# The LEGEND Project for the search of Neutrinoless Double Beta Decay

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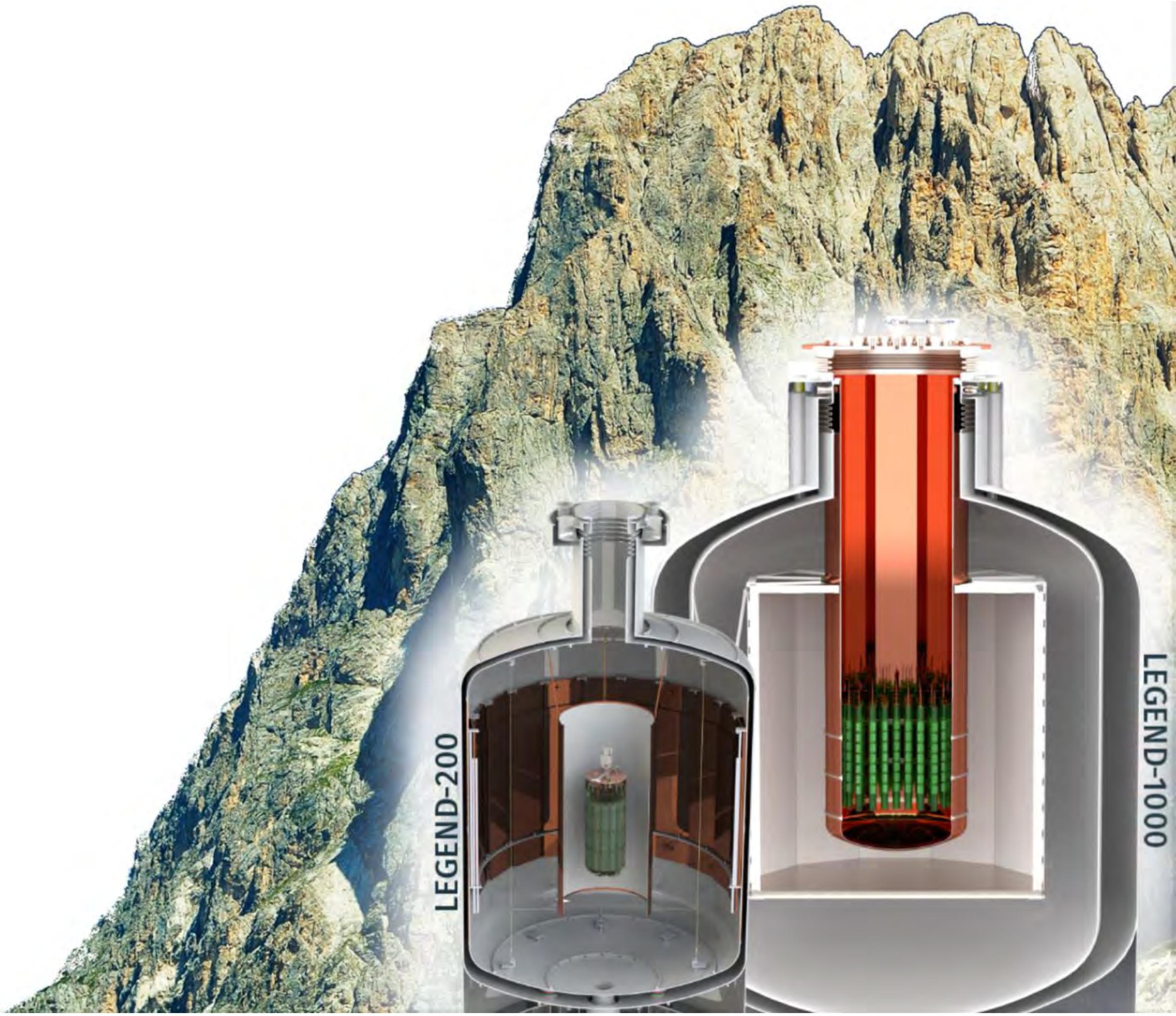
- Conclusions

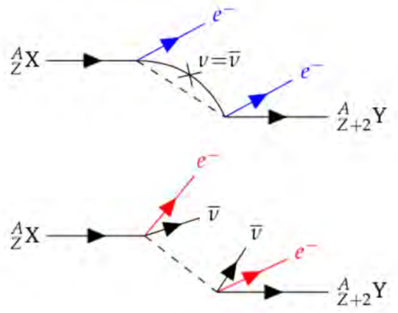


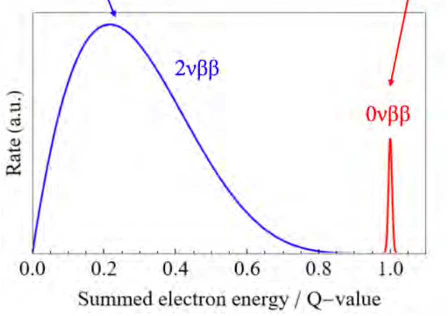
# The Physics Case

**The matter-antimatter asymmetry of the Universe as an unsolved puzzle of cosmology and particle physics**

**Theoritecal prediction of asymmetry produced by a violation of lepton number via leptogenesis**

- Neutrinos being their own antiparticles and developing a Majorana mass component
- Neutrino Majorana masses and lepton-number violation can be verified by observing a hypothetical nuclear transition (A,Z) → (A,Z+2)+2e⁻ called neutrinoless double-β (0νββ) decay
- Main experimental signature of 0νββ decay is a characteristic peak in the energy distribution located at the $Q_{\beta\beta}$ value




**Implications of 0νββ discovery**

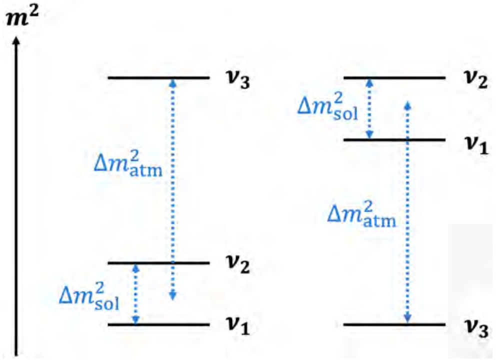
- Establishment of lepton number violation ΔL=2
- More physics beyond standard model
- Only way to determine if neutrino is its own antiparticle: $\nu=\bar{\nu}$ ⟶ ***Majorana particle***
- Access to absolute neutrino mass scale

| Experiment | Atomic phys. | | Nuclear phys. | Particle phys. |
|---|---|---|---|---|
| $(T_{1/2})^{-1}$ | $= G(Q_{\beta\beta}, Z) \cdot$ | $g_A{}^4 \cdot$ | $\lvert M_{\text{nucl}} \rvert^2 \cdot$ | $m_{\beta\beta}{}^2$ |
| Measured half-life | Phase space factor | Axial coupling | Nuclear matrix elements | Effective Majorana neutrino mass |

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} |U_{ei}^2| \, e^{i\varphi_i} \, m_i \right|$$

- Important inputs to cosmology

**Normal Ordering**

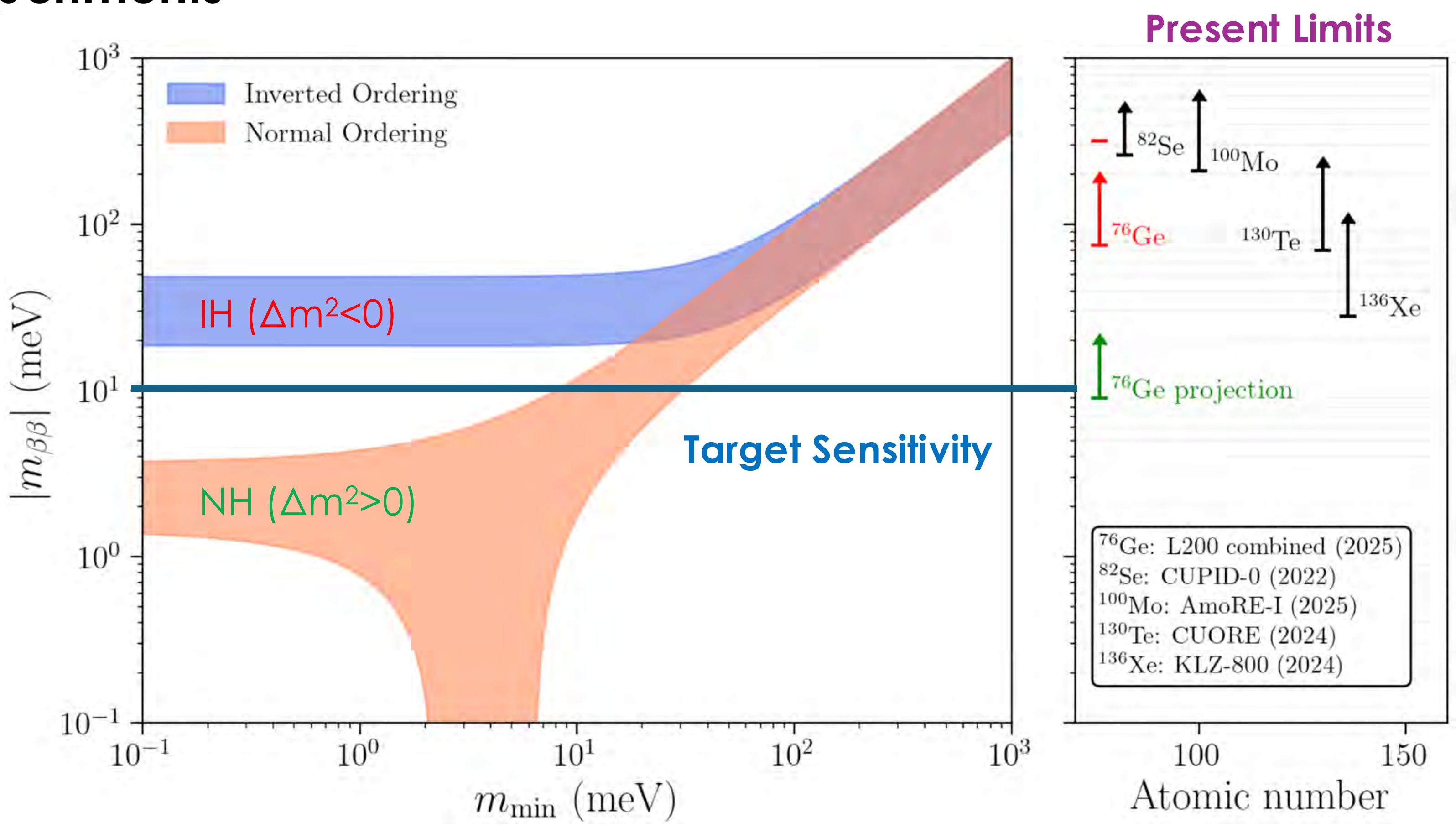



**Inverted Ordering**

# The Sensitivity Regions

**Constraints from oscillation data and limits from direct measurements of neutrino mass and neutrinoless double beta decay experiments**

- Allowed regions for $m_{\beta\beta}$ as a function of the lightest neutrino mass for both the normal and inverted mass orderings
- Current best limits for various detection concepts and techniques ($m_{\beta\beta}$~30-600 meV)
- **Target sensitivity of the next-generation experiments at 0.01 eV**



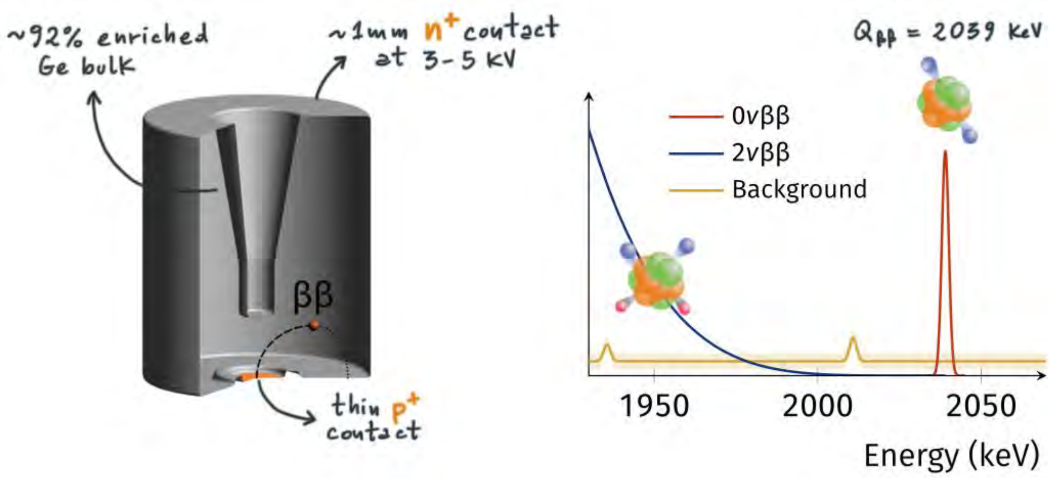
# The Experiment Prospects

**Key feature towards the detection of neutrinoless double beta decay:**
- **high sensitivity, due to ultra-low well-understood background**
- **highest detection efficiency**

**Main parameters allowing to determine the reaching potential of the experiment and its sensitivity:**
- Mass **M** of the relevant isotope
- Data-taking time **T**
- Energy resolution $\boldsymbol{\sigma_E}$
- Background Index **B** (in units of cts/(keV×kg×yr))

$$T_{1/2} \propto f\,\epsilon\sqrt{\frac{Mt}{B\sigma_E}}$$

$f$: isotope enrichment fraction
$\epsilon$: Detection efficiency
$M$: Isotope mass
$t$: Measurement time
} $Mt$: exposure
$B$: Background index = counts / [energy-range · mass · time], e.g., counts / (keV·kg·yr)
$\sigma_E$: Energy resolution at the decay Q-value ($Q_{\beta\beta}$)




**High-Purity Germanium detectors enriched in $^{76}$Ge:**

- Source same of detector → high efficiency
- Pure Germanium → low intrinsic background
- Ge crystal → outstanding energy resolution
- Solid-state TPC → topological discrimination, PSD

# The LEGEND Experiment

**LEGEND Project:**

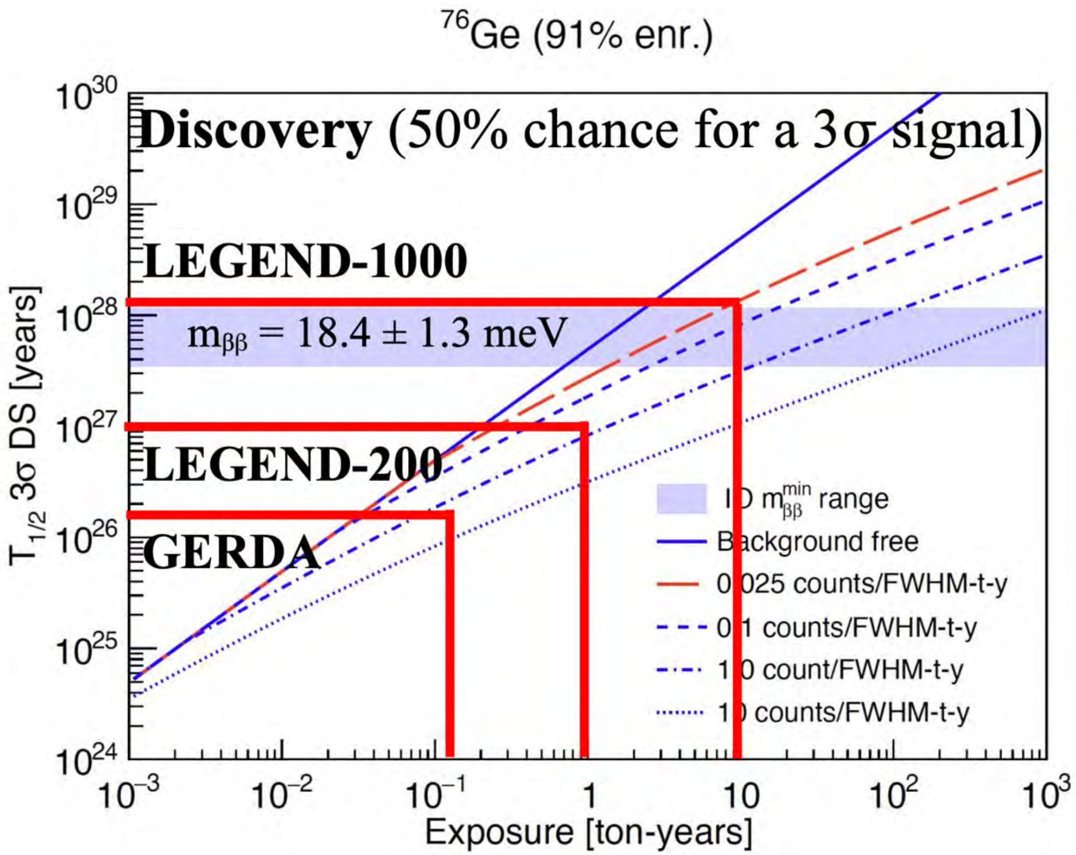
**“The collaboration aims to develop a phased $^{76}$Ge based double-beta decay experimental program with discovery potential at a half-life significantly longer than $10^{28}$ years, using existing resources as appropriate to expedite physics results”**

**First Stage (LEGEND-200):**

- Upgrade of the existing infrastructure of GERDA up to 200 kg
- Reduction of the B of a factor 5 w.r.t. GERDA Phase II goal
- Detector running and taking data from mid-March 2023

**Next Stages (LEGEND-1000):**

- Amount of Ge up to 1000 kg (staged)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- LNGS as preferred site

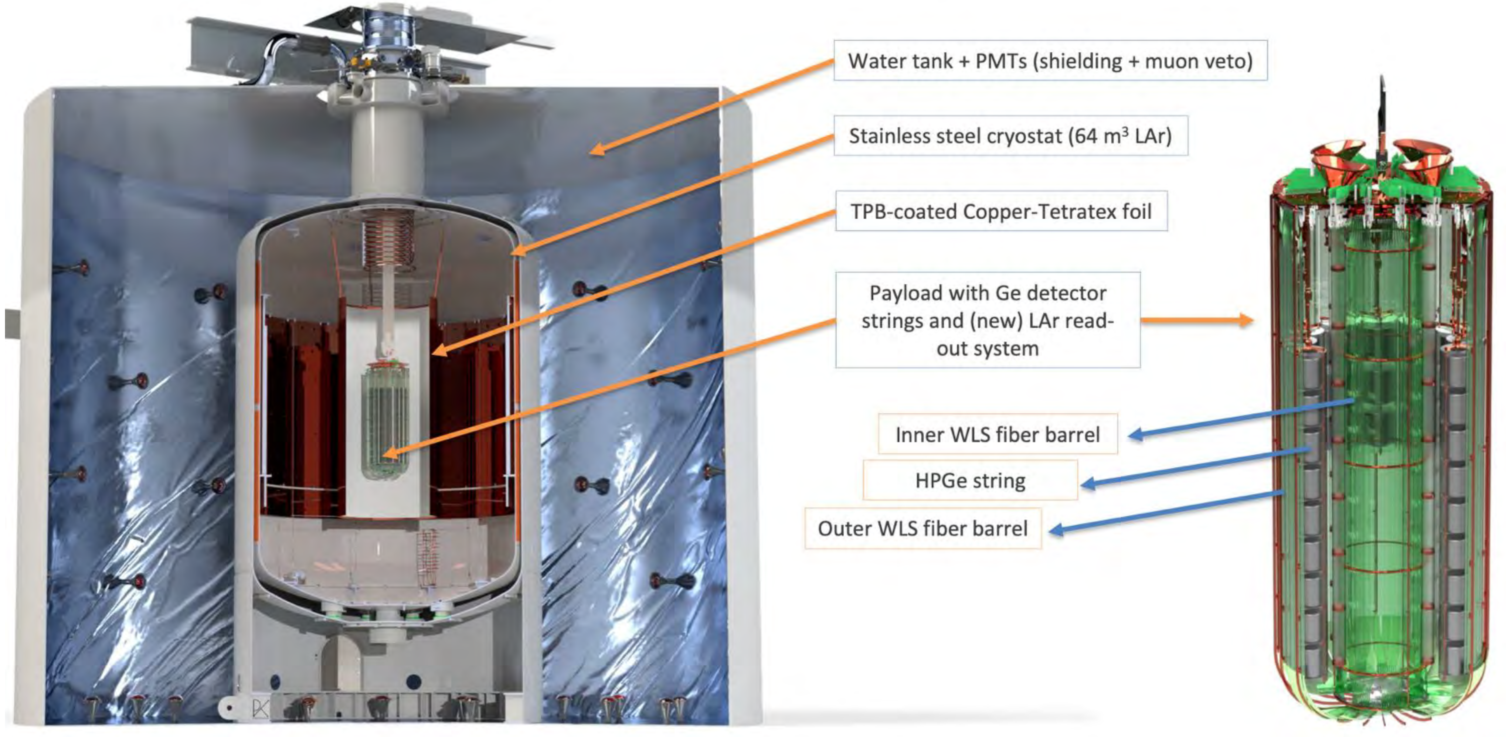



Linearity of the Half Life with Exposure:
$T_{1/2} \propto MT$ for Background free Experiment

# LEGEND-200 Experiment

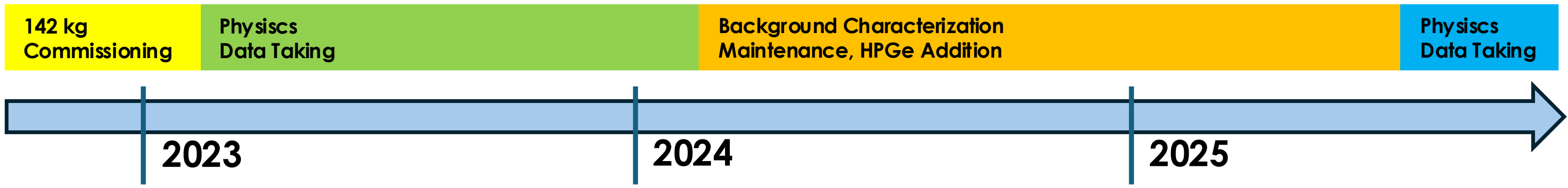
## LEGEND-200 detector located at INFN-LNGS underground laboratory and currently taking data

- Re-using of GERDA cryostat
- Amount of $^{enr}$Ge up to 200 kg
- Taking physics data since March 2023 with 142 kg of $^{enr}$Ge
- HPGe detectors deployed in liquid argon to reject external backgrounds via scintillation and as a passive shield
- Background goal $B \sim 2\times10^{-4}$ cts/(keV×kg×yr)




**Physics Goals** after 1 ton×yr of exposure:

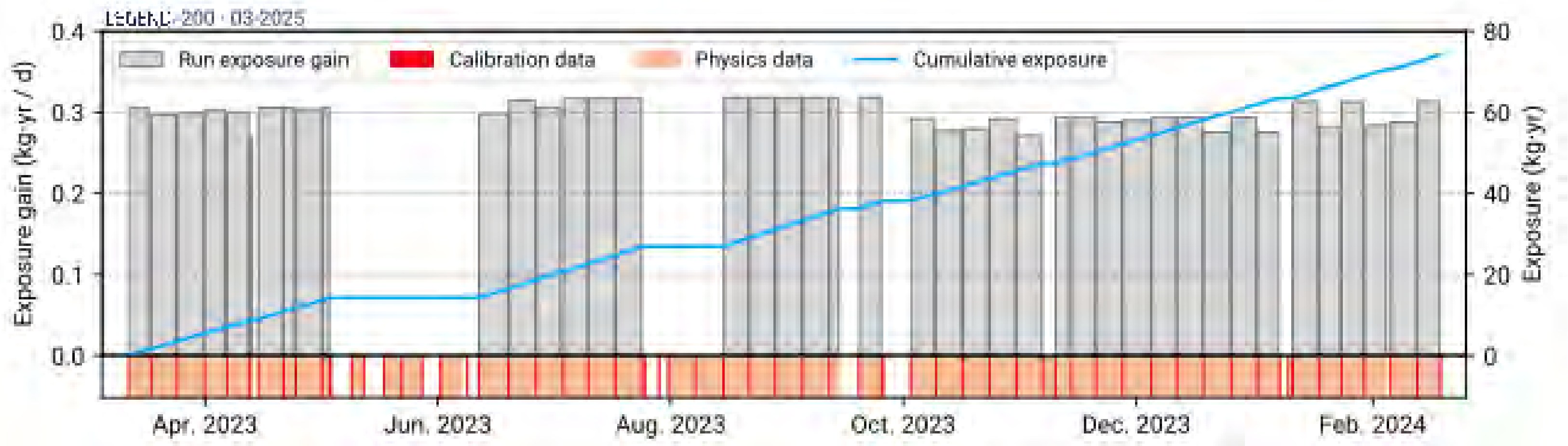
- $T^{0\nu}$:
  - $9.7\times10^{26}$ years (99.7% CL discovery)
  - $1.5\times10^{27}$ years (90% CL exclusion)
- $m_{\beta\beta}$:
  - 33–89 meV (99.7% CL discovery)
  - 26–71 meV (90% CL exclusion)



# LEGEND-200 First Results

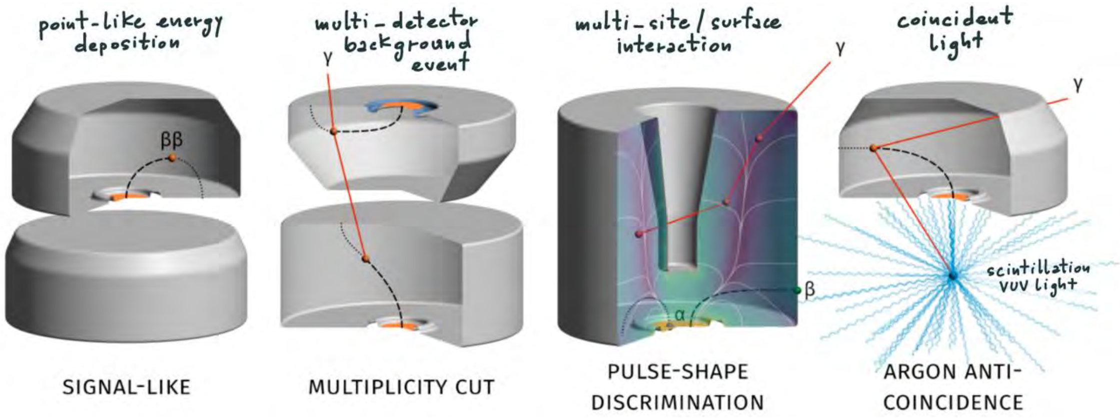
**LEGEND-200 detector accumulated exposure over 1 year**

- Background and performance characterization: 85.5 kg×yr
- First 0νββ data set: 61 kg×yr




- ~0.1% FWHM resolution at $Q_{\beta\beta}$=2039 keV
- Pulse shape discrimination (PSD) and liquid argon (LAr) anti-coincidence to actively suppress backgrounds

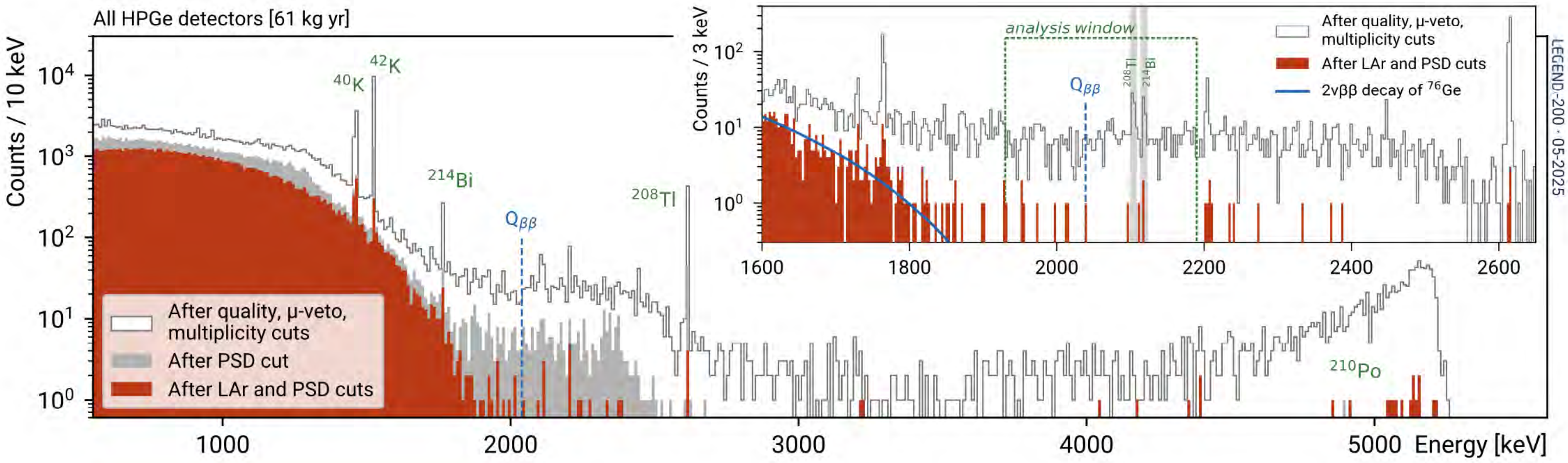
- Set of quality cuts applied to identify events incompatible with ordinary energy depositions in the HPGe array



# LEGEND-200 First Results

**LEGEND-200 detector 0νββ results from the first 142 kg deployment (recently accepted by PRL)**

- Combination of cuts suppressing nearly all backgrounds:
  - Muon veto and multiplicity cuts
  - Pulse Shape Discrimination
  - Argon anti-coincidence events
- Backgrounds near $Q_{\beta\beta}$ highly suppressed by analysis cuts

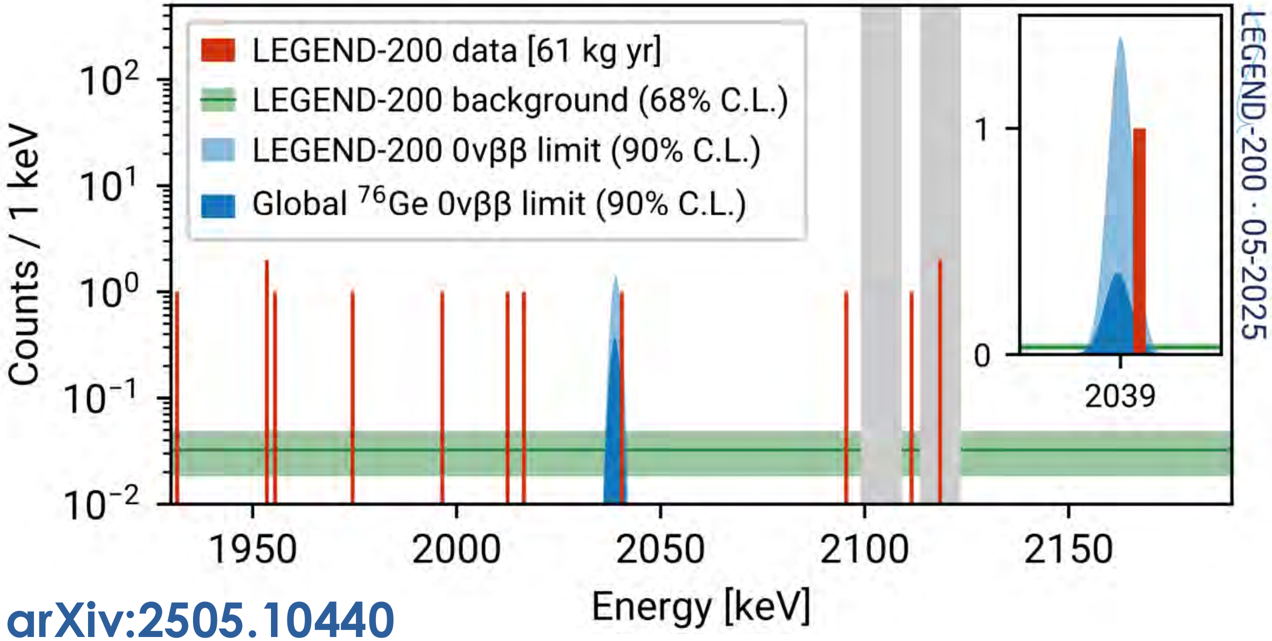


# LEGEND-200 First Results

**LEGEND-200 detector 0νββ results from the first 142 kg deployment (recently accepted by PRL)**

- Background indices:
  - $BI_1$ (12.7 kg×yr)=$1.3^{+0.8}_{-0.5}$ cts/(keV×ton×yr) (manily coaxial detectors with worse background rejection)
  - $BI_2$ (48.3 kg×yr)=$0.5^{+0.3}_{-0.2}$ cts/(keV×ton×yr) (rest of the detectors)
- LEGEND-200 observed limit $T_{1/2}$ >$0.5\times10^{26}$ years (90% CL)
- One event near $Q_{\beta\beta}$ weakens observed limit compared to exclusion sensitivity of $1.0\times10^{26}$ years

ROI = 1930–2190 keV



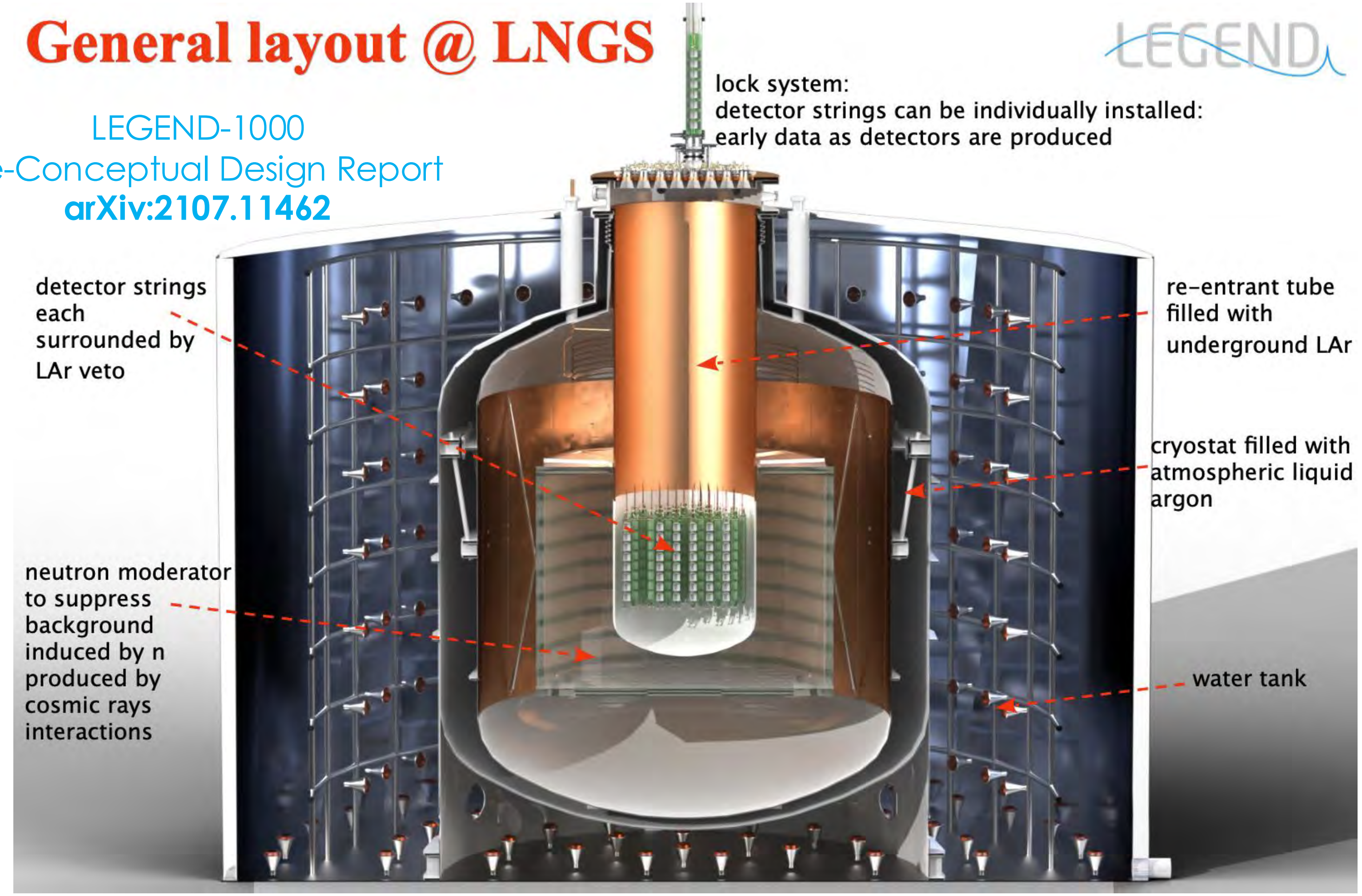

arXiv:2505.10440

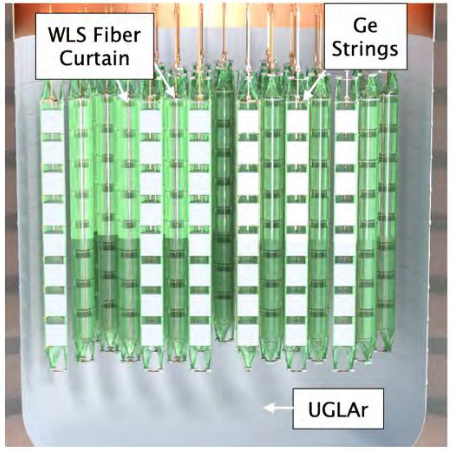
| GERDA, MAJORANA, and LEGEND $^{76}$Ge combined result | | |
|---|---|---|
| | Observed (90% CL) | Sensitivity (90% CL) |
| $T_{1/2}$ | >$1.9\times10^{26}$ yr | $2.8\times10^{26}$ yr |
| Phenomenological NME: 2.35−6.34 | | |
| $m_{\beta\beta}$<75 – 200 meV (90% CI) | | |

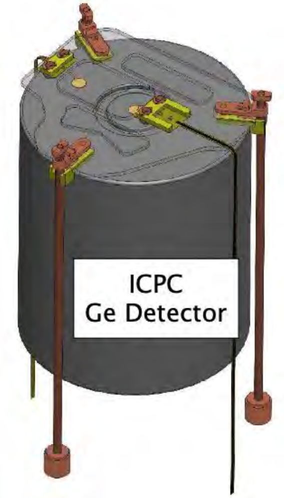
# LEGEND-1000 Experiment

**LEGEND-1000: ton scale detector with discovery potential at a half-life beyond $10^{28}$ yr**

LEGEND-1000
Pre-Conceptual Design Report
**arXiv:2107.11462**



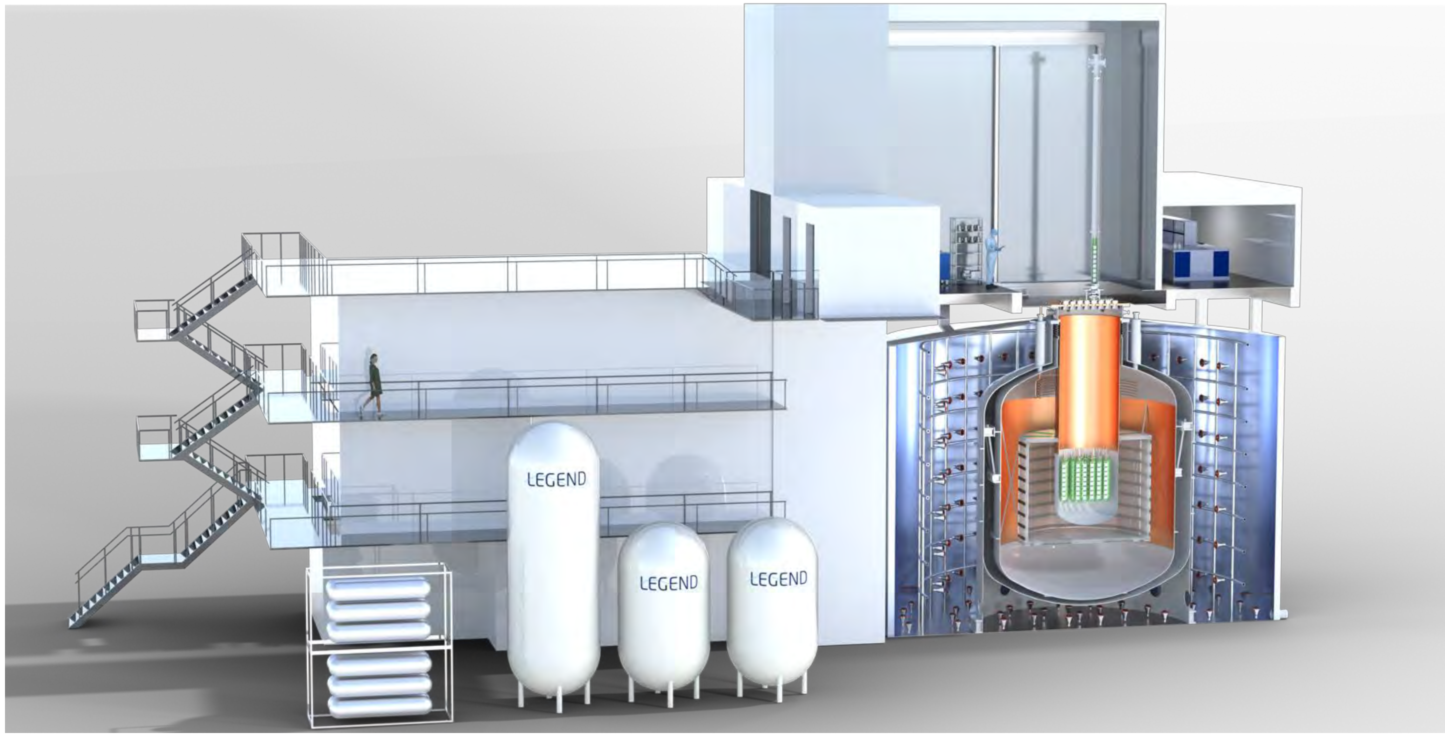

- 336 detectors 3 kg avg. mass arranged in 42 strings
- Detector strings can be individually installed allowing for early data as detectors are produced
- Almost 200 t of Atmospheric Liquid Argon used in the ATLAR-Veto
- Use of 20 t of Underground Liquid Argon in the re-entrant tube

# LEGEND-1000 Experiment

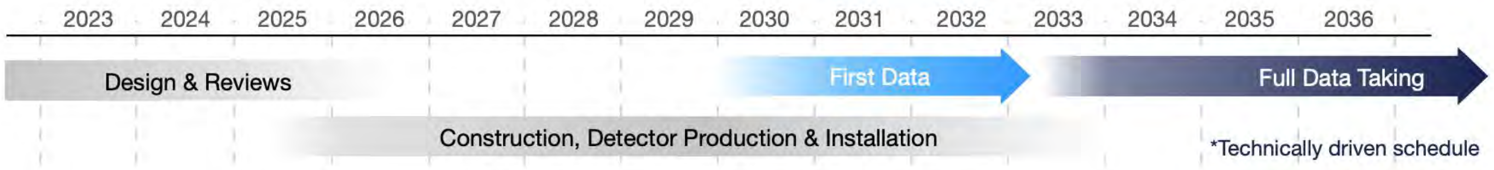
## LEGEND-1000 Sensitivity, Performance Parameters and Timeline

- Inverted ordering and large part of the normal ordering space spanned
- Discovery sensitivity <18.4 meV

| | |
|---|---|
| $0\nu\beta\beta$ decay isotope | $^{76}Ge$ |
| $Q_{\beta\beta}$ | 2039 keV |
| Total mass | 1000 kg |
| Energy resolution at $Q_{\beta\beta}$ | 2.5 keV FWHM |
| Overall signal acceptance | 0.69 |
| Total exposure | 10 t·yr |
| Background goal | $< 10^{-5}$ cts/(keV·kg·yr)<br>< 0.025 cts/(FWHM·t·yr) |
| $T^{0\nu}_{1/2}$ | $1.3\cdot10^{28}$ yr (90% C.L. discovery)<br>$1.8\cdot10^{28}$ yr (90% C.L. sensitivity) |
| $m_{\beta\beta}$ | 9.4 – 21.4 meV (99.7% C.L. discovery)<br>8.5 – 19.4 meV (90% C.L. sensivity) |

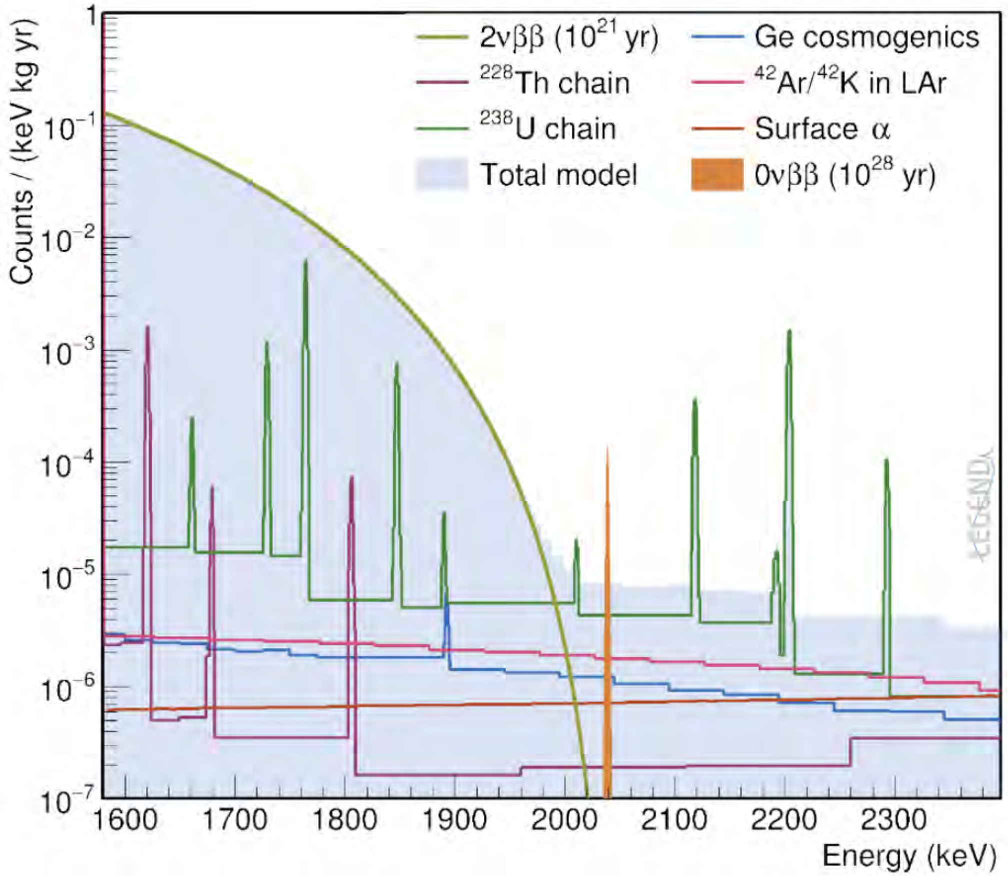



- Background Goal: $<1\times10^{-5}$ counts/(keV×kg×yr)
- $T_{1/2}$ discovery sensitivity (3σ): $1.3\times10^{28}$ yr

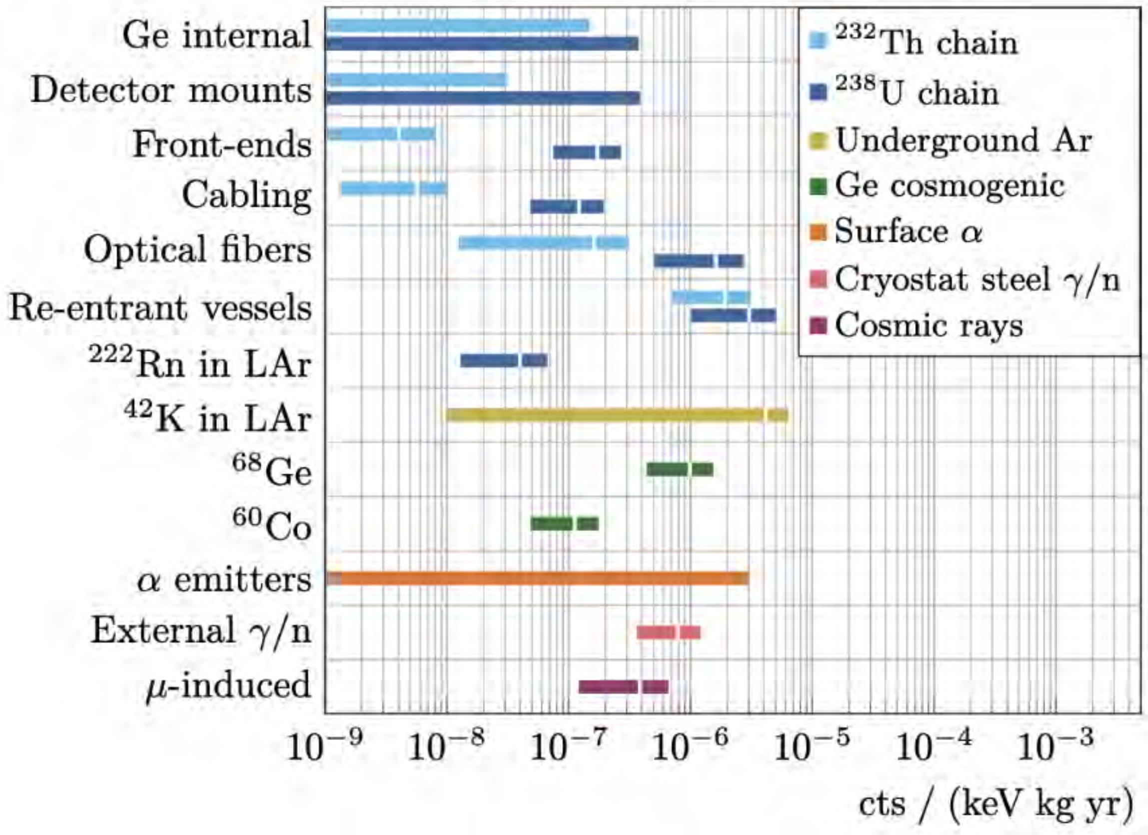


# LEGEND-1000 Experiment

**LEGEND-1000 Background Projections**




Expected total spectrum from 2νββ decay and from all background components after all cuts




Projected background index after all cuts:
**$8.5^{+4.6}_{-6.0} \times 10^{-6}$ cts/(keV×kg×yr)**

# Conclusions

- LEGEND project is a leading neutrinoless double beta decay experiment based on an enriched $^{76}Ge$ diode operating at cryogenic temperatures
- Key feature is the staged approach, leading results at each phase

- LEGEND-200 @INFN-LNGS is the first phase entering and exploring part of the inverted ordering region with the aim to reach the limit of $10^{27}$ yr in the half-life of the $0\nu\beta\beta$ decay of $^{76}Ge$
- First results from LEGEND-200 lead to a best Background Index of $0.5^{+0.3}_{-0.2}$ cts/(keV×ton×yr) for 142 kg deployment
- Combined results with Ge76 with GERDA+MAJORANA+LEGEND-200 provide $T_{1/2} > 1.9\times10^{26}$ yr and a sensitivity of $2.8\times10^{26}$ yr (90% CL)

- The next step, LEGEND-1000, will deploy a ton of isotope in order to reach an unprecedented sensitivity, to span the inverted ordering and a large part of the normal ordering space
- LEGEND-1000 is optimized for a quasi-background-free $0\nu\beta\beta$ search $<10^{-5}$ cts/(keV×kg×yr)
- Low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of $0\nu\beta\beta$ decay at $T_{1/2}=1.3\times10^{28}$ yr

# The LEGEND Collaboration


Ciemat · Comenius University Bratislava · Czech Technical University in Prague · Duke University · GSSI · Indiana University Bloomington · INFN

Jagiellonian University in Kraków · JINR · European Commission Joint Research Centre · INFN · Lancaster University · INFN · Laurentian University Université Laurentienne

Berkeley Lab · ikz · ipf Leibniz-Institut für Polymerforschung Dresden · Los Alamos National Laboratory · Max-Planck-Institut für Kernphysik Heidelberg

Max-Planck-Institut · National Research Center "Kurchatov Institute" · 國立臺灣大學 National Taiwan University · NC State University · Oak Ridge National Laboratory · Politecnico Milano 1863

Princeton University · Queens · Science & Technology Facilities Council Daresbury Laboratory · SNOLAB · South Dakota Mines · Technische Universität Dresden

TUM · Tennessee Tech · TUNL Triangle Universities Nuclear Laboratory · Università degli Studi dell'Aquila · Università degli Studi di Milano · Bicocca · Università degli Studi di Padova · Roma Tre

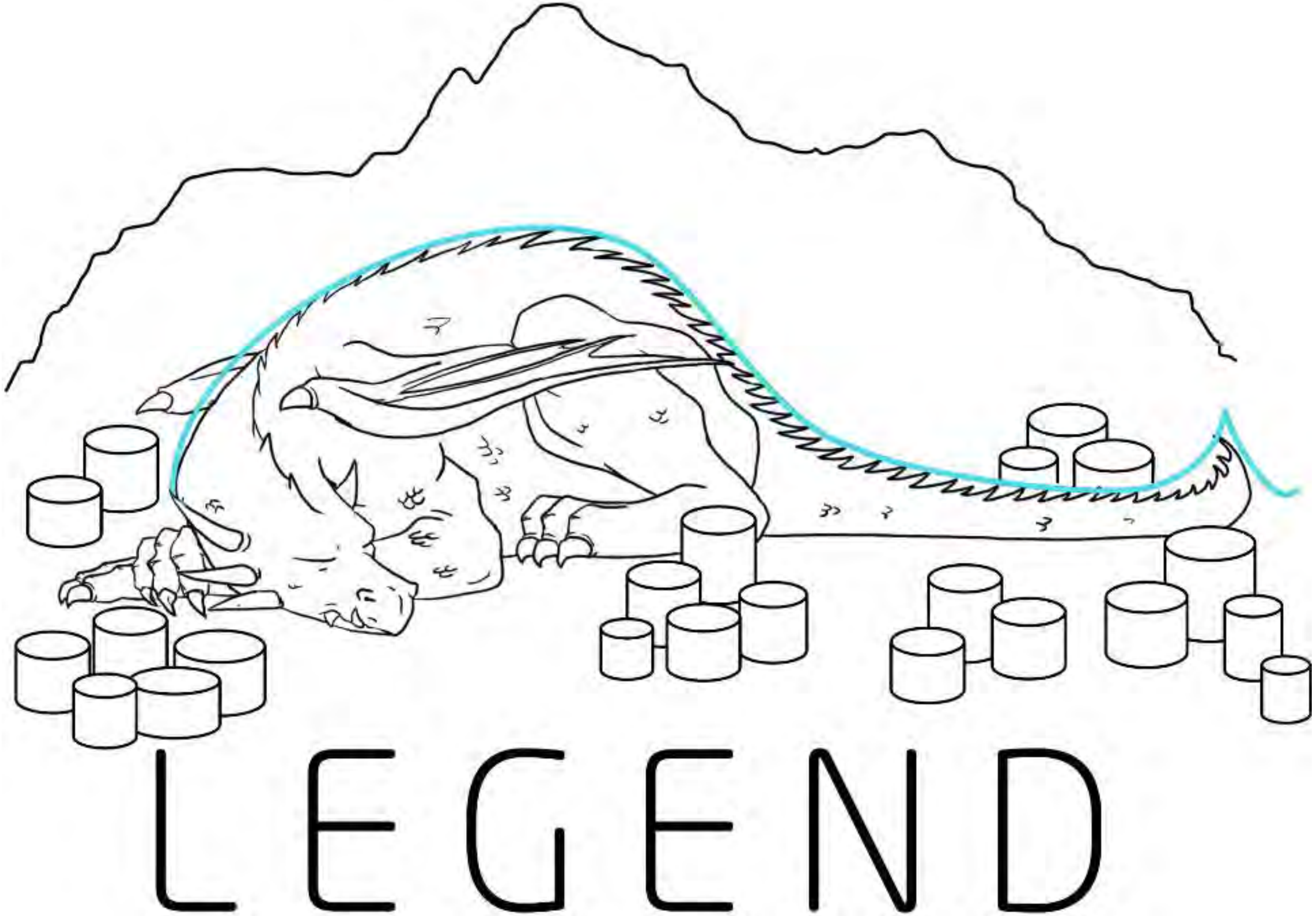
UCL · University of Houston · University of Liverpool · The University of New Mexico

The University of North Carolina at Chapel Hill · University of South Carolina · University of South Dakota · The University of Tennessee Knoxville · Texas The University of Texas at Austin · Warwick

University of Washington · Universität Zürich · Eberhard Karls Universität Tübingen

LEGEND

# Back Up Slides



# LEGEND-200 First Results