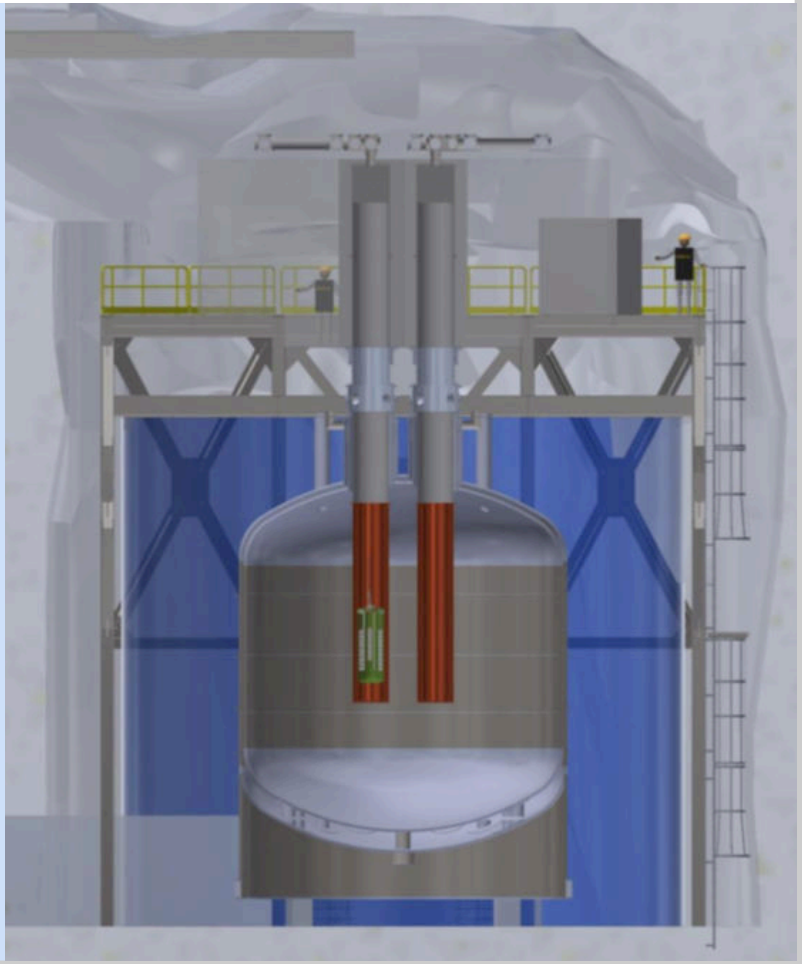
A new generation experiment for Neutrinoless Double Beta Decay

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Michele Morella

for the LEGEND collaboration



34th Rencontres de Blois

May 14–19

BLOIS

PARTICLE PHYSICS AND COSMOLOGY

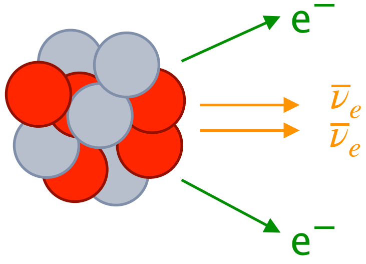
2023

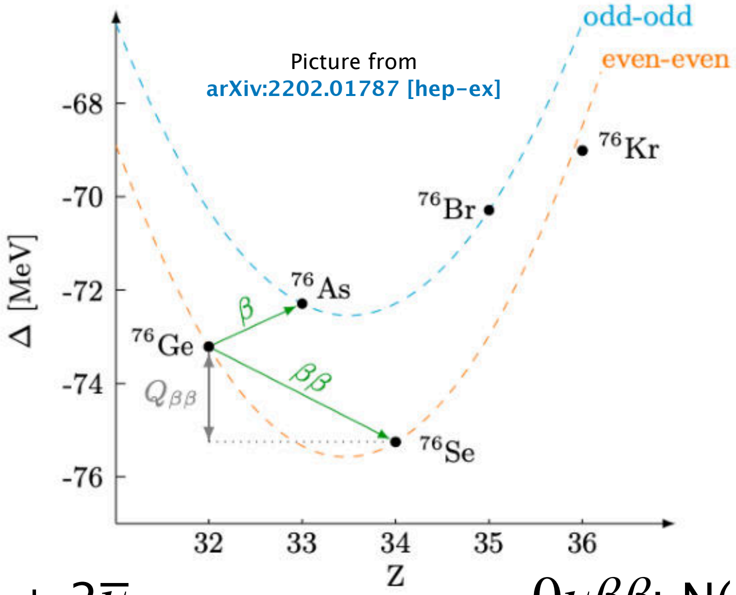
GSSI GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

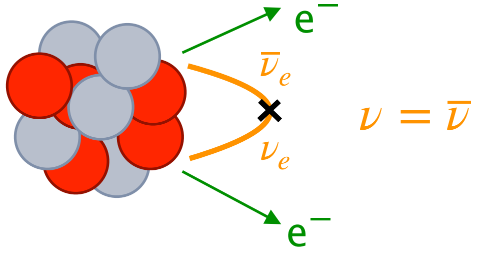
INFN LNGS

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$\bar{\nu}_e$

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

Already observed in about 10 isotopes:

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

Never observed so far, not allowed in SM:

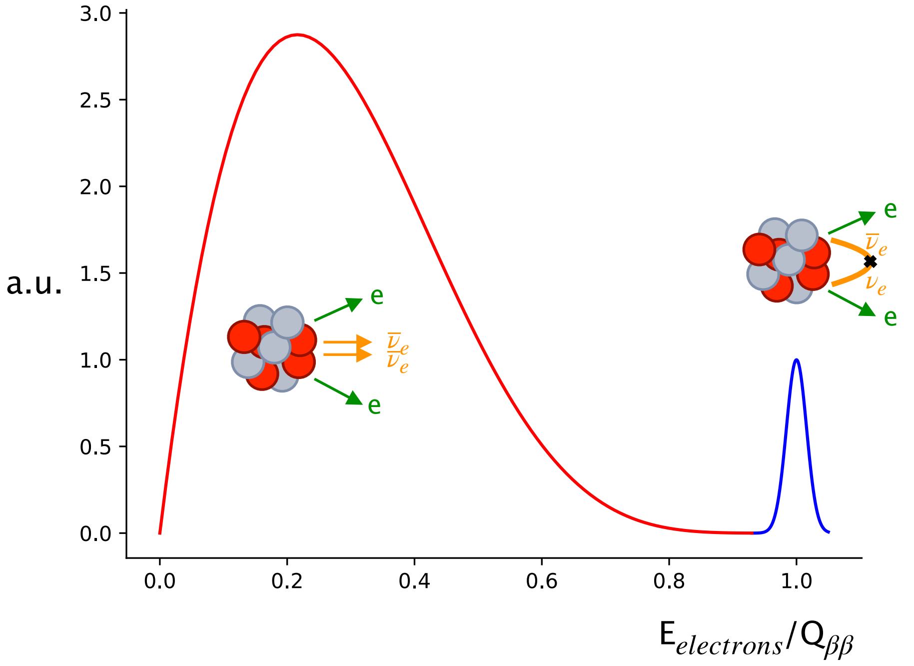
- L and B–L violation: ΔL = 2
- $\nu = \bar{\nu}$ (Majorana particle)
- hint on matter/antimatter asymmetry
- information about ν mass scale and ordering

The Collaboration

LEGEND Mission: “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.”

Collaboration Meeting in L’Aquila, October 2022

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



Advantages of Ge detectors:

- source = detector
- high density

⇒ energy deposited within ~**1mm**^{3} inside Ge detectors

- Excellent **energy resolution** FWHM/$Q_{\beta\beta}$ ~ 0.1%
- Excellent **pulse-shape** discrimination performance
- High intrinsic radiopurity

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

$$T^{0\nu}_{1/2} \propto \begin{cases} \epsilon \cdot \eta \cdot \sqrt{\dfrac{M\,t}{B\,\sigma}} \\ \epsilon \cdot \eta \cdot M\,t & \textbf{zero-background}^{1}\ \text{regime} \end{cases}$$

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

LEGEND phases

LEGEND-1000

1000 kg in new infrastructure @ SNOLAB
(Alternative Site: LNGS)

Background Index[2] Goal: $< 1 \times 10^{-5}$ counts/(keV kg yr)

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

LEGEND-200

200 kg using GERDA infrastructure at LNGS

Background Index[2] Goal: $< 2.5 \times 10^{-4}$ counts/(keV kg yr)

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

MAJORANA Demonstrator

GERDA

completed in ~2020

[2]**Background Index**: number of counts around $Q_{\beta\beta}$ divided by M, t and energy window

LEGEND Sensitivity

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

picture from
arXiv:2202.01787 [hep-ex]

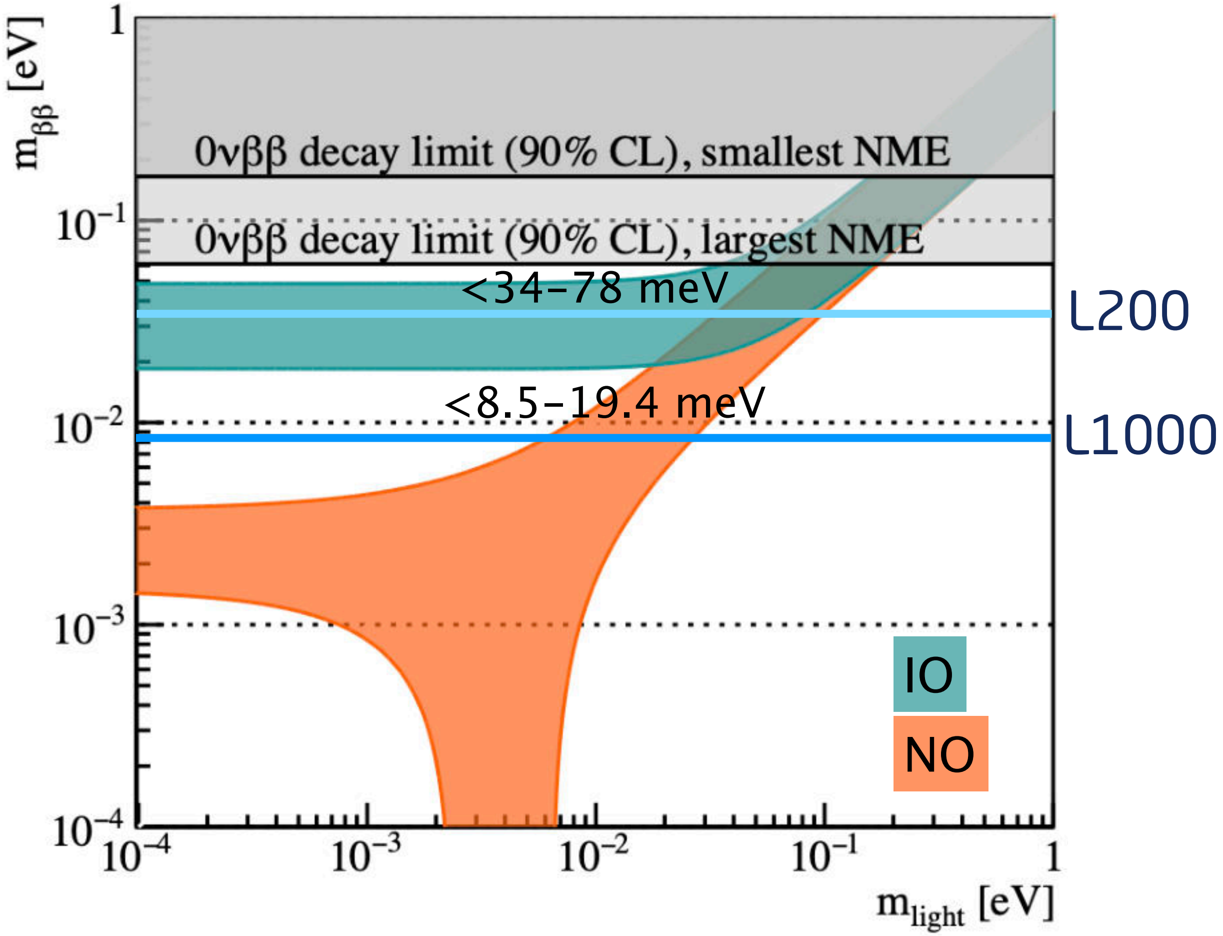
limits from
A. Gando et al. (KamLAND-Zen Collaboration) Phys. Rev Lett. 122, 192501

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**

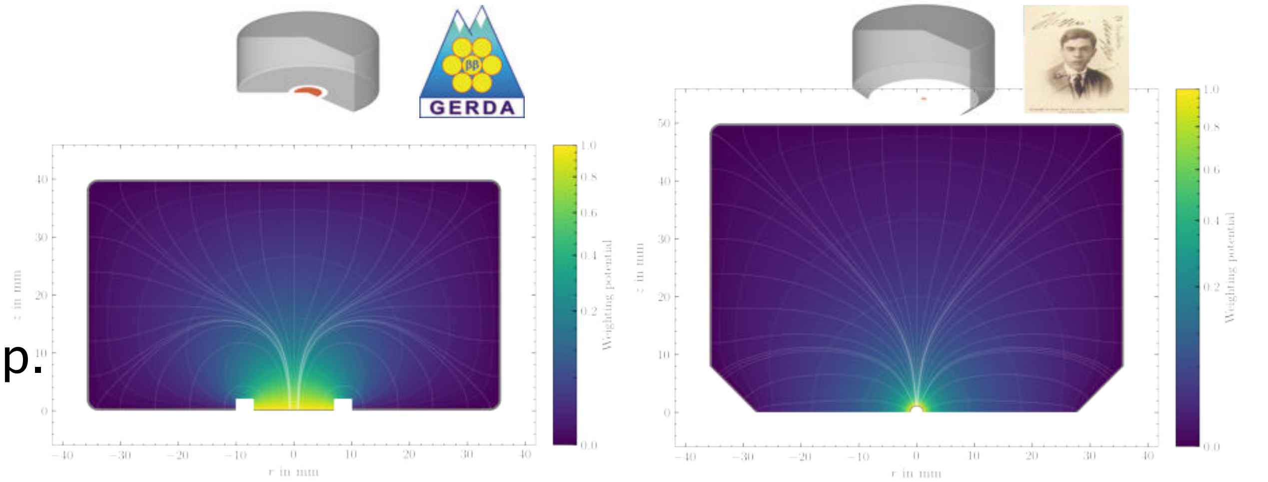
$$m_{\beta\beta} = \Sigma_k U^2_{ek} m_k$$



HPGe Detectors

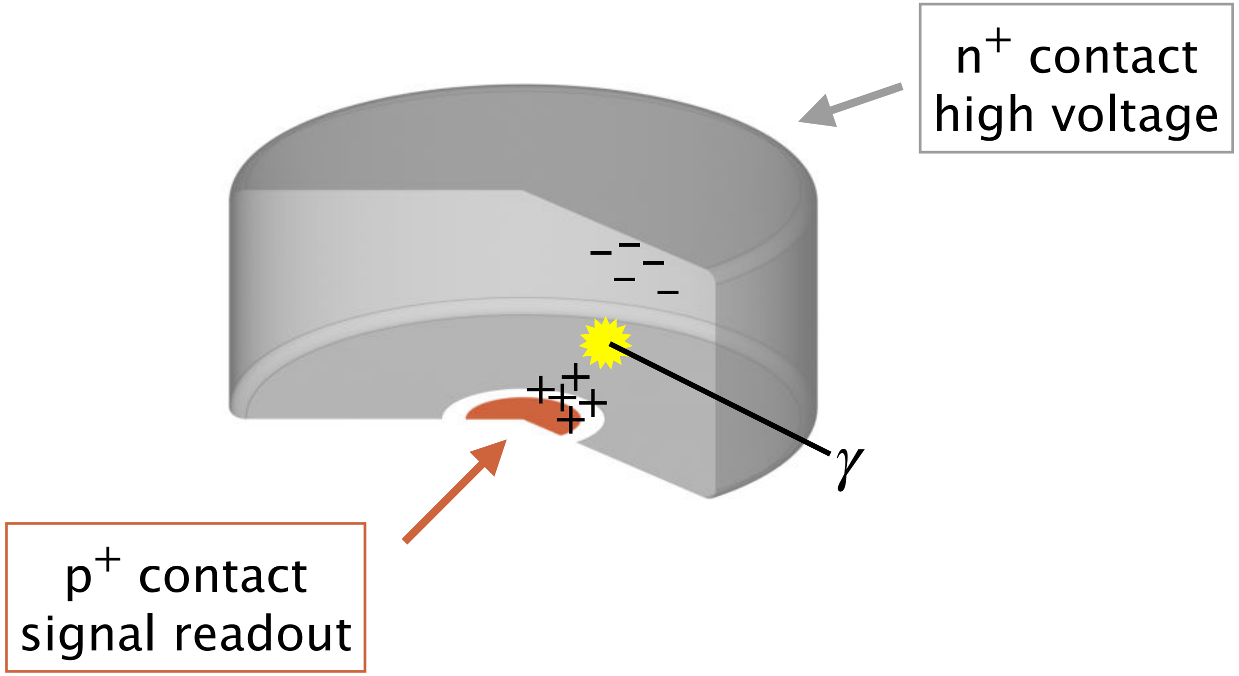
GERDA and MAJORANA detectors

- Excellent **energy resolution**
- Superb **pulse-shape** sensitivity to reject multi-site and surface background events
- **Relatively small**: <m> = 0.66 and 0.85 kg, resp.



p-type HPGe detectors

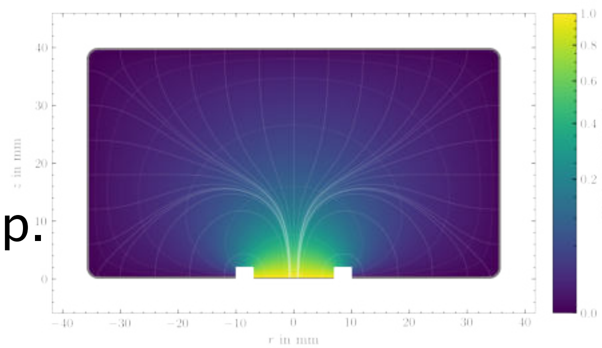
enriched in ^{76}Ge (~87%)

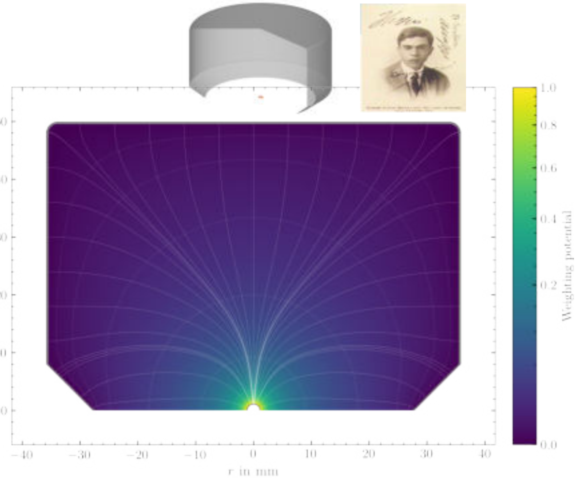


HPGe Detectors

GERDA and MAJORANA detectors

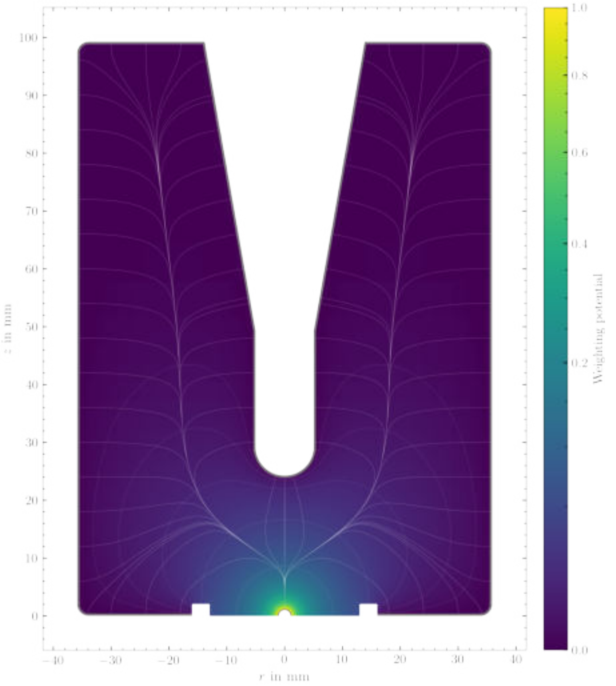
- Excellent **energy resolution**
- Superb **pulse-shape** sensitivity to reject multi-site and surface background events
- **Relatively small**: <m> = 0.66 and 0.85 kg, resp.





New Inverted-Coaxial Point Contact Detectors

- **Large active mass** up to 3kg
- Lower surface to volume ratio
- Reduced background due to lower number of channels per mass of ^{76}Ge
- Enriched >90% in ^{76}Ge
- Excellent **energy resolution**
- Excellent **pulse-shape** discrimination performance



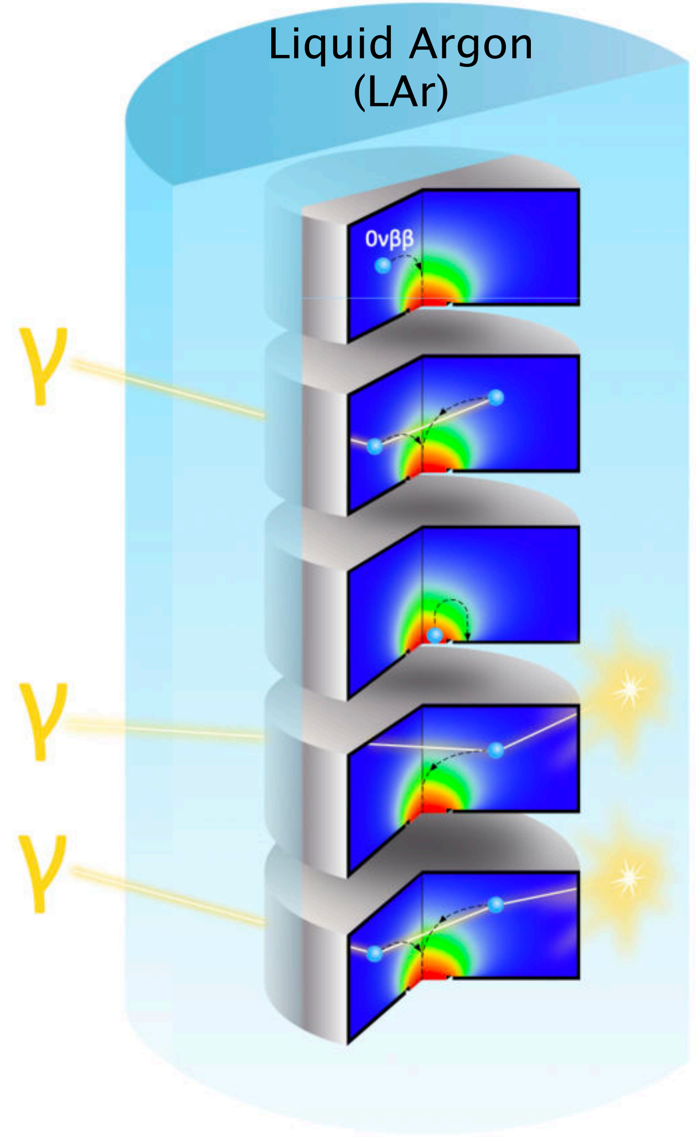
Design concept

^{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

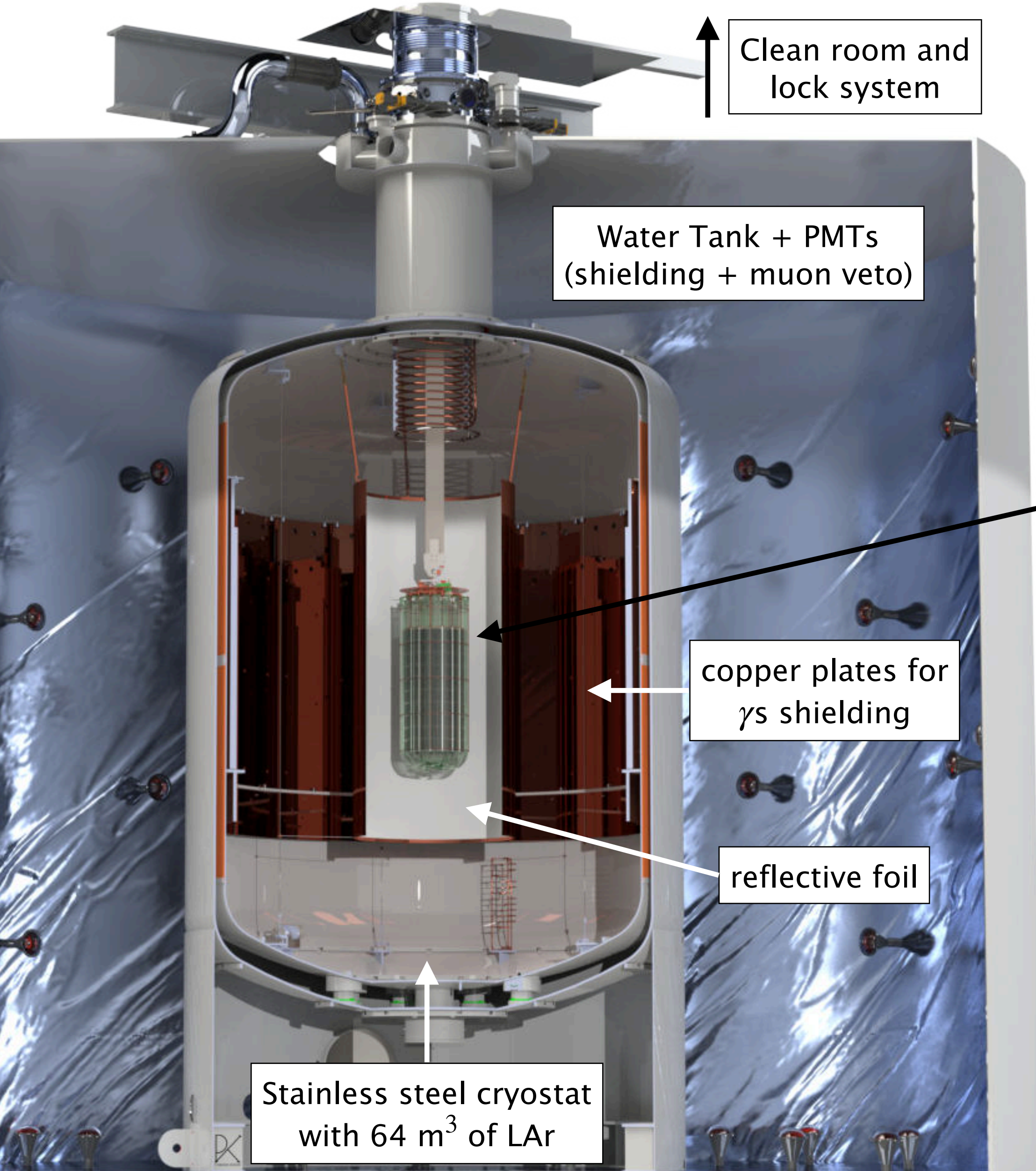
$0\nu\beta\beta$ analysis:

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

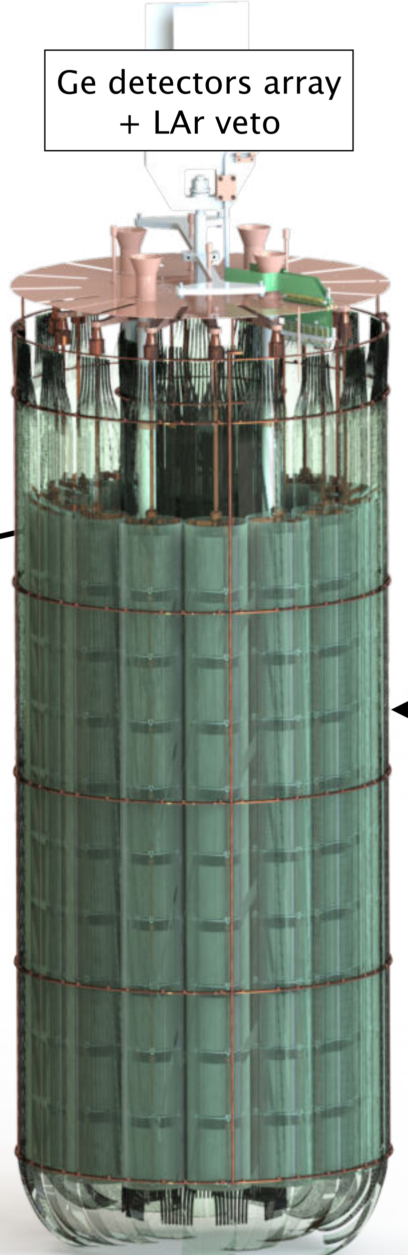


Minimize structural material around Ge detectors

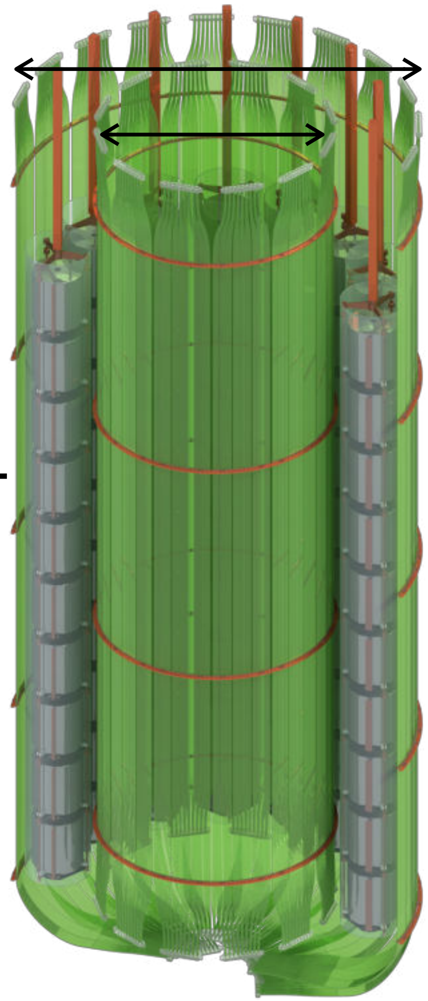
LEGEND-200



Clean room and lock system
Water Tank + PMTs (shielding + muon veto)
copper plates for γs shielding
reflective foil
Stainless steel cryostat with 64 m^3 of LAr



Ge detectors array + LAr veto

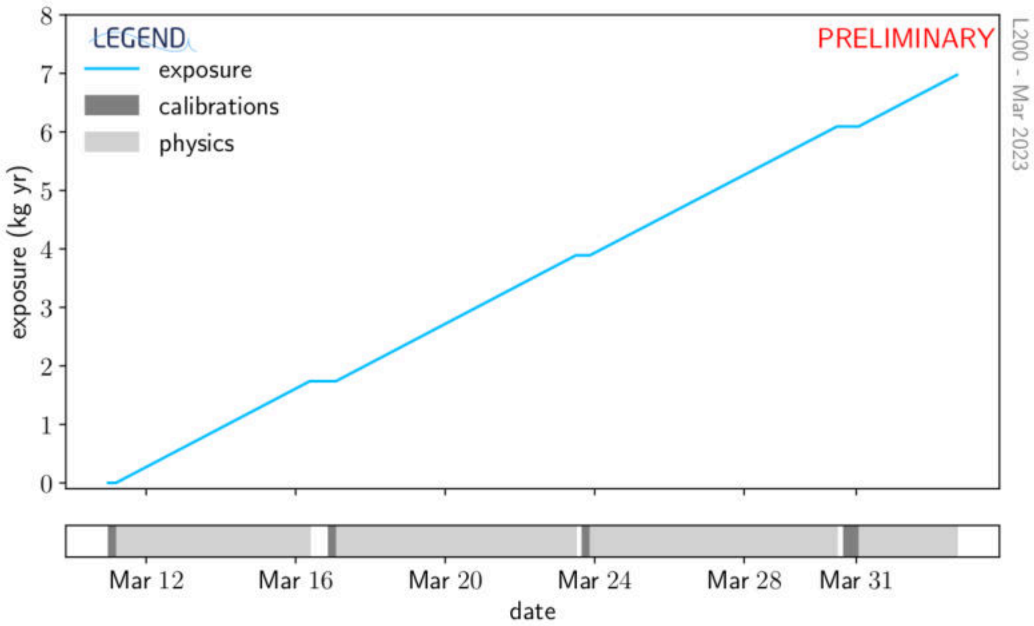


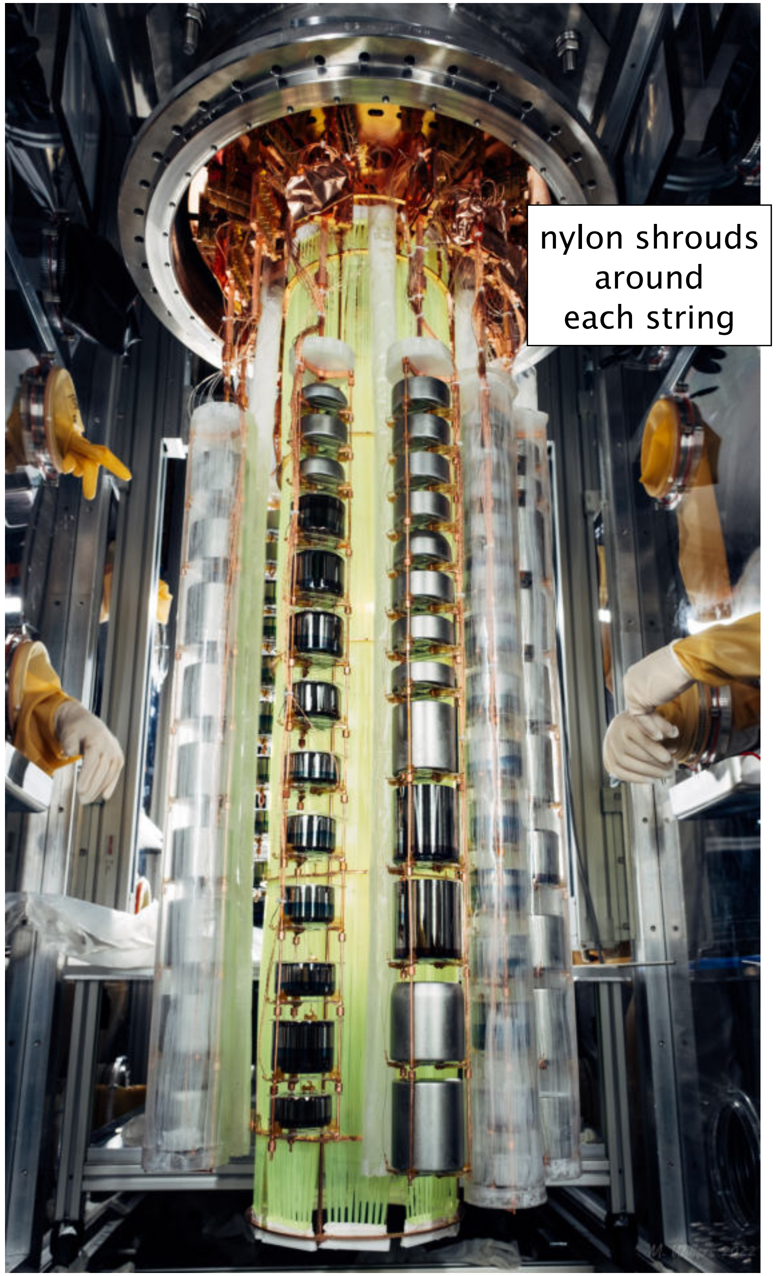
LAr veto:
scintillating fibers with SiPMs
divided into **inner** + **outer** barrel

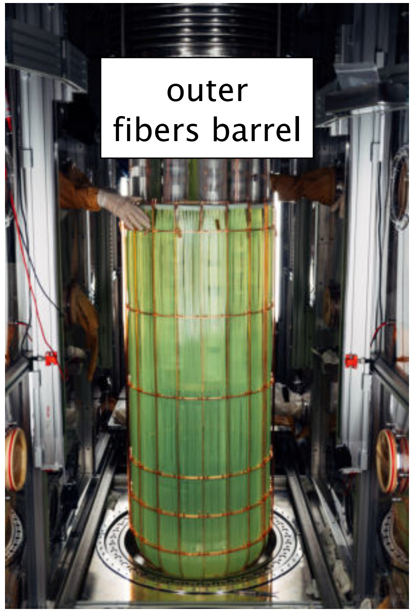
LEGEND-200: 140 kg array installation

Stably data taking since March 12^{th}:

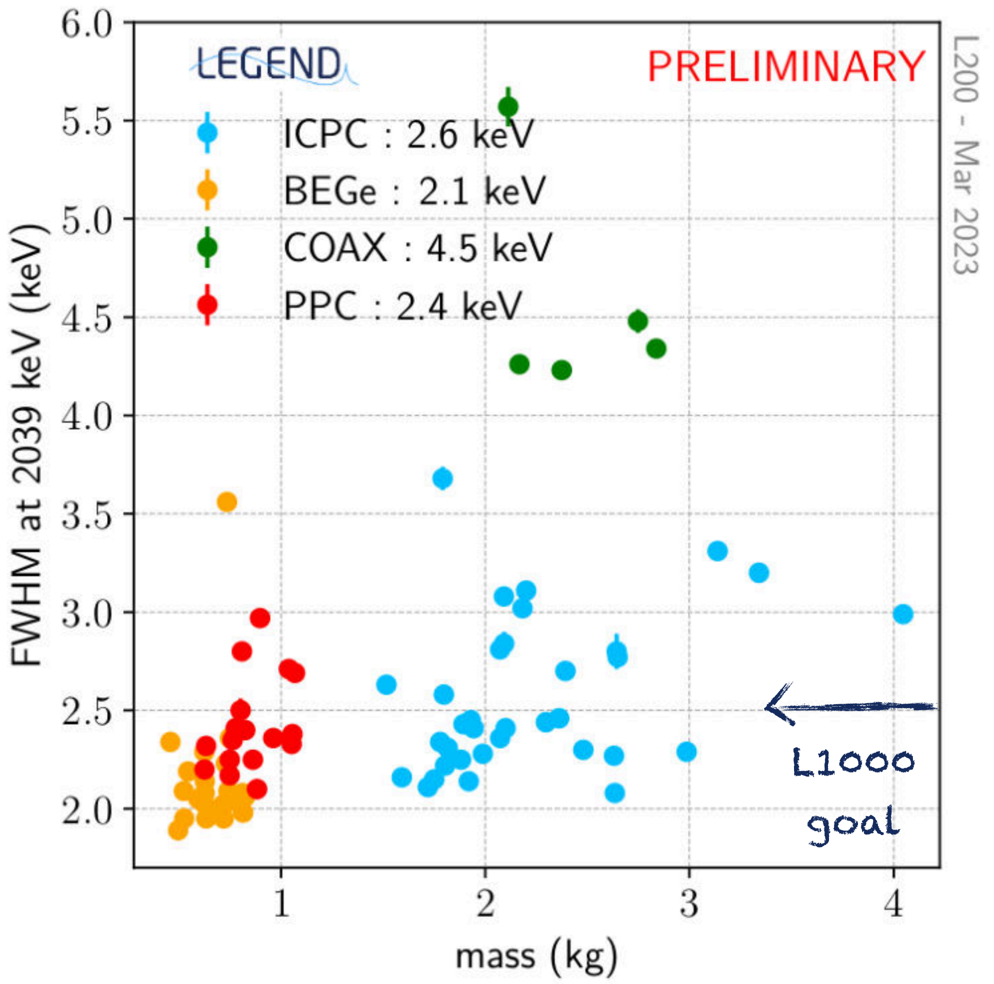
- 140 kg of detectors
- 122 kg usable for analysis
- 97–98% duty cycle
- > 2 kg·yr / week
- 100 kg·yr by the end of the year







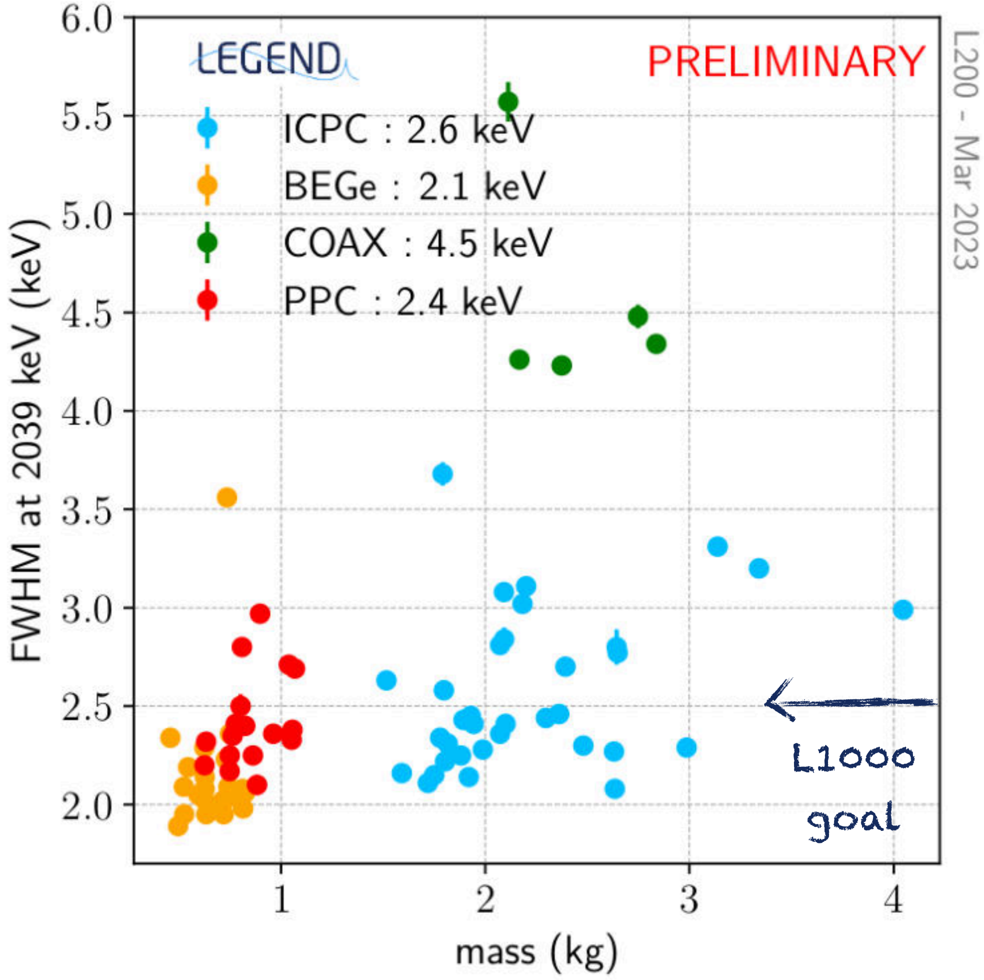
LEGEND-200: HPGe energy scale

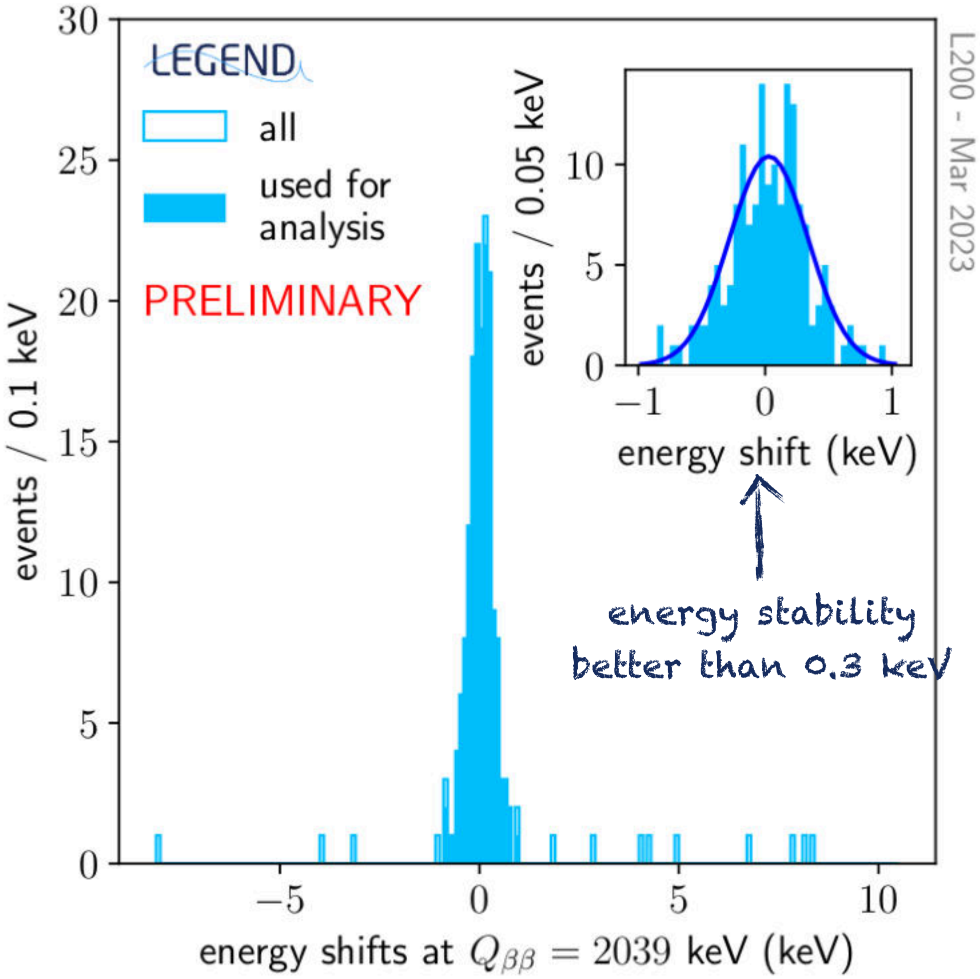


~2.5 keV FWHM resolution

ICPC detectors already fulfilling L1000 goals

LEGEND-200: HPGe energy scale





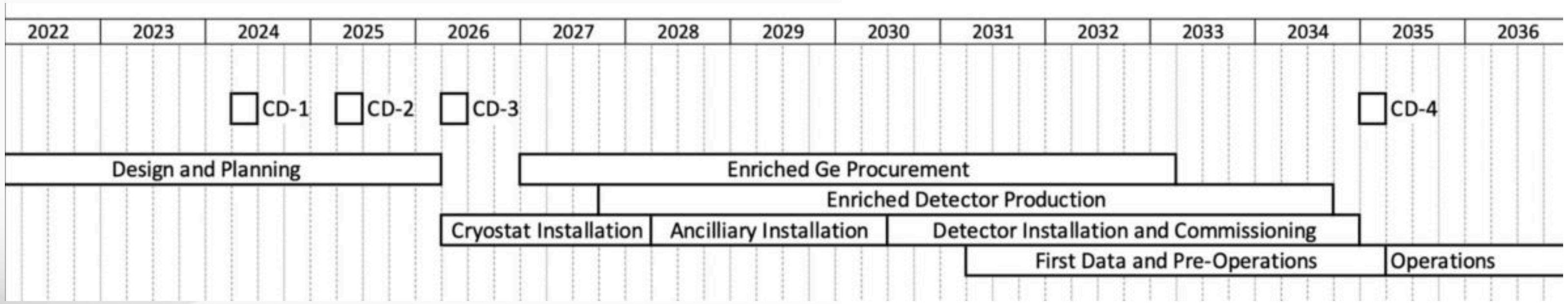
~2.5 keV FWHM resolution

ICPC detectors already fulfilling L1000 goals

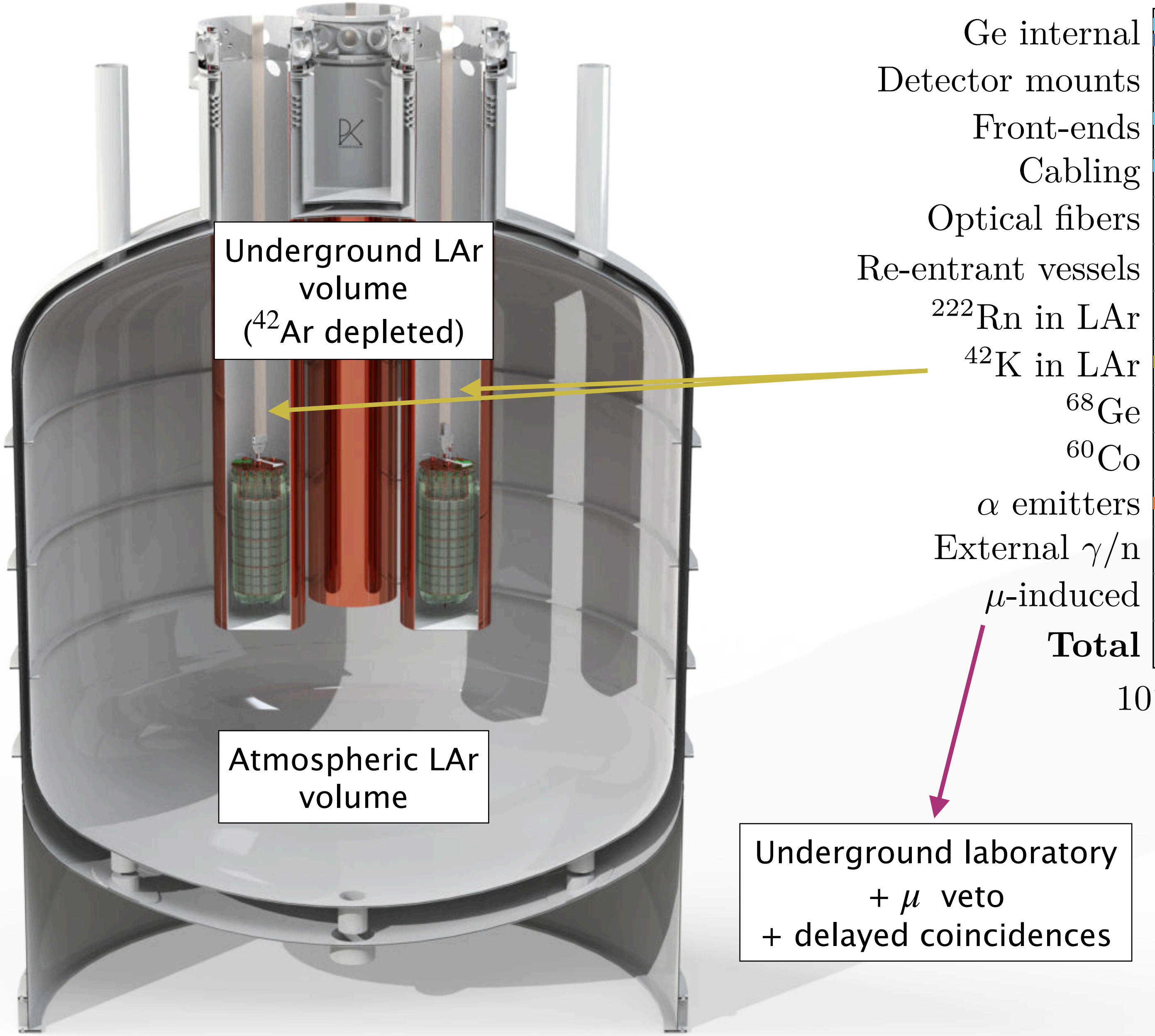
extremely stable for 120 kg of detectors

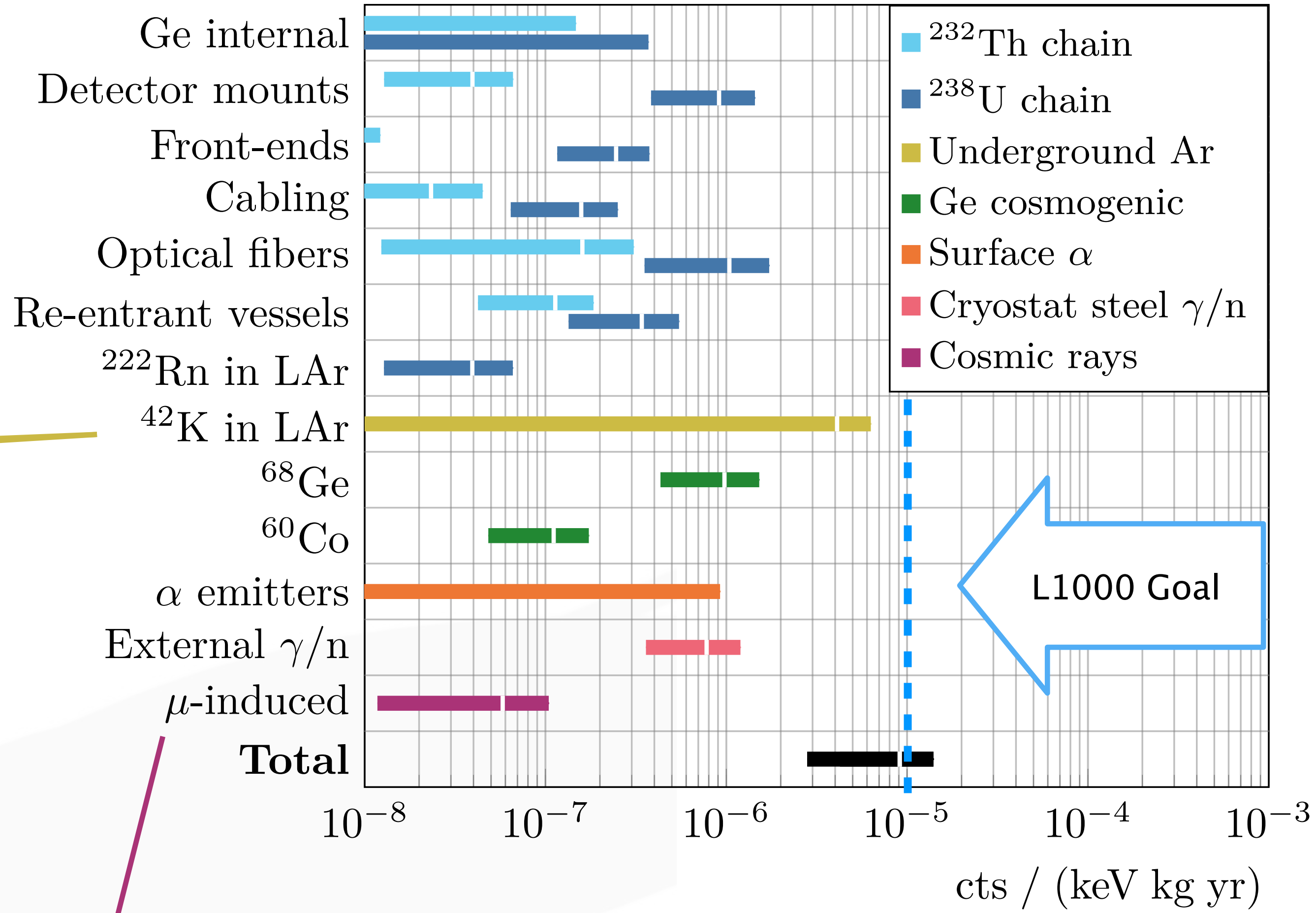
LEGEND-1000 – Timeline

- Apr 2016: LEGEND collaboration formed
- Dec 2019: LEGEND-200 commissioning starts
- July 2021: DOE Portfolio Review (LEGEND-1000, nEXO, CUPID)
- Oct 2021: DOE verbally announced that **LEGEND-1000 emerged as the portfolio review winner in all but one category**



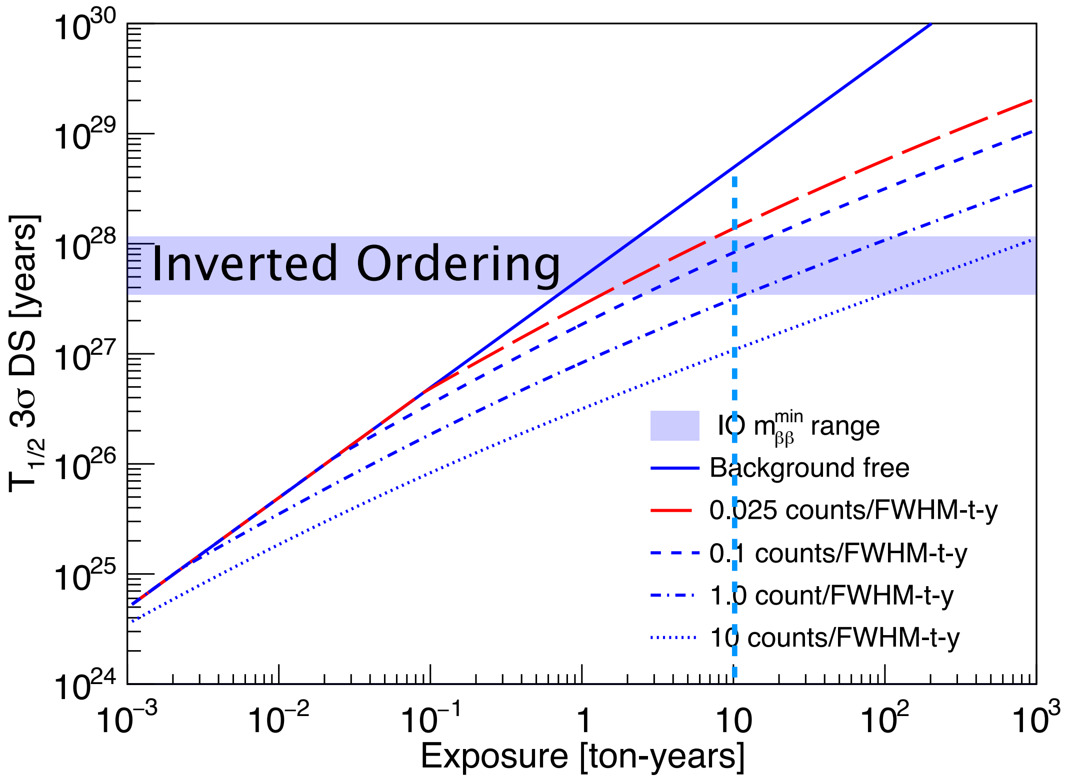
LEGEND-1000 – Background



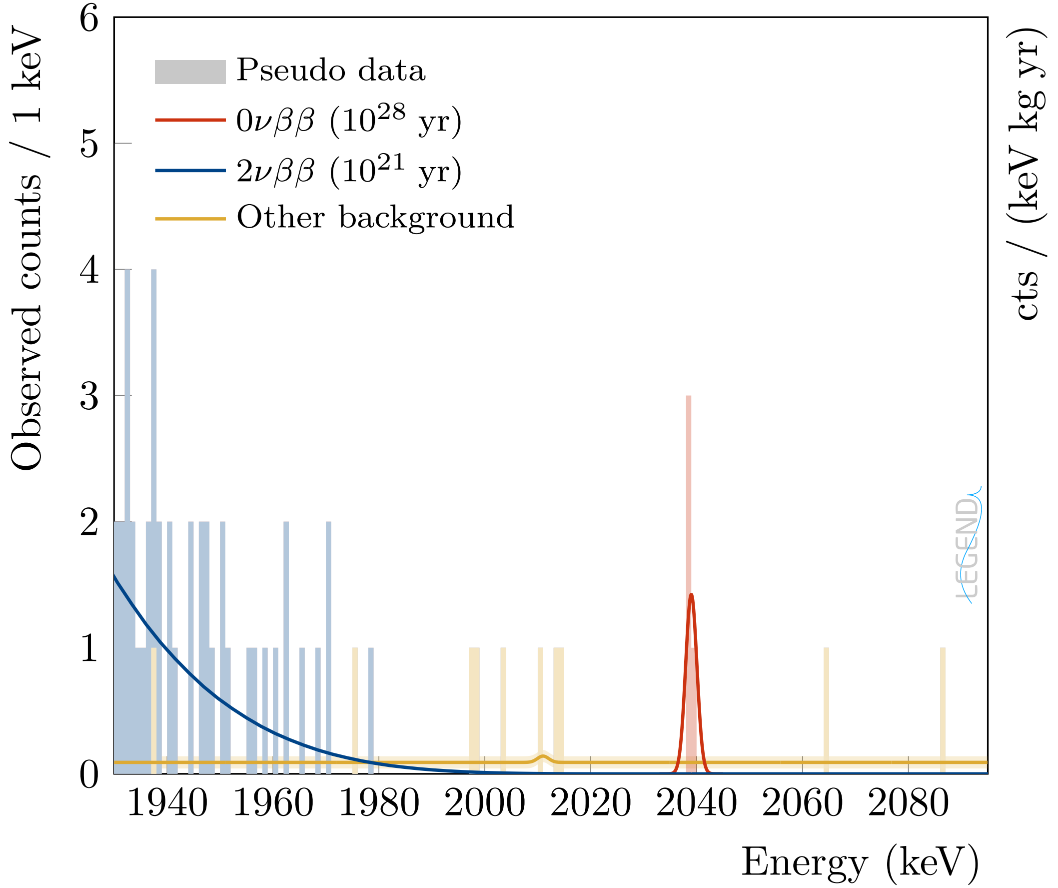


Projected Background Index after all cuts:
$9.1^{+4.9}_{-6.3} \times 10^{-6}$ counts/(keV kg yr)

LEGEND-1000 – Discovery Sensitivity



Simulated spectrum, after cuts, 10 years of data



see **LEGEND-1000 pre Conceptual Design Report**

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

$0\nu\beta\beta$ is a very promising probe to address:

- Origin of neutrinos masses,
- neutrinos mass scale,
- neutrinos mass ordering

LEGEND-200:

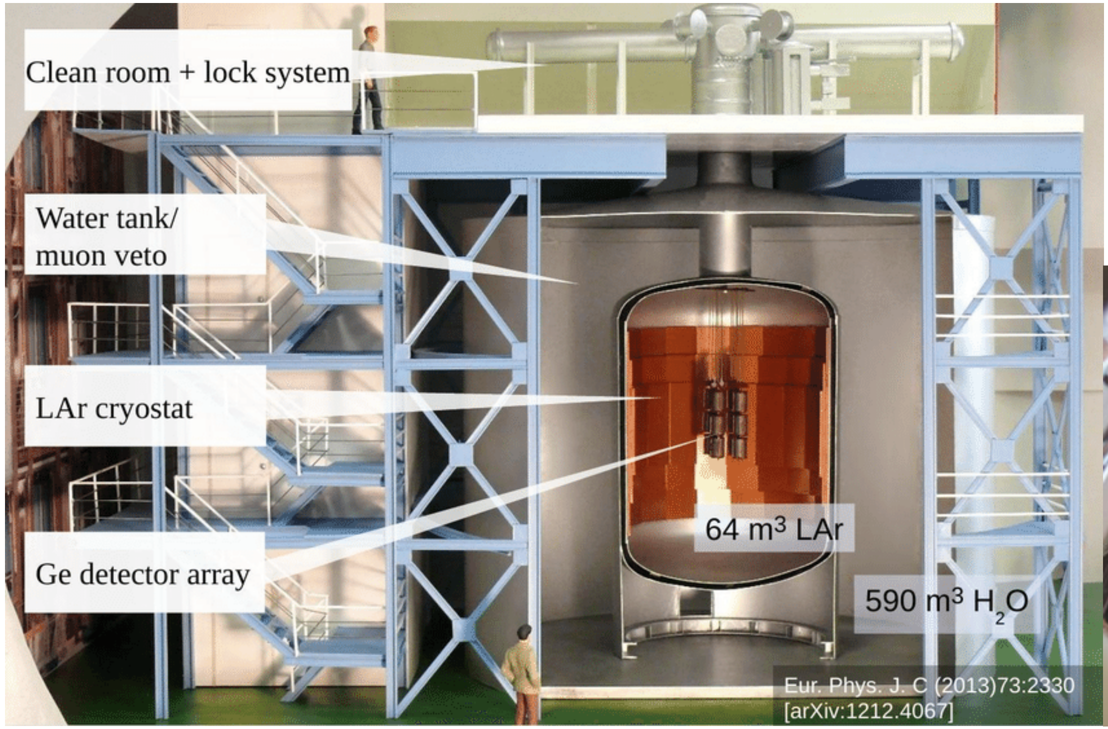
- built on top of previous successful experiments (GERDA, MAJORANA)
- >120 kg of detector taking high-quality data
- ~50 kg of detectors in hand or in production
- first $0\nu\beta\beta$ result in 2024
- installation of additional detectors based on background levels and sensitivity arguments

LEGEND-1000:

- top-ranked experiments by DOE
- low risk path to meeting its background goal
- optimized for discovering $0\nu\beta\beta$
- signal visible by eye even if at the bottom of the IO

Backup

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

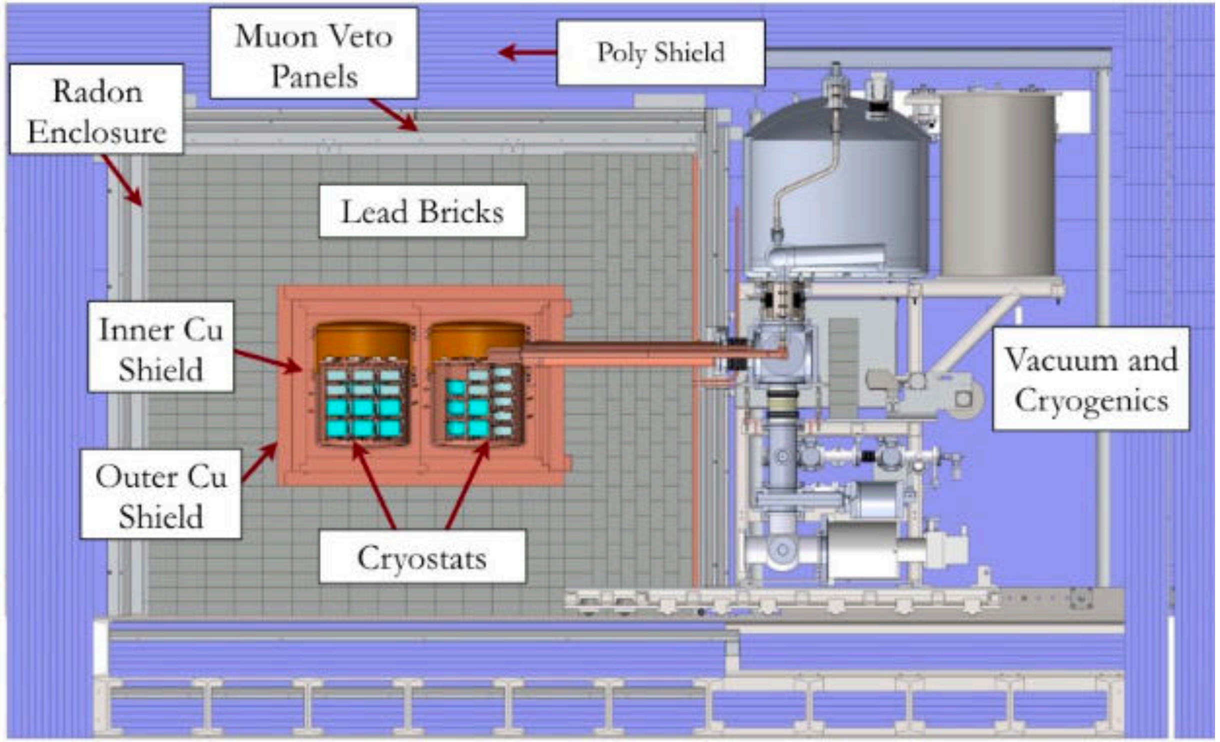
Major innovations also adopted in LEGEND:

- 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

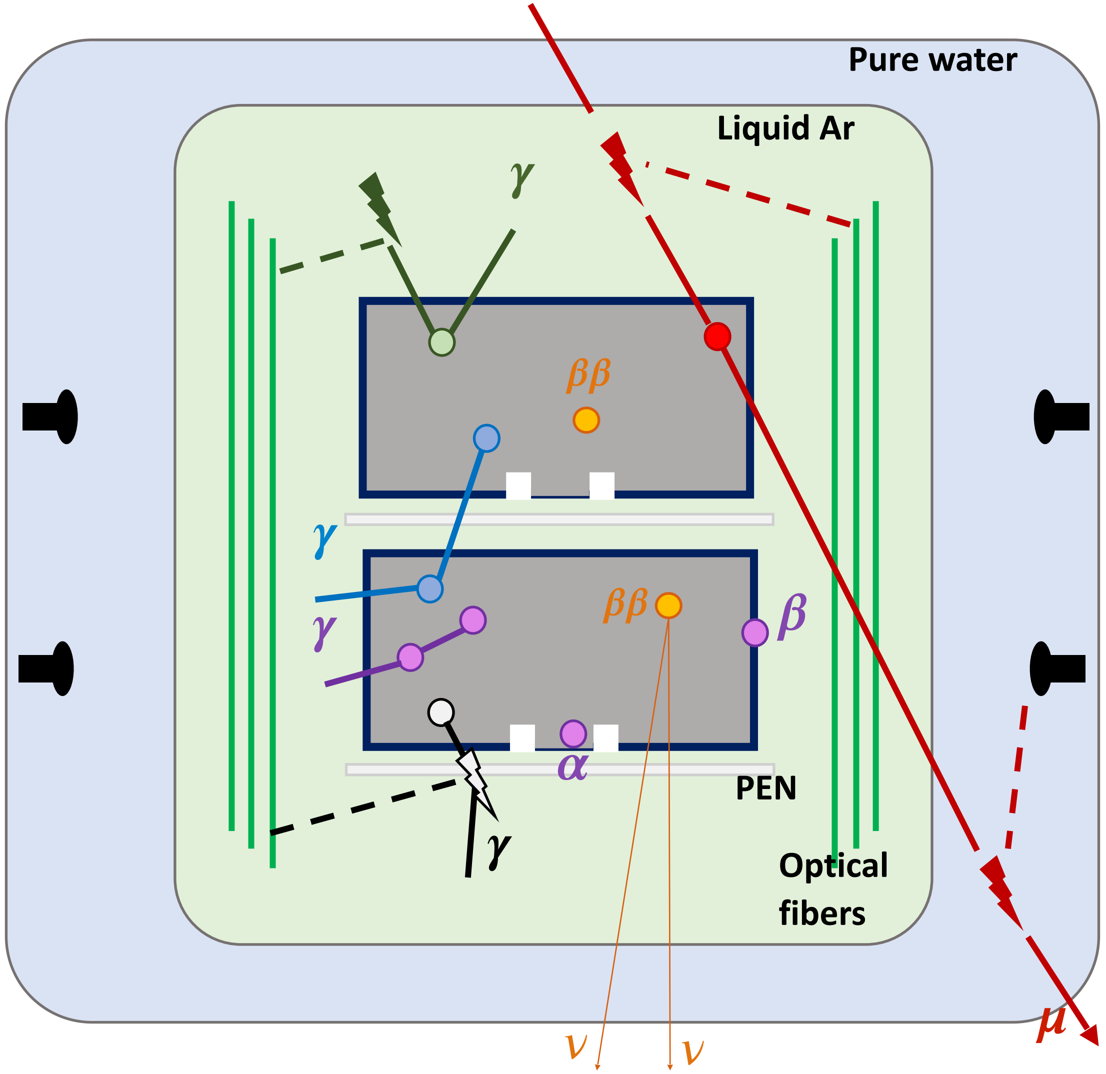
arXiv:2207.07638 [nucl-ex]

Background Reduction – Active Vetoes

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

Ge detectors anticoincidence

Scintillation light coming from PEN holders



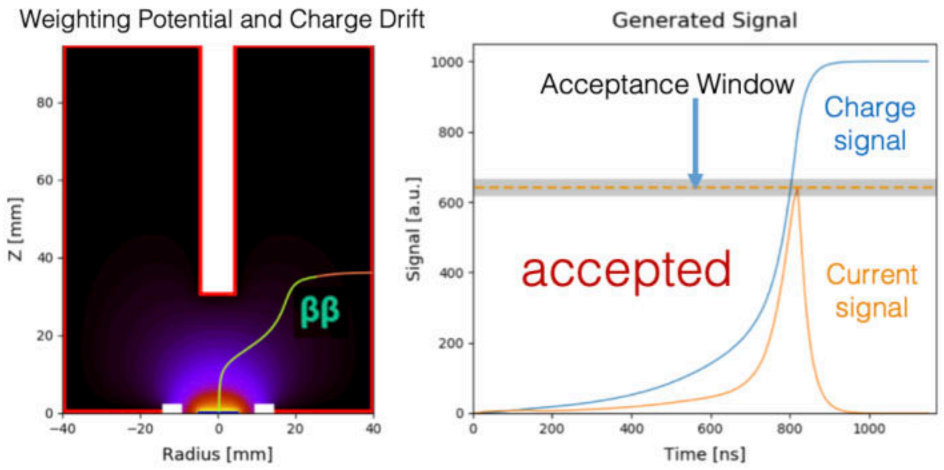
LAr veto based on Argon scintillation light read by optical fibers and Silicon PhotoMultipliers

Muon veto based on Cherenkov light

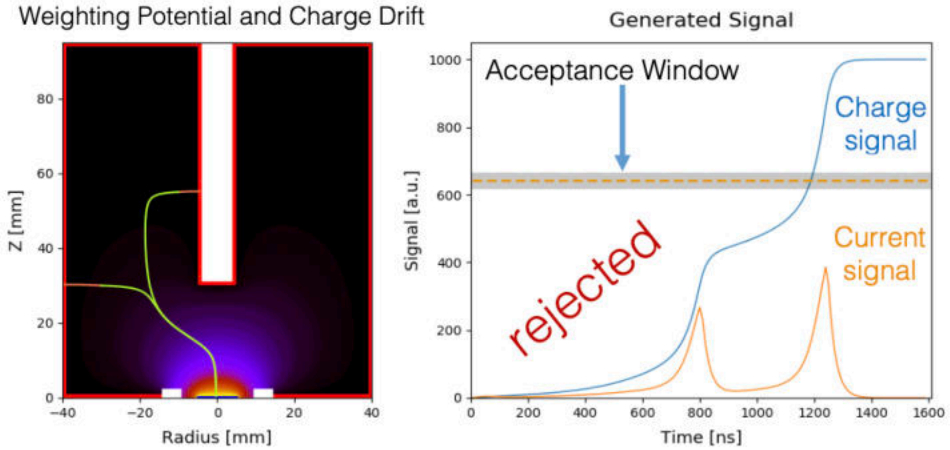
Pulse Shape Discrimination for multi-site and surface events

Background Reduction – Pulse Shape Discrimination

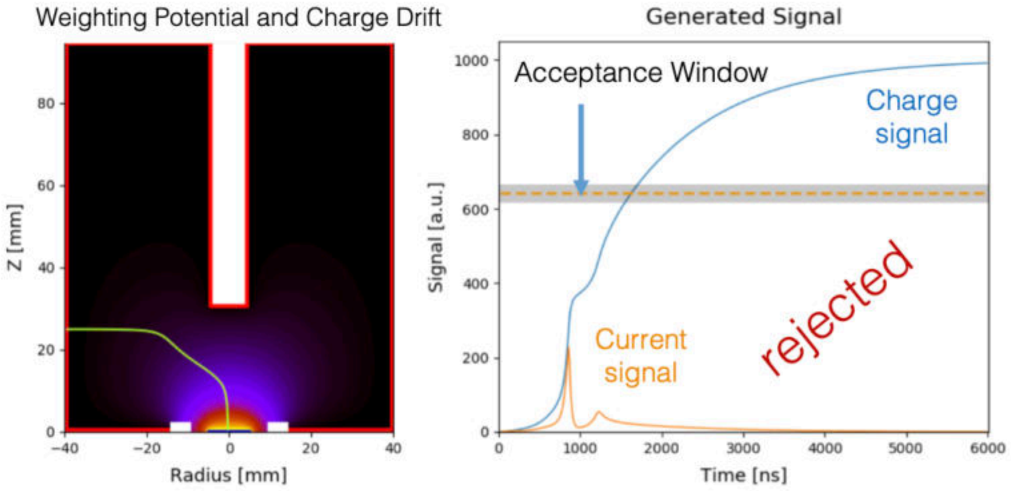
0νββ signal candidate (single-site)



γ-background (multi-site)



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



α-background on p+ contact