LEGEND-1000

A Tonne-Scale search for $0\nu\beta\beta$ with Germanium Detectors

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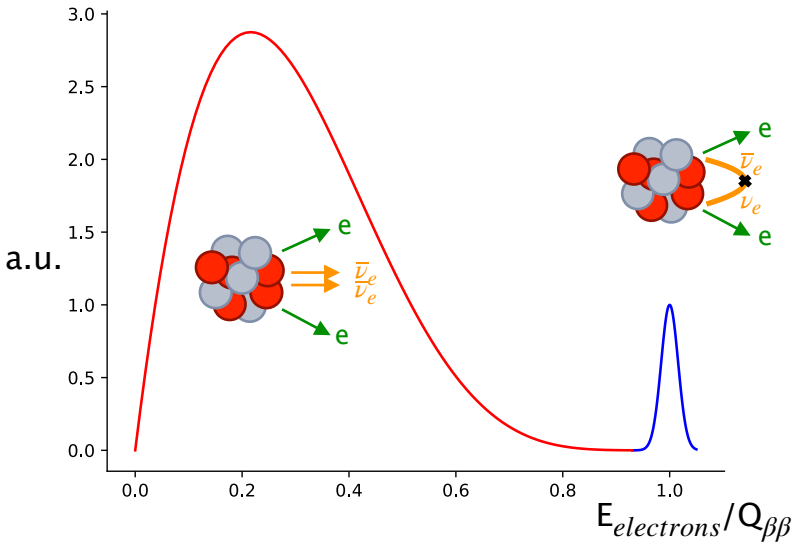
for the LEGEND collaboration

EPS-HEP 2025, Marseille

INFN LNGS

JAGIELLONIAN UNIVERSITY IN KRAKÓW

Searching for $0\nu\beta\beta$



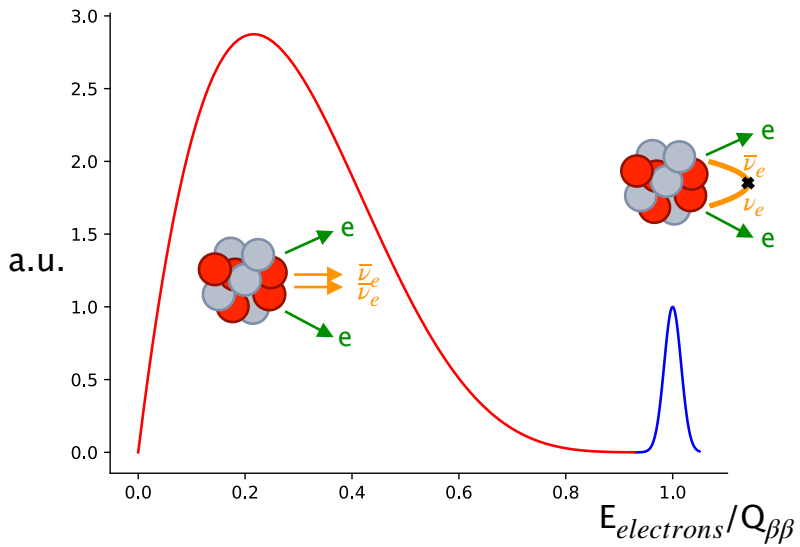
$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)|M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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

- Prove that neutrino masses are Majorana in nature
- Lepton Number Violating (LNV) process → CPV in lepton sector
- Probe the absolute neutrino mass scale and neutrino mass ordering

The search for 0νββdecay is one of the most compelling and exciting challenges in contemporary physics

Searching for $0\nu\beta\beta$ of ^{76}Ge



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

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

$^{76}Ge \rightarrow {}^{76}Se + 2e^-$ with $Q\beta\beta = 2039$ keV

Sensitivity scales linearly with exposure Mt when in (quasi) background free regime!

sensitivity on $0\nu\beta\beta$ half-life

$$T^{0\nu}_{1/2} \propto \begin{cases} \epsilon \cdot \eta \cdot \sqrt{\frac{M\,t}{B\,\sigma}} \\ \epsilon \cdot \eta \cdot M\,t \end{cases}$$

zero-background[1] regime

- ϵ: detection efficiency
- η: ^{76}Ge enrichment fraction
- M: ^{76}Ge mass
- t: measurement time
- B: background index
- σ: energy resolution

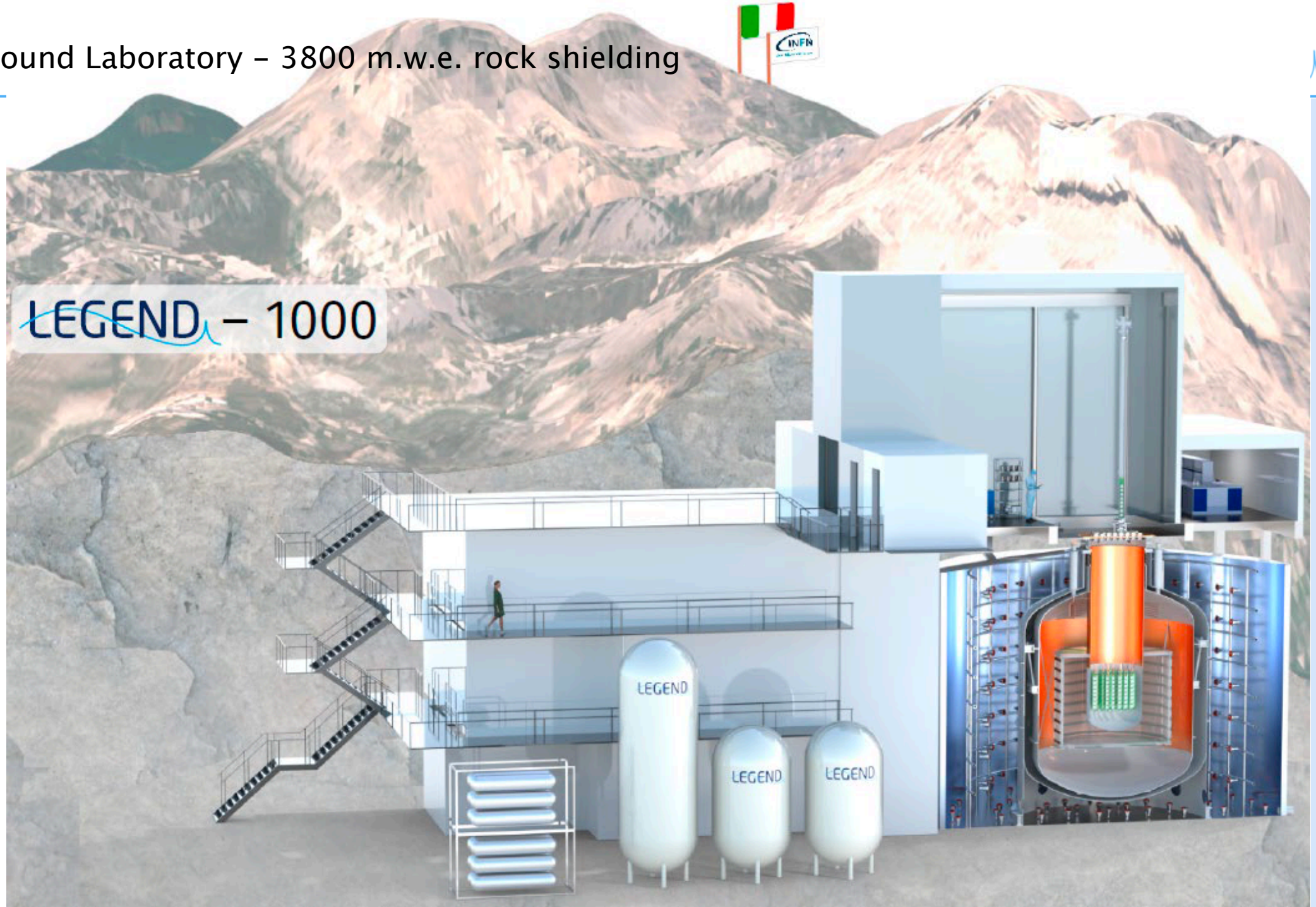
[1]**zero-background:** <1 background events expected in a FWHM range around $Q_{\beta\beta}$ for the entire live time of the experiment

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

"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."

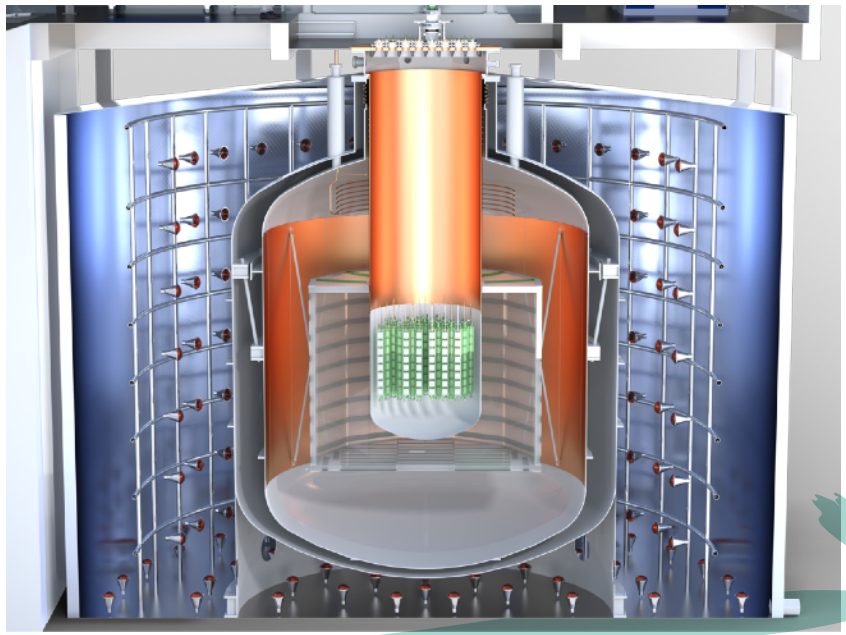
300 members, 60 institutions, 13 countries

LNGS Underground Laboratory – 3800 m.w.e. rock shielding



The LEGEND Project

Background Index: number of counts around $Q_{\beta\beta}$ divided by M, t per energy window



GERDA

MAJORANA Demonstrator

completed in ~2020

LEGEND-200

200 kg using GERDA infrastructure @LNGS

Background Index Goal: 2×10^{-4} cts/(keV kg yr)

$T^{0\nu}_{1/2} > 10^{27}$ yr after **5 years of data**

See talk by **Giovanna Saleh** for newest analysis and results

LEGEND-1000

1000 kg in new infrastructure @LNGS

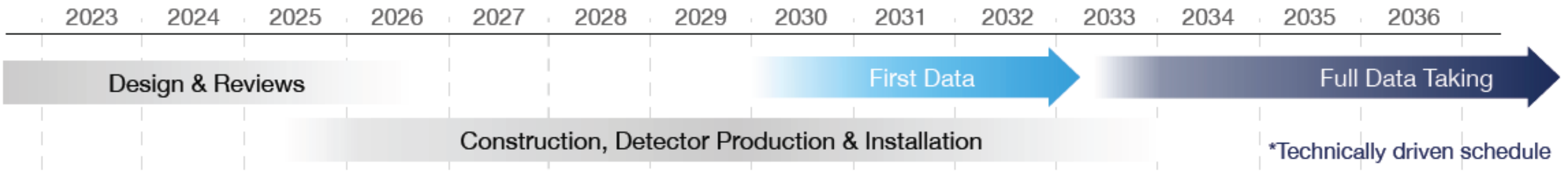
Background Index Goal: $< 1 \times 10^{-5}$ cts/ (keV kg yr)

$T^{0\nu}_{1/2} > 10^{28}$ yr after **10 years of data**

LEGEND-1000 will span the inverted ordering and part of the normal ordering space

Characteristics:

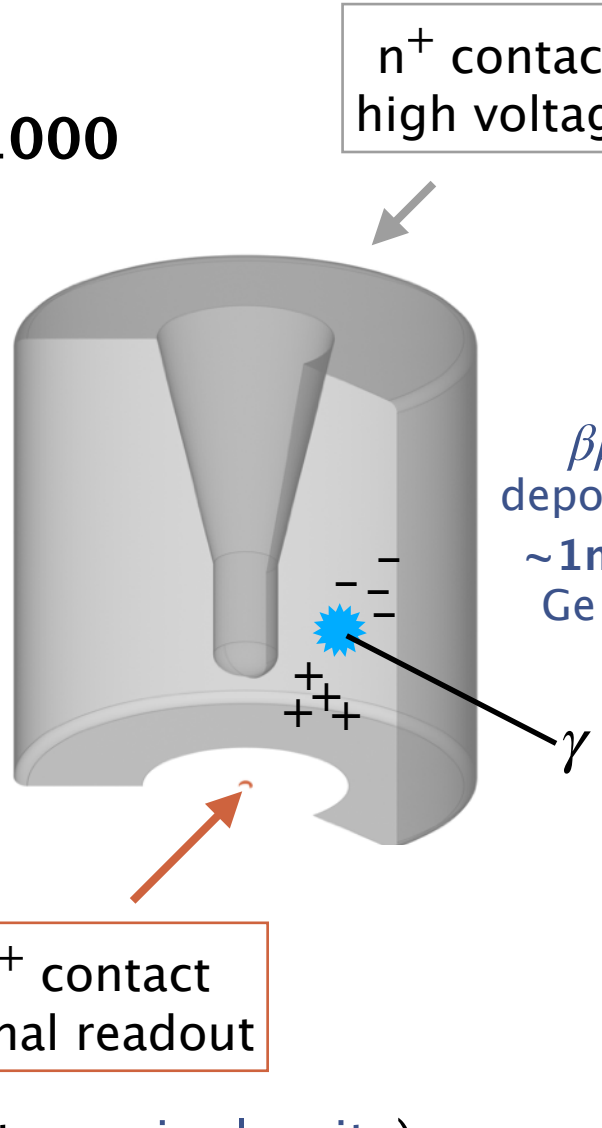
- 0νββ decay isotope: ^{76}Ge
- $Q_{\beta\beta}$: 2039 keV
- Energy resolution at $Q_{\beta\beta}$: 2.5 keV FWHM
- Total active mass: 1000 kg
- Total exposure: 10 t·yr
- Background goal: $< 10^{-5}$ cts/(keV·kg·yr); < 0.025 cts/(FWHM·t·yr)
- $T^{0\nu}_{1/2}$: $1.3 \cdot 10^{28}$ yr (90% C.L. discovery)
- $m_{\beta\beta}$: 9.4 – 21.4 meV (99.7% C.L. discovery)
- Underground location 3800 m.w.e. in LNGS, Italy

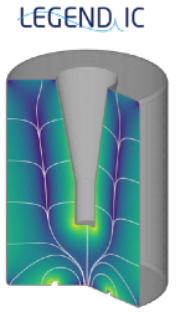


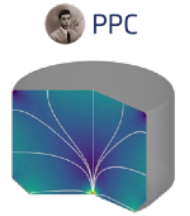
Signal enhancement: High Purity Ge Detectors

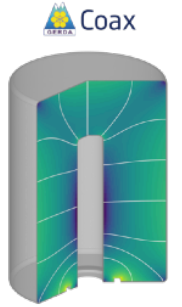
Inverted-Coaxial Detectors for LEGEND-1000

- enriched >90% in ^{76}Ge ⇒ source = detector
- $0\nu\beta\beta$ signature ⇒ peak at $Q_{\beta\beta} = 2039$ keV
- Large active mass up to 3 kg
- Reduced background due to lower number of channels per mass of ^{76}Ge
- excellent energy resolution
- excellent pulse shape discrimination (multi-site vs single-site)









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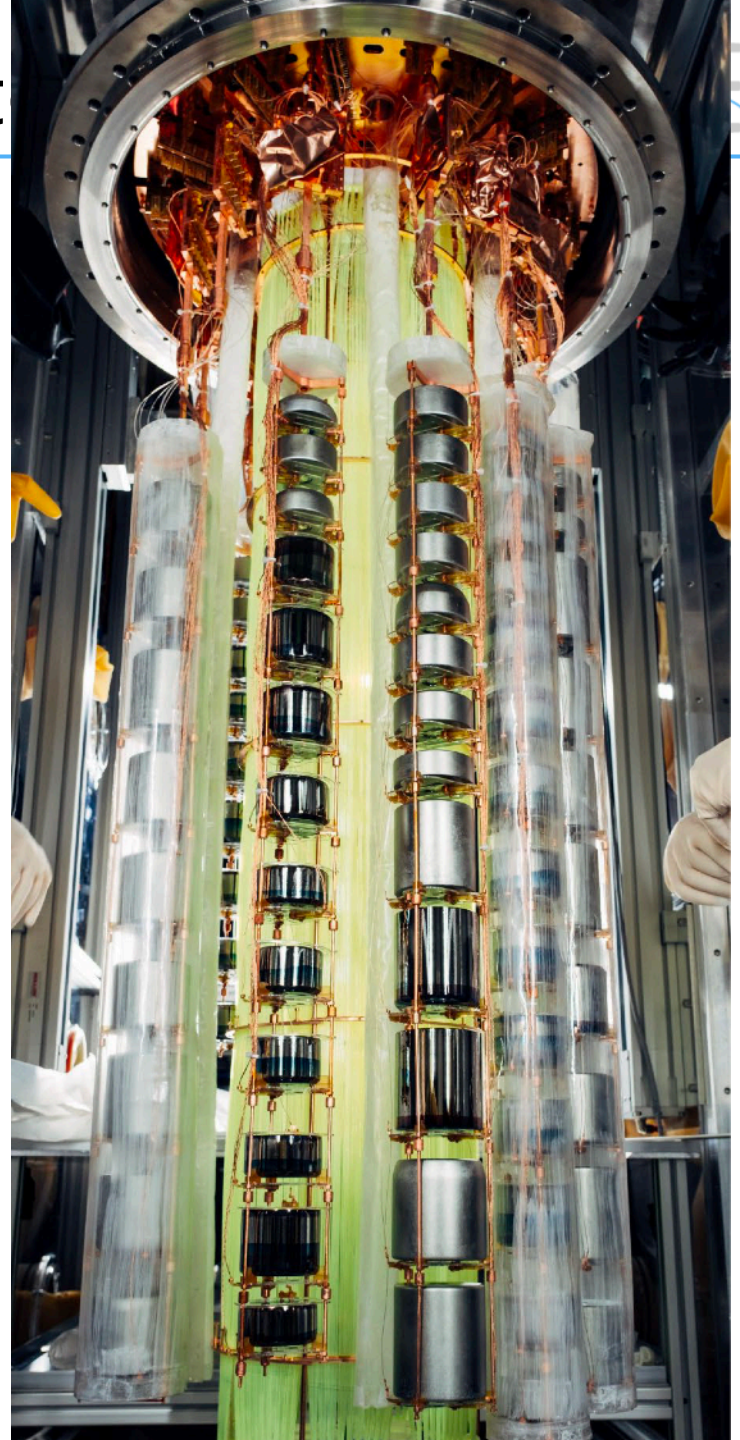
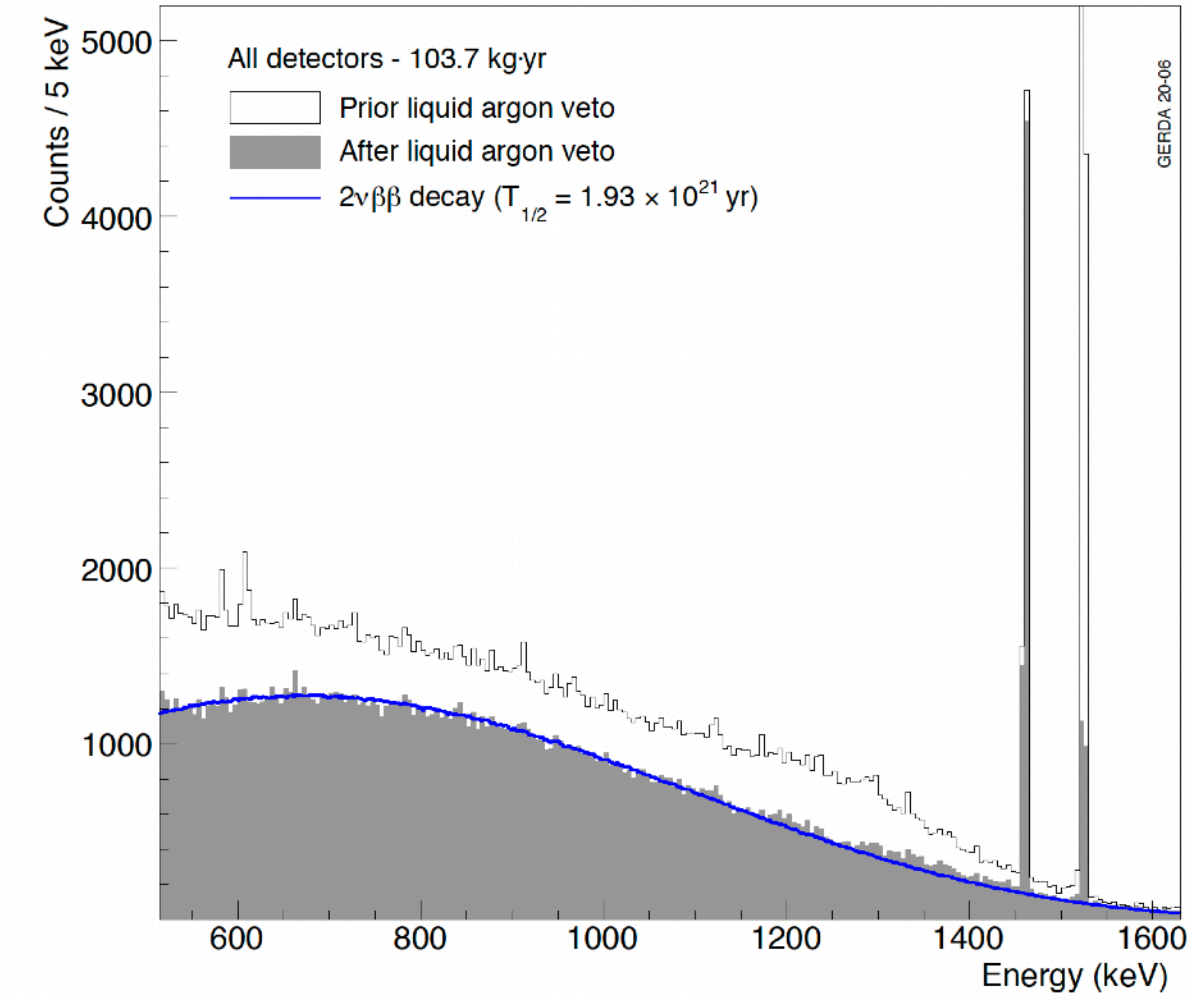


Background mitigation strategies

- LAr instrumentation



GERDA example:

LAr scintillation light detection system enclosing the Ge-detector array.

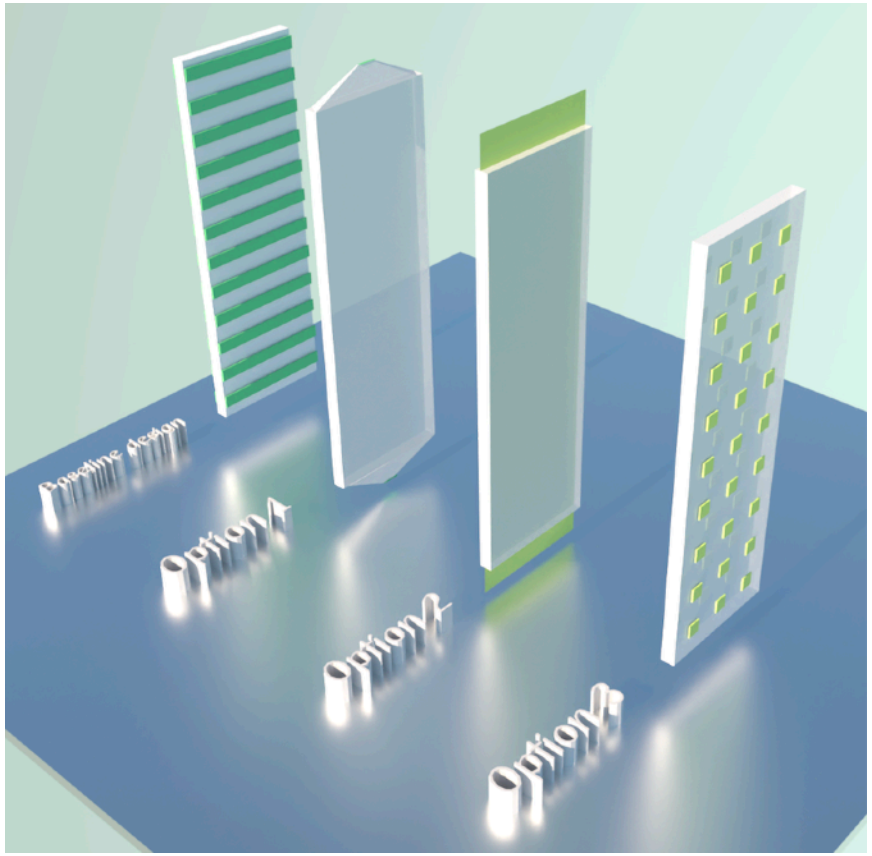
Energy spectrum measured in GERDA Phase II and 2νββ events selected by rejecting background that creates LAr scintillation light.

The expected contribution due to 2νββ decays based on the measured half-life value

^{40}K and ^{42}K lines -> use of underground Argon

Background mitigation strategies

- Inner Neutron moderator



Problem:
^{77}Ge and ^{77m}Ge isotopes – cosmogenic background

Mainly produced via neutron capture on ^{76}Ge

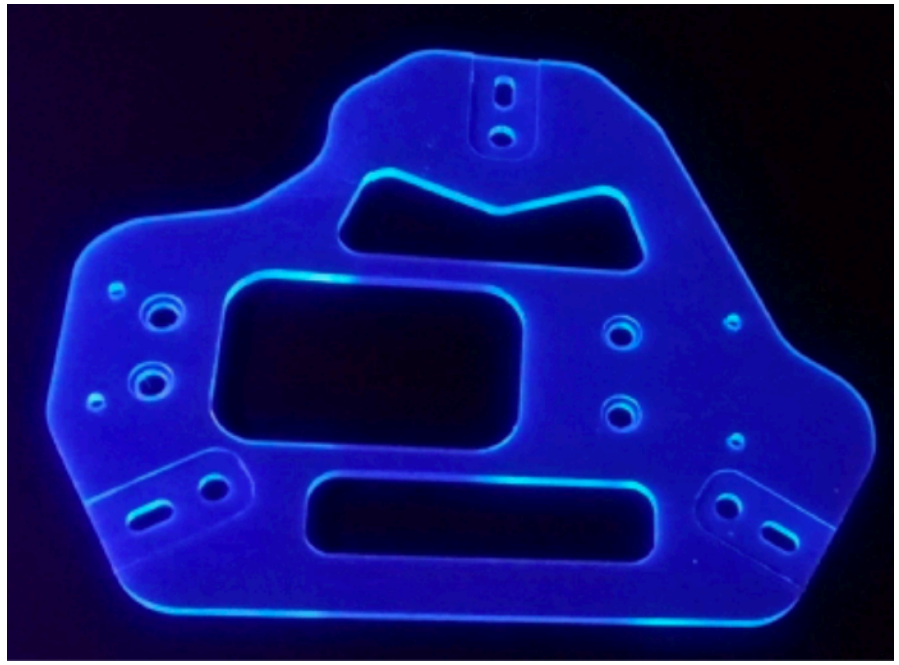
Solution:
Acrylic (PMMA) shield

A passive layer of a hydrogen-rich material to reduce the energy of fast neutrons produced by cosmic muons

+ Light detection system

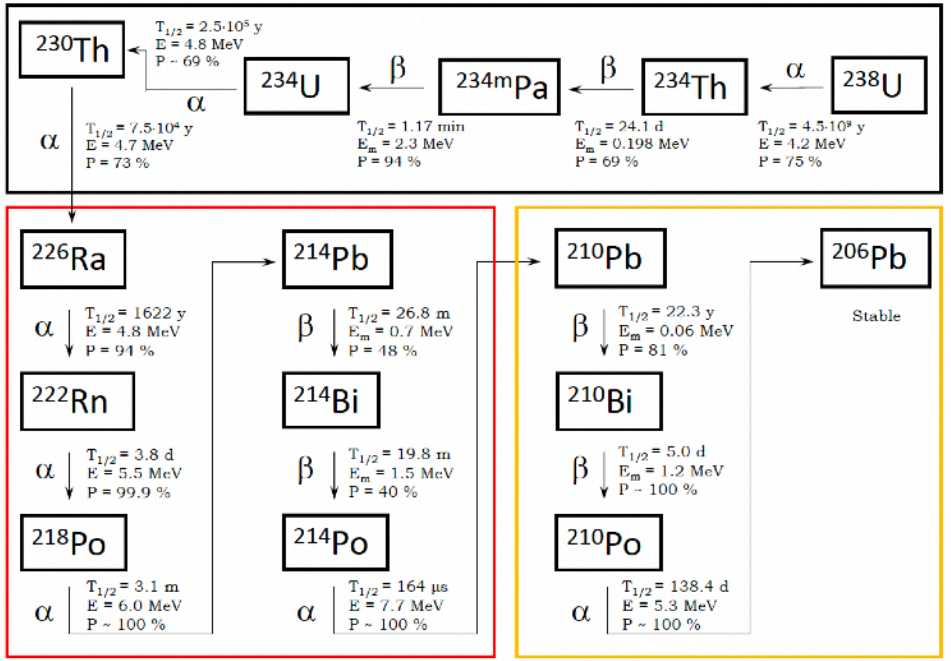
Background mitigation strategies

- Minimal mass (to extreme) of construction materials around the HPGe crystals
- Use of Electro Formed copper
- PEN plates as support (radio clean and optically active material)



Background mitigation strategies

- Construction materials radio-assay,



Monitoring of Material purity throughout the fabrication and installation of the LEGEND-1000 experiment.

Solution:
mass spectrometry,
direct γ-ray counting,
neutron activation analysis,
surface assay (contamination with long-lived Rn progeny),
Rn emanation (determination of Ra/Rn and the short-lived progeny).

The three parts of ^{238}U are usually in disequilibrium thus, they should be assayed separately…

Base design for LNGS infrastructure, Hall C

Horizontal access allows to prefabricate larger pieces of infrastructure outside of the lab

Shared with LNGS external cryogenic infrastructure for Underground Argon storage and filling.

Atm Argon purification plant

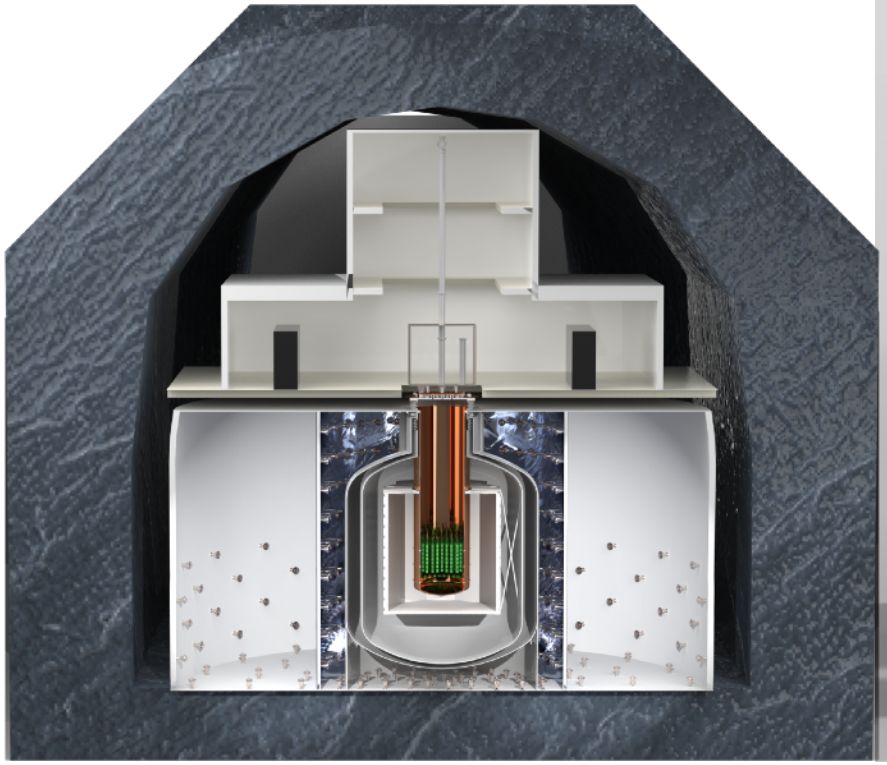
Multiple rooms for DAQ, Slow Control

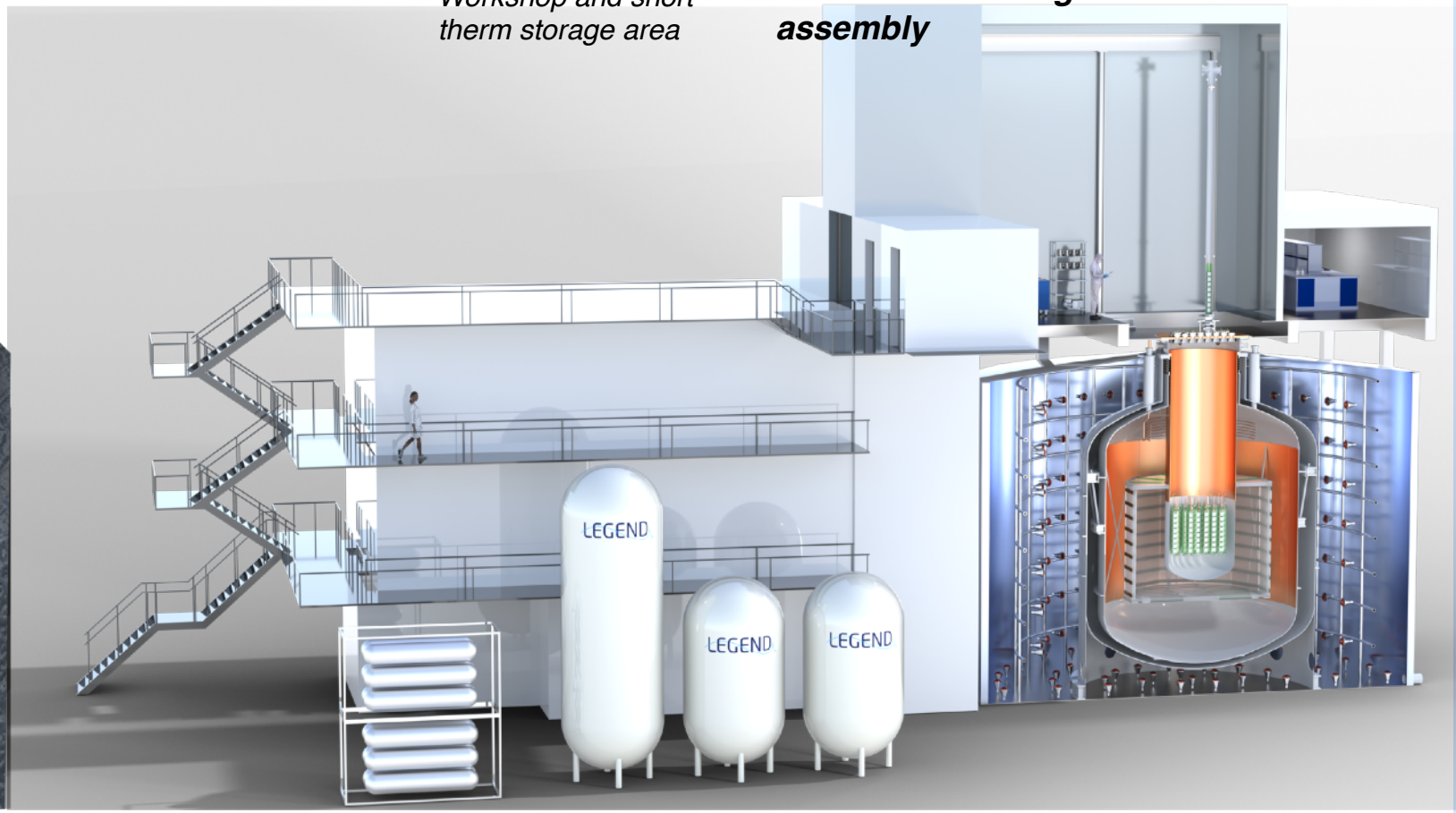
Pumping stations

Workshop and short therm storage area

Clean area (Clean room with N2 flushed gloveboxes) for HPGe detectors mounting,

Clean room for argon instrumentation assembly





Base design for LNGS infrastructure

detector strings each surrounded by ***instrumented LAr veto***

neutron moderator *(PMMA) to suppress background induced by n produced by cosmic rays interactions.*

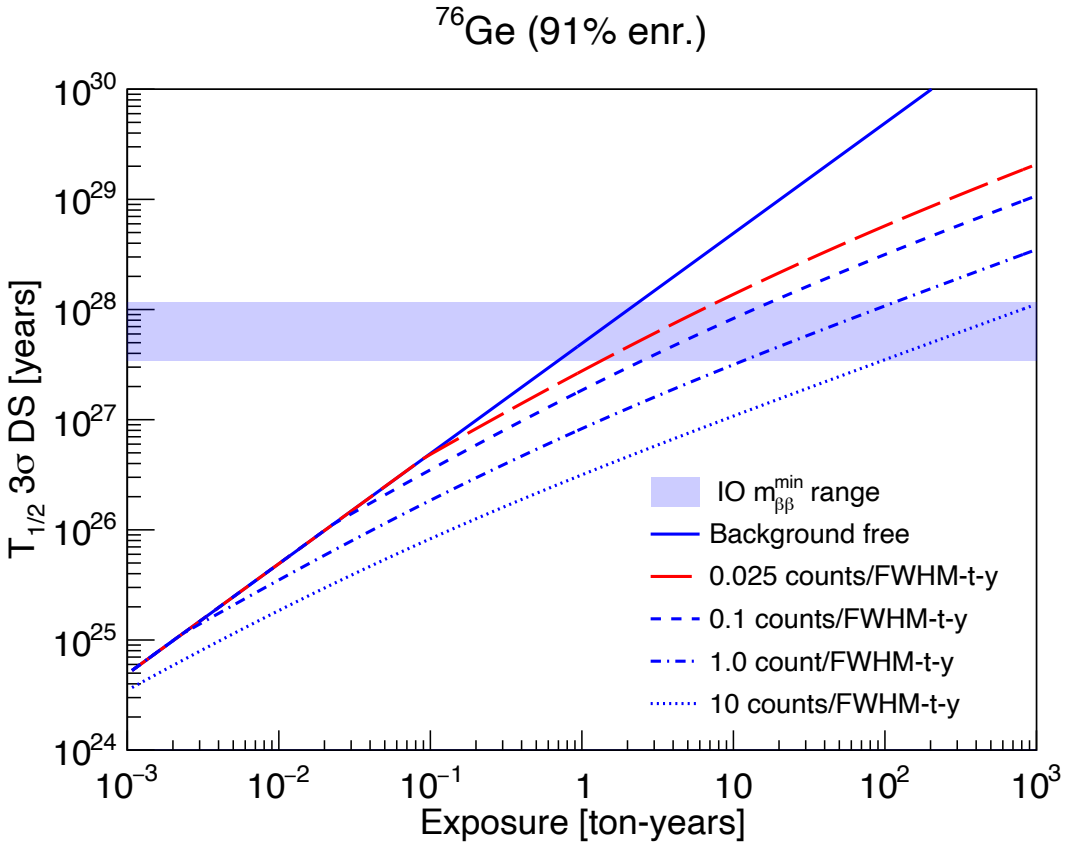
re-entrant tube (with EF Copper) filled with ***underground LAr*** *(reduction of ^{42}K background from cosmogenic ^{42}Ar isotope, similar to the reduction of ^{39}Ar)*

water tank (Cosmic muons tagging, external neutron suppression)

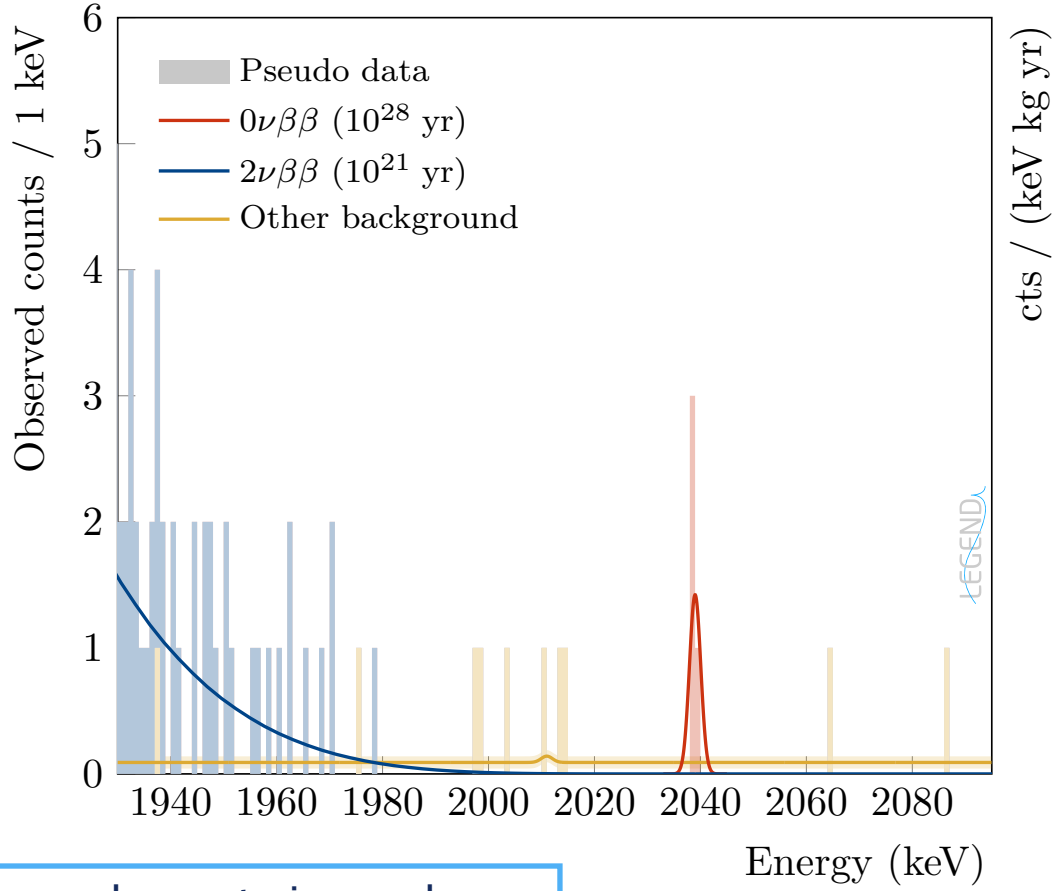
cryostat filled with purified atmospheric LAr

lock system: *detector strings can be individually installed: early data as detectors are produced*

Toward a tonne scale experiment: LEGEND-1000



Simulated spectrum, after cuts, 10 years of data



Expected number of background counts is much lower than 1 in the FWHM at full exposure!

LEGEND-1000 is designed for unambiguous discovery of $0\nu\beta\beta$ at $T_{1/2} > 10^{28}$ years

Summary

- LEGEND-1000 experiment was designed for unambiguous discovery and will cover neutrino mass inverted ordering parameter space
- wide R&D program to meet the quasi-background free operation goal
- low-risk path to meeting its goal based on MAJORANA, GERDA and LEGEND-200
- preparations underway at LNGS following Borexino decommissioning

Backup

LEGEND Sensitivity

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} \; g_A^4 \; |M_{0\nu}|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2$$

picture from
arXiv:2202.01787 [hep-ex]

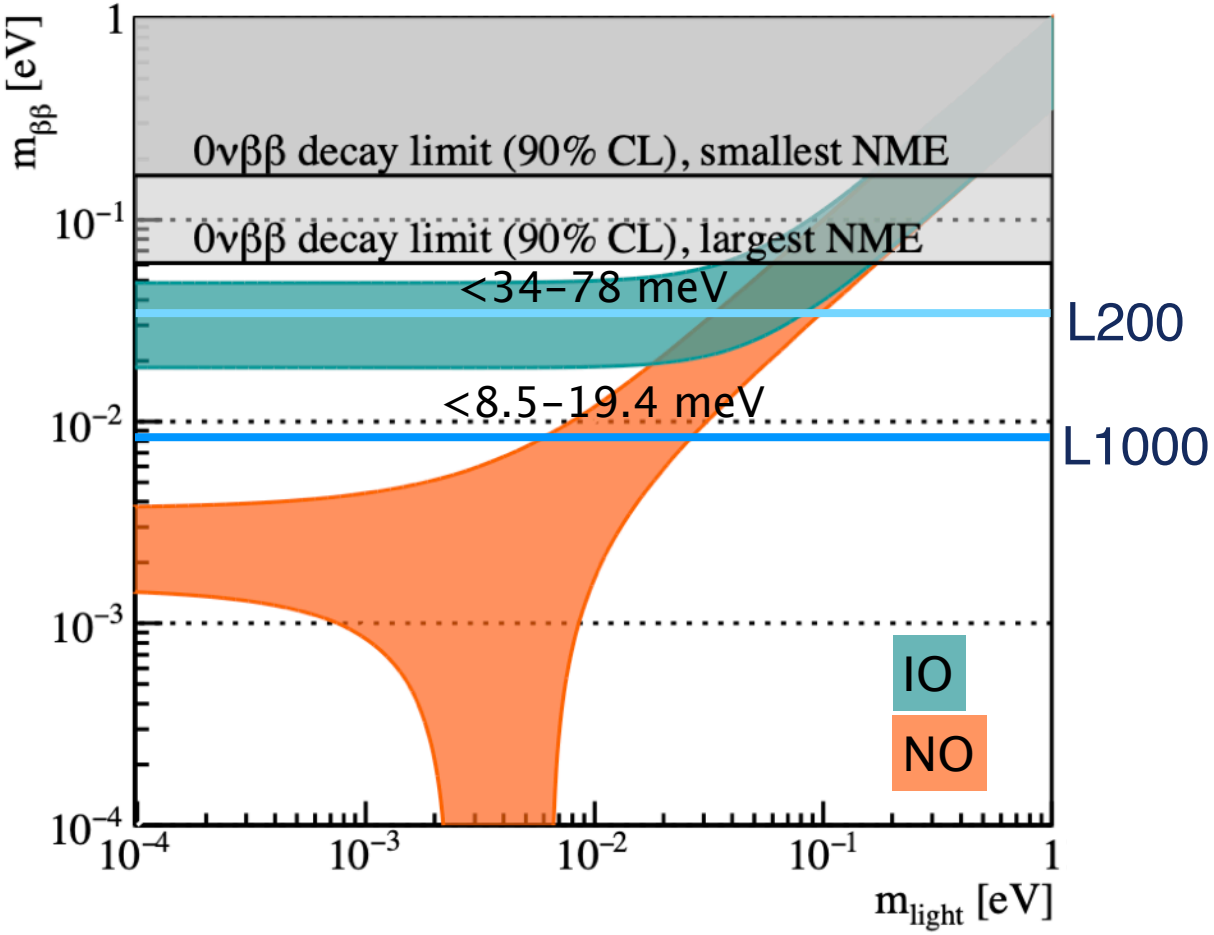
limits from
A. Gando et al. (KamLAND-Zen Collaboration) Phys. Rev Lett. 122, 192501

Phase Space Element
Information about the kinematic of the process

Nuclear Matrix Element and axial coupling
Probability amplitude of passing from initial to final state nucleus.
Different many body models used to evaluate it.

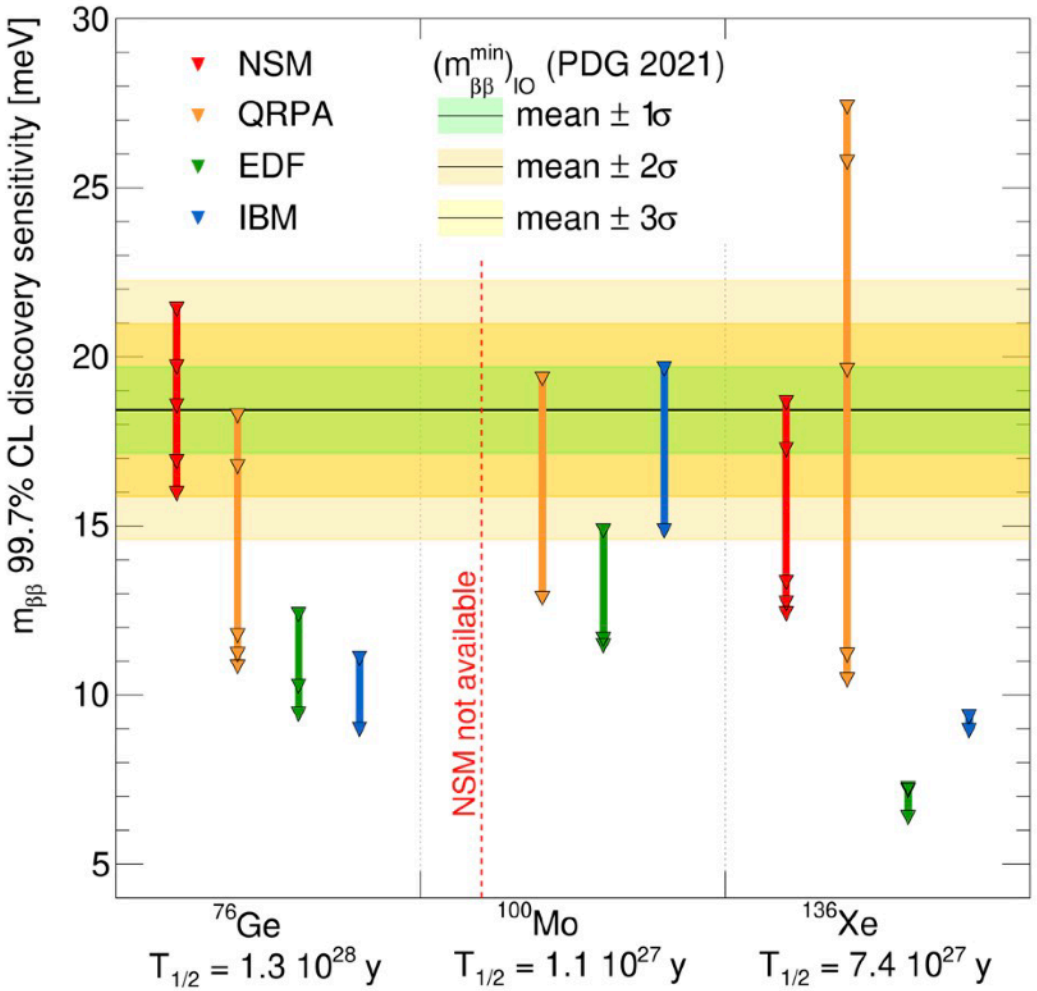
Beyond Standard Model Physics
In this case light neutrino exchange.
$m_{\beta\beta}$ is called **Effective Majorana Mass**

$$m_{\beta\beta} = \Sigma_k U_{ek}^2 m_k$$



Limits on $m_{\beta\beta}$ for different models on matrix element

Agostini, Detwiler, Benato, Menendez, Vissani
PRC, 104 (4) L042501 (2021)



LEGEND – ^{76}Ge

CUPID – ^{100}Mo

NeXO – ^{136}Xe

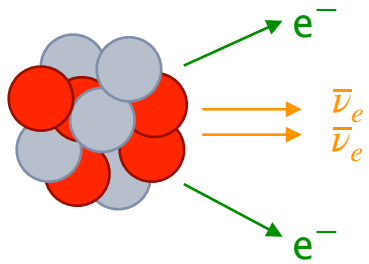
- The discovery sensitivity required depends on the matrix element used

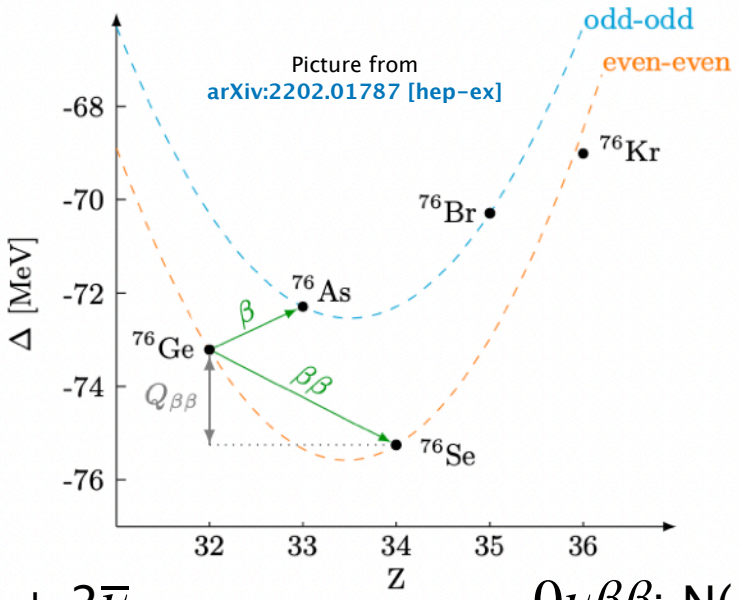
- The range of values given depends on the matrix elements that has been calculated for each isotope

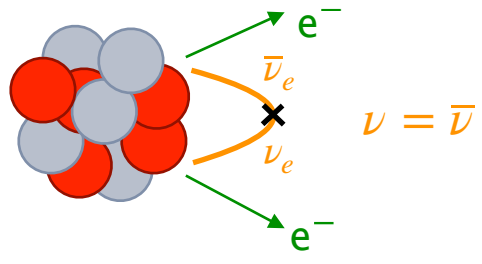
- LEGEND-1000 will fully test inverted order and a large part of the normal ordering

Double Beta Decay

When a single β decay is energetically not allowed…







$2\nu\beta\beta$: N(A,Z) → N(A,Z+2) + 2e⁻ + 2$\overline{\nu}_e$

$0\nu\beta\beta$: N(A,Z) → N(A,Z+2) + 2e⁻ ~~+ 2$\overline{\nu}_e$~~

Already observed in about 10 isotopes:

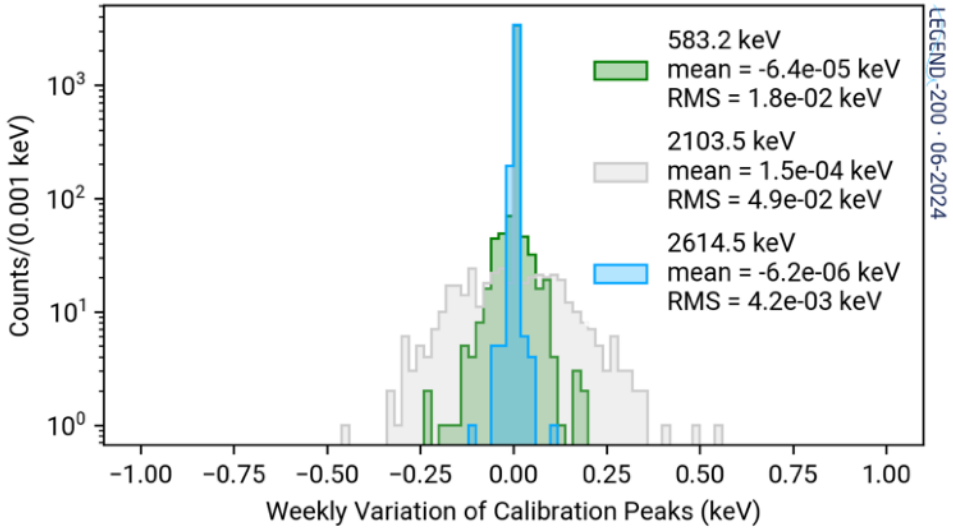
- Allowed in the Standard Model (SM)
- if β-decay final state is energetically not accessible
- $T_{1/2} \sim 10^{18} - 10^{22}$ yr

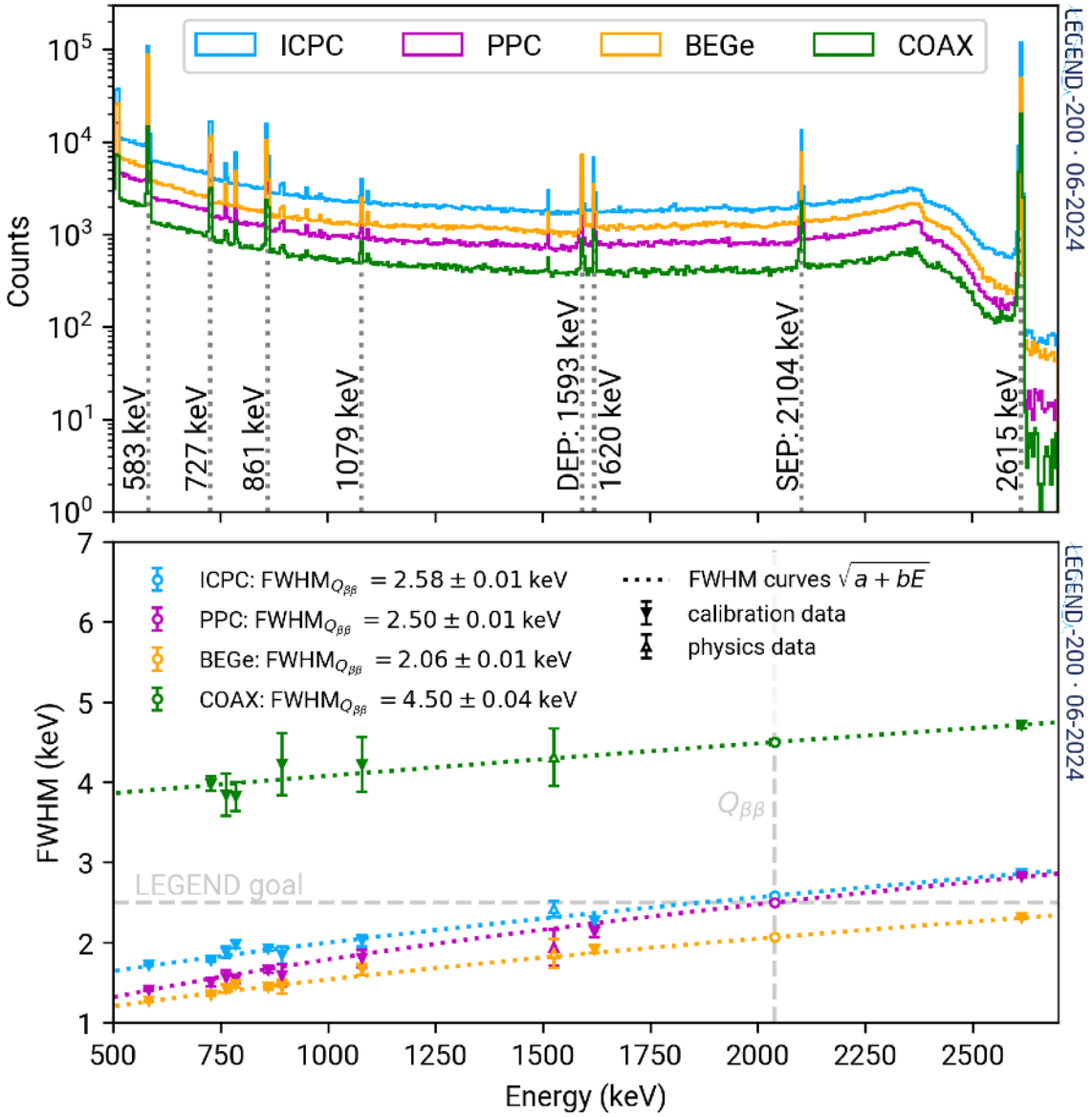
Never observed so far, not allowed in SM:

- L and B-L violation: $\Delta L = 2$
- $\nu = \overline{\nu}$ (Majorana particle)
- hint on matter/antimatter asymmetry
- information about ν mass scale and ordering

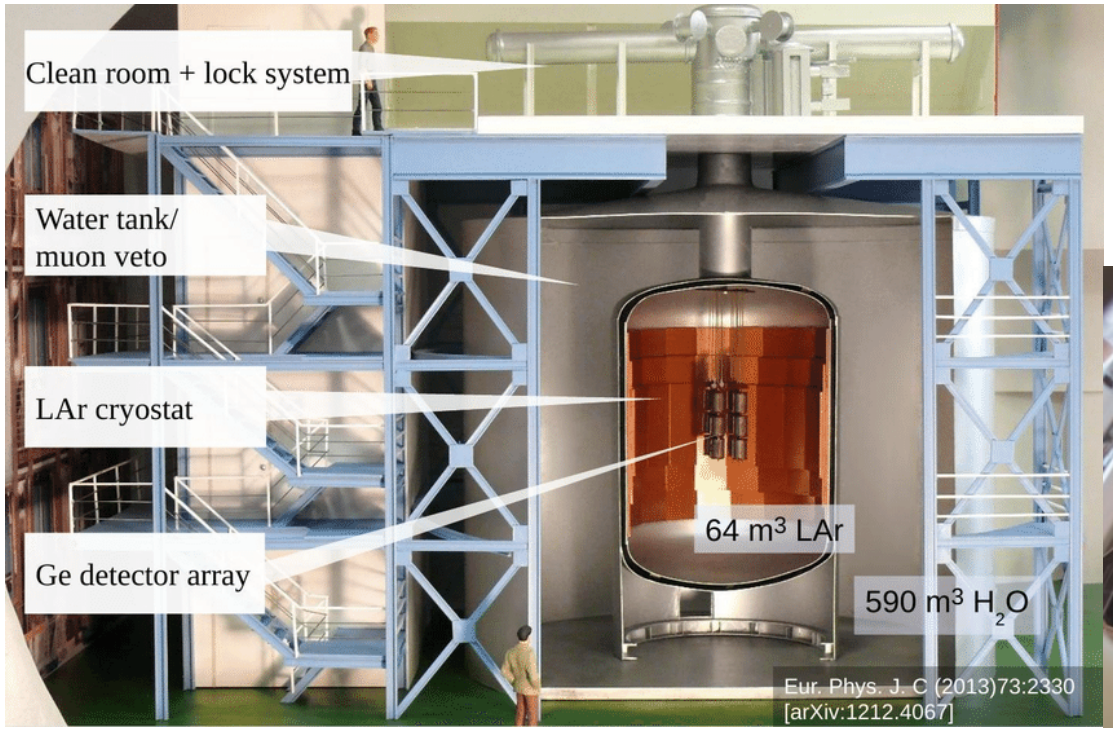
Energy Scale and Resolution

- Weekly calibrations with ^{228}Th sources
- Stable energy observables
- ~0.1% FWHM at $Q_{\beta\beta}$





GERmanium Detector Array



- Located at LNGS (Italy)
- ~40 kg of Ge detectors divided into 7 strings
- Enrichment up to 88% in ^{76}Ge
- Lasted from 2011 to 2019

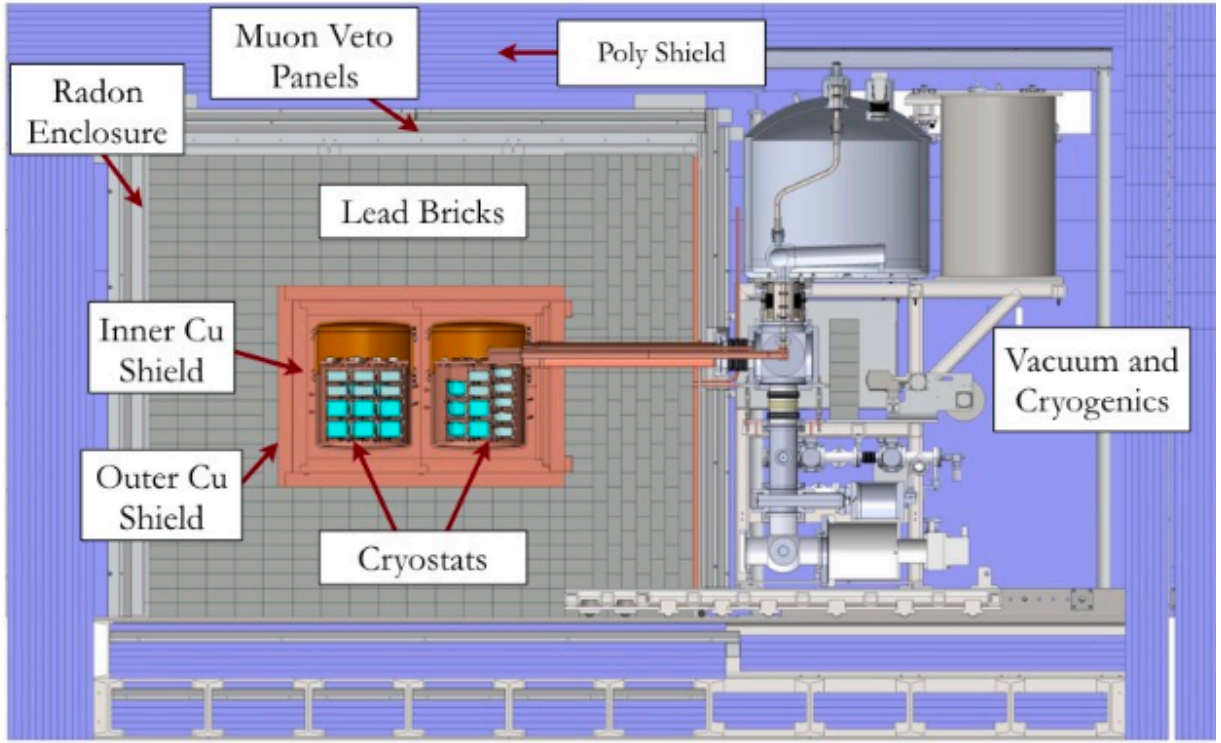
Major innovations also adopted in LEGEND:

- Ge detectors directly in contact with LAr
- LAr scintillation light read out system implemented
- Low Z shield, no Pb

Lowest Background Index in a $0\nu\beta\beta$ experiment: 5.2×10^{-4} counts/(keV kg yr)

[Phys. Rev. Lett. 125, 252502]

MAJORANA Demonstrator



- Located at SURF (South Dakota, US)
- Total of ~44 kg of Ge detectors divided into 2 modules
- 29.7 kg are enriched up to 88% in in ^{76}Ge
- Lasted from 2011 to 2022

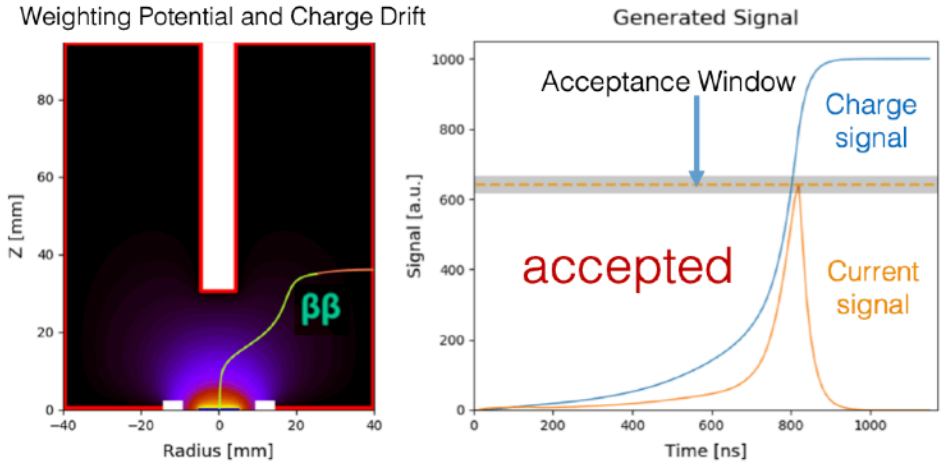
- Radiopurity of nearby parts
- Low Noise electronics (better PSD)
- Low Energy Threshold

Best Energy resolution in the field:
2.53 ± 0.08 keV

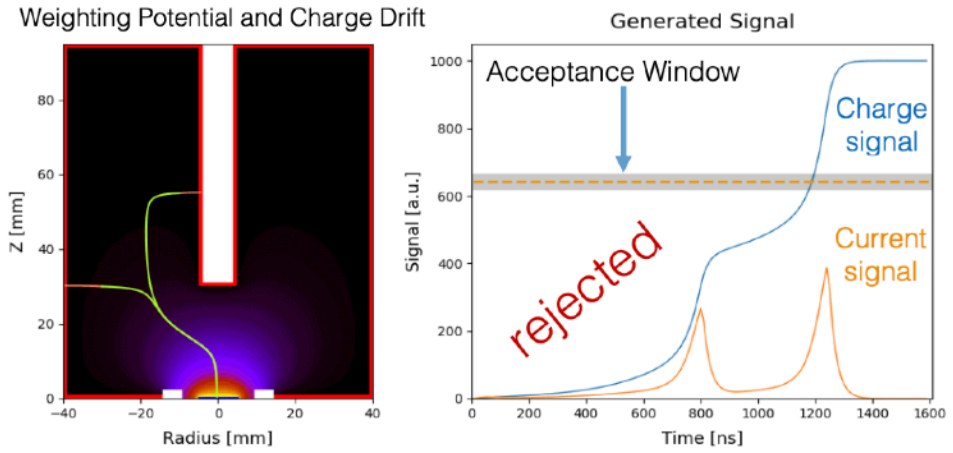
arXiv:2207.07638 [nucl-ex]

Background Reduction – Pulse Shape Discrimination

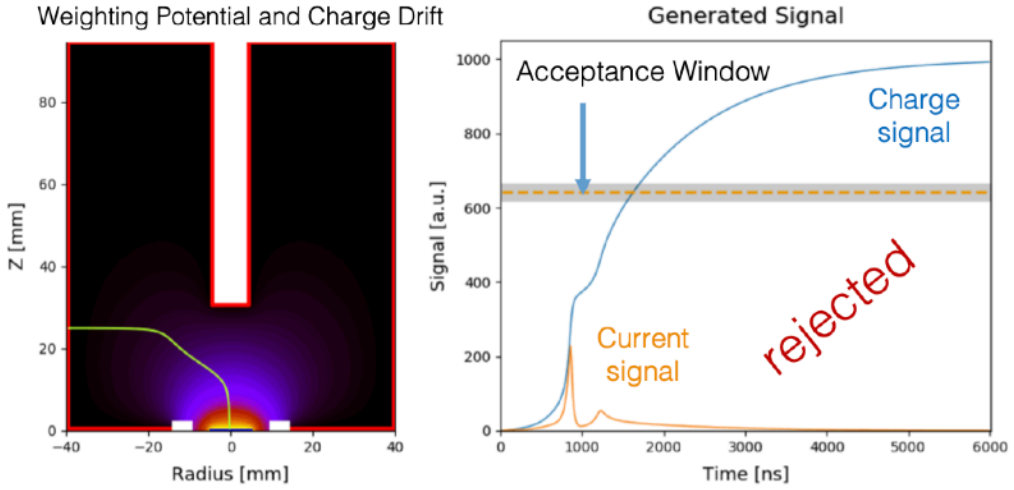
0νββ signal candidate (single-site)



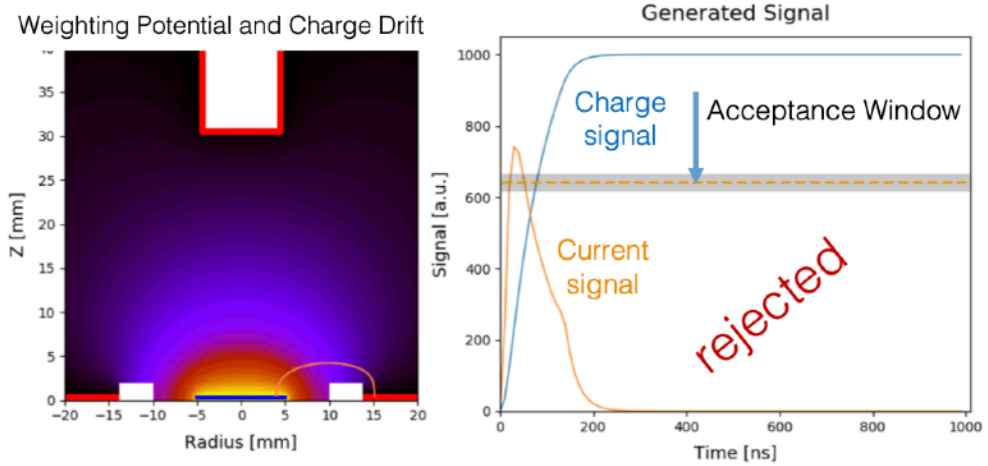
γ-background (multi-site)



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



α-background on p+ contact

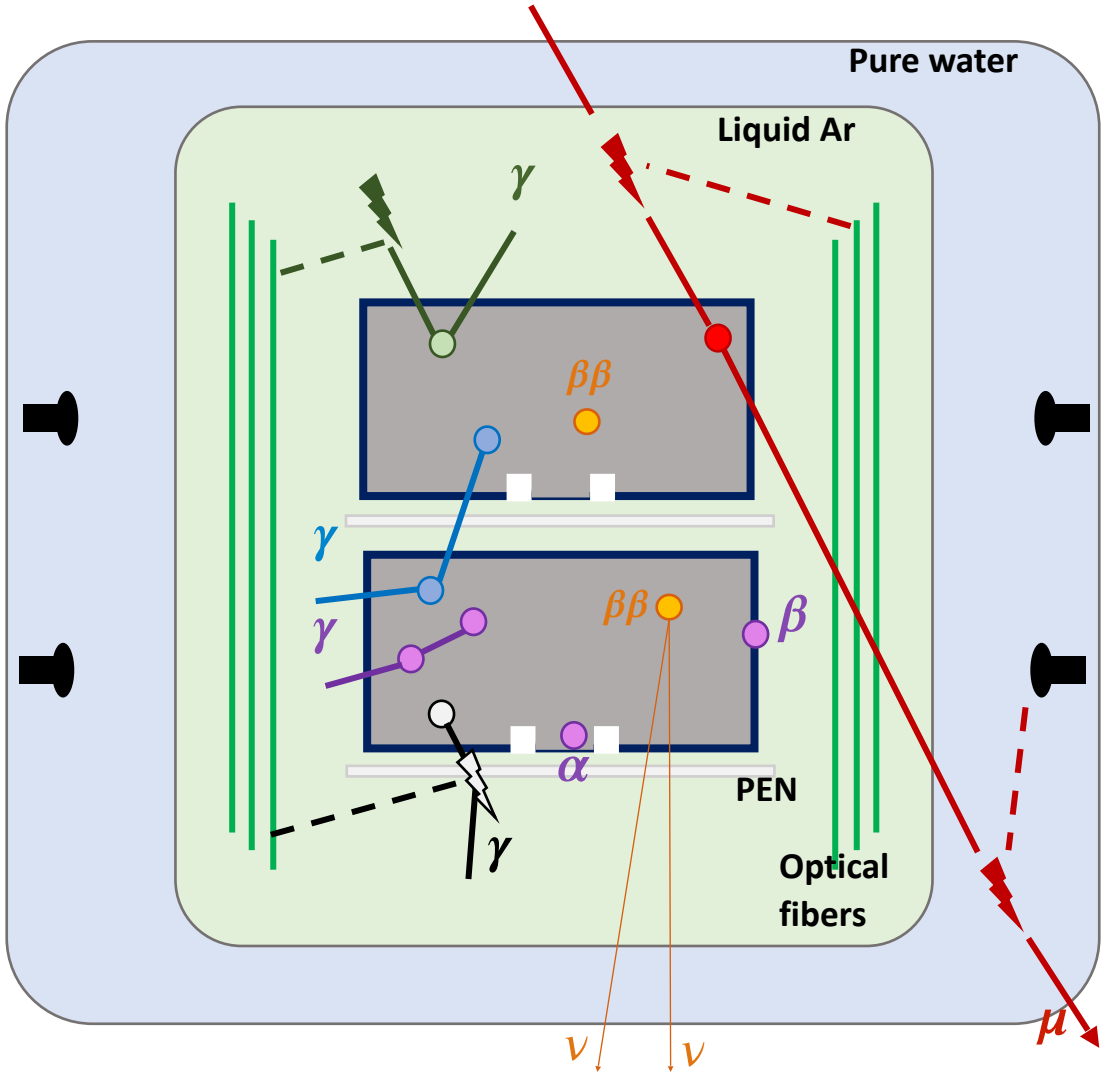


Background Reduction – Active Vetoes

$\beta\beta$ decay signal: single energy deposition in 1mm^3

Ge detectors anticoincidence

Scintillation light coming from PEN holders



LAr veto based on Argon scintillation light read by optical fibers and Silicon PhotoMultipliers

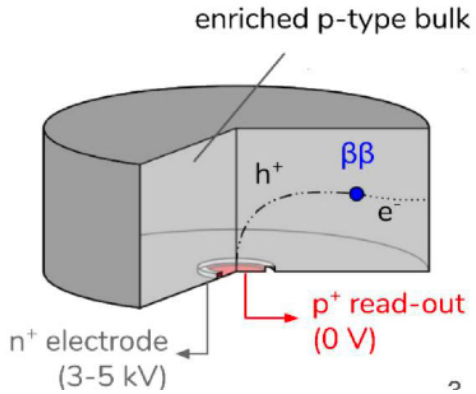
Muon veto based on Cherenkov light

Pulse Shape Discrimination for multi-site and surface events

Measurement Concept

HPGe detector directly submerged in Liquid Argon (LAr):

- minimize structural materials
- cryogenic temperature (~87K)
- good scintillator



^{76}Ge $0\nu\beta\beta$ features:

- $Q_{\beta\beta}$ = 2039 keV
- **~1mm^3** inside Ge detector
  - single Ge hit
  - single cluster event in bulk volume

$0\nu\beta\beta$ analysis:

- Ge detectors **(anti)**coincidence
- no energy in LAr
- pulse shape for surface interactions
- pulse shape discrimination for multiple energy deposition inside same detector