Search for neutrinoless double-beta decays in Ge-76 in the LEGEND experiment

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Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Outline

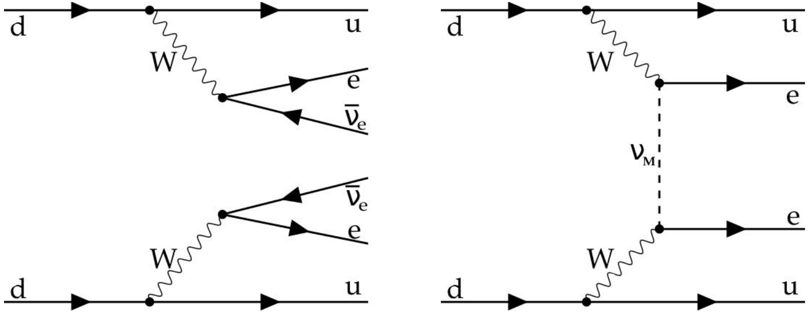
1. Motivations for Neutrinoless Double beta (0νββ) decay searches
2. Status of the art in 0νββ decay search
3. Operating ^{76}Ge based 0νββ decay experiments:
   a. MAJORANA demonstrator
   b. GERDA experiment @ LNGS
4. Future of the 0νββ decay search with ^{76}Ge
   a. The LEGEND 200/1000 project
5. Conclusions

Search for 0νββ decay

Powerful method to study the unknown neutrino properties

Observation of 0νββ decay will imply:

1. neutrino has Majorana nature
2. lepton number violation (ΔL = 2)
3. determination of ν absolute mass (nuclear model dependent)



The half life of 0νββ in case of light Majorana neutrino exchange:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu} \times \left|M_{0\nu}\right|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- **Phase Space Integral:** well known quantity
- **Nuclear Matrix Element:** most critical ingredient, produces uncertainty in the determination of $m_{\beta\beta}$ (quenching problem)
- **Neutrino Effective Mass:** estimated by measuring $T_{1/2}^{2\nu}$

Experimental signature of 0νββ

LEGEND

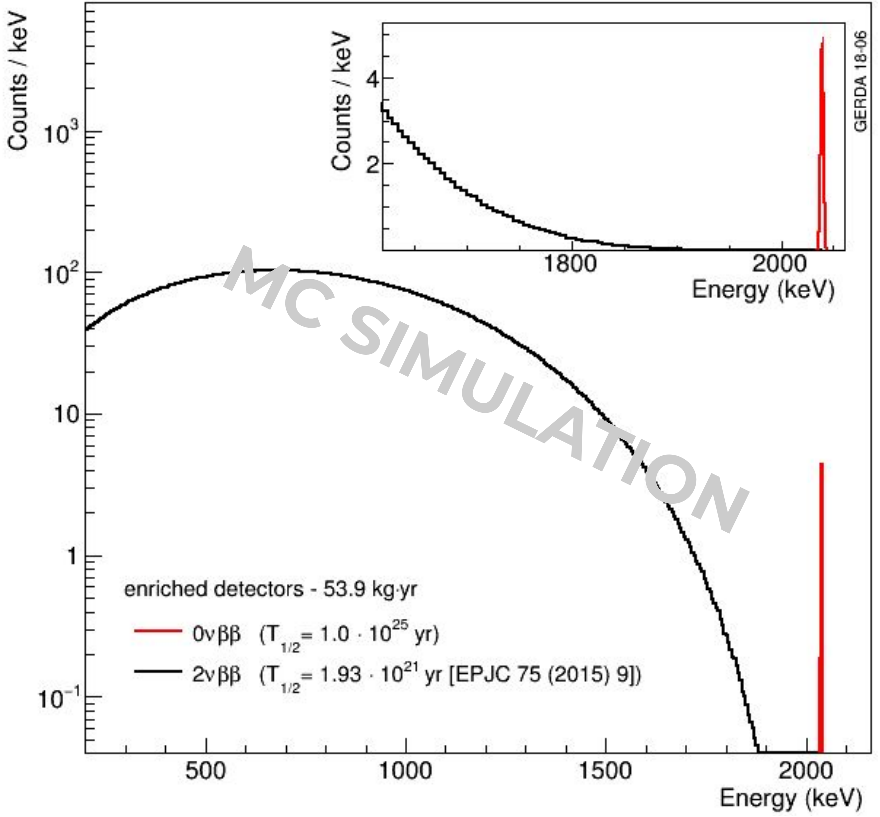
Experimental sensitivity

$$S \propto a\varepsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

efficiency (ε), exposure ($M \cdot t$), abundance (a), energy resolution (ΔE), background index (BI)

Sensitivity in case of “background-free” experiment , i.e N_{bkg}<1 at full exposure, is reduced to:

$$S \propto a\varepsilon \cdot M \cdot t$$



Status of 0νββ decay search

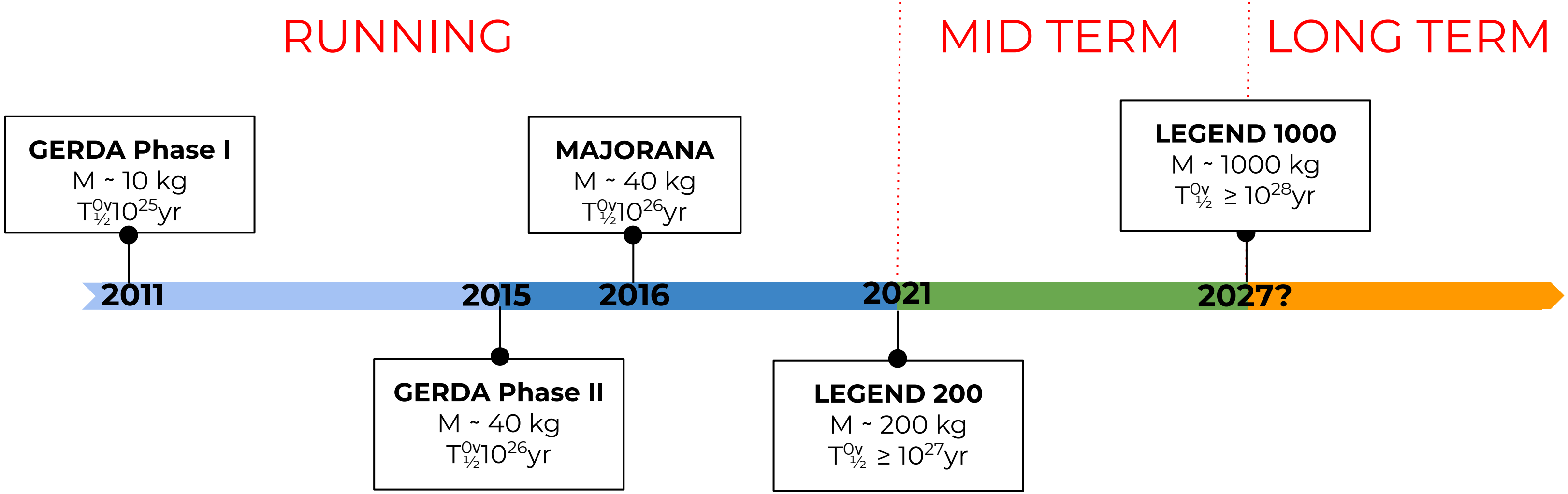
The most recent limits on the half-life, sensitivity and **$m_{\beta\beta}$ (at 90% C.L.)**

isotope	$T^{0\nu}_{1/2}$ [10^{25} yr]	$S^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]	experiment
^{76}Ge	9	11	104–228	GERDA
^{76}Ge	2.7	4.8	157–346	MAJORANA
^{130}Te	1.5	0.7	162–757	CUORE
^{136}Xe	1.8	3.7	93–287	EXO-200
^{136}Xe	10.7	5.6	76–234	KamLAND-Zen

The next generation experiment should aim to reach sensitivities of **$S^{0\nu}_{1/2}$ ~10^{27}–10^{28} yr** and improve the limit on the effective Majorana neutrino mass to **$m_{\beta\beta}$ ~ 10 meV**

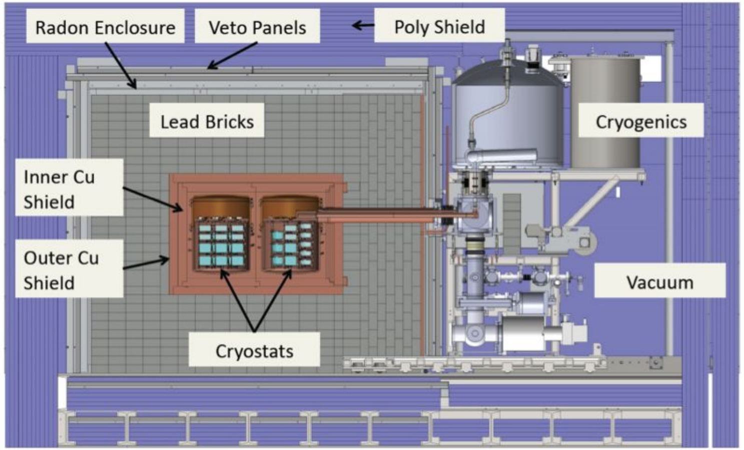
^{76}Ge based 0νββ decay experiments

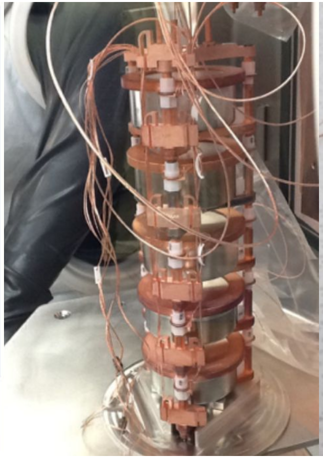
1. HPGe detectors enriched up to **~ 88%** in the **^{76}Ge ββ** emitter (Nat. ~ 8%)
2. source = detector → high detection efficiency
3. excellent energy resolution (**FWHM ~ 0.1% at Qββ)**
4. background-free experiments (Nbkg < 1 at full exposure) → S ∝ M · t

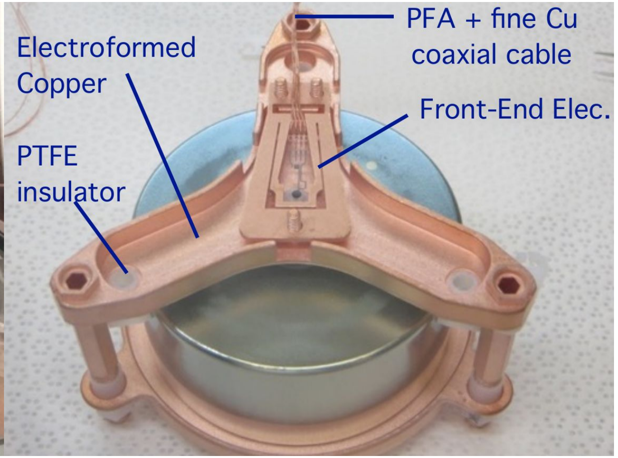


The MAJORANA demonstrator

- operating underground at the 4850-foot level of the Sanford Underground Research Facility (SURF)
- demonstrate background low enough to justify a future 1 ton experiment







- detectors: p-type point-contact, 29.7 kg of 88% enr. ^{76}Ge, 14.4 kg of natGe
- energy resolution: 2.5 keV FWHM at 2039 keV (best in the field)
- low background: 2 independent cryostat made of ultra-clean electroformed Cu and a compact Cu and Pb shield with active muon veto

The MAJORANA demonstrator

Data releases:

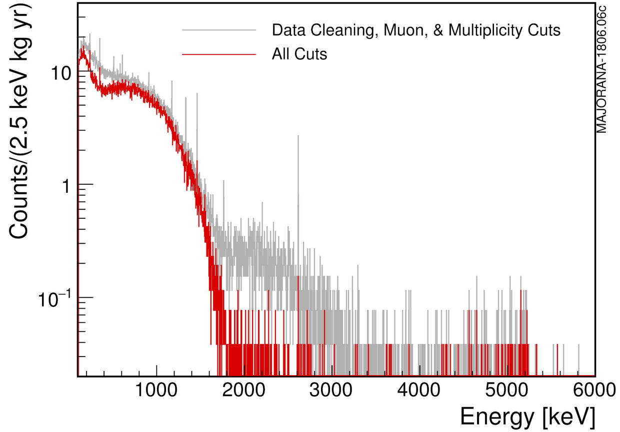
- 2017 Release: 9.95 kg·yr
  [PRL 120 132502 (2018)]
- 2018 Release: 26 kg·yr
  [Neutrino 2018, arXiv:1902.02299]

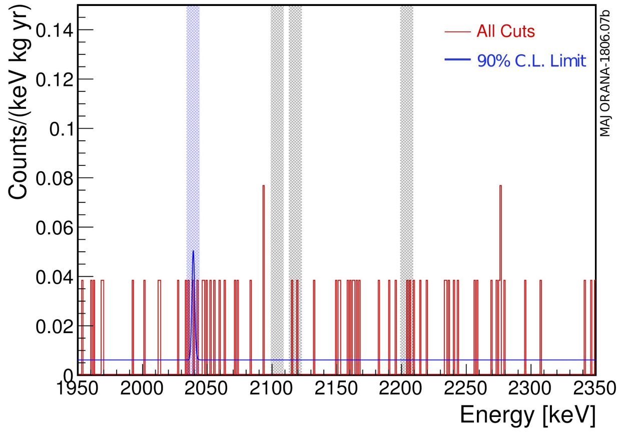
Full exposure results (26.0 kg·yr)

- Background: 15.4 ± 2.0 cts/(FWHM·t·yr)
- Median Sensitivity: $S^{0\nu}_{1/2} = 4.8 \cdot 10^{25}$ yr (90% C.L.)
- Limit on 0νββ decay: $T^{0\nu}_{1/2} > 2.7 \cdot 10^{25}$ yr (90% C.L.)

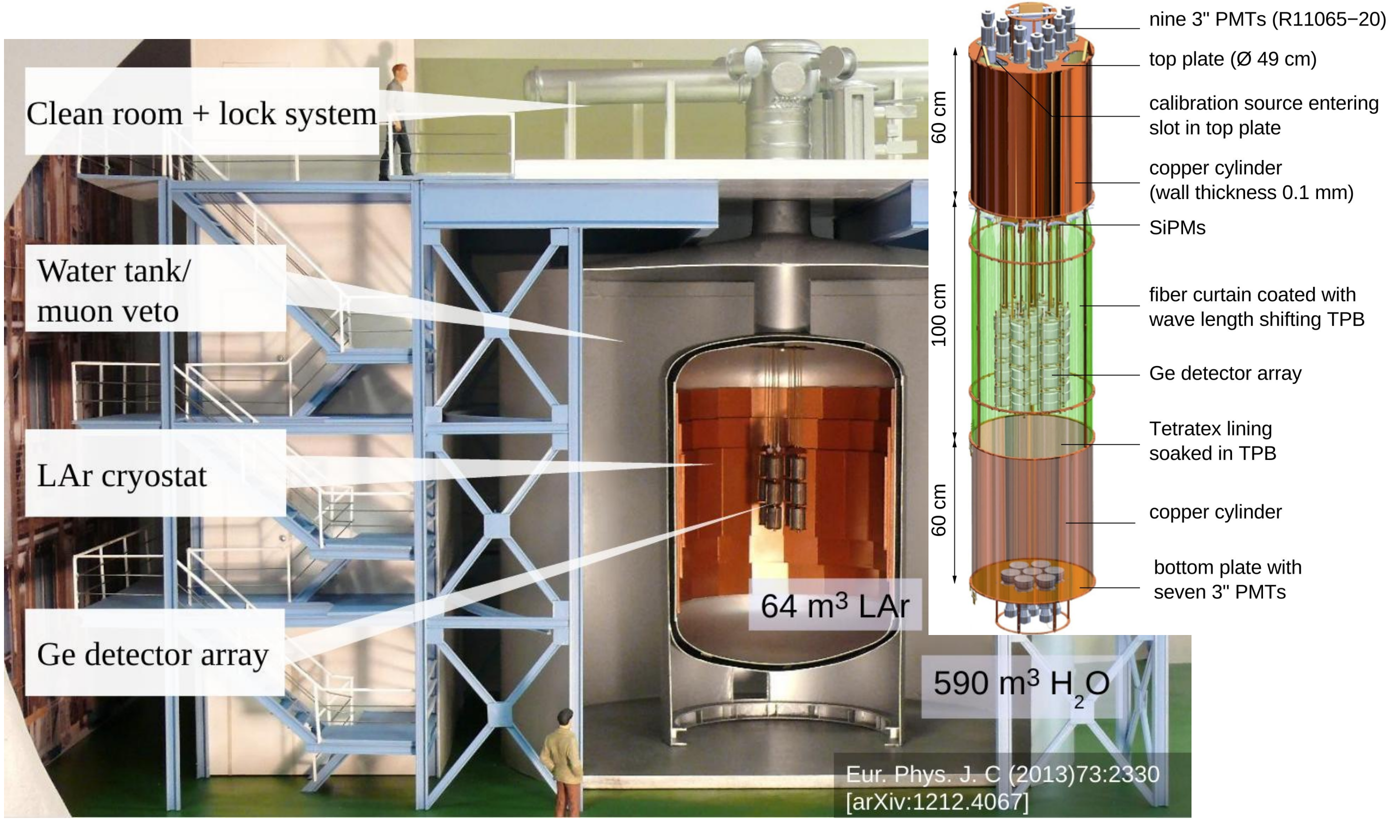
Lowest background configuration (21.3 kg·yr):

- Background: 11.9 ± 2.0 cts/(FWHM·t·yr)
  ⇒ $(4.7 \pm 0.8) \cdot 10^{-3}$ cts/(keV·kg·yr)





The GERDA experiment: design



- located at Laboratori Nazionali del Gran Sasso, ~ 1500 m of rock → 3500 m.w.e.
- bare HPGe detectors enriched in 76Ge (86%) in LAr
- water tank to shield against external radiation with Cherenkov muon veto
- Active veto: liquid Argon readout (LAr) to veto residual external background

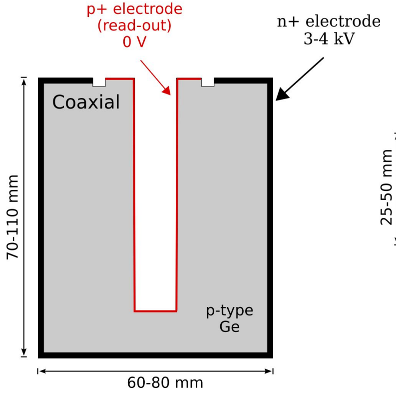
The GERDA experiment: detectors

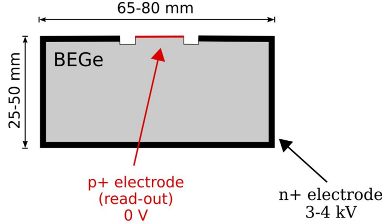
Semi-Coaxial detectors

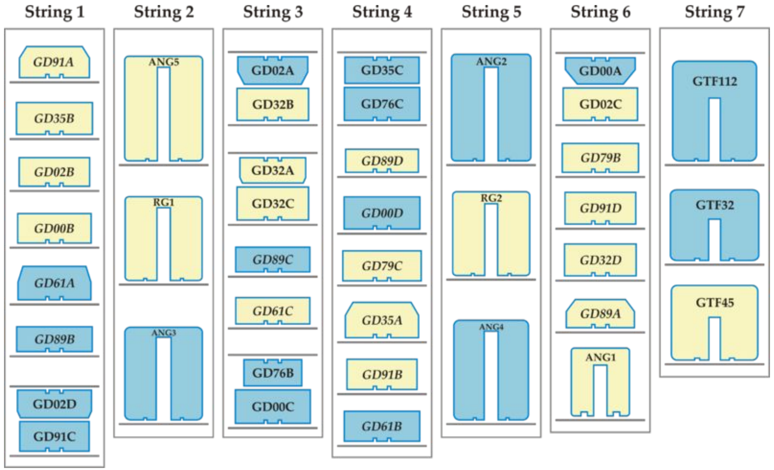
- from previous experiments (HdM, IGEX)
- total mass 17.7 kg
- energy resolution: 3.6 keV (FWHM) Qββ

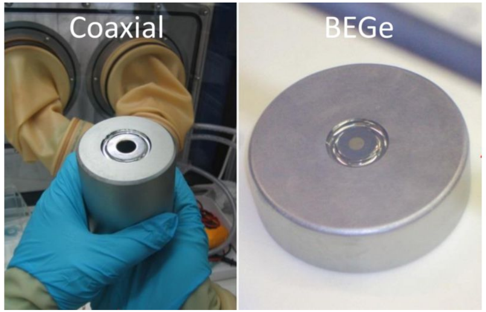
BEGe detectors

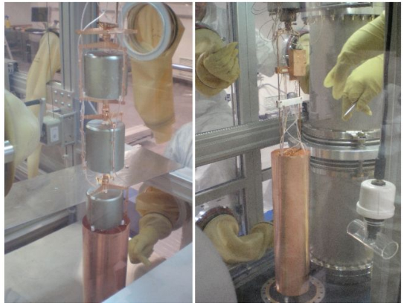
- produced for Phase II
- energy resolution: 3.0 keV (FWHM) Qββ
- better Pulse Shape Discrimination with A/E ratio (i.e current-amplitude/energy)











The GERDA experiment: results

Background in Phase II:

- Coax: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)
- BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

Blinded analysis:

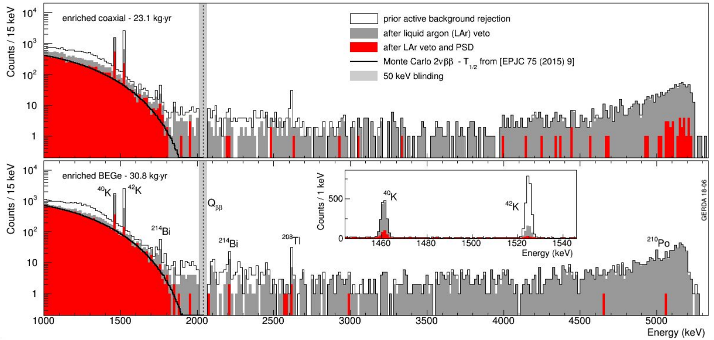
events in $Q_{\beta\beta} \pm 25$ keV not processed until all cuts finalized

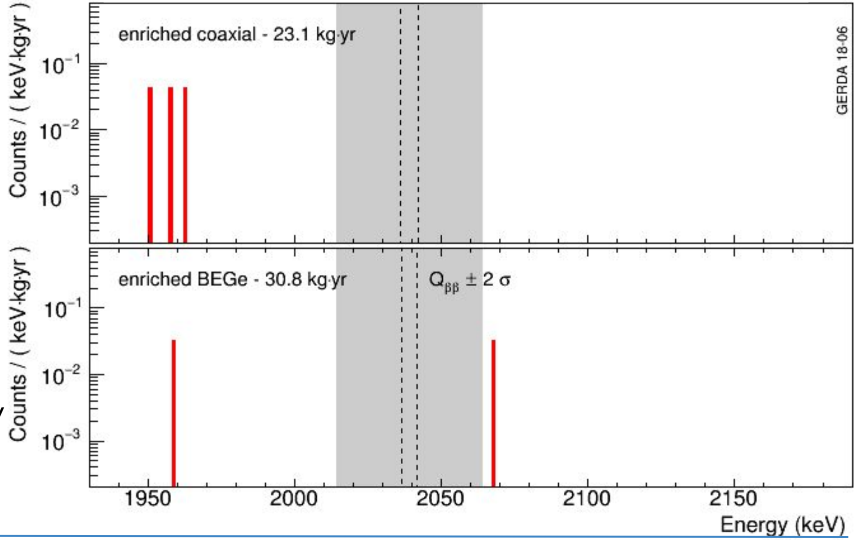
Phase II releases:

- June 2016: 10.8 kg·yr [Nature 554 (2017) 47]
- June 2017 +12.4 kg·yr (BEGe data) [PRL 120 (2018) 132503]
- June 2018 +35.7 kg·yr (BEGe and Coax data) **58.9 kg·yr exposure [Neutrino (2018)]**

Phase I + Phase II: total exposure 82.4 kg·yr

- Median Sensitivity: $S^{0\nu}_{1/2} = 1.1 \cdot 10^{26}$ yr (90% C.L.)
- Limit on 0νββ decay: $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)
- Sensitivity on the effective mass: $m_{\beta\beta} < 104 - 228$ meV
- probability of stronger limit 63%





The GERDA experiment: results

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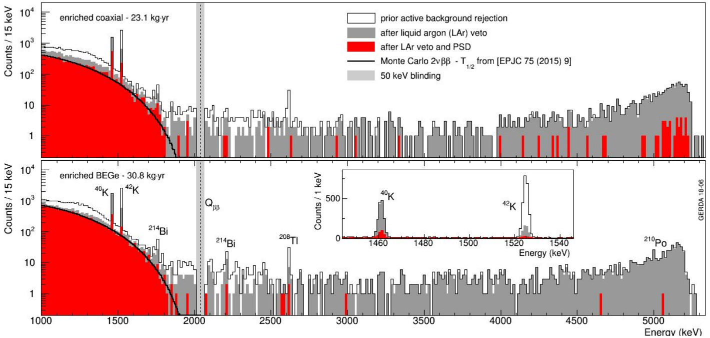

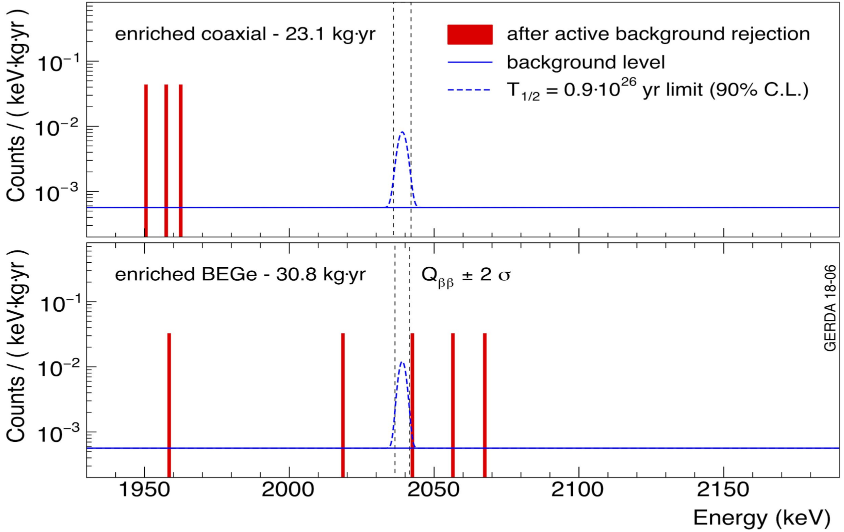

The LEGEND project

The goal is develop a phased, ^{76}Ge based ββ decay experimental program with discovery potential at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results

53 institutions, ~ 250 members from Gerda and Majorana and external contributors

Univ. New Mexico
L'Aquila University and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University
MIT
University of North Carolina
Sichuan University
University of South Carolina
Tennessee Tech University
Jagiellonian University
University of Dortmund
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University
Triangle Univ. Nuclear. Lab.
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Max Planck Institute, Heidelberg
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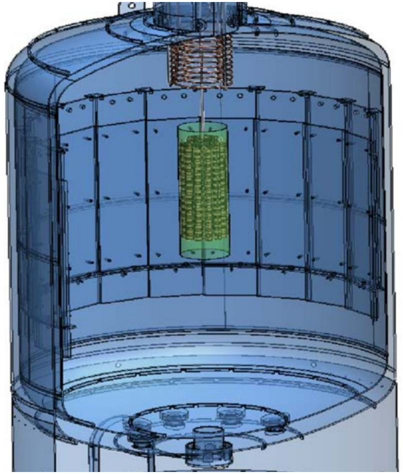
Max Planck Institute, Munich
Technical University Munich
Oak Ridge National Laboratory
Padova University
Padova INFN
Czech Technical University Prague
Princeton University
North Carolina State University
South Dakota School Mines Tech.
University Washington
Academia Sinica
University Tbingen
Banaras Hindu University
University South Dakota
University Zurich

The LEGEND project

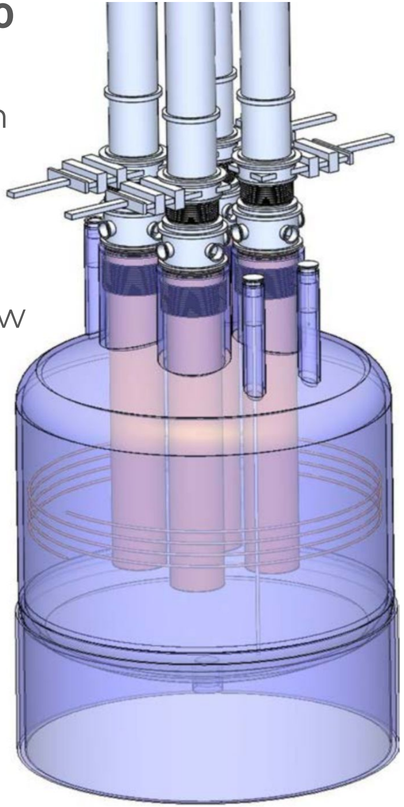
First Stage LEGEND-200

- up to 200 kg of ^{76}Ge
- modification of existing Gerda infrastructure at LNGS
- improved background: 0.6 cts/(FWHM·t·yr)
- start in ~ 2021



Subsequent Stage LEGEND-1000

- 1000 kg of ^{76}Ge
- location tbd, required depth under investigation
- background goal < 0.1 cts/(FWHM·t·yr)
- timeline connected to review process

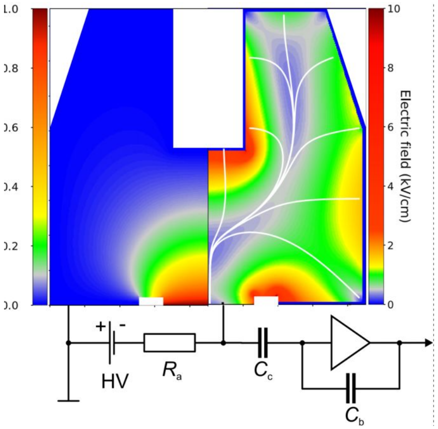


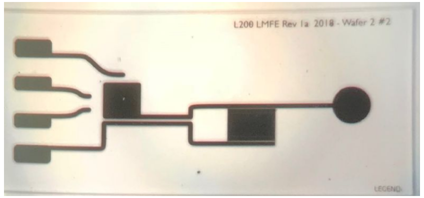
Hardware improvements of L-200

New Inverted Coaxial Point-Contact Ge detector
- first design proposed in 2011 [Cooper et al., NIMA 665 (2011)] large active mass up to 3 kg (also larger)
- excellent Pulse Shape Discrimination (PSD)
- reduced background due to smaller number of channels

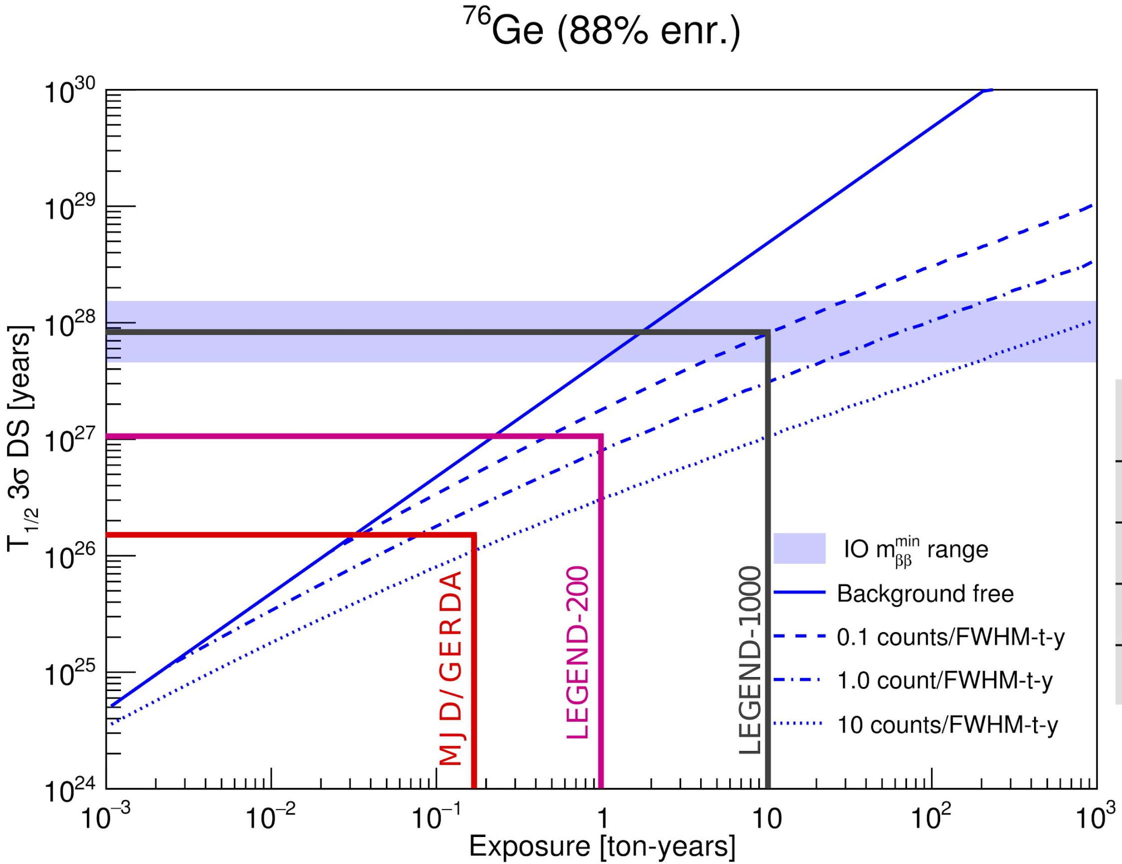
Low Mass Front End (LMFE) electronics
- reduce the signal noise w.r.t. GERDA situation experience from Majorana Demonstrator
- use of underground electroformed copper for nearby parts ongoing test in LAr
- better energy resolution + pulse shape discrimination

Improvement of the LAr veto
- take advantage of GERDA experience
- design studies ongoing
- optimization of light collection
- compromise between background and cuts efficiency





LEGEND: 3σ discovery potential



3σ discovery potential to cover inverted ordering, given matrix element uncertainty

Sensitivity	L200 BI=1e-4	L1000 BI=1e-5
$T_{1/2}$ sensitivity for LS [yr]	$1.4 \cdot 10^{27}$	$1.4 \cdot 10^{28}$
$T_{1/2}$ sensitivity for SD [yr]	$1.2 \cdot 10^{27}$	$1.2 \cdot 10^{28}$
m_{bb} sensitivity for LS [meV]	29 - 60	9 - 19
m_{bb} sensitivity for SD [meV]	32 - 66	10 - 21

Conclusions

- Important milestones on the 0νββ have been reached by GERDA and MAJORANA:
  - energy resolution ~ 0.1% at Qββ
  - lowest background ever achieved: 6 · 10−4 cts/(keV·kg·yr) exploration of the 0νββ decay at the 10^{26} yr scale
- LEGEND-200 is in preparation and will continue the search for 0νββ decay in ^{76}Ge and reach a sensitivity of 10^{27} yr
  - The experiment is fully funded Ongoing efforts to start in 2021
- Subsequent stage LEGEND-1000 to be defined