The GERDA Experiment for the Search of Neutrinoless Double Beta Decay

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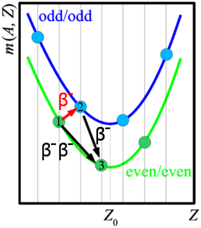
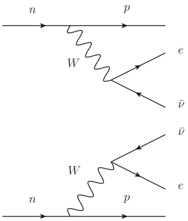
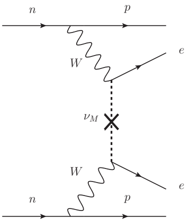
SPS Annual Meeting
Fribourg, 2 July 2014

The Double Beta Decay







Standard Model $2\nu2\beta$ decay:

- Known for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{130}Ba, ^{136}Xe
- $T^{2\nu}_{1/2}$ in the range of $10^{18\text{–}24}$ yr
- ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr*

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

- Lepton number is violated ($\Delta L = 2$)
- Requires physics beyond the Standard Model
- A likely mechanism is "massive Majorana neutrino exchange", see e.g.[†]

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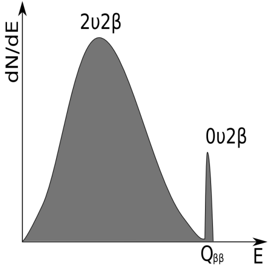
[*] GERDA Collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

[†] W. Rodejohann, Int. J. Mod. Phys. E20, 1833-1930 (2011)

Experimental Signature



Energy spectrum of $2\nu2\beta$ and $0\nu2\beta$ decay

Disadvantages of Ge

Advantages of Ge

Best resolution in GERDA: 2.86 keV (FWHM at 2.6 MeV)

Experimental signature:

- Peak at $Q_{\beta\beta} = m(A,Z) - m(A,Z-2) - 2m_e$ (2039 keV for ^{76}Ge)
- Sensitivity:

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

f_{76} = enrichment fraction

m_A = atomic mass

ε = efficiency

M = detector mass

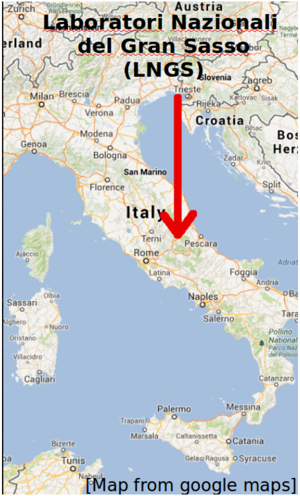
t = livetime

BI = Background Index

ΔE = energy resolution

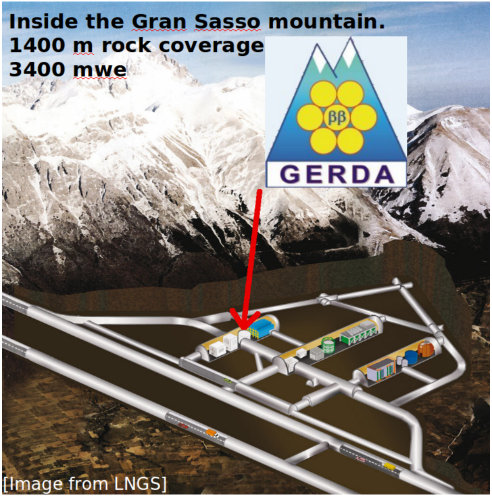
n_σ = Confidence Level

GERDA Underground Site



Laboratori Nazionali del Gran Sasso (LNGS)

[Map from google maps]



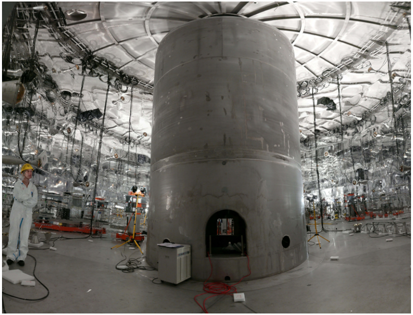
Inside the Gran Sasso mountain.
1400 m rock coverage
3400 mwe

[Image from LNGS]

Running in two Phases: Phase I from Nov 2011 to May 2013
Phase II expected start late 2014

The GERDA Experiment

Mockup of the GERDA experiment

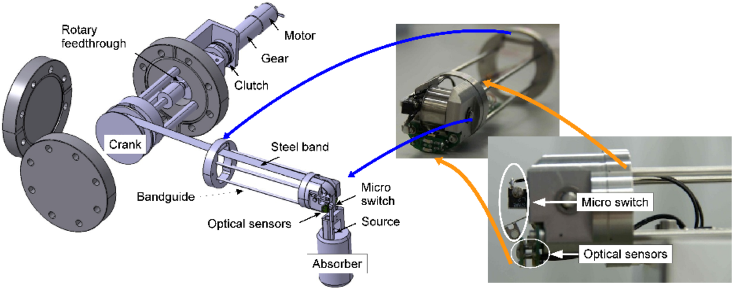


- Bare Ge diodes enriched to 86 % of ^{76}Ge directly immersed in a 5.5 m high 64 m^3 liquid Ar cryostat for cooling and shielding.
- Water Cherenkov detector (590 m^3) to veto cosmic muons and absorb neutrons
- Plastic scintillator to veto muons going through the neck of the cryostat

GERDA Collaboration, Eur. Phys. J. C 73 (2013) 2330

Calibration

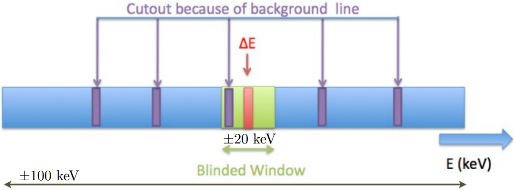
- (Bi)-weekly calibrations with three ^{228}Th sources (use $\approx$ 10 peaks, depending on statistics)
- Sources are lowered into cryostat with a systems build at UZH:
    - Two independent position measurements
    - Friction clutch to prevent over-forcing of steel band
- (α,n) reactions in commercial sources produce neutron background, just acceptable for Phase I but not Phase II:
    - Produced custom low n-flux ^{228}Th sources in collaboration with PSI and University of Mainz for Phase II



GERDA Data Taking and Unblinding

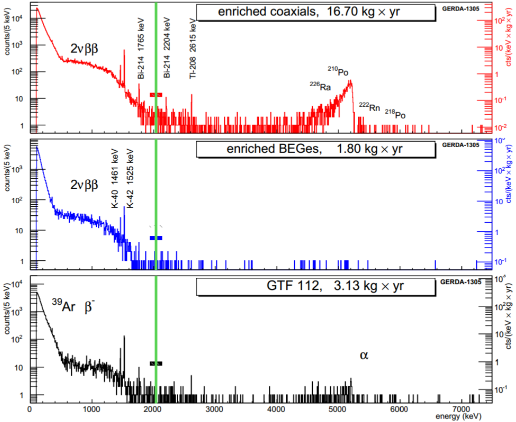
Two Phases:	Mass [kg]	BI [cts/(keV·kg·yr)]	Exposure [kg·yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
I (finished)	18	10^{-2}	21.6	$2 \cdot 10^{25}$
II (starting)	38	10^{-3}	100	$2 \cdot 10^{26}$

Blind analysis with two step unblinding:



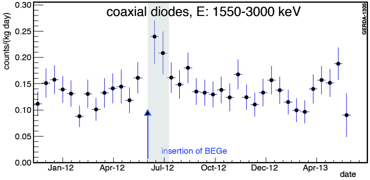
- Before unblinding published a background model and predicted BI at $Q_{\beta\beta}$ (intensity and shape) [Eur. Phys. J. C 74 (2014) 2764]
- Fix the data processing procedure, pulse shape discrimination (PSD) methods, cuts and the statistical analysis
- Opened 15 keV side-bands
- No surprise was found and the analysis was applied without changes

Phase I Datasets



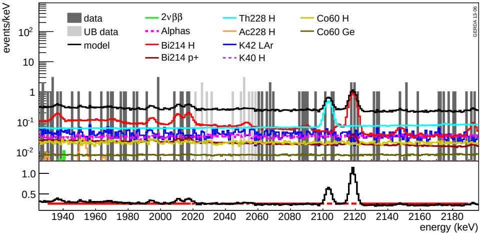
- Coaxial and BEGe type detectors (different geometry)
- Golden: all the coax data, but June and July 2012
- Silver: coax data taken in June and July 2012 (after removal of two nat-coaxial and insertion of BEGe's)
- BEGe: kept separated, due to different energy resolution and background

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



Phase I Background at $Q_{\beta\beta}$

- Background Models:
  - Minimum model containing only known and visible background sources
  - Alternative (maximum model) containing the same isotopes but more possible locations
- Both models predict a flat background at $Q_{\beta\beta}$



$[10^{-3}$cts/(keV·kg·yr)]	GOLD-coax	SUM-BEGe
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]	-

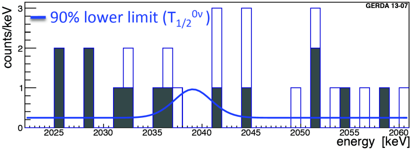
BI (before PSD) in ROI

- We use an interpolation of the background by a constant excluding known γ peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi) for $0\nu2\beta$ analysis:
  Value is consistent with models.

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:

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

Bayesian Approach

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

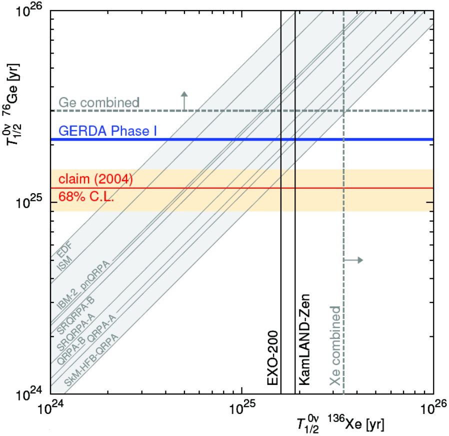
$$T_{1/2}^{0\nu} > 1.9 \cdot 10^{25} \text{ yr}$$

GERDA Collaboration, Phys. Rev. Lett. 111 (2013) 122503

Comparison with Other Experiments

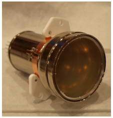
- Claimed observation of $0\nu2\beta$ decay (2004):
  - Predicts 5.9 ± 1.4 signal cts over 2.0 ± 0.3 bkg cts in $Q_{\beta\beta} \pm 2\sigma$
  - GERDA observed 3 cts in $Q_{\beta\beta} \pm 2\sigma$, 0 cts in $Q_{\beta\beta} \pm 1\sigma$
    $\Rightarrow$ claim disfavoured with high probability

- 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)
- Combined ^{76}Ge limit on effective Majorana neutrino mass: $m_{\beta\beta} < 0.2$-0.4 eV (depends on nuclear matrix element and phase space factor)
- Searches with ^{76}Ge can be compared to ^{136}Xe by $m_{\beta\beta}$ (model dependent)



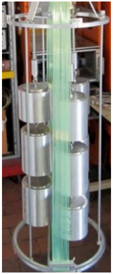
Phase II upgrade: Liquid Ar Veto

Photomultipliers

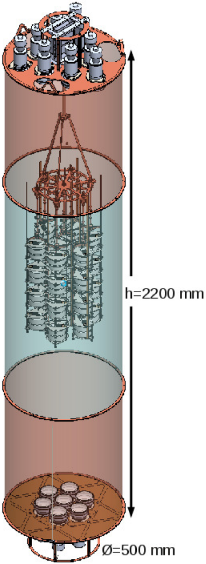


- 3“ R11065-20

Scintillating fibres

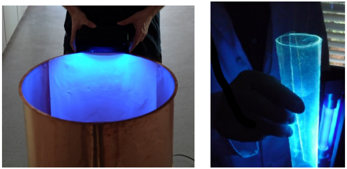


- BCF-91A, coated with WLS
- Light read out on top connection ring using SiPMs



Top/bottom Cu shroud covered by reflective foil

- Tetratex (a PTFE fabric) coated with TPB developed at UZH



Nylon mini-shrouds

- One cylinder for each Ge string
- Coated on both sides with WLS

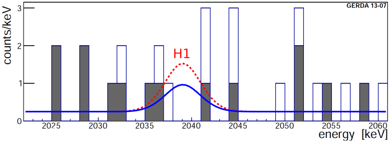
Summary and Outlook

Phase I:

- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- Combined with HdM 2001 and IGEX 2002:
  $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90%) C.L.,
  $m_{\beta\beta} < 0.2\text{-}0.4$ eV

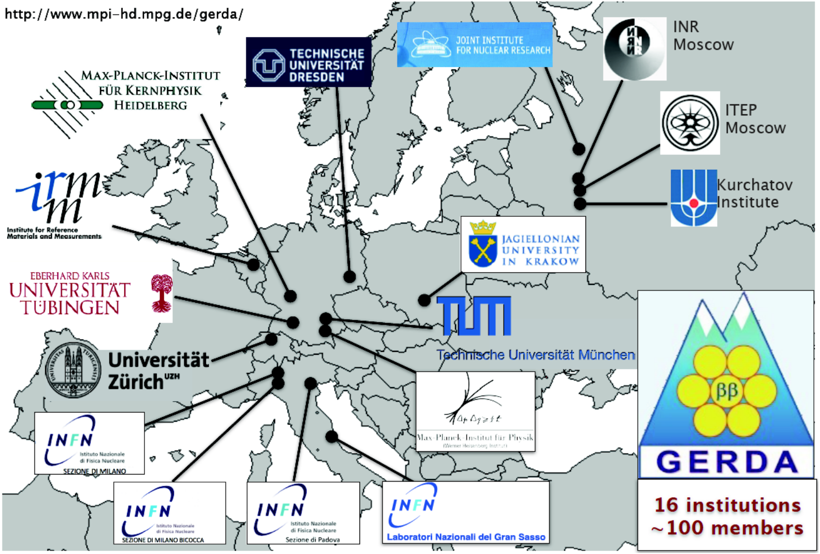
Phase II:

- Expected start late 2014
- 20 kg of additional BEGe detectors
- Liquid Ar veto
- Exposure goal 100 kg·yr
- Background Rate:
  $1 \cdot 10^{-3}$cts/(keV·kg·yr)
- Design sensitivity $T_{1/2} \approx 2 \cdot 10^{26}$ yr



The GERDA Collaboration

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

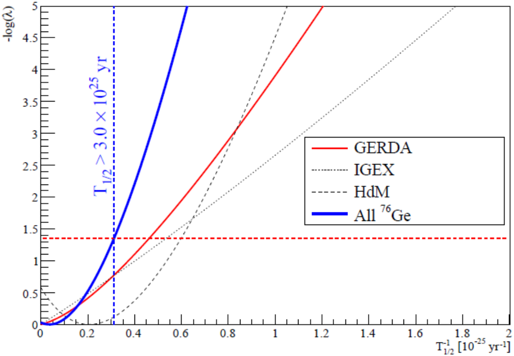


16 institutions
~100 members

Thank you for your attention!

Backup Slides

BACKUP: 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

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

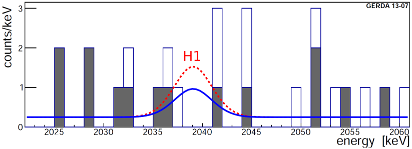
BACKUP: Comparison with Claim from 2004

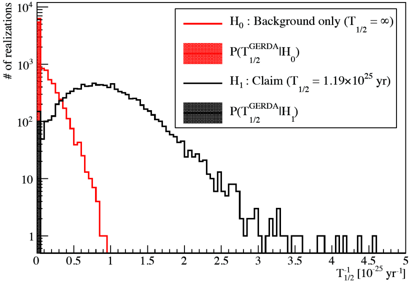
- Phys. Lett. B 586 198 (2004): $T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr
- Expected 5.9 ± 1.4 signal events over 2.0 ± 0.3 bkg events in a $\pm 2\sigma$ region
- Found 3 cts in $\pm 2\sigma$ region (0 in $\pm 1\sigma$)

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 $0\nu 2\beta$

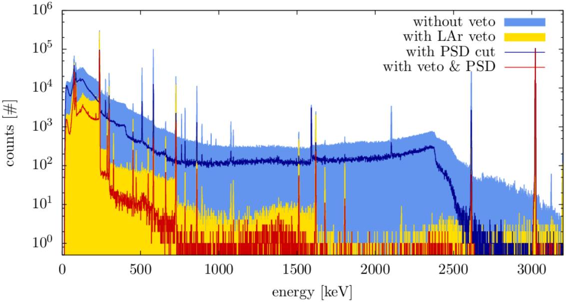
Claim strongly disfavored





BACKUP: Phase II upgrade: Liquid Ar Veto

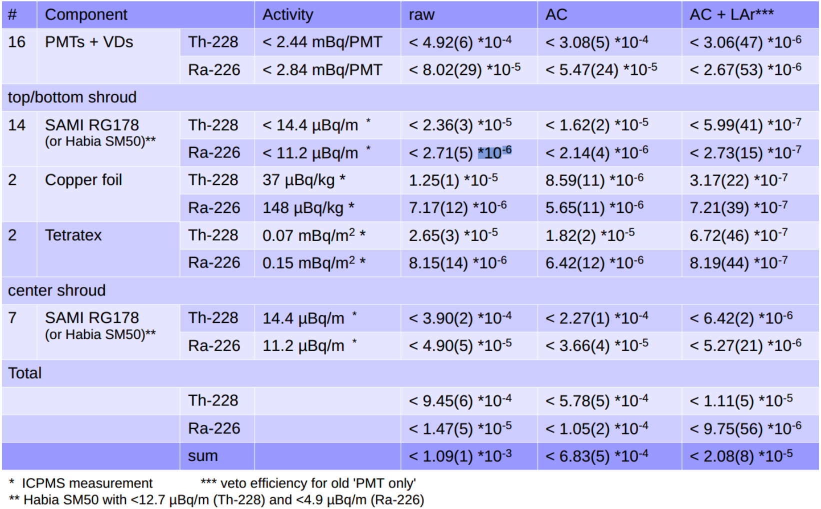
- Many background events at $Q_{\beta\beta}$ are in coincidence with an energy deposition in LAr
- Ar is a scintillator ⇒ can be used to efficiently suppress background
- Background suppression of a LAr veto and pulse shape discrimination was measured for a close ^{228}Th source (in a test set-up): Typical suppression factors in the ROI: ^{208}Tl: 1180, ^{214}Bi: 4.6 [1]



- Representative for impurities in holders, pre-amplifiers and other close objects
- Peak at 3 MeV from pulser

[1] "A liquid argon scintillation veto for Gerda", PhD thesis, M. Heisel, 2011

BACKUP: Expected PMT Veto Induced Background

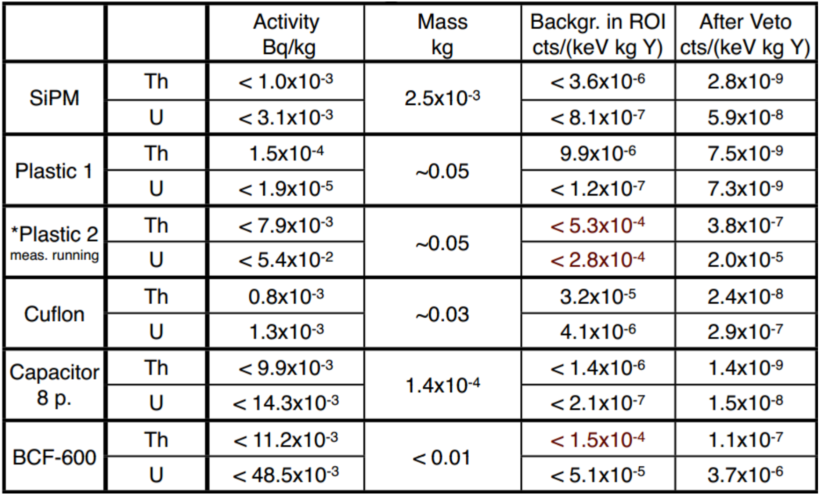


#	Component		Activity	raw	AC	AC + LAr***
16	PMTs + VDs	Th-228	< 2.44 mBq/PMT	< 4.92(6) *10^{-4}	< 3.08(5) *10^{-4}	< 3.06(47) *10^{-6}
		Ra-226	< 2.84 mBq/PMT	< 8.02(29) *10^{-5}	< 5.47(24) *10^{-5}	< 2.67(53) *10^{-6}
top/bottom shroud						
14	SAMI RG178 (or Habia SM50)**	Th-228	< 14.4 µBq/m *	< 2.36(3) *10^{-5}	< 1.62(2) *10^{-5}	< 5.99(41) *10^{-7}
		Ra-226	< 11.2 µBq/m *	< 2.71(5) *10^{-6}	< 2.14(4) *10^{-6}	< 2.73(15) *10^{-7}
2	Copper foil	Th-228	37 µBq/kg *	1.25(1) *10^{-5}	8.59(11) *10^{-6}	3.17(22) *10^{-7}
		Ra-226	148 µBq/kg *	7.17(12) *10^{-6}	5.65(11) *10^{-6}	7.21(39) *10^{-7}
2	Tetratex	Th-228	0.07 mBq/m^{2} *	2.65(3) *10^{-5}	1.82(2) *10^{-5}	6.72(46) *10^{-7}
		Ra-226	0.15 mBq/m^{2} *	8.15(14) *10^{-6}	6.42(12) *10^{-6}	8.19(44) *10^{-7}
center shroud						
7	SAMI RG178 (or Habia SM50)**	Th-228	14.4 µBq/m *	< 3.90(2) *10^{-4}	< 2.27(1) *10^{-4}	< 6.42(2) *10^{-6}
		Ra-226	11.2 µBq/m *	< 4.90(5) *10^{-5}	< 3.66(4) *10^{-5}	< 5.27(21) *10^{-6}
Total						
		Th-228		< 9.45(6) *10^{-4}	< 5.78(5) *10^{-4}	< 1.11(5) *10^{-5}
		Ra-226		< 1.47(5) *10^{-5}	< 1.05(2) *10^{-4}	< 9.75(56) *10^{-6}
		sum		< 1.09(1) *10^{-3}	< 6.83(5) *10^{-4}	< 2.08(8) *10^{-5}

* ICPMS measurement *** veto efficiency for old 'PMT only'

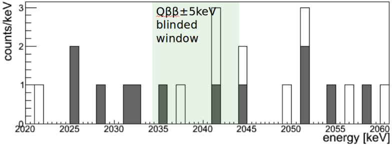
** Habia SM50 with <12.7 µBq/m (Th-228) and <4.9 µBq/m (Ra-226)

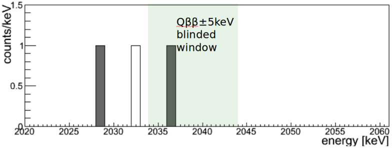
BACKUP: Expected Fibre Veto Induced Background

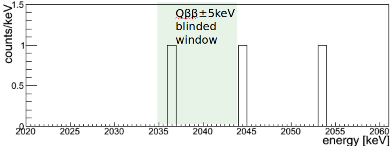


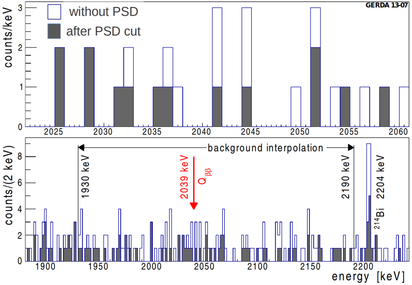
		Activity Bq/kg	Mass kg	Backgr. in ROI cts/(keV kg Y)	After Veto cts/(keV kg Y)
SiPM	Th	$< 1.0\text{x}10^{-3}$	$2.5\text{x}10^{-3}$	$< 3.6\text{x}10^{-6}$	$2.8\text{x}10^{-9}$
	U	$< 3.1\text{x}10^{-3}$		$< 8.1\text{x}10^{-7}$	$5.9\text{x}10^{-8}$
Plastic 1	Th	$1.5\text{x}10^{-4}$	~0.05	$9.9\text{x}10^{-6}$	$7.5\text{x}10^{-9}$
	U	$< 1.9\text{x}10^{-5}$		$< 1.2\text{x}10^{-7}$	$7.3\text{x}10^{-9}$
*Plastic 2 meas. running	Th	$< 7.9\text{x}10^{-3}$	~0.05	$< 5.3\text{x}10^{-4}$	$3.8\text{x}10^{-7}$
	U	$< 5.4\text{x}10^{-2}$		$< 2.8\text{x}10^{-4}$	$2.0\text{x}10^{-5}$
Cuflon	Th	$0.8\text{x}10^{-3}$	~0.03	$3.2\text{x}10^{-5}$	$2.4\text{x}10^{-8}$
	U	$1.3\text{x}10^{-3}$		$4.1\text{x}10^{-6}$	$2.9\text{x}10^{-7}$
Capacitor 8 p.	Th	$< 9.9\text{x}10^{-3}$	$1.4\text{x}10^{-4}$	$< 1.4\text{x}10^{-6}$	$1.4\text{x}10^{-9}$
	U	$< 14.3\text{x}10^{-3}$		$< 2.1\text{x}10^{-7}$	$1.5\text{x}10^{-8}$
BCF-600	Th	$< 11.2\text{x}10^{-3}$	< 0.01	$< 1.5\text{x}10^{-4}$	$1.1\text{x}10^{-7}$
	U	$< 48.5\text{x}10^{-3}$		$< 5.1\text{x}10^{-5}$	$3.7\text{x}10^{-6}$

BACKUP: Unblinded ROI


Golden dataset


Silver dataset


BEGe dataset

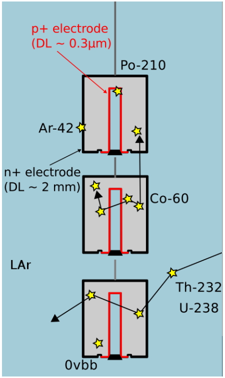

All datasets

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

BACKUP: Phase I Background

Background sources

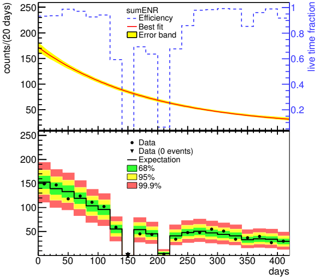
- The outer most, so called Dead Layer, of the detectors is not active.
- α decays on the p+ surface
- β decay of ^{42}K on the surface or close to the detector which comes from ^{42}Ar (contribution a factor ≈ 10 higher than expected!)
- β decay of ^{60}Co inside the detectors
- γ from ^{208}Tl, ^{214}Bi from various set-up components.

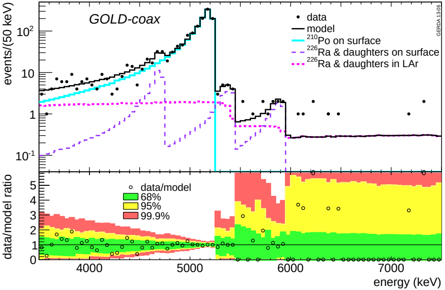


Phase I background reduction

- Cut detector coincidences
- Prevent ^{42}K ions from drifting to the detectors using minishrouds
- Use pulse shape discrimination to remove MSE

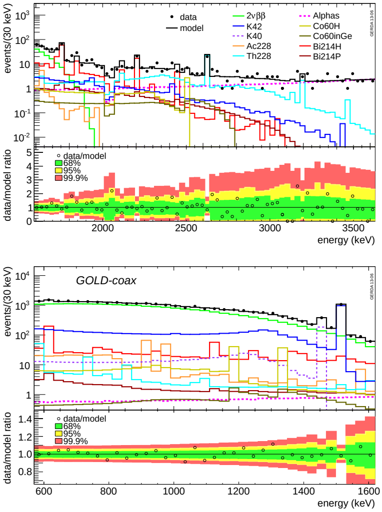
BACKUP: The Background Model at High Energy





- Duty-factor corrected time distribution of events in the 3.5-5.3 MeV compatible with ^{210}Po half-life ($T_{1/2} = 138\,\text{d}$) plus constant.
- Contribution from ^{226}Ra and daughters also visible
- α-emitter mostly located on p^{+} surface

BACKUP: The Background Model of GERDA Phase I

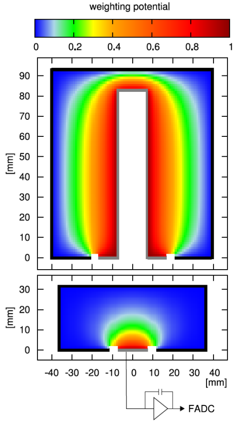


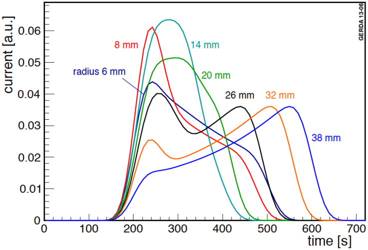
Minimum model for Golden dataset

- Simulate spectral shape of individual background sources.
- Add up minimal number of well motivated sources
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- 30 keV binning crosschecked with finer binnings
- Background Model published: arXiv:1306.5084v1
- $T_{1/2}(2\nu2\beta)$ from model consistent with previously published value

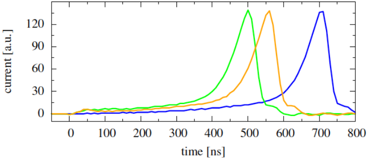
BACKUP: Pulse Shape Discrimination

- PSD: distinguish between SSE (like many $0\nu2\beta$ events) and MSE and surface events (like many background events)
- Different PSD needed for coaxial and BEGe detectors





- Simulated SSE current pulse in coaxial detector

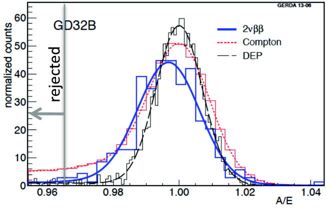


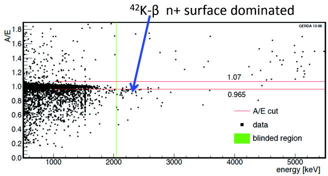
- Simulated SSE current pulse in BEGe

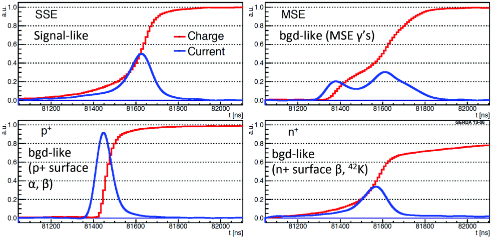
BACKUP: Pulse Shape Discrimination for BEGe

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*







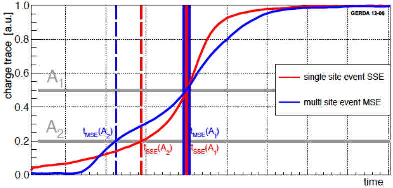
- Acceptance for $0\nu2\beta$: 0.92 ± 0.02

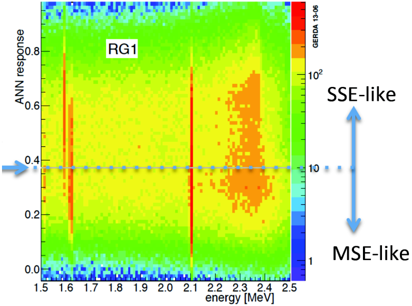
JINST 4 (2009) P10007; JINST 3 (2011) P03005; arXiv:1307.2610

BACKUP: Pulse Shape Discrimination for Coaxial Detectors

PSD discrimination method: Artificial Neural Network (ANN)

- ANN analysis of 50 rise-time info (1,3,5,. . . ,99%) using TMVA/TMIpANN
- 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% acceptance of the DEP

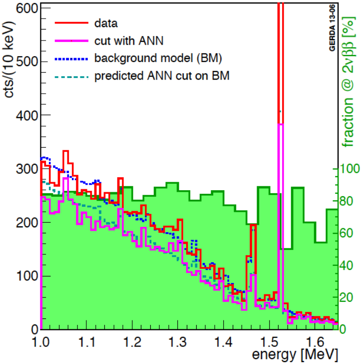




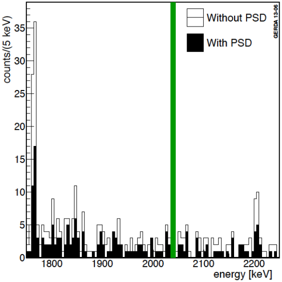
BACKUP: Pulse Shape Discrimination for Coaxial Detectors

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

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



arXiv:1307.2610



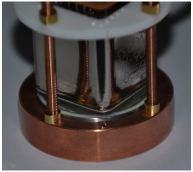
- Estimated survival fraction for $0\nu2\beta$ event: $0.90^{+0.05}_{-0.09}$
- BI after PSD in the ROI :

$[10^{-3}$cts/(keV·kg·yr)]	GOLD-coax	SUM-BEGe
interpolated	11[9, 13]	5[2, 9]

BACKUP: Neutron background of calibration sources

Neutrons from GERDA Calibration Source, Preliminary Results

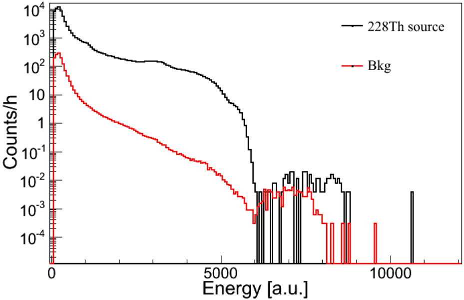
- Neutrons moderated by 5 cm of Polyethylene
- Measured using a LiI(Eu) detector
- n flux of commercial ^{228}Th sources: $7.5 \cdot 10^{-3}$ n/(sec kBq)
- Phase II ^{228}Th sources: ThO_2 deposited on gold
- n flux of custom Phase II sources: $0.97 \cdot 10^{-3}$ n/(sec kBq)



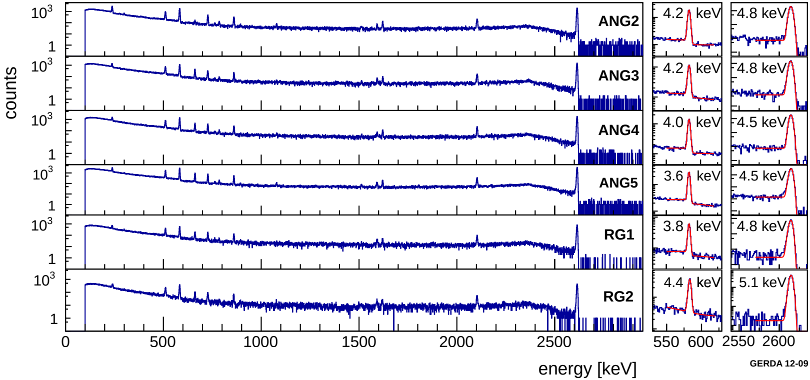
LiI Detector

- LiI crystall, 1" PMT
- n + ^{6}Li $\rightarrow {}^{4}\text{He} + {}^{3}\text{H} + 4.78\,\text{MeV}$

Measured Spectrum

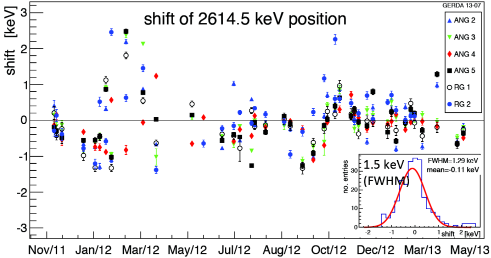


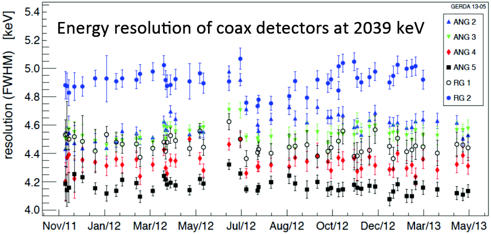
BACKUP: Calibration of the GERDA Data



- Used 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 ∼ 10% improvement with better filtering)

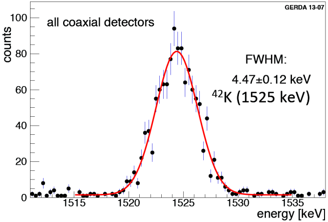
BACKUP: Time Stability and Energy Resolution



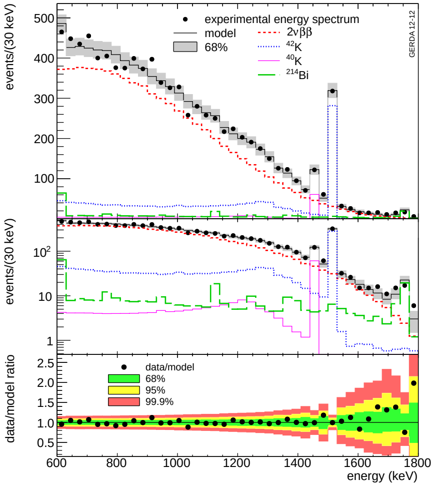


detector	FWHM [keV]
SUM-coax	
ANG2	5.8 (3)
ANG3	4.5 (1)
ANG4	4.9 (3)
ANG5	4.2 (1)
RG1	4.5 (3)
RG2	4.9 (3)
mean coax	4.8 (2)
SUM-BEGe	
GD32B	2.6 (1)
GD32C	2.6 (1)
GD32D	3.7 (5)
GD35B	4.0 (1)
mean BEGe	3.2(2)

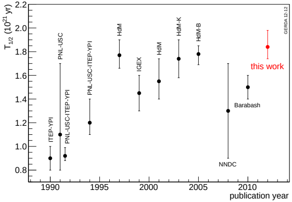
- If needed, correction term applied to FWHM to account for instabilities



BACKUP: $2\nu2\beta$ Measurement



- Measured by GERDA with 5.04 kg·yr exposure
- Very simple background model due to high signal-to-background ratio
- $T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



GERDA Collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

BACKUP: The GERDA Detectors

Coaxial detectors (Phase I)

- 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
- Two detectors turned off because of high leakage current ⇒ total mass of remaining enriched detectors: 14.6 kg
- ∼ 2‰ FWHM at 2.6 MeV

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
- One showed instabilities in the energy calibration, not used

BACKUP: GERDA Time-line

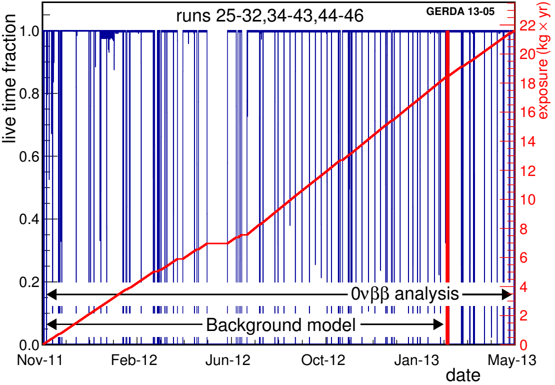
The time-line of GERDA:

- Mar. 2008: cryostat installation
- May 2010: start of commissioning
- Nov. 2011 - May 2013: Phase I data taking
- Now: preparing Phase II
- Early 2014: Start of Phase II

Two Phases:	Mass [kg]	BI [cts/(keV·kg·yr)]	Exposure [kg·yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
Phase I	18	10^{-2}	21.6	$2 \cdot 10^{25}$
Phase II (preparing)	38	10^{-3}	100	$2 \cdot 10^{26}$

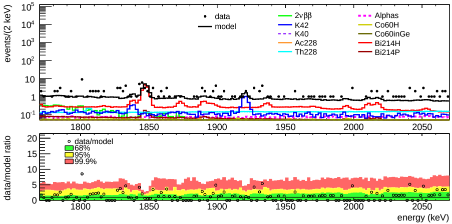
BACKUP: GERDA Phase I Data Taking

- Total livetime of 492.3 days with 88% duty factor
- 5% of data not used due to temperature originating electronics instabilities



- Spikes: (Bi)-weekly calibration runs
- June 2012: Insertion of BEGe detectors
- Dataset for background model: Nov 2011 - March 2013
- Dataset for $0\nu2\beta$ analysis: Nov 2011 - May 2013 (21.6 kg·yr)

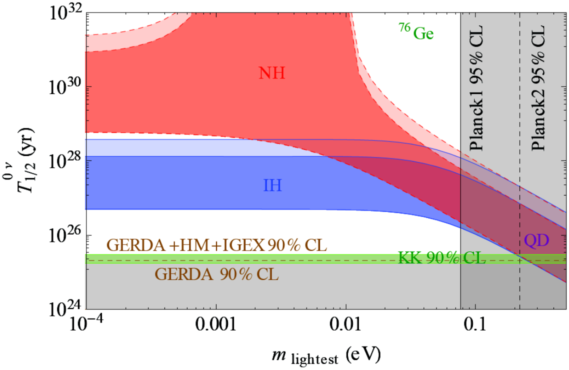
BACKUP: The Background Model of GERDA Phase I



iso-	energy	GOLD-coax		
tope	[keV]	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

BACKUP: Scanning the Inverse Hierarchy



- Need to reach a sensitivity of $\sim 10^{28}$ yr on $T^{0\nu}_{1/2}$ in order to test IH*
- GERDA Phase II will reach $\sim 2 \cdot 10^{26}$ yr
- Improved energy resolution might increase the limit both in Phase I and II

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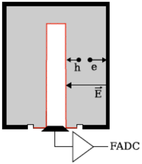
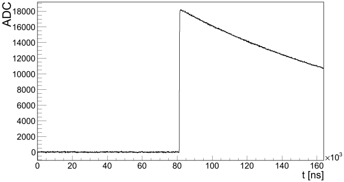
* P. S. Bhupal et al., arXiv:1305.0056v2

BACKUP: GERDA Phase I Data Processing and Selection

Data processing framework: GELATIO

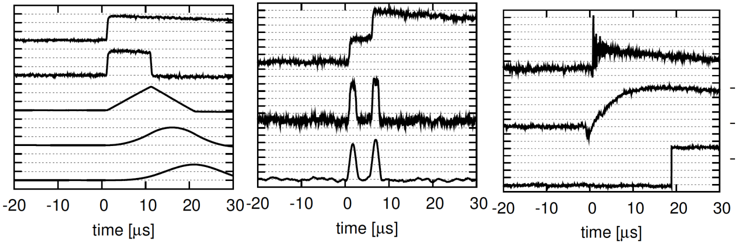
- Read-out and signal structure:





- JINST 6 (2011) P08013
- J. Phys., Conf. Ser. 368 (2012) 012047

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



BACKUP: $0\nu2\beta$ Decay Analysis

From cts 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

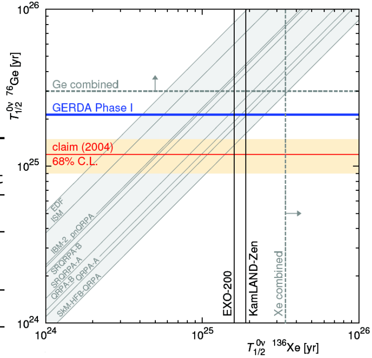
Fitting method

- Fit 3 datasets with Gaussian over flat background
- 4 parameters: 3 bkg levels and $\mathrm{T}^{0\nu}_{1/2}$ with the constraint $1/\mathrm{T}^{0\nu}_{1/2} > 0$
- 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

BACKUP: Combining Ge and Xe

- Combination with ^{76}Xe results done using conservative (=smallest) NME ratio
- NME from P. S. Buphal et al., arXiv:1305.0056

Experiment	Isotope	P(H1)/P(H0)	Model dependent
GERDA	^{76}Ge	0.024	no
GERDA + HdM + IGEX	^{76}Ge	0.0002	no
KamLAND-Zen	^{136}Xe	0.40	yes
EXO-200	^{136}Xe	0.23	yes
GERDA + KLZ + EXO	^{76}Ge + ^{136}Xe	0.02	yes



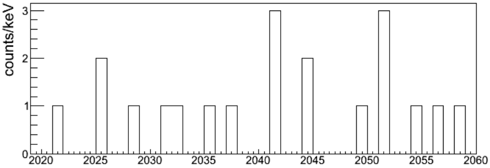
BACKUP: The events

Dataset	Exposure [kg·yr]	$\langle \varepsilon \rangle$	bkg	BI 10^{-3} cts/(keV·kg·yr)	Counts	Expected from background only
Before PSD						
Golden	17.9	0.688 ± 0.031	76	18 ± 2	5	3.3
Silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1	0.8
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1	1.0
After PSD						
Golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2	2.0
Silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1	0.4
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	1	0.1

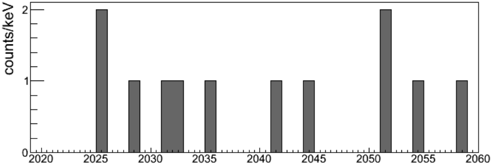
BACKUP: Non Constant Background at $Q_{\beta\beta}$?

- Count distribution in the bins around $Q_{\beta\beta}$ is compatible with Poisson fluctuations of a constant signal.

Golden dataset: measured vs expected counts



Before PSD		
Counts	Expected	Measured
0	24.2	26
1	12.1	10
2	3.0	2
> 2	0.7	2



After PSD		
Counts	Expected	Measured
0	29.6	30
1	8.9	8
2	1.3	2
> 2	0.2	0

BACKUP: Background Model of the Full Dataset

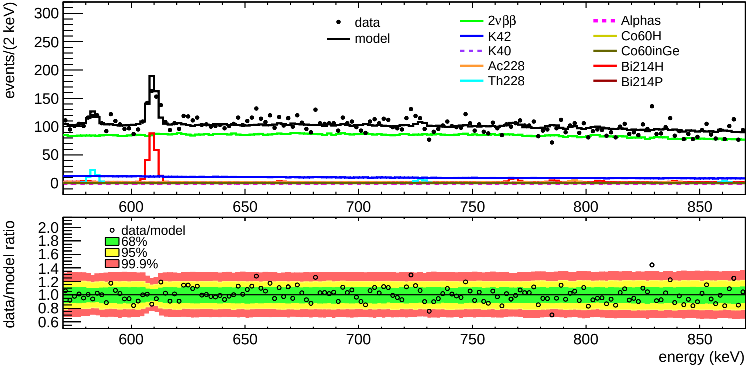
Comparison of the background model to the FULL dataset

- Final Golden dataset: 09.09.2011-21.05.2013, 17.9 kg·yr
- Golden dataset for background model: 09.09.2011-03.03.2013, 15.4 kg·yr
- Scale minimum model by factor 17.9/15.4 and compare with final Golden spectrum
- Use 2 keV binning
- Compare number of measured and expected events in the 68, 95 and 99.9% coverage regions
- No new fit is performed!

Result of the crosscheck

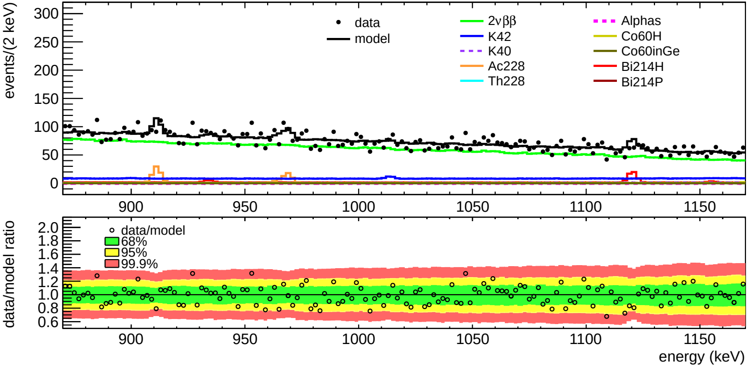
- All observed gamma lines are reproduced by the minimum model
- No clear indication of unidentified gamma ray lines
- The observed number of counts are within the expected statistical fluctuations, *i.e.* the upward/downward fluctuations in the yellow

BACKUP: Background Model of the Full Dataset



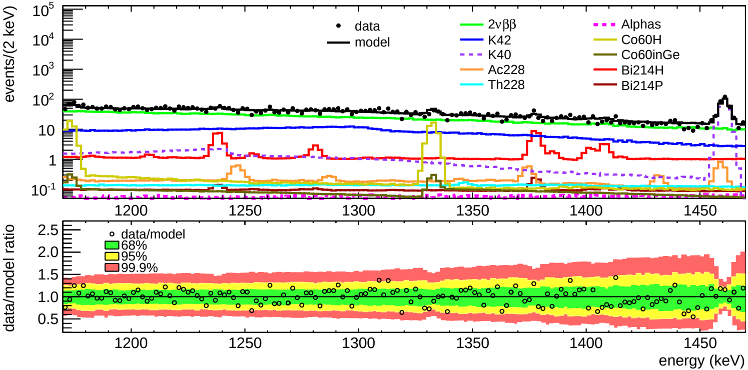
Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	110/150	73	68
Yellow	143/150	95	95
Red	149/150	99.3	99.9

BACKUP: Background Model of the Full Dataset



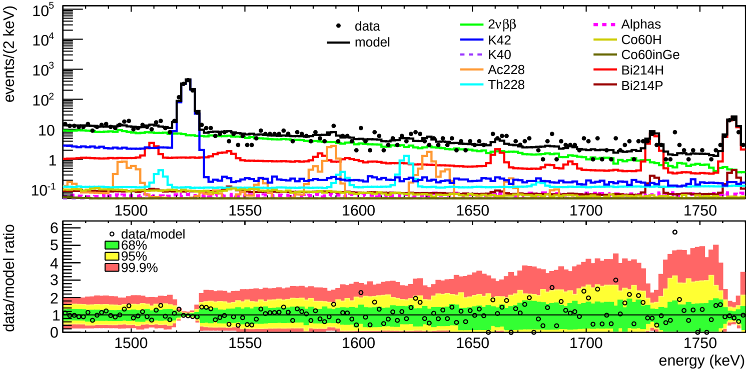
Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	101/150	67	68
Yellow	144/150	95	95
Red	150/150	100	99.9

BACKUP: Background Model of the Full Dataset



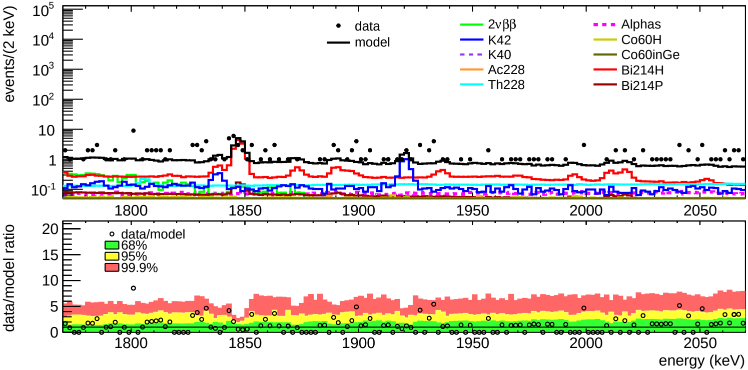
Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	110/150	73	68
Yellow	146/150	97	95
Red	150/150	100	99.9

BACKUP: Background Model of the Full Dataset



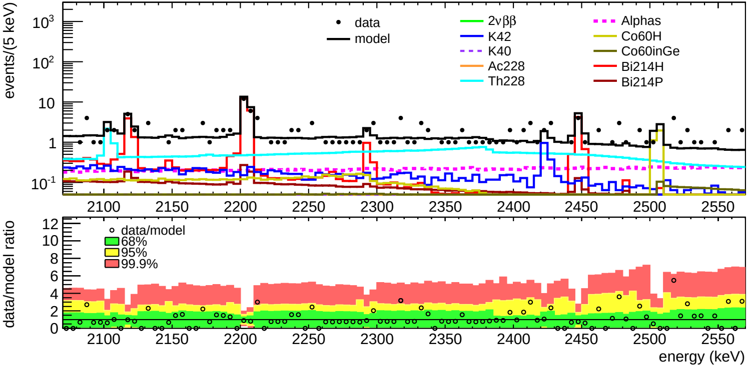
Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	111/150	74	68
Yellow	145/150	97	95
Red	149/150	99.3	99.9

BACKUP: Background Model of the Full Dataset



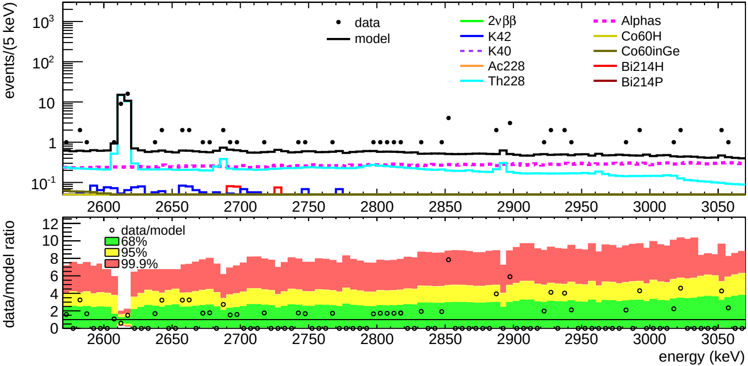
Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	112/150	75	68
Yellow	140/150	93	95
Red	149/150	99.3	99.9

BACKUP: Background Model of the Full Dataset



Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	81/100	81	68
Yellow	97/100	97	95
Red	100/100	100	99.9

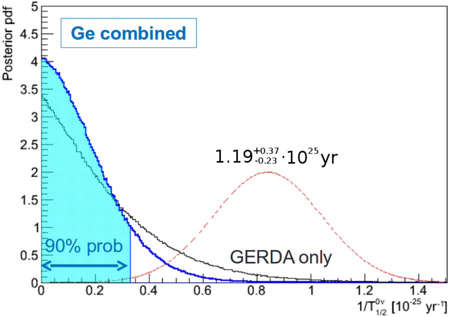
BACKUP: Background Model of the Full Dataset



Band	Measured Events [counts/total]	[%]	Expected Events [%]
Green	85/100	85	68
Yellow	98/100	98	95
Red	100/100	100	99.9

BACKUP: Bayesian Approach: Posterior PDF

- Flat prior on $1/T_{1/2}$ between 0 and 10^{-24} yr^{-1}



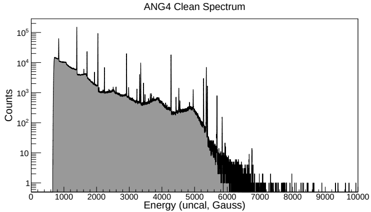
GERDA only:

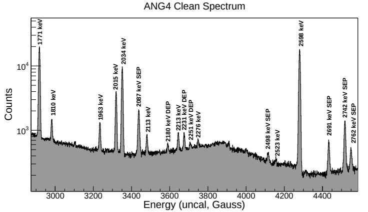
- Best fit: $N^{0\nu} = 0$
- $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr (90% C.I.)
- MC median sensitivity: $T^{0\nu}_{1/2} > 2.0 \cdot 10^{25}$ yr (90% C.I.)

Ge combined:

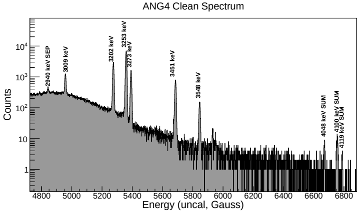
- $T^{0\nu}_{1/2} > 2.9 \cdot 10^{25}$ yr (90% C.I.)

BACKUP: Crosscheck of DEP's Positions with ^{56}Co Source





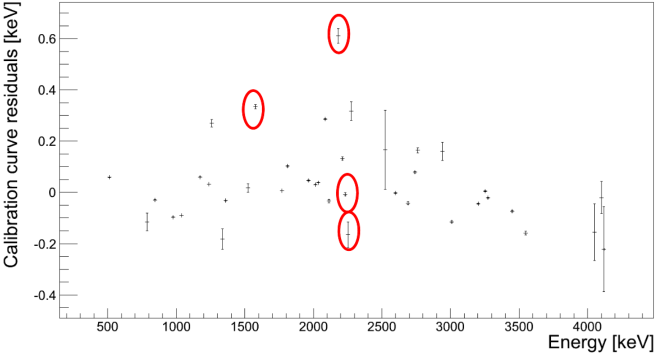
- ^{56}Co source custom produced at the TUM accelerator
- 2 weeks-long measurement performed in July 2013
- ^{56}Co: gamma lines up to 3.5 MeV, summation peaks at $\sim$ 4.2 MeV,
  3 DEPs around 2.2 MeV



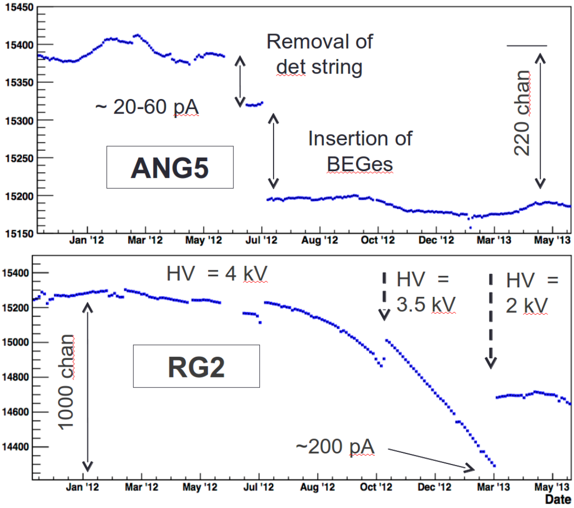
BACKUP: Crosscheck of DEP's Positions with ^{56}Co Source

- Residuals from literature values typically below 0.3 keV
- One line out by 0.6 keV, but in a region "overcrowded" by peaks ⇒ fit systematic
- The energy scale holds up to 4 MeV
- DEPs (kinetically similar to $0\nu2\beta$) reconstructed at the proper energy

  ⇒ No hints of ballistic deficit



BACKUP: LC Stability: Baseline vs Time



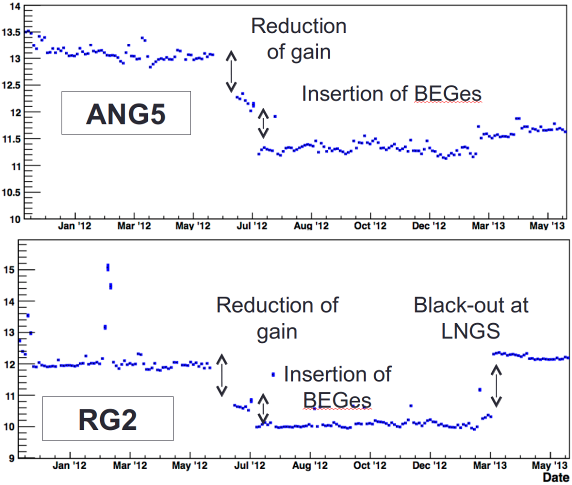
Jumps:

- Changes of hardware (e.g. installation of BEGe) and/or settings (gain, offset)

Drifts:

- Increase of LC s time ⇒ HV had to be reduced below the full depletion (not usable for physics from March 2013)

BACKUP: Noise Stability: Baseline RMS vs Time



- Jumps seen after specific events or hardware/settings changes
- Typically stable on the long-term if system untouched
- No effect seen on the energy resolution at the pulser line

BACKUP: Observed Gamma Lines in GERDA and HdM

Isotope	Energy [keV]	counts/(kg·yr) GERDA	counts/(kg·yr) HdM*
^{40}K	1460.8	13.9[12.8, 15.0]	181 ± 2
^{60}Co	1173.2	3.4[2.2, 5.2]	55 ± 1
	1332.3	2.3[1.5, 3.1]	51 ± 1
^{228}Ac	910.8	2.3[0.5, 4.6]	29.8 ± 1.6
	968.9	< 3.9	17.6 ± 1.1
^{208}Tl	583.2	6.3[4.5, 8.4]	36 ± 3
	2614.5	1.1[0.8, 1.4]	16.5 ± 0.5
^{214}Pb	352	17.6[13.8, 21.4]	138.7 ± 4.8
^{214}Bi	609.3	13.7[9.6, 17.8]	105 ± 1
	1120.3	< 1.9	26.9 ± 1.2
	1764.5	3.3[2.8, 3.8]	30.7 ± 0.7
	2204.2	0.8[0.5, 1.1]	8.1 ± 0.5
^{212}Bi	727	< 4.0	8.1 ± 1.2
^{137}Cs	662	< 4.8	282 ± 2
e^+	511	9 ± 3	30 ± 3
^{42}K	1525	60.5 ± 2.1	N.A.

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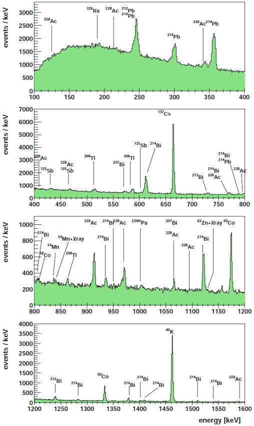
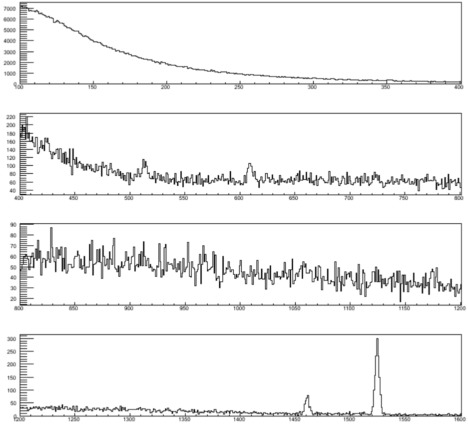
*O. Chvorets, PhD Thesis, 2008

BACKUP: Comparison of HdM and GERDA Spectra

HdM spectrum
(71.7 kg·yr)

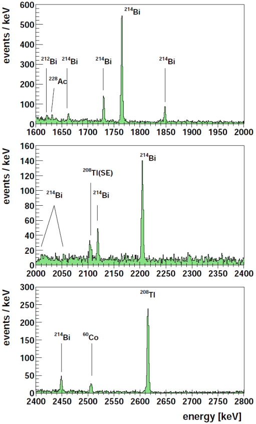


GERDA spectrum (21.6 kg·yr)

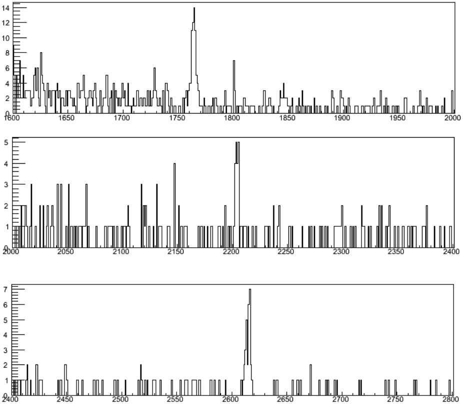


BACKUP: Comparison of HdM and GERDA Spectra

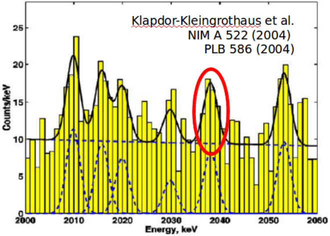
HdM spectrum (71.7 kg·yr)



GERDA spectrum (21.6 kg·yr)



Claimed observation of $0\nu2\beta$



Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported T1/20ν = 1.19 x1025 yr

N.B. Half-life T1/20ν = 2.23 x1025 yr T1/after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with εpsd = 1 (previous similar analysis εpsd ≈ 0.6)
- εfep = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: εfep = 0.9)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

BACKUP: (Some) replies to arXiv:1308.2504

The paper seems based on GERDA slides from conferences/seminars

- No mention of the GERDA papers (EPJC 73 2230, arXiv:1306.5084, arXiv:1307.2610, arXiv:1307.4720)
- Most "missing information" (e.g. identified gamma lines) readily found in the other papers

The $0\nu2\beta$ decay peak has to be searched not at $Q_{\beta\beta}$, but 2 keV away

- Why? The DEPs are at the right positions, ballistic effect is excluded.
- However, the fit of the GERDA data with expected position 2037.5 keV still gives zero signal counts.

BACKUP: (Some) replies to arXiv:1308.2504

”should be improved considerably the treatment of background data, which at present is on an unacceptable level. It is not acceptable that no list of identified lines and intensities exists and consequently no comparison with expectations.”

- See paper arXiv:1306.5084. A complete background model is built and validated
- List of gamma lines present both in EUr. Phys. J. C 73 (2013) 2330 and arXiv:1306.5084
- It is shown that the flat background model is a good approximation, given the present exposure (i.e. data not able to discriminate)
- The model also works at finer binning. No clear evidence of gamma-ray lines that are not included in the model

BACKUP: (Some) replies to arXiv:1308.2504

Missing/unidentified gamma lines between2000 and 2600 keV, mainly from ^{214}Bi

- The fit of Fig. 2 is apparently done with χ^2, not suitable for the Poisson regime
- The counts distribution is consistent with Poisson fluctuations of a constant signal
- Any peak scan will find false positives due to random fluctuations. Statistical significance of peaks is lower than reported in Fig. 2
- It pretends to ignore that ^{214}Bi has also (many) other lines to check ratios
- How can the uncertainties on the peaks position be of order of FWHM?

Line	BR (ToI)	GERDA intensity (Tab. 9 of arXiv:1306.5084)	Fig. 2 fit
2204 keV	5.08%	17.3 counts	18.8 counts
2016 keV	0.067%	[0.23]	5.0 ± 3.3 counts
2052 keV	0.069%	[0.23]	4.7 ± 3.8 counts

BACKUP: (Some) replies to arXiv:1308.2504

"Highly surprising is the statement that a so-called minimal background model not including lines from ^{214}Bi should be sufficient"

- No such statement. ^{214}Bi IS included in the minimum model.

"The original goal of background reduction to 10^{-2} counts/(kg·y·keV) [. . .] has not been reached. The background of GERDA in the energy window 2000-2060 keV around $Q_{\beta\beta}$ is 0.031 counts/(kg·y·keV)."

- The average background of the golden dataset in 2020-2060 keV is 0.023 (w/o PSD) and 0.013 (with PSD) (±30%)
- In the range 1930-2190 keV (reference window) it is 0.018 (w/o PSD) and 0.011 (with PSD) (±5%)

BACKUP: (Some) replies to arXiv:1308.2504

"The reduction of the background [by PSD] is rather modest (order of factor 2)."

- Apparently ignores the information given in arXiv: 1307.2610.
- Not only the background reduction matters, but also the signal acceptance. A modest background rejection and a high signal acceptance are optimal for the low-statistics GERDA data
- We have an alternative method having lower acceptance but much better background rejection power (factor of 4)

Pretends to ignore that the combination of Ge experiments gives a limit of $3.0 \cdot 10^{25}$ yr (90% C.L.)

BACKUP: (Some) replies to arXiv:1308.2504

"the reasons for the limited energy resolution of the detectors have to be explained, and the resolution has to be improved to an acceptable level."

- The resolution is worse than HdM because detectors are operated naked in LAr and there is a long path between the detectors and the FE (kept 30 cm away, for background reasons).
- An optimized offline energy reconstruction is under development, which improves resolution by 10% (Poster presented at TAUP 2013 by G. Benato et al.)
- The fact that the resolution is worse than HdM does not invalidate any point of the statistical analysis
- If the resolution is improved, the exclusion will get stronger $\Rightarrow$conservative now

BACKUP: (Some) replies to arXiv:1308.2504

The $0\nu2\beta$ half-life is consequently $(2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ years, and not $(1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr

- Inconsistencies (= missing efficiency factors) in the derivation of the half-life from the number of counts are pointed out in Ann. Phys. 525 (2013) 269.
- We hence regard $(2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr as "invalid" and do not compare against it. Independent authors will judge.
- By the way, the combined Ge limit is well above it.

"and the half-life of $1.19 \cdot 10^{25}$ yr, which they assumed erroneously, is less than the 2σ uncertainty of this half life (which is $(1.19^{+1.08}_{-0.39}) \cdot 10^{25}$ yr)"

- Tab. 7 of NIM A 522 371 reports 28.75 ± 6.86 signal events (1σ). Since the central value corresponds to $1.19 \cdot 10^{25}$ yr and the number of counts is proportional to $1/\mathrm{T}_{1/2}$, the 1σ range of $\mathrm{T}_{1/2}$ is $(0.96\text{-}1.56) \cdot 10^{25}$ yr, as reported by GERDA