Commissioning of LEGEND-200 experiment

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*Joint Institute for Nuclear Research

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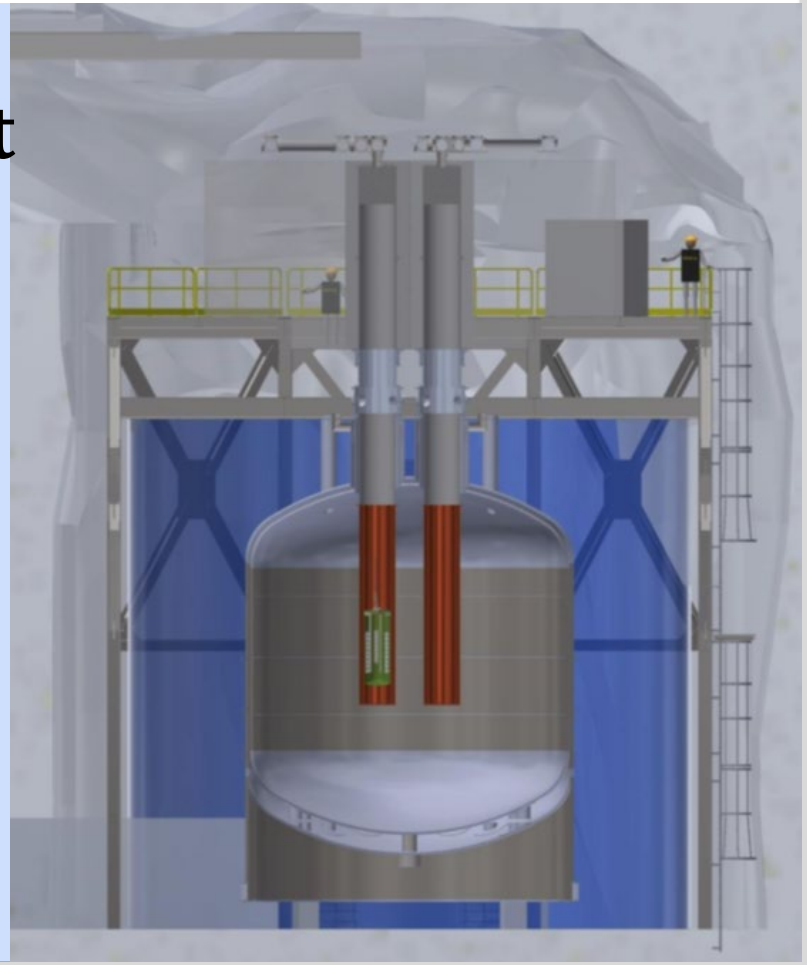
ICPPA2022, Moscow, Russia.

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



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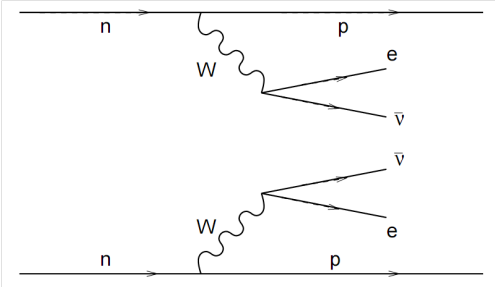
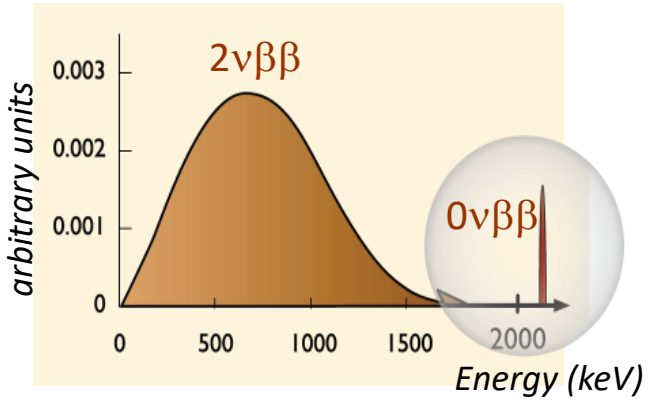
JINR

Double beta decay

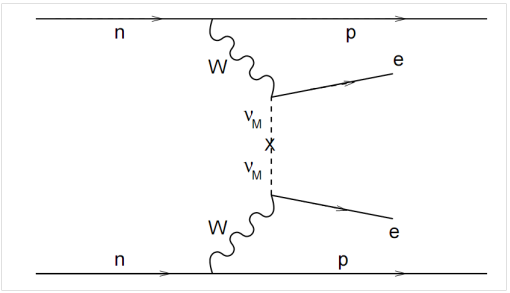
2νββ



- $(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e$
- conserves lepton number allowed in SM
- measured in several isotopes (^{48}Ca, ^{76}Ge, ^{82}Se. . .)
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



0νββ



- $(A, Z) \rightarrow (A, Z + 2) + 2e^-$
- violates lepton number forbidden in SM
- **ν** has **Majorana** mass component
- **If** light neutrino exchange->**Access to ν mass scale**
- $T_{1/2}^{0\nu}$ limits in the range $>10^{21} - 10^{26}$ yr

<u>Detection **0νββ** would:</u>

- Prove neutrinos are Majorana in nature
- Lepton-Number-Violating (LNV) process → matter-antimatter asymmetry
- Probe the absolute neutrino mass scale and neutrino mass ordering

Neutrinoless double beta decay

$$\Gamma^{0\nu} = (T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Half-life — Phase space (~Q^5) — Nuclear matrix element (NME)

Majorana neutrino mass

$$m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$$

Experimental sensitivity:

- **Zero** background:

$$T^{0\nu}_{1/2} \propto M\,t$$

- Non-zero background:

$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M\,t}{\Delta E\;BI}}$$

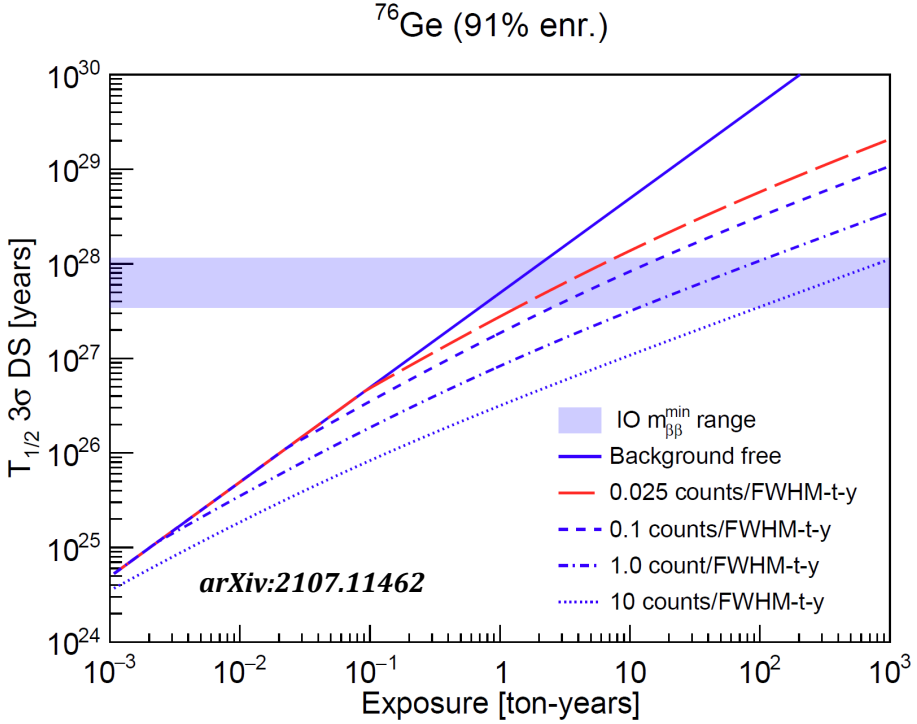
$M\,t$ – exposure (kg yr)

ΔE – energy resolution (keV)

BI – background index (counts/keV kg yr)

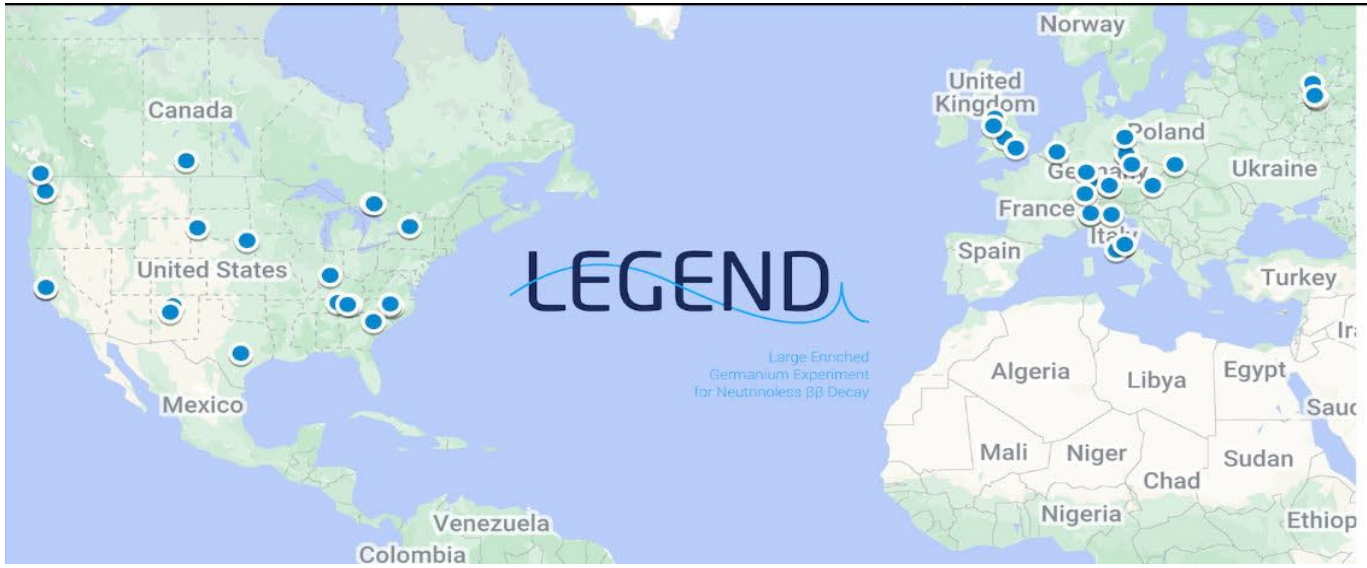
✓ Target mass and detector efficiency as high as possible

✓ "**Zero-background**" to have linear increase of sensitivity vs exposure



- The search for **0νββ** decay is one of the most compelling and exciting challenges in all of contemporary physics
- The **LEGEND** Collaboration aspires to meet this challenge through a ton-scale search for 0νββ decay of ^{76}Ge

LEGEND Collaboration



SNOLAB	Simon Fraser Univ.	Joint Res. Centre, Geel
Roma Tre	Univ. New Mexico	Lawrence Berkeley Natl. Lab.
Duke Univ.	Univ. Texas, Austin	Univ. California, Berkeley
Univ. Zurich	Univ. Washington	Polymer Research Dresden
Queens Univ.	Univ. Tuebingen	Leibniz Inst. Crystal Growth
Padova Univ.	Tech. Univ. Munich	Max Planck Inst., Munich
INFN Padova	Oak Ridge Natl. Lab.	Czech Tech. Univ. Prague
Laurentian Univ.	Univ. South Dakota	North Carolina State Univ.
Univ. Tennessee	South Dakota Mines	Joint Inst. Nucl. Res. Inst.
Univ. of Indiana	Univ. of North Carolina	Lab. Exper. Nucl. Phy. MEPhI
Comenius Univ.	Univ. of South Carolina	INFN Milano Bicocca
Lancaster Univ.	L'Aquila Univ. and INFN	Milano Univ. and INFN
Univ. of Regina	Gran Sasso Science Inst.	Triangle Univ. Nuclear. Lab.
Univ. Liverpool	Lab. Naz. Gran Sasso	Max Planck Inst., Heidelberg
Tennessee Tech	Univ. College London	Inst. Nucl. Res. Russ. Acad. Sci.
Univ. of Warwick.	Los Alamos Natl. Lab.	Natl. Res. Center Kurchatov Inst.
Jagiellonian Univ.	Tech. Univ. Dresden	

LEGEND = The Large Enriched Germanium Experiment for Neutrinoless double beta Decay

LEGEND Collaboration

- The goal of the LEGEND Collaboration is to design, construct, and field a ton-scale experiment

"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} years, using existing resources as appropriate to expedite physics results."

- The LEGEND collaboration was formed in 2016 through a merger of the Majorana and GERDA collaborations, along with several new institutions

- It includes 260 members, 50 institutions, 11 countries

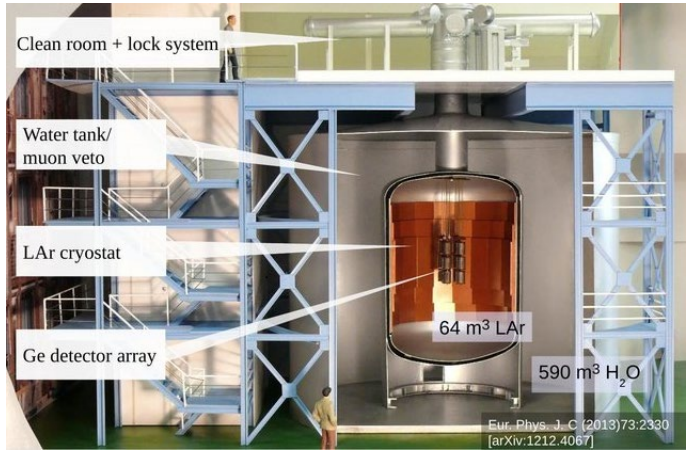
LEGEND Phases*:

L-200
- 200 kg enrGe
- Half-life ($T_{1/2}$) sensitivity: 10^{27} yrs
- Effective majorana mass ($m_{\beta\beta}$) sensitivity: 34-78 meV (99.7% CL discovery)

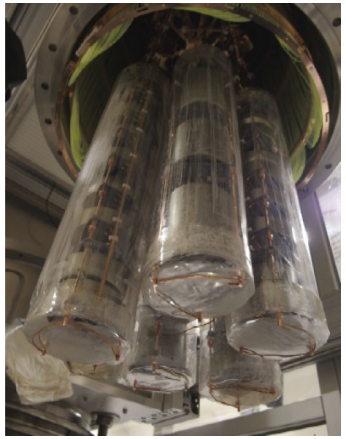
L-1000
- 1000 kg enrGe
- $T_{1/2}$ sensitivity: beyond 10^{28} yrs
- $m_{\beta\beta}$ sensitivity: 9-21 meV (99.7% CL discovery)

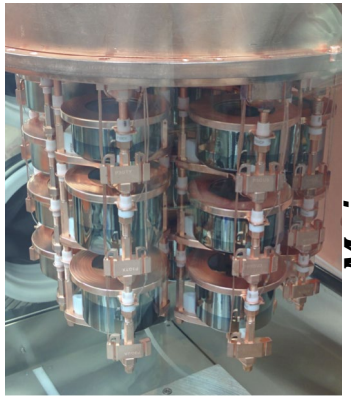
*arXiv:2107.11462

LEGEND-200 experiment

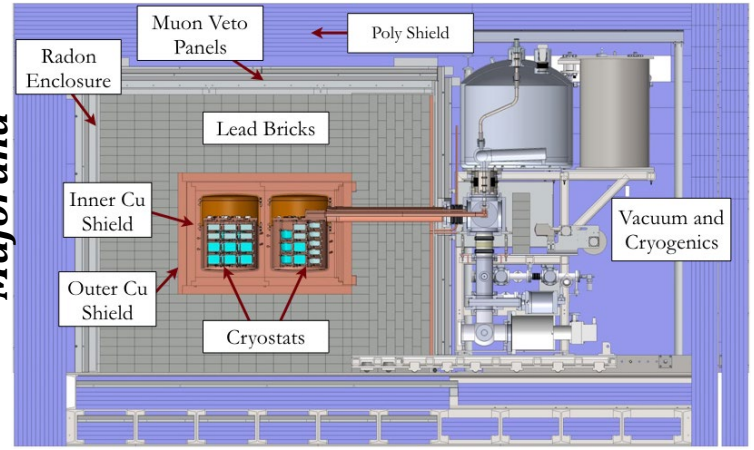


GERDA





Majorana



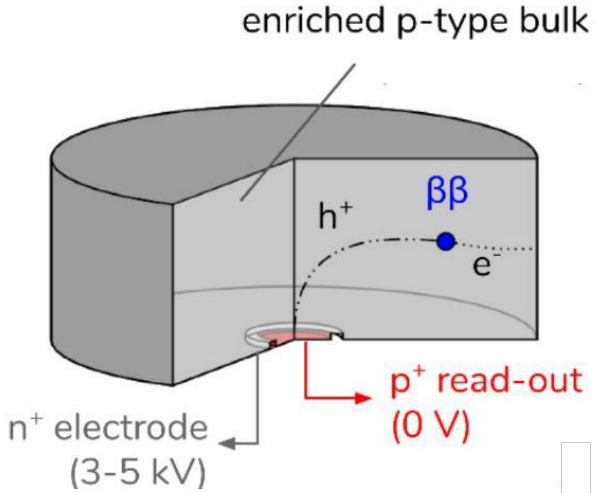
Combine the best of ***GERDA***:
- LAr active veto and instrumentation
- Low-A shielding, no Pb

… with the best of ***MAJORANA***:
- Underground production of low background copper
- Low-noise electronics & improved PSD

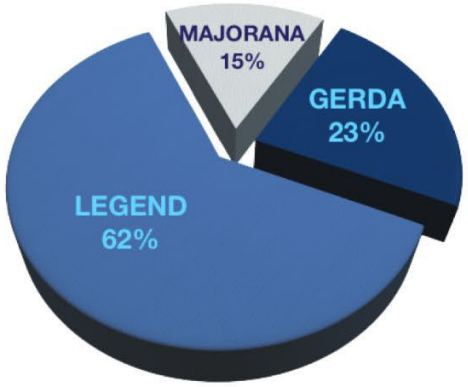
and techniques developed in both experiments:
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors

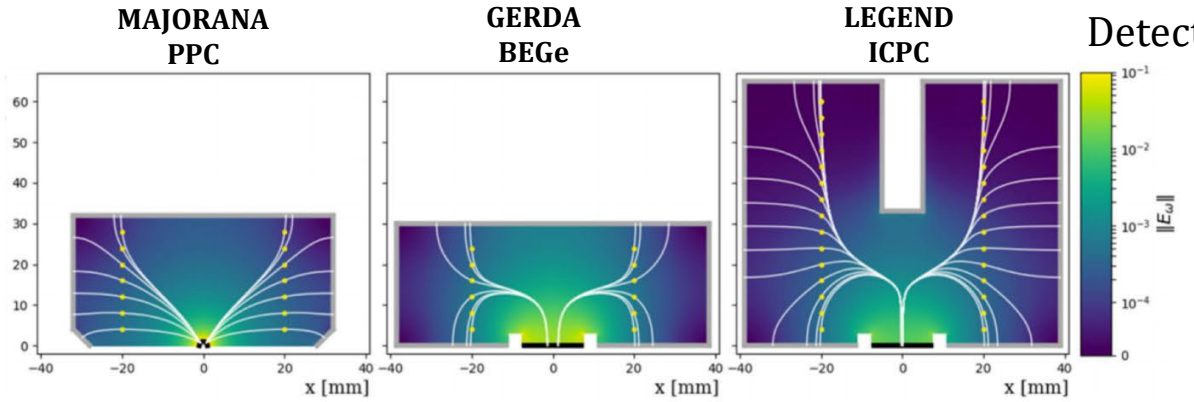
Neutrinoless double beta decay search with ^{76}Ge

- ^{76}Ge → ^{76}Se + 2e- with $Q_{\beta\beta}$ = 2039 keV
- Source and detector are the same
  → high detection efficiency
- Isotope enrichment up to 91% for detector material
- Intrinsically pure material
  → low background
- Excellent energy resolution
  → 2νββ background suppressed
- High density material → ββ point-like
  → backgrounds can be discriminated and rejected



- p-type detectors: Insensitive to alphas on n^+ contact
- Small p^+ contact: Event topology discrimination

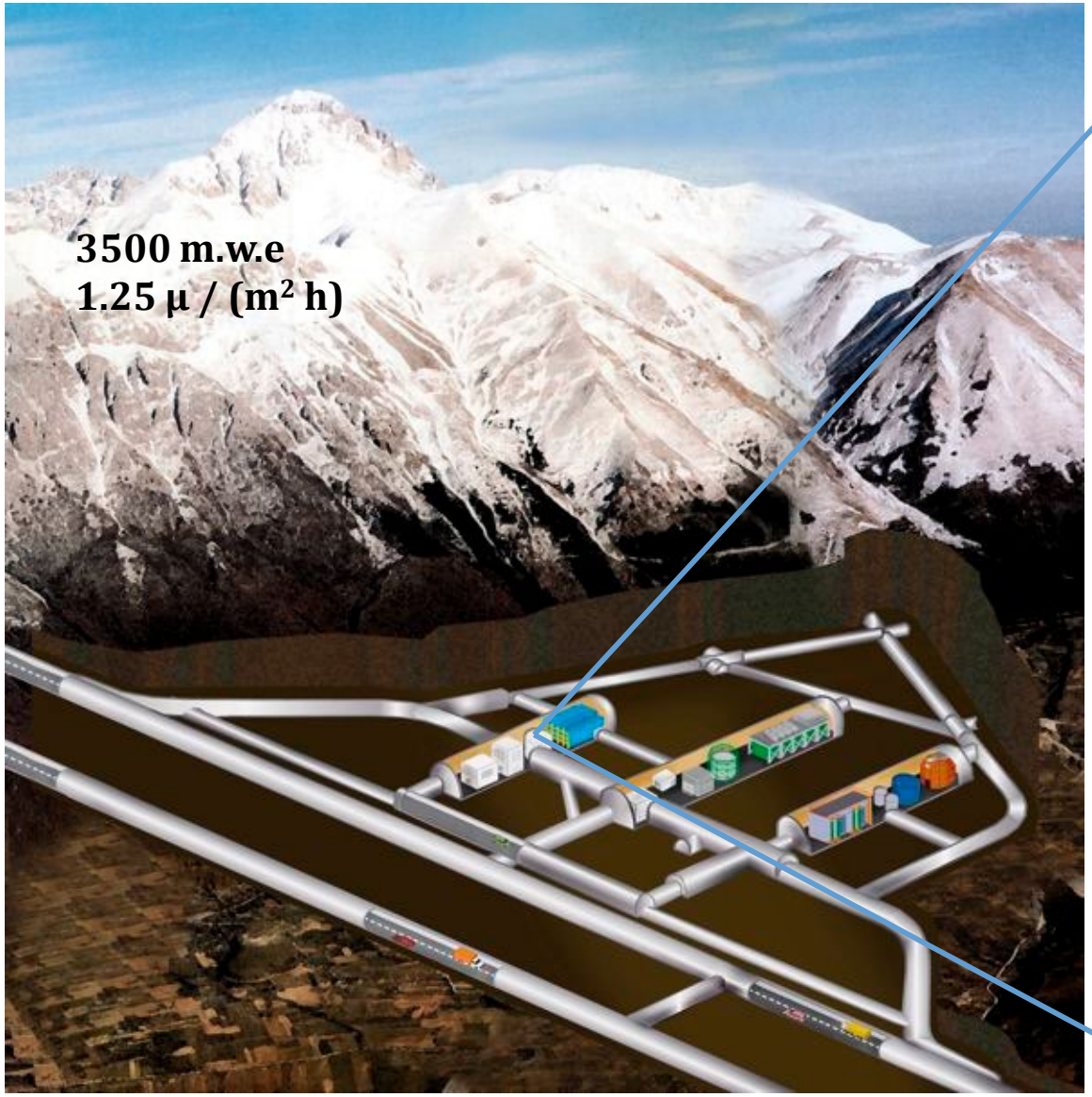


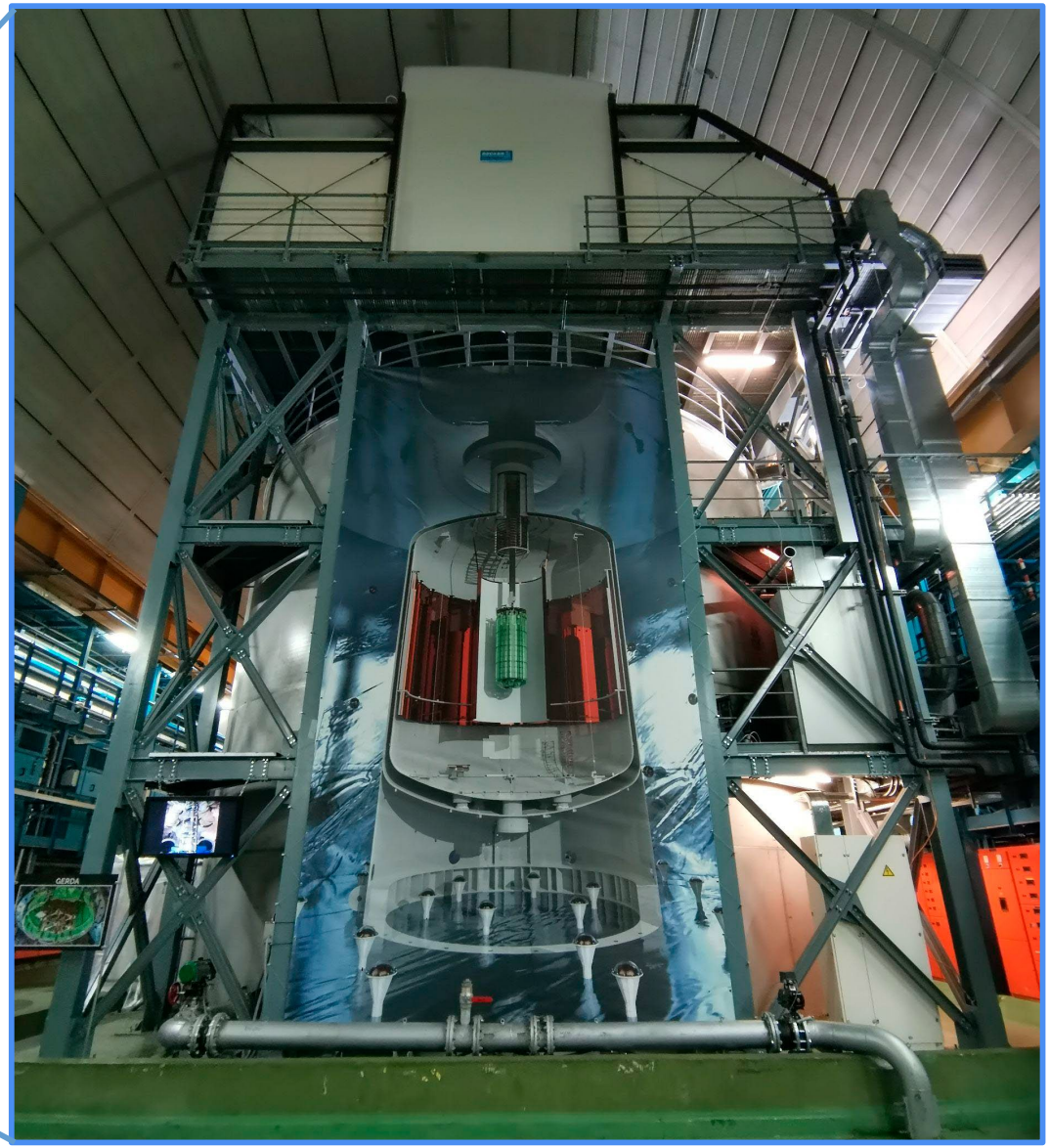


Inverted Coaxial Point Contact (**ICPC**) Detectors:

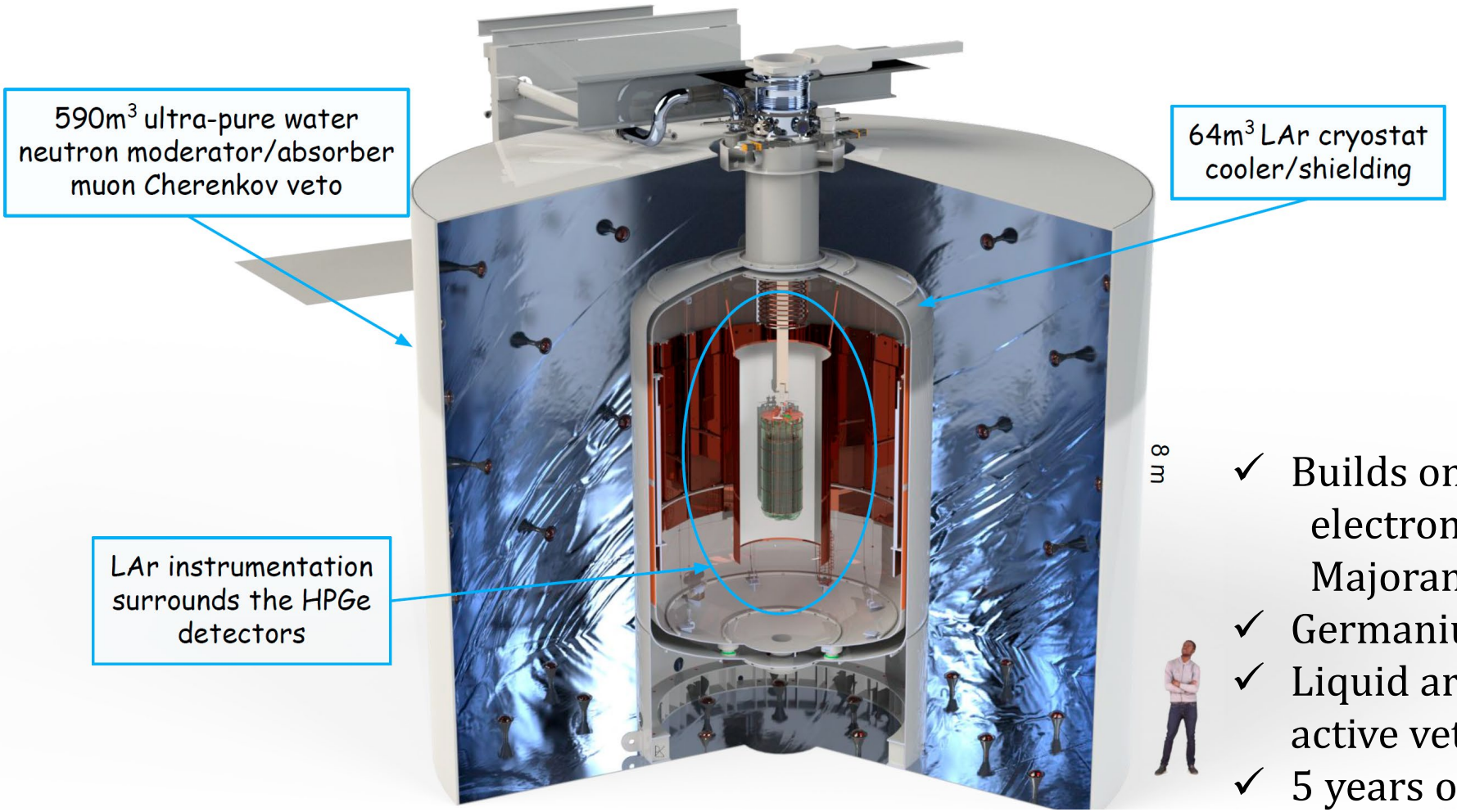
- New design with unique geometry
- Large detector mass (up to ~4 kg)
- Strong Pulse Shape Discrimination (PSD) power

LEGEND-200 experiment



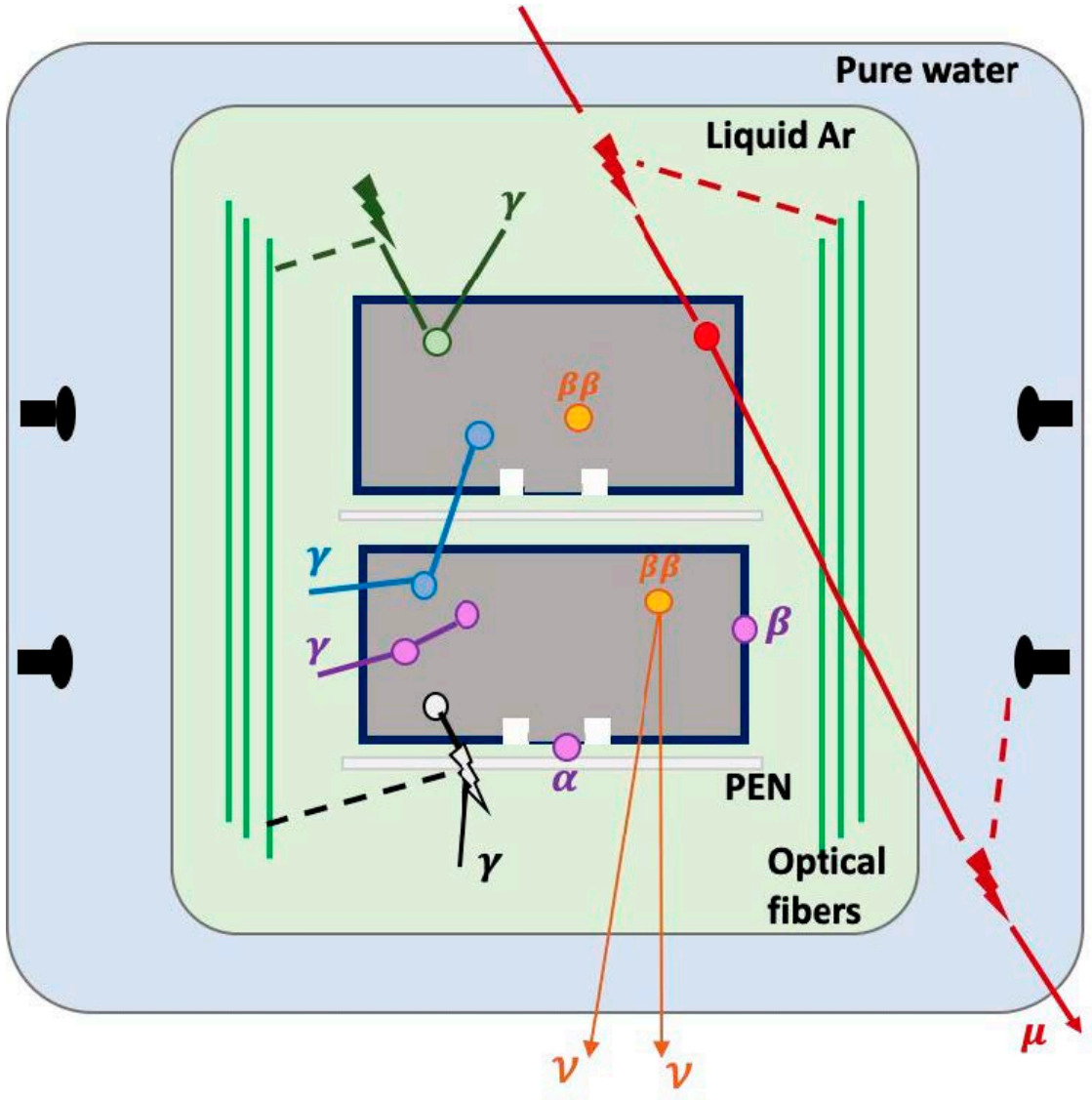


LEGEND-200 experiment: setup



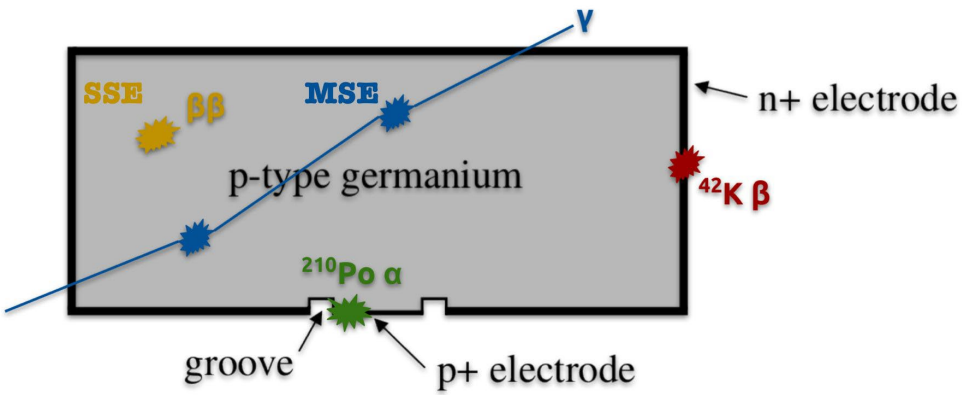
- ✓ Builds on existing infrastructure and electronics of parent GERDA and Majorana Demonstrator experiments
- ✓ Germanium detectors: source = detector
- ✓ Liquid argon scintillation light detectors: active veto
- ✓ 5 years of data taking for a 1 ton·yr exposure
- ✓ Background index target of 0.5 cts / (FWHM·ton·yr)

Background reduction concept

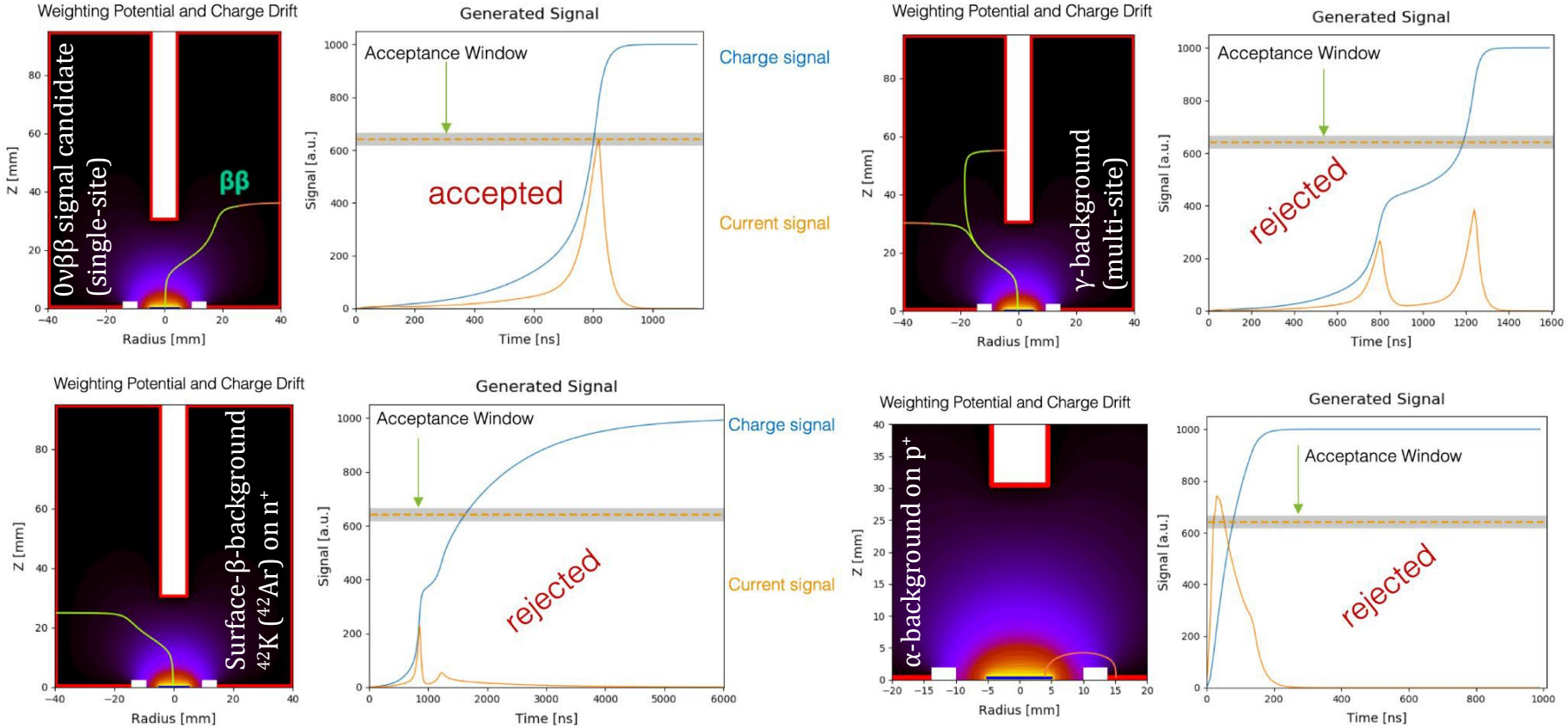


- ββ decay signal: single energy deposition within ~ 1 mm^3 of the detector volume
- Muon veto based on Cherenkov light
- LAr veto based on Ar scintillation light read by fibers coupled to SiPMs
- Scintillating PEN holder
- Detector anti-coincidence of the array
- Pulse shape discrimination (PSD) for multi-site and surface events

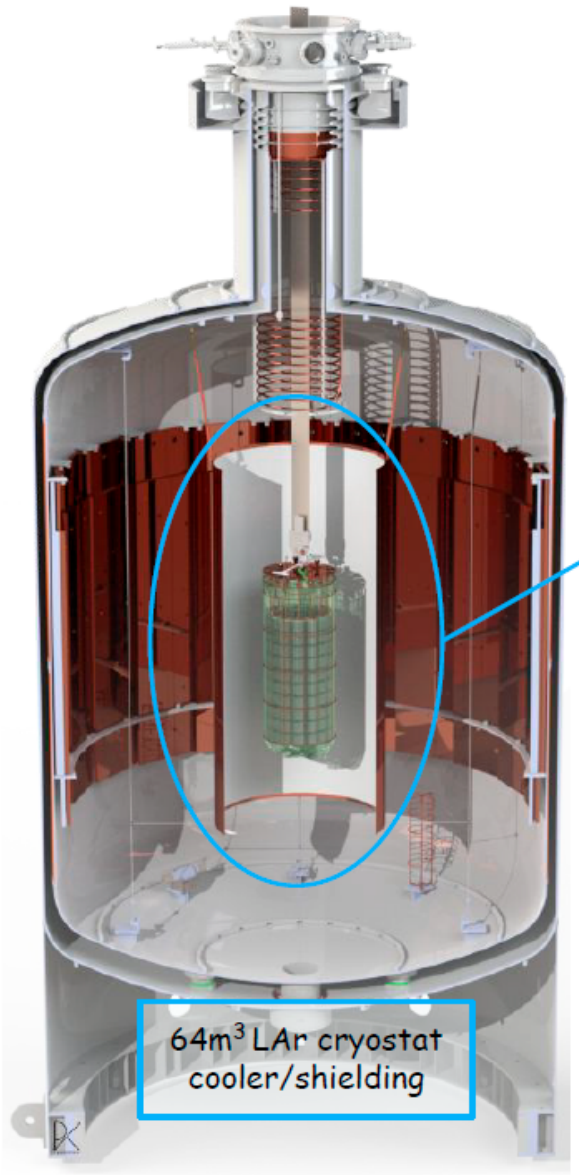
Pulse Shape Discrimination



- **PSD**: reject multi-site and surface events based on detector signal shape
- External α, β, and γ backgrounds all create distinctive pulse shapes, allowing for highly efficient ββ decay event selection

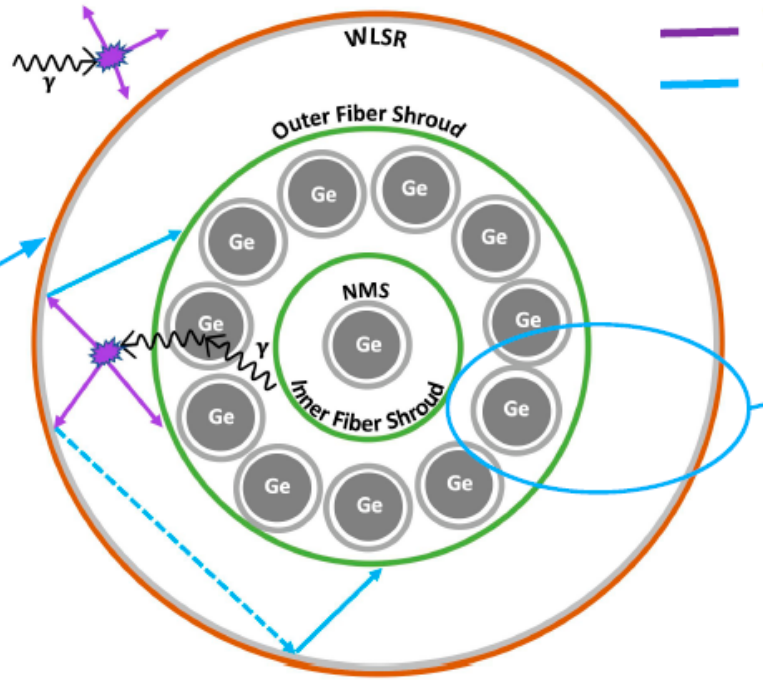


Liquid Argon Instrumentation



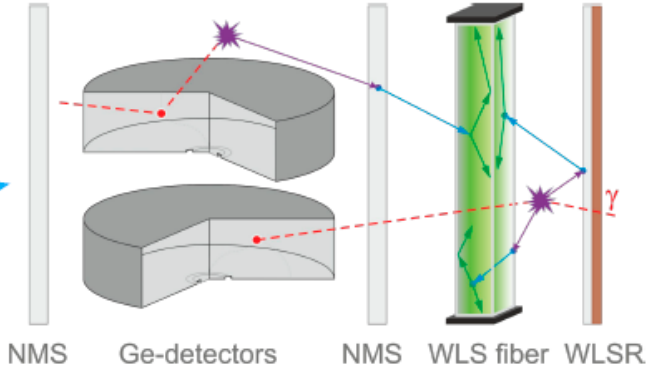
**slide from N. Burlac's talk at ICHEP2022*

Detection of Ar scintillation light created by energy depositions in the LAr that accompanies energy depositions in the HPGe detectors;



VUV light

Visible light

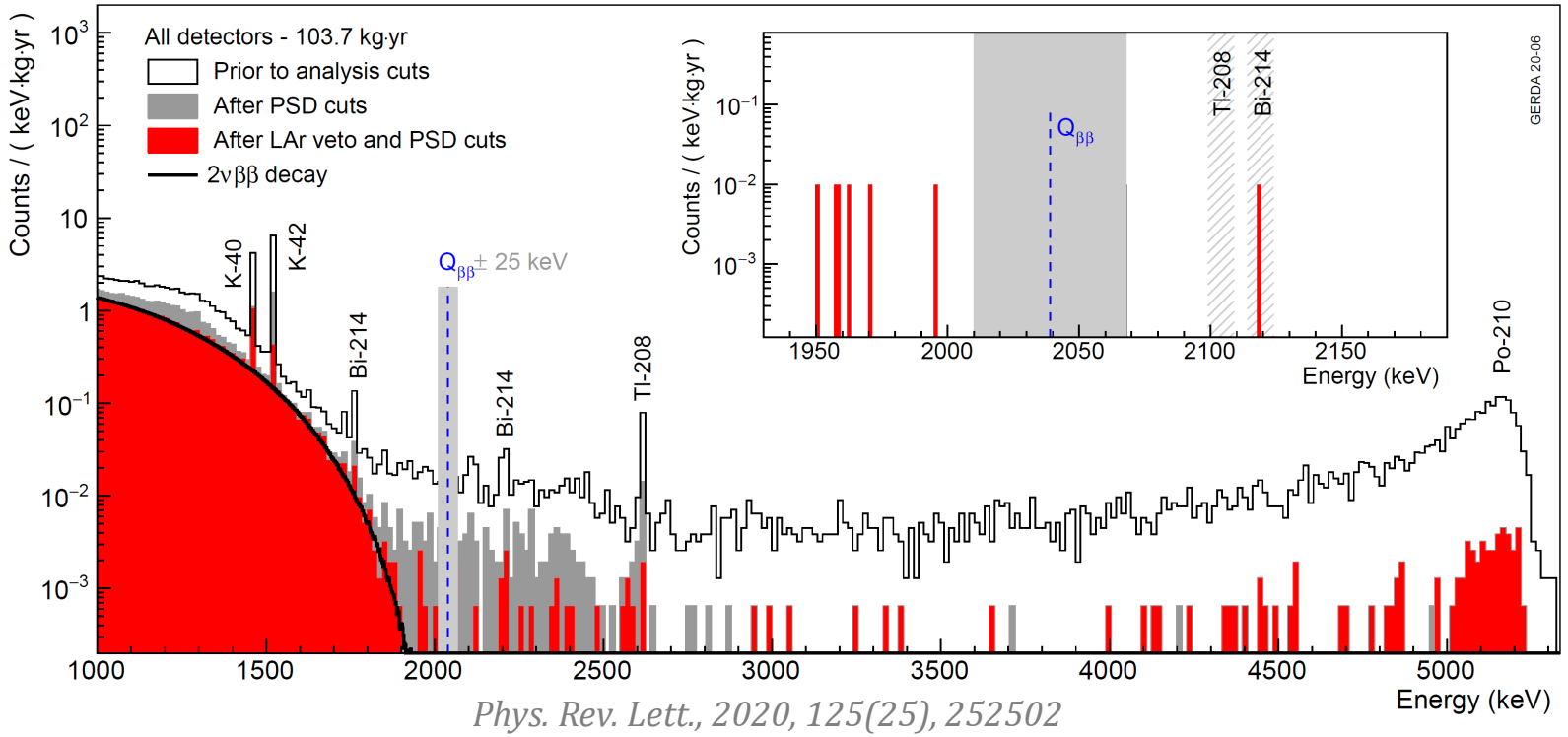


- two concentric curtains of TetraPhenyl Butadiene (TPB) coated, WaveLenght Shifting (**WLS**) fibers;
- transparent, TPB coated Nylon Mini Shrouds (**NMS**) surround each string of HPGe detectors;
- WLS-Reflector (**WLSR**) enclose the Ge strings and fiber curtains;

The TPB shifts the LAr scintillation light **from VUV to blue light**.

The **blue light** is absorbed inside the fibers and **shifted to the green light**, and guided by total internal reflection to the SiPM arrays mounted on both ends of the fiber modules.

Background reduction concept



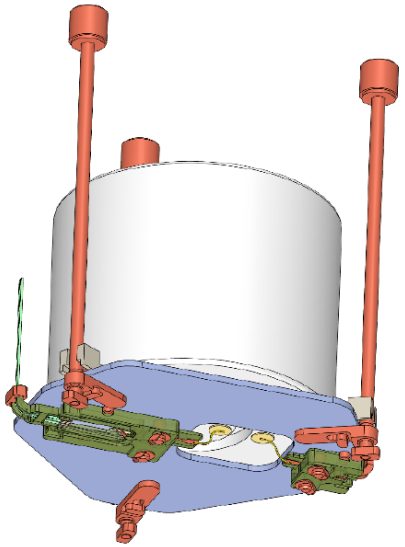
Phys. Rev. Lett., 2020, 125(25), 252502

✓ Great complementarity between LAr veto and PSD cuts was demonstrated in GERDA

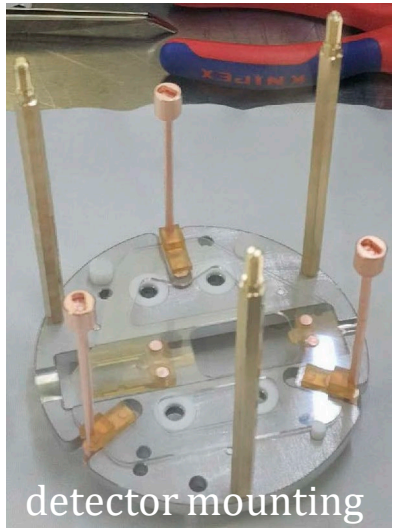
Plot courtesy of the GERDA collaboration

LEGEND-200 commissioning: preparatory work

Ge detectors mounting procedure

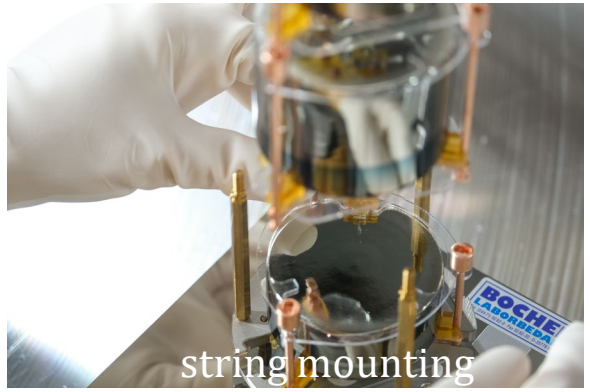


layout of bonding HV and signal contacts

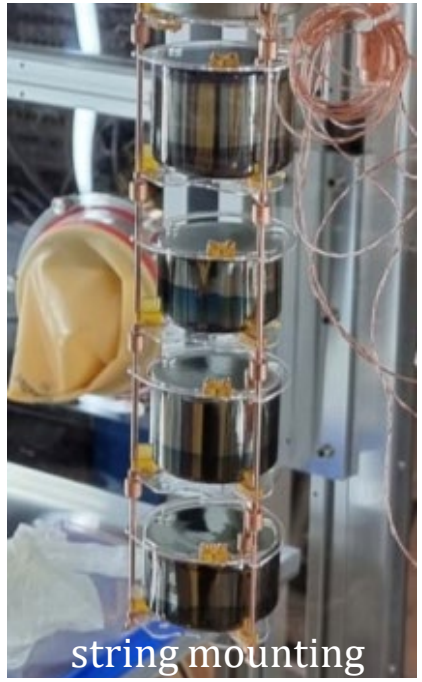


detector mounting

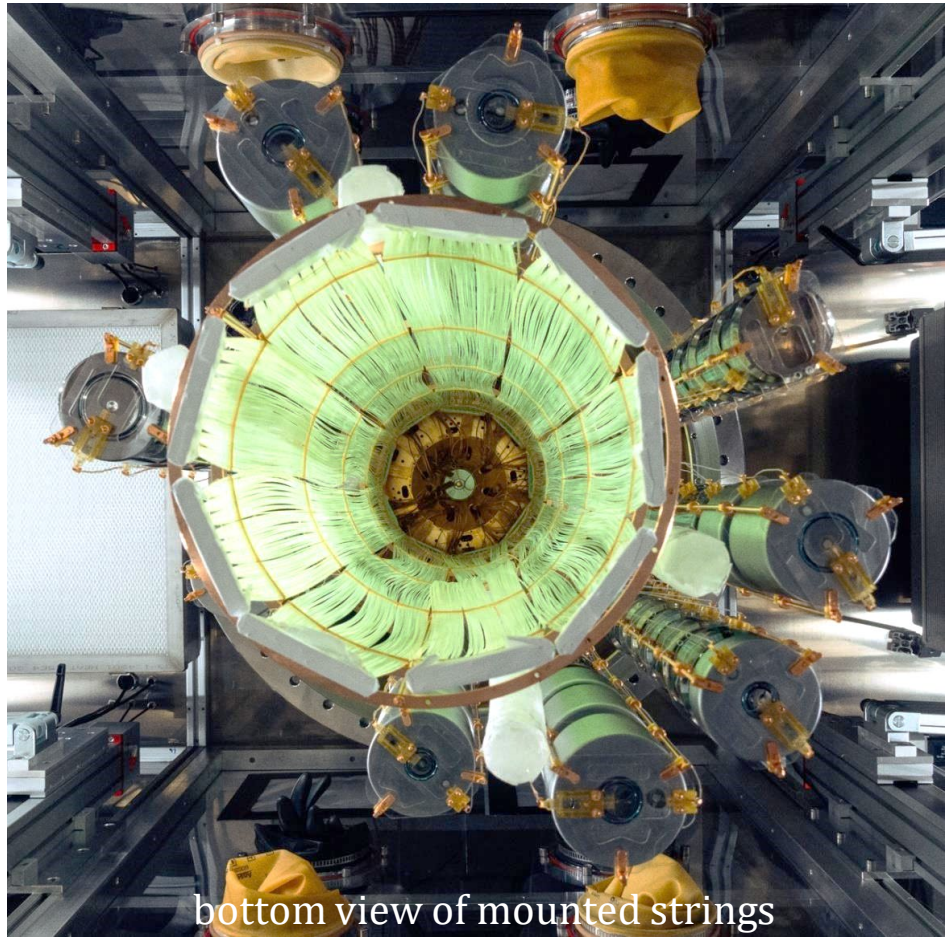
detector mounting



string mounting



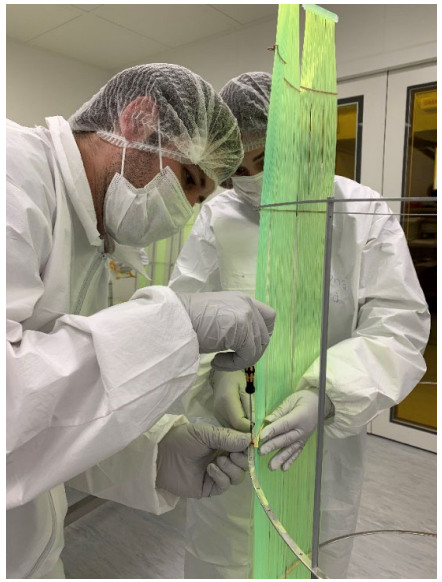
string mounting

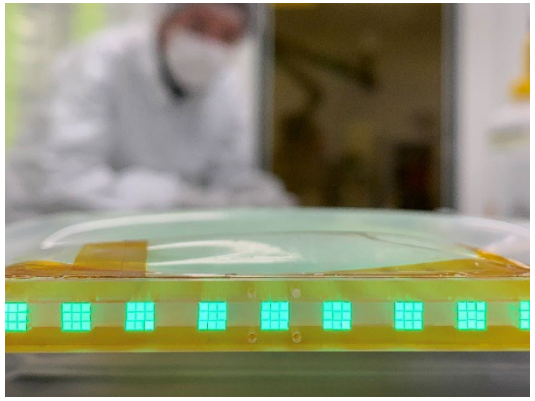


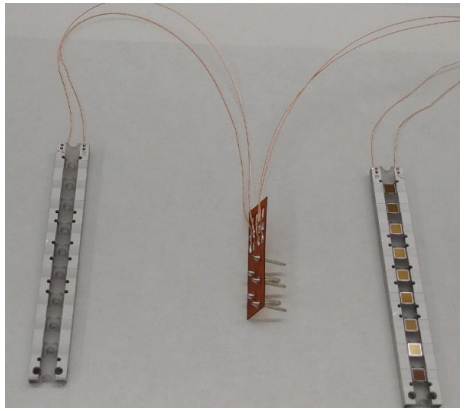
bottom view of mounted strings

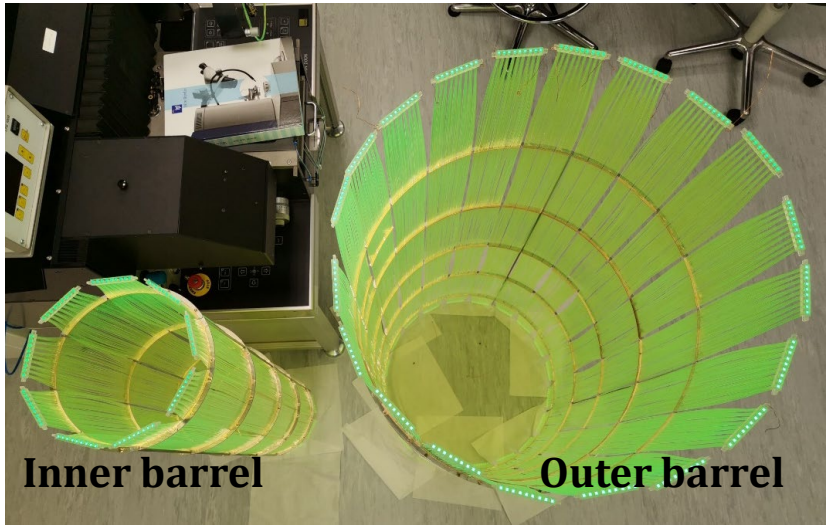
LEGEND-200 commissioning: preparatory work

LAr instrumentation mounting procedure



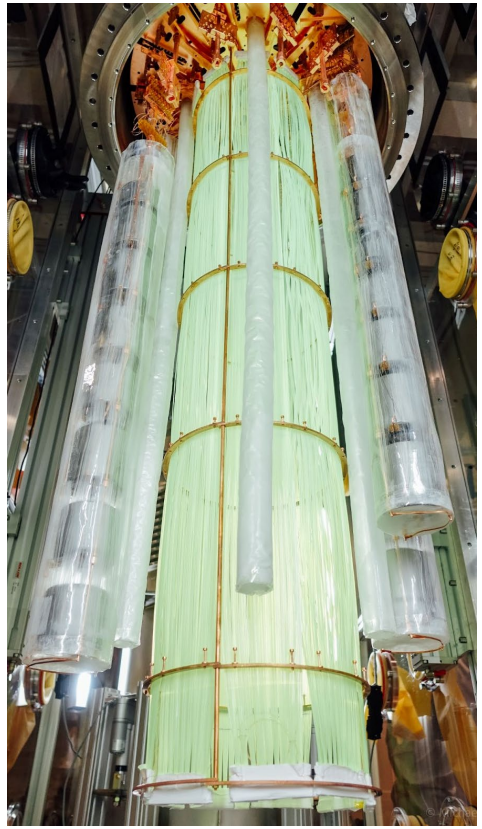


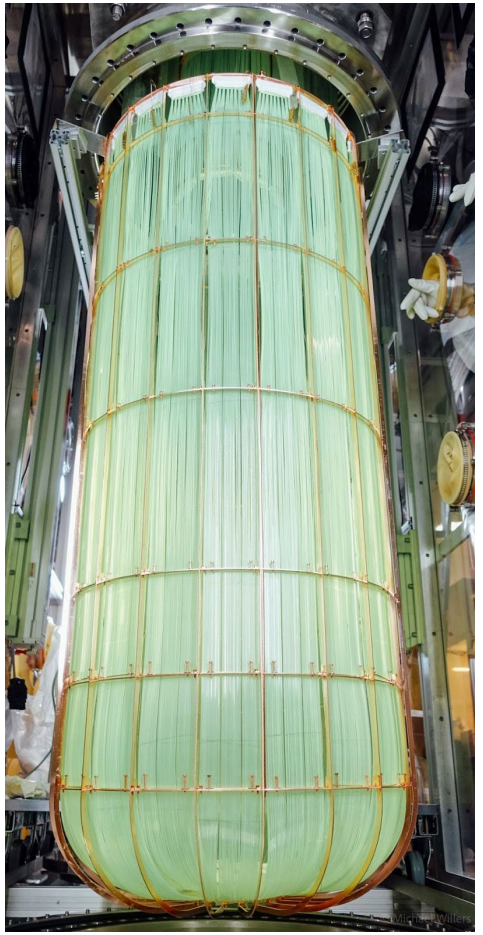




prepare modules for LAr instrumentation

Bonding of SiPMs

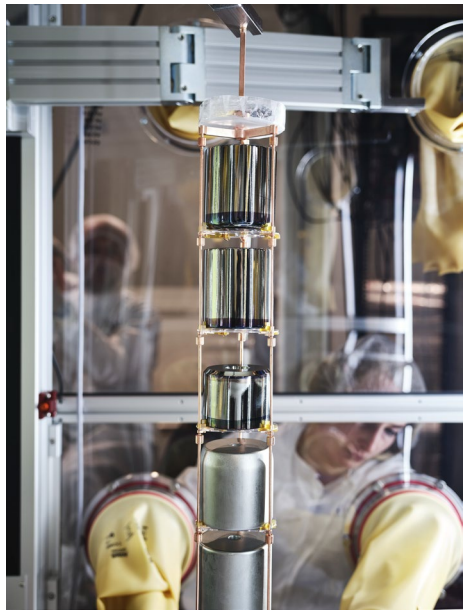




Final view of inner&outer barrel at the setup

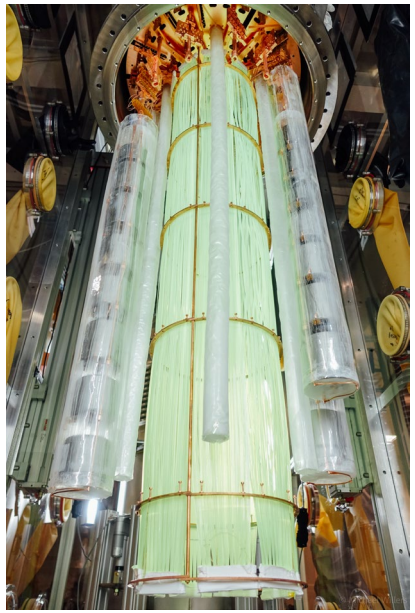
May 2022: 60 kg commissioning phase

The HPGe detector **integration**

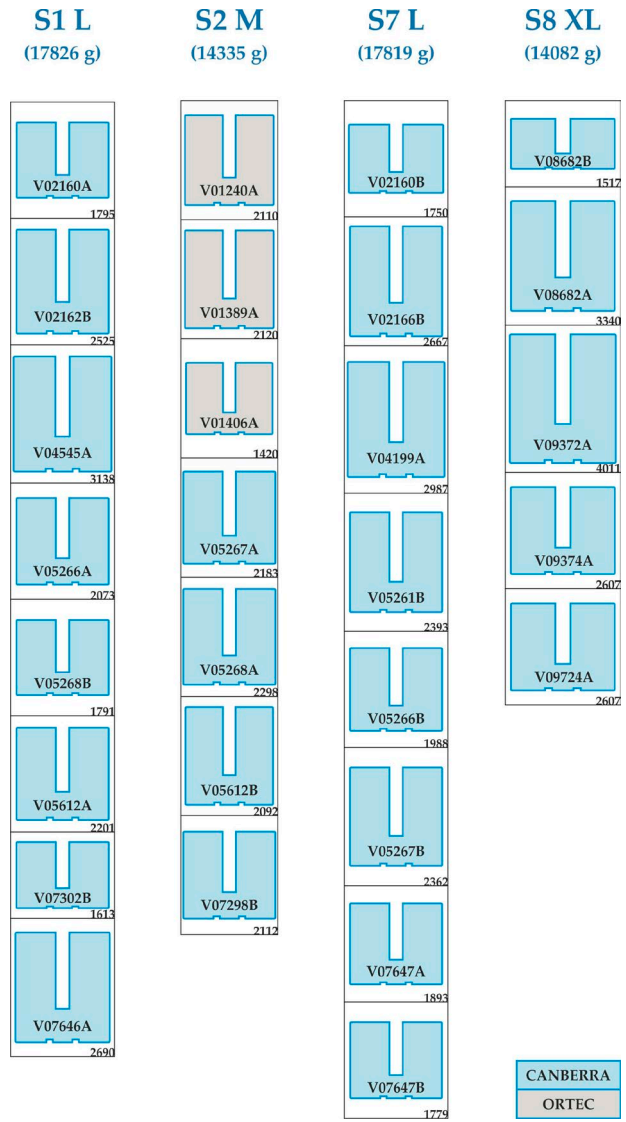


string mounting

cable connection



final view of four strings inside the nylon mini-shrouds before adding of the outer fiber barrel

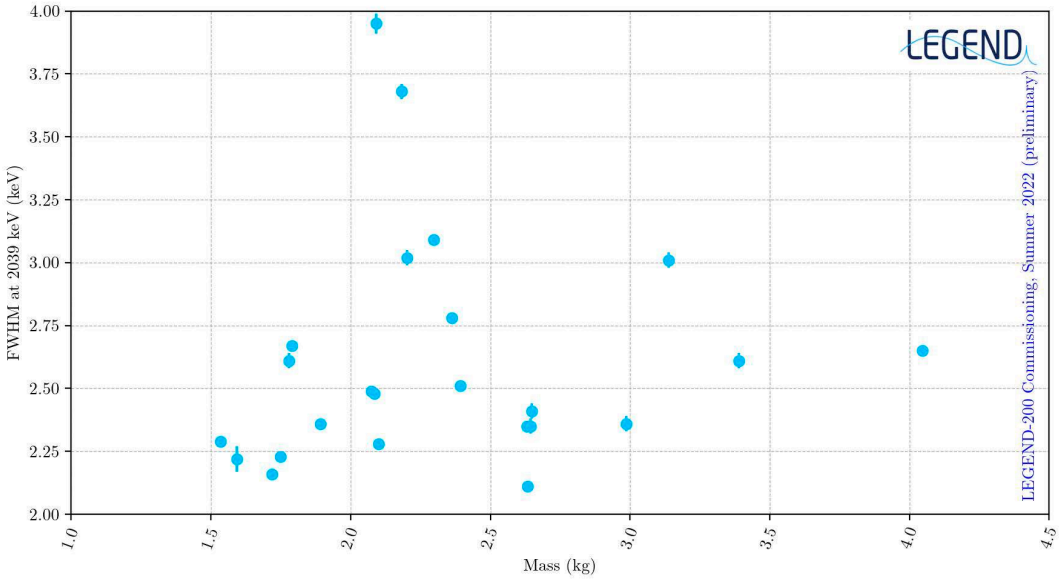


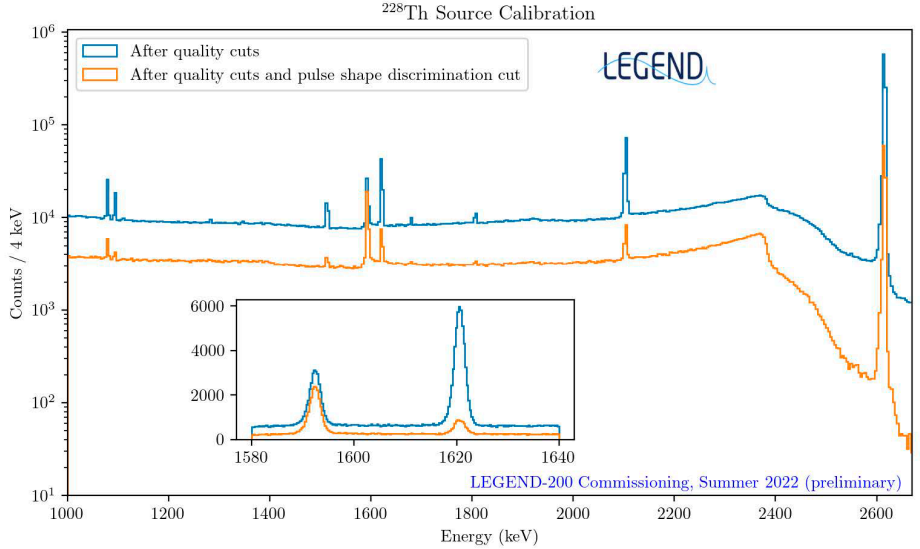
All 28 deployed HPGe detectors had working electrical contacts after the deployment in liquid argon, and no issues related to detector holders or insulators have been encountered

Photos: Enrico Sacchetti & Michael Willers

Picture: Konstantin Gusev

60 kg phase: preliminary results



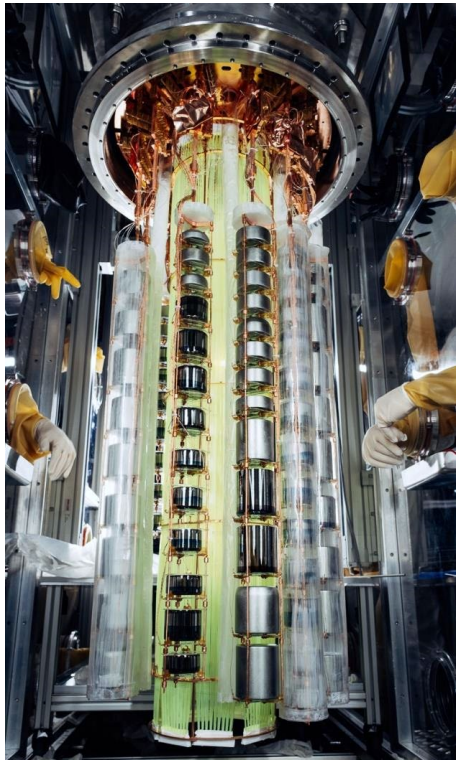


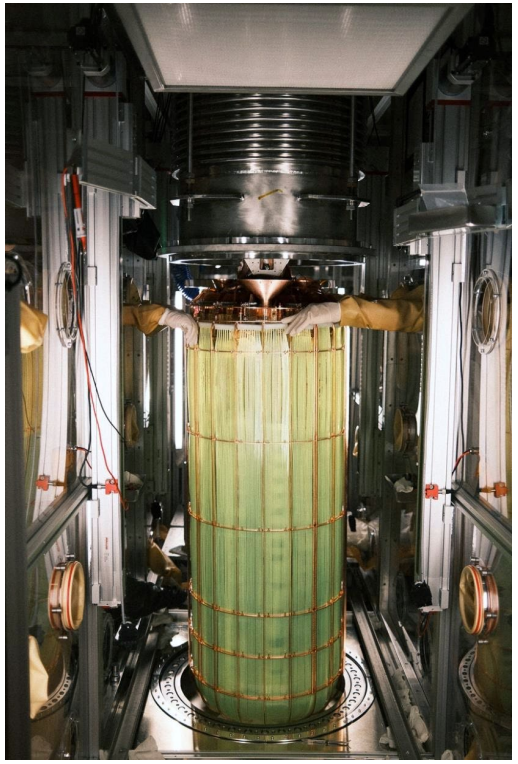
- ✓ The entire experiment, including the germanium detectors, the front-end electronics and high-voltage system, the liquid argon instrumentation and SiPM-front-end electronics, the muon veto system, the data acquisition system, and the entire analysis chain, was being commissioned with 60 kg of detectors.
- The main purpose of this commissioning was to check and optimize the overall experimental performance.

October 2022: 140 kg commissioning phase

- ✓ After carry out some repair and maintenance work and
- ✓ prepared all available detectors -> **about 140 kg detectors** started taking physics data

(about 16 additional detectors in progress now)



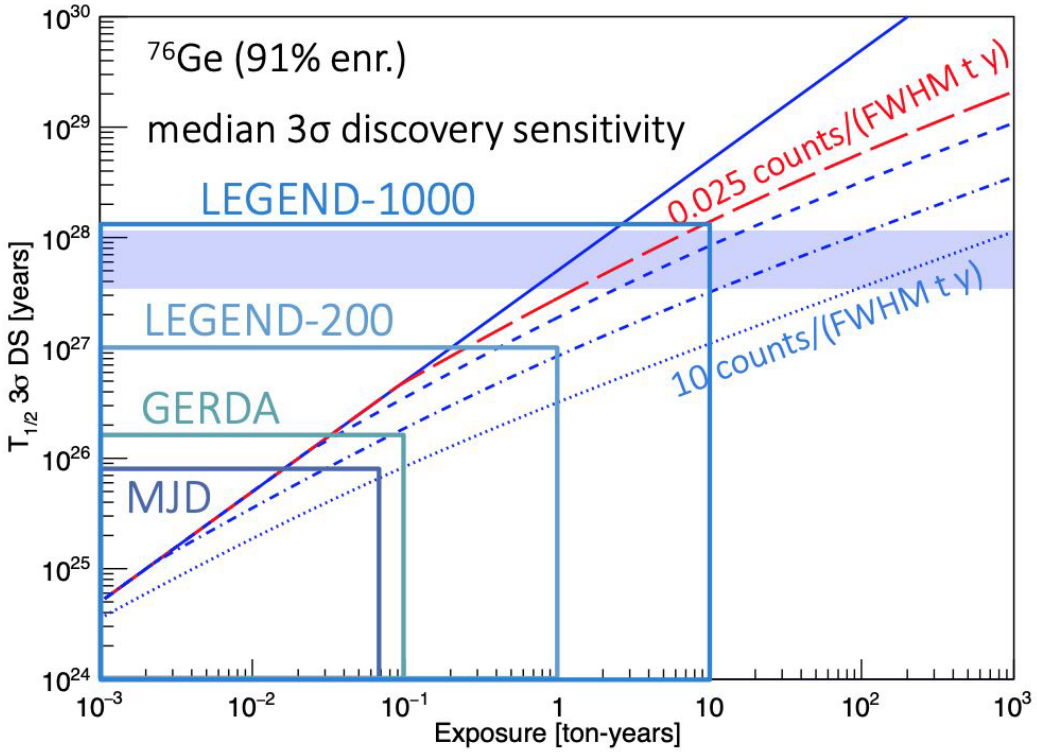


Photos: Michael Willers

Picture: Konstantin Gusev

Conclusions

- ✓ The LEGEND program builds on the successes of predecessor experiments GERDA and MAJORANA for a low-risk path to exploring half-lives beyond 10^{28} yrs
- ✓ LEGEND-200 is now commissioning:
  - ➢ More than 100 kg of enriched germanium installed in the 0νββ experiment first time ever!
  - ➢ Most detectors show good performance
  - ➢ Physics data taking in 140 kg commissioning phase is being started
- ✓ LEGEND-200 with full set of detectors planned for next year
- ✓ LEGEND-1000 pre conceptual design available, with R&D and conceptual design development ongoing *
- ✓ ^{76}Ge is a clear leading choice for a ton-scale search: thanks to the best FWHM in the field experiments are optimized for a discovery of 0νββ



arXiv:2107.11462