Large Enriched Germanium Experiment for Neutrinoless ββ Decay

JAGIELLONIAN UNIVERSITY IN KRAKÓW

Neutrino Physics: contribution from Neutrinoless Double Beta Decay by the LEGEND Experiment

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on behalf of the LEGEND Collaboration

PAiP-2025 conference ”Particle Astrophysics in Poland”, 20- 21.02.2025, Warsaw, Poland

Outline

- Status of Neutrino Physics
- Double Beta Decay
- LEGEND Overview
- LEGEND-200 Result
- Summary

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Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Status of Neutrino Physics

Open questions:

- Nature of neutrino
- Absolute neutrino mass
- Neutrino mass hierarchy
- CP violation
- Existence of sterile neutrino(s)

} β (Absolute neutrino mass)
Cosmol. (Absolute neutrino mass, Neutrino mass hierarchy)
$0\nu\beta\beta$ (Nature of neutrino, Absolute neutrino mass, Neutrino mass hierarchy)
Oscillations (Neutrino mass hierarchy, CP violation, Existence of sterile neutrino(s))

What we do know:

- Oscillating neutrinos must have mass (at least two neutrinos must be massive) – physics BSM
- Neutrino oscillation parameters measured presently with good accuracy of 1- 4 % (1σ)
- Some experimental results are in tension (e.g. T2K vs. NOvA)
- Weak (2.7σ) preference for NO from the global fit
- SBL and Ga anomaly confirmed

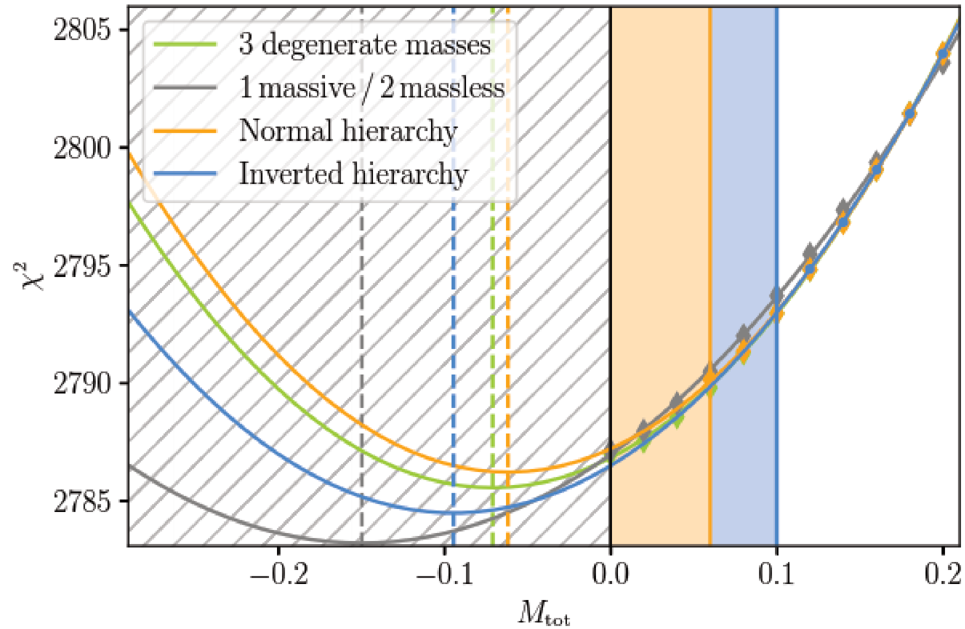
Neutrino Mass: Cosmology

- Fit various models to cosmological data (CMB, BAO, BBN, …)
- Data from varied, complimentary data sets
- Model-dependent

$$M_{\rm tot} = m_0 + \sqrt{\Delta m^2_{21} + m_0^2} + \sqrt{\Delta m^2_{31} + m_0^2} \quad \text{(NO)}$$

$$M_{\rm tot} = m_0 + \sqrt{|\Delta m^2_{32}| + m_0^2} + \sqrt{|\Delta m^2_{32}| - \Delta m^2_{21} + m_0^2} \quad \text{(IO)}$$

$$\rightarrow \quad M_{\rm tot} \gtrsim 0.06\,\text{eV}, \quad M_{\rm tot} \gtrsim 0.1\,\text{eV}$$

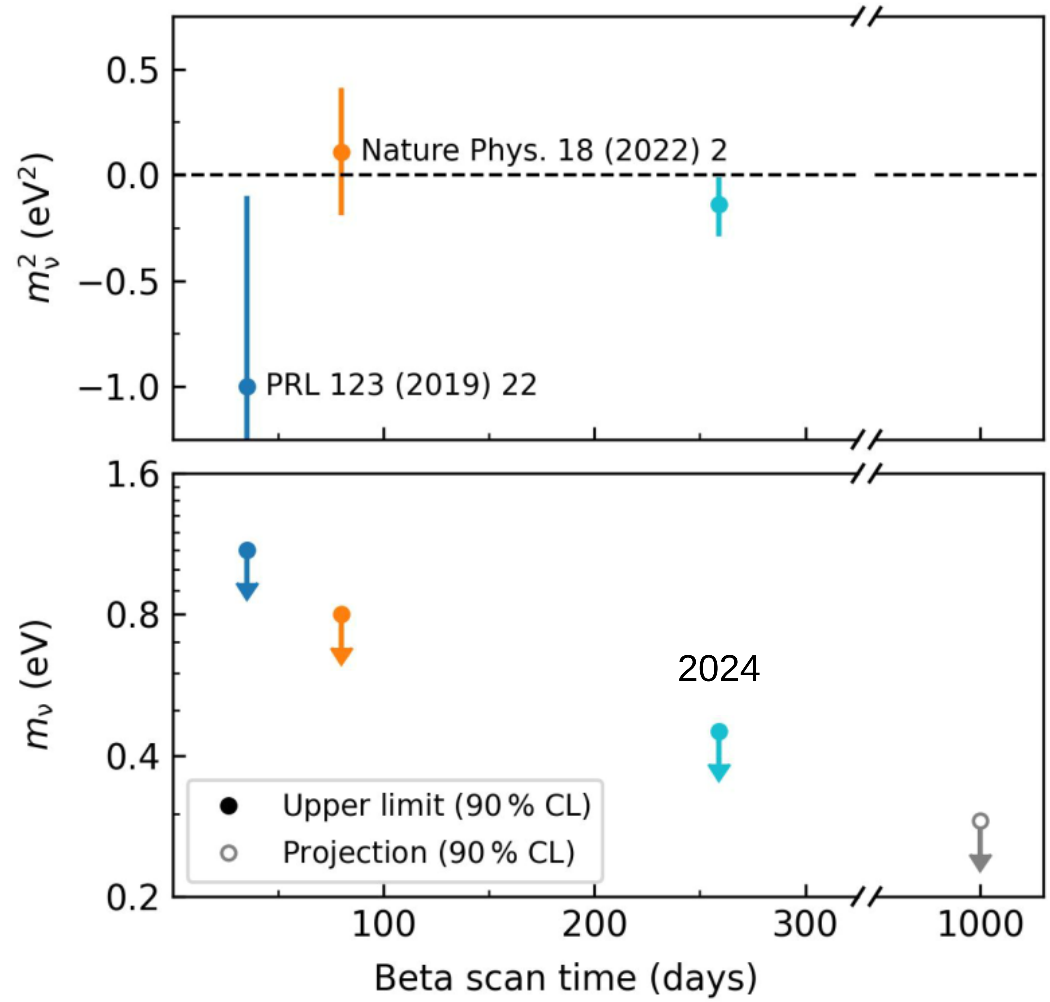


arXiv:2412.03546v1
Dec. 2024

M_{tot} < 0.13 eV (NO)
M_{tot} < 0.16 eV (IO)

M_{tot} < 0.086 eV (DM)

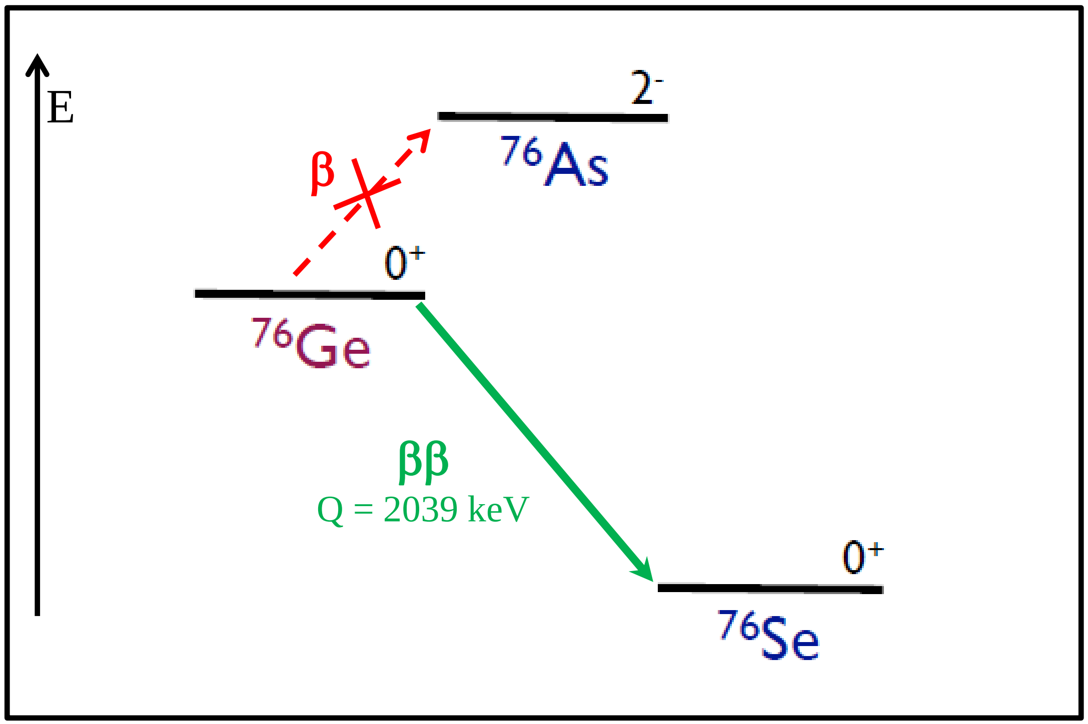
Neutrino Mass: KATRIN



m_ν < 0.45 eV (90% CL)

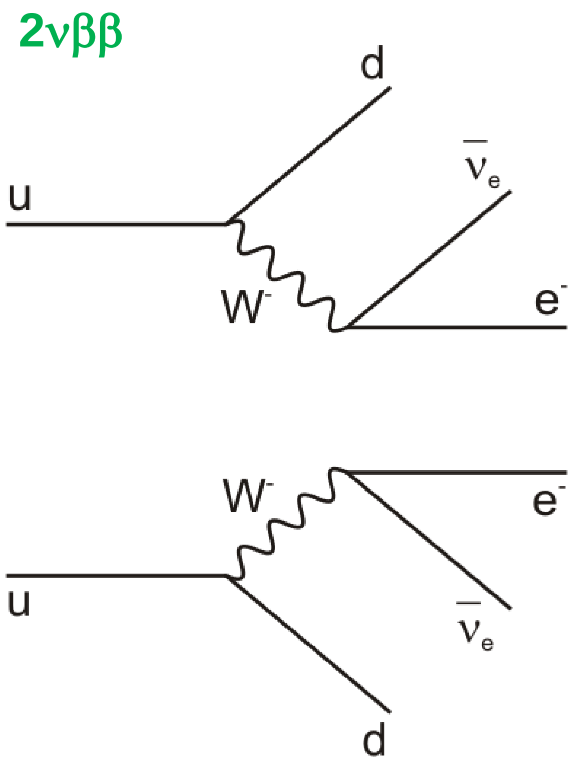
Double Beta Decay

In a number of even-even nuclei, β decay due to energy/angular momentum balance is forbidden, while double beta decay from a nucleus (A,Z) to (A, Z+2) is energetically allowed.



^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

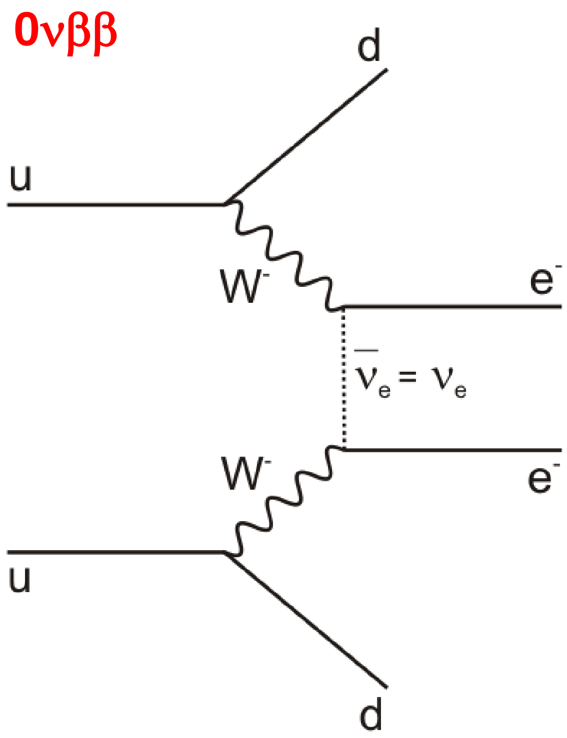
Double Beta Decay Modes



$(A,Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

ΔL = 0

$T_{1/2} \sim 10^{18} - 10^{24}$ yr

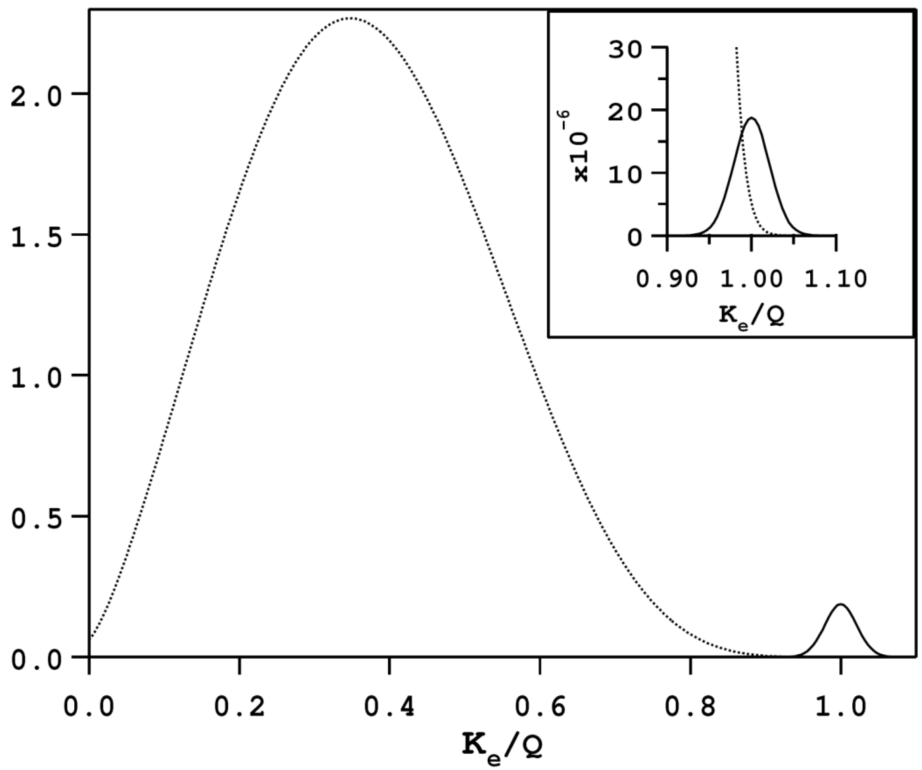


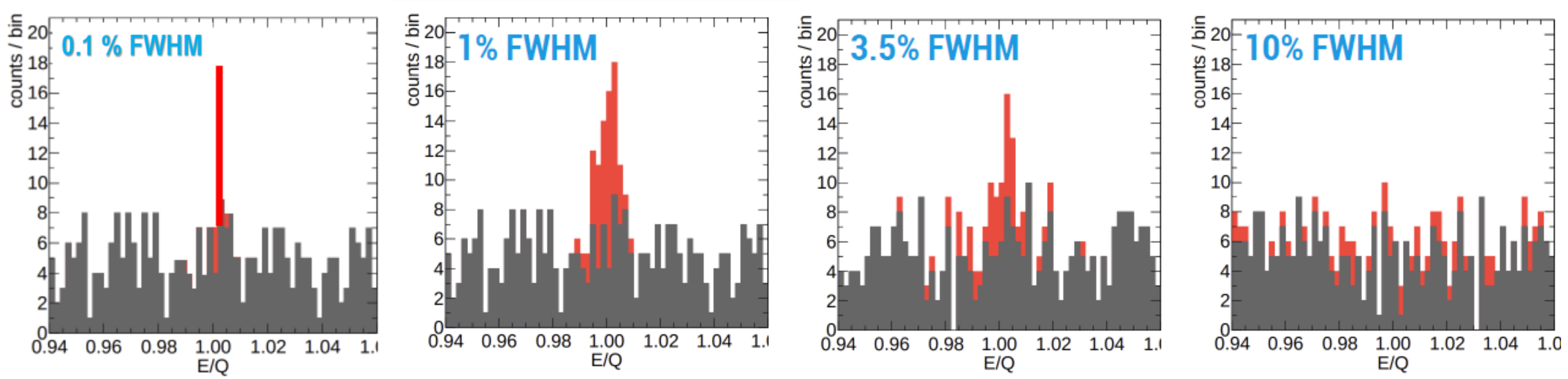
$(A,Z) \rightarrow (A, Z+2) + 2e^-$

ΔL = 2

$T_{1/2}^{exp} > 10^{26}$ yr

Double Beta Decay Modes





A. Simon

Neutrino Mass / Hierarchy

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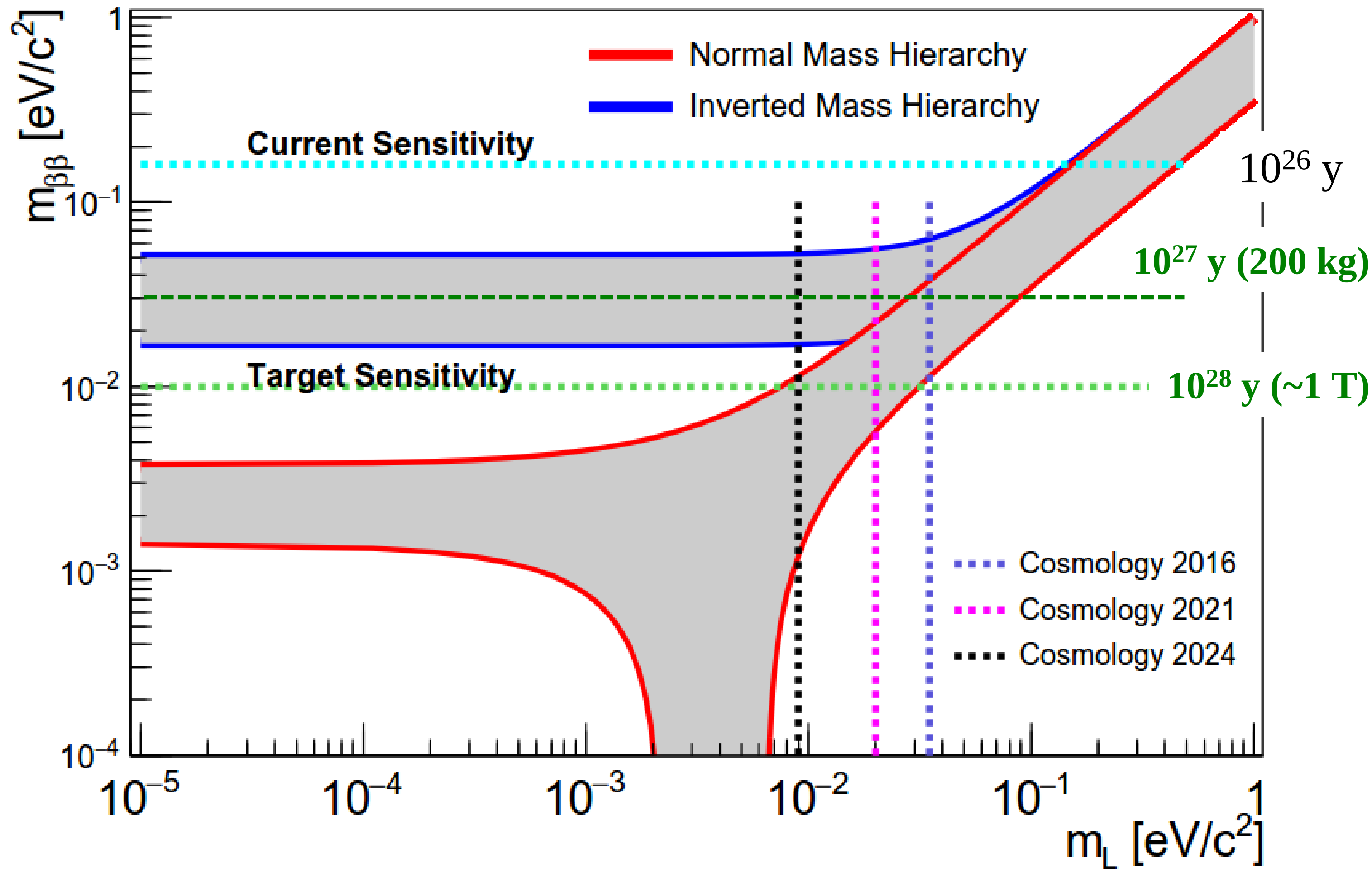


Physics Beyond the Standard Model

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

If 0νββ decay observed:

- Neutrino is a Majorana particle (its own antiparticle)
- Lepton number is not conserved
- Dealing with physics beyond the Standard Model

0νββ decay gives opportunity to determine:

- Absolute neutrino mass scale (meV scale !)
- Neutrino mass hierarchy
- CP violation in the lepton sector

Significant contribution to Particle Physics, Astrophysics and Cosmology

LEGEND concept

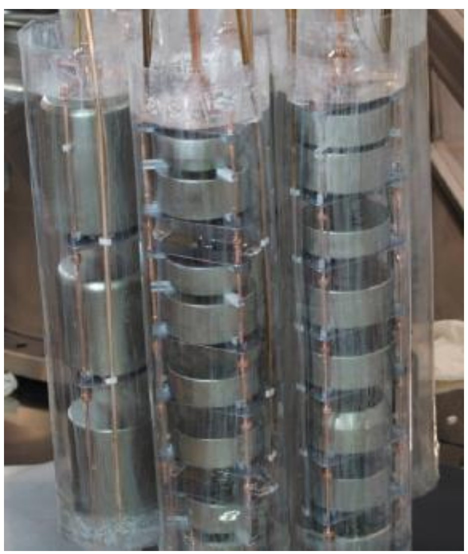
Neutrino Physics
Double β decay
LEGEND
LEGEND-200
Summary

- The goal of the LEGEND (Large Enriched Germanium Experiment for Neutrinoless Doube Beta Decay) Collaboration is to design, construct, and field LEGEND-1000, 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 by a merger of the MAJORANA and GERDA collaborations, along with several new institutions

GERDA: best background, LAr shield/instrumentation



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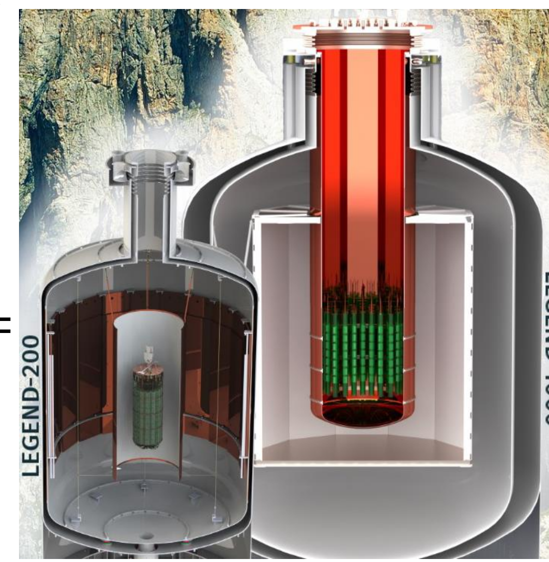
Majorana: low noise, high radio-purity electronics, low threshold

=

LEGEND-200/1000



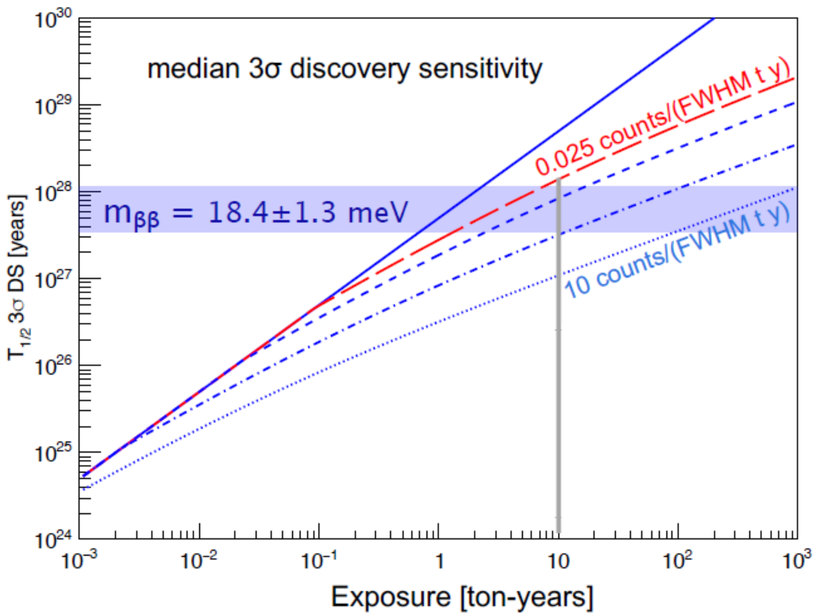
LEGEND overview

Neutrino Physics
Double β decay
LEGEND
LEGEND-200
Summary

$T_{1/2}$ (0νββ) ~ 10^{28} yr → less than one decay per year per ton of material

- 10 t×yr of data is needed to get a few counts (1 t, 10 yr of data taking)
- very good signal-to-background ratio to get statistical significance
  → extremely low background (~20 times lower compared to GERDA)
  → best possible energy resolution (~2.5 keV at $Q_{\beta\beta}$)

Our background goal is the red line on the plot, 0.025 counts/(FWHM×t×yr), "quasi-background-free" operation: ≤ 1 background event expected in a 4σ ROI for 10 t×yr exposure



Background-free operation:

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a \cdot M \cdot T$$

Non-zero background:

$$T_{1/2}(90\%\ CL) > \frac{ln2}{1.64}\frac{N_A}{A}\epsilon \cdot a\sqrt{\frac{M \cdot T}{B \cdot \Delta E}}$$

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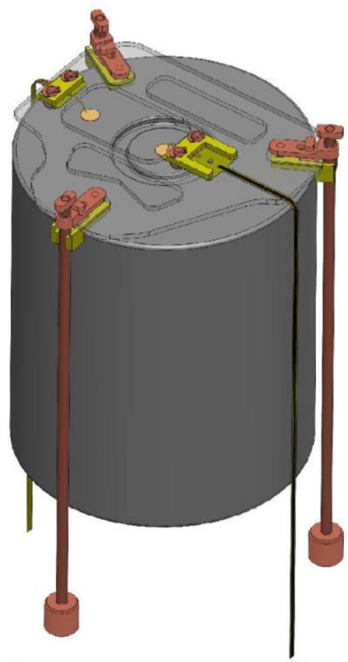
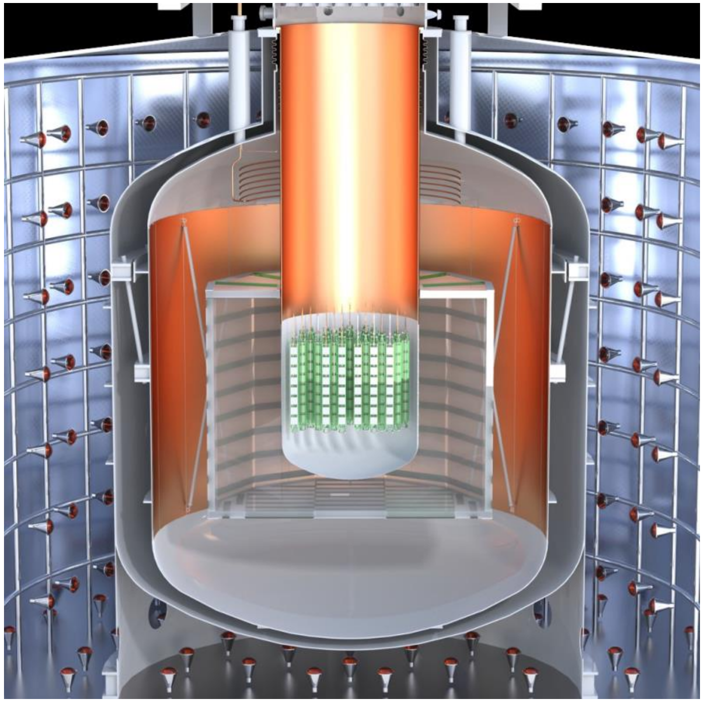
LEGEND overview

1000 kg of enriched Ge detectors (92% ^{76}Ge)

- HPGe detectors: 2.6 kg average mass
- Mounted in “strings” using components made from electro-formed Cu and scintillating plastic, PEN
- Underground/atmospheric Ar
- Fiber-curtains for LAr instrumentation
- Underground site to shield from cosmic rays: INFN-LNGS in Italy

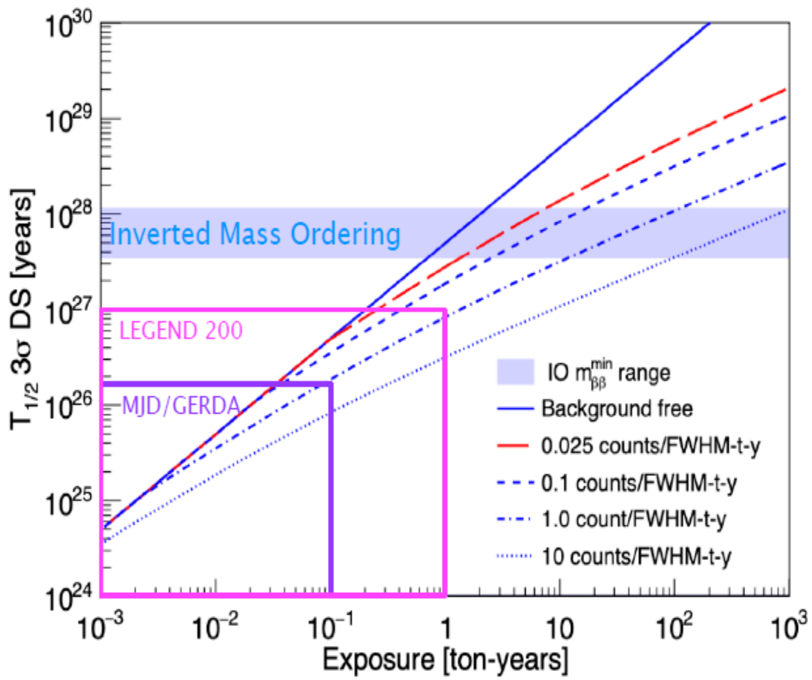


ICPC HPGe detector



LEGEND-200

- 200 kg of HP^{enr}Ge in existing GERDA infrastructure at LNGS, Italy
- Anticipated exposure: 1 t×yr
- Background goal: 3× reduction w.r.t GERDA, BI < 2×10^{-4} cts/(keV×kg×yr): quasi-background free operation for unambiguous discovery of the 0νββ decay up to 10^{27} yr
  - Improved VFE electronics
  - Improved PSD methods
  - Improved LAr instrumentation
- **Taking physics data since March 2023**
- **142 kg of ^{enr}Ge**



L-200 in Hall A of LNGS

Neutrino Physics
Double β decay
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LEGEND-200
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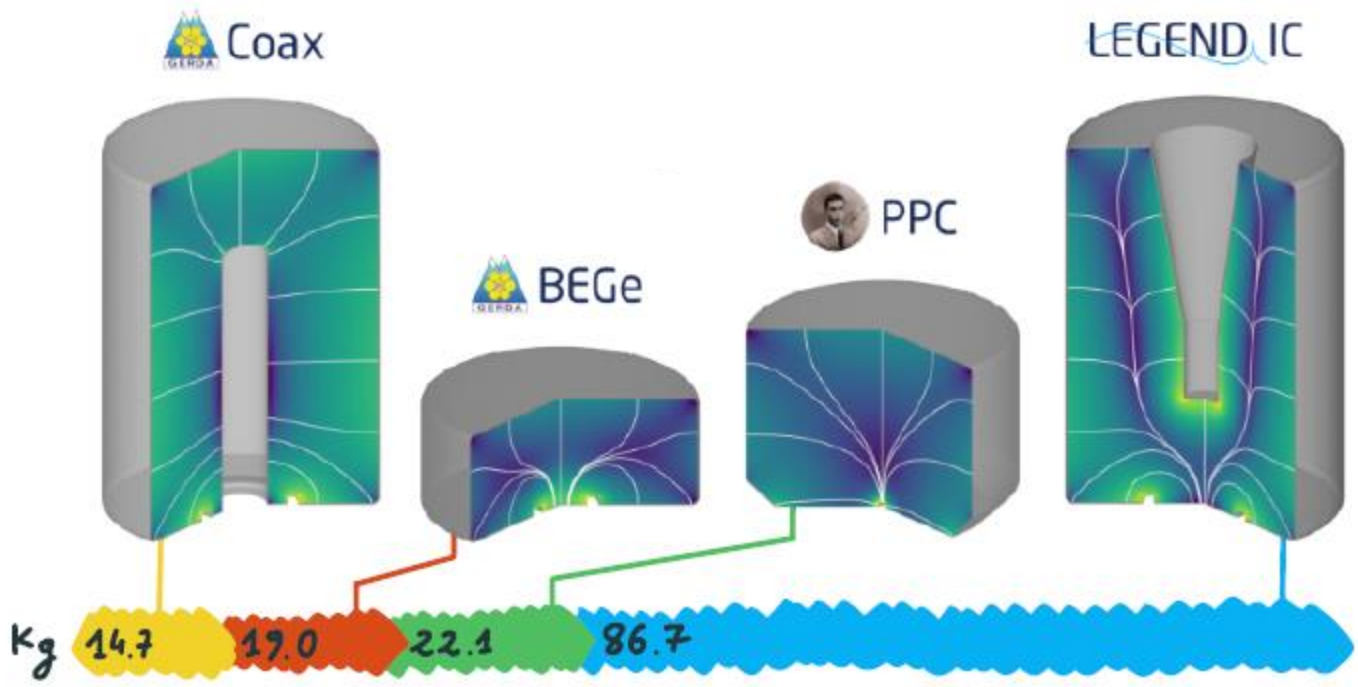
LEGEND-200 detectors

- p-type detectors: insensitive to alpha decays (^{210}Po) on n+ contact
- Large-mass semi-coaxial detectors
- Small p+ contact: event topology discrimination (PSD)
- Large-mass ICPC detectors (60 % of total detector inventory): lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon



L. Pertoldi, Neutrino 2024

LEGEND-200 LAr instrumentation

- Neutrino Physics
- Double β decay
- LEGEND
- LEGEND-200
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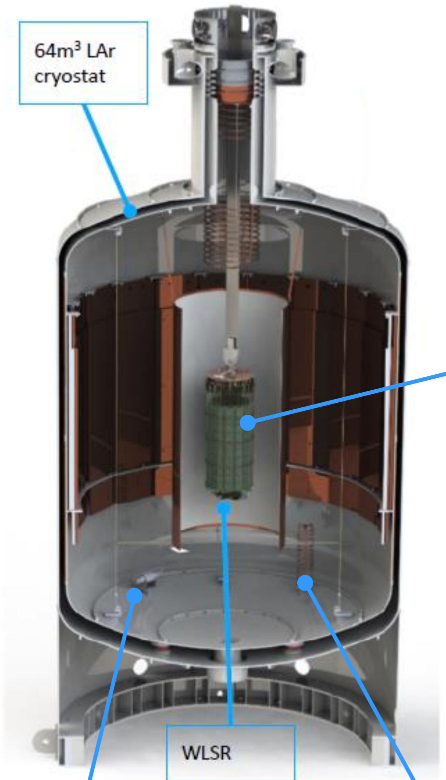
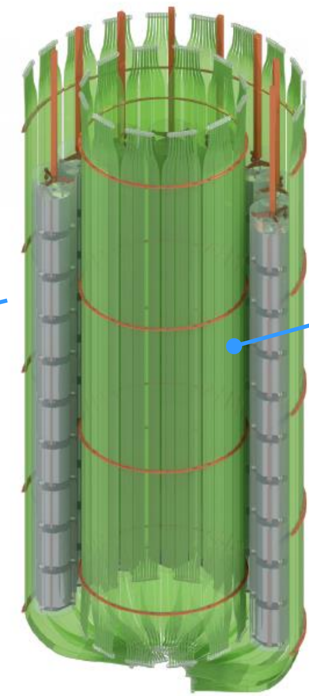


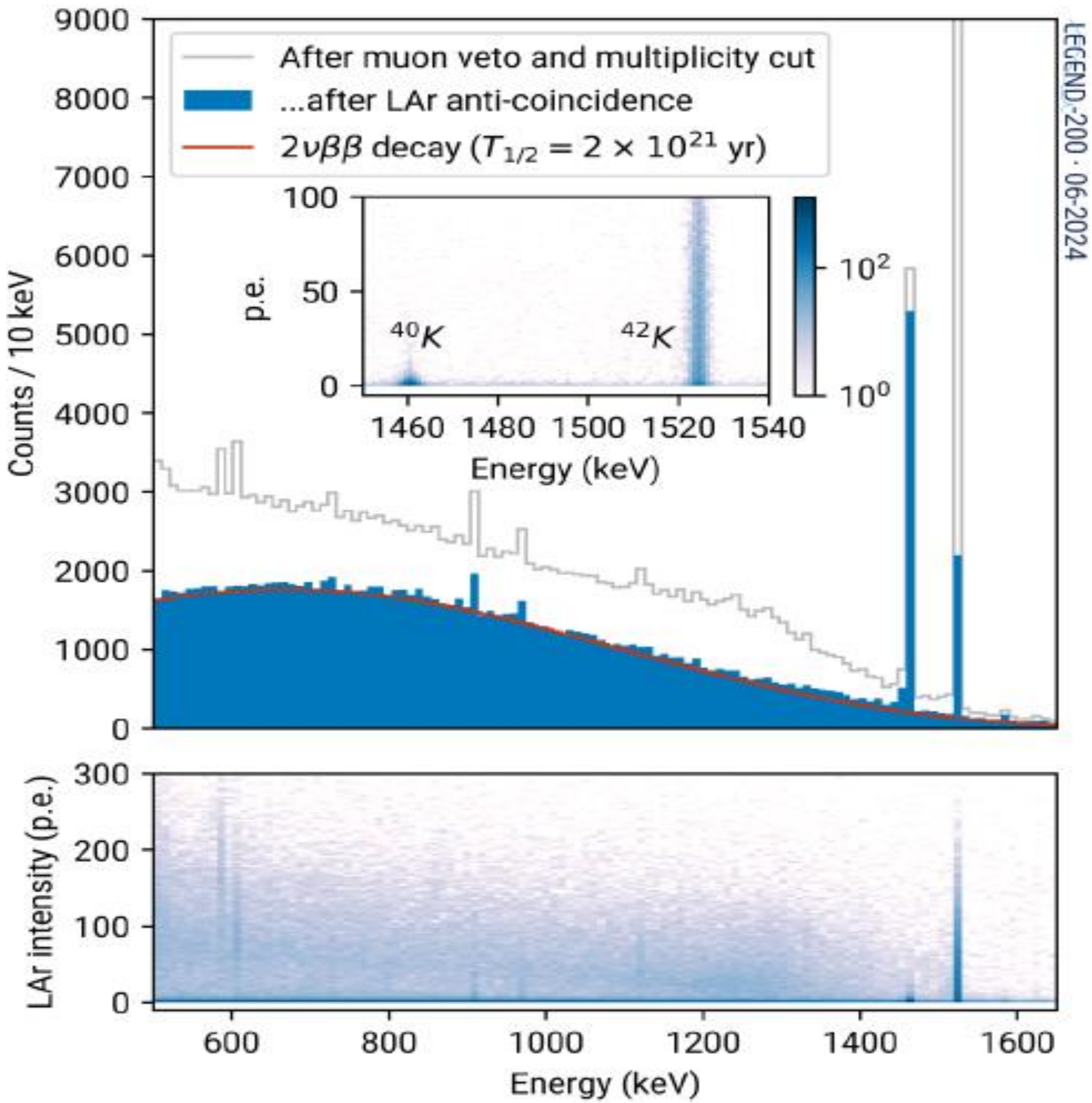


Liquid
Argon
Pump

LEGEND
Liquid
Argon
Monitoring
Apparatus

LEGEND-200 LAr instrumentation

Large Enriched Germanium Experiment for Neutrinoless ββ Decay



LEGEND-200 Result

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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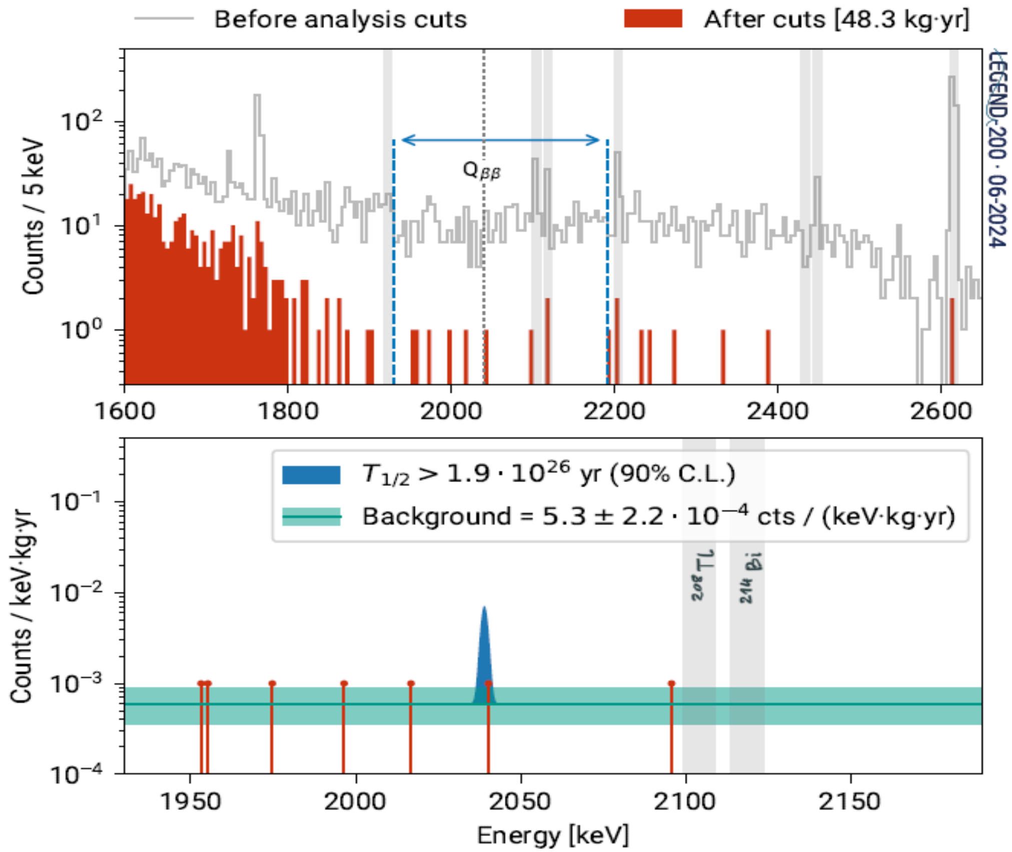

Background event 1.4σ from $Q_{\beta\beta}$

<u>Neutrino 2024 data set (48.3 kg ×yr):</u>

– BI: (5.3 ± 2.2) × 10^{-4} cts/(keV×kg×yr)
– GERDA, MAJORANA and L-200 combined limit:
$T_{1/2}$ (0νββ) > 1.9 × 10^{26} yr (sensitivity: 2.8 × 10^{26} yr) at 90% C.L.
– $m_{\beta\beta} \leq$ (80 – 182) meV

Summary

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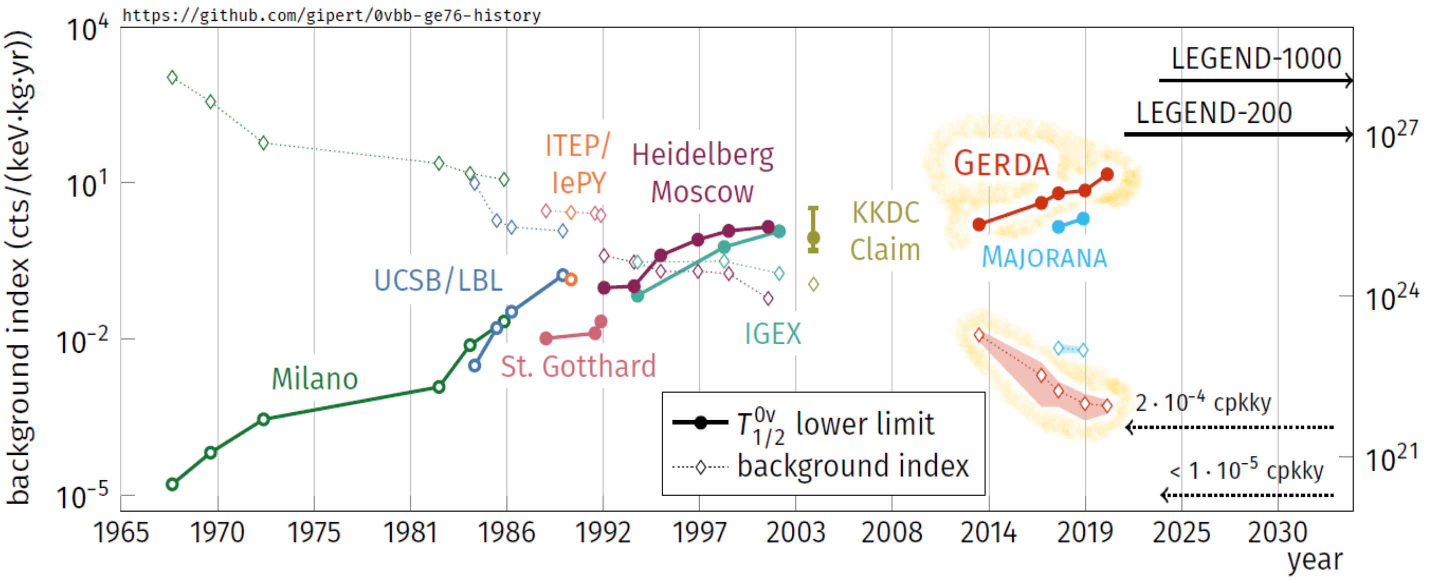
- 0νββ decay: nuclear physics but with very important contribution to neutrino physics
- Ge-based experiments have high discovery potential (low intrinsic background, high efficiency, excellent energy resolution)
- LEGEND – next generation experiment for $T_{1/2}^{0\nu} \sim 10^{28}$ yr and exploration of the inverted neutrino mass hierarchy
- Funding for LEGEND-1000 sought from U.S. (DOE and NSF) and from Europe (several European institutions contribute already)
- Pre-Conceptual Design Report available: arXiv: 2017.11462
- First data from LEGEND-1000 expected in 2030 (10 t×yr of data anticipated), detector under construction
- First phase, L-200, aims for $T_{1/2}^{0\nu} \sim 10^{27}$ yr with 200 kg of ^{enr}Ge
- First data from L-200 released for Neutrino 2024: $T_{1/2}$ (0νββ) $> 1.9 \times 10^{26}$ yr
- Next portion of data un-blinded 2 weeks ago, paper in preparation

The Polish National Science Center and the Polish Ministry of Science and Higher Education are acknowledged for their support of the LEGEND Experiment

0νββ history

50 years of 0νββ decay searches with ^{76}Ge



- Impressive technological progress and scientific production
- A new exciting era begins now with LEGEND

0νββ experiments

Experiments searching for the 0νββ decay

Experiment	Status	Isotope	$T^{0\nu}_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
GERDA	Completed	^{76}Ge	$\mathbf{1.8 \times 10^{26}}$	**79—180**
MAJORANA	Completed	^{76}Ge	$\mathbf{8.5 \times 10^{25}}$	**113—269**
LEGEND-200	Taking Data	^{76}Ge	1.5×10^{27}	34—78
LEGEND-1000	Proposed	^{76}Ge	8.5×10^{28}	9—21
CDEX-300ν	Proposed	^{76}Ge	3.3×10^{27}	18—43
KamLAND-Zen	Taking Data	^{136}Xe	$\mathbf{2.3 \times 10^{26}}$	**36—156**
EXO-200	Completed	^{136}Xe	$\mathbf{3.5 \times 10^{25}}$	**93—286**
nEXO	Proposed	^{136}Xe	1.3×10^{28}	6.1—27
NEXT-100	Construction	^{136}Xe	7.0×10^{25}	66—281
CUORE	Taking Data	^{130}Te	$\mathbf{3.8 \times 10^{25}}$	**70—240**
SNO+	Construction	^{130}Te	2.1×10^{26}	37—89
AMoRE-I	Completed	^{100}Mo	3.0×10^{24}	**210—350**
AMoRE-II	Proposed	^{100}Mo	5.0×10^{26}	17—29
CUPID-Mo	Completed	^{100}Mo	$\mathbf{1.8 \times 10^{24}}$	**280—490**
CUPID	Proposed	^{100}Mo	1.5×10^{27}	10—17
CUPID-0	Completed	^{82}Se	$\mathbf{4.6 \times 10^{24}}$	**263—545**
SuperNEMO-D	Construction	^{82}Se	4.0×10^{24}	260—500
CANDLES-III	Taking data	^{48}Ca	$\mathbf{5.6 \times 10^{22}}$	**2900—1600**