Search of Neutrinoless Double Beta Decay with the GERDA Experiment

From Majorana to LHC:
Workshop on the Origin of Neutrino Mass

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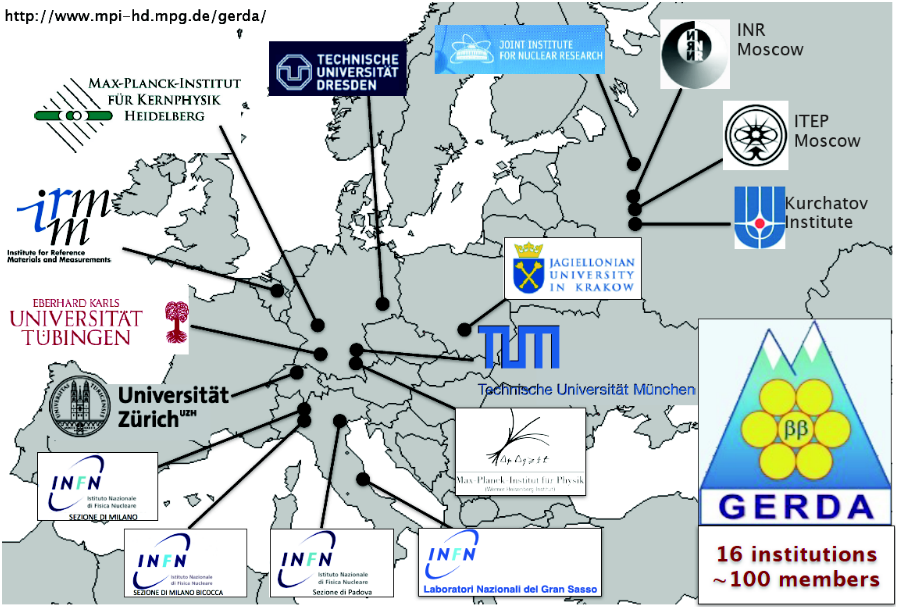
University of Zurich

ICTP, Trieste, 3 October 2013

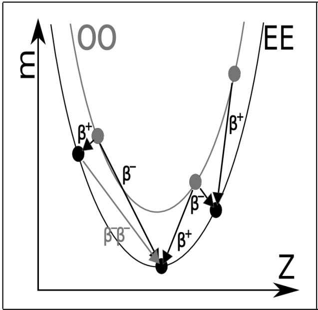
The GERDA Collaboration

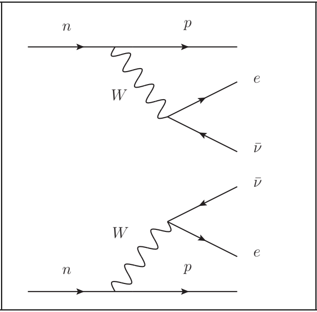
http://www.mpi-hd.mpg.de/gerda/

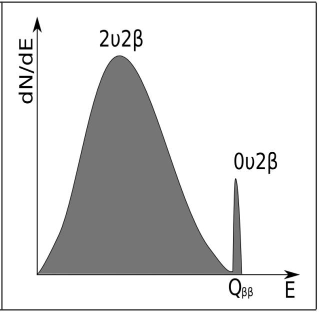


16 institutions
~100 members

The Double Beta Decay

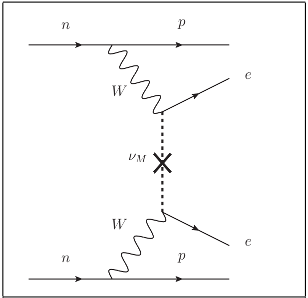


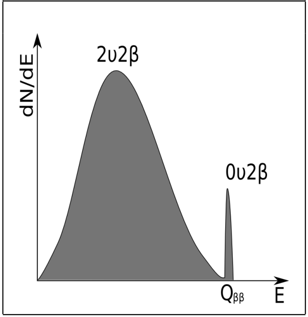




- If β-decay energetically forbidden $\rightarrow 2\nu2\beta$ decay might be possible.
- $2\nu2\beta$ decay introduced by Maria Goeppert-Mayer in 1935.
- The experimental spectrum is a continuum ending at the Q-value.
- $T^{2\nu}_{1/2}$ usually of order of 10^{19-21} years.
- For ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr*

*J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110





If $0\nu2\beta$ decay is discovered:

- Lepton number is violated ($\Delta L = 2$)
- Neutrinos are Majorana particles
- Physics beyond the Standard Model

Theoretical aspects of $0\nu2\beta$ decay

- Expected decay rate:
  $$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$
  $G^{0\nu}(Q,Z)$ = Phase Space integral
  $\left|M^{0\nu}\right|^2$ = nuclear matrix element
  $\langle m_{ee}\rangle^2 = \sum_i U_{ei}^2 m_i$ = effective ν mass
  U_{ei} = elements of the PMNS mixing matrix
- Experimental signature: peak at
  $Q_{\beta\beta} = m(A,Z) - m(A,Z-2) - 2m_e$
  (2039 keV for ^{76}Ge)

Experimental Requirements for $0\nu2\beta$ Decay Search

Number of signal events:

$$N_{sig}^{0\nu} = \frac{f_{76} \cdot N_A}{m_A} \frac{\ln 2}{T_{1/2}^{0\nu}} \varepsilon \cdot M \cdot t$$

Number of background events:

$$N_{bkg} = M \cdot t \cdot BI \cdot \Delta E$$

Experimental sensitivity:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2 \cdot N_A}{n_\sigma \sqrt{2}} \frac{f_{76} \cdot \varepsilon}{A} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

f_{76} = enrichment fraction
N_A = Avogadro number
m_A = atomic mass
ε = efficiency
M = detector mass
t = livetime
$M \cdot t$ = exposure
BI = Background Index
ΔE = energy resolution
n_σ = Confidence Level

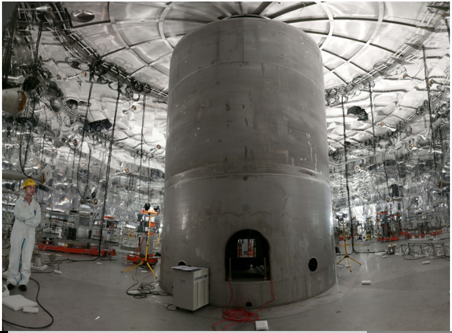
Advantages of Ge
Disadvantages of Ge

The GERDA Experiment

Experiment structure

- 590 m^3 Water Tank to absorb neutrons and veto cosmic muons
- 64 m^3 Liquid Argon (LAr) for cooling and shielding (and vetoing)
- Plastic scintillators above the cryostat to further veto cosmic

- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare enriched Ge detectors in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes



The two phases of GERDA (from the Proposal to LNGS):

	Mass [kg]	BI [counts/(keV·kg·yr)]	Livetime [yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
Phase I	15	10^{-2}	1	$2.2 \cdot 10^{25}$
Phase II	35	10^{-3}	3	$2 \cdot 10^{26}$

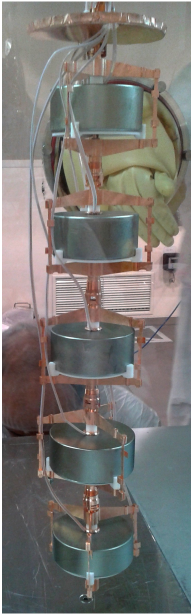
The time-line of GERDA:

- Mar. 2008: cryostat installation
- May 2008: water tank construction
- Feb. 2009: clean room installation
- May 2010: start of commissioning
- 10 Nov. 2010: inauguration
- Nov. 2011 - May 2013: Phase I data taking
- Summer/autumn 2013: preparing Phase II...

The GERDA Detectors

Coaxial detectors

- ~ 86% isotopically enriched in ^{76}Ge
- 5 enr-Ge ("ANG") detectors from Heidelberg-Moscow (HdM), 3 enr-Ge ("RG") from IGEX, 3 nat-Ge from Genius Test Facility (GTF)
- detectors reprocessed at Canberra before being used
- ~ 2‰ FWHM at 2.6 MeV
- Total enriched mass: 17.7 kg
- Two detectors turned off because of high leakage current → total enriched mass 14.6 kg

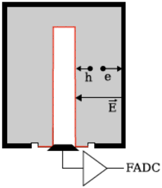


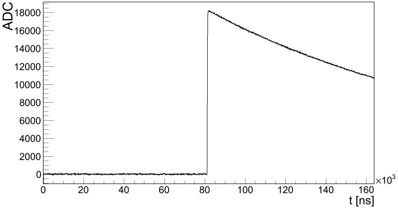
BEGe detectors (design for Phase II)

- BEGe = Broad Energy Germanium
- ~ 1‰ FWHM at 2.6 MeV
- Enhanced Pulse Shape Discrimination (PSD)
- ~ 20 kg of BEGe's successfully produced and tested in 2012
- 5 BEGe's inserted in GERDA in July 2012

Data processing framework: GELATIO

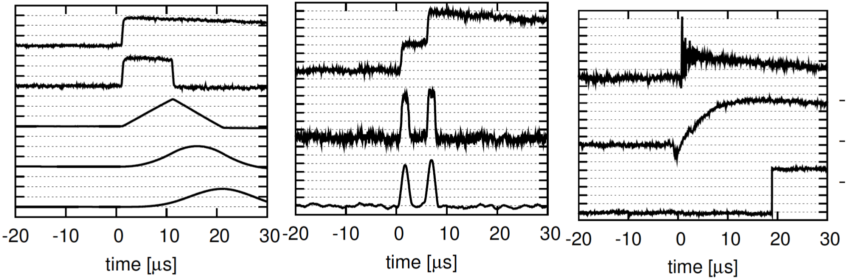
- Read-out and signal structure:





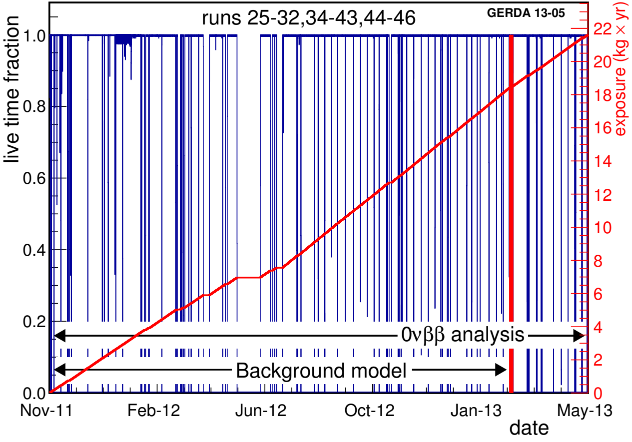
- Eur. Phys. J. C (2013) 73:2330
- JINST 6 (2011) P08013
- J. Phys., Conf. Ser. 368 (2012) 012047

- Digital signal processing to extract energy, rise time, ...



GERDA Phase I Data Taking

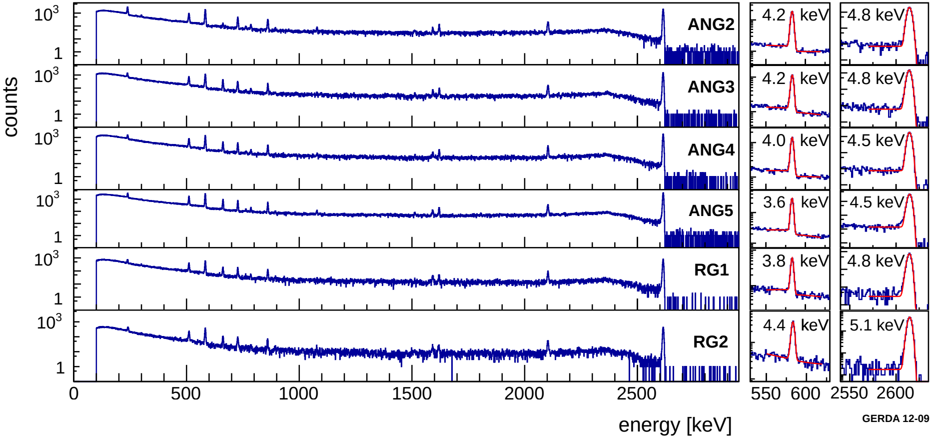
- Total Phase I exposure: 21.6 kg·yr between 9th Nov 2011 and 21st May 2013
- Total livetime of 492.3 days with 88% duty factor
- 5% of data not used due to temperature-related instability of the electronics
- Used for analysis: 6 enr-Ge coaxial detectors (14.6 kg) and 4 BEGe (3.0 kg)



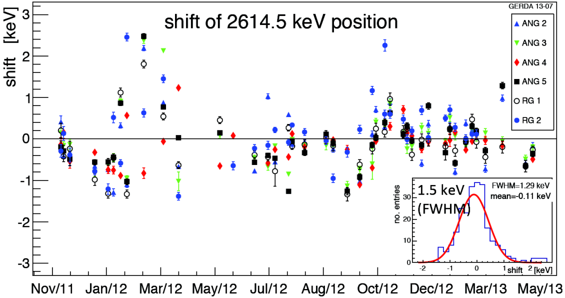
- Spikes: (Bi)-weekly calibration runs
- Flat parts: BEGe's insertion (June 2012), maintenance operations
- Dataset for background model: Nov 2011 - March 2013
- Dataset for $0\nu2\beta$ analysis: Nov 2011 - May 2013

Calibration of the GERDA Data

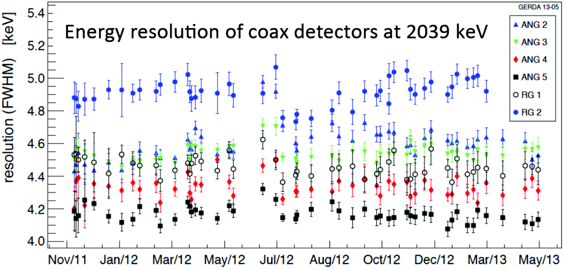
- Spectra calibrated (bi)-weekly with ^{228}Th sources
- Data useful also for monitoring the resolution and gain stability over time
- FWHM at $Q_{\beta\beta}$: 4.8 keV for the coaxial detectors, 3.2 keV for the BEGe's (space for $\sim$ 10% improvement with better filtering).



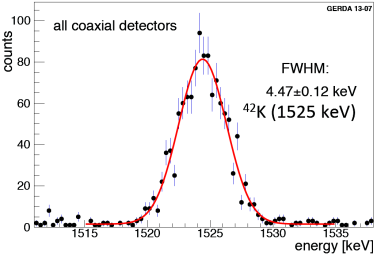
Time Stability and Energy Resolution



detector	FWHM [keV]
SUM-coax	
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)
SUM-BEGe	
GD32B	2.6 (1)
GD32C	2.6 (1)
GD32D	3.7 (5)
GD35B	4.0 (1)
mean BEGe	3.2(2)



- If needed, correction term applied to FWHM to account for instabilities



Blinding of the Region of Interest

Energy & pulse of events $\in$ [2019-2059] keV automatically removed from data flow

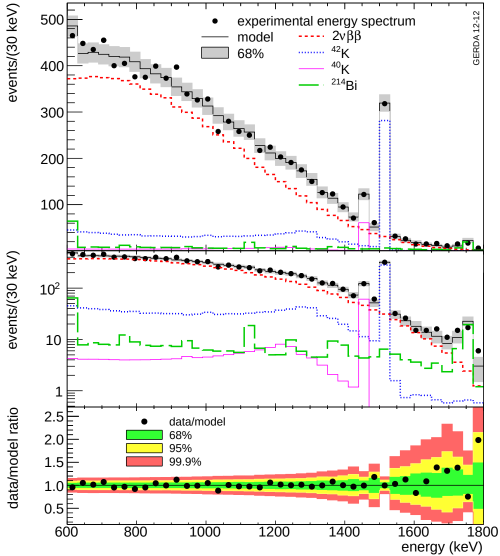
Tasks to be fulfilled before the unblinding

- Reach 20 kg·yr of exposure
- Reach sensitivity of $2 \cdot 10^{25}$ yr on $T_{1/2}^{0\nu}$
- Have (and publish: arXiv:1306.5084) a good enough background model
- Be able to predict a reliable BI at $Q_{\beta\beta}$ (intensity and shape)
- Fix the data selection and the partition
- Fix the data processing procedure (quality cuts, calibration, ...)
- Fix (and publish: arXiv:1307.2610) the PSD methods and cuts
- Fix the statistical analysis

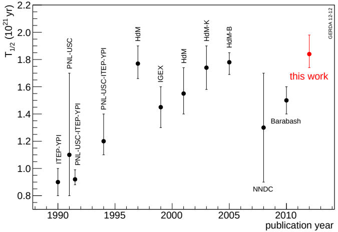
Unblinding procedure

- Once the background model is fixed, open 15keV side-bands
- If no surprise is found, proceed as stated above. And good luck!

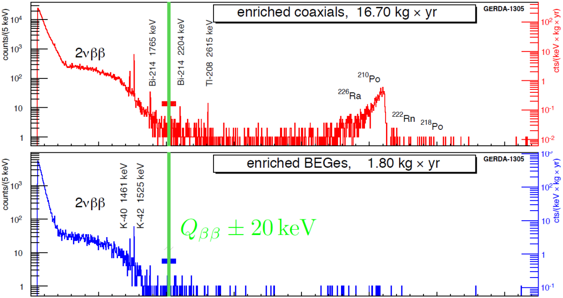
$2\nu2\beta$ Measurement

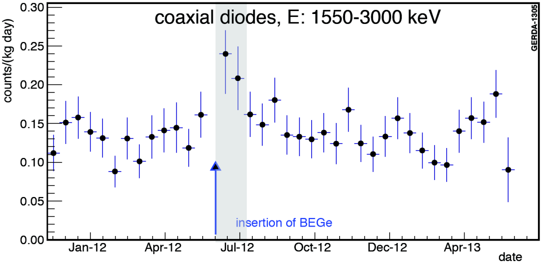


- Measured by GERDA with 5.04 kg·yr exposure
- Very simple background model due to high signal-to-background ratio
- $T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr
- J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110



The Background of GERDA Phase I

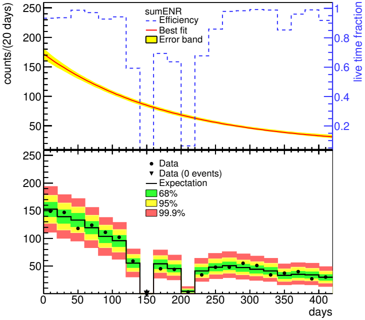


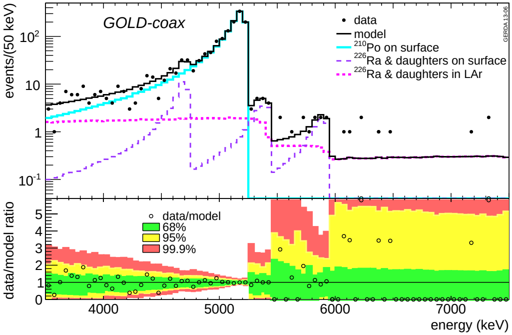


- Split coaxial data in two sets, according to the BI
- Golden: all the coax data, but July 2012
- Silver: coax data taken in June and July 2012 (removal of two nat-coaxial and insertion of BEGe's)
- BEGe data kept separated, due to different resolution and background

dataset	exposure [kg·yr]
Golden	17.90
Silver	1.30
BEGe	2.40

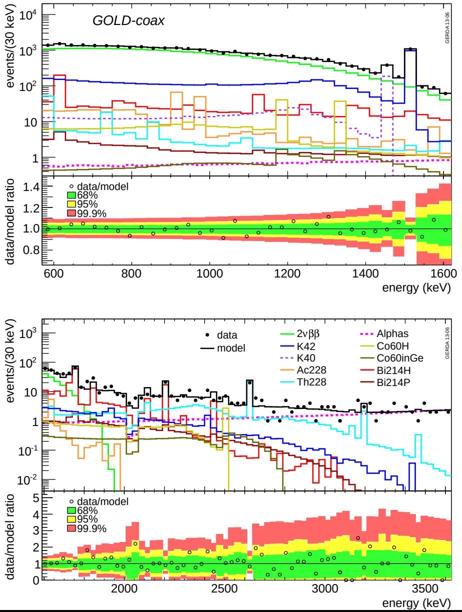
The Background Model at High Energy





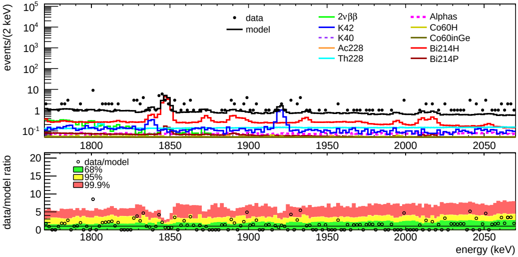
- Duty-factor corrected time distribution of events in the 3.5-5.3 MeV compatible with ^{210}Po half-life ($T_{1/2} = 138$ d)
- Contribution from ^{226}Ra and daughters also visible
- α-emitter mostly located on p^+ surface (also confirmed by PSD)
- α events account for $\sim 10\%$ of the BI at $Q_{\beta\beta}$ for coaxial detectors and $\sim 5\%$ for BEGe's.

The Background Model of GERDA Phase I



Minimum model for Golden dataset

- Only known and visible contributions considered
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- No hint for any different behavior in the last 3 months of data taking
- Official result found with 30 keV binning, crosschecks performed with thinner binnings
- Background Model published: arXiv:1306.5084v1

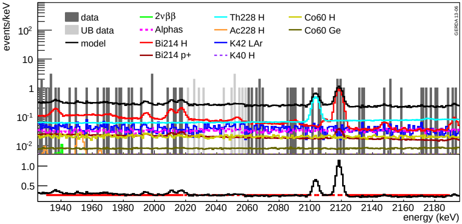


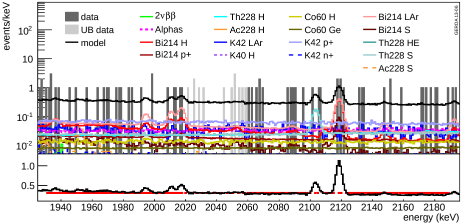
iso-tope	energy [keV]	GOLD-coax rate [cts/(kg·yr)]		
		Global analysis (min. fit)	Global analysis (max. fit)	Fit to data
^{40}K	1460.8	11.9[10.8, 13.0]	11.9[10.8, 13.0]	13.9[12.8, 15.0]
^{60}Co	1173.2	2.5[1.4, 4.2]	$<$ 3.0	3.4[2.2, 5.2]
	1332.3	2.5[0.9, 4.1]	1.6[0.5, 2.7]	2.3[1.5, 3.1]
^{228}Ac	910.8	4.4[2.6, 6.5]	3.4[1.9, 4.9]	2.3[0.5, 4.6]
	968.9	3.8[1.8, 5.8]	3.2[0.4, 6.0]	$<$ 3.9
^{208}Tl	583.2	5.7[3.9, 8.5]	$<$ 1.7	6.3[4.5, 8.4]
	2614.5	1.4[1.1, 1.7]	1.0[0.7, 1.3]	1.1[0.8, 1.4]
^{214}Pb	352	19.9[17.8, 22.0]	17.3[15.2, 19.4]	17.6[13.8, 21.4]
^{214}Bi	609.3	11.1[9.1, 13.1]	7.7[5.9, 9.5]	13.7[9.6, 17.8]
	1120.3	1.5[0.3, 2.9]	$<$ 3.0	$<$ 1.9
	1764.5	3.6[3.1, 4.1]	2.9[2.4, 3.4]	3.3[2.8, 3.8]
	2204.2	1.0[0.7, 1.3]	0.8[0.5, 1.1]	0.8[0.5, 1.1]

- No surprise found when comparing the complete Phase I spectrum and the (scaled) background model with 2 keV bins
- Maximum model with several combinations of contributions and positions $\rightarrow$ no unique determination
- No surprise in comparison between lines intensity predicted by the background model(s) and the spectral fit on data
- Same approach for BEGe's
- Crosschecked with nat-Ge detectors, too

Background prediction at $Q_{\beta\beta}$

- Both min and max model predict a flat bkg at $Q_{\beta\beta} \rightarrow$ unblind side-bands!
- BI predicted form bkg models and fitted from data are in agreement





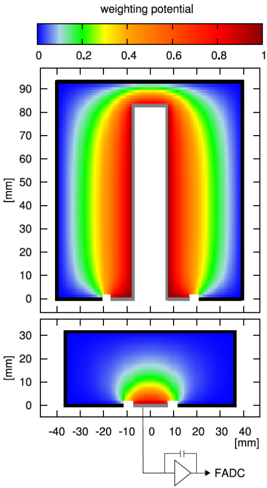
BI before PSD interpolated in the Region of Interest:

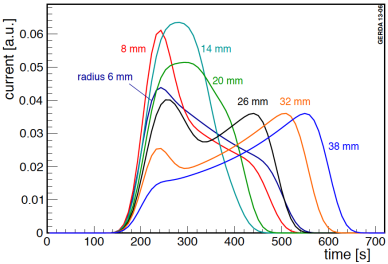
	GOLD-coax	SUM-BEGe
	BI in ROI before PSD (10 keV for coaxial, 8 keV for BEGe) $[10^{-3}\text{cts}/(\text{keV}\cdot\text{kg}\cdot\text{yr})]$	
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-

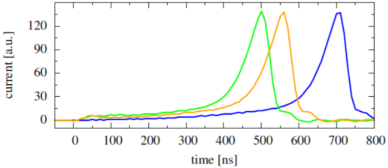
Analysis recipe: fit with Gaussian peak and flat background in the 1930-2190 keV region, excluding known gamma peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi).

Pulse Shape Discrimination: arXiv:1307.2610

- PSD: distinguish between ($0\nu2\beta$) signal-like events (SSE) and background-like events (MSE, p^+)
- Different PSD needed for coaxial and BEGe detectors





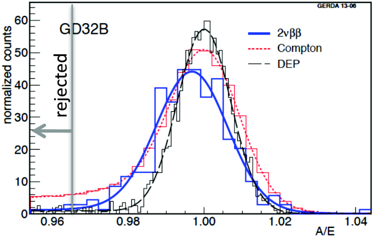


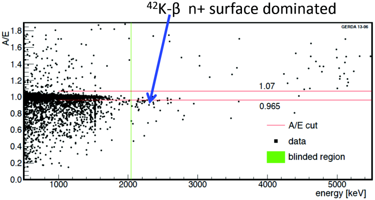
- Simulated current pulse in coaxial detector
- Simulated current pulse in BEGe

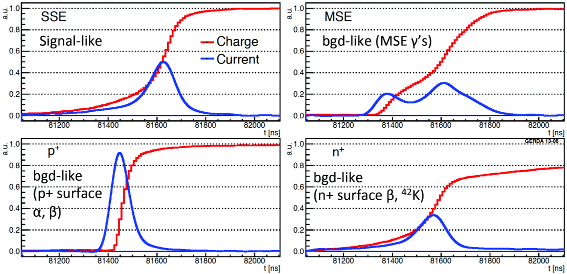
Pulse Shape Discrimination for BEGe

PSD discrimination parameter: A/E

- A = amplitude of current pulse
- E = energy
- High capability of distinguishing SSE from MSE, p^+ and n^+ events
- Well tested and documented method*





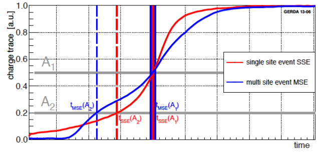


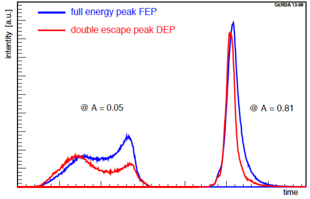
- Acceptance for $2\nu2\beta$: 0.91 ± 0.05
- Acceptance for $0\nu2\beta$: 0.92 ± 0.02

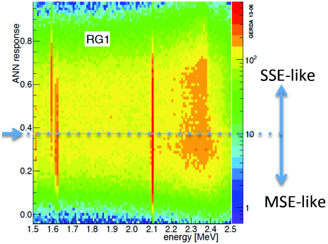
* JINST 4 (2009) P10007; JINST 3 (2011) P03005; arXiv:1307.2610

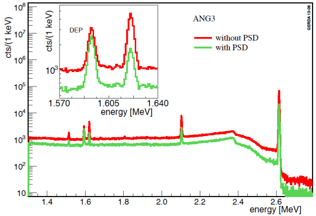
PSD discrimination method: Artificial Neural Network (ANN)

- ANN analysis of 50 rise-time info (1,3,5,. . . ,99%) with TMVA/TMlpANN
- SSE training with signal-like ^{208}Tl DEP at 1592 keV
- MSE training with background-like ^{212}Bi FEP at 1621 keV
- Cut adjusted for each detector to have 90% survival probability on DEP







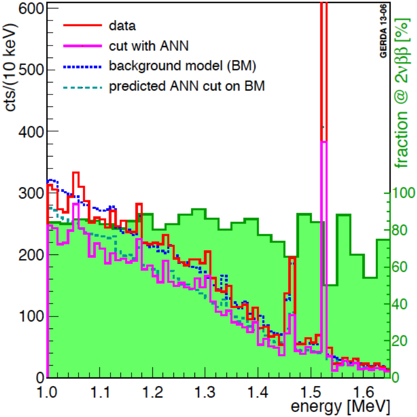


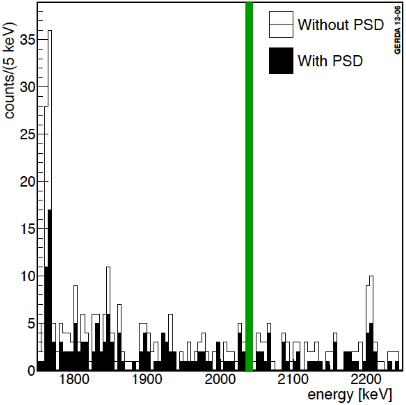
*arXiv:1307.2610

Pulse Shape Discrimination for coaxial detectors*

PSD selection in $2\nu2\beta$ and $0\nu2\beta$ energy ranges

- For $2\nu2\beta$ data and model are in good agreement
- $2\nu2\beta$ survival fraction: 0.85 ± 0.02





- Estimated survival fraction for $0\nu2\beta$ event: $0.90^{+0.05}_{-0.09}$

*arXiv:1307.2610

$0\nu2\beta$ Decay Analysis

From counts to half-life

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot \varepsilon$$

$$\varepsilon = f_{76} \cdot f_{AV} \cdot \varepsilon_{FEP} \cdot \varepsilon_{PSD}$$

Dataset	Exposure M·t [kg·y]	f_{76}	f_{AV}	ε_{FEP}	ε_{PSD}
Golden	17.9	0.86	0.87	0.92	0.90
Silver	1.3	0.86	0.87	0.92	0.90
BEGe	2.4	0.88	0.92	0.90	0.92

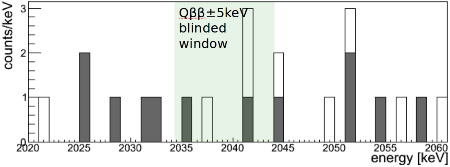
N_A = Avogadro number
m_{enr} = molar mass of enr-Ge
$N^{0\nu}$ = signal counts/limit
t = livetime
f_{76} = enrichment fraction
f_{AV} = active volume fraction
ε_{FEP} = FEP efficiency for $0\nu2\beta$
ε_{PSD} = signal acceptance

Fitting method

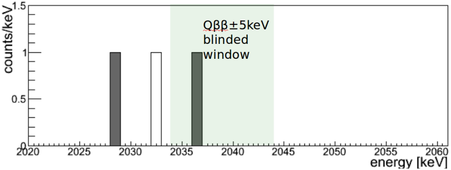
- Fit 3 datasets with Gaussian over flat background
- 4 parameters: 3 bkg levels and $T^{0\nu}_{1/2}$ with the constraint $1/T^{0\nu}_{1/2} > 0$
- Fixed parameters: $\mu = 2039.07 \pm 0.007$ keV and $\sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)$ keV for coaxial/BEGe
- Systematic uncertainties on f, ε, μ, σ: MC sampling and averaging

Unblinding of GERDA Phase I Data

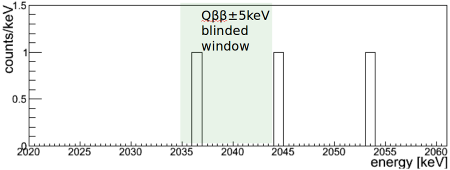
Golden dataset



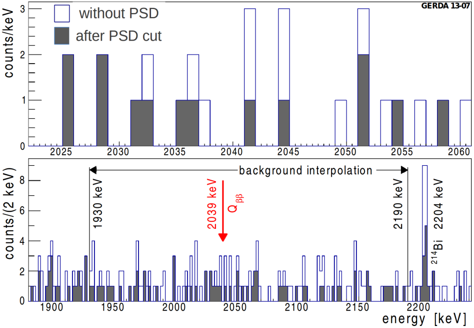
Silver dataset



BEGe dataset



All datasets

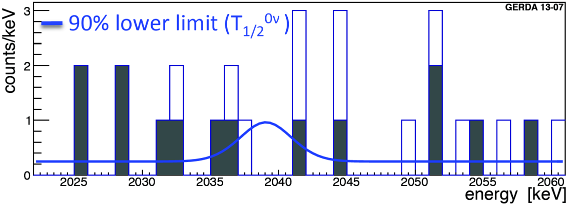


data set	detector	energy [keV]	date	PSD passed
golden	ANG5	2041.8	18-Nov-2011 22:52	no
silver	ANG5	2036.9	23-Jun-2012 23:02	yes
golden	RG2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG1	2035.5	29-Jan-2013 03:35	yes
golden	ANG3	2037.4	02-Mar-2013 08:08	no
golden	RG1	2041.7	27-Apr-2013 22:21	no

GERDA Phase I Results

Events at $Q_{\beta\beta} \pm 5$ keV

PSD	Dataset	Obs.	Exp. bkg
no	Golden	5	3.3
	Silver	1	0.8
	BEGe	1	1.0
yes	Golden	2	2.0
	Silver	1	0.4
	BEGe	0	0.1



Profile Likelihood Method

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25} \text{ yr}$$

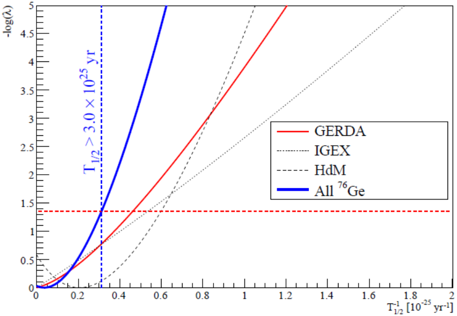
Bayesian Approach

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]$ yr^{-1}
- best fit $N^{0\nu} = 0$
- 90% credibility interval:

$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25} \text{ yr}$$

Phys. Rev. Lett. 111 (2013) 122503

Combination with HdM 2001 and IGEX



Previous limits

- HdM 2001:
  $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr (90% C.L.)
  EPJ A12 (2001) 147-154
- IGEX 2002:
  $T^{0\nu}_{1/2} > 1.57 \cdot 10^{25}$ yr (90% C.L.)
  Phys. Rev. D65 (2002) 092007

Combining the limits

- Same result with Profile Likelihood and Bayesian approach

$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25} \text{ yr (90\%) C.L.}$$

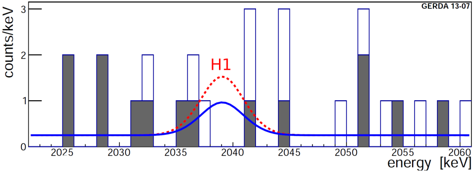
Comparison with Phys. Lett. B 586 198 (2004) Claim

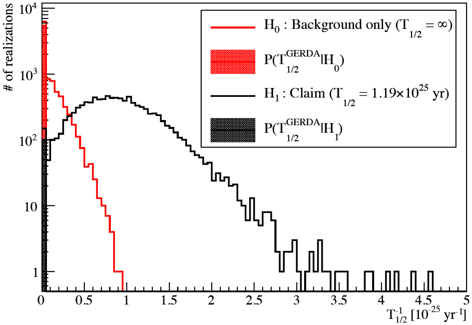
- Phys. Lett. B 586 198 (2004): $T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr
- Expected 5.9 ± 1.4 signal events over 2.0 ± 0.3 bkg events in a $\pm 2\sigma$ region
- Found 3 counts in $\pm 2\sigma$ region (0 in $\pm 1\sigma$)

Hypothesis comparison

- H1: claimed signal (5.9 ± 1.4)
- H0: background only
- Bayes factor: $P(H1)/P(H0) = 0.024$
- P-value from profile likelihood: $P(N^{0\nu} = 0|H1) = 0.01$
- Bayes factor lowered to $2 \cdot 10^{-4}$ when combining with IGEX and HdM 2001
- Comparison independent of NME and physical mechanism generating $0\nu2\beta$

Claim strongly disfavored





Conclusion and Outlook

Summary of the results

- Best fit gives 0 counts both for PL and BA: no excess is visible.
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- 2004 claim predicted 5.9 ± 1.4 signal events over 2.0 ± 0.3 bkg events in $Q_{\beta\beta} \pm 2\sigma$.
- 3 events are observed in $Q_{\beta\beta} \pm 2\sigma$, 0 in $Q_{\beta\beta} \pm \sigma$.
- Claim disfavoured with high probability.

Combination with other experiments

- Combining with HdM 2001 and IGEX 2002:
  $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90%) C.L. (same with Bayesian approach).
- Limit on effective Majorana neutrino mass:
  $m_{ee} < 0.2\text{-}0.4$ eV

Outlook

- Work is ongoing with the preparation of GERDA Phase II...