Experimental progress in neutrinoless double beta decay

– with a focus on LEGEND

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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On behalf of the LEGEND collaboration

Department of Physics
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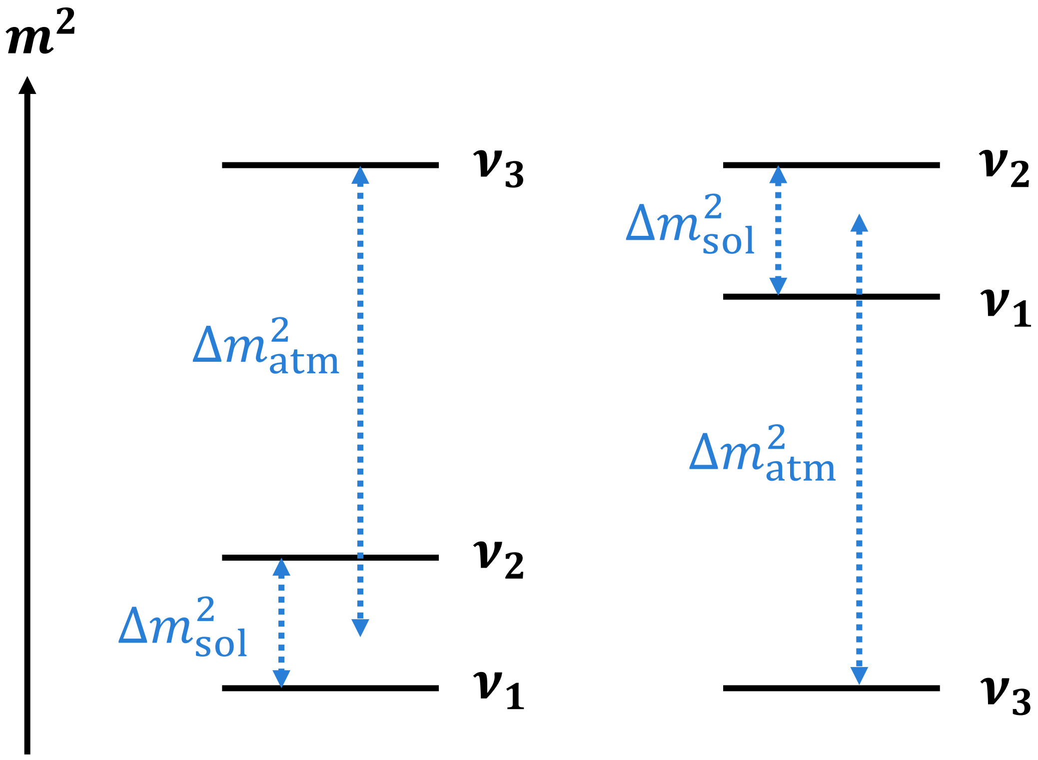
Peking University, Beijing, China

Open questions in neutrino physics

See Yu-Feng Li's talk on Monday

- **Neutrino mass ordering and absolute scale**

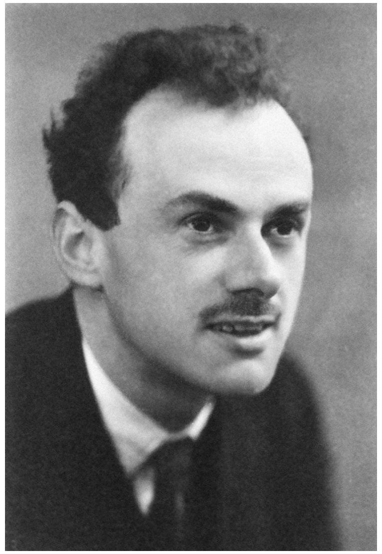


Normal Ordering

Inverted Ordering

- **Nature**

Observed: ν_L and $\overline{\nu_R}$



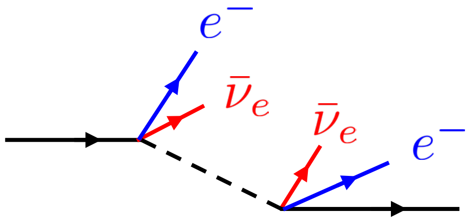
Dirac mechanism
$\nu \neq \overline{\nu}$

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

Neutrinoless double beta decay

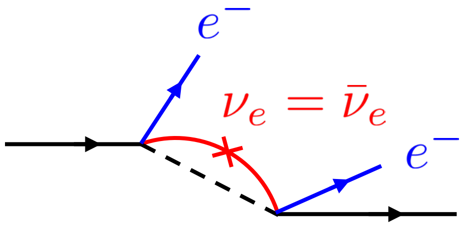
- **Two neutrino double beta decay 2νββ**
  - Standard-Model-allowed process
  - Nature provides 35 isotopes, e.g., ^{76}Ge, ^{100}Mo, ^{136}Xe

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



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

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



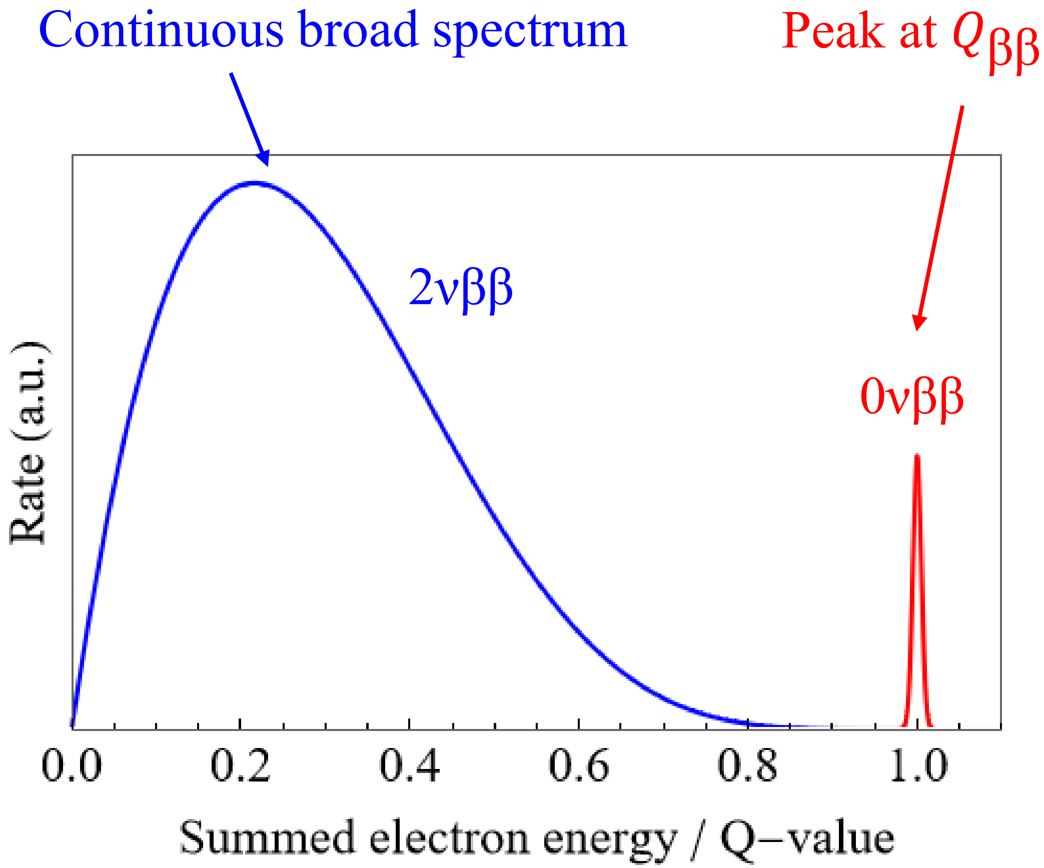
If observed:

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

Experimental detection approach

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

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



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 ($Q_{\beta\beta}$)

Various detection concepts

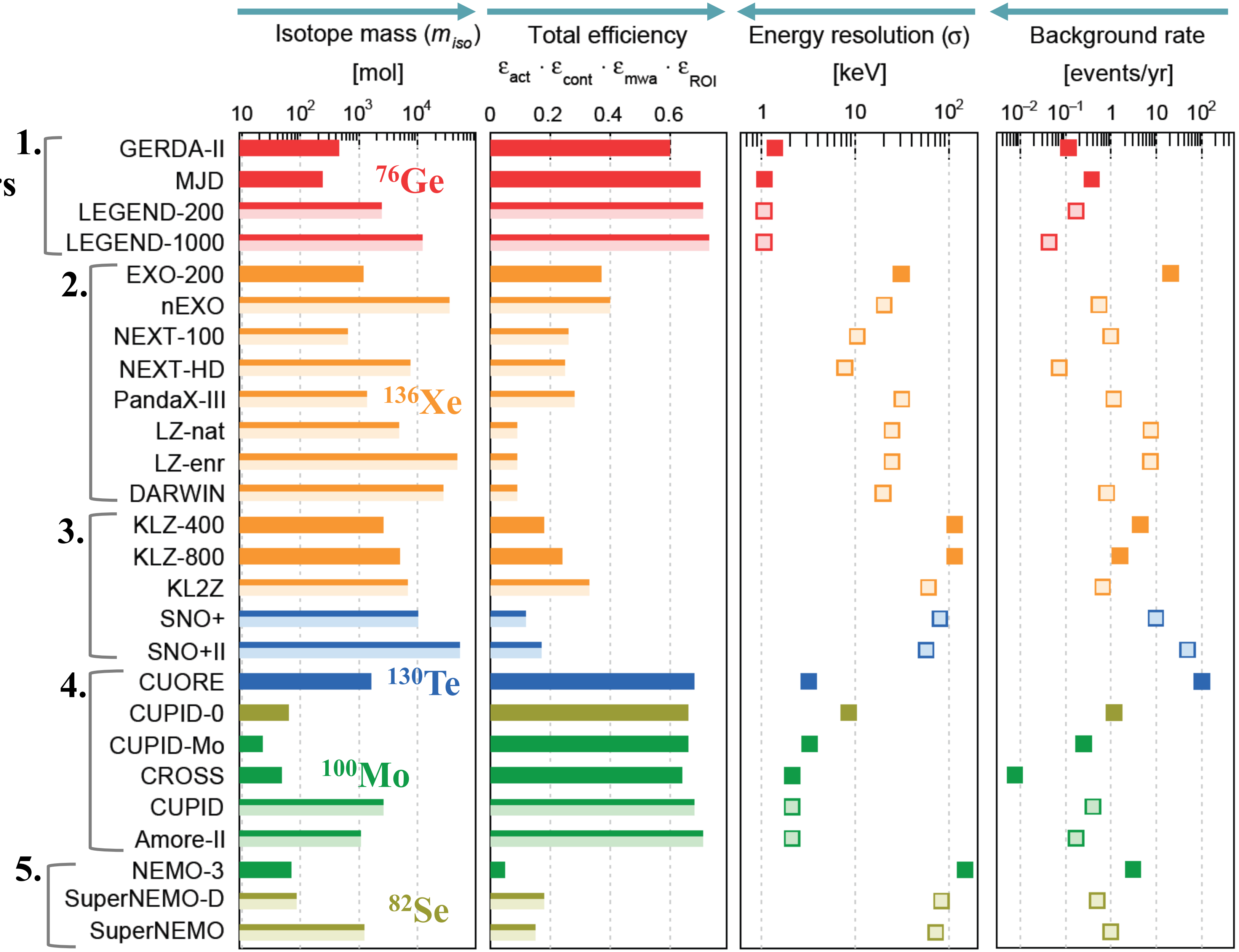
1. **High-purity germanium detectors**
   energy resolution, efficiency, background

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

3. **Large liquid scintillators**
   isotope mass

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

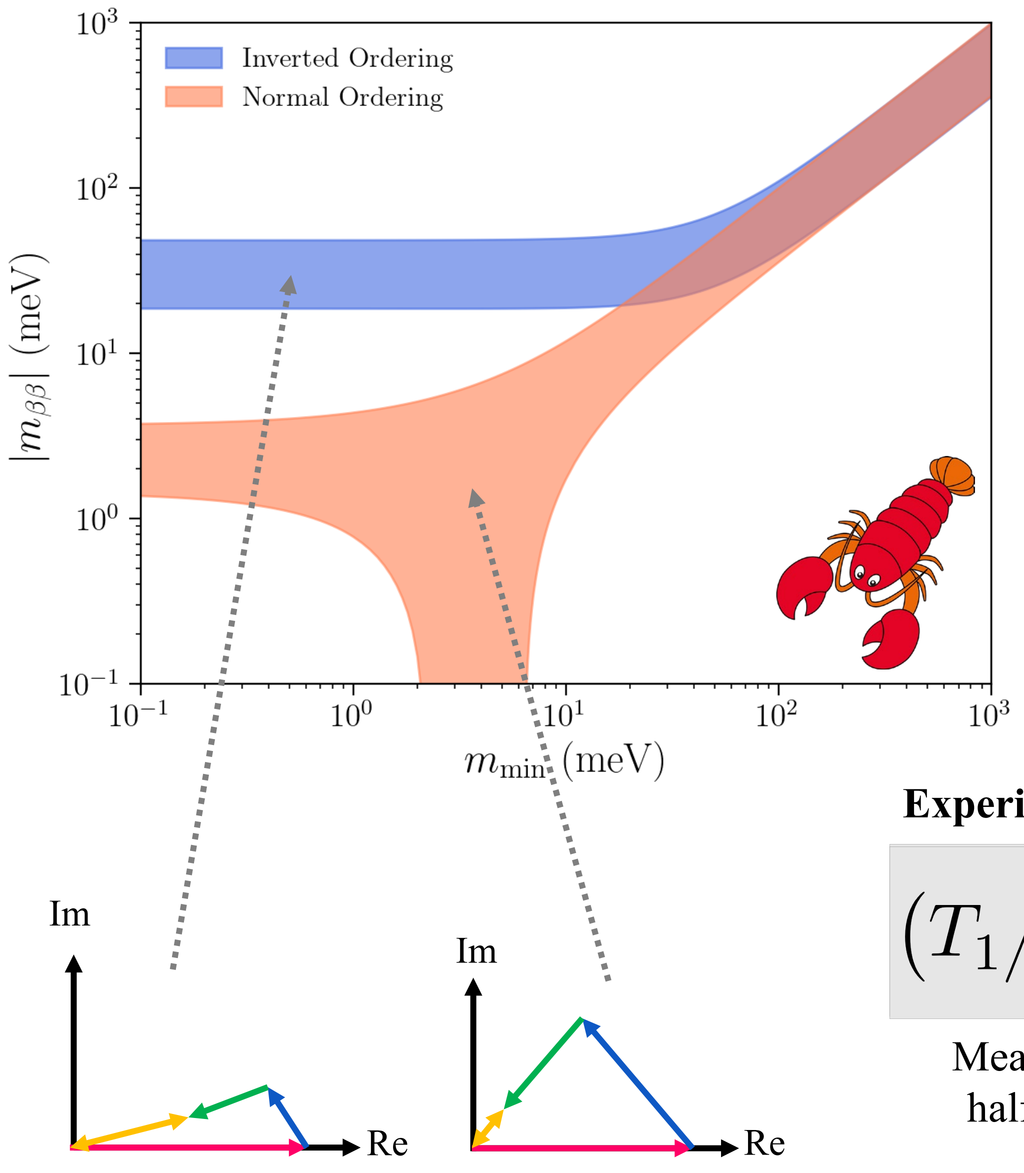
5. **Tracking calorimeters**
   particle tracking



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

Effective Majorana neutrino mass

LEGEND



$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right|$$

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

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

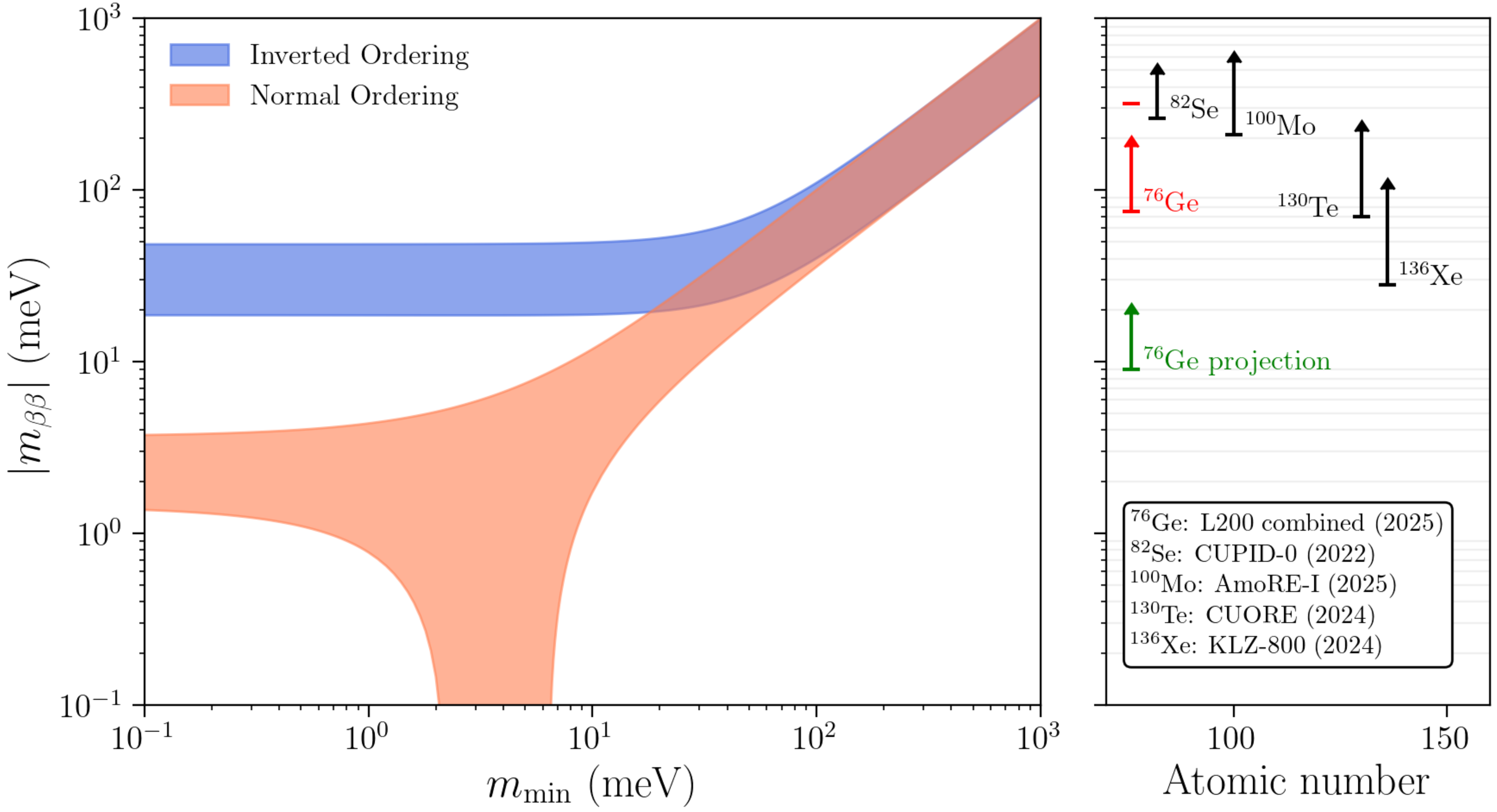
Recently best limits

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)

Where the community is standing

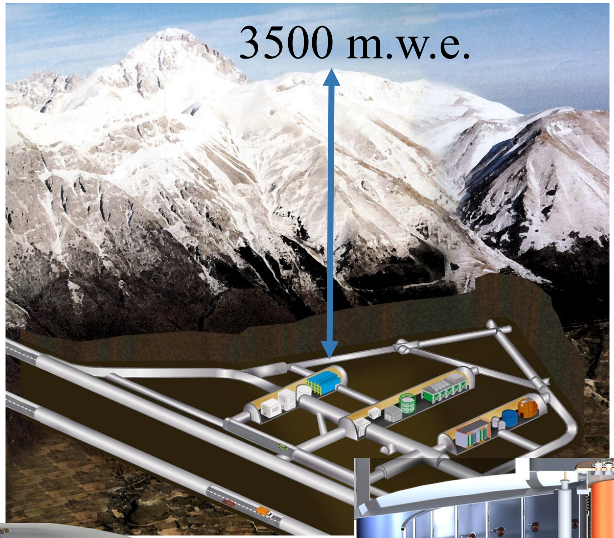


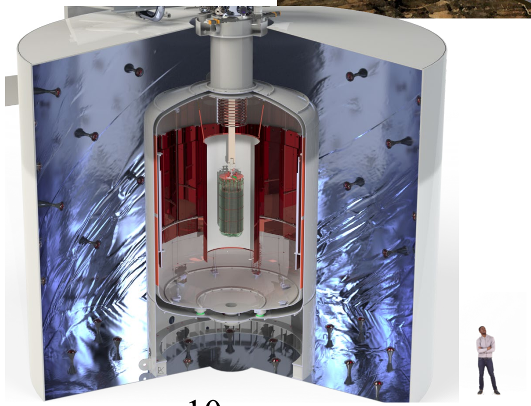
The LEGEND project

Phase I: LEGEND-200

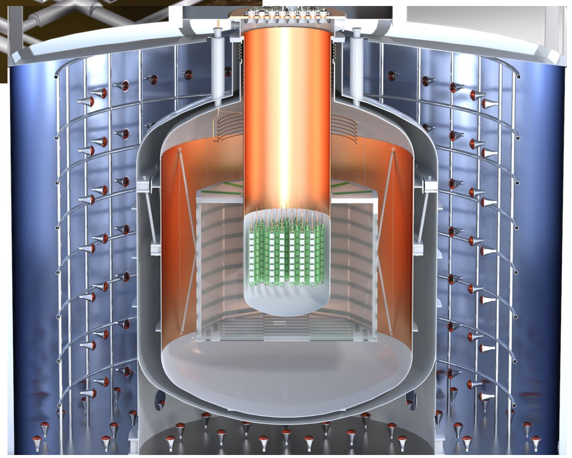
- Up to 200 kg of Ge detectors in modified existing GERDA infrastructure
- Taking physics data since 2023. Will continue until 1 t · yr of exposure is reached
- BI goal: 2×10^{-4} counts/(keV·kg·yr)
- $T_{1/2} > 10^{27}$ yr

Laboratori Nazionali del Gran Sasso, Italy





10 m



12 m

Phase II: LEGEND-1000

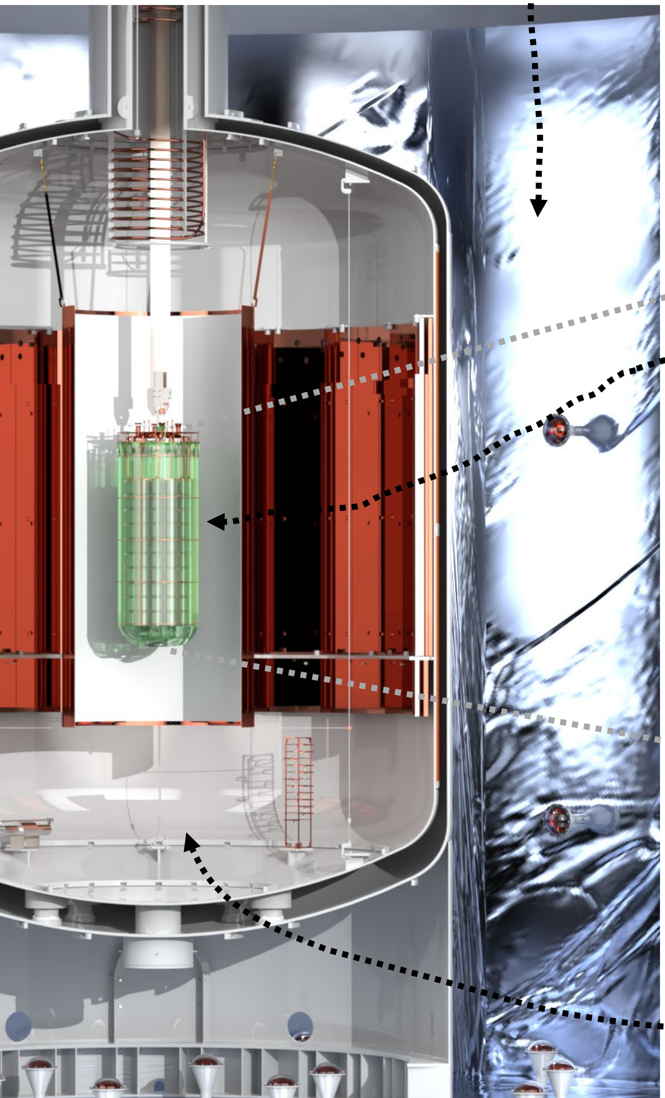
- 1000 kg of Ge detectors
- 10 t · yr of exposure
- BI goal: 1×10^{-5} counts/(keV·kg·yr)
- $T_{1/2} > 10^{28}$ yr
- $m_{\beta\beta}$ would cover full $m_{\beta\beta}$ inverted ordering regime

Ref.: LEGEND-1000 Preconceptual Design Report

LEGEND-200 at LNGS

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

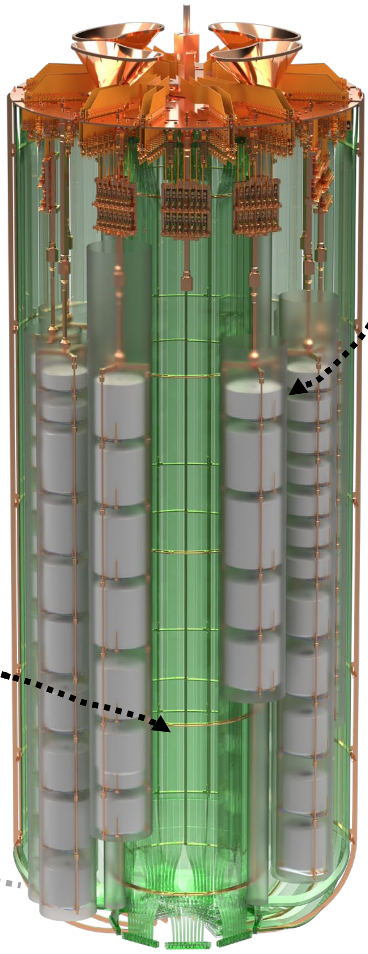
Detector array with max. 12 detector strings



Wavelength-shifting reflector

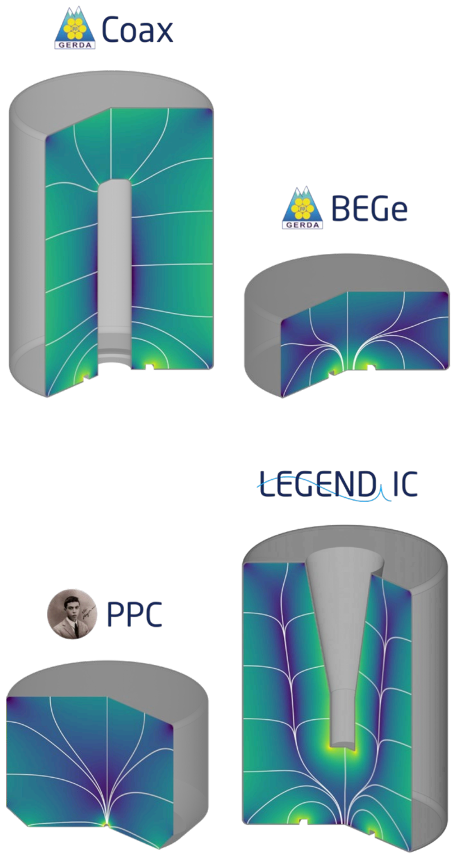
Inner and outer fiber barrels with silicon photomultiplier (SiPM) readouts at top and bottom

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



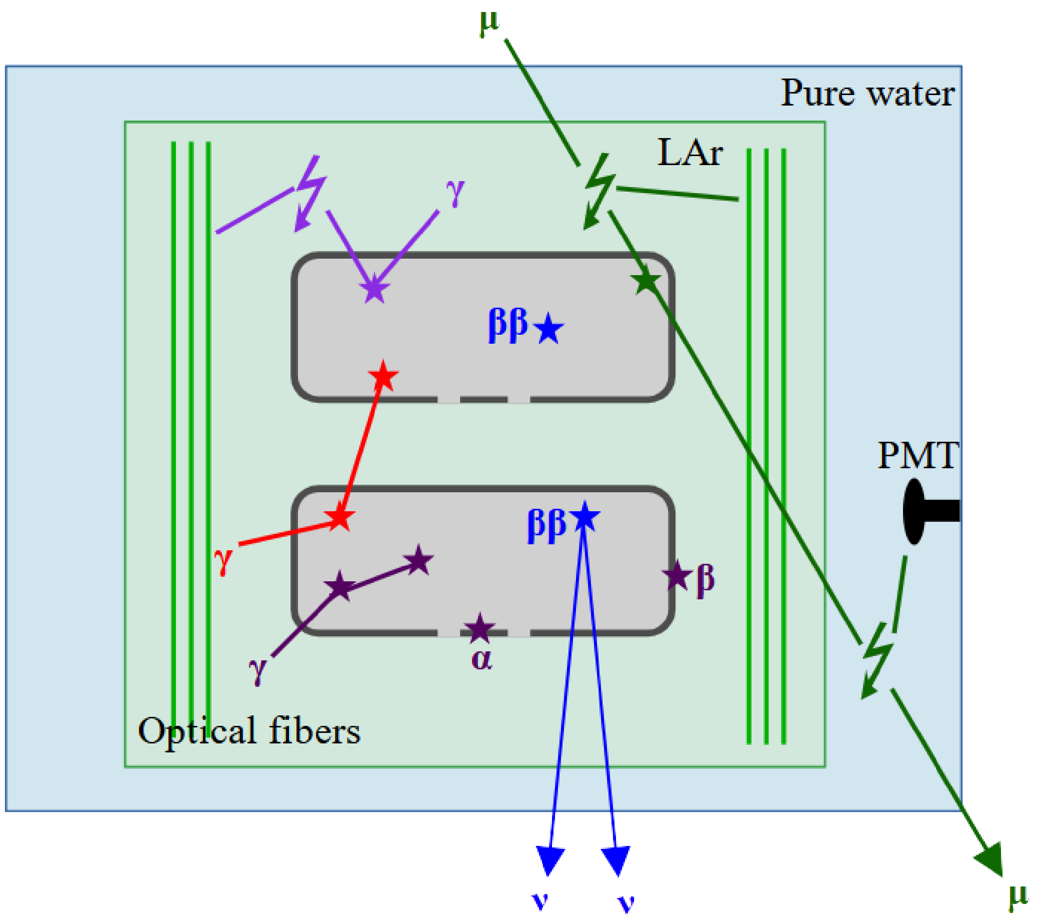
Detector unit

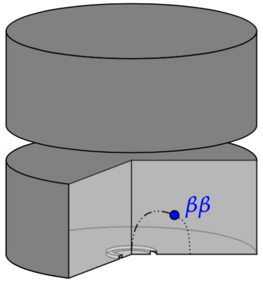
Four detector types



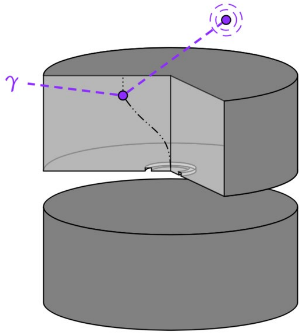
Background mitigation

- 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

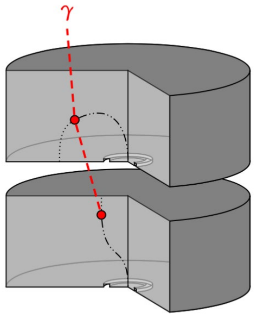




Single Ge



Ge + LAr

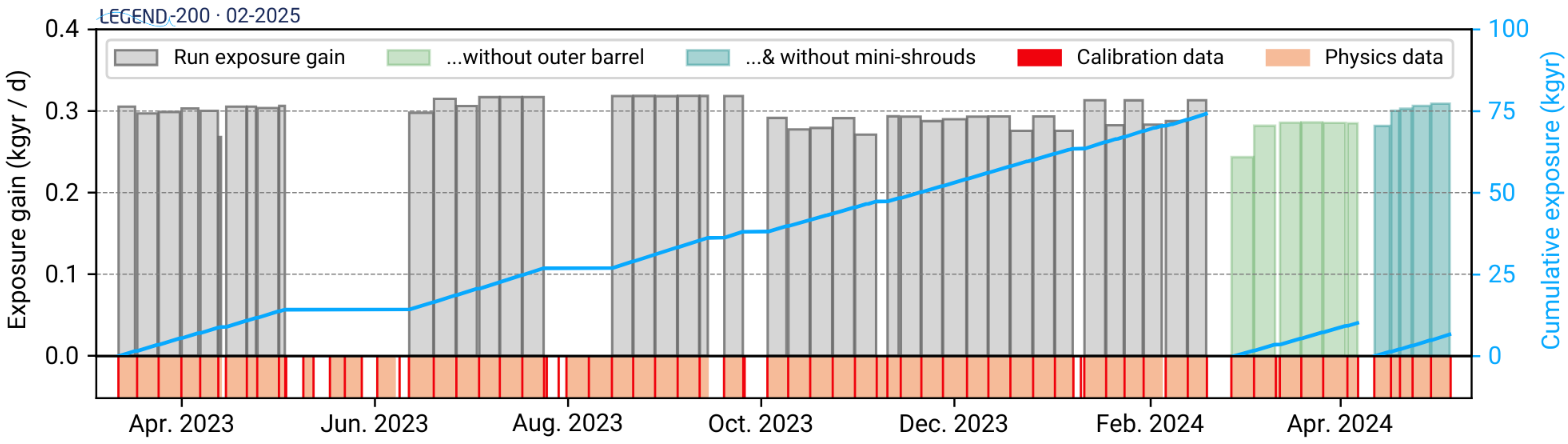


Multiple Ge

New LEGEND-200 results

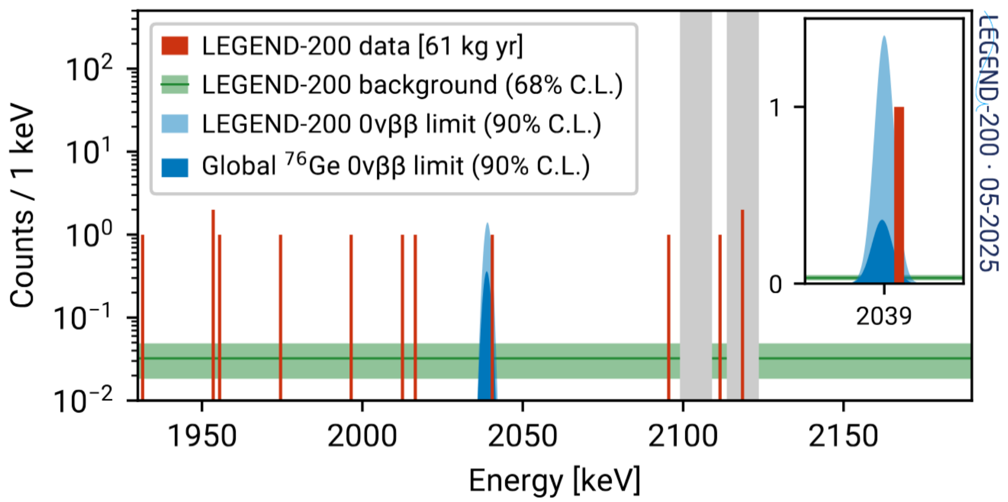
Ref.: LEGEND Collab., arXiv:2505.10440 [hep-ex] (2025)

- 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



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 $T^{0\nu}_{1/2} > 0.5 \times 10^{26}$ 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)
$T^{0\nu}_{1/2}$	$> 1.9 \times 10^{26}$ yr	2.8×10^{26} yr

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

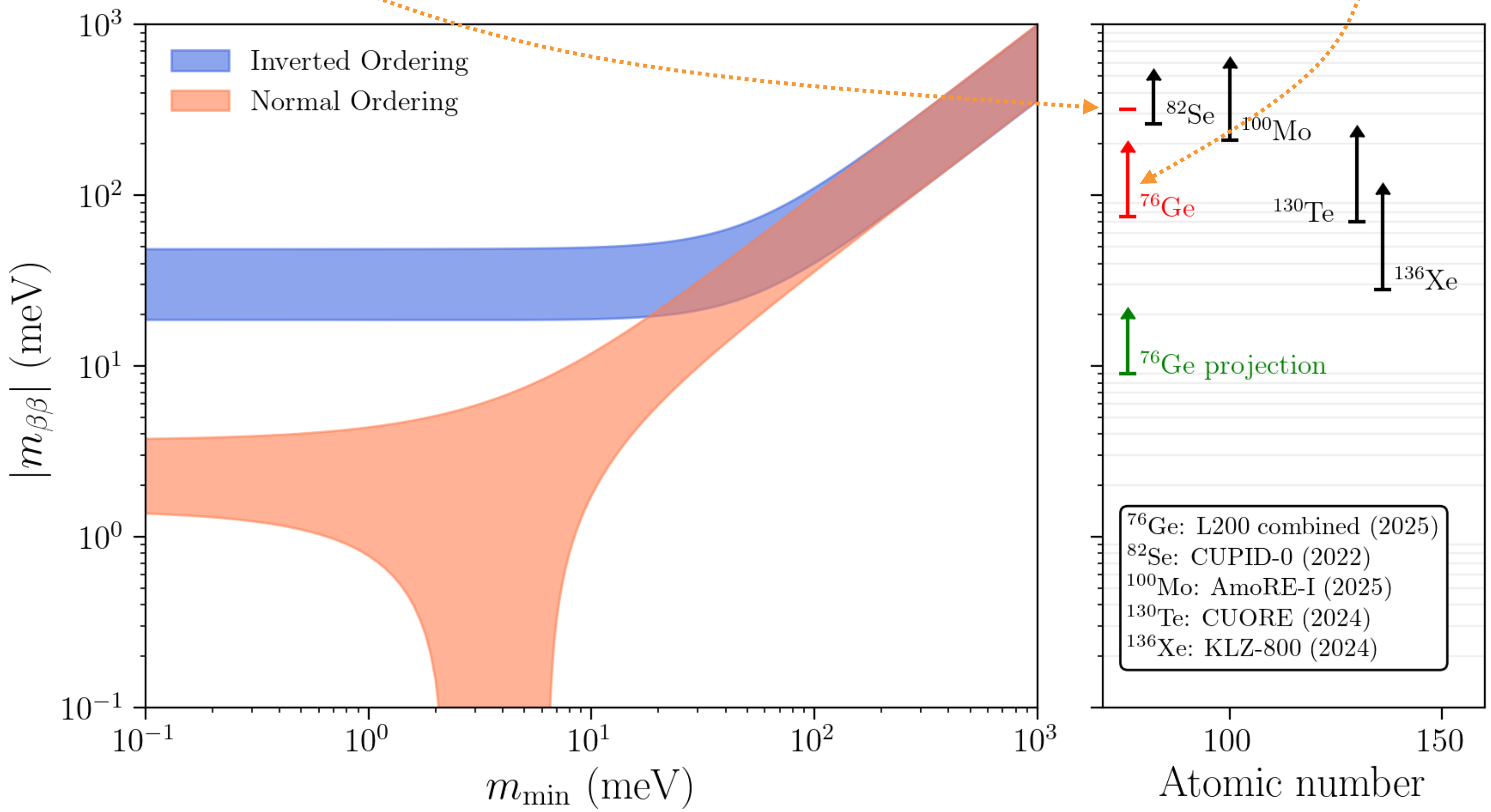
$$\left(T_{1/2}\right)^{-1} = G\left(Q_{\beta\beta}, Z\right) \cdot {g_A}^4 \cdot \left|M_{\text{nucl}}\right|^2 \cdot {m_{\beta\beta}}^2$$

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

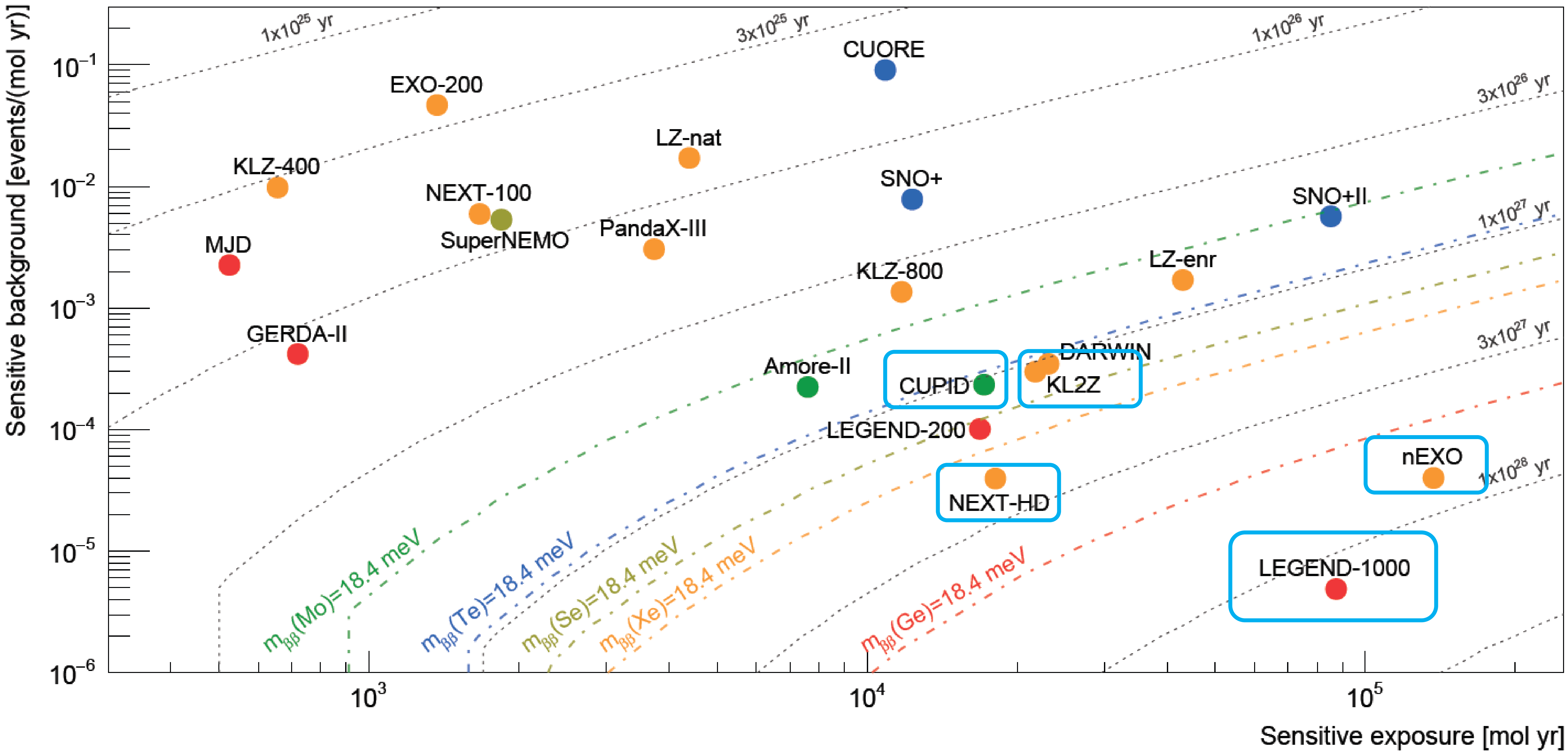
$m_{\beta\beta} < 320$ meV (Bayesian 90% CI)

Phenomenological NME: $2.35 - 6.34$

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



Sensitivity overview



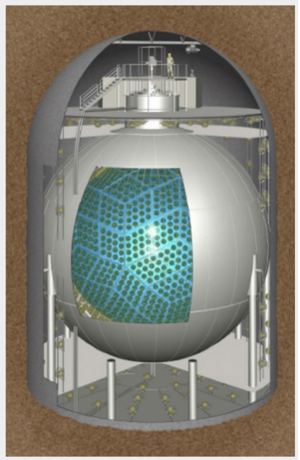
Ref.: M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)

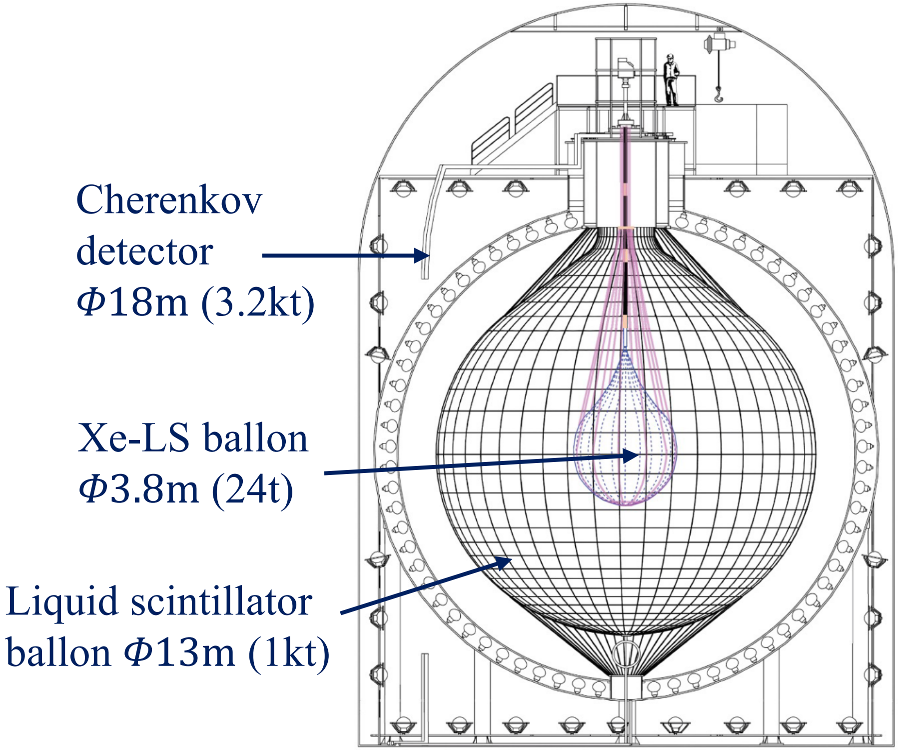
Walking towards LEGEND-1000

- 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

KamLAND-Zen

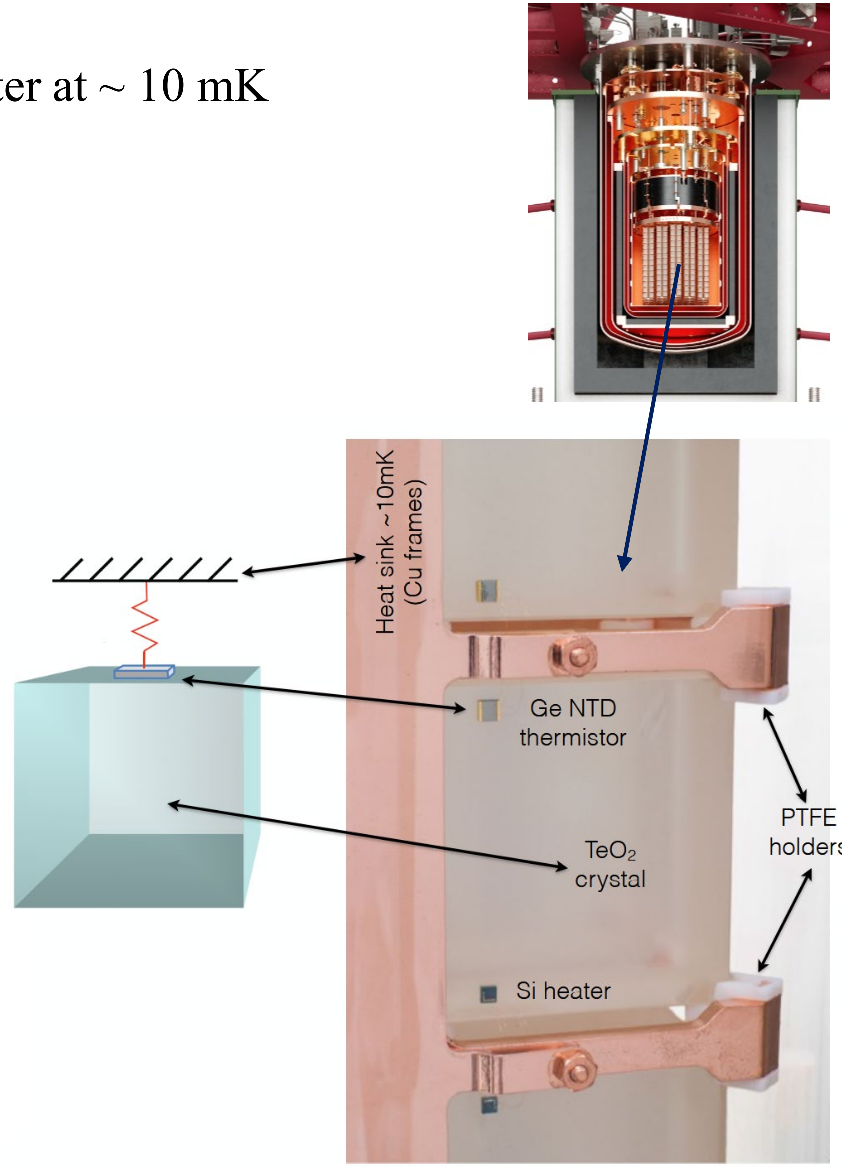
- KamLAND: general purpose detector (solar, geo, reactor, accelerator, astrophysical neutrinos, 0νββ)
- KamLAND-Zen
  - ^{136}Xe-loaded liquid scintillator (91% enriched)
  - $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e^-$ (Q-value 2458 keV)
  - Zen-400: 380 kg Xe (Oct. 2011– Oct. 2015) / Zen-800: 750 kg Xe (Feb. 2019 – Jan. 2014)
- KamLAND-Zen-800
  - 2.1 t yr exposure
  - Currently best limit: $T_{1/2}^{0\nu} > 3.8 \times 10^{26}$ yr; $m_{\beta\beta} < (28\text{–}122)$ meV
- Upgrade to KamLAND2-Zen
  - Scintillating inner ballon
  - Improved energy resolution
  - New electronics for enhanced tagging efficiency
  - KamLAND dismantling & KamLAND2 construction ongoing
  - Expected launch in 2027
  - Target sensitivity $m_{\beta\beta} = 20$ meV



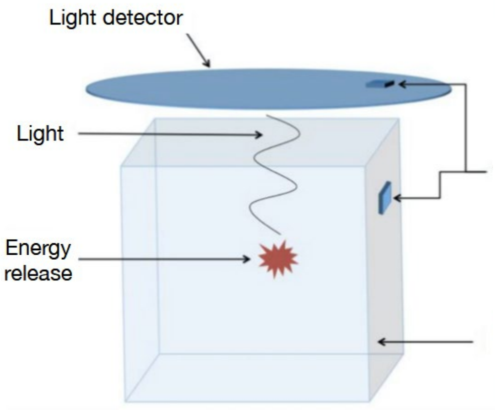


CUORE/CUPID

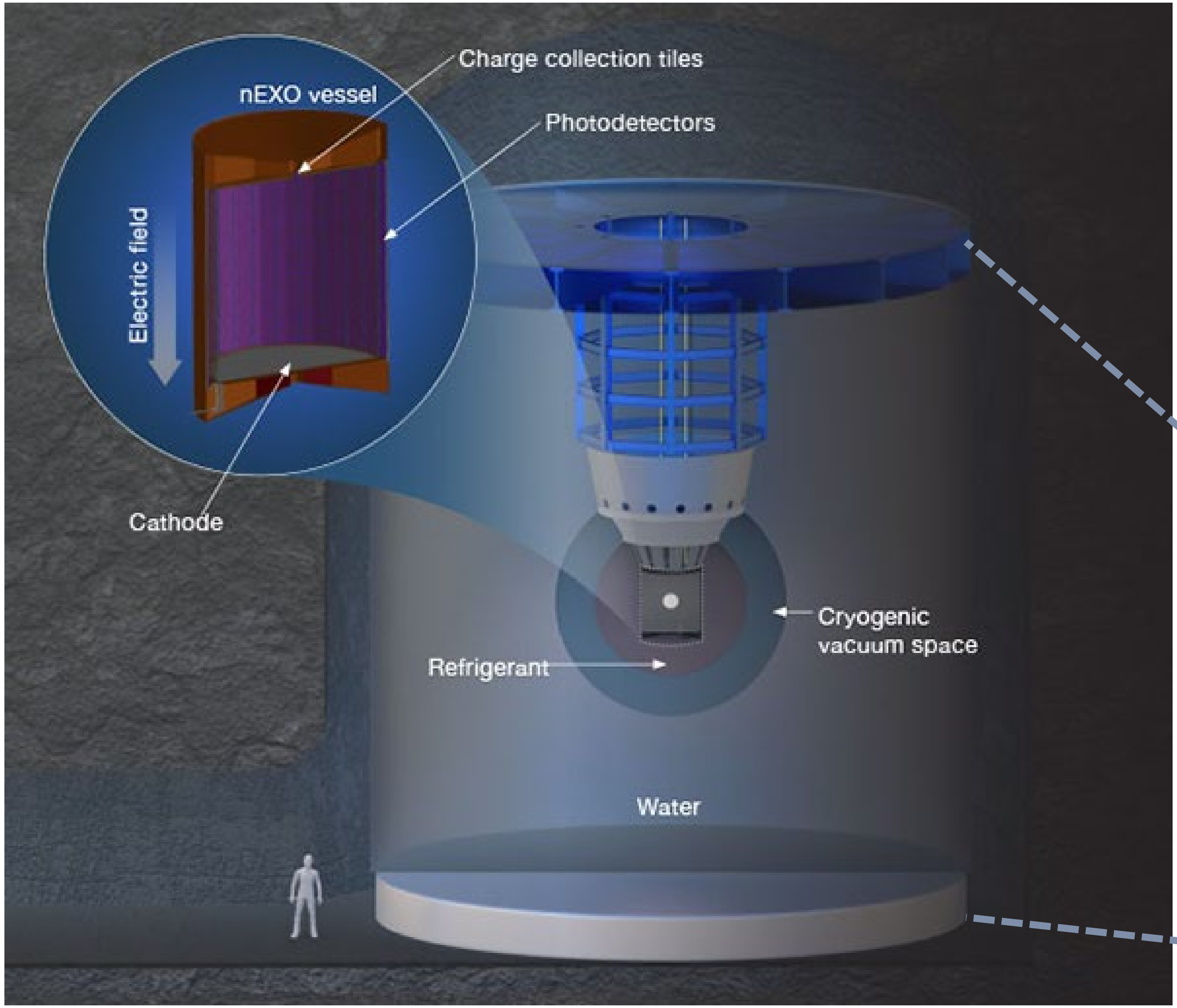
- 988 closely packed TeO_2 crystals (750 g each) working as cryogenic calorimeter at ~ 10 mK
- $^{130}Te \rightarrow {}^{130}Xe + 2e^-$ (Q-value 2527 keV)
- Latest results on ^{130}Te 0νββ search
  - May 2017 – Apr. 2023
  - 567.0 kg yr ^{130}Te (= 2039.0 kg yr TeO_2) exposure
  - $T_{1/2}^{0\nu} > 3.8 \times 10^{25}$ yr; $m_{\beta\beta} < (70\text{–}240)$ meV
  - Will continue until reaching 3 t yr of TeO_2 exposure (~ end of 2025)
  - Upgrade of the cryogenic system in view of CUPID



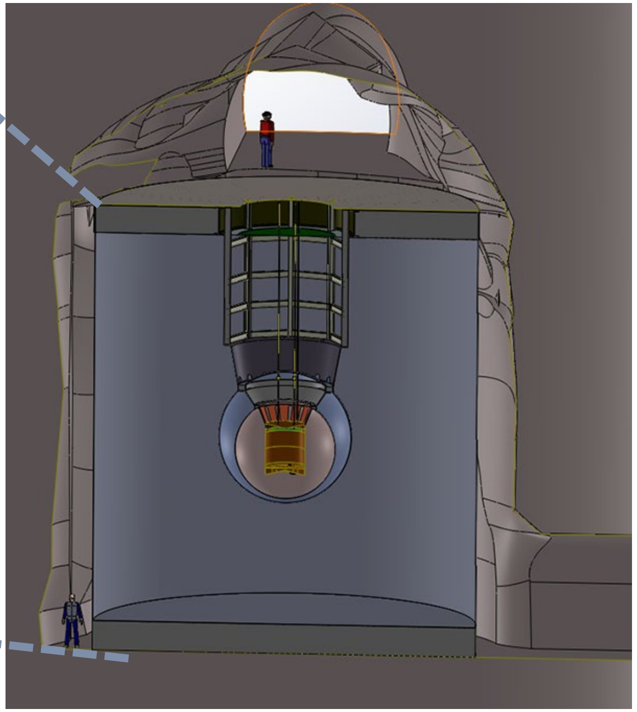
- CUPID
  - $TeO_2 \rightarrow$1596 Li_2MoO_4 scintillating crystals
  - $^{100}Mo \rightarrow {}^{100}Ru + 2e^-$ (Q-value 3034 keV)
  - 450 kg total mass (240 kg of ^{100}Mo)
  - Double readout for particle identification:
    heat + light (top and bottom Ge light detectors)



nEXO

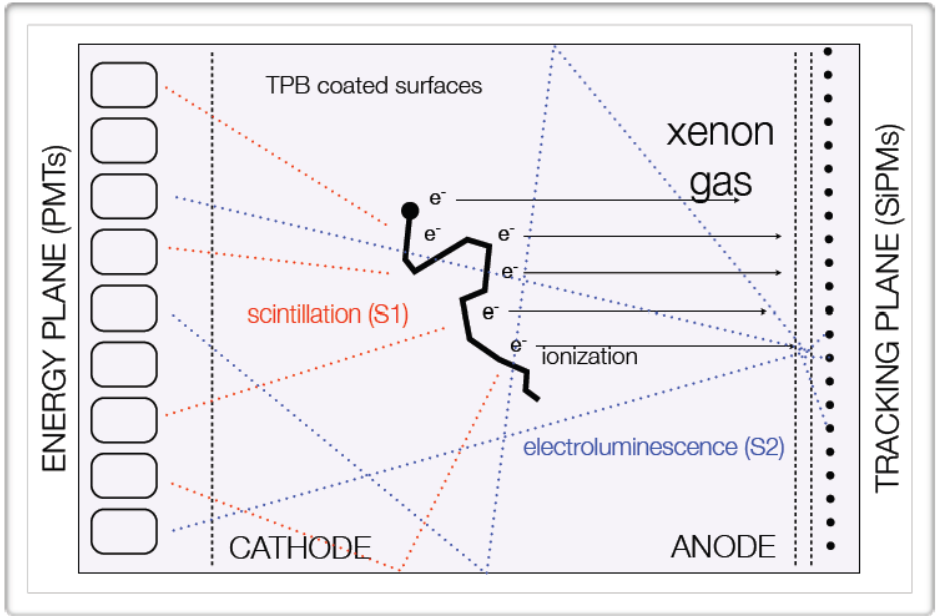


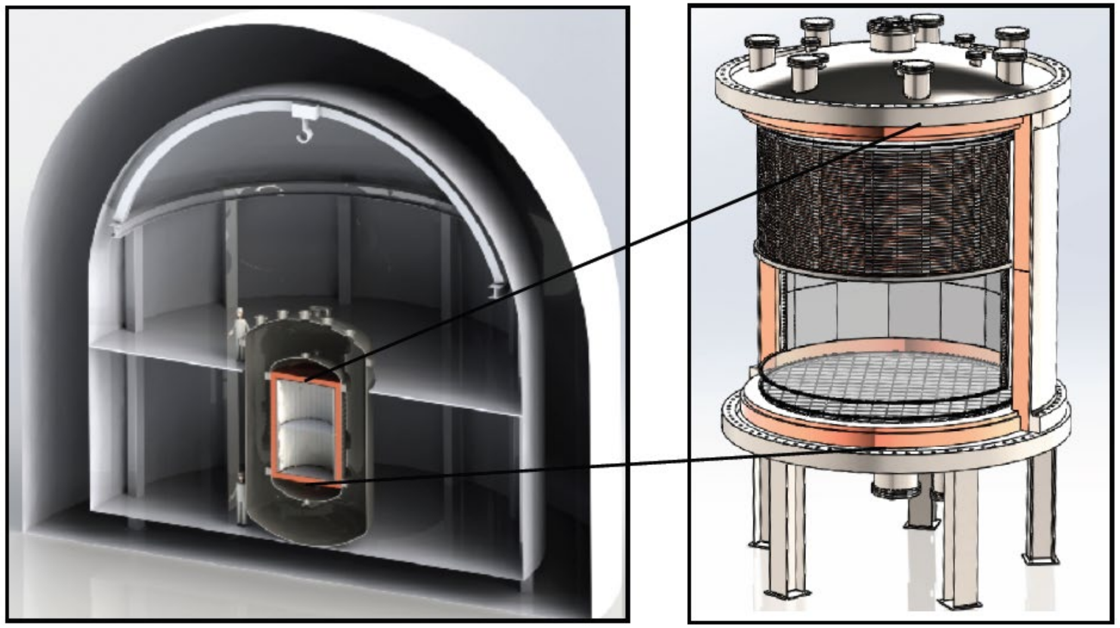
- Builds on successful EXO-200 predecessor
- 5 t enriched LXe TPC (^{136}Xe)
- 50 kV voltage difference
- Sensitivity: 10^{28} yr in 6.5 yr data taking



NEXT-HD & NEXT-BOLD

- Module(s) of 1 t of ^{136}Xe building in NEXT technologies
- High pressure xenon gas TPC with electroluminescence
- NEXT program:
  - NEXT-white (2015–2021): background model assessment and $2\nu\beta\beta$ measurement
  - NEXT-100 (2022–2026): $0\nu\beta\beta$ search with 10^{27} yr sensitivity
  - NEXT-HD & NEXT-BOLD: ton scale and background with 10^{28} yr sensitivity





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

Thank you ~

https://legend-exp.org/

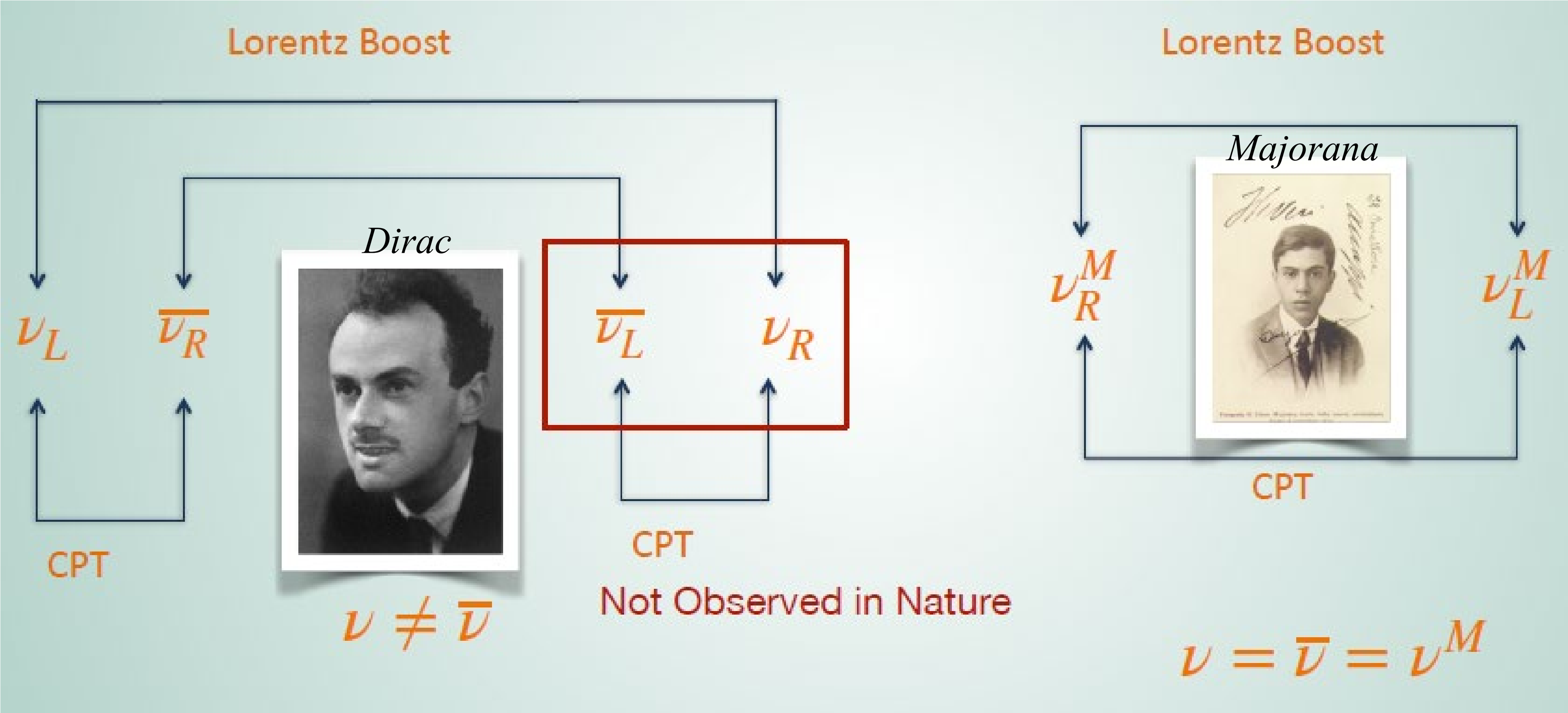
Backup slides

Where does neutrino mass come from?

Slide from R. Henning

Neutrino nature: Dirac or Majorana?

N.B.: only valid if neutrinos are massive



Where does neutrino mass come from?

- Dirac mass: couple left-handed particles to right-handed particles (generated by Higgs mechanism)

$$\mathcal{L}_D = -m_D \left(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R\right)$$

- Majorana mass: couple left-handed particles to right-handed antiparticles

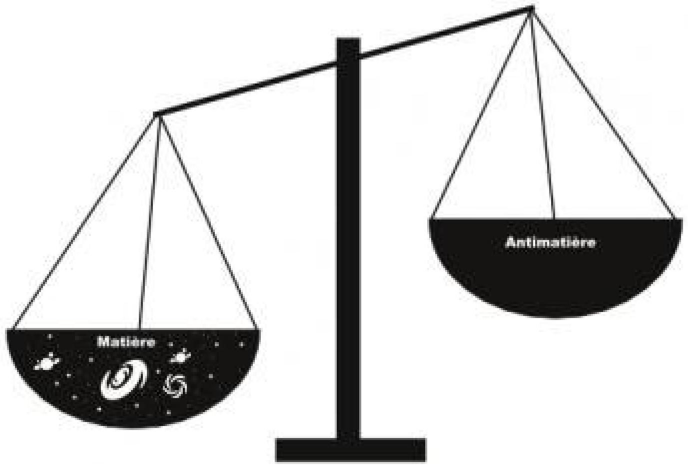
$$\mathcal{L}_L = -\frac{1}{2}m_L \left(\overline{\nu_L}\nu_L^c + \overline{\nu_L^c}\nu_L\right)$$

$$\mathcal{L}_R = -\frac{1}{2}m_R \left(\overline{\nu_R}\nu_R^c + \overline{\nu_R^c}\nu_R\right)$$

The origin of matter

- Why is there more matter than antimatter in the Universe?
- Lepton number violation (leptogenesis) → explanations to baryon asymmetry of the Universe

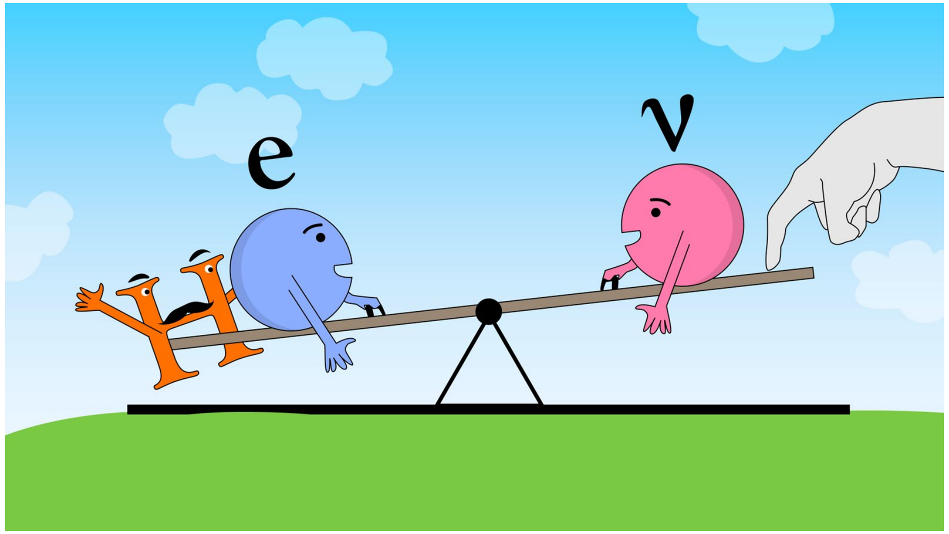
Credit: Atronomy



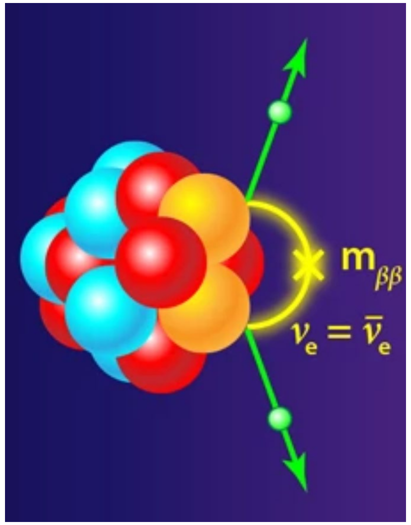
Credit: GANIL

Observation of 0νββ

- Lepton number violation
- Information about matter asymmetry of the Universe
- Neutrinos have a Majorana mass
- Hints on neutrino mass scale and mass ordering



Credit: Symmetry magazine



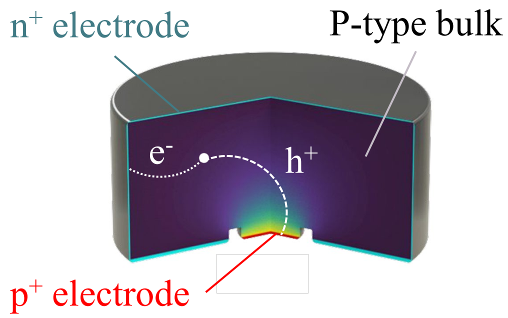
Credit: APS/A. Stonebraker

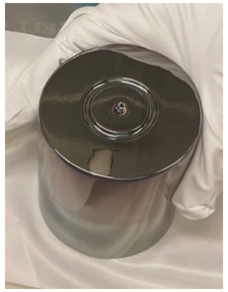
Advantages of using germanium detectors enriched in ^{76}Ge

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

Made from high-purity germanium (HPGe) materials

- Best energy resolution of any ββ detector
- Commercial semiconductor detectors
- Excellent detection efficiency
- High enrichment level
- No measurable internal background



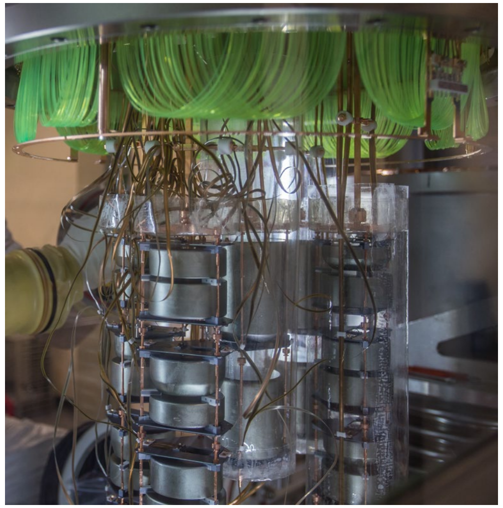


Source = Detector

~100% in the active volume

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

^{76}Ge-based 0νββ experiments

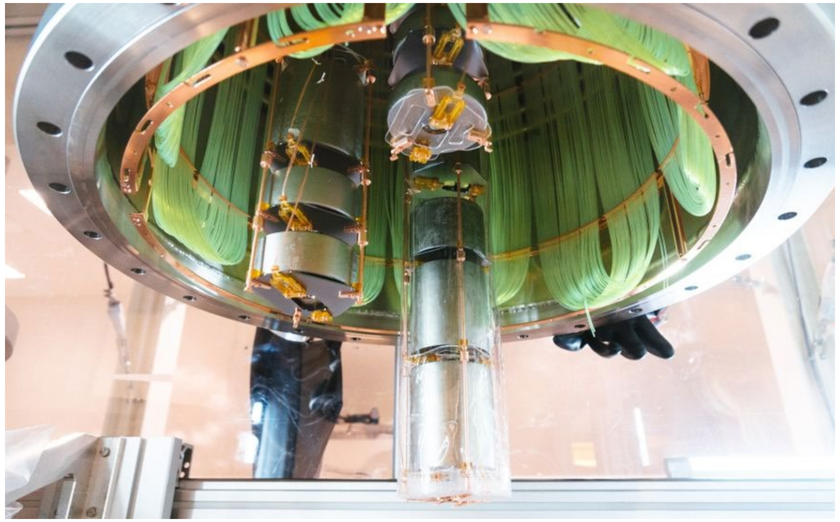


Credit: GERDA Collab.

LNGS, Italy

Credit: MAJORANA Collab.

SURF, US



LNGS, Italy

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

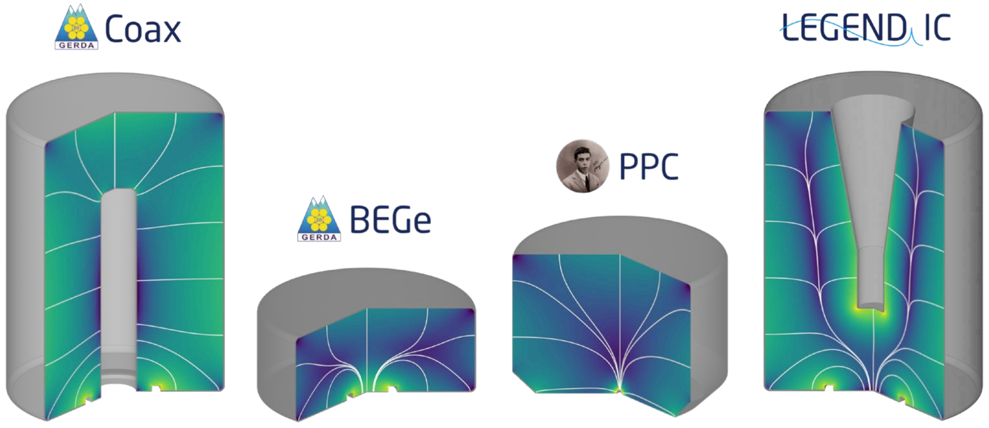
Lowest background level for 0νββ:
Mean background in ($Q_{\beta\beta}\pm2\sigma$) is 0.3 counts
(with 103.7 kg·yr of exposure)

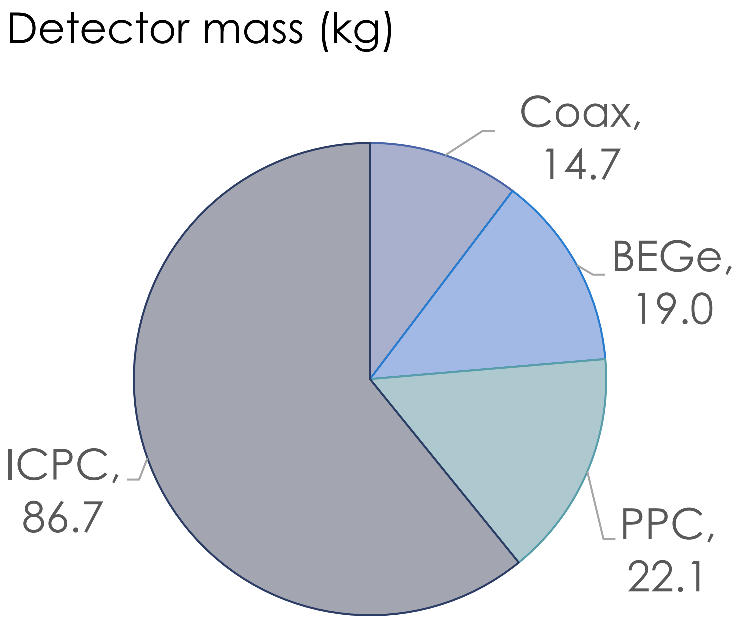
Ref.: GERDA Collab., PRL 125, 252502 (2020)

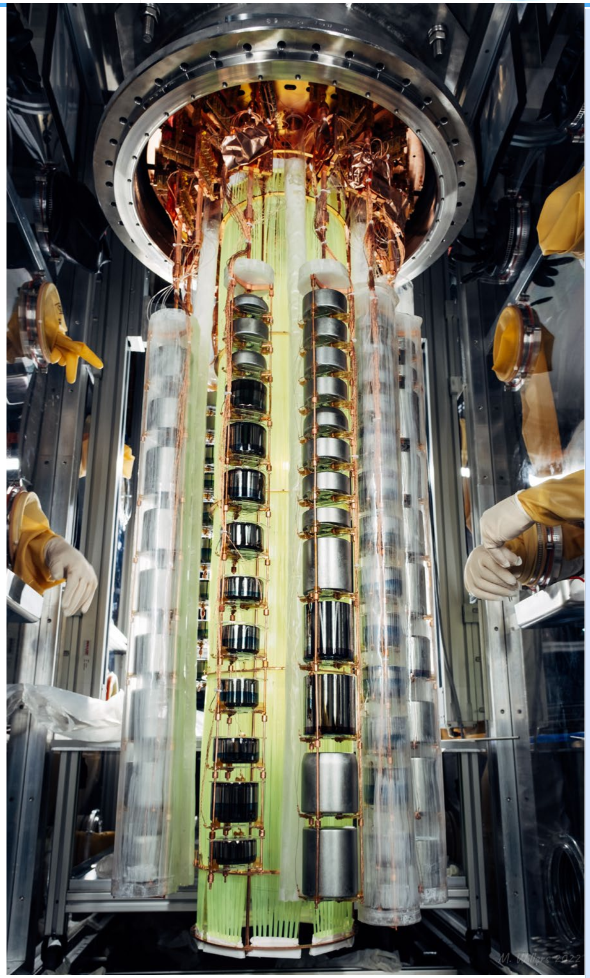
Best energy resolution for 0νββ:
2.52 keV (FWHM) at $Q_{\beta\beta}$
(with 64.5 kg·yr of exposure)

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

HPGe detectors



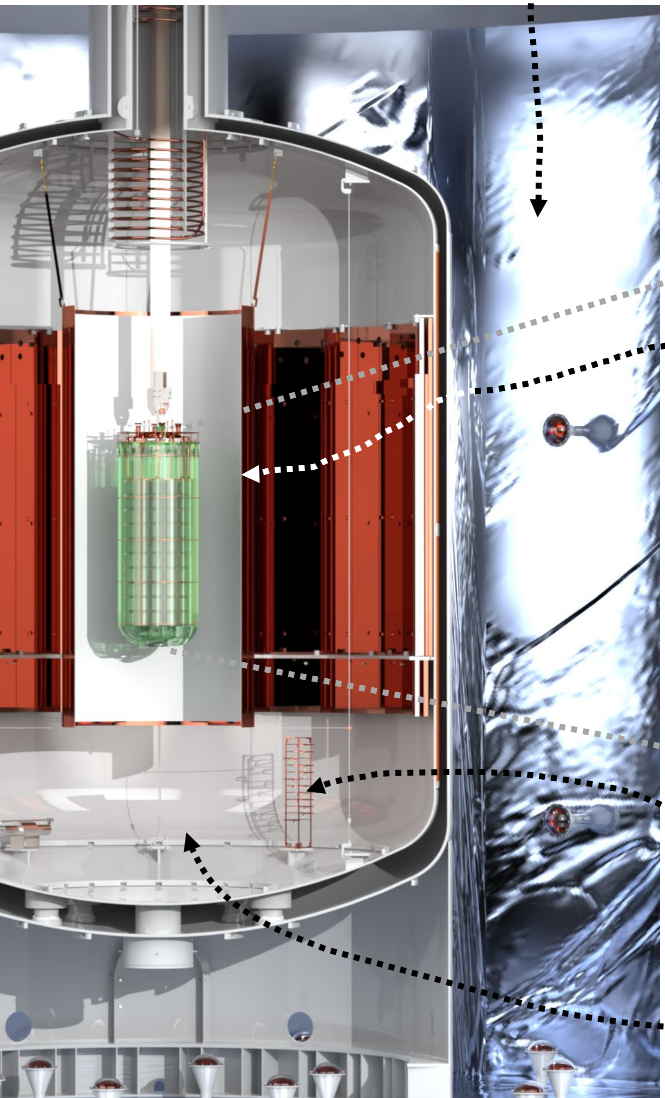




- First inserted 142 kg of detectors (Oct. 2022)
- Took data for ~ 1 yr (spring 2023 – spring 2024) with 130 kg of operational detectors

LEGEND-200 at LNGS

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

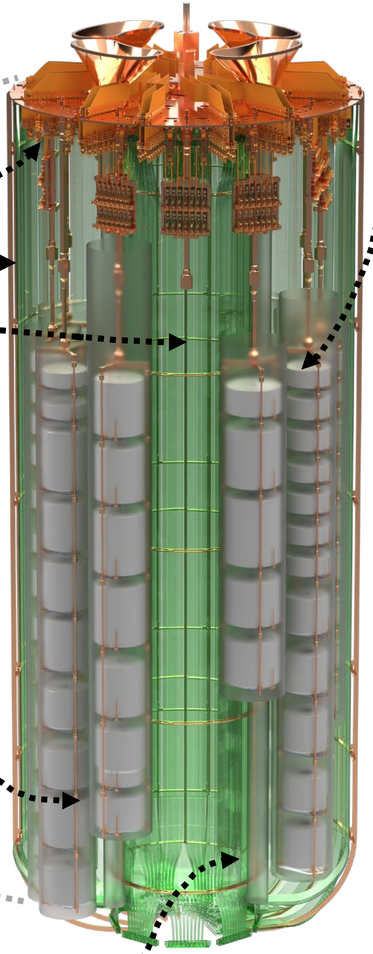


LAr instrumentation: inner and outer fiber barrels with silicon photomultiplier (SiPM) readouts at top and bottom, wavelength-shifting reflector

LLAMA argon purity monitor

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

Detector array with max. 12 detector strings

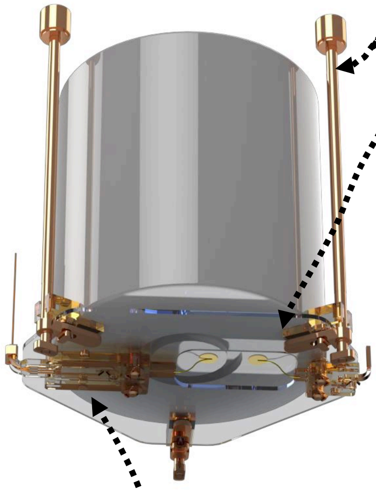


Detector unit

Nylon mini-shroud

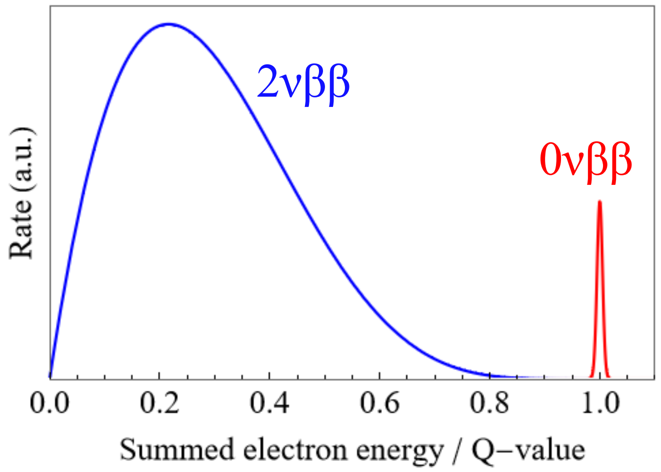
Calibration source tube

Detector mount: underground electroformed copper, optically active PEN scintillating plate



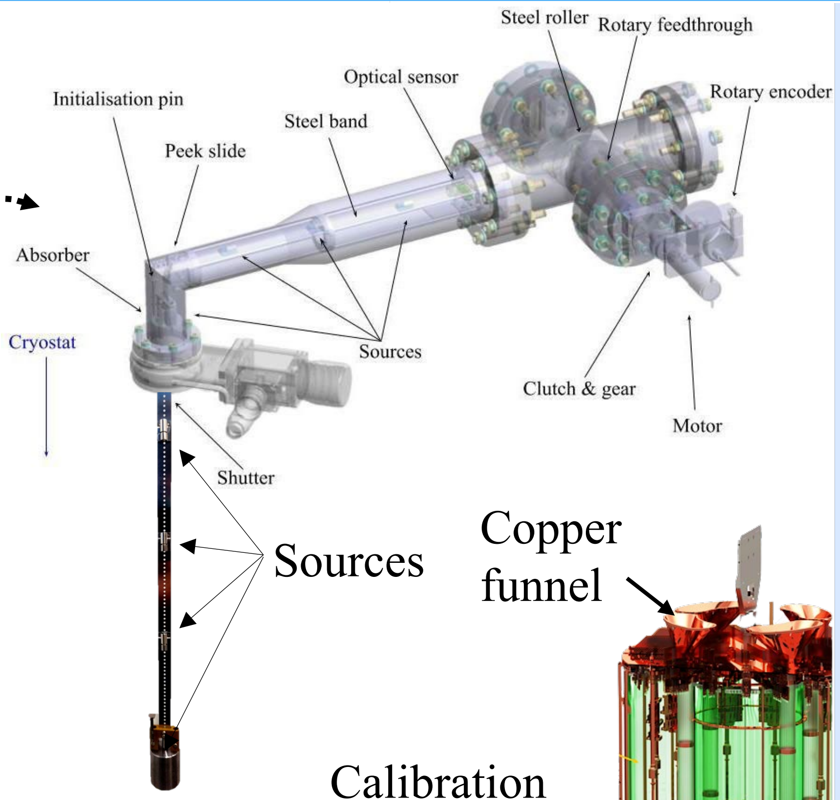
HPGe readout electronics: low-mass front-end and charge-sensitive amplifiers

Energy calibration of HPGe Detectors



Calibration source insertion systems

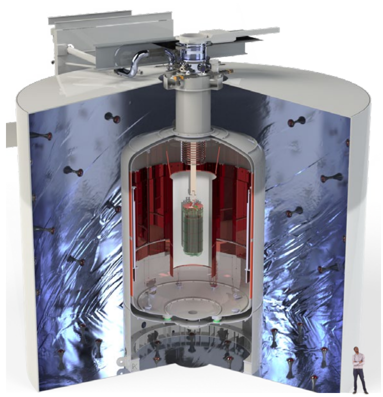
- Large-distance vertical movements of ~ 9 m
- Precision of 1 mm
- Reliability over the experimental duration

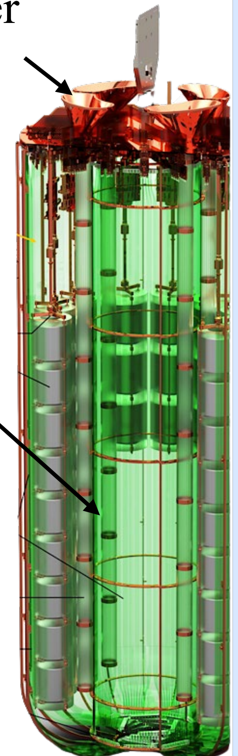


Sources

Copper funnel

Calibration source tube





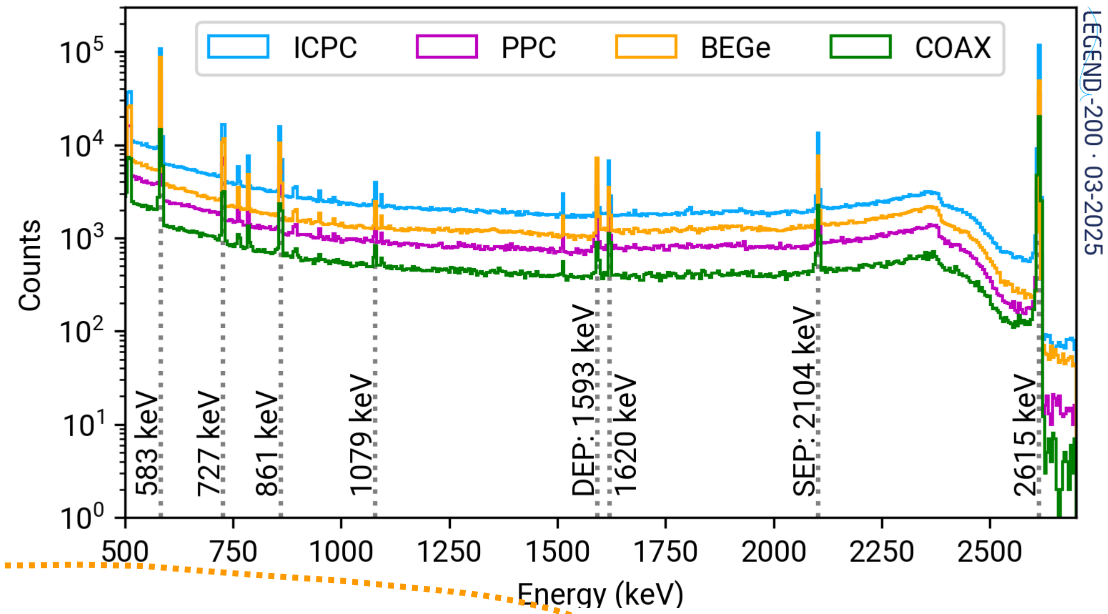
Precise identification of 0νββ requires:

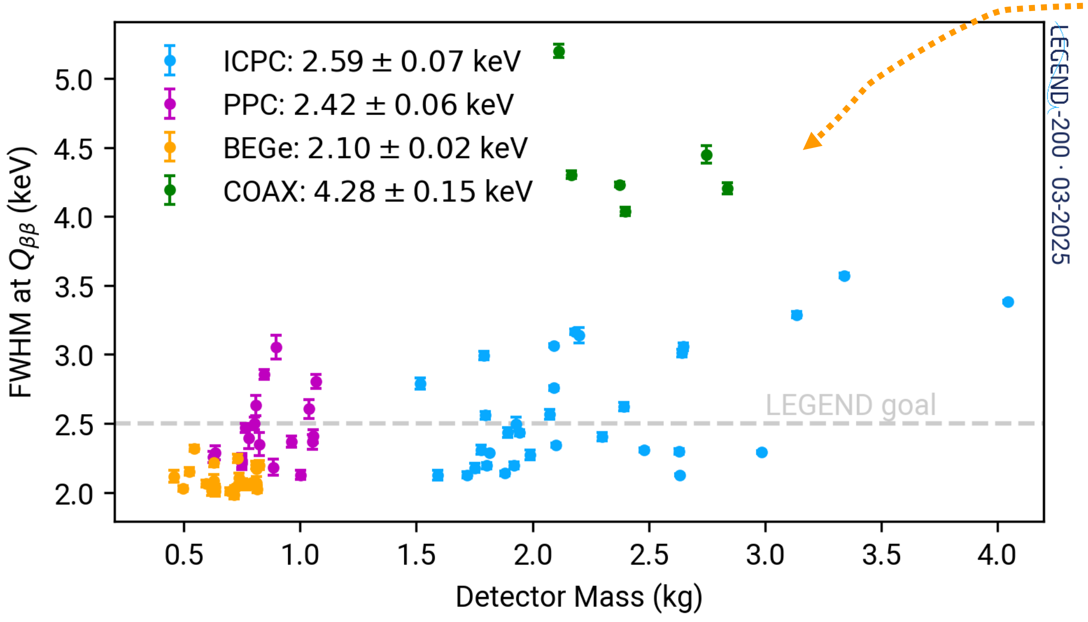
- Stable energy scale
- Excellent energy resolution

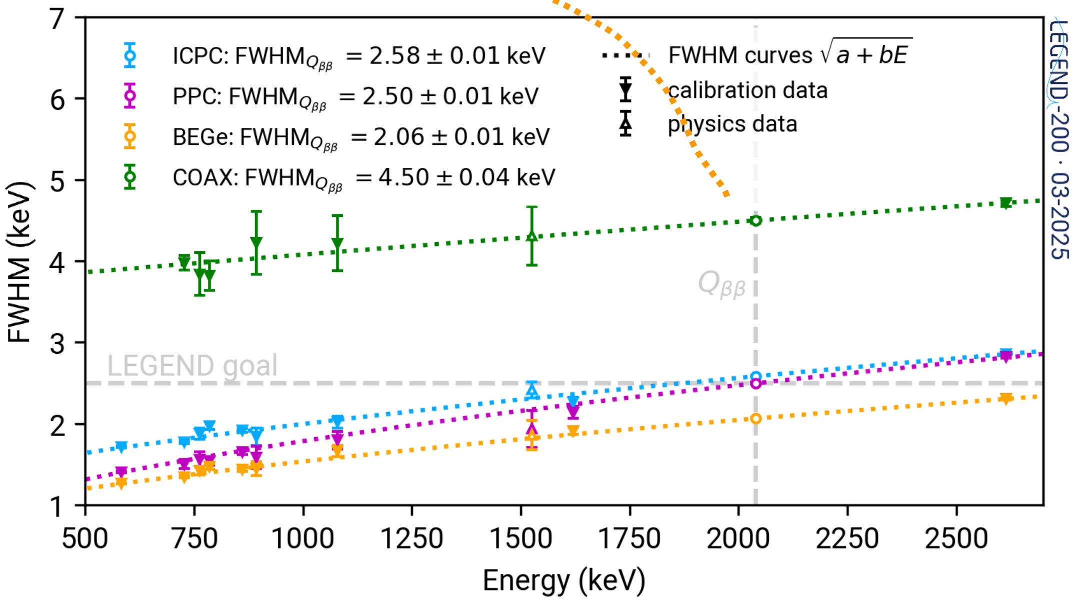
→ Monitored with **weekly calibrations** using ^{228}Th sources

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

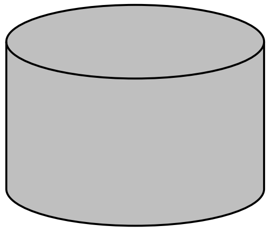




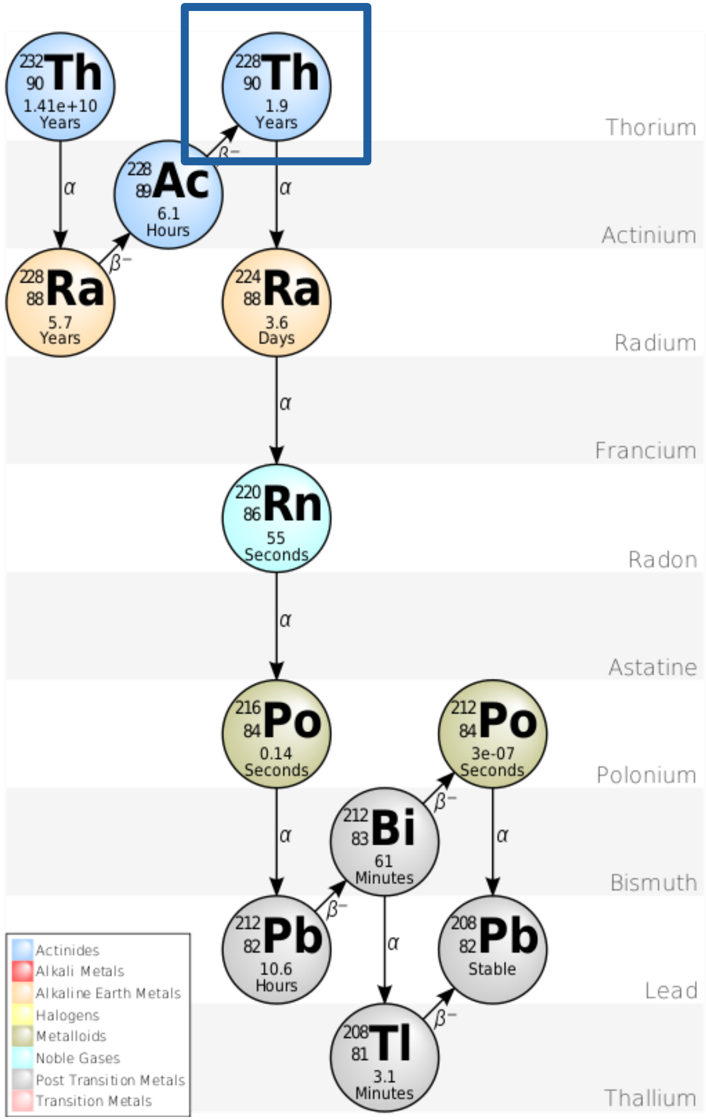


Why do we use ^{228}Th sources?

- ^{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…

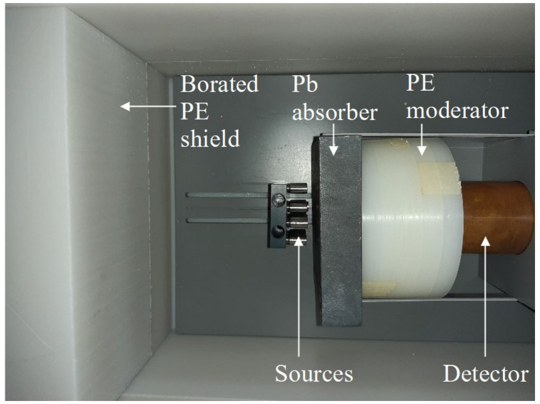
- ^{228}Th emits α with energies in the range of 5.2 – 8.8 MeV
  → yields neutron fluxes via (α, n) reaction
- Parasitic neutrons can
  - activate ^{76}Ge, producing ^{77}Ge (half-life 11.3 h) and ^{77m}Ge (half-life 53.7 s)
    → β decays with Q values > 2 MeV
  - be captured by surrounding materials,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

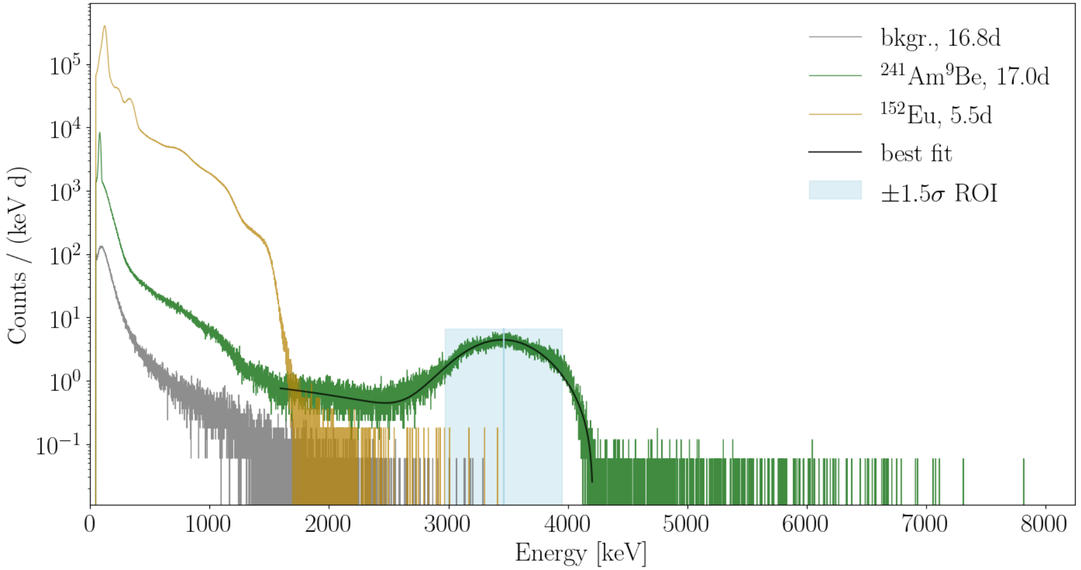
Low background environment underground at LNGS

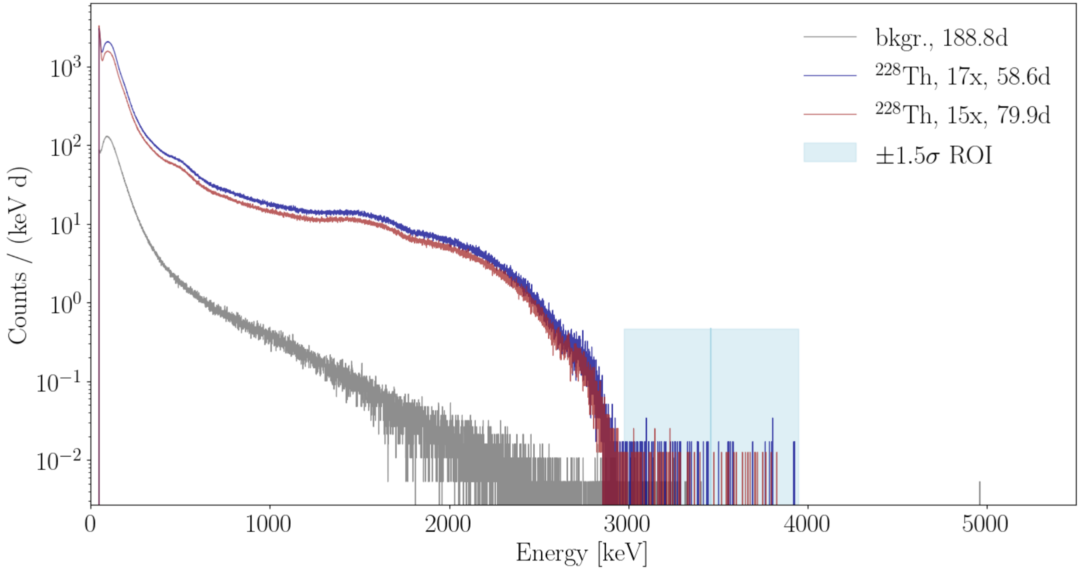


Calibration-induced background:
$\mathcal{O}(10^{-7})$ events/(keV kg yr)
after background reductions cuts
→ three orders of magnitude lower than the L200 background goal

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

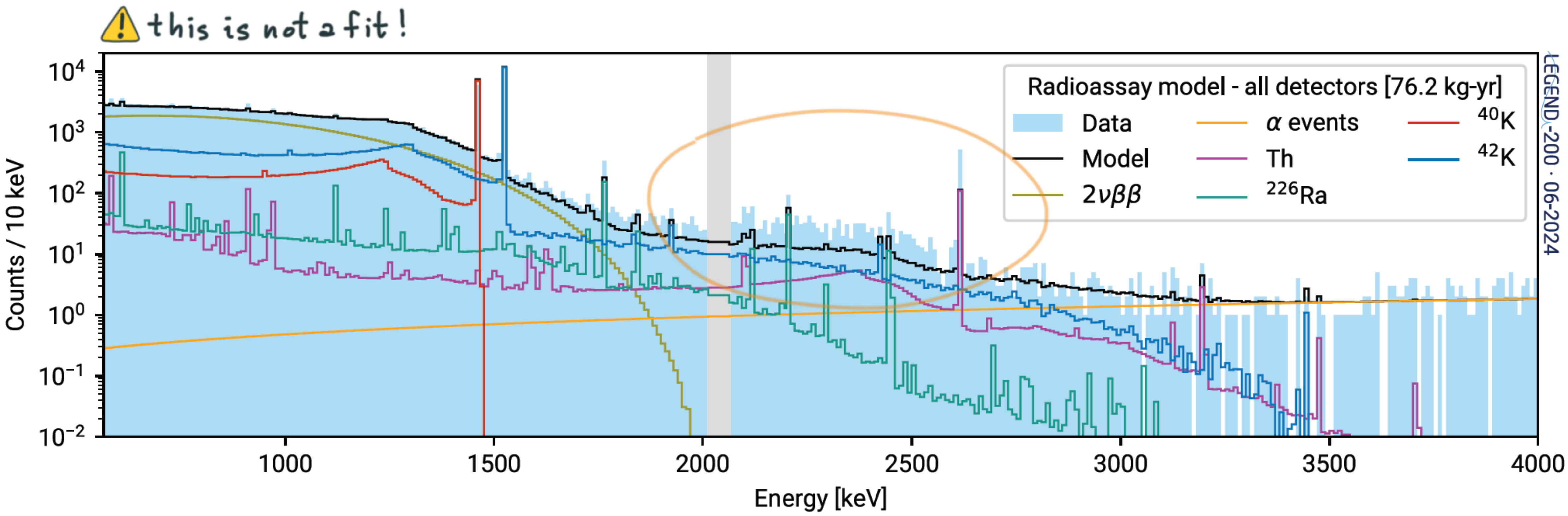
Combined neutron flux is
$\psi = (4.27 \pm 0.60_{stat} \pm 0.92_{sys}) \times 10^{-4}$ n/(kBq s)





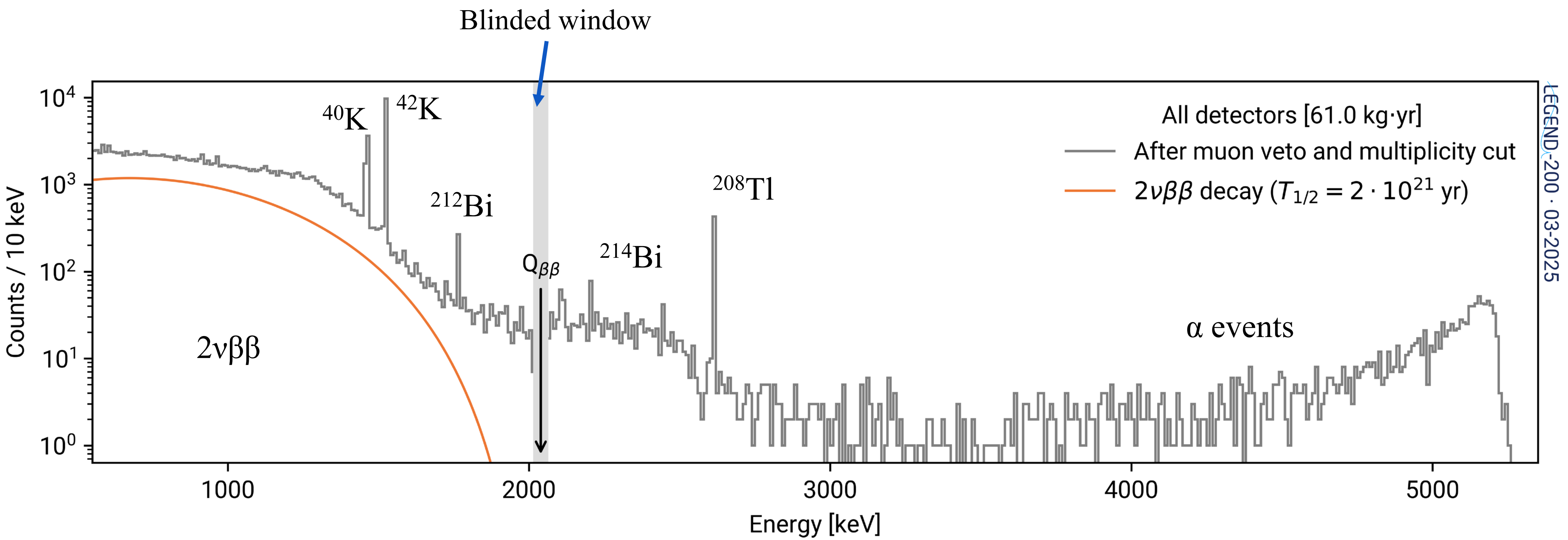
Data modeling before analysis cut

- Simulations and material radioassay underpredict the background, especially from the ^{232}Th chain
  - Hard to estimate systematic uncertainty on the assay results
  - Material radioassays currently underway to identify possible sources
  - Cleaning campaigns (e.g., PEN plates) recently finished
- However, **analysis cuts** well suppress the background



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

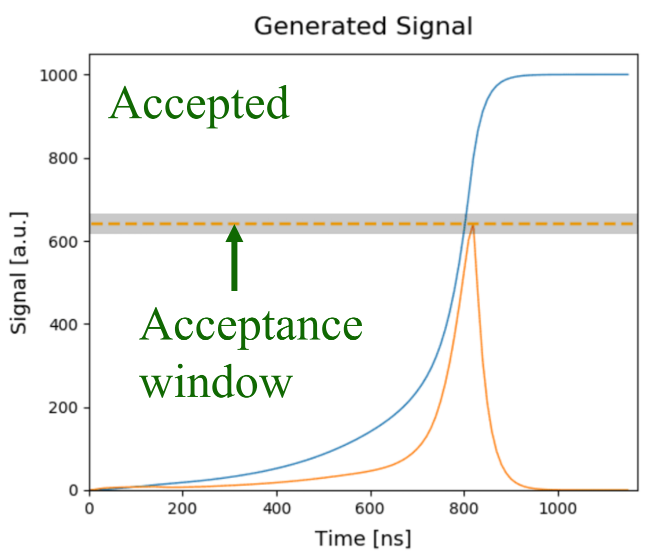


Pulse shape discrimination (PSD)

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

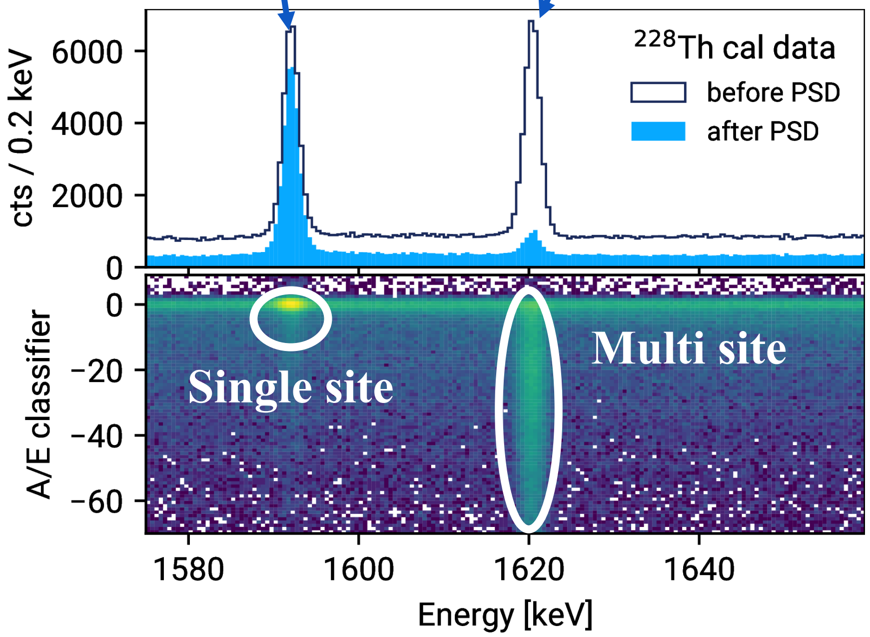
Signal-like

Charge signal
Current signal

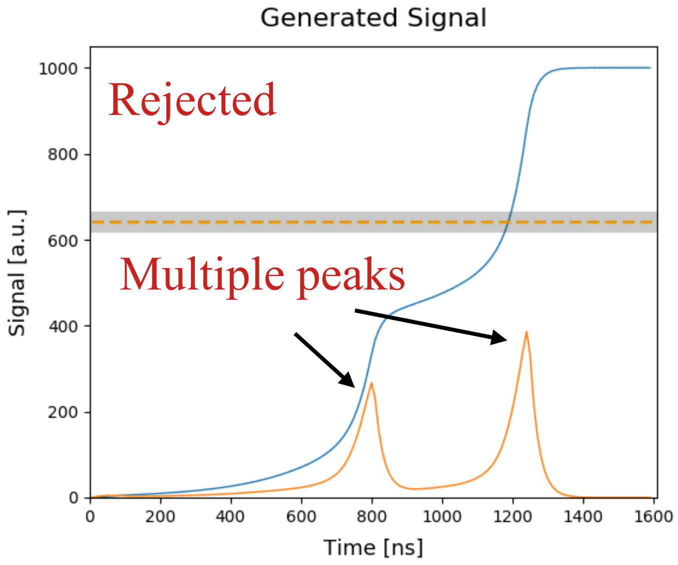


^{208}Tl double escape peak

^{212}Bi full energy peak



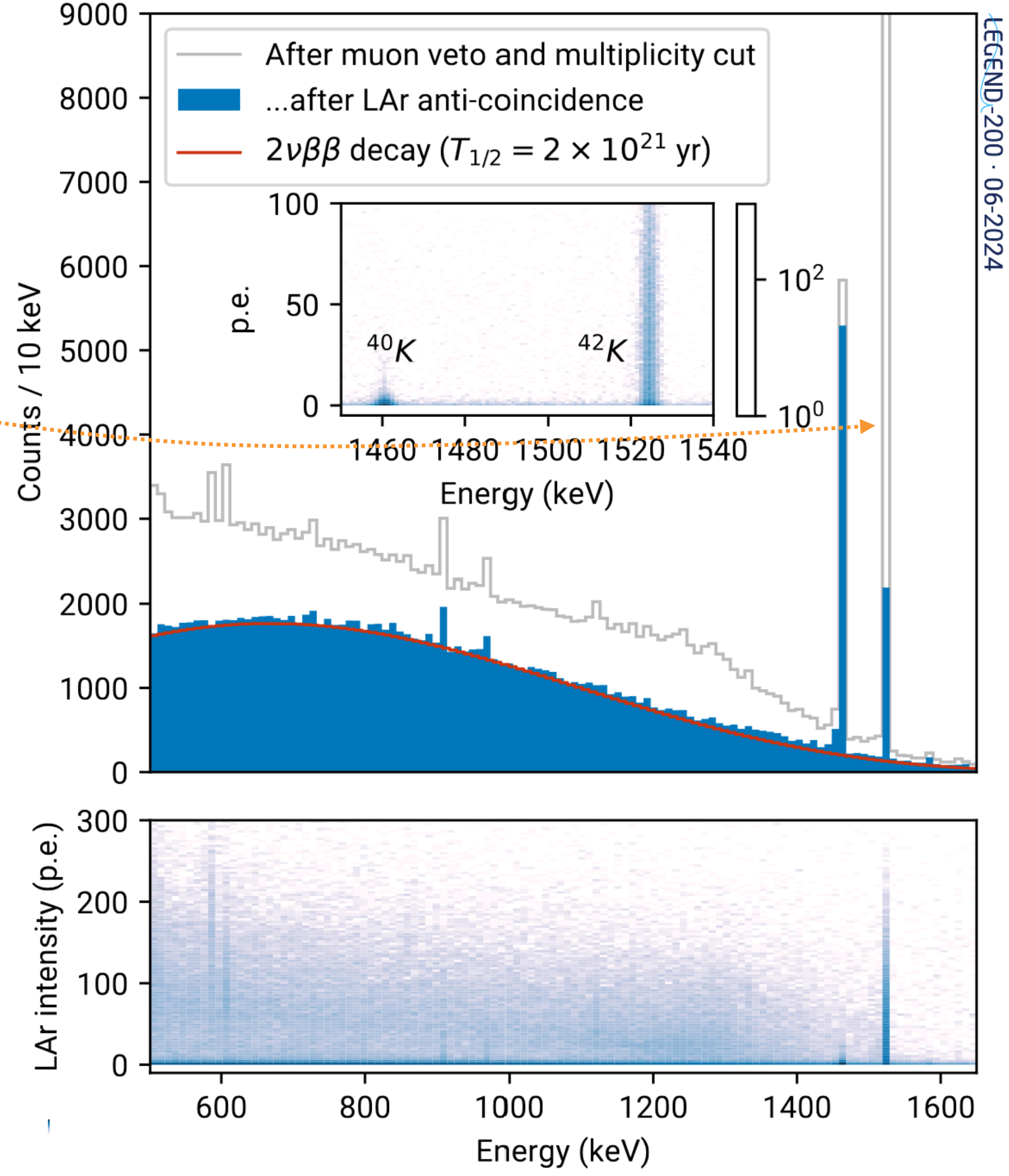
Background-like

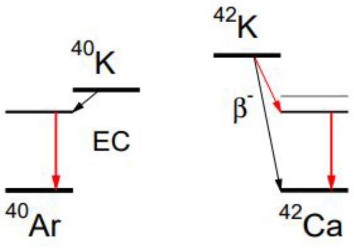


LAr anti-coincidence

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

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



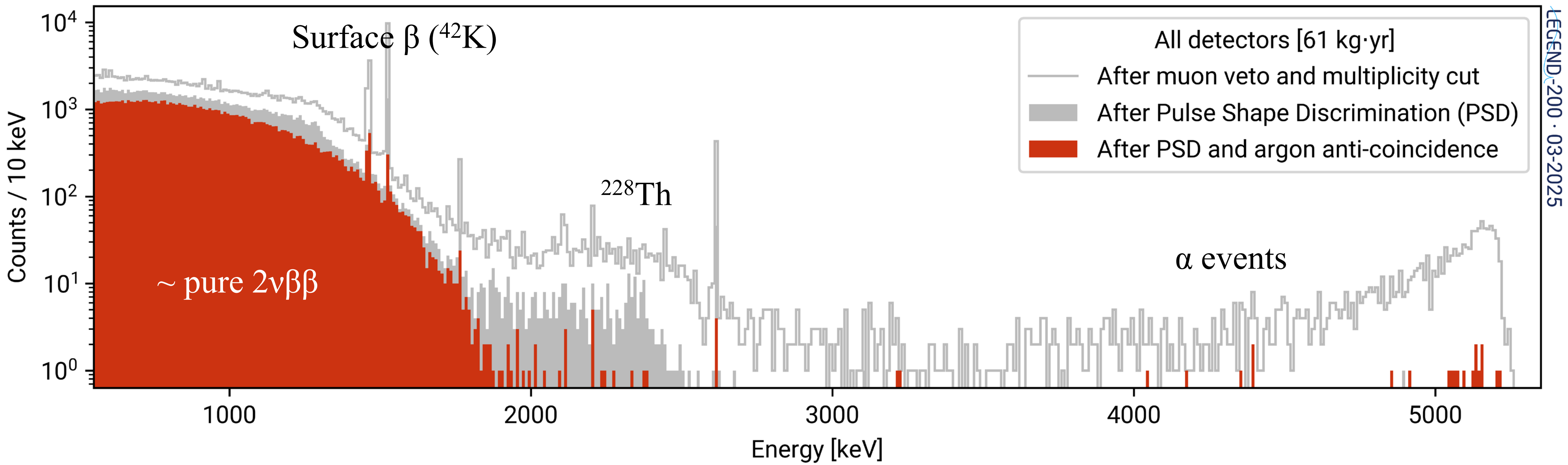


Credit: K. v. Sturm

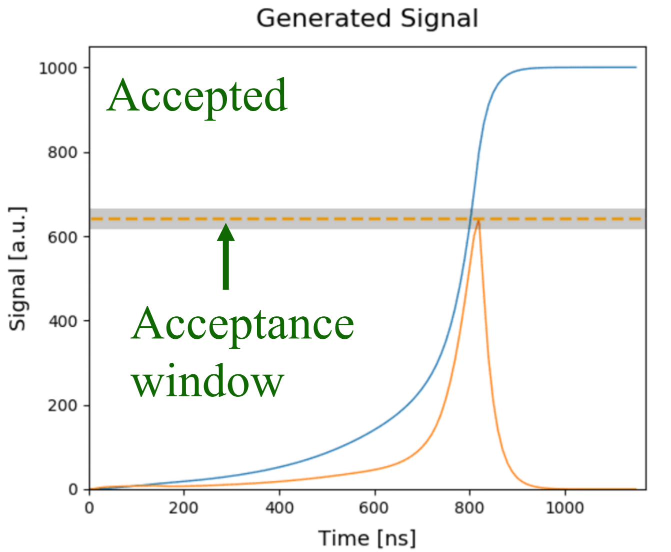
Data after PSD and LAr anti-coincidence

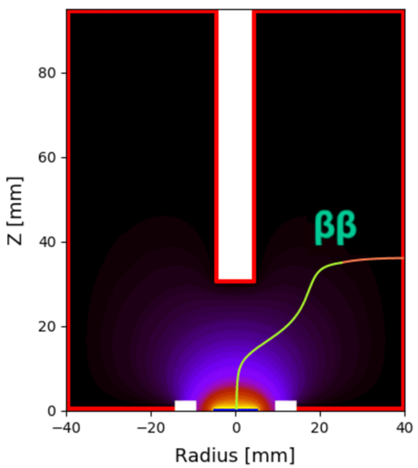
- PSD
  - Strong suppression of surface α and β (^{42}K) events
  - ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$

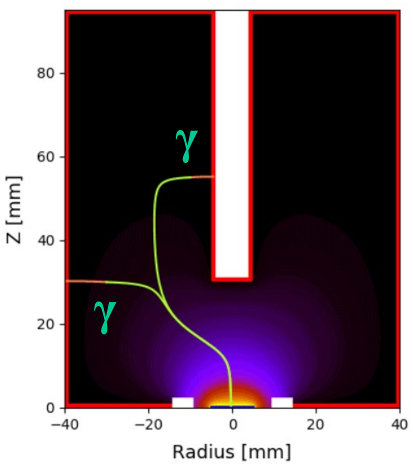
- + LAr
  - Pure 2νββ distribution

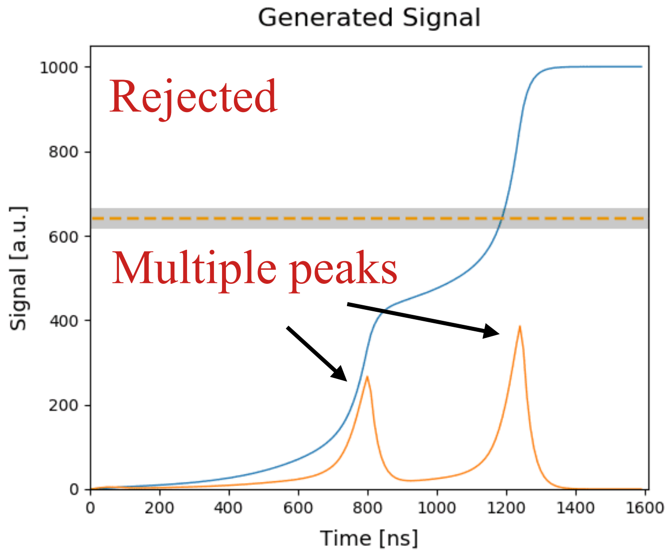


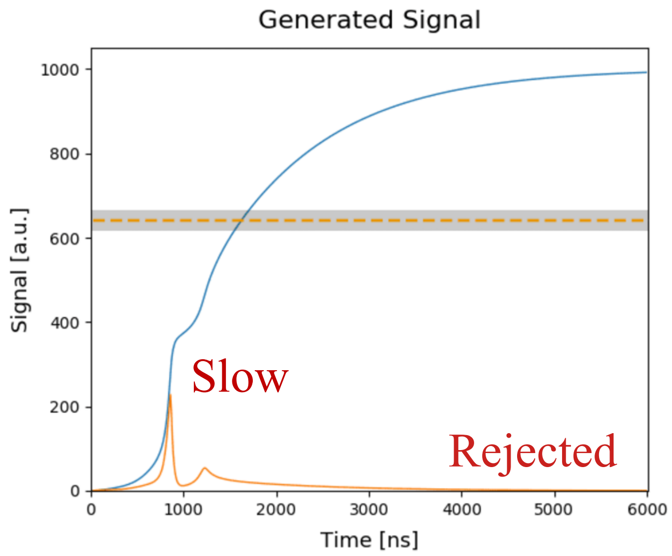
Pulse shape discrimination (PSD)

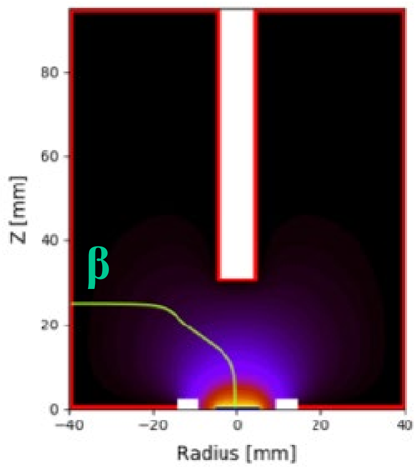




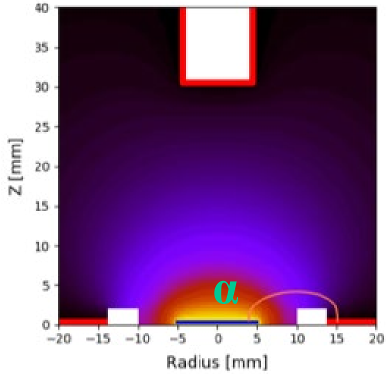


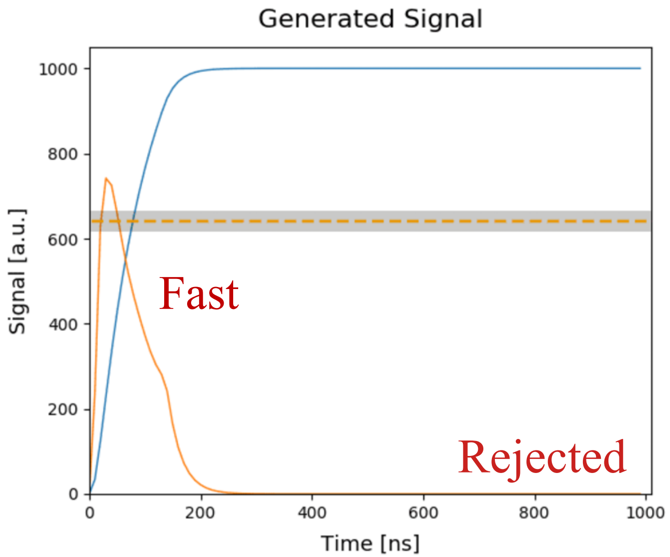






Charge signal
Current signal



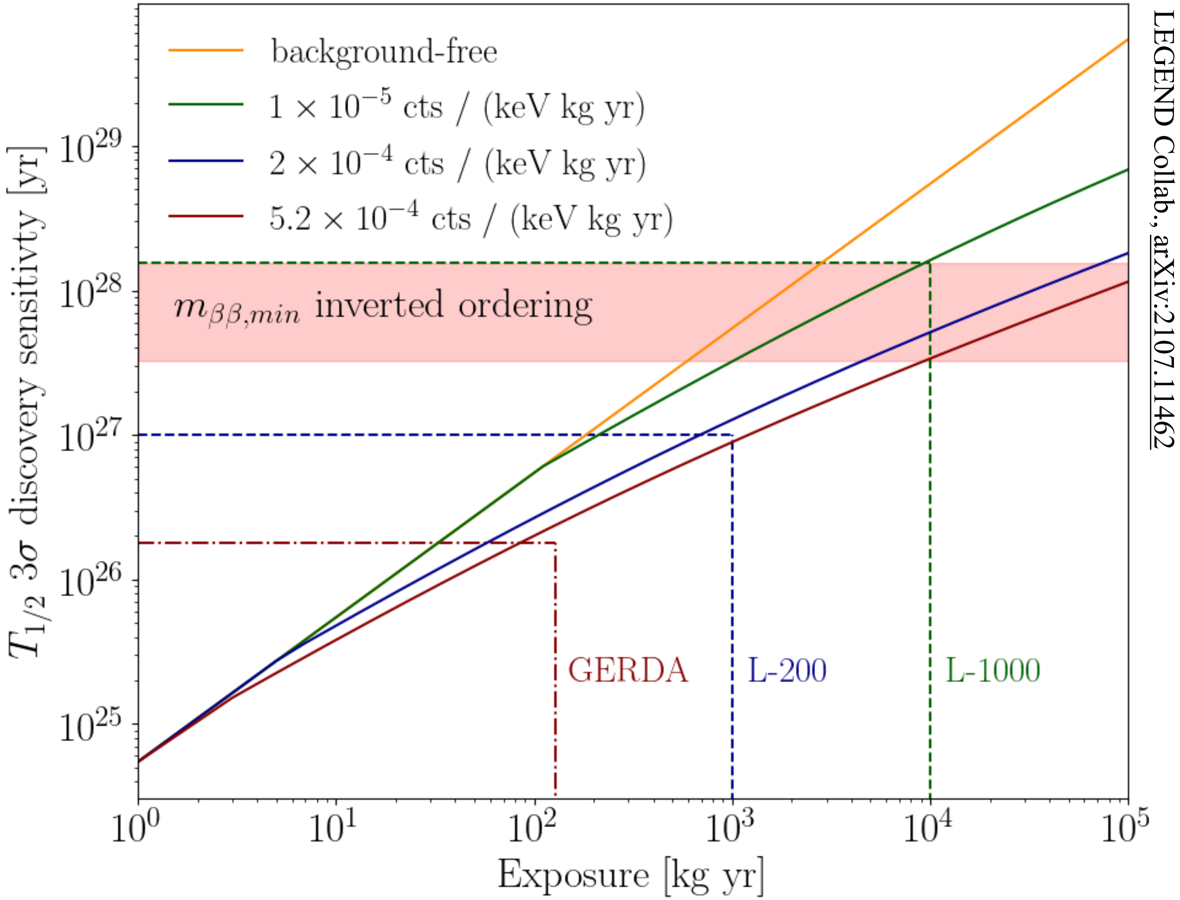


From L-200 towards L-1000

Larger exposure

Lower background

Phase	I (L-200)	II (L-1000)
HPGe (kg)	200	1000
LAr (tonne)	90	350
Live time (yr)	5	10
BI (counts/(keV·kg·yr))	$\sim 2 \times 10^{-4}$	$< 1 \times 10^{-5}$
$T_{1/2}$ (yr)	$> 10^{27}$	$> 10^{28}$
$m_{\beta\beta}$ (meV)	33–71	Cover full $m_{\beta\beta}$ inverted ordering regime



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

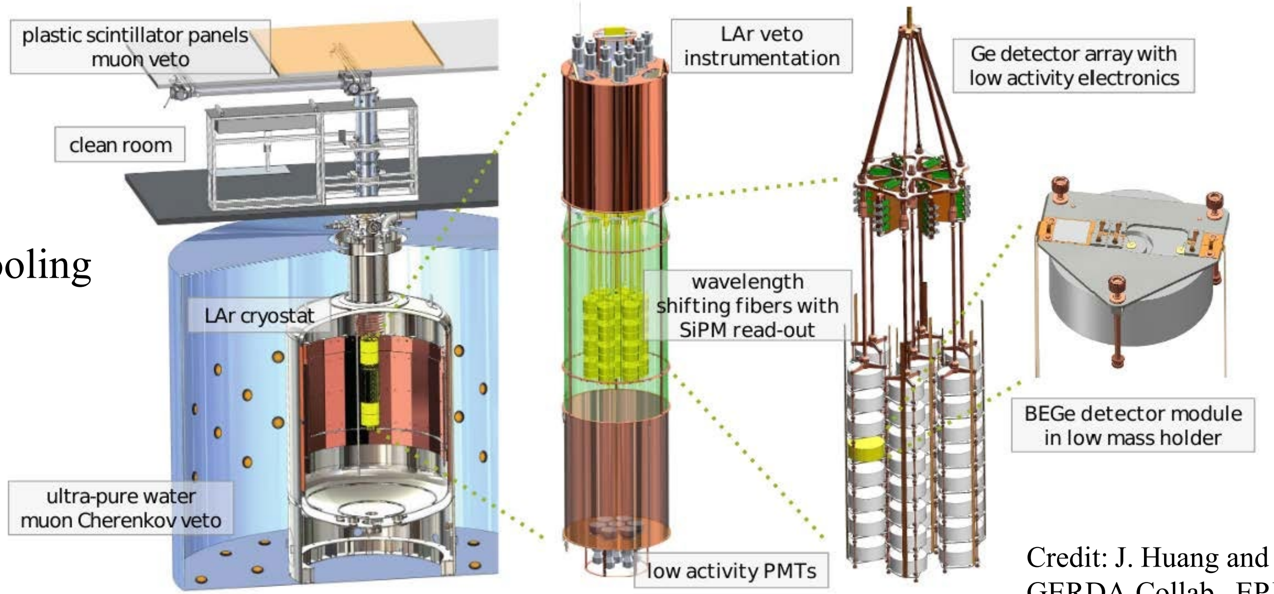
The GERmanium Detector Array

- 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



Credit: J. Huang and C. Ransom
GERDA Collab., EPJC 78:388 (2018)

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

Credit: GERDA Collab.

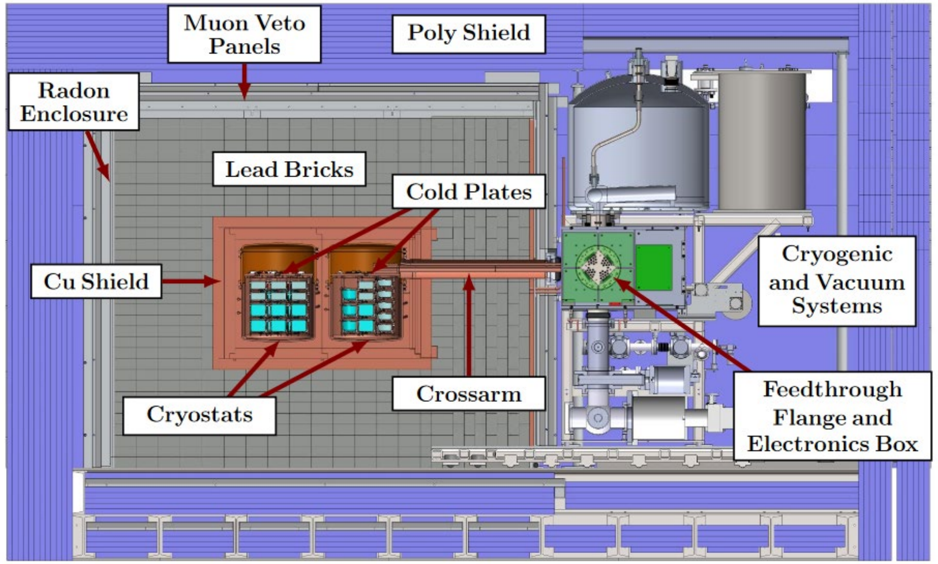
GERDA's final result (with 127.2 kg·yr of exposure) :
- Unprecedentedly low background index: 5.2×10^{-4} counts/(keV·kg·yr)
  → 0.3 counts in ($Q_{\beta\beta}\pm2\sigma$) for phase II (with 103.7 kg·yr of exposure)
- Half-life limit on $0\nu\beta\beta$ decay: $T_{1/2} > 1.8\times10^{26}$ yr (90% C.L.)
  → Effective Majorana neutrino mass: $m_{\beta\beta} < 79 - 180$ meV

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

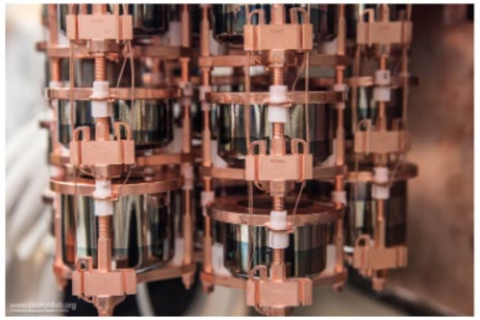
The MaJorana Demonstrator

- 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

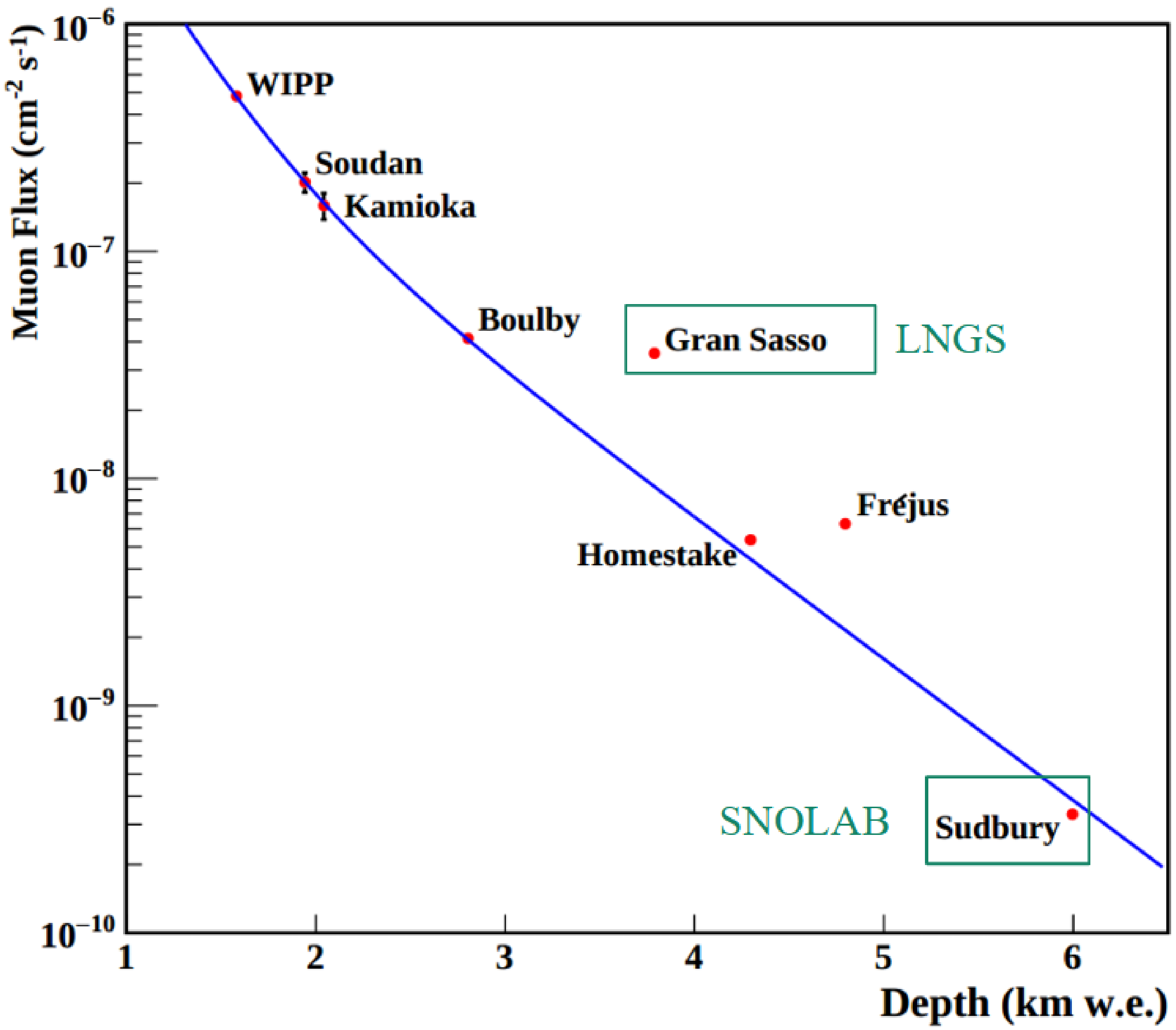


MJD's final result (with 64.5 kg·yr of exposure) :
- Best energy resolution in the field: 2.52 keV (FWHM) at $Q_{\beta\beta}$
- Measured background 16.6 ×10^{-3} counts / (FWHM·kg·yr)
- Half-life limit on 0νββ decay: $T_{1/2}$ > 8.3×10^{25} yr (90% C.L.)
  → Effective Majorana neutrino mass: $m_{\beta\beta}$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

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



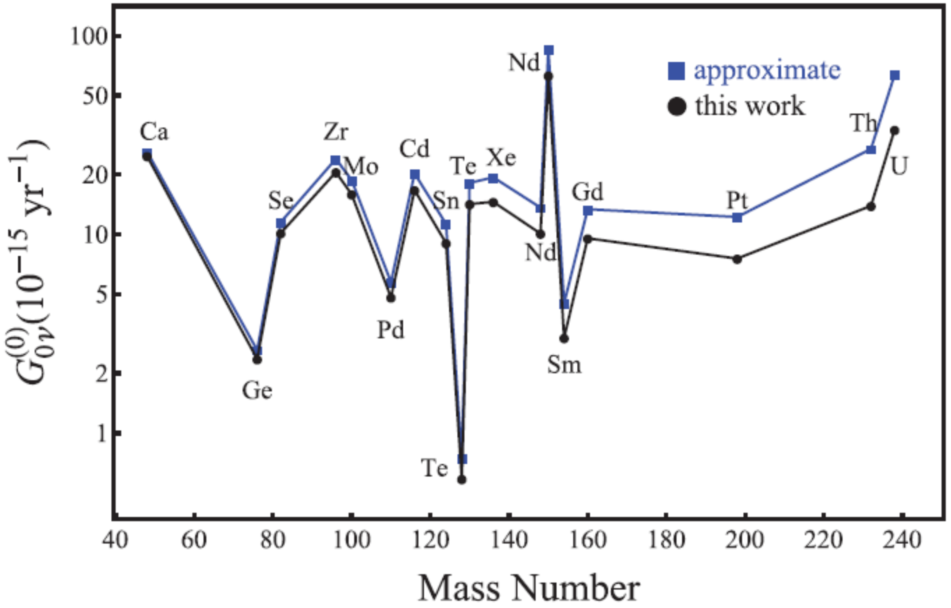
Credit: J. J. Cuenca-García, (2022), Ref.: D.-M. Mei and A. Hime, PRD 73, 053004 (2006)

Decay half-life vs. effective Majorana neutrino mass

Experiment	Atomic phys.		Nuclear phys.	Particle phys.

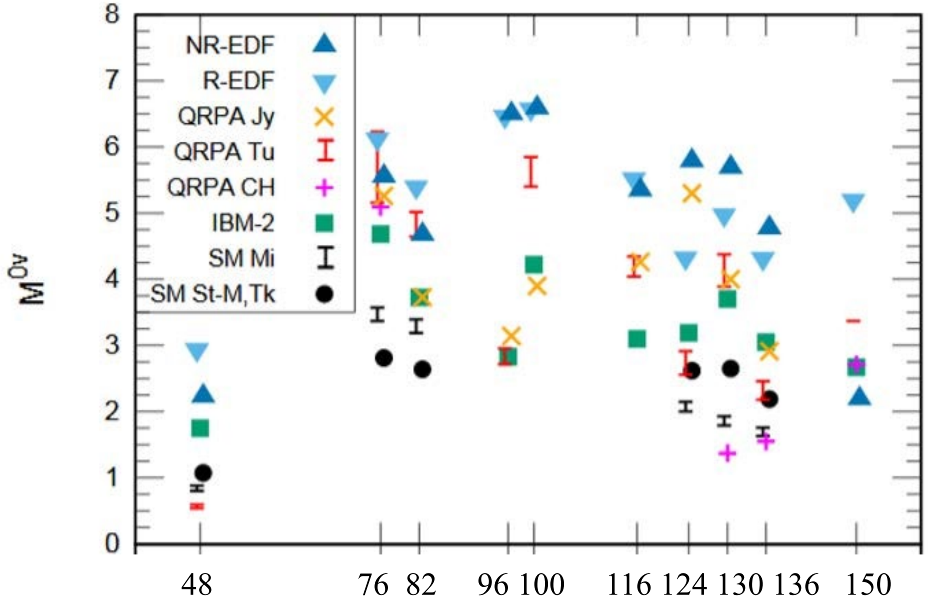
$$\left(T_{1/2}\right)^{-1} = G\left(Q_{\beta\beta}, Z\right) \cdot {g_A}^4 \cdot \left|M_{\mathrm{nucl}}\right|^2 \cdot {m_{\beta\beta}}^2$$

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)

$g_A = 1.27$

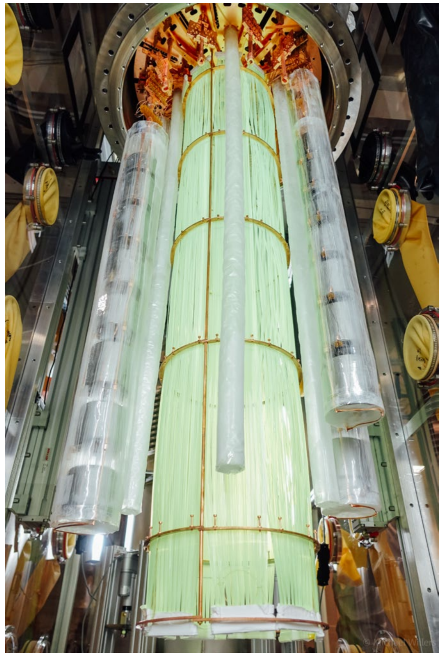


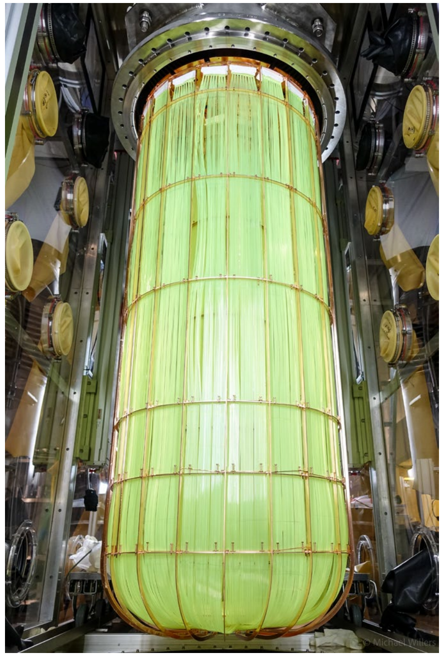
Ref.: J. Engel and J. Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

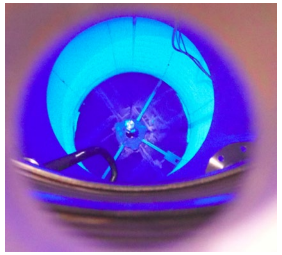
LAr veto systems

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

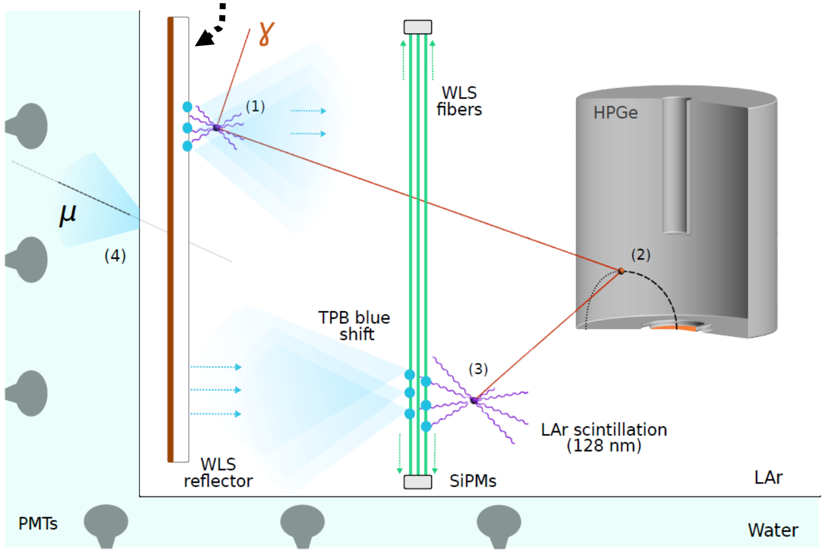
Wavelength-shifting fibers connected to SiPMs consisting 18 (inner) and 40 (outer) readout channels



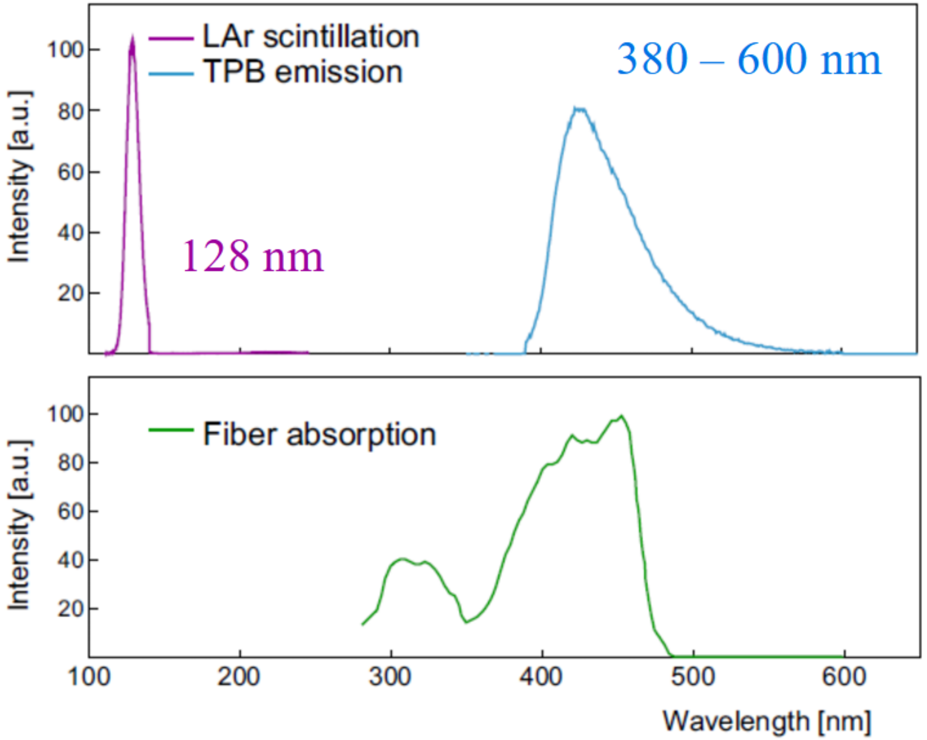




Wavelength-shifting reflector

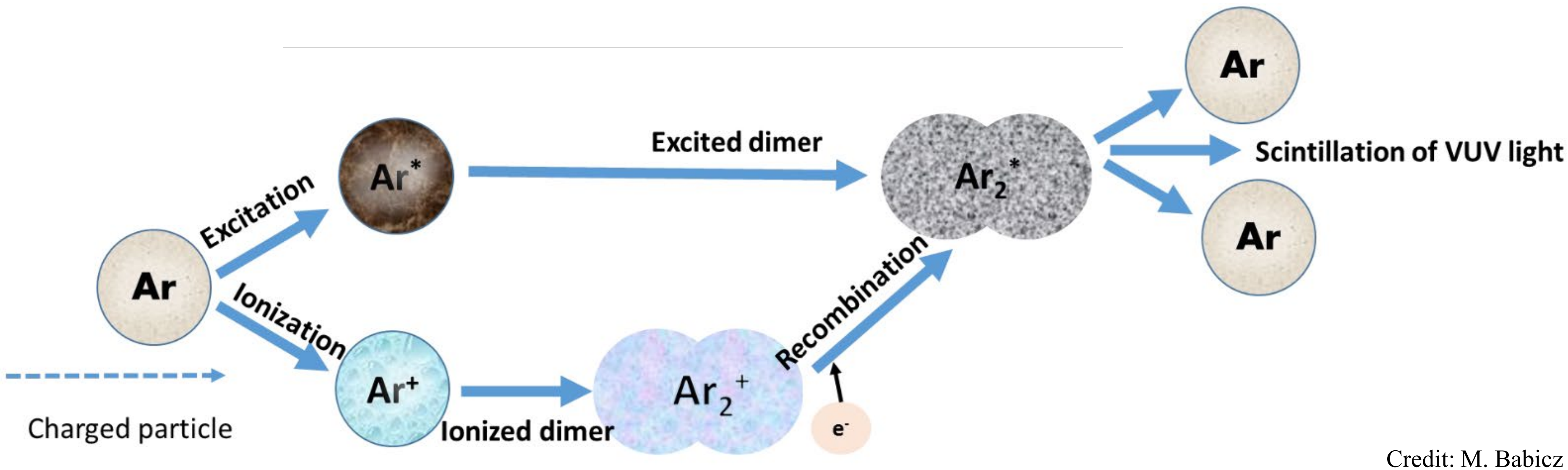


Credit: G. R. Araujo



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

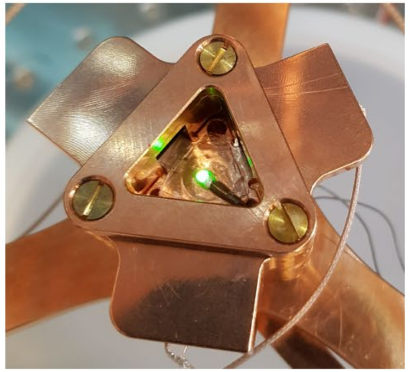
Ar scintillation

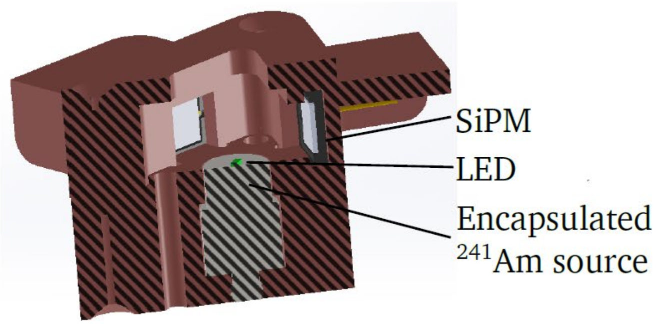


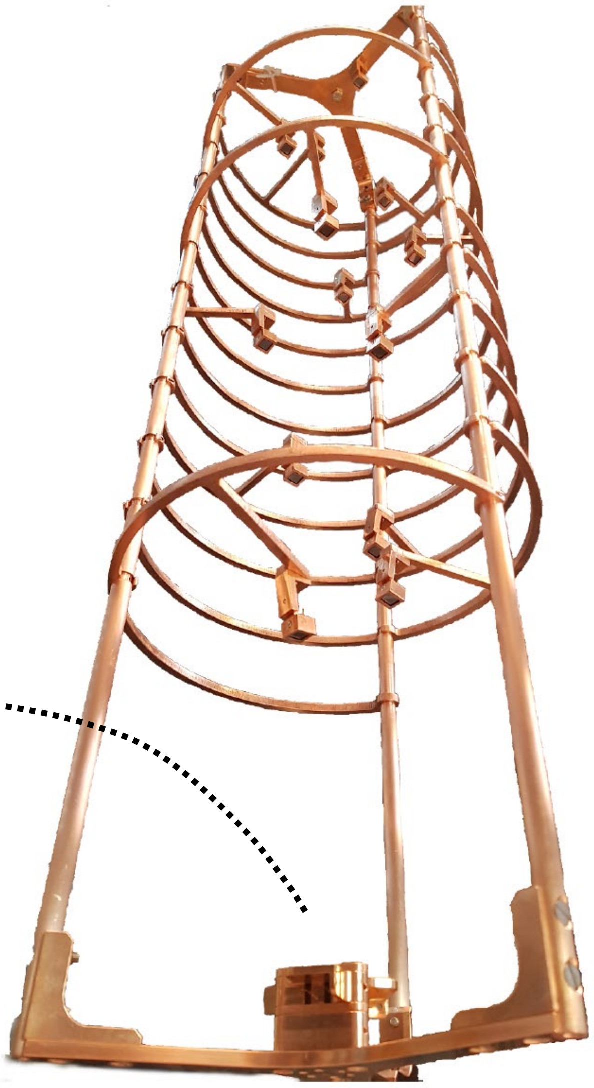
Credit: M. Babicz

LLAMA

LEGEND Liquid Argon Monitoring Apparatus

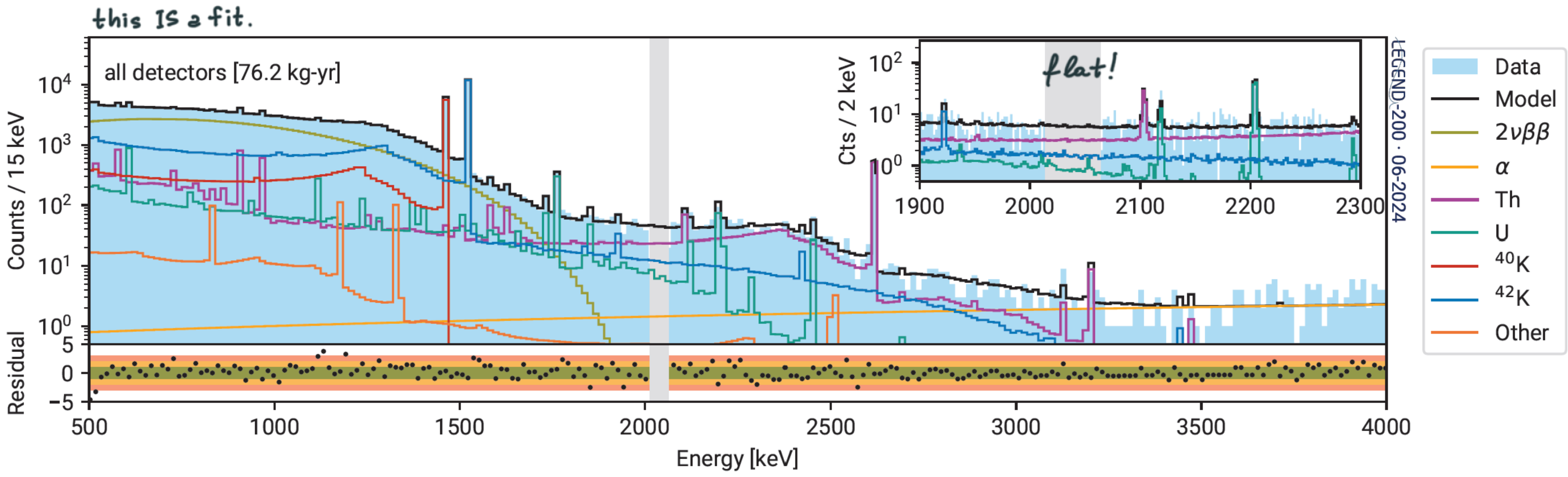






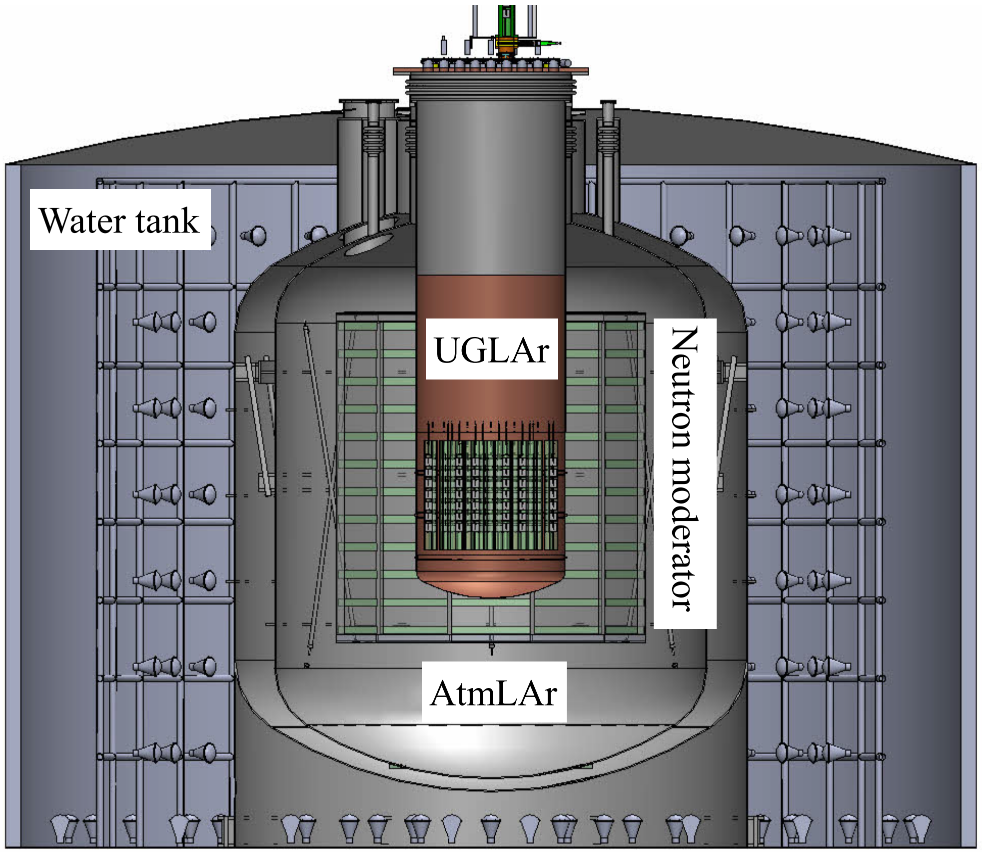
Data modeling before analysis cut

- Bayesian background model using data before analysis cuts
- Data well reproduced, model is flat at $Q_{\beta\beta}$
- Model can test hypotheses on the origin of ^{228}Th excess



Ongoing R&D projects for LEGEND-1000

- 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

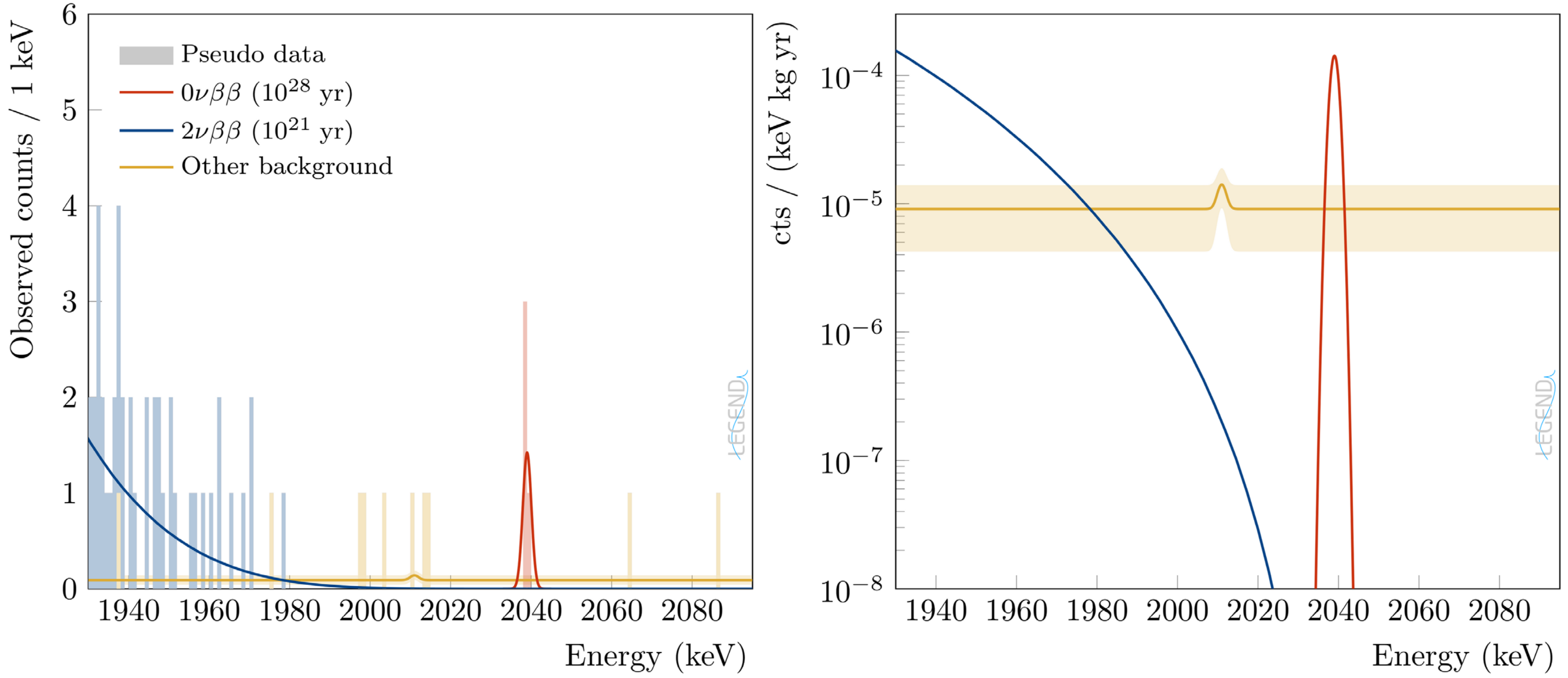


Ref.: LEGEND Collab., arXiv:2107.11462

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