Unveiling the nature of neutrinos: the search for neutrinoless double beta decay with the LEGEND experiment

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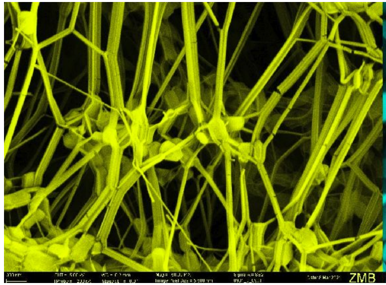
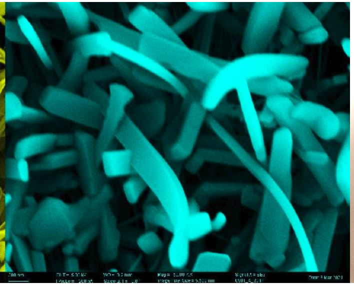
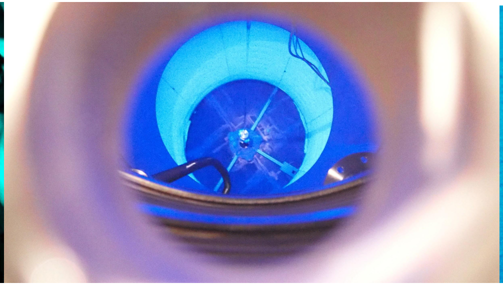
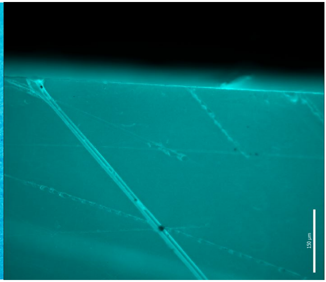
CHIPP school - January 2023

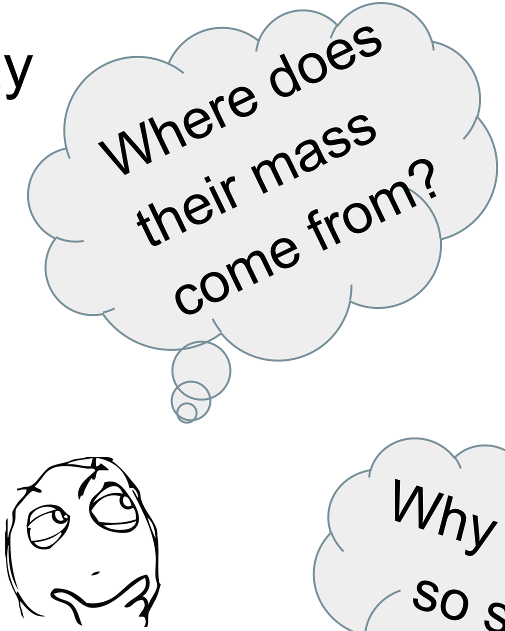
University of Zurich[UZH]

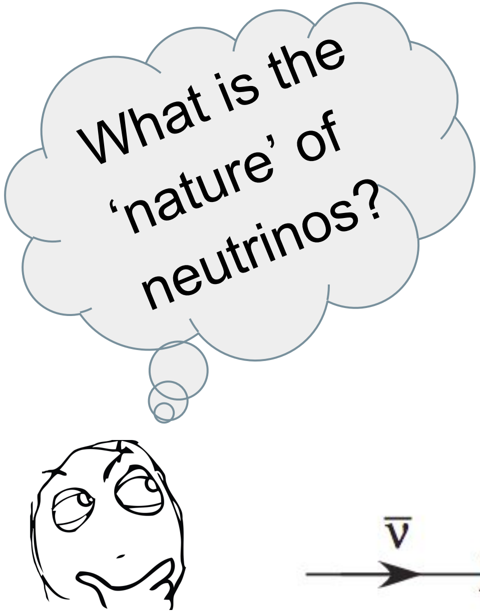
LEGEND

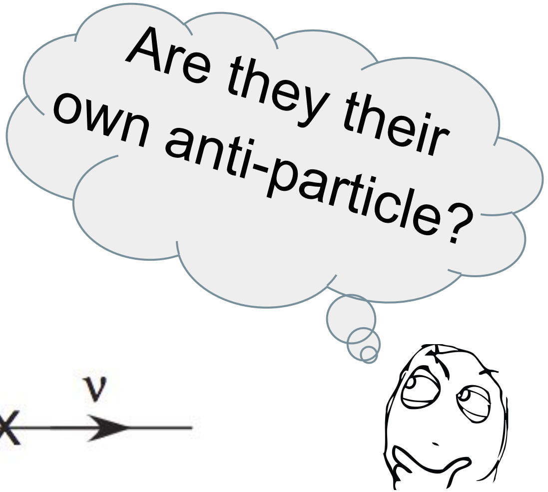




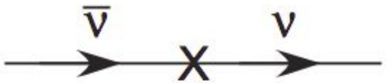


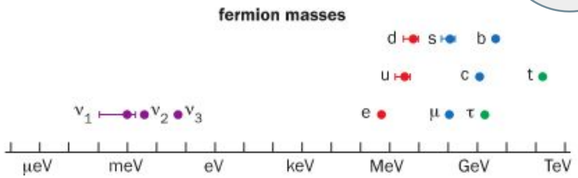
The motivation to search for 0νββ decay is to answer many open questions

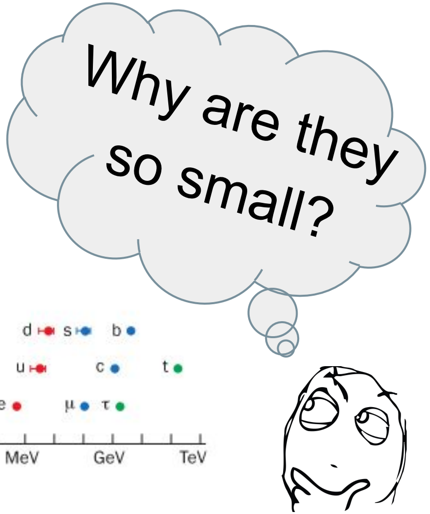


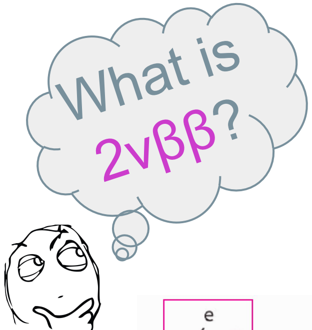




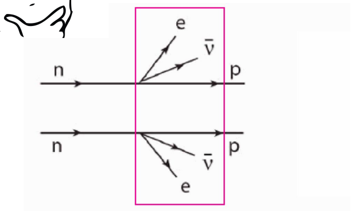






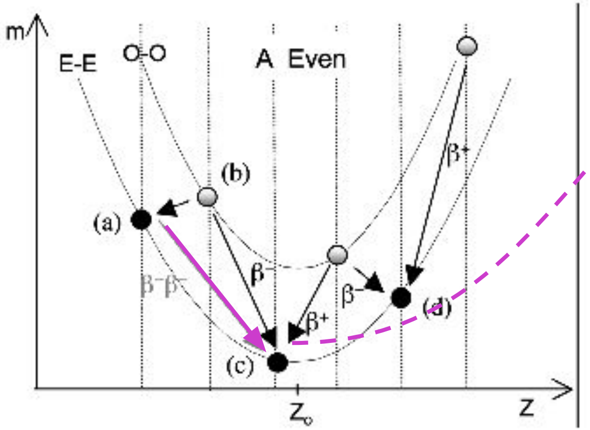


A few isotopes in nature decay emitting 2 electrons and 2 anti-neutrinos (2νββ decay).



Two neutrino double beta decay (2νββ):

- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (in a nucleus)

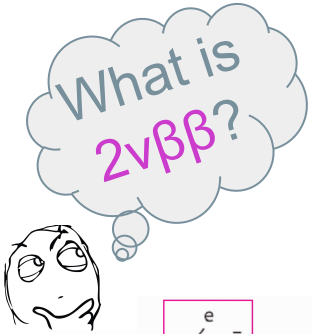


decaying from even-even to odd-odd wouldn't be energetically favorable !

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

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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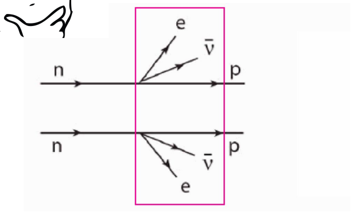

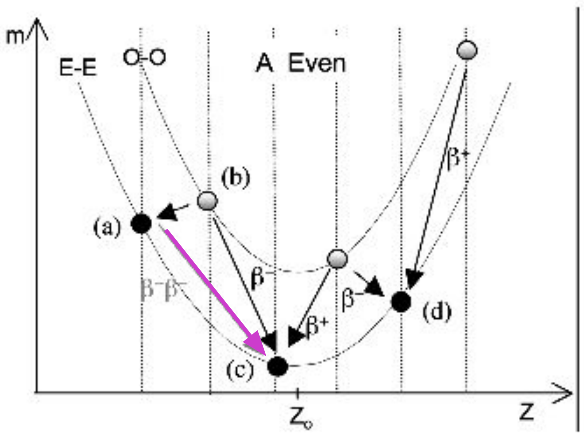

Two neutrino double beta decay (2νββ):

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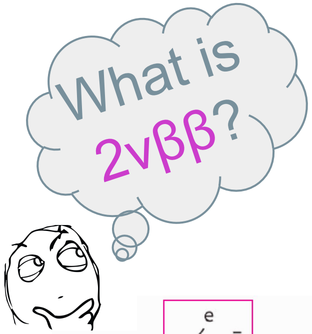
Rare process! First observed by S. Elliot et al in $^{82}Se \rightarrow {}^{82}Kr + 2e- + 2\bar{\nu}$, $\tau_{1/2} > 10^{20}$ yr (1987)

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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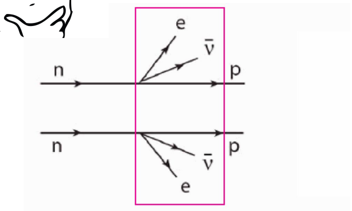

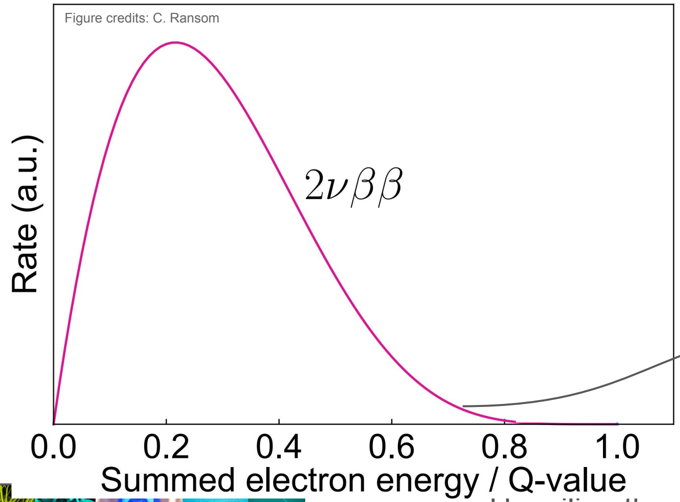

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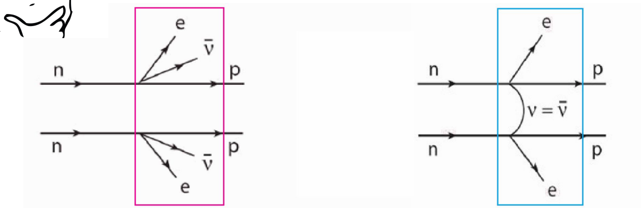
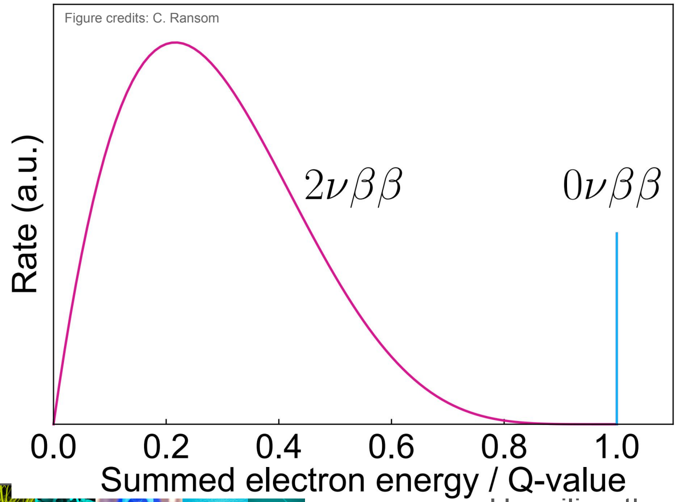
The electrons share the energy with the neutrinos and produce a broad spectrum. !

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





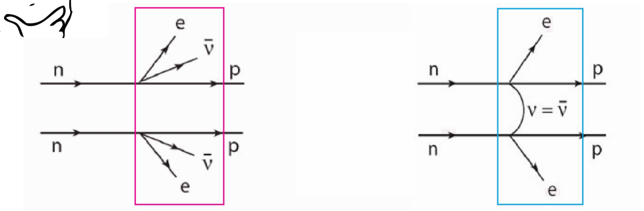
Two neutrino double beta decay (2νββ):

- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (in a nucleus)

Neutrinoless double beta decay (0νββ):

- $2n \rightarrow 2p + 2e^-$ (in a nucleus)

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

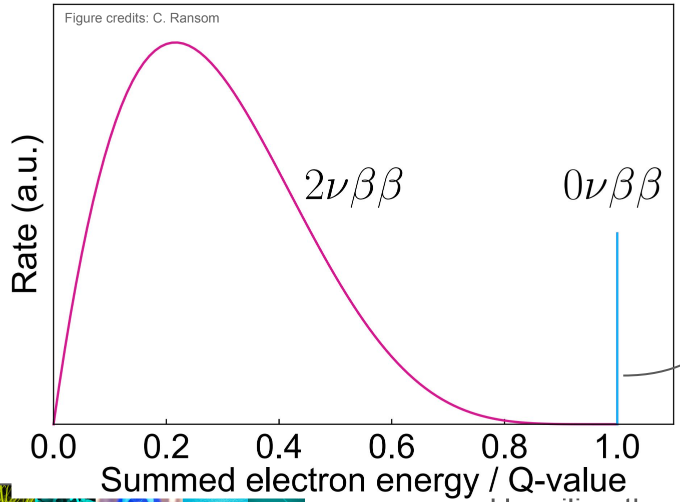
Two neutrinos emitted ($2\nu\beta\beta$):

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

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

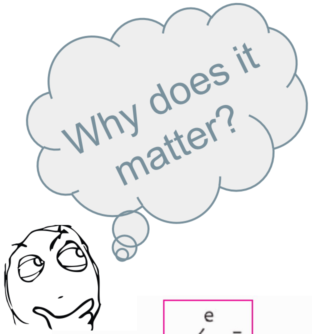
No neutrinos emitted ($0\nu\beta\beta$):

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



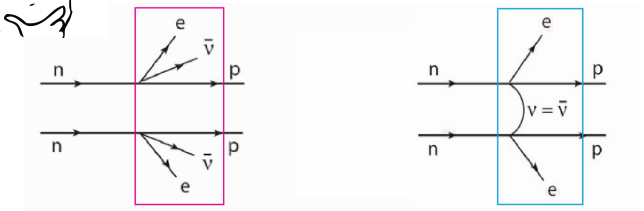
Ge detectors have the excellent energy resolution needed for the detection of the peak at the end of the $2\nu\beta\beta$ spectrum !

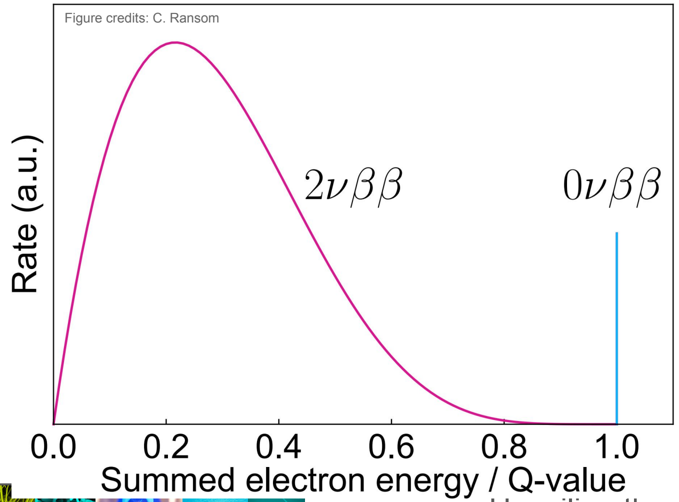
Resolution of ~3 keV (FWHM at $Q_{\beta\beta}$=2039 keV)



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):

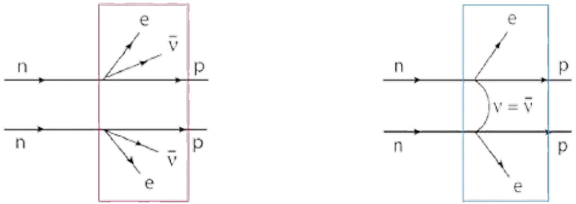
- $^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$ (ΔL=0)

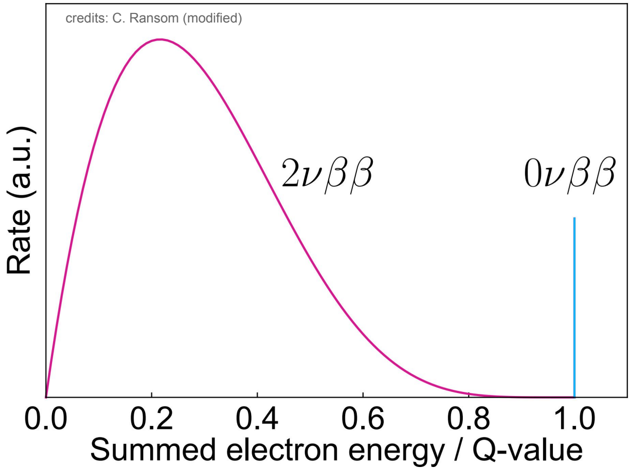
No neutrinos emitted (0νββ):

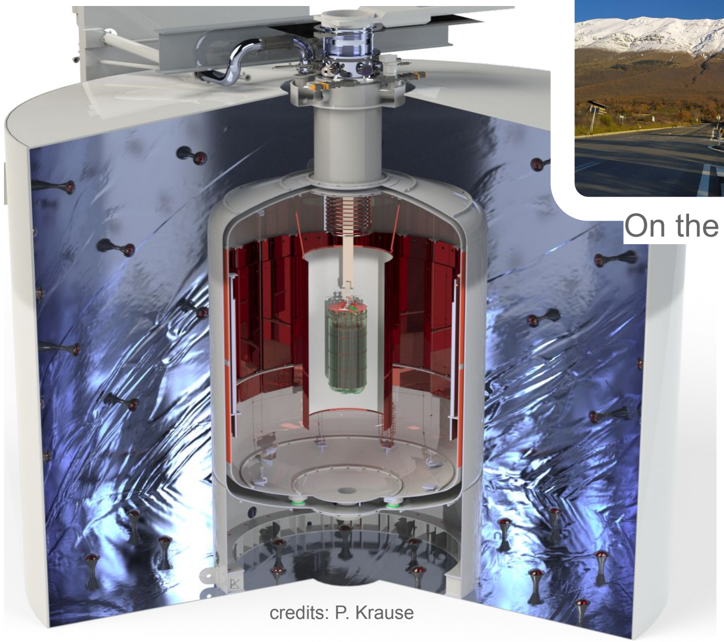
- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$ (ΔL=+2)

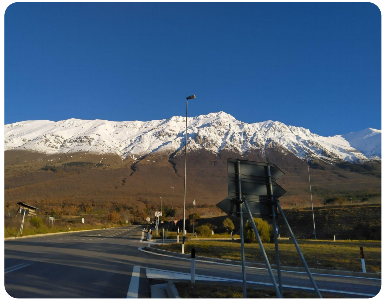
Violation of lepton number conservation could explain the **matter-antimatter asymmetry of the universe**

Large Enriched Germanium Experiment for Neutrinoless ββ (0νββ) Decay



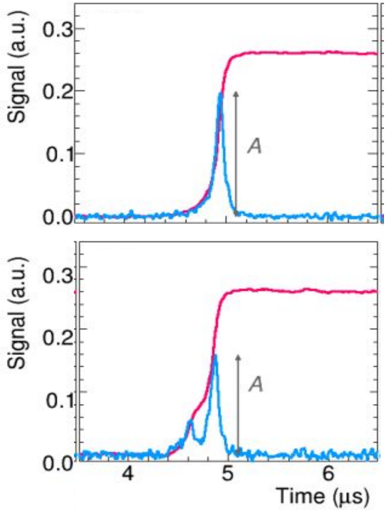





On the way to LNGS

[1] N. Abgrall *et al.* The large enriched germanium experiment for neutrinoless double beta decay (LEGEND) [2] N. Abgrall *et al.* LEGEND-1000 Preconceptual Design Report

HPGe crystals provide different signals for 0νββ and multi-scatter events.



(0ν)ββ: single-site signal

Multi-scatter background, eg. γ (*)

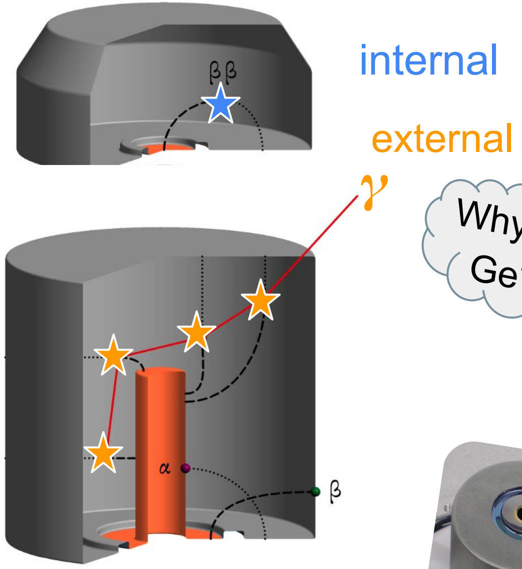
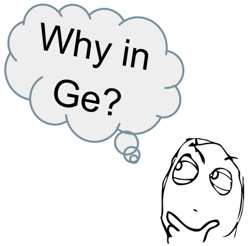
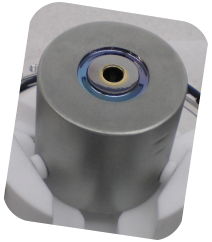


Figure from L. Pertoldi (modified)



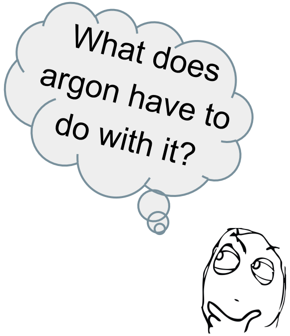


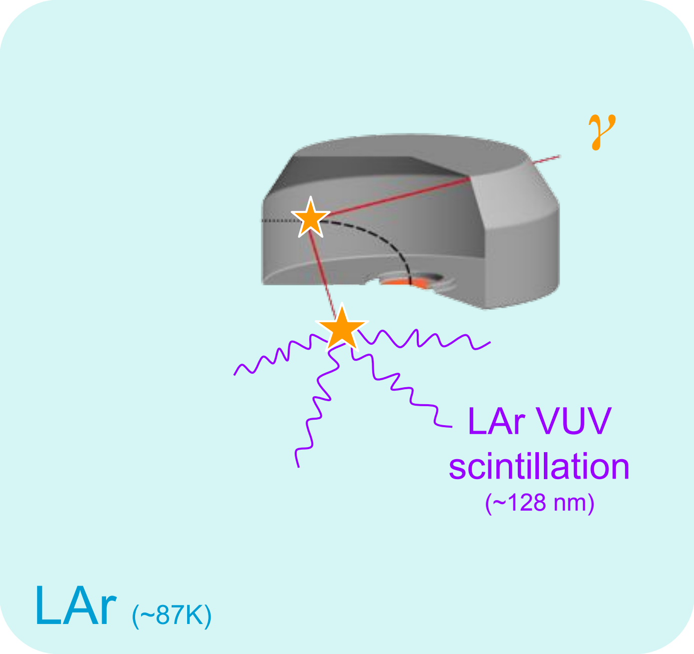
Pulse-shape discrimination[4]: The charge and current show different shapes for single or multi-site events.

[4] M. Agostini, *et al.* EPJ. C **82,** 284 (2022).

(*) γ-rays that deposit full energy in the detector are usually not a source of background, as there are no γ-lines around $Q_{\beta\beta}$.

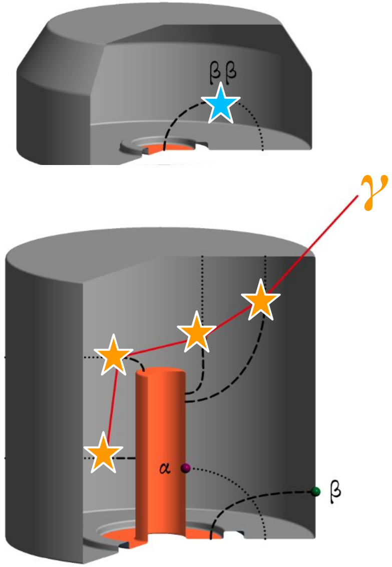
HPGe crystals can be operated in liquid argon (LAr), which serves as a coolant, passive shield and active veto





(0ν)ββ: single-site signal

Multi-scatter background, eg. γ (*)



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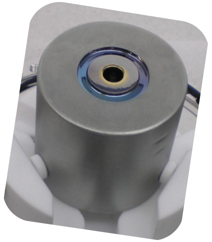
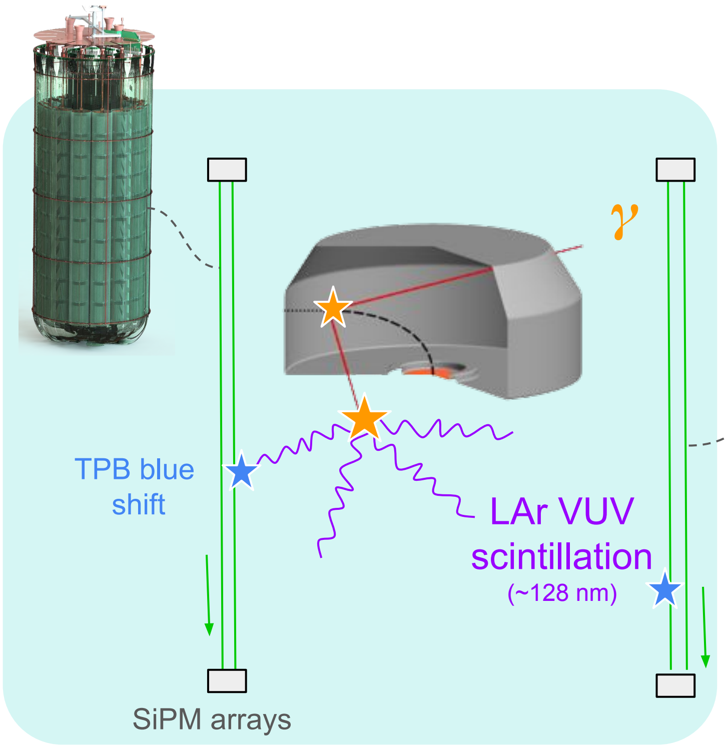
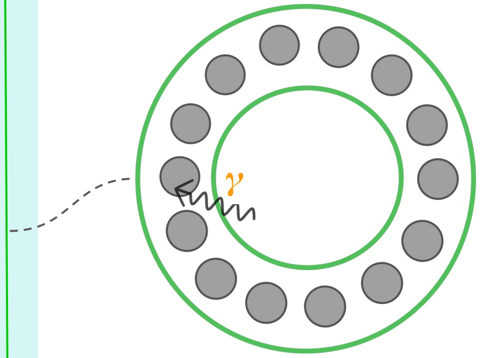
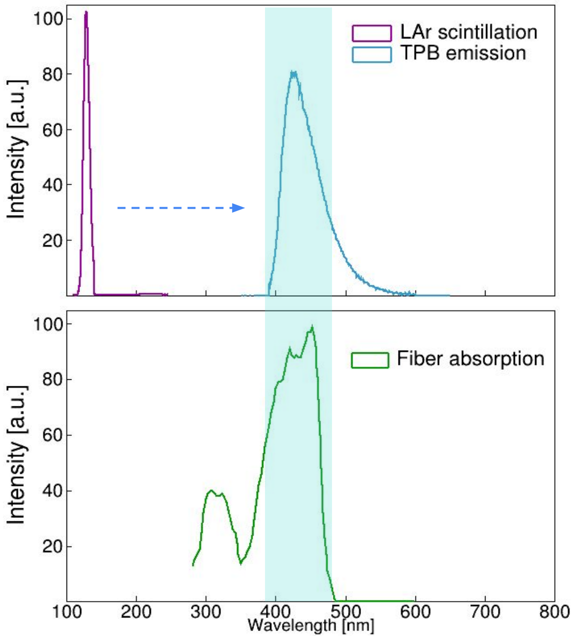


The fibers are coated with TPB[*], which shifts the VUV light to the blue. This light is shifted again by the fibers and then guided to SiPM arrays.





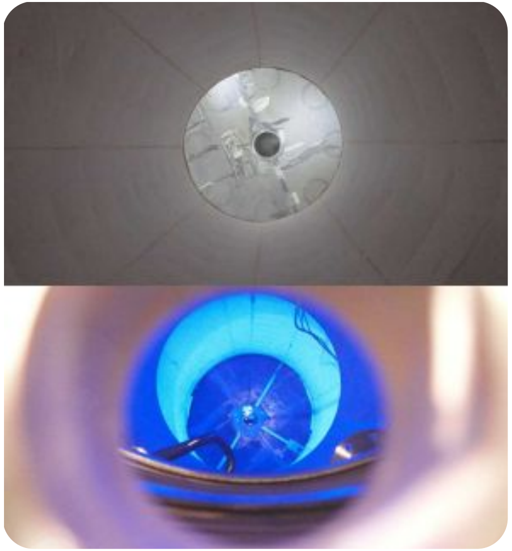
Top view of HPGe crystals and fibers

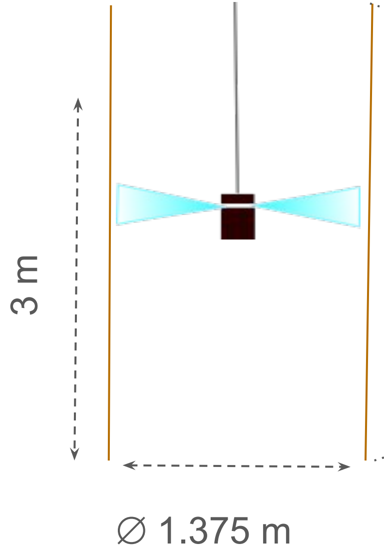


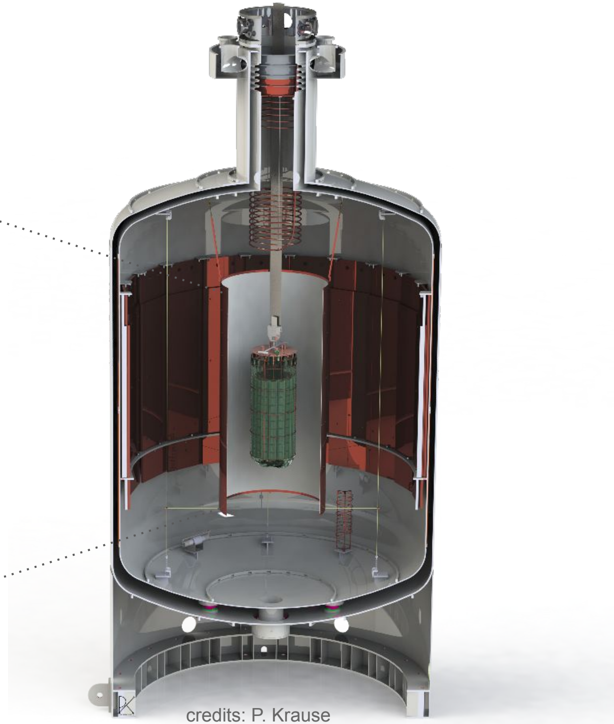
The fibers first absorb the blue light and then shit it to the green region.

[*] For details see [5] M. Schwarz, *et al*, EPJ Web **253**, 11014 (2021) [*] Tetraphenylbutadiene

LEGEND-200 WLSR: reflective thin Tetratex (TTX) membrane lined up on copper foils **and coated with the wavelength-shifter TPB**



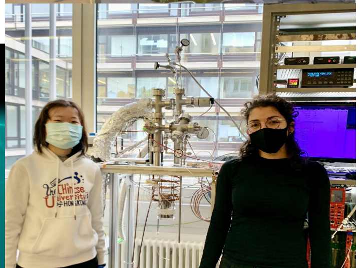




[*] used as a reflector in GERDA & in ArDM: [5] L. Baudis, *et al* 2015 JINST 10 P09009 [6] M. Walter. PhD thesis, UZH, 2015 [7] ArDM Collab. 2009 JINST 06 P06001

My work @LEGEND & next steps

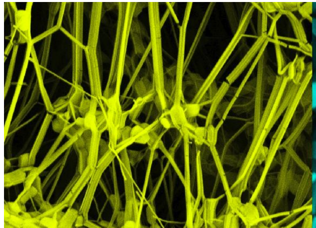
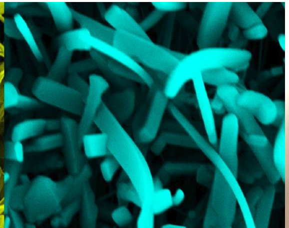
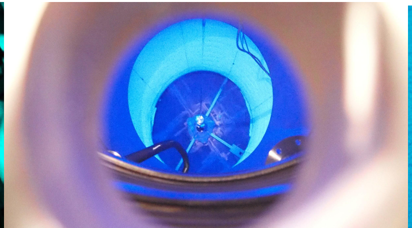
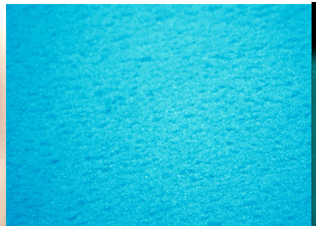
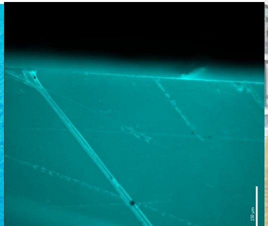


- ➔ For the LAr veto of LEGEND-200, ~13 m^2 of Tetratex were coated in-situ with TPB.
- ➔ Samples from it were then characterized with spectrophotometers, microscopes and in a LAr setup.
- ➔ The quantum efficiency of TPB and **polyethylene naphthalate** (PEN) thin films in LAr were estimated for the first time.

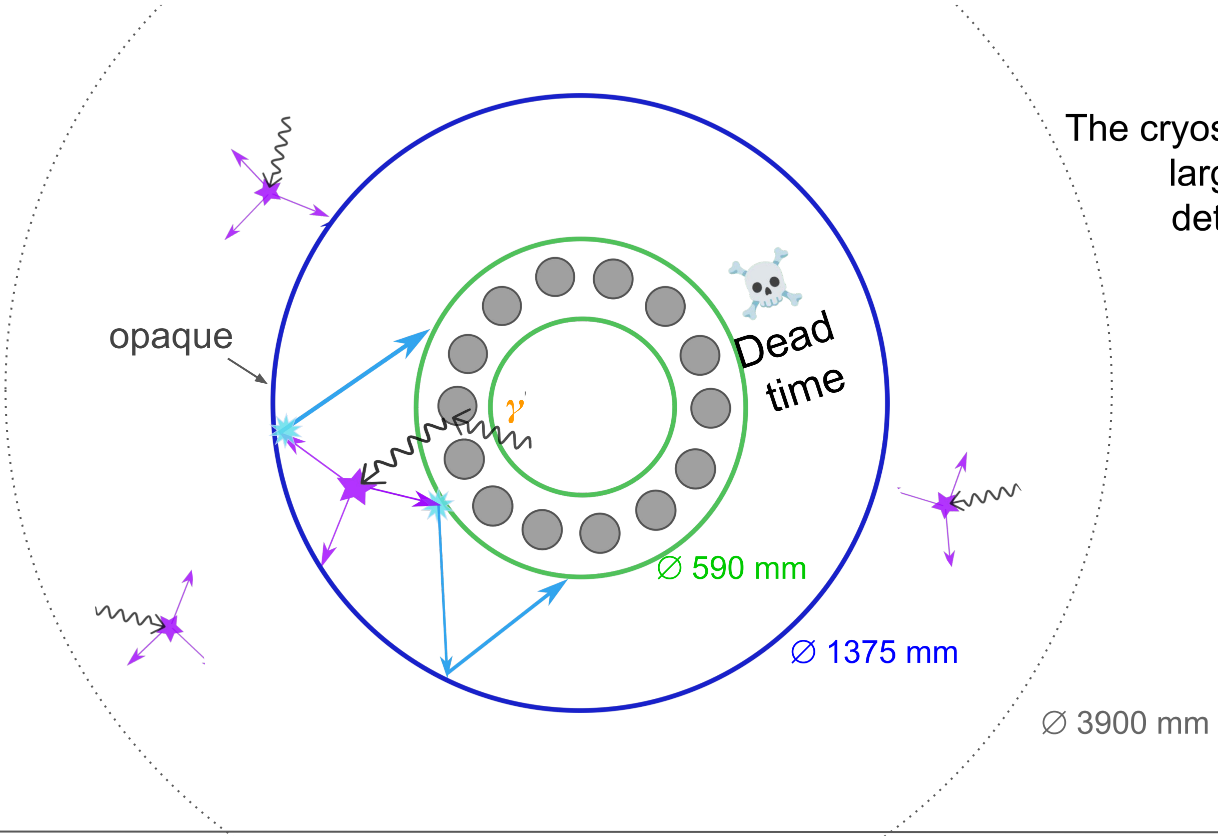
G. R. Araujo, *et al.* [*Eur. Phys. J. C (2022) 82*]

- ➔ The results from TPB can now be input in the simulations of the LAr instrumentation of LEGEND-200
- ➔ Current collaboration with other institutions for further PEN-based R&D

The WLSR is opaque from the outside, thus reducing the dead time of the LAr instrumentation caused by “far” events

The cryostat is much larger than the detector array.



“Far” decays are a source of photons that do not contribute to background, but to the dead-time