NEUTRINOLESS DOUBLE BETA DECAY SEARCH WITH THE GERDA EXPERIMENT

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on behalf of the GERDA Collaboration

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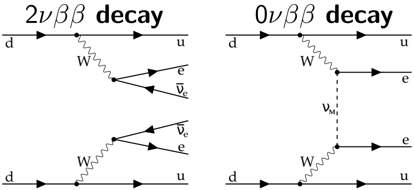
Why search for Neutrinoless Double Beta ($0\nu\beta\beta$) decay

Powerful method to study the unknown neutrino properties
Observation of $0\nu\beta\beta$ decay implies:

- neutrino ν has Majorana nature
- lepton number violation ($\Delta L = 2$)
- determination of ν absolute mass (nuclear model dependent)



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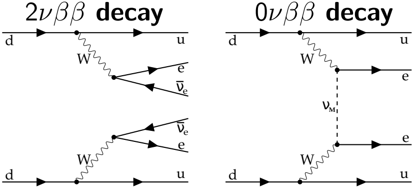

Half life of $0\nu\beta\beta$ (in case of light Majorana neutrino exchange):

$$(T_{1/2}^{0\nu})^{-1} =$$

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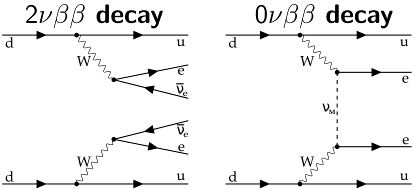

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- **Phase Space Integral**: well known quantity

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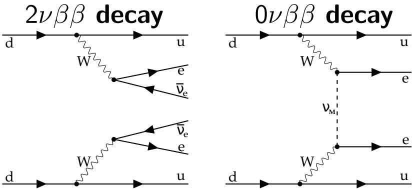

Half life of $0\nu\beta\beta$ (in case of light Majorana neutrino exchange):

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \times \left|M_{0\nu}\right|^2 \times$$

- **Phase Space Integral**: well known quantity
- **Nuclear Matrix Element**: most critical ingredient, produces uncertainty in the determination of $m_{\beta\beta}$ (quenching problem)

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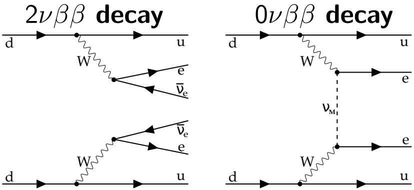

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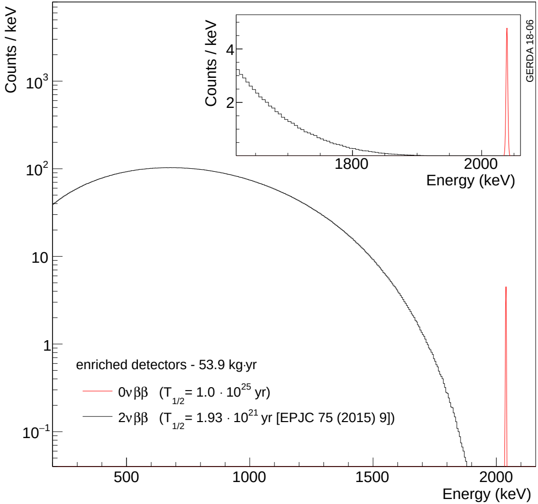
$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu} \times |M_{0\nu}|^2 \times \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

- **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**: by measuring $T^{0\nu}_{1/2}$, $m_{\beta\beta}$ can be estimate

Search for $0\nu\beta\beta$ decay

signature: sharp peak at Q-value of the decay



Experimental sensitivity

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

efficiency, exposure, abundance, energy resolution, background index

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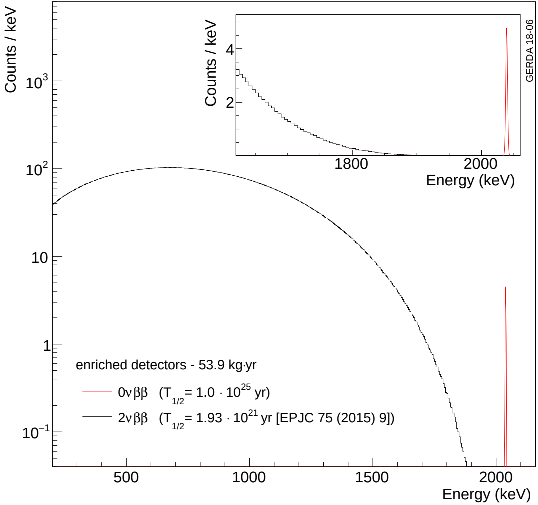

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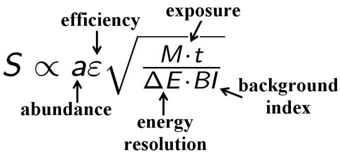

$$S \propto a\varepsilon \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

in case of background-free:
($N_{bkg} < 1$ at full exposure)

$$\boxed{S \propto a\varepsilon \cdot M \cdot t}$$

Status of neutrinoless double beta decay search

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
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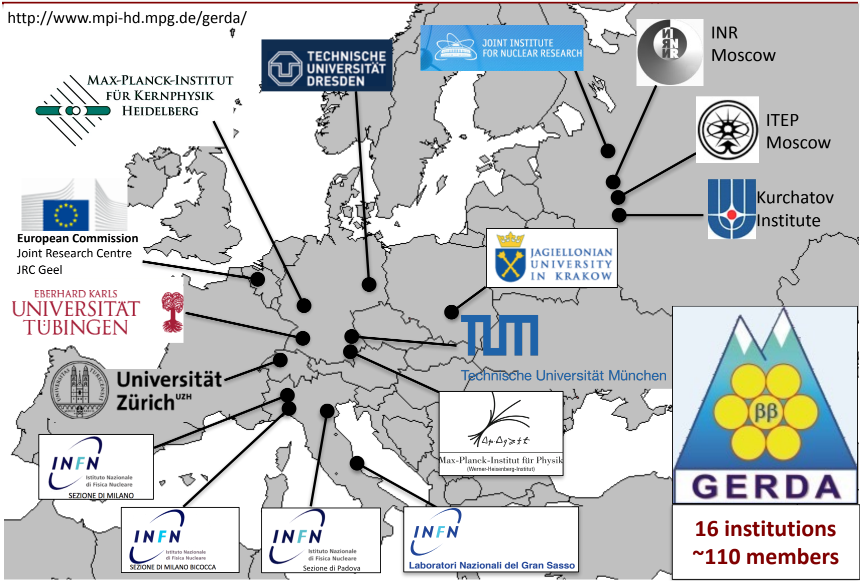
$\Downarrow$

the future goal is reach sensitivities of $S^{0\nu}_{1/2} \sim 10^{27}$–$10^{28}$ yr and improve the limit on the **effective Majorana neutrino mass** to $m_{\beta\beta} \sim 10$ meV

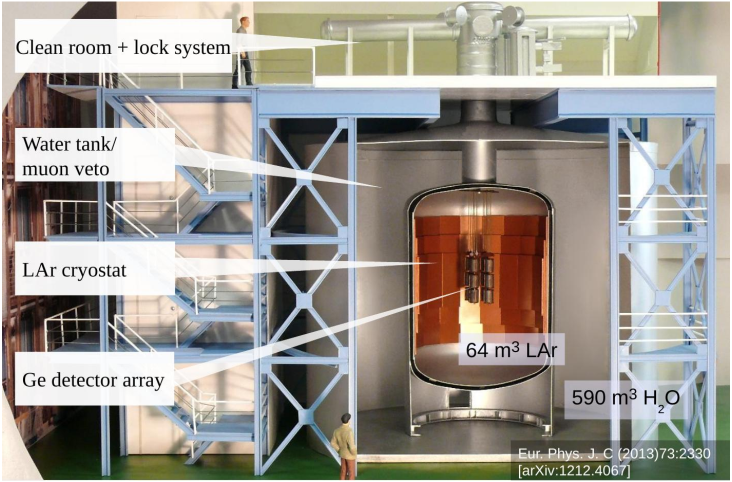
The GERDA Collaboration



16 institutions
~110 members

Design of the GERDA experiment

- location: Laboratori Nazionali del Gran Sasso, $\sim$ 1500 m of rock $\rightarrow$ 3500 m.w.e.
- bare HPGe detectors enriched in ^{76}Ge (86%) in LAr
- water tank to shield against external radiation with Cherenkov muon veto
- program with 2 phases: Phase I from 2011 to 2013, Phase II started in December 2015



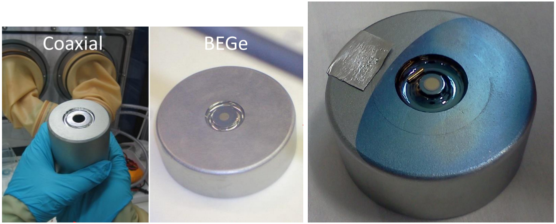
GERDA detectors

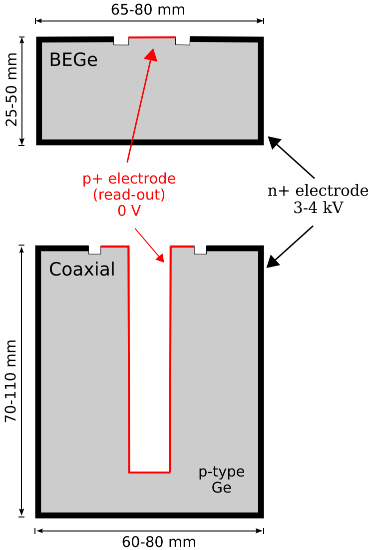
Semi-Coaxial detectors

- from previous experiments (HdM, IGEX)
- total mass 17.7 kg
- energy resolution: 3.6 keV (FWHM) at $Q_{\beta\beta}$

BEGe detectors

- produced for Phase II
- energy resolution: 3.0 keV (FWHM) at $Q_{\beta\beta}$
- better Pulse Shape Discrimination with **A/E ratio** (= current-amplitude/energy)





Upgrade to GERDA Phase II [EPJC 78 (2018) 388]

- 30 BEGe detectors produced and tested
- increase the exposure to 100 kg·yr
  - more active mass (35.8 kg of ^{enr}Ge)
  - longer data acquisition ($\sim$ 3 yr)
- background to $\sim 10^{-3}$ /(keV·kg·yr)

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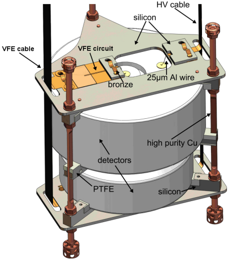

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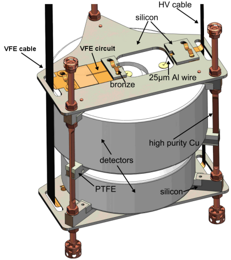

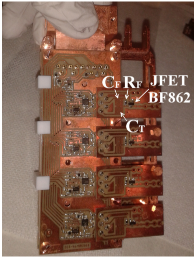

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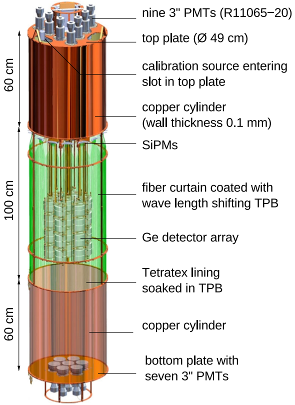

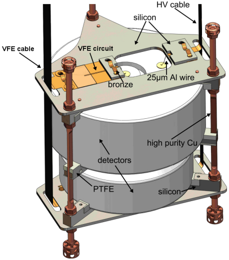

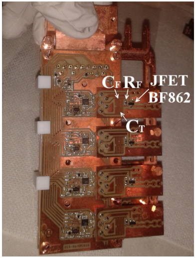

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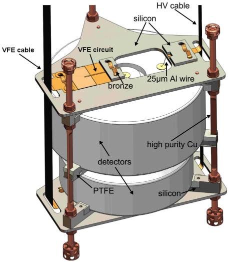
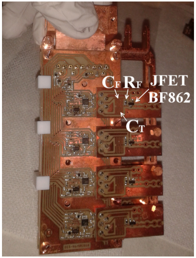
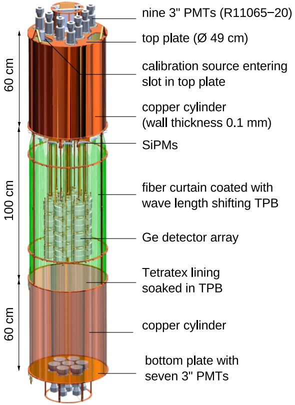
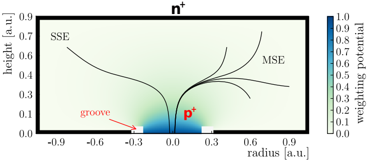
  - liquid Ar readout to veto external background
  - improved pulse shape discrimination with BEGes

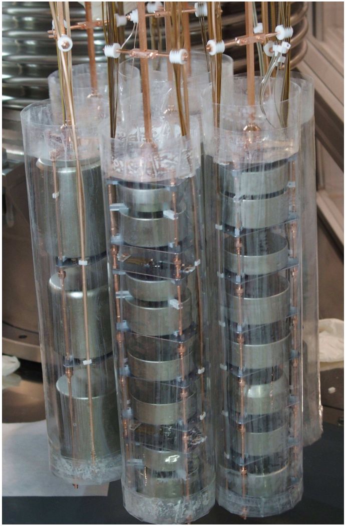








GERDA Phase II Configuration

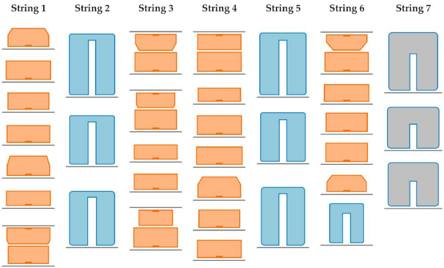


strings surronded by a nylon shroud,
prevent ^{42}K from reaching Ge

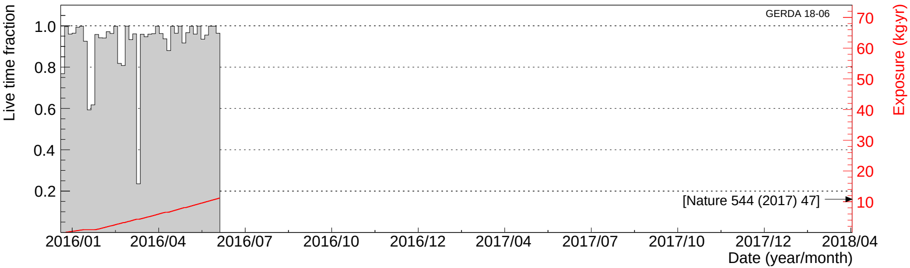
40 detectors arranged in 7 strings:

- 30 ^{enr}Ge BEGes (20 kg)
- 7 ^{enr}Ge coaxials (15.6 kg)
- 3 natural coaxials (7.6 kg)

$\Rightarrow$ **35.6 kg of ^{enr}Ge**



Phase II Data Taking



Phase II release:

- June 2016: 10.8 kg·yr [Nature 554 (2017) 47]

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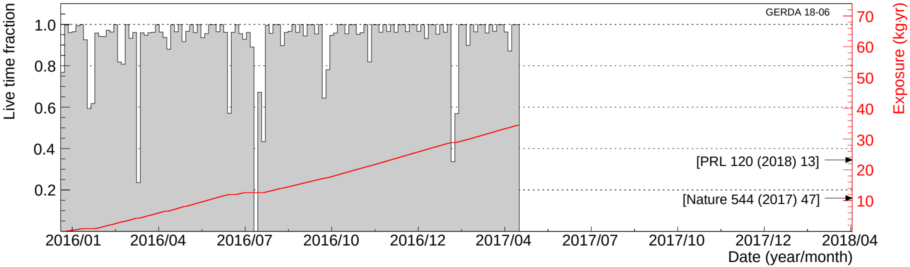

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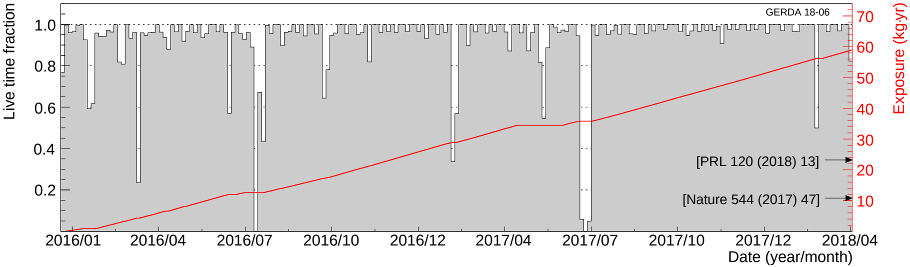

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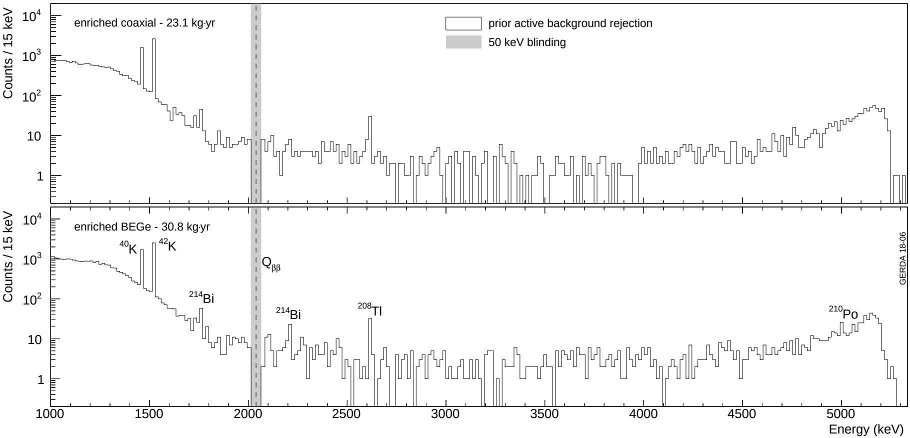
- June 2018 +35.7 kg·yr (BEGe and Coax data) **58.9 kg·yr exposure**

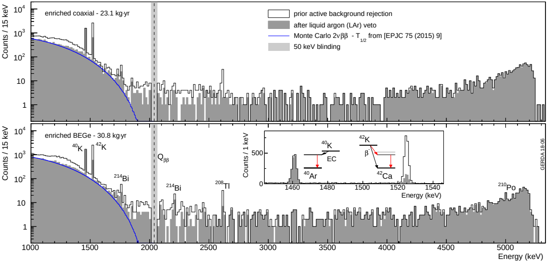
Phase II Background Spectra



- after muon veto and detector anti-coincidence cuts
- peaks from ^{42}K, ^{40}K and Th/Ra chains
- α from ^{210}Po at high energies

Background suppression: LAr veto + PSD

Active suppression by detection of LAr scintillation light



- $^{40}K/^{42}K$ Compton continua completely suppressed
- γ-rays survival fractions: ^{40}K (EC) $= 100$ %, ^{42}K (β^-) ~ 20 %
- **LAr veto cut signal acceptance 97.7$\pm$1%**

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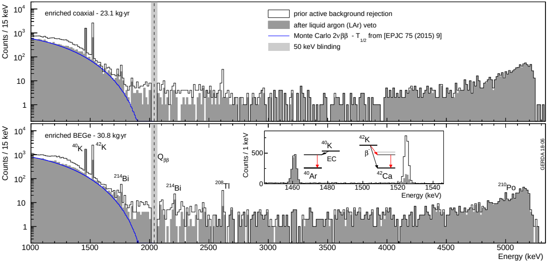

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Pulse Shape Discrimination

Coaxial detectors: 2 methods

- Multiple site event suppression with Artificial Neural Network
- cut on the charge collection time for the α surface contamination

Combined $0\nu\beta\beta$ **acceptance**:

$$\varepsilon^{PSD}_{coax} = \varepsilon^{MSE}_{coax} \cdot \varepsilon^{\alpha}_{coax} = (71.2 \pm 4.3)\%$$

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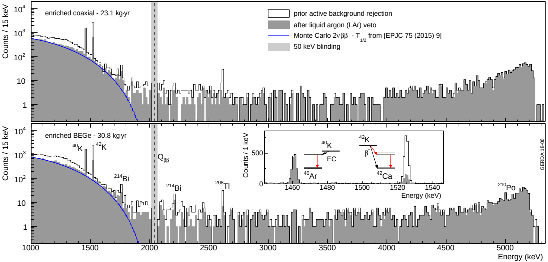

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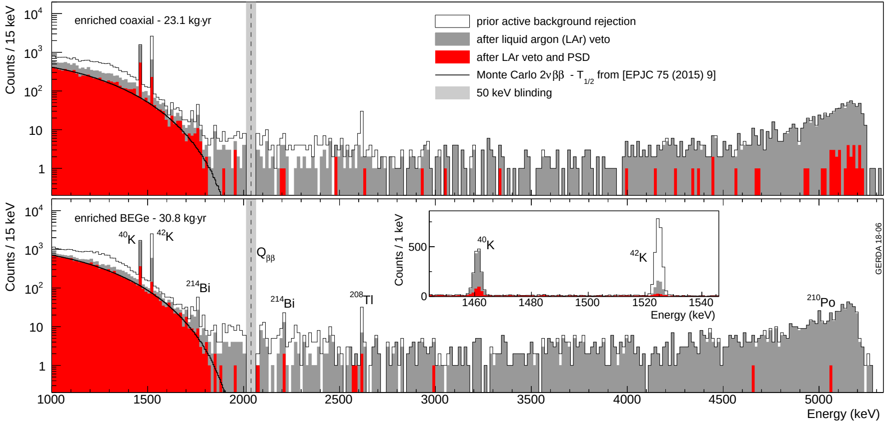
BEGe detectors: based on the A/E ratio

- **high A/E**: events on p$^+$ electrode (e.g. αs from ^{210}Po)
- **low A/E**: events on n$^+$ electrode, multiple scattering

$0\nu\beta\beta$ **acceptance (^{228}Th calibrations):**

$$\varepsilon^{PSD}_{BEGe} = (87.6 \pm 2.5)\%$$

Background spectra after LAr veto and PSD



Both K-lines and high energy α-events strongly suppressed

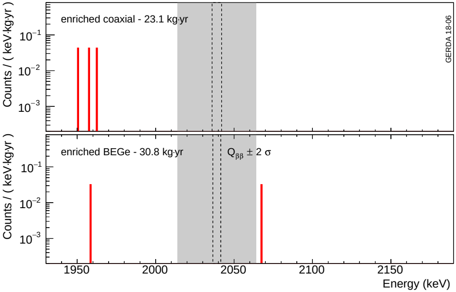
GERDA Phase II results

Background in Phase II:
evaluated in the region 1930-2190 keV, excluding known γ-lines ±5 keV around 2 and around $Q_{\beta\beta}$:

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)

Best value in the $0\nu\beta\beta$ field, GERDA is in the background-free condition



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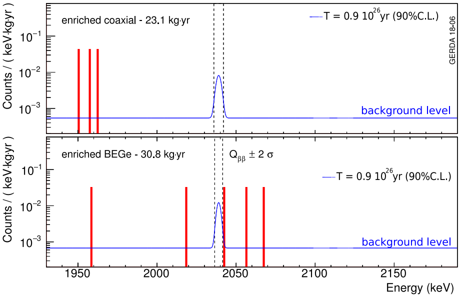

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Results: Phase I + Phase II total exposure 82.4 kg·yr

Median Sensitivity: $S^{0\nu}_{1/2} = 1.1 \cdot 10^{26}$ yr (90% C.L.)

Limit on $0\nu\beta\beta$ 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%

Conclusions and Outlook

GERDA reached important milestones in the $0\nu\beta\beta$ decay search:

- **energy resolution ~ 0.15% at $Q_{\beta\beta}$**
- **lowest background ever achieved:** $6 \cdot 10^{-4}$ cts/(keV·kg·yr)
- **exploration of the $0\nu\beta\beta$ decay at the 10^{26} yr scale**

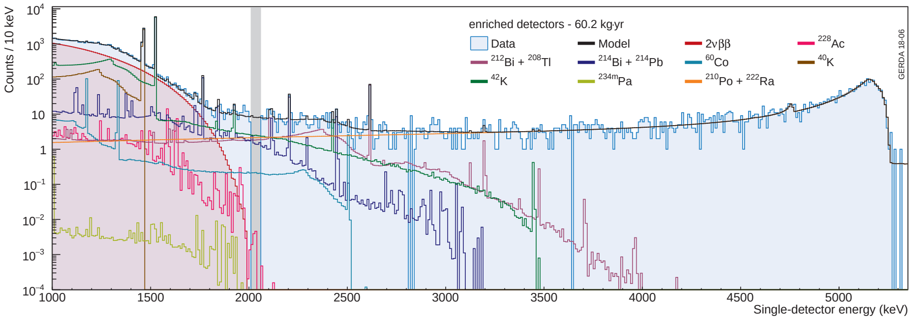
the search for $0\nu\beta\beta$ decay in ^{76}Ge will be continued by **LEGEND-200** in order to reach a sensitivity of 10^{27} yr

The experiment is fully funded and now is in preparation

Ongoing efforts to start in 2021!

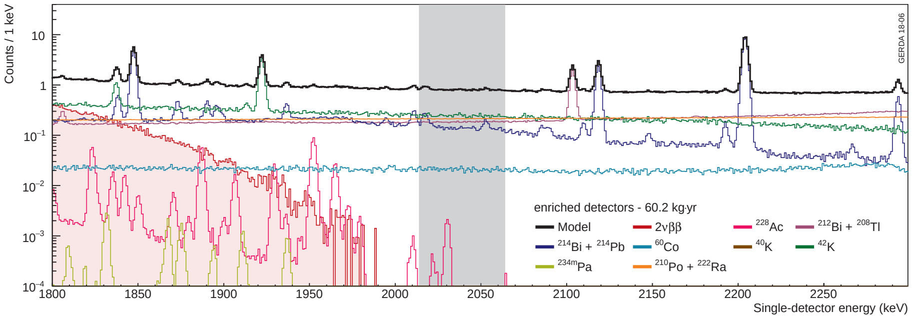
Backup Slides

Background model



- fit various sources at different locations to spectra based on screening measurements
- take into account events with energy in two detectors

Background model



expected flat background in the ROI, main components:

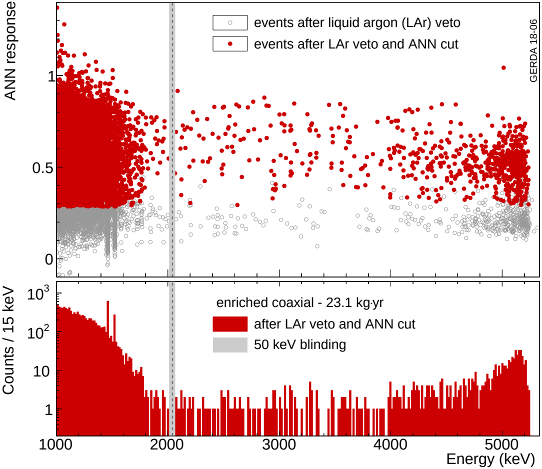
- β from ^{42}K
- α for ^{210}Po and ^{222}Ra
- γ from ^{212}Bi and ^{208}Tl
- γ from ^{214}Bi and ^{214}Pb

Pulse Shape Discrimination for Coaxial detectors

Multiple site event suppression with Artificial Neural Network (ANN) [EPJC 73 (2013) 2583]

Suppression of the α surface contamination

- ANN rejects events around the bore-hole of coaxial detectors
- cut on the charge collection time (10-90%) rejects fast surface events



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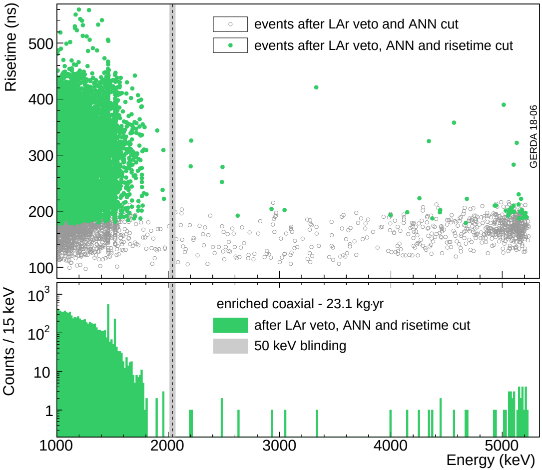


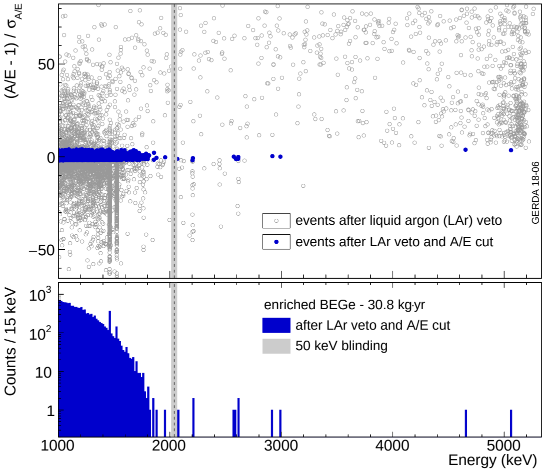
Combined $0\nu\beta\beta$ acceptance:

$$\varepsilon^{PSD}_{coax} = \varepsilon^{MSE}_{coax} \cdot \varepsilon^{\alpha}_{coax} = (71.2 \pm 4.3)\%$$

Pulse Shape Discrimination for BEGe detectors

Based on the selection of the A/E parameter (A=current amplitude, E=energy):

- **high A/E**: events on p^+ electrode (e.g. αs from ^{210}Po)
- **low A/E**: events on n^+ electrode, multiple scattering



$0\nu\beta\beta$ acceptance from ^{228}Th calibrations (DEP):

$$\varepsilon^{PSD}_{BEGe} = (87.6 \pm 2.5)\%$$

(double check at low energy with $2\nu\beta\beta$ events)

GERDA data sets

data sets	esposure [kg·yr]	FWHM [keV]	efficiency	background [cts/(keV·kg·yr)]
Phase I golden	17.9	4.3 (1)	0.57 (3)	$11 \pm 2 \cdot 10^{-3}$
Phase I silver	1.3	4.3 (1)	0.57 (3)	$30 \pm 10 \cdot 10^{-3}$
Phase I BEGe	2.4	2.7 (2)	0.66 (2)	$5^{+4}_{-3} \cdot 10^{-3}$
Phase I extra	1.9	4.2 (2)	0.57 (3)	$5^{+4}_{-3} \cdot 10^{-3}$
Phase II Coax-1	5.0	3.6 (1)	0.52 (4)	$3.5^{+2.1}_{-1.5} \cdot 10^{-3}$
Phase II Coax-2	23.1	3.6 (1)	0.48 (4)	$0.6^{+0.4}_{-0.3} \cdot 10^{-3}$
Phase II BEGe	30.8	3.0 (1)	0.60 (2)	$0.6^{+0.4}_{-0.2} \cdot 10^{-3}$

TOTAL EXPOSURE: 82.4 kg·yr

the efficiency includes active volume fraction, enrichment, reconstruction of $0\nu\beta\beta$, PSD efficiency, LAr veto loss

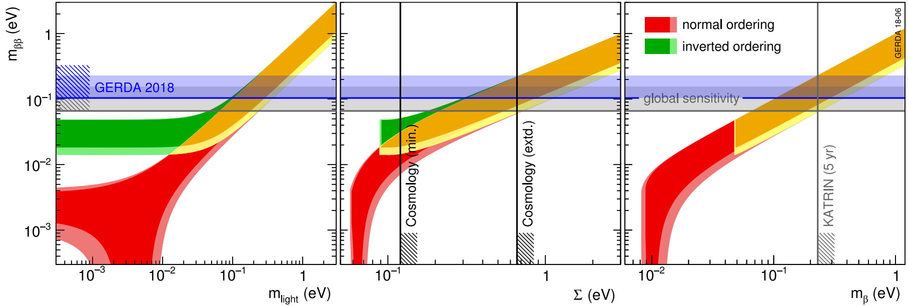
GERDA $0\nu\beta\beta$ decay results

	Profile Likelihood 2-side test-stat	**Bayesian flat prior**
$0\nu\beta\beta$ cts best fit value	0	0
$T^{0\nu}_{1/2}$ lower limit	$0.9 \cdot 10^{26}$ yr (90% CL)	$0.8 \cdot 10^{26}$ yr (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity	$1.1 \cdot 10^{26}$ yr (90% CL)	$0.8 \cdot 10^{26}$ yr (90% CI)
Probability of stronger limit	63%	59%

- **unbinned profile likelihood**: flat background (1930-2190 keV) + Gaussian signal
- **frequentist test-statistics** and methods [EPJC 71 (2011) 1554]

Status of $0\nu\beta\beta$ decay search

Constraints on the effective Majorana neutrino mass



- as function of the lightest neutrino mass m_{light} with GERDA 2018 and combined sensitivities
- as function of the sum of neutrino masses Σ with limits from cosmology
- as function of the effective neutrino mass m_β with the 5 yr sensitivity of the KATRIN experiment

^{76}Ge based $0\nu\beta\beta$ decay experiments

- HPGe detectors enriched up to $\sim 88\%$ in the ^{76}Ge $\beta\beta$ emitter
- source $=$ detector $\rightarrow$ high detection efficiency
- excellent energy resolution (FWHM $\sim 0.1\%$ at $Q_{\beta\beta}$)
- background-free experiments ($N_{bkg} < 1$) $\rightarrow$ $S \propto M \cdot t$

RUNNING

$M \sim 40$ kg

$T^{0\nu}_{1/2} \gtrsim 10^{26}$ yr

GERDA

^{76}Ge based $0\nu\beta\beta$ decay experiments

- HPGe detectors enriched up to $\sim 88\%$ in the ^{76}Ge $\beta\beta$ emitter
- source $=$ detector $\rightarrow$ high detection efficiency
- excellent energy resolution (FWHM $\sim 0.1\%$ at $Q_{\beta\beta}$)
- background-free experiments ($N_{bkg} < 1$) $\rightarrow$ $S \propto M \cdot t$

RUNNING

$M \sim 40$ kg

$T_{1/2}^{0\nu} \gtrsim 10^{26}$ yr

GERDA

MID TERM

$M \sim 200$ kg

$T_{1/2}^{0\nu} \gtrsim 10^{27}$ yr

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND-200

^{76}Ge based $0\nu\beta\beta$ decay experiments

- HPGe detectors enriched up to $\sim 88\%$ in the ^{76}Ge $\beta\beta$ emitter
- source $=$ detector $\rightarrow$ high detection efficiency
- excellent energy resolution (FWHM $\sim 0.1\%$ at $Q_{\beta\beta}$)
- background-free experiments ($N_{bkg} < 1$) $\rightarrow$ $S \propto M \cdot t$

RUNNING

$M \sim 40$ kg

$T^{0\nu}_{1/2} \gtrsim 10^{26}$ yr

GERDA

MID TERM

$M \sim 200$ kg

$T^{0\nu}_{1/2} \gtrsim 10^{27}$ yr

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND-200

LONG TERM

$M \sim 1$ ton

$T^{0\nu}_{1/2} \gtrsim 10^{28}$ yr

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

LEGEND-1000

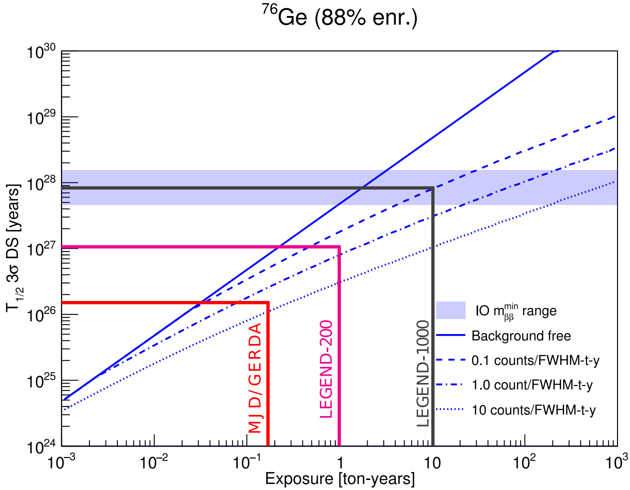
The LEGEND Experiment

The goal is develop a phased, ^{76}Ge based $\beta\beta$ 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, $\sim$ 250 members
- from GERDA and MAJORANA and external contributors

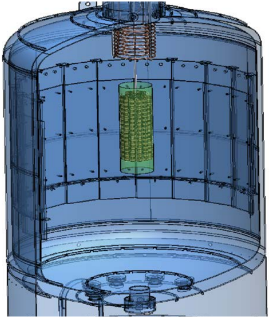
Univ. New Mexico
L'Aquila University and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University
MIT
University of North Carolina
Sichuan University
University of South Carolina
Tennessee Tech University
Jagiellonian University
University of Dortmund
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University
Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Chalmers University Tech.
Max Planck Institute, Heidelberg
Dokuz Eylul University
Queens University
University Tennessee
Lancaster University
University Liverpool
University College London
Los Alamos National Lab.
Lund University
INFN Milano Bicocca
Milano University and Milano INFN
Institute Nuclear Research Russ.
National Research Center Kurchatov
Lab. Exper. Nucl. Phy. MEPhI
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

LEGEND: 3σ discovery sensitivity projection



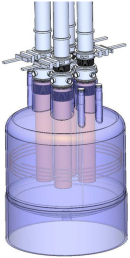
3σ discovery Level to cover inverted ordering, given matrix element uncertainty

The LEGEND Experiment [arXiv:1709.01980]



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 $\sim$ 2021



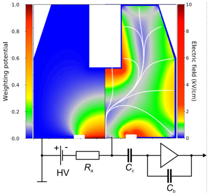
Subsequent Stage LEGEND-1000

- 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 LEGEND-200

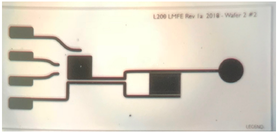
New Inverted Coaxial Point-Contact Ge detector

- 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