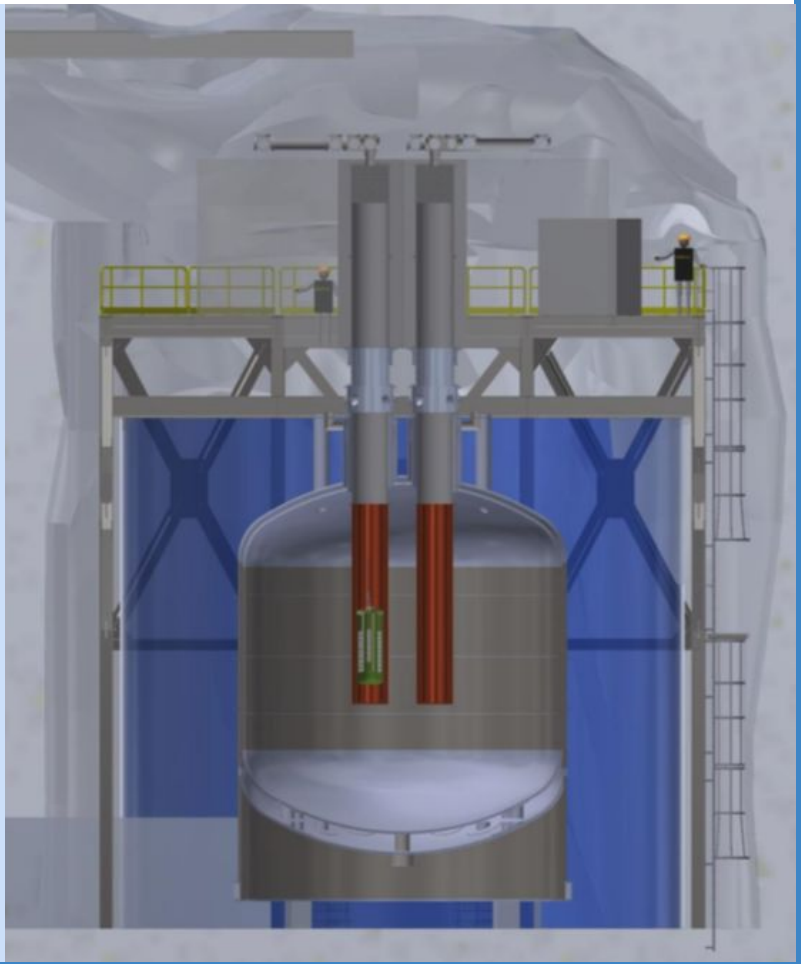
Searching for neutrinoless double beta decay with LEGEND experiment

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Nina Burlac* on behalf of LEGEND Collaboration
*University & INFN of Roma Tre

6 - 13 July 2022

ICHEP2022, Bologna, Italy.

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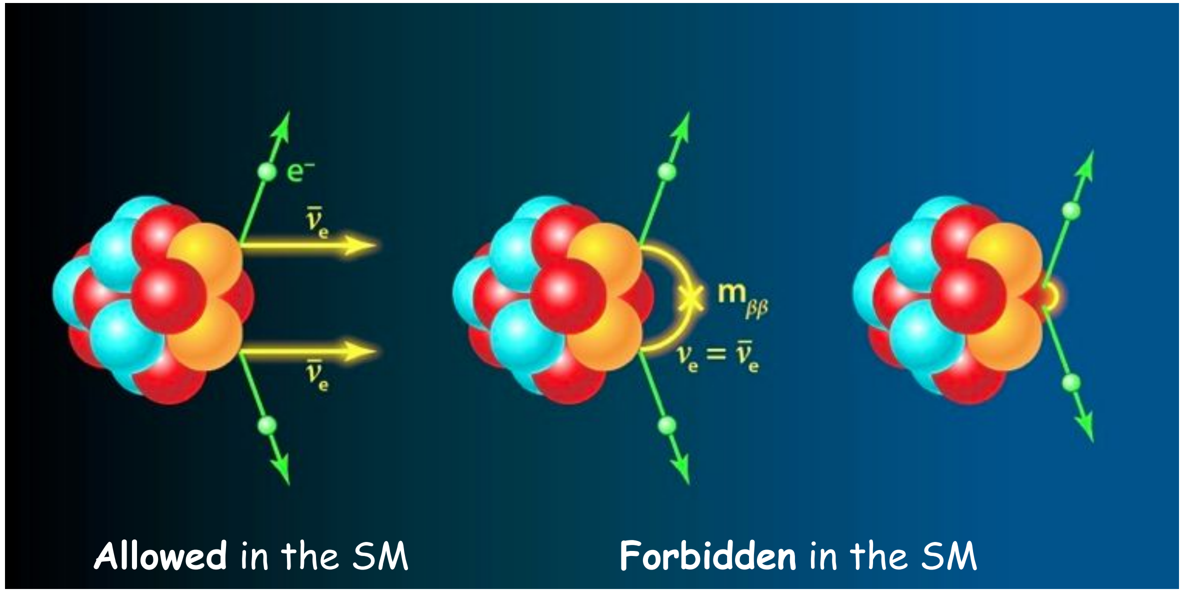
Neutrinoless Double Beta Decay

The neutrinos fundamental properties are still open issues in the neutrino sector beyond the SM:

- which is the size and the ordering of the eigenstate masses?
- are neutrinos Dirac or Majorana particles?

Possible answers from experiments searching for a hypothetical process called 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

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

Background Limited

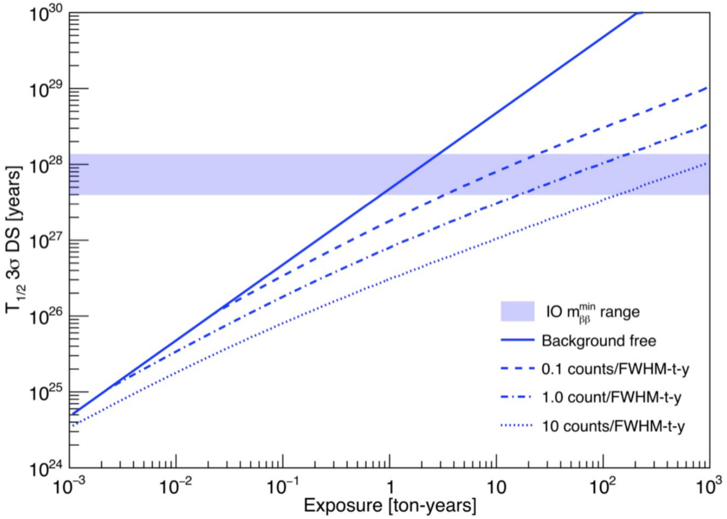
$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M.t}{b.\Delta E}}$$

Background Free

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

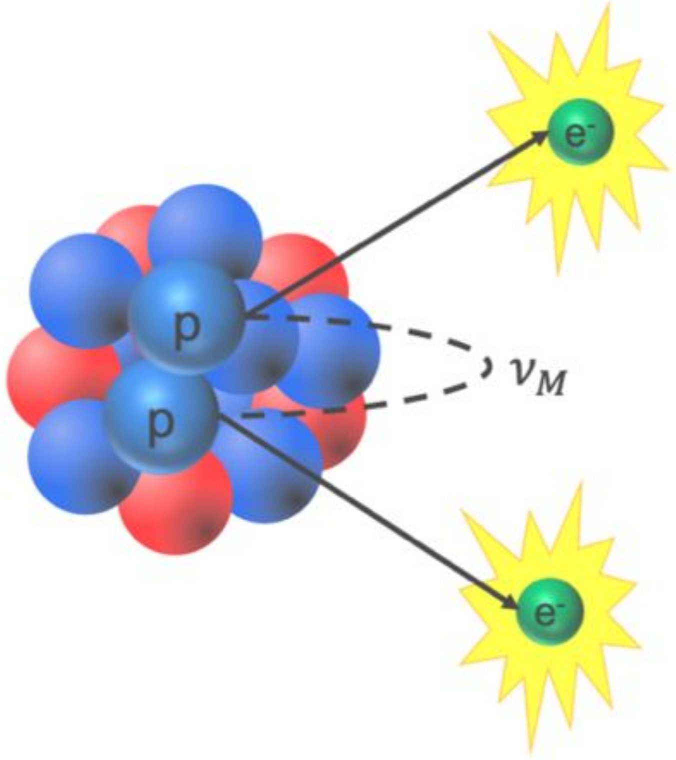
Half life sensitivity

M = active mass, t = time, b = background index, ΔE = energy resolution



Neutrinoless Double Beta Decay

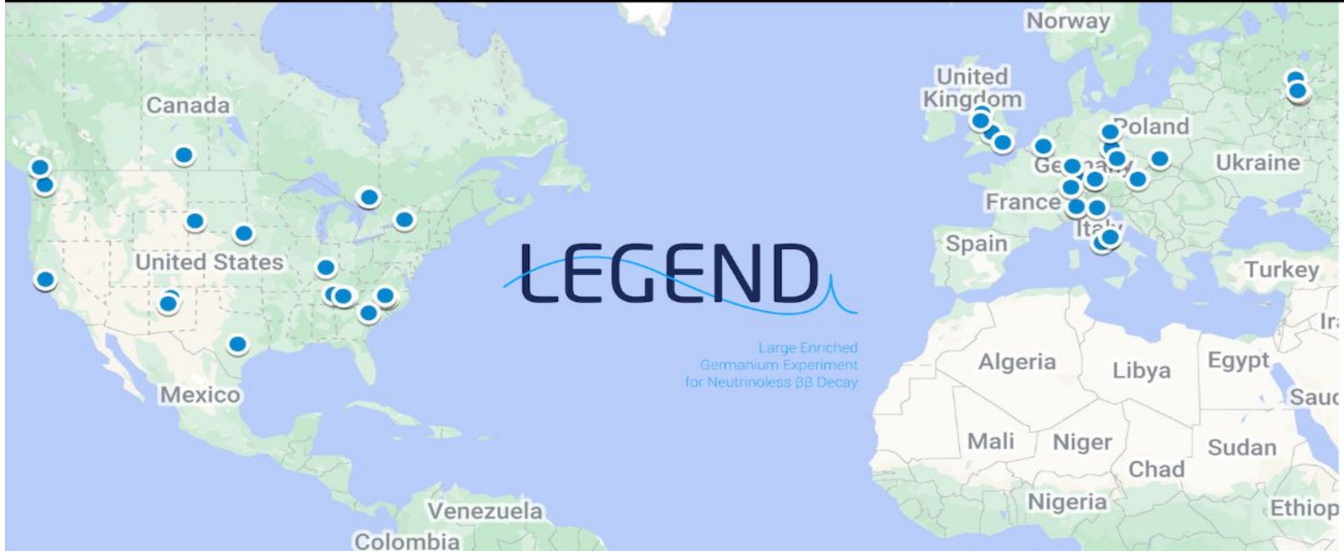
- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved
  - The neutrino is a fundamental Majorana particle
  - There is a potential path for understanding the matter - antimatter asymmetry in the cosmos, through leptogenesis
  - There is a new mechanism demonstrated for the generation of mass



- 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

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



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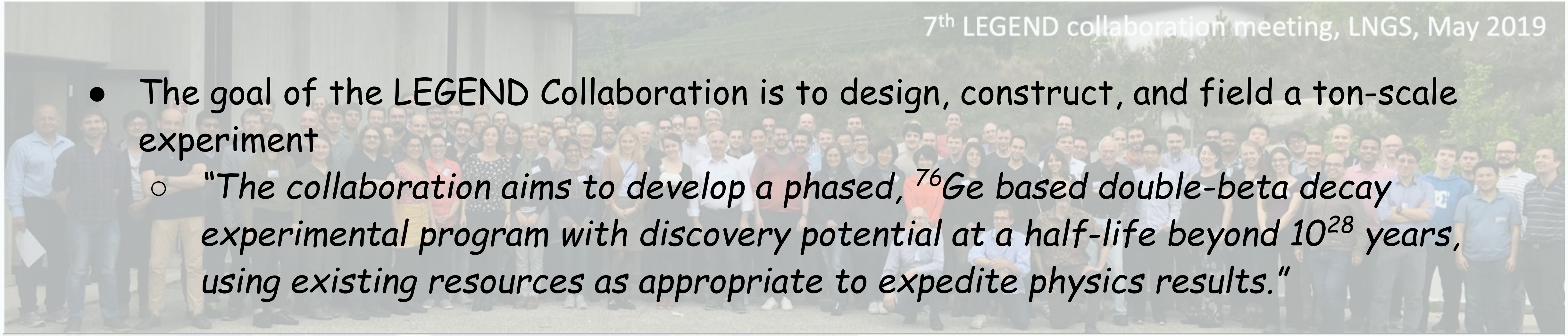
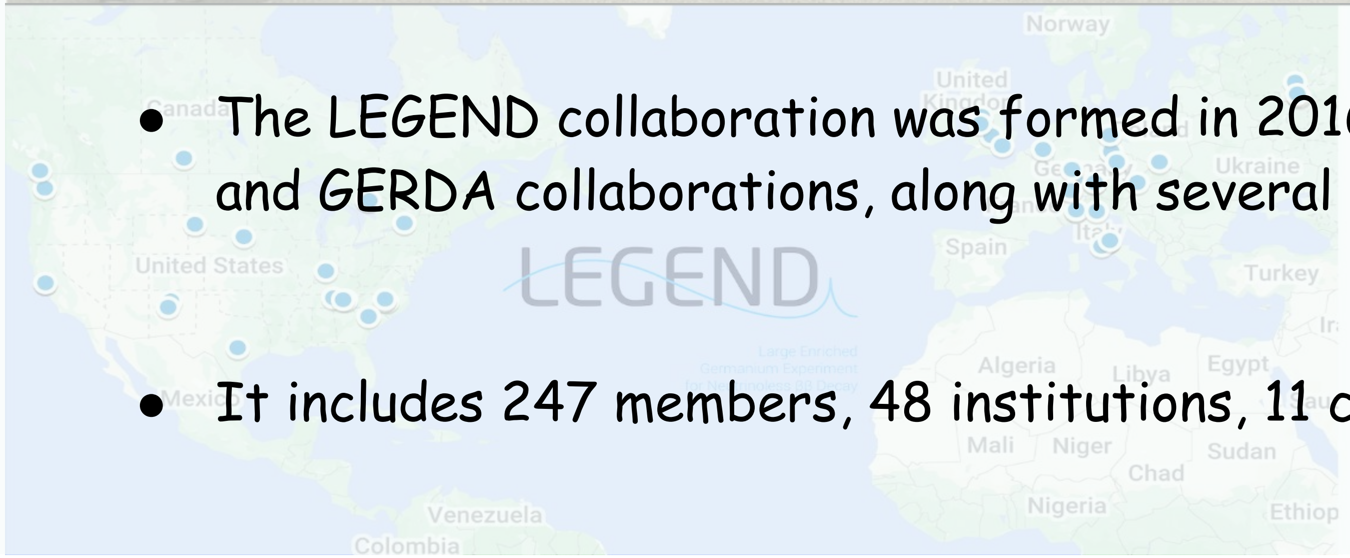


- The goal of the LEGEND Collaboration is to design, construct, and field a ton-scale experiment
  - *"The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate 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 247 members, 48 institutions, 11 countries

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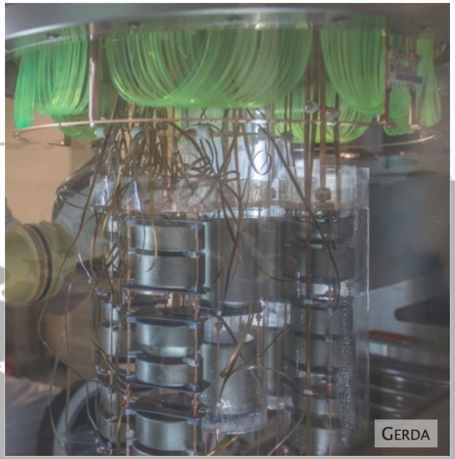
LEGEND: the best of GERDA and Majorana

Majorana Demonstrator

29.7 kg of enriched p+ point contact (PPC) detectors with **low noise electronics** in compact shield from u**nderground electroformed copper**

background:	$(6.2 \pm 0.6) \cdot 10^{-3}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>8.3 \cdot 10^{25}$ yr (90% C.L.) [J. Gruzko, Nu2022]
where:	SURF (SD)
when:	completed

best energy resolution: FWHM@$Q_{\beta\beta}$= 2.5 keV



GERDA

GERDA Phase II

44.2 kg of enriched BEGe/coaxial/ICPC detectors operated in low A **active LAr shield**

background:	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
$T_{1/2}$ sensitivity:	$>1.8 \cdot 10^{26}$ yr (90% C.L.) [accepted by Phys.Rev.Lett.]
where:	LNGS (IT)
when:	**completed**

LEGEND: the best of GERDA and Majorana

? SNOLAB

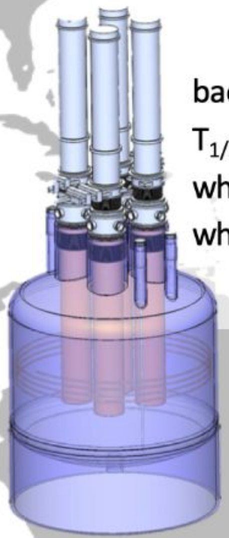
?

LNGS

LEGEND-1000

1000 kg, staged via individual payloads

background:	10^{-5} cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	$>10^{28}$ yr
where:	**to be selected**
when:	contingent on funding decisions



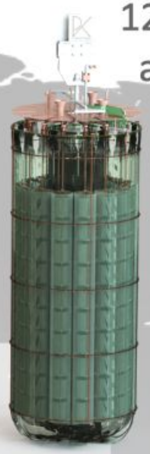
4 payloads in UAr

LEGEND-200

up to **200 kg** of enriched ICPC(/BEGe/PPC) detectors in GERDA infrastructure

background:	$< 2\cdot10^{-4}$ cts/(keV·kg·yr)
$T_{1/2}$ sensitivity:	$>10^{27}$ yr
where:	LNGS (IT)
when:	**2021**

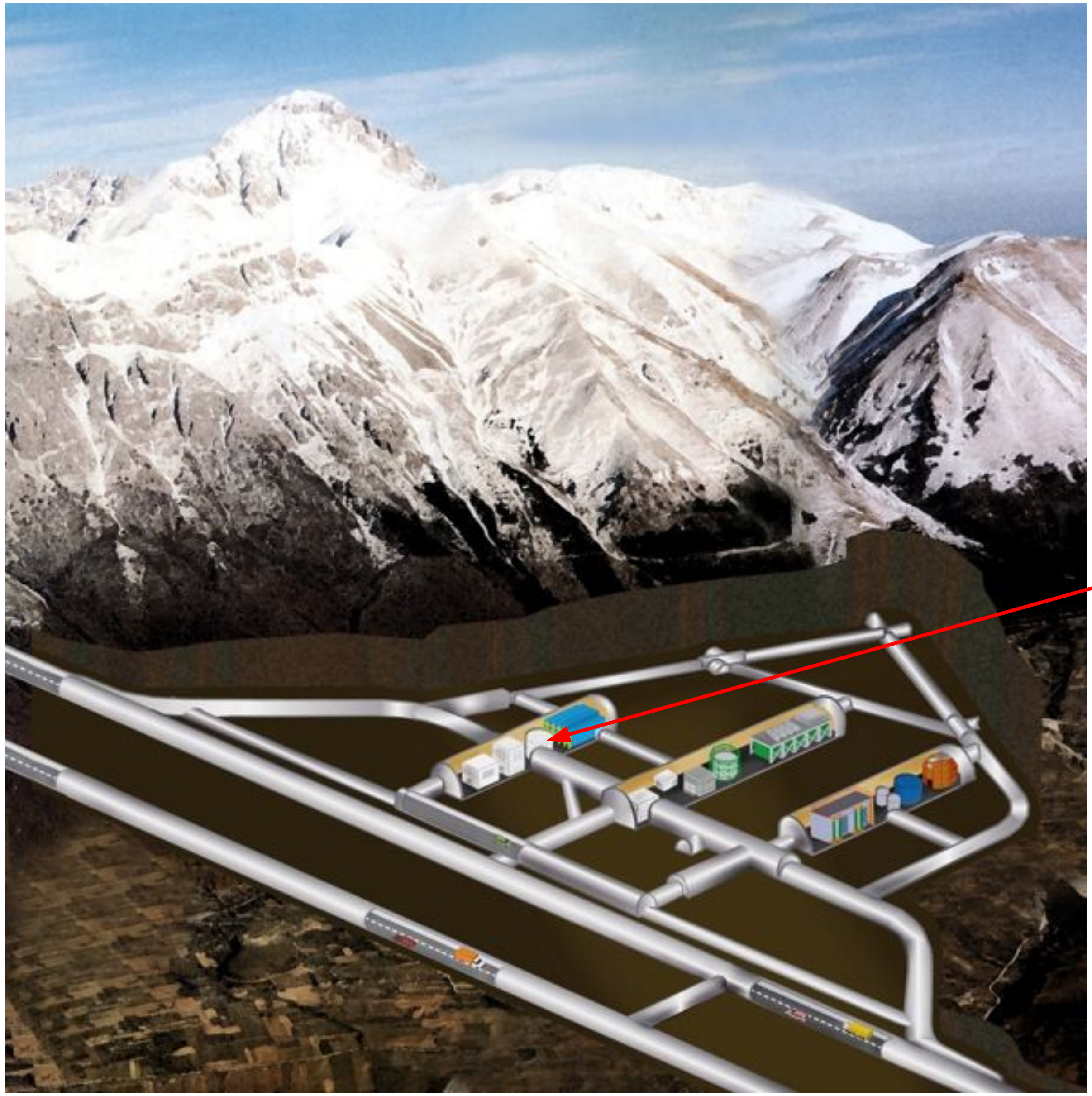
1/3 of GERDA

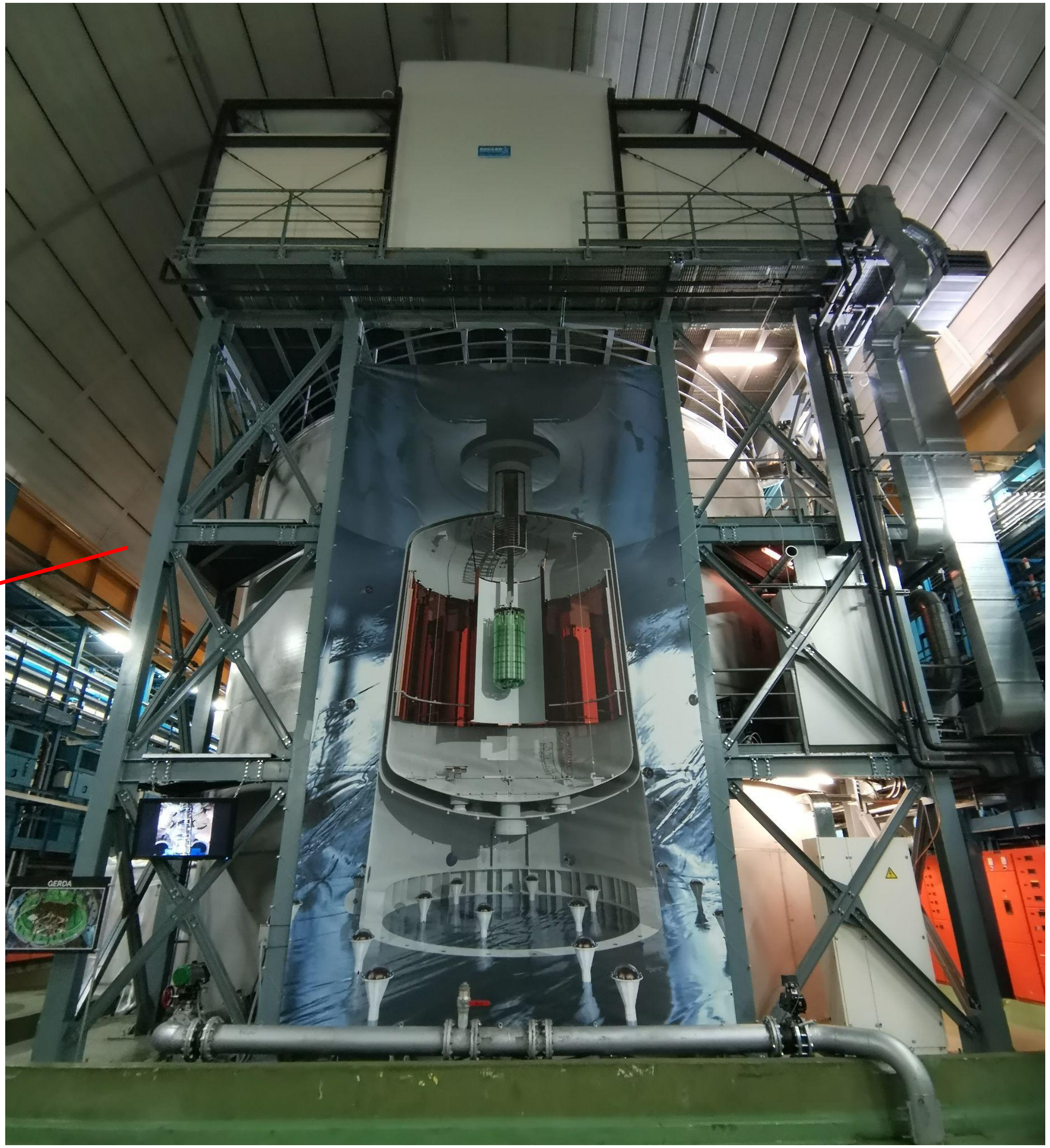


12-string array

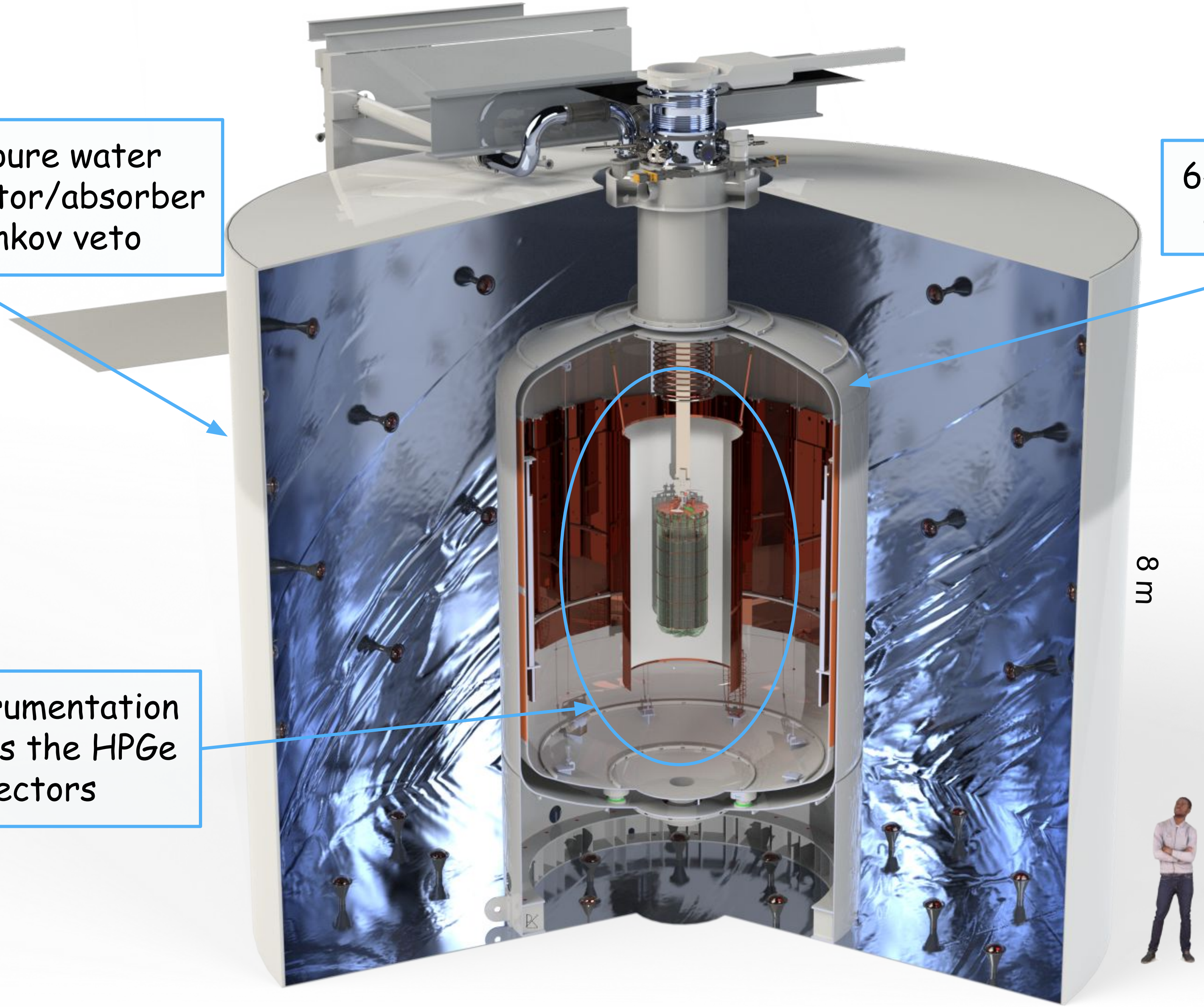
In this talk

LEGEND-200 at LNGS



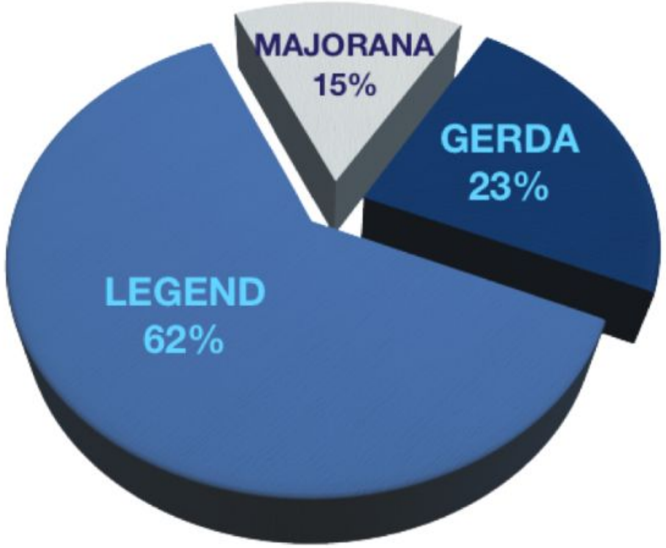


LEGEND-200 SETUP

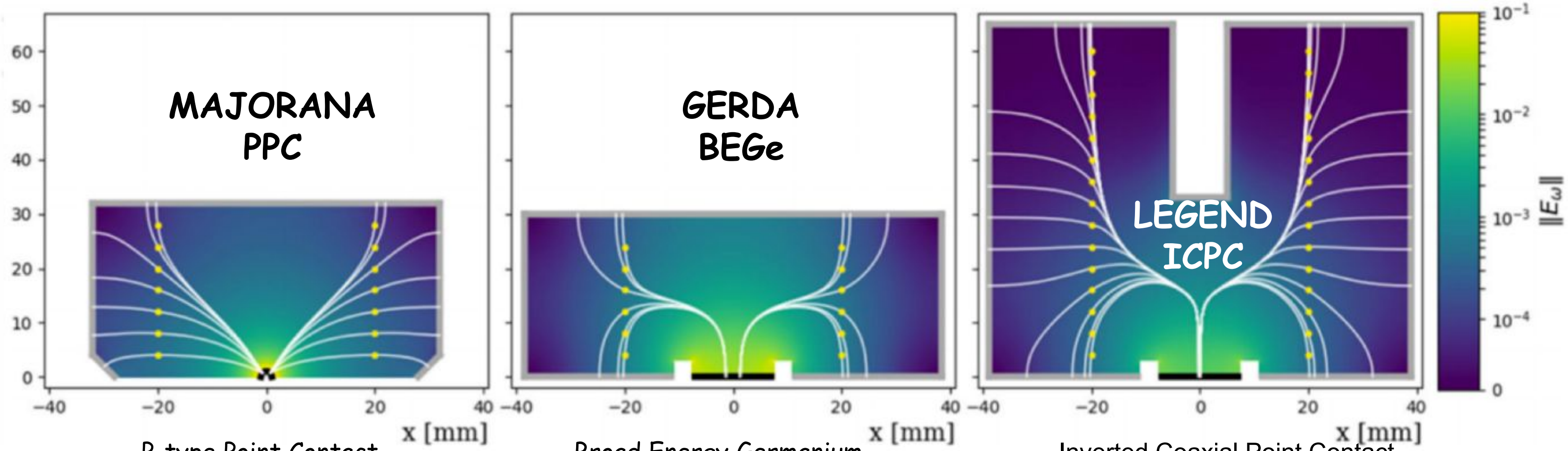


[Inside LEGEND]

High Purity Germanium detectors



Semiconductor diodes sensitive to ionizing radiation and γ rays



P-type Point Contact

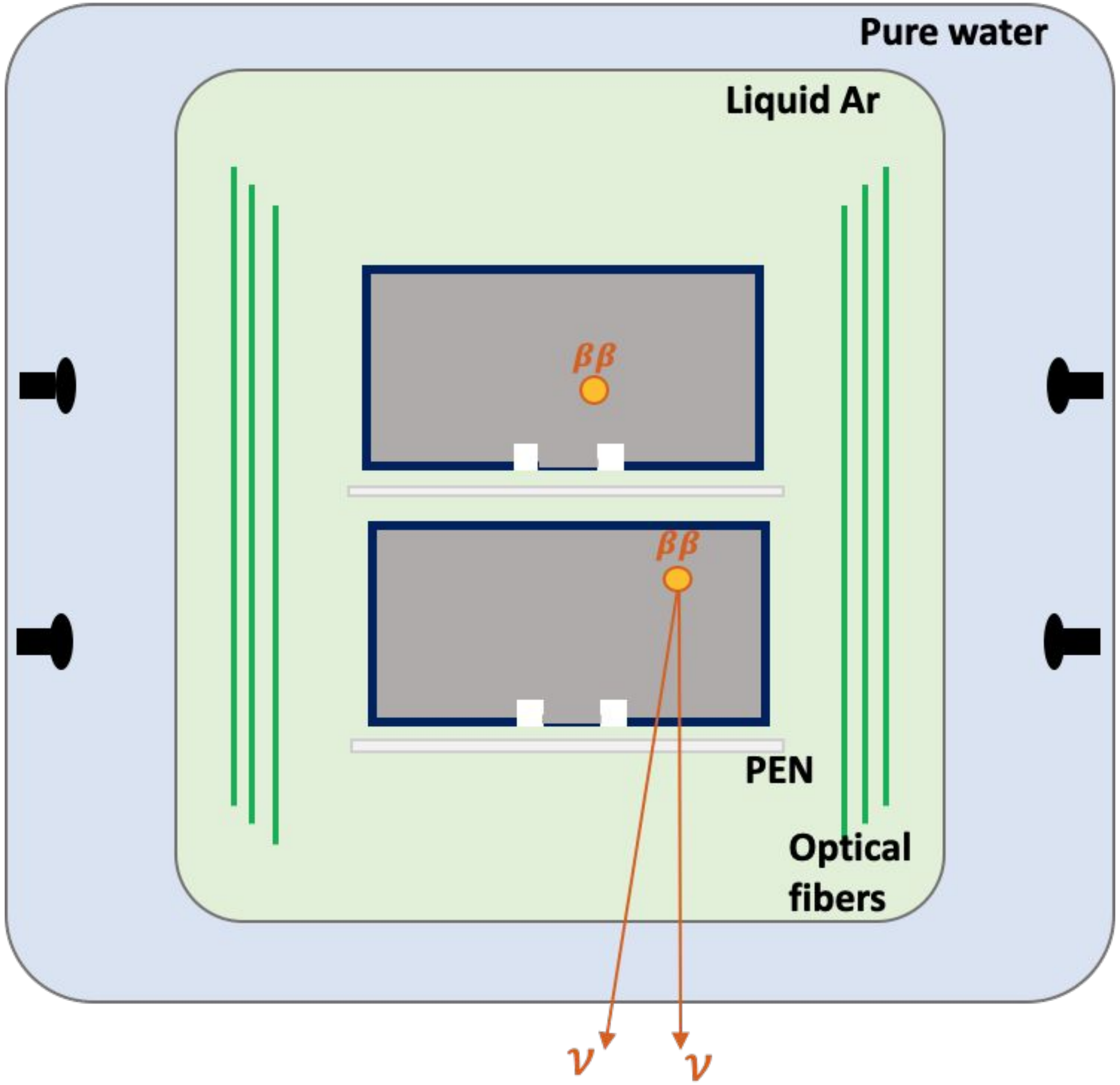
Broad Energy Germanium

Inverted Coaxial Point Contact

Why HPGe detectors?

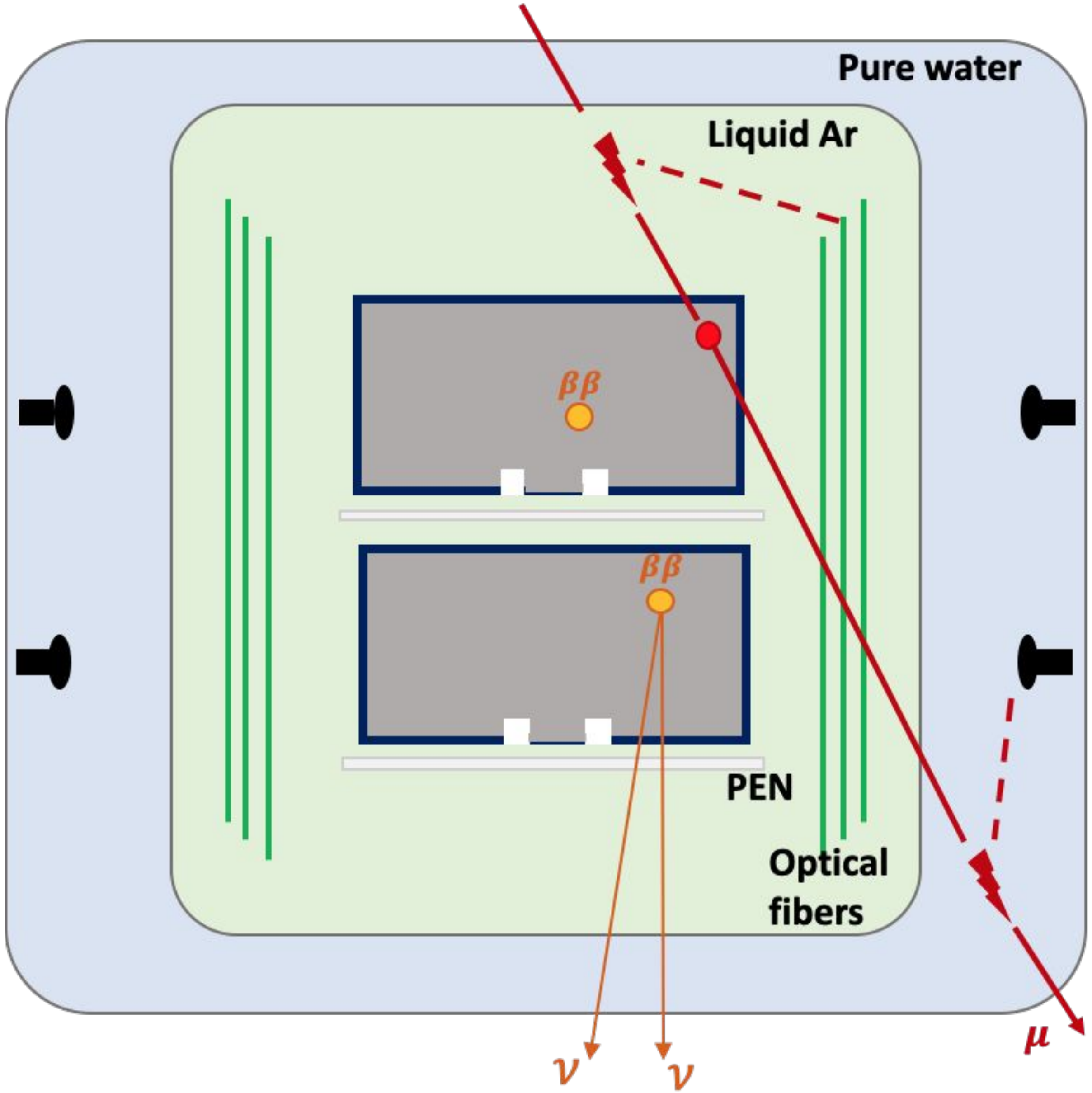
- High detection efficiency (detector = $\beta\beta$ source)
- Enrichment from 7.7% up to 87÷92% in $\beta\beta$ emitter
- Best proved energy resolution at the Q-value (~ 0.13% FWHM)
- Intrinsic radiopurity (best background/FWHM in the field)

Active Background Reduction Strategy



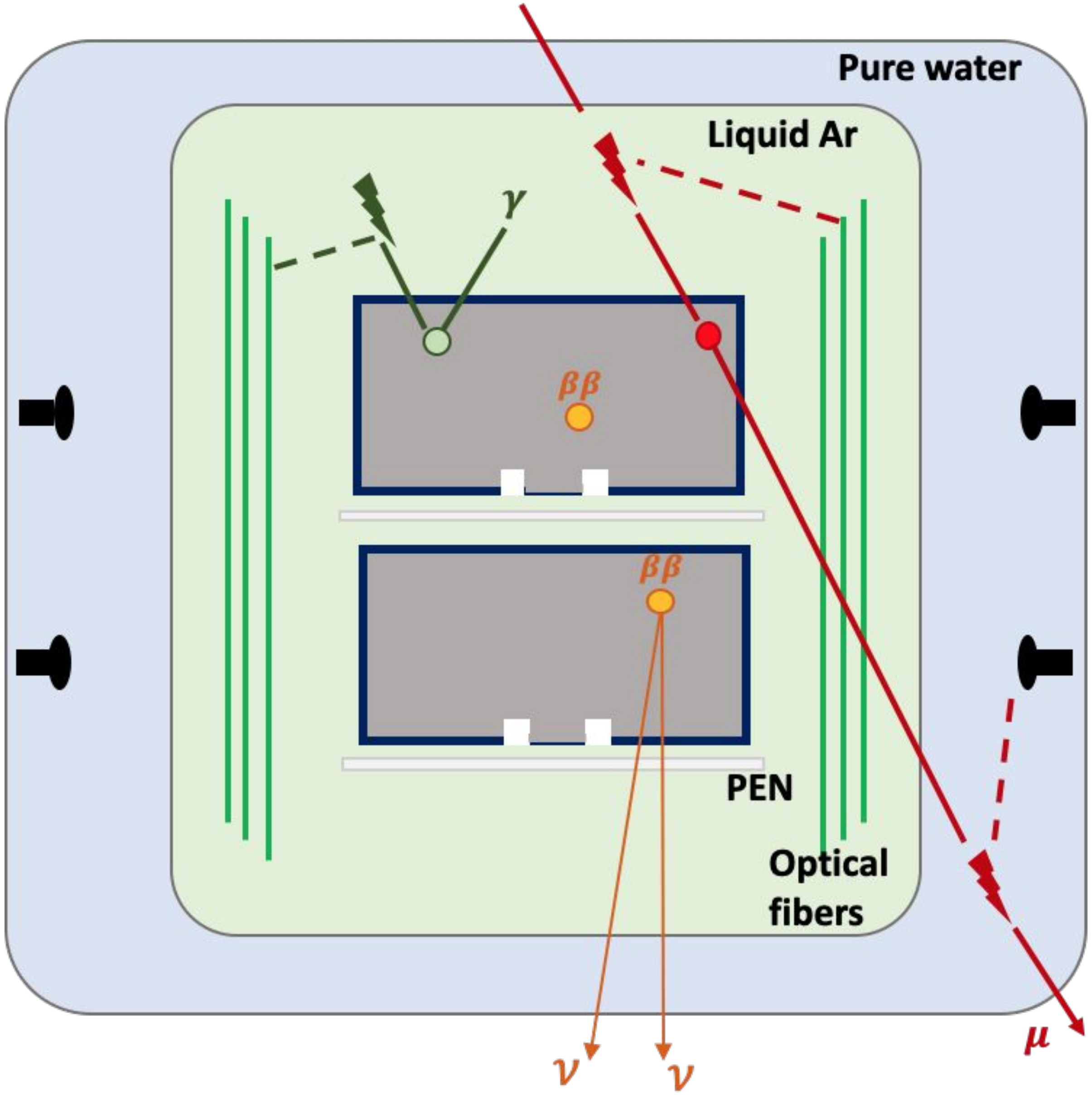
- ββ decay signal: single energy deposition in a 1 mm^3 volume

Active Background Reduction Strategy



- ββ decay signal: single energy deposition in a 1 mm^3 volume
- Muon veto based on Cherenkov light and plastic scintillator

Active Background Reduction Strategy



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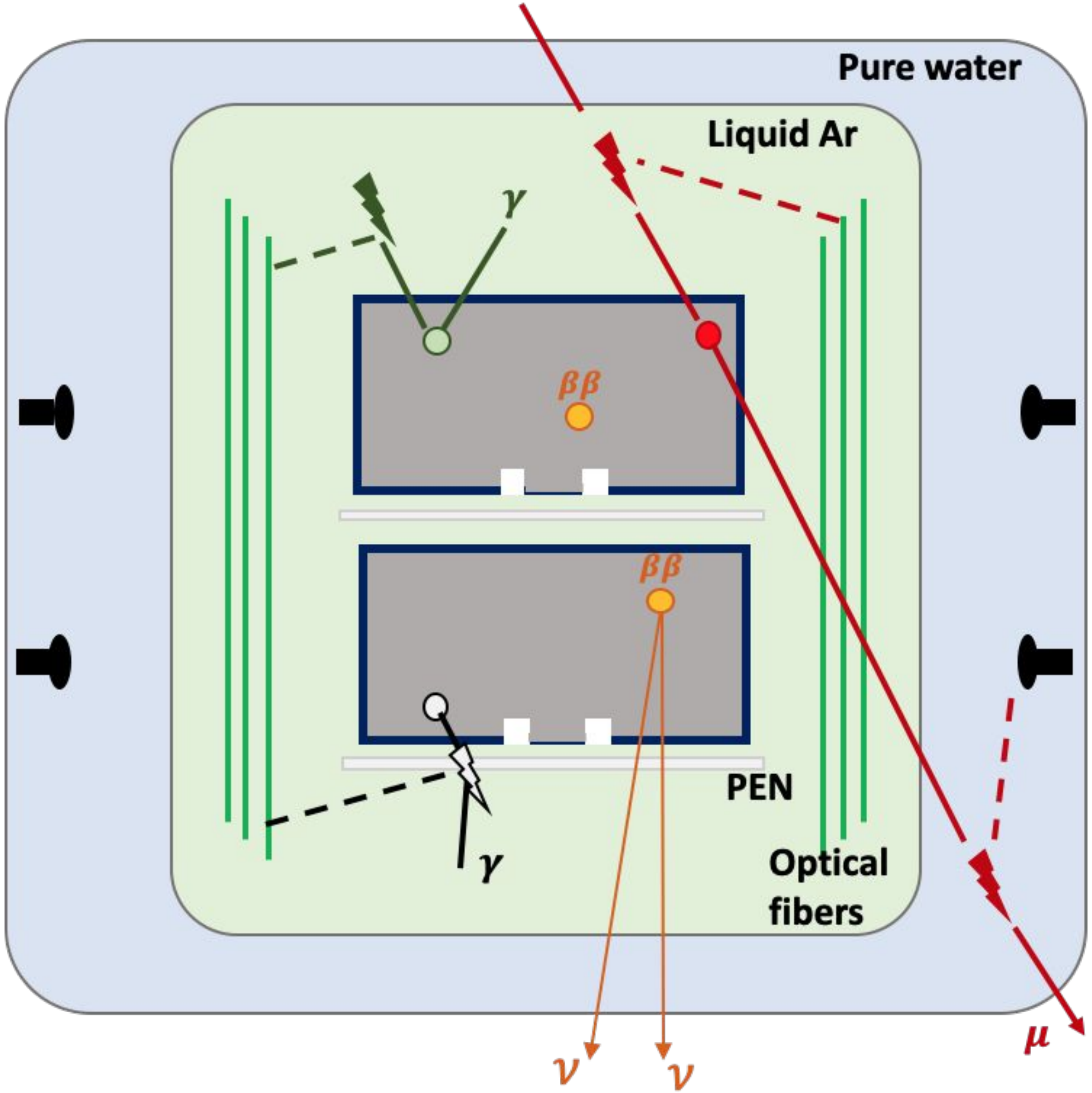
Active Background Reduction Strategy



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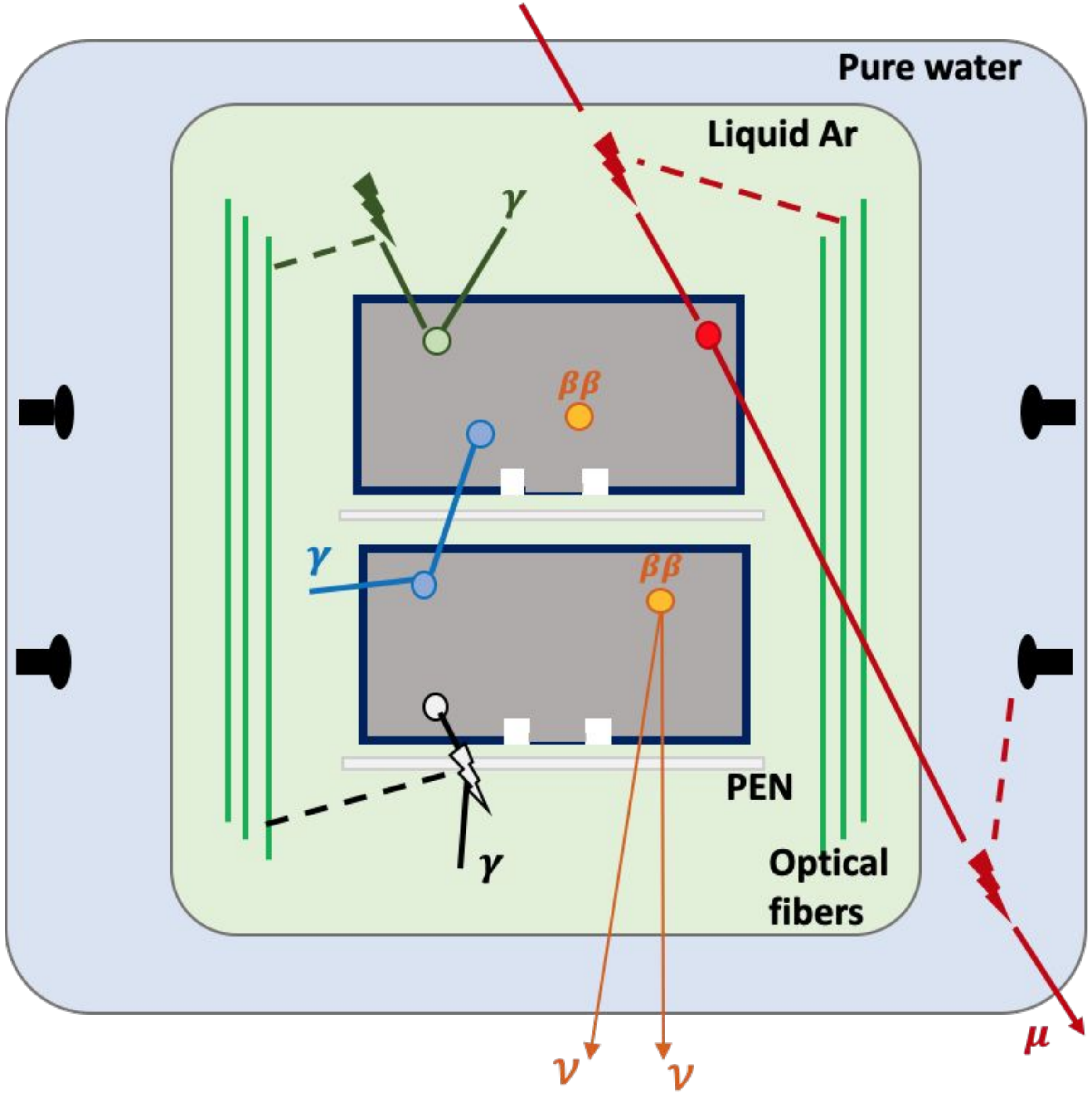
Active Background Reduction Strategy



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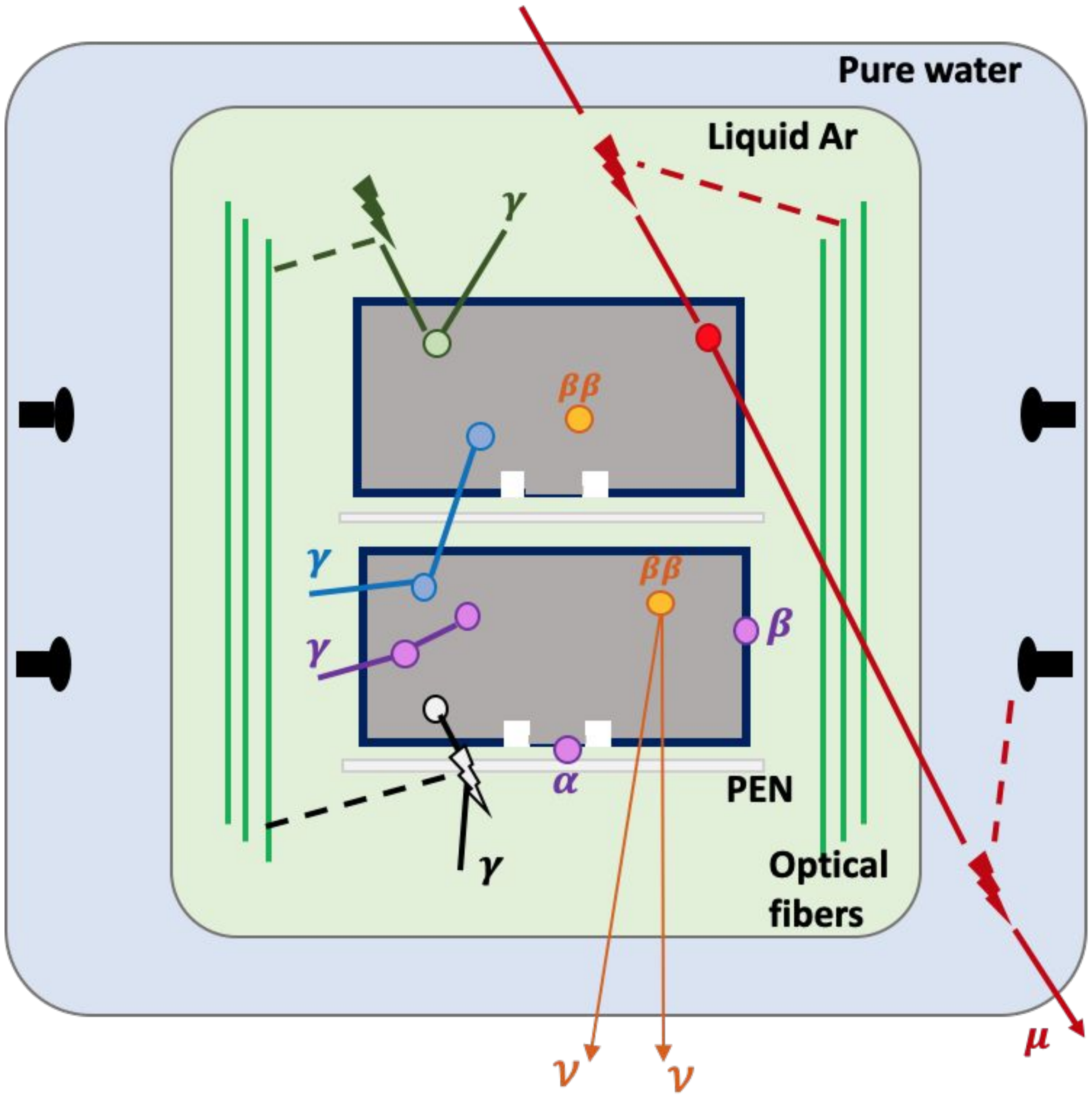
- Ge detector anti-coincidence

Active Background Reduction Strategy



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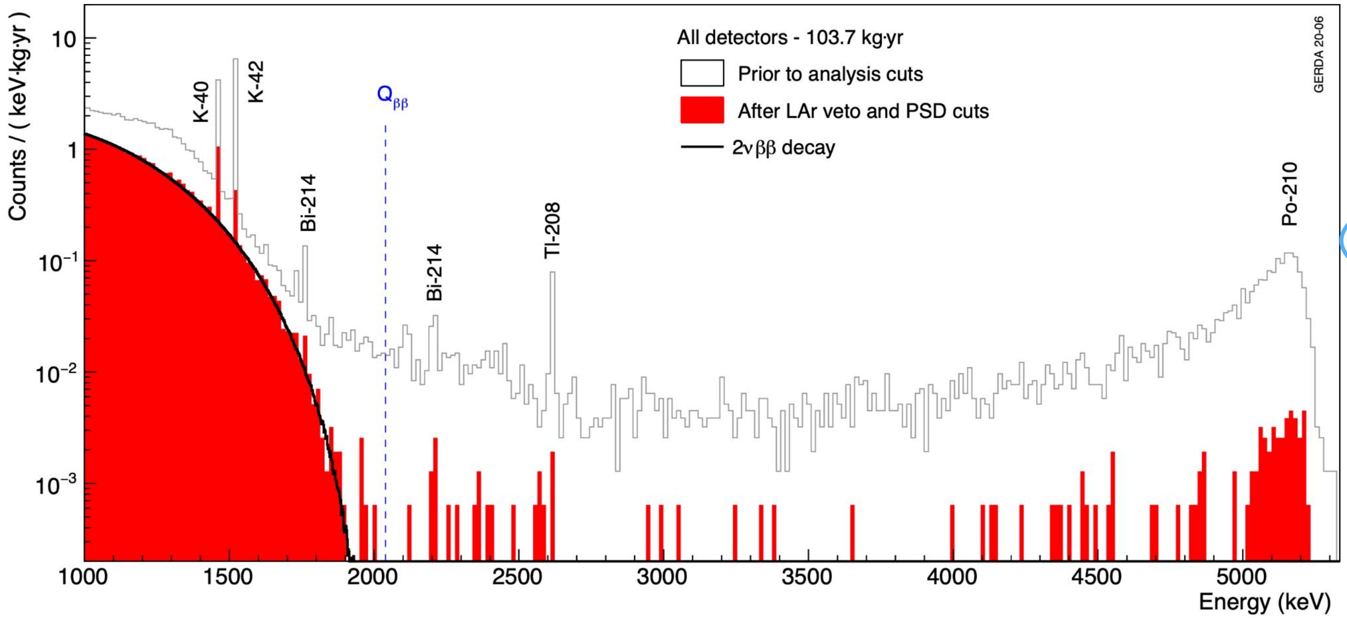
- Ge detector anti-coincidence
- Pulse shape discrimination (PSD) for multi-site and surface events

Active Background Reduction Strategy

Extremely powerful complementarity between LAr veto and PSD cuts was demonstrated in GERDA



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

- LAr veto based on Ar scintillation light readout by fibers coupled to SiPMs
- Pulse shape discrimination (PSD) for multi-site and surface events

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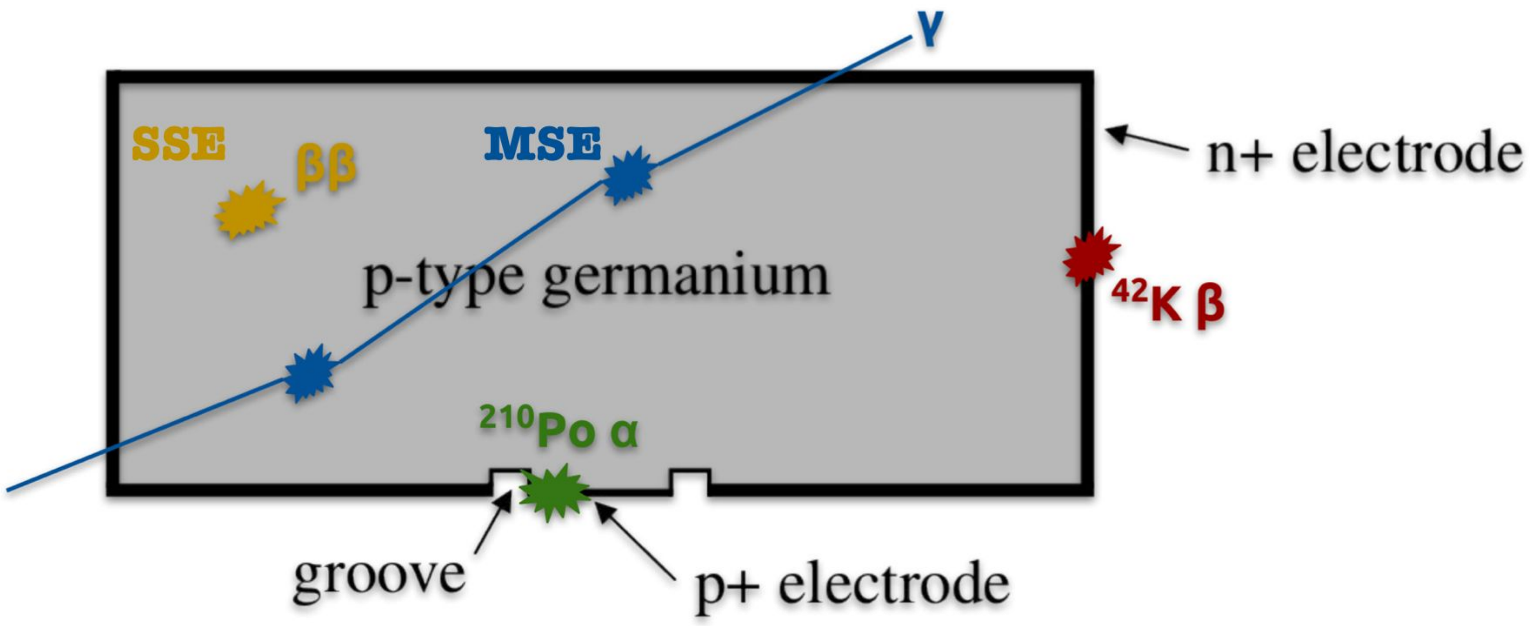
Pulse shape discrimination

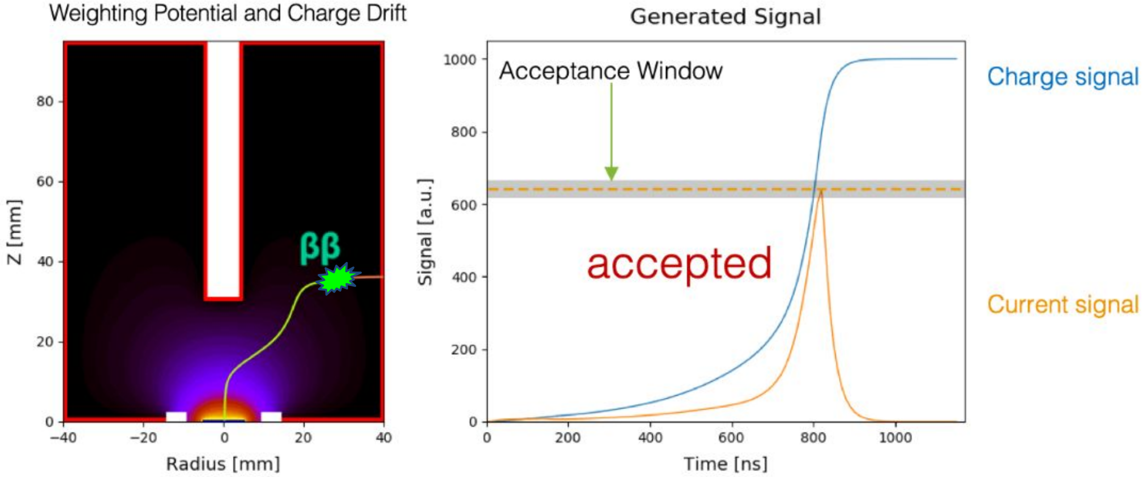
PSD: reject multi-site and surface events based on detector signal shape

External α, β, and γ backgrounds all create distinctive pulse shapes, allowing for highly efficient ββ decay event selection

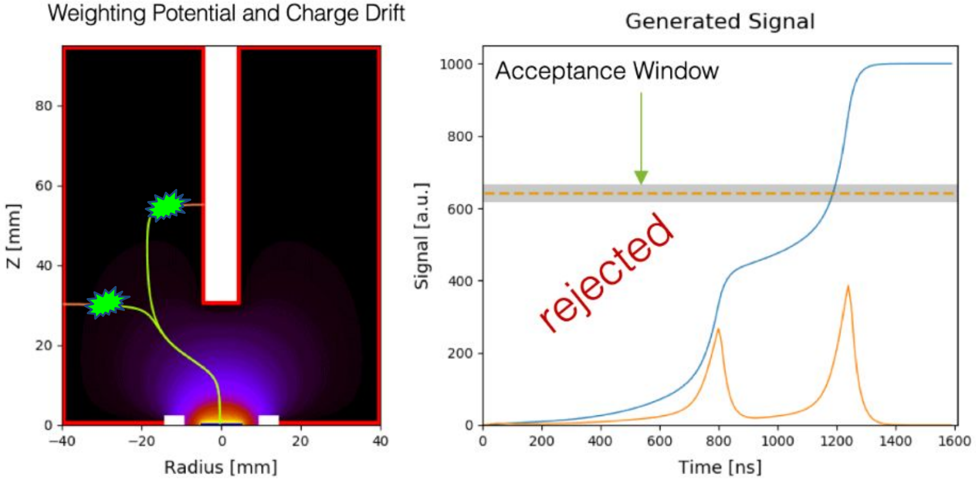


Pulse shape discrimination: Event Topologies

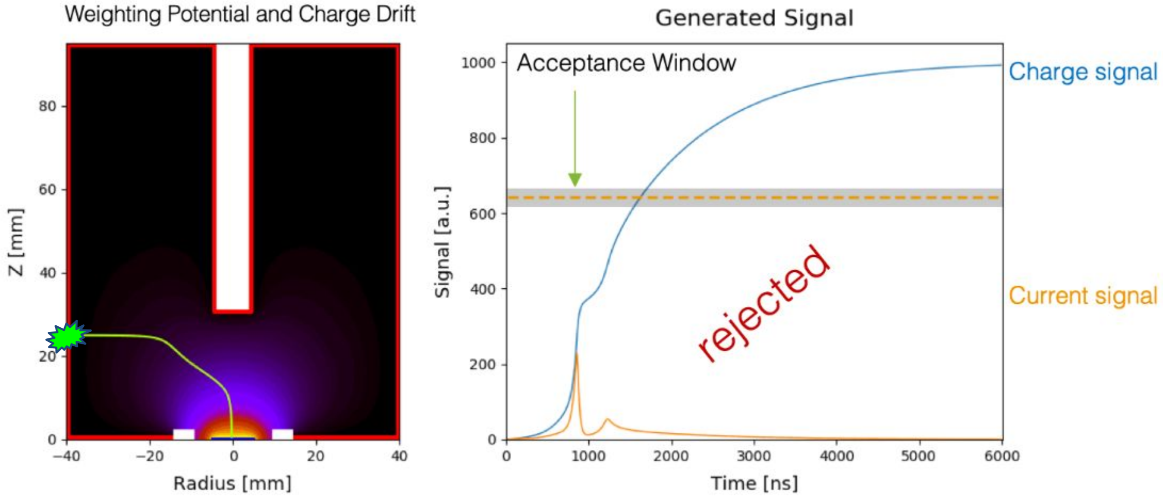
0νββ signal candidate (single-site)



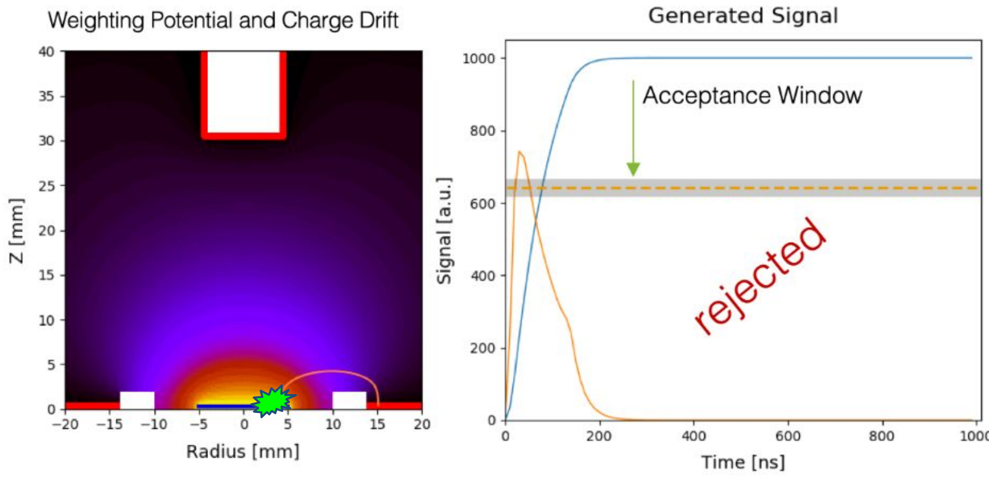
γ-background (multi-site)



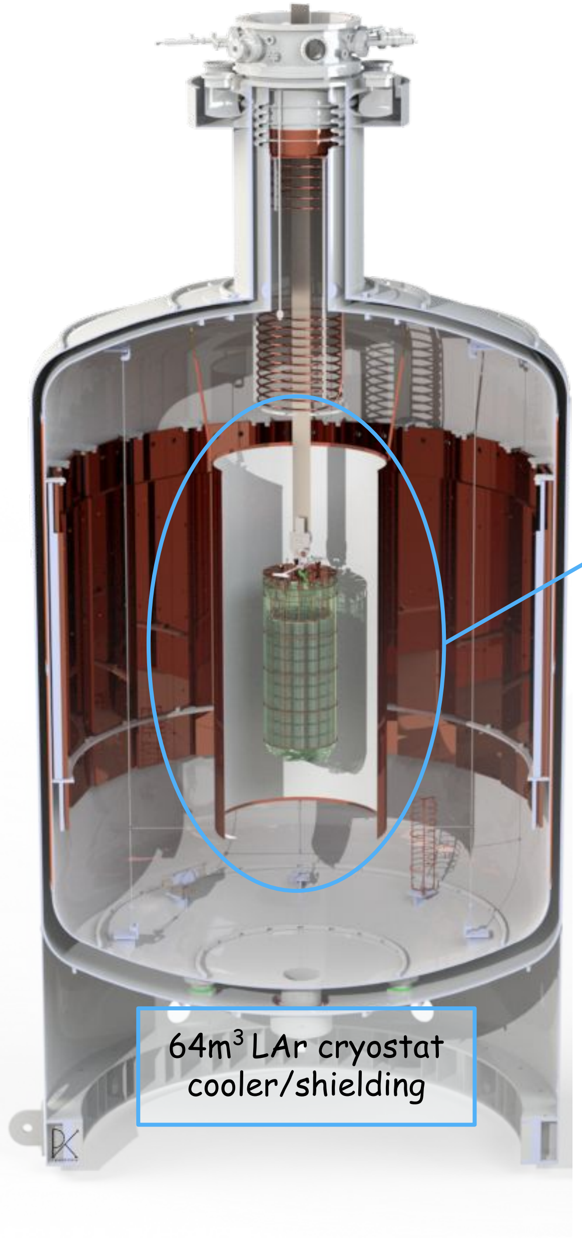
Surface-β-background ^{42}K (^{42}Ar) on n+ contact



α-background on p+ contact

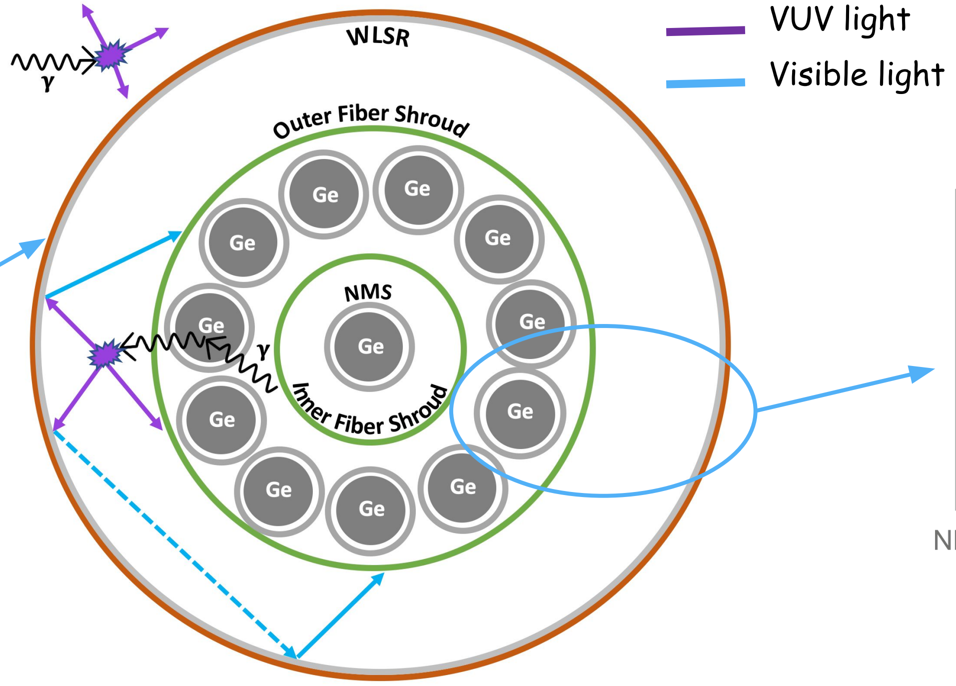


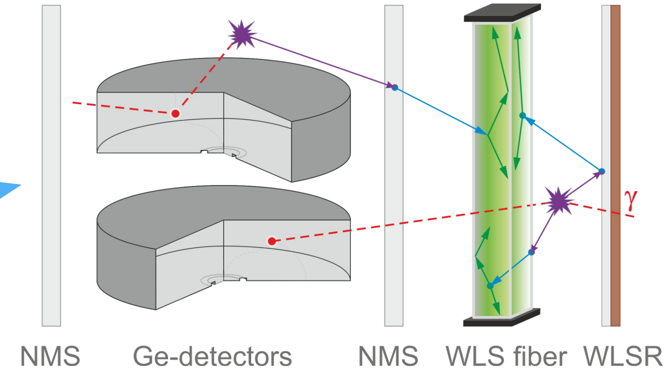
Liquid Argon instrumentation



64m^3 LAr cryostat
cooler/shielding

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





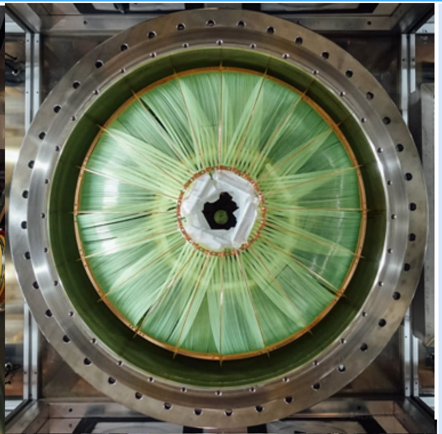
- two concentric curtains of TetraPhenyl Butadiene (TPB) coated, WaveLenght Shifting (**WLS**) fibers;
- transparent, TPB coated Nylon Mini Shrouds (**NMS**) surround each string of HPGe detectors;
- WLS-Reflector (**WLSR**) enclose the Ge strings and fiber curtains;

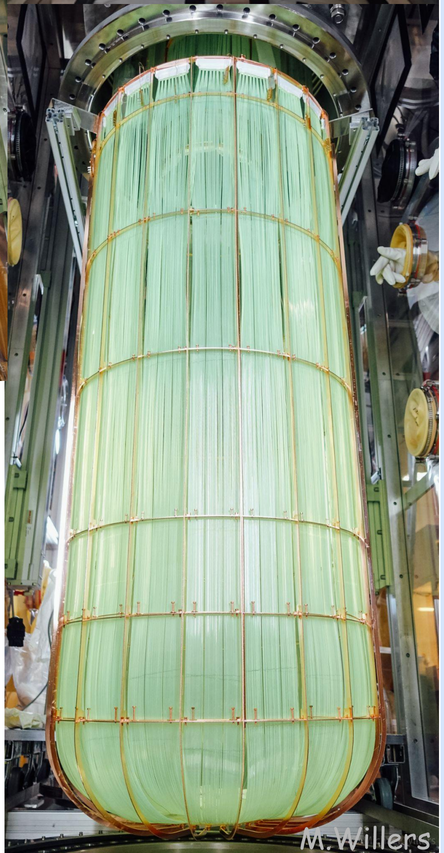
The TPB shifts the LAr scintillation light **from VUV to blue light**.

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.

Status of LEGEND-200

- Upgrade and stand-alone commissioning of the LAr system completed;
- First integrated commissioning run now underway: 4 strings of HPGe detectors, operating with full LAr instrumentation
- First physics data-taking this year.





Initial Commissioning: 4 Detector Strings *Ongoing*;

→ Follow-up Commissioning & Physics Data:10 Detector Strings ***Fall 2022***

→ LEGEND-200 Final Goal: 12 Detector Strings ***2023***

Conclusions

- ^{67}Ge is a clear leading choice for a ton-scale search: experiments are optimized for an unambiguous discovery of 0νββ
- Current-generation experiments have led the field
  - Full-exposure results from GERDA: $T_{1/2} > 1.8\times10^{26}$ yr
  - New full-exposure results from the MAJORANA DEMONSTRATOR: $T_{1/2} > 8.3\times10^{25}$ yr

- The LEGEND program builds on these successes for a low-risk path to exploring half-lives beyond 10^{28} yrs
  - LEGEND-200 is in commissioning, with data-taking beginning later this year
  - LEGEND-1000 pre conceptual design available, with R&D and conceptual design development ongoing - Next talk