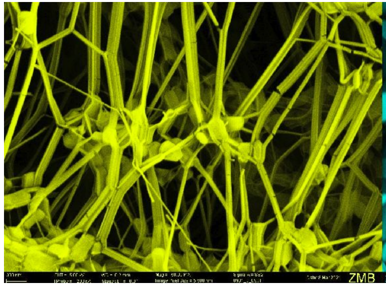
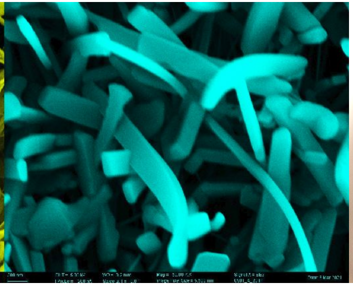
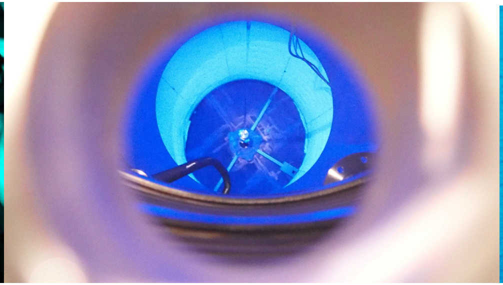
Wavelength-shifting materials & liquid argon instrumentation of the neutrinoless double beta (0νββ)-decay search experiment LEGEND

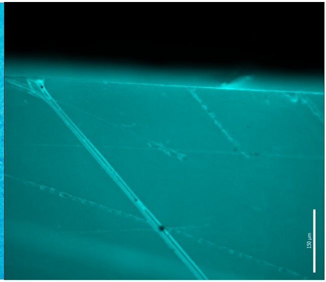
Gabriela R. Araujo

Zurich PhD Seminar - 26.01.2023

University of Zurich[UZH]

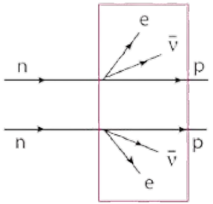
LEGEND

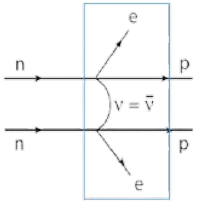




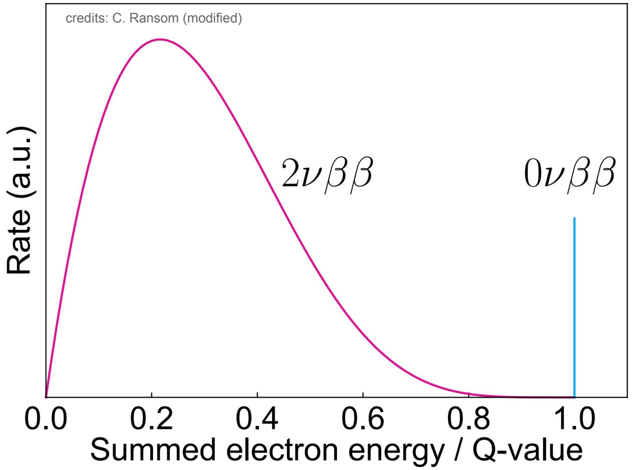


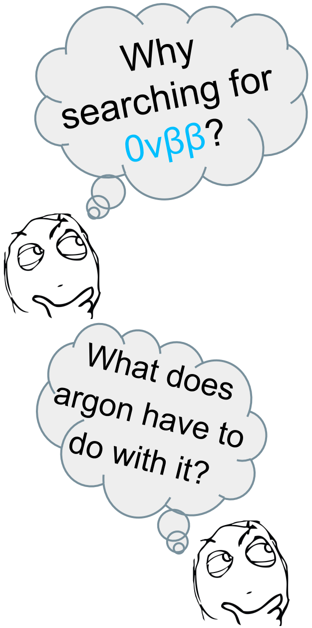
Wavelength-shifting materials & liquid argon instrumentation of the neutrinoless double beta (0νββ)-decay search experiment LEGEND

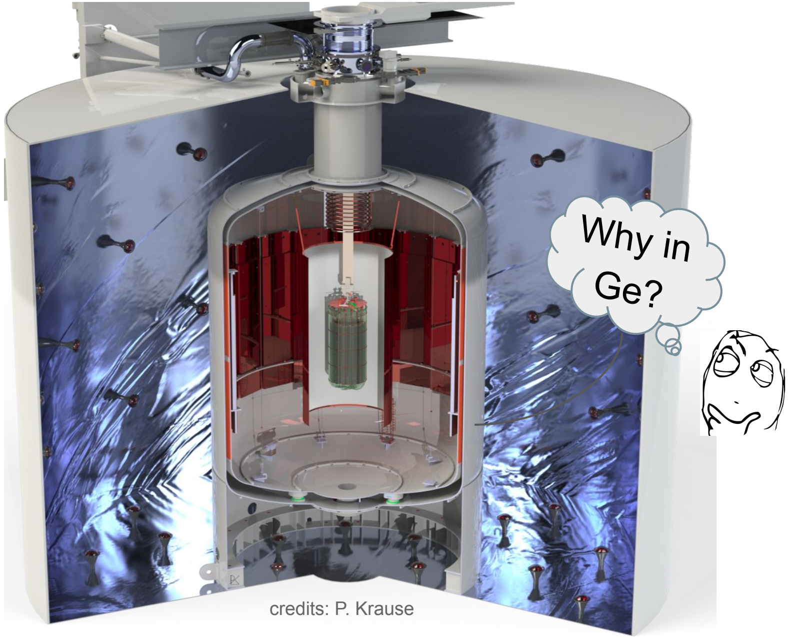
Large Enriched Germanium Experiment for Neutrinoless ββ Decay







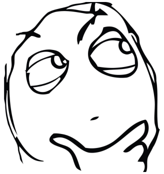




[1] N. Abgrall *et al.* The large enriched germanium experiment for neutrinoless double beta decay (LEGEND) [2] N. Abgrall *et al.* LEGEND-1000 Preconceptual Design Report

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

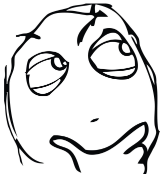
Where does their mass come from?

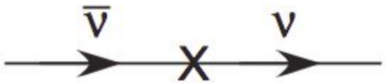


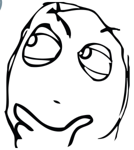
What is the 'nature' of neutrinos?

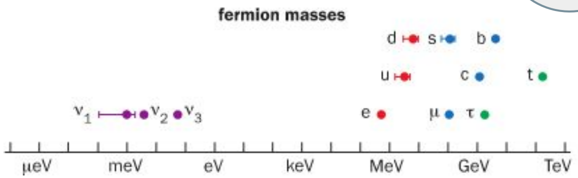
Are they their own anti-particle?

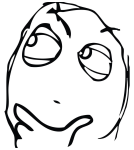
Why are they so small?

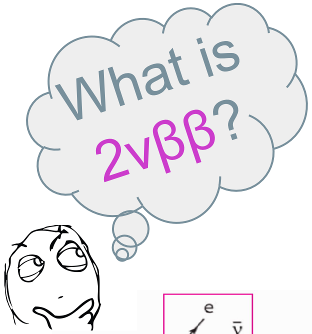




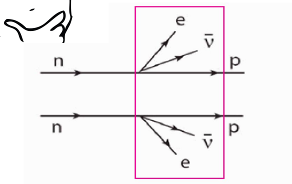






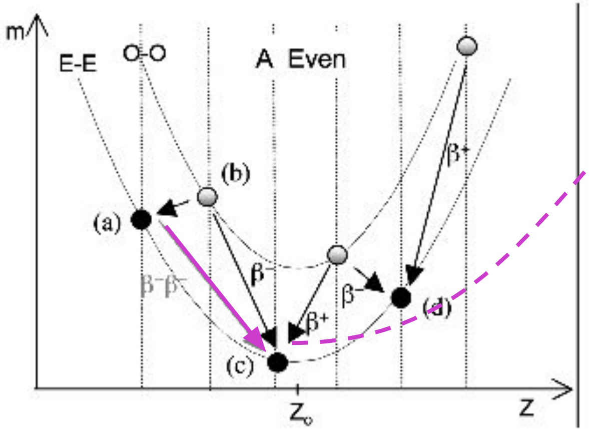


A few isotopes in nature decay emitting 2 electrons and 2 anti-neutrinos (2νββ decay).



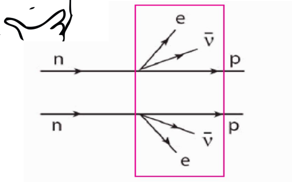
Two neutrino double beta decay (2νββ):

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



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

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

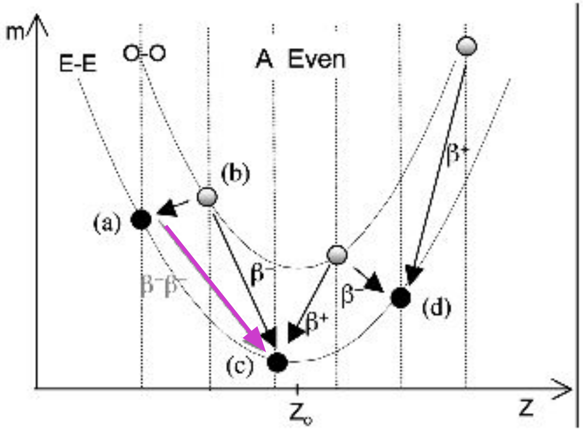


Two neutrino double beta decay (2νββ):

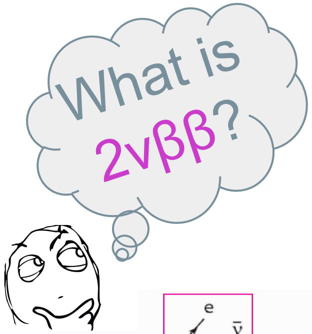
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (in a nucleus)

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)

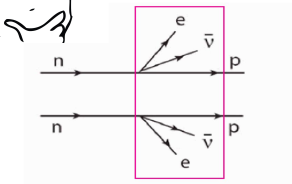
It was back then the decay with the longest lifetime ever observed [*]



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



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

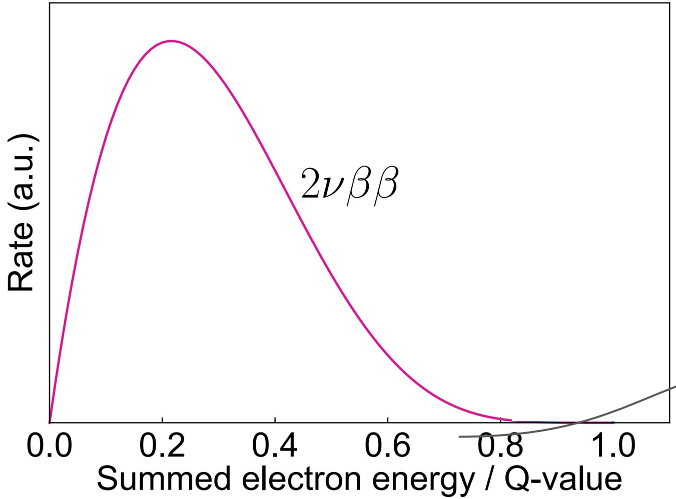


Two neutrino double beta decay (2νββ):

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

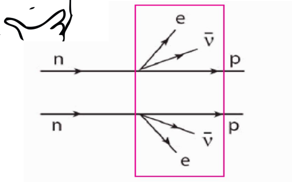
Rare process! First observed by S. Elliot et al in $^{82}Se \rightarrow {}^{82}Kr + 2e^- + 2\bar{\nu}$, $\tau_{1/2} > 10^{20}$ yr (1987)

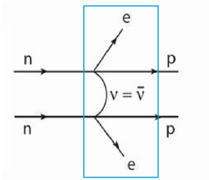
It was back then the longest lifetime ever observed [*]

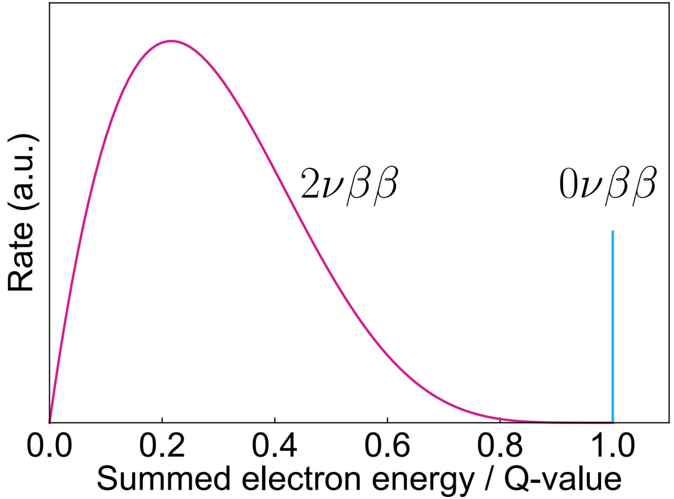


The electrons share the energy with the neutrinos and produce a broad spectrum. !

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







Two neutrino double beta decay (2νββ):

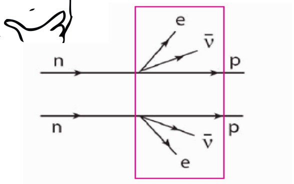
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (in a nucleus)

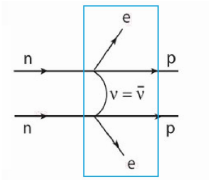
Neutrinoless double beta decay (0νββ):

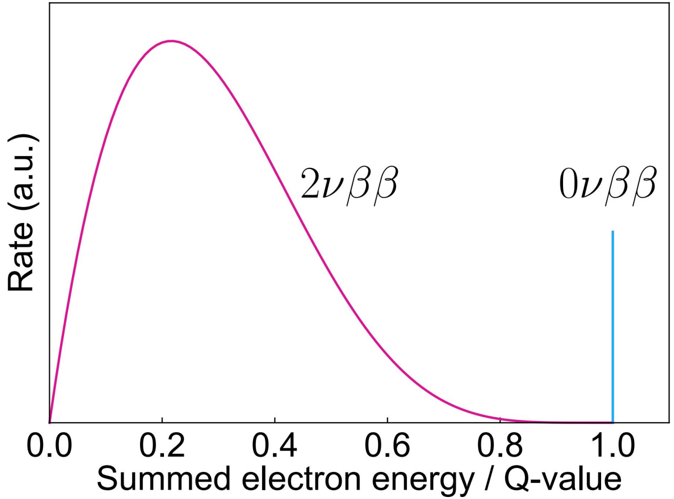
- $2n \rightarrow 2p + 2e^-$ (in a nucleus)

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

Origin of neutrino mass! !





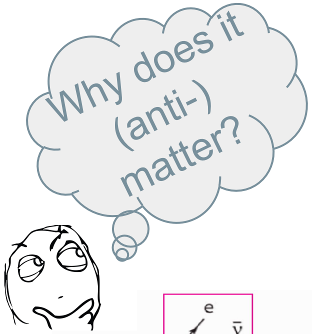


Two neutrino double beta decay (2νββ):

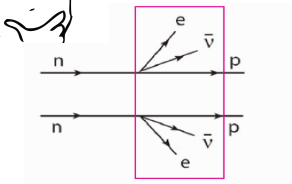
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (in a nucleus)

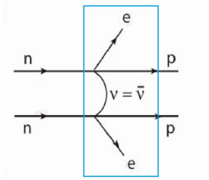
Neutrinoless double beta decay (0νββ):

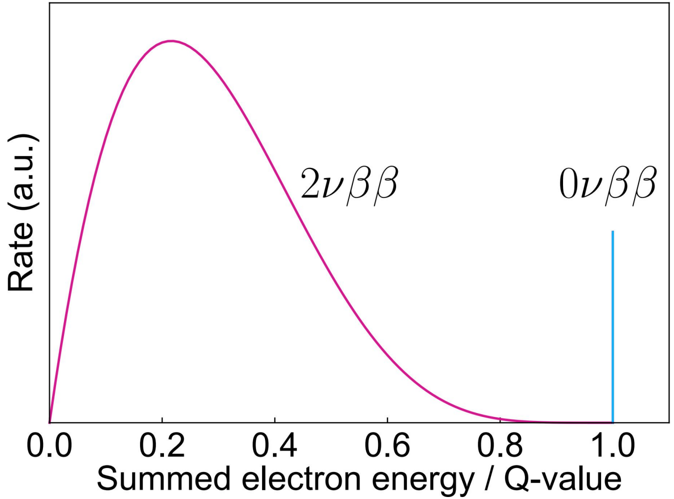
- $2n \rightarrow 2p + 2e^-$ (in a nucleus)



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







Two neutrinos emitted (2νββ):

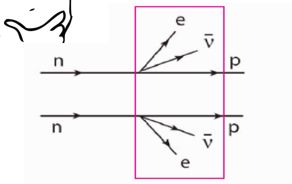
- $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$ (ΔL=0)

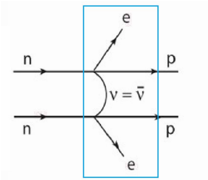
No neutrinos emitted (0νββ):

- $2n \rightarrow 2p + 2e^-$ (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: source = detector → high Efficiency!





continuous spectrum

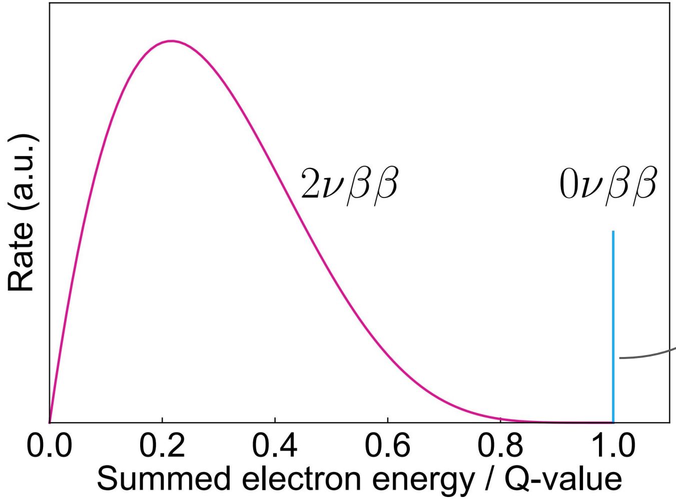
Two neutrinos emitted (2νββ):

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

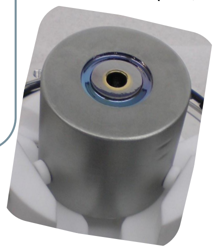
Single peak at $Q_{\beta\beta}$=2039 keV

No neutrinos emitted (0νββ):

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



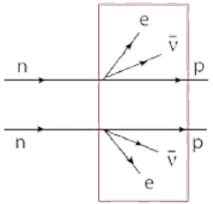
Ge detectors have the excellent energy resolution needed for the detection of the peak at the end of the 2νββ spectrum !

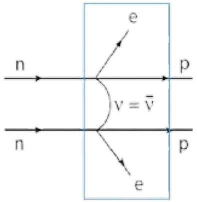


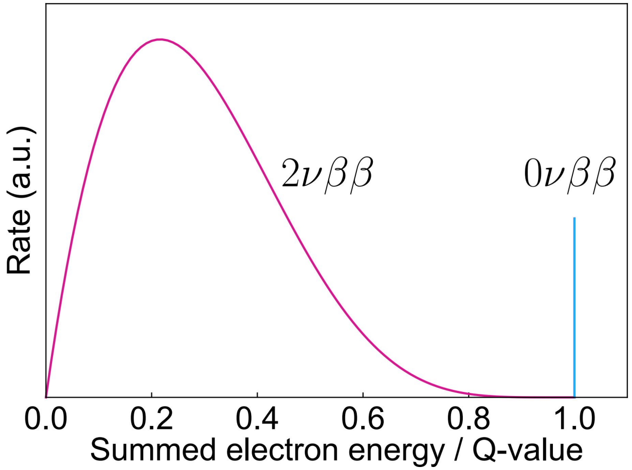
(*) ~2.1 keV FWHM at $Q_{\beta\beta}$ [3]

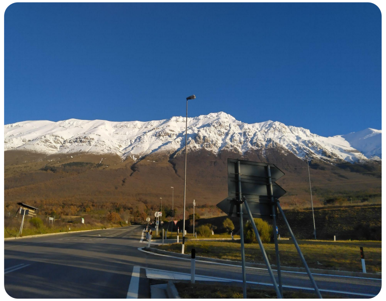
[3] M. Agostini, *et al.* EPJ. C **81**, 505 (2021).

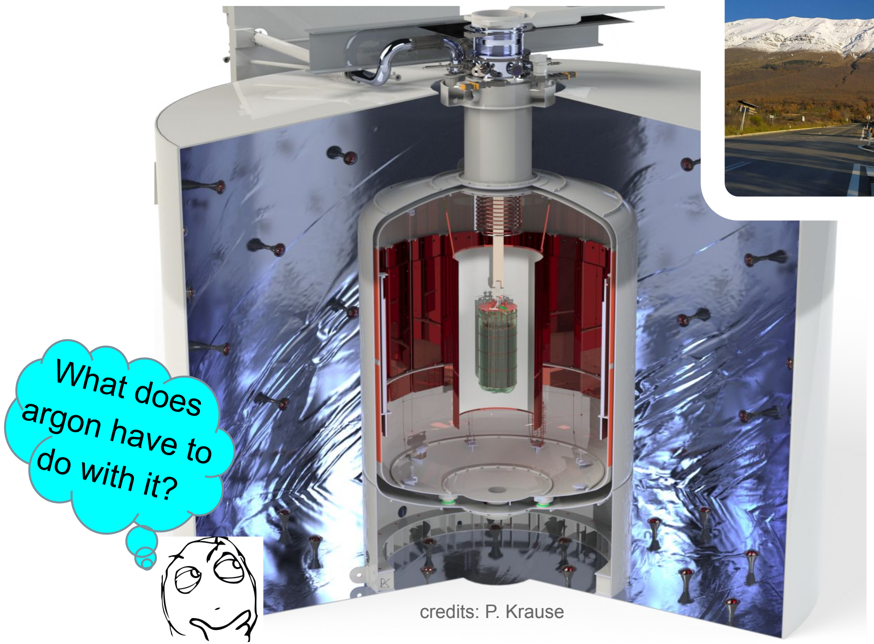
Large Enriched Germanium Experiment for Neutrinoless ββ (0νββ) Decay







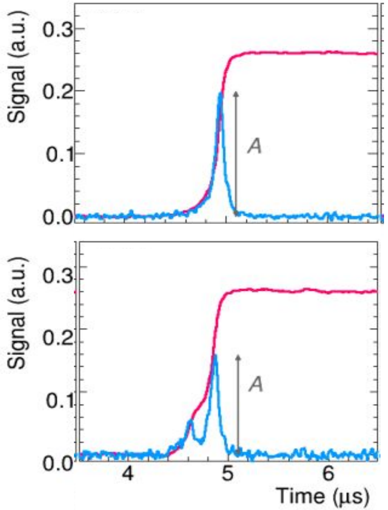




credits: P. Krause

[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

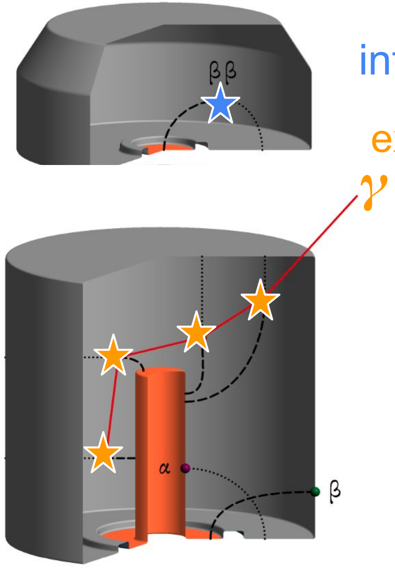
HPGe crystals provide different signals for 0νββ and multi-scatter events.



(0ν)ββ: single-site signal

Multi-scatter background, eg. γ (*)

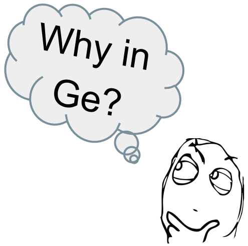
Pulse-shape discrimination[4]: The charge and current show different shapes for single or multi-site events.

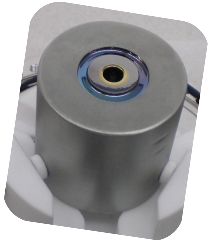


internal

external

Figure from L. Pertoldi (modified)

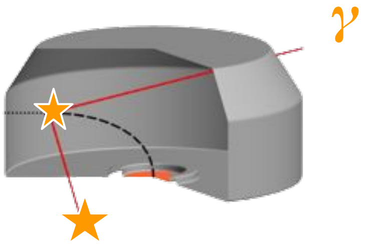




[4] M. Agostini, *et al.* EPJ. C **82**, 284 (2022).

(*) 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 provide different signals for 0νββ and multi-scatter events.



(0ν)ββ: single-site signal

Multi-scatter background, eg. γ (*)

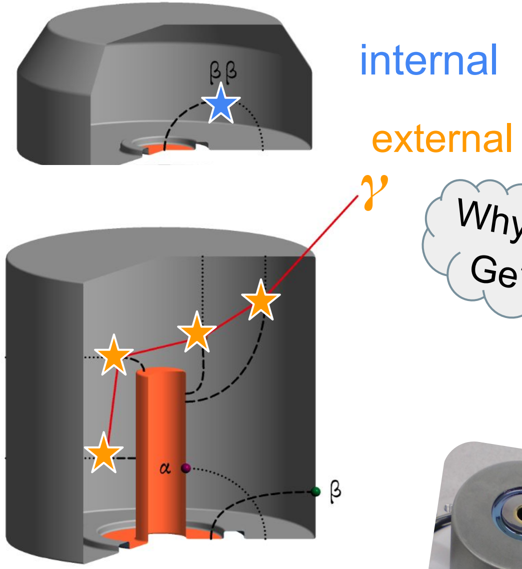
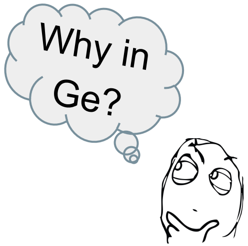
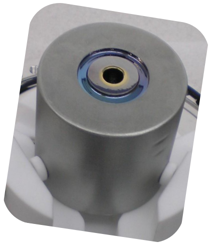


Figure from L. Pertoldi (modified)



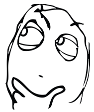


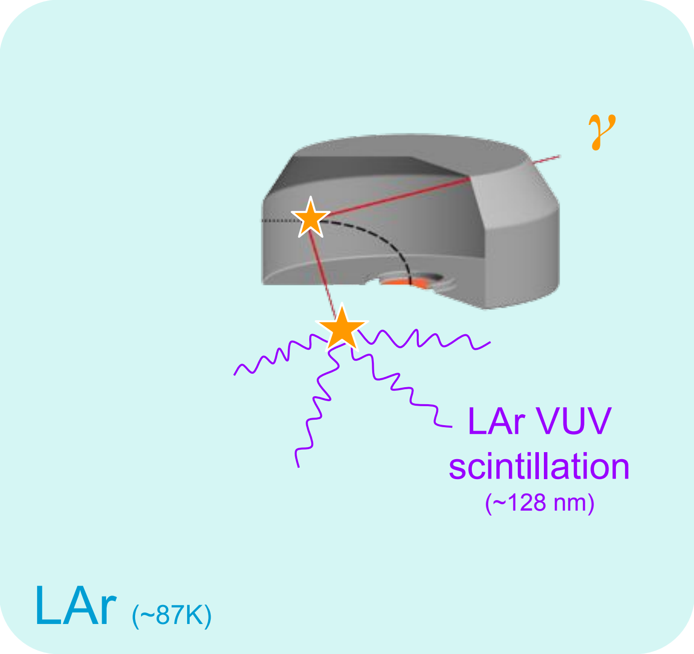
[4] M. Agostini, *et al.* EPJ. C **82,** 284 (2022).

(*) 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

What does argon have to do with it?





(0ν)ββ: single-site signal

Multi-scatter background, eg. γ (*)

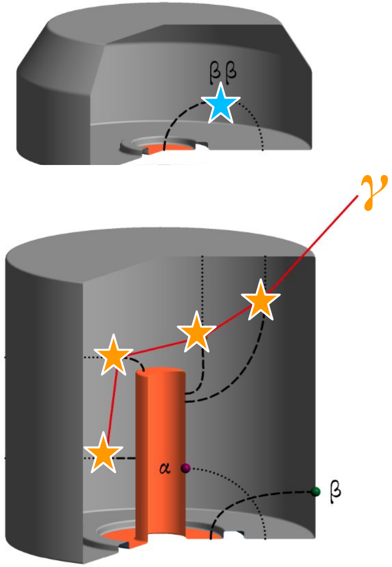
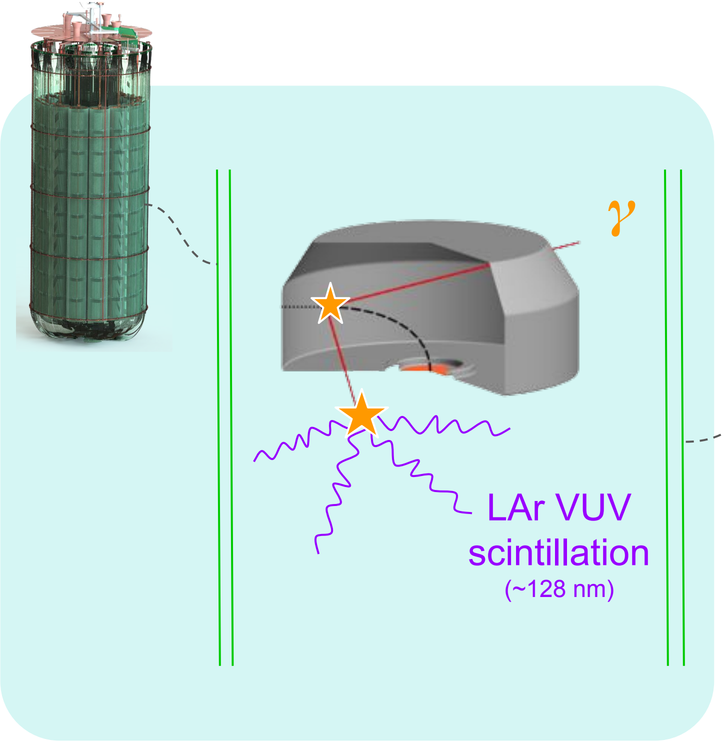
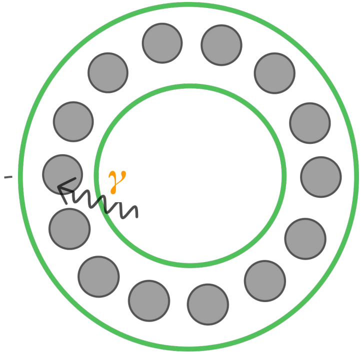


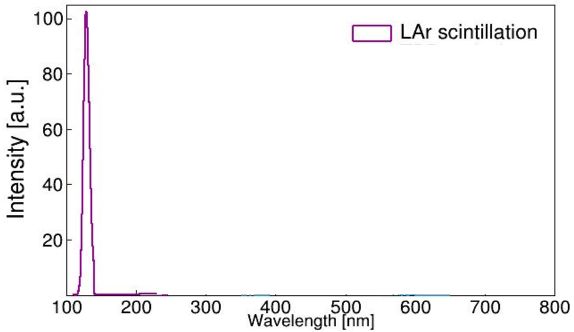
Figure from L. Pertoldi (modified)

To collect this scintillation, wavelength-shifting (WLS) fibers surround the detectors.



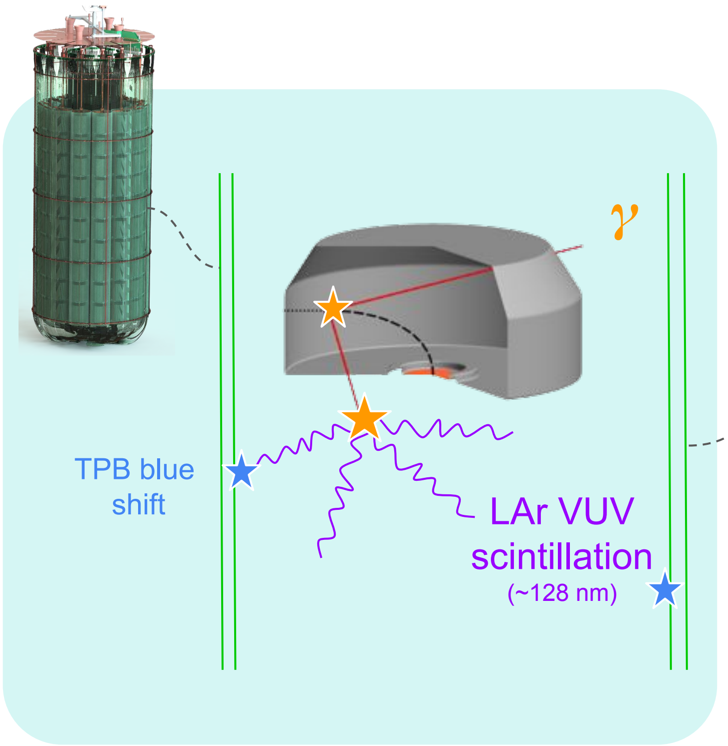


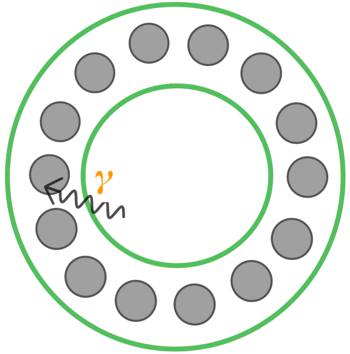
Top view of HPGe crystals and fibers



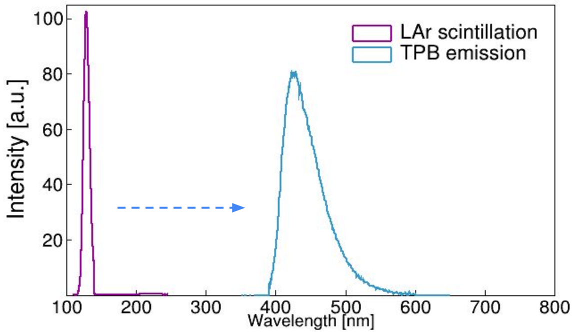
[*] For details see [5] M. Schwarz, *et al*, EPJ Web **253**, 11014 (2021)

The fibers are coated with TPB[*], which shifts the VUV light to the blue.



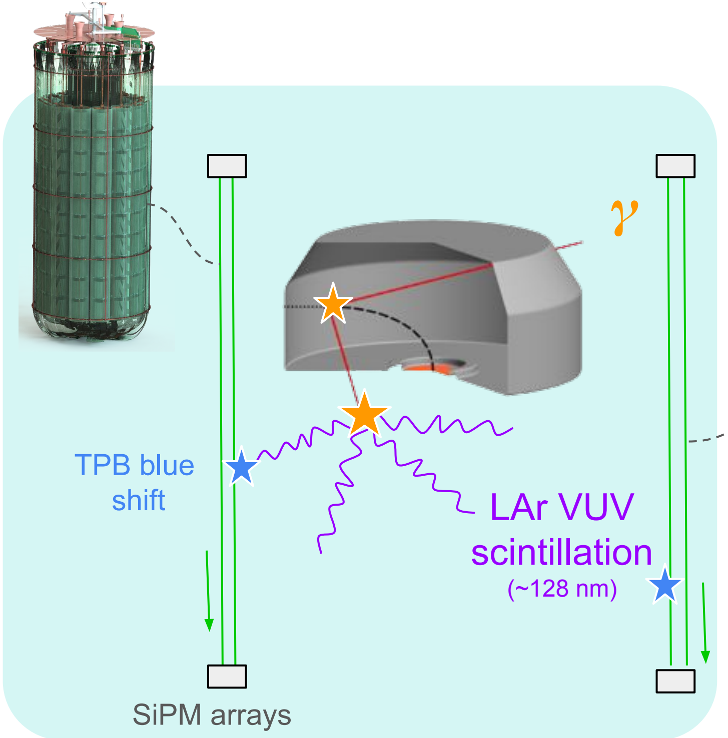


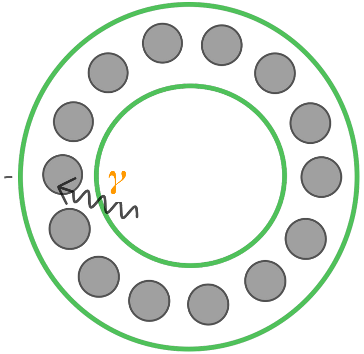
Top view of HPGe crystals and fibers

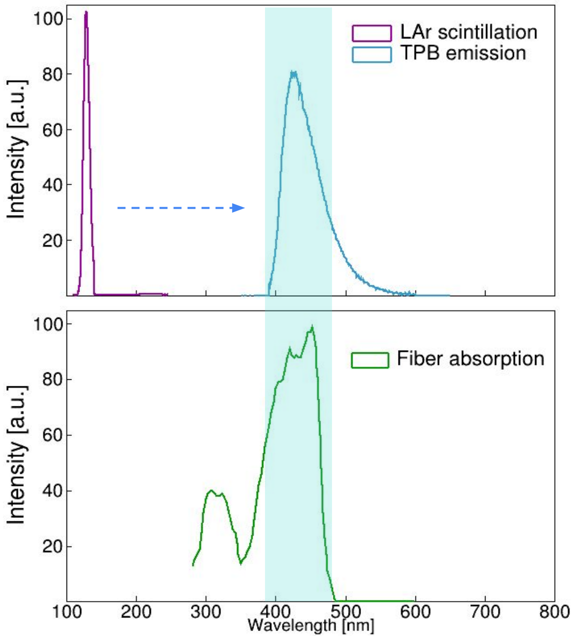


[*] For details see [5] M. Schwarz, *et al*, EPJ Web **253**, 11014 (2021) [*] Tetraphenylbutadiene

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.



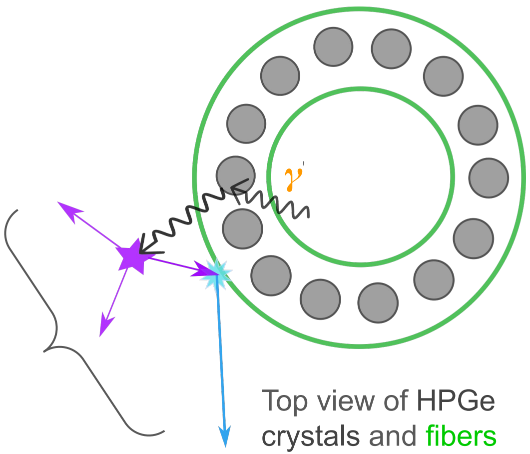

Top view of HPGe crystals and fibers



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

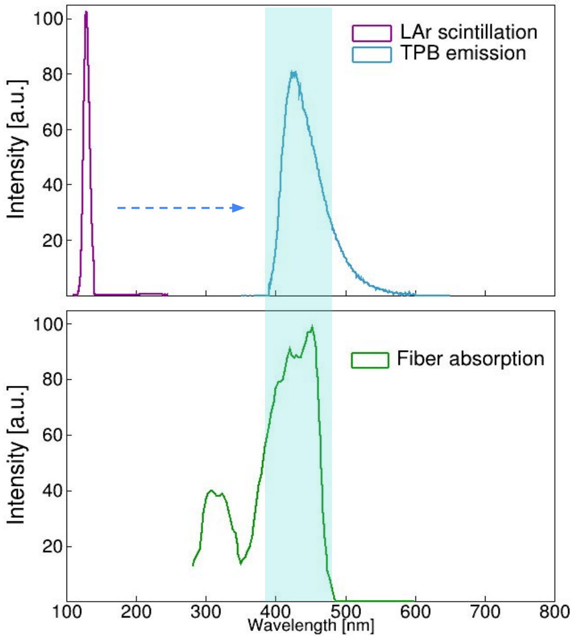
[*] For details see [5] M. Schwarz, *et al*, EPJ Web **253**, 11014 (2021) [*] Tetraphenylbutadiene

The fibers are coated with TPB[*], which shifts the VUV light to the blue -> **isotropically**.



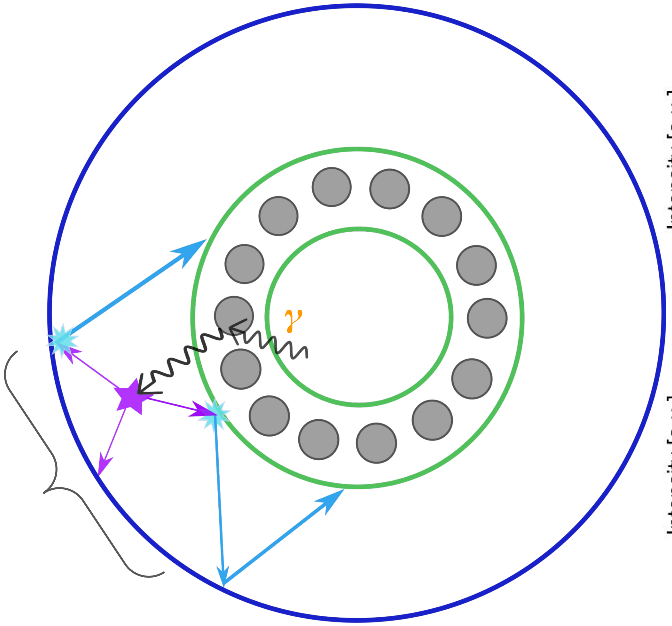
… but in this way, only part of the light is collected by the fibers

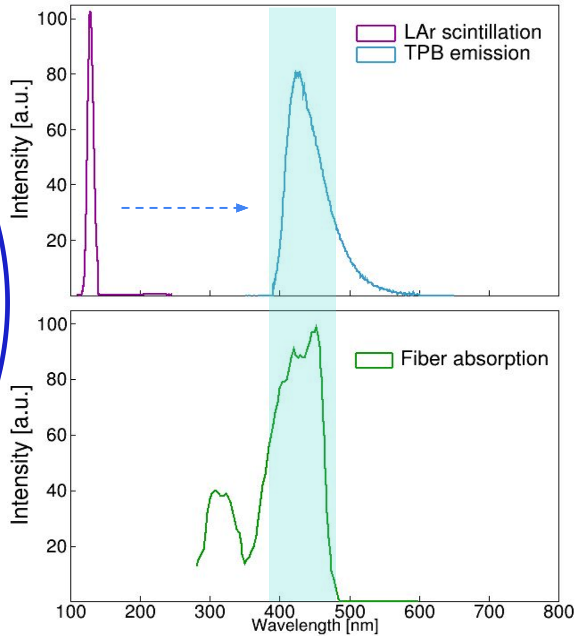
Top view of HPGe crystals and fibers



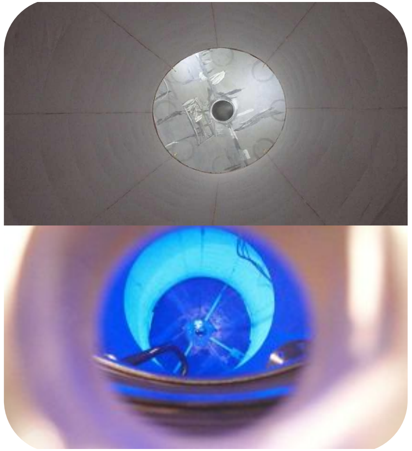
A shroud of Wavelength-Shifting Reflectors (WLSR) surrounds the fibers, increasing its light collection by shifting VUV light and reflecting blue light

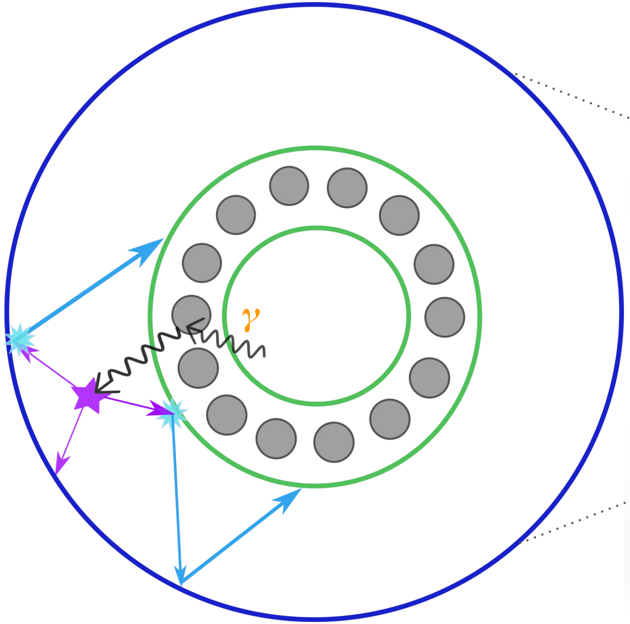
Now this light is not lost. It is shifted and/or reflected towards the fibers.



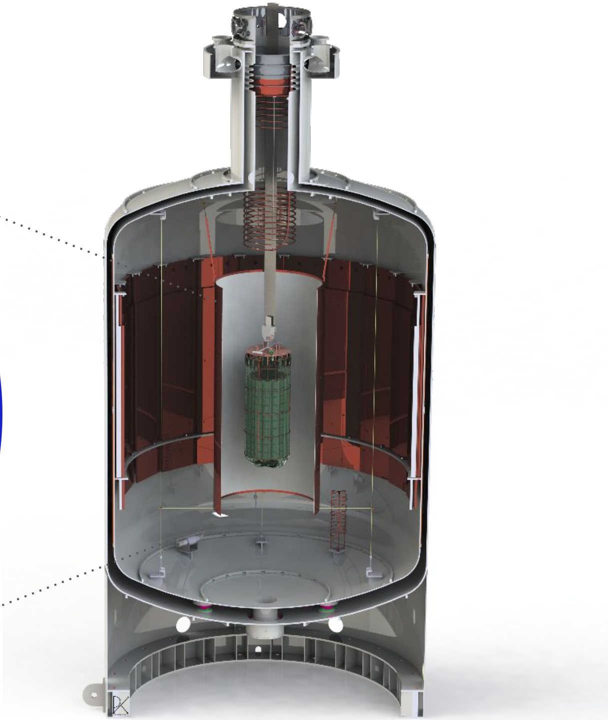


Wavelength-shifting materials & liquid argon instrumentation of (...) LEGEND





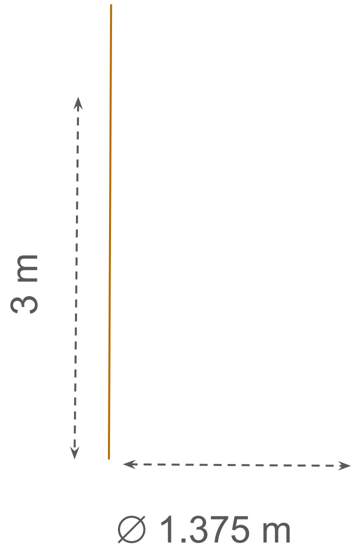
WLSR

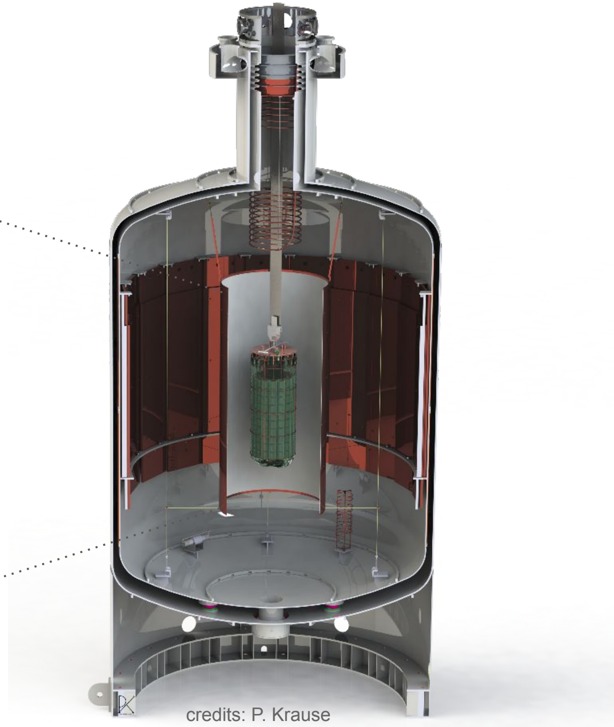


LEGEND-200 WLSR: reflective thin Tetratex (TTX) membrane lined up on copper foils

Top view

~13 m^2



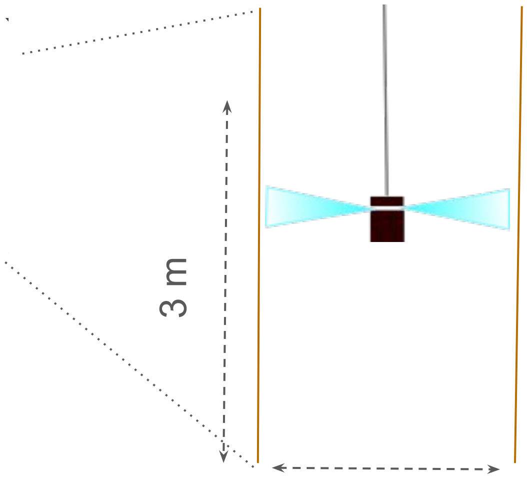


Advantages of TTX[*,5,6,7]:

- ★ highly - reflective[*]
- ★ Light-weight
- ★ Radio-pure[5]
- ★ Low-outgassing[6]

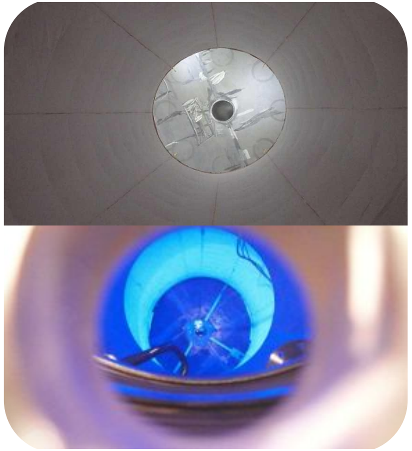
[*] used as a reflector in GERDA & in ArDM, and again characterized for LEGEND G. R. Araujo, *et al.* *Eur. Phys. J. C (2022) 82*.
[5] L. Baudis, *et al* 2015 JINST 10 P09009 [6] M. Walter. PhD thesis, UZH, 2015 [7] ArDM Collab. 2009 JINST 06 P06001

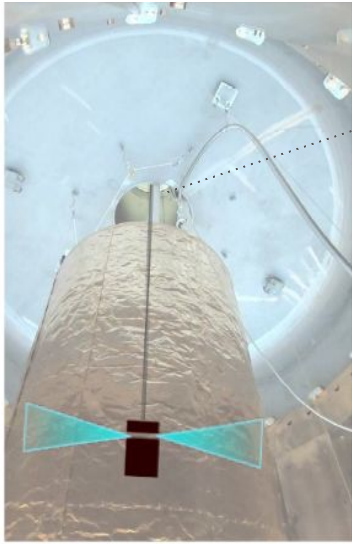
LEGEND-200 WLSR: reflective thin Tetratex (TTX) membrane lined up on copper foils **and coated with the wavelength-shifter TPB**

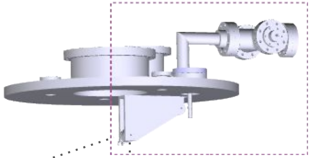


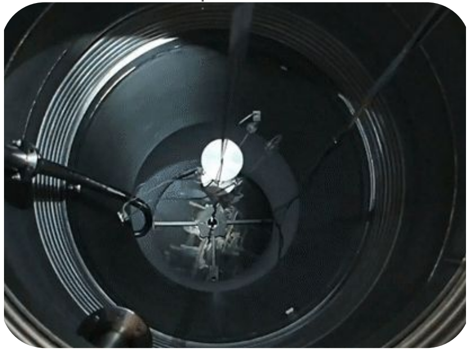
WLSR: wavelength shifting reflector

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







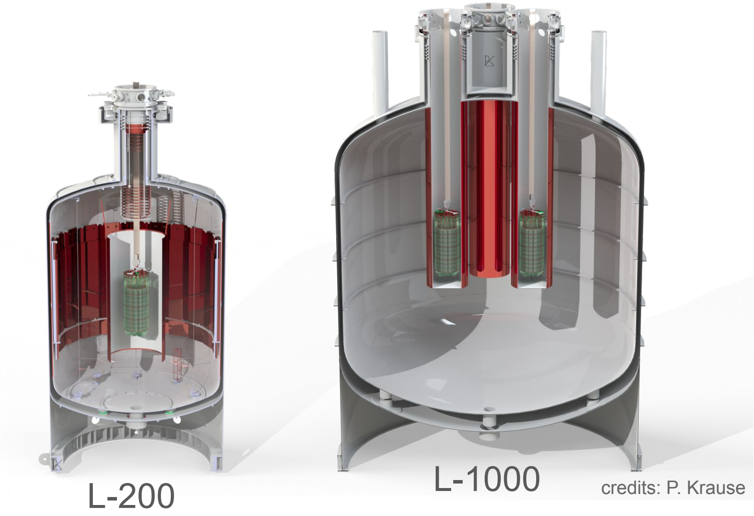


WLSR: wavelength shifting reflector

Characterization & R&D of WLSRs

① LEGEND's "witness" WLSR

② Alternative WLSR for large LAr-based detectors: polyethylene naphthalate (PEN)[8]

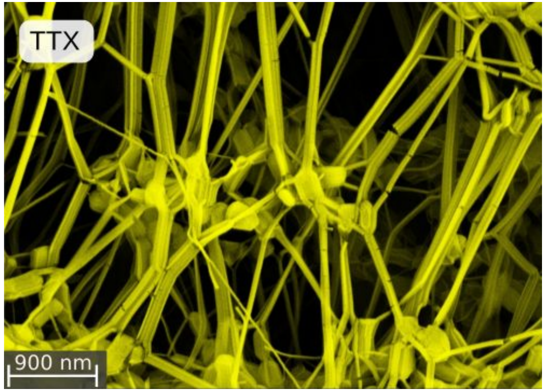


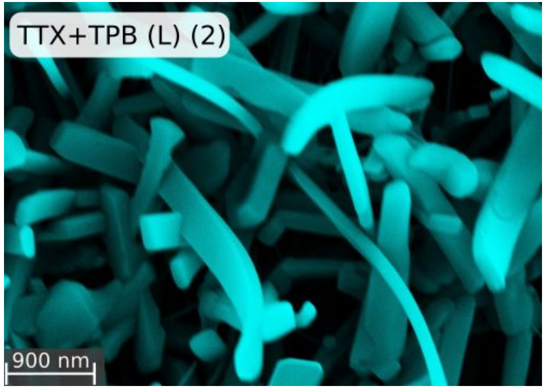
Homogeneity, VUV-shifting efficiency, vis-reflectivity

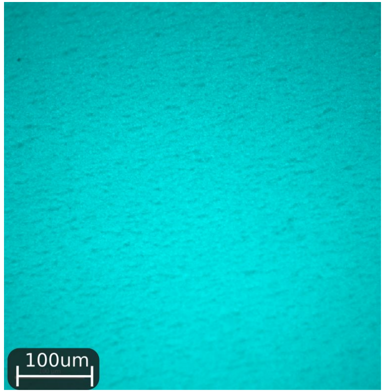
WLSR: wavelength shifting reflector

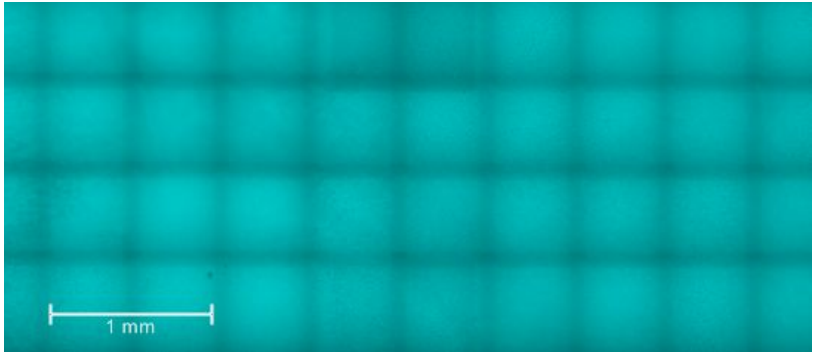
[8] Kúzniak, *et al.* Eur. Phys. J. C (2019) 79, G. R. Araujo, *et al.* Eur. Phys. J. C (2022) 82.

Characterization with microscopy: Tetratex is homogeneously covered with TPB





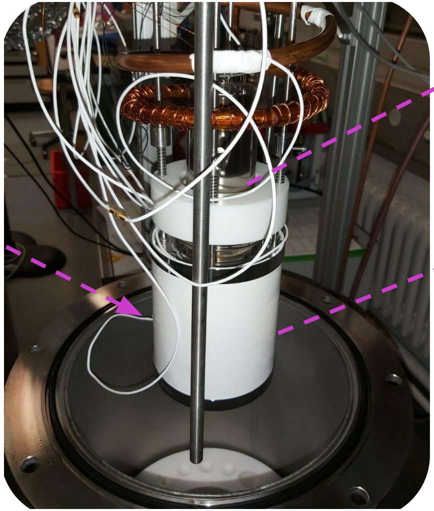


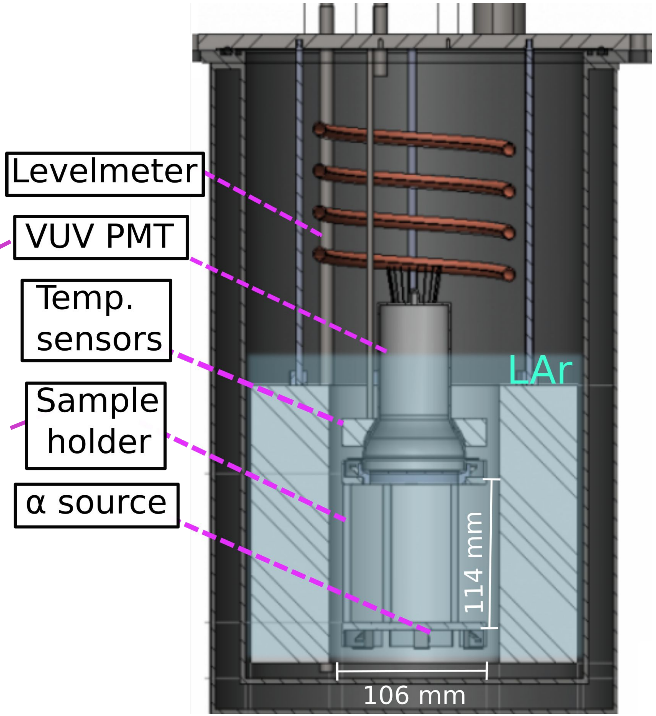


Light is always observed from the coating in a range from tens of μm to cm

Characterization in liquid argon (LAr): Measurement of WLS films coupled to reflectors in response to LAr scintillation induced by alphas.

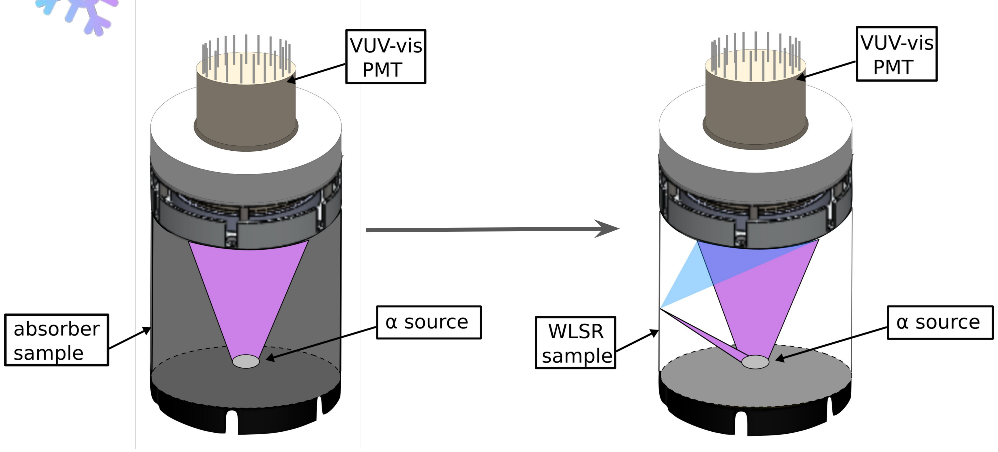
- WLS (wavelength shifter):
  - TPB
  - PEN
    - Various thickness
    - Grades
    - Surface treatment
- Coupling:
  - Vacuum
  - optical
- Reflectors
  - Tetratex (TTX)
  - Tyvek
  - ESR



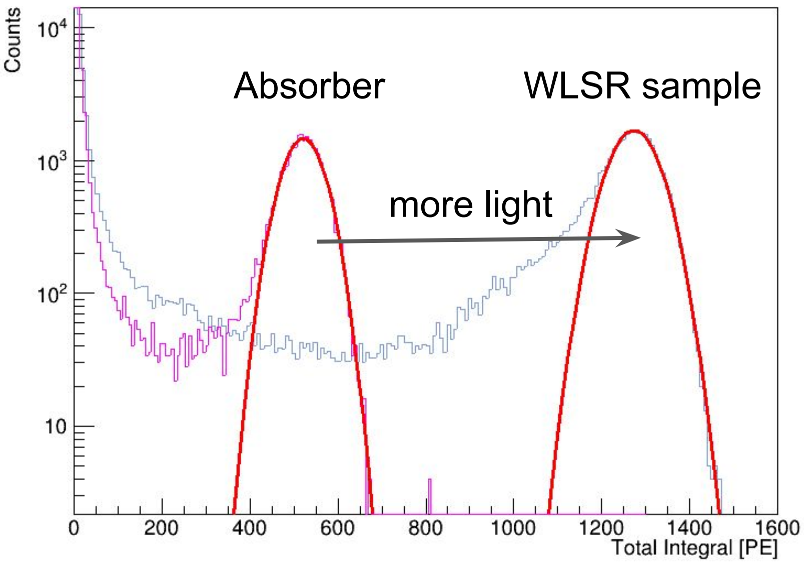


[5] The setup is detailed in: G. R. Araujo, *et al.* Eur. Phys. J. C (2022) 82.

Characterization in LAr: Comparison of different wavelength shifters + reflector

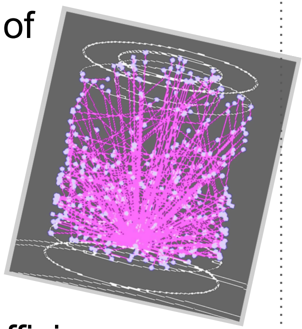


mean of Am-241 alpha peak in PE: figure of merit for **light yield (LY) comparison**



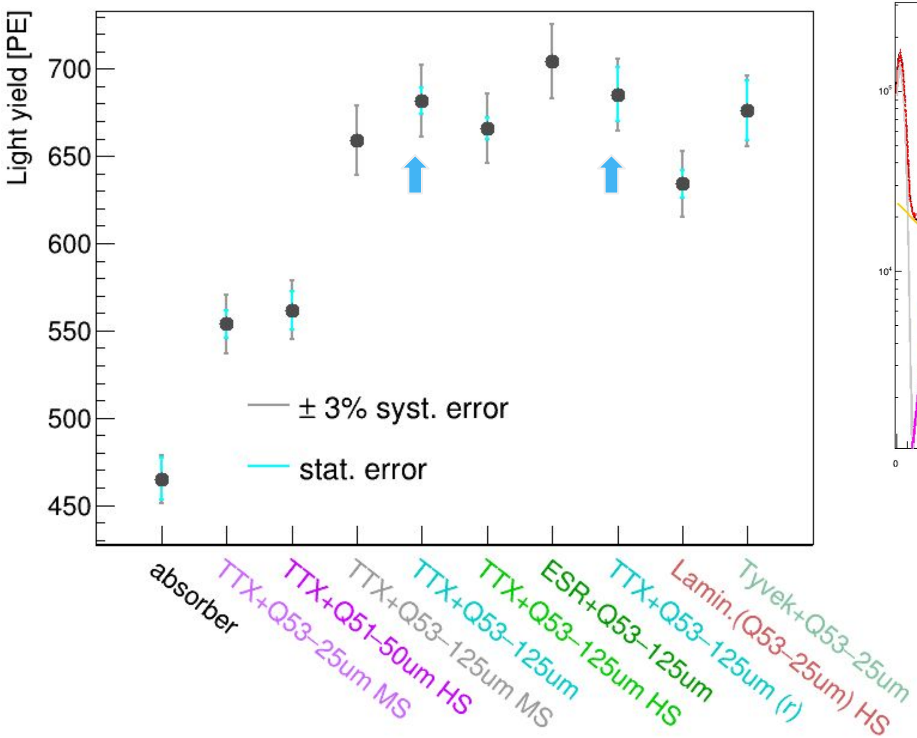
Understand the influence on light yield of

- WLS / reflector type
- Vendor / grade
- thickness
- surface treatment
- coupling (adhesive)



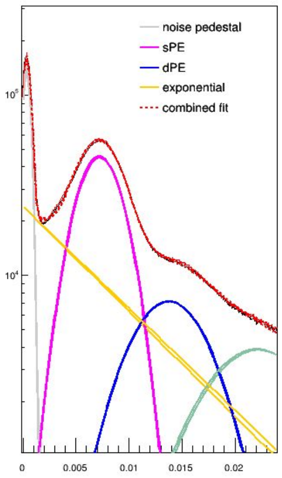
\+ Use simulations to estimate the efficiency

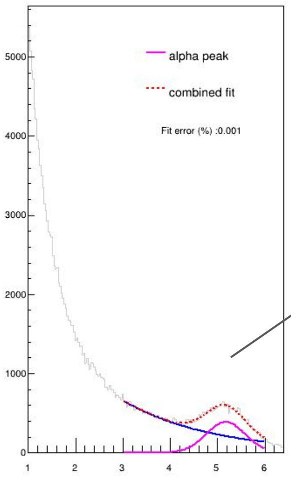
Comparison of PEN+Reflector configurations



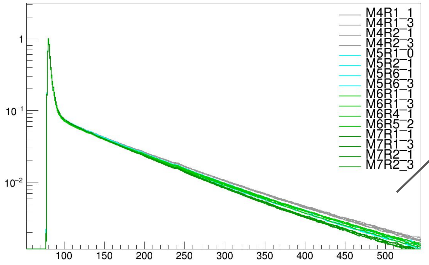
MS = machine-sanded, HS = hand-sanded, lamin = laminate, r = repeated

(*)Monitoring of $\tau_{triplet}$ and correction of LY for lower τ values (see back-up)





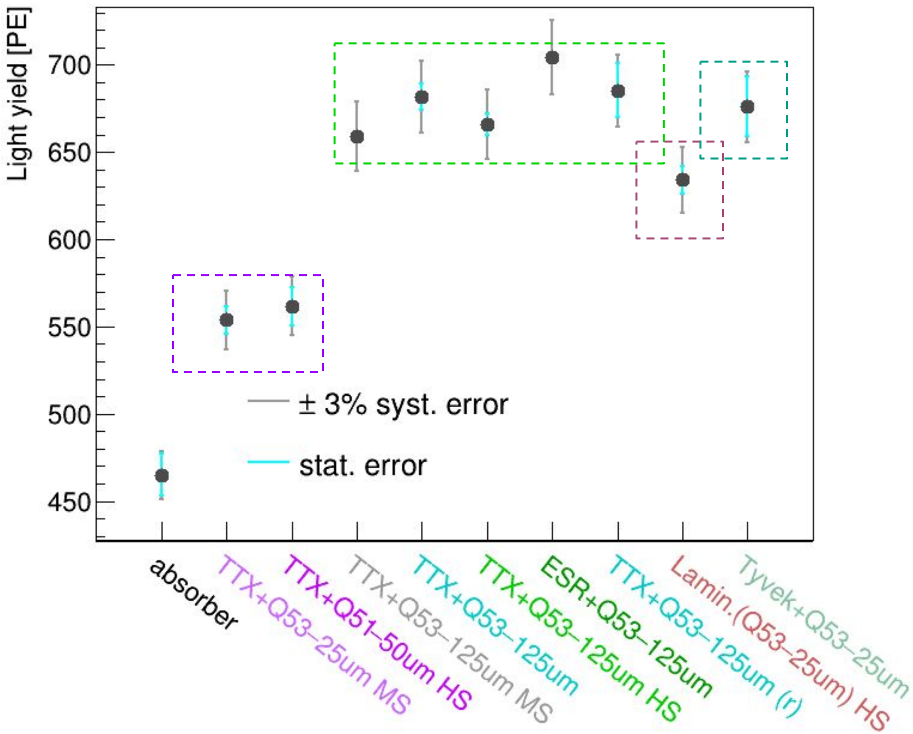
Light yield (LY) in PE: sPE calibration of each run - Results are independent of gain drift



LY stability: $\tau_{triplet}$(*) & repeated measurements

Thickness (25, 50, 125 um); reflectors: ESR, Tyvek, TTX; & optical couplings (laminated, noc)

Comparison of PEN+Reflector configurations



Thin films(noc) yield less light

(noc): not optically coupled

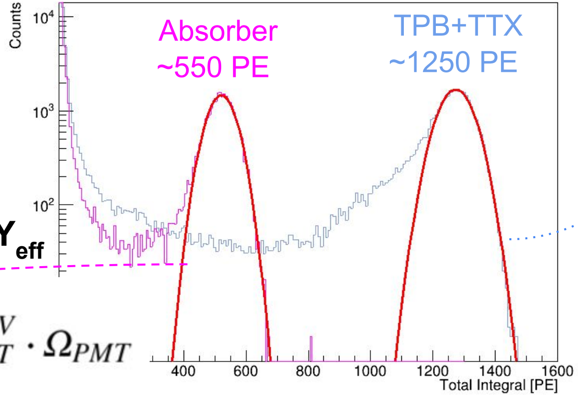
125 um films: different surface treatments (smooth, MS, HS) and reflectors yield the same result.

Laminated thin PEN is better than thin films(noc) but not as good as thick PEN + uncoupled TTX/ESR or thin film optically coupled to Tyvek.

MS = machine-sanded, HS = hand-sanded, lamin = laminate, r = repeated

Thickness (25, 50, 125 um); reflectors: ESR, Tyvek, TTX; & optical couplings (laminated, noc)

Then the simulated number of photoelectrons (PE) is matched to that detected in the measurements **of the WLSR samples**

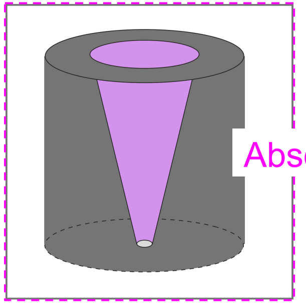


$$N_{PMT}^{det} \sim LY_{eff} \cdot (QE_{PMT}^{VUV} \cdot \Omega_{PMT} + E_s \cdot QE_{PMT}^{vis})$$

WLSR Sample enhancement (E_s)

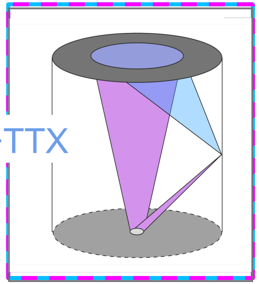
From the **absorber** measurement, we find **LY_{eff}**

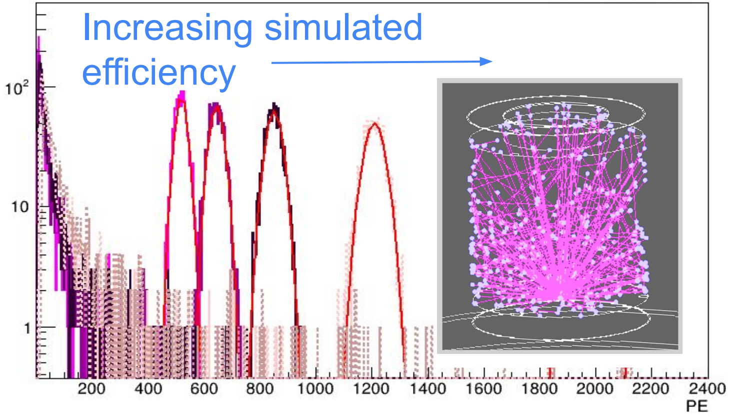
$$N_{PMT}^{det} = LY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega_{PMT}$$



Absorber

TPB+TTX





Summary of main results:

First estimate of the QE of TPB in LAr.

First measurement of PEN's efficiency independent of TPB

Optimization of PEN: Thick films performed better in LAr, all reflectors performed well.

WLS	QE[(*)]
TPB	85 ± 8 %
PEN	69 ± 6 %


Eur. Phys. J. C (2022) 82:442
https://doi.org/10.1140/epjc/s10052-022-10383-0

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

R&D of wavelength-shifting reflectors and characterization of the quantum efficiency of tetraphenyl butadiene and polyethylene naphthalate in liquid argon

G. R. Araujo[1,a], L. Baudis[1], N. McFadden[1], P. Krause[2], S. Schönert[2], V. H. S. Wu[1]

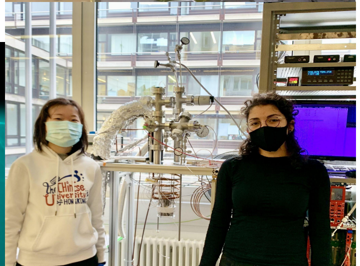
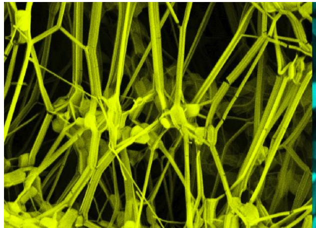
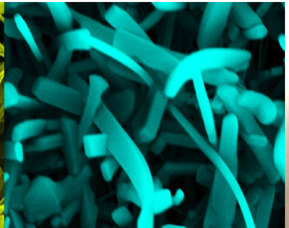
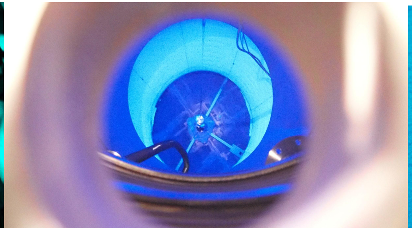
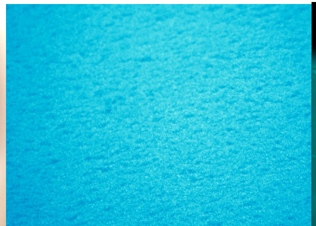
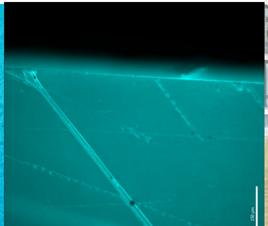
[1] Department of Physics, Physik-Institut, Universität Zürich, 8057 Zurich, Switzerland
[2] Physik Department, Technische Universität München, 85748 Munich, Germany

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

Outlook & next steps

- ➔ For the Liquid argon veto of LEGEND-200, ~13 m^2 of Tetratex were coated in-situ with TPB.
- ➔ We measured the specific WLSR from LEGEND-200 and PEN+TTX with spectrophotometers, microscopes and in a LAr setup.
- ➔ The quantum efficiency of TPB and PEN thin films in LAr were estimated for the first time.
- ➔ 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 optimization of PEN in wavelength shifting reflectors



References

[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*

[3] M. Agostini, *et al.* *EPJ. C* **81,** 505 (2021).

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

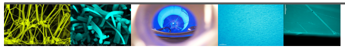
[5] L. Baudis, *et al* 2015 JINST 10 P09009

[6] M. Walter. PhD thesis, UZH, 2015

[7] ArDM Collab. 2009 JINST 06 P06001

[8] Kúzniak, *et al.* Eur. Phys. J. C (2019) 79

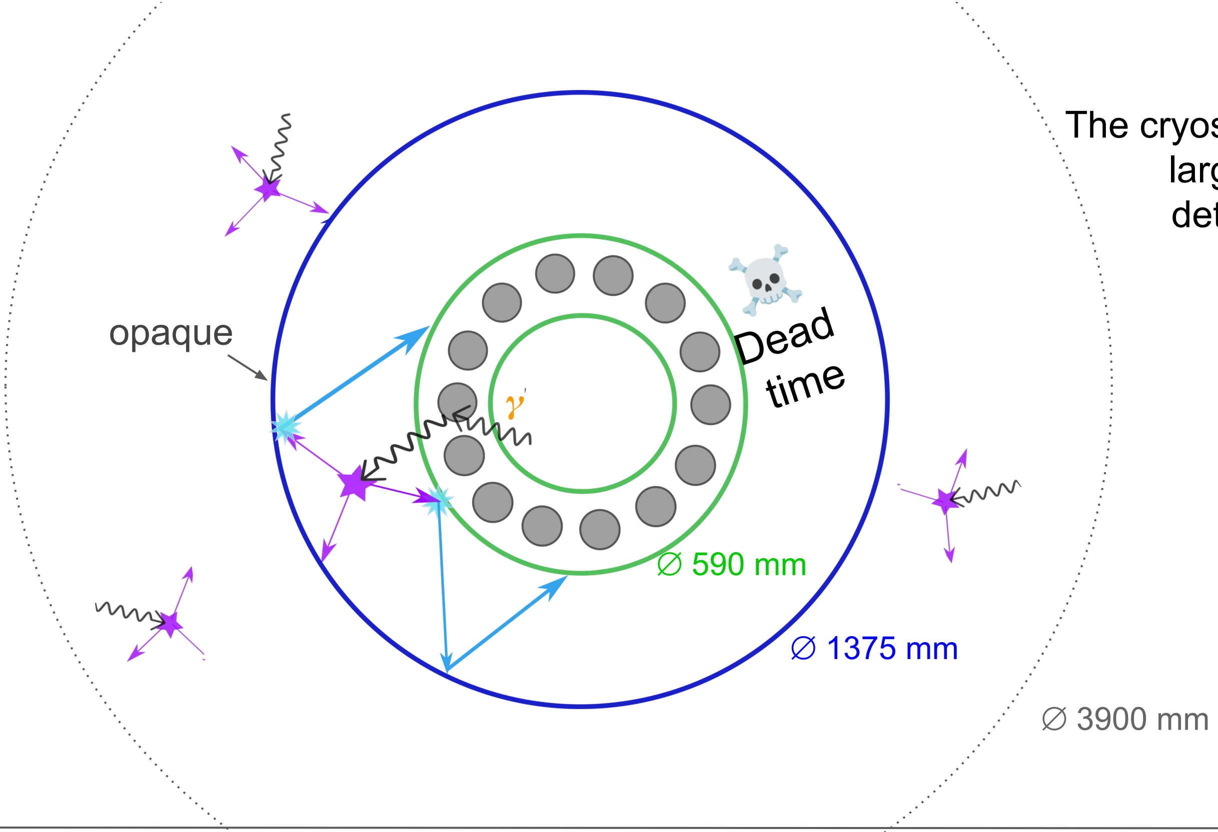
This work: G. R. Araujo, *et al.* *Eur. Phys. J. C (2022) 82*



Back up slides

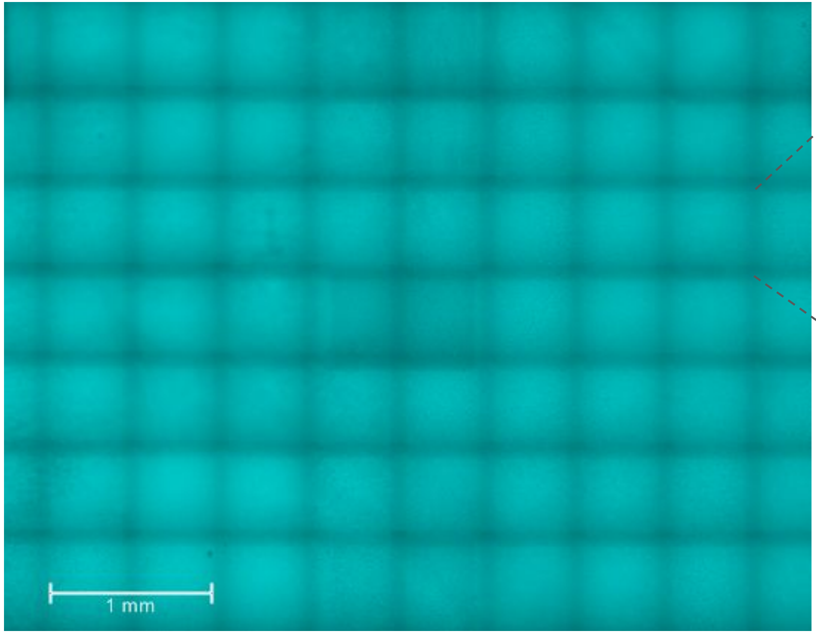
The WLSR is opaque from the outside, thus reducing the dead time of the LAr instrumentation caused by "far" events

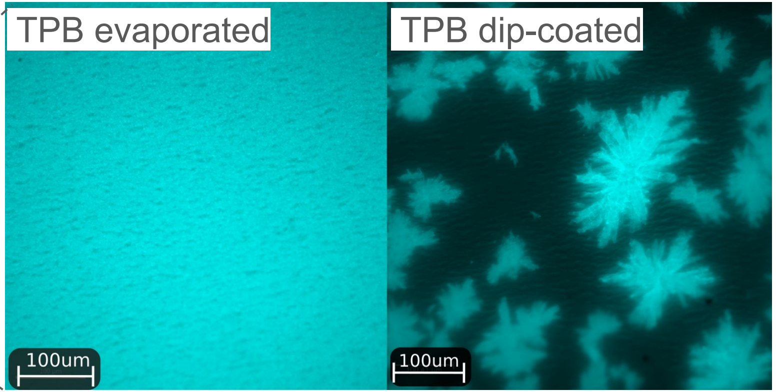
The cryostat is much larger than the detector array.



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

The uniformity of the TPB coating at larger scales is verified with fluorescence microscopy

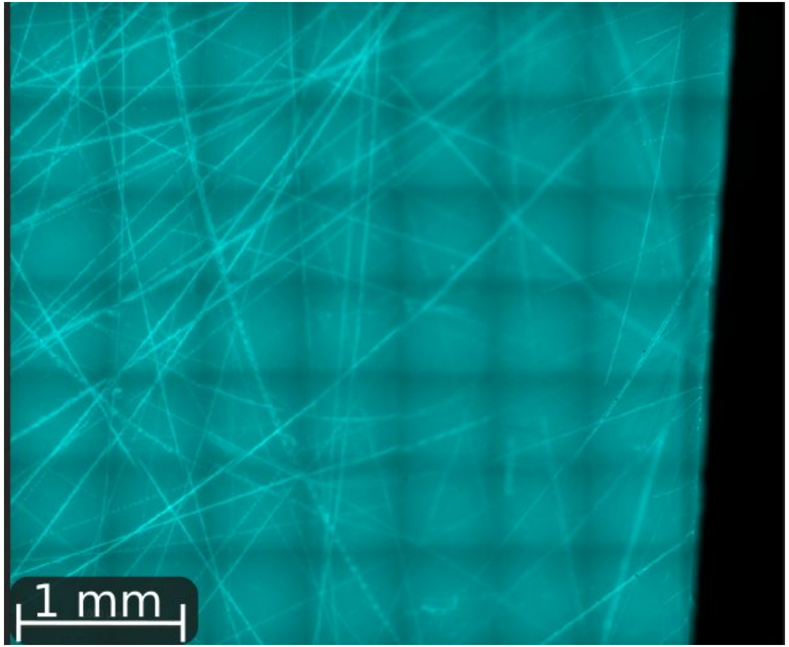


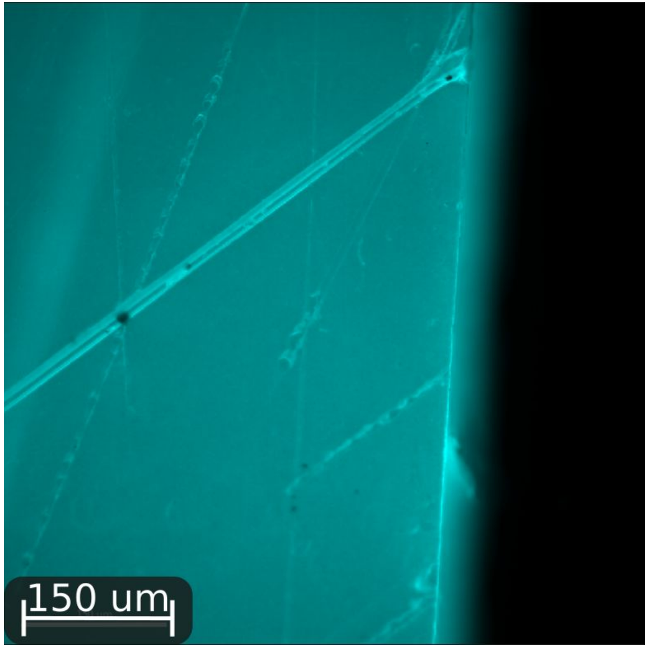


TPB dip-coated (from GERDA) is shown for comparison: gaps where less/no light is emitted are observed.

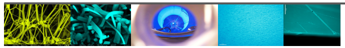
Our sample: Light is always observed from the coating in a range from tens of μm to cm

For PEN, lights seems to undergo internal reflection in the film: sanding the surface produces diffusive scratches that seem to make it easier for photons to exit.



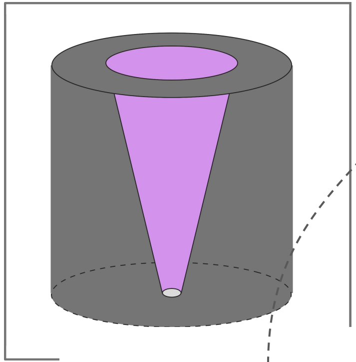


[*] sanded with grade P240 sandpaper in random directions



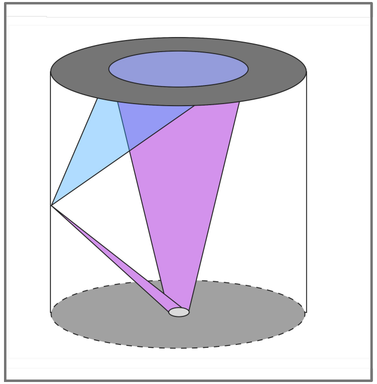
Optical parameters used in the simulation

- Scintillation spectrum [M. Hofmann, et al., Eur. Phys. J. C 73:2618 (2013)]
- n_{index} and $\lambda_{Rayleigh}$ from [M. Babicz, S. Bordoni, JINST 15(09):P09009, 2020]
- Light yield (LY) in LAr: ~25 ph/keV [from absorber measurement]
- VUV Absorption length of LAr: 60 cm [A. Neumeier, et al. EPL 111(1):12001, 2015]
- Vis Absorption length of LAr: 10 m. [not much relevant, since the setup is small]
- QE of the PMT at 128 and 420 nm light: 22 and 27% [data sheet]



$$N_{PMT}^{det} = LY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega_{PMT}$$

VUV-only absorber measurement



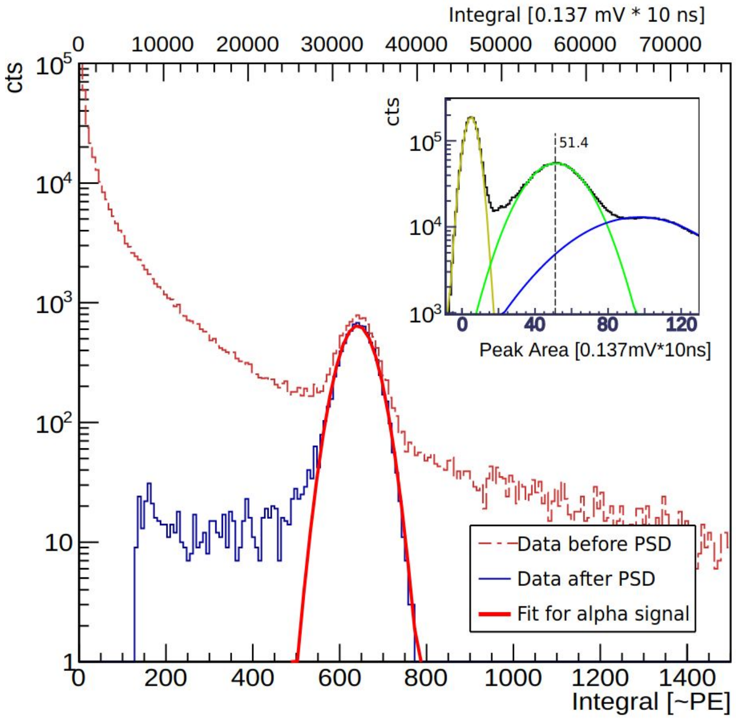
- Vis. reflectivity of TTX: ~95% (this work)
- VUV reflectivity of TTX: <17% (this work)
- Vis. absorption lengths of TPB and PEN (this work)
- VUV absorption of PEN: 100%
- VUV absorption length of TPB: 250 - 450 nm

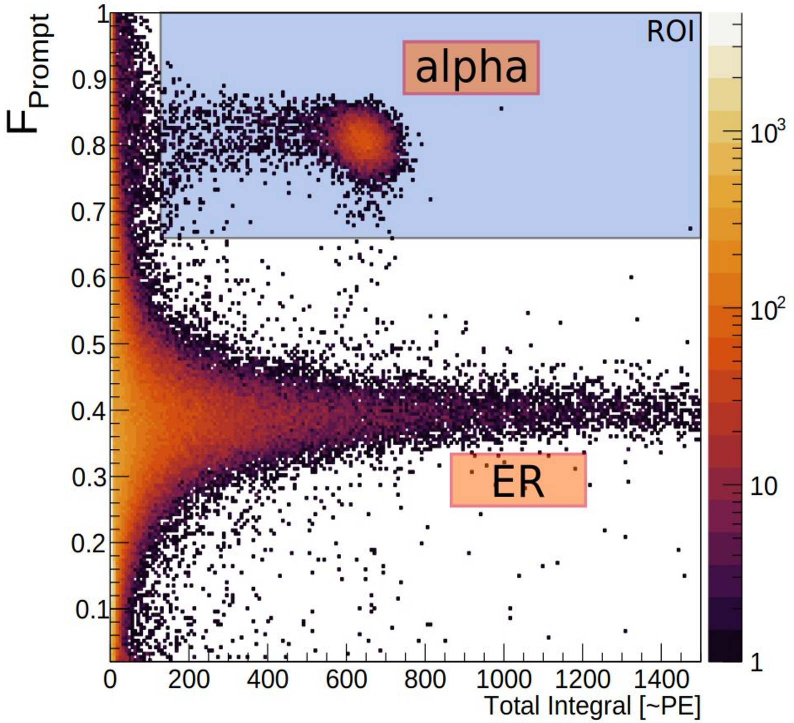
(Benson et. al, Eur. Phys. J. C (2018) 78: 329 and adapted from A. Leonhard, M. Thesis, 2021)

$$N_{PMT}^{det} \sim LY_{eff} \cdot (QE_{PMT}^{VUV} \cdot \Omega_{PMT} + E_s \cdot QE_{PMT}^{vis})$$

VUV+vis WLSR measurement

Data analysis: PE calibration and PSD cut





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