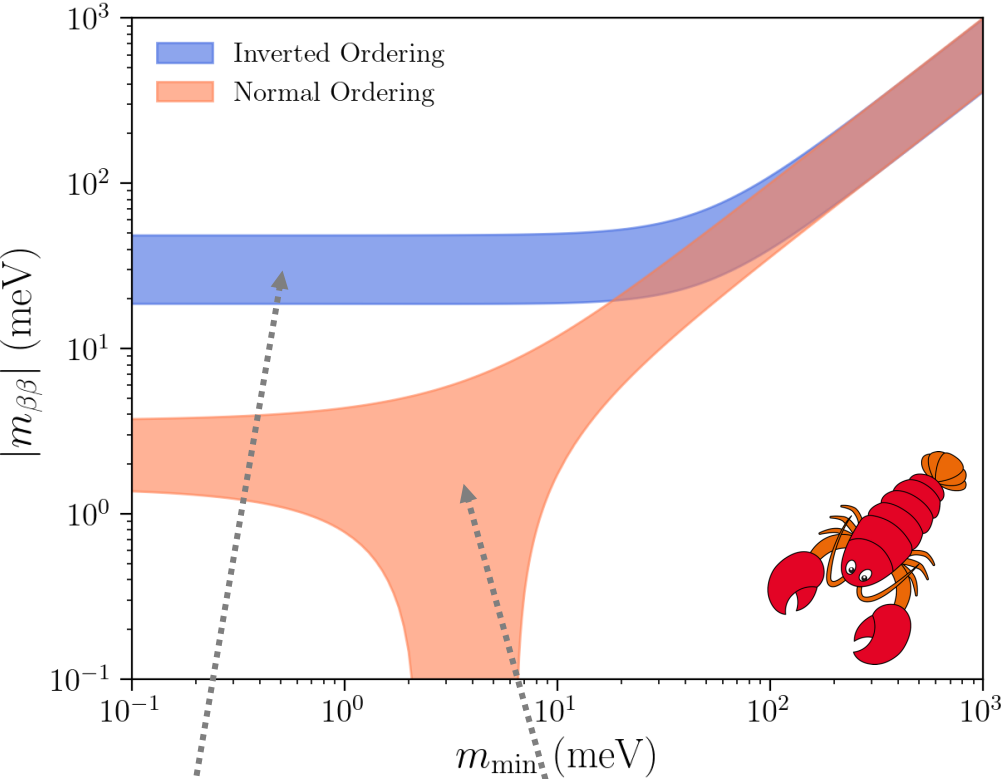
$$2n \longrightarrow 2p^+ + 2e^-$$



If observed:

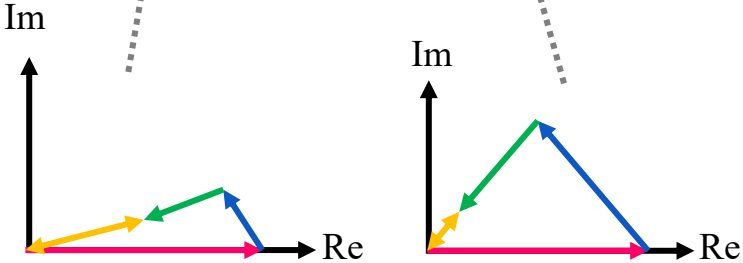
- Majorana nature of ν : $\nu = \bar{\nu}$
- Lepton number violation: $\Delta L = 2$

Effective Majorana neutrino mass



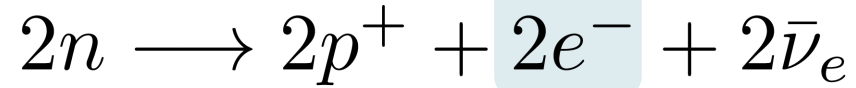
$$\begin{aligned}
 \underline{m_{\beta\beta}} &\equiv \left| \sum_k m_k U_{ek}^2 \right| \\
 &= \left| \underline{m_1} |U_{e1}|^2 + \underline{m_2} |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + \underline{m_3} |U_{e3}|^2 e^{-i(\alpha_1 + 2\delta)} \right|
 \end{aligned}$$

α_1, α_2 : Majorana phases
 δ : Dirac phase

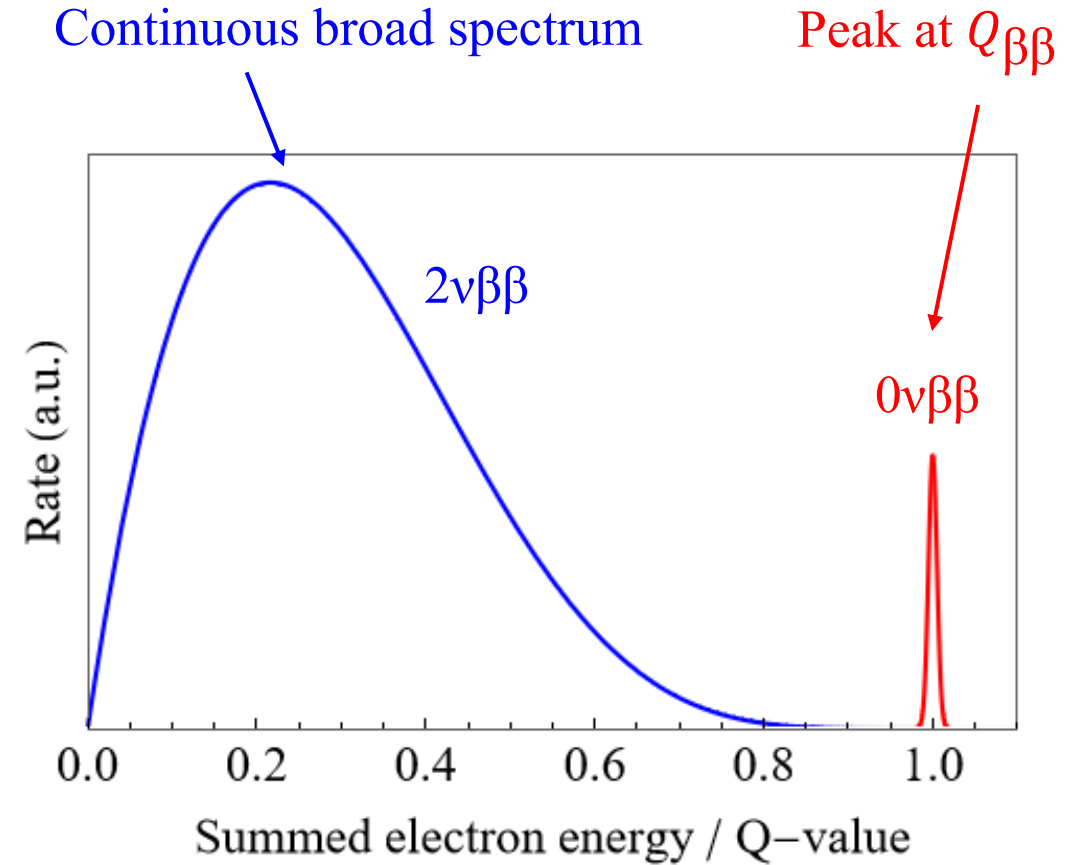


Experiment	Atomic phys.	Nuclear phys.	Particle phys.
$(T_{1/2})^{-1}$ Measured half-life	$G(Q_{\beta\beta}, Z)$ Phase space factor	g_A^4 Axial coupling	$ M_{\text{nuc}} ^2$ Nuclear matrix elements
			$m_{\beta\beta}^2$ Effective Majorana neutrino mass

Experimental detection approach



Measure the summed energy
of the **two emitted electrons**

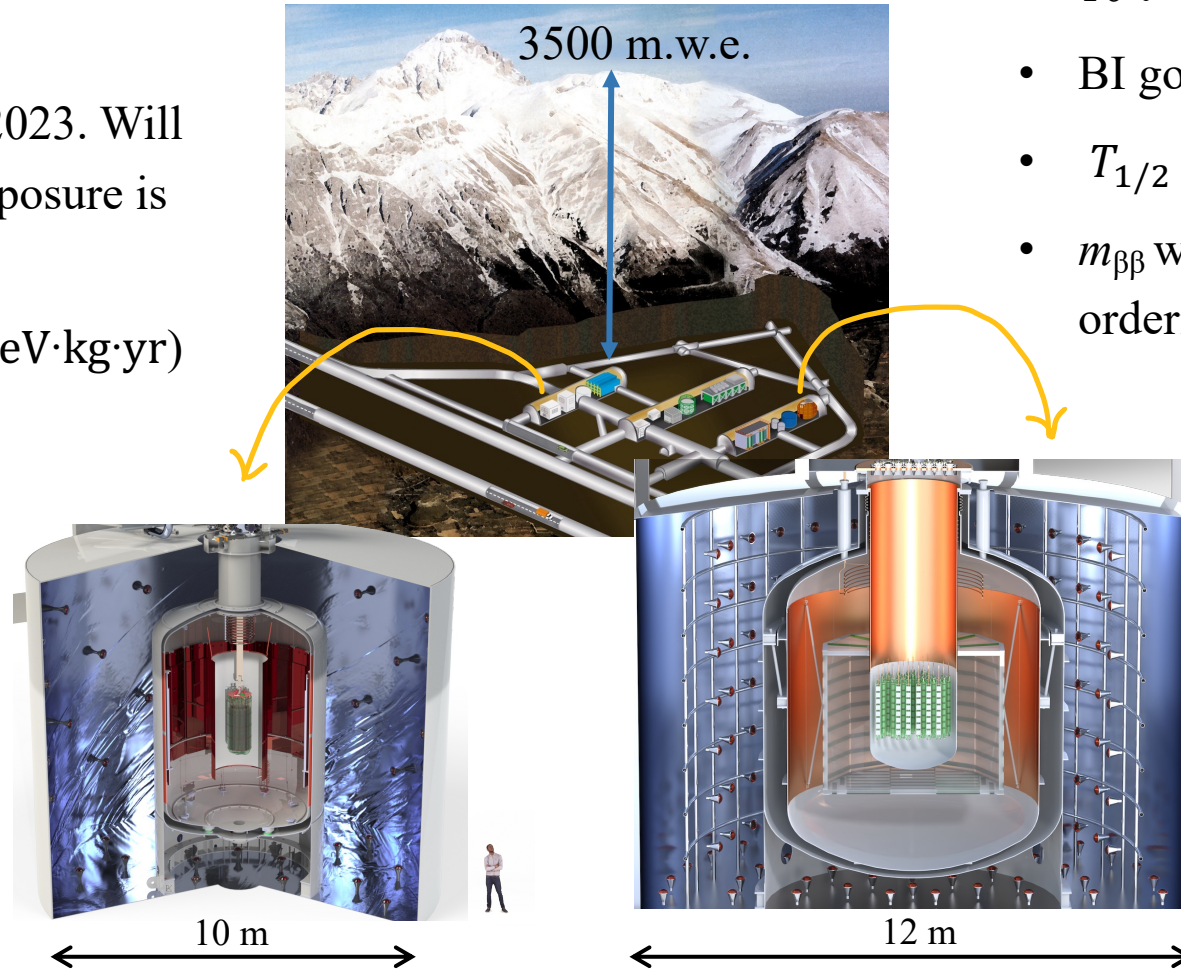


The LEGEND project

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



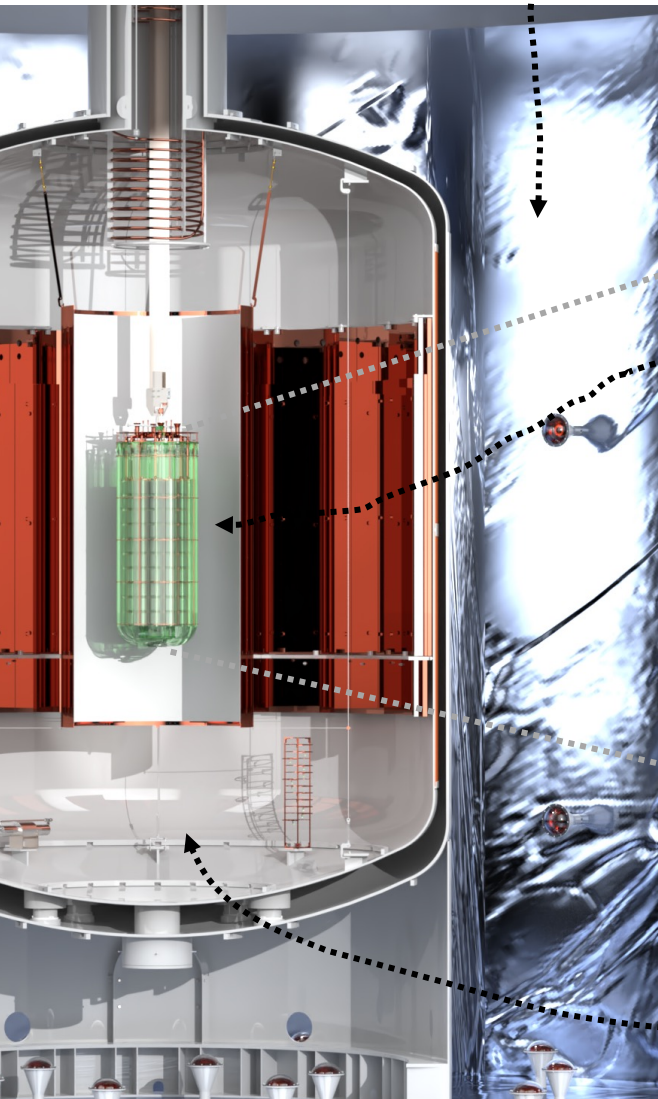
Phase II: LEGEND-1000

- 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

Water tank with PMTs for muon veto ($\Phi = 10$ m, $H = 9$ m)

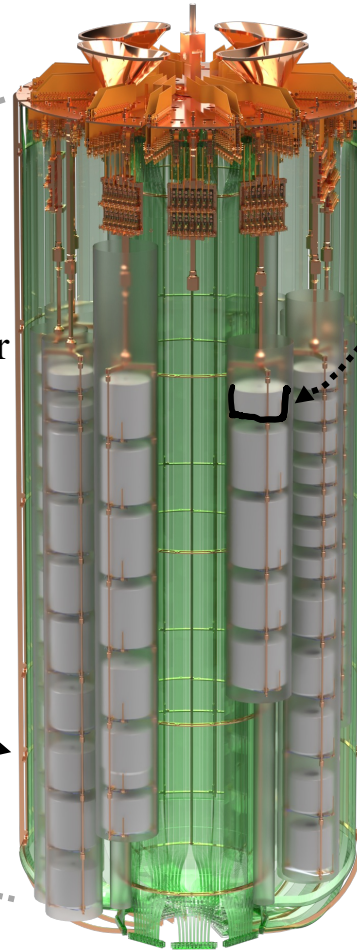
Detector array with max. 12 detector strings



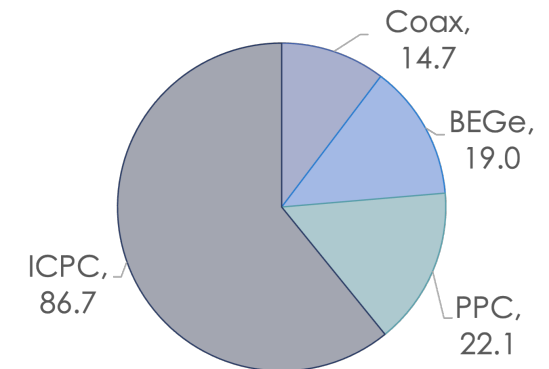
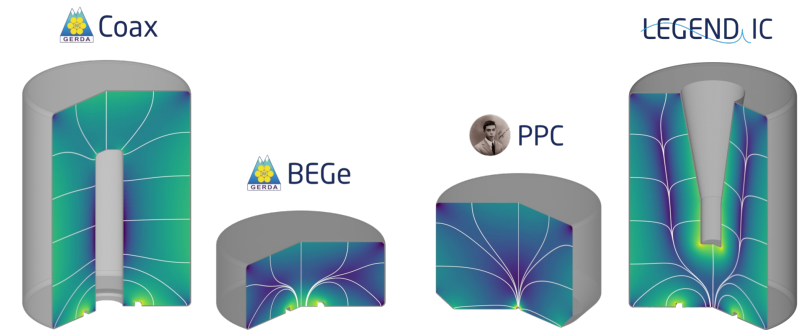
Wavelength-shifting reflector

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

LAr cryostat cryostat ($\Phi = 4.2$ m, $H = 6$ m)



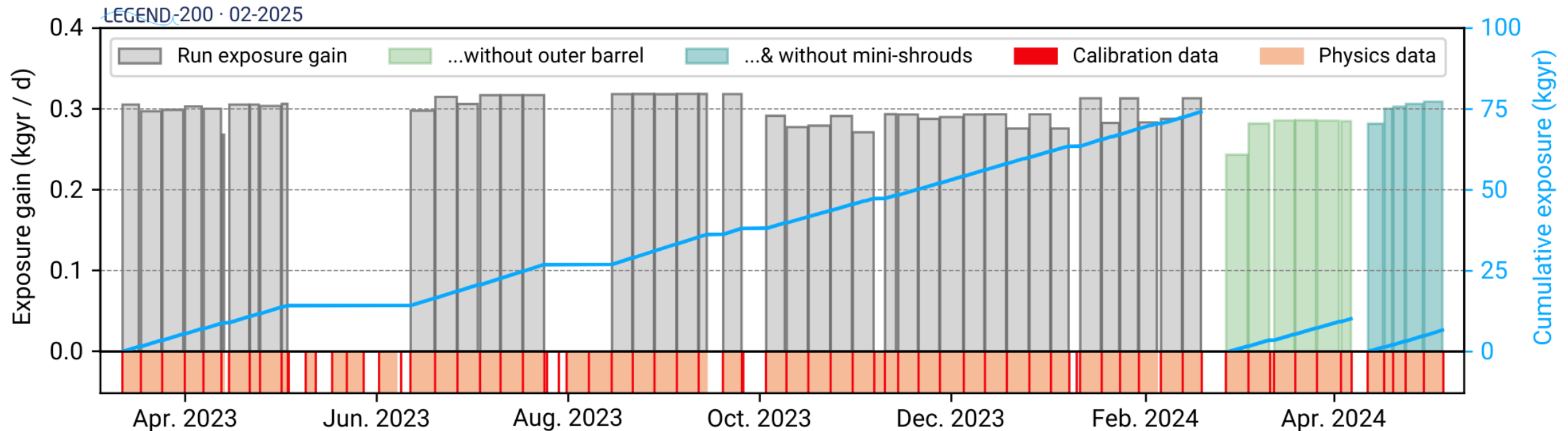
Detector unit
Four detector types



New LEGEND-200 results

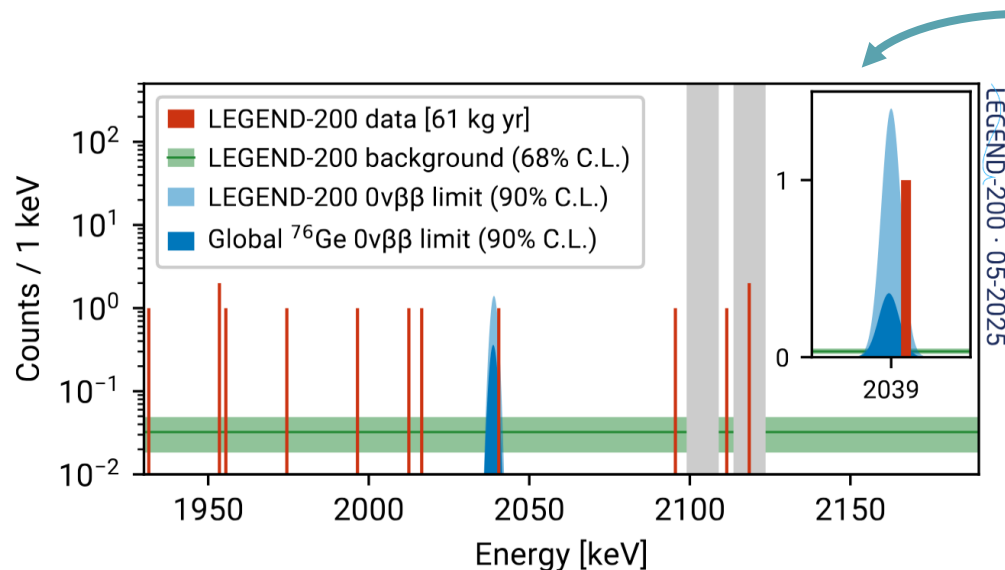
- Exposure accumulated over one year (spring 2023 – spring 2024)
- Taken with 130 kg operating detectors out of 142 kg detectors installed in Oct. 2022
- Usable physics data summing up to 61.0 kg yr

Ref.: LEGEND Collab.,
[arXiv:2505.10440 \[hep-ex\]](https://arxiv.org/abs/2505.10440) (2025)



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 $T_{1/2}^{0\nu} > 0.5 \times 10^{26}$ 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)

$T_{1/2}^{0\nu}$

$> 1.9 \times 10^{26}$ yr

2.8×10^{26} yr

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

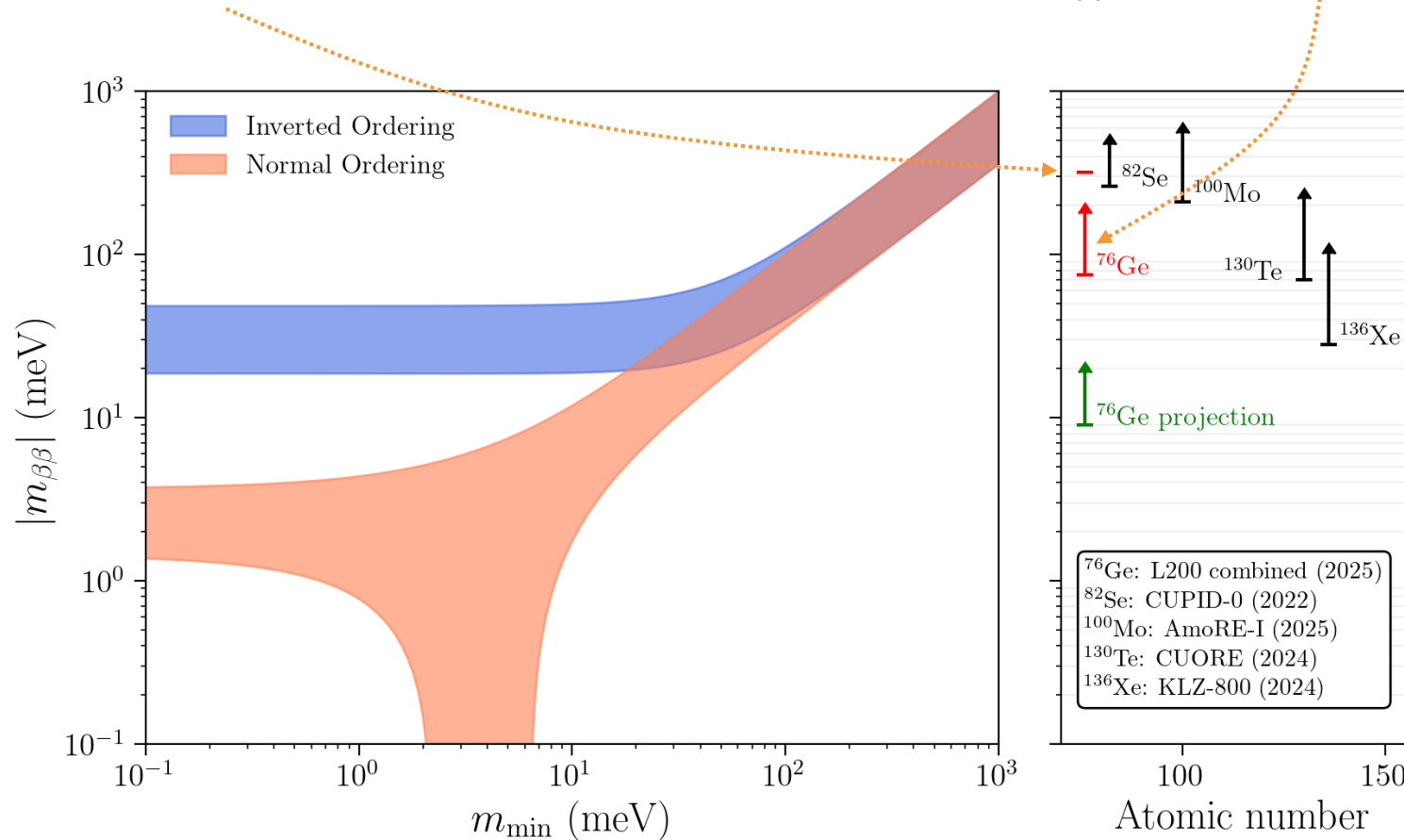
$$(T_{1/2})^{-1} = G(Q_{\beta\beta}, Z) \cdot g_A^4 \cdot |M_{\text{nuc}}|^2 \cdot m_{\beta\beta}^2$$

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

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

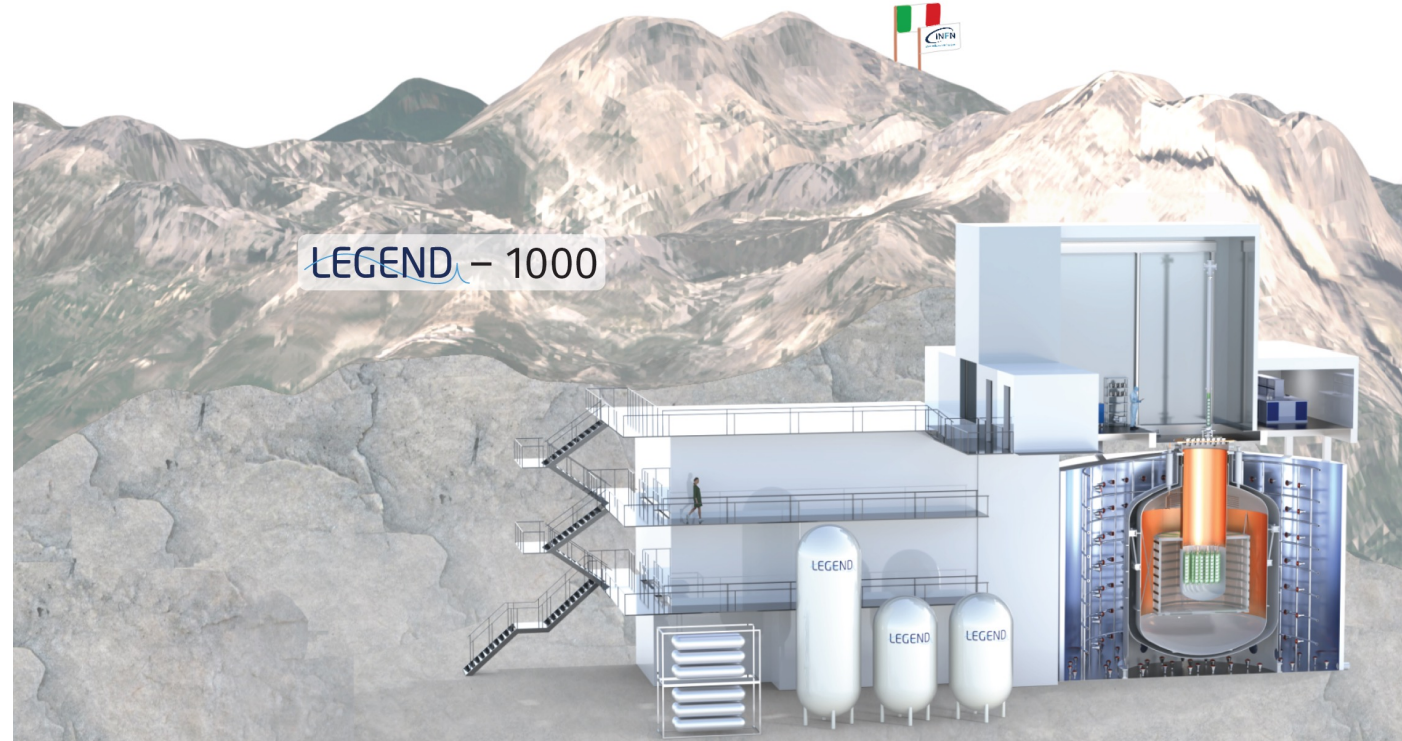
Phenomenological NME: $2.35 - 6.34$

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

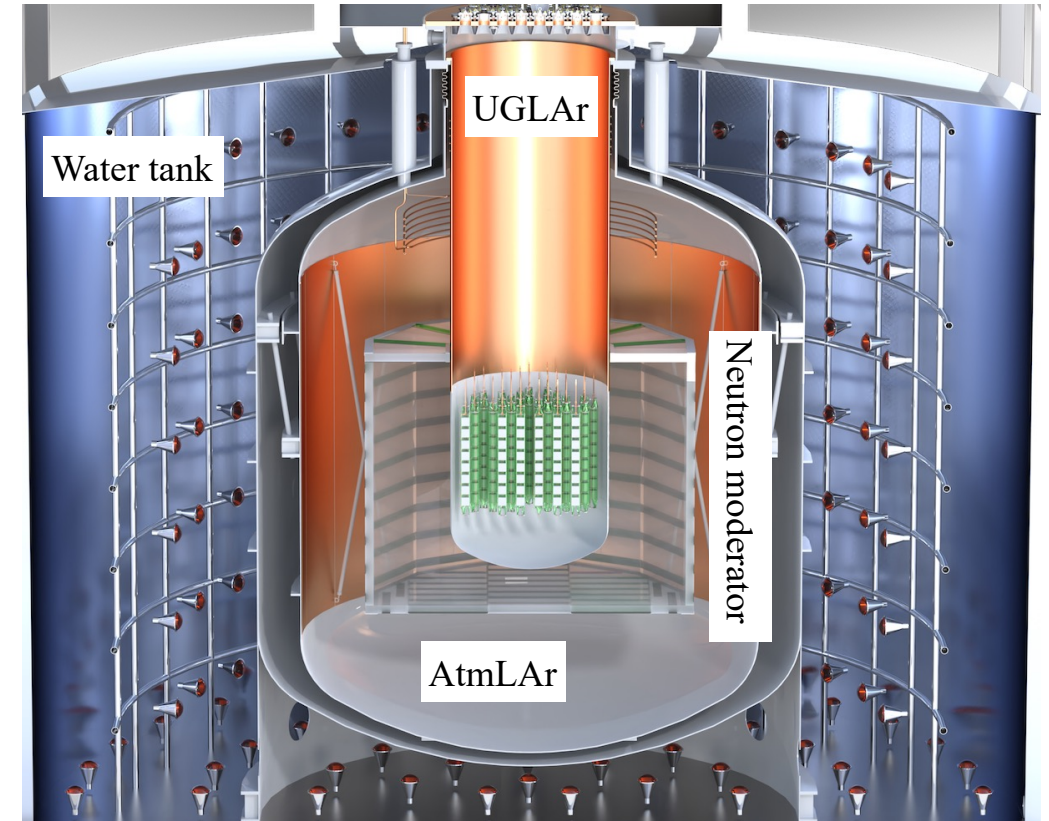


Walking towards LEGEND-1000

- R&D ongoing in preparation for the second phase experiment
 - Deploys 5x isotope mass with upscaled infrastructure
 - Requires 20x improvement in background index
- Pursuing fundings in the US and Europe



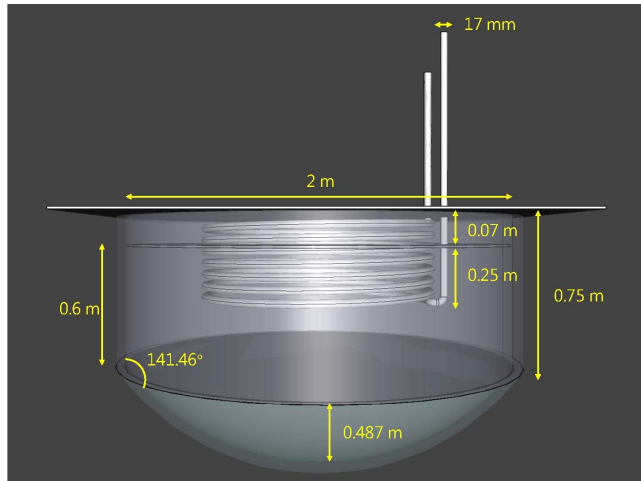
- Background reductions:
 - Radiopure underground argon (UGLAr):
direct mitigation of ^{42}K (from ^{42}Ar) background
 - Underground electroformed copper (EFCu)
 - Neutron moderator in LAr
 - Neutron shielding materials around Ge detectors
- ICPC detectors:
 - Increasing mass reduces surface to volume ratio
 - ^{76}Ge enrichment up to 92%
- LAr veto:
 - Optimal wavelength-shifting material combinations
(shifter + reflector) required given larger surfaces



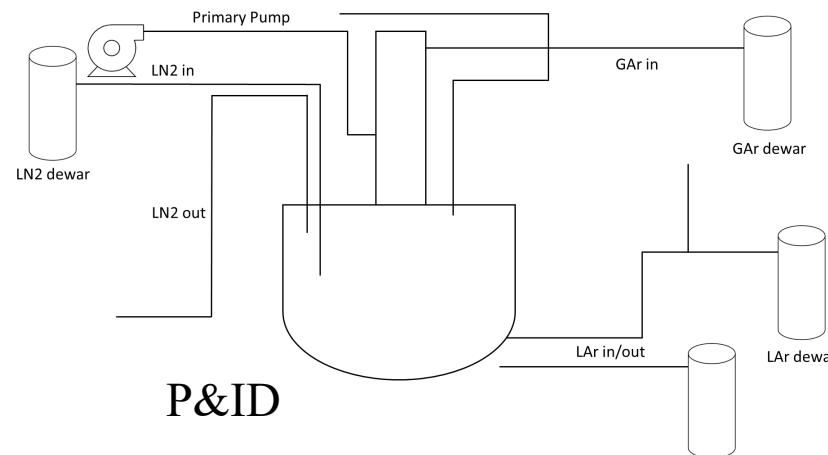
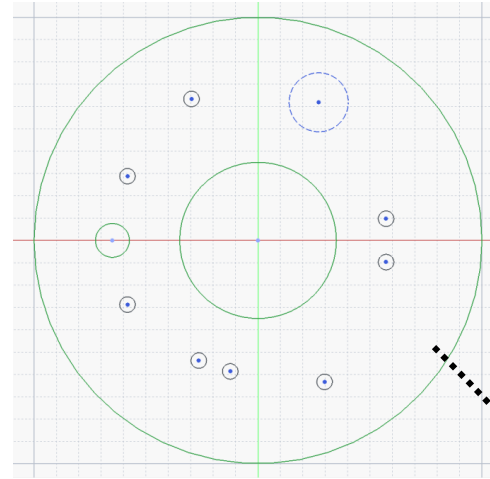
What we are doing at NTU

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

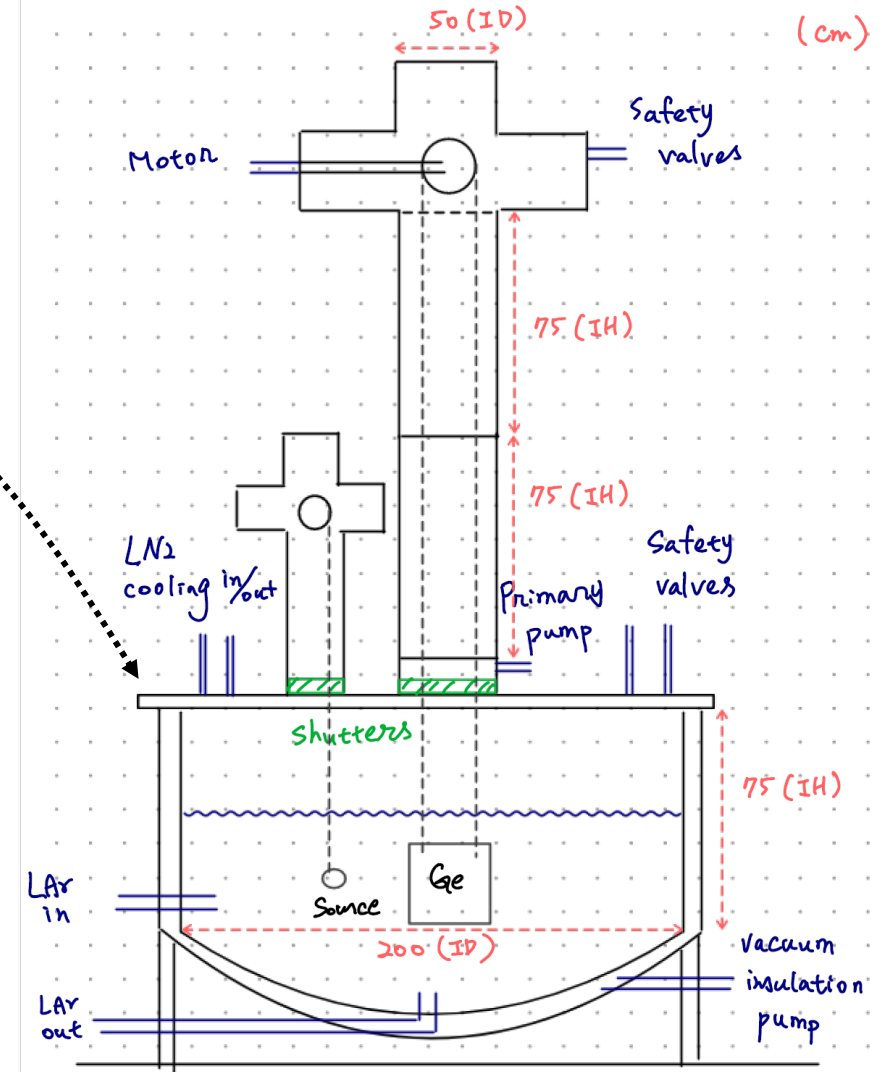
Steel chamber



Top flange



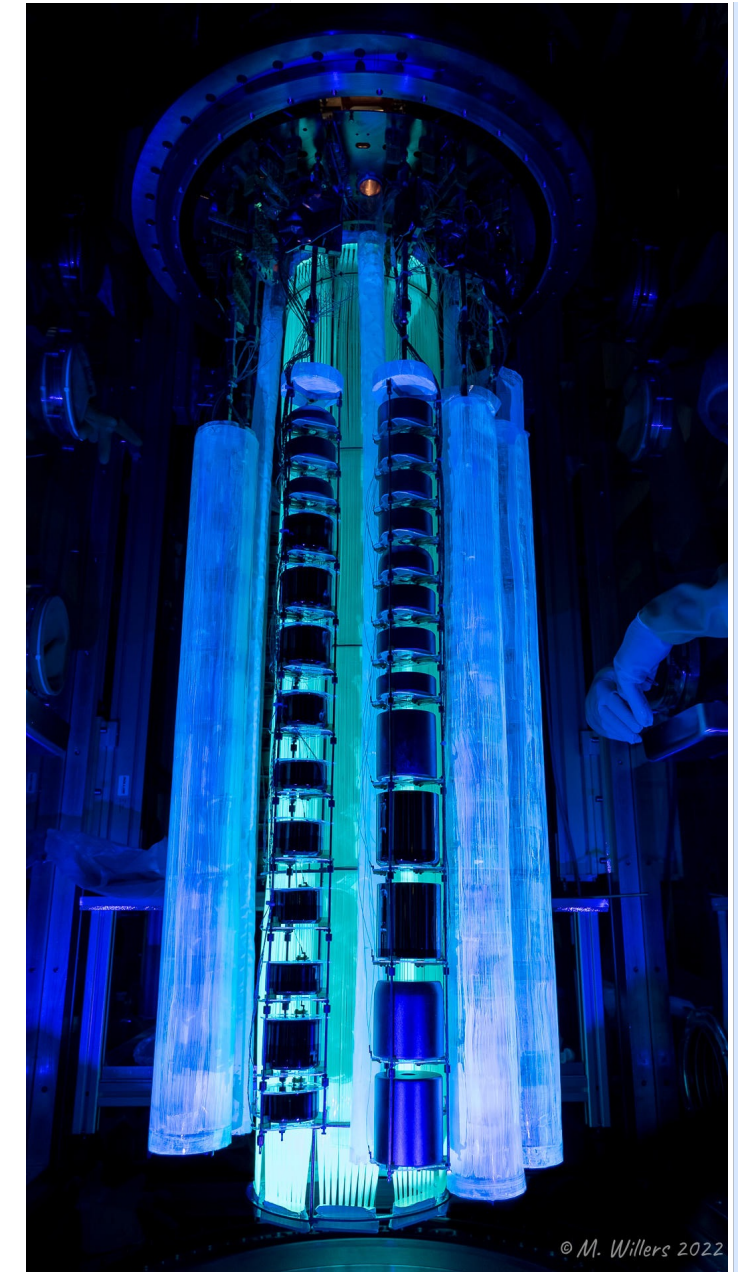
Preliminary



Summary

- A number of experiments worldwide are searching for $0\nu\beta\beta$ in different isotopes using various detection techniques
- If $0\nu\beta\beta$ is observed, it would be the first evidence of lepton-number violation and would prove the Majorana nature of neutrinos
- $0\nu\beta\beta$ has not been observed. Background-free search in ^{76}Ge is a promising way to go forwards
- LEGEND is a two-phase project whose ultimate goal is to probe the full inverted-mass-ordering phase space
- LEGEND-200 has collected data over the last year and published its first $0\nu\beta\beta$ results, whereas various R&D projects are ongoing pushing forward the LEGEND-1000 deployment
- 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

Credit: M. Willers



Acknowledgement



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

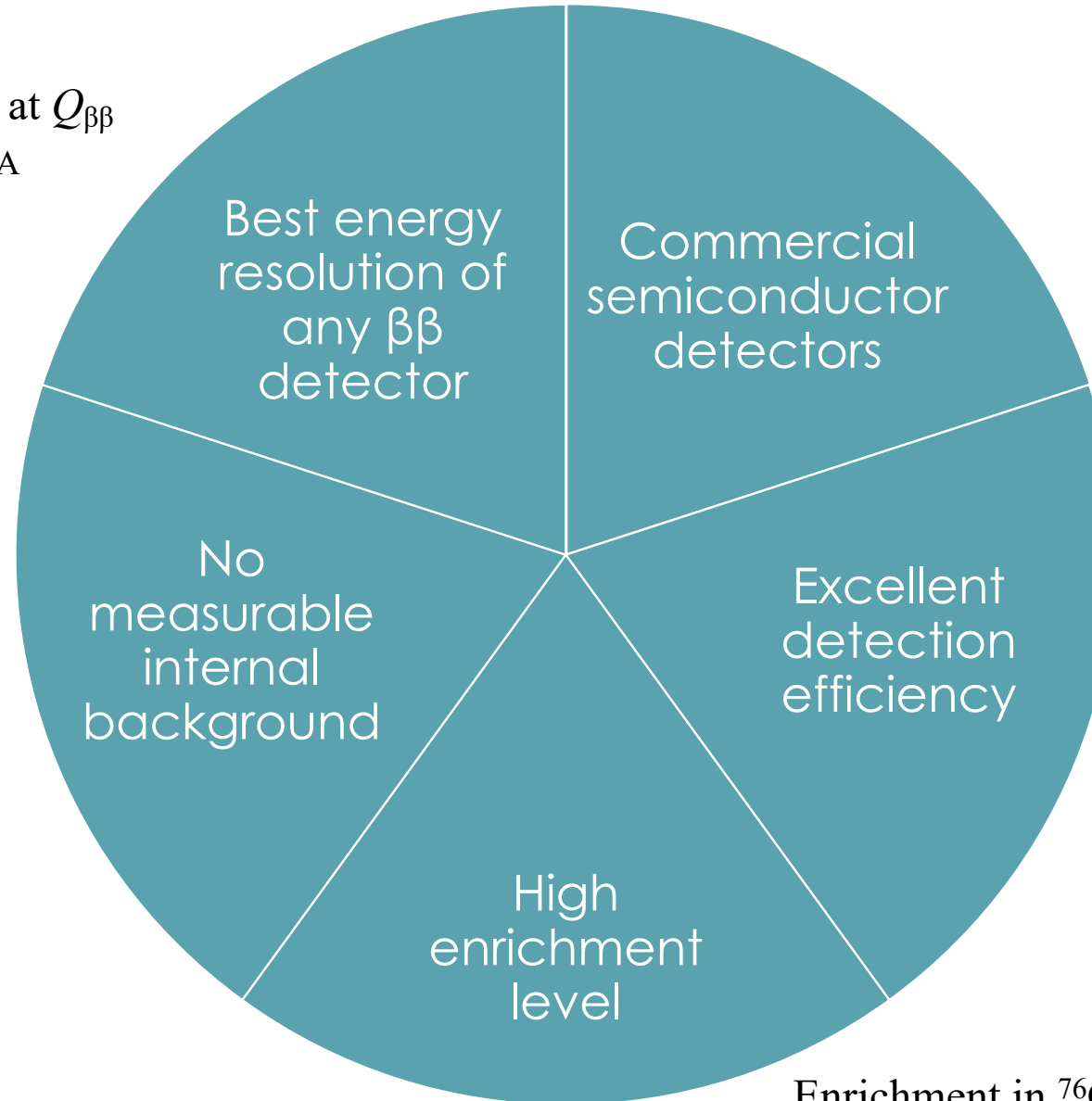


<https://legend-exp.org/>

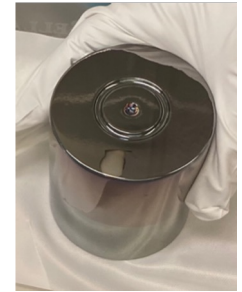
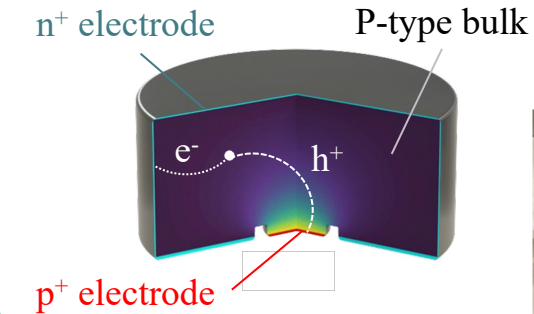
Thank you

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

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



Made from high-purity germanium (HPGe) materials



Source = Detector
~100% in the active volume

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

^{76}Ge -based $0\nu\beta\beta$ experiments



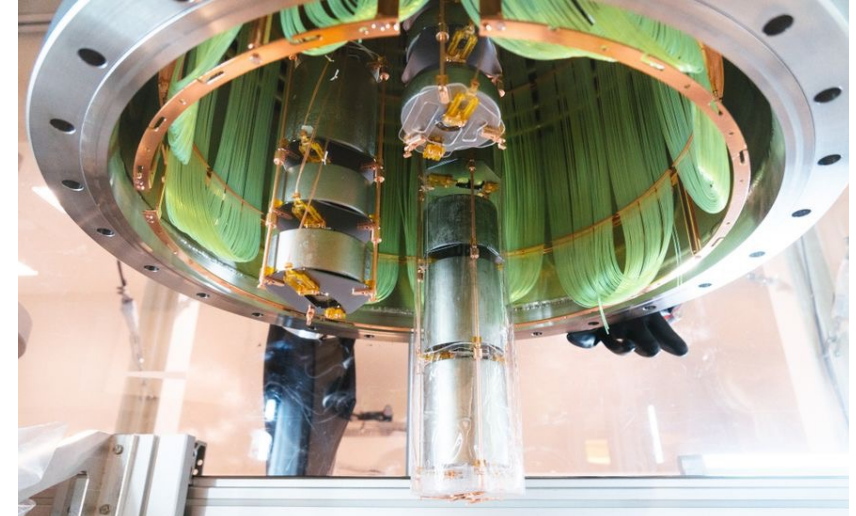
Credit: GERDA Collab.

LNGS, Italy



Credit: MAJORANA Collab.

SURF, US



LNGS, Italy

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

Lowest background level for $0\nu\beta\beta$:

Mean background in $(Q_{\beta\beta} \pm 2\sigma)$ is 0.3 counts
(with 103.7 kg·yr of exposure)

Ref.: GERDA Collab., [PRL 125, 252502 \(2020\)](#)

Best energy resolution for $0\nu\beta\beta$:

2.52 keV (FWHM) at $Q_{\beta\beta}$
(with 64.5 kg·yr of exposure)

Refs.: MAJORANA Collab., [PRL 130, 062501 \(2023\)](#)

- Half-life sensitivity

$$T_{1/2} \propto f \epsilon \sqrt{\frac{Mt}{B\sigma_E}}$$

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 ($Q_{\beta\beta}$)

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**

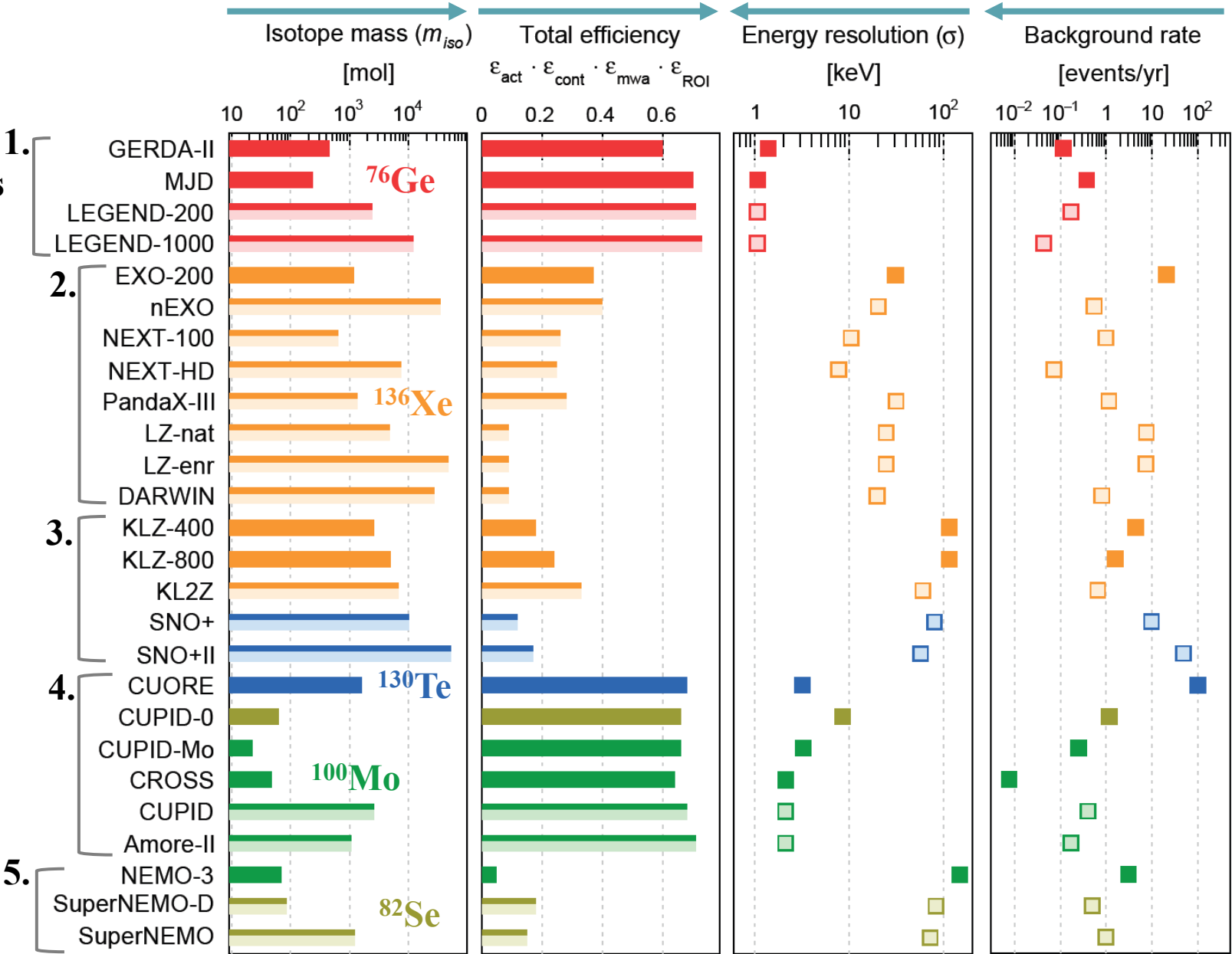
isotope mass

4. **Cryogenic calorimeters**

energy resolution, efficiency,
granularity

5. **Tracking calorimeters**

particle tracking



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 ($\text{Li}_2^{100}\text{MoO}_4$ and $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$)	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)

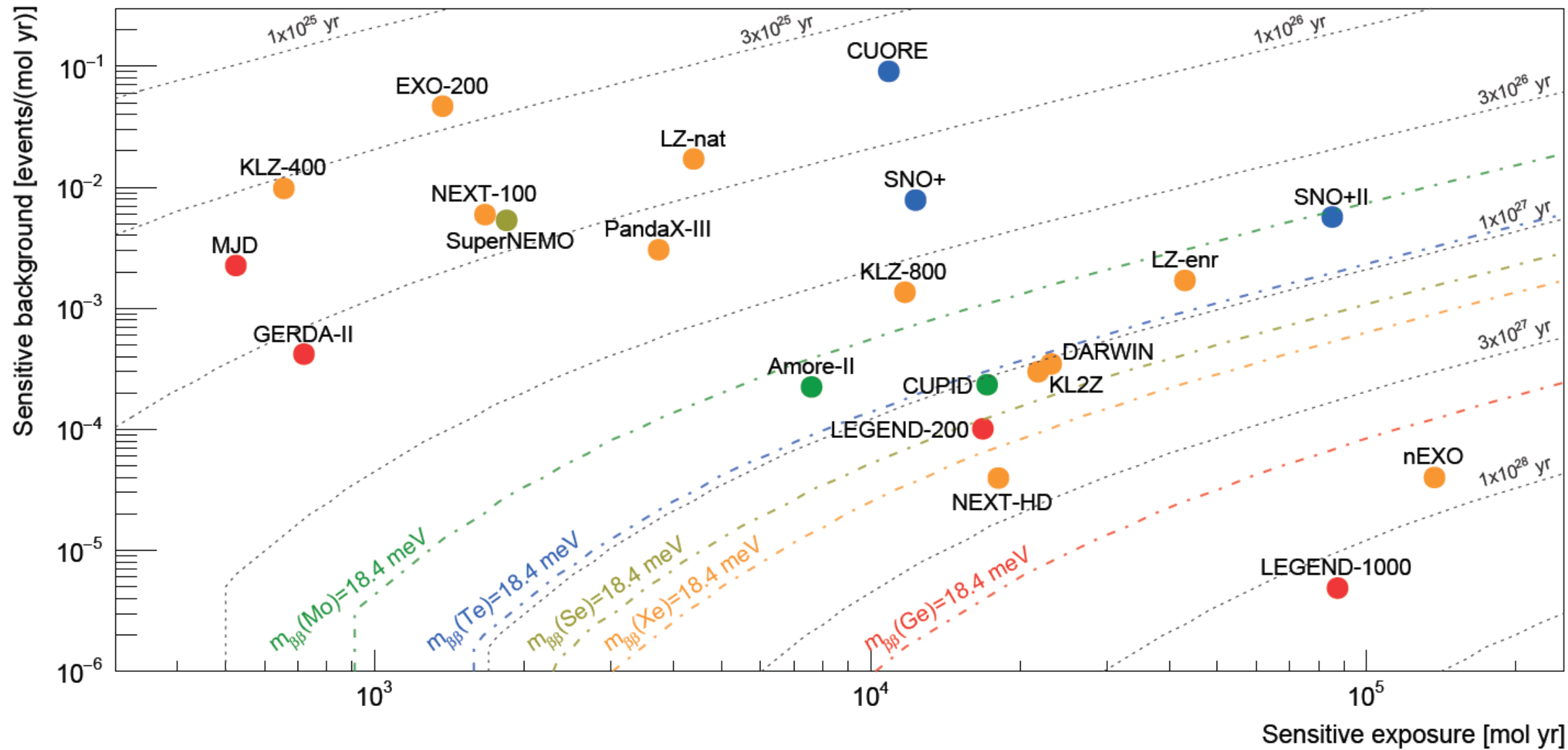
[2] CUORE Collab., [arXiv:2404.04453 \[nucl-ex\]](#) (2024)

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

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

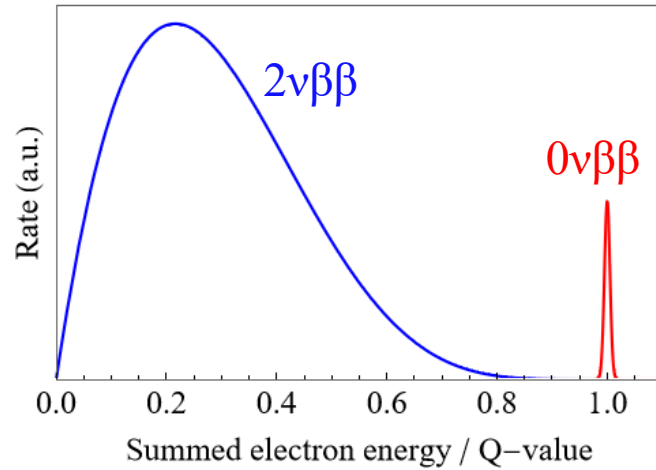
[5] O. Azzolini *et. al.*, [PRL 129, 111801](#) (2022)

Sensitivity overview



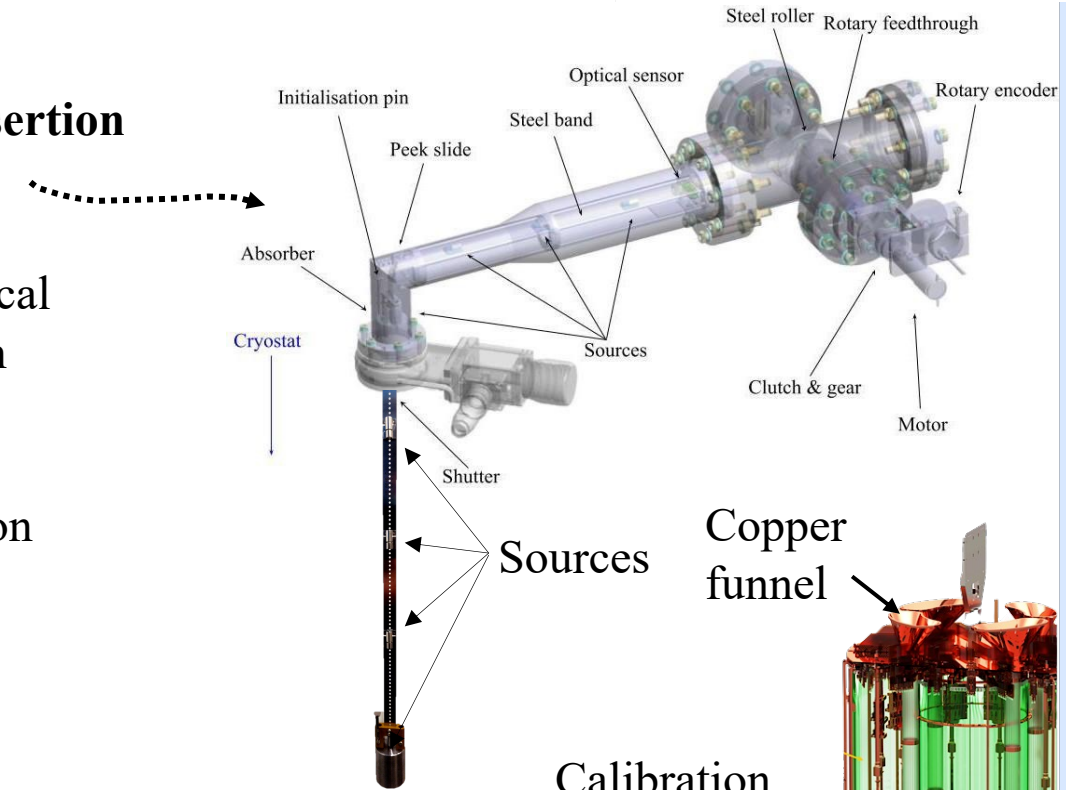
Ref.: M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

Energy calibration of HPGe Detectors



Calibration source insertion systems

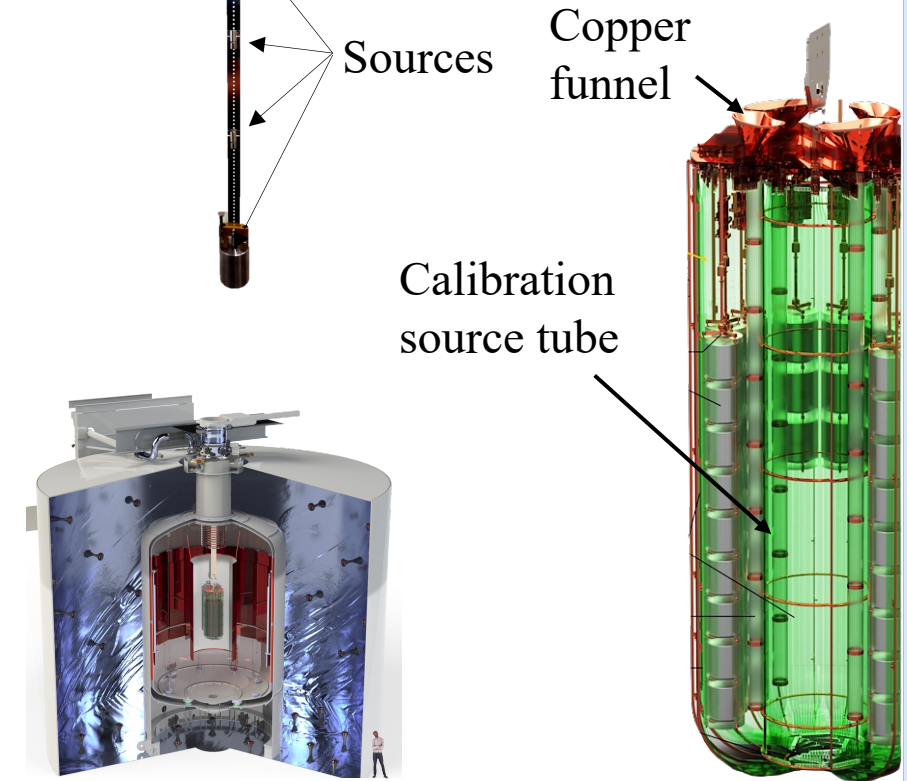
- Large-distance vertical movements of ~ 9 m
- Precision of 1 mm
- Reliability over the experimental duration



Precise identification of $0\nu\beta\beta$ requires:

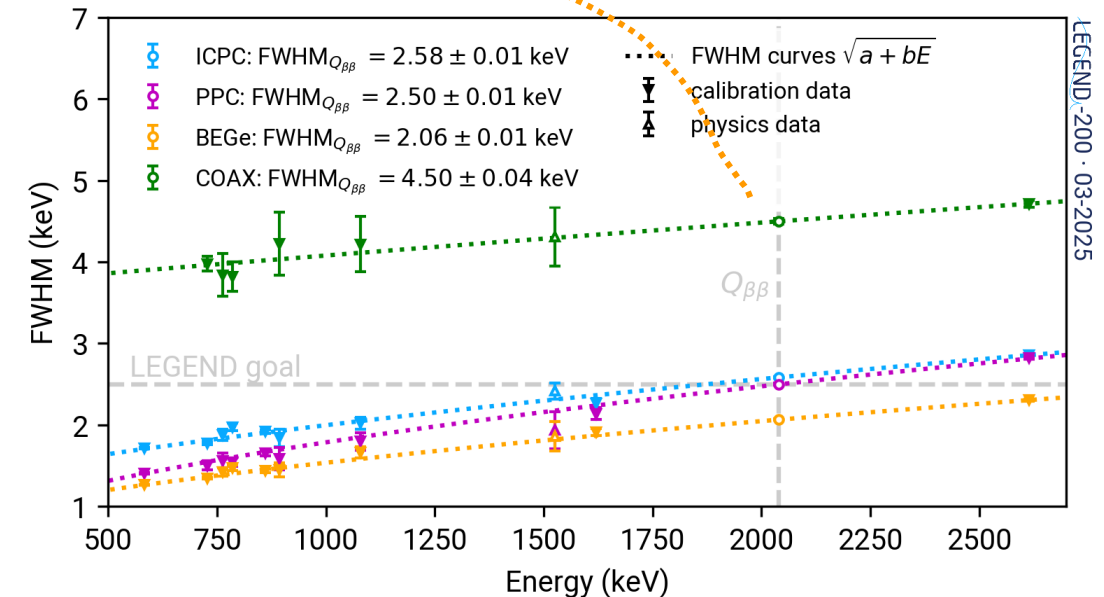
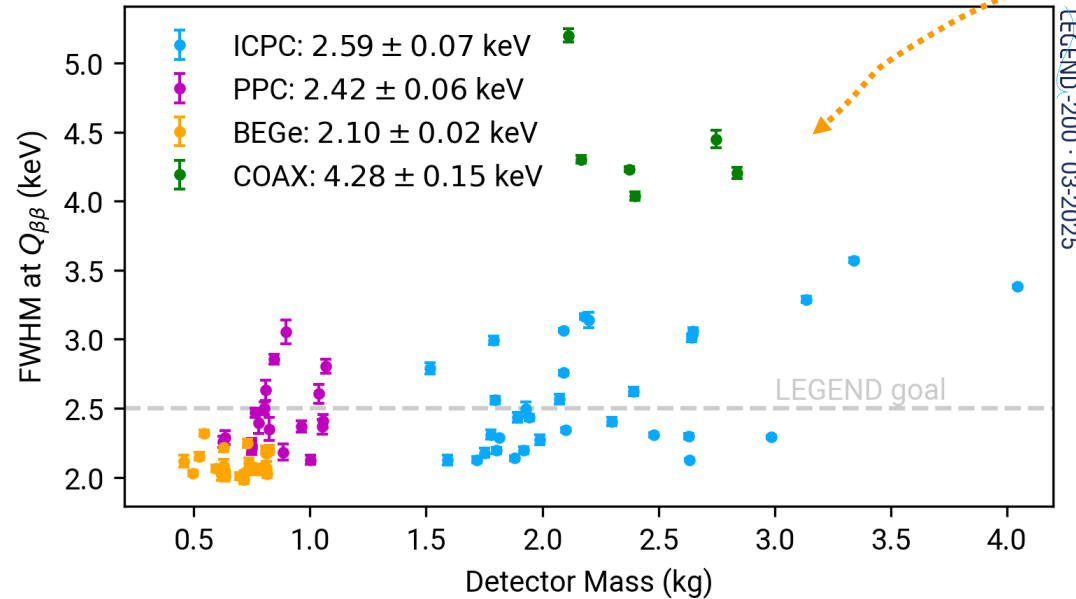
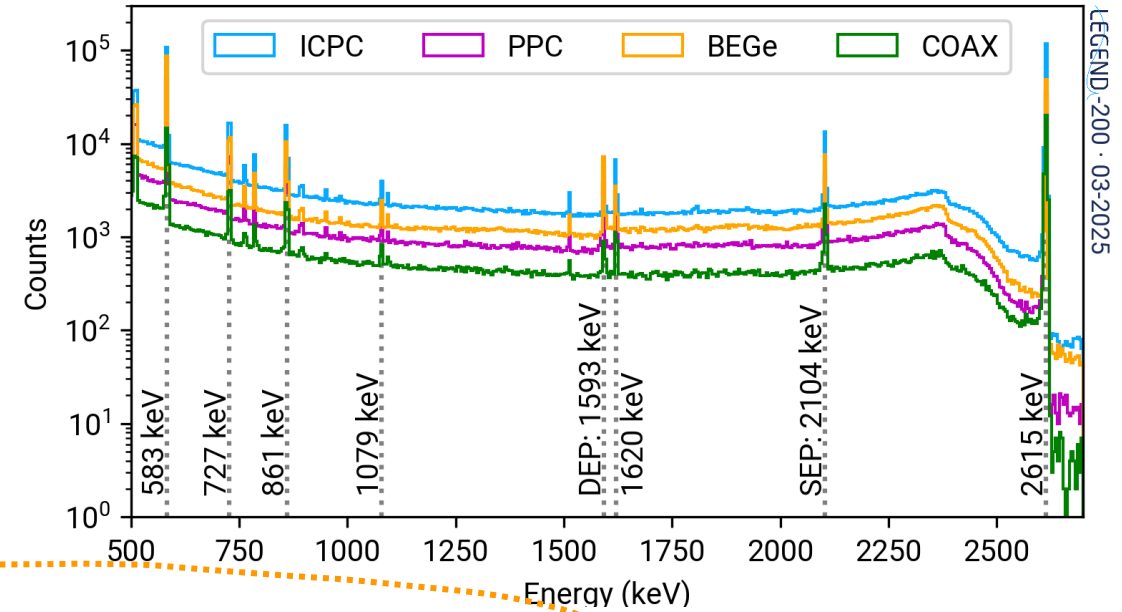
- Stable energy scale
- Excellent energy resolution

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



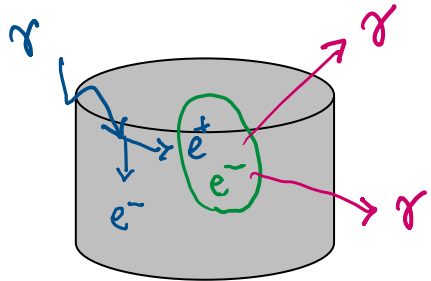
Energy scale and resolution

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

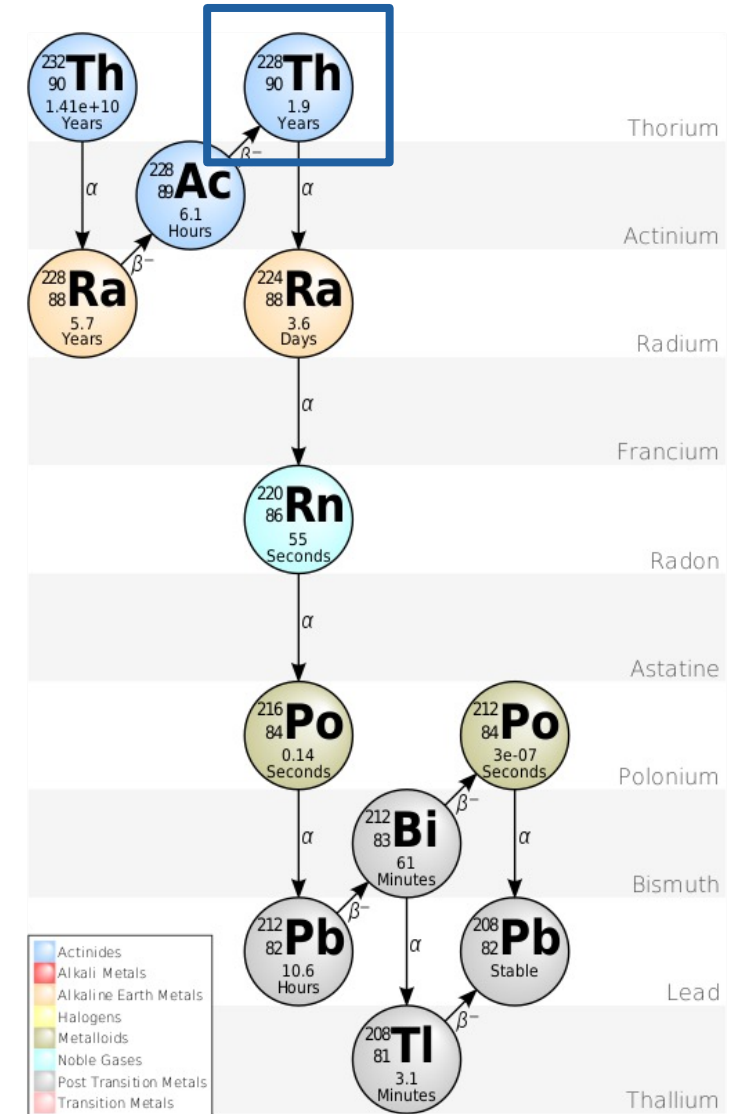


Why do we use ^{228}Th sources?

- ^{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](#)



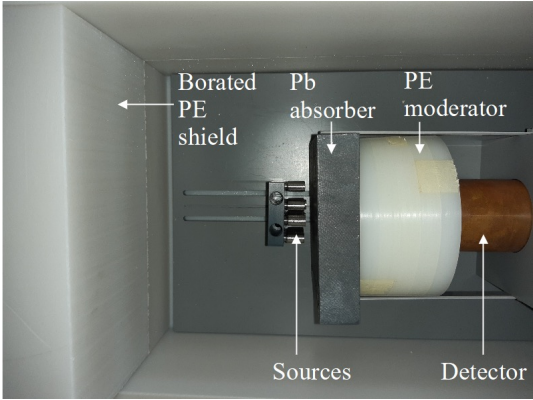
Nevertheless...

- ^{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 $^{77\text{m}}\text{Ge}$ (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

Low background environment underground at LNGS

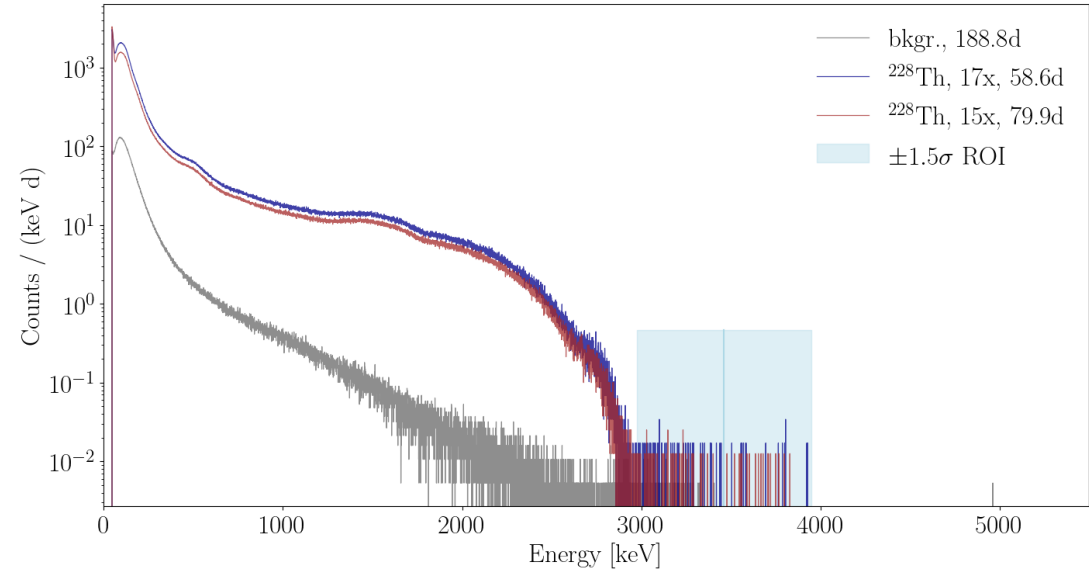
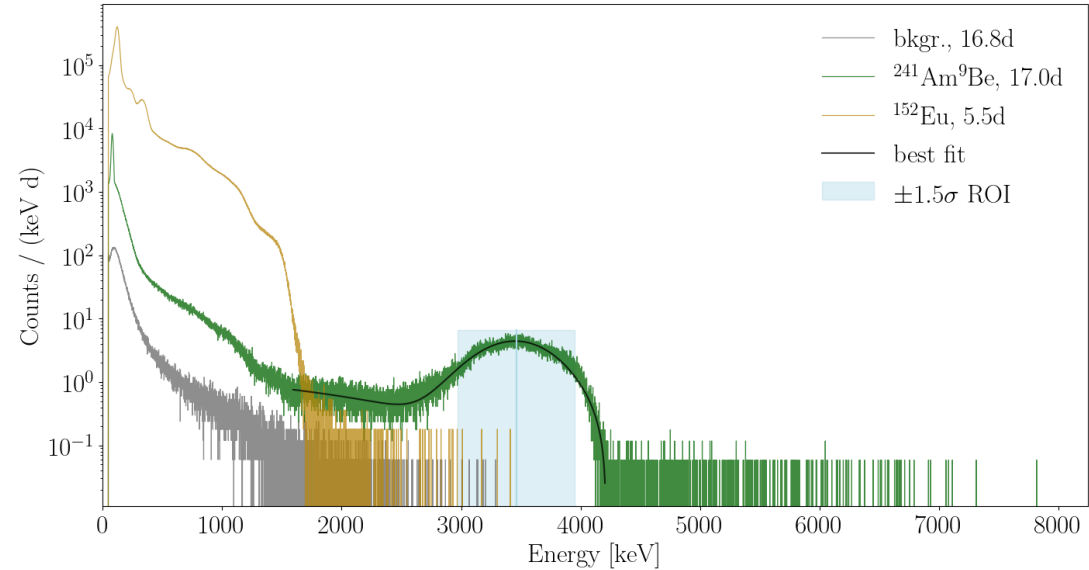


Ref. L. Baudis et al., JINST 18, P02001 (2023)

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

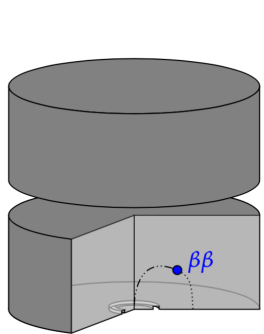
^{152}Eu γ source for energy calibration
 $^{241}\text{Am}^9\text{Be}$ n source for efficiency determination (activity 160(4) n/s in 2013)

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

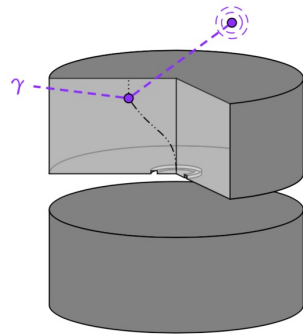


Background mitigation

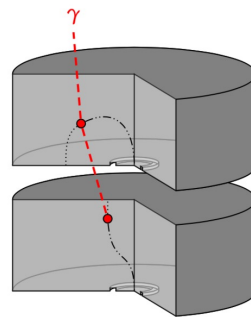
- $\beta\beta$ decay signal: localized energy deposition $\sim \mathcal{O}(1 \text{ mm})$
→ Single-site event (SSE)
- μ : water Cherenkov → muon veto
- γ with MeV energies: multiple energy depositions $\sim \mathcal{O}(1 \text{ cm})$
 - Anti-coincidence from multiple detectors → multiplicity
 - Multi-site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



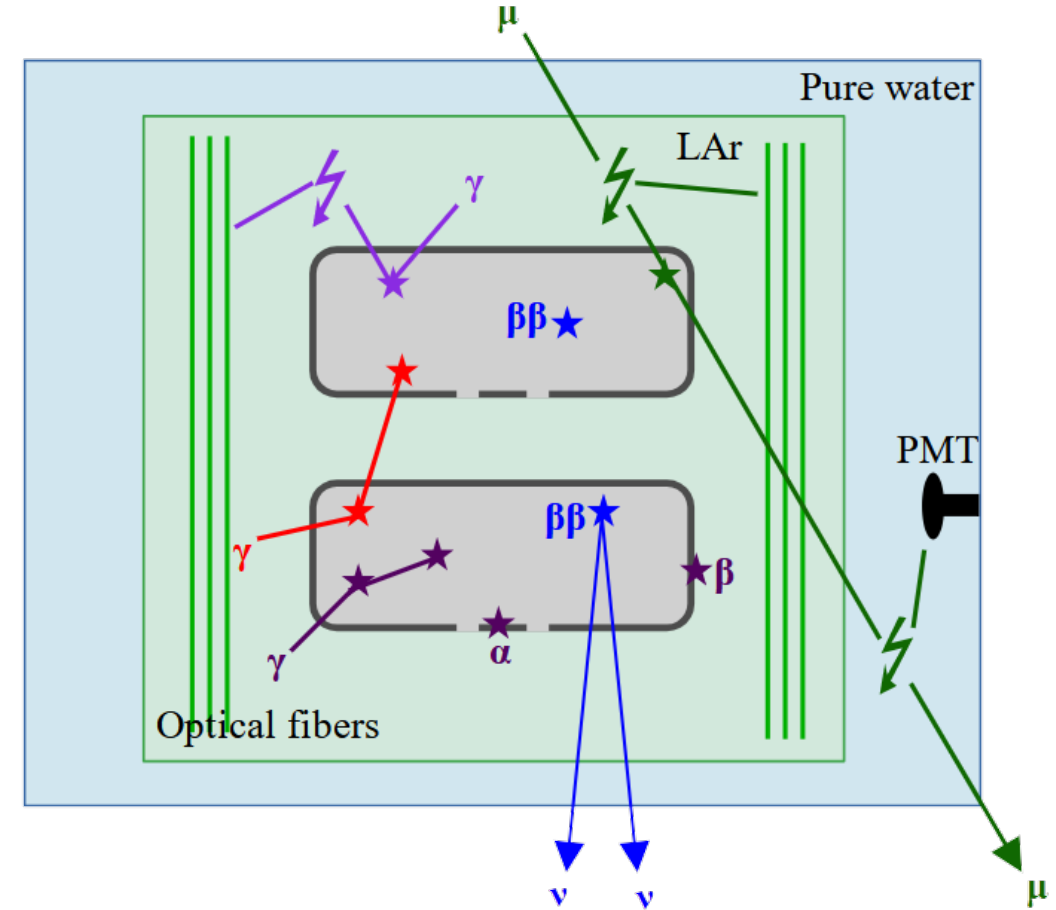
Single Ge



Ge + LAr

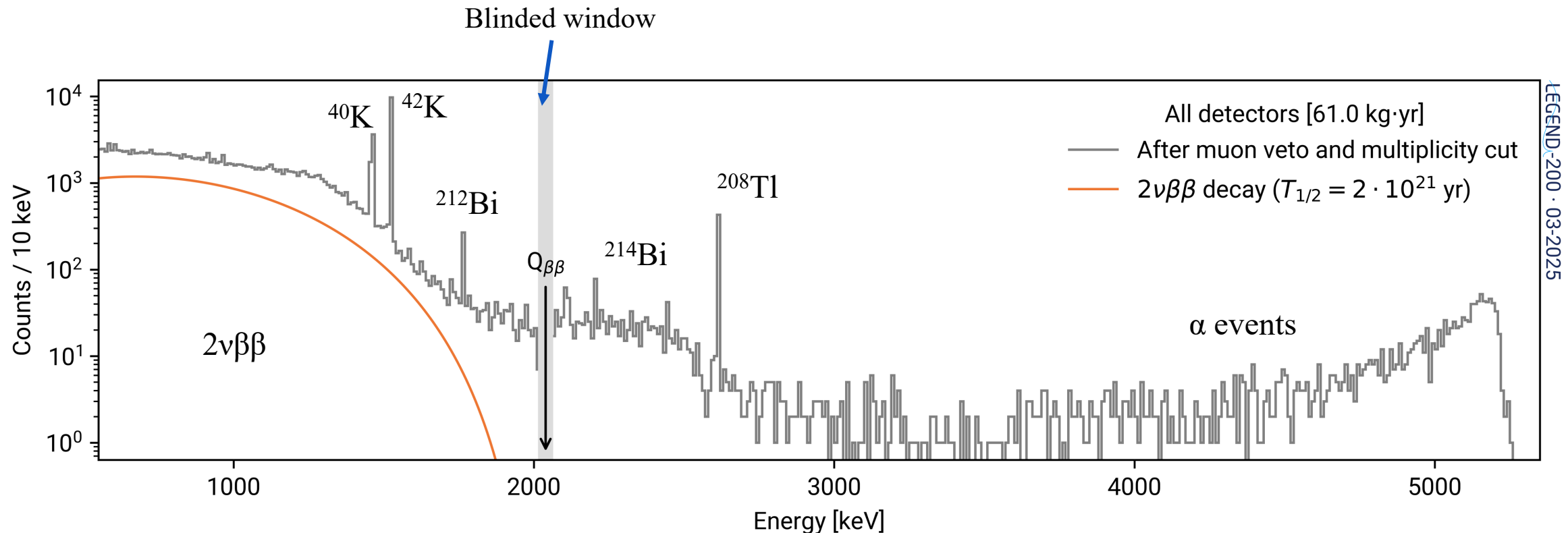


Multiple Ge



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**

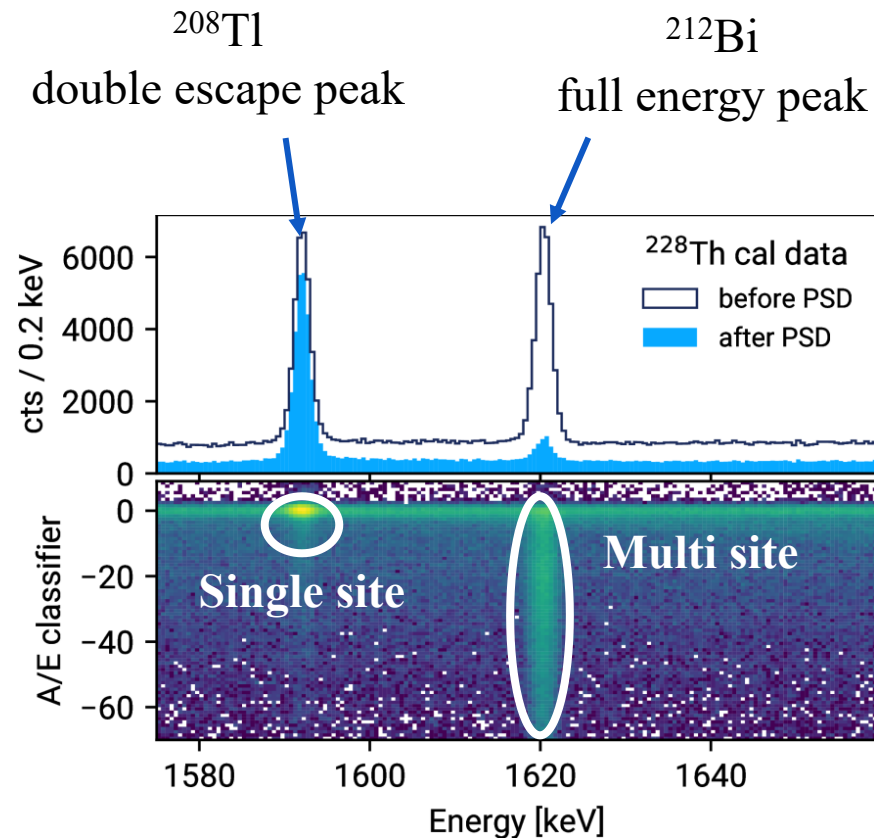
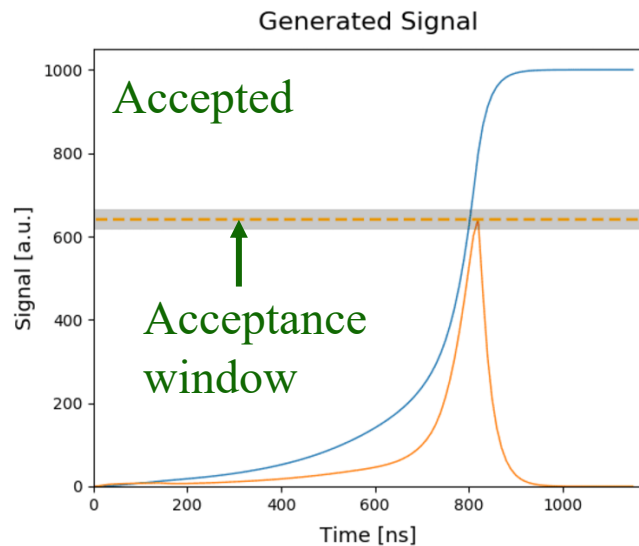


Pulse shape discrimination (PSD)

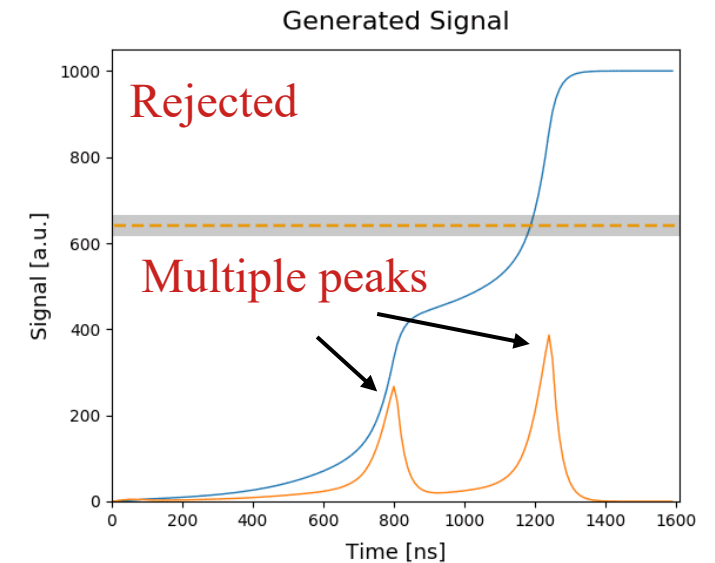
- Pulse shape classifier: $A/E = \max(\text{current}) / \text{energy}$
- Monitored with weekly ^{228}Th calibrations

Signal-like

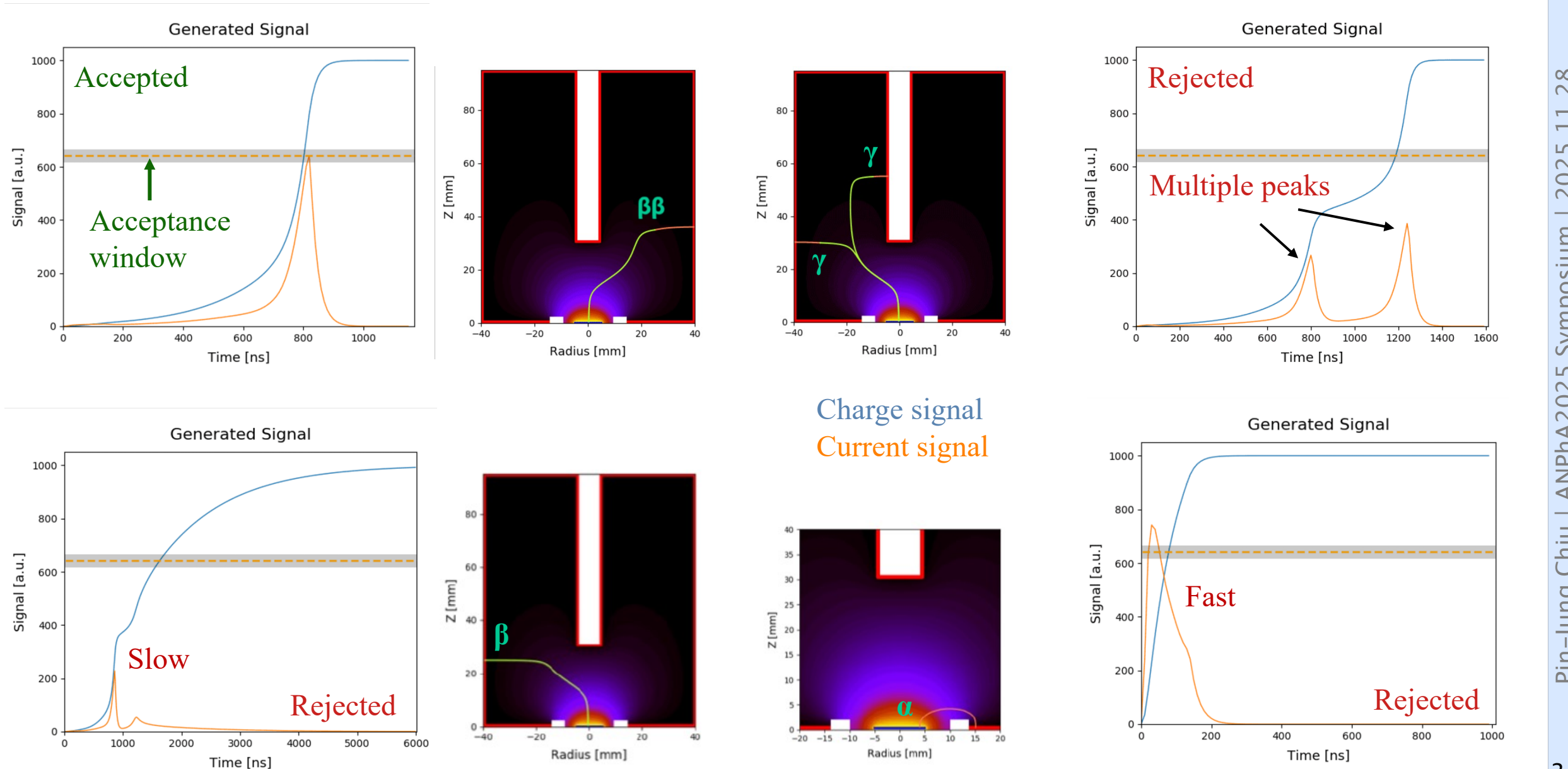
Charge signal
Current signal



Background-like

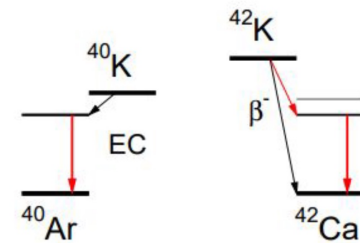


Pulse shape discrimination (PSD)

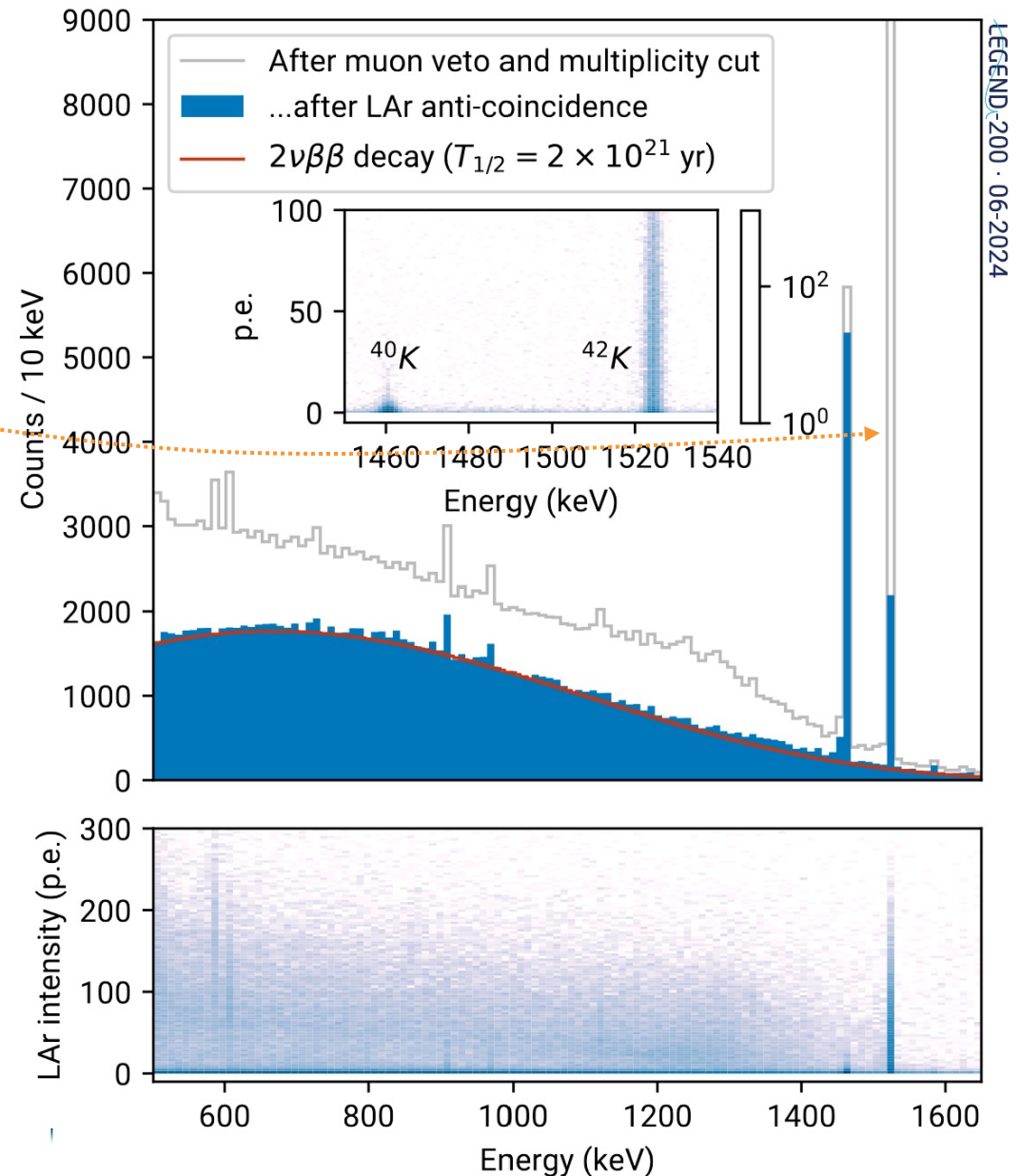


LAr anti-coincidence

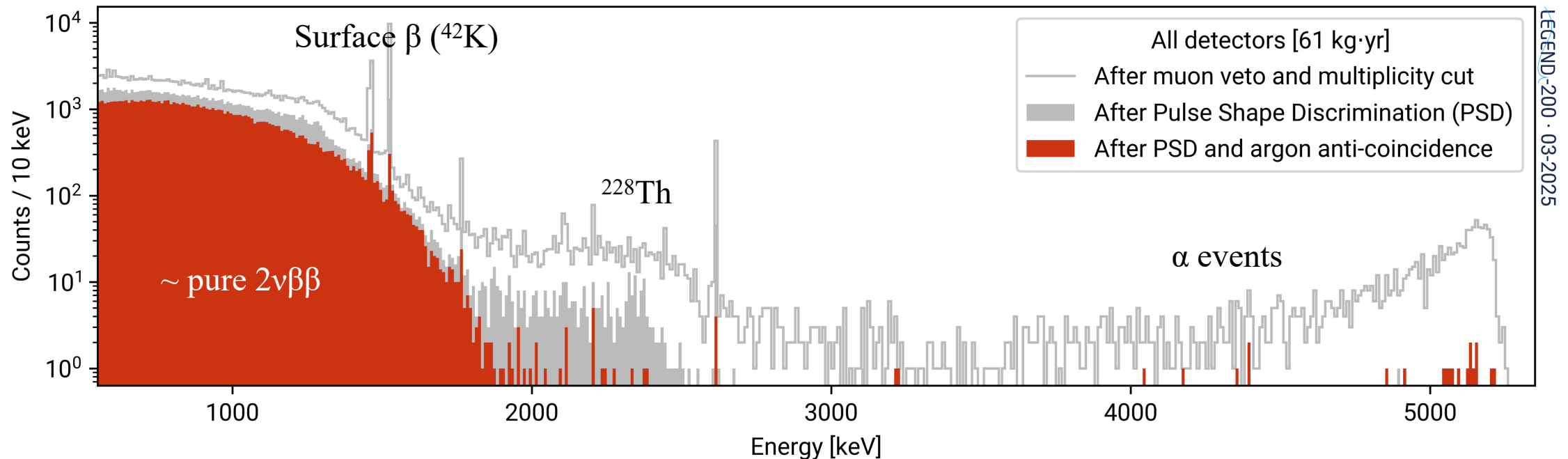
- Characterized with special calibration runs
 - 1 photoelectron / 10 keV
- Strong suppression of background above $2\nu\beta\beta$, e.g., from ^{42}K



Credit: K. v. Sturm



- PSD
 - Strong suppression of surface α and β (^{42}K) events
 - $\sim 60\%$ suppression of Compton multi-site events at $Q_{\beta\beta}$
- + LAr
 - Pure $2\nu\beta\beta$ distribution



Decay half-life vs. effective Majorana neutrino mass

Experiment

$$(T_{1/2})^{-1}$$

Measured half-life

Atomic phys.

$$G(Q_{\beta\beta}, Z)$$

Phase space factor

Nuclear phys.

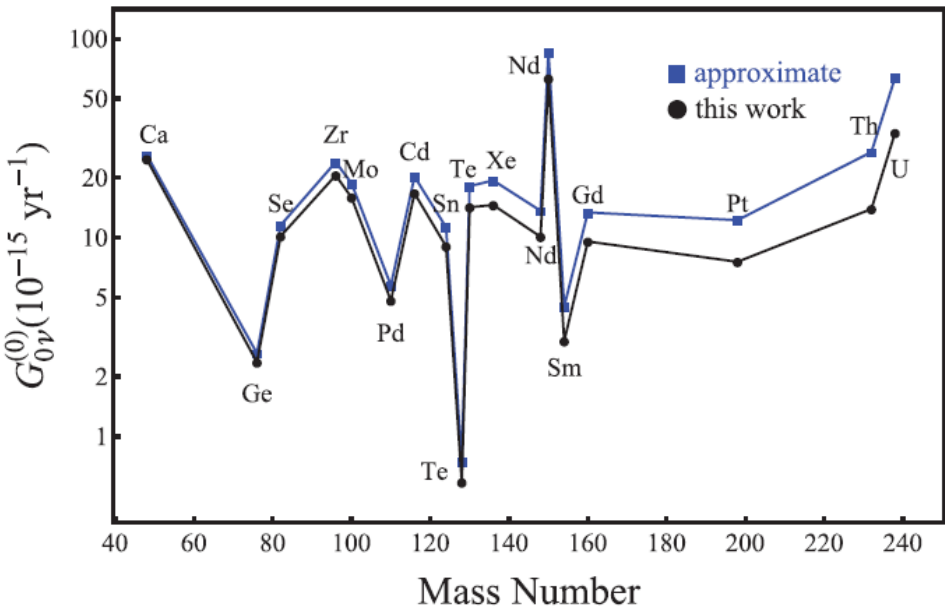
$$g_A^4 \cdot |M_{\text{nuc}}|^2$$

Axial coupling

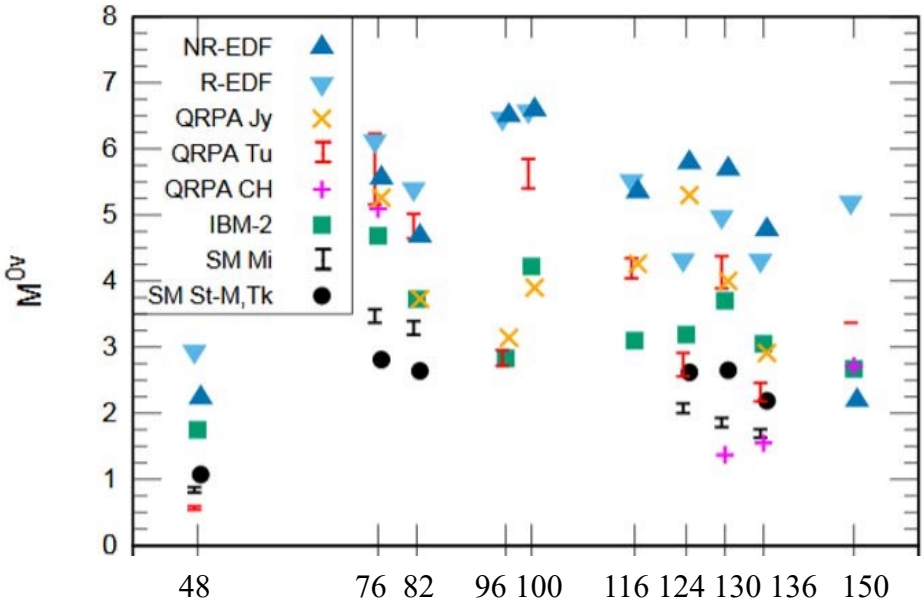
Particle phys.

$$m_{\beta\beta}^2$$

Effective Majorana neutrino mass



$$g_A = 1.27$$

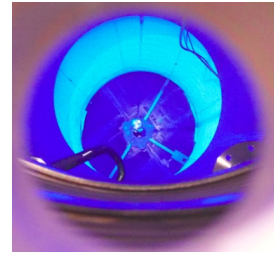
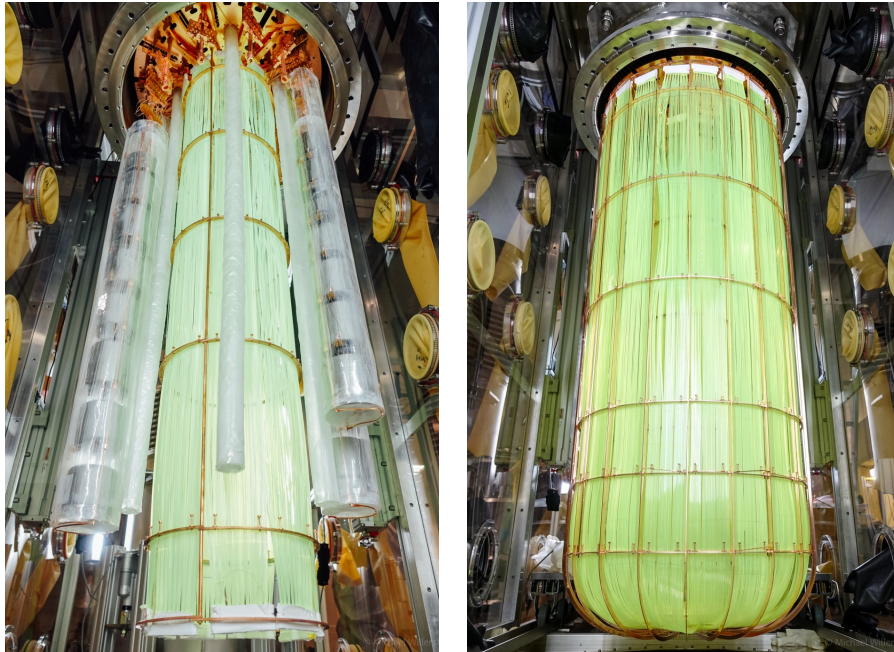


Ref.: J. Engel and J. Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

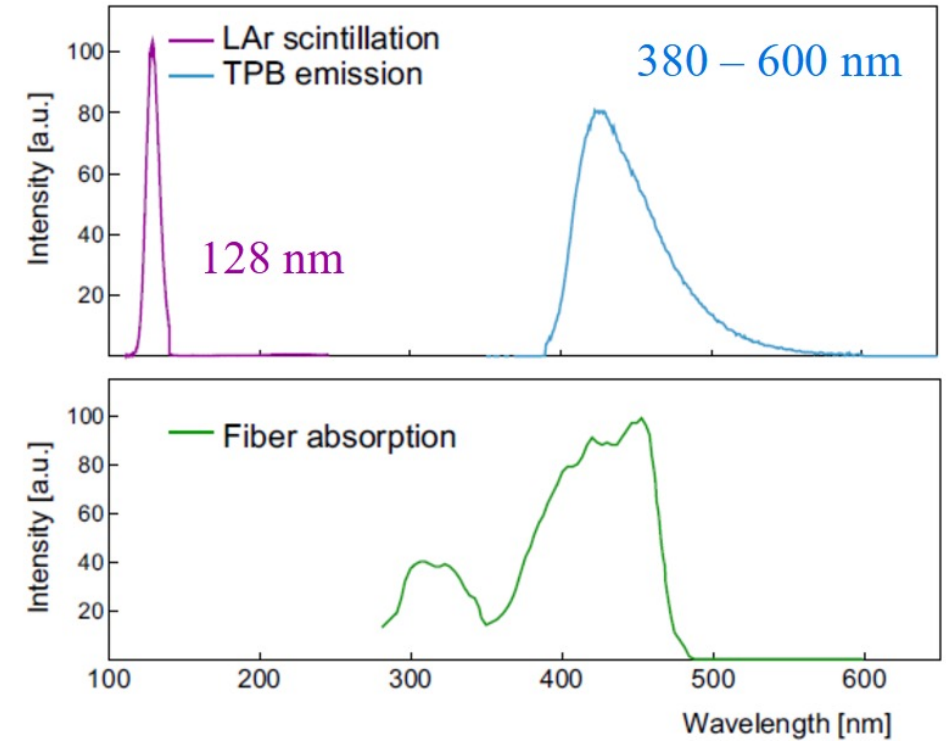
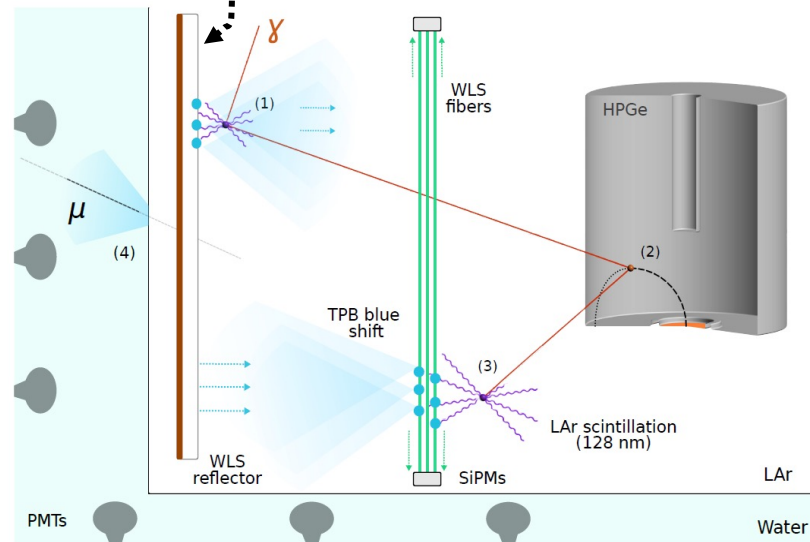
LAr veto systems

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

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

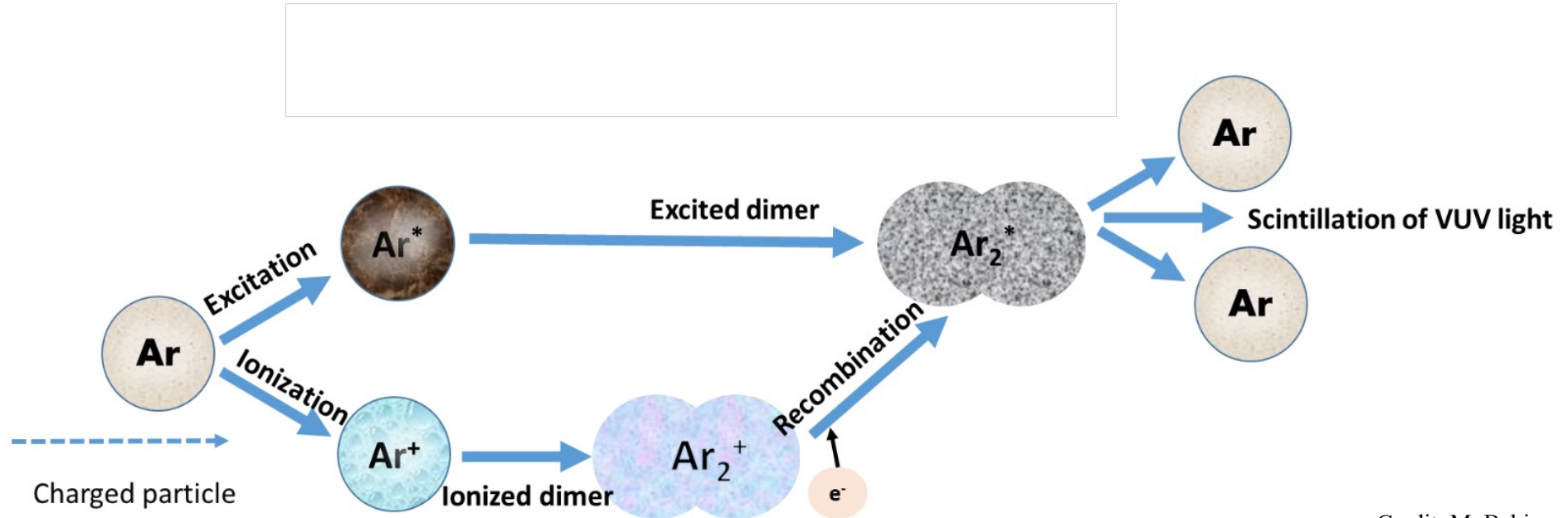


Wavelength-shifting reflector



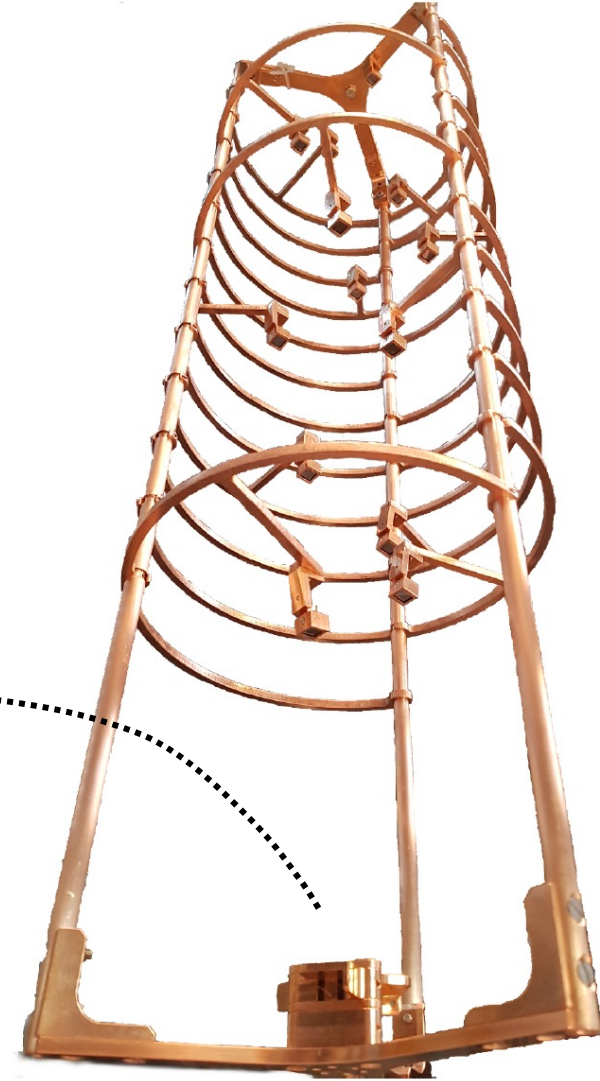
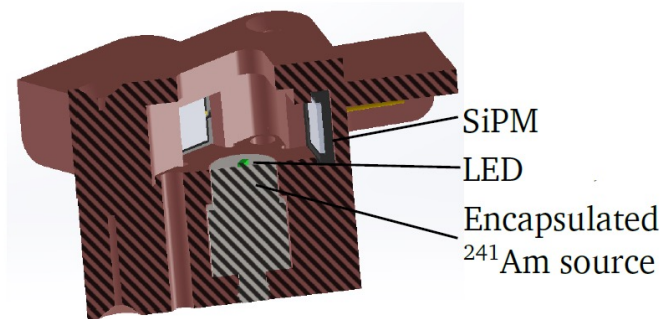
Ref.: G. R. Araujo et al.,
EPJC 82, 442 (2022)

Credit: G. R. Araujo



Credit: M. Babicz

LEGEND Liquid Argon Monitoring Apparatus

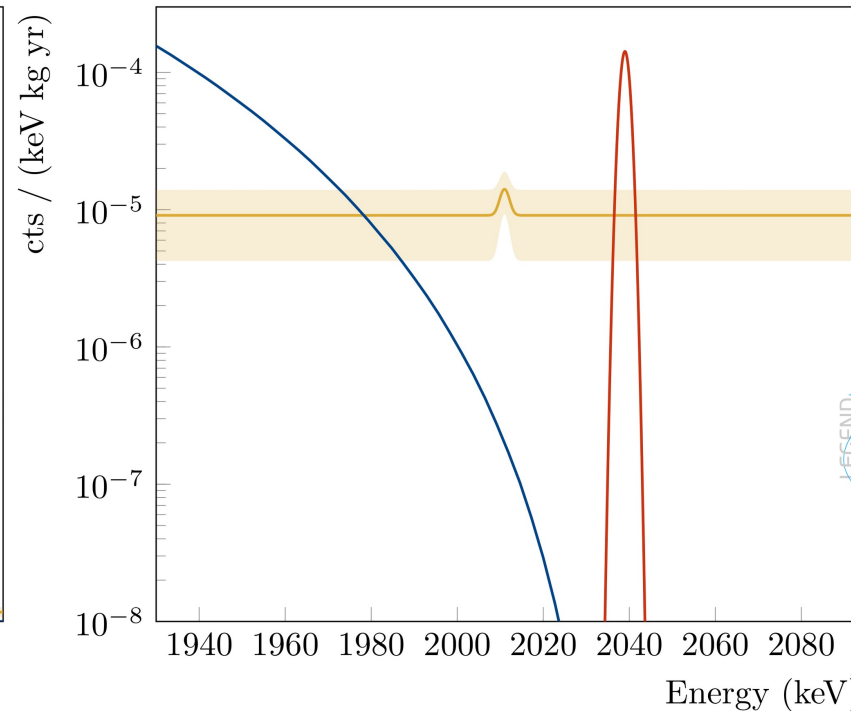
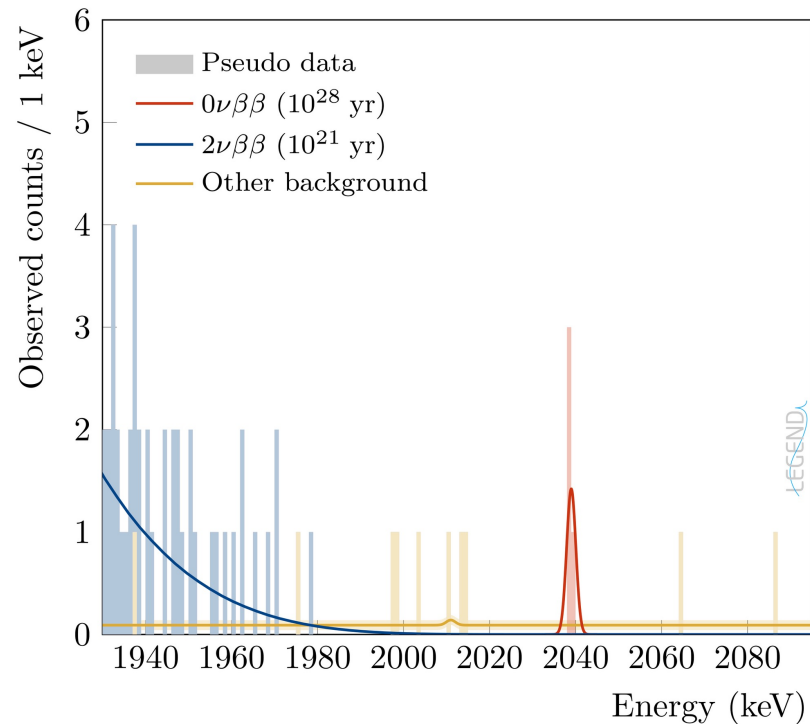


Our background goal:

1×10^{-5} counts / (keV kg yr) $\rightarrow$ < 1 count in 10 years of measurement

$\rightarrow$ “Quasi background free”

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



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

Planned staged
commissioning ~ 2030