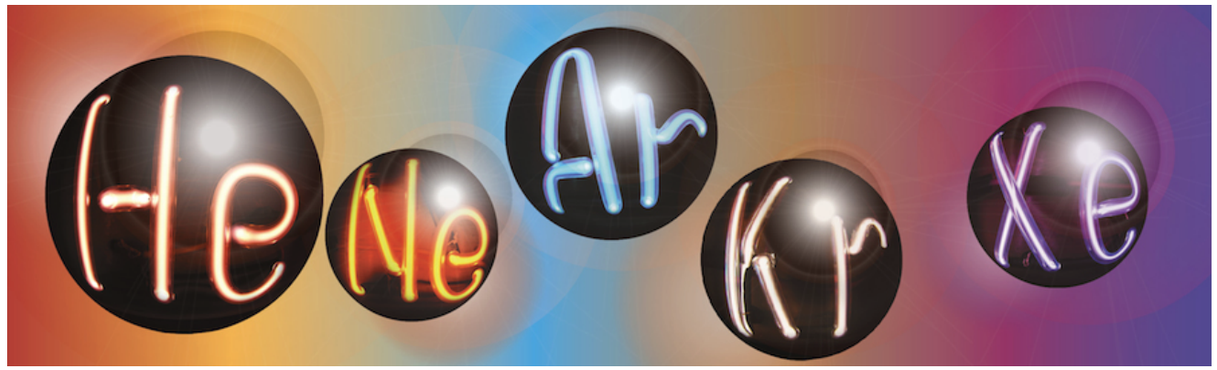



# The Liquid Argon Atmospheric system for LEGEND-1000

**L. Canonica**
on behalf of the LEGEND Collaboration
INFN & Università Milano-Bicocca

LIDINE 2025, 21st Oct 2025, Hong Kong

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

# Searching for 0νββ with Germanium

0νββ decay of $^{76}$Ge: $^{76}Ge \rightarrow {}^{76}Se + 2e^-$

$Q_{\beta\beta}$ = 2039 keV

Natural abundance: ~8%

High-purity, isotopically enriched Ge detectors (HPGe)

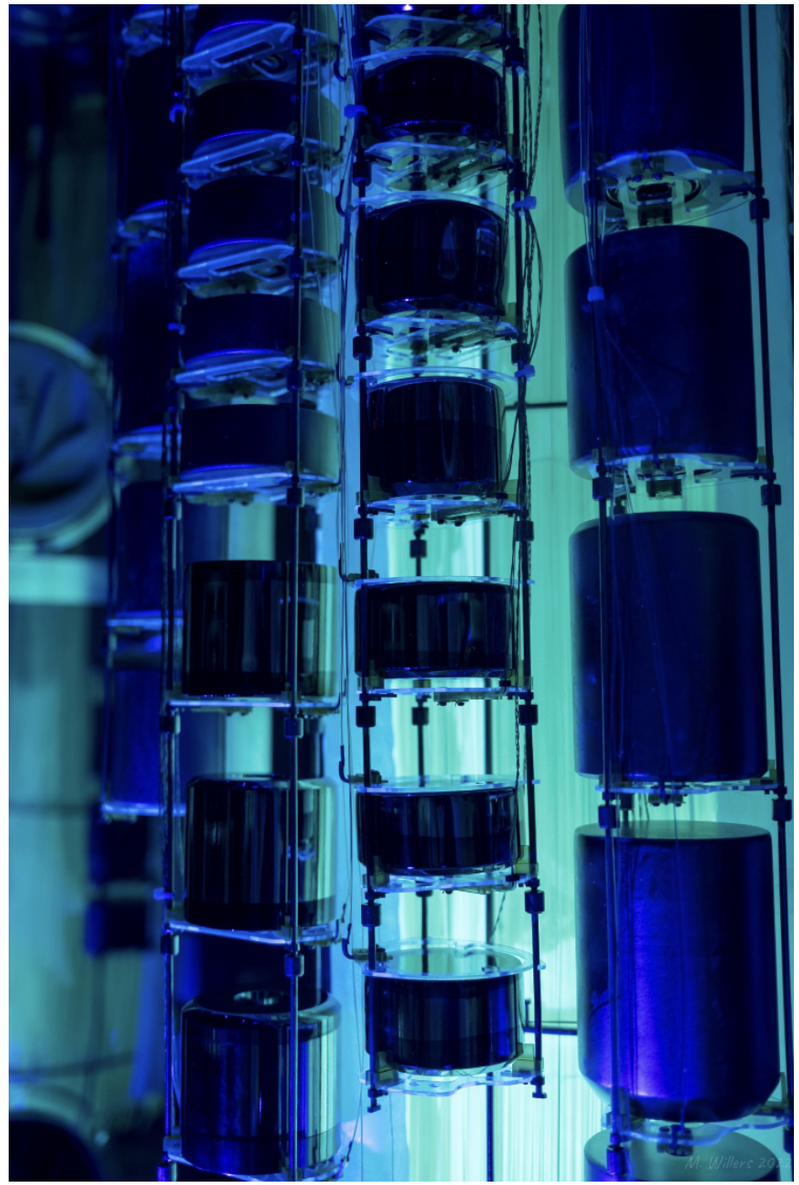
source = detector → **high efficiency**

enriched to ~ 90% → **high 0νββ mass**

radiopure → **low background**

Ge-crystal diode → **excellent energy resolution**

signal topology → **event discrimination**



# The LEGEND project

See talk from L. Pertoldi,
R. Deckert and m H. SHI at this conference

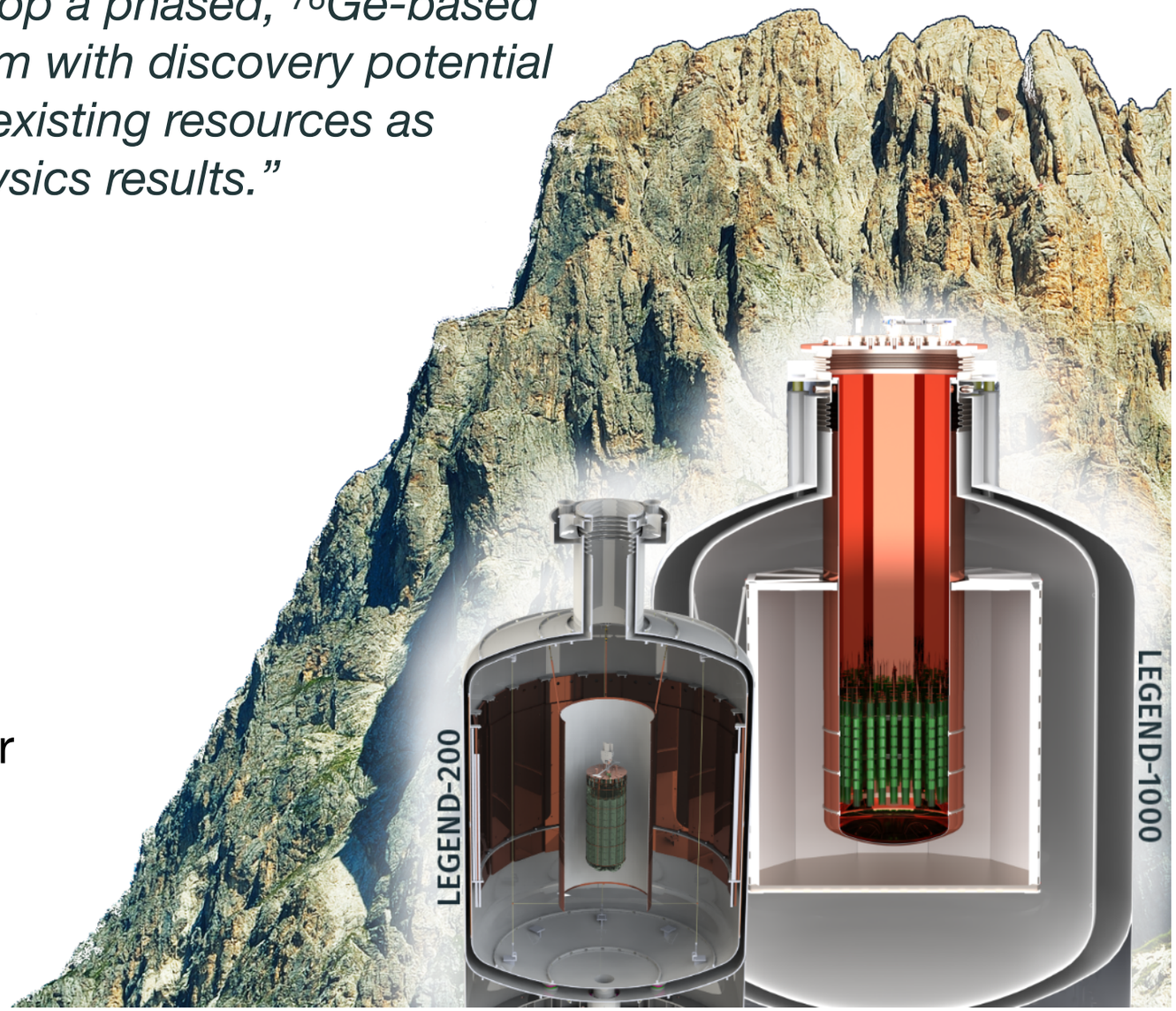
*"The collaboration aims to develop a phased, $^{76}$Ge-based double-beta decay experimental program with discovery potential at a half-life beyond $10^{28}$ yr, using existing resources as appropriate to expedite physics results."*

## LEGEND-200

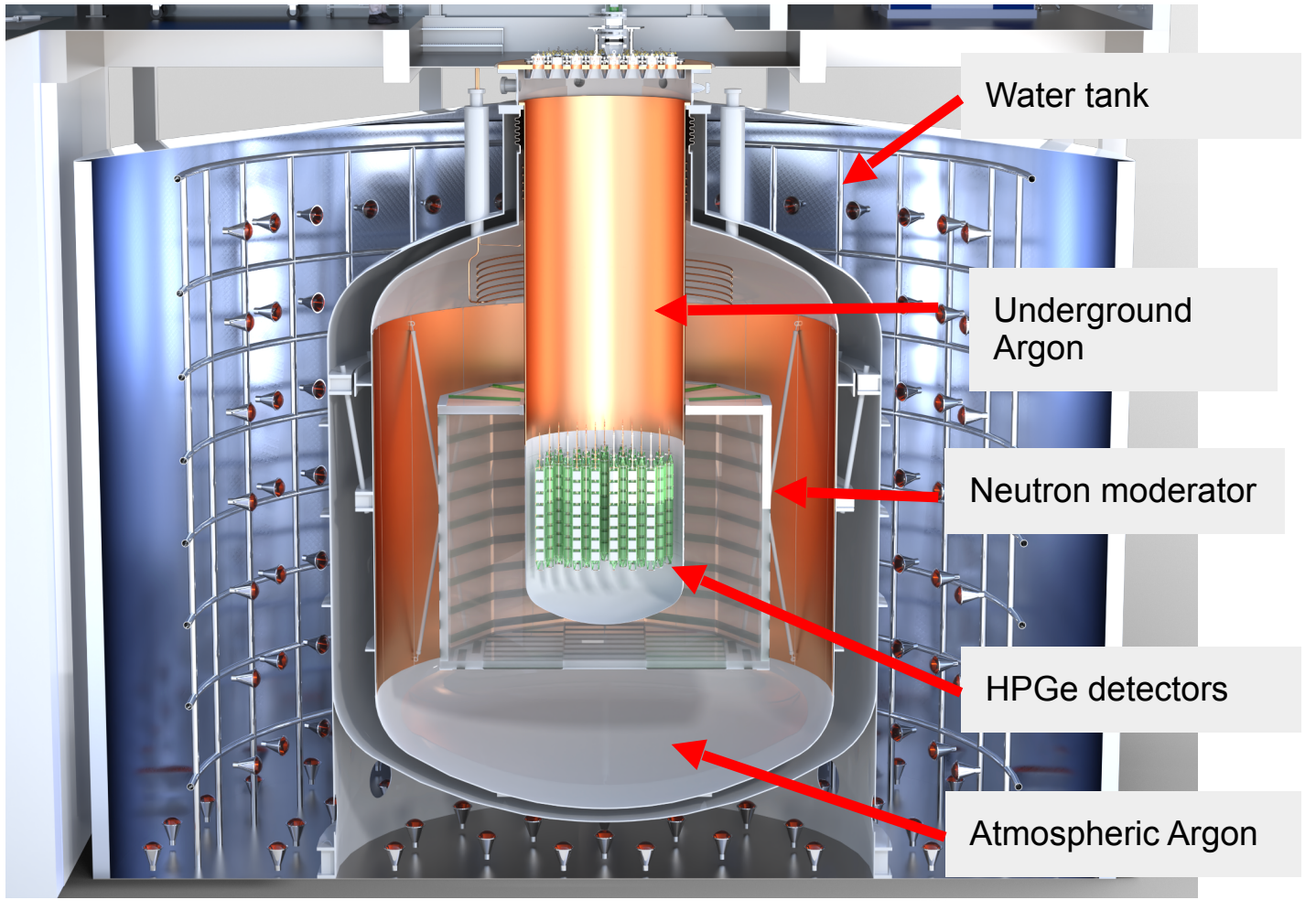
- Data taking since 2023
- GERDA infrastructure at LNGS
- Up to 200 kg of HPGe detectors
- Target: $T_{1/2}^{0\nu} > 10^{27}$yr after 1 ton-yr

## LEGEND-1000

- Improved background (20x)
- Up to 1,000 kg of HPGe detectors
- Target: $T_{1/2}^{0\nu} > 10^{28}$yr after 10 ton-yr
- Currently securing financial support

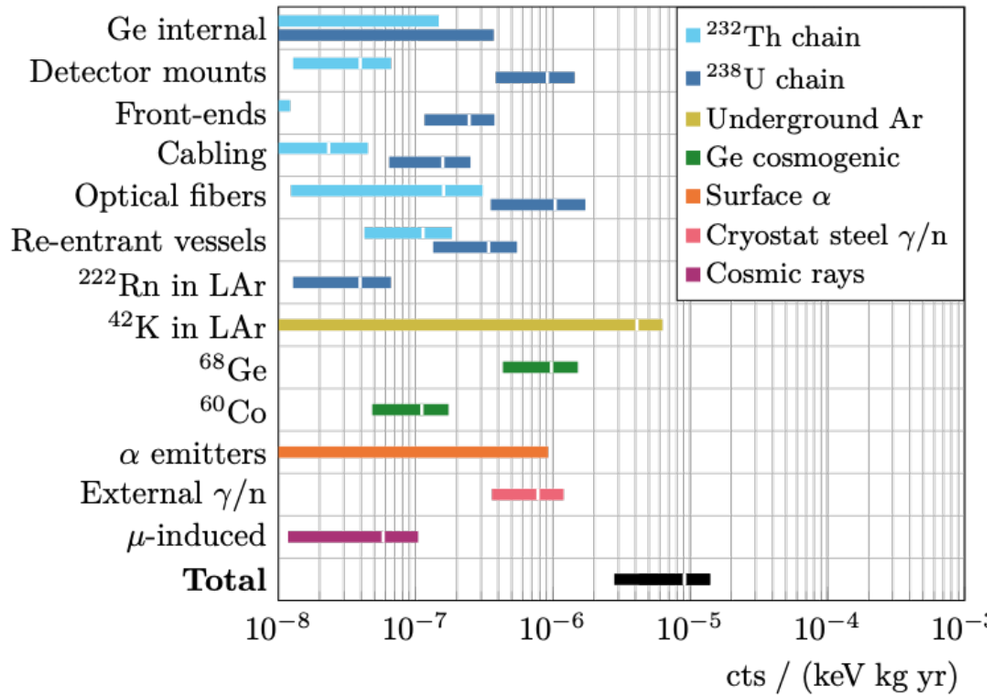


# From LEGEND-200 to LEGEND-1000




Improvements wrt LEGEND-200:

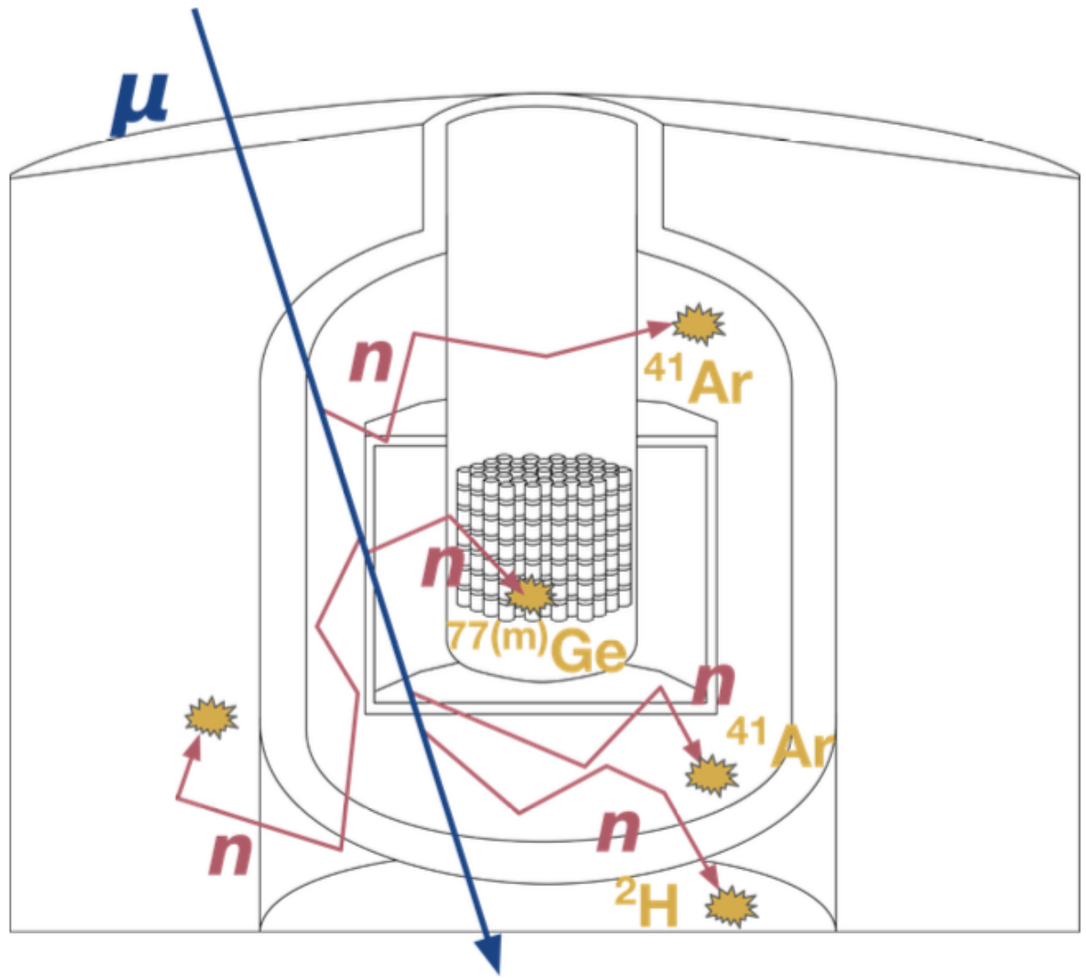
- Ge detectors in reentrant tube filled with underground LAr to reduce $^{42}$Ar background
- Higher mass HPGe detectors (336 ICPC $^{enr}$Ge det. ~3 kg each)
- Independent deployment of strings



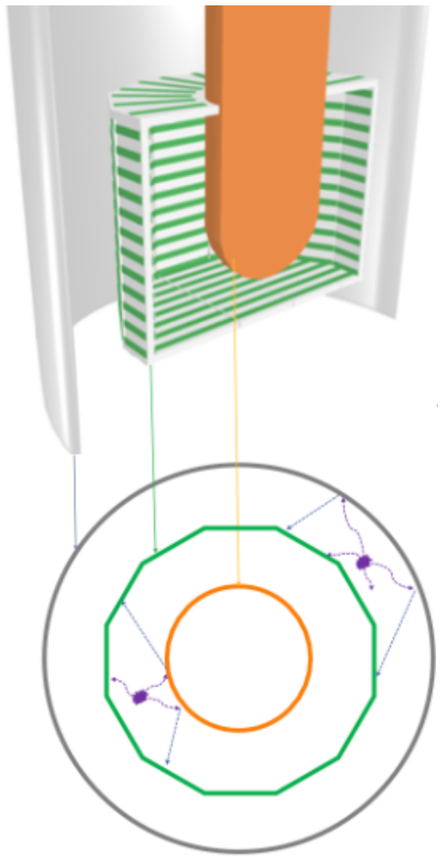
# Outer LAr system: Motivation and strategy

- Cosmic-ray induced neutrons:
  - $n + {}^{40}Ar \rightarrow {}^{41}Ar + \gamma_s$
  - $n + H \rightarrow {}^{2}H + \gamma$
- Purpose: tag $^{77}Ge$ and $^{77m}Ge$ cosmogenic isotopes by **detecting siblings neutrons**, i.e.neutrons captured on nuclei other than $^{76}Ge$.
- LAr AtmVeto complements underground shielding ($H_2O$, UAr)
- Essential to reach the target: BI < $1\times10^{-5}$ cts/(keV·kg·yr) at the LNGS site
- Double strategy:
  - passive layer of a hydrogen-rich material to reduce the energy of fast neutrons produced by the interaction of cosmic muons with the experimental setup
  - $^{atm}$LAr instrumentation to detect captures and for applying and improving the delayed coincidence methods

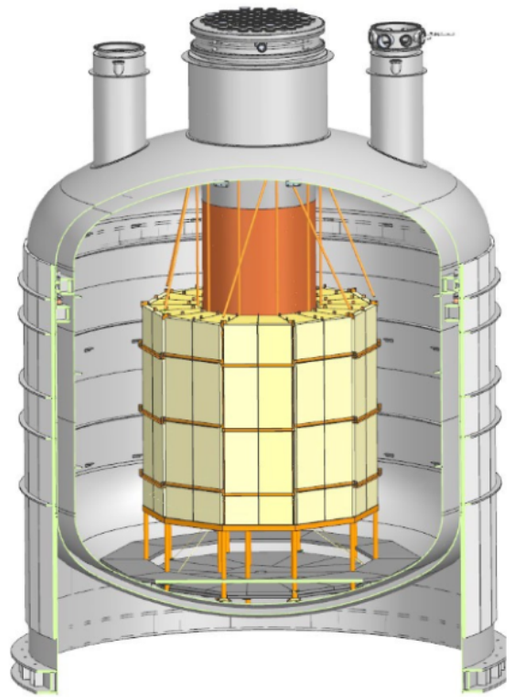
*μ flux @ LNGS: 3.5 x $10^{-4}$ $m^{-2}$ $s^{-1}$*

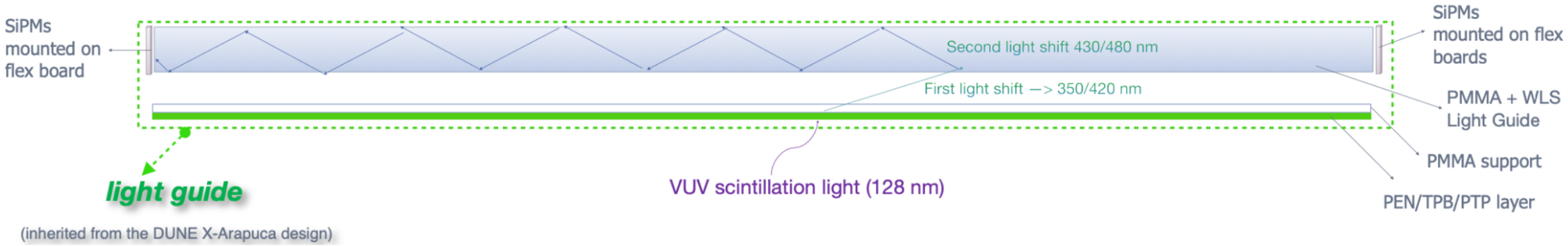


# The outer LAr system design



- n-moderator: Polymethyl methacrylate (PMMA) is the best compromise between moderation performance and radiogenic background level
- 12 horizontal light guides (100 × 10 × 0.6 cm³) on each side of the moderator panel: 288 SiPMs/panel.
- Each side of the top and bottom lids is equipped with 24 and 45 light guides, respectively.
- Mechanical support structure in Cu





# Simulations for optimization design

## Physics

which process to detect?
how much energy?
where is being released?

## Photons Transport

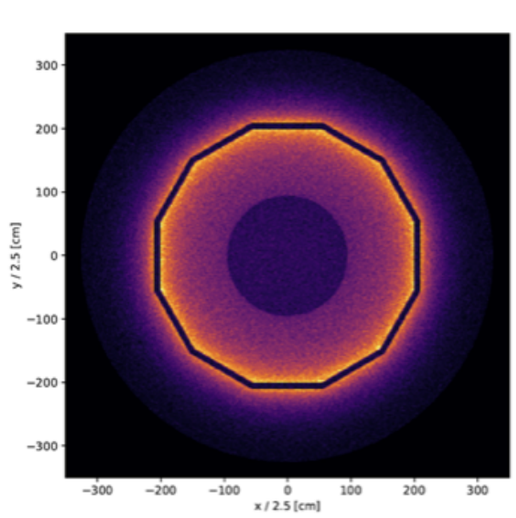
probability for 128nm photons produced in LAr to arrive at the moderator surface

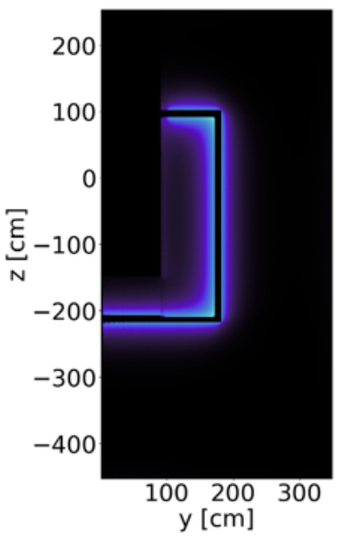
## Light Guides Geometry and Efficiency

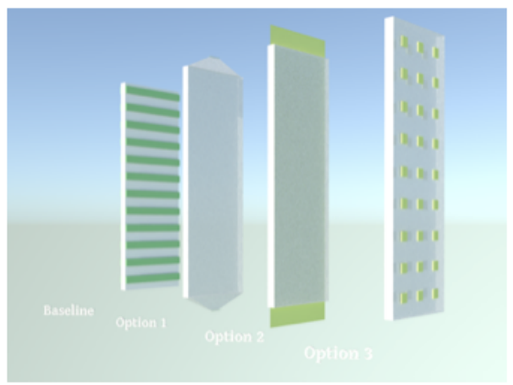
rectangular light guides
1 x 0.1 $m^2$ (<1cm thick)

## Output

PE per light guide per $\mu$ event



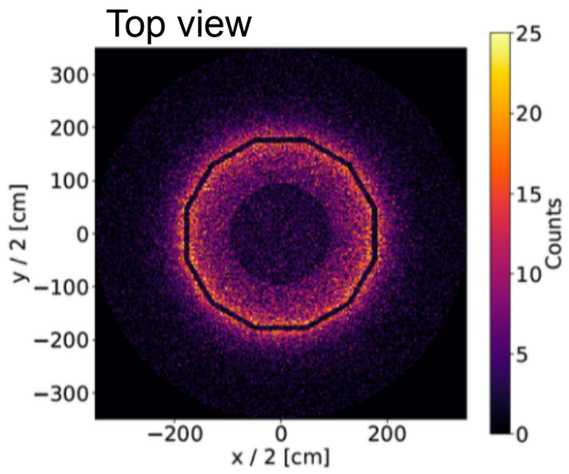



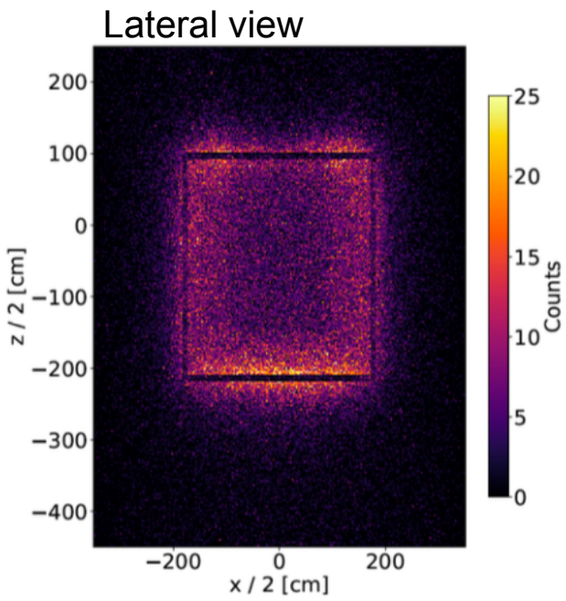
# Physics

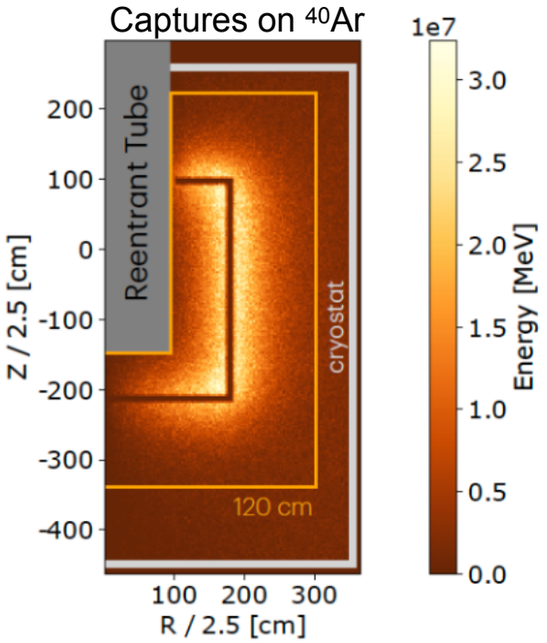
M. Morella, PhD Thesis (GSSI, 2025)

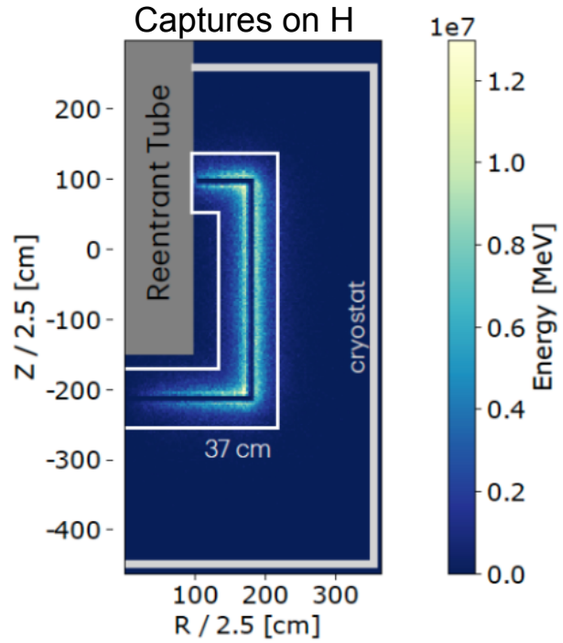
$$^{40}\mathrm{Ar} + \mathrm{n} \rightarrow {}^{41}\mathrm{Ar}^{*} \rightarrow {}^{41}\mathrm{Ar} + x\gamma, \qquad \mathrm{E}_{\gamma,\mathrm{tot}} \simeq 6.1\,\mathrm{MeV},$$

$$\mathrm{H} + \mathrm{n} \rightarrow {}^{2}\mathrm{H}^{*} \rightarrow {}^{2}\mathrm{H} + \gamma, \qquad \mathrm{E}_{\gamma} = 2.2\,\mathrm{MeV}.$$



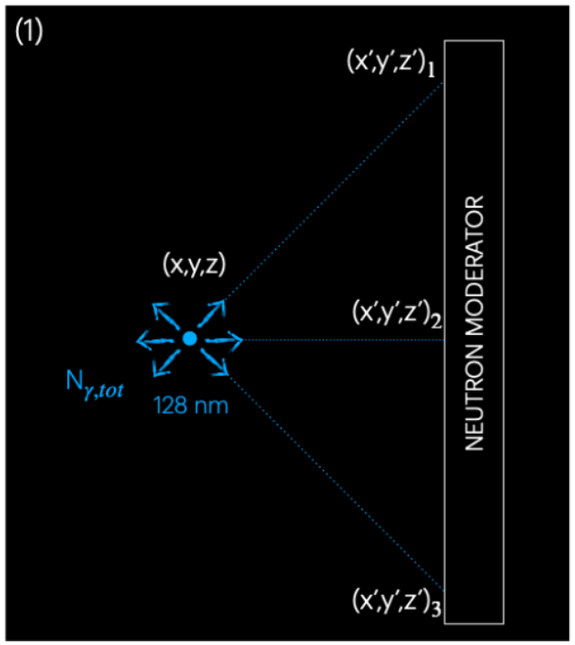



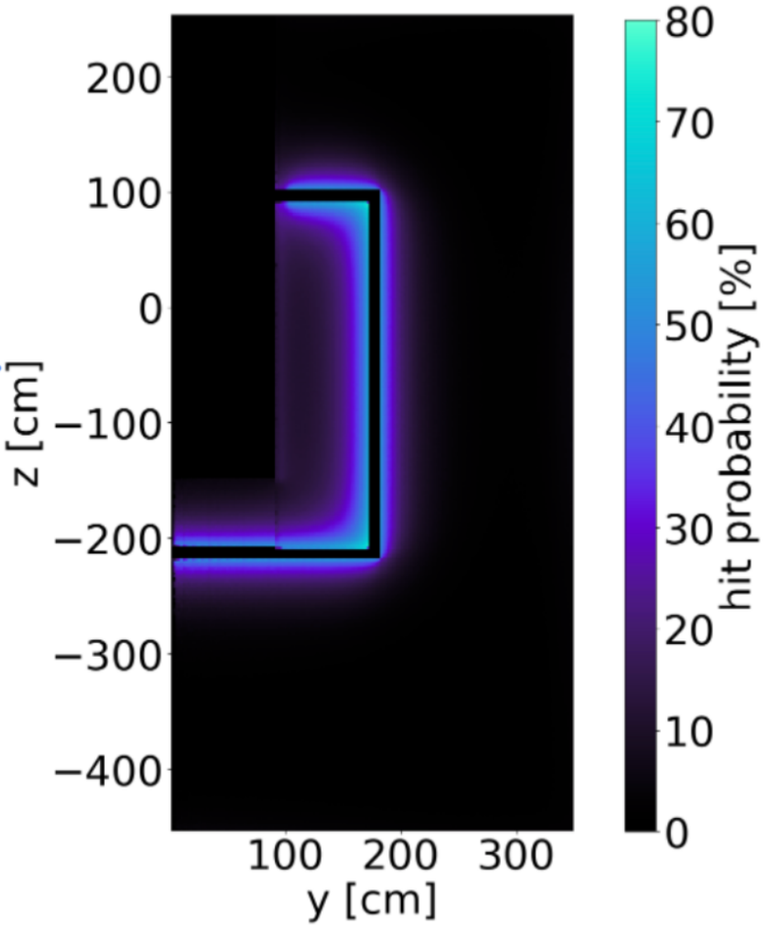

Neutron captures mainly in the LAr volume near the moderator panel

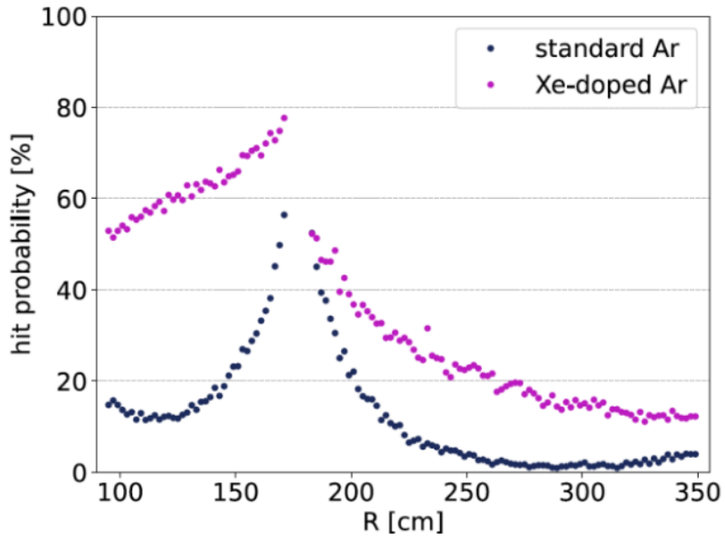
Spatial distribution of energy released in muon cascades

# Photon transport

Probability for 128 nm photons produced in LAr to reach the moderator surface



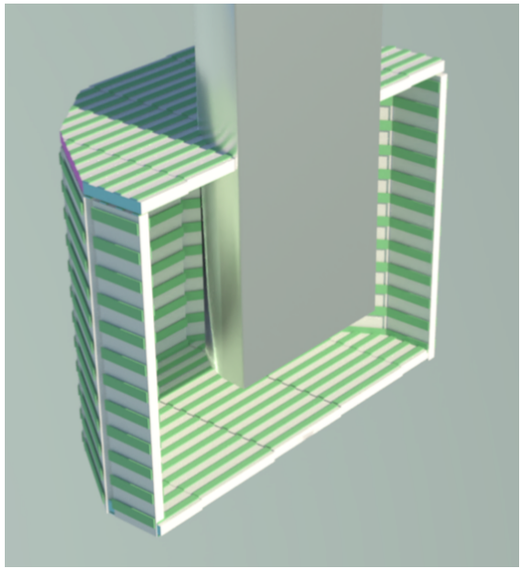



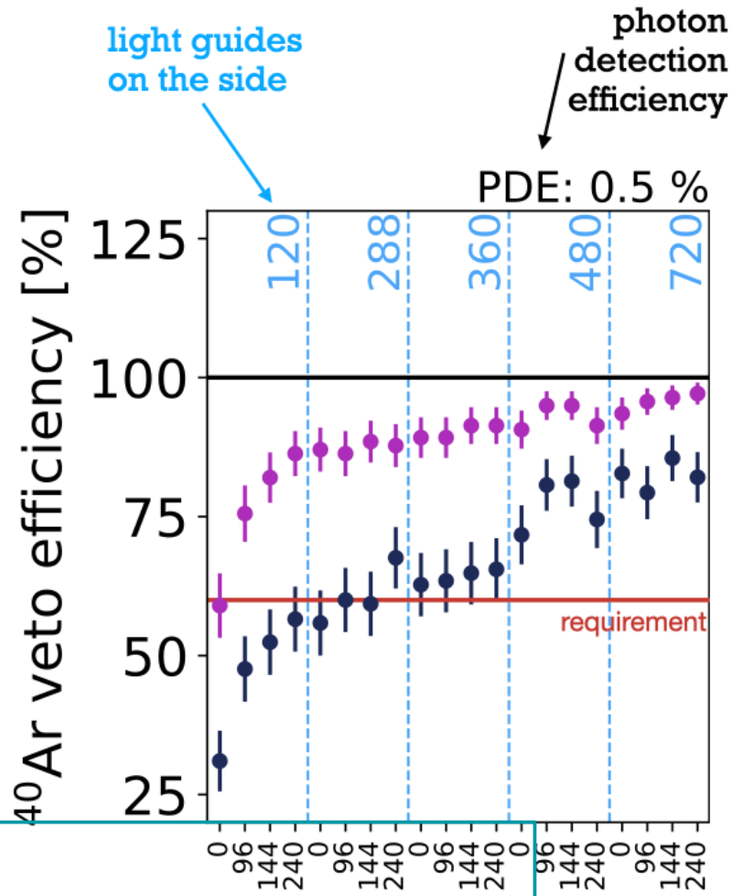




Credits CJ Barton (RM3)

# Readout instrumentation and final design

| Moderator Panels | LG per Panel | Total LG | Coverage [%] |
|---|---|---|---|
| Lateral | 5 | 120 | 17 |
| | 12 | 288 | 40 |
| | 15 | 360 | 50 |
| | 20 | 480 | 67 |
| | 30 | 720 | 100 |
| Top Lid | 0 | 0 | 0 |
| | 2 | 48 | 28 |
| | 3 | 72 | 42 |
| | 5 | 120 | 70 |
| Bottom Lid | 0 | 0 | 0 |
| | 2 | 48 | 18 |
| | 3 | 72 | 27 |
| | 5 | 120 | 45 |






Final design:

- 384 (288+96) light guides
- PDE [0.5,1, 2] %
- **>60-80% of events producing $^{77(m)}$Ge and $^{40}$Ar are correctly tagged**

# LegendArYno setup

## R&D setup @ LNGS for developing and characterizing the optical readout of LEGEND-1000 Outer LAr Instrumentation




Goals:

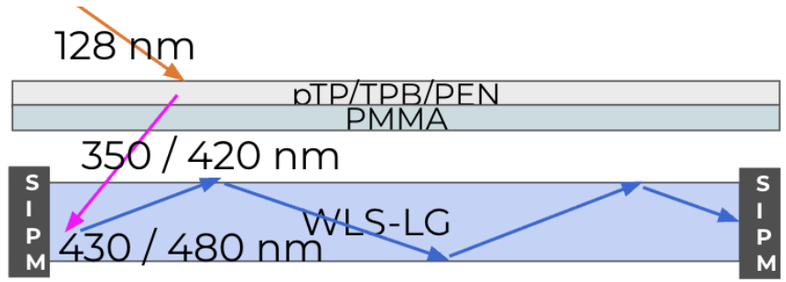
- evaluate Light Guides Photon Detection Efficiency and performances of WLS-LG system coupled with SiPMs and readout electronics
- WLS optimization ( pTP or TPB coating adhesion resistance, PEN stability, etc.)
- comparison and optimization of the components of light readout systems
- characterisation of neutron moderator

Commissioning on-going!

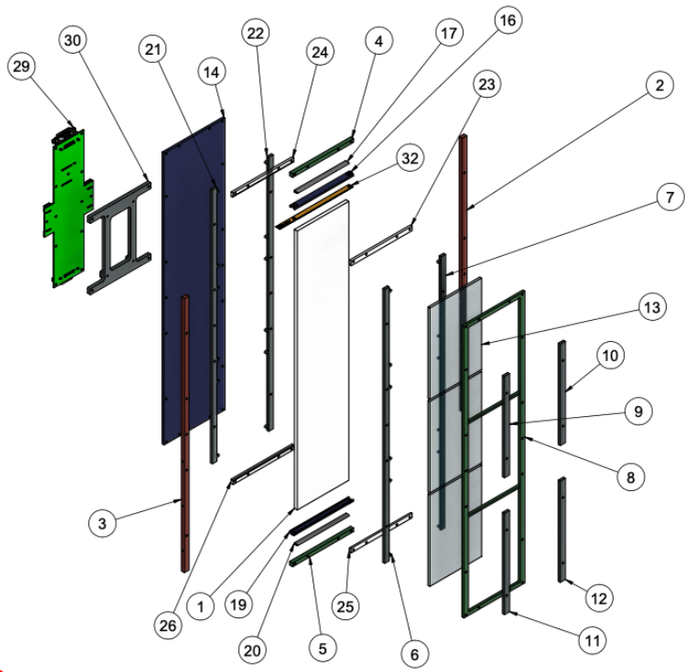
# Photon detection unit (PDU) prototype

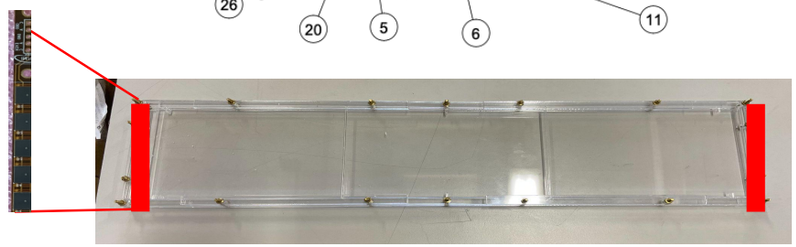
VUV light detector based on: double conversion stage and SiPMs coupled to the second stage (WLS-LG). Design derived from DUNE X-Arapuca with important differences:

- Frame design and production in PMMA (with cold-compensation mechanism to maintain optical contact SiPM–WLS LG) to minimize radiogenics bkg level
- PMMA entrance window (no glass, no DF)
- First-stage WLS (PEN, pTP on PMMA)
- PMMA-LG with different properties (depending on the primary)
- SiPMs on flex circuits with high radiopurity



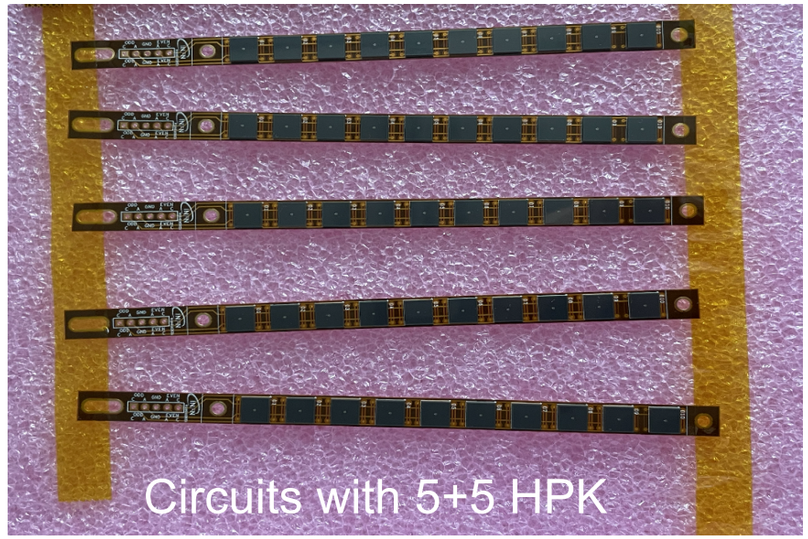

Adapted from DUNE X-Arapuca

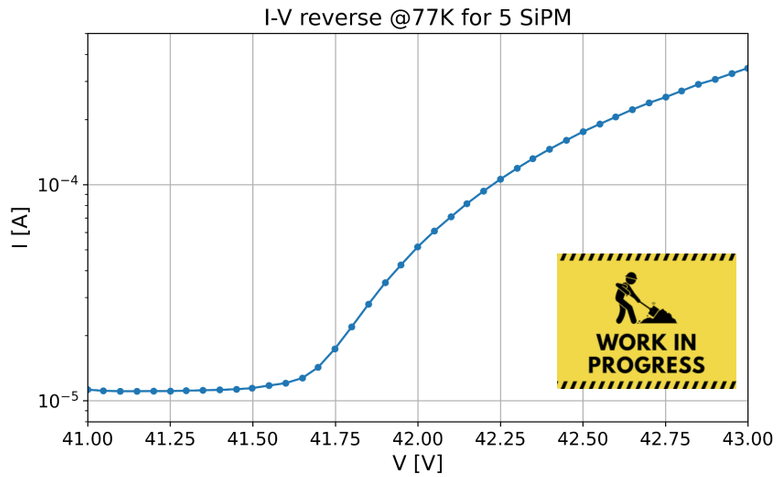


# Prototype fabrication: SiPMs

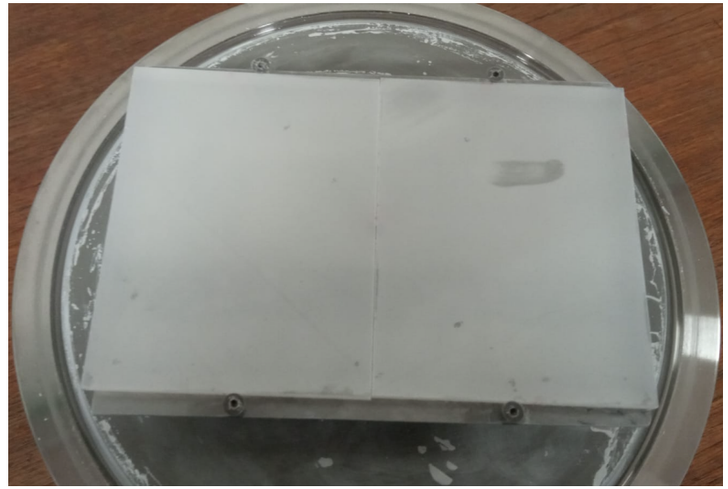
- 50 x Hamamatsu SiPMs (75um-HQR) mounted on 5 flex boards (10 SiPMs/board: two groups of 5) https://doi.org/10.1088/1748-0221/19/01/T01007
- SiPMs on same flex have Vbd within 50 mV
- One/two cold FE output channel for each flex
- From previous experience: typical performances of the DUNE flexes mounted on a FD2 XArapuca, in repeated Coldbox & pDUNE environment at CERN-NP02 extremely reproducible
  - S/N > 4 achieved for (20 SiPMs/flex x 4 flexes) coupled to Cold-FE

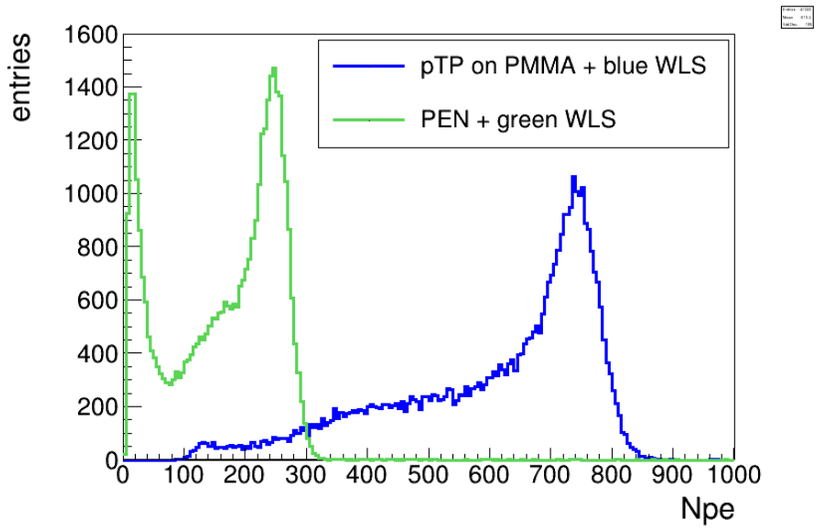


# Preliminary results

- Finalization of the frame design with a cold-compensation mechanism to maintain optical contact SiPM-WLS LG.
- Procurement of high-transparency PMMA for the first conversion stage (VUV → NUV) and for the secondary stage (WLS-LG)
- Definition of a procedure for pTP deposition on PMMA substrates (in collaboration with INFN-PV) and cryogenic comparison measurement with PEN.
- Preliminary results: $PDE_{pTP} \approx 2.6\ PDE_{PEN}$ (3.9% SiPM coverage)





# Summary

- Outer LAr system essential to achieve LEGEND-1000 background goal
- R&D setup at LNGS for optical readout development and optimization
- VUV light detector design and prototype fabrication ongoing
- Simulations guiding detector design and performance optimization
- Preliminary performance results obtained