Calibration in Large Germanium-Detector-Based Experiments

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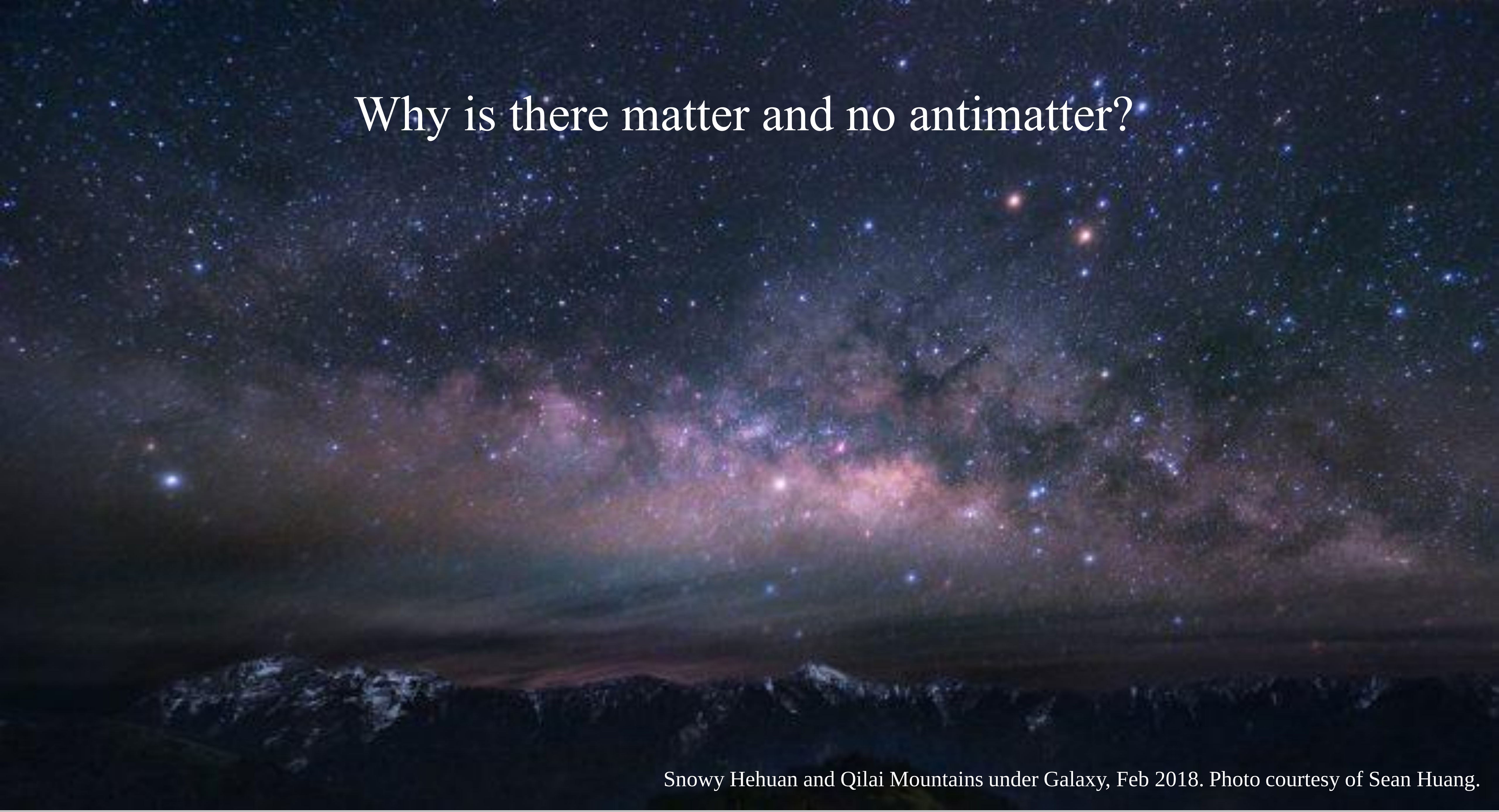
Why is there matter and no antimatter?



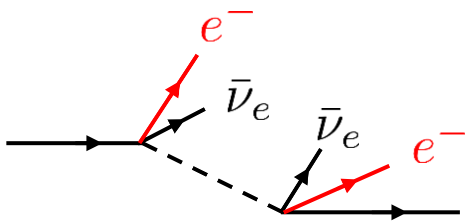
Snowy Hehuan and Qilai Mountains under Galaxy, Feb 2018. Photo courtesy of Sean Huang.

Double beta decay in ^{76}Ge

I. Guinn, Thu., May 25th

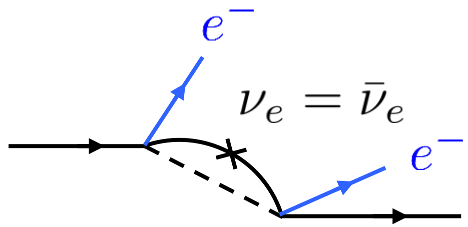
$\boxed{2\nu\beta\beta}$ $\quad {}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^- + 2\bar{\nu}_e$

$$\Delta L = 0$$



$\boxed{0\nu\beta\beta}$ $\quad {}^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$

$$\Delta L = +2$$

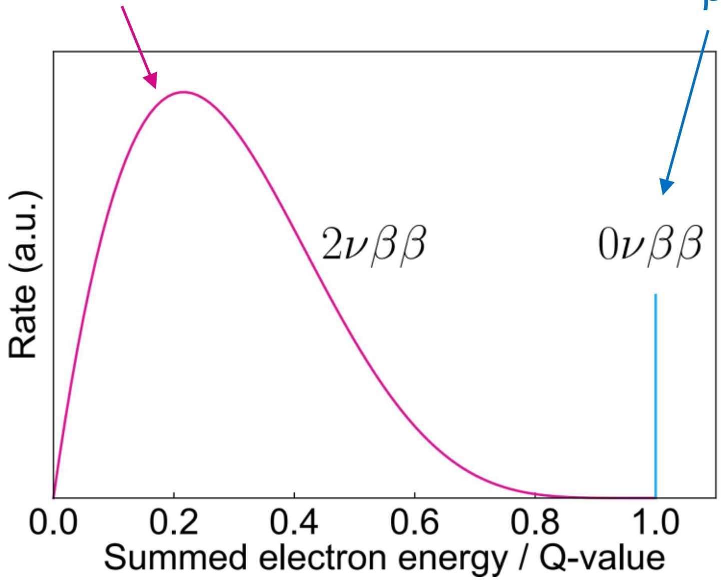


- Baryon asymmetry of the Universe
- Majorana nature of neutrinos
- Lepton number violation $\Delta L \neq 0$
- Neutrino mass scale and ordering (normal vs. inverted)

R. Henning, Neutrino Phys.

Continuous broad spectrum

Peak at $Q_{\beta\beta} = 2039\,\mathrm{keV}$



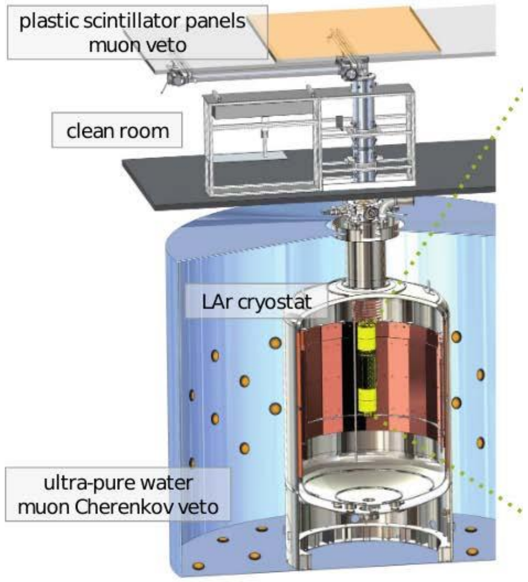
Half-life ($T_{1/2}$) sensitivity

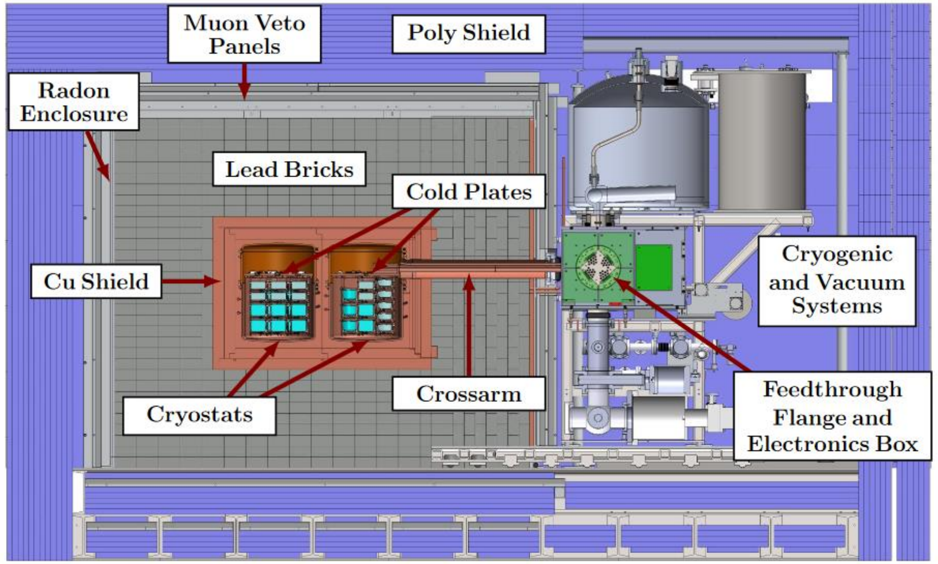
$$T_{1/2} \propto f\epsilon\sqrt{\frac{Mt}{B\sigma_E}}$$

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

A stable **energy scale** and an excellent **energy resolution** is crucial → calibration of Ge detectors

^{76}Ge-based experiments searching for 0νββ





GERDA at LNGS, Italy

The MAJORANA DEMONSTRATOR at SURF, US

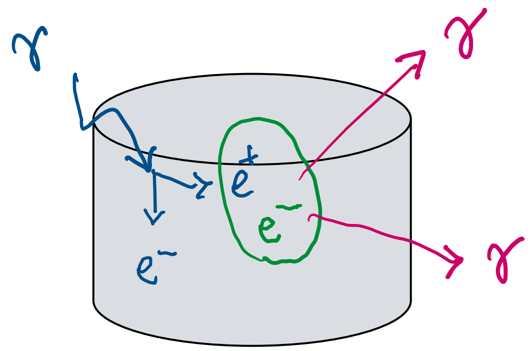
LEGEND-200 at LNGS, Italy

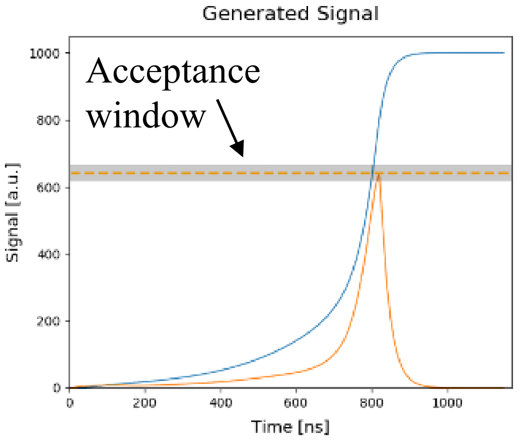
All use ^{228}**Th** as standard calibration sources

Refs.: L. Baudis et al., NIMA, 729 (2013),
L. Baudis et al., JINST, 10, P12005 (2015),
N. Abgrall et al., Nucl. Inst. Meth. A 872 16-22 (2017),
L. Baudis et al., JINST 18, P02001 (2023)

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

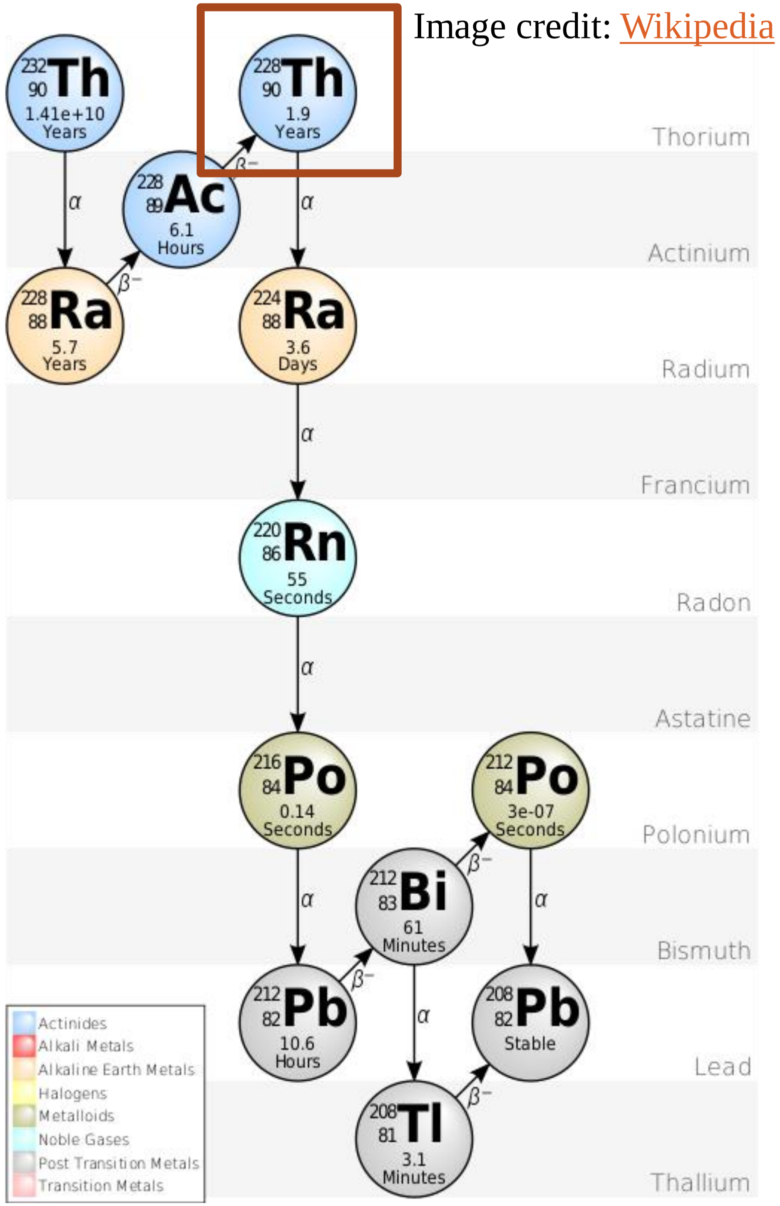




Charge/current signals

- 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



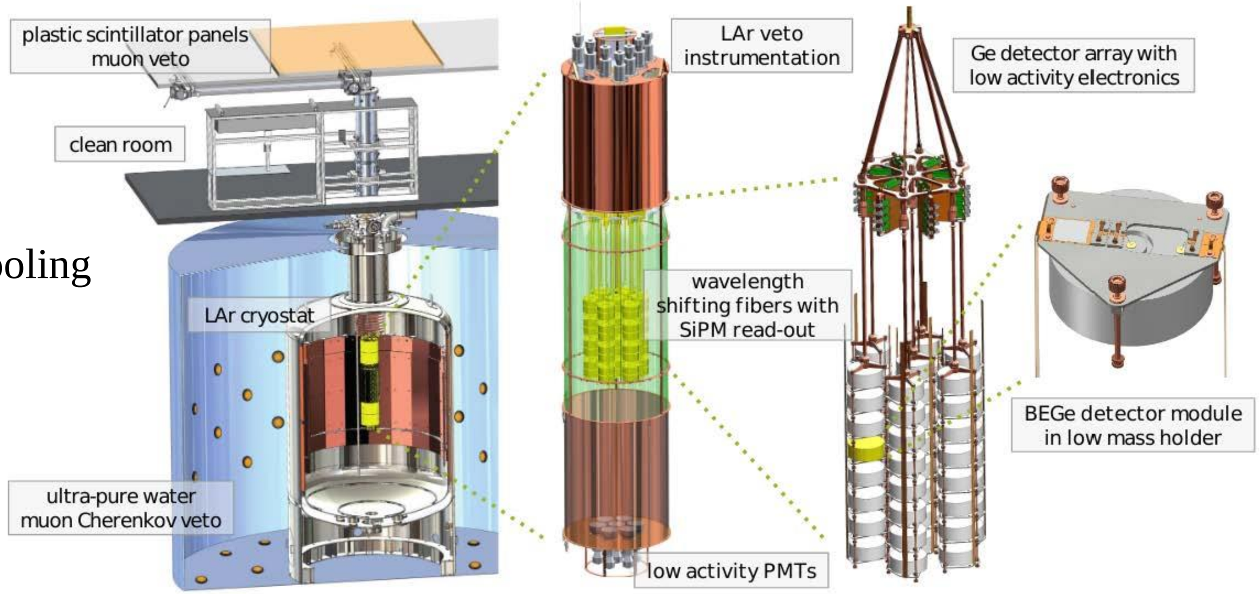
The GERmanium Detector Array

- 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

Also shield neutrons and natural radioactivity

$64\ m^3$ LAr: shielding and cooling

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

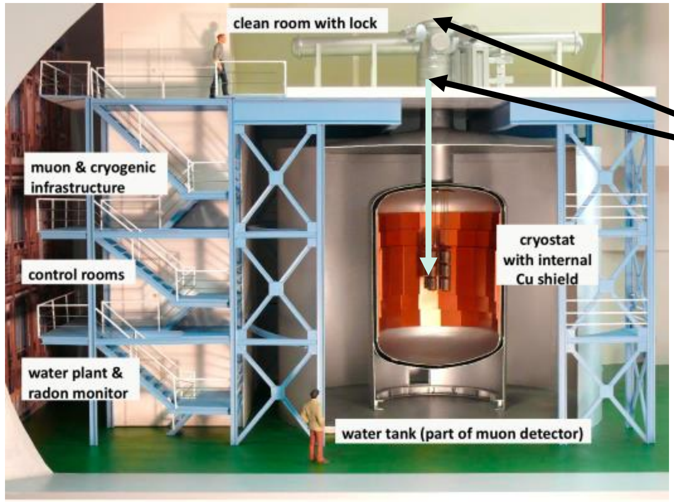


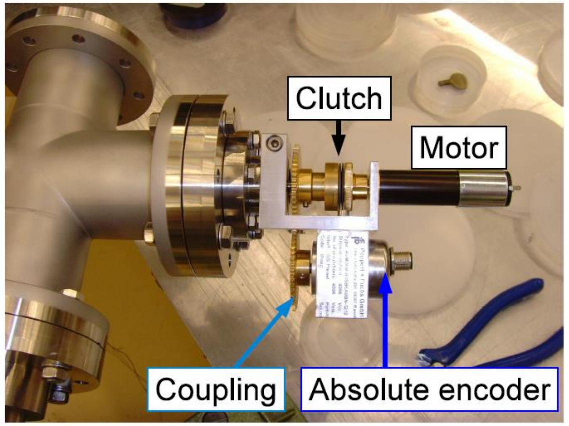
Phase II+: 41 detectors (44.2 kg), enriched in ^{76}Ge up to 87%, in 7 strings

GERDA's final result (with 103.7 kg yr of exposure) :
- Unprecedentedly low background index: 5.2×10^{-4} counts / (keV kg yr) → 0.3 counts in ($Q_{\beta\beta} \pm 2\sigma$)
- Half-life limit on 0νββ decay: $T_{1/2} > 1.8 \times 10^{26}$ 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)

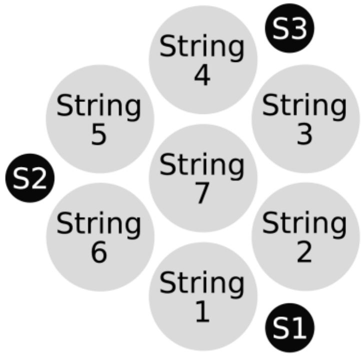
The GERDA Source Insertion System



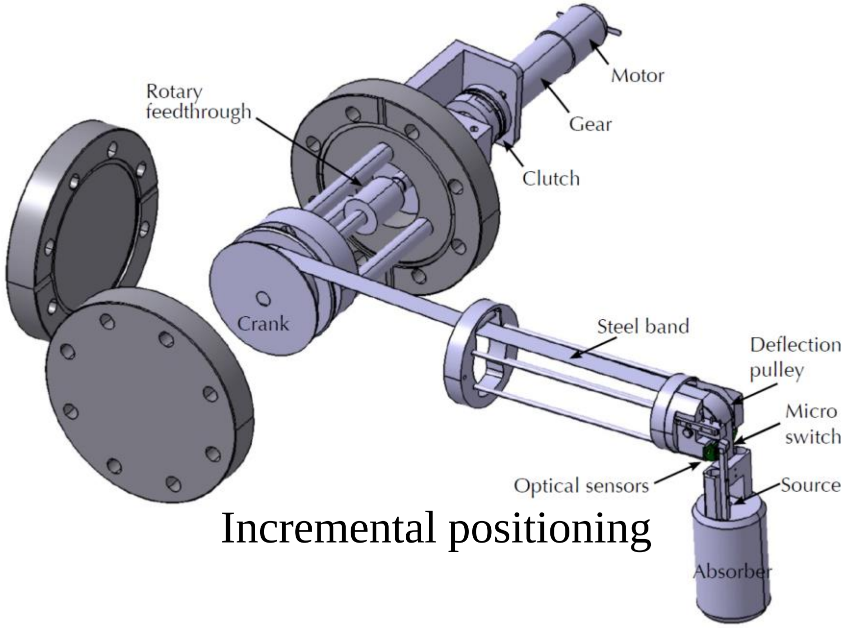


Absolute positioning

Three calibration systems were installed on the top flange



Top view of the detector array and the SIS positions (not to scale)



Initialization

Single source per system

Incremental positioning

Tantalum absorber shields radiation at the parking position during physics data-taking

Refs. and image credits: GERDA collab.,
F. Froborg, PhD thesis (2012), M. Tarka, PhD thesis (2012)
C. Ransom, PhD thesis (2021), L. Baudis et al., NIMA, 729 (2013),
L. Baudis et al., JINST, 10, P12005 (2015)

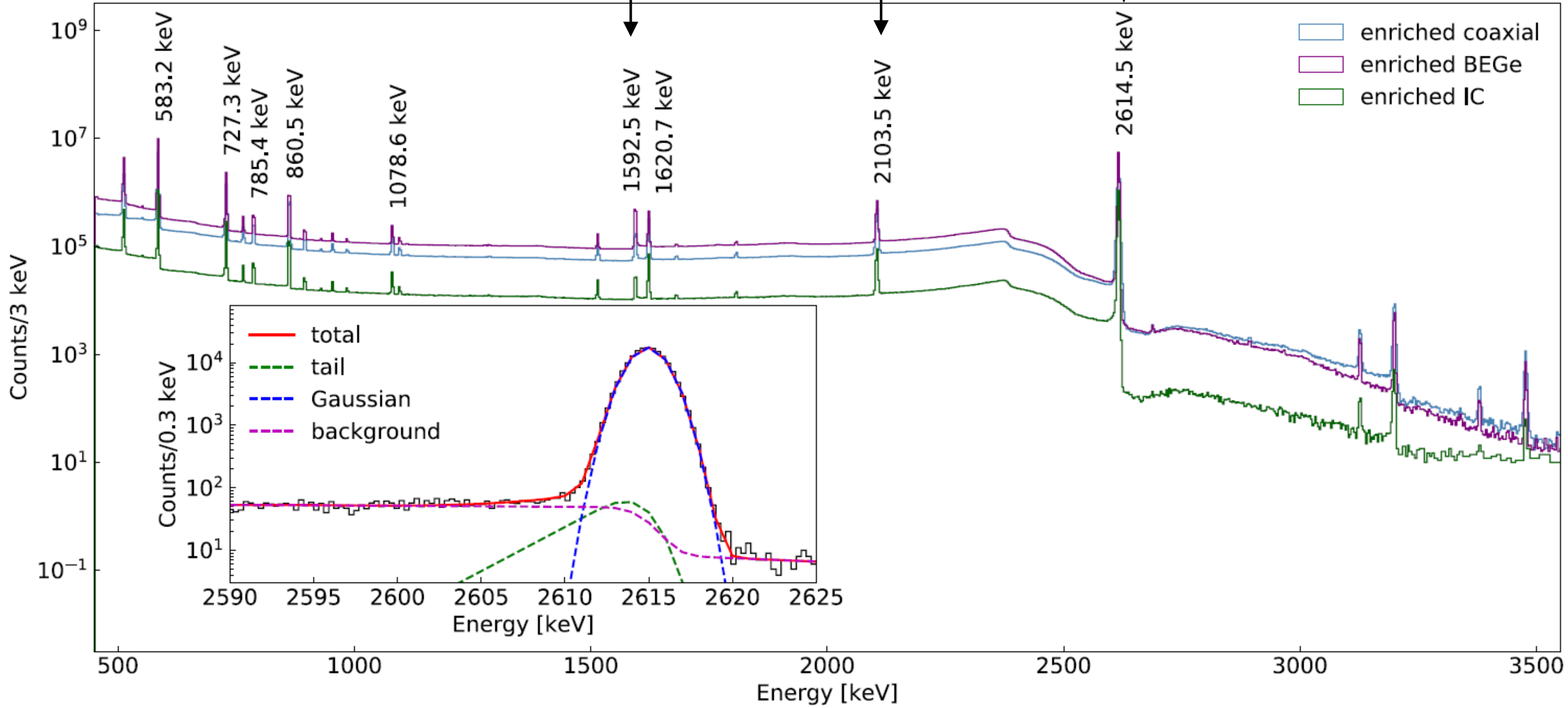
Combined Phase II calibration spectrum

- Three custom-made **low-neutron emission** ^{228}Th calibration sources, each with an activity of ~10 kBq
- Weekly calibrations: each source was placed at three different heights, and data were acquired at each location for up to 30 min

Double escape peak

Single escape peak

Full energy peak



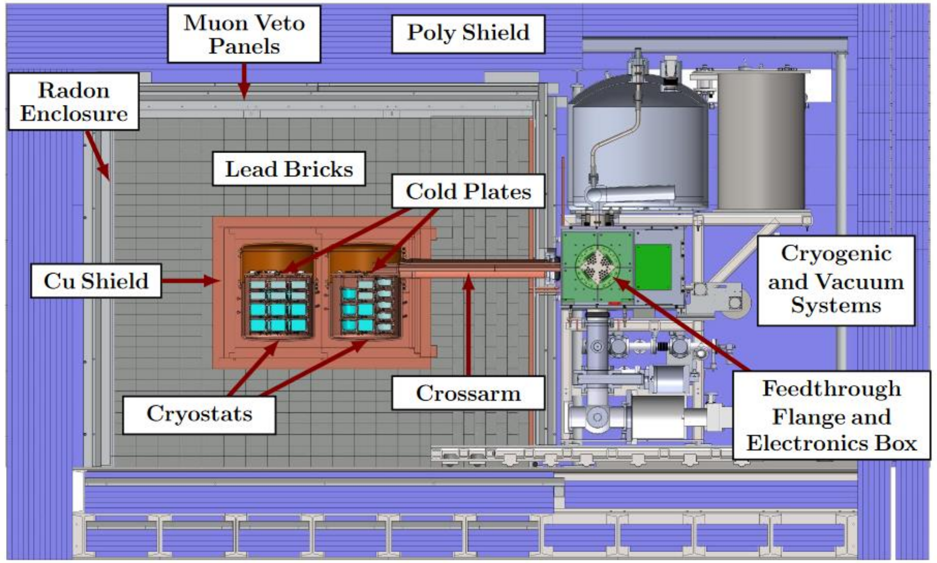
For the final Phase II result, FWHM resolutions of different detector types range from 2.6 to 4.9 keV, < 0.3% of $Q_{\beta\beta}$.

Ref.: GERDA Collab., Eur. Phys. J. C 81, 682 (2021)

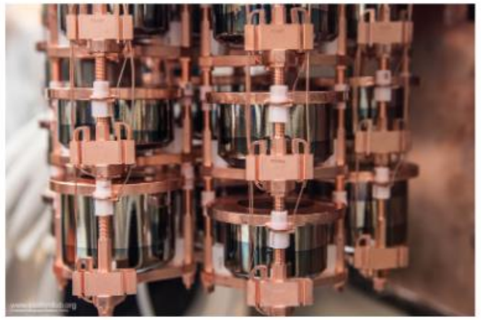
The MaJorana Demonstrator

- 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



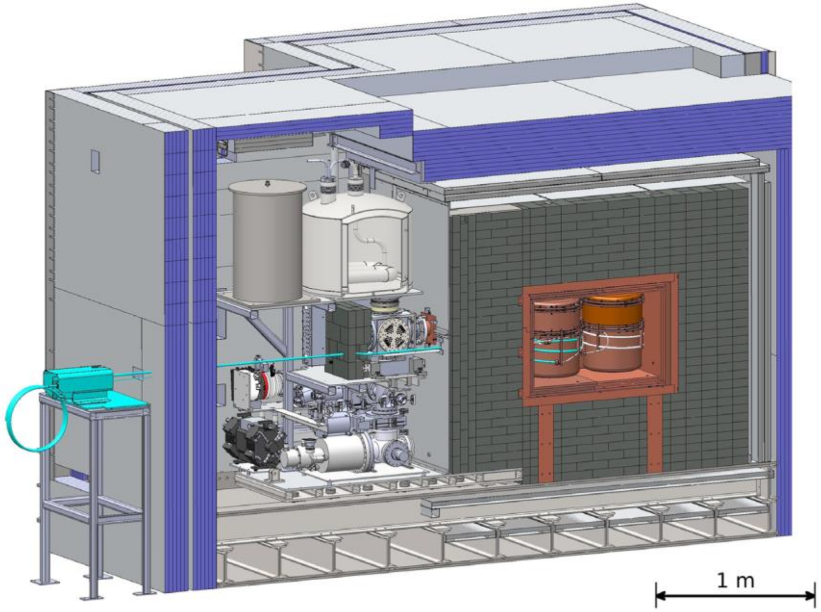
MJD's final result (with 26 kg yr of exposure) :
- Best energy resolution in the field: 2.53 $\pm$ 0.08 keV (FWHM) at $Q_{\beta\beta}$
- Measured background 11.9 $\pm$ 2.0 counts / (FWHM ton yr)
- Half-life limit on 0νββ decay: $T_{1/2} > 2.7 \times 10^{25}$ yr (90% C.L.)
  $\rightarrow$ Effective Majorana neutrino mass: $m_{\beta\beta} < 200 – 433$ meV

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

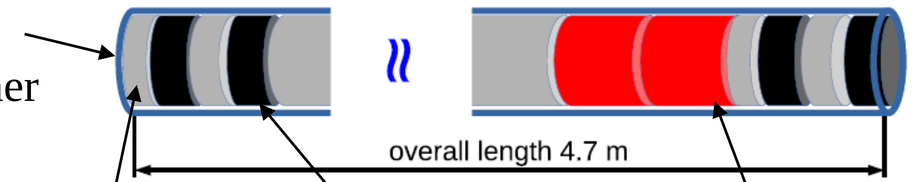
The MJD calibration system

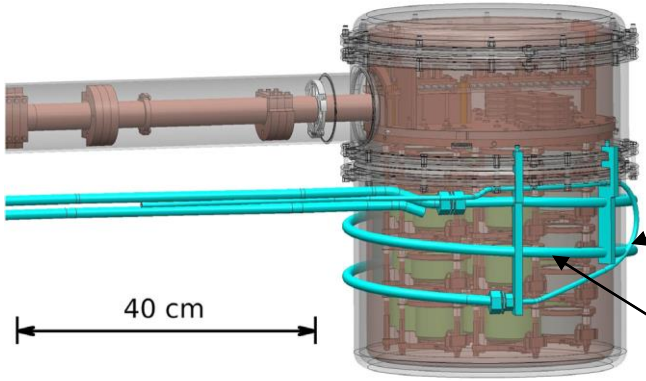
Two calibration systems were located outside of the shields

Calibration controls



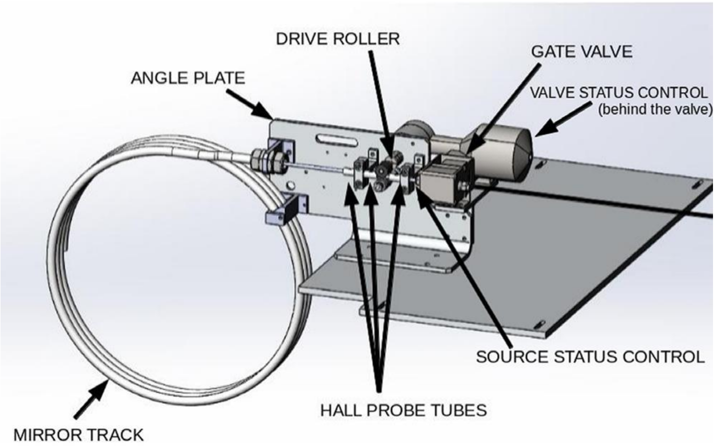
Line source assembly





Two-turn calibration track allows a simultaneous calibration of all detectors (cf. GERDA)

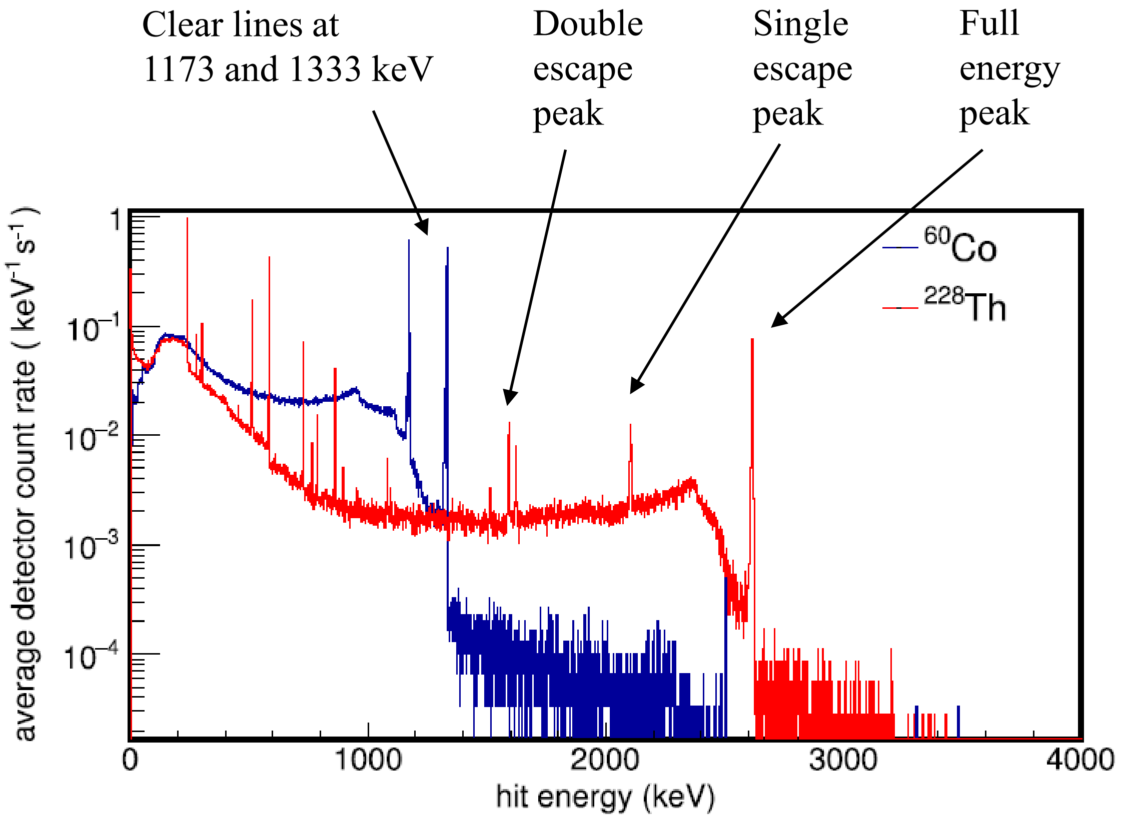
Without LAr (cf. GERDA)



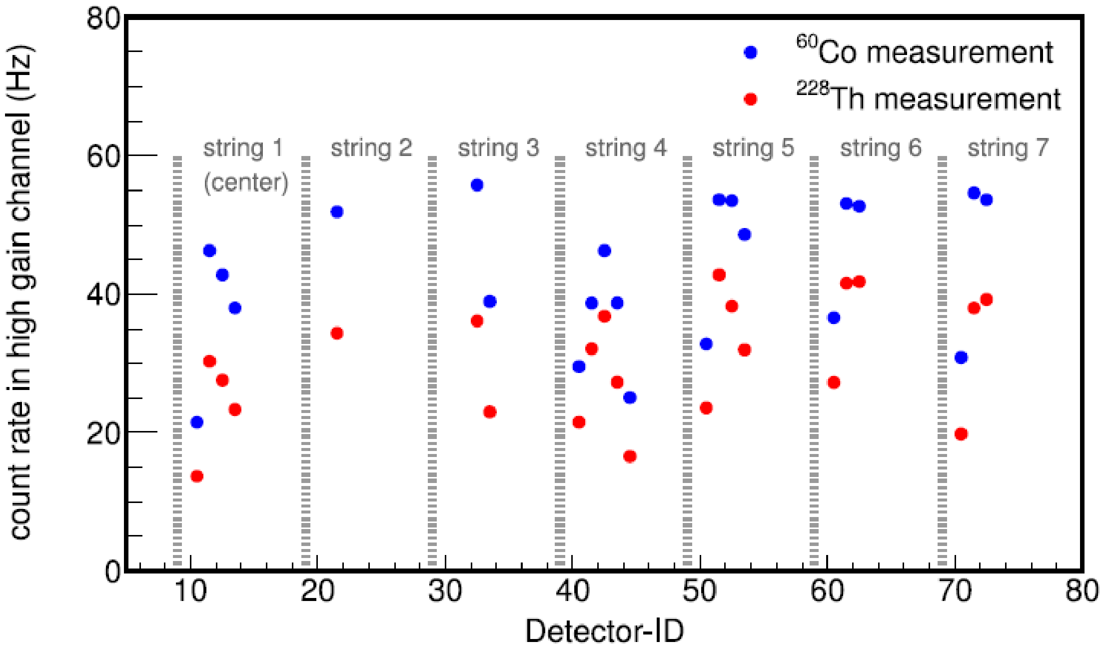
Ref.: N. Abgrall et al., Nucl. Inst. Meth. A 872 16-22 (2017)

Commissioning and performance

Detector energy spectrum of Module 1 averaged over all detectors (1 h measurement)



Integral count rate per detector in the high gain channel between 20 and 4000 keV (first data set of Module 1) → balanced count rate within the array

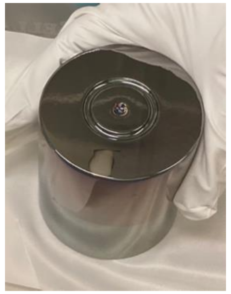


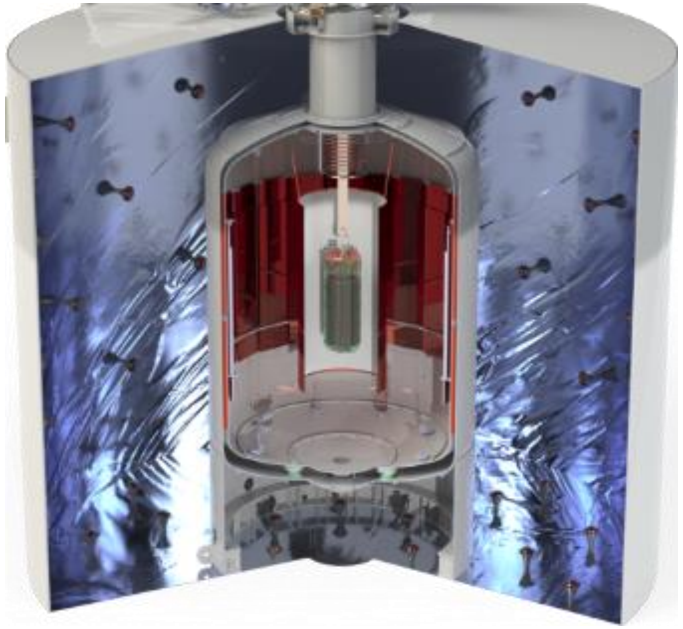
Ref.: N. Abgrall et al., Nucl. Inst. Meth. A 872 16-22 (2017)

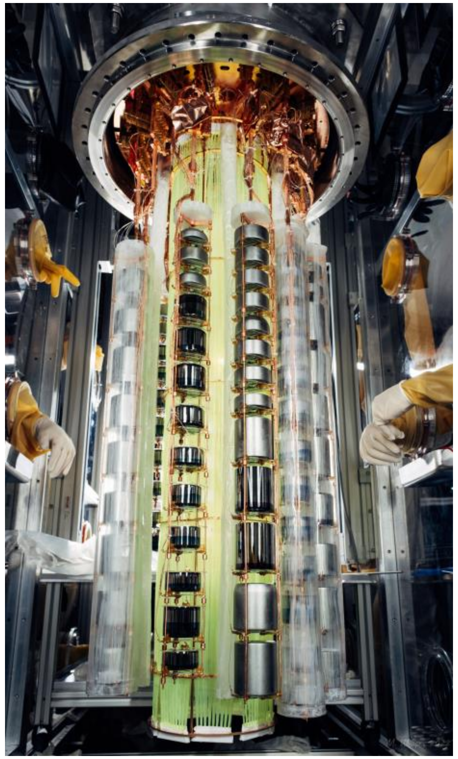
The Large Enriched Germanium Experiment for Neutrinoless double-beta Decay

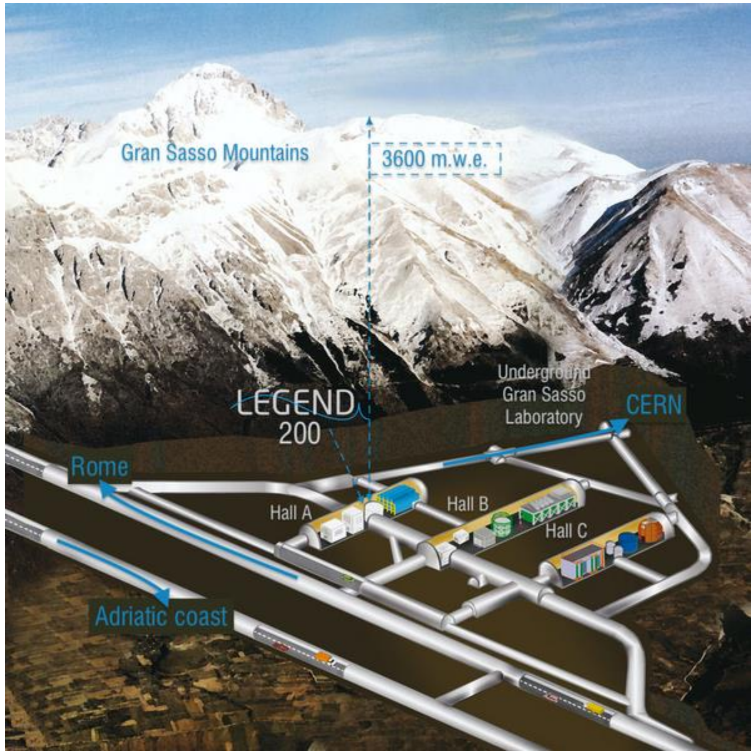
- First phase LEGEND-200 (L200) locates underground at LNGS, Italy
- Took over from GERDA facilities (in Feb. 2020), after upgrades on various subsystems
- The final design will include ~ 200 kg of detectors distributed over 12 strings
- Reuse of detectors from GERDA and MJD + 140 kg of additional *inverted-coaxial point-contact (ICPC)* detectors:
  - Active mass could be > 3 kg
  - Excellent pulse shape discrimination performance

ICPC detector



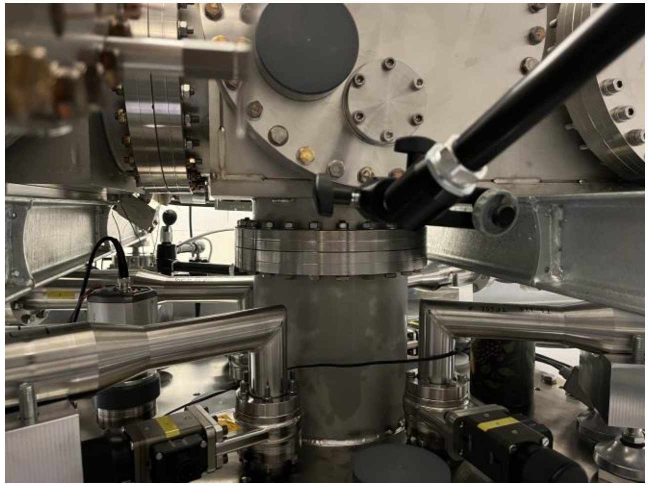


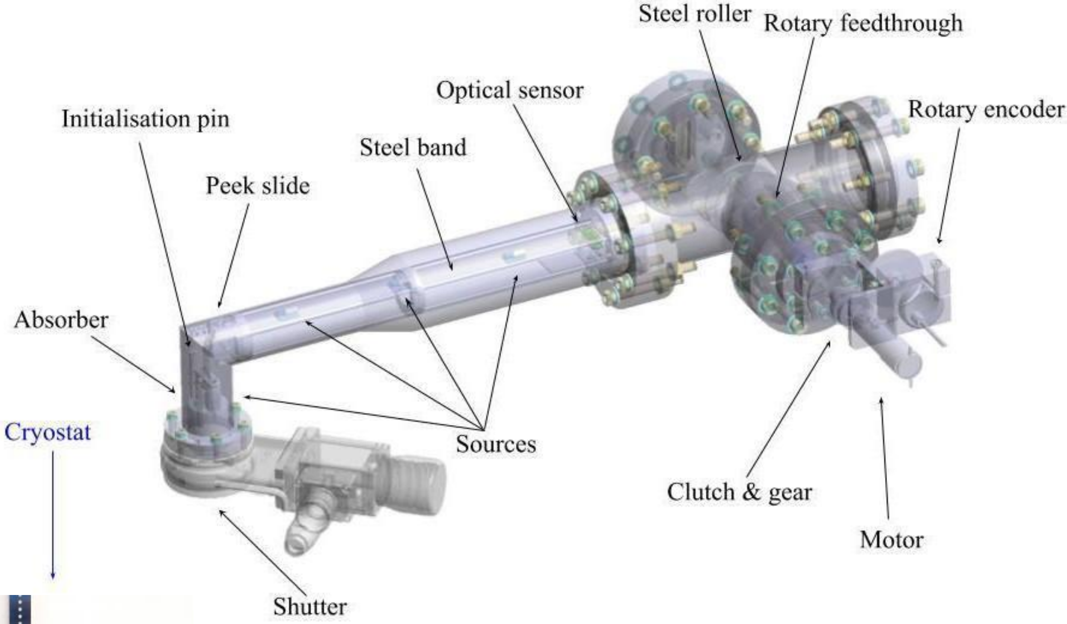




The L200 calibration system

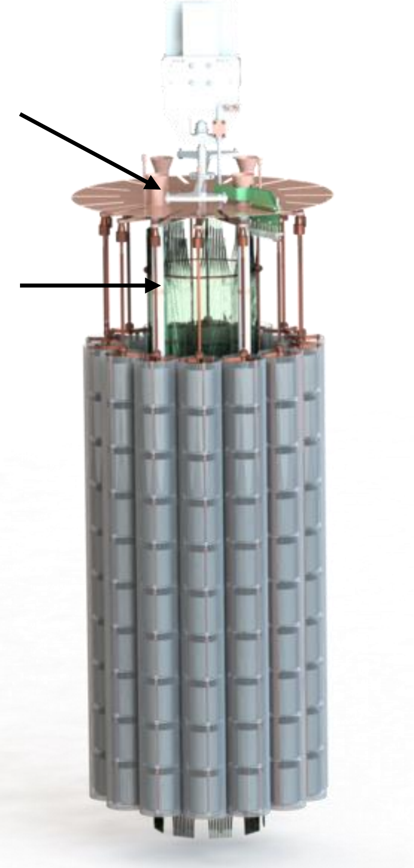
Follows the concept of the GERDA SIS, four calibration systems are installed above the cryostat

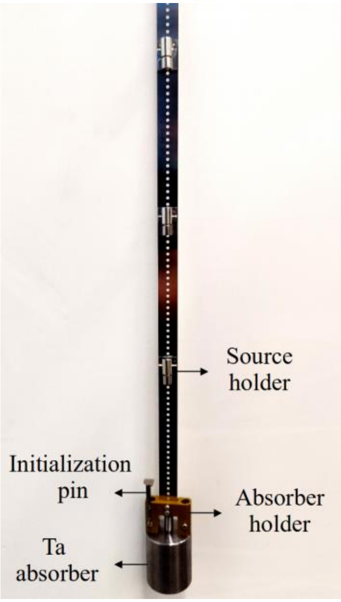




Cu funnel

Nylon tube



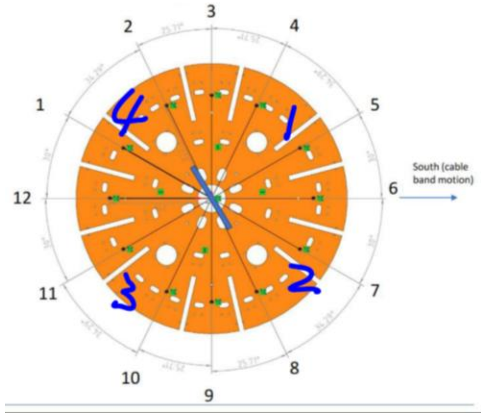


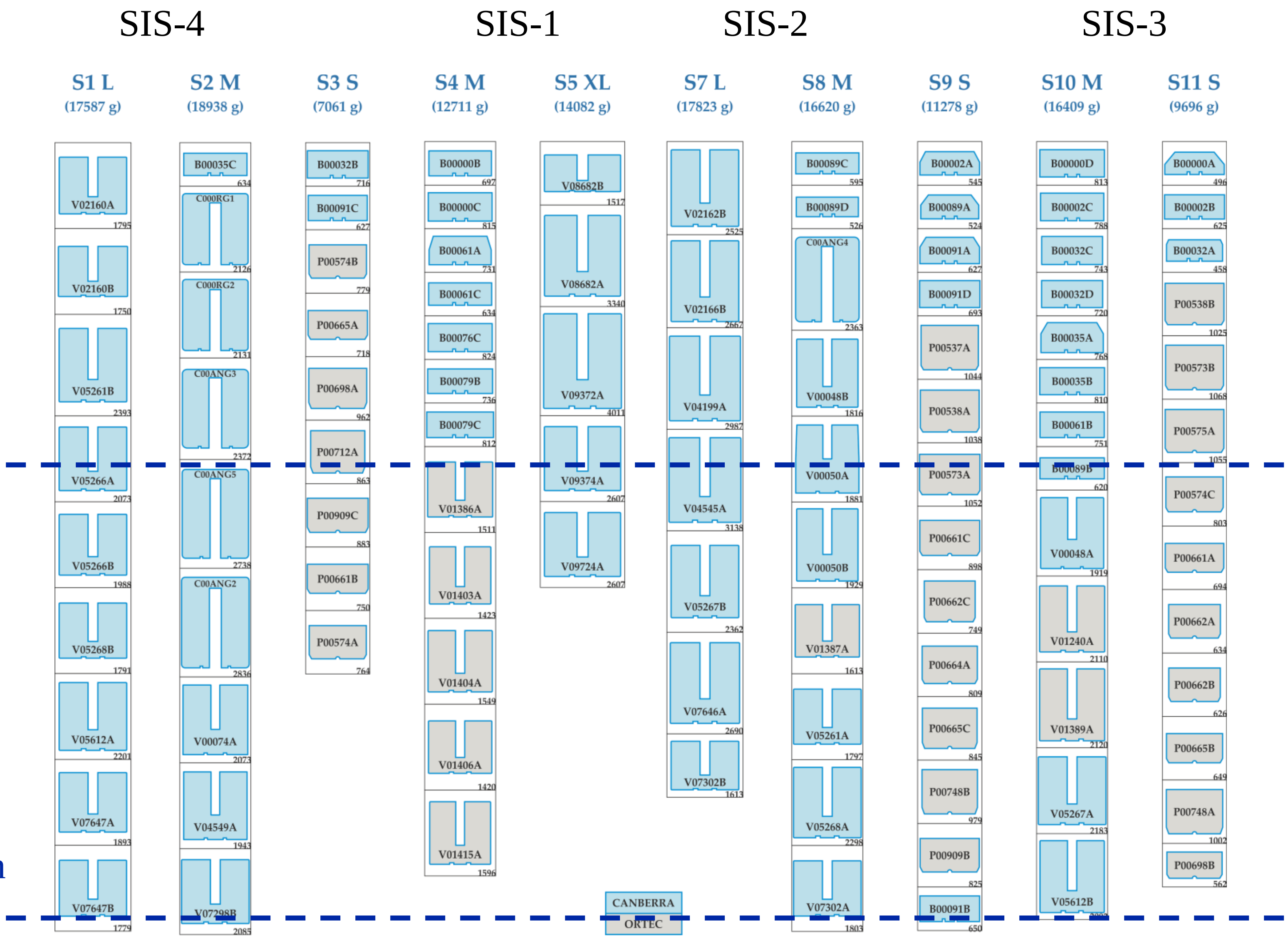
Multiple sources per system

Image credits and Ref.:
M. Willers, Y. Mueller, and LEGEND Collab., L. Baudis et al., JINST 18, P02001 (2023)

Current status of L200

- 10 strings consisting of 101 detectors with a total mass of ~ 142 kg
- Started physics data-taking recently. Will take physics data for ~ 1 yr; afterwards, install more detectors to ~ 200 kg
- Requires only ×2–3 background improvement w.r.t. GERDA (background index from 5.2×10^{-4} to 2×10^{-4} counts / (keV kg yr))
- Goal (5 yr runtime):
  Discovery sensitivity $T_{1/2} > 10^{27}$ yr (99.7% C.L.) → $m_{\beta\beta} < 33 – 71$ meV





Calibration positions

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)

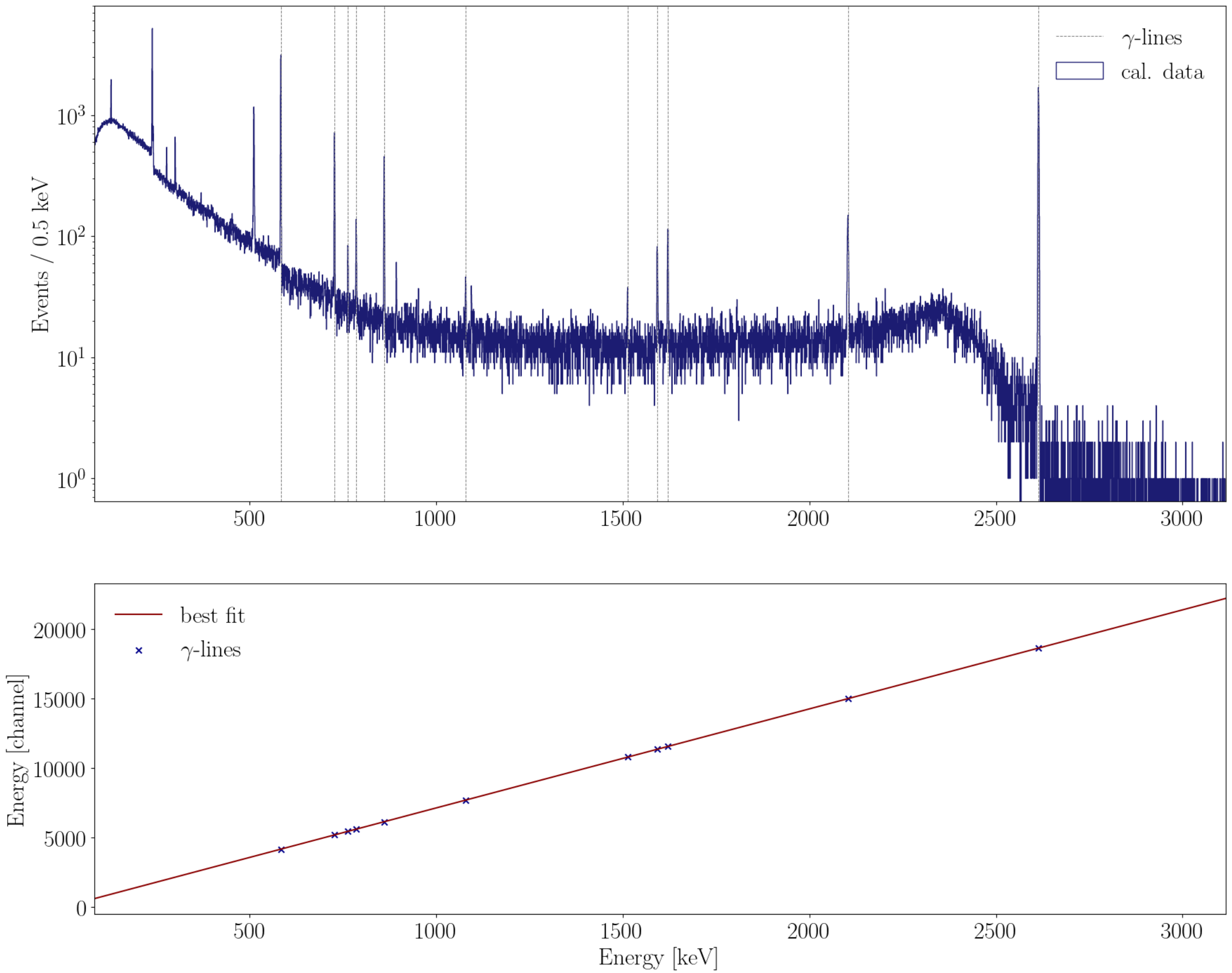
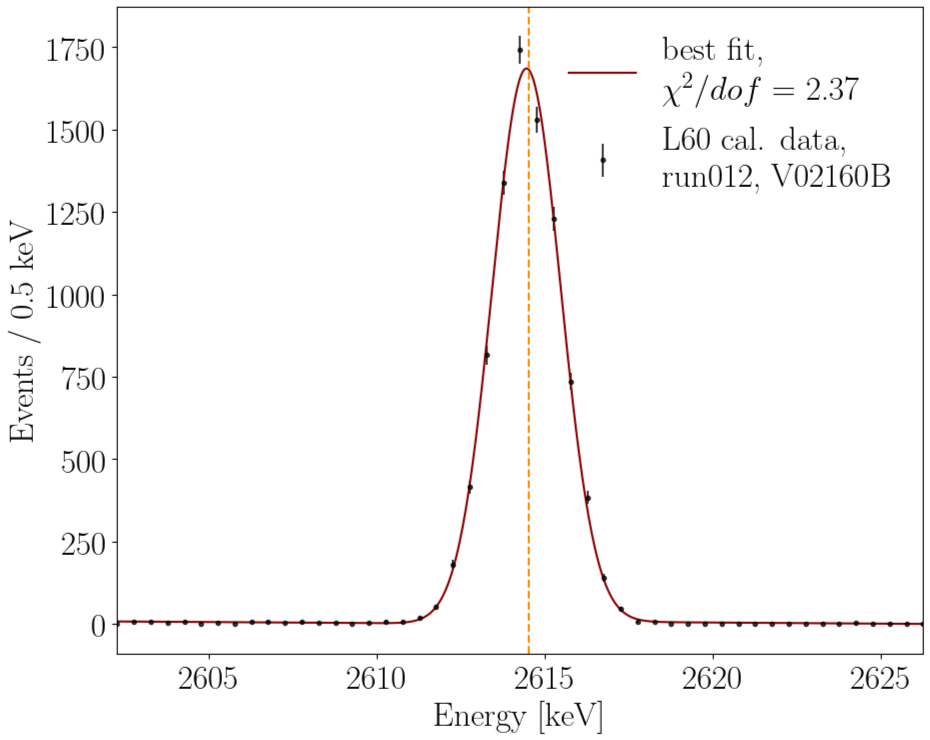


Image credit: Y. Mueller

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



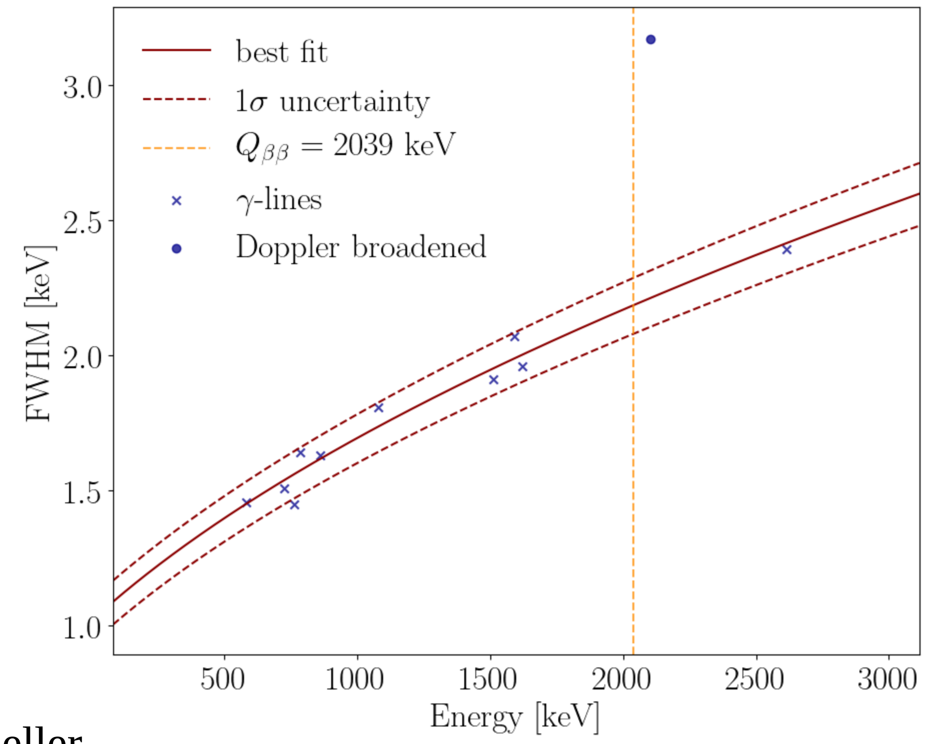
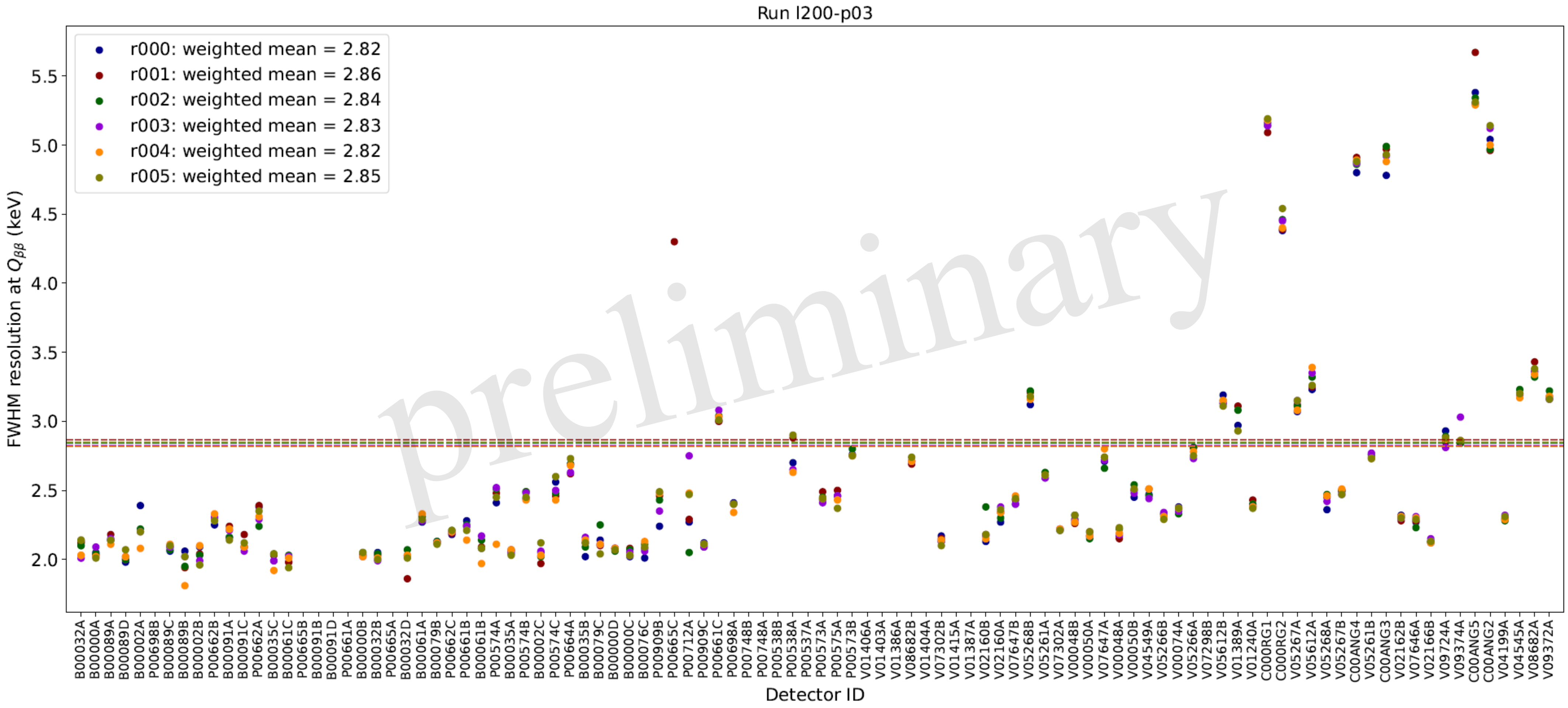


Image credit: Y. Mueller

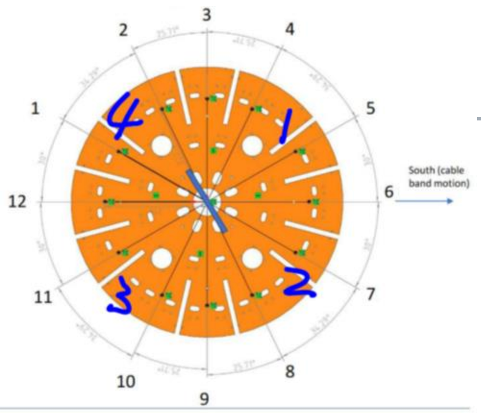
FWHM resolution at $Q_{\beta\beta}$

- FWHM resolution at $Q_{\beta\beta}$ for all installed detectors ordered by mass
- Exposure weighted average of $Q_{\beta\beta}$ ~ 2.8 keV



Increasing mass

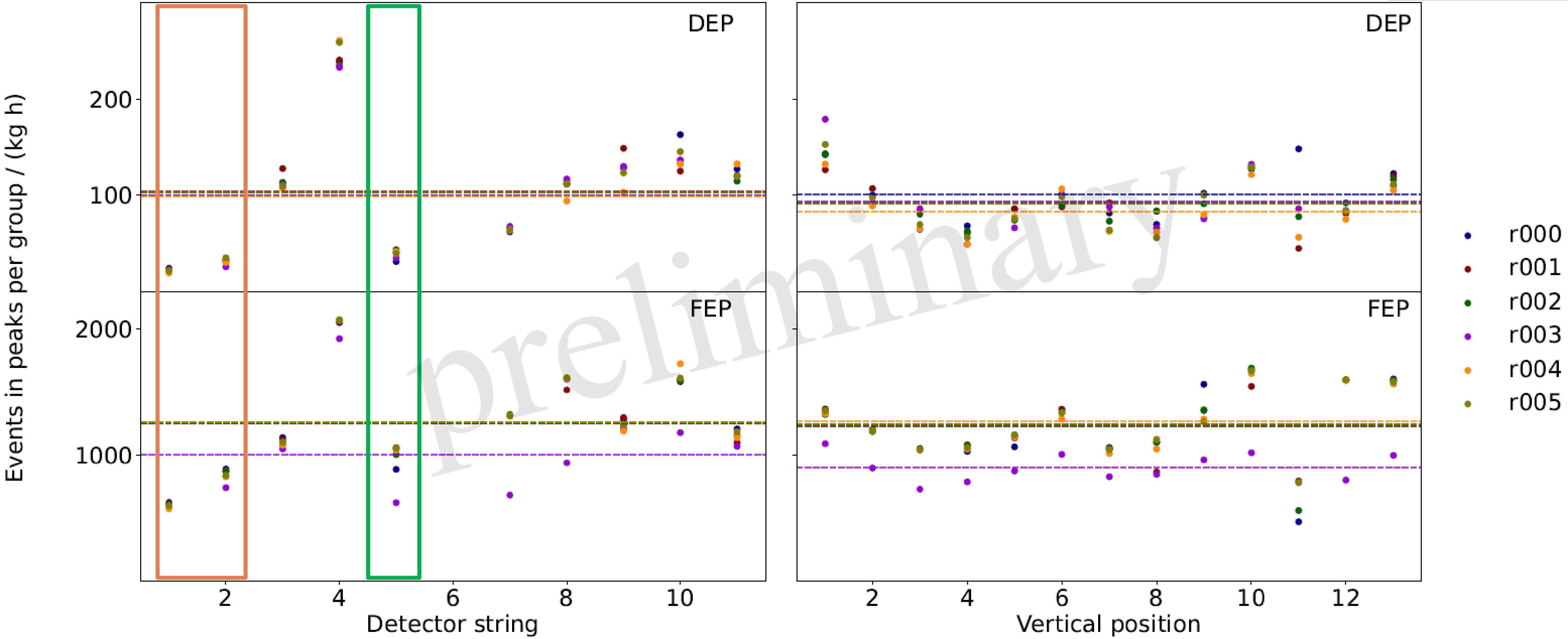
Average exposure per detector group



SIS 4 was not deployed

Only 5 detectors

Sufficiently uniform in vertical position



Potential backgrounds from ^{228}Th sources

Nevertheless…

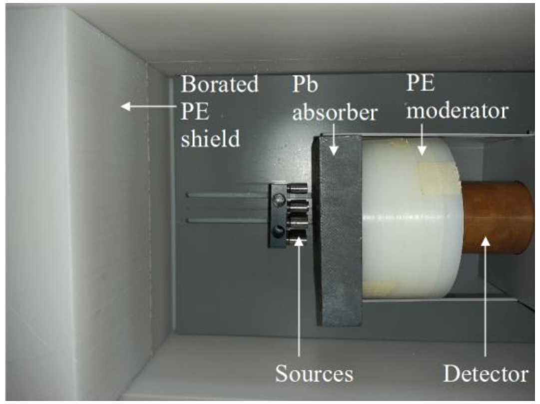
- ^{228}Th emits α with energies in the range of 5.2 – 8.8 MeV
  → yields neutron fluxes via (α, n) reaction
- Parasitic neutrons can
  - activate ^{76}Ge, producing ^{77}Ge (half-life 11.3 h) and ^{77m}Ge (half-life 53.7 s)
    → β decays with Q values > 2 MeV
  - be captured by surrounding materials,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

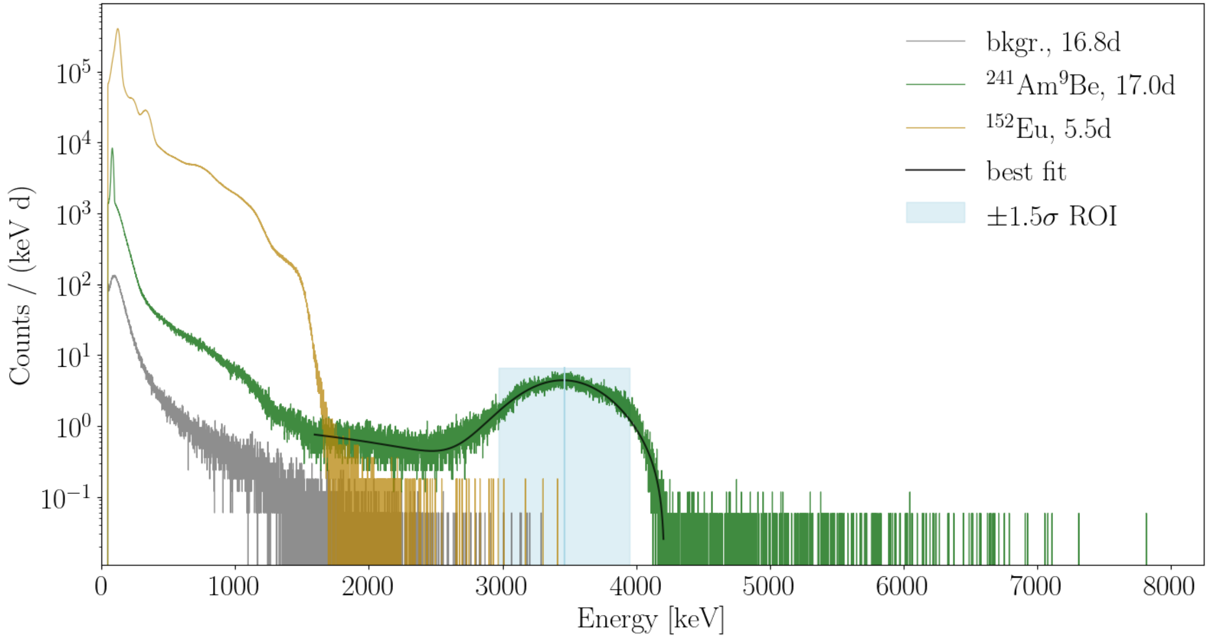
Low background environment underground at LNGS

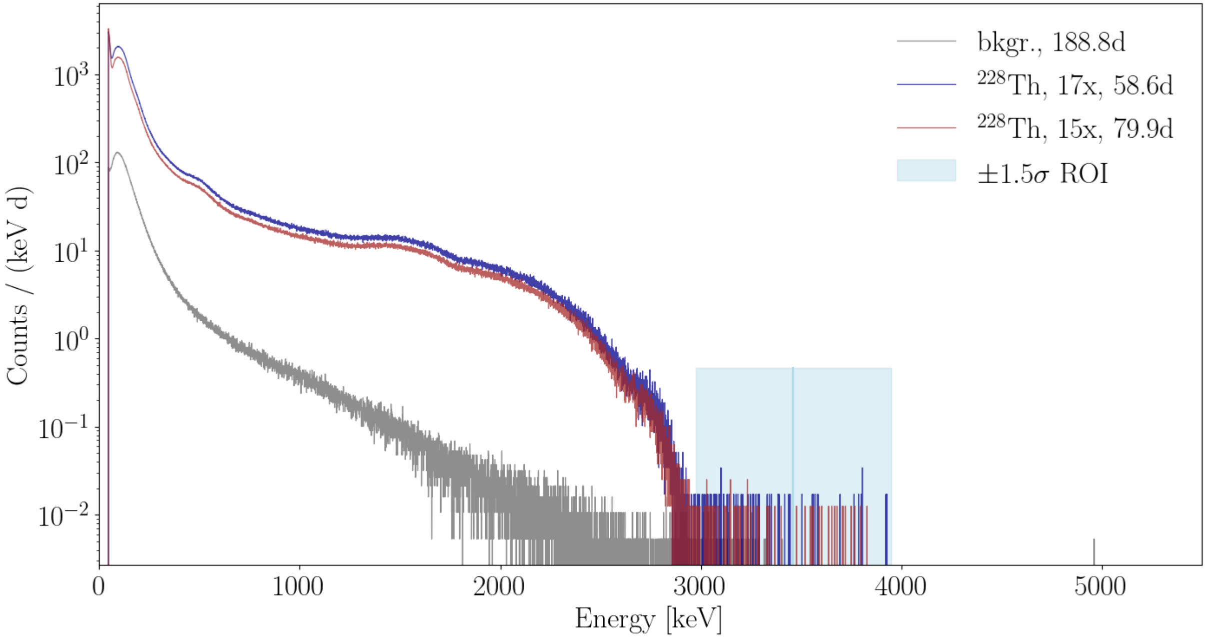


Calibration-induced background:
$\mathcal{O}(10^{-7})$ events/(keV kg yr)
after background reductions cuts
→ three orders of magnitude lower than the L200 background goal

^{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
$\psi = \left(4.27 \pm 0.60_{\mathrm{stat}} \pm 0.92_{\mathrm{sys}}\right) \times 10^{-4}$ n/(kBq s)



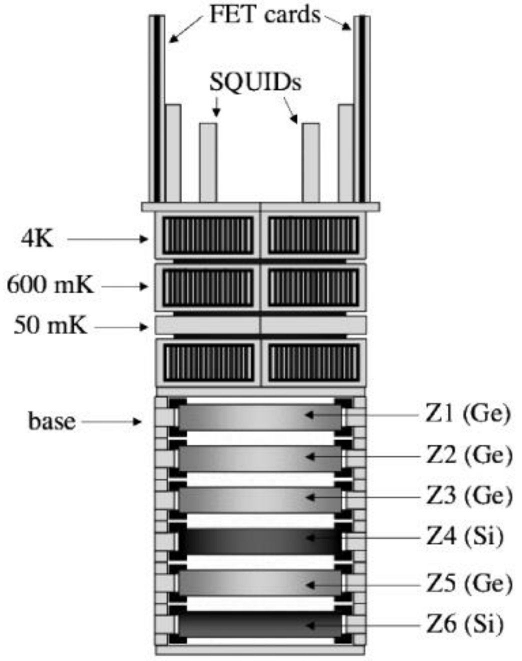


What is dark matter?

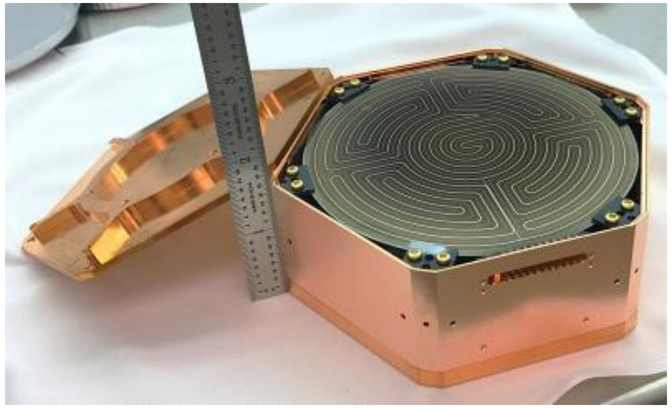
NASA/CXC/M. Weiss, Chandra X-Ray Observatory: 1E 0657-56

Super Cryogenic Dark Matter Search

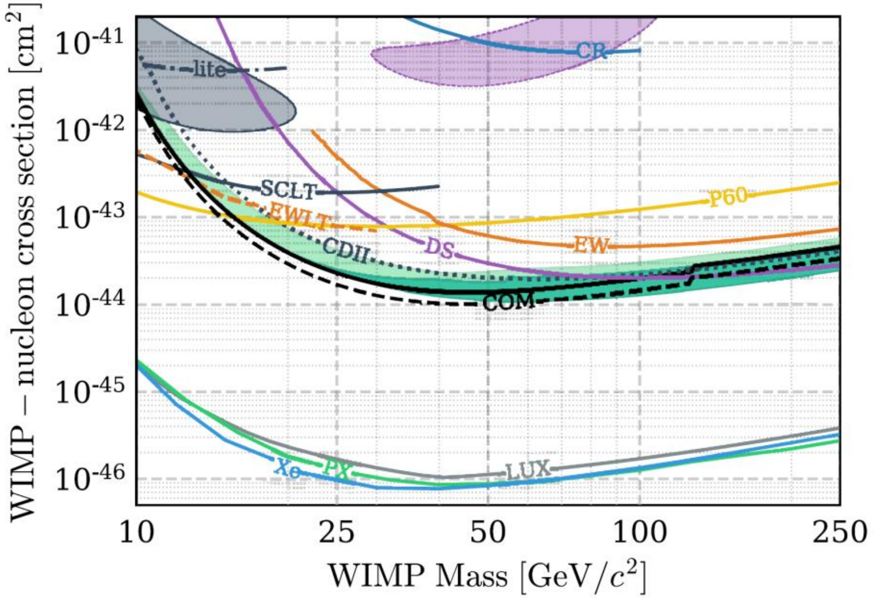
- The **Cryogenic Dark Matter Search** (**CDMS**) is a series of experiments to search for WIMPs:
  - CDMS I (tunnel underground of Stanford University) → CDMS II (Soudan) → SuperCDMS Soudan (collected data 2011–2015) → SuperCDMS SNOLAB (started construction 2018)



Each 0.6 kg iZIP detector consists of a 76-mm diameter, 25-mm thick, cylindrical, high-purity germanium substrate



Refs and image credits.:
D. MacDonell, Master thesis (2018)
SuperCDMS Collab., PRL120, 061802 (2018)
CDMS Collab., PRD72, 052009 (2005)

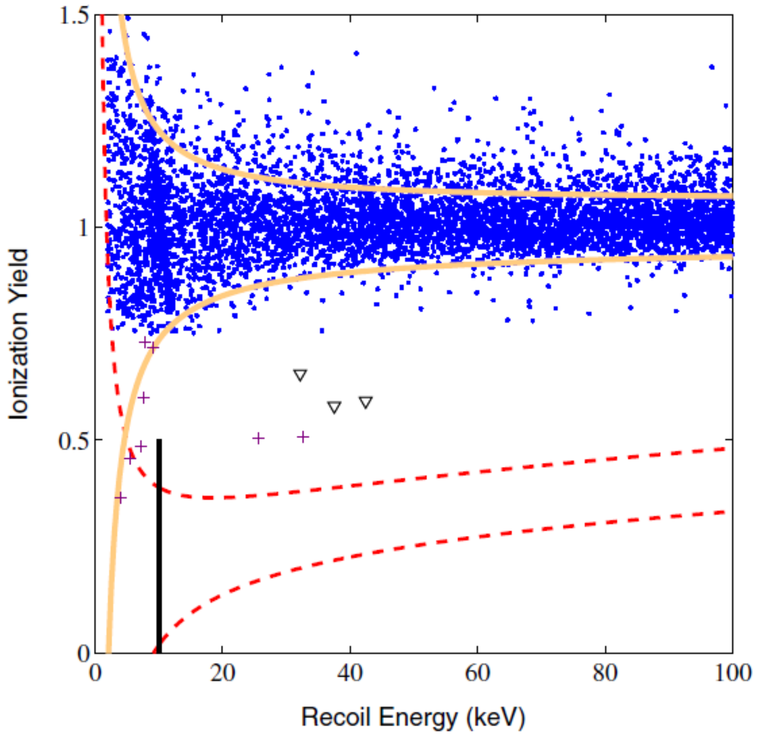


$1.4 \times 10^{-44} (1.0 \times 10^{-44})$ cm^2 at 46 GeV$/c^2$
Strongest limits for WIMP-Ge interaction for masses > 12 GeV$/c^2$

Event signal

- Nuclear recoils (WIMPs, neutrons) vs. electron recoils (electrons, photons)
- Ionization yield (ratio of the measured ionization energy to the total recoil energy)

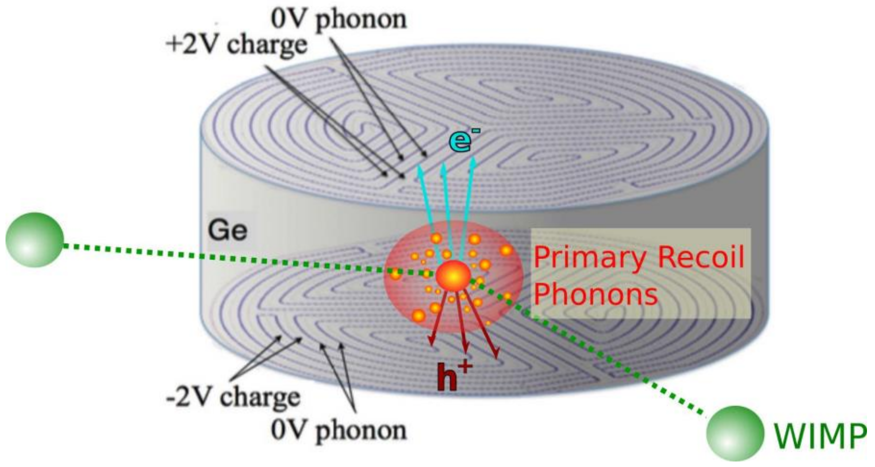
$$Y = \frac{E_{\mathrm{e/h}}}{E_{\mathrm{r}}} = \frac{E_{\mathrm{e/h}}}{E_{\mathrm{p}} - \frac{eV_{\mathrm{b}}}{\epsilon} E_{\mathrm{e/h}}}$$



Electron recoils: background particles, e.g., electrons, photons

Nuclear recoils: background neutrons, WIMPs

Phonon detection: superconducting transition edge sensors read out by SQUID amplifiers



Ionization detection: FET amplifiers

Refs: CDMS Collab., Phys. Rev. Lett. 93. 21 (2004), D. MacDonell, Master thesis (2018)

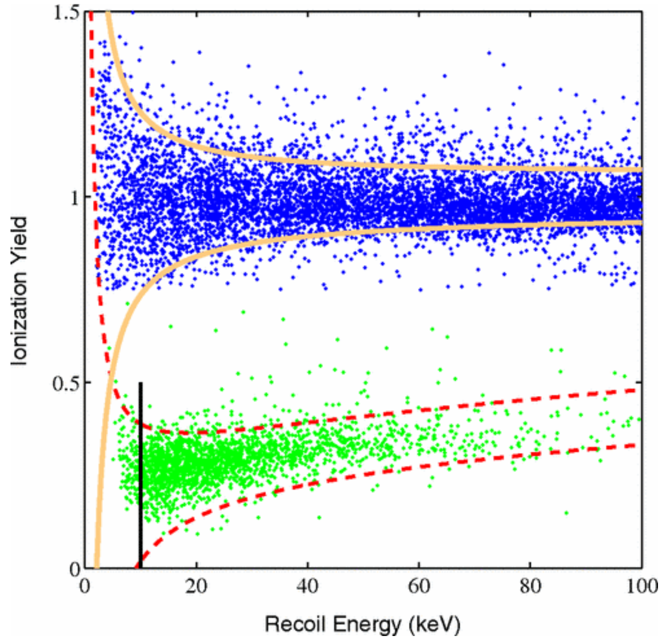
Calibration for CDMS detectors

- Ionization-energy calibration: bulk electron recoil of a ^{113}Ba source (known energy peaks of 302.8, 356.0, and 383.8 keV)
- Phonon-energy calibration: $Y = \frac{E_{\mathrm{e/h}}}{E_{\mathrm{r}}} = \frac{E_{\mathrm{e/h}}}{E_{\mathrm{p}} - \frac{eV_{\mathrm{b}}}{\epsilon} E_{\mathrm{e/h}}} \equiv 1$ for electron-recoil events

Luke-Neganov gain

$E_{\mathrm{e/h}}$: measured ionization energy
E_{p}: measured primary phonon energy
e: fundamental electric charge
V_{b}: bias voltage across the detector
ϵ: energy required to ionize a single electron-hole pair

^{252}Cf γ and neutron source



Different neutron sources are being studied for SuperCDMS nuclear-recoil calibrations, e.g., passing ^{124}Sb or ^{88}Y through a ^{9}Be wafer via (γ,n) reaction

Refs: CDMS Collab., Phys. Rev. Lett. 93. 21 (2004), D. MacDonell, Master thesis (2018)

Summary

- Germanium is used in many experiments related to fundamental neutrino studies and dark-matter searches
- Regular calibrations are indispensable to properly identify event signals
- In $0\nu\beta\beta$ searches (GERDA, MJD, LEGEND), ^{228}Th sources were/are used to maintain stable energy scale and resolution
- In DM searches (SuperCDMS), ^{113}Ba sources are used to calibrate the ionization and the phonon energies, and ^{252}Cf sources are used to specify nuclear-recoil-event signal region
- Calibration performances of individual experiments were demonstrated

Thank you for your attention ~

Low-energy calibrations of MJD

- ^{212}Pb x rays at ~ 80 keV
- ^{212}Pb γ ray at ~ 238 keV → multiplicity-2 coincidence tagging

Useful for low-energy BSM searches

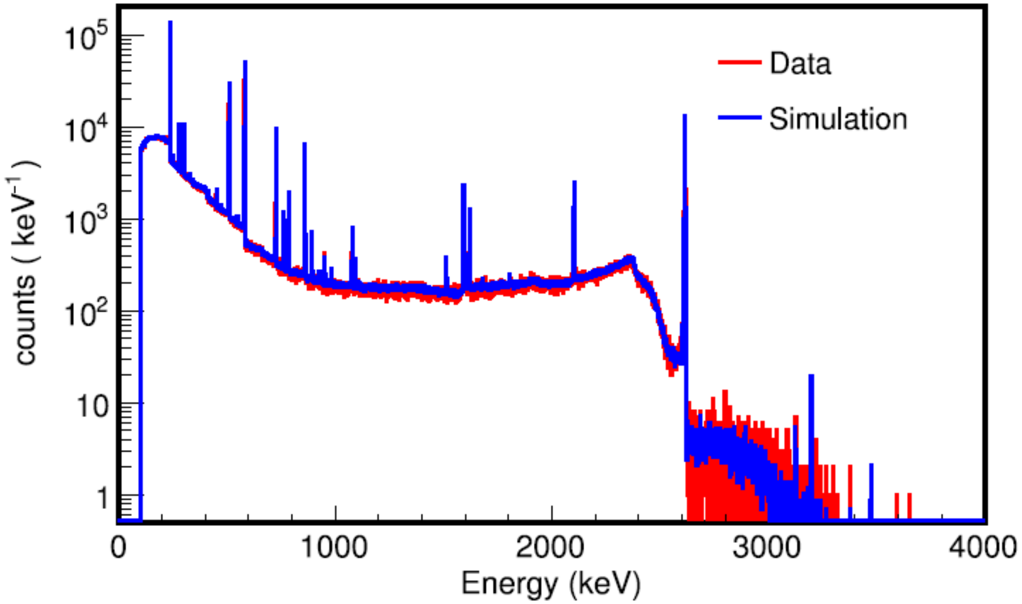
Ref: NuDat

Gamma and X-ray radiation:

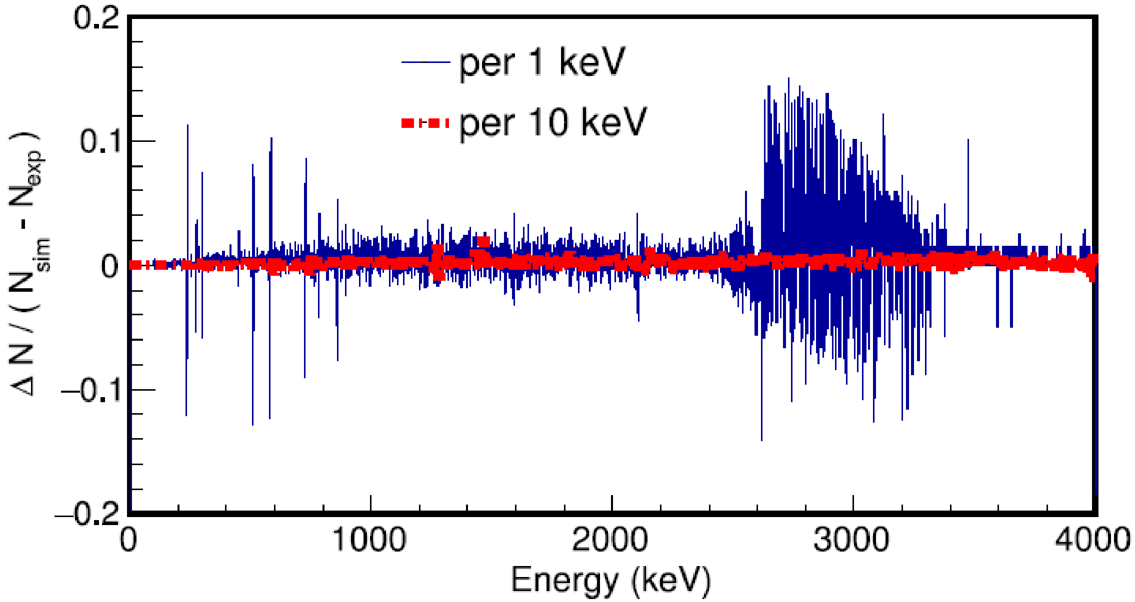
	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
XR l	10.8	13.7 % 6	0.00148 6
XR kα2	74.815	9.9 % 3	0.00738 20
XR kα1	77.107	16.4 % 4	0.0127 3
XR kβ3	86.83	1.99 % 5	0.00173 4
XR kβ1	87.349	3.81 % 10	0.00333 8
XR kβ2	89.784	1.40 % 4	0.00126 3
	115.183 5	0.596 % 9	6.87E-4 11
	176.68 5	0.052 % 6	9.2E-5 11
	238.632 2	43.6 % 5	0.1040 13
	300.087 10	3.30 % 4	0.00990 13
	415.2	0.0131 % 22	5.4E-5 9

MJD calibration measurements for the simulation campaign

- The simulations using Geant4 are compared to measurements to validate the implementation of the geometry.
- The simulation geometry includes the track, the full copper cryostat, structural material, shielding, and a thin ‘‘dead layer’’.



The simulated distribution was normalized by matching the integrals of both curves in the range from 2595 keV to 2635 keV



Residual between simulation and experiment for the 1-keV binning (blue) averaged over a 10-keV wide window (red)

- Also uses ^{212}Pb x/γ rays at ~80 and 238 keV for low-energy calibrations

Ref.: N. Abgrall et al., Nucl. Inst. Meth. A 872 16-22 (2017)