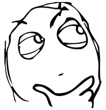
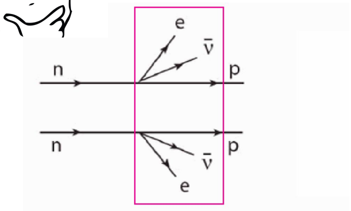
# Search for neutrinoless double beta decay with GERDA and LEGEND-200

A Flash talk by Gabriela R. Araujo
CHIPP Plenary 2021 in Spiez

What is 0νββ?



# A few isotopes in nature decay emitting 2 electrons and 2 neutrinos (2νββ decay).



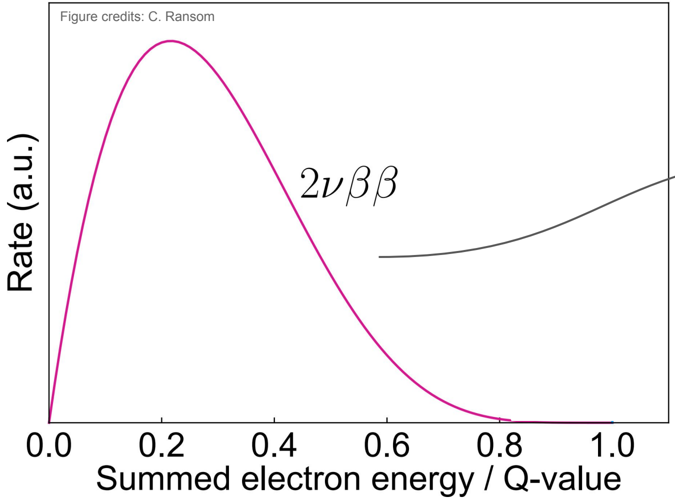
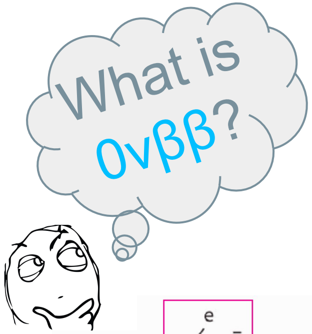


Figure credits: C. Ransom

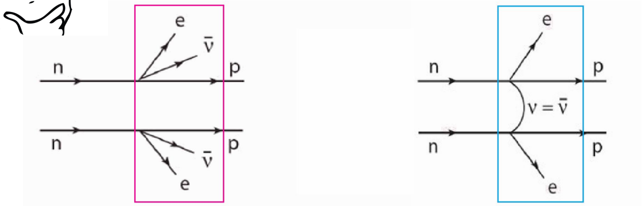
## Two neutrino double beta decay (2νββ):

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

The electrons share the energy with the neutrinos and produce a broad spectrum.



# In a 0νββ decay no neutrinos are emitted. This process can happen if neutrinos are Majorana particles



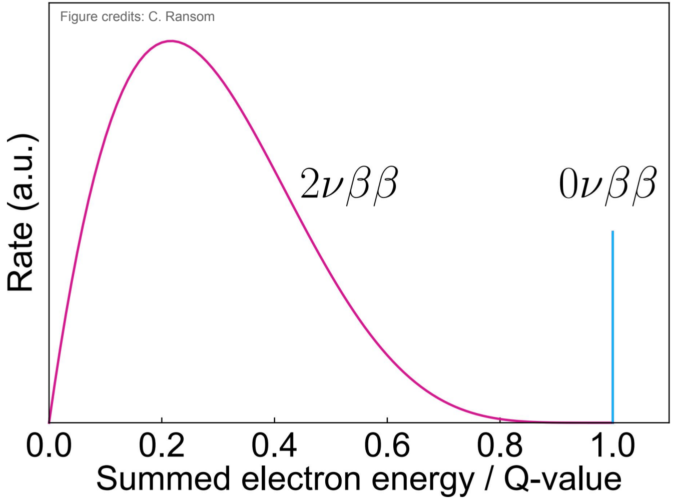


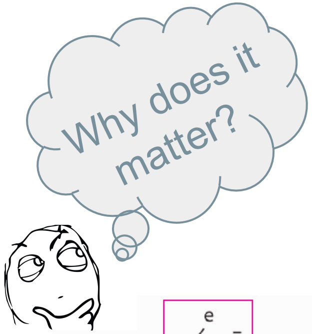
Figure credits: C. Ransom

Two neutrino double beta decay (2νββ):

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

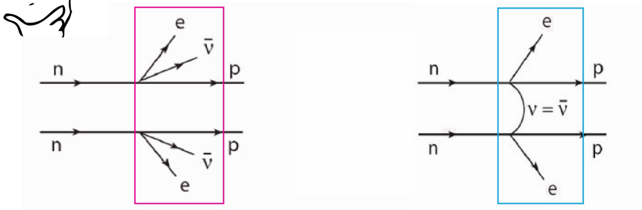
Neutrinoless double beta decay (0νββ):

- 2n → 2p + 2e-



# In a 0νββ decay no neutrinos are emitted. This process can happen if neutrinos are **Majorana particles**

Origin of neutrino mass!



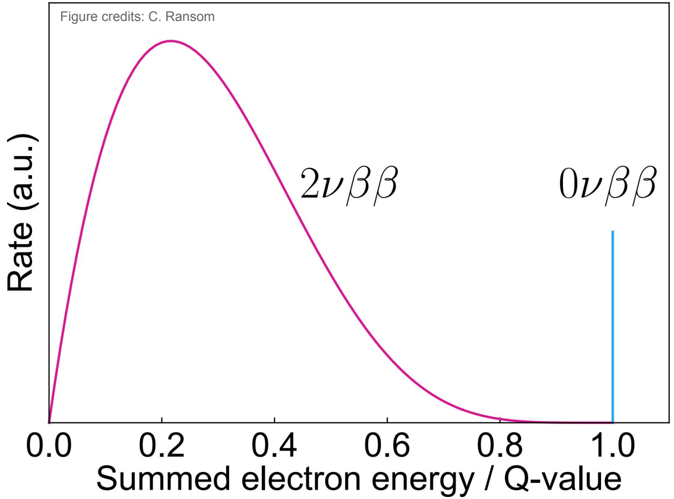


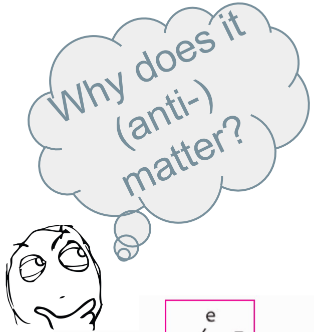
Figure credits: C. Ransom

Two neutrinos emitted (2νββ):

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

No neutrinos emitted (0νββ):

- 2n → 2p + 2e-



# In a 0νββ-decay no neutrinos are emitted. **In this case, lepton-number conservation would be violated.**

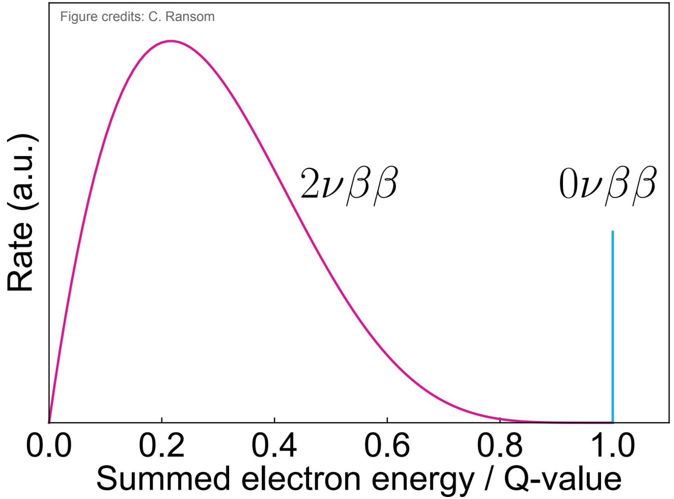


Figure credits: C. Ransom

Two neutrinos emitted (2νββ):

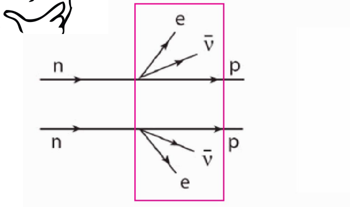
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ ($\Delta L=0$)

No neutrinos emitted (0νββ):

- $2n \rightarrow 2p + 2e^-$ ($\Delta L=+2$)

Violation of lepton number conservation could explain the **matter-antimatter asymmetry of the universe**

# We search for 0νββ in isotopes that undergo 2νββ decay, such as $^{76}$Ge:



continuous spectrum

Two neutrinos emitted (2νββ):

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$

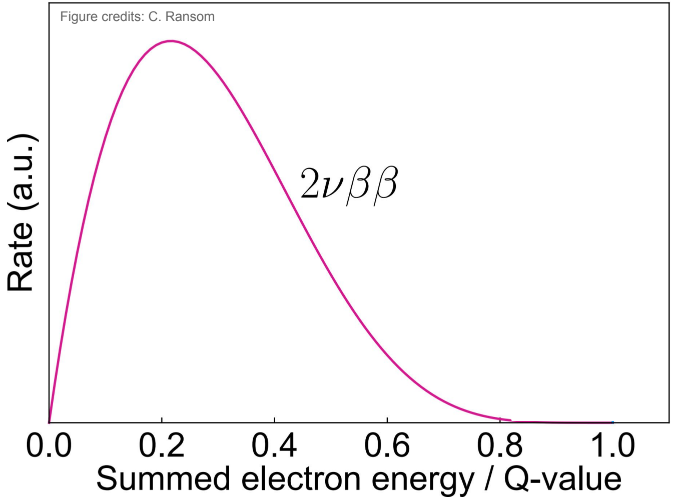
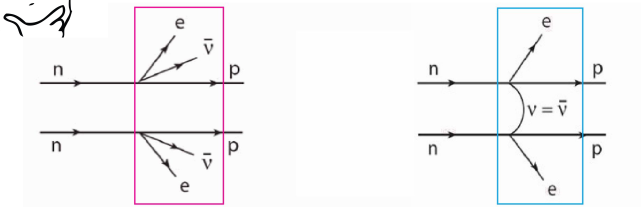


Figure credits: C. Ransom

# We search for 0νββ in isotopes that undergo 2νββ decay, such as $^{76}$Ge, and scan their energy spectrum, close to $Q_{\beta\beta}$



continuous spectrum

Single peak at $Q_{\beta\beta}$=2039 keV

Two neutrinos emitted (2νββ):

- $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^{-} + 2\bar{\nu}_{e}$

No neutrinos emitted (0νββ):

- $^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^{-}$

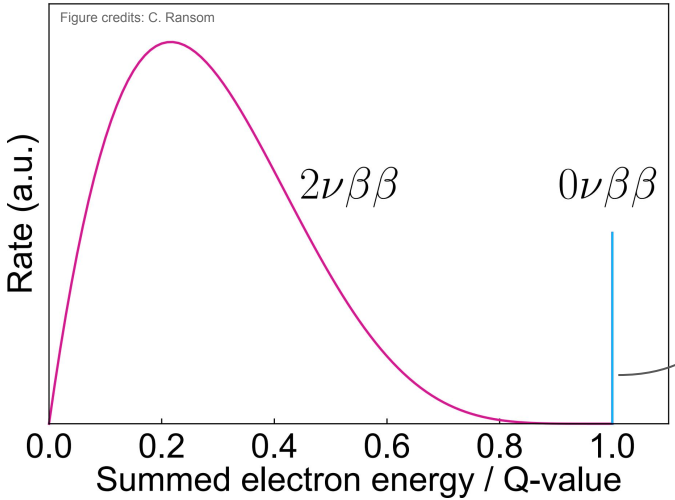
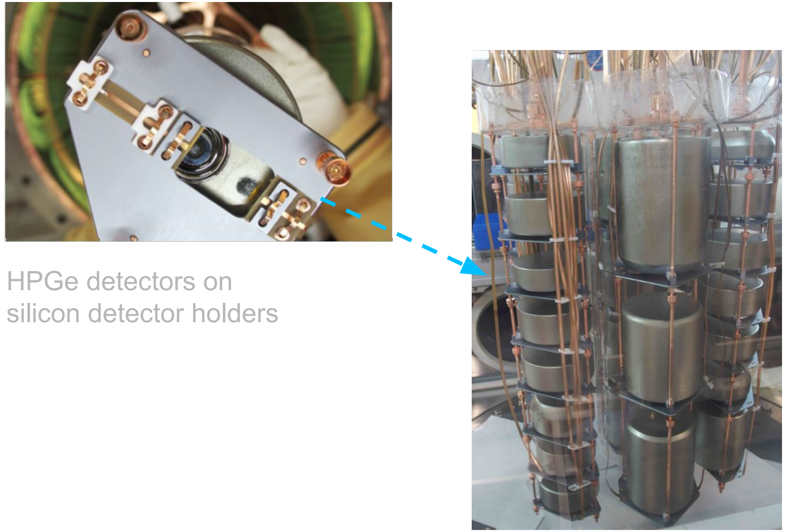


Figure credits: C. Ransom

Ge detectors have the excellent energy resolution needed for the detection of the peak at the end of the 2νββ spectrum !

# GERDA/Majorana and LEGEND are experiments that search for a signal from a 0νββ decay in high purity germanium (HPGe) crystals enriched in $^{76}$Ge



HPGe detectors on
silicon detector holders

Advantages of $^{76}$Ge:

- Source and detector are the same
- Enrichment up to ~90% is possible
- Pulse shape descrimination (PSD)
- Resolution of ~3 keV (FWHM at $Q_{\beta\beta}$=2039 keV )

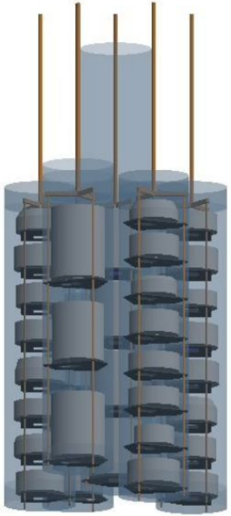
🏆 Best energy resolution and lowest background index in all 0νββ decay experiments

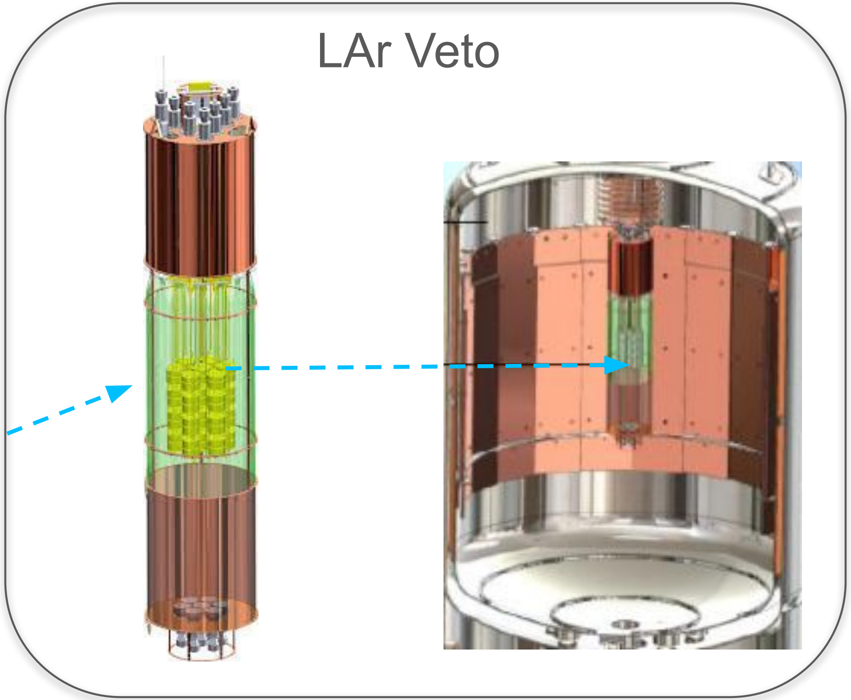
Figures from GERDA

# GERDA[1] successfully operated Ge detectors in an active Liquid argon (LAr) shield[2]

HPGe detectors on silicon detector holders

Mounted in Cu strings

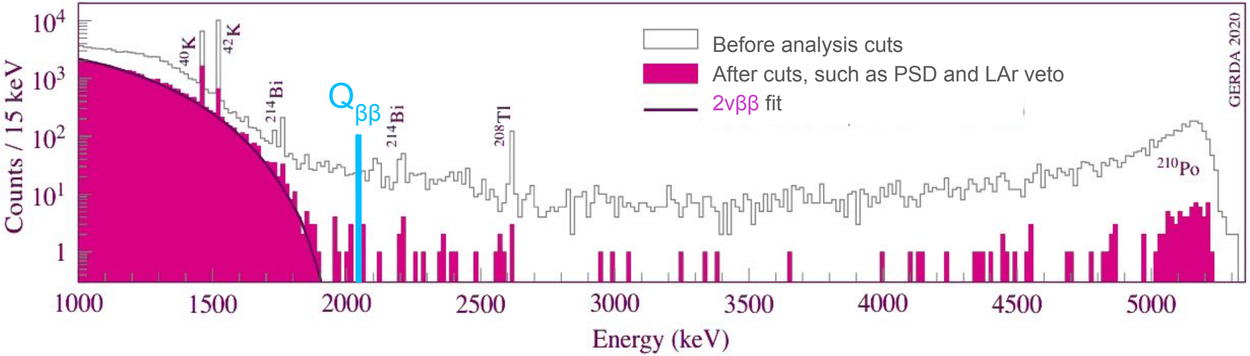




LAr Veto

[1] *Probing Majorana neutrinos with double-β decay.* Science 365, 1445 (2019)
[2] *Upgrade for Phase II of the GERDA Experiment* Eur. Phys. J. C 78 (2018) 388.

# In its recent final results, GERDA set the world's best half-life limit[3] on 0νββ:



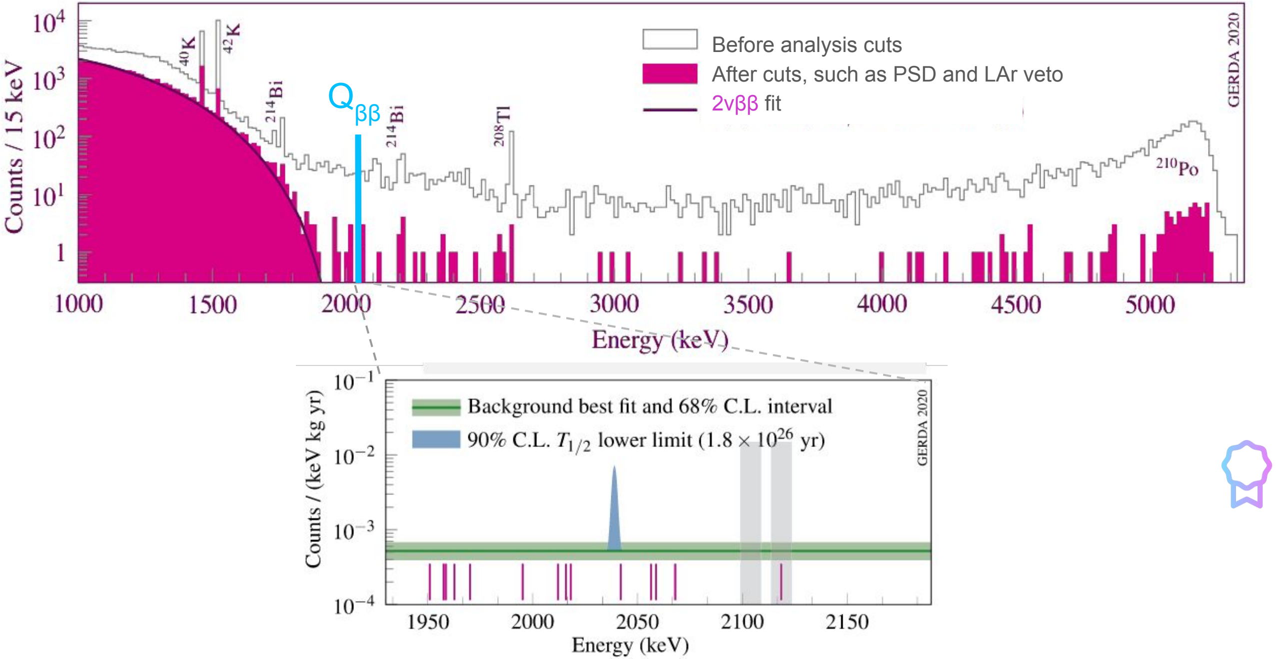
$T_{1/2} > 1.8 \times 10^{26}$ yr

(at 90% CL)

100 kg.yr exposure

[3] GERDA Collaboration: M. Agostini, G. R. Araujo, et al. *Final results of GERDA on the search for neutrinoless double-β decay*. PRL, 125:252502, 2020

# GERDA's strong background suppression, allowed it to run background-free up to its designed exposure



World's best limit

$T_{1/2} > 1.8 \times 10^{26}$ yr

(at 90% CL)

100 kg.yr exposure

World's best background:

$5.2\times10^{-4}$counts/(keV.kg.yr)

[3] GERDA Collaboration: M. Agostini, G. R. Araujo, et al. *Final results of GERDA on the search for neutrinoless double-β decay*. PRL, 125:252502, 2020

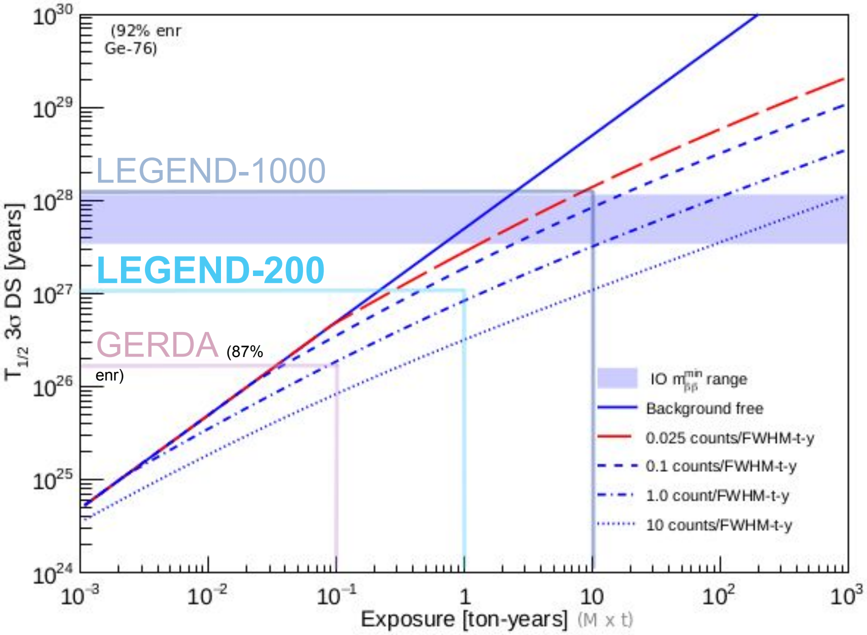
# LEGEND-200 is the next step to GERDA in the search for 0νββ decay: it aims to increase the sensitivity by one order of magnitude[4]

detector mass

1 ton

200 kg

40 kg



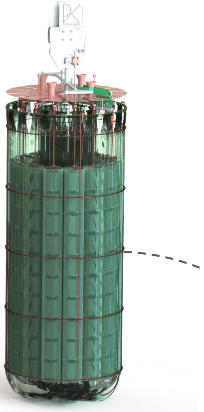
$T_{1/2} > 10^{27}$ yr

1 ton.year exposure

Background better than $10^{-4}$counts/(keV.kg.yr)

[4] The Legend Collaboration: *The large enriched germanium experiment for neutrinoless double beta decay (LEGEND)* arxiv:1894:020027

# To achieve the target sensitivity and background level, LEGEND builds on the knowledge from GERDA/Majorana



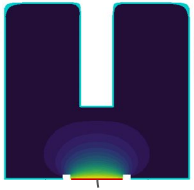
Operation of detectors in LAr surrounded by veto instrumentation

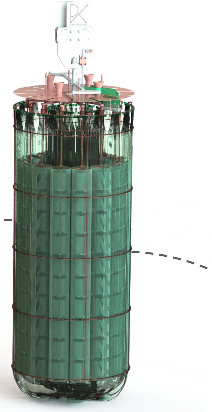
Inside a muon veto (water tank) and underground location at LNGS

LNGS: Laboratori Nazionali del Gran Sasso

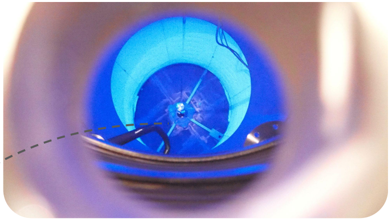
Figure credits: P. Krause

# To achieve the target sensitivity and background level, LEGEND builds up on the knowledge from GERDA/Majorana, **but with improved detectors and veto**





Use of large inverted coaxial detectors with enhanced PSD [5]



Wavelength shifting reflectors increase the veto efficiency of LAr

See my poster "Wavelength-Shifting Reflectors for the liquid argon veto of LEGEND-200" in today's session!

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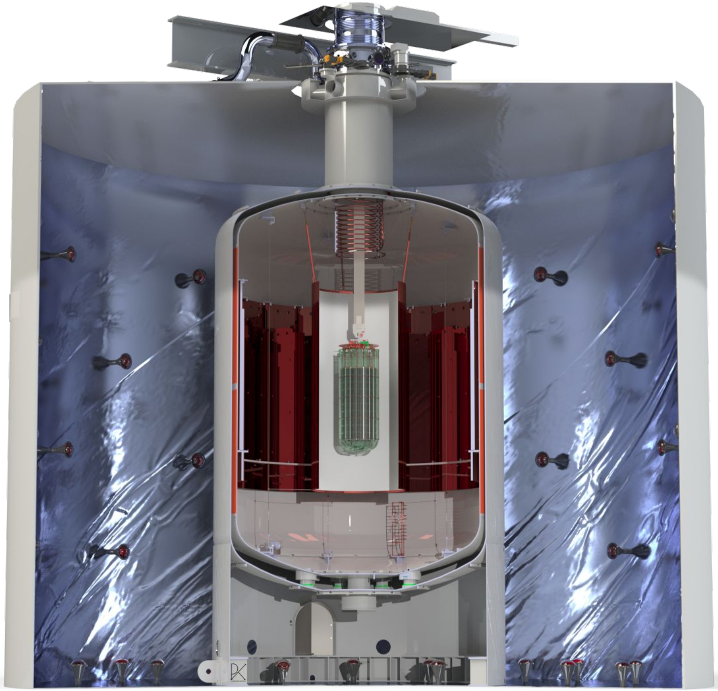
[5] GERDA Collaboration: M. Agostini, G. R. Araujo, et al. *Characterization of inverted coaxial Ge detectors in GERDA for future double-β decay experiments*. arXiv:2103.15111

# LEGEND-200 is currently finishing construction and will start physics run in late 2021 - Stay tuned!

- Higher detector mass: 200 kg
- Detectors with enhanced PSD
- Improved LAr veto efficiency
- Large international collaboration
- UZH work on calibration systems

See poster for more!



$T_{1/2} > 10^{27}$ yr

1 ton.yr exposure

Background better than $10^{-4}$counts/(keV.kg.yr)

Thanks for your attention!

# Back up slides

# An observation of 0νββ decay would:

- Explain matter-dominated universe: non conservation of lepton number (leptogenisis)
- Provide an explanation to neutrino's mass: not yet given by the SM
- Explain why neutrino's mass is so small (eV vs MeV scale for other quarks/leptons): Majorana mass component in the see-saw mechanism gives the neutrino a heavy partner (the heavy right-handed neutrino)

The most stringent limits on 0νββ come from searches with $^{76}$Ge, $^{130}$Te, $^{136}$Xe, ($T_{1/2} > 10^{26}$ yr and $m_{\beta\beta} < 100$ meV)

# The most stringent limits on 0νββ come from searches with $^{76}$Ge, $^{130}$Te, $^{136}$Xe, ($T_{1/2} > 10^{26}$ yr and $m_{\beta\beta}$<100 meV)

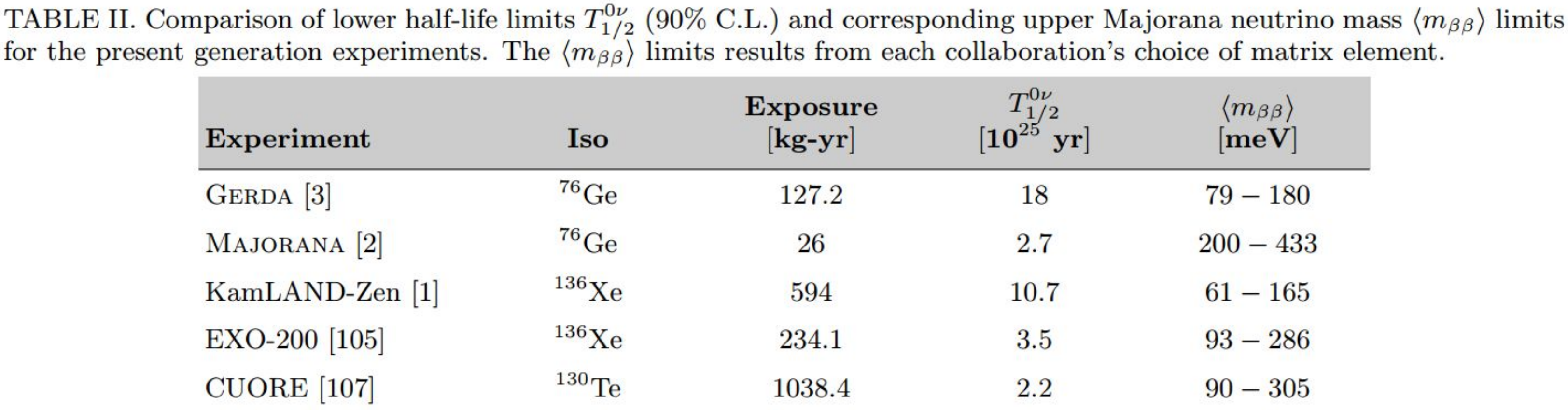


TABLE II. Comparison of lower half-life limits $T^{0\nu}_{1/2}$ (90% C.L.) and corresponding upper Majorana neutrino mass $\langle m_{\beta\beta}\rangle$ limits for the present generation experiments. The $\langle m_{\beta\beta}\rangle$ limits results from each collaboration's choice of matrix element.

| **Experiment** | **Iso** | **Exposure [kg-yr]** | $T^{0\nu}_{1/2}$ **[$10^{25}$ yr]** | $\langle m_{\beta\beta}\rangle$ **[meV]** |
|---|---|---|---|---|
| GERDA [3] | $^{76}$Ge | 127.2 | 18 | 79 – 180 |
| MAJORANA [2] | $^{76}$Ge | 26 | 2.7 | 200 – 433 |
| KamLAND-Zen [1] | $^{136}$Xe | 594 | 10.7 | 61 – 165 |
| EXO-200 [105] | $^{136}$Xe | 234.1 | 3.5 | 93 – 286 |
| CUORE [107] | $^{130}$Te | 1038.4 | 2.2 | 90 – 305 |

Source: LEGEND-1000 Portfolio Review Proposal

# Advantages of $^{76}$Ge:

- Enrichment up to ~90% is possible
- Source and detector are the same
- Resolution of ~3 keV (FWHM at $Q_{\beta\beta}$=2039 keV)
- Pulse shape descrimination (PSD)
- High detection efficiency
- Very low $^{232}$Th- and $^{238}$U-chain internal contamination
- No known background peak close to $Q_{\beta\beta}$.
- The lowest background of any 0vββ decay experiment, with no contamination from two-neutrino double-beta (2vββ) decays.

*A signal from a 0vββ decay in germanium would be like a lone peak in a featureless background continuum - visible to the eye. The extraction of a 0vββ decay signal does not rely on background modeling, and so has negligible systematic uncertainty*

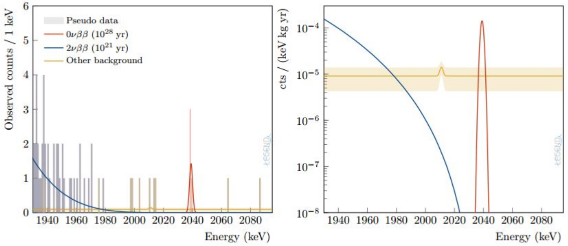


FIG. 10. An illustrative Monte-Carlo pseudo-dataset of LEGEND-1000, generated for the full background model, 10 ton years of exposure, and a $0\nu\beta\beta$ decay half life of $10^{28}$ years. The $2\nu\beta\beta$ decays do not leak in the $0\nu\beta\beta$ signal region, and their contribution is shown separately from the rest of the background sources. The uncertainty on the overal background model is covered by the yellow band.

Source: LEGEND-1000 Portfolio Review Proposal

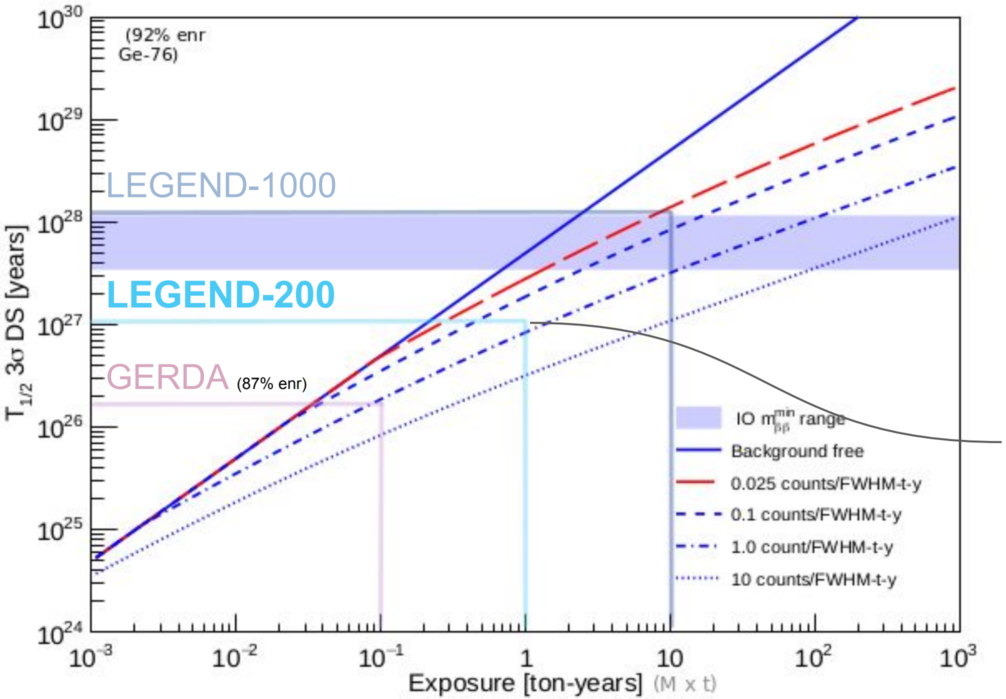
# LEGEND-200 is will increase the sensitivity by one order of magnitude[2], LEGEND-1000 will cover the inverted mas ordering region, performing a quasi-background free search.

detector mass

1 ton

200 kg

40 kg



$$\boxed{T_{1/2} \propto \epsilon M t}$$

$$T_{1/2} \propto \epsilon \sqrt{\frac{Mt}{B\Delta E}}$$

~0.3 counts/FWHM.t.y

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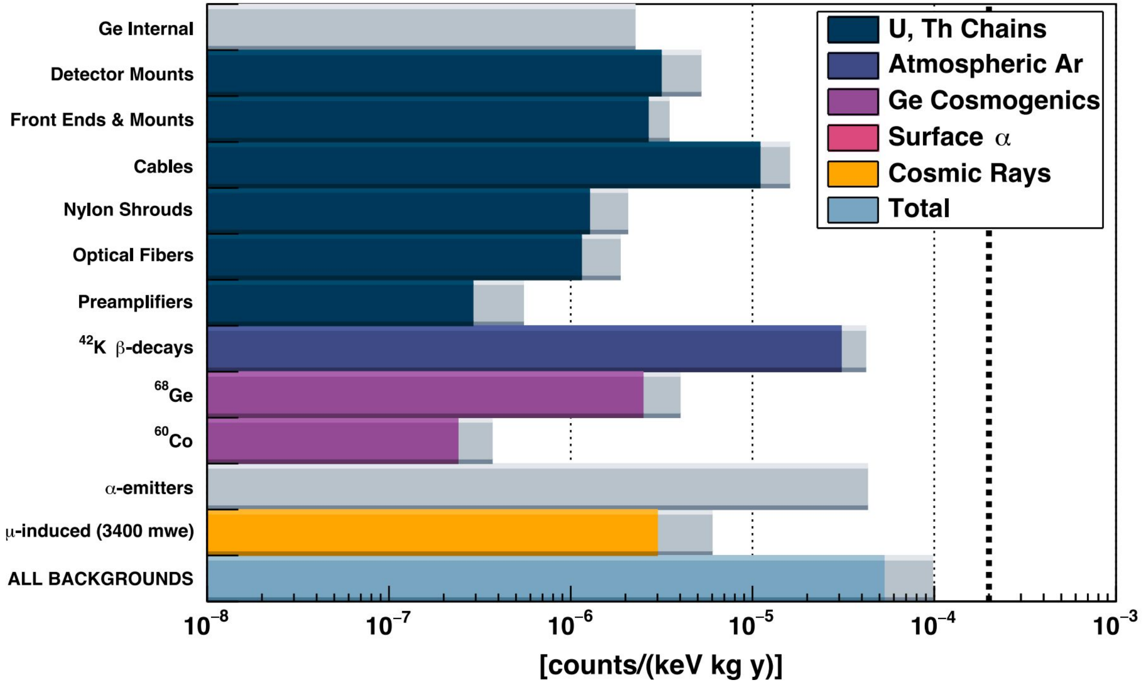
[2] The Legend Collaboration: The large enriched germanium experiment for neutrinoless double beta decay (LEGEND) arxiv:1894:020027

# Background in LEGEND-200



~0.3 counts/FWHM.t.y

# One order of magnitude background improvement in LEGEND-1000:

- 400 ICPC detectors (~of 2.6 kg each) in four 250-kg modules
- Mitigation of $^{42}$Ar by using underground argon inside the electroformed copper modules

# The ICPC detectors of LEGEND

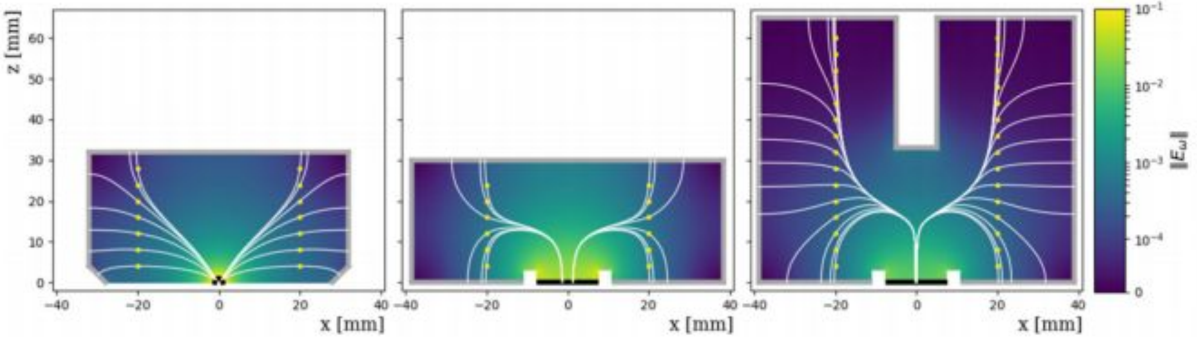


FIG. 3. The three detector geometries developed by the MAJORANA (PPC detector, left), GERDA (BEGe detector, middle), and LEGEND (ICPC detectors, right) collaborations. The mass of ICPC detectors is up to a factor 3 larger than that of its predecessors. Taken from Ref.[63].

Larger size = much less cable and electronics, less background

# Energy resolution of ICPC Germanium detectors

New ICPC detectors: Resolution of ~2.4 keV (FWHM at $Q_{\beta\beta}$=2039 keV )

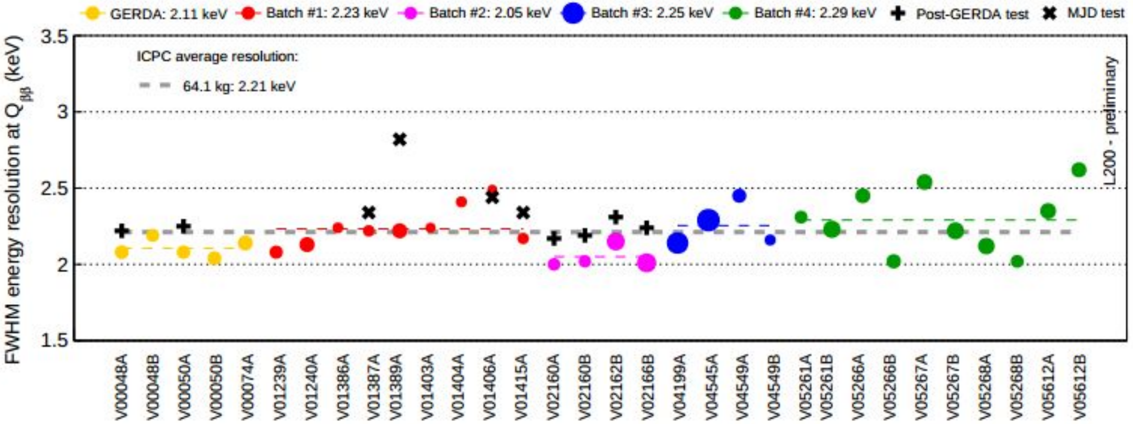
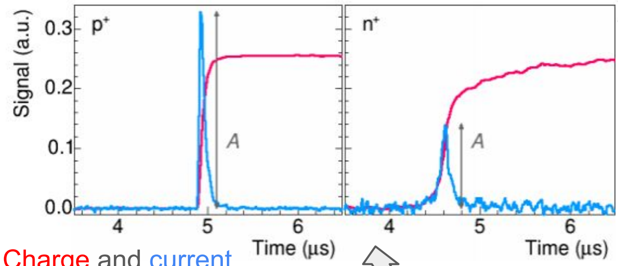
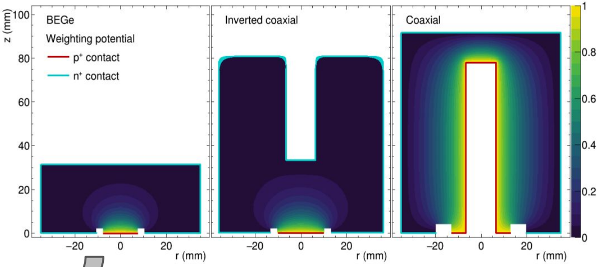


FIG. 12. FWHM energy resolution of all delivered to date LEGEND-200 ICPC detectors as measured in vendor vacuum cryostats (colored circles). The dashed lines indicate the mass-weighted average per production batch (colored) and for all detectors combined (gray). Each data-point diameter scales with its detector mass; uncertainties are on the order of or smaller than the marker sizes. Also shown are the values measured during testing in the Gerda (black plus) and Majorana Demonstrator (black cross) cryostats.

# Pulse Shape Discrimation (PSD) of surface events (p$^+$ and n$^+$ contacts) and single-site (SSE) vs multi-site events (MSE)

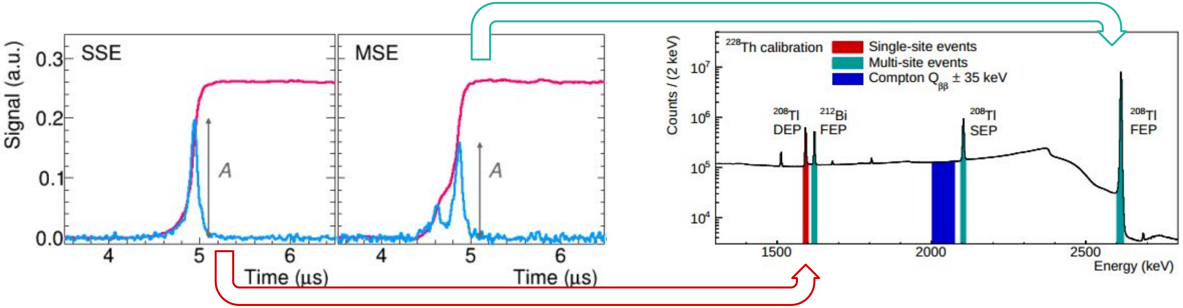


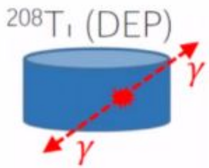
Charge and current pulses from a BEGe detector

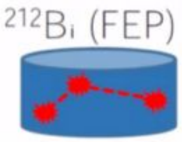


PSD is very effective on rejecting surface events, like $\alpha$'s. This works for all detector types: IC, BeGe and Coax (with special cuts for the Coax)

PSD can discriminate between “point-like” events (like DEP or 0nubb) and







(*) this rejection is slightly dependent on energy. (**) This rejection is not dependent on energy but on detector type/size