Searching for matter creation via neutrinoless double beta decay

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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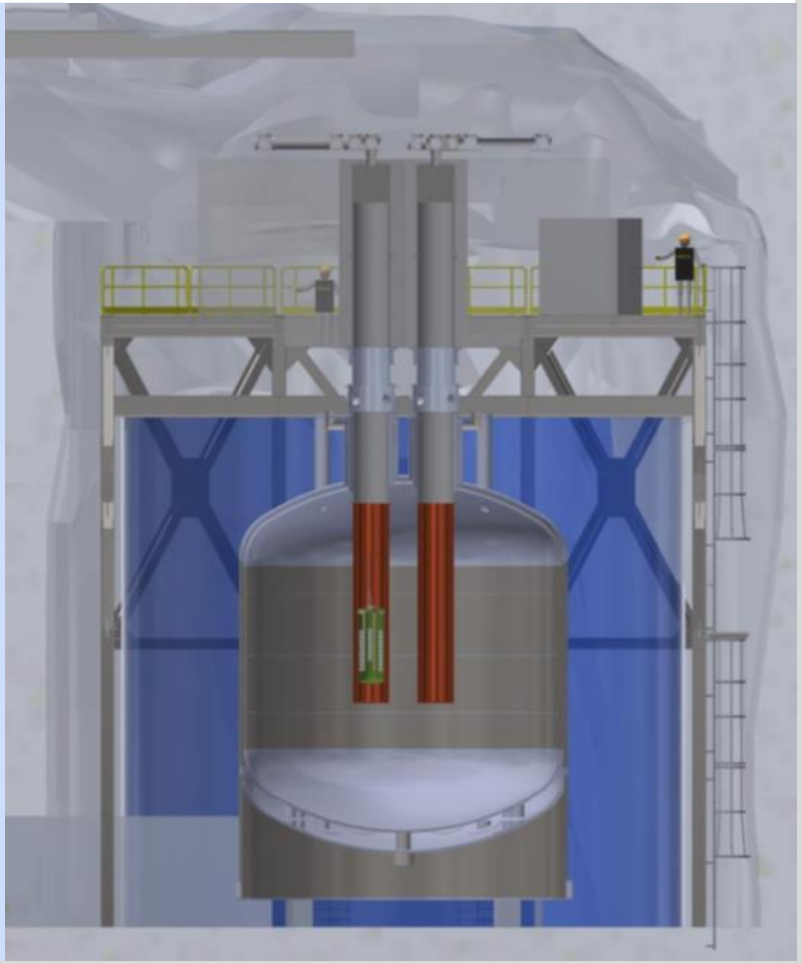
on behalf of the LEGEND collaboration



University of Zurich UZH

June 12th, 2023
PPC2023, Daejeon, South Korea

Why is there matter but no antimatter?

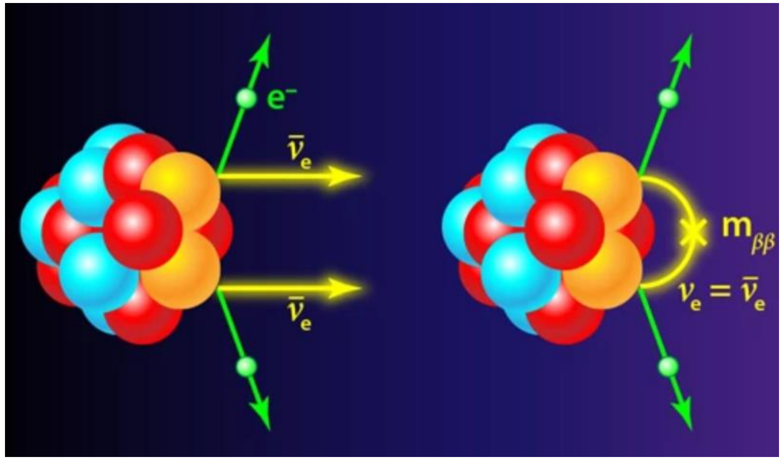
Ref.: https://www.astronomy.com/science/one-third-of-humanity-cant-see-the-milky-way/

Double beta decay

Double beta decays:

$$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e, \quad \Delta L = 0$$

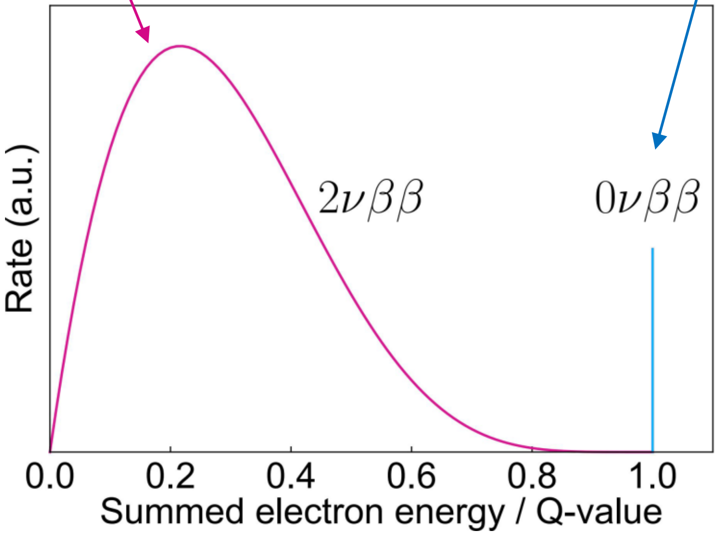
$$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-, \quad \Delta L \neq 0$$



Event signature:

Continuous broad spectrum

Peak at $Q_{\beta\beta}$



$0\nu\beta\beta$ observations:

- Lepton number violation $\Delta L = 2$
- Neutrinos have a Majorana mass
- Information about matter asymmetry

Standard mechanism: light neutrino exchange

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

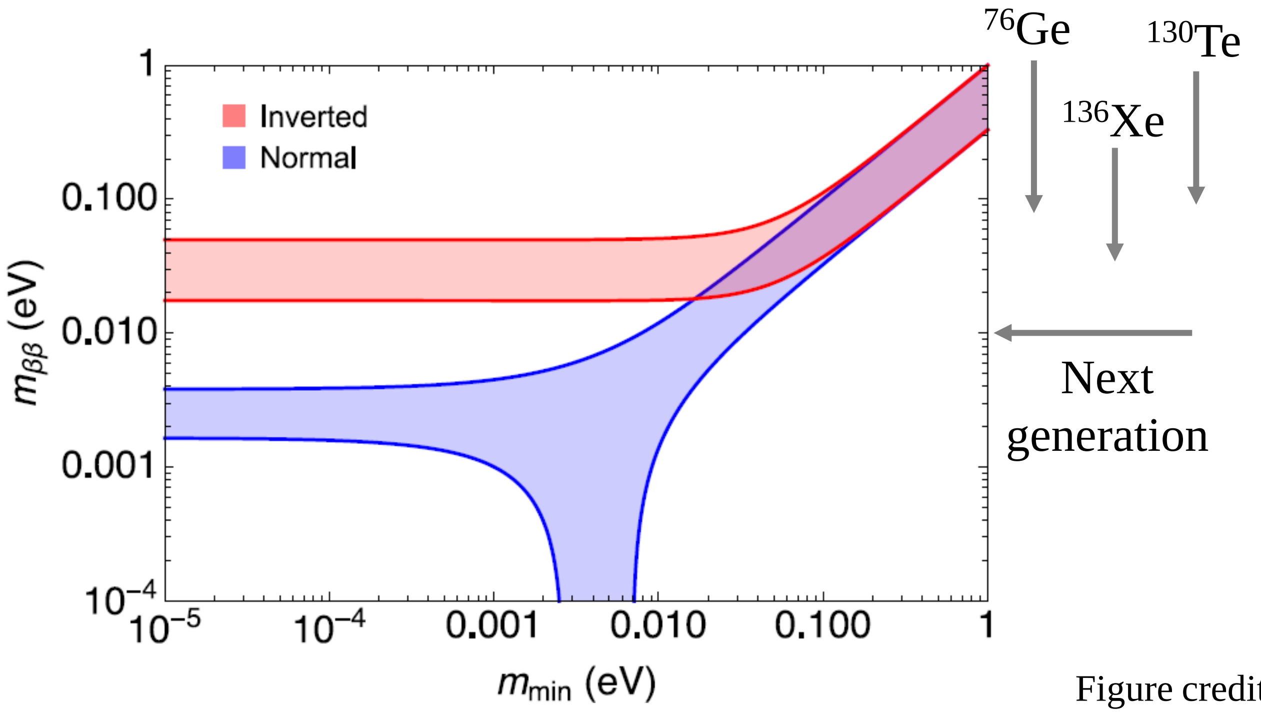


Figure credit: J. Huang

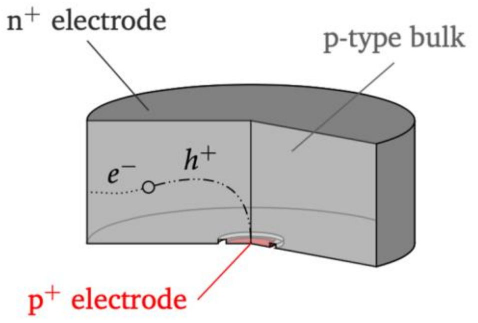
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} \left|U_{ei}^2\right| e^{i\varphi_i} m_i \right|$$

φ: Majorana phases

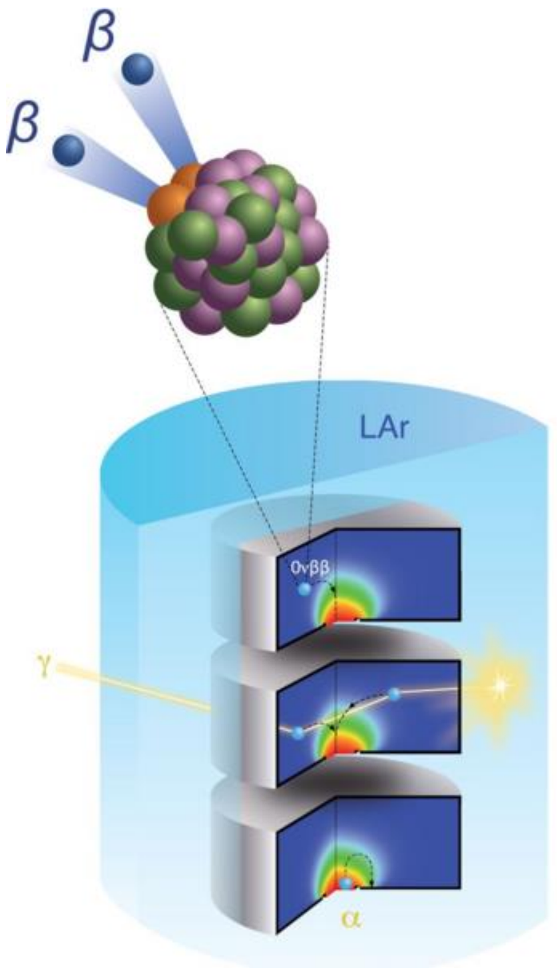
0νββ of ^{76}Ge

Why germanium? $$^{76}\mathrm{Ge} \longrightarrow {}^{76}\mathrm{Se} + 2e^- \; (+2\bar{\nu}_e)$$

- Source = detector → excellent detection efficiency (e.g., ~100% in the active volume)
- Commercial, semiconductor detectors made from high-purity germanium (HPGe) material



- Enrichment in ^{76}Ge isotope at the level of > 90% is possible
- Best energy resolution of any ββ detector (e.g., 2.52 keV FWHM at $Q_{\beta\beta}$ from the MAJORANA DEMONSTRATOR)



Ref.: M. Agostini et al., Science 10.1126/science.aav8613 (2019)

0νββ decay life-time

Half-life sensitivity

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

$$T_{1/2} \propto f\epsilon Mt$$ (background free)

f : ^{76}Ge enrichment fraction
ϵ : Detection efficiency
M : HPGe mass
t : Measurement time
} Mt: Exposure
B : Background index = counts / (energy mass time)
σ_E : Energy resolution at $Q_{\beta\beta}$

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)

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

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

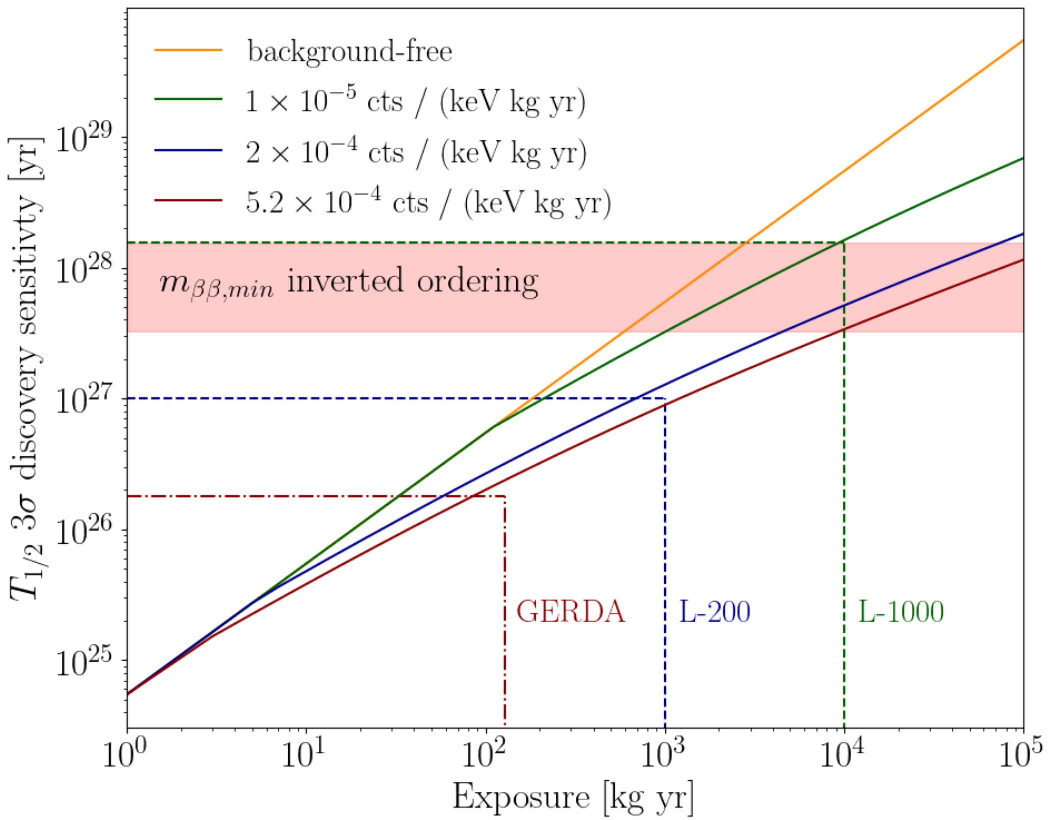
Refs.: MAJORANA Collab., PRL130, 062501 (2023)

Large
Enriched
Germanium
Experiment for
Neutrinoless double-beta
Decay

The LEGEND project

"The collaboration aims to develop a phased, ^{76}Ge-based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years..."

- **LEGEND-200**
  - 200 kg of enriched ^{76}Ge detectors
  - $B \sim 2 \times 10^{-4}$ counts/(keV·kg·yr)
  - $T_{1/2} > 10^{27}$yr (5 yr of run time) (99.7% C.L.) → $m_{\beta\beta} < 33 - 71$ meV
- **LEGEND-1000**
  - 1 tonne of enriched ^{76}Ge detectors
  - $B < 10^{-5}$ counts/(keV·kg·yr)
  - $T_{1/2} > 10^{28}$yr (10 yr of run time)
  - Cover full $m_{\beta\beta}$ inverted ordering regime

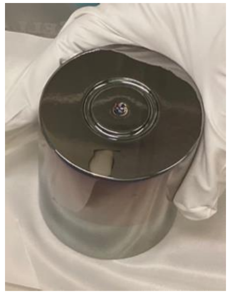


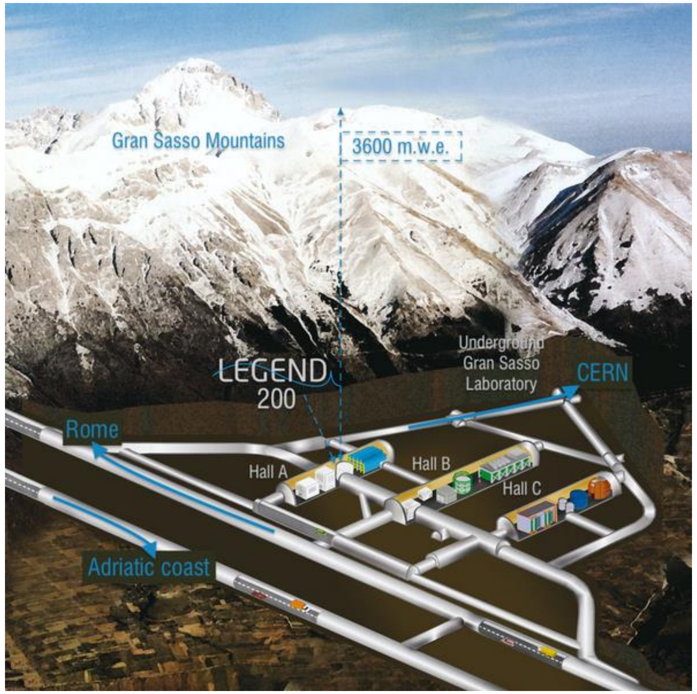
Refs.: GERDA Collab., PRL 125, 252502 (2020)
LEGEND Collab., arXiv:2107.11462

LEGEND-200

- Locates underground (3500 m.w.e.) at Laboratori Nazionali del Gran Sasso, Italy
- Reuses detectors from GERDA and MJD + 140 kg of additional ***inverted-coaxial point-contact (ICPC)*** detectors:
  - Active mass > 3 kg achievable
  - Excellent pulse shape discrimination performance
- Current status:
  - Consists 101 detectors with a total mass of ~ 142 kg
  - Started physics data-taking in spring 2023

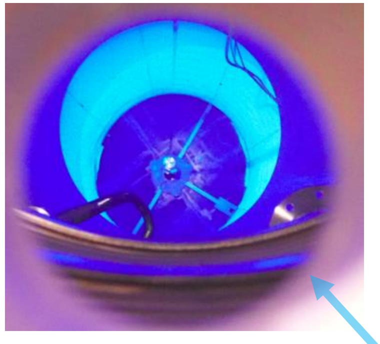
ICPC detector



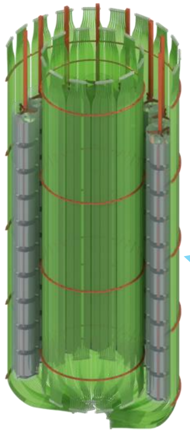


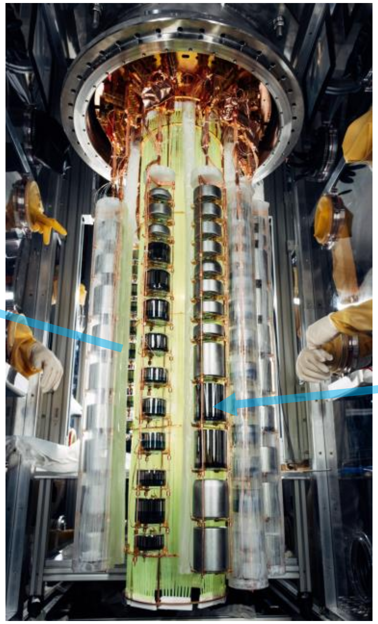
Experimental apparatus

Wavelength-shifting reflector:
Tetratex® coated with
tetraphenyl butadiene (TPB)

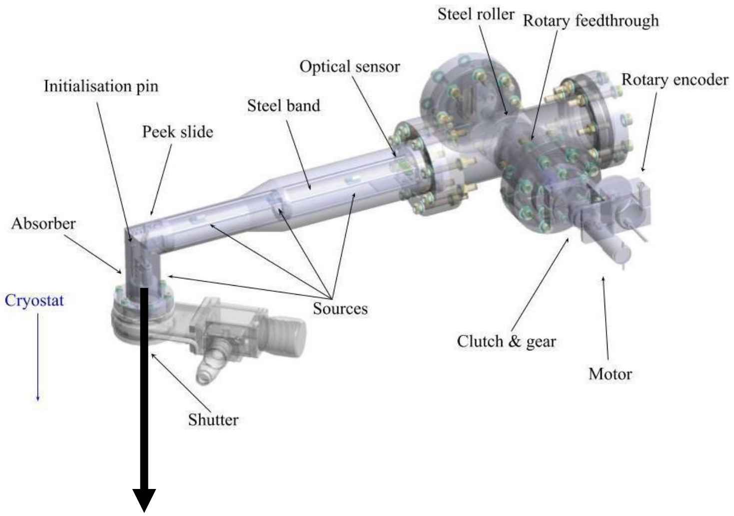


Wavelength-shifting
(inner/outer) fiber shrouds

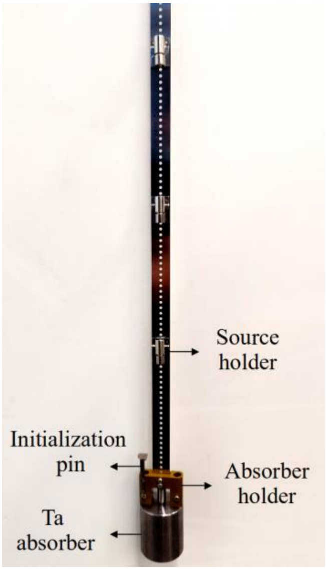


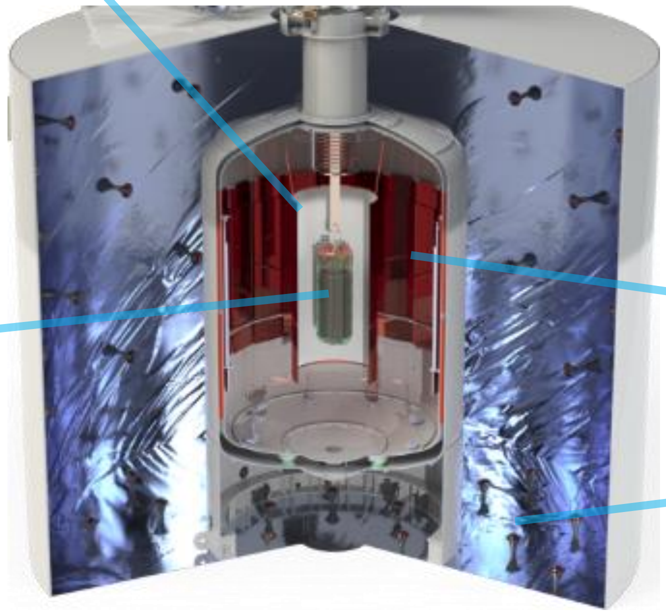


Detector array:
101 detectors distributed
into 10 strings



Calibration system



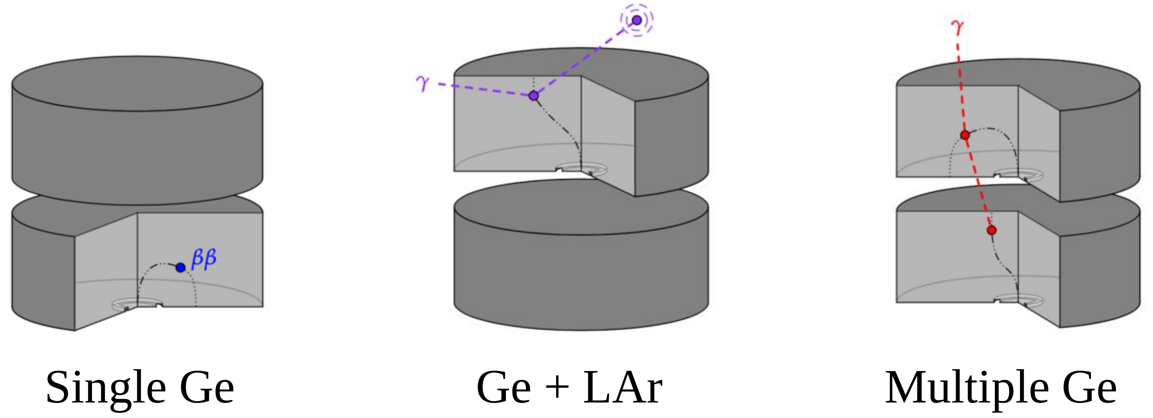


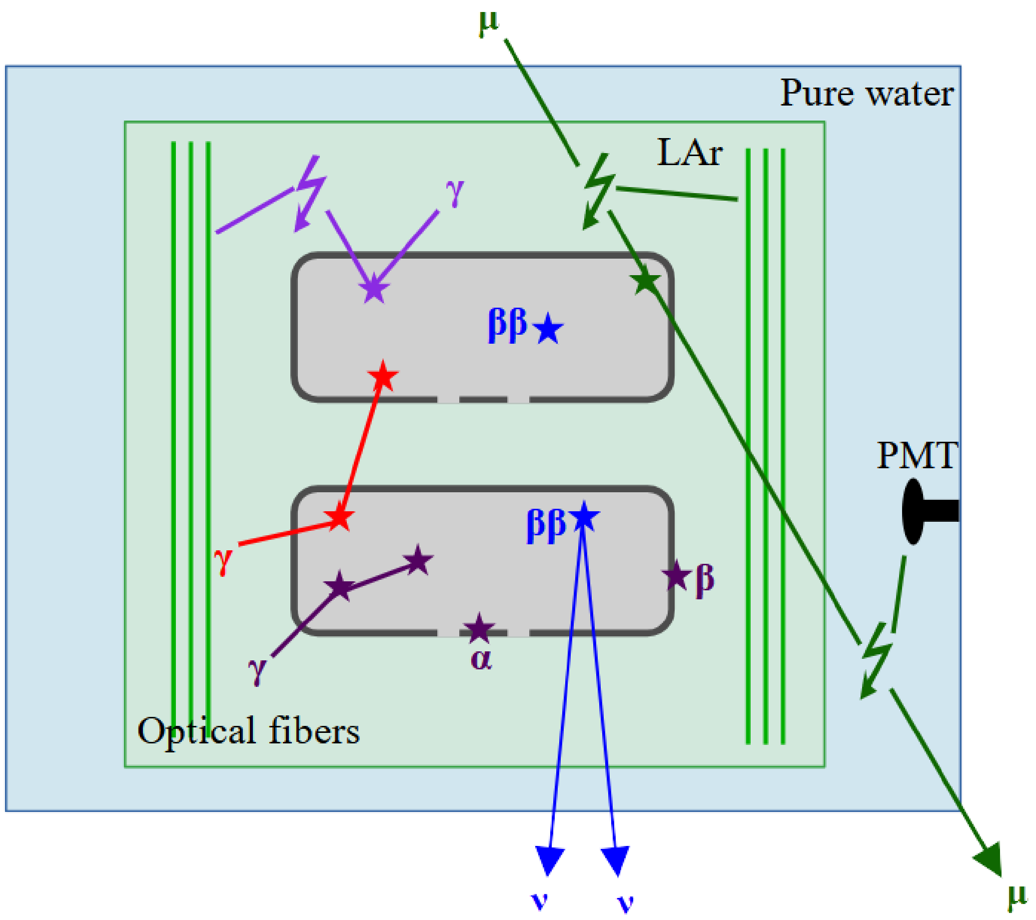
LAr cryostat and
veto system

Water tank with
PMTs installed within

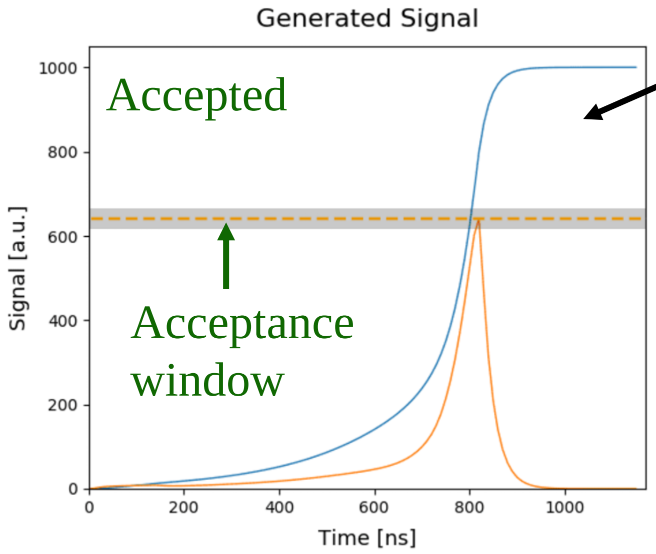
Background reduction

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

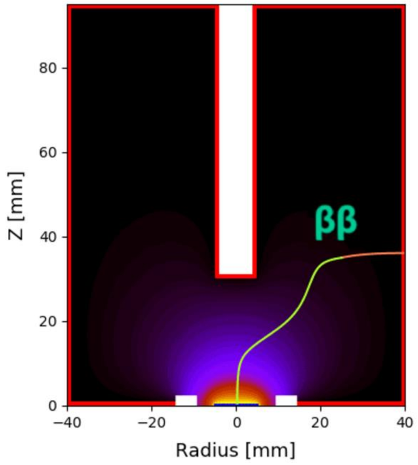




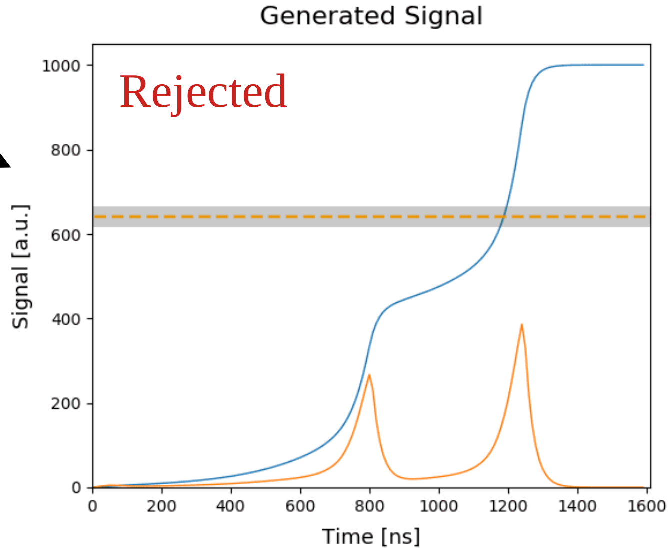
Pulse shape discrimination



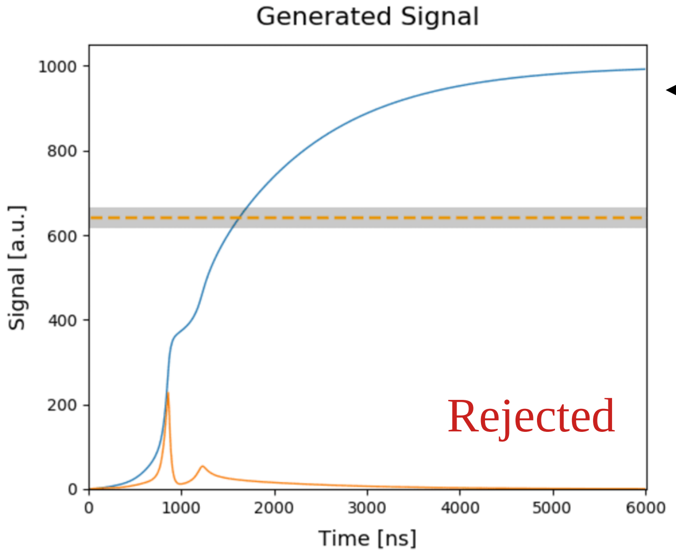
ββ signal (SSE)



γ background (MSE)

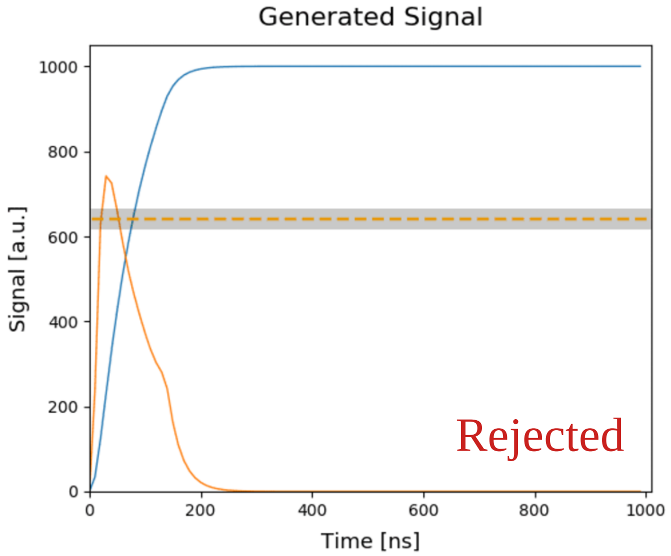


Charge signal
Current signal



β background on n+ contact

α background on p+ contact

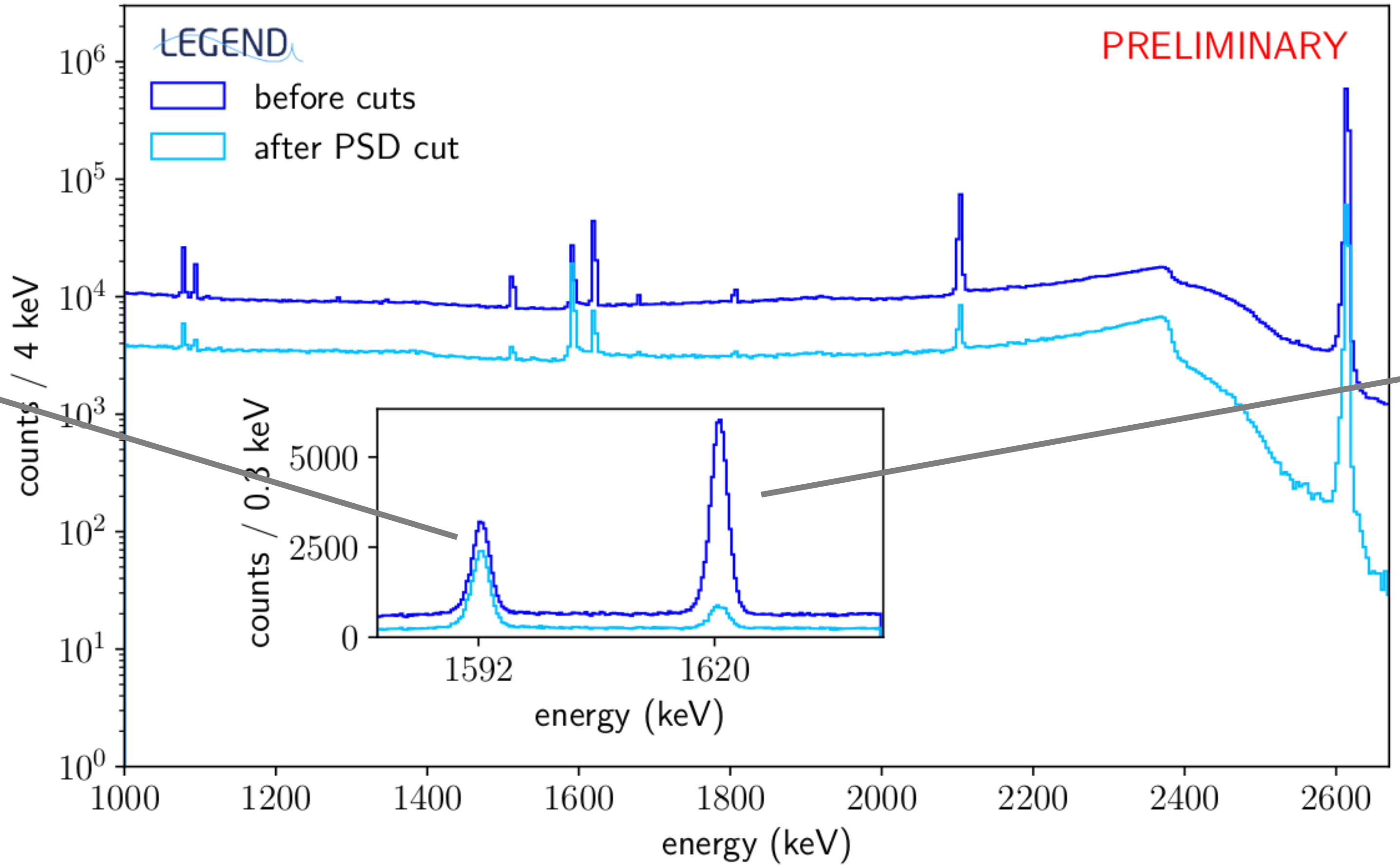


Refs.: S. Schönert, North America - Europe Workshop on Future of Double Beta Decay (2021)
GERDA Collab., EPJC 82, 284 (2022)
M. Agostini et al., EPJC 73, 2583 (2013)

Energy spectrum of calibrations

- Energy spectrum using ^{228}Th as calibration sources
- Pulse-shape discrimination (PSD) is nicely preserving the single-site events while supressing the multi-site events

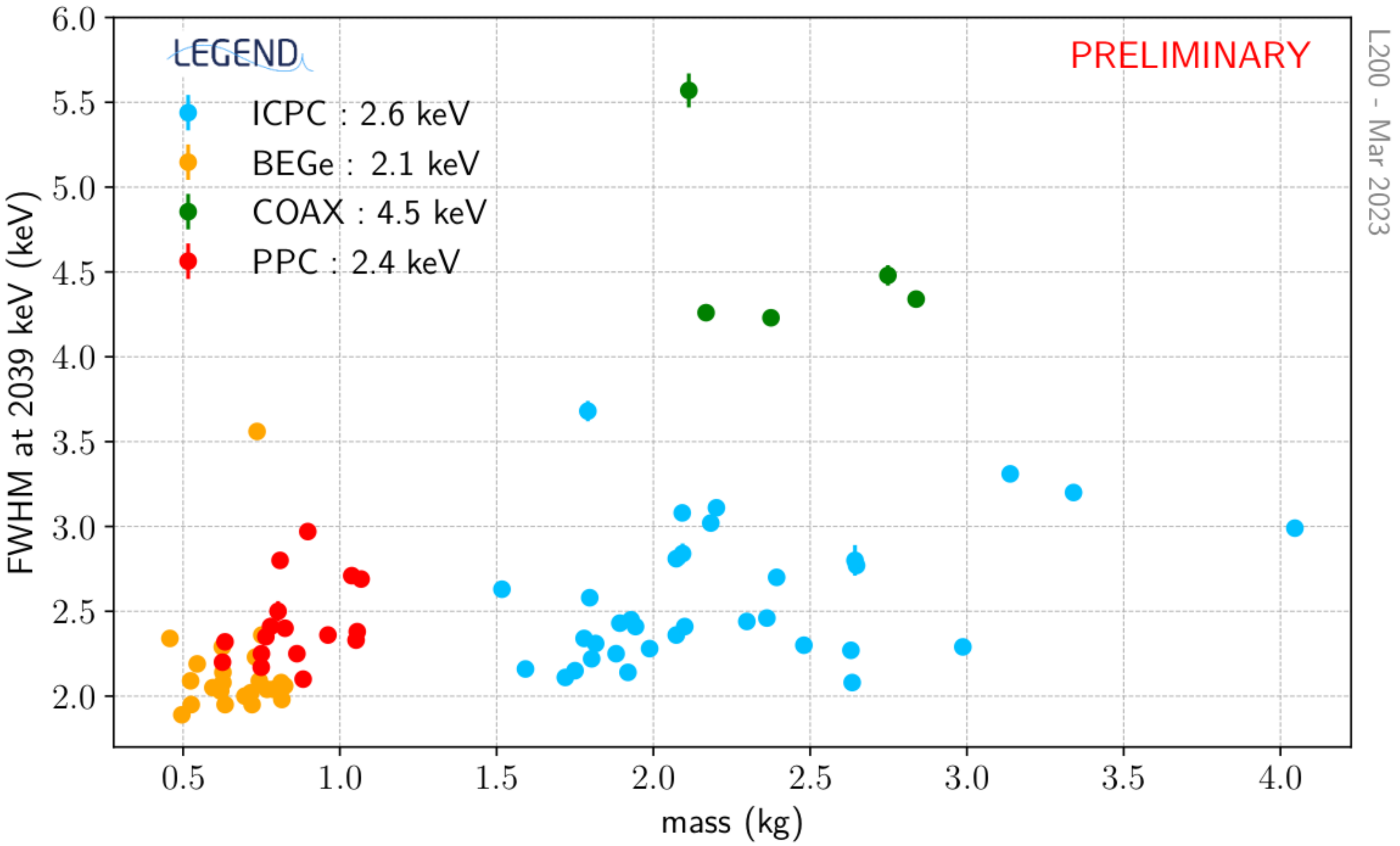
Double-escape peak of ^{208}Tl (single-site event)



Full energy peak of ^{212}Bi (multi-site event)

Detector energy resolutions

- Energy resolutions of all detectors
  - are between 2.1 to 4.5 keV for different detectors
  - do not depend on mass

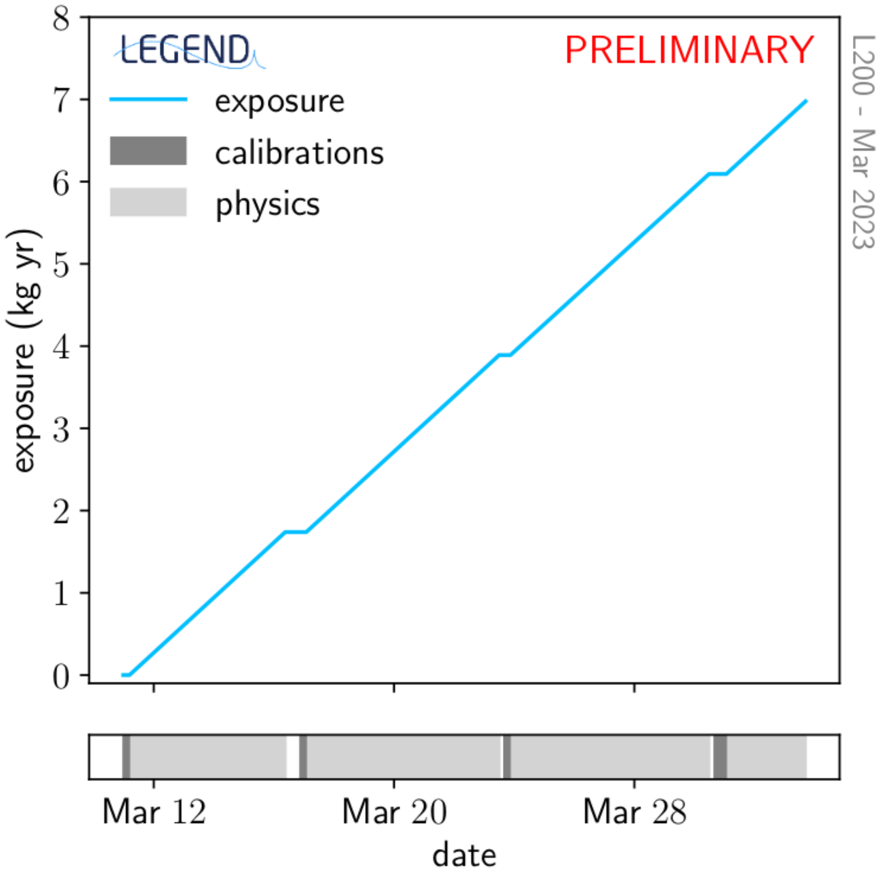


Pin-Jung Chiu | PPC2023 Daejeon | 2023.06.12.

Where do we stand now?

- Will take physics data for ~ 1 yr with 142 kg of detectors; afterwards, install more detectors to ~ 200 kg
- Requires only ×2–3 background improvement w.r.t. GERDA (B from 5.2×10^{-4} to 2×10^{-4} counts/(keV·kg·yr))
- Goal:
  reach a discovery sensitivity of $T_{1/2} > 10^{27}$ yr with 1 tonne·yr of exposure (~ 5 yr)

Photo: Enrico Sacchetti

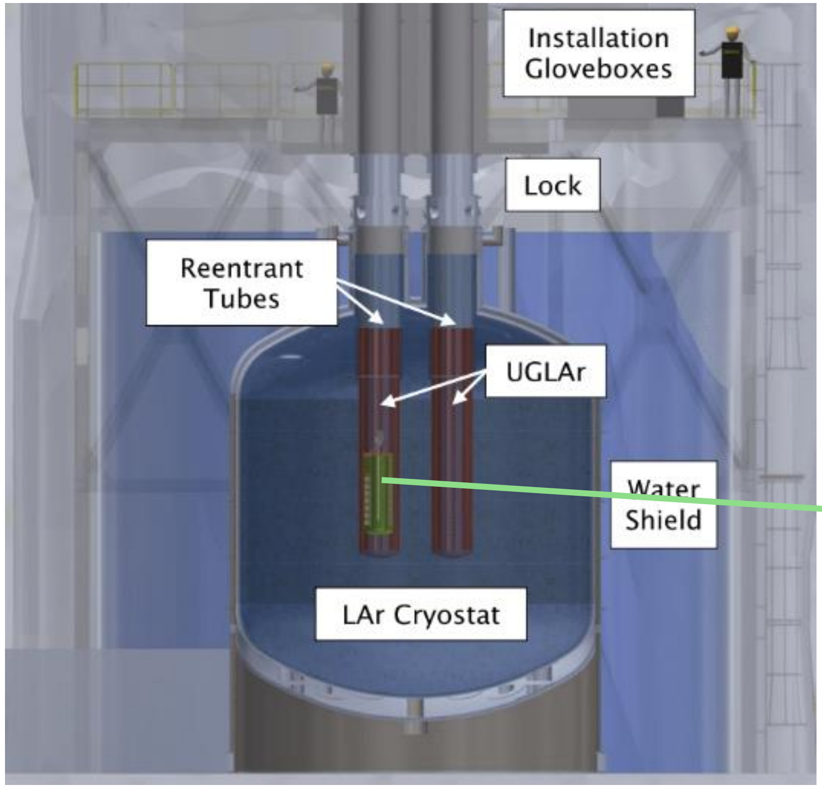


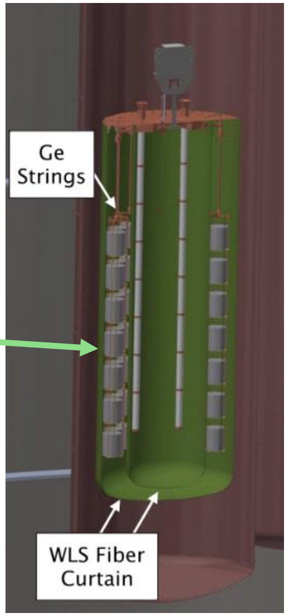
From LEGEND-200 towards LEGEND-1000

LEGEND-1000 (proposed design)

- A total of ~1000 kg of ^{76}Ge detectors (ICPC detectors enrichment up to 92%)
- Experimental site and detector array design to be determined
  - SNOLAB (CA): four, 250-kg modules
  - LNGS (IT): single reentrant tube (ϕ = 1.9 m) with > 50 strings
- Background improvement of ~ ×20 ($B < 10^{-5}$ counts/(keV·kg·yr) w.r.t. LEGEND-200:
  - Radiopure *underground argon* (UGLAr) provides direct mitigation of ^{42}K background
- Many R&D projects on-going:
  - Increasing Ge detector mass
  - Neutron moderator in LAr
  - Polyethylene naphthalate (PEN) as wavelength-shifting materials for LAr scintillation

- Planned staged commissioning ~ 2030
- Goal:
  reach a discovery sensitivity of $T_{1/2}$ > 10^{28} yr (99.7% C.L.) with 10 tonne·yr of exposure (10 yr runtime)





Ref.: LEGEND Collab., arXiv:2107.11462

Summary

- Majorana neutrinos may solve several fundamental issues in particle physics and cosmology:
  - Origin of neutrino mass, mass scale, and ordering
  - Matter-antimatter asymmetry
- $0\nu\beta\beta$ is a promising probe → HPGe approach provides **excellent energy resolution** and **low background**
- LEGEND-200 has started taking data in spring 2023
- Tonne-scale LEGEND-1000 will reach a discovery sensitivity of $T_{1/2} > 10^{28}$ **yr**, aiming to cover the inverted mass ordering regime

Thank you for your attention ~

The GERmanium Detector Array

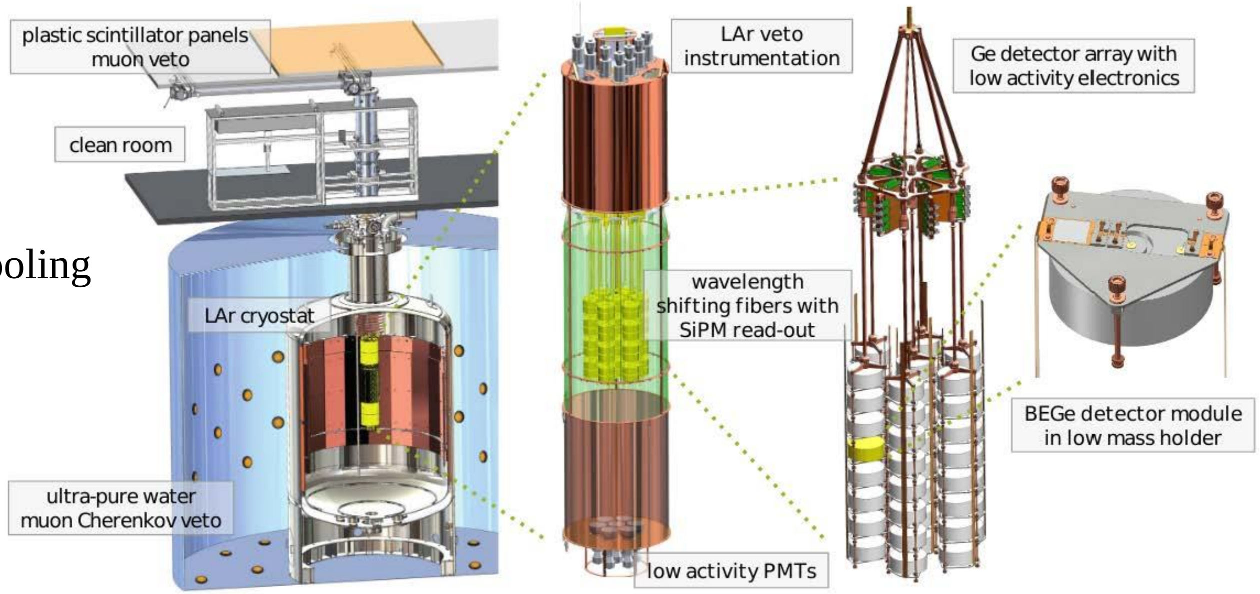
- Underground at Laboratori Nazionali del Gran Sasso (LNGS) of INFN, Italy:
  - 1400 m rock overburden (3600 m.w.e.): reduces cosmic muons by $\mathcal{O}(10^6)$
  - Ran from 2011/11 to 2019/11

Phase II+: 41 detectors (44.2 kg), enriched in ^{76}Ge up to 87%, in 7 strings

Also shield neutrons and natural radioactivity

64 m^3 LAr: shielding and cooling

590 m^3 water + 66 PMTs: residual muon veto



GERDA's final result (with 127.2 kg·yr of exposure) :

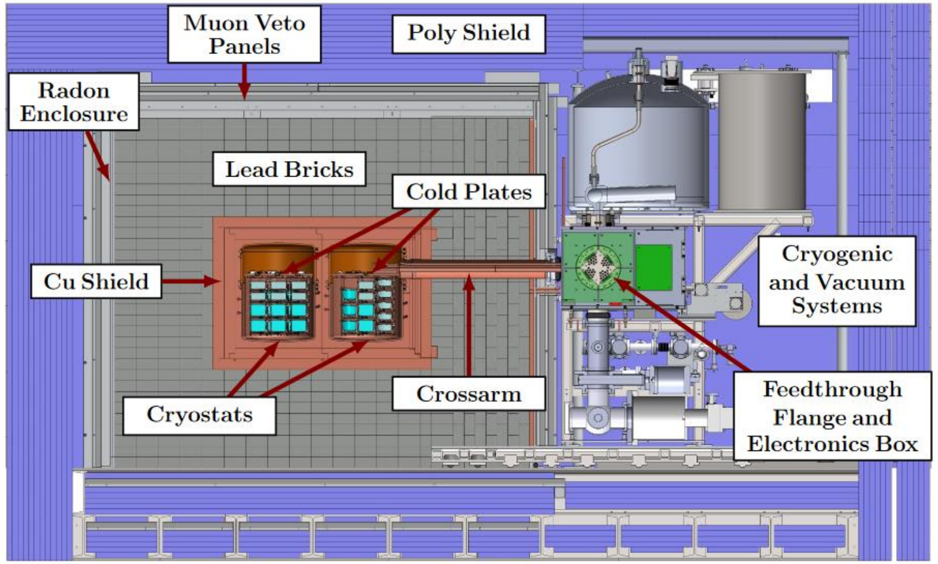
- Unprecedentedly low background index: 5.2×10^{-4} counts/(keV·kg·yr)
  → 0.3 counts in ($Q_{\beta\beta}\pm2\sigma$) for phase II (with 103.7 kg·yr of exposure)
- Half-life limit on 0νββ decay: $T_{1/2} > 1.8\times10^{26}$ yr (90% C.L.)
  → Effective Majorana neutrino mass: $m_{\beta\beta} < 79 - 180$ meV

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

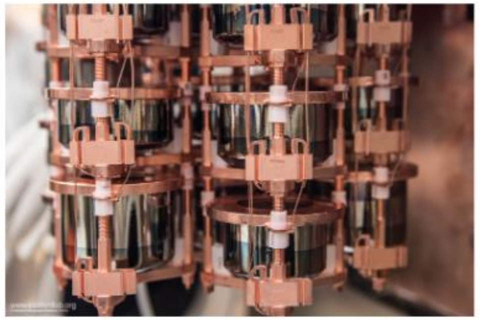
The MaJorana Demonstrator

- Located at Sanford Underground Research Facility (SURF) in Lead, South Dakota, US:
  - 1490 m rock overburden (4300 m.w.e.)
  - Ran from 2015/07 to 2018/04

Two modules each within an electroformed copper cryostat installed within a compact graded shield



44.1 kg of Ge detectors: 14.4 kg natural detectors and 29.7 kg (enriched to 88% in ^{76}Ge) p-type point contact (PPC) detectors



MJD's final result (with 64.5 kg·yr of exposure) :
- Best energy resolution in the field: 2.52 keV (FWHM) at $Q_{\beta\beta}$
- Measured background 16.6 ×10^{-3} counts / (FWHM·kg·yr)
- Half-life limit on 0νββ decay: $T_{1/2} > 8.3\times10^{25}$ yr (90% C.L.)
  → Effective Majorana neutrino mass: $m_{\beta\beta} < 113$–269 meV

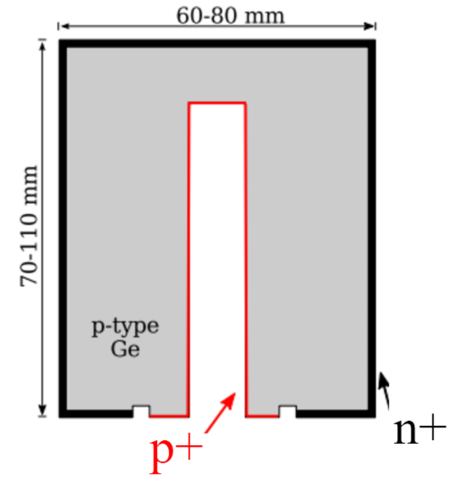
Refs. and image credit: MAJORANA Collab.
MAJORANA Collab., PRL130, 062501 (2023)
MAJORANA Collab., JINST, 17, T05003 (2022)
MAJORANA Collab., PRC 100, 025501 (2019)

Detector types

Refs.: S. Schönert, North America - Europe Workshop on Future of Double Beta Decay (2021)
T. Comellato et al., EPJC 81, 76 (2021)
M. Agostini et al., EPJC 74, 2764 (2014)

- P-type detectors: insensitive to alphas on n^+ contact
- Small p^+ contact: event topology discrimination
- Large-mass ICPC detectors: ~ ×4 lower backgrounds w.r.t. BEGe/PPC
- Proven long-term stable operation in LAr

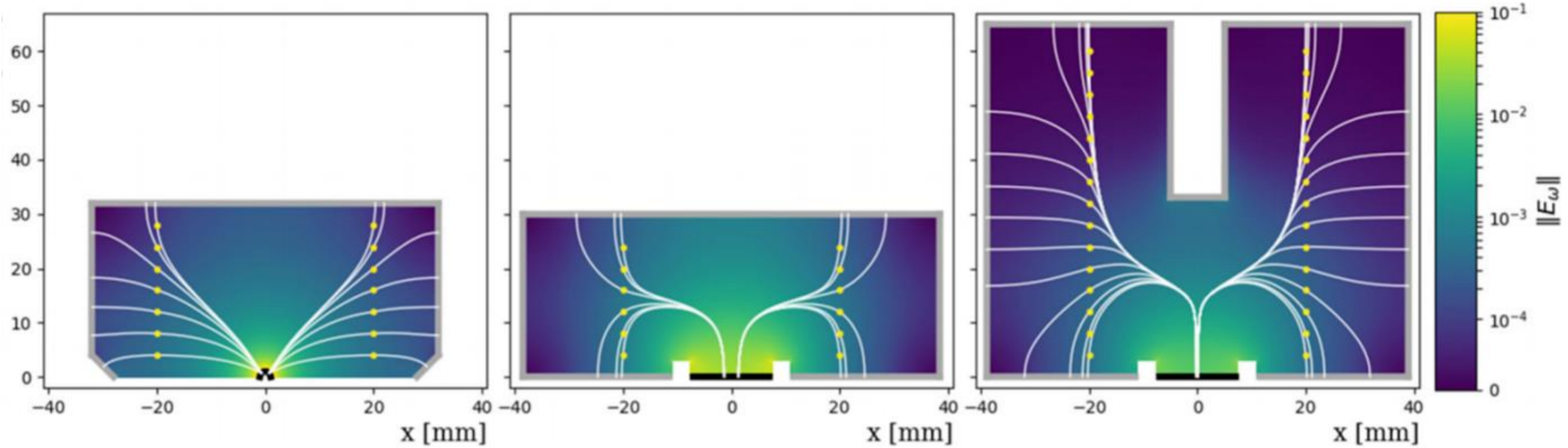
GERDA (Coax)

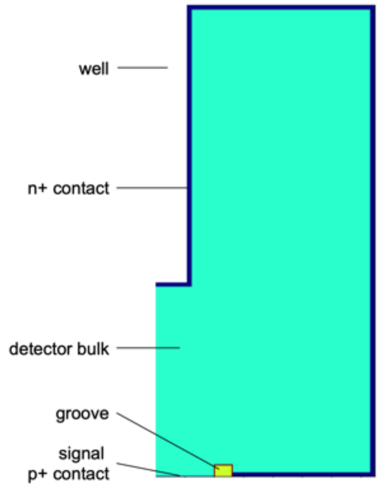


MJD (PPC)
P-type Point Contact

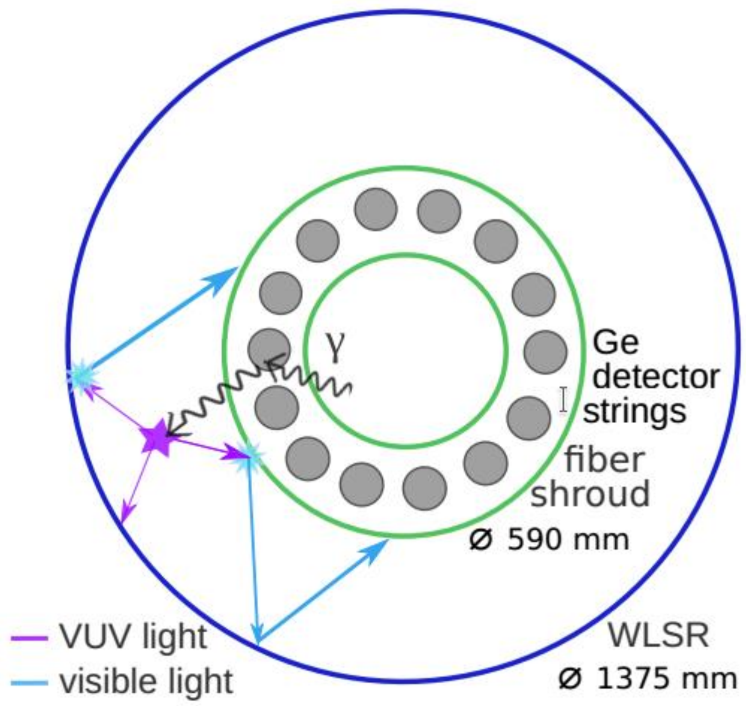
GERDA (BEGe)
Broad Energy Germanium

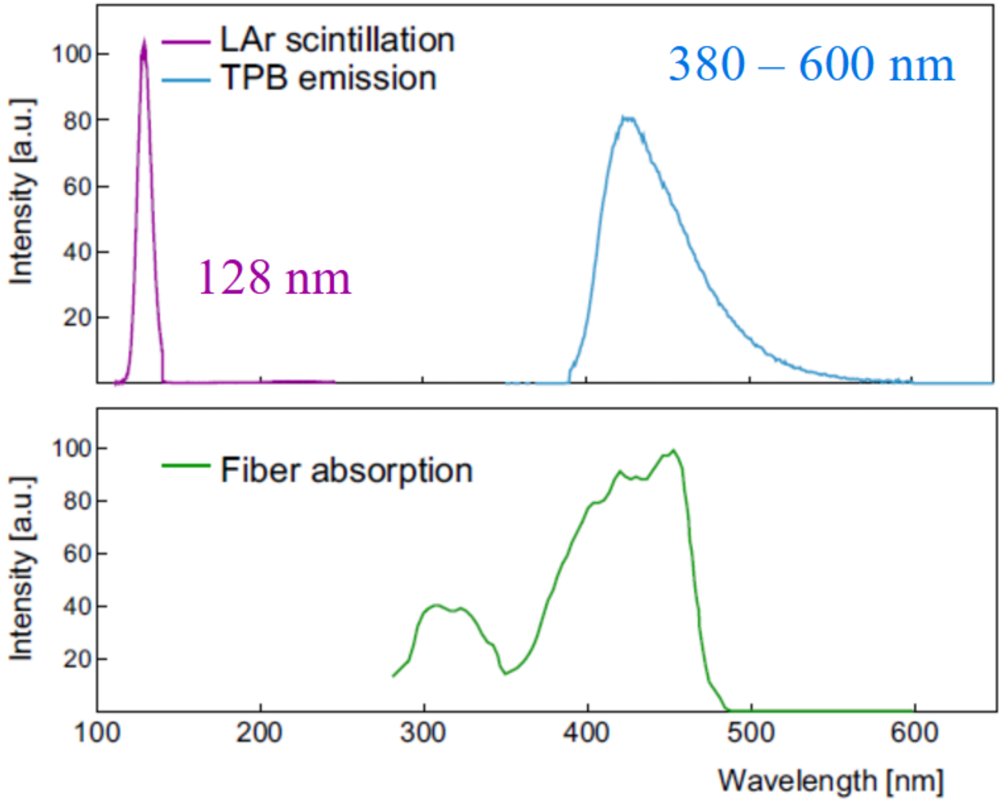
LEGEND (ICPC)
Inverted-Coaxial p-type Point Contact





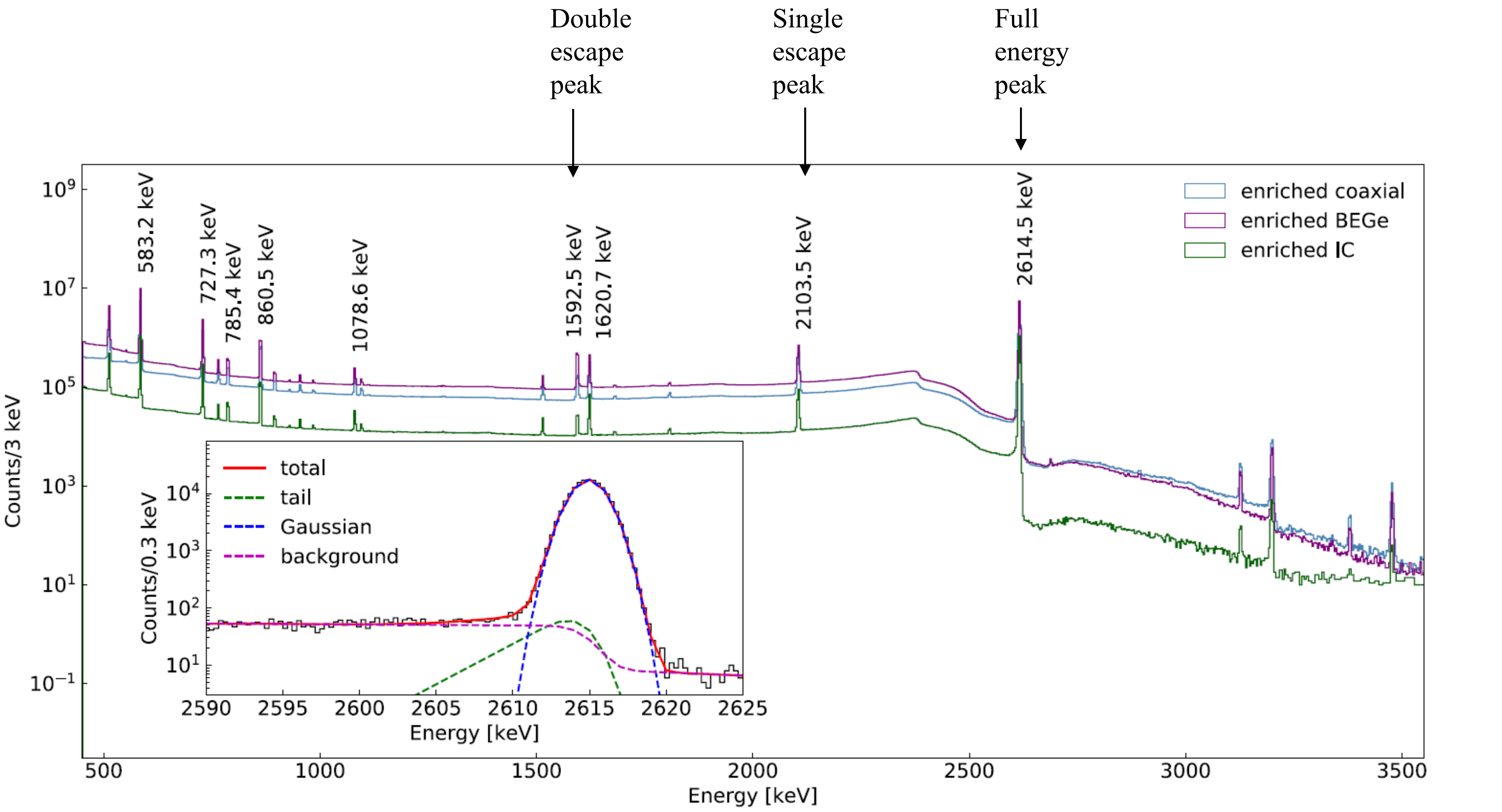
Wavelength shifter





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

Energy calibration with ^{228}Th



Ref.: GERDA Collab., EPJC 81, 682 (2021)

Muon flux from various underground labs

- Waste Isolation Pilot Plant (WIPP), United States:Store transuranic radioactive waste
- Soudan underground lab, United States:E.g., MINOS, CDMS, NOvA
- Kamioka observatory, Japan:E.g., Super-K, T2K, KamLAND
- Boulby underground lab, United Kingdom: E.g., material screening, dark-matter search
- LNGS, Gran Sasso, Italy:E.g., LEGEND-200, XENON, Borexino
- Sanford underground research facility (SURF), Homestake, United States:E.g., LUX, MJD
- Laboratoire Suoterrain de Modane (LSM), Fréjus, France:E.g., NEMO, EDELWEISS
- Sudbury neutrino observatory, Canada:E.g., SNO+, DEAP-3600

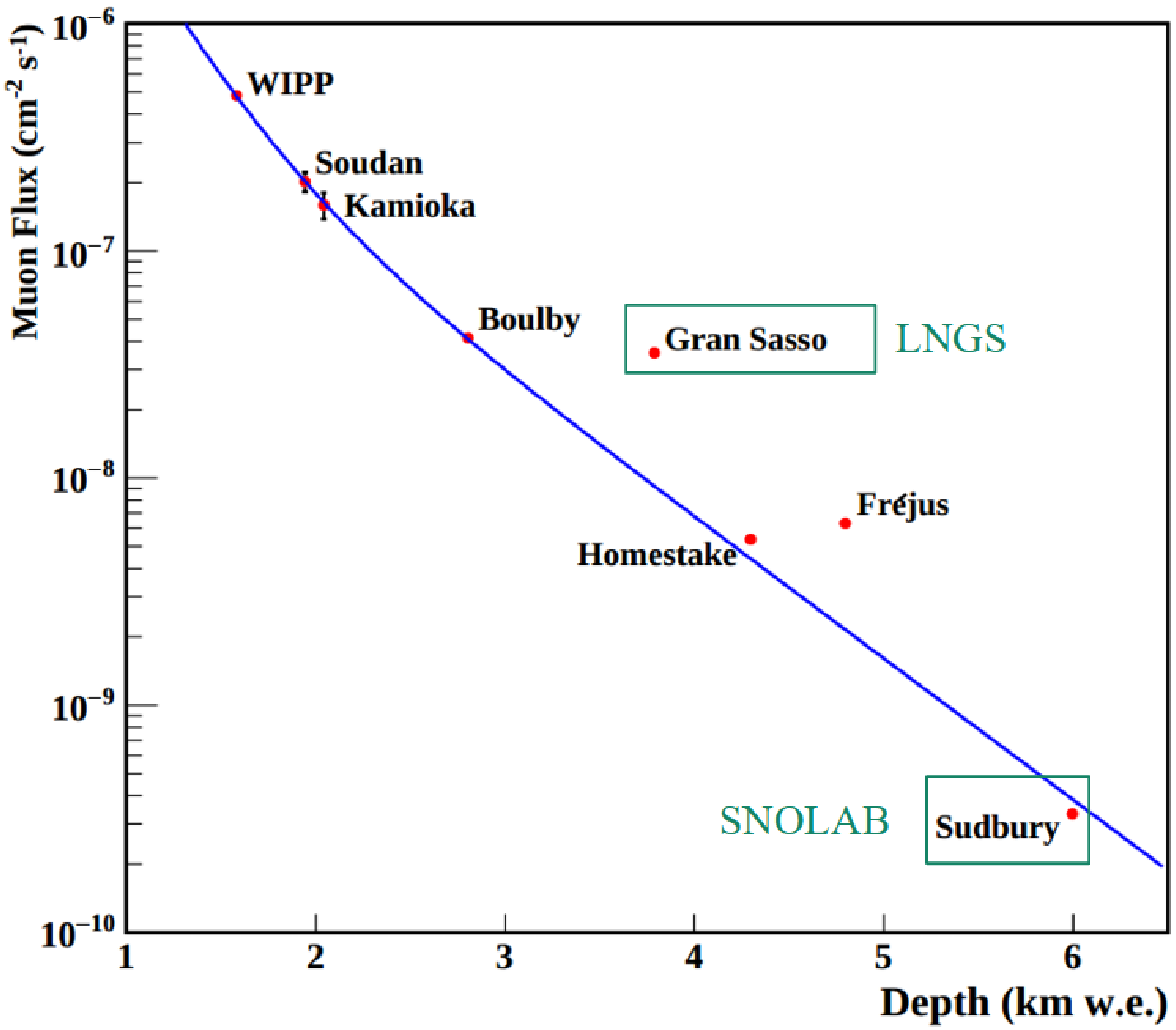


Image credit: J. J. Cuenca-García, (2022)
Ref.: D.-M. Mei and A. Hime, PRD 73, 053004 (2006)

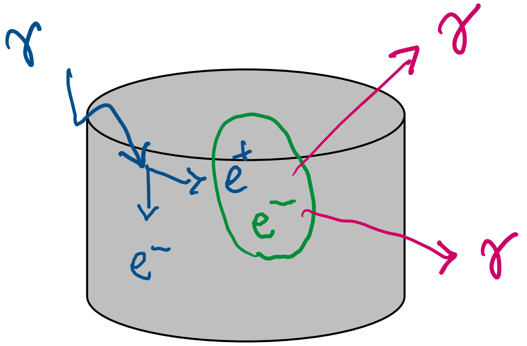
Majorana mass and mass ordering

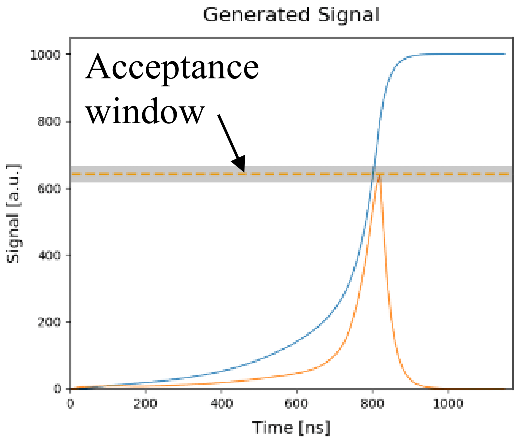
Isotope	Experiment	Year	$T_{1/2}$ limit	$m_{\beta\beta}$ (meV)	Ref.
^{76}Ge	Majorana Demonstrator	2023	8.3×10^{25}	113–269	[1]
^{76}Ge	GERDA	2020	1.8×10^{26}	79 – 180	[2]
^{136}Xe	KamLAND-Zen	2022	2.3×10^{26}	36 – 156	[3]
^{136}Xe	EXO-200	2019	3.5×10^{25}	93 – 286	[4]
^{130}Te	CUORE	2022	2.2×10^{25}	90 – 305	[5]

Refs.: [1] MAJORANA Collab., PRL130, 062501 (2023)
[2] GERDA Collab., PRL 125, 252502 (2020)
[3] KamLAND-Zen Collab., PRL 130, 051801 (2023)
[4] EXO-200 Collab., PRL 123, 161802 (2019)
[5] CUORE Collab., Nature 604, 53–58 (2022)

Why do we use ^{228}Th as the source?

- ^{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 pulse shape discrimination (PSD) technique

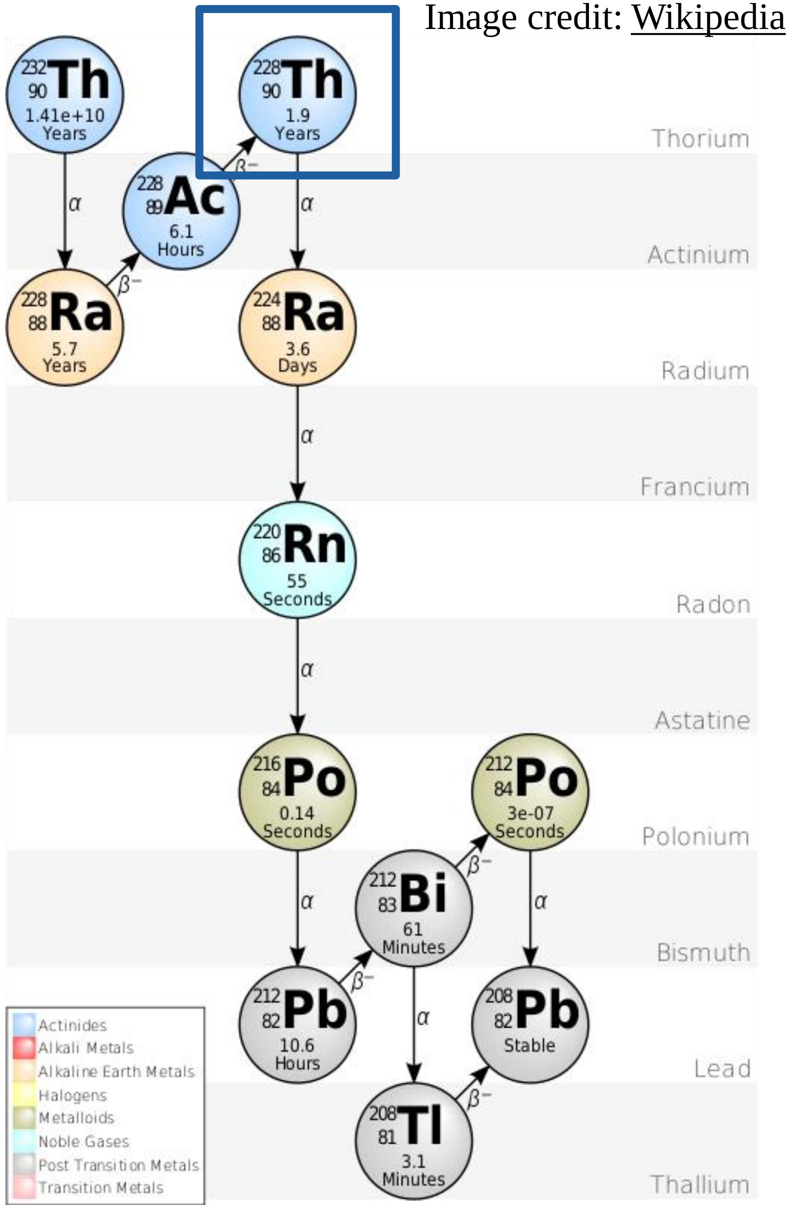




Charge/current signals

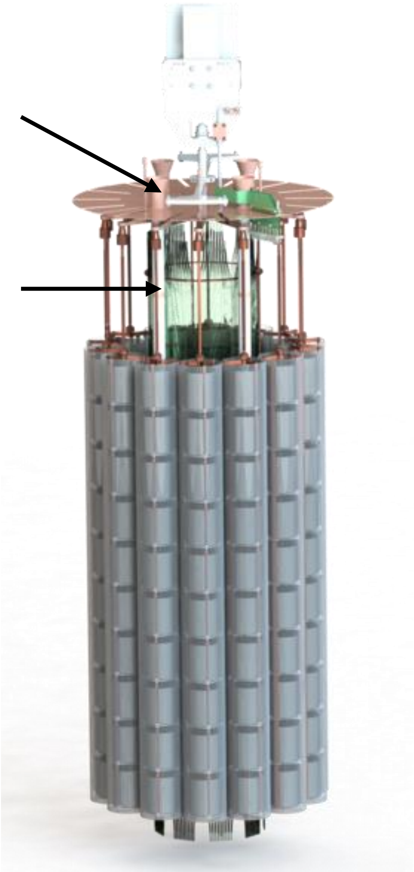
- The more abundant and cheaper ^{232}Th would also provide the same γ lines. However, its progeny ^{228}Ac emits a γ with an energy of 1588.2 keV, which would partially overlap with the ^{208}Tl DEP and could spoil the PSD calibration

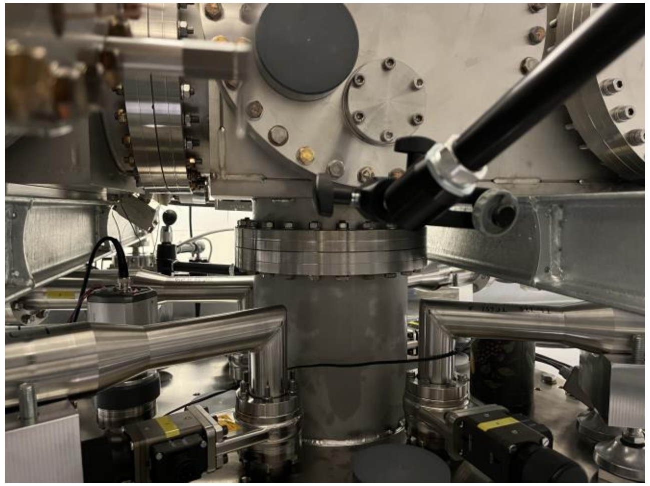
Image credit: Wikipedia

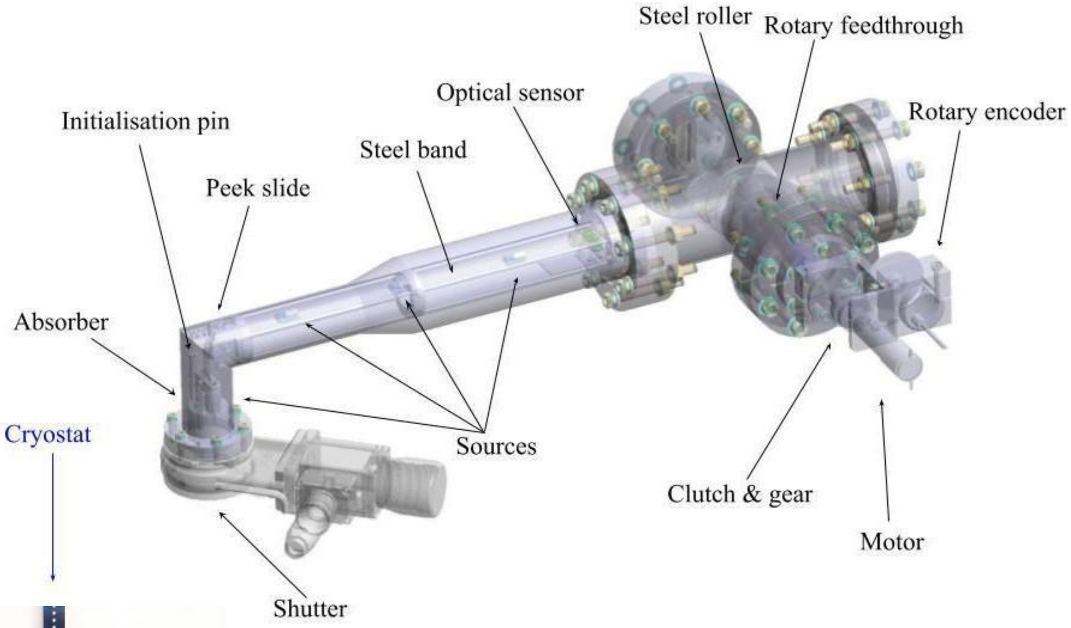


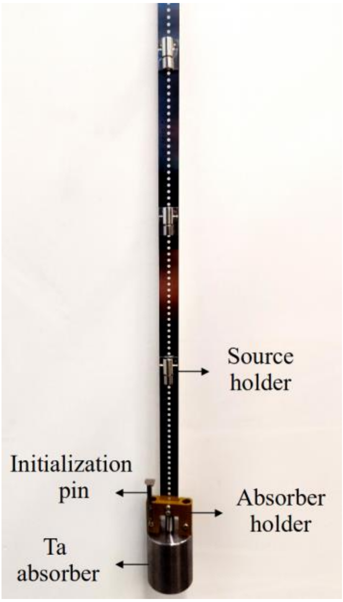
Calibration system

Follows the concept of the GERDA's source insertion system four calibration systems are installed above the cryostat







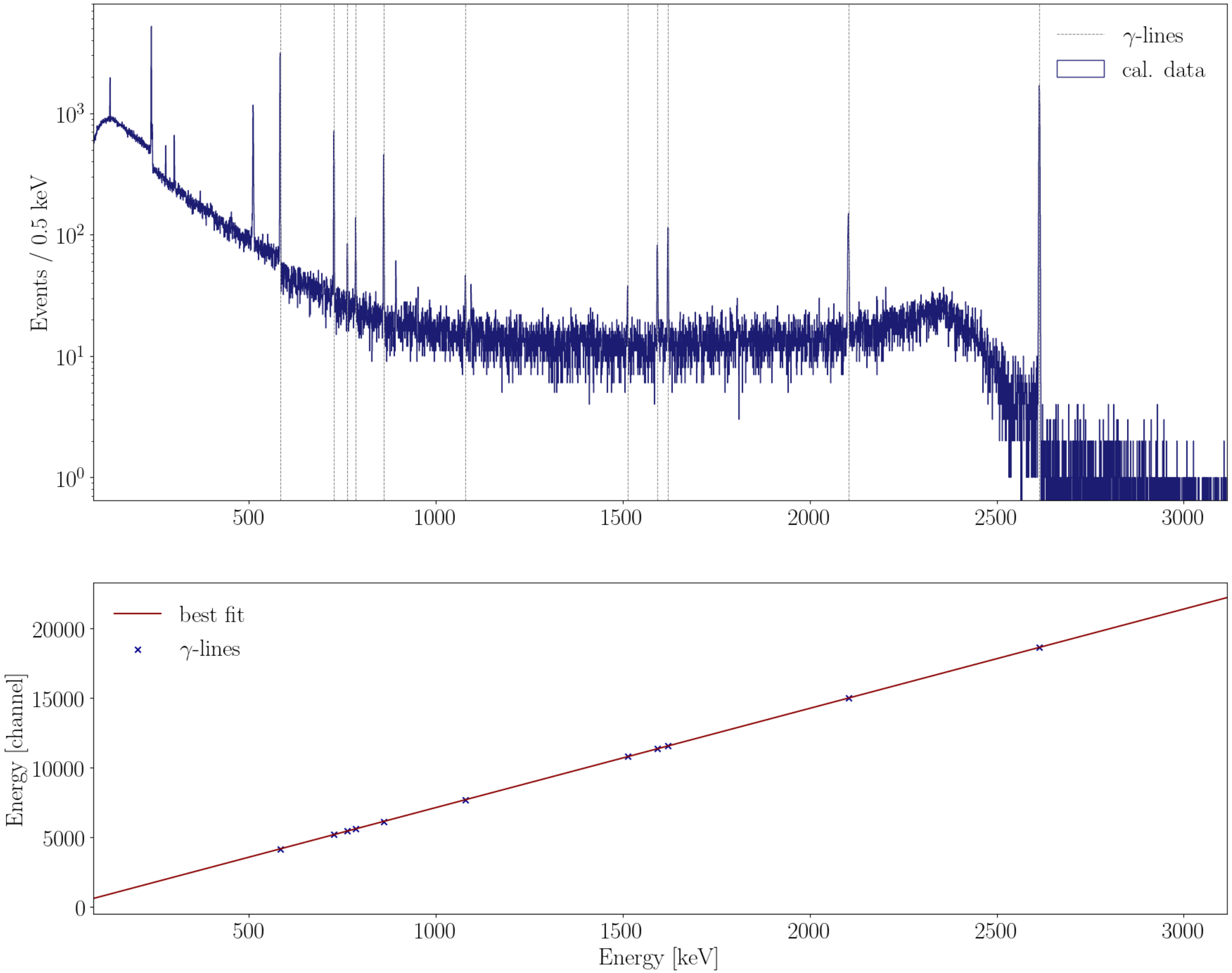


Multiple sources per system

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

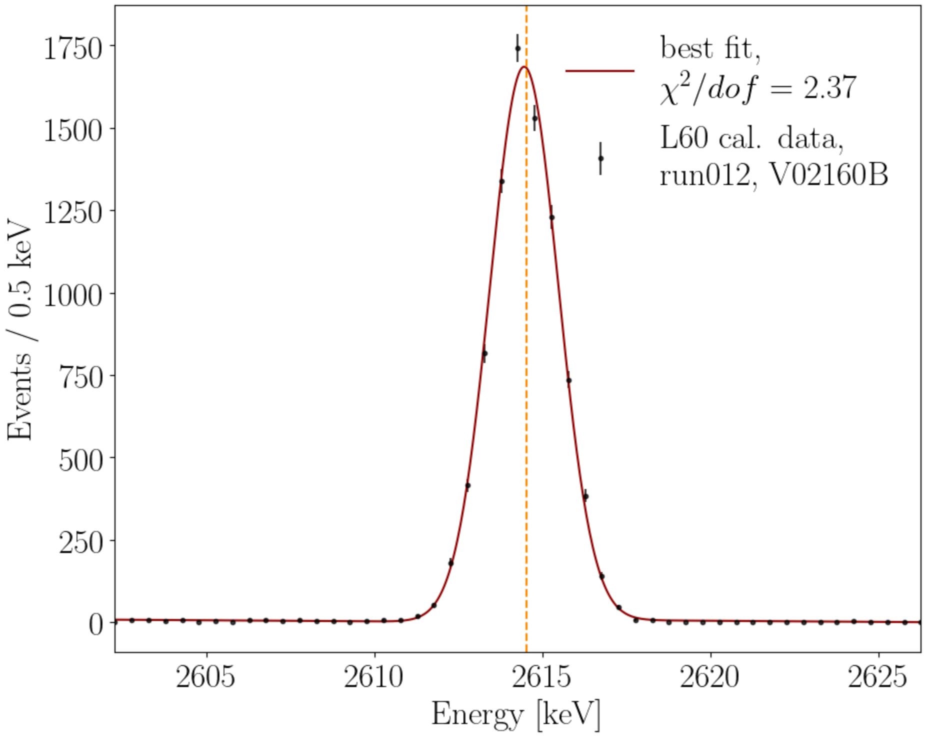
Calibration procedure (1) — energy scale

- Use a "peak-finding" algorithm to locate physical energy peaks from ^{228}Th
- Create a linear calibration function to convert ADC values detected by HPGe detectors to a physical unit (keV)

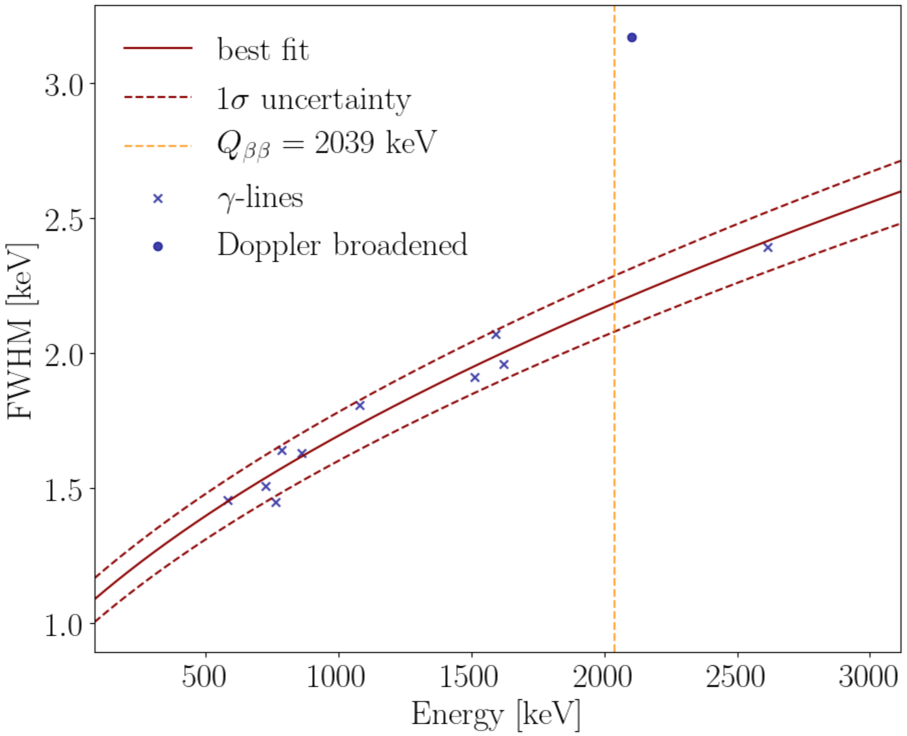


Calibration procedure (2) — energy resolution

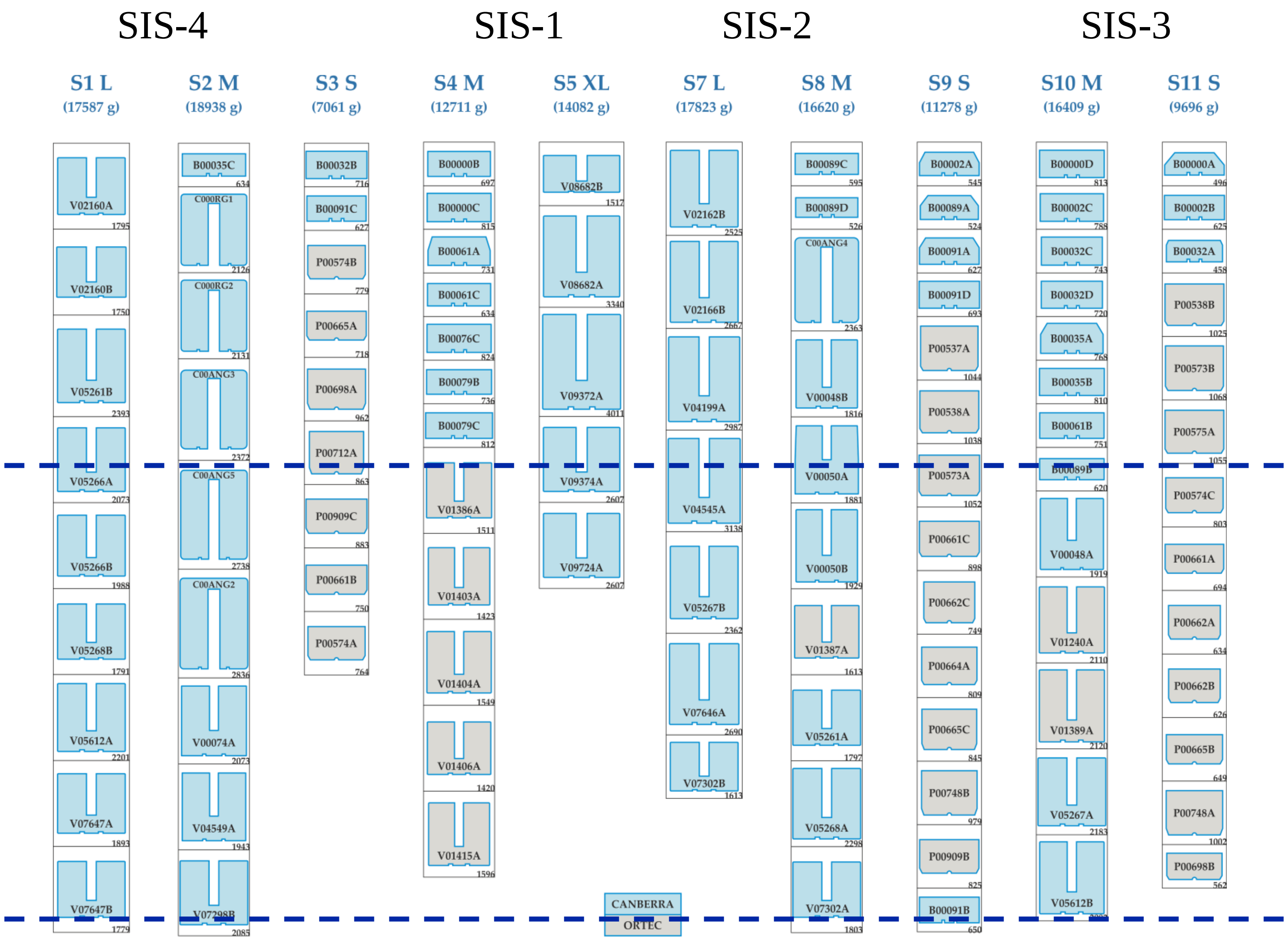
- Use a custom-designed function to fit detected energy peaks
  - Gaussian peak with low energy tail
  - Compton step/continuum



- The FWHM resolution at each energy is determined from the fit width
- Interpolate the FWHM resolution at $Q_{\beta\beta}$ via $FWHM(E) = \sqrt{a + bE}$ (or $\sqrt{a + bE + cE^2}$) fit of detected peak resolutions, neglecting the single-escape peak (SPE) because of the Doppler broadening



LEGEND-200 detector map



Calibration positions