LEGEND

The Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay

Yannick Müller
On behalf of the LEGEND collaboration

September 01, 2021
Physik-Institut,
University of Zurich

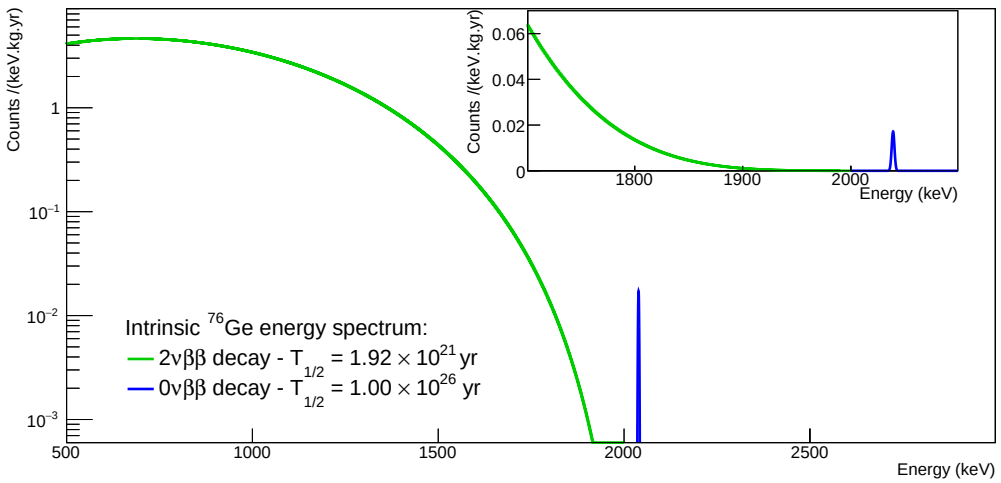
Signature and implications

$2\nu\beta\beta$ decay in ^{76}Ge:

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^- + 2\bar{\nu}_e$
- continuous, broad spectrum, measured

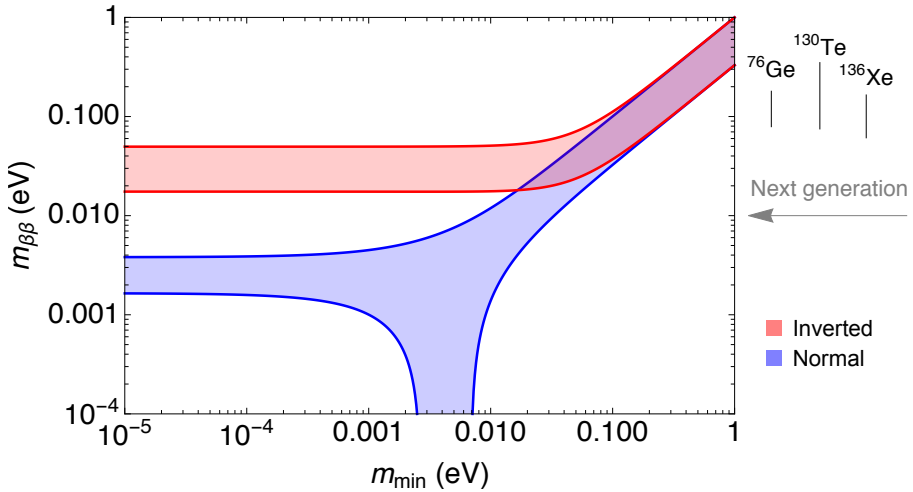
$0\nu\beta\beta$ decay in ^{76}Ge:

- $^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$
- peak at $Q_{\beta\beta} = 2039$ keV



Physics implications:

- nature of neutrinos (Dirac vs Majorana)
- neutrino mass scale & ordering (normal vs inverted)
- violation of lepton number conservation
- matter-antimatter asymmetry in the Universe



Probing the Majorana mass

Majorana mass sensitivity:

$$|m_{\beta\beta}| \propto \frac{m_e}{\sqrt{\mathcal{M}^2\,\mathcal{G}\;T_{1/2}}}$$

- Majorana mass definition $|m_{\beta\beta}| = \left|\sum_i U_{ei}^2 m_i\right|$
- nuclear matrix element $\mathcal{M}$
- phase space factor $\mathcal{G}$
- half-life of $0\nu\beta\beta$ $T_{1/2}$

Half-life sensitivity:

non background-free vs background-free

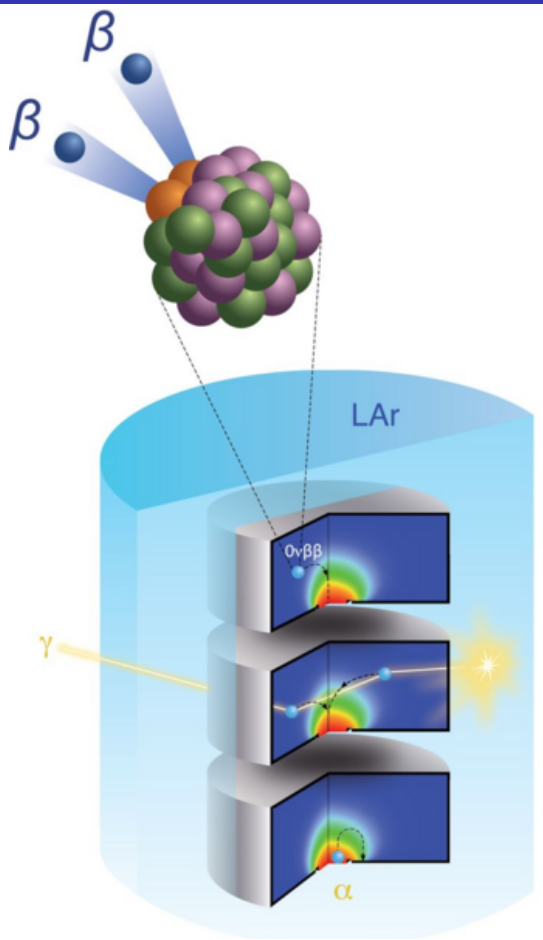
$$T_{1/2} \propto f\epsilon\sqrt{\frac{Mt}{B\,\sigma_E}} \quad \text{vs} \quad T_{1/2} \propto f\epsilon Mt$$

- enrichment fraction f
- efficiency ϵ
- mass M
- measurement time t
- background index B
- energy resolution σ_E at $Q_{\beta\beta}$

$\rightarrow$ low background level & good energy resolution crucial

Germanium approach

- $0\nu\beta\beta$ source = detector:
  high detection efficiency
- high-purity Ge (HPGe) detectors:
  semiconductors, bandgap $\mathcal{O}(1\text{eV})$,
  best energy resolution in the field,
  commercial technology,
  modest cryogenic requirements,
  high enrichment possible,
  no measurable internal background contamination,
  allow for event pulse shape discrimination (PSD)
- cryostat filled with liquid argon (LAr),
  serving as:
  coolant,
  shield,
  active veto

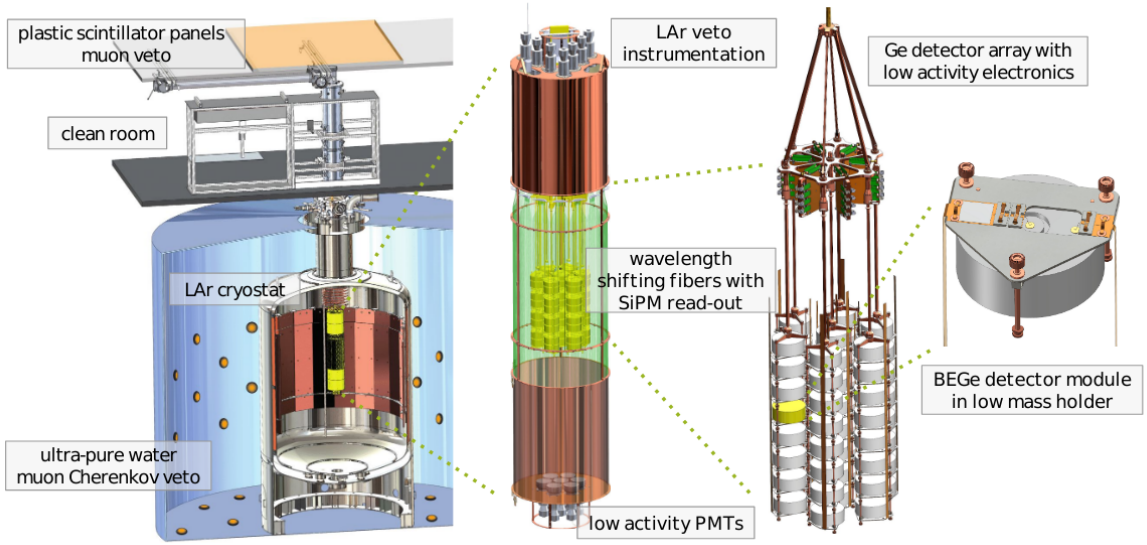


→ LEGEND, a merger of the GERDA & MAJORANA DEMONSTRATOR (MJD) experiments & new institutions, will strongly benefit from their experiences in operating HPGe detectors to search for $0\nu\beta\beta$

GERDA collaboration, Science 365, 1445 (2019)

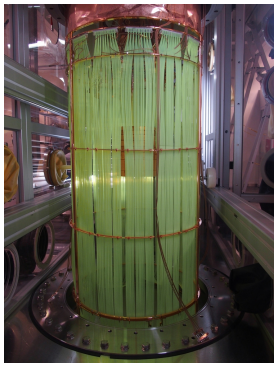
GERDA

- operated $\sim$ 40 detectors enriched in ^{76}Ge (up to 87% enrichment) in LAr at Laboratori Nazionali del Gran Sasso (LNGS)
- 1400m rock overburden (3500 mwe), cosmic muon reduction $\mathcal{O}\left(10^6\right)$
- water tank with 10 m diameter equipped with PMTs



$\rightarrow$ lowest background level:
$B = 5.2 \times 10^{-4}$ cts / keV / kg / yr

$\rightarrow$ best half-life limit:
$T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.L.),
$|m_{\beta\beta}| \lesssim 79 - 180$ meV



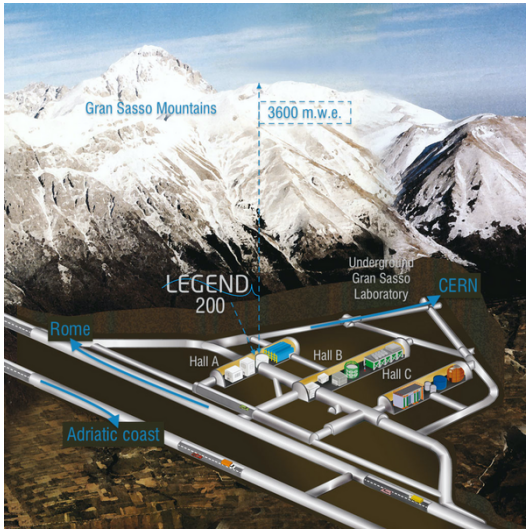
GERDA collaboration, PRL 125, 252502 (2020)

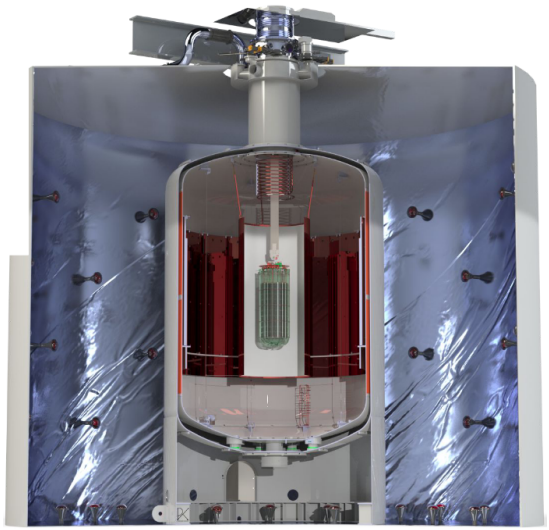
Information on the MAJORANA DEMONSTRATOR can be found in the backup slides

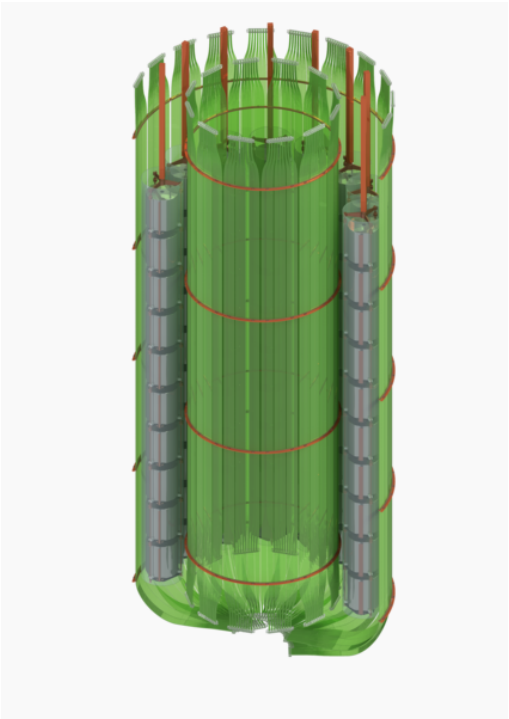
LEGEND-200

- up to 200 kg of detector material, distributed over 14 strings
- reuse of detectors from GERDA & MJD + $\sim$ 150 kg of newly developed inverted coaxial detectors (tested in both experiments)
- reuse of GERDA infrastructure at LNGS, with upgraded lock system, piping structure, LAr veto instrumentation, & calibration system, designed & assembled by UZH
- assembly ongoing, start of physics data taking end of 2021, planned runtime 5 yr
- only modest background improvement of $\sim$ 2.5 needed compared to measured value of GERDA

$\rightarrow$ discovery sensitivity:
$T_{1/2} \gtrsim 10^{27}$ yr (90% C.L.),
$|m_{\beta\beta}| \lesssim 33 - 71$ meV





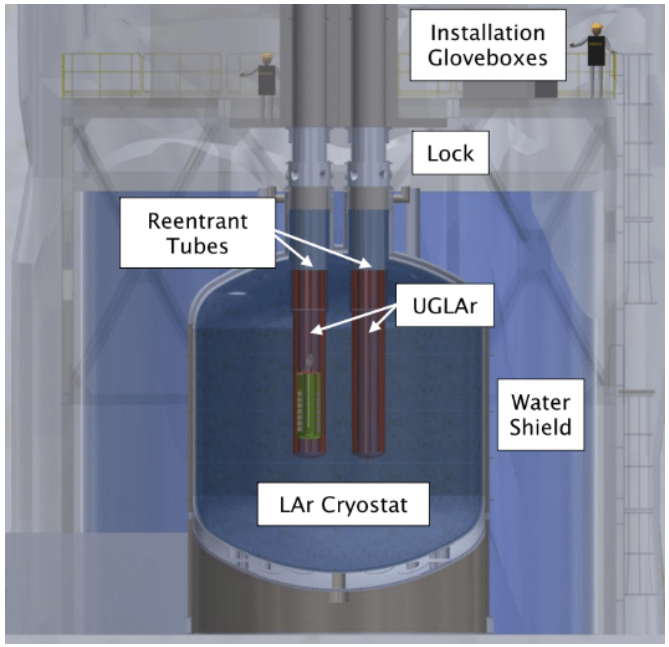


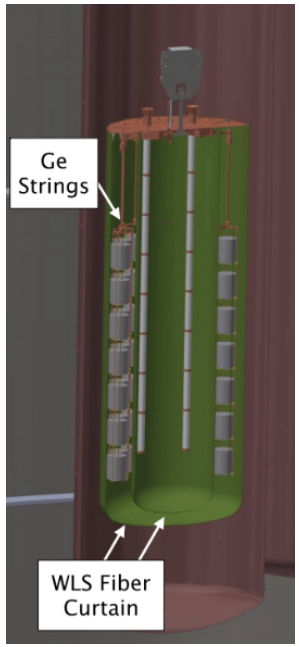
LEGEND collaboration, AIP 894:020027 (2017)

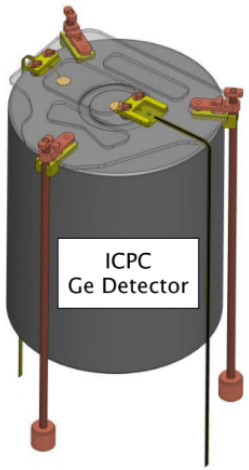
LEGEND-1000

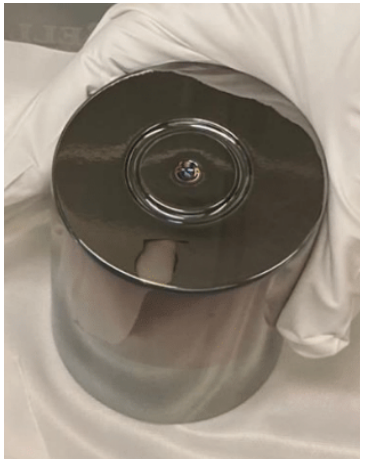
- staged installation of four $\sim$ 250 kg modules of inverted coaxial point-contact detectors (ICPC)
- detector strings immersed in radiopure underground LAr (UGLAr), surrounded by natural LAr
- SNOLab & LNGS as potential underground facilites
- planned staged commissioning $\sim$ 2030, planned runtime 10 yr
- background improvement of $\sim$ 20 compared to LEGEND-200 expected

$\rightarrow$ discovery sensitivity:
$T_{1/2} \gtrsim 10^{28}$ yr (90% C.L.),
$|m_{\beta\beta}| \lesssim 10 - 20$ meV





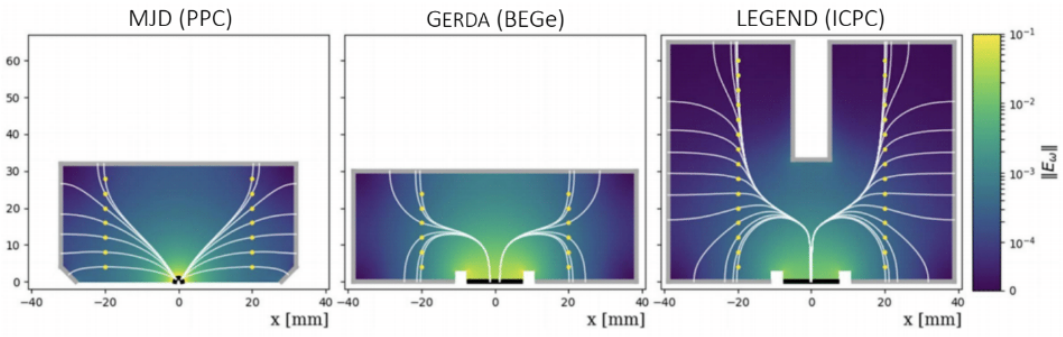


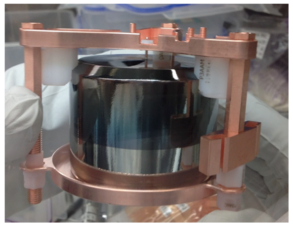


LEGEND collaboration, arxiv: 2107.11462 (2021)

Detector types

- coaxial shaped (Coax):
  1 to 3 kg weight
- broad energy germanium (BEGe):
  $\sim$ 0.7 kg weight,
  excellent resolution &
  PSD properties
- p-type point contact (PPC): $\sim$
  0.75 kg weight,
  superior resolution
- inverted coaxial point-contact (ICPC):
  dominating type,
  combine $\sim$ 2 kg weight,
  excellent resolution &
  PSD properties

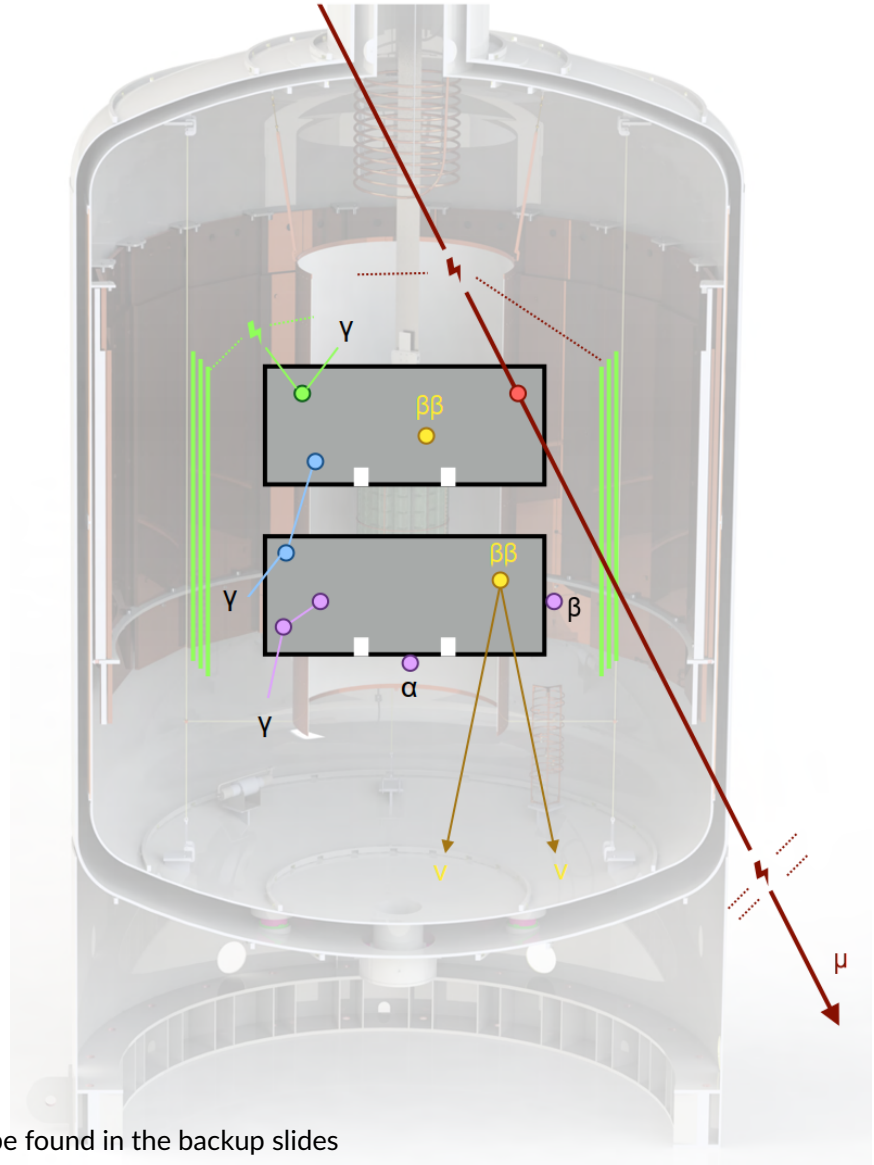




GERDA collaboration, Eur. Phys. J. C. 79 11 978 (2019)
GERDA collaboration, Eur. Phys. J. C, 81 6 505 (2021)
MAJORANA collaboration NIM A 665 25-32 (2011)

Background reduction

- SIGNAL!
  single-site event with energy deposition in $\sim$ 1 mm^3 volume
- PSD / event topology cut
  for multi-site & surface α, β event rejection
- detector multiplicity / anti-coincidence cut
- LAr veto instrumentation to reject γ's via coincident scintillation signal
- muon veto to reject events causing coincident Cherenkov signal in water tank

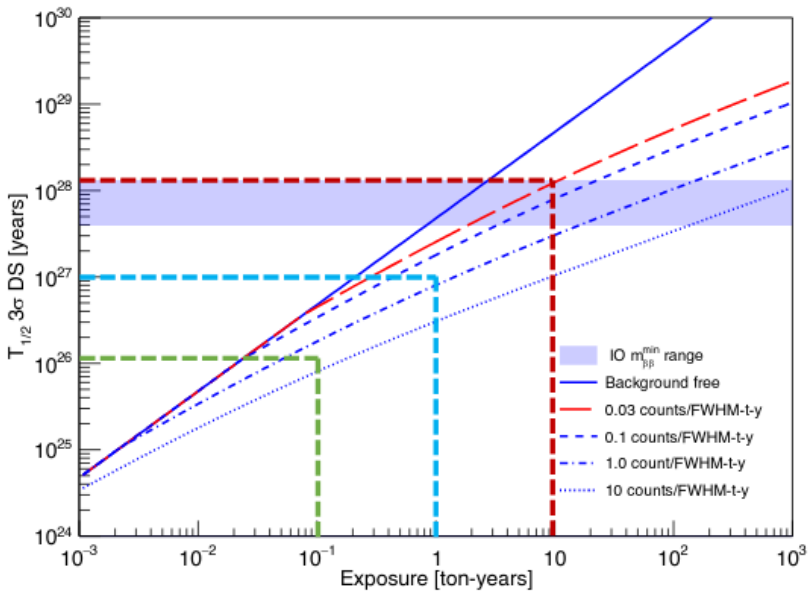


GERDA collaboration, Nature 544 7648 (2017)

Detailed information on the PSD & the LAr cut can be found can be found in the backup slides

Path towards discovery

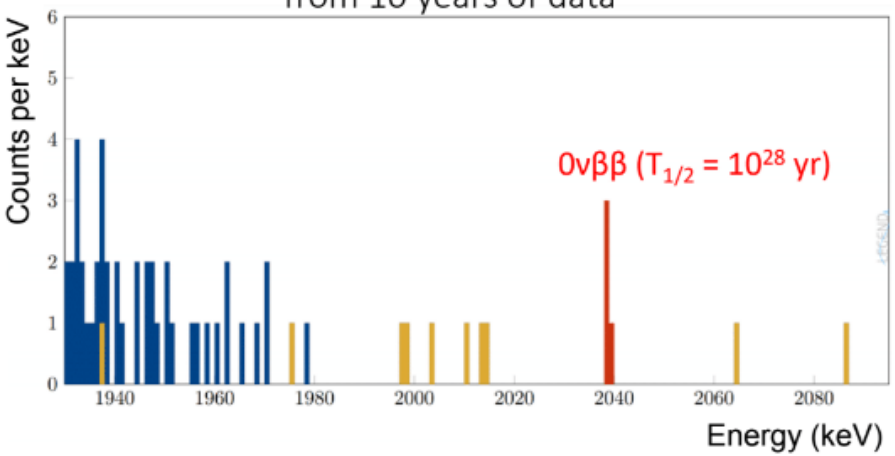
- GERDA:
  $B = 5.2 \times 10^{-4}$ cts / keV / kg / yr
  $T_{1/2} \gtrsim 10^{26}$ yr (90% C.L.)
- LEGEND-200:
  $B \sim 2 \times 10^{-4}$ cts / keV / kg / yr
  $T_{1/2} \gtrsim 10^{27}$ yr (90% C.L.)
- LEGEND-1000:
  $B \sim 1 \times 10^{-5}$ cts / keV / kg / yr
  $T_{1/2} \gtrsim 10^{28}$ yr (90% C.L.)



$\rightarrow$ flat background,
no γ-peaks close to $Q_{\beta\beta}$,
energy resolution of $\sim 0.1\%$ at $Q_{\beta\beta}$

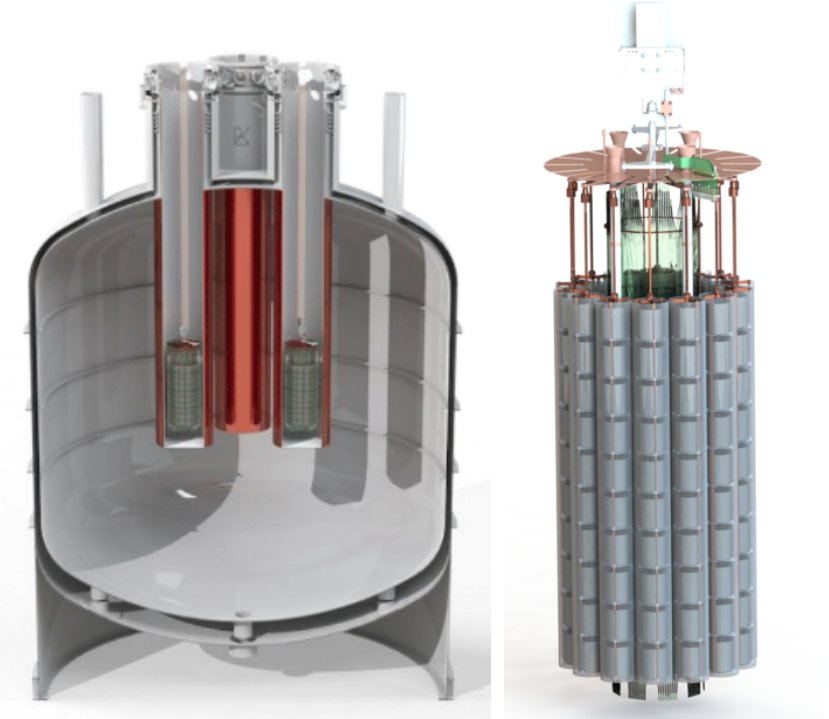
$\longrightarrow$ ***unambiguous discovery of*** $0\nu\beta\beta$ ***achievable,***
signal will be visible to the eye

Simulated example spectrum, after cuts, from 10 years of data



LEGEND summary

- staged experiment operating HPGe detectors in LAr to search for $0\nu\beta\beta$
- merger of GERDA, MAJORANA DEMONSTRATOR & new institutions, benefiting from previous experience
- LEGEND-200 under construction, start of data taking end of 2021, discovery sensitivity $T_{1/2} \gtrsim 10^{27}$ yr
- ton-scale experiment LEGEND-1000 will reach discovery sensitivity $T_{1/2} \gtrsim 10^{28}$ yr, aiming to fully cover inverted hierarchy

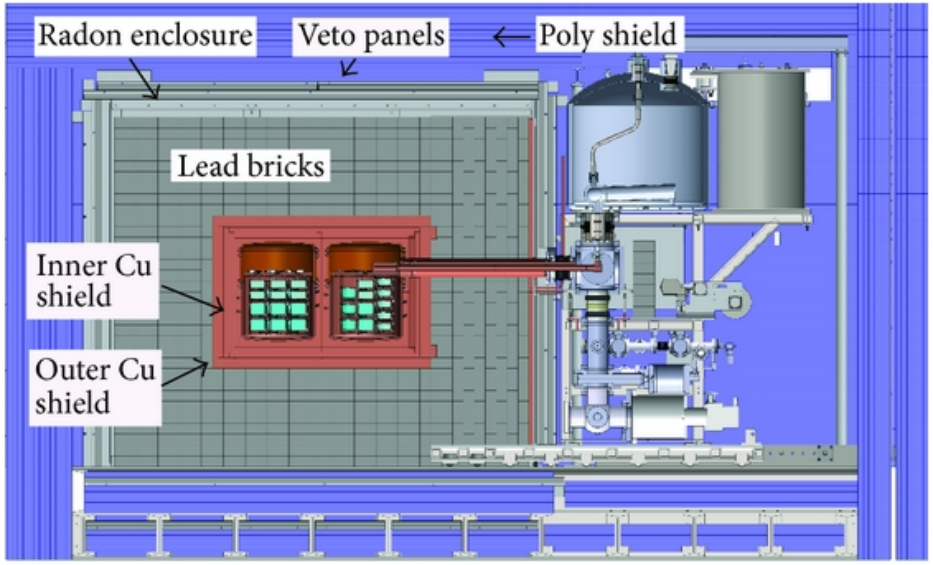


We thank our sponsors for their continuous support of the LEGEND project: US Department of Energy, US National Science Foundation, Canada Foundation for Innovation, Research Council of Canada, Max Planck Gesellschaft, Istituto Nazionale di Fisica Nucleare, DE Bundesministerium für Bildung und Forschung

Deutsche Forschungsgemeinschaft, Swiss National Science Foundation, Foundation for Polish Science, European Research Council, UK Science and Technology Facilities Council, RU Joint Institute for Nuclear Research, National Research Center Kurchatov Institute, RU Institute for Nuclear Research, Russian Foundation for Basic Research (RFBR)

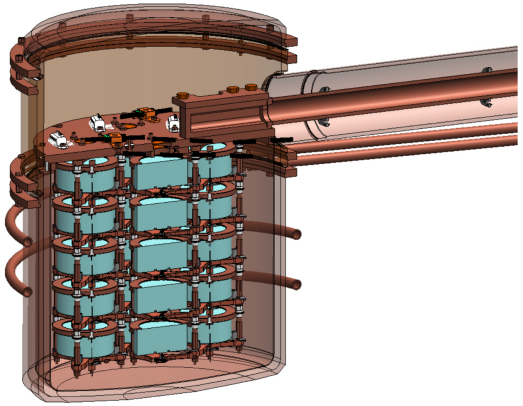
Backup: MAJORANA DEMONSTRATOR

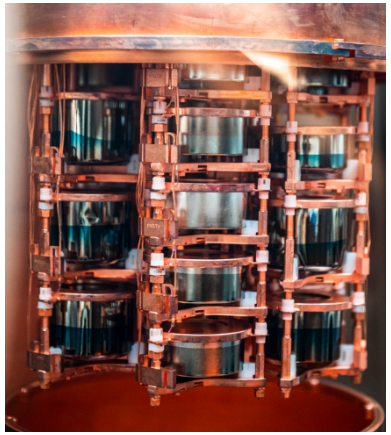
- array of 58 p-type, point contact detectors (88% enrichment) operated at Sanford Underground Research Facility (1490m rock overburden, 4300 mwe)
- 2 modules within a high-purity electroformed copper cryostat, equipped with an active muon veto, & ultra-clean detector near-parts



$\rightarrow$ best energy resolution:
2.5 keV FWHM at $Q_{\beta\beta}$ (0.13%)

$\rightarrow$ half-life limit:
$T_{1/2} > 2.7 \times 10^{25}$ yr (90% C.L.),
$|m_{\beta\beta}| \lesssim 200 - 433$ meV

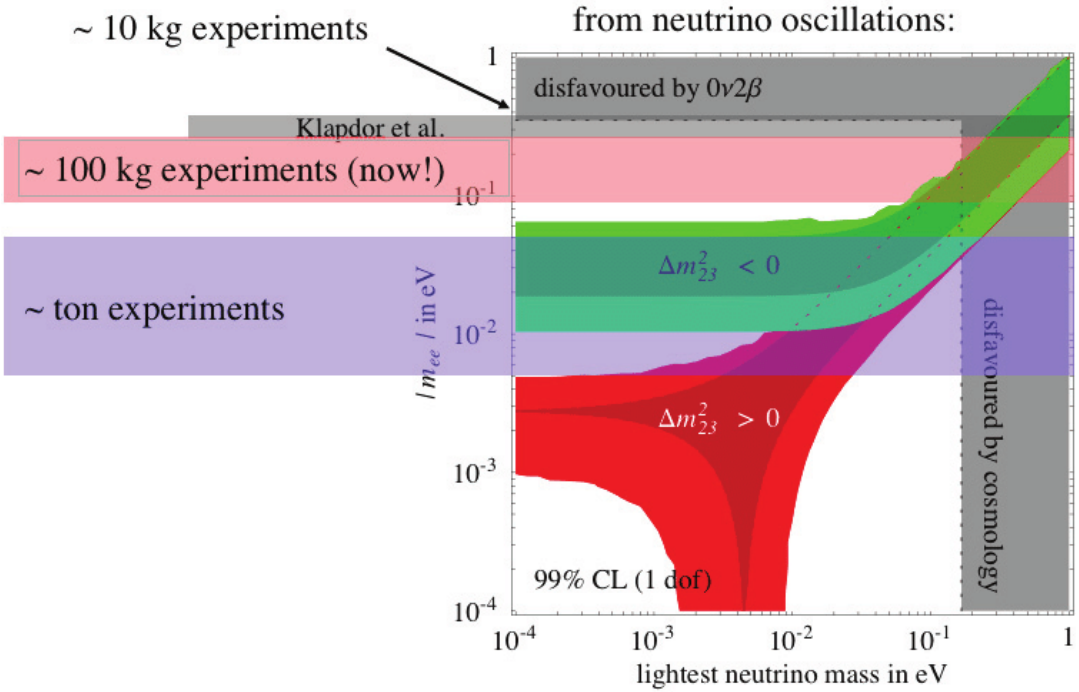




MAJORANA collaboration, PRC 100, 025501 (2019)

Backup: sensitivity to neutrino mass hierarchy

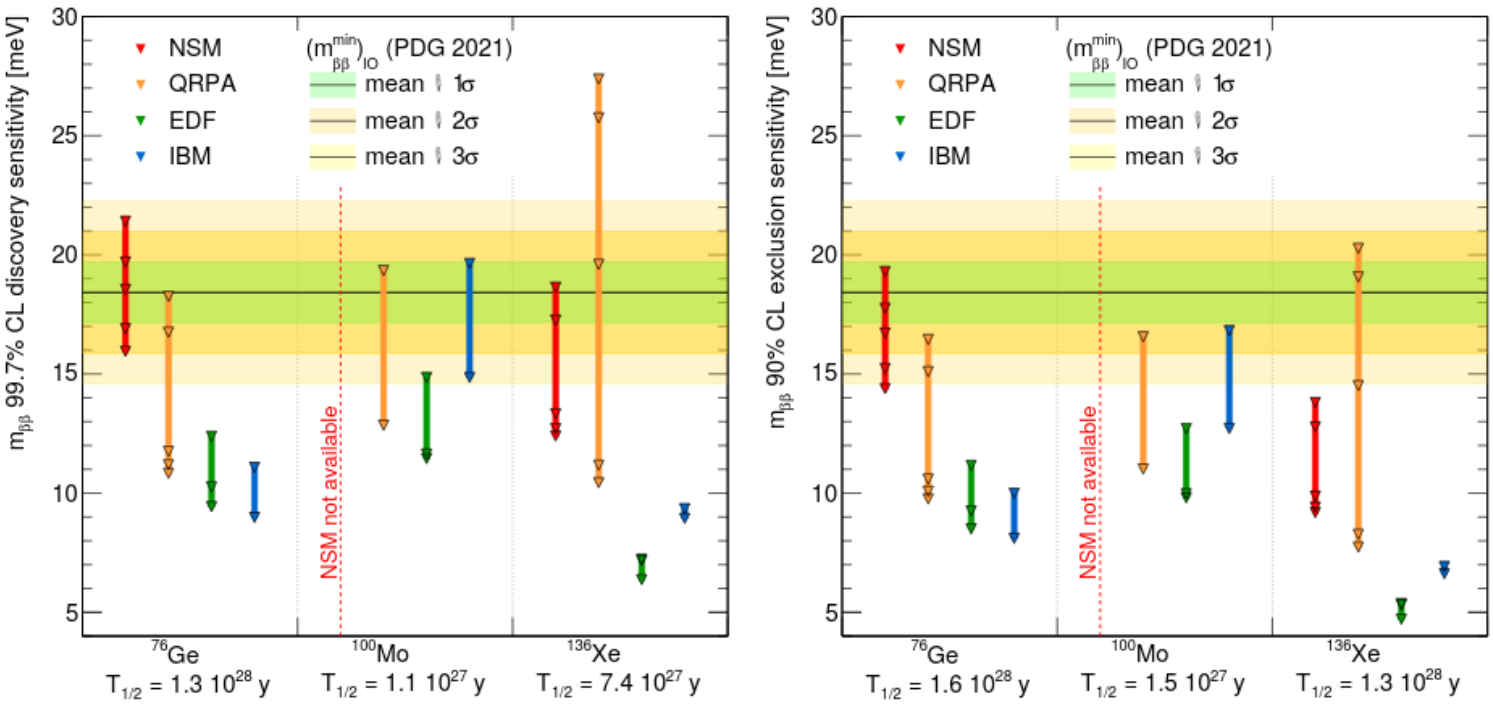
Constraints on the two neutrino mass ordering regimes:



Pocar, Physics Procedia 37:6-15 (2012)

Backup: comparison of experiments

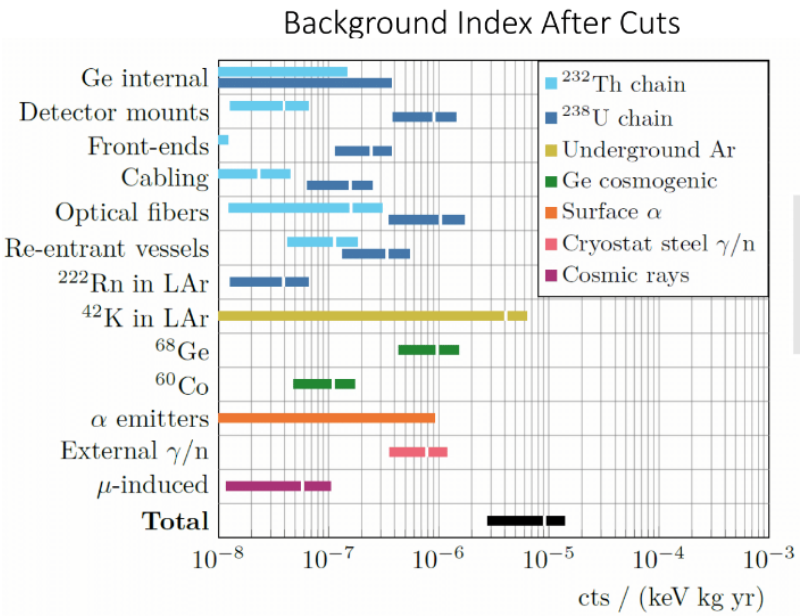
Comparison of discovery sensitivity & exlusion limit sensitivity for different nuclear matrix elements for proposed ton-scale experiments

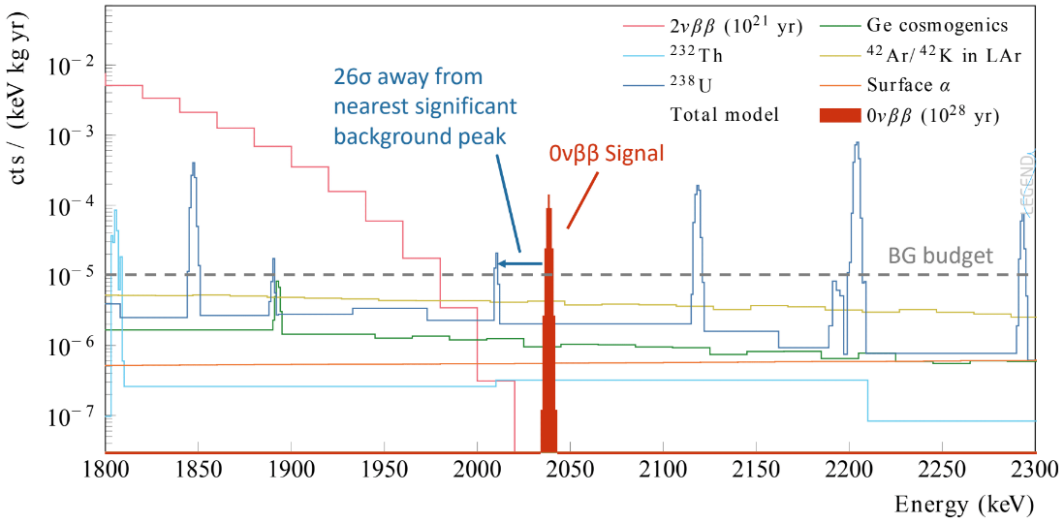


Agostini, Benato, Detwiler, Menendez, Vissani, arxiv: 2107.09104 (2021)

Backup: background model

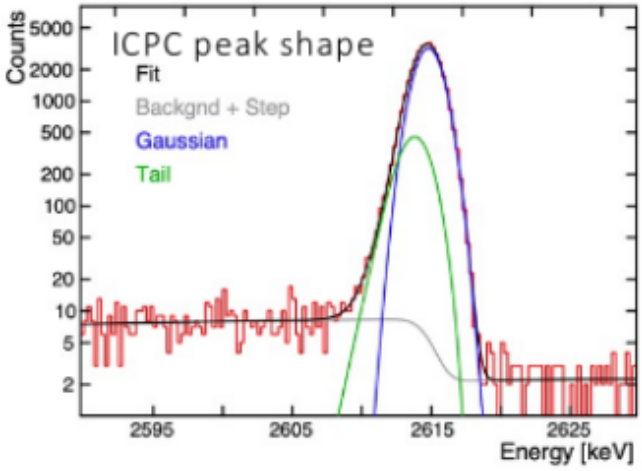
Components of the projected background model of LEGEND-1000 & simulated spectrum using the GEANT4-based MaGe simulation framework:

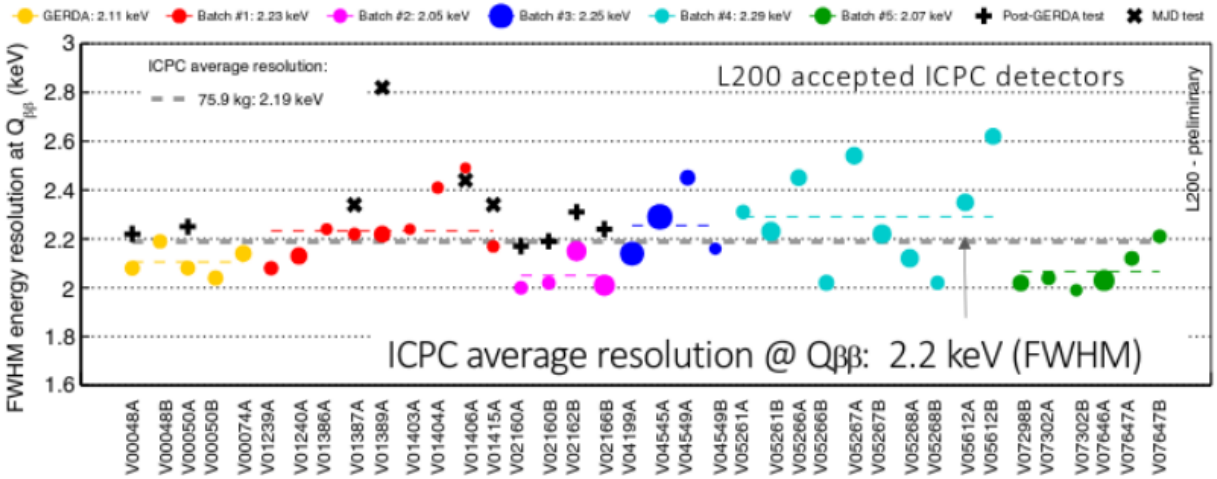




Backup: energy resolution

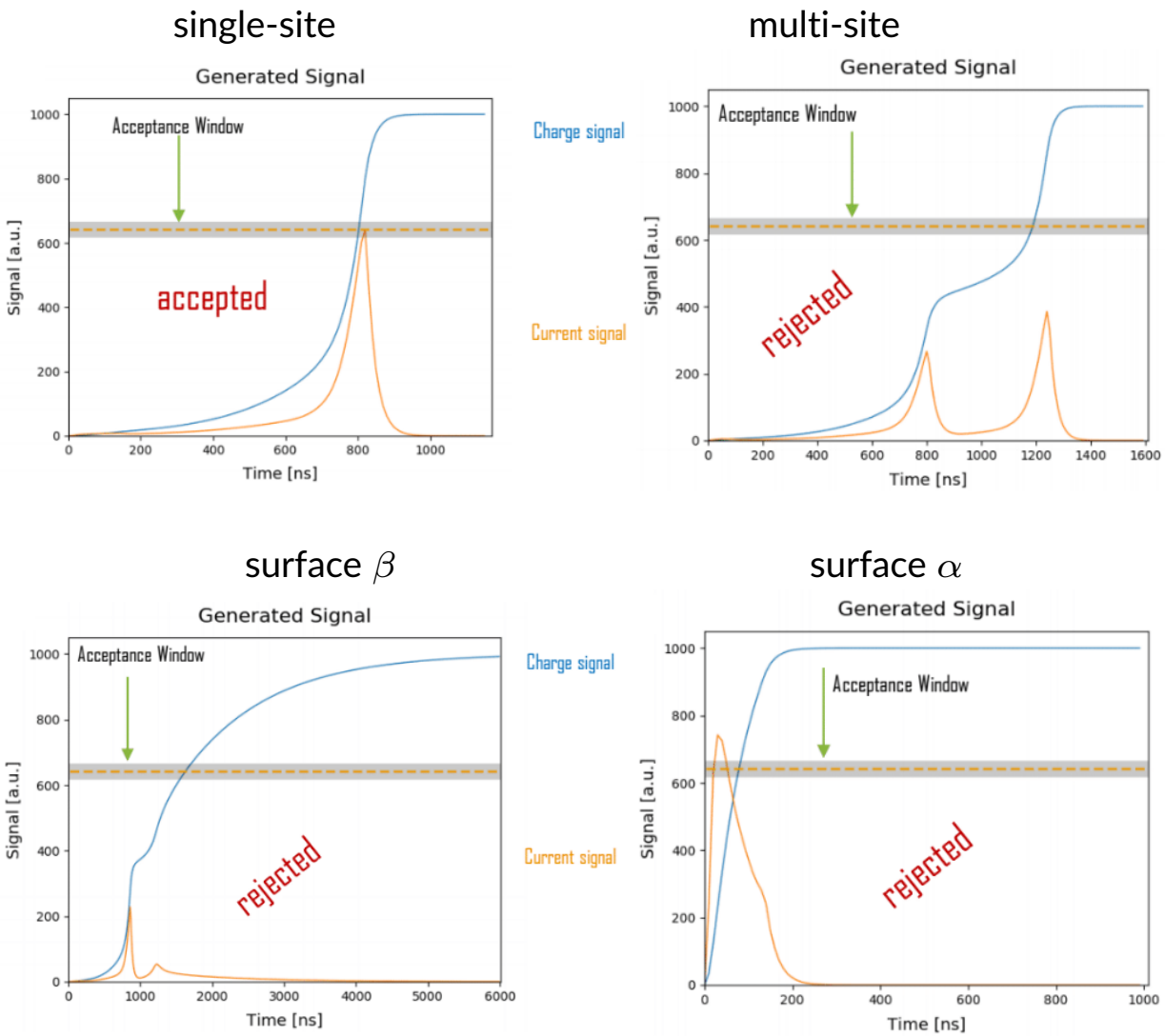
Peak fit example & energy resolution stability of the ICPC detectors:





Backup: PSD principle

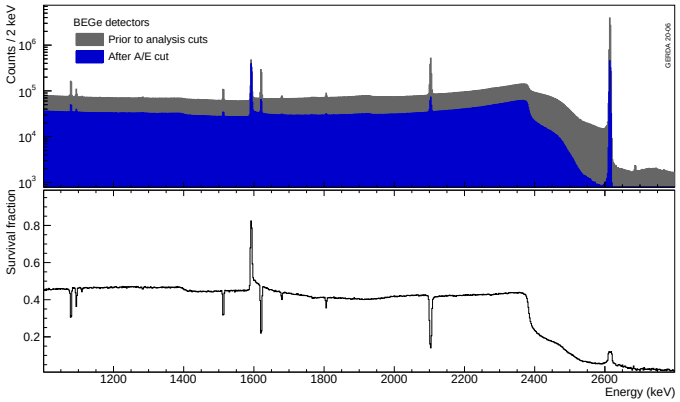
- single-site events: signal-like
- multi-site events: induce double-peak structure
- surface β events: distorted charge & current signal shape
- surface α events: fast risetime, high current

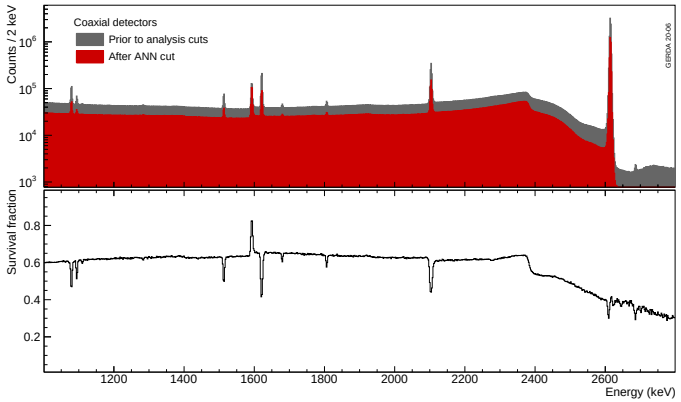


GERDA collaboration, Eur. Phys. J. C 73 2583 (2013)

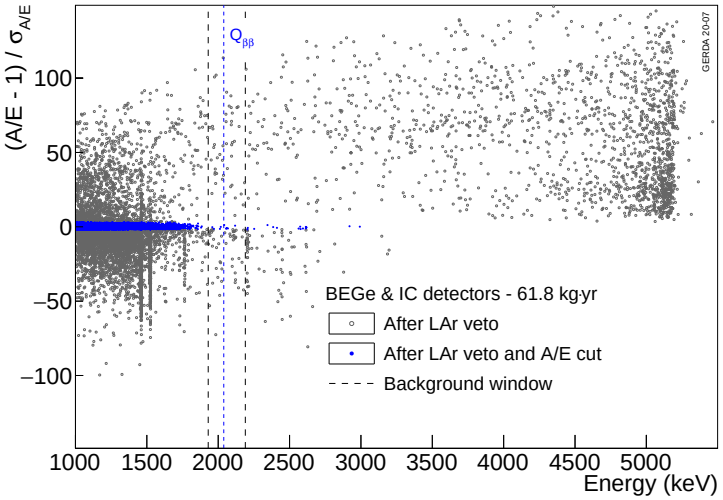
Backup: PSD performance

Survival fraction of calibration data events after applying pulse shape discrimination, data from GERDA:



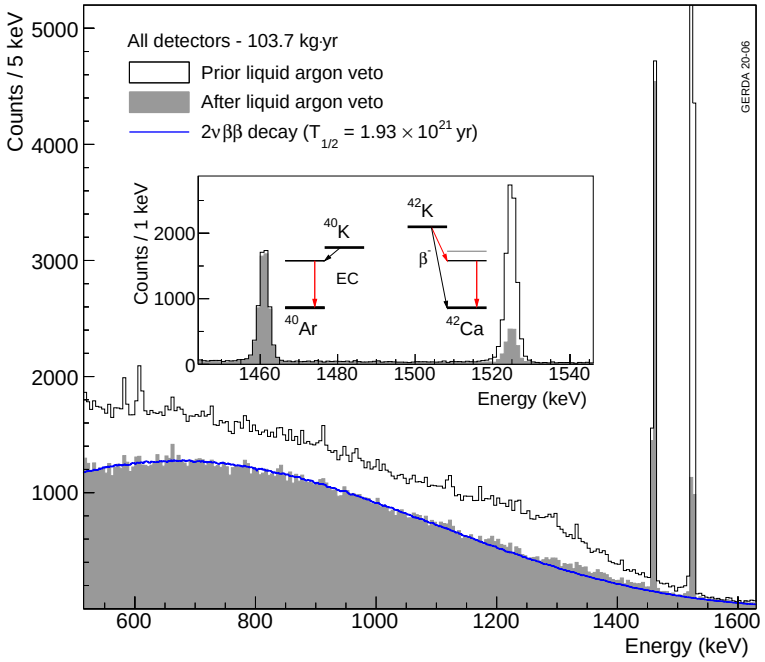


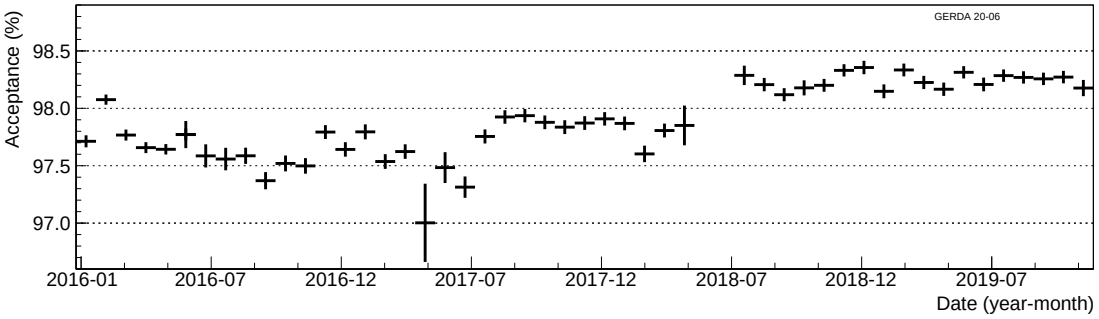
A/E (current amplitude over energy) cut applied to physics data:



Backup: LAr veto cut

Background event reduction by applying the LAr veto cut, data from GERDA:

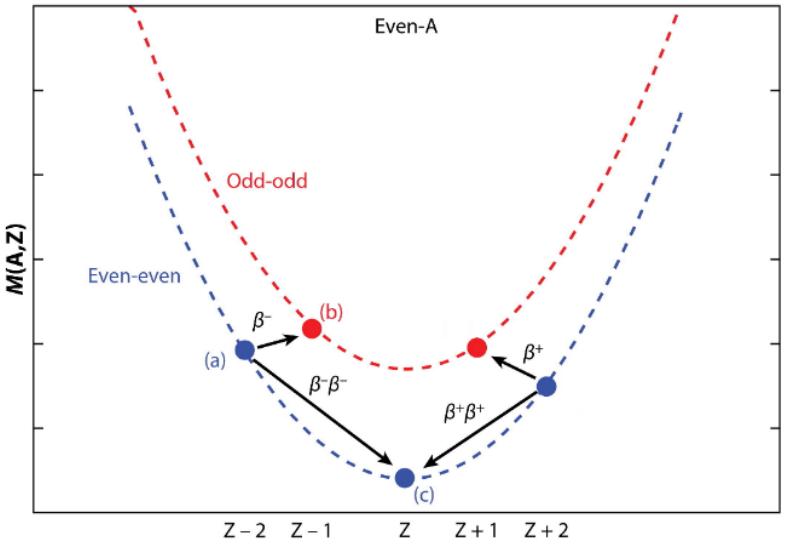




Backup: double beta decay

Comparison of the different isotopes undergoing double beta decay:

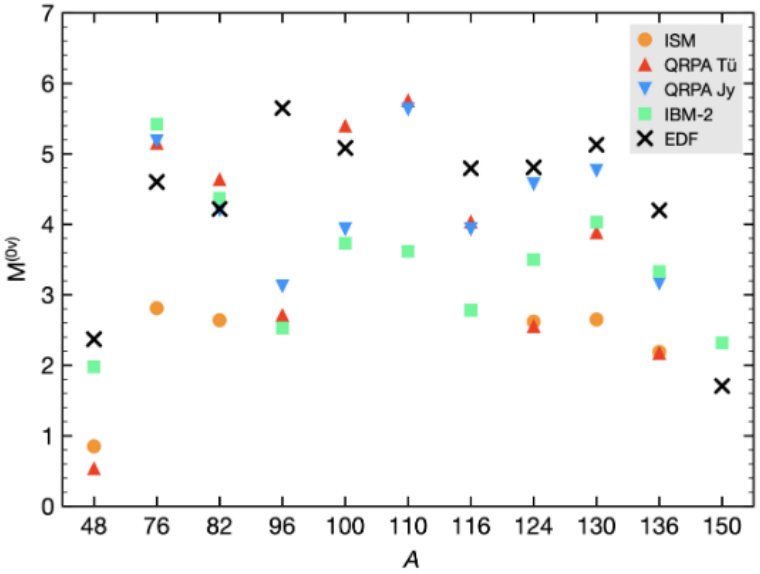
isotope	Q-value [MeV]	nat. abundance [%]
^{110}Pd	2.02	11.7
^{76}Ge	2.04	7.73
^{124}Sn	2.29	5.8
^{136}Xe	2.46	8.86
^{130}Te	2.53	34.1
^{116}Cd	2.81	7.5
^{82}Se	3.00	8.7
^{100}Mo	3.03	9.8
^{96}Zr	3.35	2.8
^{150}Nd	3.37	5.6
^{48}Ca	4.27	0.187



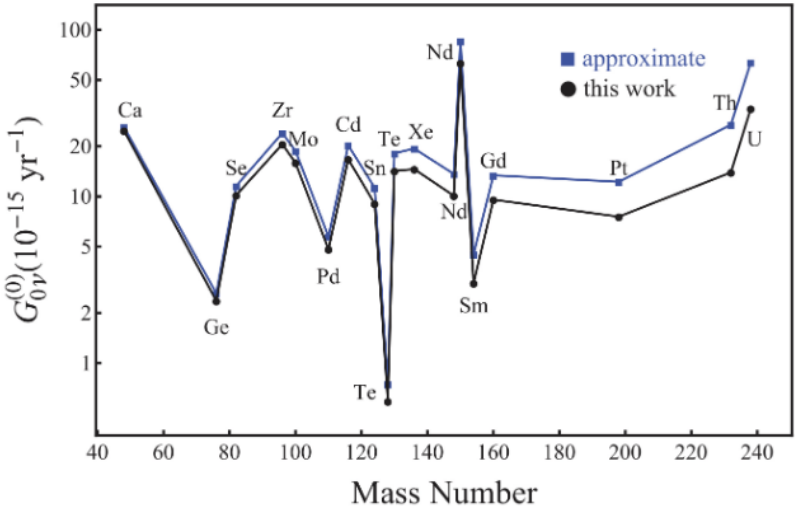
Saakyan, Review of Nuclear and Particle Science 63 503 (2013)

Backup: nuclear matrix element & phase space factors

Comparison of nuclear matrix elements & phase space factors of different isotopes:



Gomez-Cadenas, Martin-Albo, PoS GSSI 14 004 (2015)



Kotila, Iachello, Phys. Rev. C 85 034316 (2012)