GERDA & the future of ^{76}Ge-based experiments

Matteo Agostini on behalf of the GERDA Collaboration

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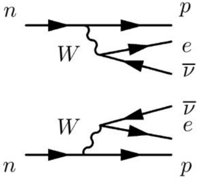
Double-β decays

2-neutrino double-β decay ($2\nu\beta\beta$):

- $(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$
- allowed in the Standard Model
- measured in several isotopes
- $T_{1/2}^{2\nu}$ in the range $10^{19} - 10^{24}$ yr



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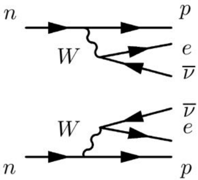
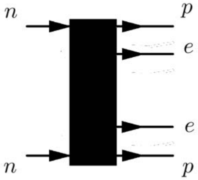


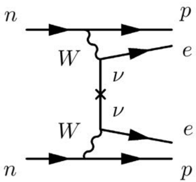
Neutrinoless double-β decay ($0\nu\beta\beta$):

- $(A, Z) \to (A, Z+2) + 2e^-$
- lepton number violation ($\Delta L = 2$)
- ν has non-null Majorana mass component
- $T^{0\nu}_{1/2}$ limits in the range $10^{21} - 10^{26}$ yr (10^{25} yr for ^{76}Ge)
- claim for a signal (subgroup of HdM experiment)

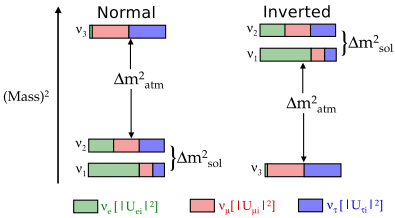


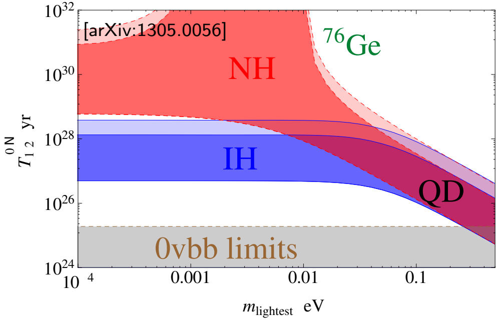
Neutrinoless double-β decay & neutrino physics

Assuming light-Majorana neutrino exchange as dominant $0\nu\beta\beta$ channel:

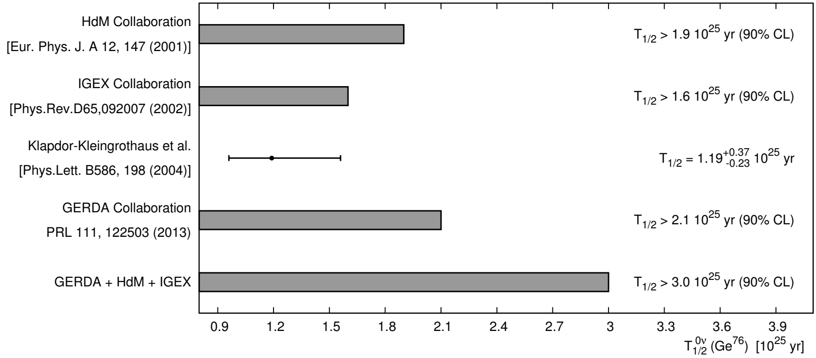


- $(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|\mathcal{M}_{0\nu}(A,Z)|^2|m_{\beta\beta}|^2$
- effective Majorana mass:
  $|m_{\beta\beta}| \equiv \left|\sum_i U^2_{ei} m_i\right| = \left|c^2_{12}\, c^2_{13}\, m_1 + s^2_{12}\, c^2_{13}\, m_2\, e^{i2\alpha} + s^2_{13}\, m_3\, e^{i2\beta}\right|$

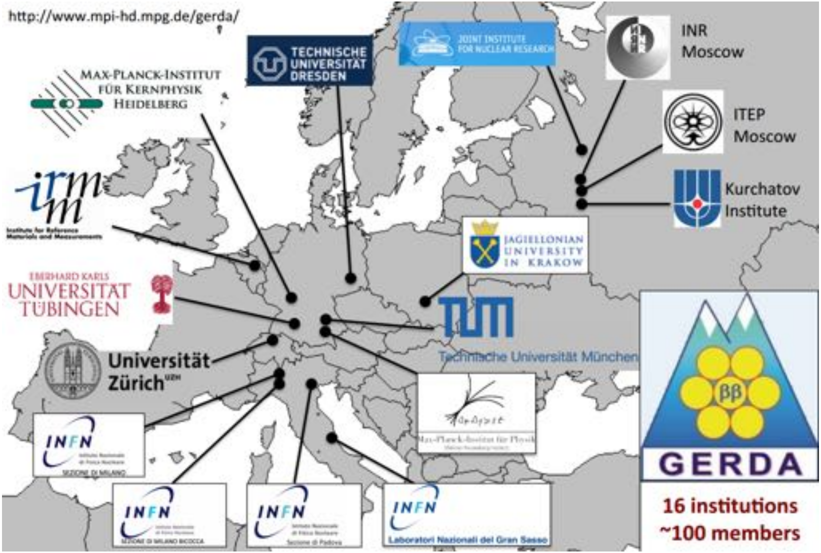




State of the art of $0\nu\beta\beta$ search with ^{76}Ge



GERDA collaboration



Sensitivity and background goals

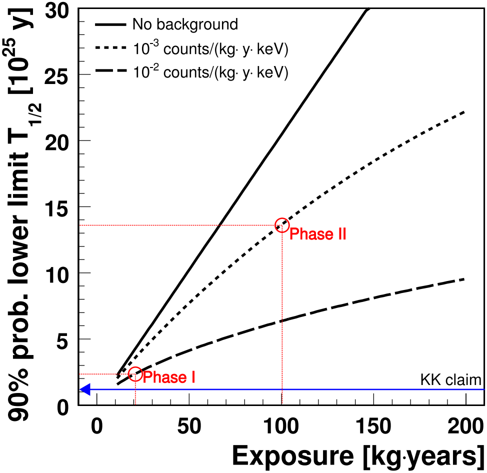
Phase I (Nov 2011 - May 2013):

- 15 – 20 kg of target mass (87% ^{76}Ge)
- bkg $\sim 10^{-2}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$
- exposure 21.6 kg·yr
- sensitivity to scrutinize KK claim

Phase II (migration ongoing):

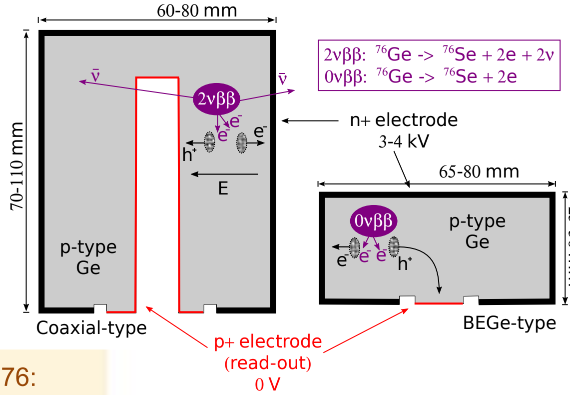
- new custom-produced BEGe detectors (additional 17 kg, 87% ^{76}Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV· kg· yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim$ 100 kg·yr
- start exploring $T_{1/2}^{0\nu}$ in the 10^{26} yr range

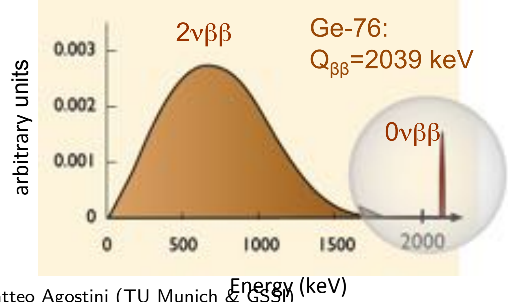
[Phys.Rev.D75, 092003 (2006)]



Detectors

- HPGe detectors from material enriched in ^{76}Ge (~87%)
- detectors well established technology
- optimal spectroscopy performance:
  - long-term stability
  - $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$
  - radio purity

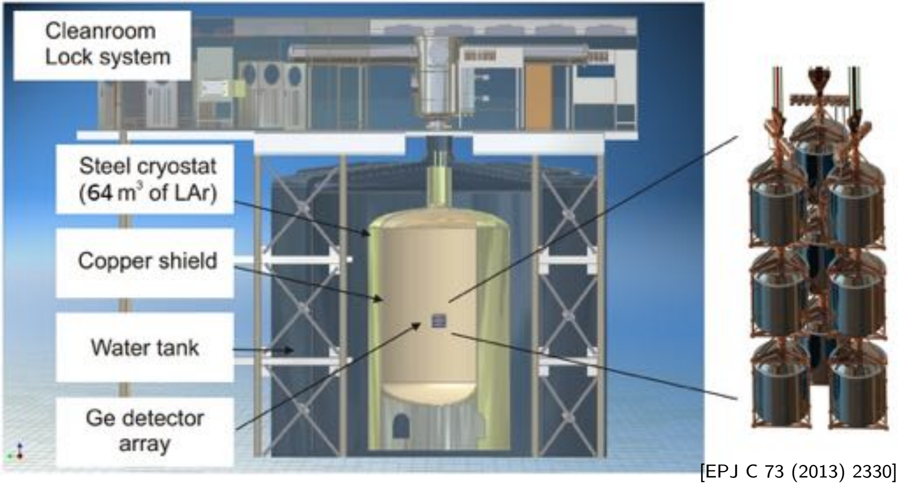




Calorimeter detectors:
- source=detector
- high detection efficiency
- peak at Q-value ($Q_{\beta\beta}$)

Shielding strategy and apparatus

- bare Ge detectors in liquid Argon (LAr)
- shield: high-purity LAr/H_2O
- radio-pure material selection
- deep underground (LNGS, 3800 m.w.e.)

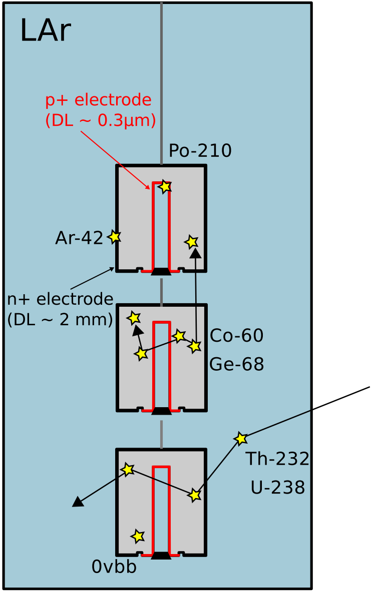


[EPJ C 73 (2013) 2330]

Backgrounds and mitigation techniques

Background sources:

- natural radioactivity (^{232}Th and ^{238}U chains):
  - γ-rays (e.g. ^{208}Tl, ^{214}Bi)
  - α-emitting isotopes from surface contamination (e.g. ^{210}Po) or ^{222}Rn in LAr
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)
- cosmogenic isotopes activated in Ge (^{68}Ge, ^{60}Co)



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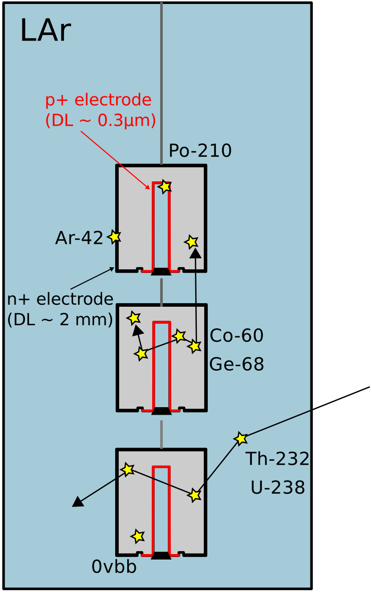
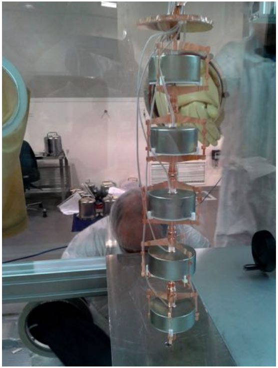
Mitigation strategy:

- detector anti-coincidence
- time-coincidence (Bi-Po or ^{68}Ge)
- pulse shape analysis
- detection of LAr-scintillation light



Phase I detector array configuration



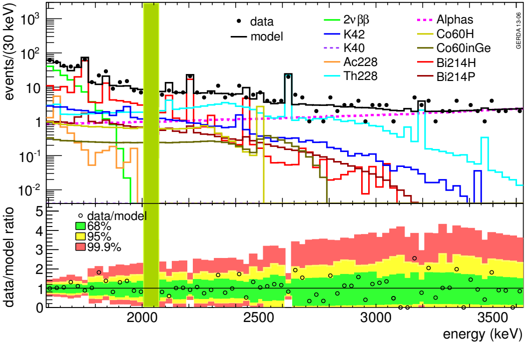
- $3 + 1$ strings
- 8 ^{enr}Ge coaxial detectors (2 not considered in the analysis)
- 5 ^{enr}Ge BEGe detectors (1 not considered in the analysis)
- 1 ^{nat}Ge coaxial detectors

^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

Data taking of Phase I

Data taking of Phase I

Background modeling

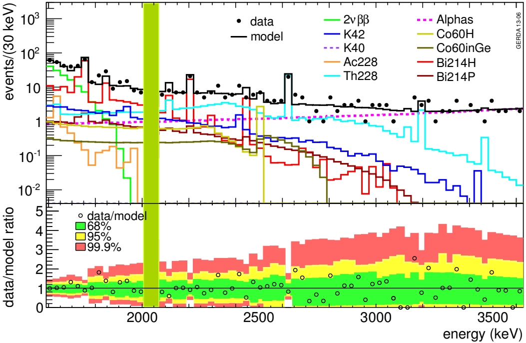


Contribution at $Q_{\beta\beta}$:

- γ-rays (close sources): Bi-214, Tl-208, K-42
- α- and β-rays (surface decays): Ra-226 daughter, Po-210, K-42

more details in [EPJ C74 (2014) 2764]

Background modeling



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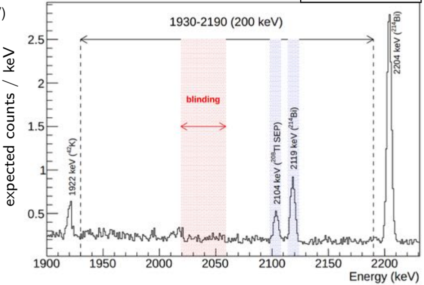
more details in [EPJ C74 (2014) 2764]

- no line expected in the blinded window
- background flat between 1930-2190 keV (excluding peaks at 2104 and 2119 keV)
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

  coax —> 4.8±0.2 keV

  BEGe —> 3.2±0.2 keV

MC simulation



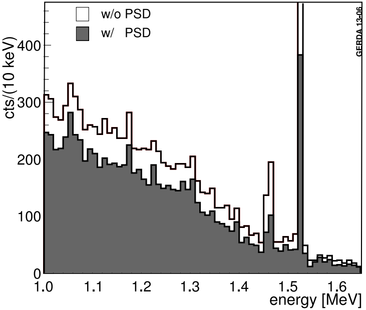
Pulse shape discrimination

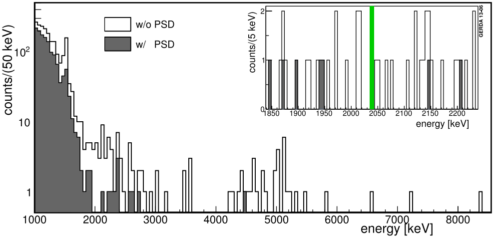
Coaxial detectors:

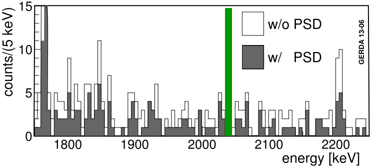
- artificial neural network
- $0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}\%$
- background acc at $Q_{\beta\beta} = \sim 45\%$

BEGe detectors:

- A/E parameter (mono-parametric PSD)
- $0\nu\beta\beta$ acceptance $92\pm2\%$
- background acc at $Q_{\beta\beta} \leq 20\%$

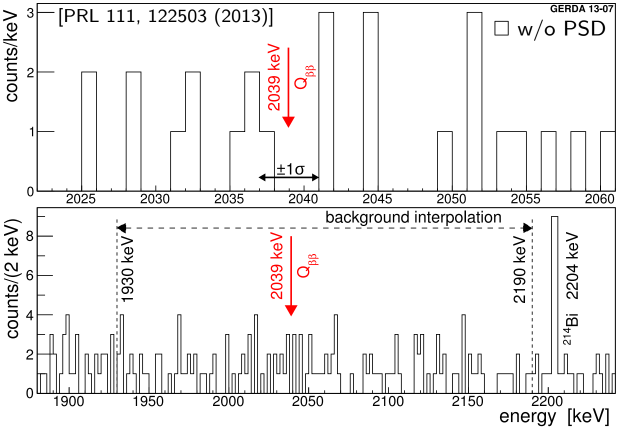






[Eur.Phys.J C73 (2013) 2583]

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)

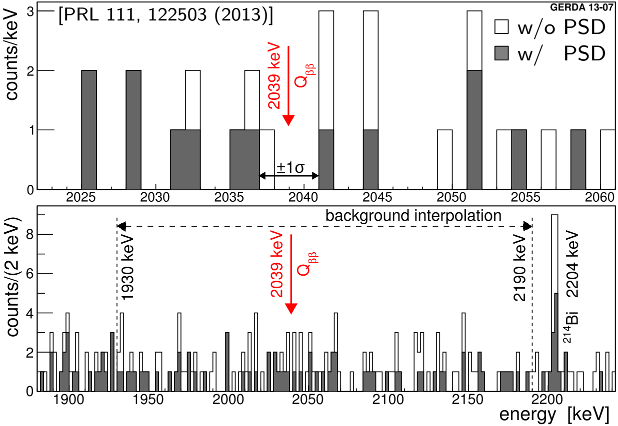
Survival fraction at $Q_{\beta\beta}$:	
1	∼99%
2+3	∼60%
4	∼100%

w/o PSD

w/ PSD

data set	exposure [kg·yr]	background 10^{-2} cts/(keV· kg· yr)	expected cts ($Q_{\beta\beta}$±5 keV)	observed cts ($Q_{\beta\beta}$±5 keV)
golden	17.3	1.8	3.3	5
BEGe	2.4	4.2	1.0	1

Unblinding: spectrum around $Q_{\beta\beta}$



Analysis cuts applied:

1) signals quality cuts
2) detector anti-coincidence
3) muon-veto anti-coincidence
4) single-detectors time coincidence (BiPo cut)
5) **PSD**

Survival fraction at $Q_{\beta\beta}$:

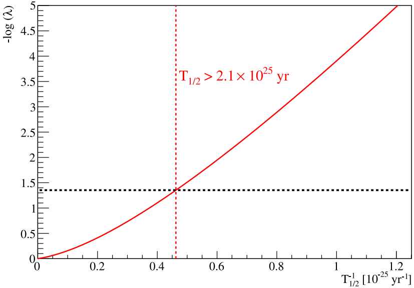
1	~99%
2+3	~60%
4	~100%
5	**~50%**

w/o PSD

w/ PSD

data set	exposure [kg·yr]	background 10^{-2} cts/(keV· kg· yr)		expected cts ($Q_{\beta\beta}\pm$5 keV)		observed cts ($Q_{\beta\beta}\pm$5 keV)	
		w/o PSD	w/ PSD	w/o PSD	w/ PSD	w/o PSD	w/ PSD
golden	17.3	1.8	1.1	3.3	2.0	5	2
BEGe	2.4	4.2	0.5	1.0	0.1	1	0

Statistical analysis



Profile likelihood analysis:

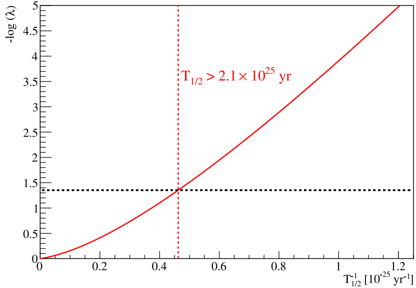
- ML fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $T_{1/2}^{0\nu}$)
- $T_{1/2}^{0\nu} \geq 0$ (coverage tested)

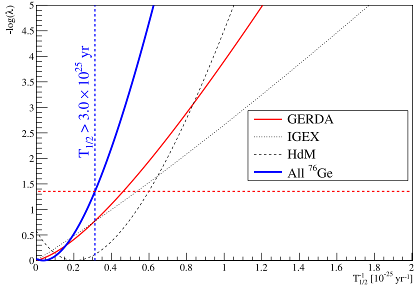
Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Statistical analysis





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- MC Median sensitivity (for no signal): $T_{1/2}^{0\nu} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

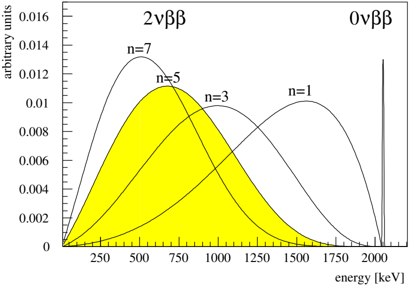
Results (GERDA + IGEX [1] + HdM [2]):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}$ yr (90% C.L.)

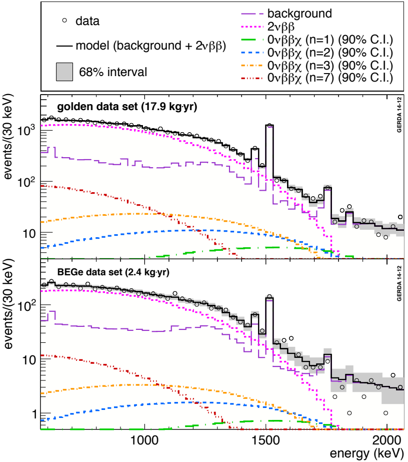
PRL 111, 122503 (2013); [1] Phys.Rev. D65, 092007 (2002); [2] Eur.Phys.J. A12, 147 (2001)

Double-β decay with 2ν or Majorons emission

- Global fit of the energy spectrum
- Most accurate measurement of:
  $T^{2\nu}_{1/2}(^{76}\text{Ge}) = 1.926(95) \times 10^{21}$ yr
  (68% probability)
- Most stringent limits on exotic processes:
  $T^{0\nu\chi}_{1/2} > 10^{23}$ yr for n=1,3,5,7



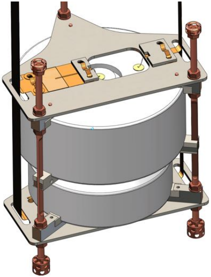
[Acta Phys. Polon. B **37** (2006) 1905]



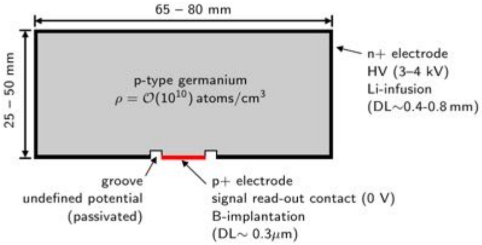
[arxiv:1501.02345]

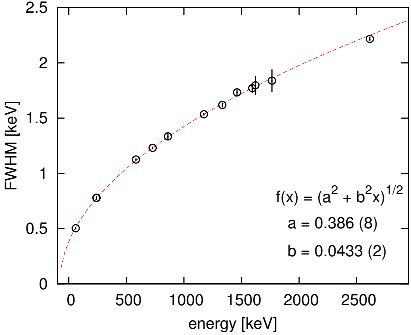
Phase II upgrade

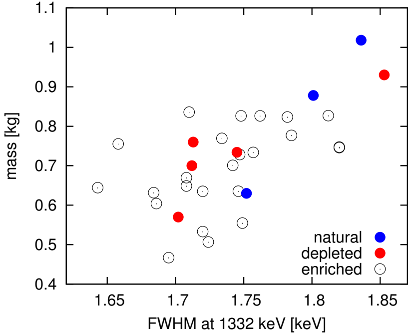
- Installation of additional 17 kg of BEGe detectors:
  - increased array granularity (anti-coincidence cut)
  - enhanced pulse shape discrimination performance
  - excellent energy resolution
- PMT and fibers+SiPM to detect LAr scintillation light
- lower-mass holders



Broad Energy Germanium (BEGe) detectors







Signal formation and development

Signal formation and development

Signal formation and development

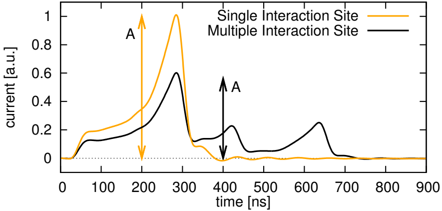
Signal formation and development

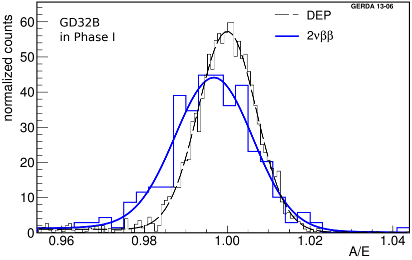
Signal formation and development

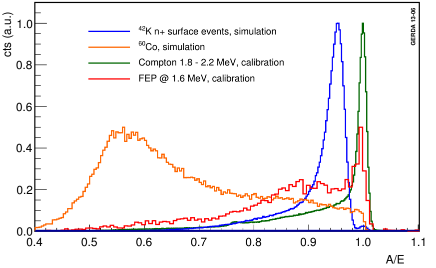
Pulse shape discrimination technique

A/E method:

E: integral of the current signal (energy)
A: maximum of the current signal

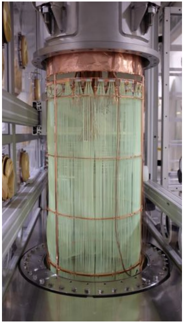






[Budjas et al. JINST 4 P10007,M.A et al. JINST 6 P03005, Eur.Phys.J C73 (2013) 2583]

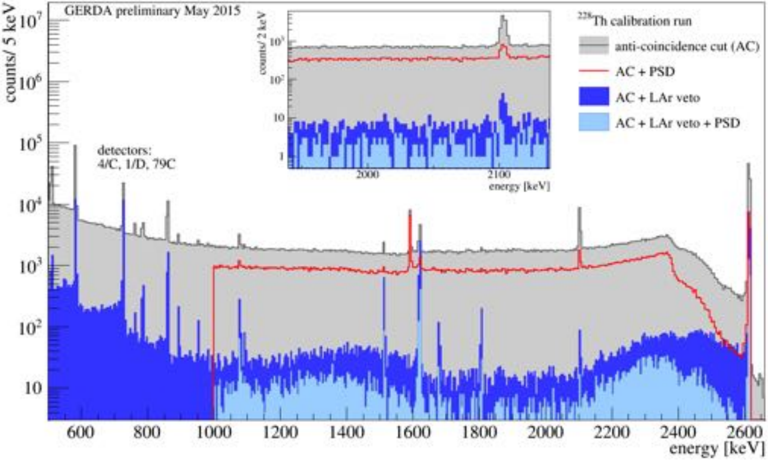
Detection of LAr scintillation light

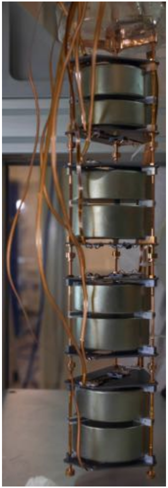


Design:

- low-background photo-multipliers (9 top, 7 bottom)
- wave-length-shifting fibers read-out by SiPMs
- wave-length-shifting nylon mini-shroud

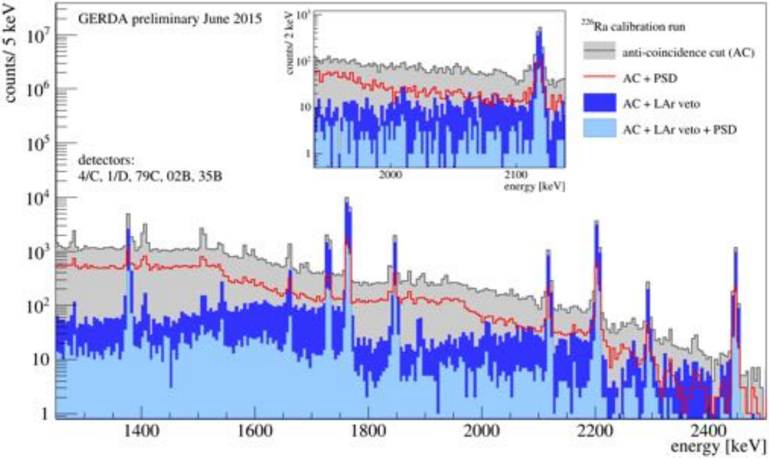
Last commisioning results (Th-228 irradiation)

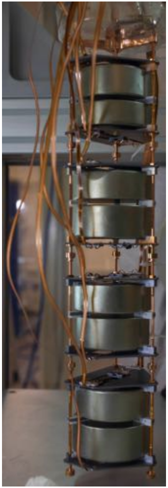




About two orders of magnitude suppression at $Q_{\beta\beta}$!

Last commisioning results (Ra-226 irradiation)



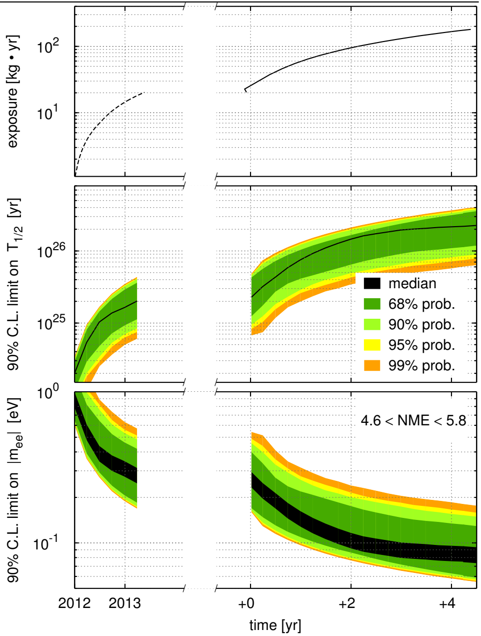


Almost two orders of magnitude suppression at $Q_{\beta\beta}$!

GERDA sensitivity projection for limit setting

- profile likelihood analysis
- MC-realizations of the data sets
- limit extraction performed for each realization
- global analyis:
  - GERDA Phase I
  - GERDA Phase II: (37 kg of ^{76}Ge, 1e-3 cts/(keV· kg· yr))
- median sensitivity after 2 yr of data taking:

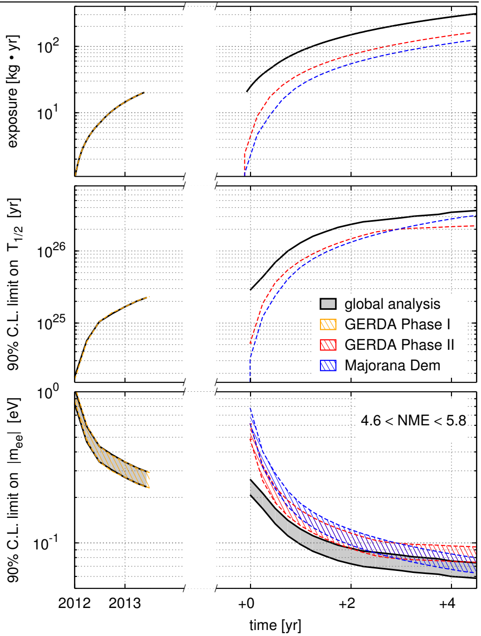
$$T^{0\nu}_{1/2} \gtrsim 10^{26}\,\text{yr}$$
$$|m_{ee}| \lesssim 100\,\text{meV}$$



sensitivity projection for GERDA + Majorana

- profile likelihood analysis
- MC-realizations of the data sets
- limit extraction performed for each realization
- global analyisi of:
  - GERDA Phase I
  - GERDA Phase II: (37 kg of ^{76}Ge, 1e-3 cts/(keV· kg· yr))
  - Majorana demonstrator (30 kg of ^{76}Ge, 8e-4 cts/(keV· kg· yr))
- median sensitivity after 4 yr of data taking:

$$T^{0\nu}_{1/2} \gtrsim 3 - 4 \cdot 10^{26}\ \mathrm{yr}$$
$$|m_{ee}| \lesssim 60 - 80\ \mathrm{meV}$$



Conclusions

GERDA Phase I (21.6 kg·yr of exposure):

- background order of magnitude lower than previous Ge experiments:

  $\sim$0.01 cts/(keV· kg· yr) at $Q_{\beta\beta}$ (after PSD)

- blind analysis —> no positive $0\nu\beta\beta$ signal:

  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA only)

- Long standing claim excluded at 99% C.L. (model-independent result)
- NEW: most accurate measurement of $T^{2\nu}_{1/2}$
- NEW: stongest limits on $T^{0\nu\chi}_{1/2}$ and $T^{2\nu}_{1/2}$ decay to excited states

GERDA Phase II:

- commissioning ongoing
- quasi background-free experiment
- start exploration of $T^{0\nu}_{1/2} > 10^{26}$ yr in a $\sim$2 yr of data taking

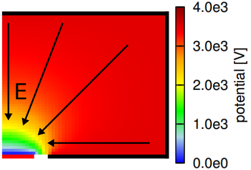
Collaboration

backup slides

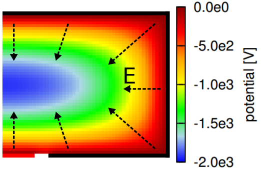
Electric field and charge collection

Contributions to the electric field (E):

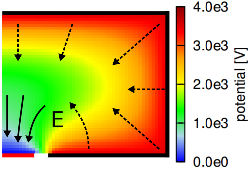
1) electrodes potentials:
$\phi_{p+} = 0\,\text{V}$, $\phi_{n+} = 4\,\text{kV}$



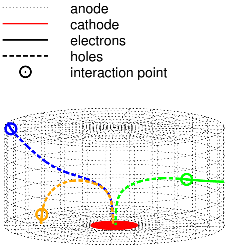
2) impurity concentration:
negative charges for depleted p-type Ge



Total field (1+2):
holes are pushed to the detector central slice (2) and then collected to the p+ electrode (1)



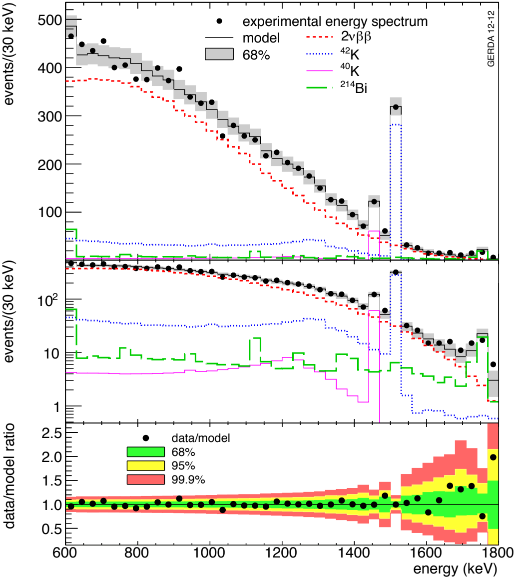
Interplay between (1) and (2) results in the **funnel effect**:



final part of hole trajectories independent of interaction positions

[JINST 6 (2011) P03005]

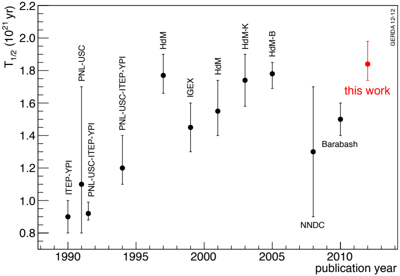
Background model – $2\nu\beta\beta$ half-life



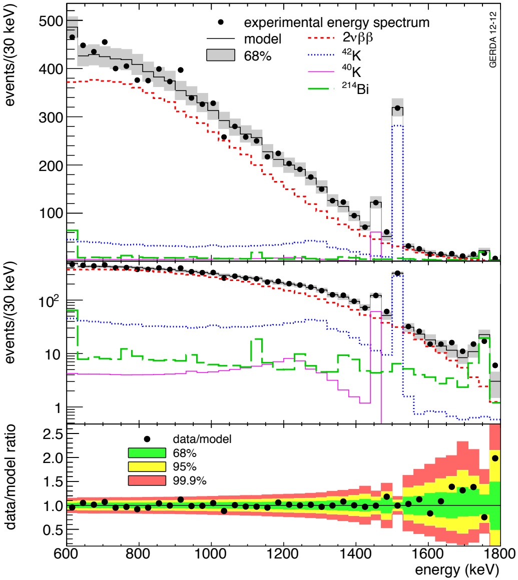
- Binned maximum likelihood (5 kg·yr)
- Nuisance parameters:
  - Active detector masses (6+1)
  - Ge-76 fractions (6)
  - Background contributions (3x6)
- $T_{1/2}^{2\nu}$ common to all detectors
- After marginalizing:

$$T_{1/2}^{2\nu} = (1.84^{+0.09}_{-0.08}\,_{\text{fit}}\ ^{+0.11}_{-0.06}\,_{\text{syst}}) \cdot 10^{21}$$

[J.Phys.G 40 (2013) 035110]



Background model – $2\nu\beta\beta$ half-life



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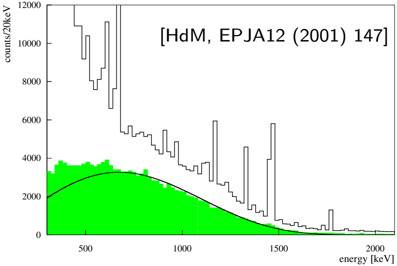
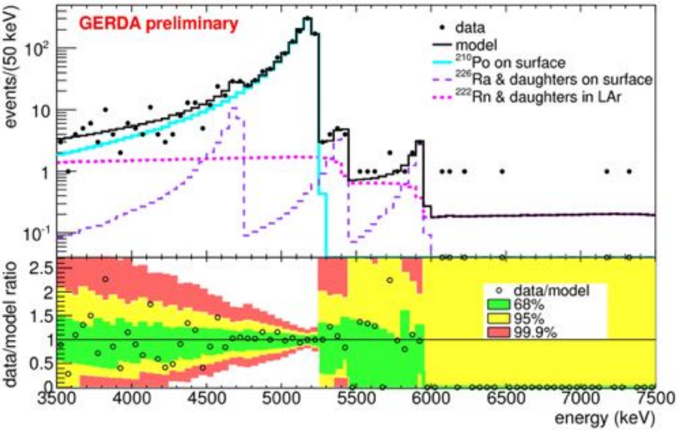
[J.Phys.G 40 (2013) 035110]



Background model – α-emitting isotopes



Colored probability intervals: [R. Aggarwal and A. Caldwell, Eur. Phys. J. Plus 127 24 (2012)]

- fit window 3500-7500 keV
- p-value of the fit: 0.7
- 80 bins of width 50 keV:

  79% in the green band

  98% in the yellow band

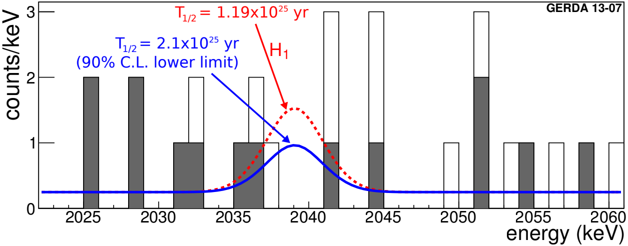
Comparison with Phys.Lett. B586 198 (2004)

Hypothesis test: H_0 (bkg only) vs H_1 ($T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr + bkg)

In $Q_{\beta\beta} \pm 2\sigma_E$ (after PSD):

- expected 2.0±0.3 bkg cts
- expected 5.9±1.4 signal cts (assuming H1)
- observed 3 cts

[PRL 111, 122503 (2013)]



GERDA only:

- Frequentist p-value ($N_{0\nu\beta\beta} = 0 | H_1$) = 0.01
- Bayes factor $P(H_1)/P(H_0)$=$2.4 \cdot 10^{-2}$

GERDA + IGEX + HdM:

- Bayes factor $P(H_1)/P(H_0)$=$2 \cdot 10^{-4}$

Long standing claim strongly disfavoured!

$T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2006) 1547 is not considered because of inconsistencies (i.e. missing efficiency factors, problem in the conversion from counts to $T^{0\nu}_{1/2}$) pointed out in Ann. Phys. 525 (2013) 269.