First results on the neutrinoless double beta decay from GERDA

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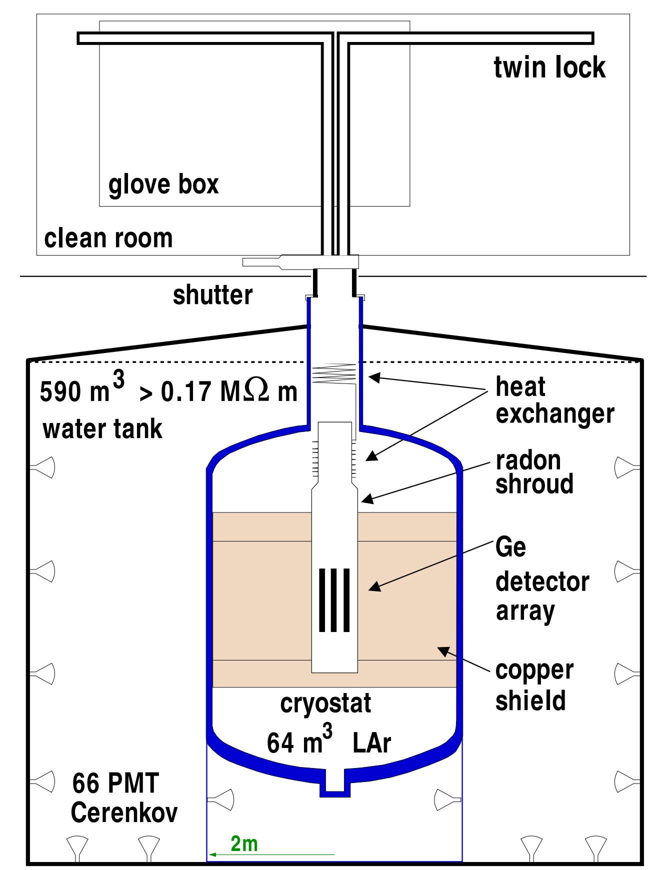
Invisibles workshop
Durham, July 17, 2013



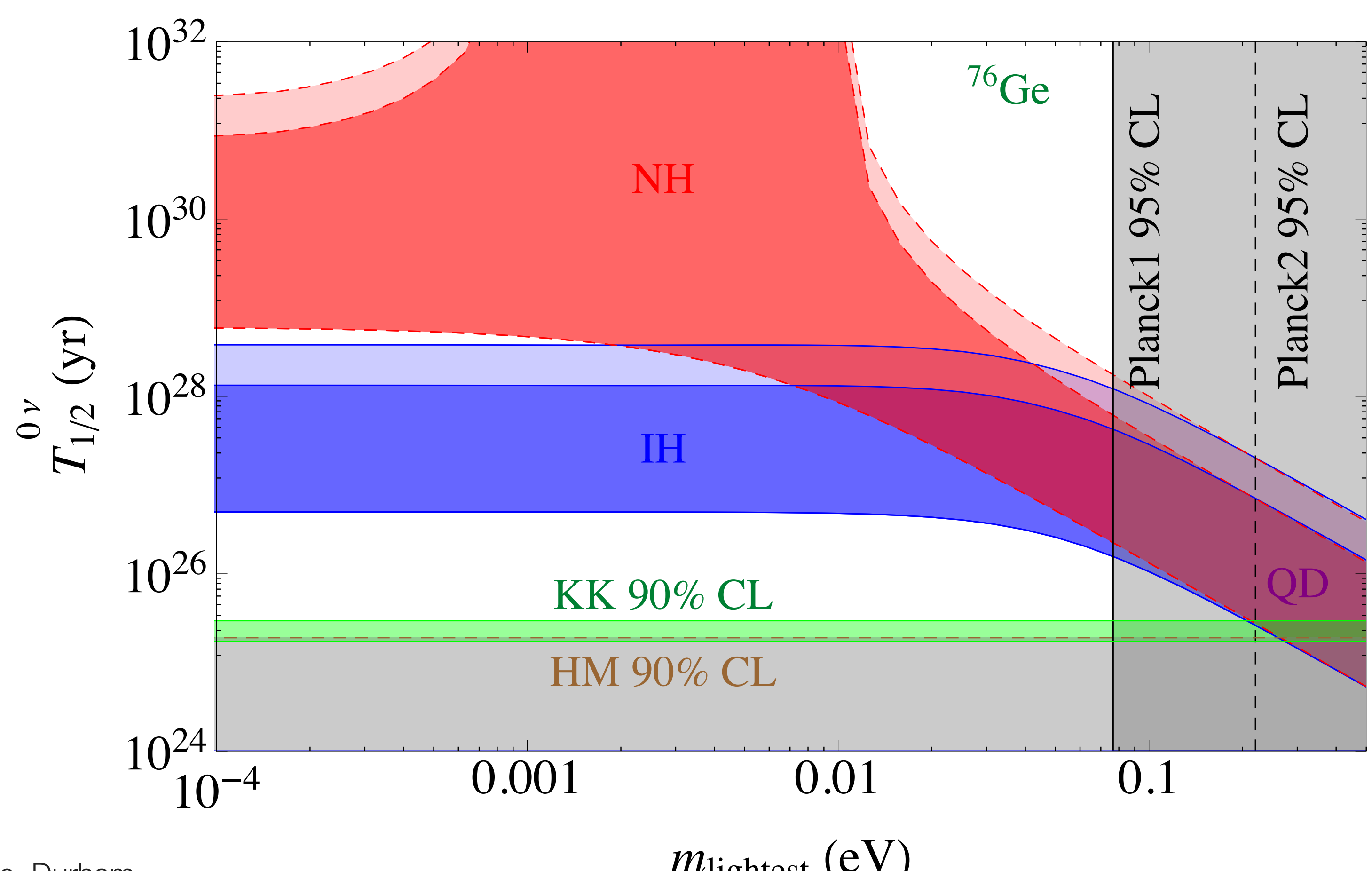
The physics

- Detect the neutrinoless double beta decay in ^{76}Ge:
  - ➡ lepton number violation
  - ➡ information on the nature of neutrinos and on the effective Majorana neutrino mass

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Alonso, Gavela, Isidori, Maiani
(4x10[25] - 8x10[26] yr)
arXiv:1306.5927 [hep-ph]

current sensitivities



arXiv:1305.0056v1 [hep-ph] 30 Apr 2013

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$

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

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

large detector masses (M)
enriched materials (a)
ultra-low background noise (B)
excellent energy resolution (ΔE)
high detection efficiency

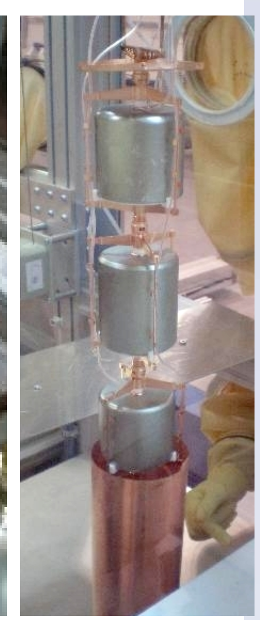
Additional tools to distinguish signal from background:

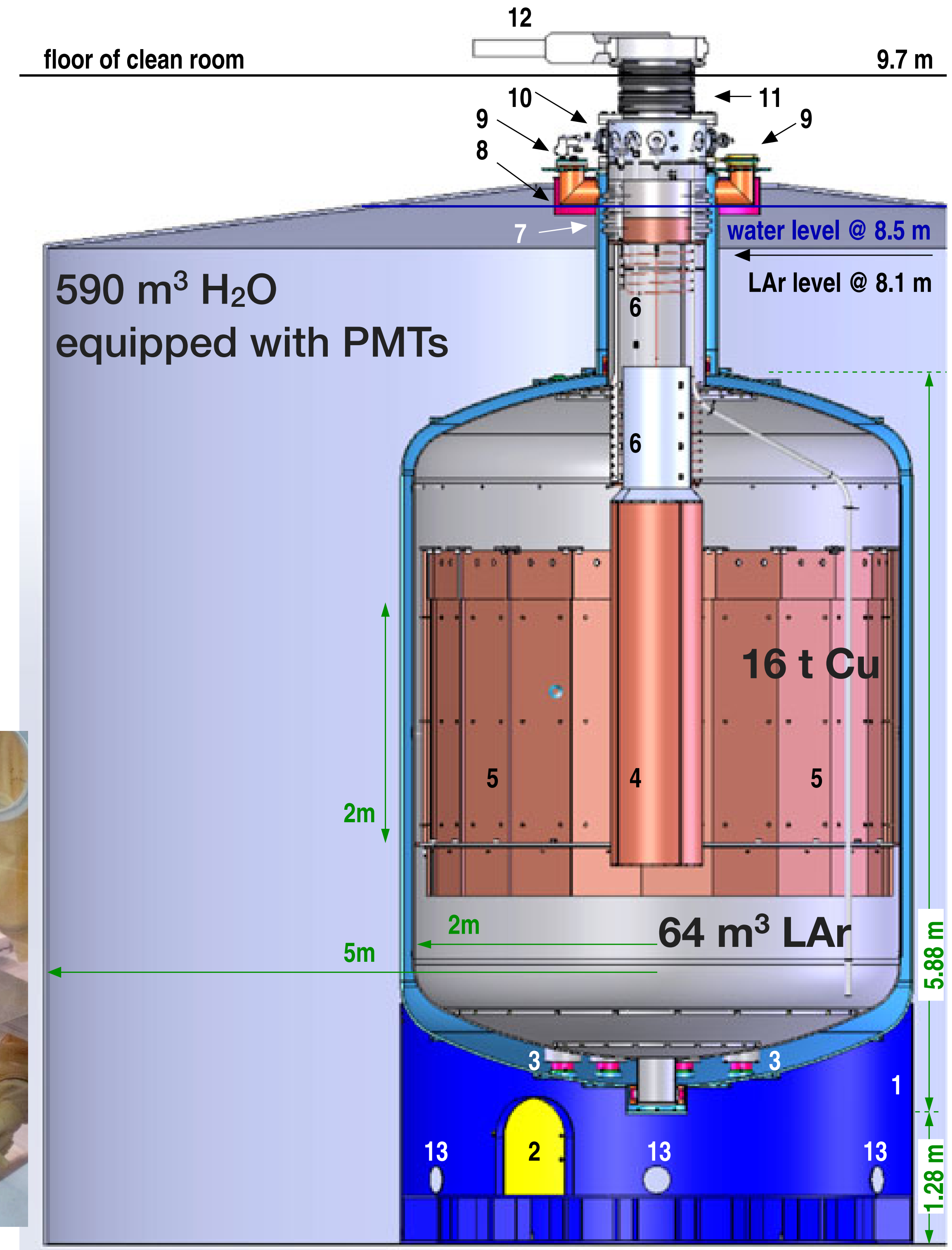
angular distribution
identification of daughter nucleus
pulse shape information
...

The GERDA experiment at LNGS

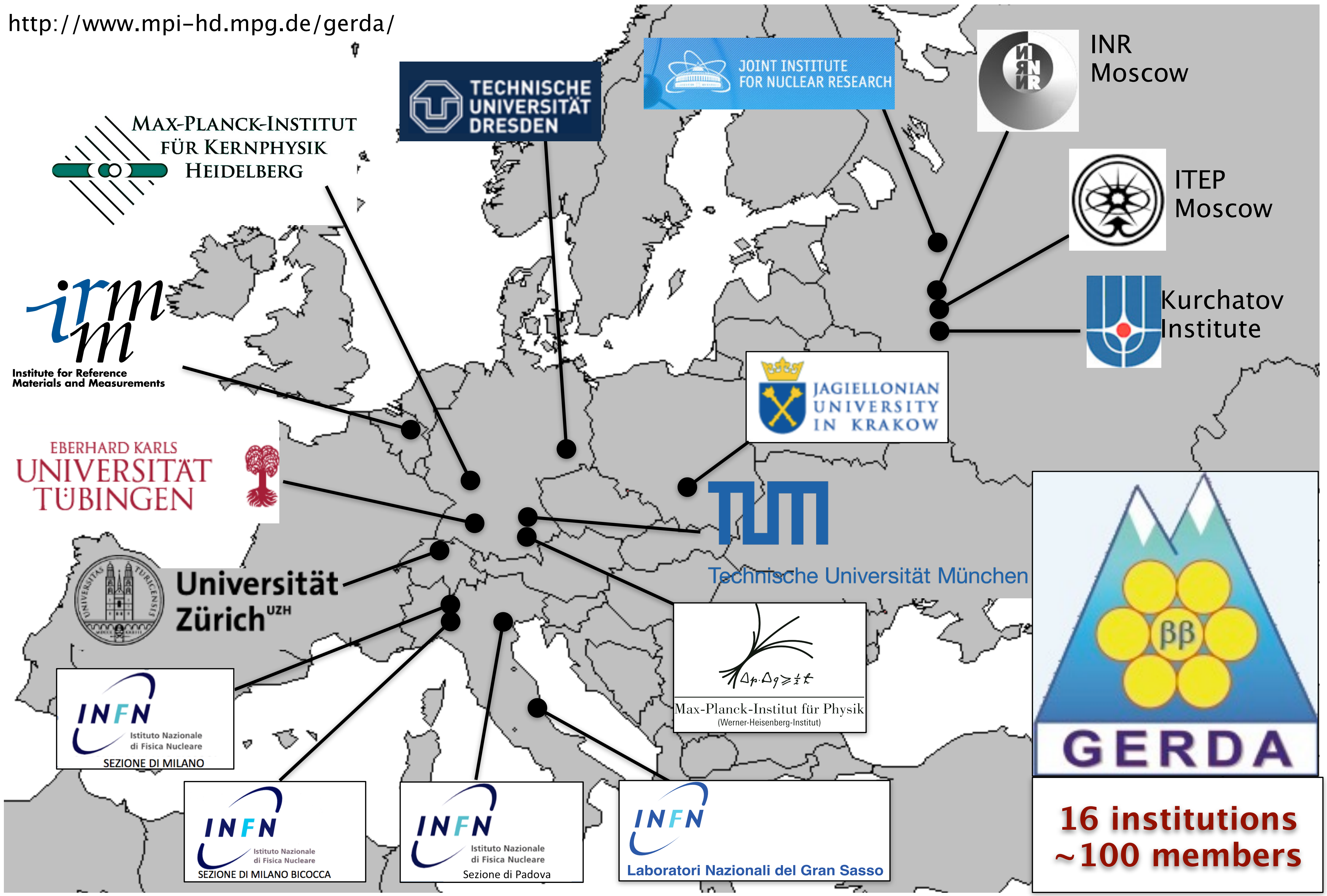
Eur. Phys. J. C (2013) 73:2330

- Ge detectors directly submersed in LAr
  - ➡ LAr as cooling medium and shielding (U/Th in LAr < 7×10^{-4} μBq/kg)
  - ➡ a minimal amount of surrounding materials
- Phase I
  - ➡ ~18 kg HdM and IGEX detectors
- Phase II
  - ➡ additional 20 kg BEGe detectors





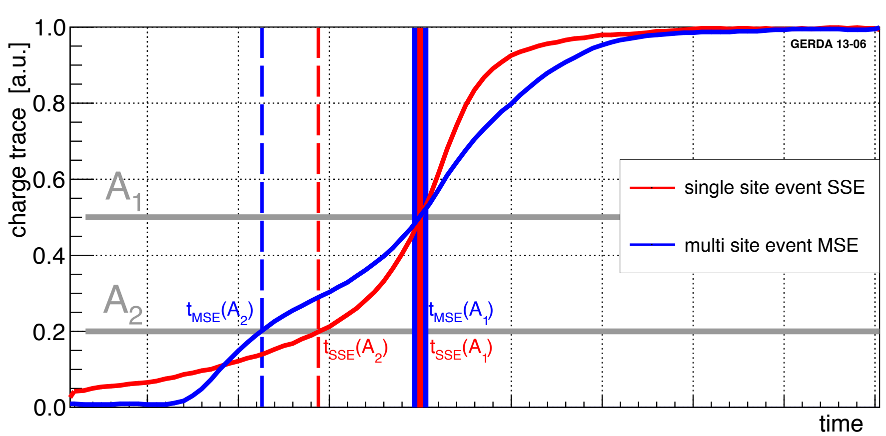
The GERDA collaboration

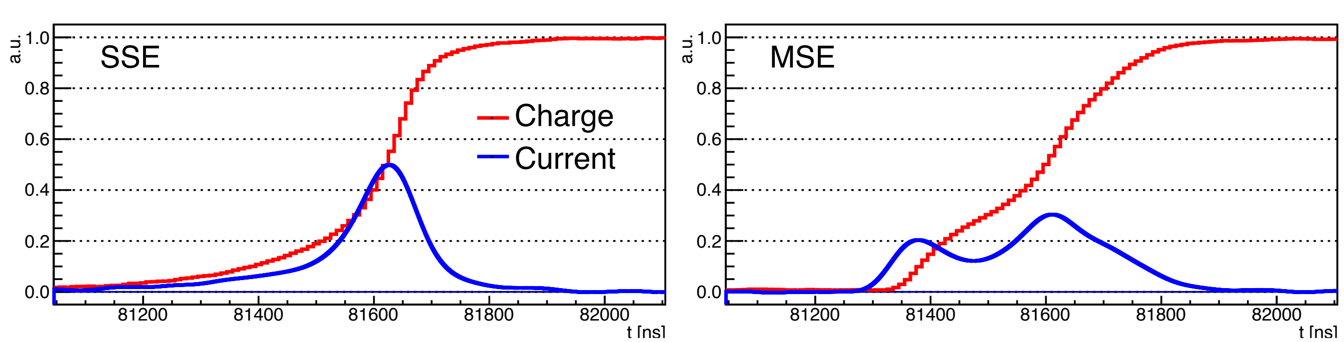


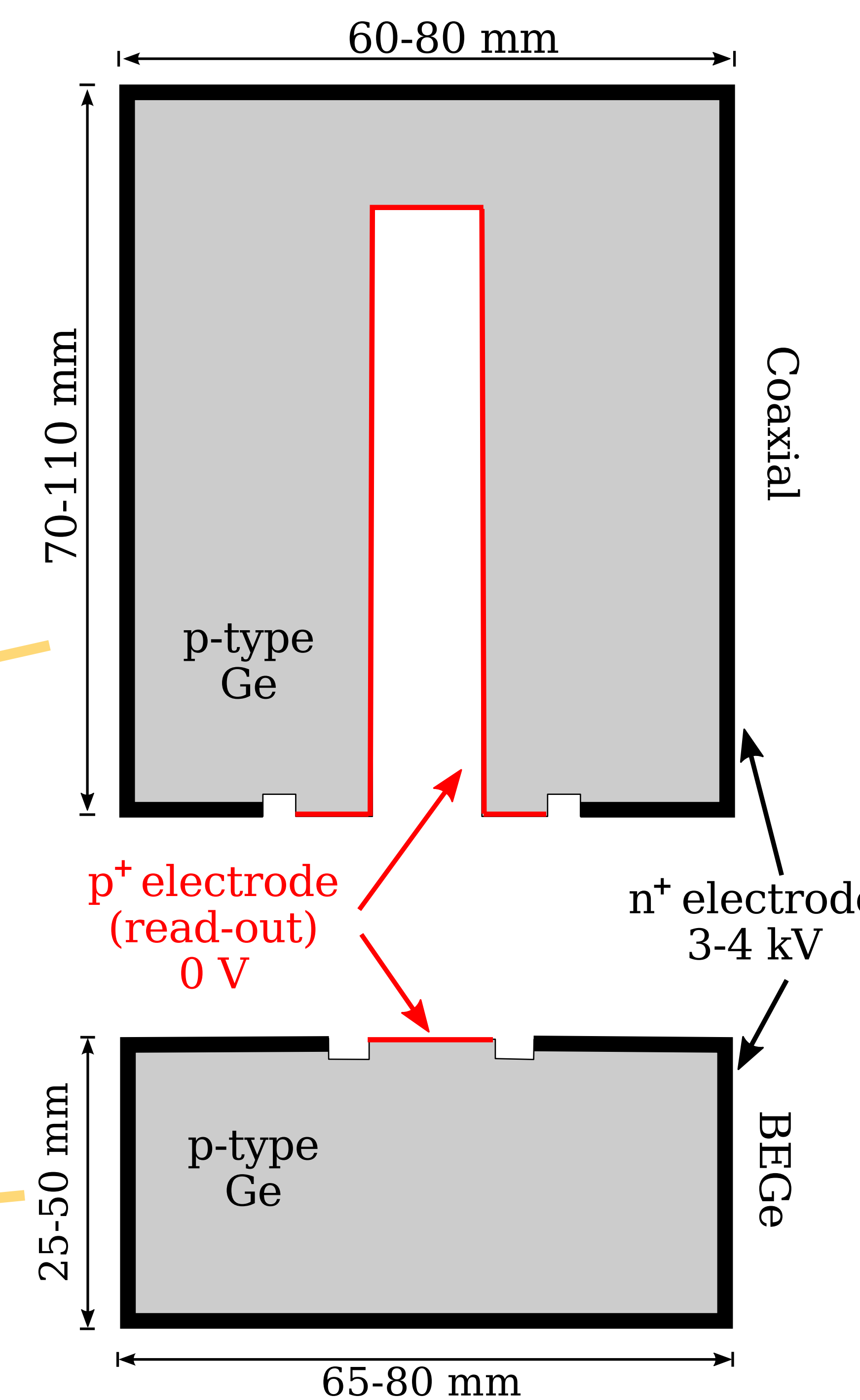
Collaboration meeting in Dubna, June 2013

GERDA detectors

- Phase I: p-type semi-coaxial
- Phase II: p-type, BEGe (broad energy germanium)
- n^+ conductive Li layer, separated by a groove from the boron implanted p^+ contact
- Signal structure allows to distinguish between *single site events (SSE)* = signal-like and *multiple site events (MSE)* = background-like





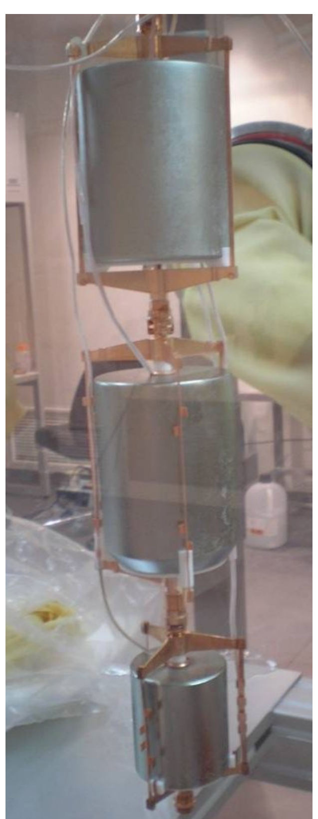
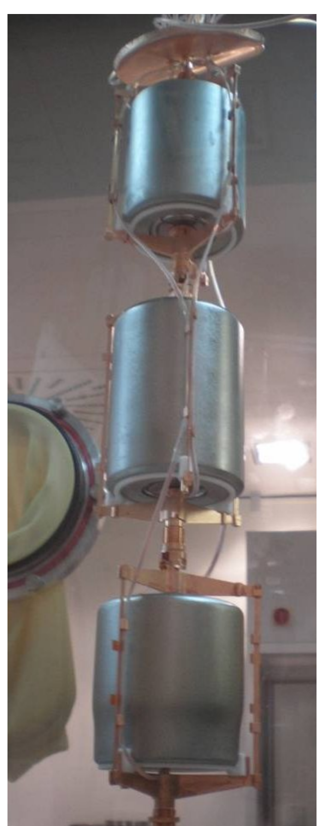


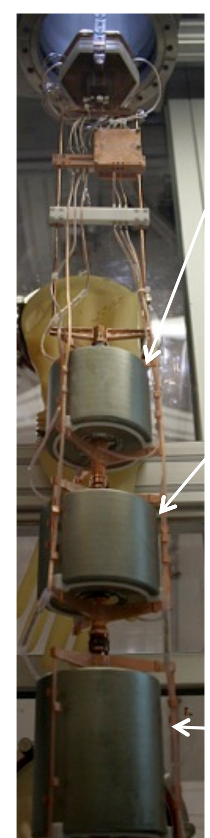
arXiv:1307.2610v1

GERDA detectors

- From HdM and IGEX experiments: total mass = 17.7 kg
  - ➡ HdM: ANG1, ANG2, ANG3, ANG4, ANG5; IGEX: RG1, RG2, RG3
  - ➡ Isotopically enriched in ^{76}Ge: 86%

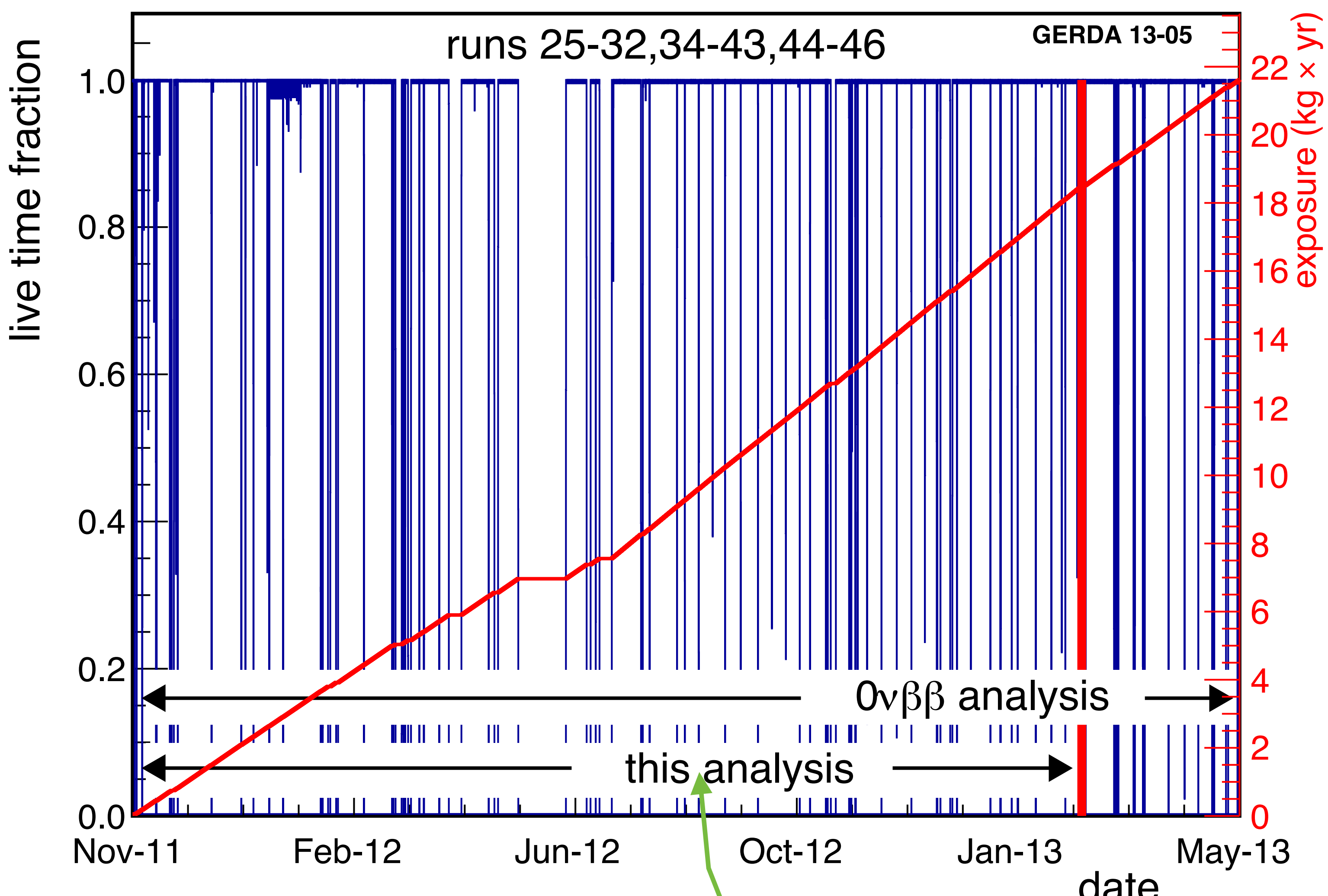
- Two ^{76}Ge detectors turned off because of high leakage current => m = 14.6 kg
- In addition, natural Ge detectors from Genius-TF
- And 5 phase II, enriched BEGe detectors added in July 2012



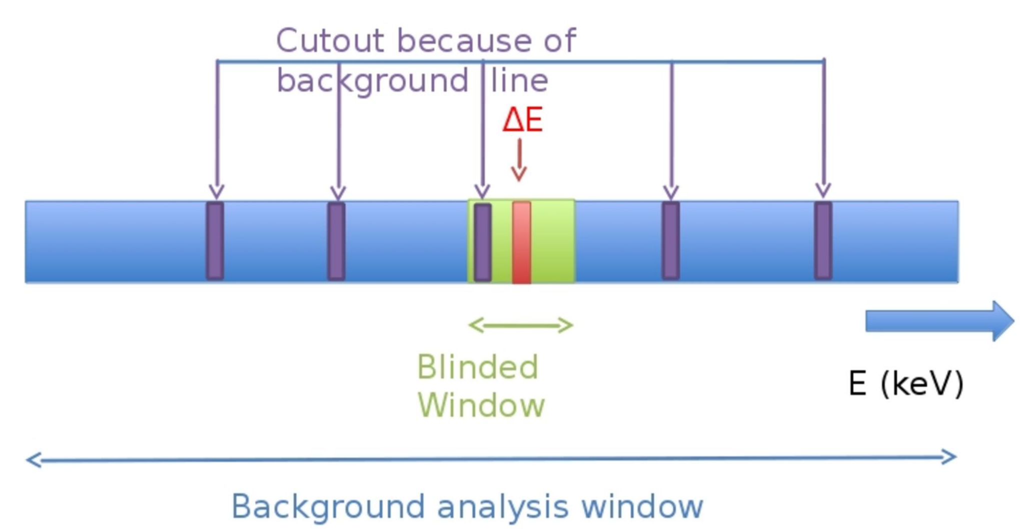

Overview of physics runs

total exposure Phase I, used in neutrinoless double beta analysis: 21.6 kg yr (215.2 mol yr ^{76}Ge in active volume)

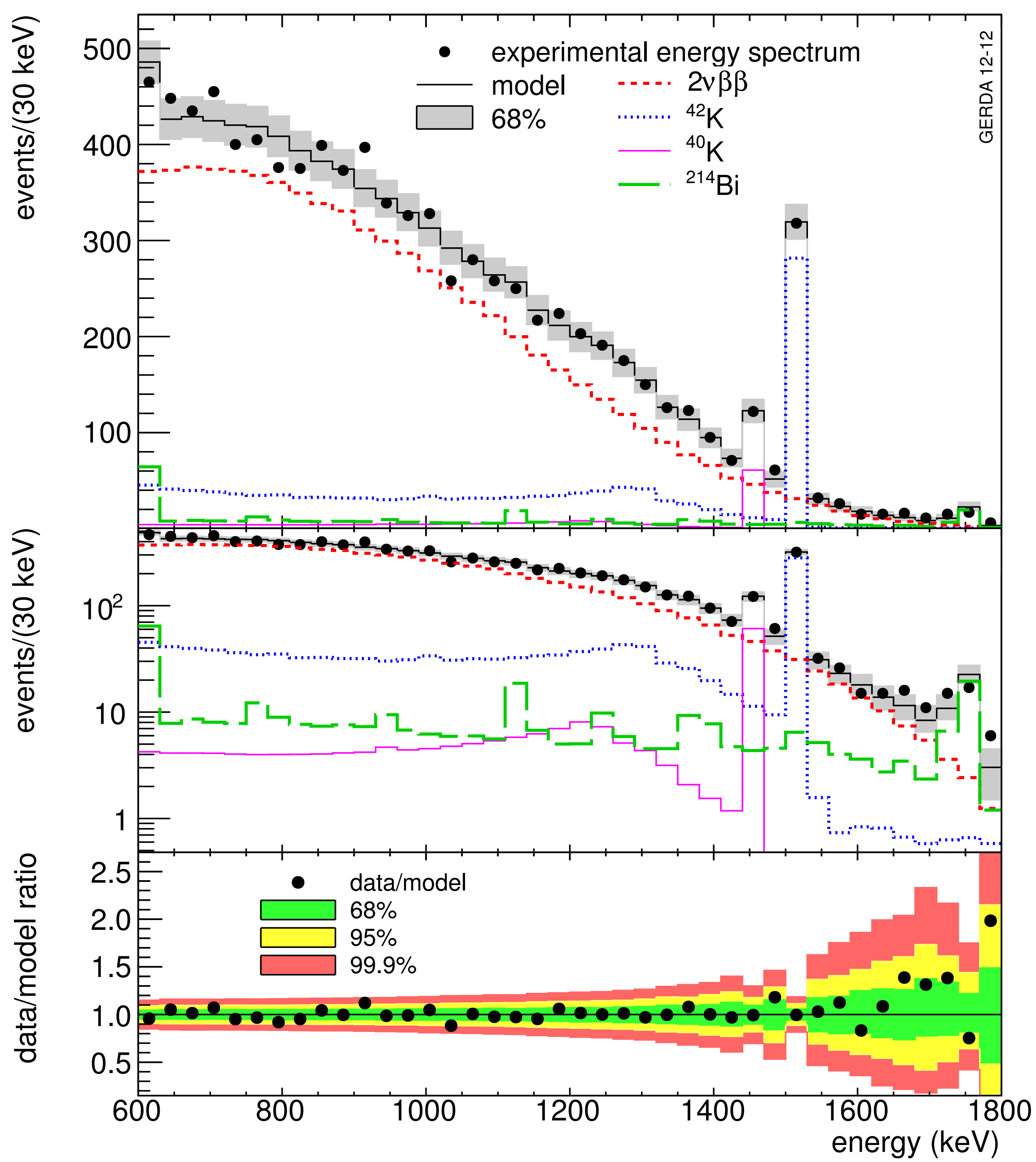


data used for background model

- Blue 'spikes': (bi) weekly calibrations runs with 3 ^{228}Th sources
- Data in signal region was kept blind: Q ± 20 keV



Half life of the 2-neutrino decay mode



IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

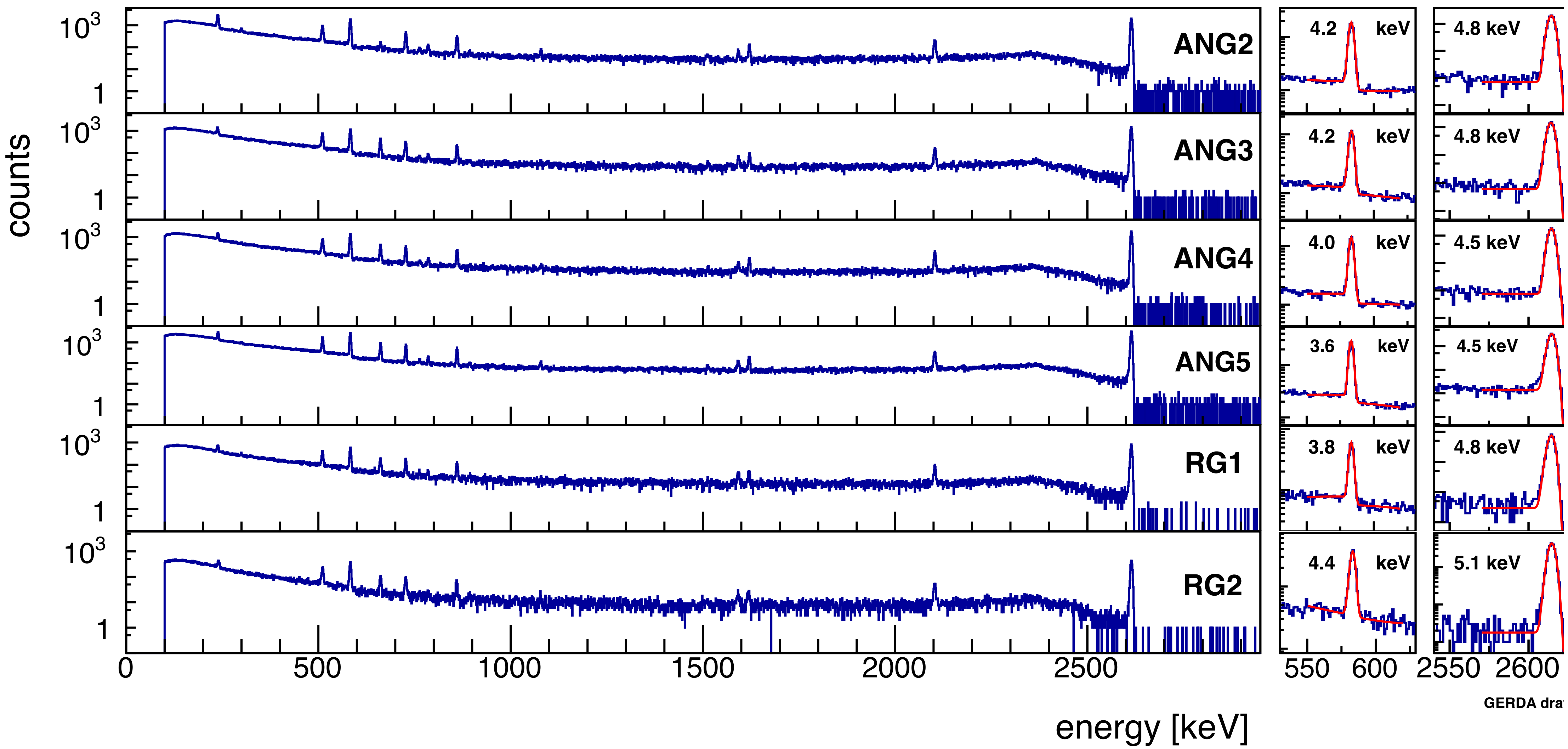
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment

$$T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08}\right) \times 10^{21}\ \mathrm{yr}$$

Item	Uncertainty on $T^{2\nu}_{1/2}$ (%)	
Non-identified background components	+5.3	
Energy spectra from ^{42}K, ^{40}K and ^{214}Bi	±2.1	
Shape of the $2\nu\beta\beta$ decay spectrum	±1	
Subtotal fit model		$^{+5.8}_{-2.3}$
Precision of the Monte Carlo geometry model	±1	
Accuracy of the Monte Carlo tracking	±2	
Subtotal Monte Carlo		±2.2
Data acquisition and selection		±0.5
Grand total		$^{+6.2}_{-3.3}$

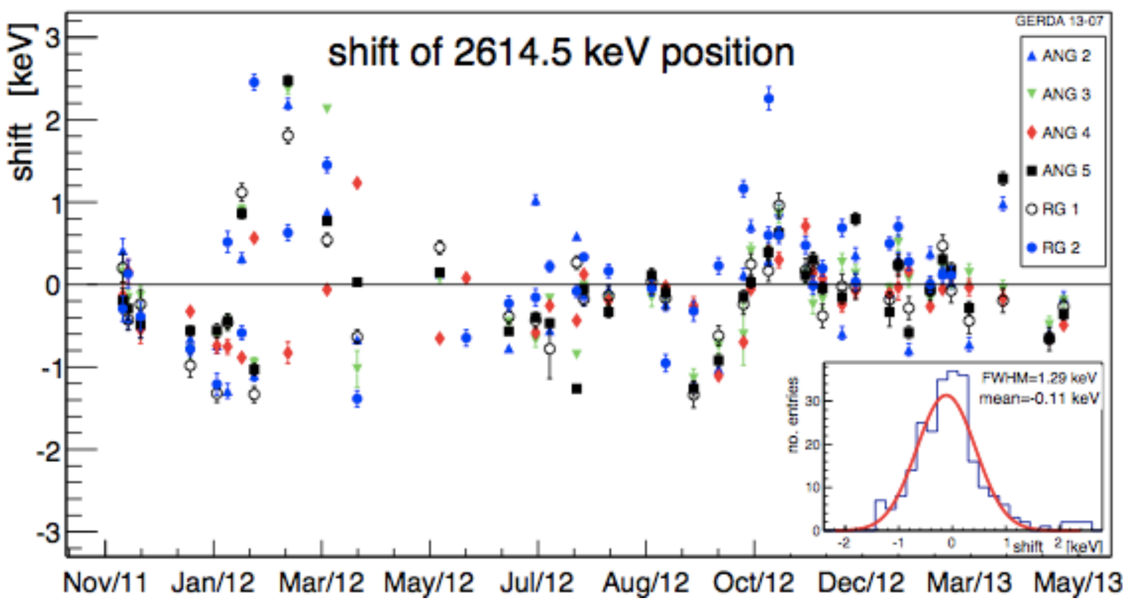
GERDA Calibration

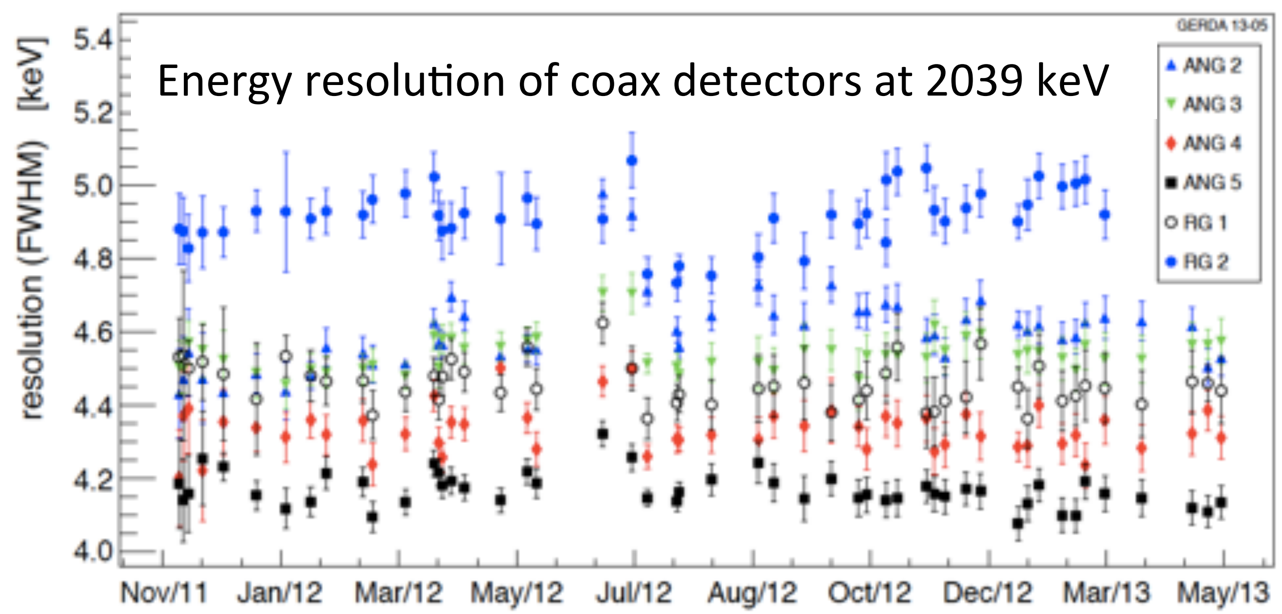
- Determine energy resolution and stability in time
- Energy resolution: ~ 4.5 - 5.1 keV (FWHM) at 2.6 MeV
- Mean energy resolution at Q=2039 keV: 4.8 keV and 3.2 keV for coaxial and BEGe (FWHM)



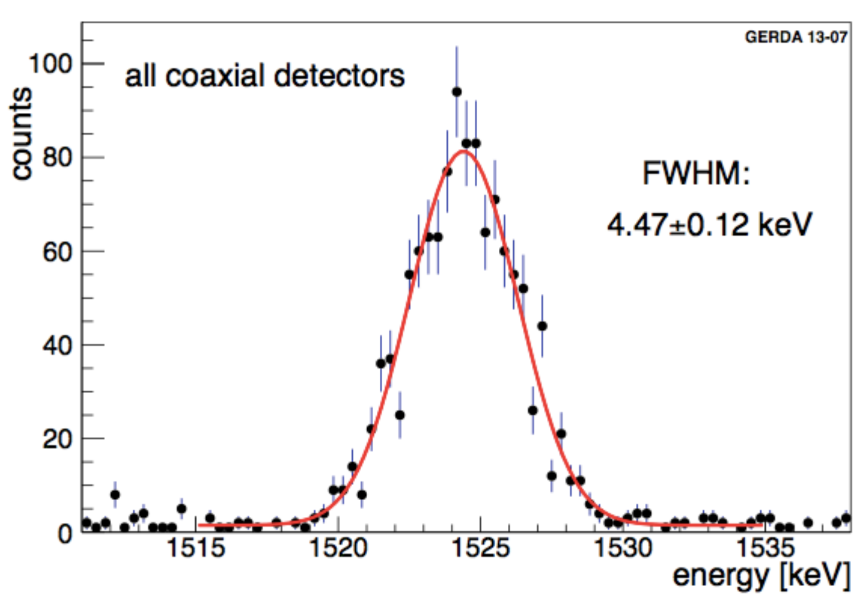
Calibration stability

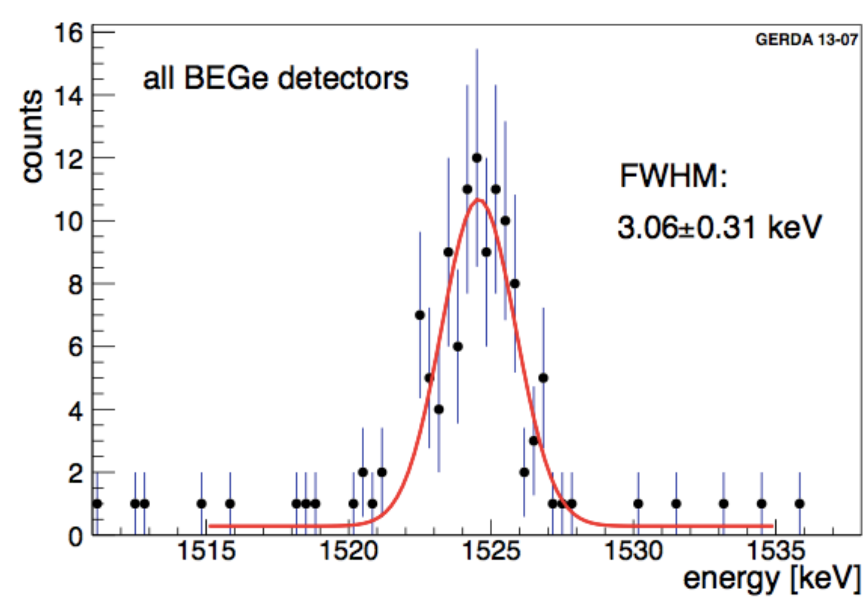
- Mean energy resolution at Q=2039 keV: 4.8 keV and 3.2 keV for coaxial and BEGe (FWHM)





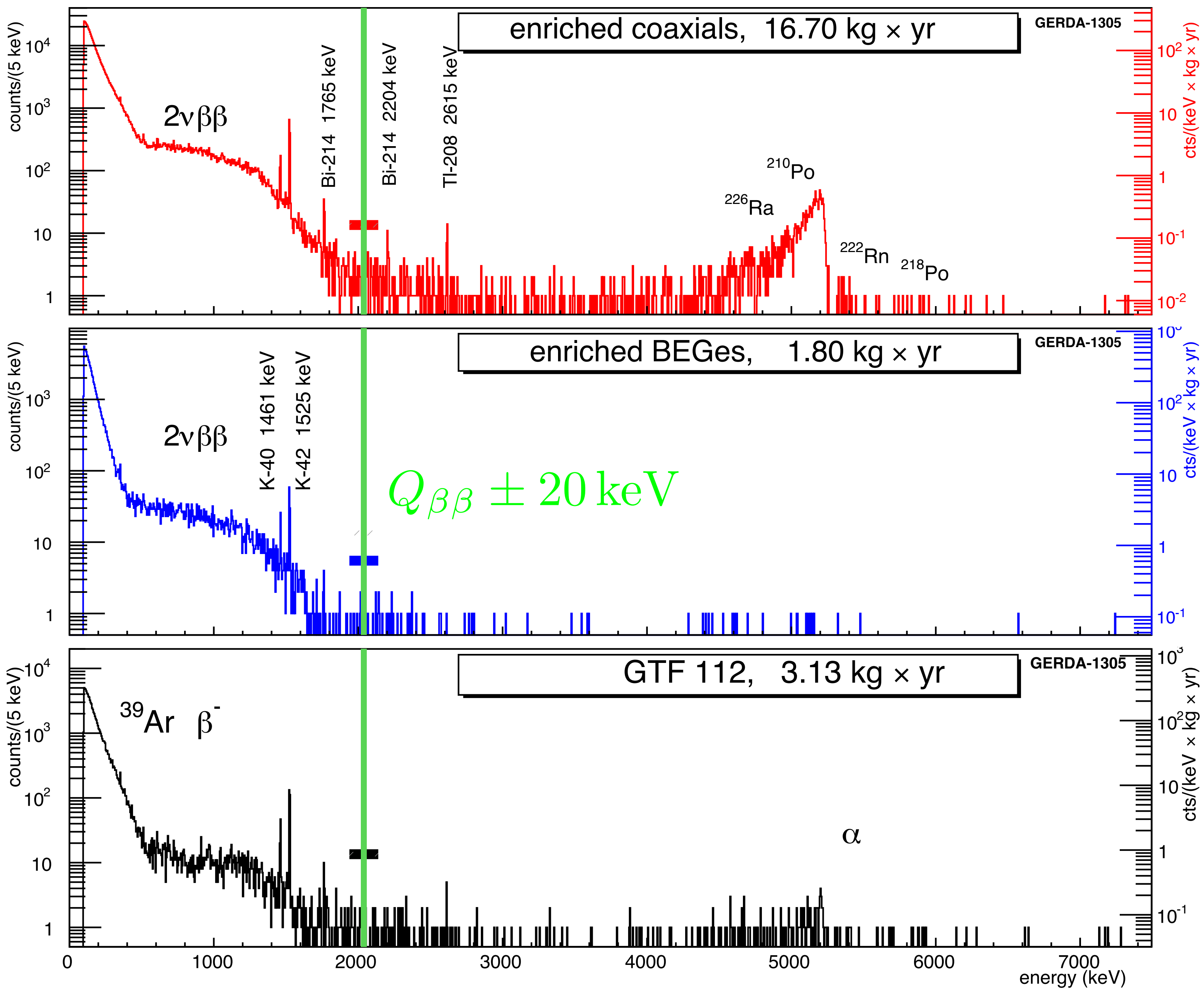
^{42}K background line





Backgrounds

arXiv:1306.5084v1 [physics.ins-det] 21 Jun 2013

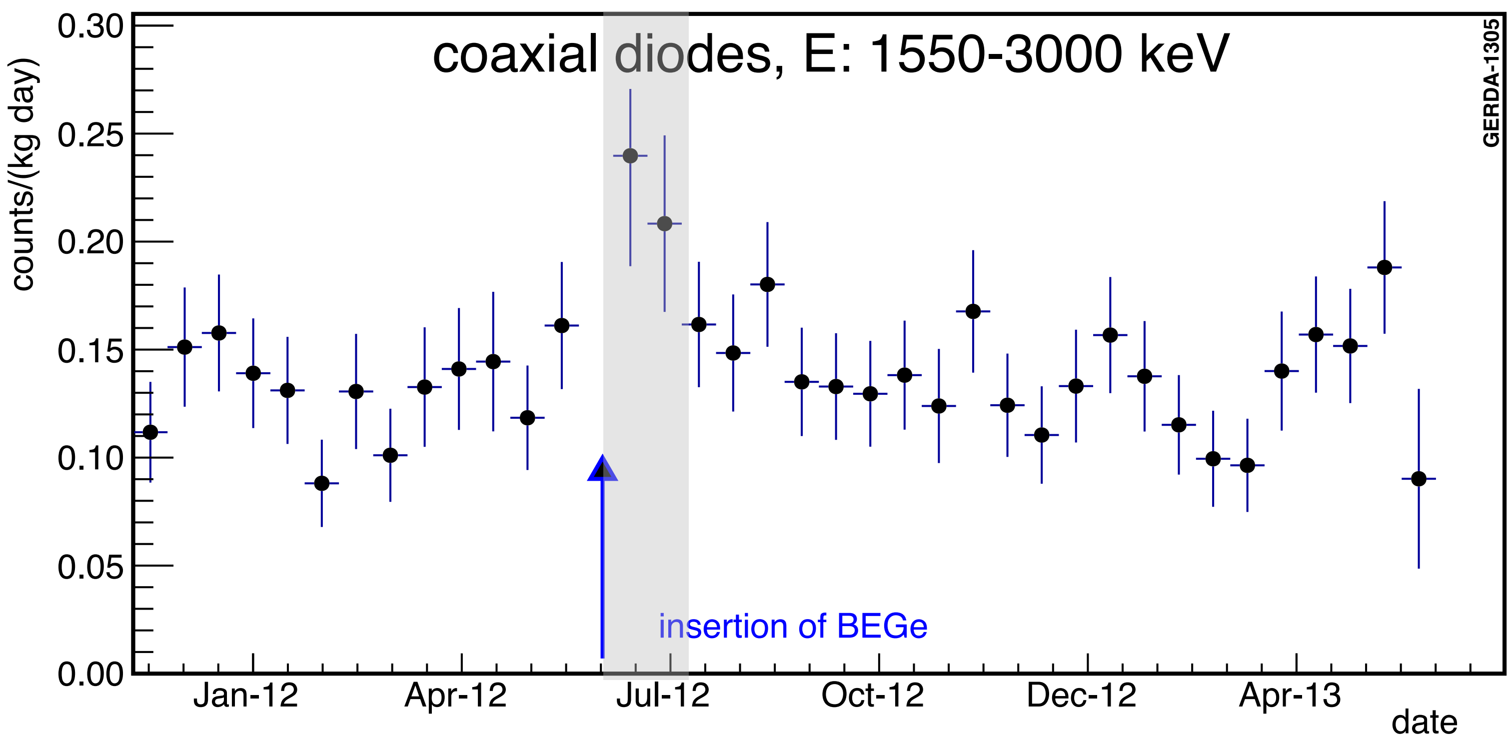


- main sources considered in the background model

source	location
^{210}Po ^{226}Ra chain ^{222}Rn chain	p^+ surface p^+ surface LAr in bore hole
^{214}Bi and ^{214}Pb	n^+ surface mini-shroud detector assembly p^+ surface radon shroud LAr close to p^+ surface
^{208}Tl and ^{212}Bi	detector assembly radon shroud heat exchanger
^{228}Ac	detector assembly radon shroud
^{42}K	homogeneous in LAr n^+ surface p^+ surface
^{60}Co	detectors detector assembly
$2\nu\beta\beta$	detectors
^{40}K	detector assembly

Three data sets

- The *BEGe set*; the coaxial data, which is split into *gold* and *silver*



background rate in the coaxial ^{76}Ge detectors versus time

grey band = silver-coax
rest = gold-coax

data set	detectors	exposure $\mathcal{E}$ this analysis kg·yr	exposure $\mathcal{E}$ $0\nu\beta\beta$ analysis kg·yr
SUM-coax	all enriched coaxial	16.70	19.20
GOLD-coax	all enriched coaxial	15.40	17.90
SILVER-coax	all enriched coaxial	1.30	1.30
GOLD-nat	GTF 112	3.13	3.98
GOLD-hdm	ANG 2, ANG 3, ANG 4, ANG 5	10.90	12.98
GOLD-igex	RG 1, RG 2	4.50	4.93
SUM-bege	GD32B, GD32C, GD32D, GD35B	1.80	2.40

detailed exposures for all three data sets

The background model

arXiv:1306.5084v1 [physics.ins-det] 21 Jun 2013

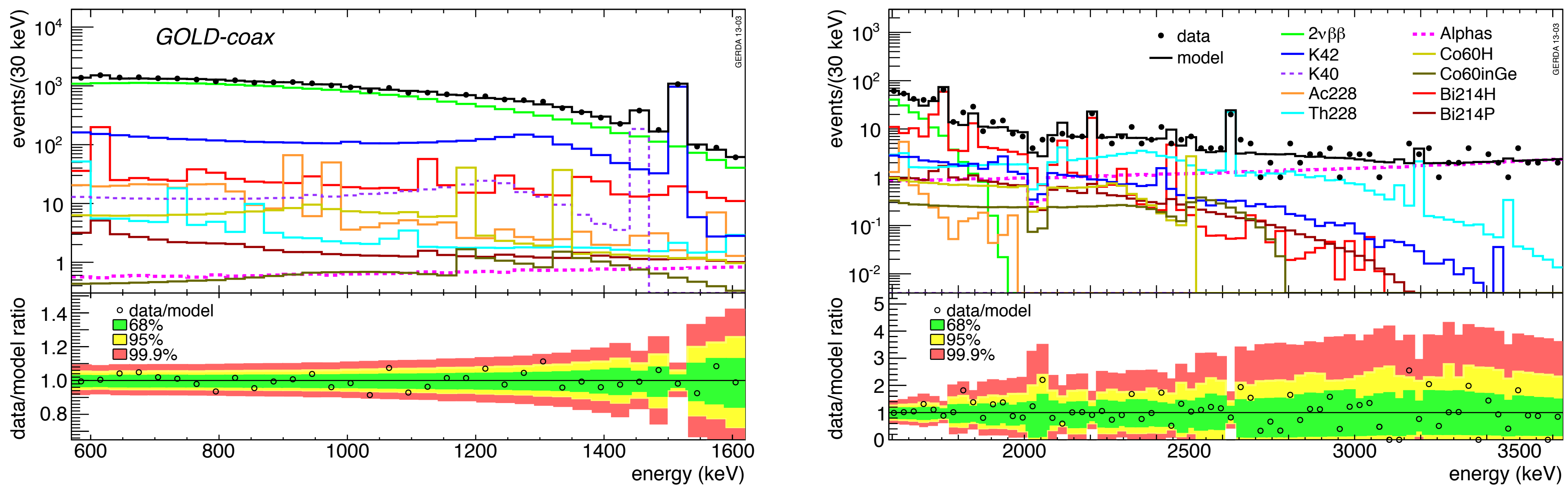
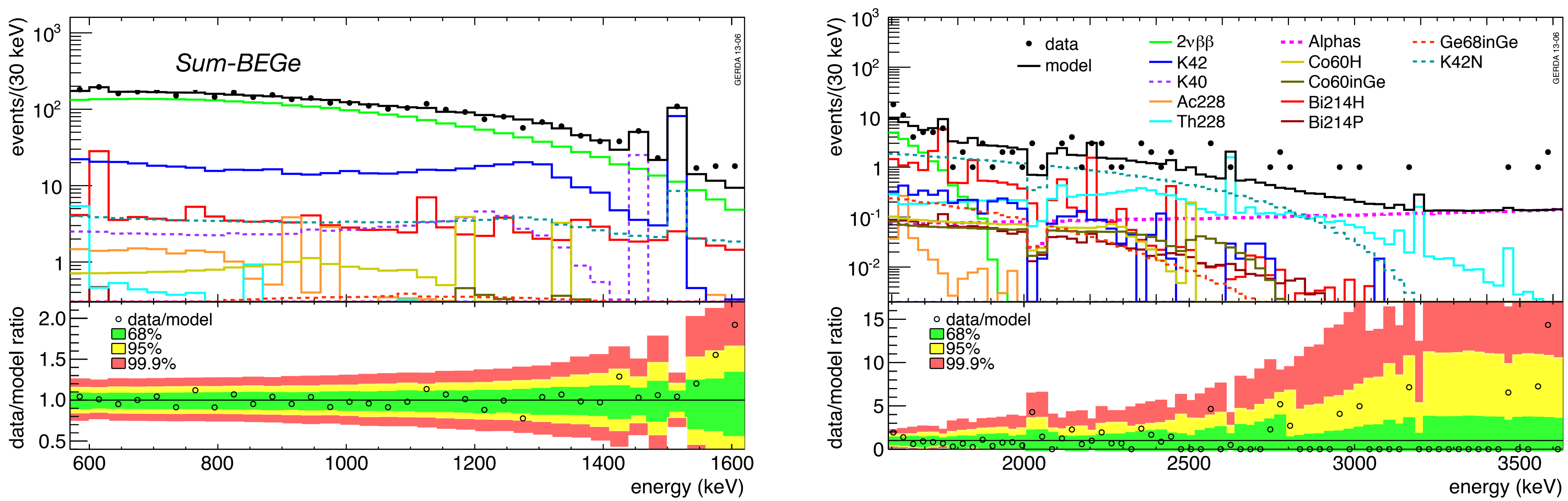
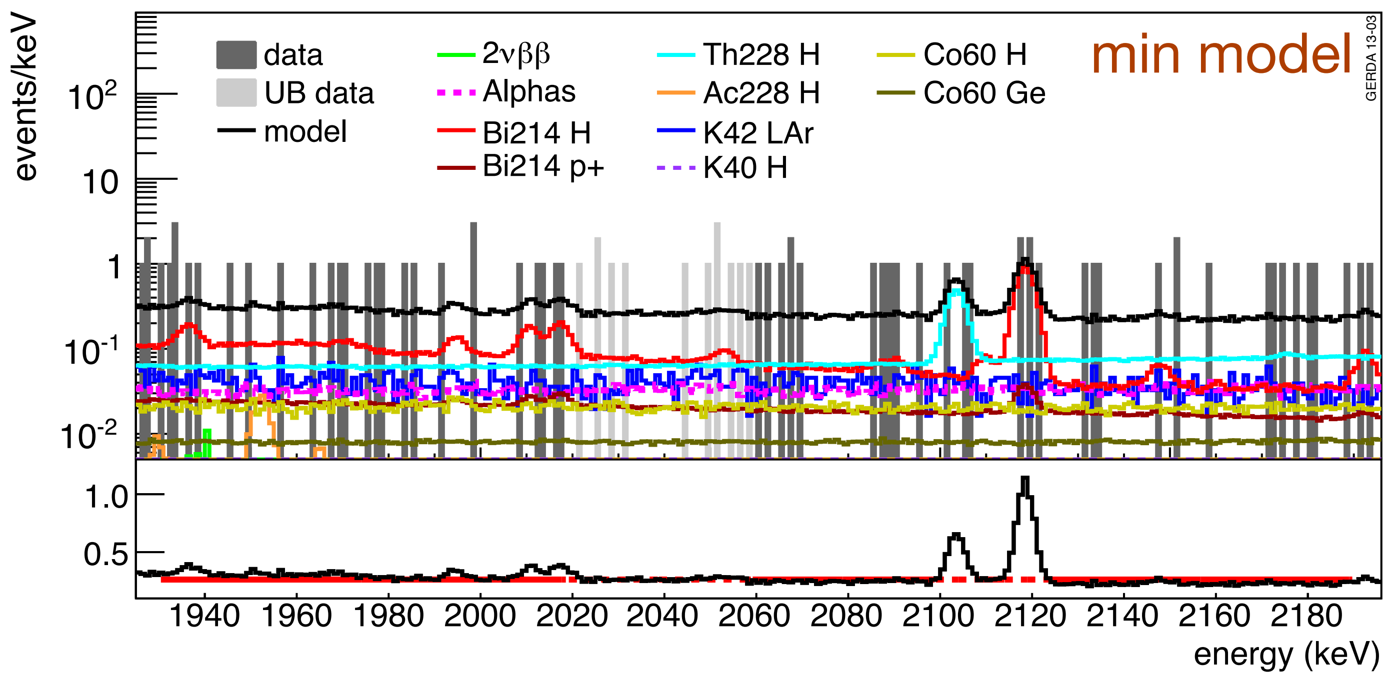


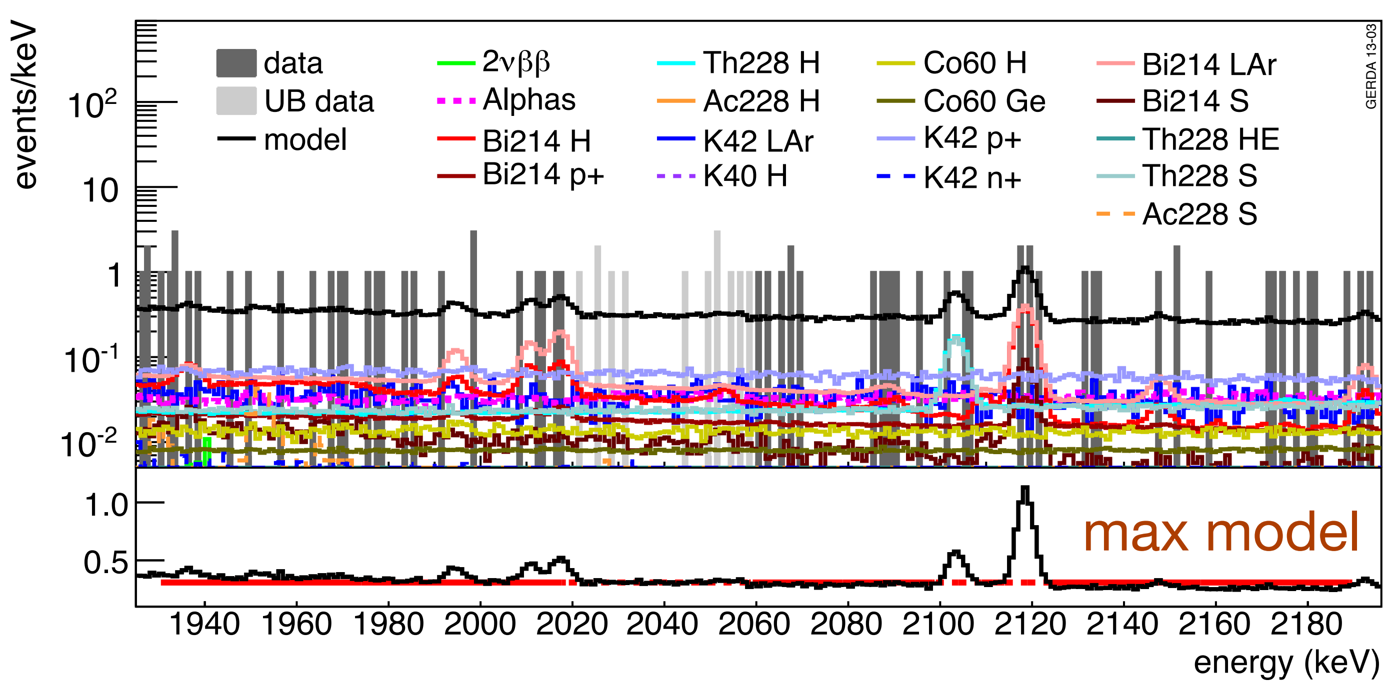
Fig. 12 Background decomposition according to the best fit minimum model of the *GOLD-coax* data set. The lower panel in the plots shows the ratio between the data and the prediction of the best fit model together with the smallest intervals of 68 % (green band), 95 % (yellow band) and 99.9 % (red band) probability for the ratio assuming the best fit parameters.



Background in the ROI for the double beta decay

- Consistent with a flat background in the energy region: 1930 keV - 2190 keV





The background level interpolated into the region of interest, before PSD, is:

Coaxial:

$$\left(1.75^{+0.26}_{-0.24}\right) \cdot 10^{-2}\,\mathrm{events/(keV\,kg\,yr)}$$

BEGe

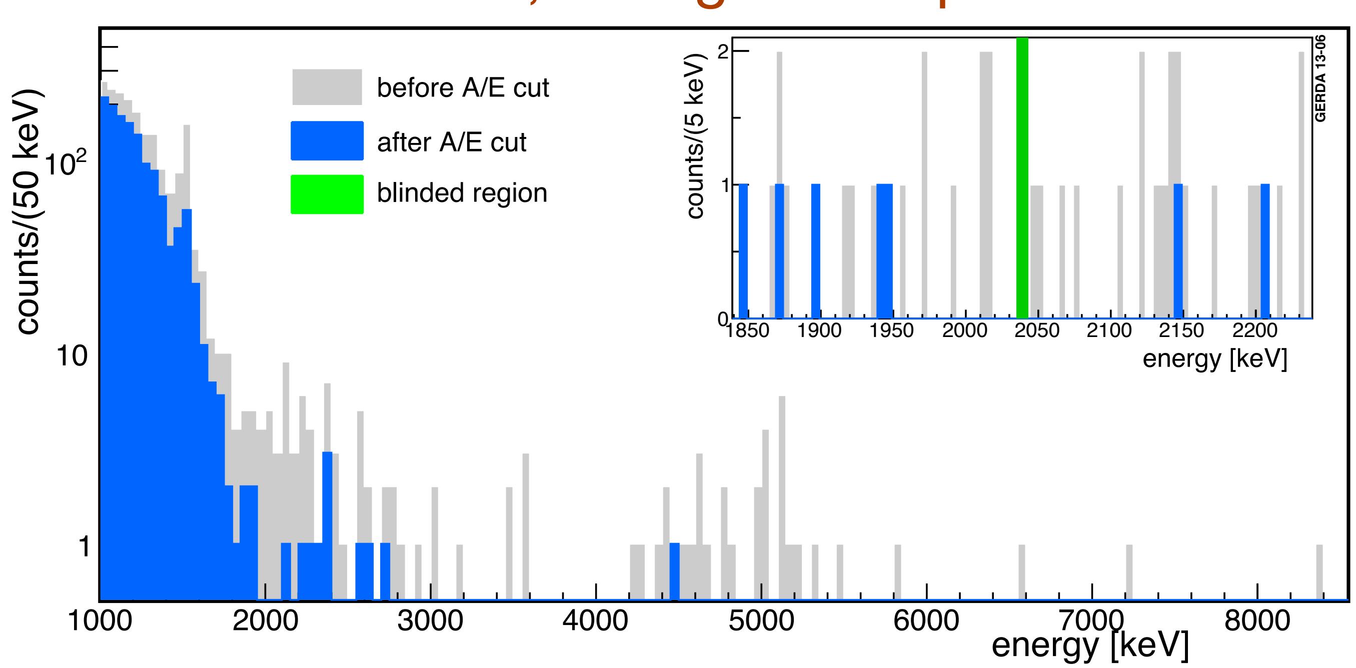
$$\left(3.6^{+1.3}_{-1.0}\right) \cdot 10^{-2}\,\mathrm{events/(keV\,kg\,yr)}$$

Linear fit with flat background in 1930 keV - 2190 keV, excluding peaks at 2104 keV and 2119 keV

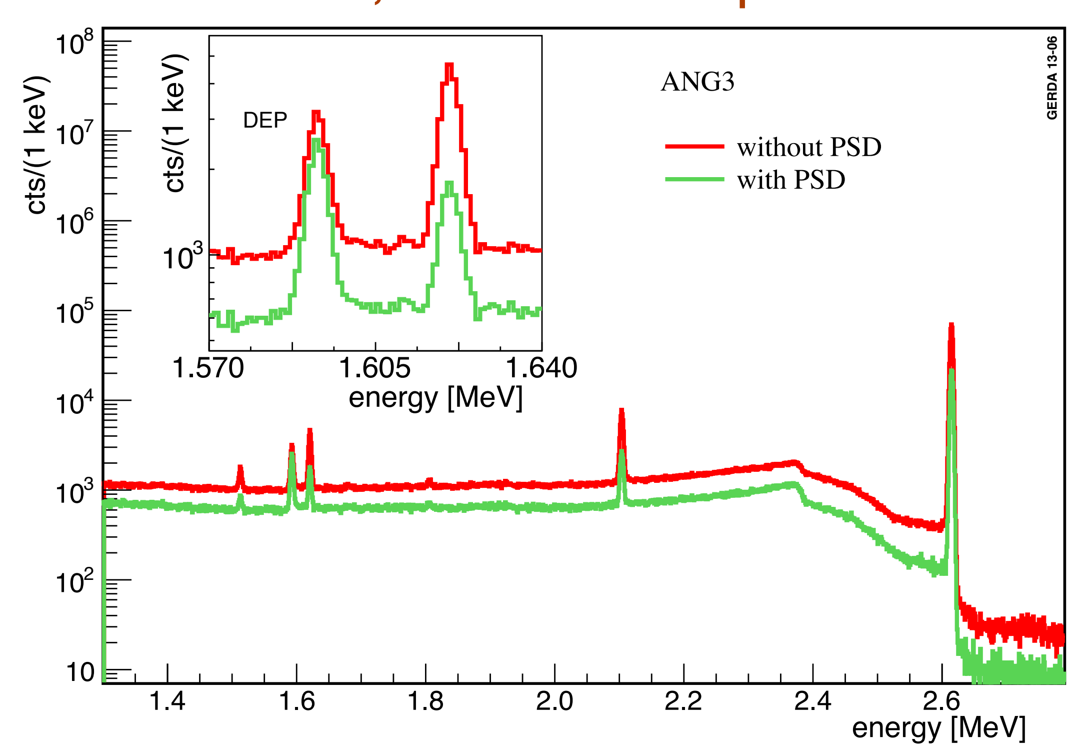
Pulse shape discrimination

- BEGes: simple *A/E-parameter* cut (A= max of current pulse; E = energy)
  - ➡ rejects 80% of background events
  - ➡ keeps 92% of signal-like events
- Coaxial Ge: *neural network analysis* (cross-checked by two additional methods)
  - ➡ rejects 45% of background events
  - ➡ keeps 90% of signal-like events
- Tested on events in double-escape peak (DEP), Compton-edge, 2nbb spectrum (all signal-like), and full energy peak (background-like)

BEGe, background spectrum

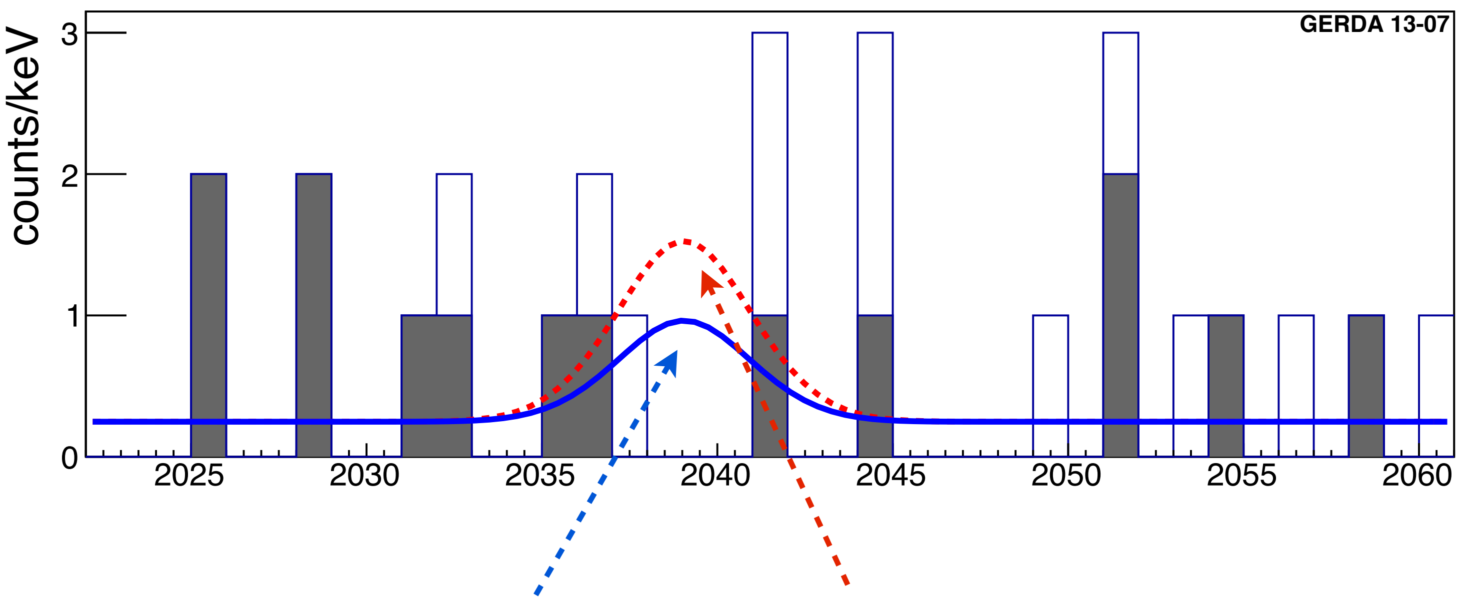


Coaxial, ^{228}Th calib spectrum



arXiv:1307.2610v1

After unblinding



"Claim", PLB586 (2004)

$$T_{1/2}^{0\nu} = 1.19 \times 10^{25}\,\mathrm{yr}$$

GERDA lower limit from PL fit of the 3 data sets, with constant term for background (3 parameters for the 3 data sets) and Gaussian term for signal: *best fit is $N_{signal} = 0$*

$$T_{1/2}^{0\nu} > \; 2.1 \times 10^{25}\,\mathrm{yr}\ (90\%\,\mathrm{C.L.})$$

- the limit on the half life corresponds to $N_{signal} < 3.5$ counts

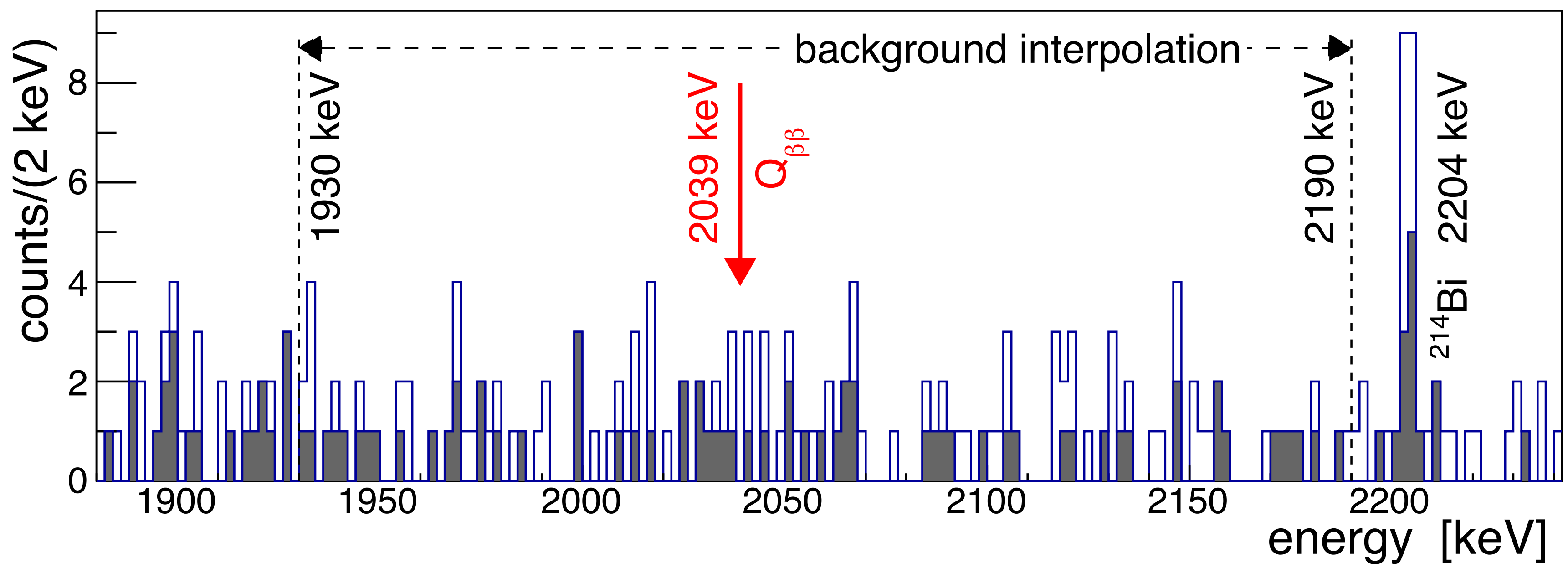
- Observed and predicted number of background events in the energy region $Q_{\beta\beta} \pm 5$ keV

	Observed	Predicted background
No PSD	7	5.1
PSD	3	2.5

- 5.9 ± 1.4 events are expected for "claim", and 2.0±0.3 signal events

Claim of evidence for 0vbb-decay:
signal: 28.8 ± 6.9 events
BG level: 0.11 counts/(keV kg yr)
HVKK et al., PLB 586 (2004) 198-212

After unblinding



data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

†) in units of 10^{-3} cts/(keV·kg·yr).

data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 1	2041.7	27-Apr-2013 22:21	no

Bayesian analysis with flat prior on $1/T_{1/2}$: $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% credible interval)

Bayes factor = P(H1)/P(H0) = 0.024 disfavors signal claim
H(1): model that includes background + claimed signal; H(0): model with background only

Combination with previous ^{76}Ge results (from HdM and IGEX)

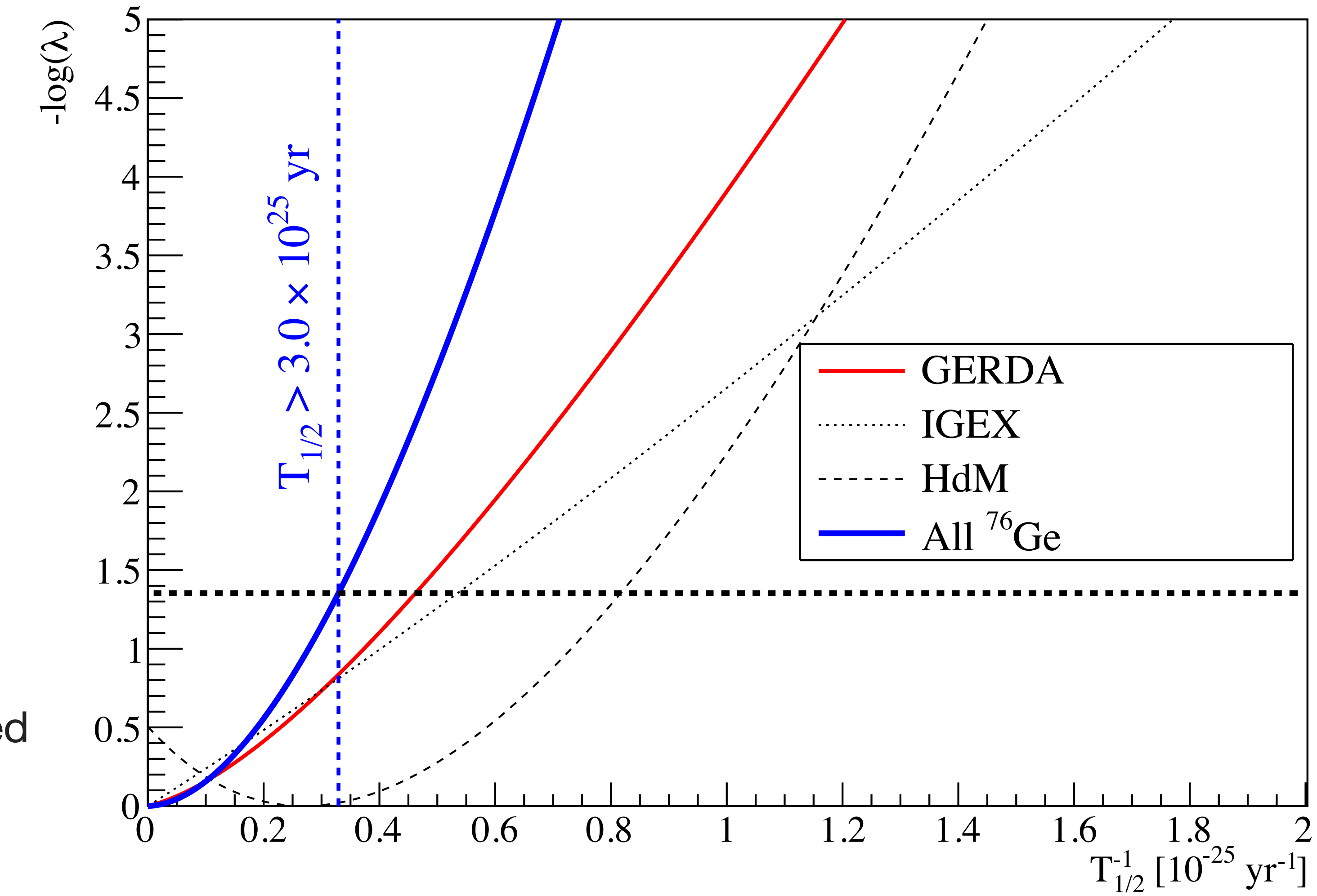
HdM: Eur. Phys. J A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002)
and Phys. Rev. D 70, 078302 (2004)

$$T^{0\nu}_{1/2} > \ 3 \times 10^{25}\,\mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

Bayes factor = P(H1)/P(H0) = 2x10^{-4} strongly disfavors signal claim

H(1): model that includes background + claimed signal; H(0): model with background only

Profile likelihood, all Ge data



Comparison is independent of nuclear matrix elements and mechanism which generates the neutrinoless double beta decay

Summary and outlook

- No indication for a peak at Q = 2039 keV in GERDA phase I data

- GERDA provides a model-independent test of the signal claim

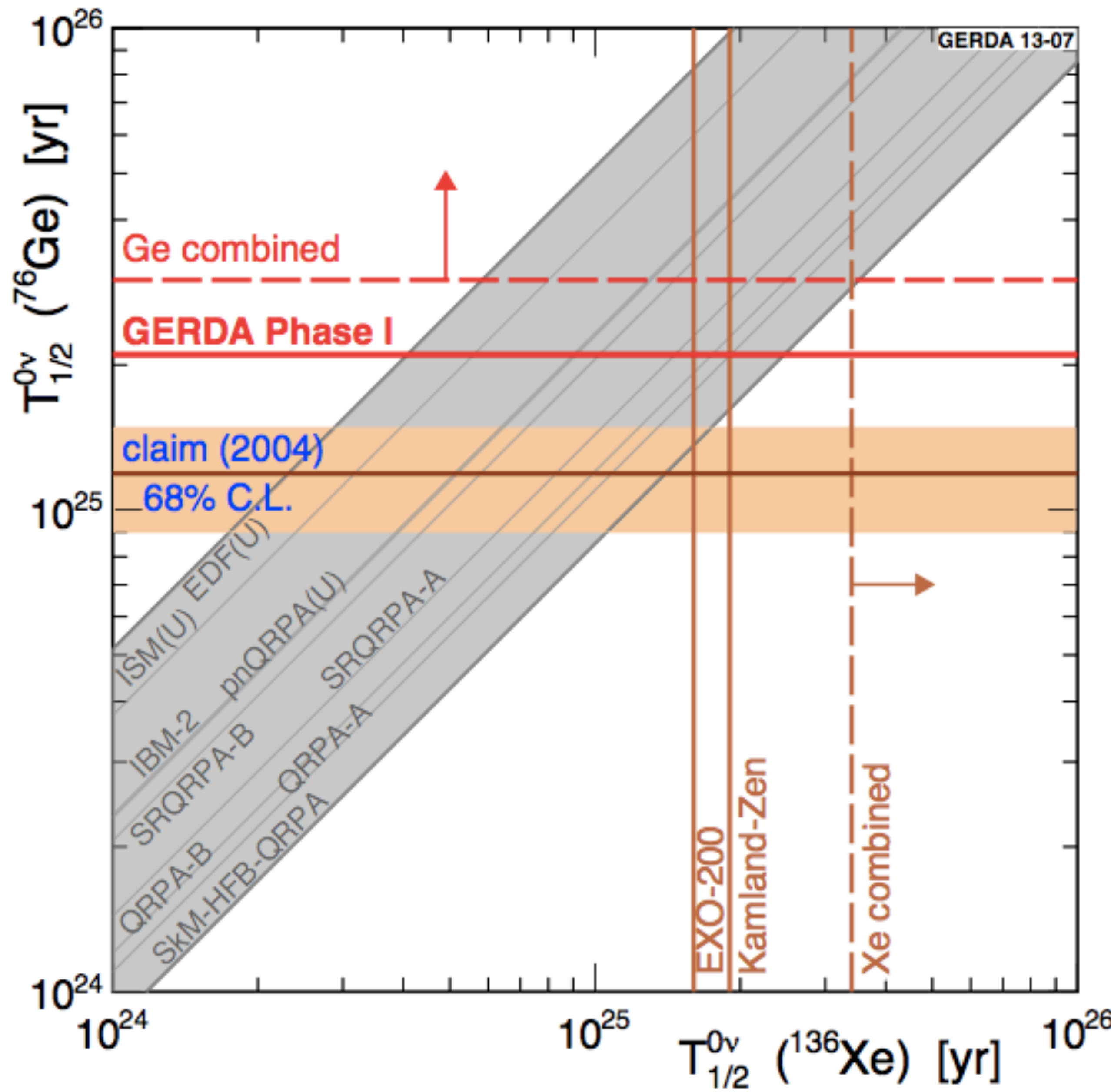
- Combined with HdM and IGEX:

$$T_{1/2}^{0\nu} > \ 3 \times 10^{25}\,\mathrm{yr}\ (90\%\,\mathrm{C.L.})$$

- This yields an upper limit on the effective Majorana neutrino mass in the range:

$$m_{\beta\beta} < 0.2 - 0.4\,\mathrm{eV}$$

- GERDA phase II will start later in 2013



arXiv:1307.4720 [nucl-ex]

End

Ge detectors: isotopic composition

Table 2 The relative number of nuclei for the different isotopes is shown for the different detector batches. The isotopic composition of the depleted material is the average of measurements by the collaboration and ECP; that for natural germanium is given for comparison

detector batch	Ref.	germanium isotope				
		70	72	73	74	76
natural	[64]	0.204(2)	0.273(3)	0.078(1)	0.367(2)	0.078(1)
HDM–ANG 1	[73]	0.0031(2)	0.0046(19)	0.0025(8)	0.131(24)	0.859(29)
IGEX	[63]	0.0044(1)	0.0060(1)	0.0016(1)	0.1329(1)	0.8551(10)
GERDA depleted		0.223(8)	0.300(4)	0.083(2)	0.388(6)	0.006(2)
GERDA Phase II ⋆	[66]	0.0002(1)	0.0007(3)	0.0016(2)	0.124(4)	0.874(5)
MAJORANA	[74]	0.00006	0.00011	0.0003	0.0865	0.914

detector name	serial nr. ORTEC	diam. (mm)	length (mm)	total mass (g)	operat. bias (V)	abundance f_{76}
ANG 1	⋆	58.5	68	958	3200	0.859 (13)
ANG 2	P40239A	80	107	2833	3500	0.866 (25)
ANG 3	P40270A	78	93	2391	3200	0.883 (26)
ANG 4	P40368A	75	100	2372	3200	0.863 (13)
ANG 5	P40496A	78.5	105	2746	1800	0.856 (13)
RG 1†	28005-S	77.5	84	2110	4600	0.8551 (10)
RG 2†	28006-S	77.5	84	2166	4500	0.8551 (10)
RG 3†	28007-S	79	81	2087	3300	0.8551 (10)
GTF 32	P41032A	89	71	2321	3500	0.078 (1)
GTF 42	P41042A	85	82.5	2467	3000	0.078 (1)
GTF 44	P41044A	84	84	2465	3500	0.078 (1)
GTF 45	P41045A	87	75	2312	4000	0.078 (1)
GTF 110	P41110A	84	105	3046	3000	0.078 (1)
GTF 112	P41112A	85	100	2965	3000	0.078 (1)

Two-neutrino double beta decay

- The 2nbb half life derived when using the full background model:

model	$\mathcal{E}$ [kg·yr]	$T_{1/2}^{2\nu} \cdot 10^{21}$yr
GOLD-coax minimum	15.40	$1.92^{+0.02}_{-0.04}$
GOLD-coax maximum	15.40	$1.92^{+0.04}_{-0.03}$
GOLD-nat minimum	3.13	$1.74^{+0.48}_{-0.24}$
SUM-BEGe	1.80	$1.96^{+0.13}_{-0.05}$
Analysis in Ref. [18]	5.04	$1.84^{+0.09}_{-0.08\ fit}\ {}^{+0.11}_{-0.10\ syst}$

Background prediction in the ROI

Table 10 The total background index and individual contributions in 10 keV (8 keV for BEGes) energy window around $Q_{\beta\beta}$ for different models and data sets. Given are the values due to the global mode together with the uncertainty intervals [upper,lower limit] obtained as the smallest 68 % interval (90 %/10 % quantile for limit setting) of the marginalized distributions.

component	location	*GOLD-coax*				*GOLD-nat*		*SUM-bege*	
		minimum model		maximum model		minimum model		minimum + n^+	
		BI 10^{-3} cts/(keV·kg·yr)							
Total		18.5	[17.6,19.3]	21.9	[20.7,23.8]	29.6	[27.1,32.7]	38.1	[37.5,38.7]
^{42}K	LAr homogeneous	3.0	[2.9,3.1]	2.6	[2.0,2.8]	2.9	[2.7,3.2]	2.0	[1.8,2.3]
^{42}K	p^+ surface			4.6	[1.2,7.4]				
^{42}K	n^+ surface			0.2	[0.1,0.4]			20.8	[6.8,23.7]
^{60}Co	det. assembly	1.4	[0.9,2.1]	0.9	[0.3,1.4]	1.1	[0.0,2.5]		<4.7
^{60}Co	germanium	0.6	>0.1 †)	0.6	>0.1 †)	9.2	[4.5,12.9]	1.0	[0.3,1.0]
^{68}Ge	germanium								1.5 (<6.7)
^{214}Bi	det. assembly	5.2	[4.7,5.9]	2.2	[0.5,3.1]	4.9	[3.9,6.1]	5.1	[3.1,6.9]
^{214}Bi	LAr close to p^+			3.1	<4.7				
^{214}Bi	p^+ surface	1.4	[1.0,1.8] †)	1.3	[0.9,1.8] †)	3.7	[2.7,4.8] †)	0.7	[0.1,1.3] †)
^{214}Bi	radon shroud			0.7	<3.5				
^{228}Th	det. assembly	4.5	[3.9,5.4]	1.6	[0.4,2.5]	4.0	[2.5,6.3]	4.2	[1.8,8.4]
^{228}Th	radon shroud			1.7	<2.9				
α model	p^+ surface	2.4	[2.4,2.5]	2.4	[2.3,2.5]	3.8	[3.5,4.2]	1.5	[1.2,1.8]

Background prediction in the ROI

Table 11 BI as predicted by the minimum and maximum models as well as by interpolation in 10 keV (8 keV for BEGe) energy window around $Q_{\beta\beta}$. Comparison of counts in the previously blinded window (width differs for different data sets) and model predictions is also given. Values in the parentheses show the uncertainty interval.

	GOLD-coax	*GOLD-nat*	*SUM-bege*
	BI in central region around $Q_{\beta\beta}$ (10 keV for coaxial, 8 keV for BEGe) 10^{-3} cts/(kg keV yr)		
interpolation	17.5 [15.1,20.1]	30.4 [23.7,38.4]	36.1 [26.4,49.3]
minimum	18.5 [17.6,19.3]	29.6 [27.1,32.7]	38.1 [37.5,38.7]
maximum	21.9 [20.7,23.8]	37.1 [32.2,39.2]	
	background counts in the previously blinded energy region		
	30 keV	40 keV	32 keV
data	13	5	2
minimum	8.6 [8.2,9.1]	3.5 [3.2,3.8]	2.2 [2.1,2.2]
maximum	10.3 [9.7,11.1]	4.2 [3.8,4.6]	