

R&D on wavelength-shifting reflectors for the LAr instrumentation of LEGEND-1000

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LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless $\beta\beta$ Decay



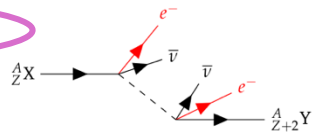
Universität
Zürich^{UZH}

Search for $0\nu\beta\beta$ decay

- $2\nu\beta\beta$ decay:

Allowed by the Standard Model

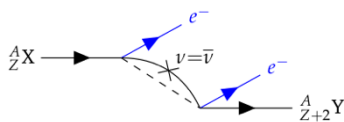
- Broad distribution of the summed electron energies



- $0\nu\beta\beta$ decay:

Only possible if neutrino is a Majorana fermion!

- Peak energy distribution @ $Q_{\beta\beta}$



- Experimental sensitivity

$$T_{1/2}^{0\nu} \propto \begin{cases} \sqrt{\frac{M \cdot t}{B \cdot \sigma}} \cdot f & \text{with background} \\ M \cdot t \cdot f & \text{without background} \end{cases}$$

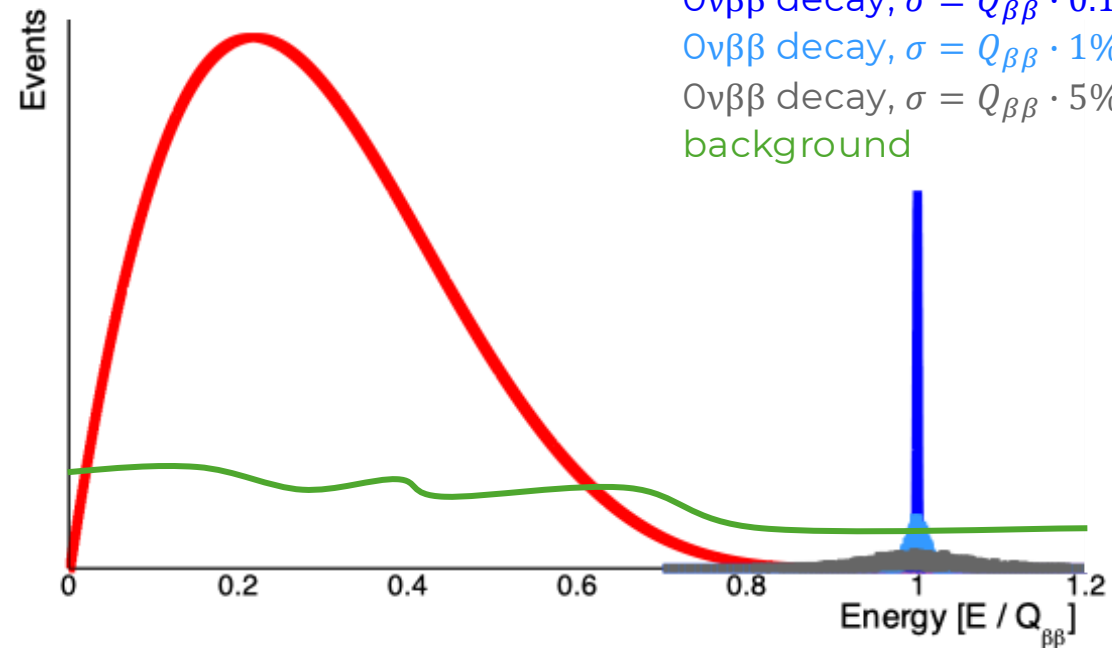
M = target mass

t = acquisition time

B = background fraction

σ = energy resolution @ $Q_{\beta\beta}$

f = fraction of $\beta\beta$ decaying isotope



$2\nu\beta\beta$ decay

$0\nu\beta\beta$ decay, $\sigma = Q_{\beta\beta} \cdot 0.1\%$

$0\nu\beta\beta$ decay, $\sigma = Q_{\beta\beta} \cdot 1\%$

$0\nu\beta\beta$ decay, $\sigma = Q_{\beta\beta} \cdot 5\%$

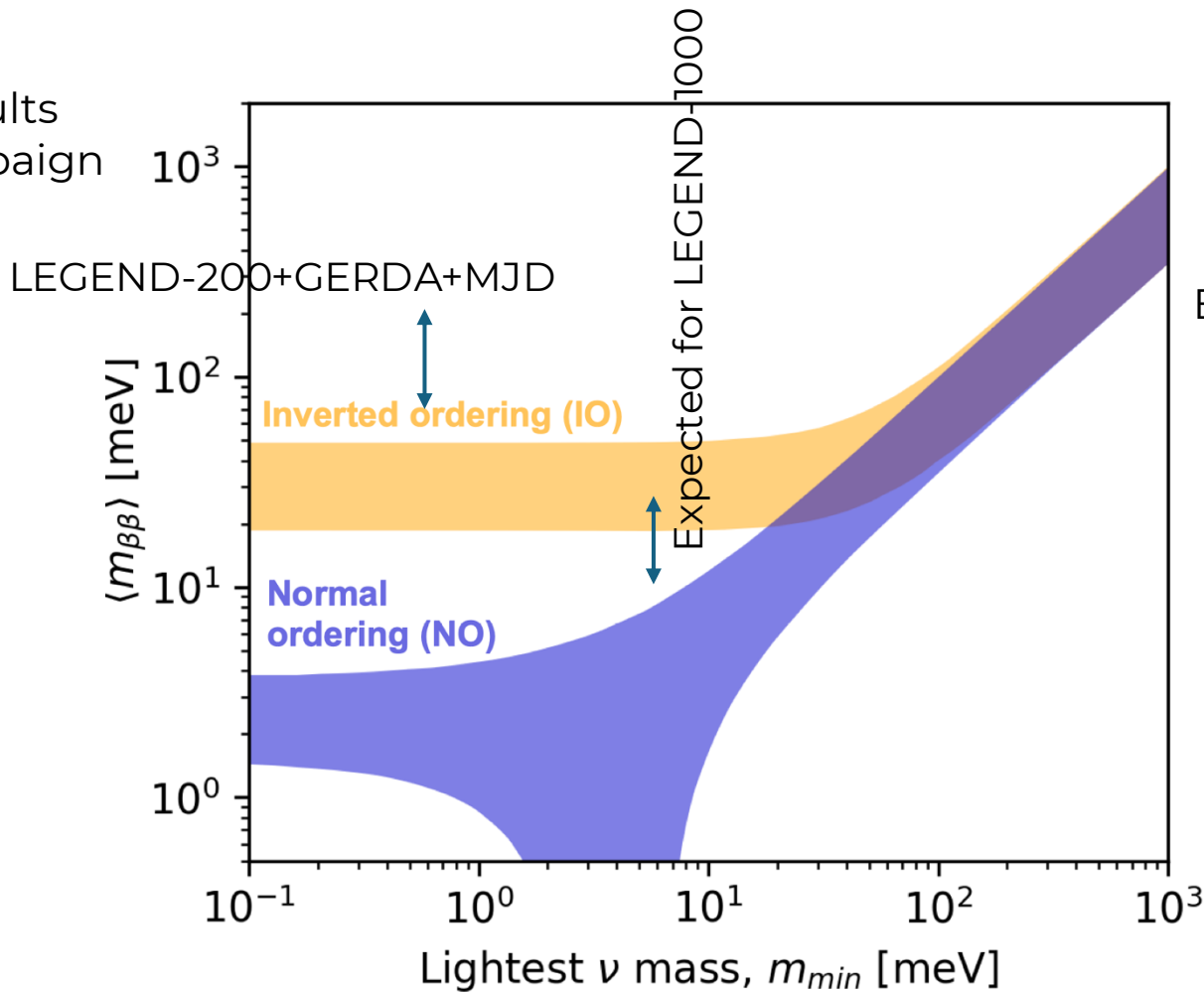
background

- Implications of a $0\nu\beta\beta$ decay observation

- Neutrino would be Majorana particle! = identical to its antiparticle**
- Demonstrates lepton number violation, thus providing a possible mechanism for matter-antimatter asymmetry in the Universe
- Offers crucial insights for neutrino mass ordering and absolute mass scale

Upper limits on $m_{\beta\beta}$

Calculated with the results of the first science campaign here presented



$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

Effective Majorana neutrino mass

$$\frac{\Gamma^{0\nu}}{\ln 2} = (T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) g_A^4 |M^{0\nu}|^2 \frac{\langle m_{\beta\beta}^2 \rangle}{m_e^2}$$

Nuclear matrix element

Phase space

Adapted from Giuseppe Salamanna's talk at ICRC 2025 [\[link\]](#)

The LEGEND experiment

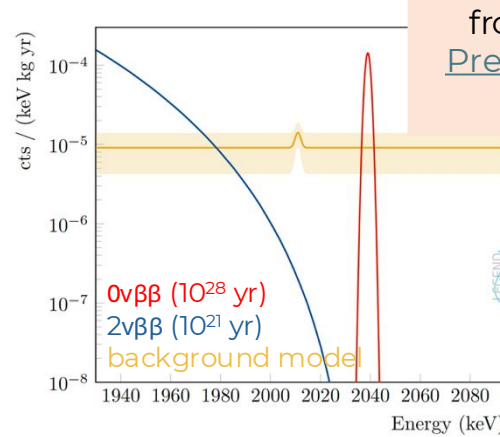
Goal: detecting the neutrinoless double beta decay ($0\nu\beta\beta$) in high-purity germanium (HPGe) detectors enriched in ^{76}Ge .

First phase: LEGEND-200 – taking data since Spring 2023. First results published recently [[Phys. Rev. Lett. 136, 022701 \(2026\)](#)]

Second phase: LEGEND-1000 – will achieve a half-life discovery sensitivity of 10^{28} yr in 10 yr of data-taking and a background index $< 1 \cdot 10^{-5}$ counts / (kg · yr · keV).

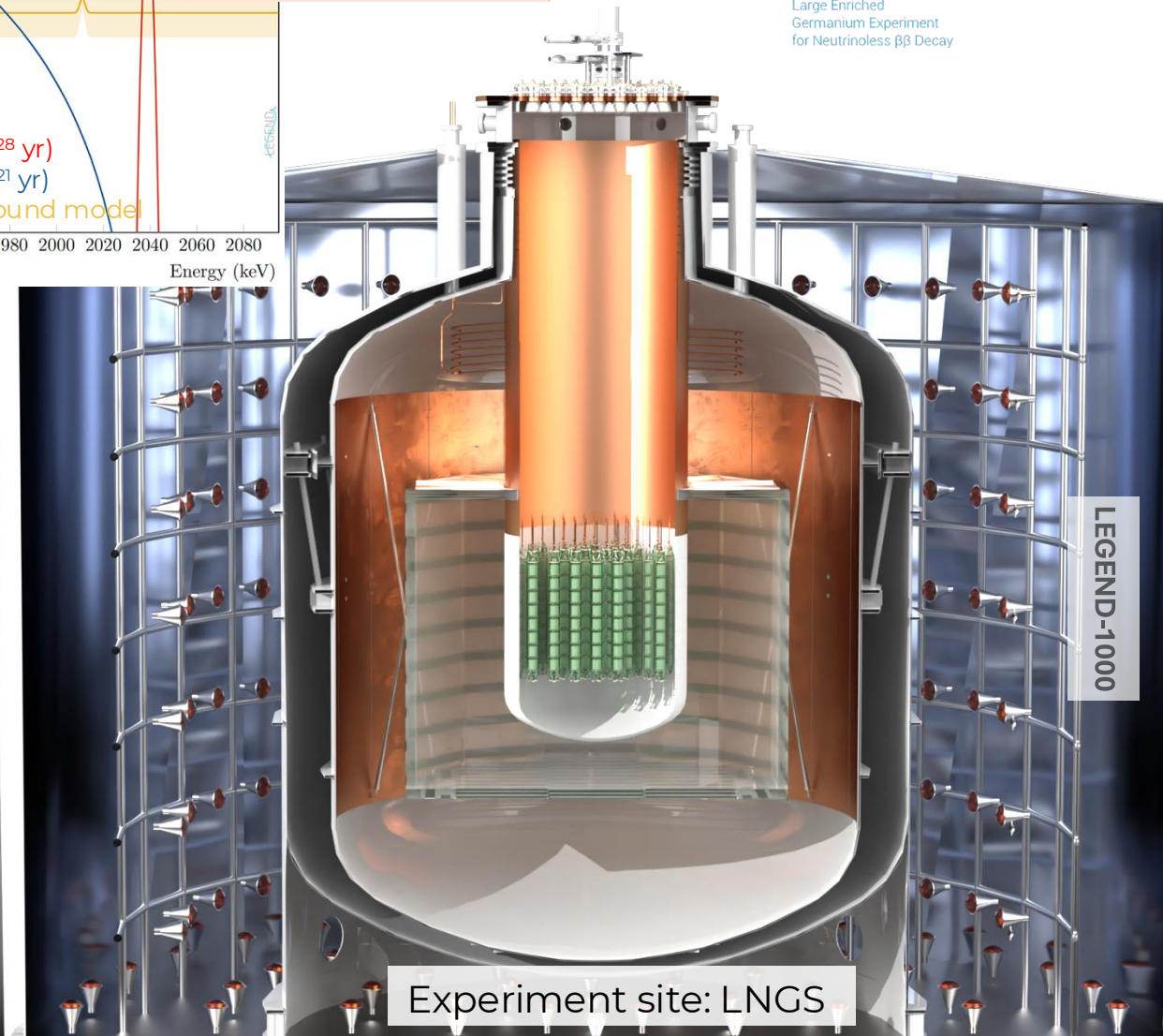
HPGe detectors immersed in an instrumented liquid argon (LAr) volume as coolant and as passive + active veto.

WLSR → increase light collection → veto efficiency towards BI goal.



LEGEND

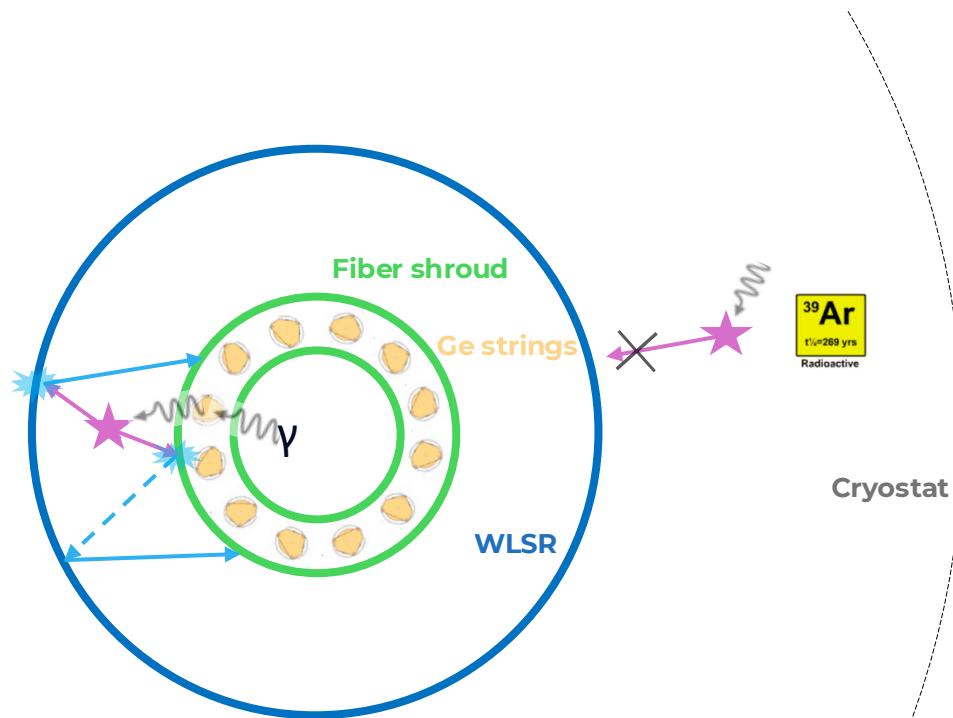
Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay



Brief overview of WLSR in LEGEND-200

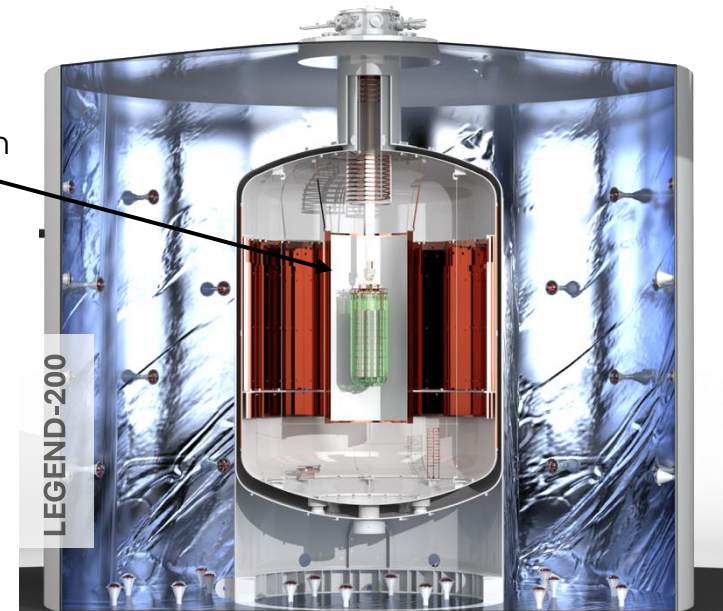
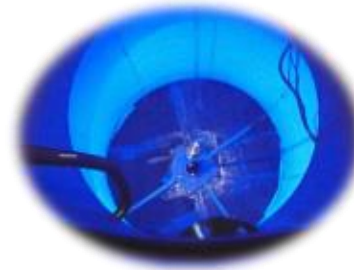
Wavelength-shifting reflector (WLSR) – a very important part of LEGEND LAr instrumentation:

- TPB coated fibers shift 128 nm \rightarrow \sim 430 nm; re-emission is isotropic, so collection depend strongly on surrounding reflectivity;
- A WLSR improves local light collection near HPGe strings and shapes the veto response spatially.

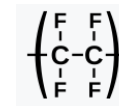


- VUV light
- Visible light
- - - Visible light to be reflected again to reach the fibers

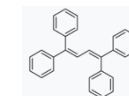
WLSR for L200: copper foil lined with Tetratex (reflector, 13 m²) in-situ evaporated with TPB (WLS)



Tetratex: microporous expanded PTFE-based (polytetrafluoroethylene) material from Donaldson



TPB: 1,1,4,4-tetraphenylbutadiene



Quantum Efficiency, QE, in LAr expected value: 85%
[[Eur. Phys. J. C 82, 442 \(2022\)](#)]

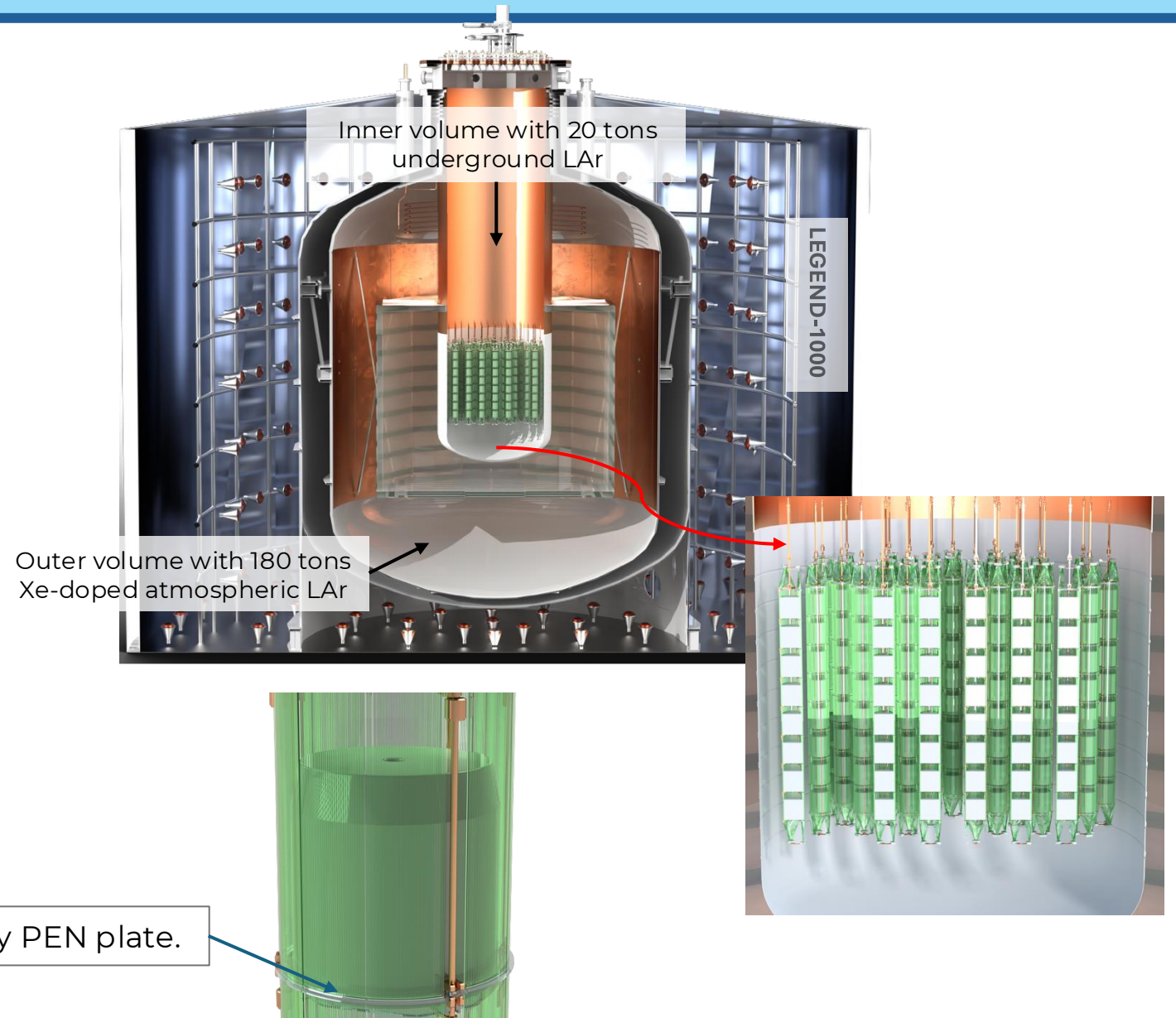
WLSR in LEGEND-1000

Inside the reentrant copper tube:
underground LAr will reduce ^{39}Ar & ^{42}Ar
background.

Internal surfaces covered with WLSR to
enhance LAr scintillation light collection.

Outside volume: filled with atmospheric LAr
and equipped with neutron moderators to
detect cosmogenically activated neutrons.

Outer reentrant tube surface also covered
with WLSR to tag γ s correlated with neutron
capture in HPGe detectors.



Motivations for R&D on WLSR

Our goal: search and characterize new reflectors and WLS, or materials that are at both reflective and WLS, for the LAr instrumentation of L1000. The desired QE would be ~80% and blue-light reflectivity ~95%.

Why?

Tetratex (TTX) is no longer commercially available and requires in-situ vacuum evaporation with TPB to achieve the desired reflectivity;

The larger scale of L1000 and separation of volumes make TPB in-situ vacuum evaporation process more difficult. An ex-situ application is in principle possible, but challenging for large-scale installation; seeking mechanically robust alternatives;

It has been observed in LEGEND-200 that evaporated TPB may generate particulate → it floats in LAr and accumulates on the HPGe groove → leakage current;

Find materials with even lower radio-content than TTX+TPB (from recent remeasurement of TTX @ Boulby for 1 kg: Th-228 < 0.2 mBq and Ra-226 < 0.5 mBq) given the radiopurity goal of L1000.

Reflectors and properties under investigation

We firstly selected commercially available reflective materials, based on their mechanical resistance in LN₂ and their opacity by visual inspection. We are studying:

- polytetrafluoroethylene (PTFE), sintered and expanded
- polyethylene terephthalate (PET)
- high density polyethylene (HDPE)

Properties under investigation:

- reflectivity to blue & VUV light in LAr;
- radiopurity → our requirement is $\sim 10^{-6}$ cts/(keV kg yr) in U and $< 3 \cdot 10^{-8}$ cts/(keV kg yr) in Th;
- gas emanation;
- mechanical stability & resistance in LAr;
- possibility to be coupled to a WLS, like PEN foils, or to be embedded with a WLS molecule.

More on the reflectors already collected

Sample	Thickness [mm]	Comments after a test in LN2 (77K)
MC-PETM4 by Furukawa, distributed by ErgaTapes (link here)	0.5 1	Good: non transparent and doesn't shrink
ePTFE/Porous UHMW-PE film inside by Rogers Corporation (link here)	0.15 0.18	Quite transparent, observable shrinkage
Skived porous PTFE Film by Rogers Corporation (link here)	0.51	A bit transparent, doesn't shrink
Sintered PTFE by Porex Filtration Group (link here)	0.10 0.19 0.25	Quite transparent, slight shrinkage
WhiteOptics F-16A HDPE by Ingemann Components, distributed by Erga Tapes (link here)	0.205	Good: almost non transparent and doesn't shrink
Porous sintered PTFE distributed by Thorlabs (link here)	0.75	Good: non transparent and doesn't shrink



More on the reflectors already collected

First results on this later

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LArS: Liquid Argon Setup @ UZH

Optical characterization of the reflective and/or WLS samples in Lar (purity of GAR 99.9999%).

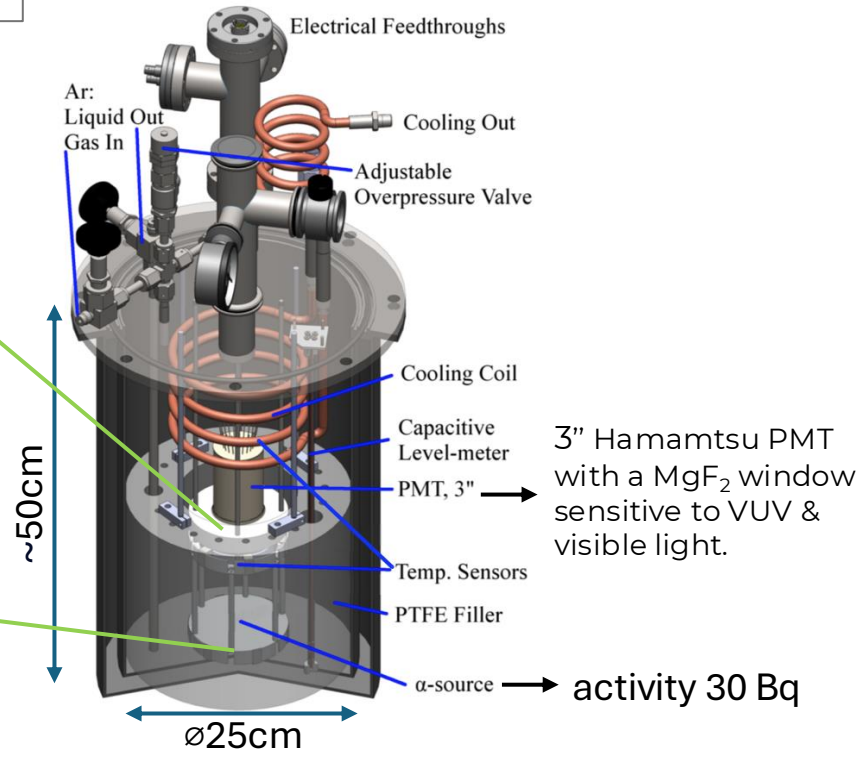
Typical run duration ~2 days

LArS test cell (recent hardware upgrade)

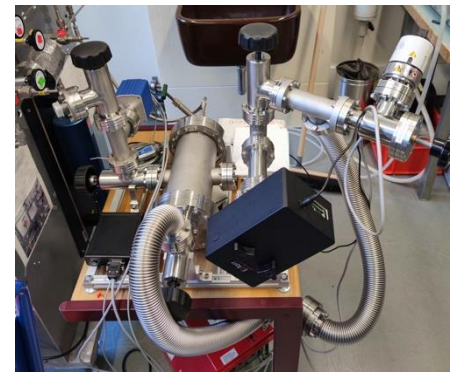


~11cm

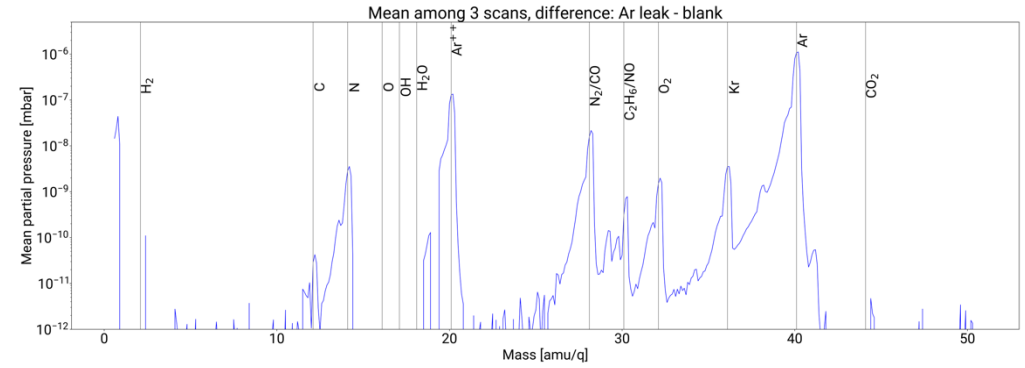
LArS



GAr purification system pumping continuously GAR



Residual gas analyser (RGA) and mass spectrum acquired with it

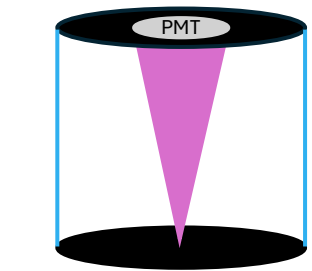


More on the setup: L. Baudis et al., [2015 JINST 10 P09009](#)

With this setup, the quantum efficiencies of TPB and PEN in LAr were measured for the first time. TTX VUV-reflectivity in LAr was also measured. Article: G.R. Araujo et al., [Eur. Phys. J. C 82, 442 \(2022\)](#)

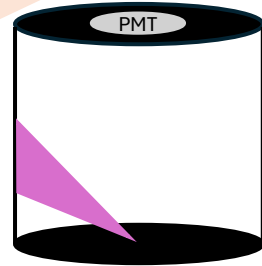
LArS: Liquid Argon Setup @ UZH

LAr scintillation light is triggered by the decays of an Am-241 alpha source. The light can then:



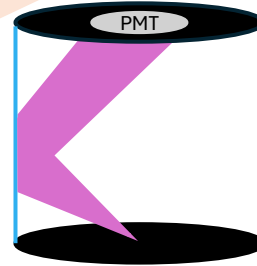
reach the PMT directly;

Absorber run



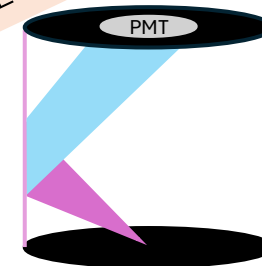
hit the wall and be absorbed if the absorber is there;

Reflector run



hit the wall and be reflected by the reflector;

Reflector+WLS run



hit the wall, be shifted by the WLS and be reflected by the reflector.

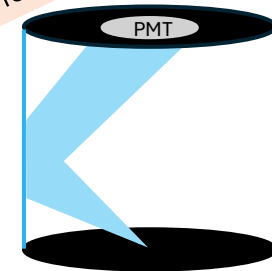
If a WLS is there

For each sample we measure how many photoelectrons (PE) are produced in the PMT. We compare each measurement to the case in which no sample covers the test cell internal wall (in the old test cell: black optical absorber).

If a WLS is being tested, an acrylic disk can be placed on the PMT window to block VUV light and measure the amount of light shifted to blue.

Instead of using the alpha source, we can shine blue light to study the sample light yield with blue light.

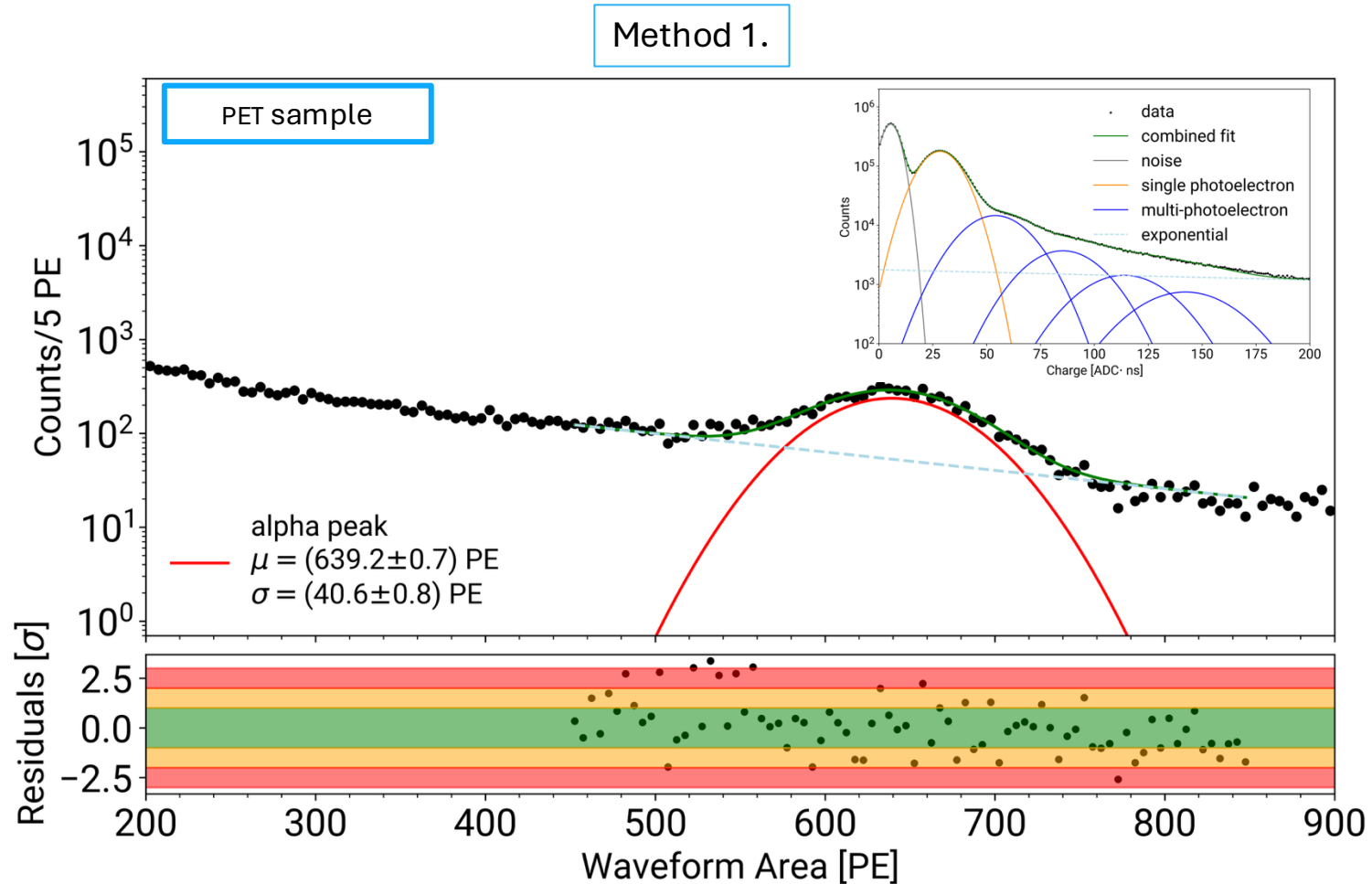
Reflector run with blue LED



Data analysis with LArS

After calibrating the PMT and cleaning the data, the number of PE generated in the PMT can be evaluated in two ways:

1. by fitting the alpha peak with a gaussian + exponential, as a proxy for background;



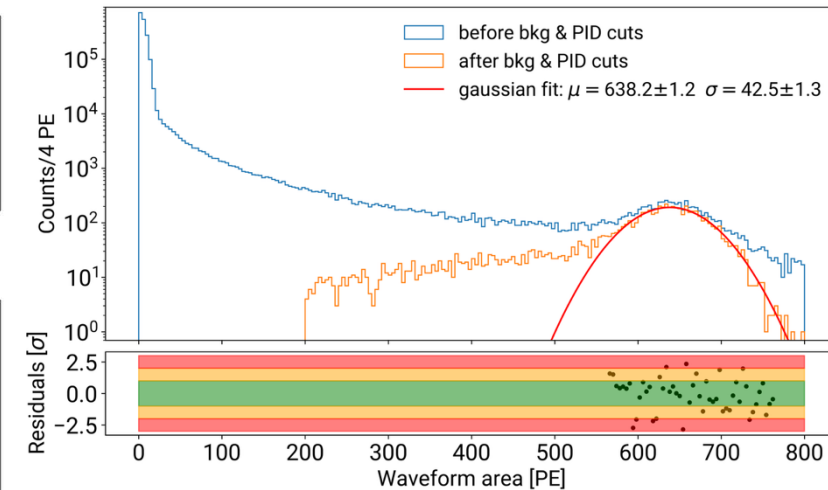
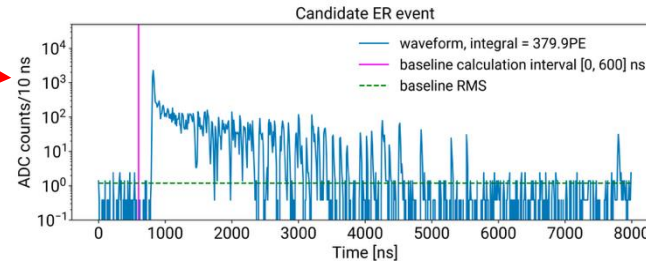
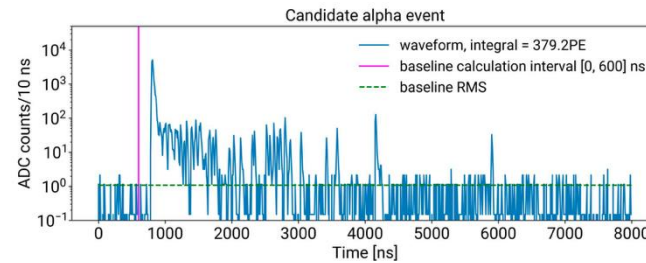
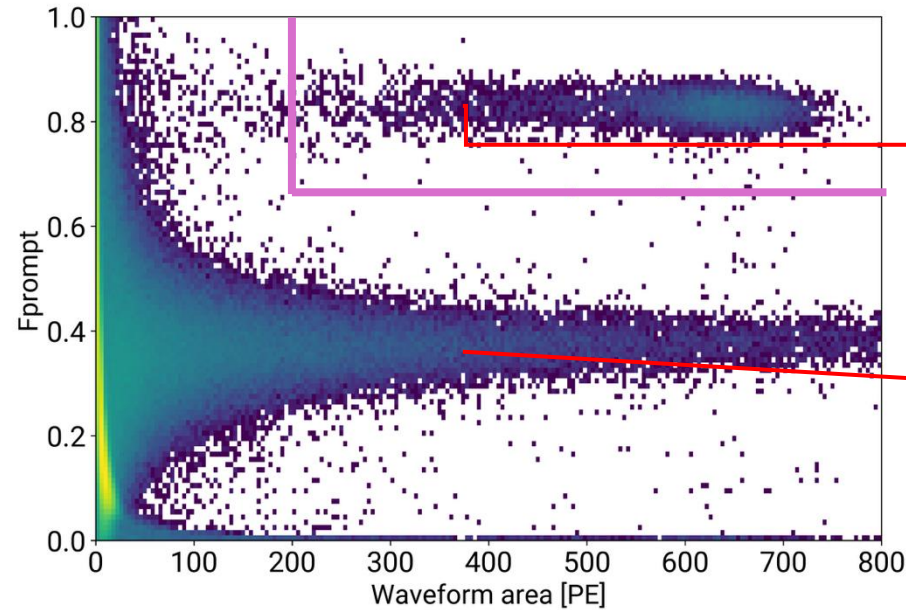
Data analysis with LArS

by removing background (beta and gammas) with a particle identification technique and fitting the surviving events with a gaussian.

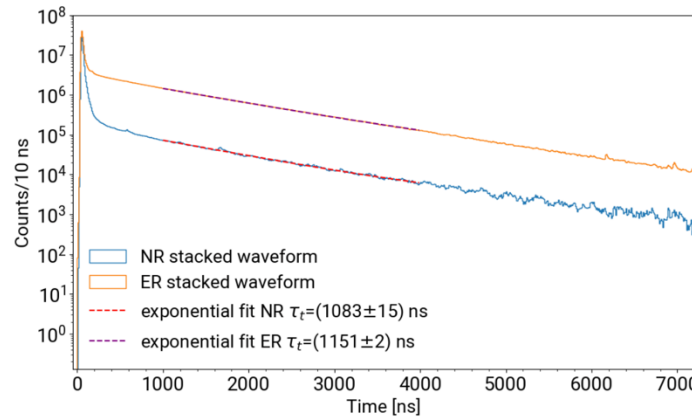
$$F_{prompt} = \frac{\text{waveform area in the first 200ns}}{\text{total waveform area}}$$

> In both cases, the number of PE is the mean value of the fitting gaussian. The two methods give compatible results.

Method 2.



Apart from with the RGA, another estimation of the Ar purity comes from the measurement of the de-excitation LAr triplet state lifetime:



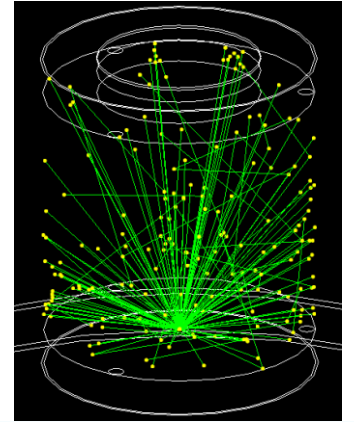
Typical triplet lifetime ~900 ns – ~1200 ns

LArS simulation

Needed because:

- the measurements with LArS are not absolute;
- decouple measurement from experimental setup features (solid angle, refraction across optical boundaries) -> intrinsic reflectivity of reflectors to VUV and the QE of WLS;
- understand systematic uncertainties.

Work in progress:
modifying the sim to
estimate reflectivity to
blue light



Geant4 simulation of LArS with the PET sample

Sources of uncertainties:

- statistical uncertainty arising from the measured PE value from the absorber;
- alpha source disk reflectivity (aluminium). Depending on its reflectivity and the amount of specular vs lambertian component, the LAr effective photon yield changes.

Optical parameters determination reference run

Step 1

$$N_{det} = PY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega$$

Varying the **LAr photon yield** -> range of values that matches the real number of photons detected by the PMT in the absorber run.

Estimated uncertainty on PY_{eff} : $\pm 7\%$.

Sample reflectivity estimation

Step 2

$$N_{det} = PY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega \cdot \epsilon$$

We assume completely diffuse reflection (no transmission)

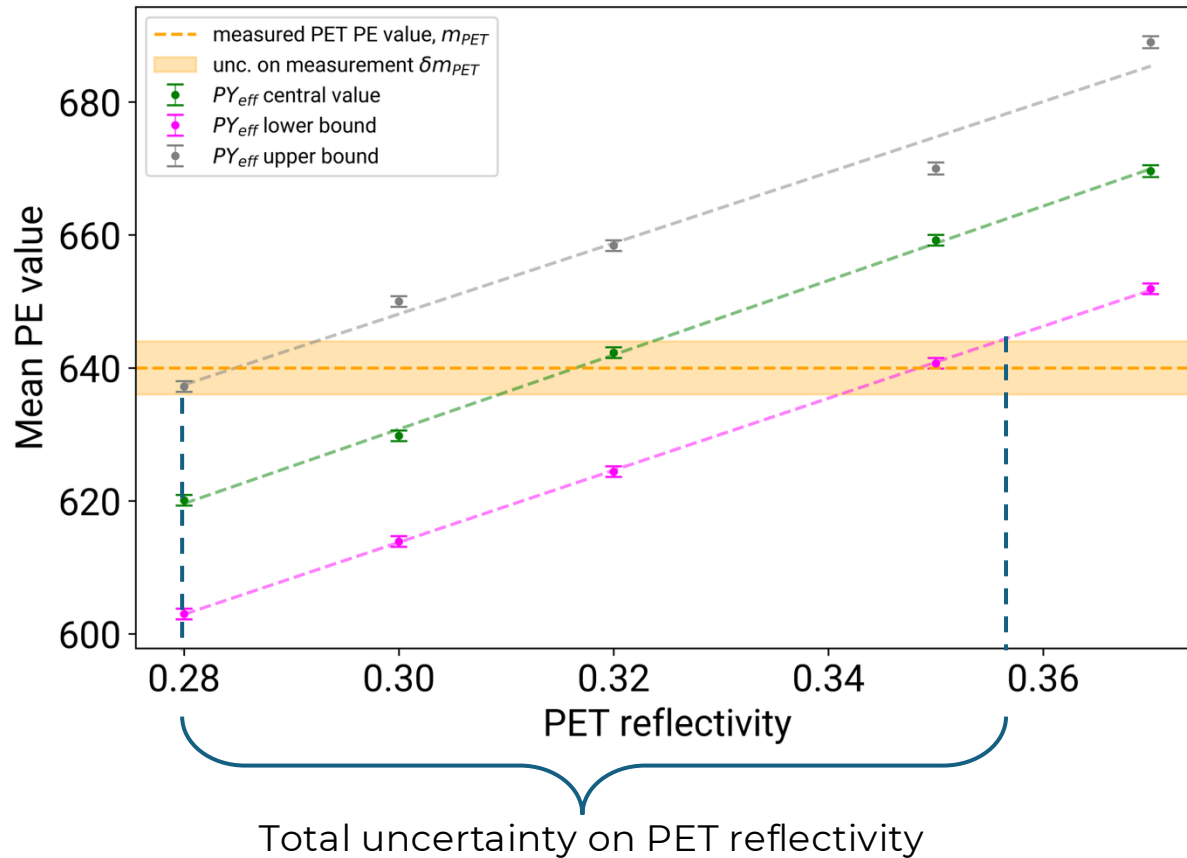
Tuning the reflectivity of the sample to match the real number of photons detected in the sample run -> **estimation of the sample reflectivity.**

First results

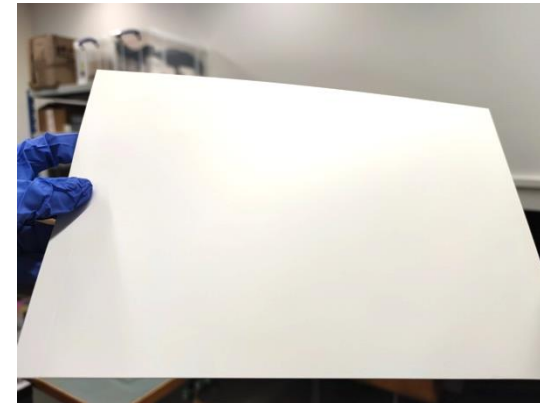
Measurements performed with the alpha source and the **PET sample***, 0.5 mm thickness:
 $PE_{\text{reflector}}/PE_{\text{absorber}} : (29 \pm 3)\%$;
Simulation: **preliminary PET VUV-reflectivity value of $(32 \pm 4$ (stat&syst))%**.

This is already more than what observed for the TTX (VUV reflectivity $(9 \pm 6(\text{stat}) \pm 2(\text{syst}))\%$).

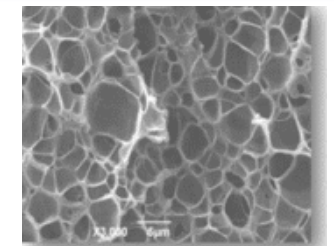
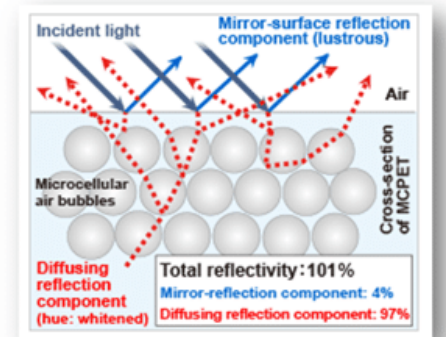
Measurements with blue light will be performed soon.



*MicroCellular PET satin finish M4 grade by Furukawa, distributed by ErgaTapes ([link here](#))

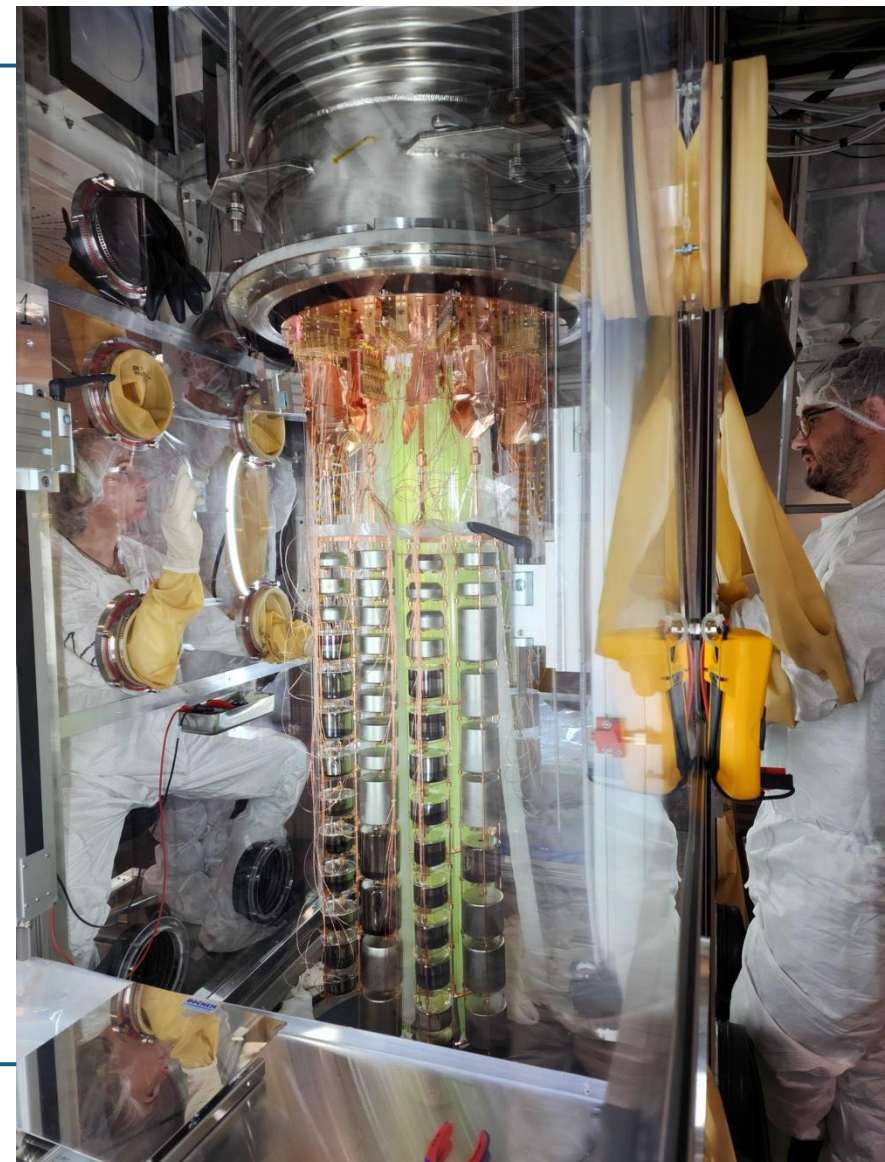


From producer's website:



Summary & next steps

- Goal: identify a WLSR for LEGEND-1000 that improves light collection while meeting mechanical and radiopurity constraints.
- Status: candidate commercial reflector materials have been collected and are under test in LArS; PET shows a promising increase in detected light yield in the current configuration.
- Next steps: quantify VUV and blue reflectivity with a systematic uncertainty budget, then evaluate coupling to WLS (PEN foils and embedded shifters) and check cryogenic durability.
- Additional scope: measure performance at 175 nm for Xe-doped LAr regions.
- Qualification: ICP-MS radiopurity screening of top candidates, followed by larger-scale optical validation for integration readiness.



Summary & next steps

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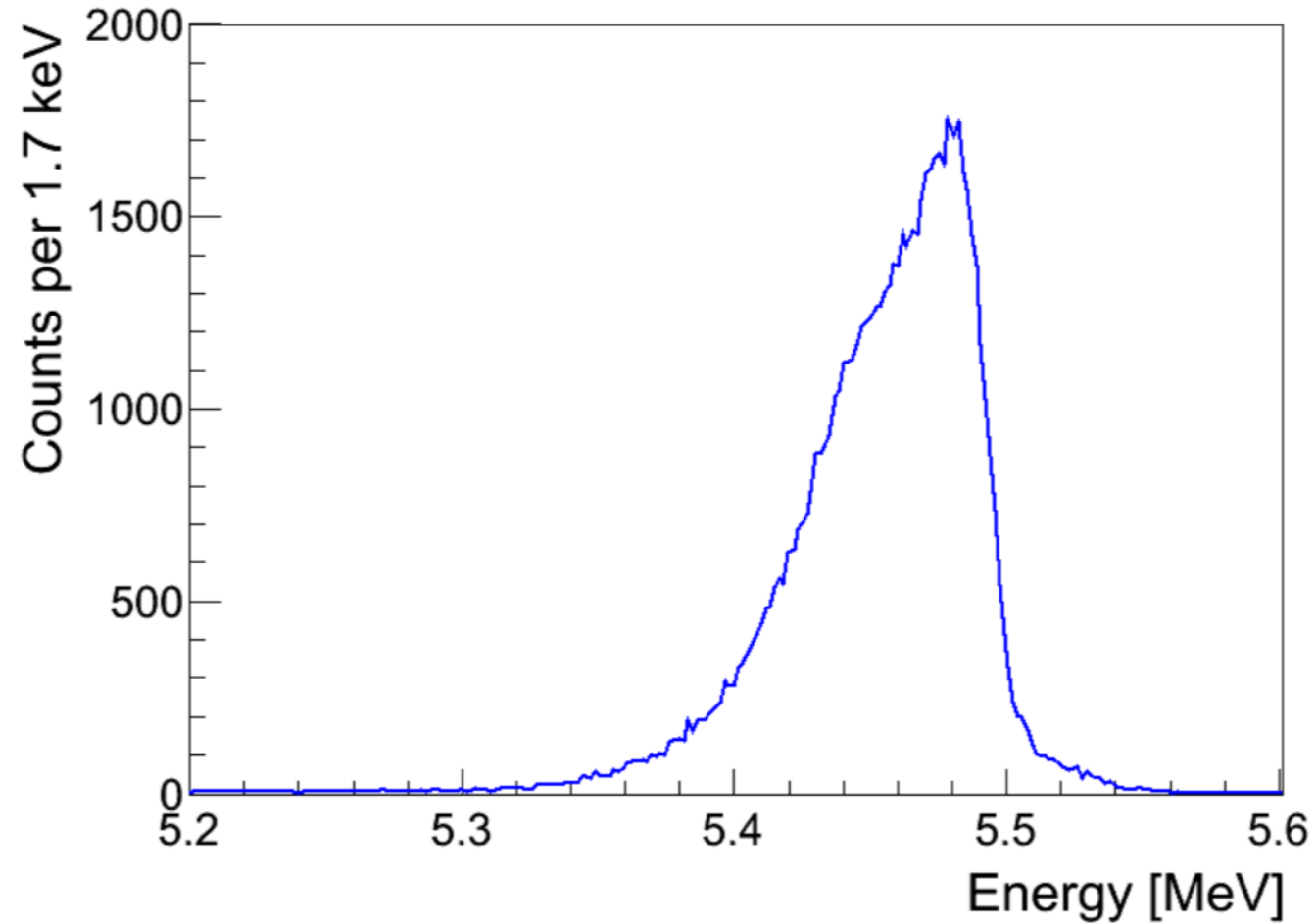
Thank you for the attention!



Backup

LArS alpha source spectrum

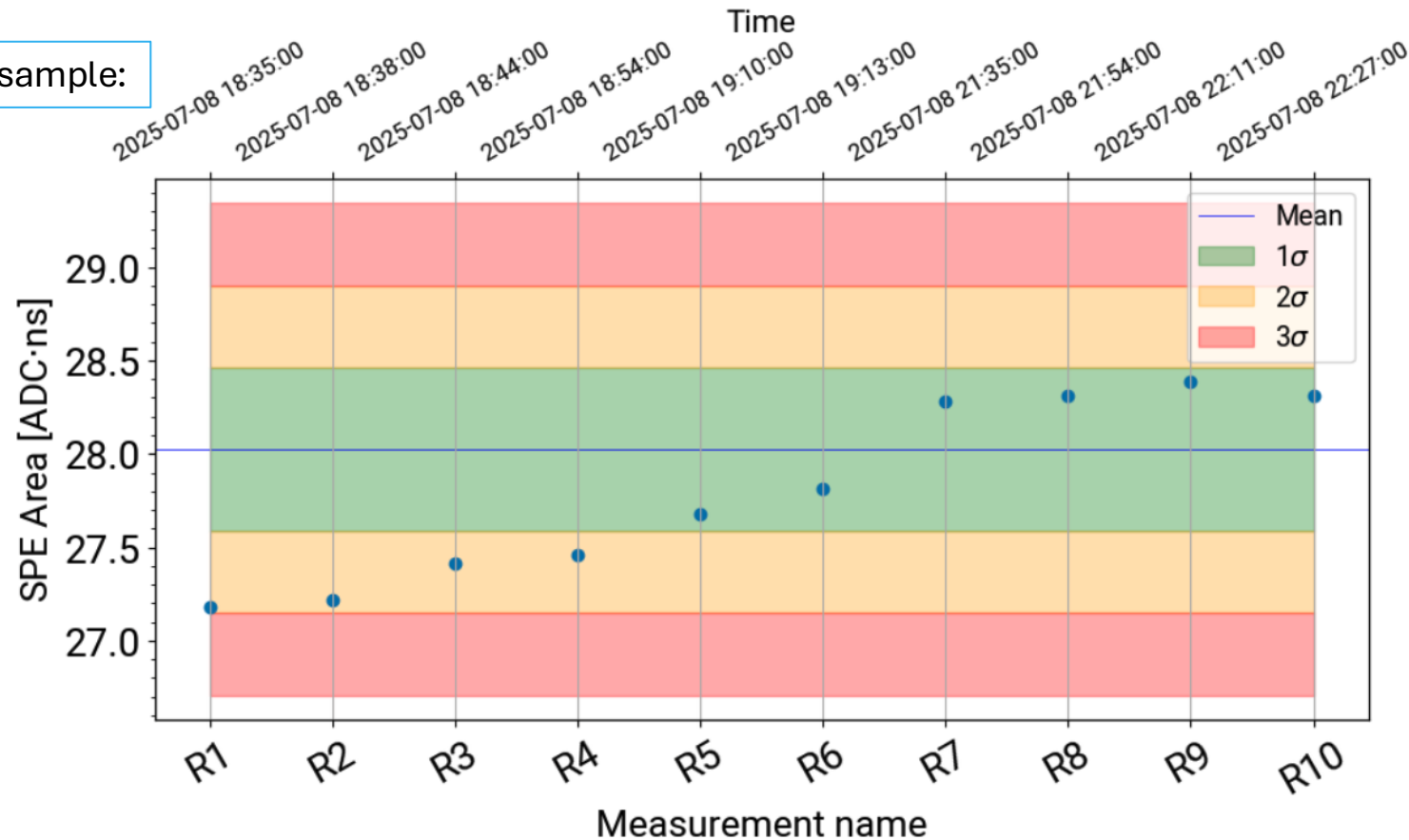
- The alpha particles interact with the argon nucleus and induce NR scintillation light in LAr. Low energy gammas are also emitted along with the alpha particles, inducing ER scintillation light.



PMT calibration

- Done by fitting the small area pulses (dark count events). We can do that for every measurement → robust PMT stability check.
- We cross-check the SPE value found by shining very faint pulses of blue light at the beginning and end of each run with the same sample.

Run with the PET sample:



More on LArS simulation

Quantity measured:

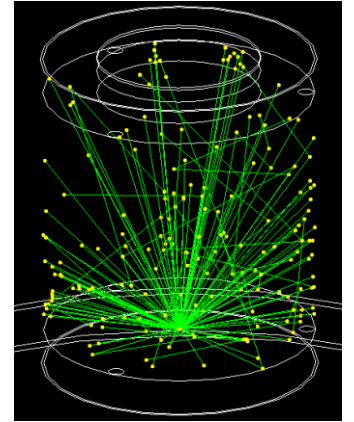
- PE distribution with our geometry setup

Variable quantities in simulation:

- LAr effective photon yield PY_{eff} ;
- Source disk reflectivity model;
- Sample reflectivity (we assume completely diffuse reflectivity no transmission).

Fixed quantities in simulation:

- PMT QE vs wavelength;
- Absorption/scattering length of VUV and vis light in LAr.



Geant4 simulation of LArS with the PET sample

Optical parameters determination reference run

Step 1
$$N_{det} = PY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega$$

Varying the **LAr photon yield** -> range of values that matches the real number of photons detected by the PMT in the absorber run.

Estimated syst. uncertainty on PY_{eff} : $\pm 7\%$.

Sample reflectivity estimation

Step 2
$$N_{det} = PY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega \cdot \epsilon$$

Tuning the reflectivity of the sample to match the real number of photons detected in the sample run -> **estimation of the sample reflectivity.**

More details on finding optical parameters with LArS sim.

- The number of photons detected by the PMT is given by:
$$N_{det} = PY_{eff} \cdot QE_{PMT}^{VUV} \cdot \Omega$$

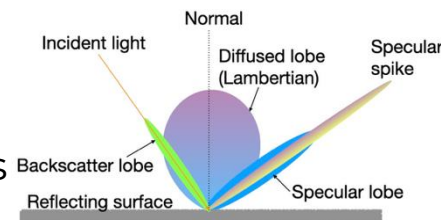
PY_{eff} = LAr VUV photon yield, $QE_{VUV,PMT}$ = VUV quantum efficiency of the PMT (22.8%), Ω = solid angle covered by the PMT above the source. Our PY_{eff} is found by matching the N_{det} simulated with those measured.

- The LAr VUV photon yield depends on two factors:

$$PY_{eff} = E \cdot SY_{LAr} \cdot 0.5 \cdot (1 + SD_{ref})$$

- One explaining the “intrinsic” photon yield from an alpha particle depositing energy E (considering that the mean energy to produce a photon in LAr is 19.5eV, and that the α particles have a quenching factor of 0.72, SY_{LAr} should be equal to 37ph/keV. Actually, in the simulation we introduce an extra factor q to lower this value ($SY_{LAr} = q \cdot 37\text{ph/keV}$), so that we can match the measured photons detected by the PMT).
- The other factor considers that some of the scintillation photons may be reflected, or absorber, by the aluminium of the source disk. If the source reflects light isotropically (called Lambertian reflection), then half of the photons directly propagates through the cell, and the other half reaches the surface of the disk, where it is absorbed or reflected with a probability of being reflected SD_{ref} . We set the value of SD_{ref} to **(8±4)%**.

- Note that the source disk reflectivity can also be non-isotropical (called specular). This introduces a source of systematic uncertainty affecting PY_{eff} . Therefore, it is necessary to simulate several scenarios of source disk reflectivity. We keep the back scattering reflectivity to 5% (this doesn't make much difference), set the specular lobe to 0, and just play with the specular spike. According to [*this reference], the specular component of aluminium VUV reflectivity is $\geq 30\%$ and $\leq 60\%$, so we simulate the following value of specular spike: 25%, 40%, 60%.



[*] Birgit Zatschler's Thesis: Attenuation of the scintillation light in liquid argon and investigation of the double beta decay of ^{76}Ge into excited states of ^{76}Se in the Gerda experiment

LAr modeling in the simulation

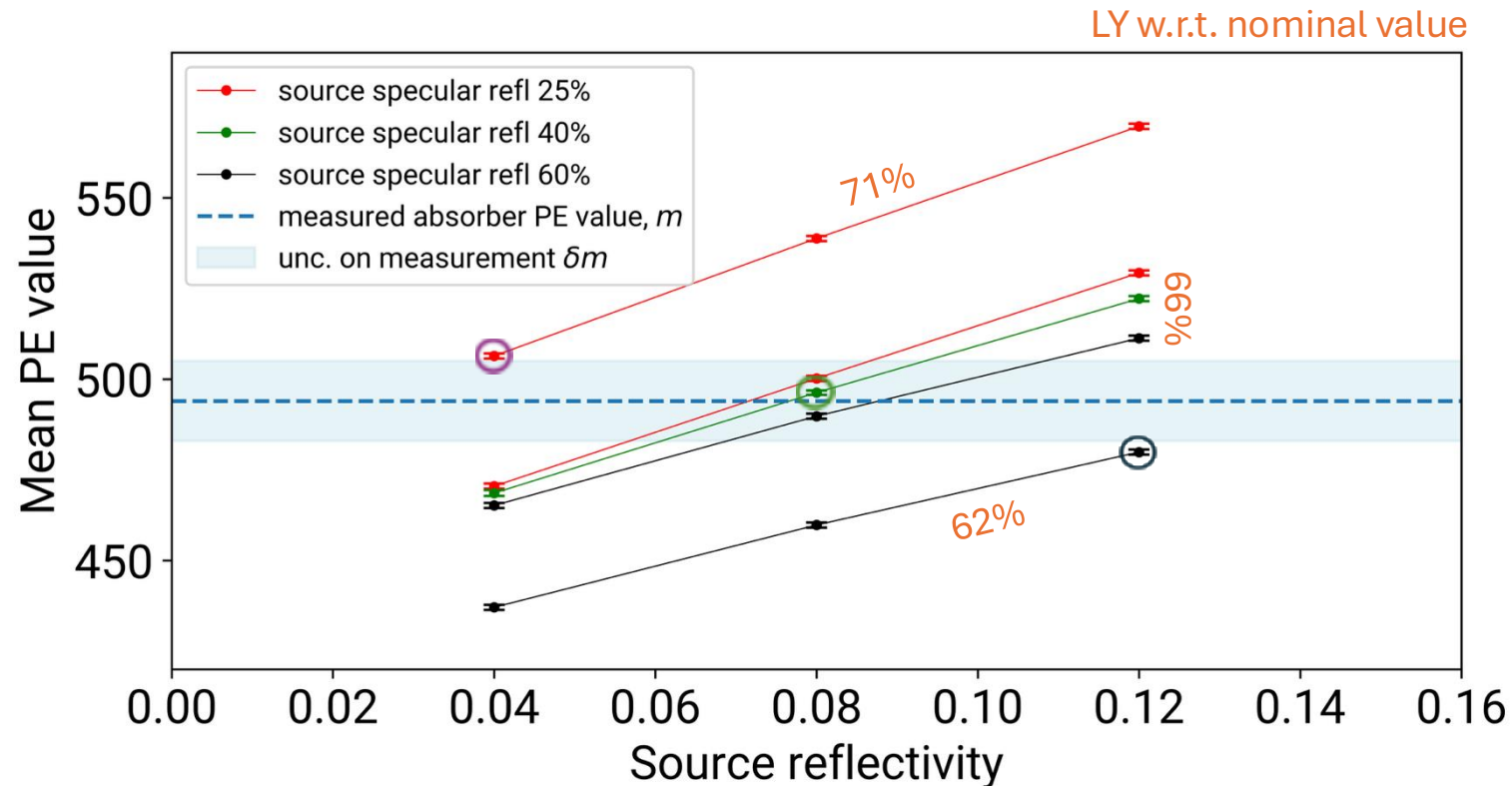
- Scintillation spectrum peaked at 128 nm [M. Hofmann, T. Dandl, T. Heindl, arXiv:1511.07721, 2013]
- Light yield in LAr: 37 photons/keV [A. Hitachi, T. Doke, Phys. Rev. B, 46:11463–11470, 1992.]
- Refractive indexes (Sellmeier coefficients) [M. Babicz, S. Bordoni, JINST 15(09):P09009–P09009, 2020]
- Rayleigh scattering calculated using the refractive indexes
- VUV absorption length of LAr: 60 cm [A. Neumeier, et al. EPL 111(1):12001, 2015]
- Vis absorption length of LAr: 10 m [considering that LAr is very transparent and the setup is small]

Other quantities in the simulation

- If impurity level (and number of PE) does not vary significantly across measurements (as in the PET run), we assume uncertainties due to impurities is covered by the $\pm 7\%$ on PY_{eff} .
- PMT QE value taken from the PMT data-sheet. Since it is degenerate with PY_{eff} , we assign no uncertainty to it.
- Acrylic disk transmittance was measured at room temperature in [Eur. Phys. J. C 82, 442 \(2022\)](#): it is 92.3% above 350 nm, and 0 below. Absorption length above 350 nm set to 1 m.
- For now, we consider that uncertainty on source position is negligible and is well covered by the final uncertainty quoted.

More details on finding optical parameters with LArS sim. (2)

- By simulating different q factors, we found out that the sets of parameters that lead to a PE value matching the measured one within its statistical uncertainties. I will refer as lower, central and upper values on PY_{eff} to the following sets of parameters:
 - Lower: LY 62%, source reflectivity 12% with specular component 60%
 - Central: LY 66%, source reflectivity 8% with specular component 40%
 - Upper: LY 71%, source reflectivity 4% with specular component 25%
- The upper and lower bounds lead to a systematic uncertainty on PY_{eff} of $\pm 7\%$.



Details on PET VUV-reflectivity

- Similarly to what done with the absorber, by varying PET reflectivity, we match the real number of PE with the simulated one. We then repeat the simulation with the parameters boundary values on PY_{eff} :
- We can set for the PET VUV reflectivity a value of **(32±4)%**.

