Neutrinoless double beta decay search with GERDA and LEGEND

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NBIA PhD summer school 2021

Outline

- Motivation for $0\nu\beta\beta$ decay search
- What $0\nu\beta\beta$ is
- How to search for it
- GERDA experiment and its recent results on the search for $0\nu\beta\beta$
- LEGEND Experiment and its current status

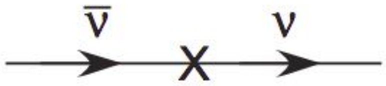
The motivation to search for 0νββ decay is to answer many open questions

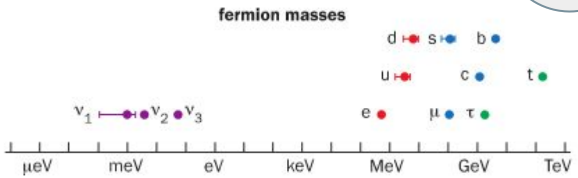
What is the 'nature' of neutrinos?

Are they their own anti-particle?

Where does their mass come from?

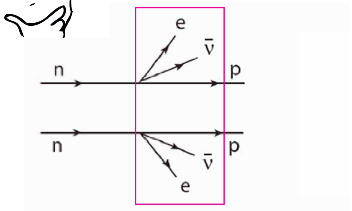
Why are they so small?





What is 2νββ?

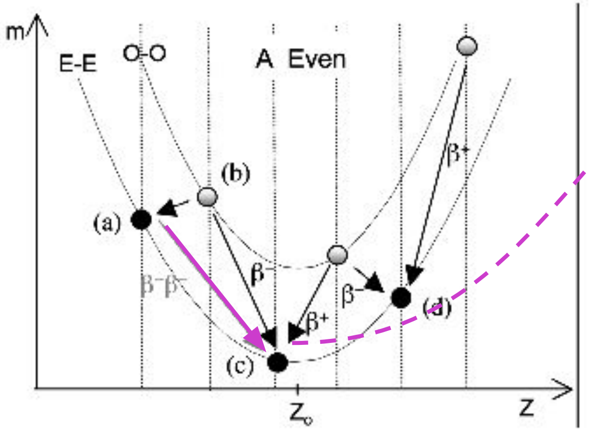
A few isotopes in nature decay emitting 2 electrons and 2 anti-neutrinos (2νββ decay).



Two neutrino double beta decay (2νββ):

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

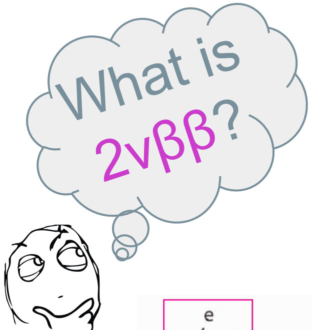
decaying from even-even to odd-odd wouldn't be energetically favorable !



$$E_B = a_V A - a_S A^{2/3} - a_A \frac{(A-2Z)^2}{A^{1/3}} - a_C \frac{Z(Z-1)}{A^{1/3}} + \boxed{\delta(A,Z)}$$

Volume term | Surface term | Asymmetry term | Coulomb term | Pairing term

$$\delta(A,Z) = \begin{cases} +\delta_0 & Z, N \text{ even } (A \text{ even}) \\ 0 & A \text{ odd} \\ -\delta_0 & Z, N \text{ odd } (A \text{ even}) \end{cases}$$



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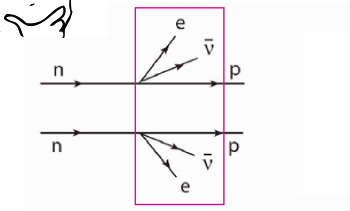
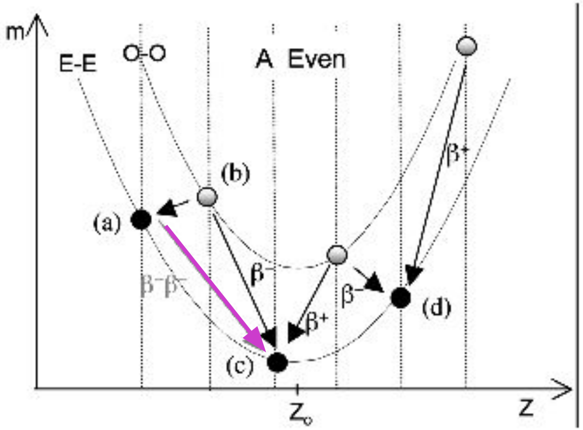


Two neutrino double beta decay (2νββ):

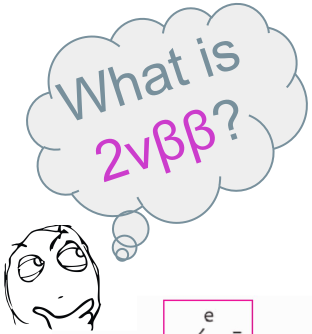
- $2n \rightarrow 2p + 2e^{-} + 2\bar{\nu}_e$

Rare process! First observed by S. Elliot et al in $^{82}Se \rightarrow {}^{82}Kr + 2e^{-} + 2\bar{\nu}$, $\tau_{1/2} > 10^{20}$ yr (1987)

It was back then the longest lifetime ever observed [*]



[*] Surpassed now by the observation of DBD of other isotopes and the DEC of Xe-124 (Nature 568, 532–535, 2019)



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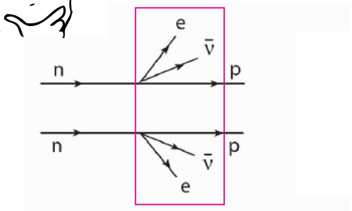

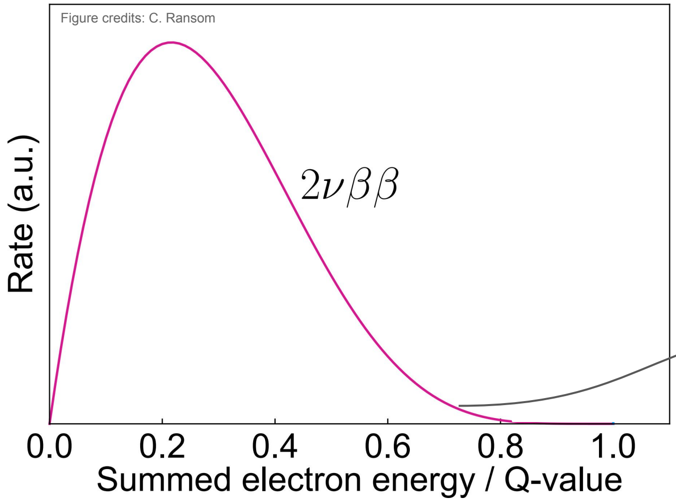

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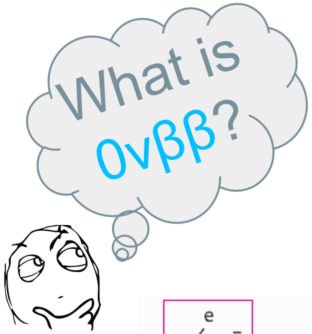
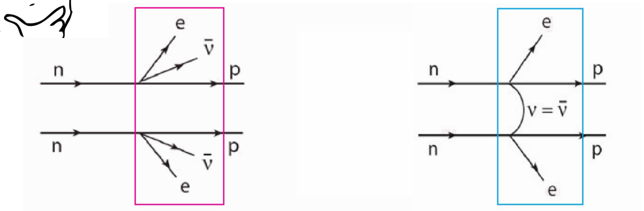
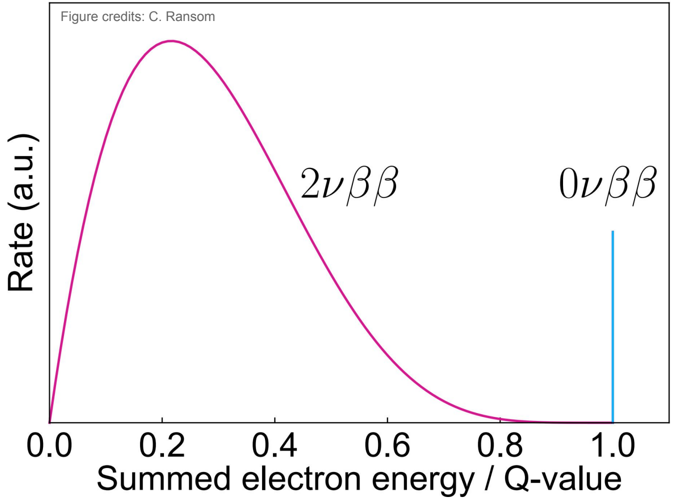
It was back then the longest lifetime ever observed [*]

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



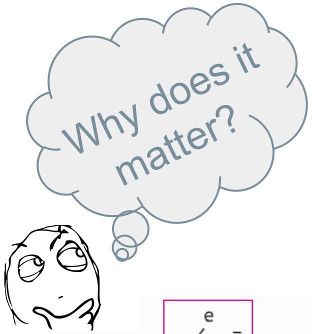


Two neutrino double beta decay (2νββ):

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

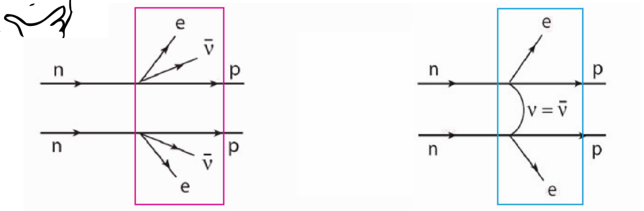
Neutrinoless double beta decay   (0νββ):

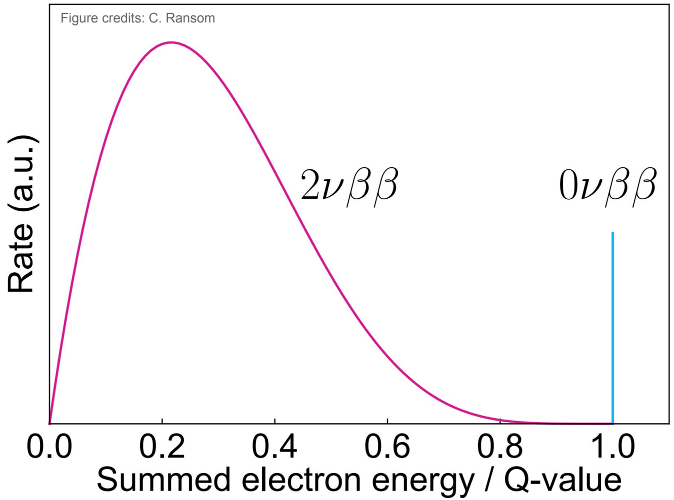
- $2n \rightarrow 2p + 2e^{-}$



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

Origin of neutrino mass! !



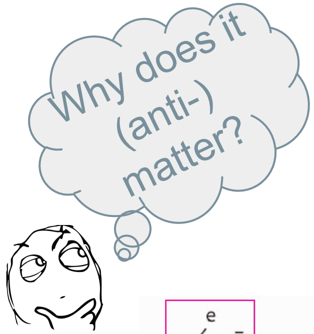


Two neutrinos emitted (2νββ):

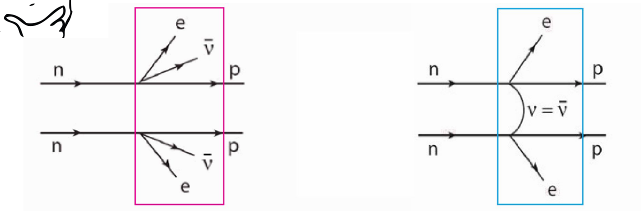
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

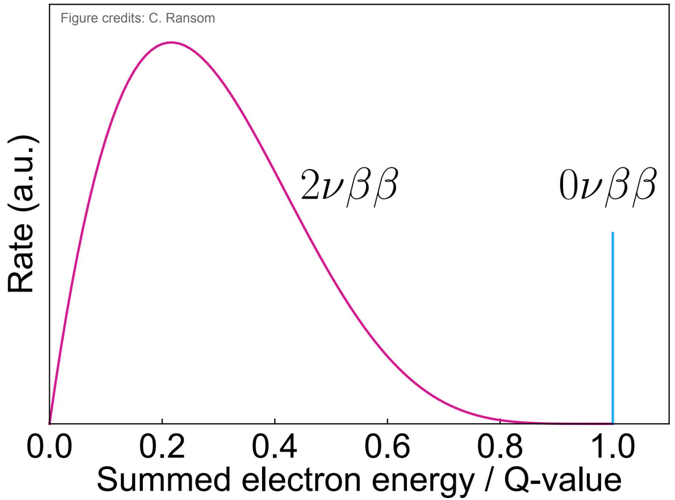
No neutrinos emitted (0νββ):

- $2n \rightarrow 2p + 2e-$



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





Two neutrinos emitted (2νββ):

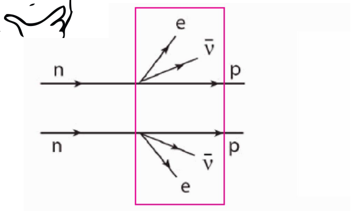
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (ΔL=0)

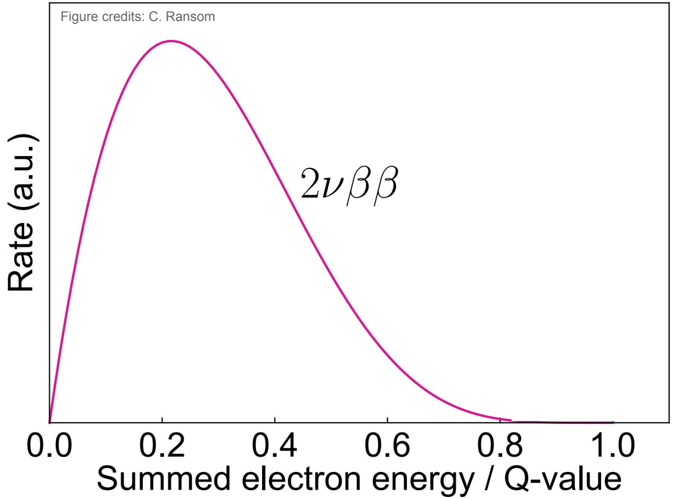
No neutrinos emitted (0νββ):

- $2n \rightarrow 2p + 2e^-$ (ΔL=+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:



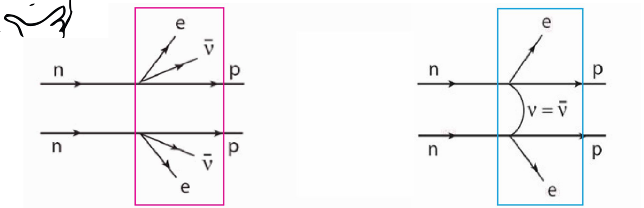


continuous spectrum

Two neutrinos emitted (2νββ):

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

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



continuous spectrum

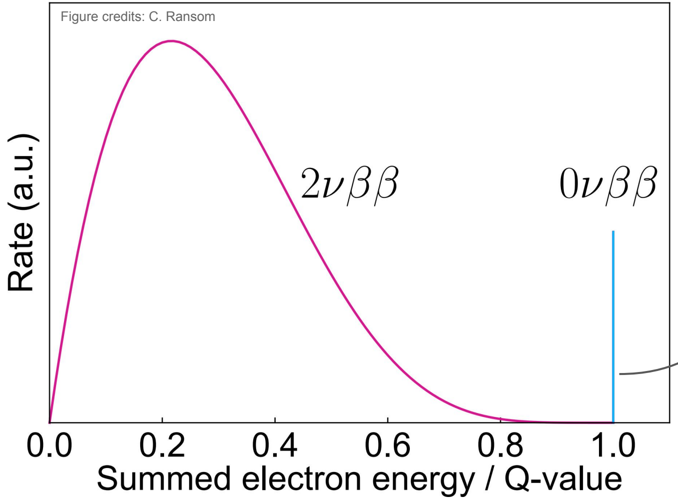
Two neutrinos emitted ($2\nu\beta\beta$):

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

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

No neutrinos emitted ($0\nu\beta\beta$):

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



Ge detectors have the excellent energy resolution needed for the detection of the peak at the end of the $2\nu\beta\beta$ spectrum !

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

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

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)

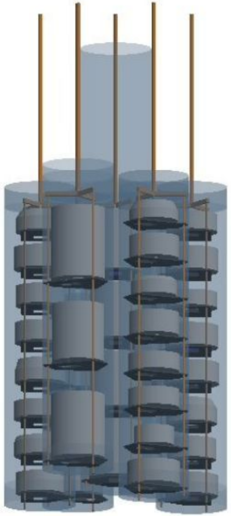
Best energy resolution and lowest background index in all 0νββ decay experiments

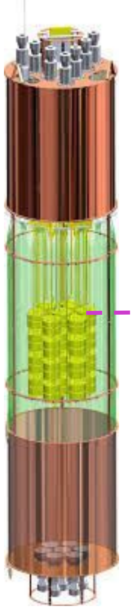
Figures from GERDA

To suppress background, GERDA[1] operated Ge detectors in an active Liquid Argon (LAr) shield[2], instrumented with optical fibers and photodetectors

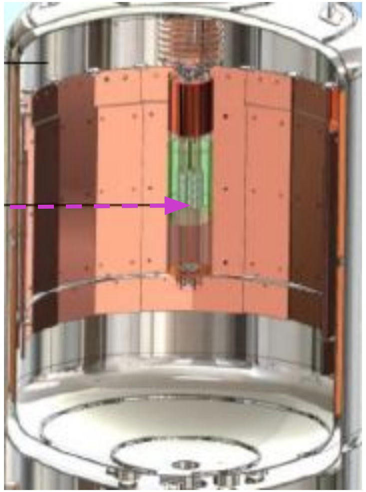
HPGe detectors on silicon detector holders

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.

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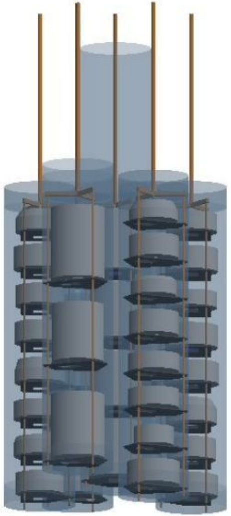
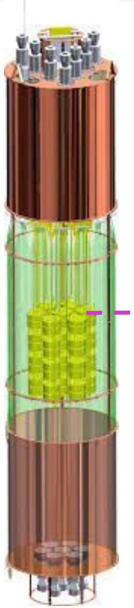
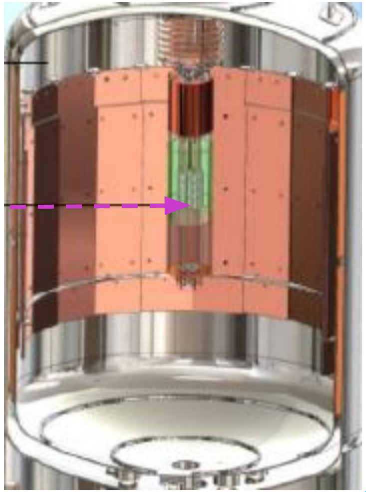


inside a water tank

LAr Veto

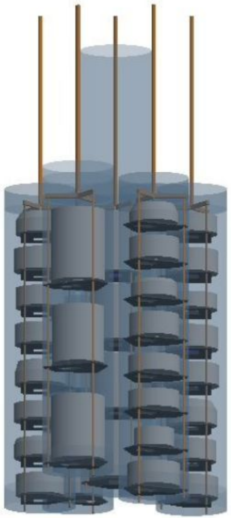


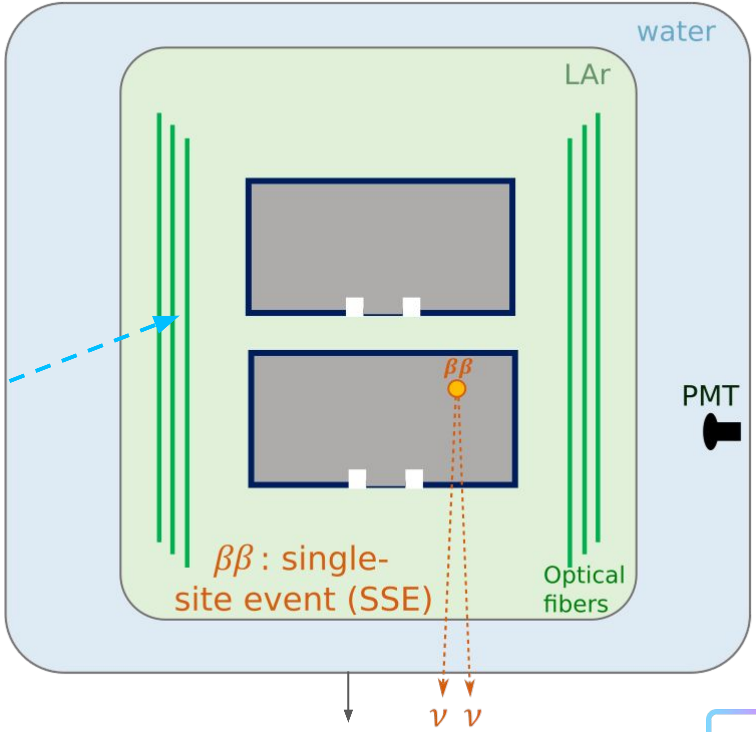


Under 1.4 km of mountain rock

[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.

The detectors are immersed in liquid argon (LAr). The signal (ββ) is a single-site event: the energy is fully deposited within mm^3 in a detector and nothing is observed in the LAr or water.

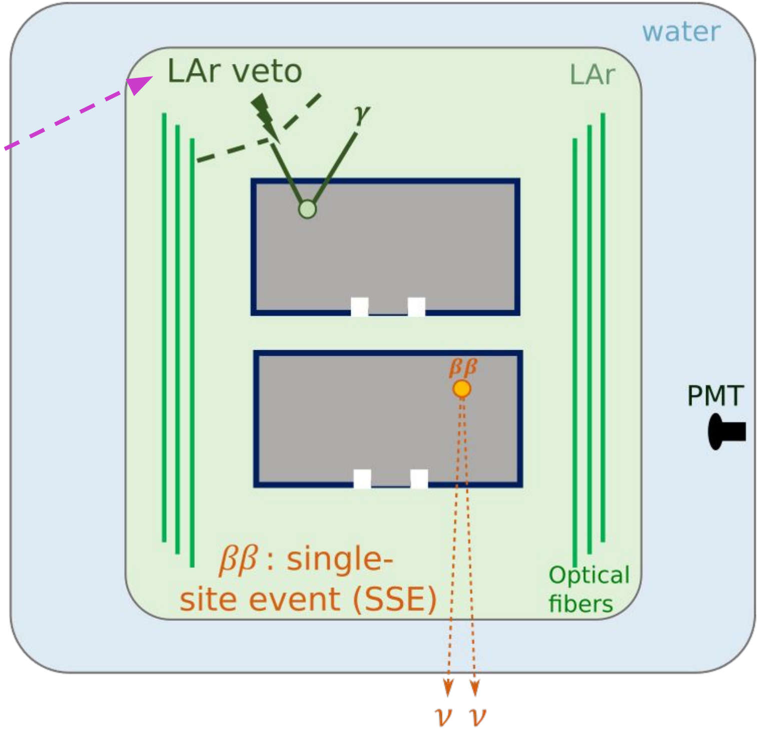




Water tank 1.4 km underground

Background events (like γ's) are often multi-site events, which can be discriminated by the **LAr veto**

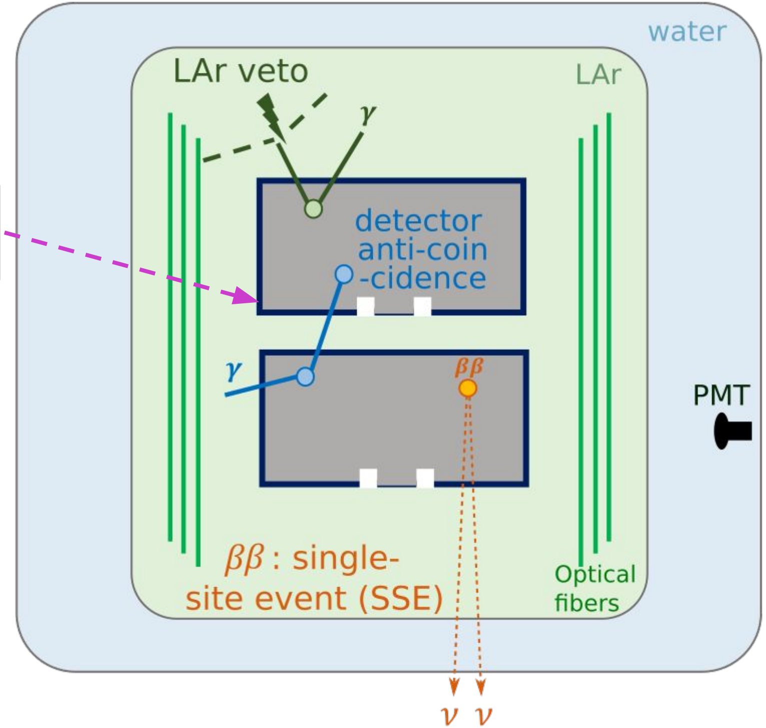
Liquid argon (LAr) scintillates when energy is deposited. The photons are then collected by the fibers and the event is vetoed.



The signal (ββ) is a single-site event

Background events (like γ's) are often multi-site events, which can be discriminated by the LAr veto, and by a **detector anti-coincidence** cut

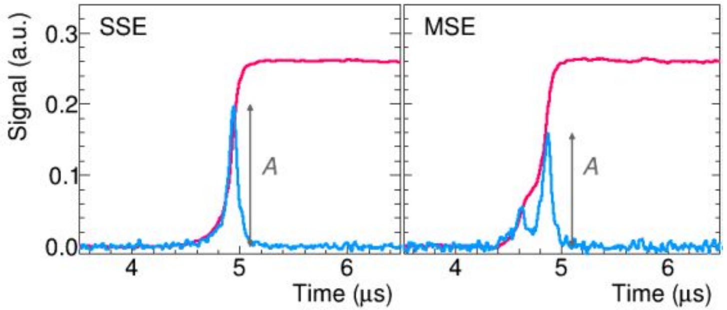
Energy deposited in more than one detector

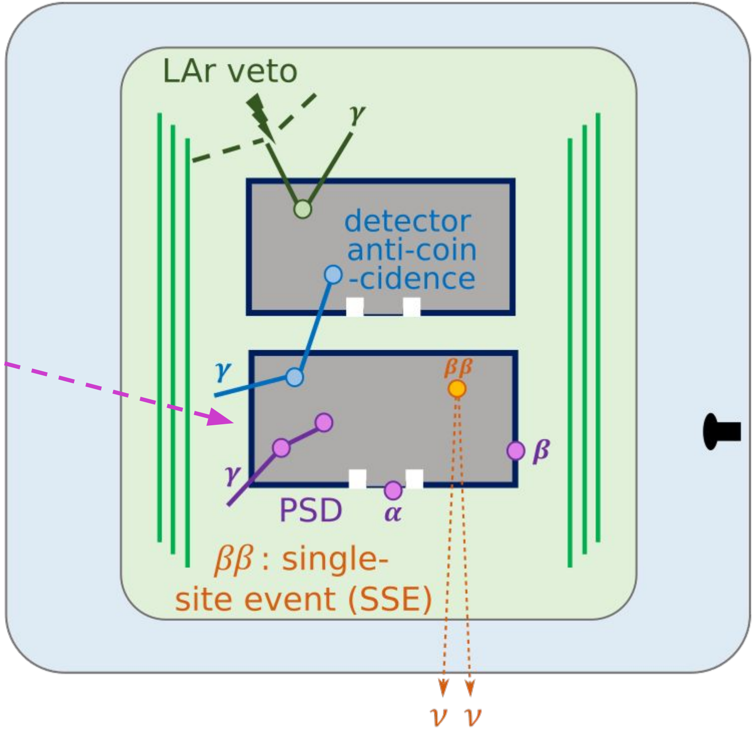


The signal (ββ) is a single-site event

Background events (like γ's) are often multi-site events, which can be discriminated by the LAr veto, by a detector anti-coincidence cut and by Pulse Shape Discrimination (**PSD**).

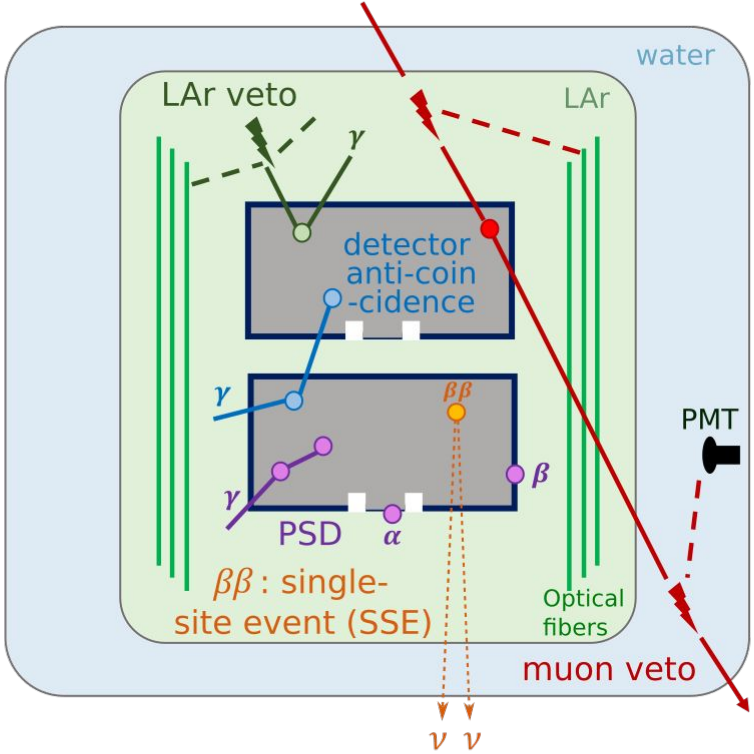
PSD: The charge and current collected from a multi-site event (MSE) has a different shape.





The signal (ββ) is a single-site event

Multi-site events (like ɣ’s) can be discriminated by the LAr veto, by a detector anti-coincidence cut and by Pulse Shape Discrimination (PSD). Muons are detected by the LAr or muon veto.

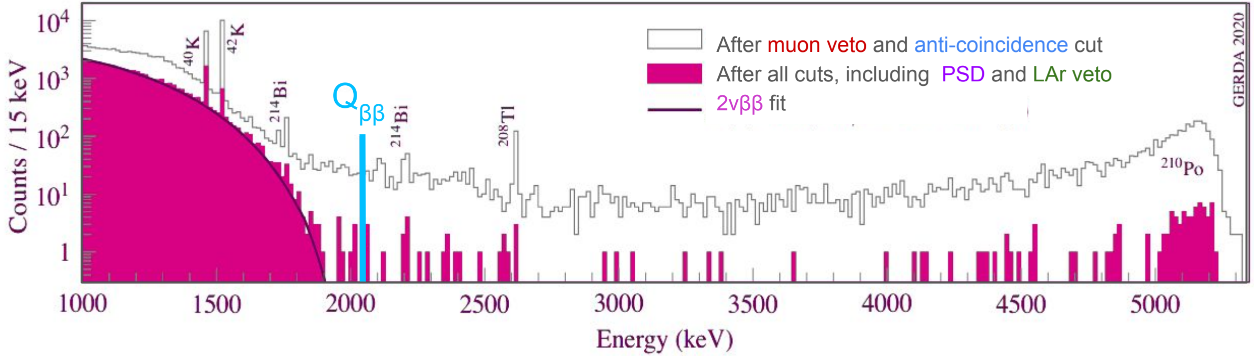


Muons can create cherenkov light in the water tank, which is detected by photomultipliers (PMTs)

The muon flux under 1.4 km of rock is suppressed by 10^6

The signal (ββ) is a single-site event

GERDA's strong background suppression along with its excellent energy resolution allowed it to run background-free up to its designed exposure of 100 kg.yr[3]:



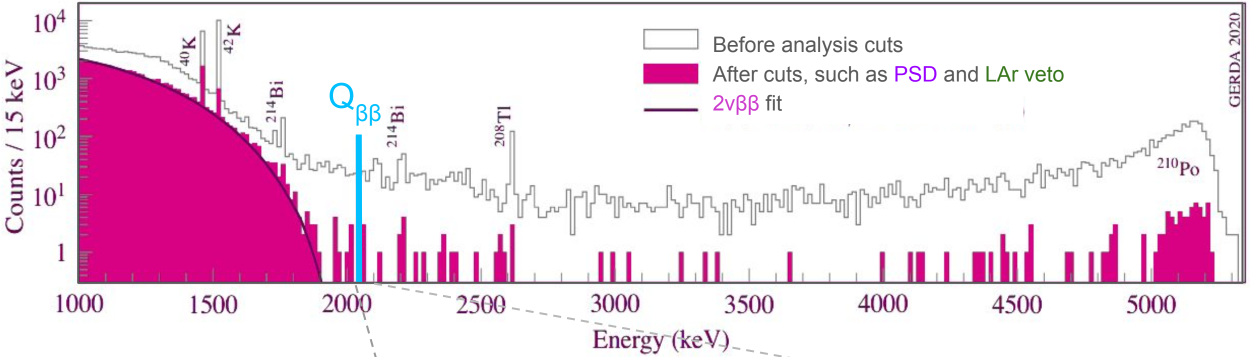
100 kg.yr exposure

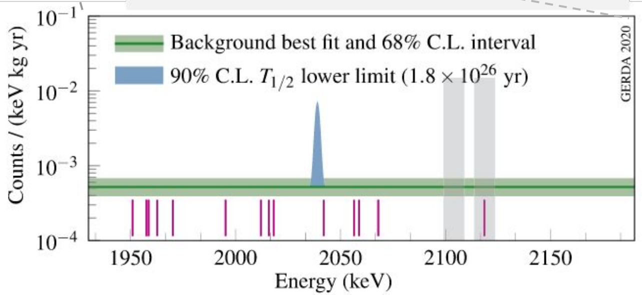
Background free data: sensitivity to $T_{1/2} \propto$ to the efficiency (ε), and exposure (Mt).
Otherwise, it also depends on the background index (B) and the energy resolution (ΔE)

$$T_{1/2} \propto \varepsilon Mt, \quad T_{1/2} \propto \varepsilon \sqrt{\frac{Mt}{B \triangle E}}$$

[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

No events were observed in the ROI (around $Q_{\beta\beta}$) and GERDA set the world's best half-life limit[3] on $0\nu\beta\beta$:





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

(at 90% CL)

100 kg.yr exposure

$$T_{1/2} \propto \varepsilon Mt, \quad T_{1/2} \propto \sqrt{\frac{Mt}{B \triangle E}}$$

ε

World's best background: 5.2×10^{-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

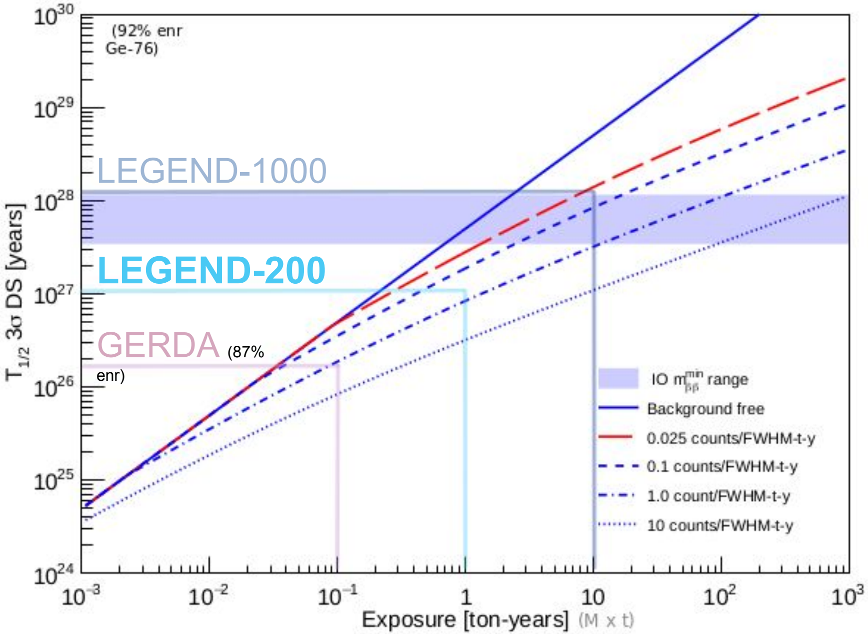
LEGEND-200 is the next step to GERDA in the search for $0\nu\beta\beta$ decay: it aims to increase the sensitivity by one order of magnitude[4]

detector mass

1 ton

200 kg

40 kg



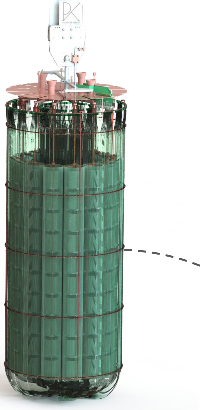
$T_{1/2} > 10^{27}$ yr

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/MJD (Majorana Demonstrator)



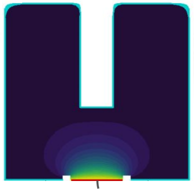
Operation of detectors in 63 tons of LAr surrounded by veto instrumentation

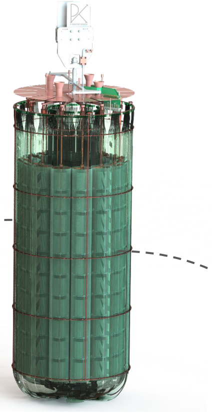
Inside a muon veto (water tank) and underground location at LNGS

LNGS: Laboratori Nazionali del Gran Sasso

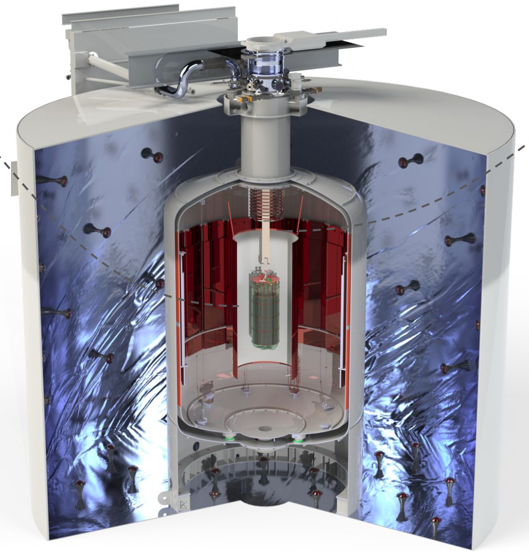
Figure credits: P. Krause

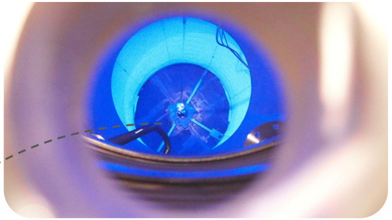
To achieve the target sensitivity and background level, LEGEND builds up on the knowledge from GERDA/Majorana, **but with improved detectors and veto**





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



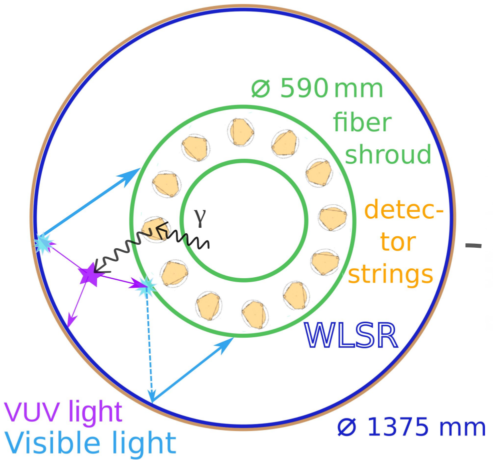


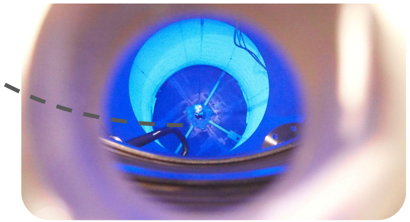
Wavelength shifting reflectors increase the veto efficiency of LAr

These have been developed with the help of our group!

[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

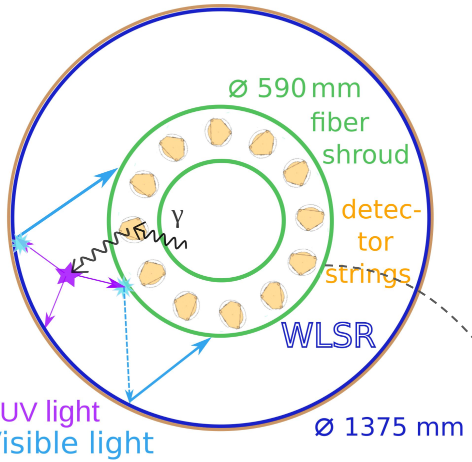
The wavelength shifting reflectors (WLSR) surround the fibers of the LAr veto: re-emitting light toward the fibers that would be otherwise lost.

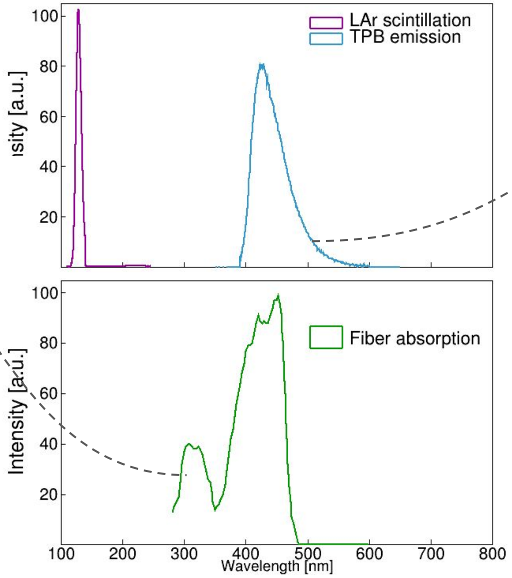


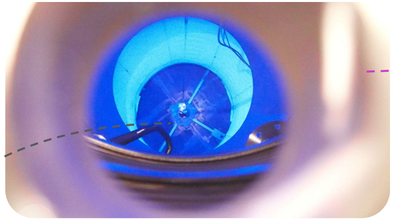


Wavelength shifting reflectors increase the veto efficiency of LAr

The wavelength shifting reflectors (WLSR) are coated with a wavelength shifter (TPB) which absorbs VUV scintillation light and re-emits it in blue. This light can be now reflected and go toward the fibers and the event is then vetoed

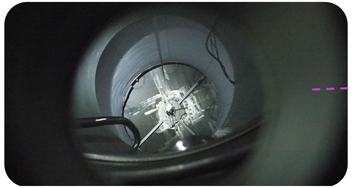






WLSR under UV light

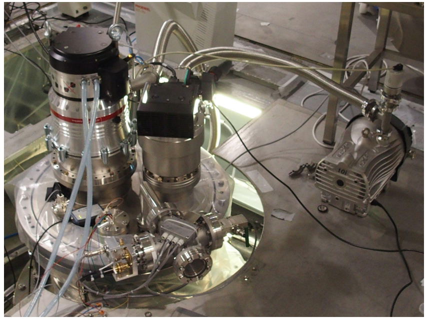
Wavelength shifting reflectors increase the veto efficiency of LAr

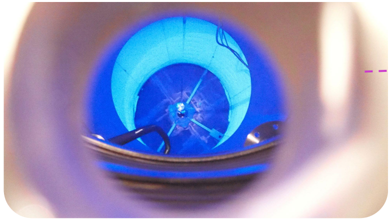


White reflector

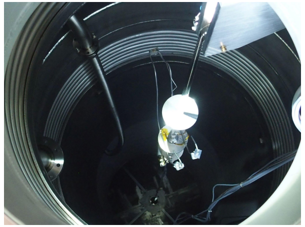
[*] LAr's scintillation wavelength: 128 nm

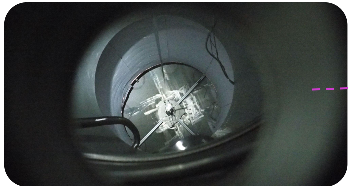
A few pictures of the work on the installation and coating of the WLSR in the cryostat





WLSR under UV light

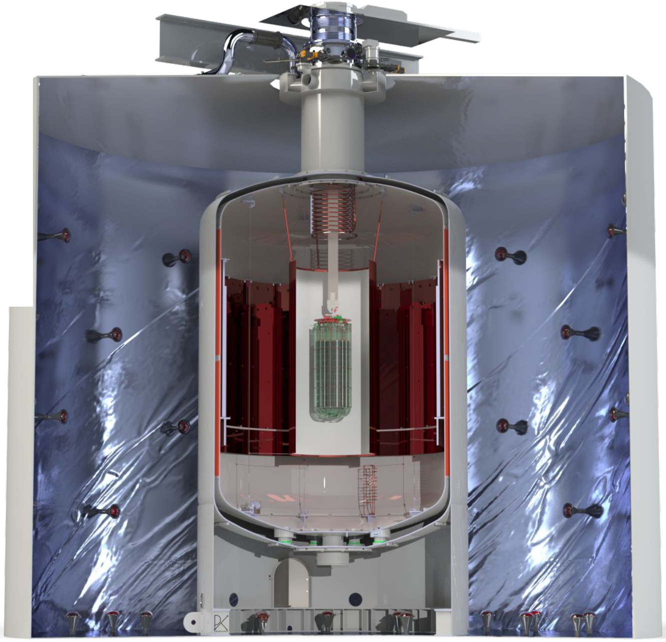




White reflector

In summary, GERDA did not find $0\nu\beta\beta$ but set the best limit on it and paved the way to LEGEND-200, which 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



- $T_{1/2} > 10^{27}$ yr
  1 ton.yr exposure
- Background better than 10^{-4}counts/(keV.kg.yr)

Thanks for your attention!

Back up slides