LEGEND: Searching for Neutrinoless Double Beta Decay

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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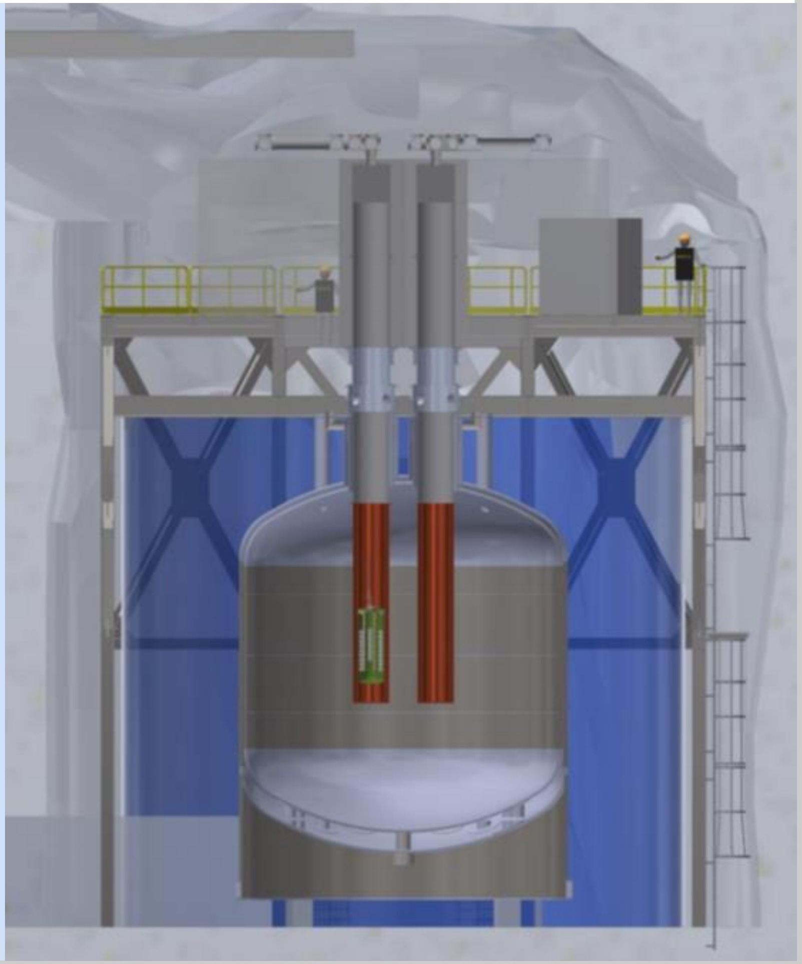
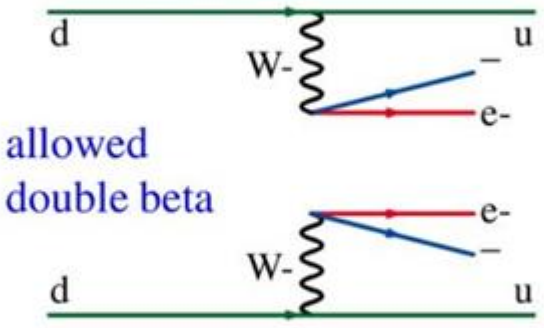
24 Feb 2022

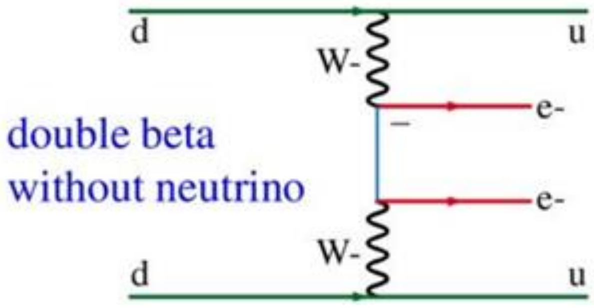
Lake Louise Winter Institute



Neutrinoless double beta decay $0\upsilon\beta\beta$



$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^- + \bar{\upsilon}_e + \bar{\upsilon}_e$$



ΔL=2

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^-$$

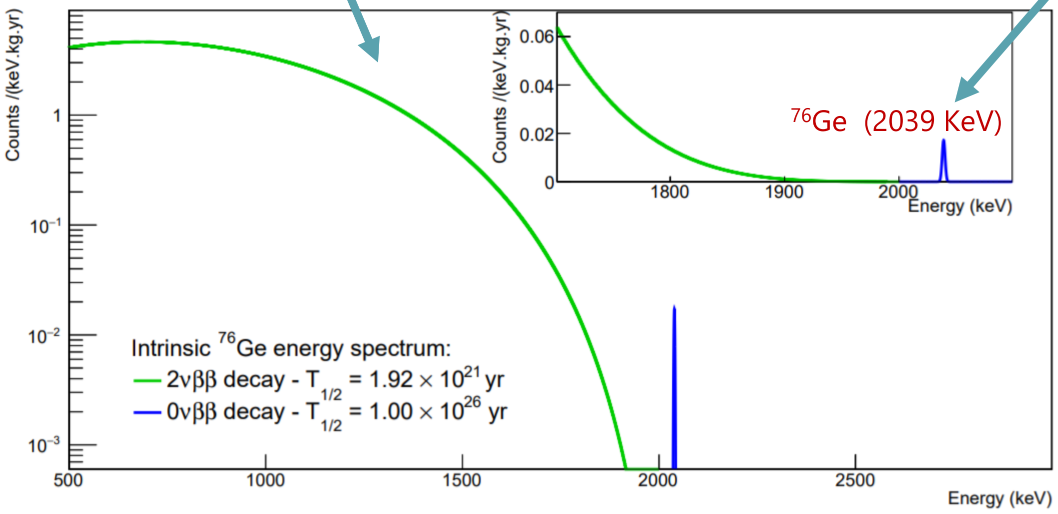
$T_{1/2}$~$10^{19} - 10^{20}$ **Years!**

$^{76}Ge,\ ^{100}Mo,\ ^{82}Se,\ ^{116}Cd,$

$^{130}Te,\ ^{96}Zr,\ ^{48}Ca,\ ^{150}Nd,\ \ldots$

Adnd.2001.0873

arXiv 2109.07575 ,2021

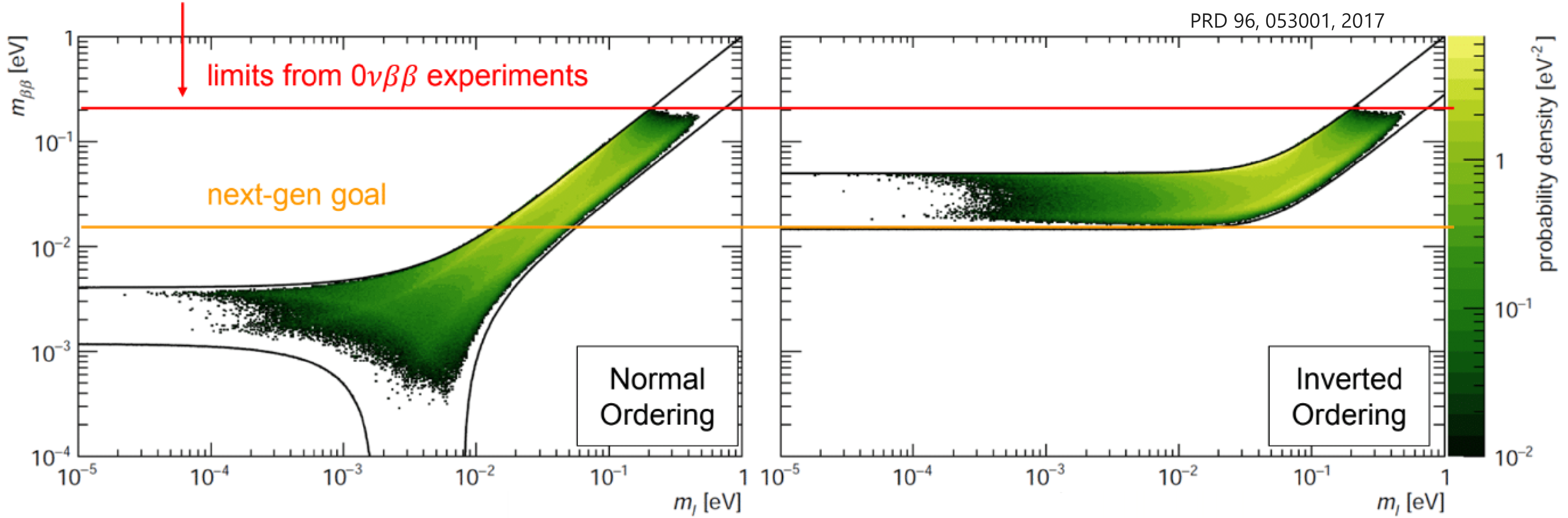


^{76}Ge GERDA

$T_{1/2}$ ~1.8×10^{26} **Years!**

Phy.Rev.Lett. 125, 252502, 2020

Majorana neutrino mass

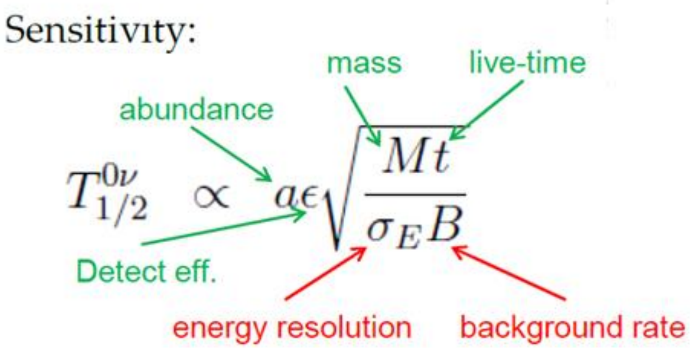


NO: $m_1 < m_2 < m_3$ **IO:** $m_3 < m_2 < m_1$

- The green area shows the allowed regions for all possible CP-phases by assuming 3σ intervals of the neutrino oscillation observables.

Most recent experimental results

LEGEND



&

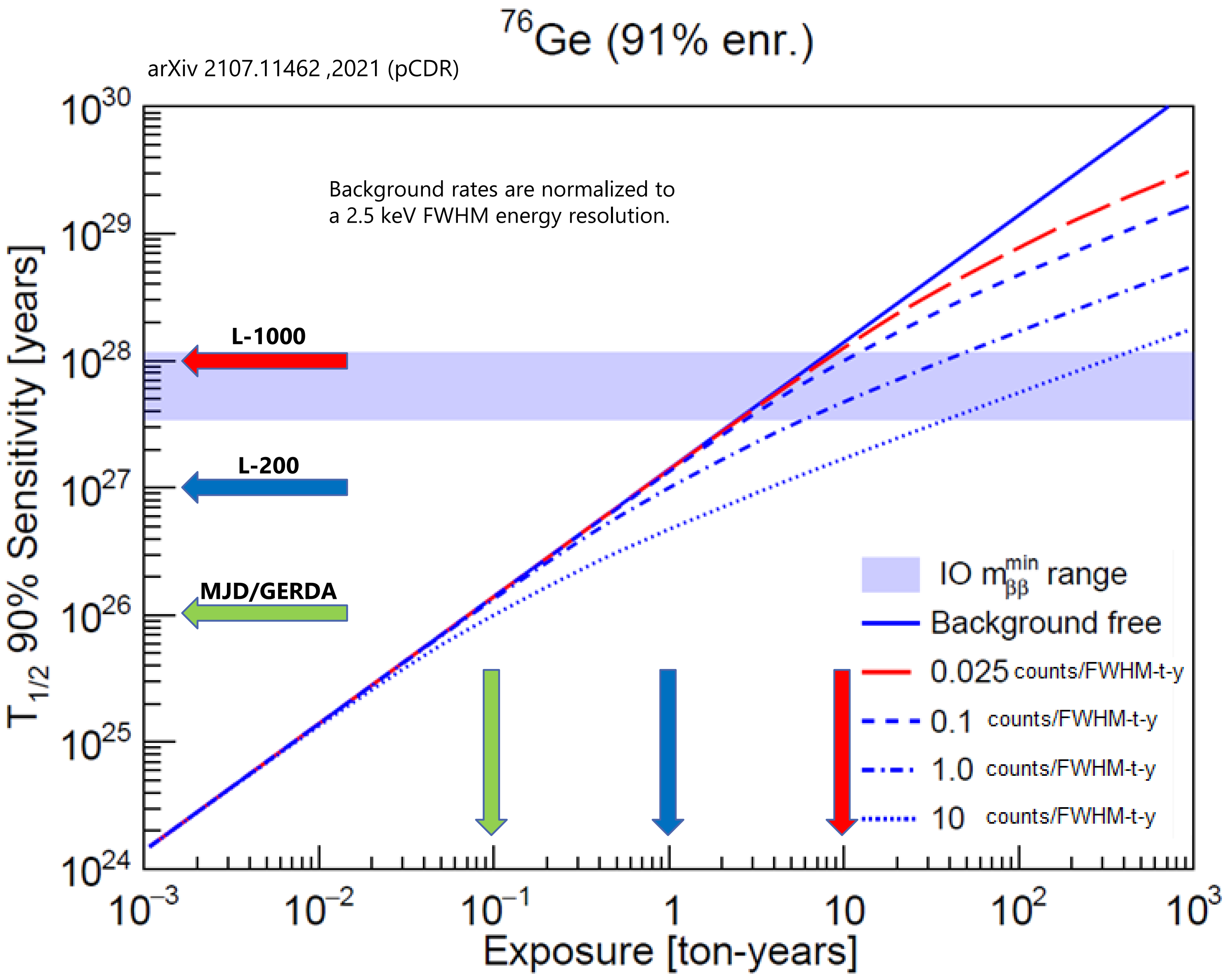
$$T_{1/2}^{-1} \propto \langle m_{\beta\beta} \rangle^2$$

Comparison of lower half-life limits $T^{0\upsilon}_{1/2}$(90% CL) and corresponding upper Majorana neutrino mass $m_{\beta\beta}$ limits for the present-generation experiments

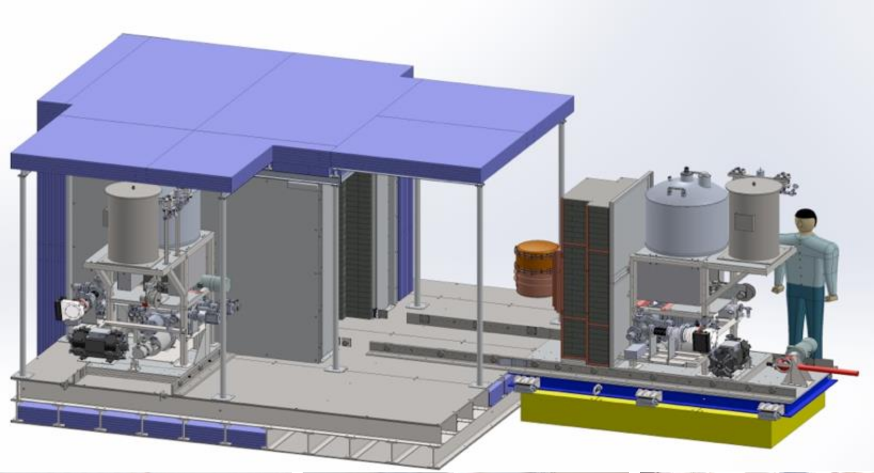
Experiment	**Isotope**	**Exposure [kg-yr]**	$T^{0\nu}_{1/2}$ **[10^{25} yr]**	$m_{\beta\beta}$ **[meV]**	
GERDA	^{76}Ge	127.2	18	79 – 180	Phy.Rev.Lett. 125, 252502, 2020
MAJORANA	^{76}Ge	26	2.7	200 – 433	Phy.Rev.C100. 025501, 2020
KamLAND-Zen	^{136}Xe	594	10.7	61 – 165	Phy.Rev.Lett. 117, 082503, 2016
EXO-200	^{136}Xe	234.1	3.5	93 – 286	Phy.Rev.Lett. 123, 161802, 2019
CUORE	^{130}Te	1038.4	2.2	90 – 305	arXiv 2104.6906, 2021

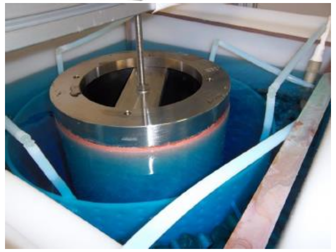
Ge experiments sensitivity & discovery

- Excellent energy resolution
- Accurate reconstruction event and clear topological discrimination using PSD
- Provide excellent discovery power even for small exposures
- Higher detection efficiency as almost all decay contribute to the sensitivity
- In order to probe the region of inverted mass hierarchy, need exposures of 10 tonne.year with background rates of < 0.1 $cts/FWHM/tonne/year$



MAJORANA DEMONSTRATOR & GERDA

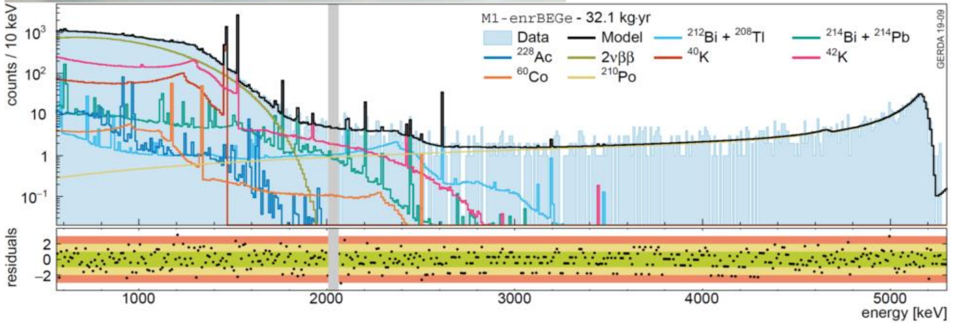




Phy.Rev.C100. 025501, 2020

<u>MAJORANA DEMONSTRATOR at SURF:</u>

- Two compact vacuum cryostats + shielding (Cu/Pb)
- 30kg enriched detectors, 14kg natural abundances
- Custom Low Mass Front End electronics
- Extensive use of underground electroformed copper
- **Best energy resolution(0.12 % FWHM at 2039 KeV)**



<u>GERDA at LNGS:</u>

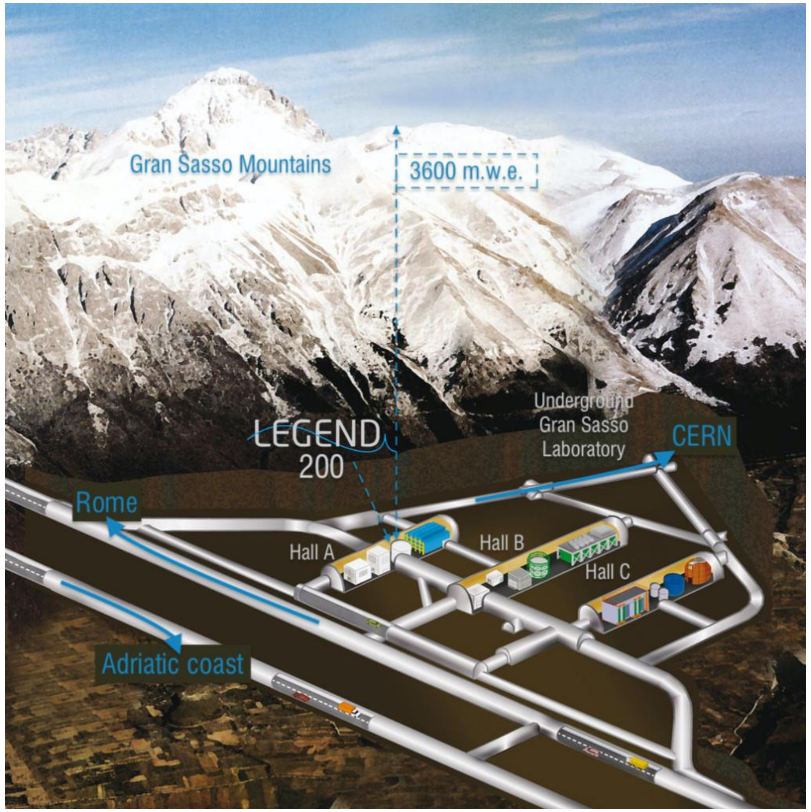
Phy.Rev.Lett. 125, 252502, 2020

- Detectors deployed in liquid argon as scintillating veto
- 35kg of enriched detectors (coax + BEGe)
- Complete background modelling over large energy range
- **Lowest background index (5.2×10^{-4}cts/(keV kg yr))**

The LEGEND program

- LEGEND: Large Enriched Germanium Experiment for Neutrinoless bb Decay arXiv 1810.00849 ,2018
- Formed from the MAJORANA and GERDA collaborations
- **Goal**: 3σ detection of a $0\nu\beta\beta$ signal in ^{76}Ge for half-lives of **10^{27}** years for **L-200** & **10^{28}** years for **L-1000** (inverted mass hierarchy)
- **Method**:
  - Reuse of best technologies from MJD and GERDA:
    - Electroformed copper
    - Low mass front-end electronics
    - Immersion in liquid argon
  - Develop new technologies:
    - New detector type (ICPC detectors)
    - Scintillating structural materials
    - Electronics
- **Program**:
  - L-200 experiment to deploy 200kg of enriched detectors and make use of the existing GERDA infrastructure at LNGS
  - L-1000 proposed for 1000kg of enriched detectors (baseline is **SNOLAB**)

L-200 Location

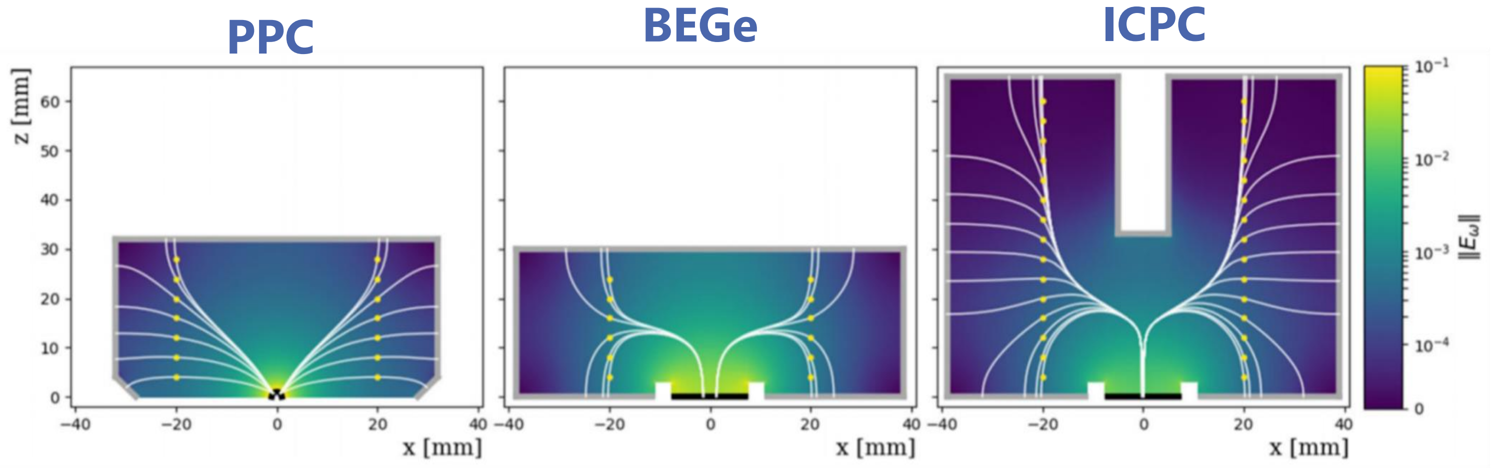


Speaker Name | Talk Title | Date

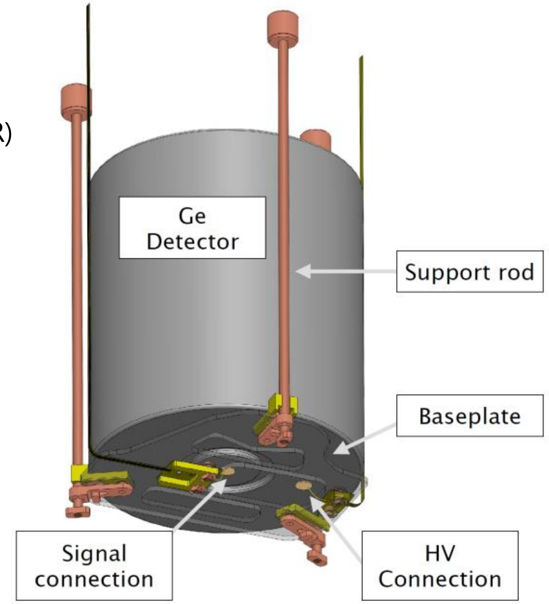
Germanium Detectors

- Inverted Coaxial Point Contact detectors:
  - The semi-coaxial "well" allows for larger mass detectors that will still deplete with a "reasonable" (<5kV) reverse-bias voltage
  - More than 3kg per detector (compare with ~1kg for "standard" PPC)
  - Larger detectors → Less detectors → Less radioactive components near detectors
  - Larger detectors → Larger volume/passivated surface → Less backgrounds from alpha radiation

Eur. Phy. J. C 81,76, 2021



arXiv 2107.11462 ,2021(pCDR)



LEGEND-200

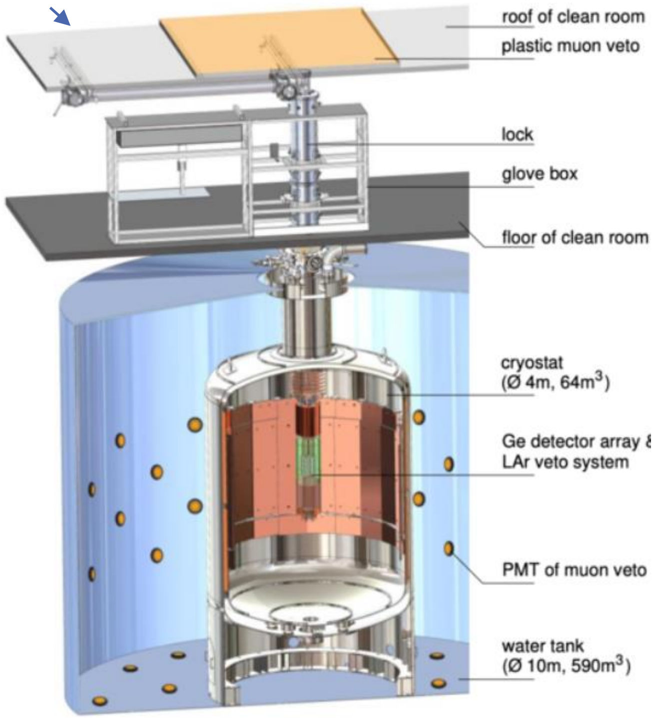
- It uses the existing GERDA cryostat and structure of low-Z shielding (water and argon) and an active veto and ultra-clean low mass materials and cables and electronics including those developed for the MAJORANA DEMONSTRATOR
- Simulated background index of 2×10^{-4}cts/(keV kg yr) and reduction by a factor of 2.5 compared to GERDA
- Half-life sensitivity measurement of **10^{27}** years equal to **29-60** meV
- L-200 reuses approximately 70 kg of enriched detectors from MAJORANA and GERDA and an additional 130 kg of newly fabricated ICPC enriched detectors

Current Status

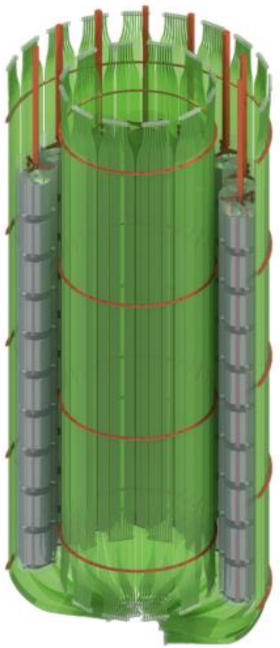
- construction is well-underway and 185 kg of enriched germanium have been acquired with initial commissioning of 150 kg fabricated detectors
- Filling with liquid argon was completed in September 2021
- Commissioning of the first strings of detectors, in-situ, has been started.

Same layout as GERDA

Credit: legend-exp.org



arXiv 2107.11462 ,2021 (pCDR)

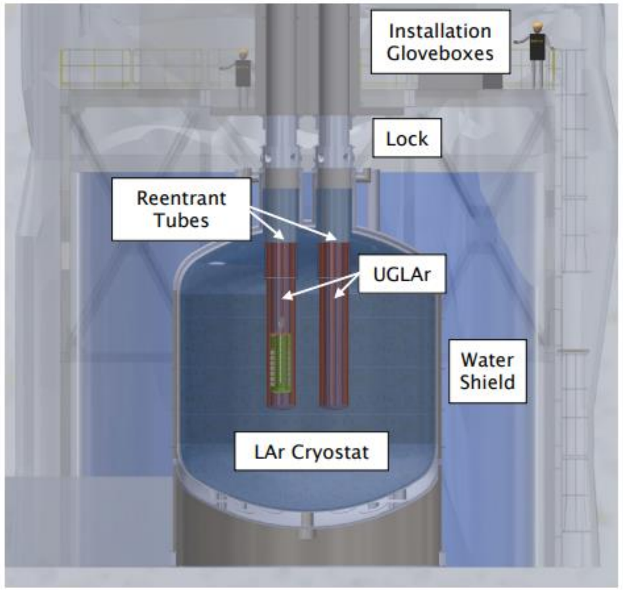


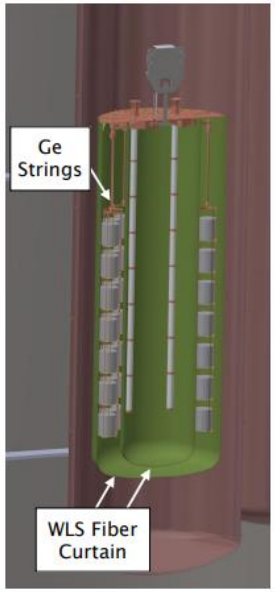
LEGEND-1000

- The goal for LEGEND-1000 is to reach a half-life discovery sensitivity of 1.3×10^{28} yr, corresponding to a $m_{\beta\beta}$ upper limit in the range of 9-21meV in 10 yr of live time. This projected background index of 10^{-5} cts/(keV kg yr) or less than 0.025 cts/(FWHM t yr) will meet this sensitivity.
- The additional 20-fold background reduction anticipated for LEGEND-1000 with respect to LEGEND-200 is obtained primarily by the use of underground-sourced Ar, new less-radioactive electronics and cables, and the presence of only ICPC detectors.
- Approximately 400 individual ICPCs with an average mass of 2.6 kg will be instrumented for a total detector active mass near 1000 kg

arXiv 2107.11462 ,2021 (pCDR)

A baseline conceptual design of the LEGEND-1000



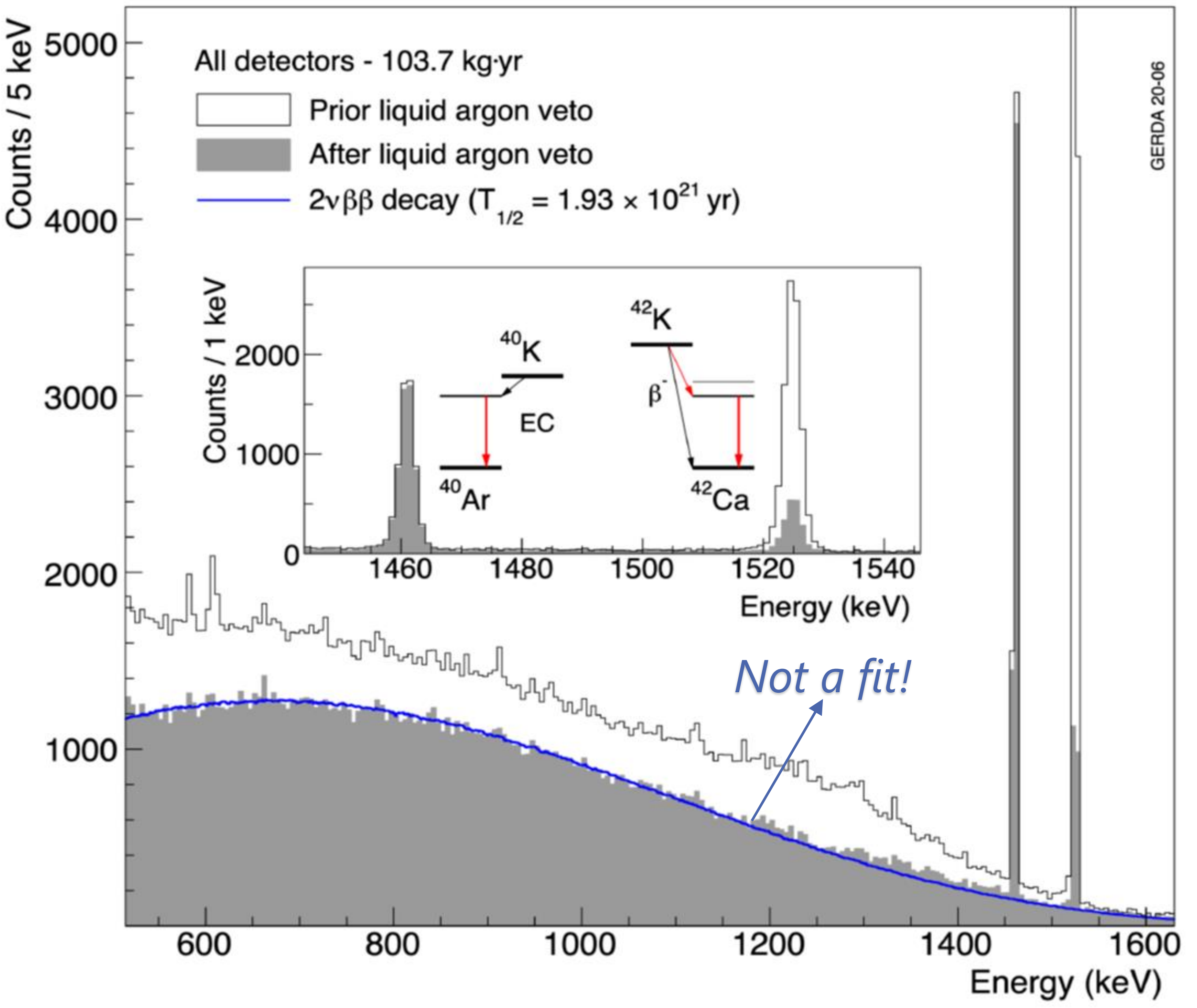


Parameter	Value
Performance Parameters	
$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance[a]	0.69
Live time goal	10 yr
Total exposure goal	10 t yr
Background goal	$< 1 \times 10^{-5}$ cts/(keV kg yr)
	< 0.025 cts/(FWHM t yr)
$T_{1/2}^{0\nu}$	1.3×10^{28} yr (99.7% CL discovery)
	1.6×10^{28} yr (90% CL sensitivity)
$m_{\beta\beta}$	9.4–21.4 meV (99.7% CL discovery)
	8.5–19.4 meV (90% CL sensitivity)

LEGEND-Liquid argon

- GERDA pioneered the use of liquid argon as:
  - Cooling medium
  - Shielding
  - Active veto
- ^{42}Ar is a background of concern (the subsequent decay of ^{42}K has a Q-value of 3.5 MeV)
- Reduction in ^{42}Ar by procuring "Underground Liquid Argon", UGLAr
- ^{42}Ar is cosmogenically produced, much like ^{39}Ar which is of interest to the dark matter community
- Reduction of order 1400x for ^{39}Ar & ^{40}Ar
- LEGEND and dark matter community collaborating on UGLAr extraction and purification
- DarkSide-20k is developing a plant to extract underground argon from Colorado and purify it in Italy, at 90 tonnes/year → after 1 year (~2025), can easily produce ~20 tonnes required for L-1000 (to fill the re-entrant tubes)

arXiv 2107.11462 ,2021(pCDR)

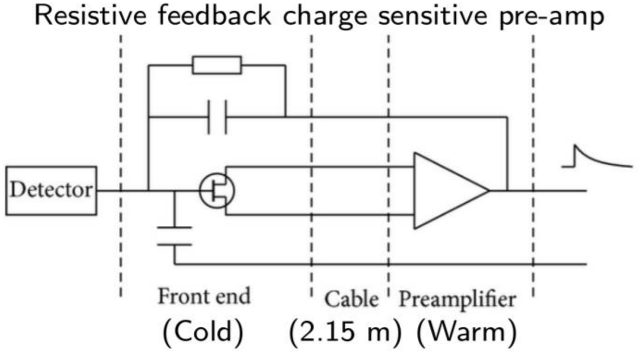


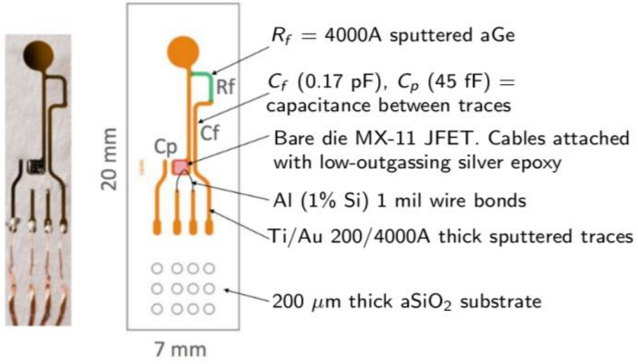
Front-End Electronics

- For L-200 we use low mass front end (LMFE)-JFET preamp from MAJORANA DEMONSTRATOR
- Legend-1000 will use CMOS ASICs charge sensitive preamp which are self-contained in a cubic mm
- The equivalent noise charge (ENC) of L1K for typical ICPC detectors with capacitance of 5 pF and leakage current of 20 pA, the simulated ENC is 130 eV FWHM.
- The L1K ASIC was observed to have a bandwidth of >35 MHz and consume < 40 mW.

J.Myslik, LBNL,2018

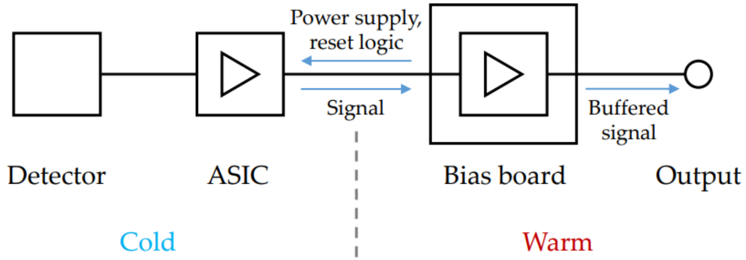
LMFE

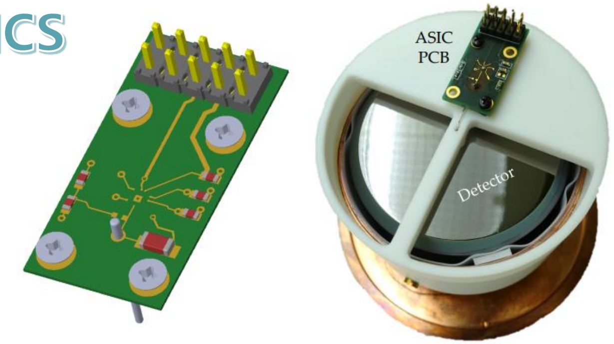




JINST 15, P09022, 2020

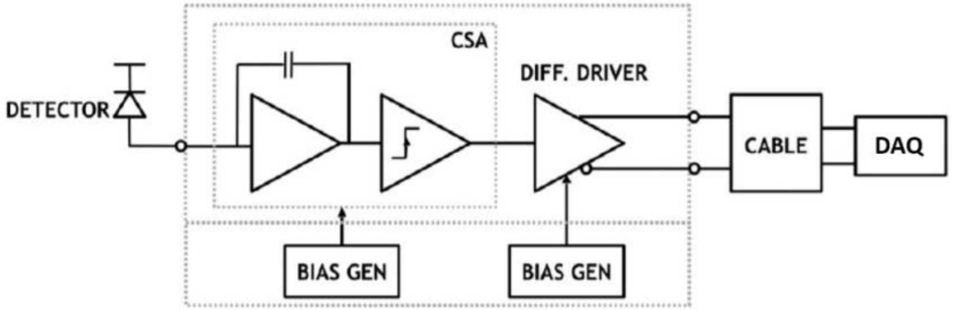
CUBE ASICS

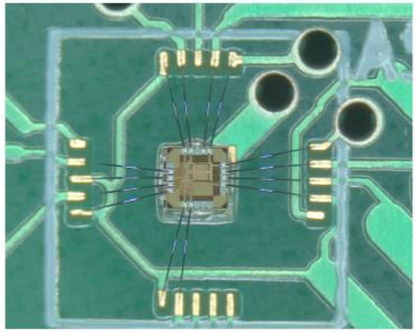




arXiv 2107.11462 ,2021(pCDR)

L1K

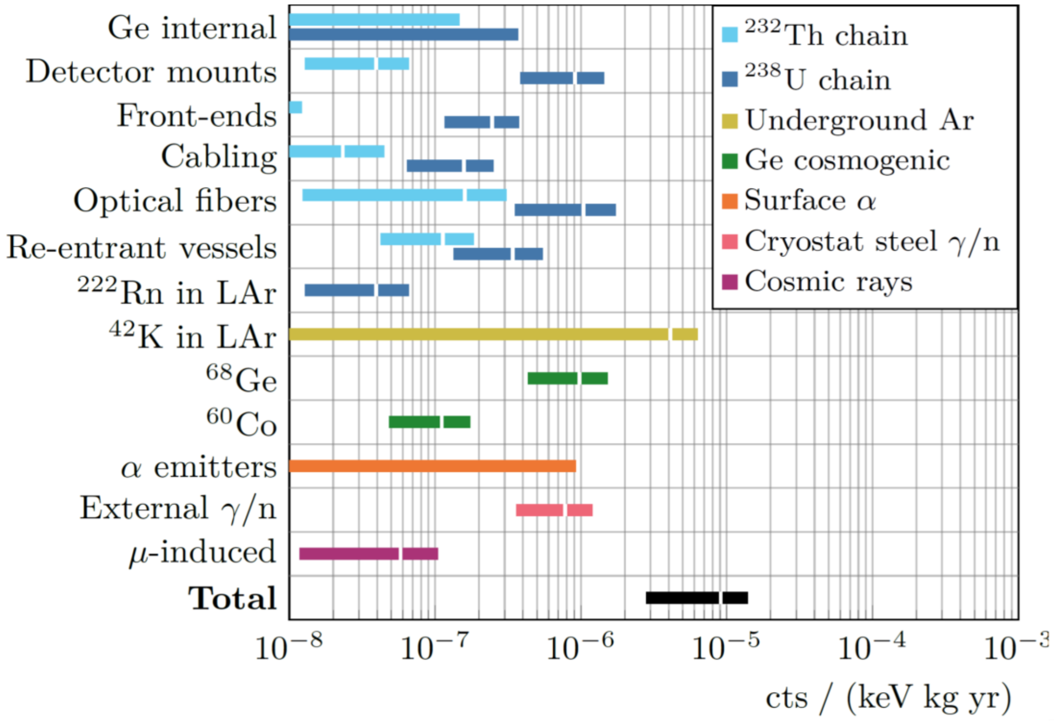




LEGEND-1000 projected backgrounds

Main backgrounds in LEGEND-1000:

- **U/Th decay chains**: Gamma rays from the chain can deposit energy above the Q-value. Reduced by using larger detectors with fewer smaller and cleaner readout components.
- **^{42}K decays**: Reduced by using UGLAr
- **Alpha decays on detector surfaces**: Reduced by a factor ~4 compared to GERDA (larger volume/surface)
- **Cosmogenically produced isotopes in Ge**: Will be comparable or slightly increased if detectors have less cooldown time (^{68}Ge has 271d)



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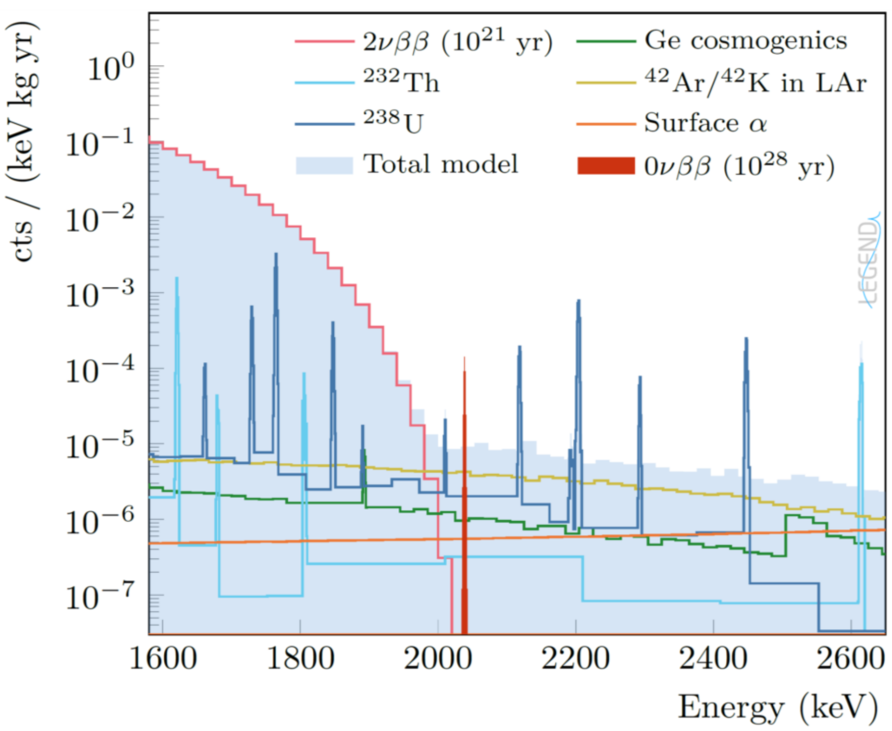

Summary

- The LEGEND collaboration was formed to bring together the technical expertise and leadership from both the MAJORANA and GERDA collaborations, as well as add new members to strengthen core capabilities.
- Technical advancements have resulted in larger detectors with better energy resolution, operating within a scintillating medium for enhanced background suppression, cleaner materials, and low-noise electronics to expand the overall reach of the technology.
- LEGEND-200 uses the GERDA design of low-Z shielding (water and argon) and an active veto through the detection of argon scintillation light. Muon and γ-induced backgrounds are reduced or vetoed. It is projected to have a background index of 2×10^{-4}cts/(keV kg yr) resulting in a sensitivity of as low as 29meV for $m_{\beta\beta}$ and half-life discovery sensitivity of 10^{27} yr.
- LEGEND-1000 combines the fundamental strengths of the GERDA, MAJORANA, and LEGEND-200 experiments. it is yielding a projected background index of 10^{-5} cts/(keV kg yr) equal to sensitivity of as low as 10meV for $m_{\beta\beta}$ and half-life discovery sensitivity of 1.3×10^{28} yr.
- SNOLAB is baseline host lab for LEGEND-1000. New collaborators are welcome!

Interested in joining LEGEND-1000 in Canada?

Contact Prof. Ryan Martin (LEGEND PI in Canada, Queen's University)

Link to conceptual design report:

https://arxiv.org/abs/2107.11462

Questions?