First GERDA results on the neutrinoless double beta decay search of ^{76}Ge

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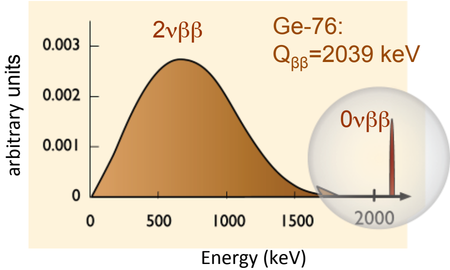
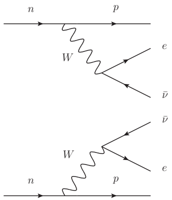
PASCOS 2013 - 25 Nov 2013 - Taipei, Taiwan

Neutrinoless double beta decay ($0\nu\beta\beta$)

- $2\nu\beta\beta$ possible in isotopes where $\beta-$decay is energetically forbidden.
  - Continuous spectrum ending at Q-value.
  - $T^{2\nu}_{1/2} \sim 10^{19-21}$ yr.
  - For ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr (GERDA)
- $0\nu\beta\beta$ prohibited by the S. M.
  - Lepton number violation.
  - Physics beyond the standard model.
  - Shed light on neutrino mass (and possibly hierarchy).

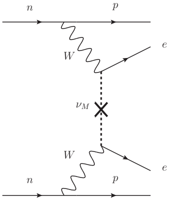


$2\nu\beta\beta$



$\Delta L = 0 \Rightarrow$ Predicted by the S.M.

$0\nu\beta\beta$



$\Delta L = 2 \Rightarrow$ Prohibited by the S.M.
Light Majorana neutrino exchange

Neutrinoless double beta decay ($0\nu\beta\beta$)

- Expected decay rate:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

with:

$G^{0\nu}$: Phase space integral

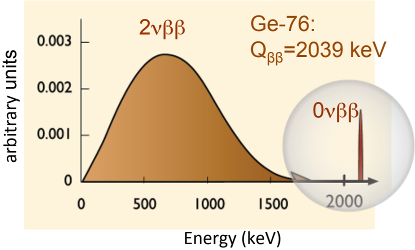
$\left|M^{0\nu}\right|^2$: Nuclear matrix element

- Effective Majorana mass:

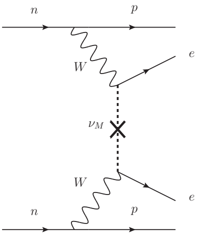
$$\langle m_{\beta\beta}\rangle \equiv \left|\sum_i U_{ei}^2 m_i\right| = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$$

- Signature: Monoenergetic peak at

$$Q_{\beta\beta} = m(A,Z) - m(A,Z+2)$$



$0\nu\beta\beta$



$\Delta L = 2 \Rightarrow$ Prohibited by the S.M.
Light Majorana neutrino exchange

Experimental requirements for $0\nu\beta\beta$

Sensitivity: $T^{0\nu}_{1/2} \propto \epsilon \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$

ϵ	detection efficiency	$\geq 85\%$
ε	enrichment fraction	high natural or enrivhment
M	active target mass	
T	measuring time	
B	background index $\left(\frac{cts}{keV \cdot kg \cdot yr}\right)$	veto, select radio pure materials,...
ΔE	Energy resolution	use high resolution spectroscopy

GERDA technique: Low background High-Purity Germanium Detectors

Advantages:

- Well established enrichment technique ($\varepsilon|_{^{76}Ge} = 86\%$)
- Very good resolution (FWHM $\Delta E \approx 0.1\% - 0.2\%$)
- Very good detection efficiency (source = detector $\Rightarrow \epsilon \approx 0.92$)

Disadvantages:

- Low $Q_{\beta\beta}$ value
  - Background from ^{208}Tl and ^{214}Bi
- Need enrichment from 7% to 86% (expensive)

State of the art in $0\nu\beta\beta$

Ge-76:

- IGEX collaboration

  [Phys.Rev. D65, 092007 (2002)]:

  $$T^{0\nu}_{1/2}(^{76}\text{Ge}) \geq 1.6{\cdot}10^{25}\ \text{yr}\ (90\%\ \text{C.L.})$$

- HdM collaboration

  [Eur. Phys. J. A 12, 147 (2001)]:

  $$T^{0\nu}_{1/2}(^{76}\text{Ge}) \geq 1.9{\cdot}10^{25}\ \text{yr}\ (90\%\ \text{C.L.})$$

- Klapdor-Kleingrothaus et al.

  [Phys.Lett. B586, 198 (2004)]:

  $$T^{0\nu}_{1/2}(^{76}\text{Ge}) = 1.19^{+0.37}_{-0.23} \cdot 10^{25}\ \text{yr}$$

Xe-136:

- EXO collaboration

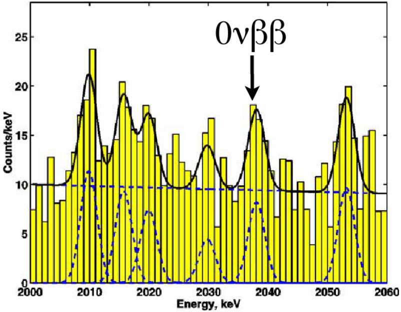
  [Phys. Rev. Lett. 109 (2012)]:

  $$T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.6{\cdot}10^{25}\ \text{yr}\ (90\%\ \text{C.L.})$$

- KamLAND-Zen collaboration

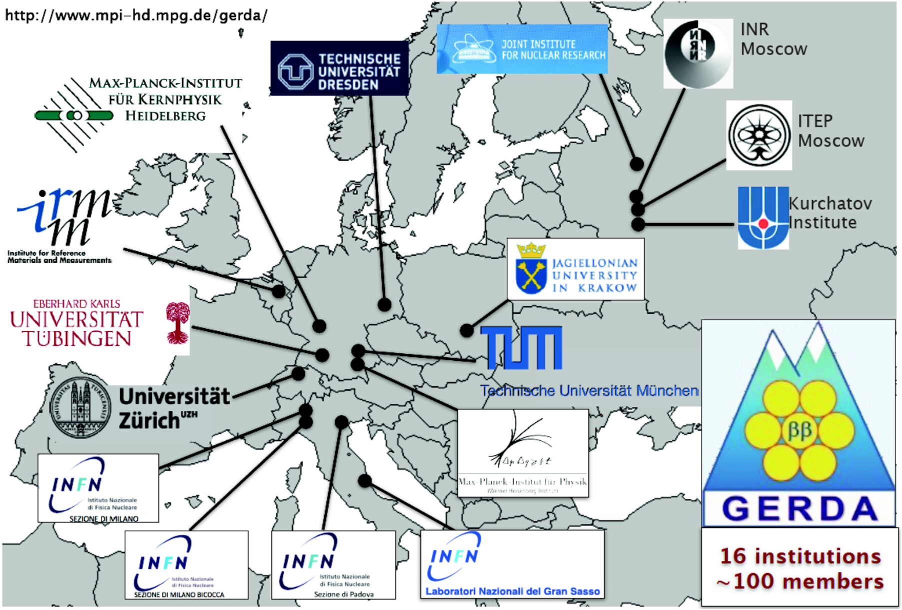
  [Phys.Rev.Lett. 110, 062502 (2013)]:

  $$T^{0\nu}_{1/2}(^{136}\text{Xe}) > 1.9{\cdot}10^{25}\ \text{yr}\ (90\%\ \text{C.L.})$$



The GERDA collaboration

http://www.mpi-hd.mpg.de/gerda/



The GERDA experiment

Located at Hall A of LNGS.

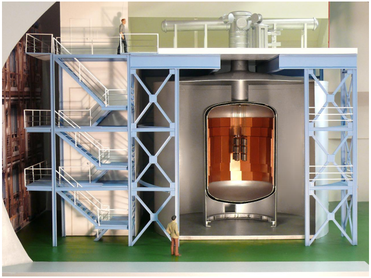
- 3800 m.w.e.

Phase I (Nov 2011 - May 2013):

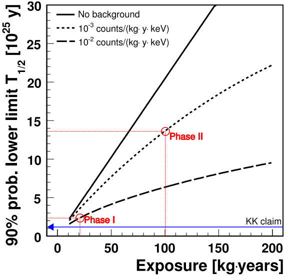
- $15-20\,$kg of target mass (87% ^{76}Ge)
- bkg $\sim 10^{-2}$ cts/(keV$\cdot$ kg$\cdot$ yr) at $Q_{\beta\beta}$
- exposure 21.6 kg$\cdot$yr
- sensitivity to scrutinize KK claim

Phase II (migration ongoing):

- new custom-produced BEGe detectors (additional 20 kg, 87% ^{76}Ge)
- bkg $\lesssim 10^{-3}$ cts/(keV$\cdot$ kg$\cdot$ yr) at $Q_{\beta\beta}$ (active techniques for bkg suppression)
- exposure $\gtrsim 100$ kg$\cdot$yr
- start exploring $T^{0\nu}_{1/2}$ in the 10^{26} yr range



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



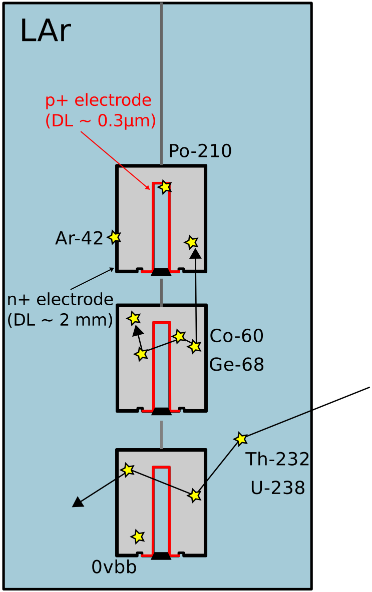
Backgrounds and mitigation techniques

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
- cosmogenic isotopes in Ge decaying inside the detectors (^{68}Ge, ^{60}Co)
- long-lived cosmogenic Ar isotopes (^{39}Ar,^{42}Ar)

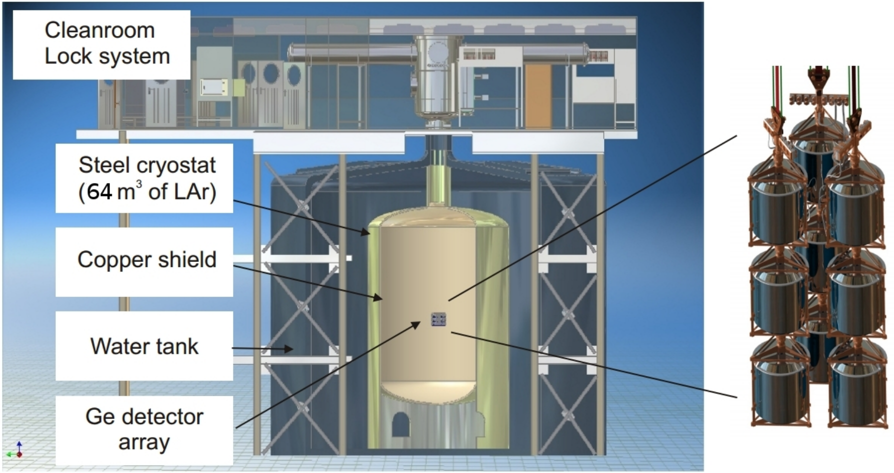
Mitigation strategy:

- Gran Sasso suppression μ flux (10^6)
- Muon veto
- detector anti-coincidence
- time-coincidence (Bi-Po or ^{68}Ge)
- pulse shape analysis (bulk localized energy deposition)
- LAr-scintillation (in Phase II)



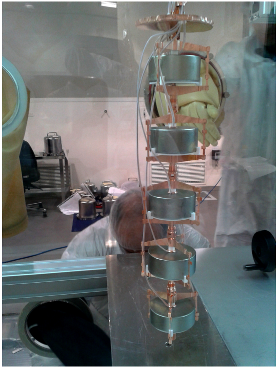
GERDA: detector apparatus

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



GERDA collaboration, EPJ C 73 2330 (2013), arXiV: 1212.3210

Detector array assembly



- 3 + 1 strings
- 8 ^{enr}Ge coaxial detectors : 14.6 kg working mass
  (2 not considered in the analysis due to high leakage current)
- 3 ^{nat}Ge coaxial detectors : 3.0 kg
- 5 ^{enr}Ge BEGe detectors : 3.0 kg working mass
  (testing Phase II concept in the real environment)

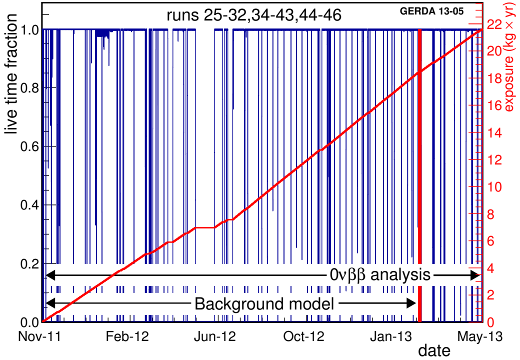
^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) + 3.0 kg (BEGe)

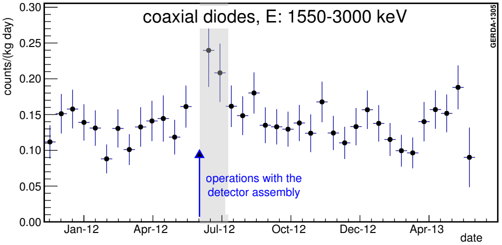
Overview of the data taking

- data taking Nov11 - May13 (492 d)
- total exposure 21.6 kg·yr
- (bi)weekly calibration with Th-228
- BEGe detectors from June 2012

Blinding

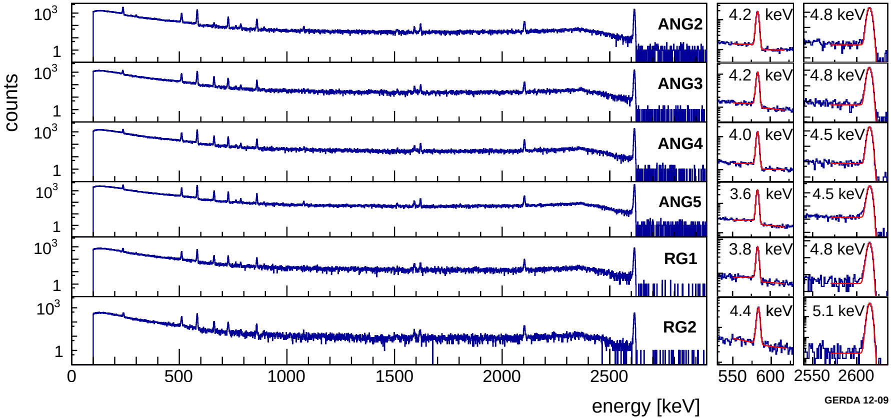
- All events within $Q_{\beta\beta} \pm 20 keV$ are not reconstructed.
- Dataset unblinded only after freezing analysis procedure and background model.





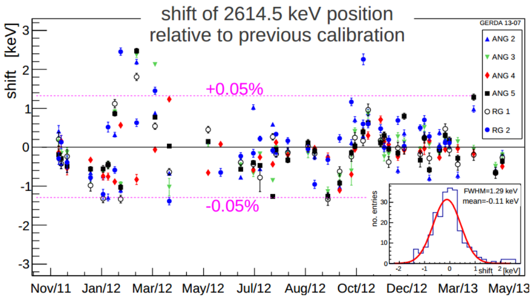
Calibration of the GERDA data

- Spectra calibrated weekly with ^{228}Th sources and pulser with 0.05 Hz
- Calibration data also useful for monitor energy resolution and gain stability over time
- FWHM at $Q_{\beta\beta}$: 4.8 keV for coaxial detectors, 3.2 keV for BEGe's



Time stability

detector	FWHM [keV]
Coaxial	
ANG2	5.8 (3)
ANG3	4.5 (1)
ANG4	4.9 (3)
ANG5	4.2 (1)
RG1	4.5 (3)
RG2	4.9 (3)
mean coax	**4.8 (2)**
BEGe	
GD32B	2.6 (1)
GD32C	2.6 (1)
GD32D	3.7 (5)
GD35B	4.0 (1)
mean BEGe	**3.2 (2)**

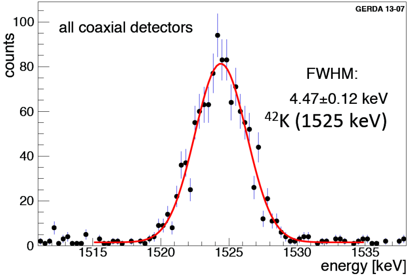


$0\nu\beta\beta$ data set:

- peak position within 0.3 keV at correct position
- resolution 4% larger than in calibration runs
- mean FWHM at $Q_{\beta\beta}$ (mass/exposure weighted):

  coax —> 4.8 ± 0.2 keV

  BEGe —> 3.2 ± 0.2 keV

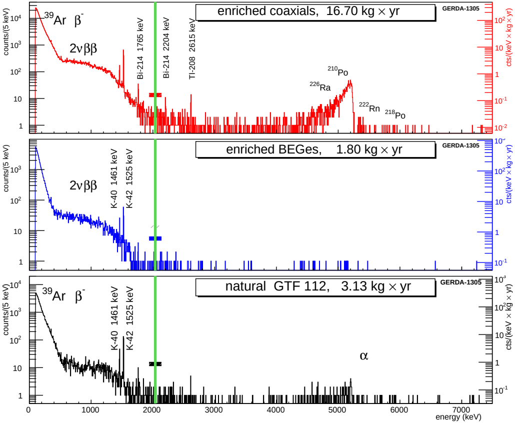


Energy spectra

Golden coax: Data from coaxial detectors

Silver coax: Data from coaxial detectors during BEGe deployment (higher BI)

BEGe: Data from BEGe detectors



- Data split in 3 data sets:

dataset	exposure
coaxial (golden)	17.9 kg·yr
coaxial (silver)	1.3 kg·yr
BEGe	2.4 kg·yr

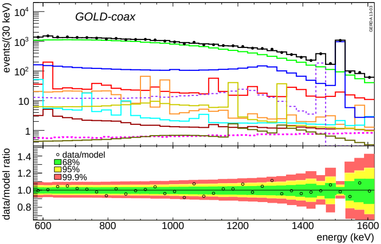
- Background level:

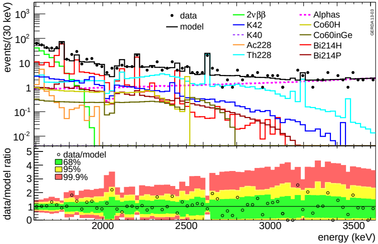
energy [keV]	BI [cts/(keV kg yr)]
2614	1.1 ± 0.3
1764	3.3 ± 0.5
2039 ($Q_{\beta\beta}$)	0.018 ± 0.002

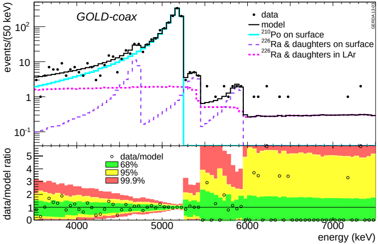
- **Events in $Q_{\beta\beta} \pm 20$ keV blinded**

The background model of GERDA Phase I

The GERDA collaboration, submitted to Eur. Phys. Journ. C (arXiV:1306.5084)







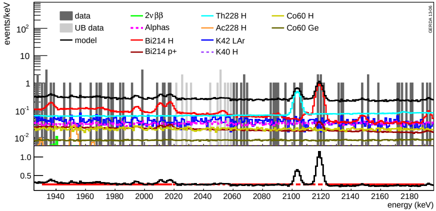
- Simulation of known and observed backgrounds
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested

Main contributions from sources close by: ^{228}Th and ^{226}Ra in holders, ^{42}Ar, α on detector surface

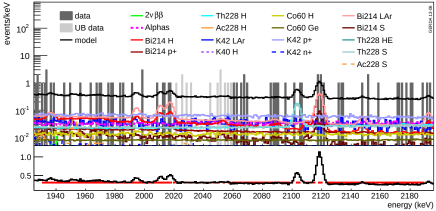
The background model @ $Q_{\beta\beta}$

The GERDA collaboration, submitted to Eur. Phys. Journ. C (arXiV:1306.5084)

Minimum model (all known contributions)



Maximum model (many possible contributions added)



- No line expected in the blinded window
- Background flat between 1930 and 2190 keV
- 2140 ± 5 keV and 2119 ± 5 keV excluded

Interpolated BI in ROI:

Golden coax: $\mathrm{BI} = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)

BEGe's: $\mathrm{BI} = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)

Pulse shape discrimination

GERDA collaboration, Eur.Phys.J C73 2583 (2013), arXiv:1307.2610

Motivation:

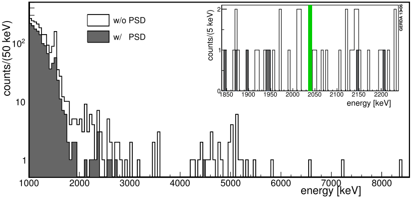
- $0\nu\beta\beta$ signals are contained in small region $\rightarrow$ Single site event (SSE)
  - 1 MeV electron drifts $\approx$ 1 mm in Ge
- γ events generate multiple energy depositions$\rightarrow$ Multi site event (MSE)

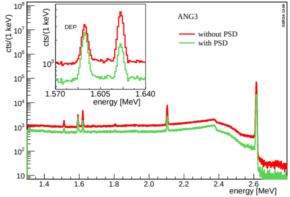
PSD for BEGe's: A/E parameter

- A = Pulse amplitude ; E = Energy
- A/E range defined from ^{208}Tl ($E_\gamma = 2614$ keV) DEP ($E_{DEP} = 1592$ keV) from ^{228}Th calibrations
- Rejects 80% of background-like events
- $92 \pm 2\%$ efficiency for $0\nu\beta\beta$

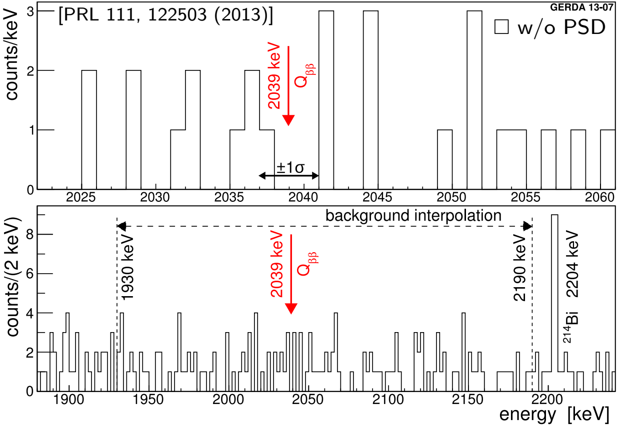
PSD for Coaxial: Artificial Neural Network (ANN)

- Trained on signal SSE: ^{208}Tl DEP ($E_{DEP} = 1592$ keV)
- Rejects 45% of background like events
- $90^{+5}_{-9}\%$ efficiency for $0\nu\beta\beta$





Energy spectra 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 around $Q_{\beta\beta}$:

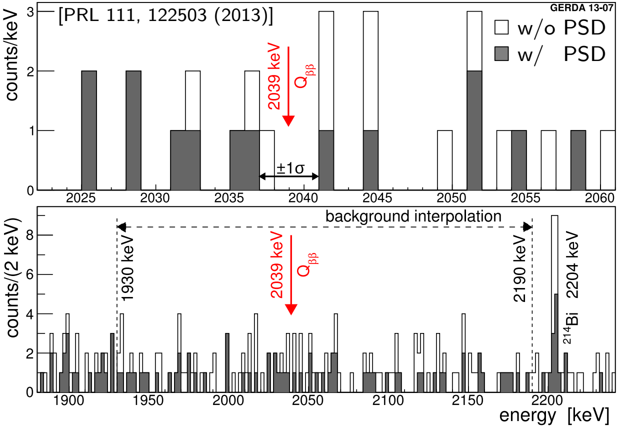
1	~99%
2+3	~60%
4	~100%
5	~50%

w/o PSD

w/ PSD

data set	exposure [kg· 10yr]	background 10^{-2} cts/(keV· kg· yr)	expected cts ($Q_{\beta\beta}\pm5$ keV)	observed cts ($Q_{\beta\beta}\pm5$ keV)
golden	17.3	1.8	3.3	5
silver	1.3	6.3	0.8	1
BEGe	2.4	3.6	1.0	1

Energy spectra around $Q_{\beta\beta}$



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1	∼99%
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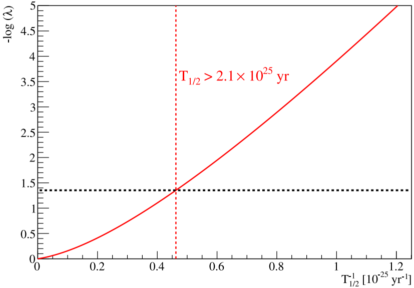
w/o PSD

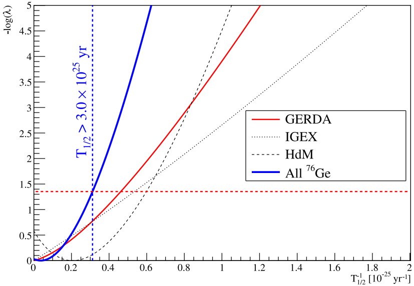
w/ PSD

data set	exposure [kg· 10yr]	background 10^{-2} cts/(keV· kg· yr)		expected cts ($Q_{\beta\beta}$±5 keV)		observed cts ($Q_{\beta\beta}$±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
silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	3.6	0.5	1.0	0.1	1	0

Statistical analysis

GERDA collaboration, PRL 111, 122503 (2013), arXiv:1307.4720





Baseline analysis (profile likelihood):

- maximum likelihood spectral fit (constant+Gauss in 1930-2190 keV range)
- multiple data sets (common $\left[T^{0\nu}_{1/2}\right]^{-1}$)
- $\left(T^{0\nu}_{1/2}\right)^{-1} \geq 0$ (coverage tested)

Results (GERDA only):

- best fit for $N_{0\nu\beta\beta} = 0$ signal cts
- $N_{0\nu\beta\beta} < 3.5$ cts at 90% C.L.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- MC Median sensitivity (for no signal): $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

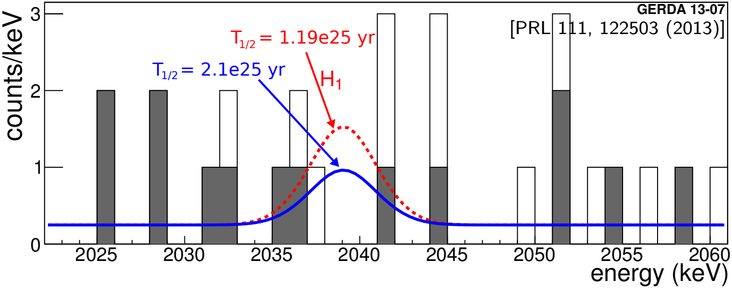
Results (GERDA + IGEX [1] + HdM [2]):

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

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

Comparison with Phys.Lett. B586 198 (2004)

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



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

expected 5.9±1.4 signal cts

expected 2.0±0.3 bkg cts

observed 3 cts

GERDA only:

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

GERDA+IGEX+HdM:

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

⇒ claim strongly disfavoured

$T_{1/2}^{0\nu}$ 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 $T_{1/2}^{0\nu}$) pointed out in Ann. Phys. 525 (2013) 269.

Conclusions

- GERDA collected 21.6 kg·yr of exposure between 11.2011 and 05.2013
- Background an order of magnitude lower than previous Ge experiments:
  - ~0.01 cts/(keV· kg· yr) at $Q_{\beta\beta}$ (after PSD)
- 3 events observed while 2.5 ± 0.3 expected in $Q_{\beta\beta} \pm 2\sigma$
  - No events in $Q_{\beta\beta} \pm \sigma$
- GERDA limit:
  - $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L. (GERDA only)
  - $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr at 90% C.L. (GERDA+IGEX+HdM)
- Previous claim refuted by GERDA at 99% C.L.

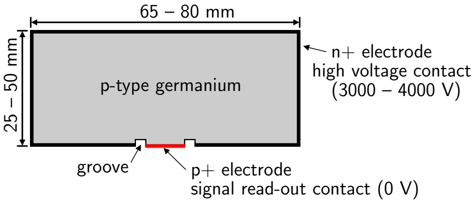
The GERDA Collaboration

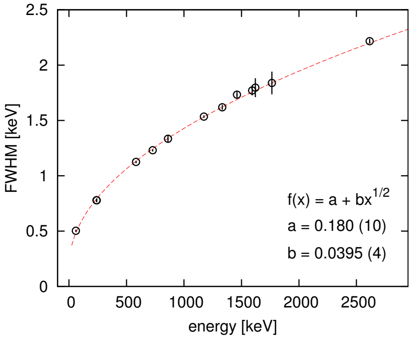
GERDA Collaboration Meeting in Dubna, Russia
June 2013

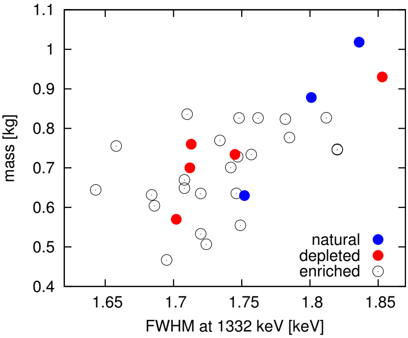
backup slides

Phase II detector design and performance

- Broad Energy Ge (BEGe) detectors:
  - ▷ commercial product (Canberra)
  - ▷ excellent spectroscopic performance (resolution, low threshold, low noise)
  - ▷ pulse shape discrimination (PSD)
- >30 BEGe detectors produced and tested



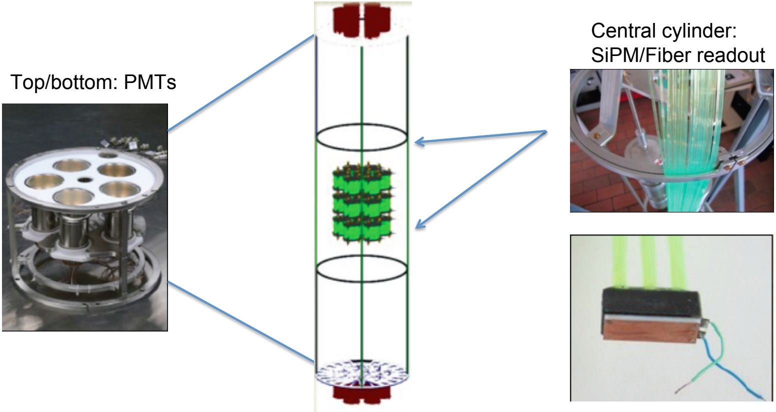




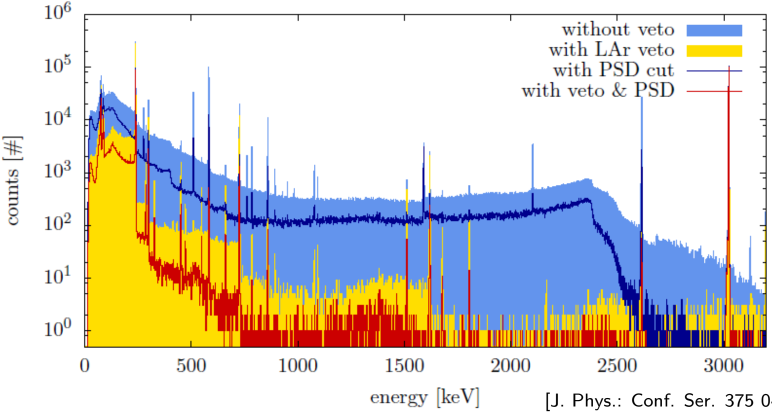
Detection of LAr scintillation

LAr-scintillation (combined design):

- low-background photo-multipliers
- WLS fibers read-out with Si photo-multipliers



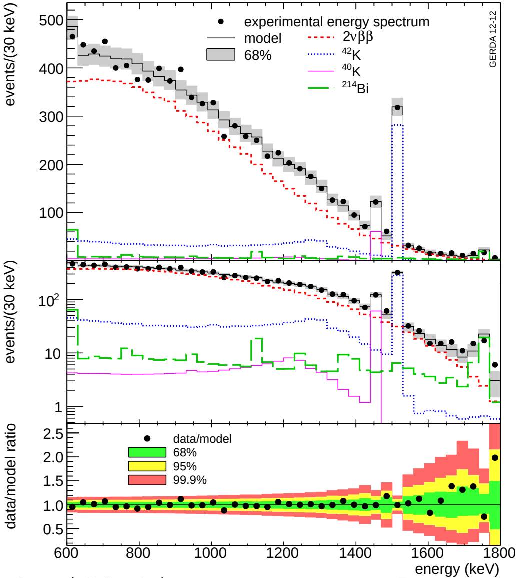
Use of PSD and LAr scintillation signal



[J. Phys.: Conf. Ser. 375 042009]

Pulse shape analysis combined with LAr-scintillation (in LArGe setup): measured suppression factor of $(5.2 \pm 1.3) \cdot 10^3$ at $Q_{\beta\beta}$ for close Th-228

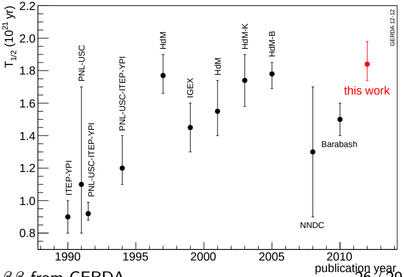
Background model – $2\nu\beta\beta$ half-life



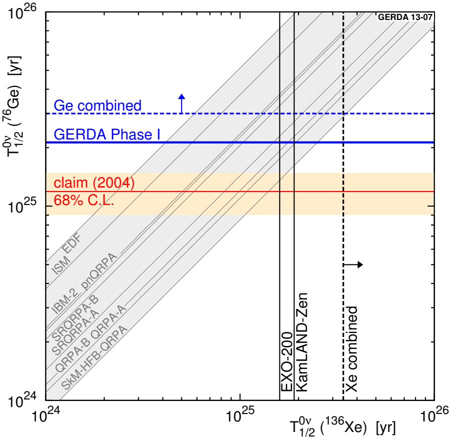
- Binned maximum likelihood (5 kg·yr)
- Nuisance parameters:
  - Active detector masses (6+1)
  - Ge-76 fractions (6)
  - Background contributions (3x6)
- $T_{1/2}^{2\nu}$ common to all detectors
- After marginalizing:

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

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



Comparison with ^{136}Xe experiments



- GERDA provides a model-independent test of the signal claim
- comparison with ^{136}Xe experiments possible only through:
  - assumptions on the leading channel (e.g. exchange of light Majorana neutrinos)
  - matrix element computations (selection used in the plot is taken from arXiv:1305.0056)

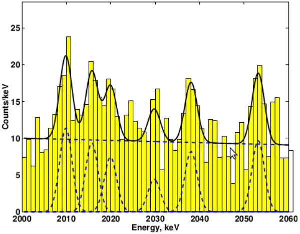
GERDA+EXO+KamLAND-Zen:

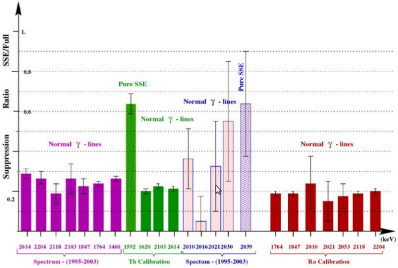
Bayes factor $P(H_1)/P(H_0) = 2.2 \cdot 10^{-3}$

(computed for the smallest NME ratio Xe/Ge)

Why GERDA does not use KK 2006 result?

b) 2004 publications: [1] NIM A522 371 & [2] Phys Lett B586 198





Entire data set: 71.7 kg· yr (active mass)

- 28.75 ± 6.86 signal events
- $T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr

Data for PSD analysis: 51.4 kg· yr

- 19.58 ± 5.41 signal events
- $T^{0\nu}_{1/2} = \left(1.25^{+0.49}_{-0.27}\right) \cdot 10^{25}$ yr

With PSD applied

- 12.36 ± 3.72 events
- DEP survival fraction $\sim 62\%$
- $T^{0\nu}_{1/2} = 1.23 \cdot 10^{25}$ yr

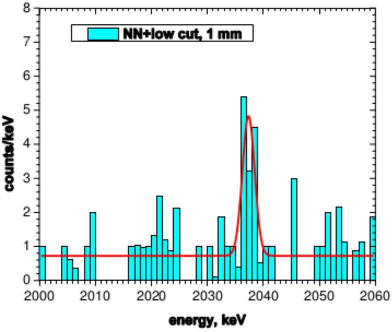
Without efficiency correction:

- $T^{0\nu}_{1/2} = 1.98 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!

Why GERDA does not use KK 2006 result?

b) 2006 publication : Mod Phys Lett A21 p. 1547-1566



- Fit to the data yields 11.32 ± 1.75 signal events
  $\Rightarrow T^{0nu}_{1/2} = \left(2.23^{0.44}_{-0.31}\right) \cdot 10^{25}$ yr
- error on signal count not correct
  - smaller than Poisson error

PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses: Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks. **NO event overlap between the 2 sets!?**

Statement from publication:

- "multi site events are suppressed by 100%"
- $0\nu\beta\beta$ efficiency = 1 used for $T^{0\nu}_{1/2}$

Efficiency factor not considered:

- Calculation of $T^{0\nu}_{1/2}$ not correct
- GERDA does not use this result