THE FIRST YEAR OF LEGEND-200 PHYSICS DATA IN THE QUEST FOR 0νββ

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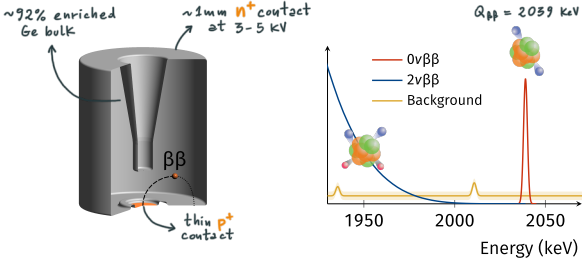
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND

On behalf of the LEGEND collaboration

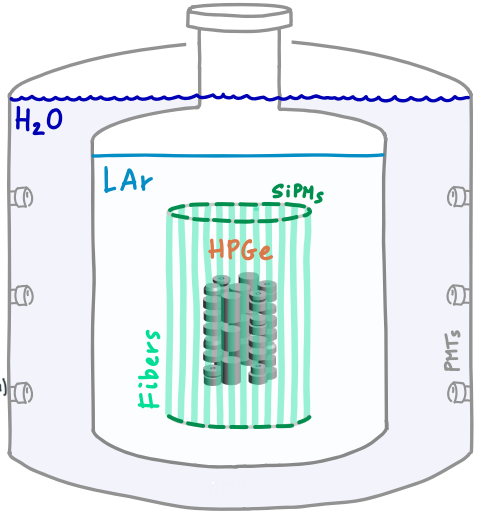
Searching for 0νββ with Germanium: concept



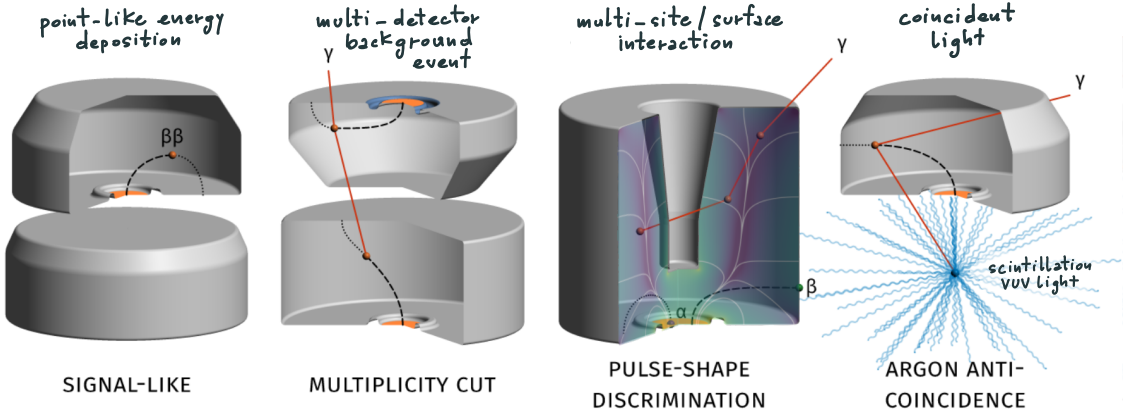
High-Purity Germanium detectors enriched in ^{76}Ge

- source = detector ⟼ *high efficiency*
- pure ⟼ *low intrinsic background*
- Ge crystal ⟼ *outstanding energy resolution* 0.1% @ $Q_{\beta\beta}$ (FWHM)
- "solid-state TPC" ⟼ *topological discrimination* Pulse Shape Analysis

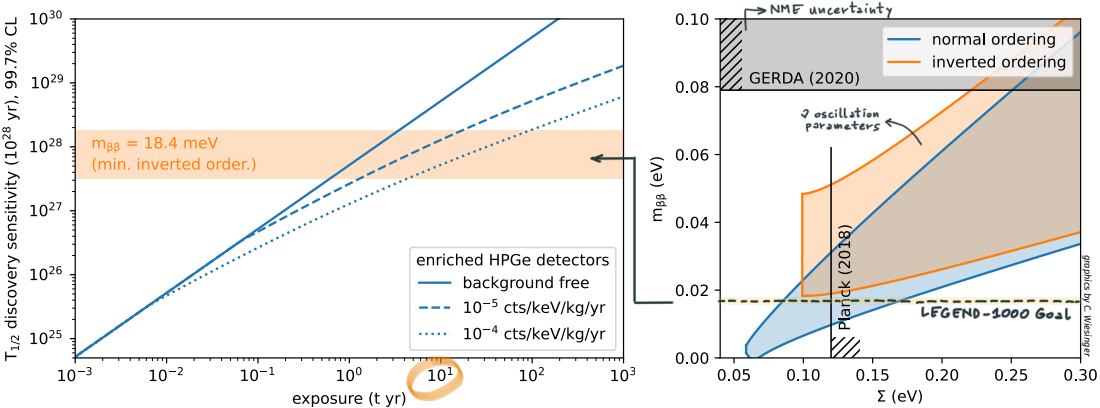
GERDA and MAJORANA constraints among the most stringent



SIGNAL AND BACKGROUND DISCRIMINATION TECHNIQUES



"...an era in which a discovery could come at any time!"



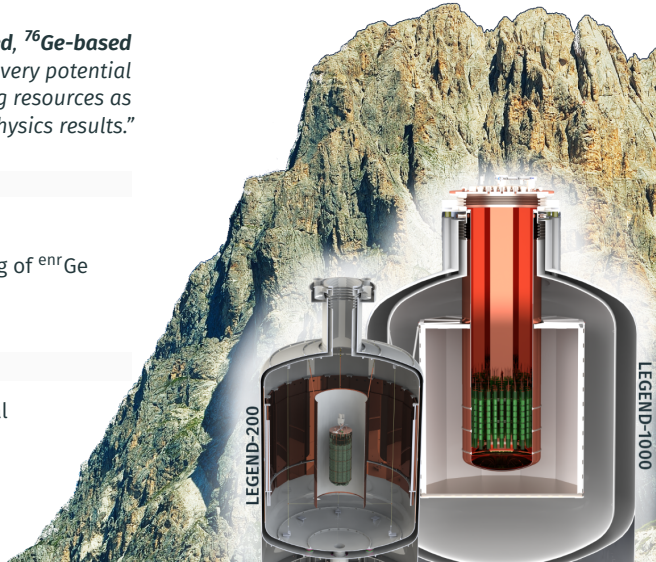
*"The collaboration aims to develop a **phased**, **^{76}Ge-based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} yr**, using existing resources as appropriate to expedite physics results."*

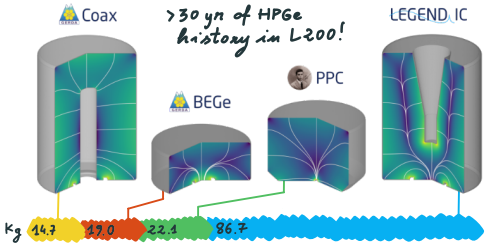
LEGEND-200

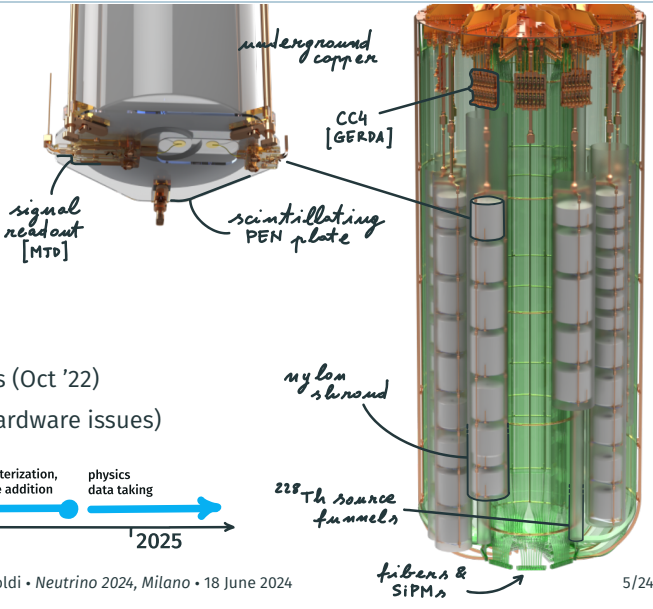
- **200 kg** of ^{enr}Ge (×5 yr), in GERDA cryostat
- Taking physics data since March 2023 with 142 kg of ^{enr}Ge
- $B \sim 2 \cdot 10^{-4}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{27}$ **yr**

LEGEND-1000 arXiv 2107.11462 "pre-Conceptual Design Report"

- **1 ton** of ^{enr}Ge (×10 yr), pending funding approval
- $B < 10^{-5}$ cts / (keV kg yr) $\longmapsto$ $T^{0\nu}_{1/2} > 10^{28}$ **yr**
- Fully cover $m_{\beta\beta}$ inverted ordering region

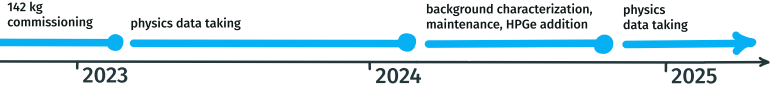






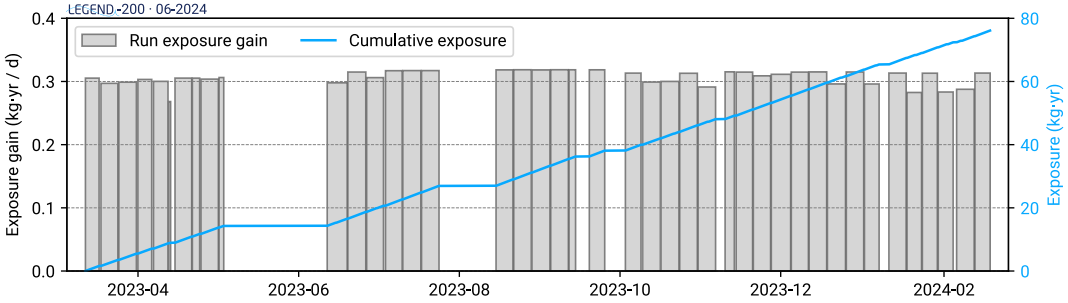
Hardware status — see talk at [TAUP23]

- Installed first **142 kg** of HPGe detectors (Oct '22)
- 130 kg operational (12 kg OFF due to hardware issues)

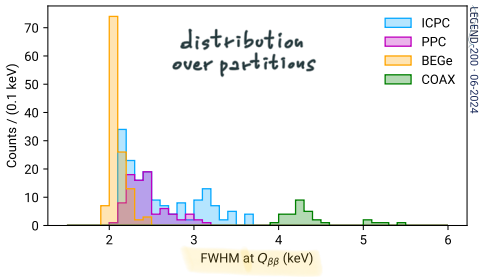


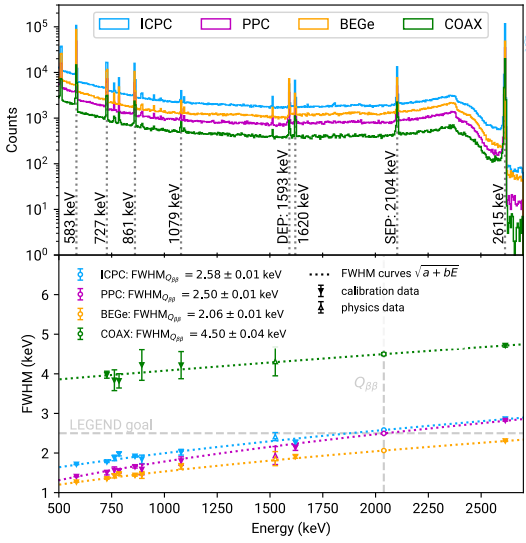
Exposure accumulated over 1 year valid for:

- [SILVER] Background and performance characterization: 76.2 kg yr
  - *plus 10.2 kg yr of special "background characterization" runs*
- [GOLDEN] 0νββ data set: 48.3 kg yr
  - *includes only data with fully vetted Pulse Shape Discrimination (PSD) parameters*

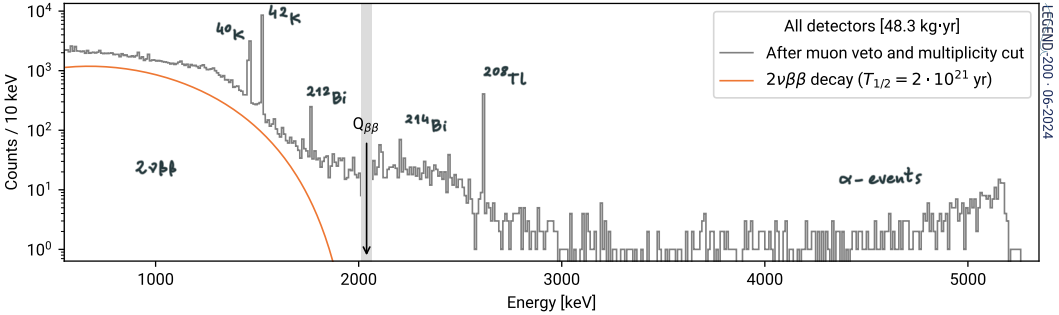


- ~0.1% FWHM at $Q_{\beta\beta}$
  - *including large inverted-coaxial detectors*
- **Stable** energy observables
  - *monitored with weekly ^{228}Th calibrations*
- Second-order variations **tracked in time**
  - *data set partitioned according to stability*



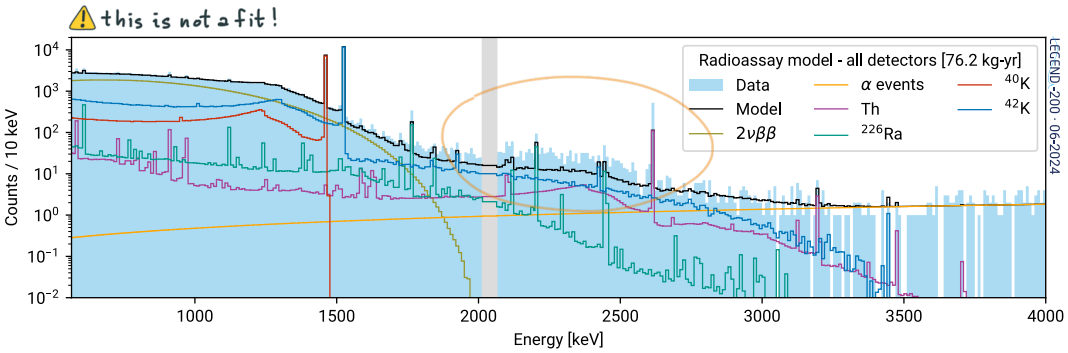


Data after Muon Veto and multiplicity cut [golden]



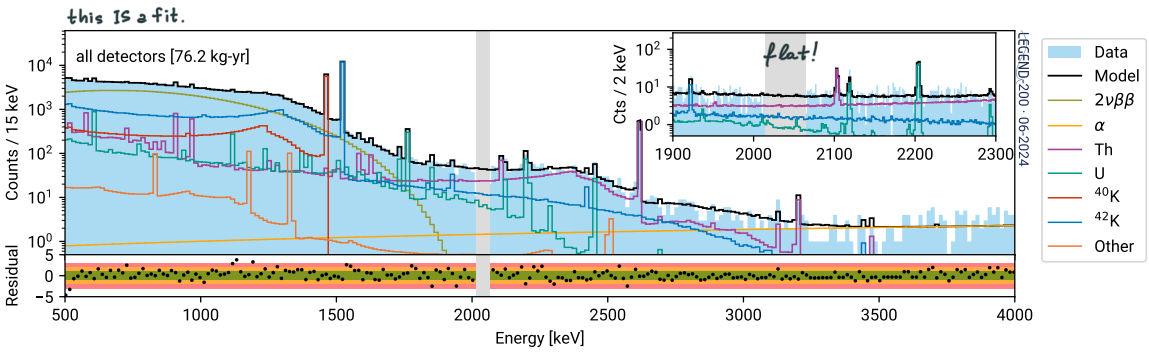
- Blinding applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- 95–99% survival of physical events after data cleaning at $Q_{\beta\beta}$
- Multiplicity cut rejects 26% of events at $Q_{\beta\beta}$
- 2 events removed by Muon Veto at $Q_{\beta\beta}$ POSTER *Muon Veto of the LEGEND Experiment* • G. Grünauer

MODELING DATA BEFORE ANALYSIS CUTS [SILVER]



- Simulations and material radioassay underpredict ^{228}Th in physics data
  - *Hard to estimate systematic uncertainty on the assay results*
  - *ICP-MS not predictive if secular equilibrium is broken*
- This background is efficiently suppressed by analysis cuts

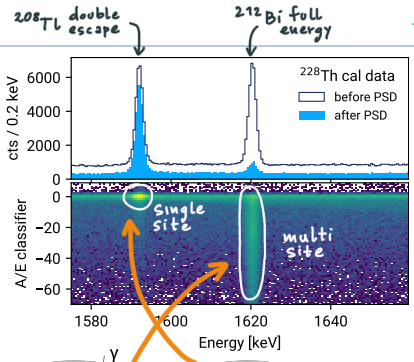
Modeling data before analysis cuts [silver]

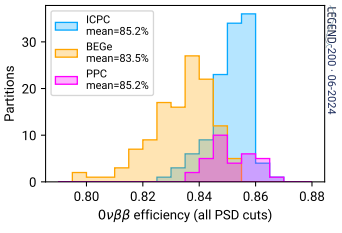


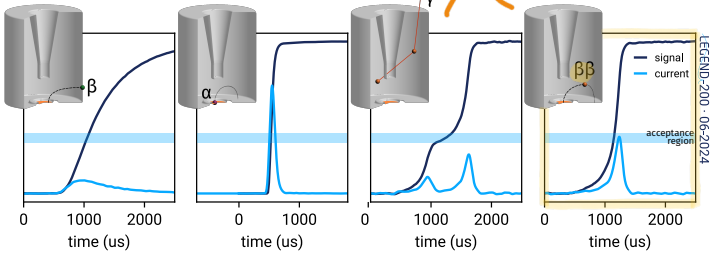
- Bayesian background model using data before analysis cuts [silver]
  - *Includes 10.2 kg yr from special "background characterization" runs*
- Data well reproduced, model is flat at $Q_{\beta\beta}$
  - *No "hotspot" or significant asymmetry observed in data*
  - *Model can test hypotheses on the origin of ^{228}Th*

Pulse Shape Discrimination (PSD)

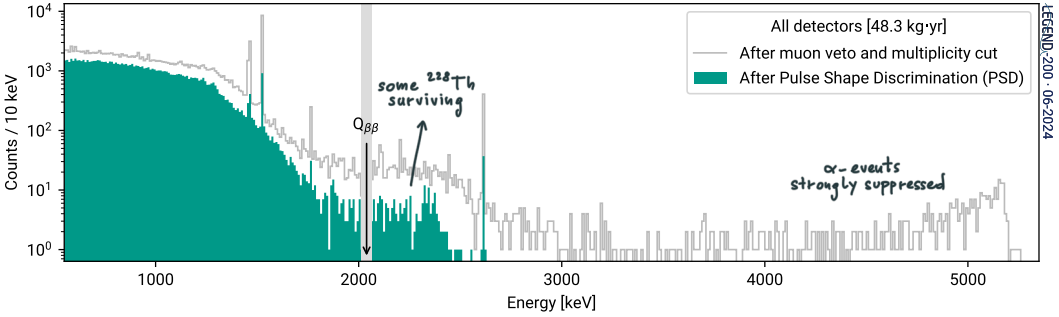
- Pulse shape classifier: A/E = *max(current) / energy*
  - *"Late Charge" (LQ) cut instead of high A/E cut for detectors with large passivated surfaces*
- **Stable** PSD observables
  - *monitored with weekly ^{228}Th calibrations*
- Second-order variations **tracked in time**
  - *data set partitioned according to performance stability*
- PSD methods for Coaxial detectors under development







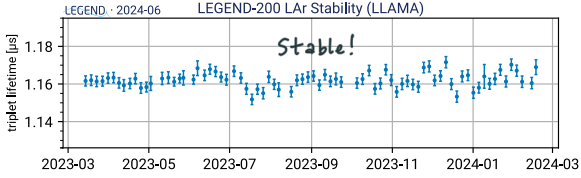
Data after pulse shape discrimination [golden]

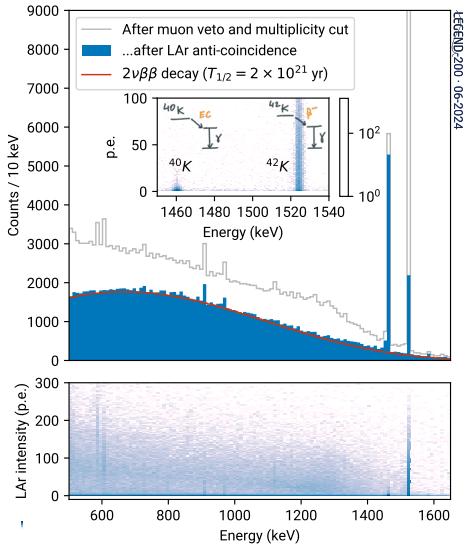


- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- 0νββ survival fraction of ~85%

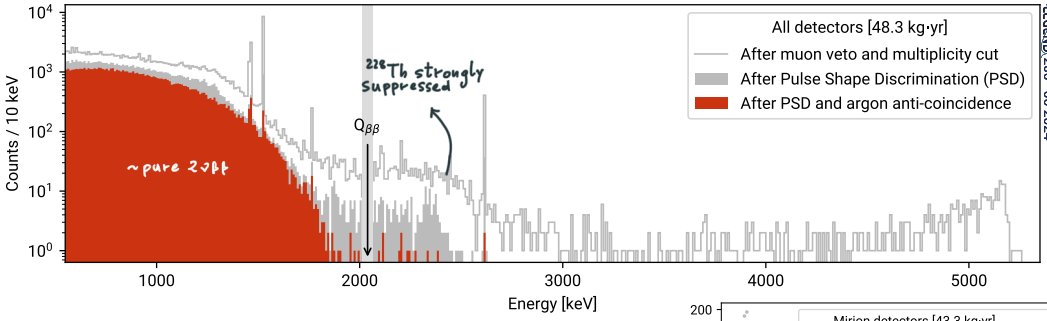
POSTER *LIQUID ARGON INSTRUMENTATION IN LEGEND-200* • N. Burlac, R. Deckert

- Improved light yield compared to GERDA (×3)
- **Stable** argon properties
  - *Monitoring through LLAMA instrumentation*
- **Characterized** with special calibration runs
  - *~1 photoelectron per 10 keV deposited in argon*
- **Strong suppression** of background above 2νββ
  - ββ *decay signal acceptance of ~93%*

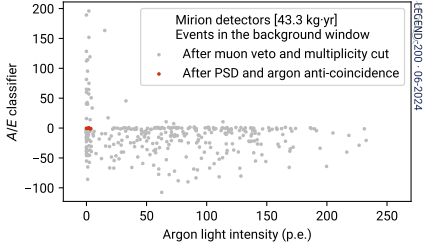




Data after pulse shape discrimination and argon anti-coincidence cut [golden]

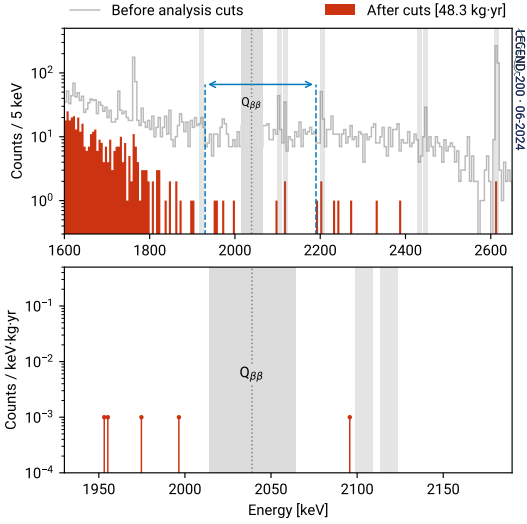


- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%
- "Pure" 2νββ distribution, few events surviving at $Q_{\beta\beta}$



Data in the region of interest!

5 events surviving in the
“background estimation window”



Data in the region of interest — after unblinding last week!

- 7 events surviving. Background index
  BI = 5.3 ± 2.2 · 10^{-4} cts / (keV kg yr)

PRELIMINARY!

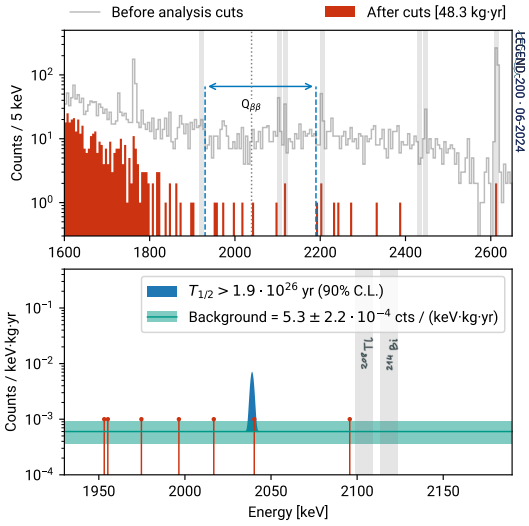
Gerda, Majorana and LEGEND combined fit

- *p*-value of background-only = 26%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

Observed	Sensitivity
> 1.9 · 10^{26} yr	2.8 · 10^{26} yr

LEGEND-200 contribution

- +30% of limit median expectation
- event at 1.4 σ from $Q_{\beta\beta}$ weakens combined limit

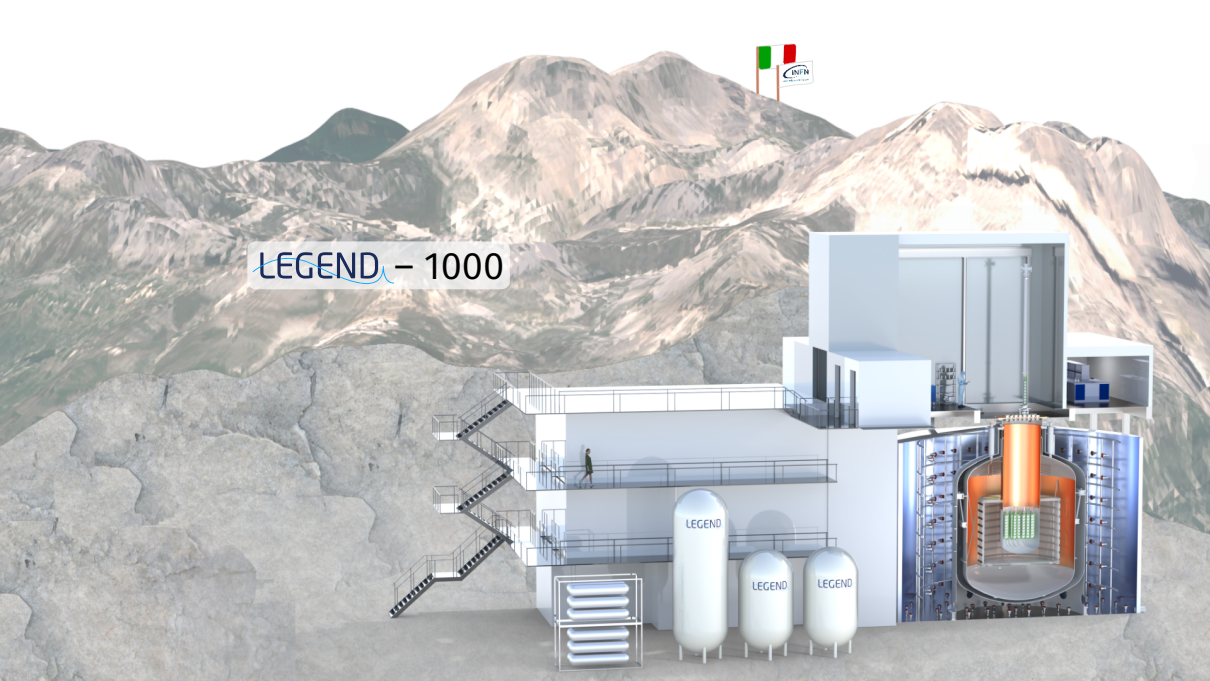


- Currently in "background characterization" phase, informed by the background model
  - *measurements with special setup configurations to test background hypotheses*
  - *starting radioassay campaign to measure and improve the radiopurity*
- Scheduled maintenance work is also underway
  - *preparing to install additional ~35 kg of HPGe detectors*
  - *repair of HPGe and SiPM channels — gain in background rejection power!*
- Restart physics data taking later in 2024

LEGEND-200 is a versatile, "quick turnaround" experimental instrument. Enabling prompt investigation of issues and a swift return to data taking. A powerful test bench for LEGEND-1000

In parallel:

- Analysis of special "background hunting" and performance characterization measurements
- Quantitative modeling of argon and PSD background suppression


LEGEND – 1000
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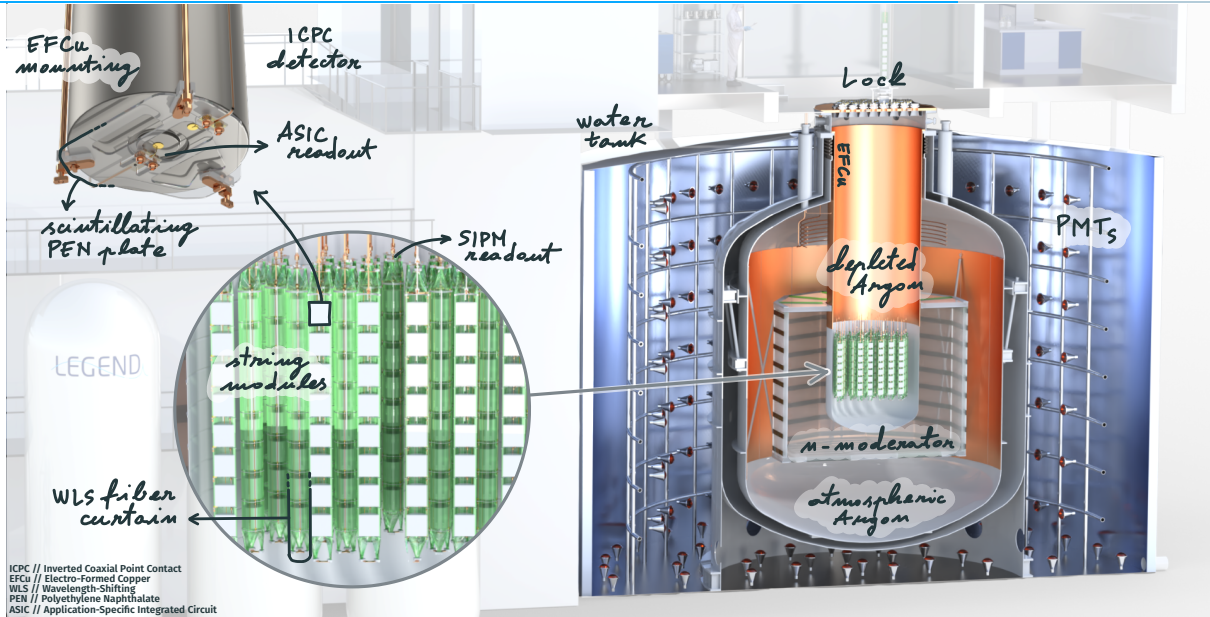
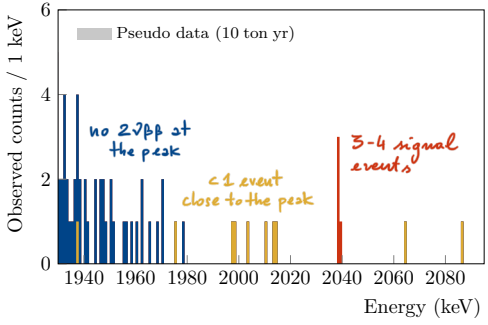
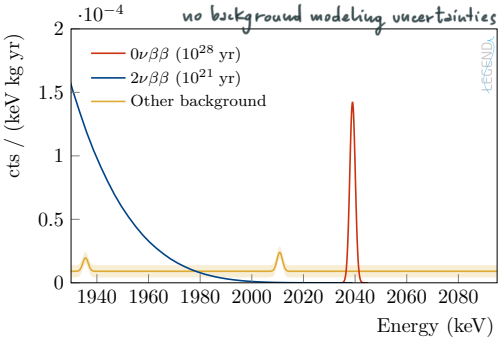
THE LEGEND -1000 BASELINE DESIGN AT LNGS

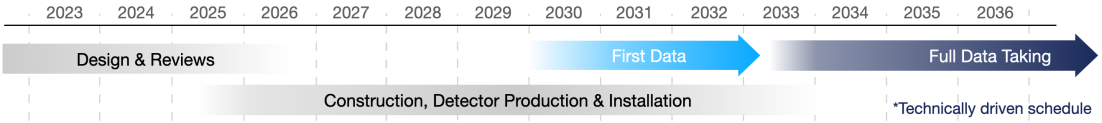


ICPC // Inverted Coaxial Point Contact
EFCu // Electro-Formed Copper
WLS // Wavelength-Shifting
PEN // Polyethylene Naphthalate
ASIC // Application-Specific Integrated Circuit

- Optimized for 0νββ *discovery* sensitivity beyond 10^{28} yr
- Background goal: 10^{-5} cts / (keV kg yr) ⟼ quasi-background-free for 10 ton yr exposure
- Has a low-risk path to meeting its goal based on MAJORANA, GERDA and LEGEND-200





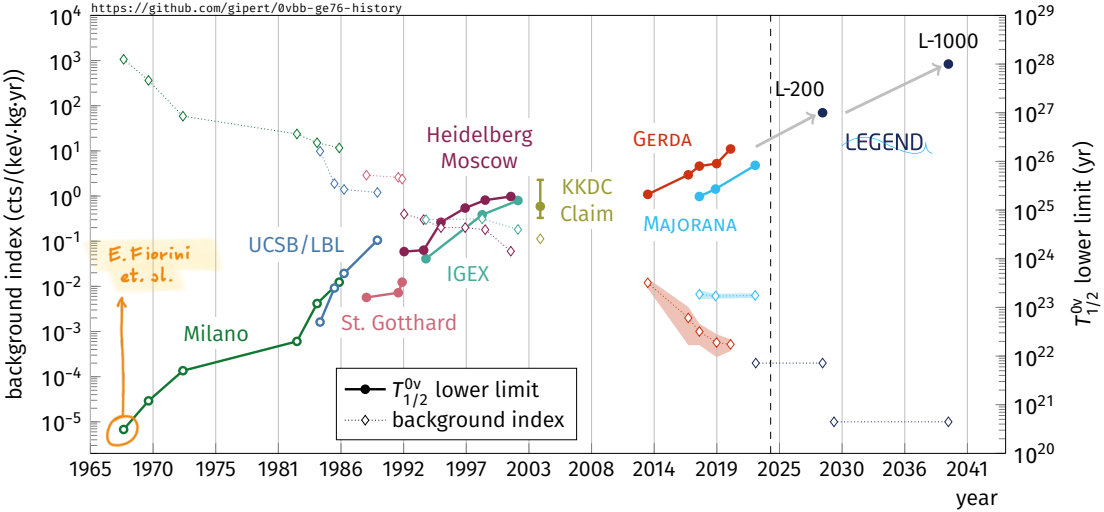


- Funding sought from U.S. (DOE and NSF) and from Europe
- Funding already in hand from several European institutions
- LEGEND-1000 preparations underway at LNGS following Borexino decommissioning

Summary

- LEGEND-200 has collected data over the last year and completed its first 0νββ unblinding
- We have observed a background after cuts comparable to GERDA, but elevated compared to expectations
- We have developed a background model to understand how to mitigate it
- We are taking advantage of the scheduled maintenance & detector deployment work to radioassay components of the array
- We plan to restart data taking later in 2024
- We are preparing for LEGEND-1000 and pursuing funding in the US and Europe. Meanwhile preparations are underway at LNGS

50+ YEARS OF ββ DECAY WITH ^{76}Ge



POSTER ***Performance of the Active Background Suppression of LEGEND-200 and Background Index*** • G. Marshall

POSTER ***Muon Veto of the LEGEND Experiment*** • G. Grünauer

POSTER ***Liquid Argon Instrumentation for Background Suppression in the LEGEND-200 Experiment*** • N. Burlac, R. Deckert

POSTER ***First Results from the Background Model of the LEGEND-200 Experiment*** • T. Dixon, S. Calgaro

POSTER ***Improving Background Suppression in LEGEND with the Novel Scintillating Material — PEN*** • B. Hackett

POSTER ***Alternative Searches for Physics Beyond the Standard Model in LEGEND-200*** • R. Bouabid

POSTER ***LEGEND-1000 Overview*** • E. van Nieuwenhuizen

POSTER ***Atmospheric Argon Instrumentation for LEGEND-1000*** • R. Cesarano, M. Morella

POSTER ***Machine learning based design optimization for the search of neutrinoless double-beta decay with LEGEND*** • A-K. Schütz

POSTER ***Surface events pulse shape simulation for the LEGEND experiment*** • A. Leder

POSTER ***Exploring position reconstruction of HPGe detector events in LEGEND with a deep neural network*** • C. Seibt

POSTER ***Faithful Pulse Shape Analysis by using Feature Importance Supervision*** • K. Klingus