FIRST GERDA RESULTS ON $0\nu\beta\beta$ OF ^{76}Ge

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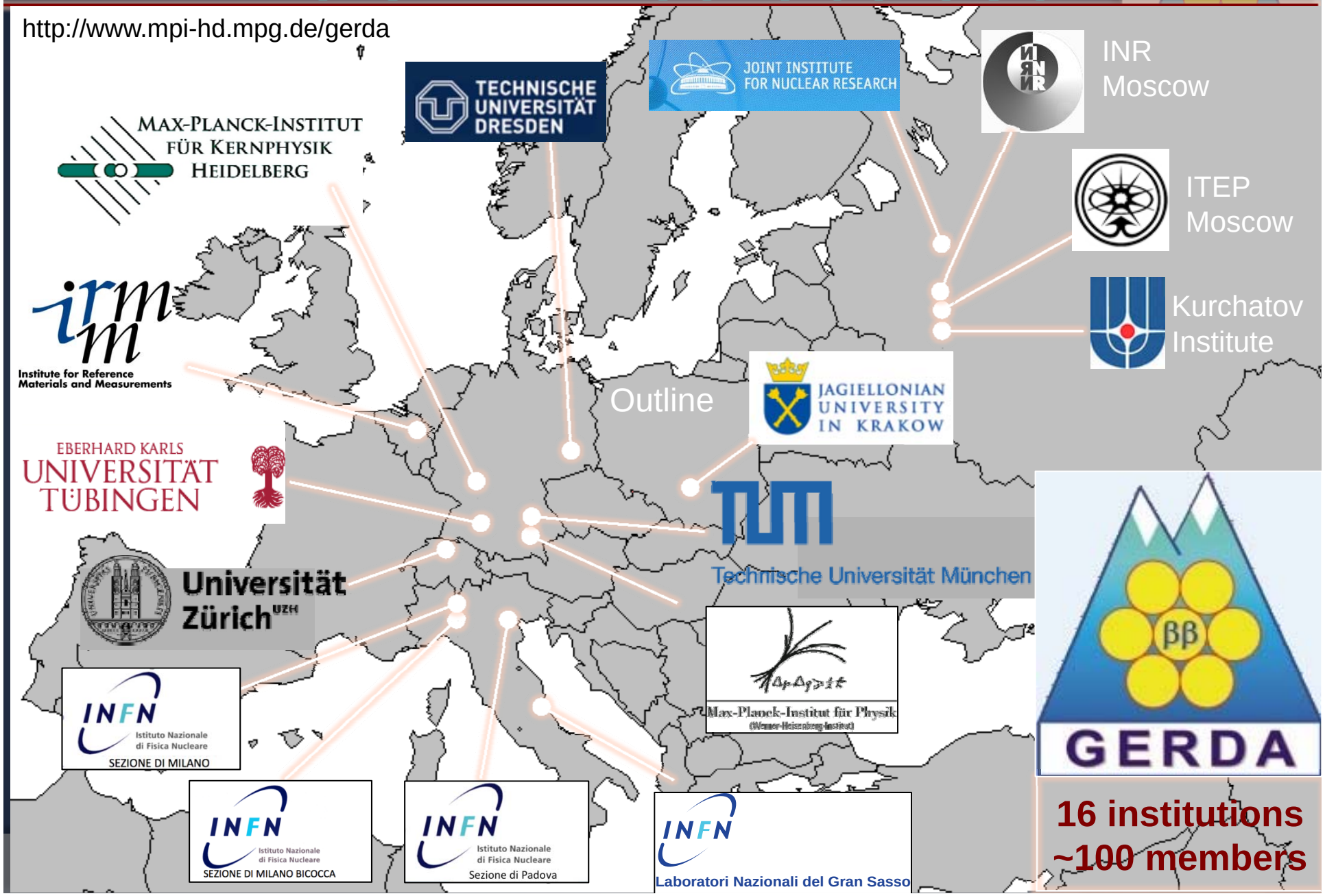
on behalf of the GERDA Collaboration

EPS 2013, 18-24 July 2013

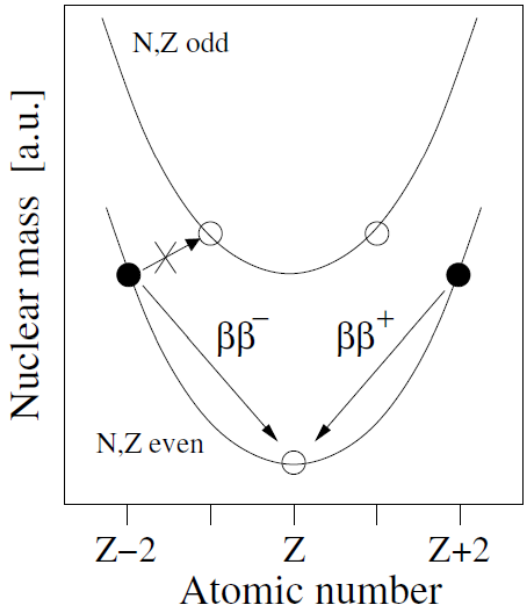
The GERDA Collaboration

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



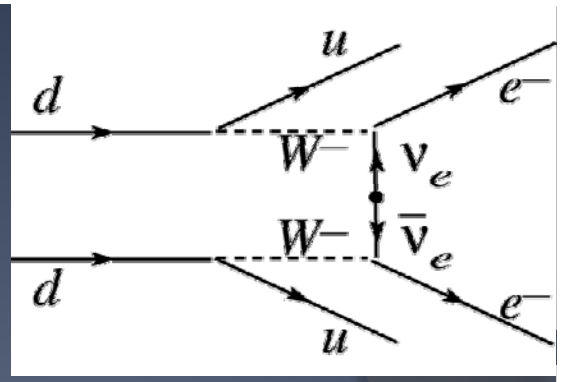
Outline

- The experiment
- The Energy scale
- The Background model
- Data Treatment
  - The Pulse shape discrimination
- ……results
- Conclusion



ββ Decay

2ν 0ν



Proposed by Majorana (and Racah) in 1937:

A ν is exchanged between two neutrons

It is a forbidden process in SM and requires

- Lepton number violation $\Delta L = 2$ $\nu_e = \bar{\nu}_e$
- Can be mediated by a light Majorana ν finite mass $< m_\nu > \neq 0$

Experimental sensitivity on T1/2

$$T_{1/2}^{0\nu} \propto a\varepsilon\sqrt{\frac{MT}{BR}}$$

$$\frac{1}{T_{1/2}^{0\nu}} \propto G_{0\nu}|M_\nu|^2 \frac{< m_{\beta\beta} >^2}{m_e}$$

$< m_{\beta\beta} > = effective\ \nu\ mass$

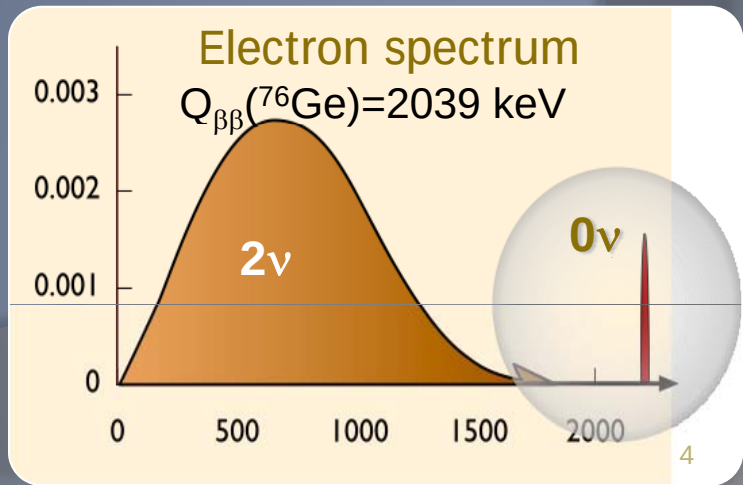
$M_\nu = Nuclear\ Matrix\ Element$

$G_{0\nu} = Phase\ Space\ Factor$

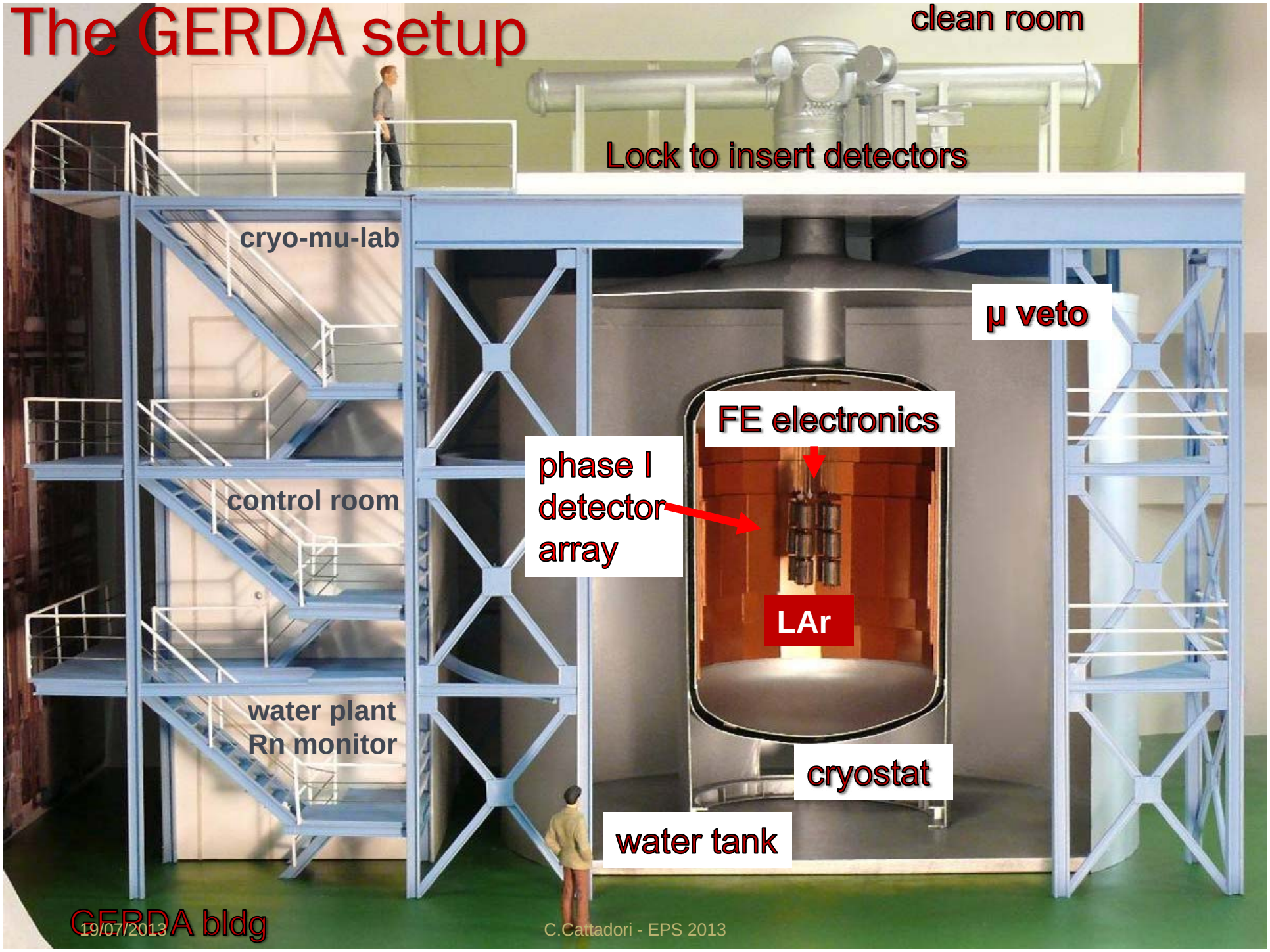
$$< m_{\beta\beta} > = \left|\sum_i U_{ei}^2 m_{\nu i}\right|$$

Ideal case: no bckgd

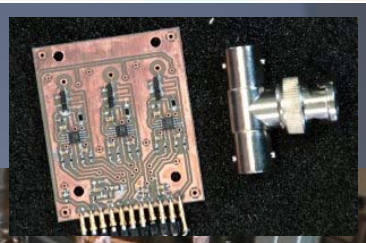
$$T_{1/2}^{0\nu} \propto a\varepsilon MT$$

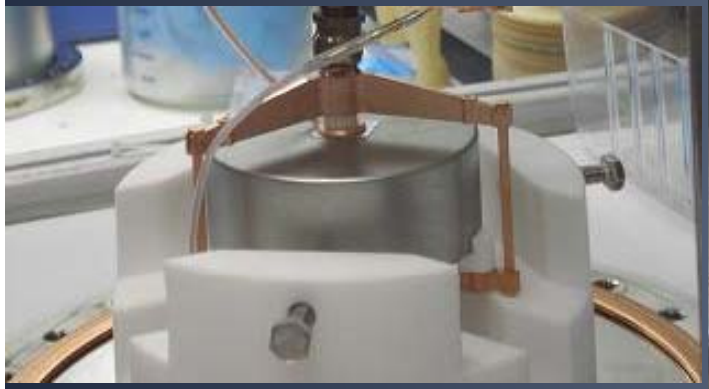


The GERDA setup



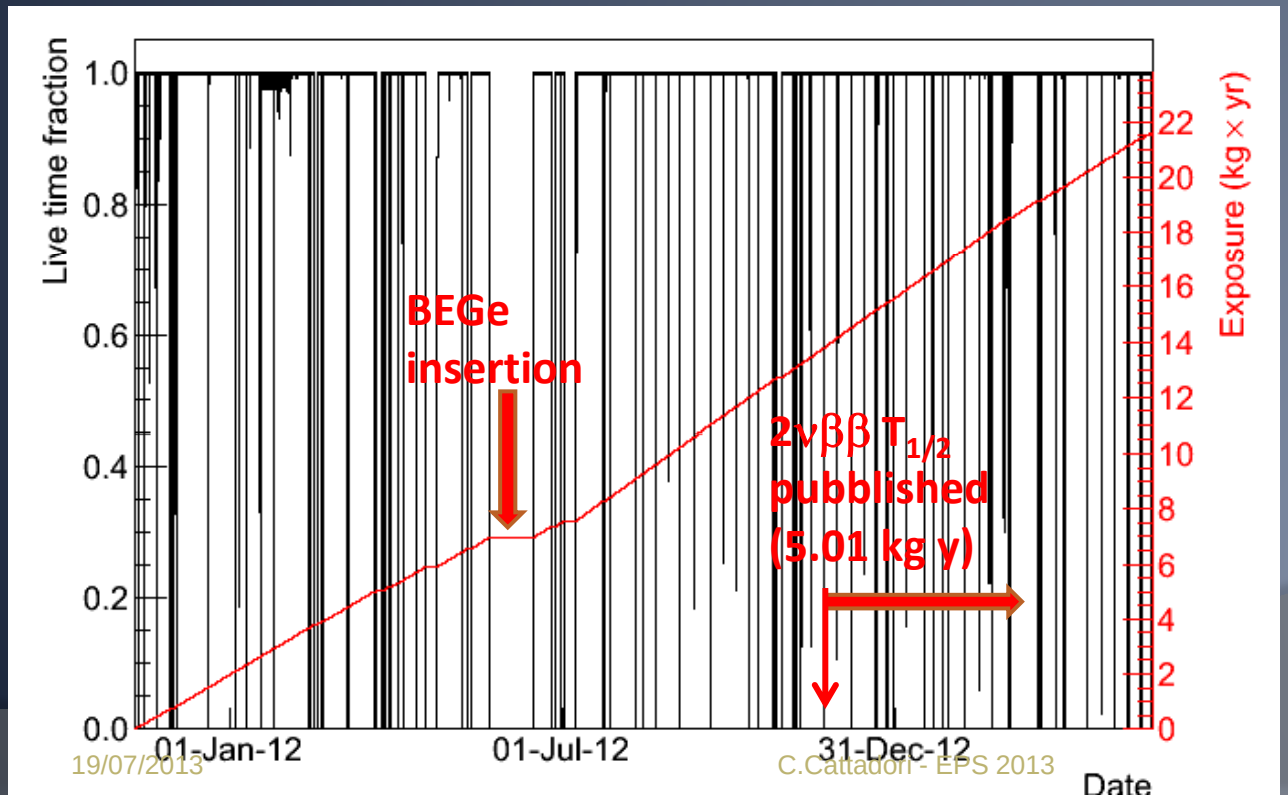
A tour in GERDA





Building the exposure up.....

- Total of 21.6 kg y: from 6 November 2011 to 3rd May 2013
- 6 of 8 Coaxial ^{enr}Ge detectors of the former IGEX and HdM in the $0\nu\beta\beta$ data sets (2 diodes high LC)
- 1 ^{nat}Ge coaxial detector (not in the $0\nu\beta\beta$ data set)
- June 2012: 5 new ^{enr}BEGe detectors deployed to compensate the lost of two coax.



Exposure is monitored by:
- Weekly ^{228}Th calibrations
- Pulser

Main detectors parameters remeasured

arXiv: 1306.5084v1

Balance

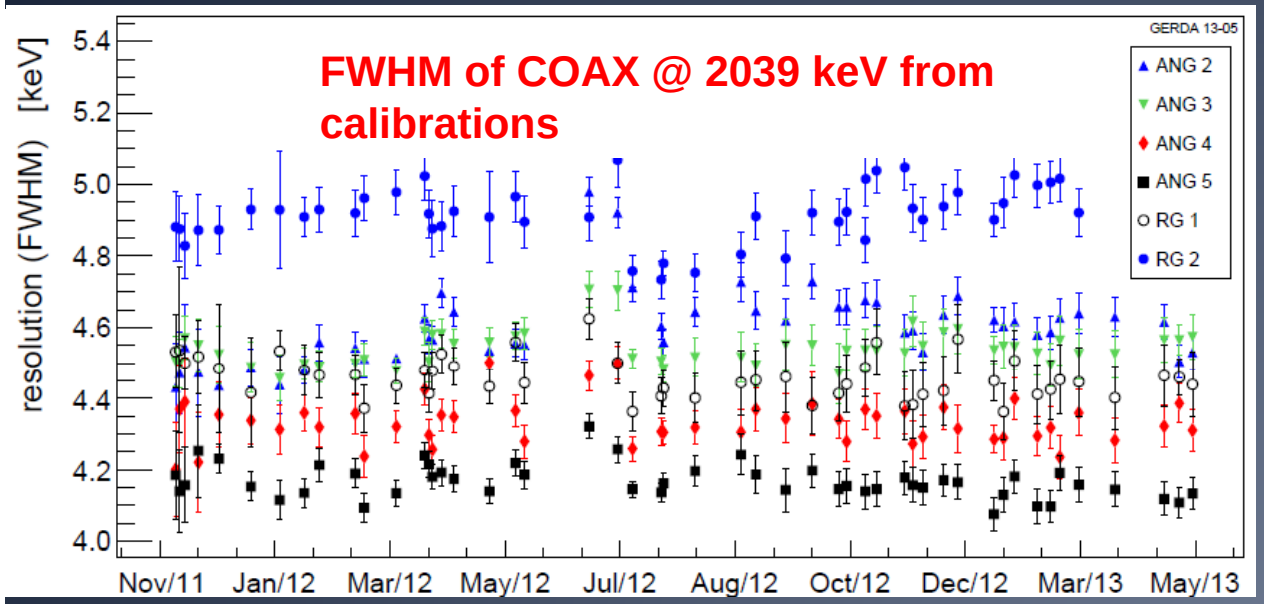
detector	f_{76}	M g	$M_{act}(\Delta M_{act})$ g	$f_{av}(\Delta f_{av_t})$	d_{dl} mm
enriched coaxial detectors					
ANG 1 †)	0.859(29)	958	795(50)	0.830(52)	1.8(5)
ANG 2	0.866(25)	2833	2468(145)	0.871(51)	2.3(7)
ANG 3	0.883(26)	2391	2070(136)	0.866(57)	1.9(7)
ANG 4	0.863(13)	2372	2136(135)	0.901(57)	1.4(7)
ANG 5	0.856(13)	2746	2281(132)	0.831(48)	2.6(6)
RG 1	0.855(15)	2110	1908(125)	0.904(59)	1.5(7)
RG 2	0.855(15)	2166	1800(115)	0.831(53)	2.3(7)
RG 3 †)	0.855(15)	2087	1868(113)	0.895(54)	1.4(7)
enriched BEGe detectors					
GD32B	0.877(13)	717	638(19)	0.890(27)	1.0(2)
GD32C	0.877(13)	743	677(22)	0.911(30)	0.8(3)
GD32D	0.877(13)	723	667(19)	0.923(26)	0.7(2)
GD35B	0.877(13)	812	742(24)	0.914(29)	0.8(3)
GD35C †)	0.877(13)	635	575(20)	0.906(32)	0.8(3)
natural coaxial detectors					
GTF 32 †)	0.078(1)	2321	2251(116)	0.97(5)	0.4(8)
GTF 45 †)	0.078(1)	2312			
GTF 112	0.078(1)	2965			

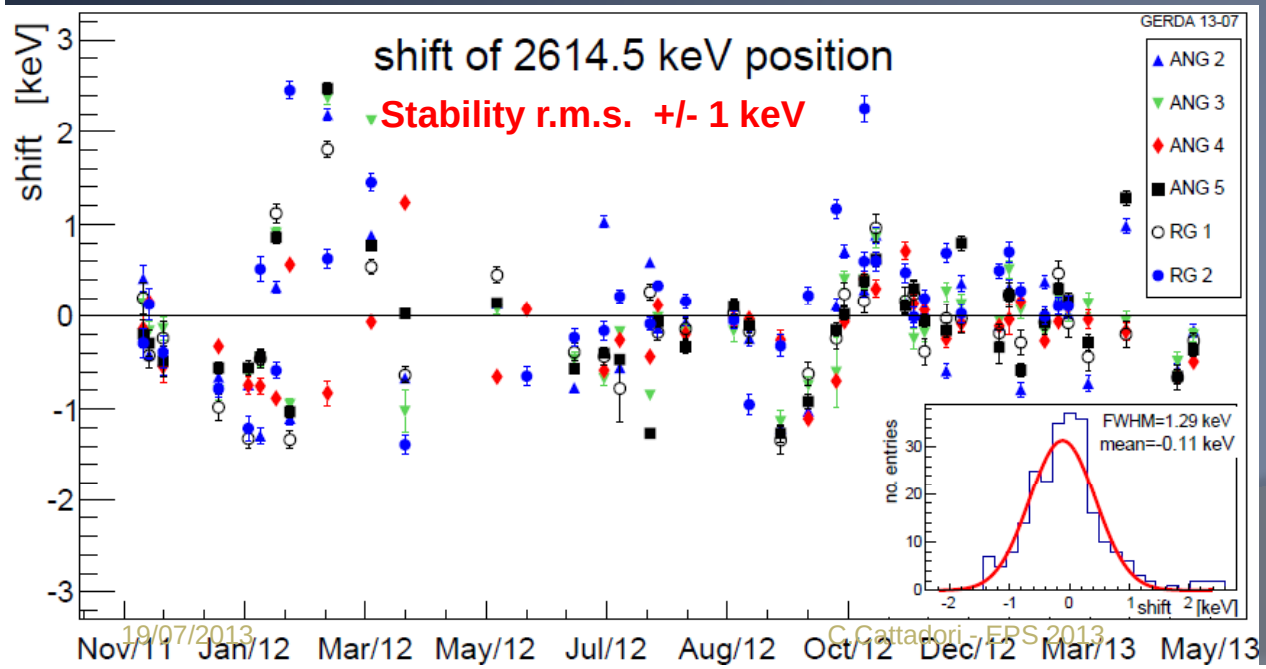
ICPMS

Low E γ-sources

The Energy Scale: COAX

arXiv: 1306.5084v1





From 1525 keV ^{42}K γ-line summed COAX spectra

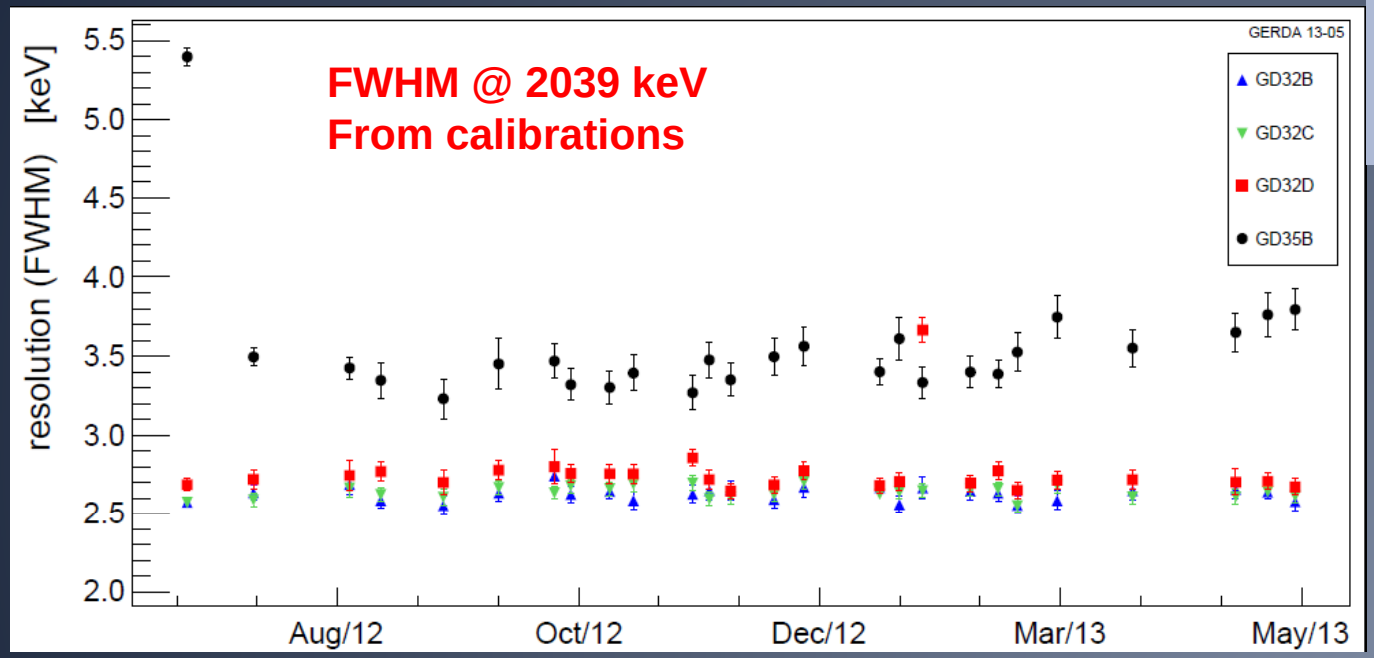
detector	FWHM @ 2039 keV
ANG2	5.8 ± 0.3
ANG3	4.5 ± 0.1
ANG4	4.9 ± 0.3
ANG5	4.2 ± 0.1
RG1	4.5 ± 0.3
RG2	4.9 ± 0.3
Mean COAX	4.8 ± 0.2

Energy :
From semi-gaussian DSP of the acquired waveforms

DAQ facts:
14 bit, 100 MHz continuos running ADC.
TRG thrsd:40-100 keV

arXiv: 1306.5084v1

The Energy Scale: BEGEs



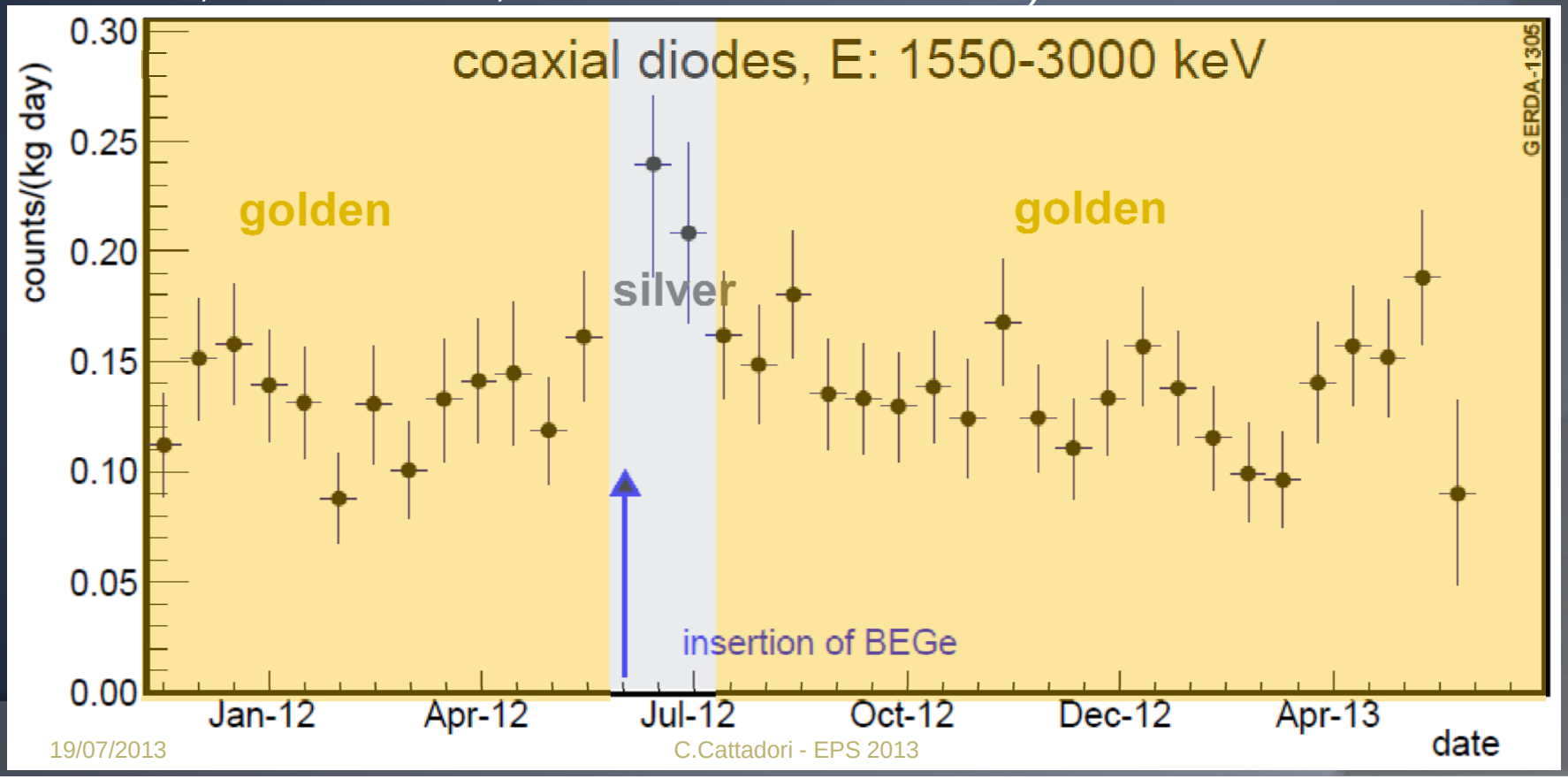
From 1525 keV ^{42}K γ-line summed BEGe spectra

detector	FWHM @ 2039 keV
GD32B	2.6 ± 0.1
GD32C	2.6 ± 0.1
GD32D	3.7 ± 0.5
GD35B	4.0 ± 0.1
Mean BEGE	3.2 ± 0.2

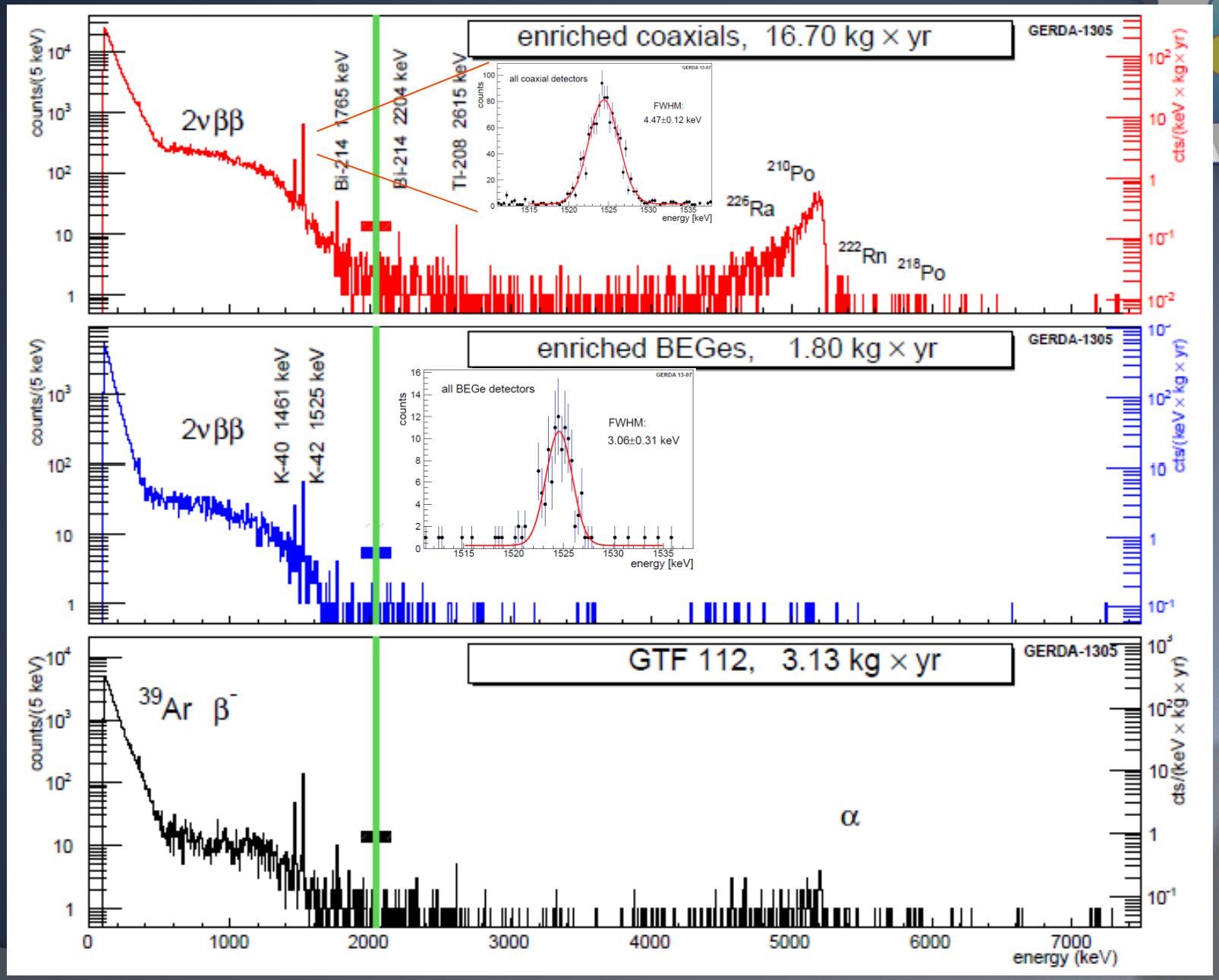
1 ^{enr}BEGe not used in the 0νββ data sets because of instabilities

GERDA Data Sets

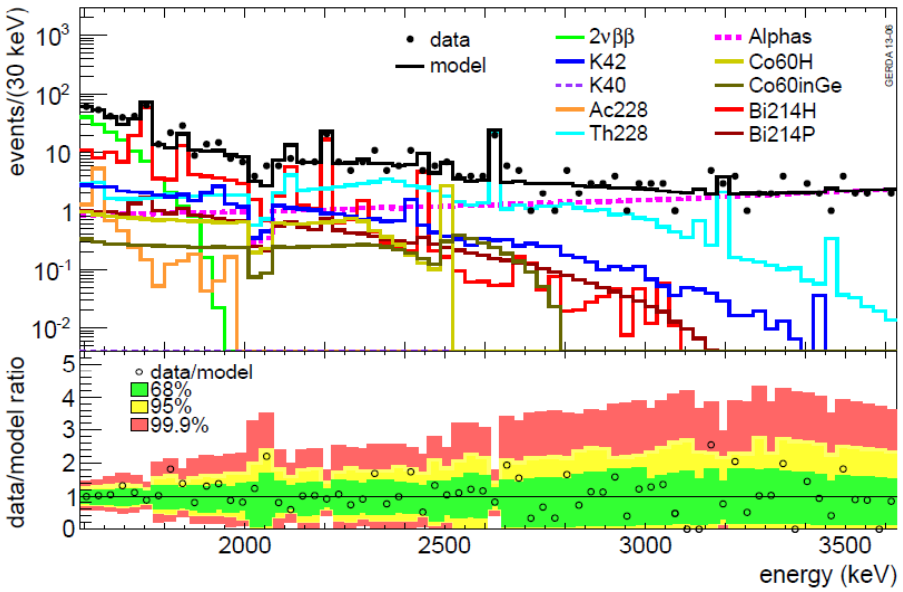
- Golden coax: all the coax runs apart from 30 days just after the BEGe insertion in june 2012
- Silver coax: The coax data collected in the 30 days following the BEGe insertion
- BEGe: Treated separately because of intrinsic differences (better FWHM, intrinsic PSD, lower alfa contamination)



The energy spectra

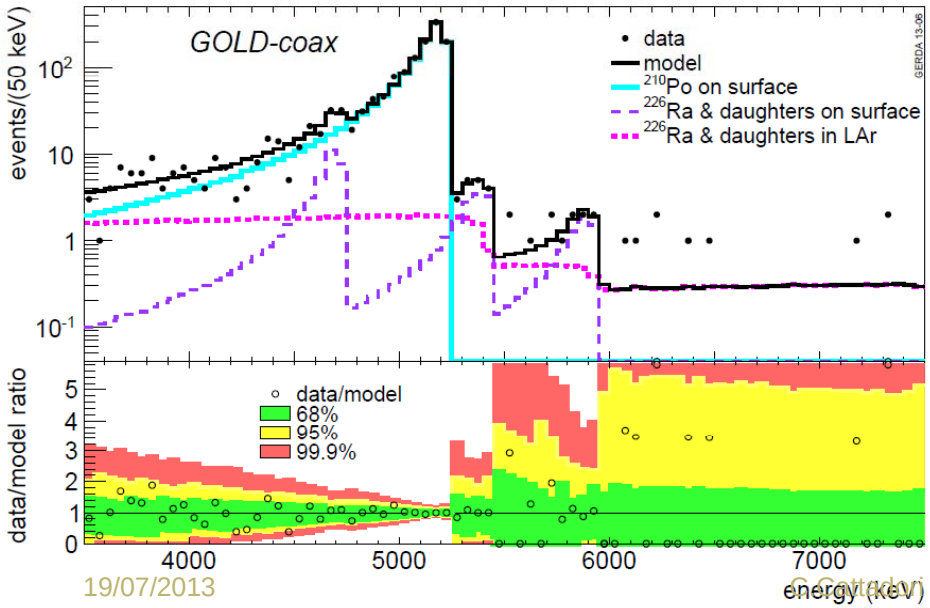


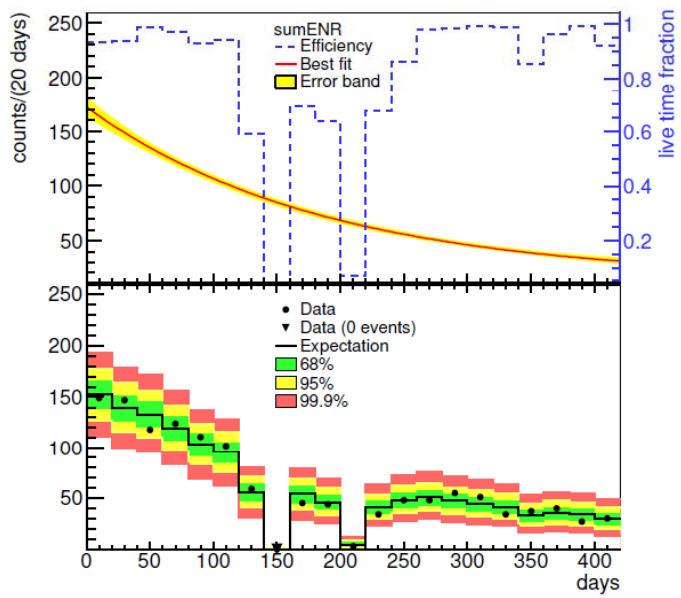
Identification of Background Components



arXiv: 1306.5084v1

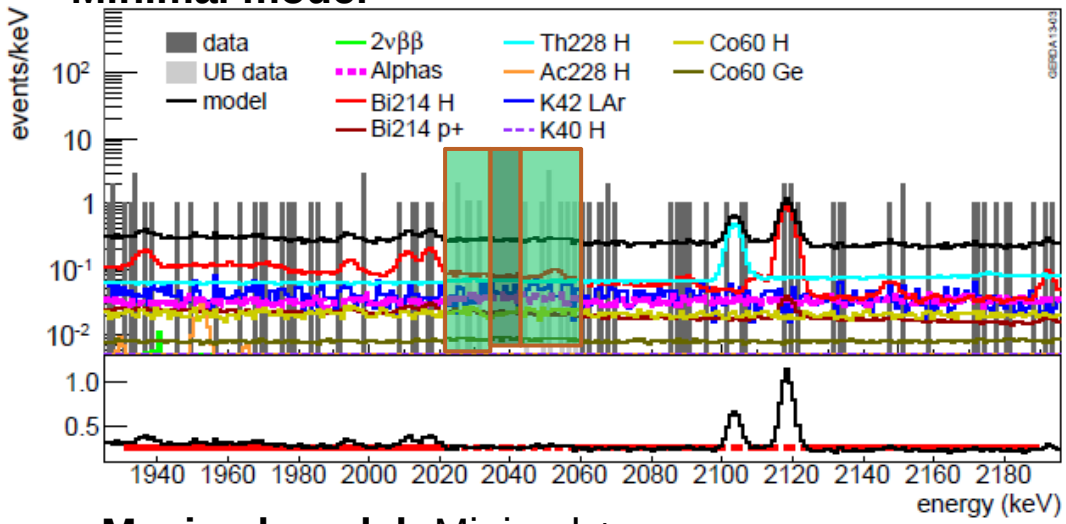
- α contamination from ^{210}Po.
- contamination at time of refurbishment mostly on thin p+ contact
- ^{210}Po decaying away ($t_{1/2}$=138 d)
- Large differences among detectors
- BEGes much cleaner (> factor 10)



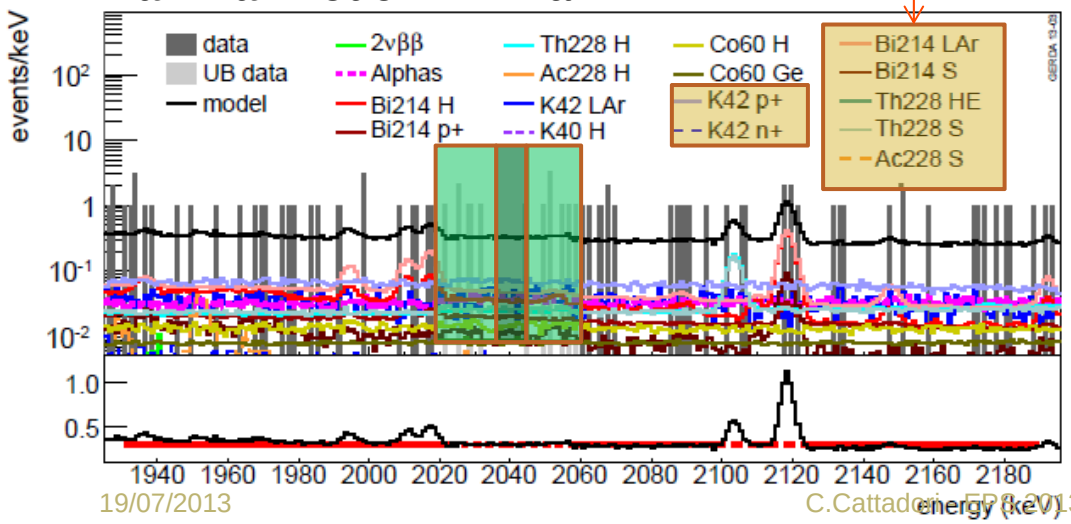


Background model predictions vs data in 260 keV range around Q_ββ

Minimal model



Maximal model: Minimal +



- The model reproduces a flat bckgrd around Q_ββ
- No γ-lines visible in the 30 keV around the Q_ββ

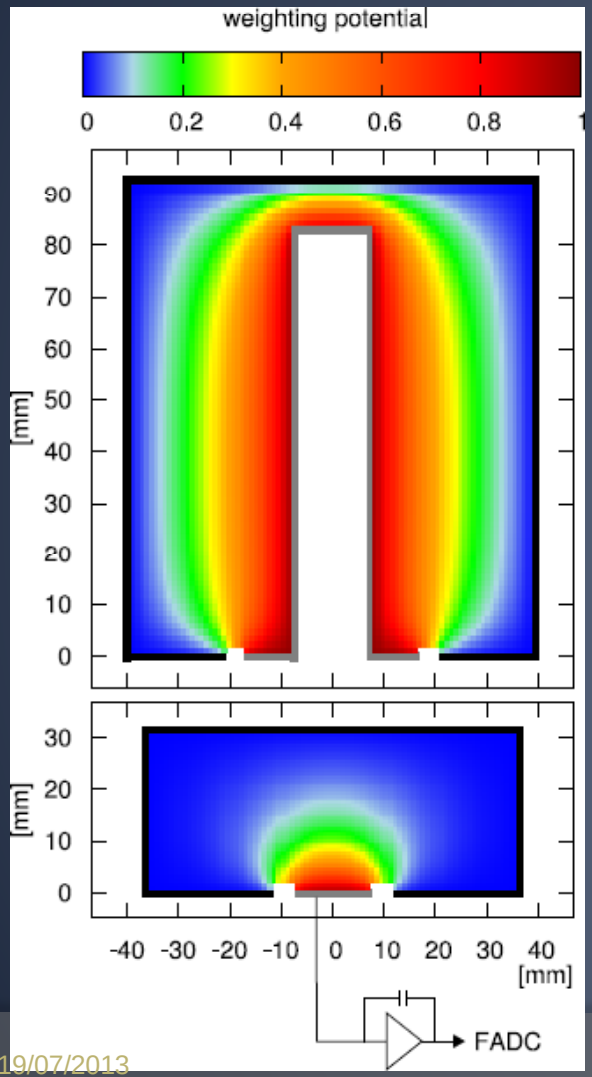
→ spectra can be fitted with a flat background apart from ^{214}Bi lines @ 2104 keV and 2119 keV

arXiv: 1306.5084v1

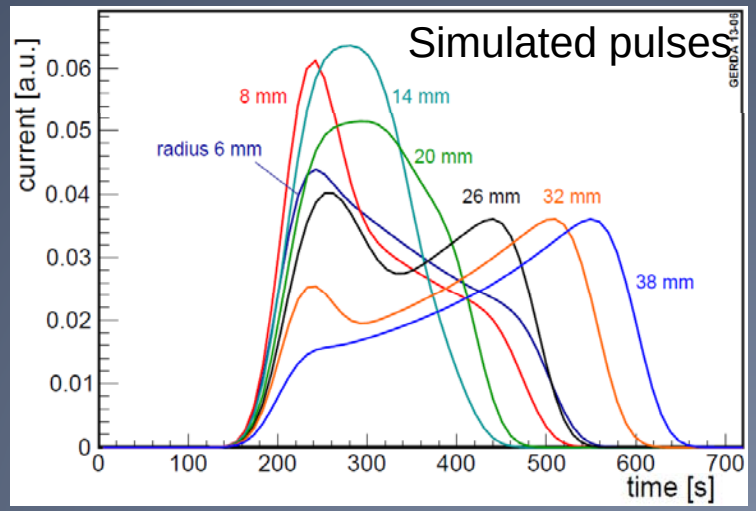
PSD to discriminate ββ-like (SSE) to γ-like (MSE) events

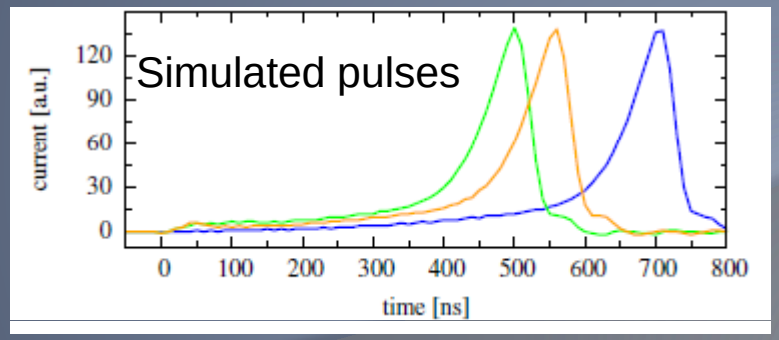
arXiv: 1307.2610

Different weighting potentials for Coax and BEGe



COAX: Artificial Neural Network (ANN) estimator used as PSD parameter



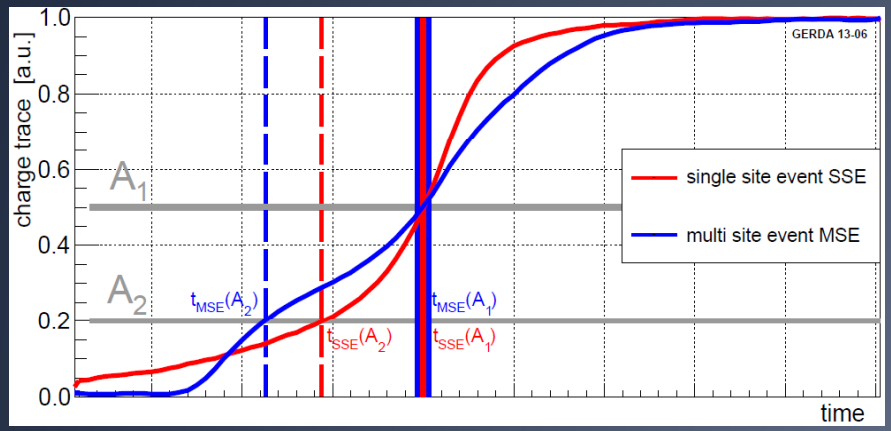


BEGe: Amplitude of Current/Amplitude of Charge Pulse (A/E) is the PSD parameter

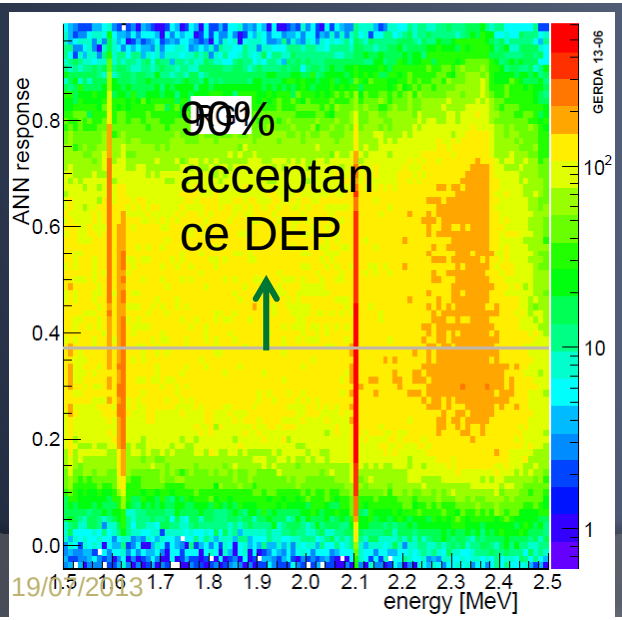
PSD for coax

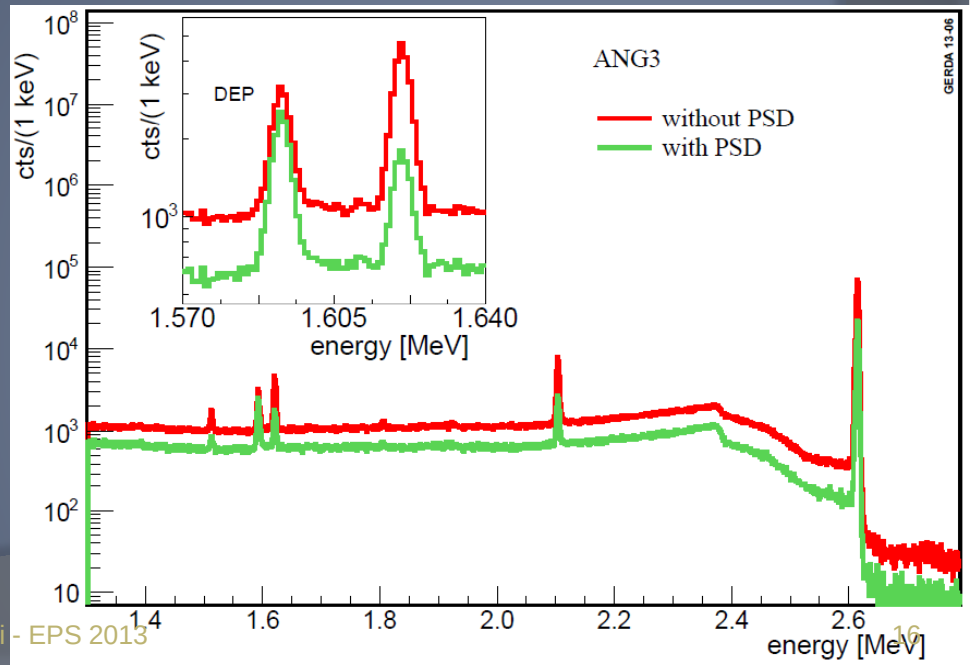
arXiv: 1307.2610

ANN trained on
SIGNAL (SSE) : ^{208}Tl (2614 keV) Double Escape Peak (DEP) @ 1592 keV line
BACKGROUND (MSE): ^{212}Bi @ 1620 keV γ-line



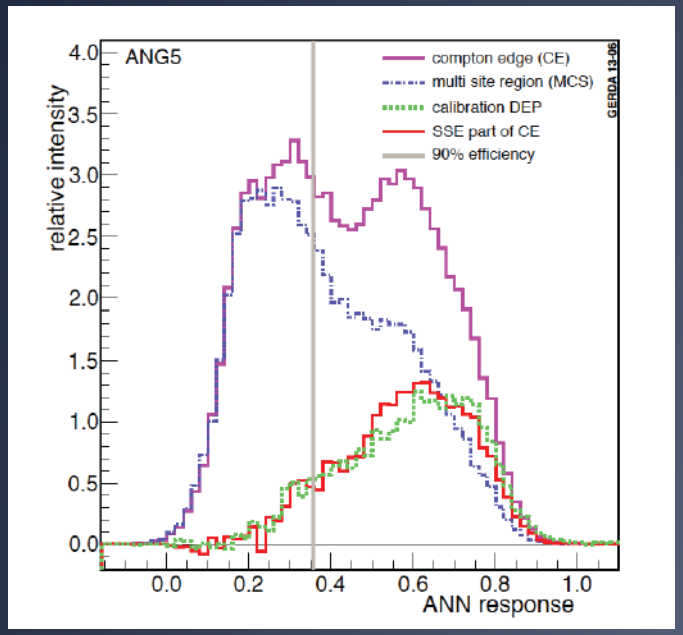
- Required 90% acceptance of DEP
- ε for other classes of events derived
- acceptance of SSE verified on Compton edges (CE) and $2\nu\beta\beta$



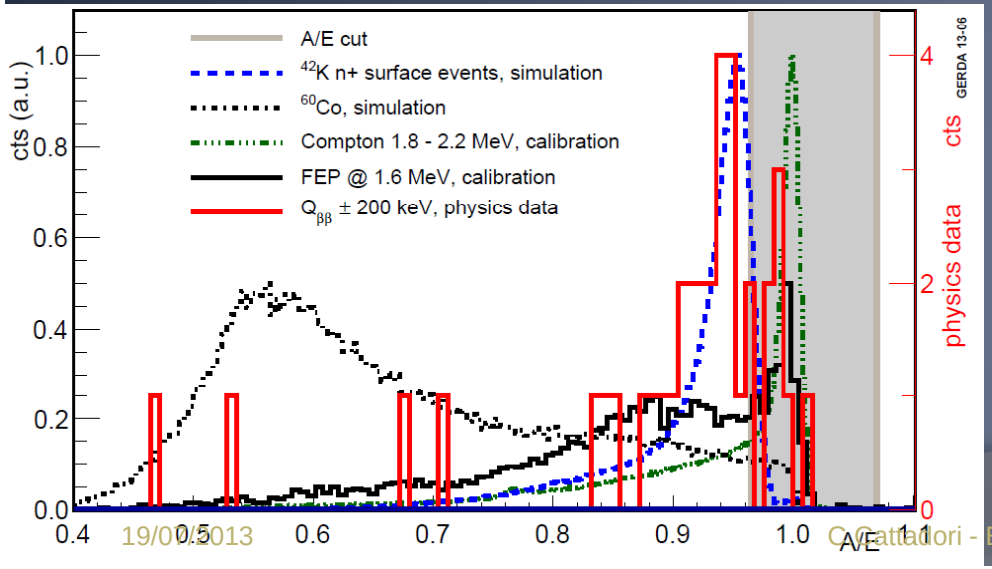


..to conclude PSD efficiencies and their systematics are evaluated

arXiv: 1307.2610



	$\varepsilon_{2\nu\beta\beta}$	$\varepsilon_{0\nu\beta\beta}$
Coax	0.85 ± 0.02	0.90 ± 0.1
BEGe	0.91 ± 0.05	0.92 ± 0.02



Bckgrd rejection= 33 of 40 events rejected in ±200 keV range.

BI_{PSD} = 0.7 10^{-2} cts/(keV kg y)

Summary of parameters and systematics relevant to $T_{1/2}^{0\nu}$

Energy Windows at $Q_{\beta\beta}$=2039 keV

76Ge fraction

Active volume fraction

ββ FEP efficiency

PSD efficiency

Total efficiency

Data set	FWHM [keV]	ROI [keV]	$\langle f_{76} \rangle$	$\langle f_{av} \rangle$	$\langle \varepsilon_{fep} \rangle$	$\langle \varepsilon_{PSD} \rangle$	$\langle \varepsilon \rangle$
Coax	4.8 ± 0.2	± 5	0.86	0.87	0.92	$0.90^{+0.05}_{-0.09}$	$0.619^{+0.044}_{-0.070}$
BEGe	3.2 ± 0.2	± 4	0.88	0.92	0.90	0.92 ± 0.02	0.663 ± 0.022

The blinded/unblinded data

- Data blinded since january 2012:
Events in ± 20 keV around $Q_{\beta\beta}$ removed from Tier1
- Unblinding in two steps:
  - May 2013: Unblinded ± 15 keV around still blinded ± 5 keV @ $Q_{\beta\beta}$
  - 17 June 2013 @ GERDA Plenary meeting in Dubna (RU):
    Unblinded the ± 5 keV region @ $Q_{\beta\beta}$

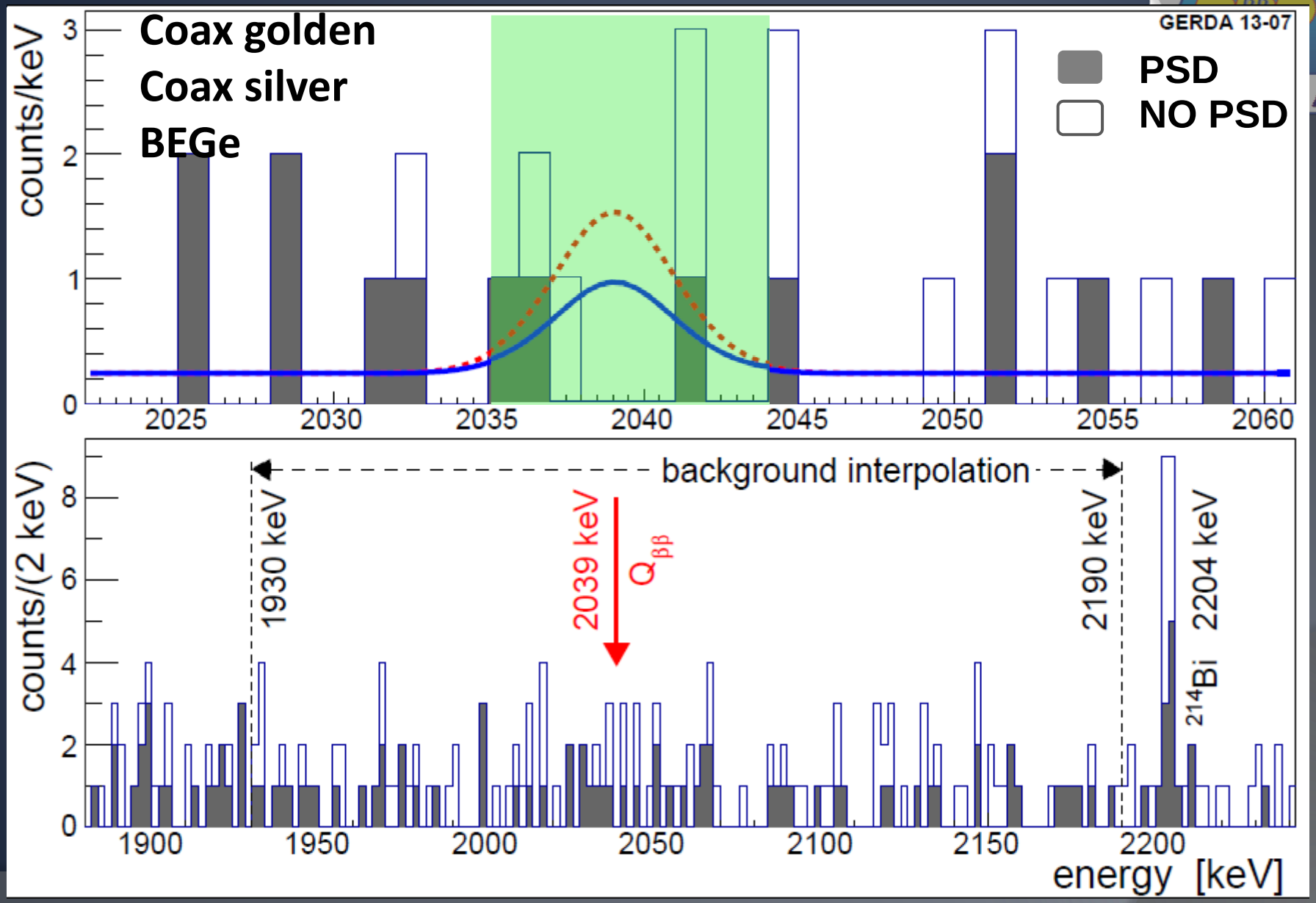
arXiv: 1307.4720v1

Table 1: List of all events within $Q_{\beta\beta} \pm 5$ keV

data set	detector	energy [keV]	date	PSD passed	ANN	A/E	Cut Threshold
golden	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
golden	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no		0.750	0.965÷1.070
golden	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
golden	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
golden	RG 1	2041.7	27-Apr-2013 22:21	no	0.369		0.372

arXiv: 1307.2610

The unblinded spectrum @ Q_bb



From counts to $T_{1/2}^{0\nu}$: the relevant numbers

arXiv: 1307.2610

$$T_{1/2}^{0\nu} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

In 230 keV @$Q_{\beta\beta}$

In ± 5 keV @ $Q_{\beta\beta}$

Expected bckgd only

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	5.1
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	2.5
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).

BI Rej $_{PSD}$ ^{Coax} ~ 43%

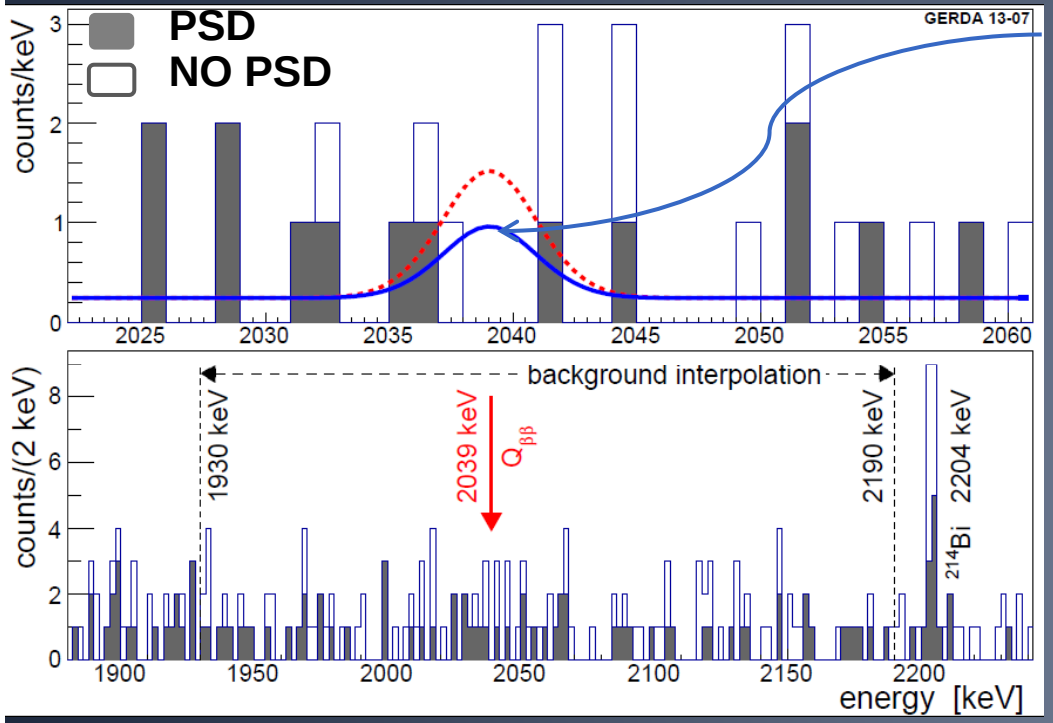
BI Rej $_{PSD}$ ^{BEGe} ~ 87%

$T_{1/2}^{0\nu}$ from GERDA data sets

arXiv: 1307.2610

Performed Profile Likelihood fit of the 3 data sets

- B+S: described by constant term + Gaus($Q_{\beta\beta}$,σ_E)
- 4 free parameters in the fit B_{gold}, B_{silv},B_{BEGe},1/ $T_{1/2}^{0\nu}$
- Systematics folded in



Frequentist approach

Best fit: $N^{0\nu} = 0$

$N^{0\nu} < 3.5$ cts @ 90% C.L.

$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL

Bayesian approach

Flat prior for 1 / $T_{1/2}^{0\nu}$

Best fit: $N^{0\nu} = 0$

$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ yr @ 90% CI

Median sensitivity:

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

GERDA (all data sets) vs KK (2004) claim

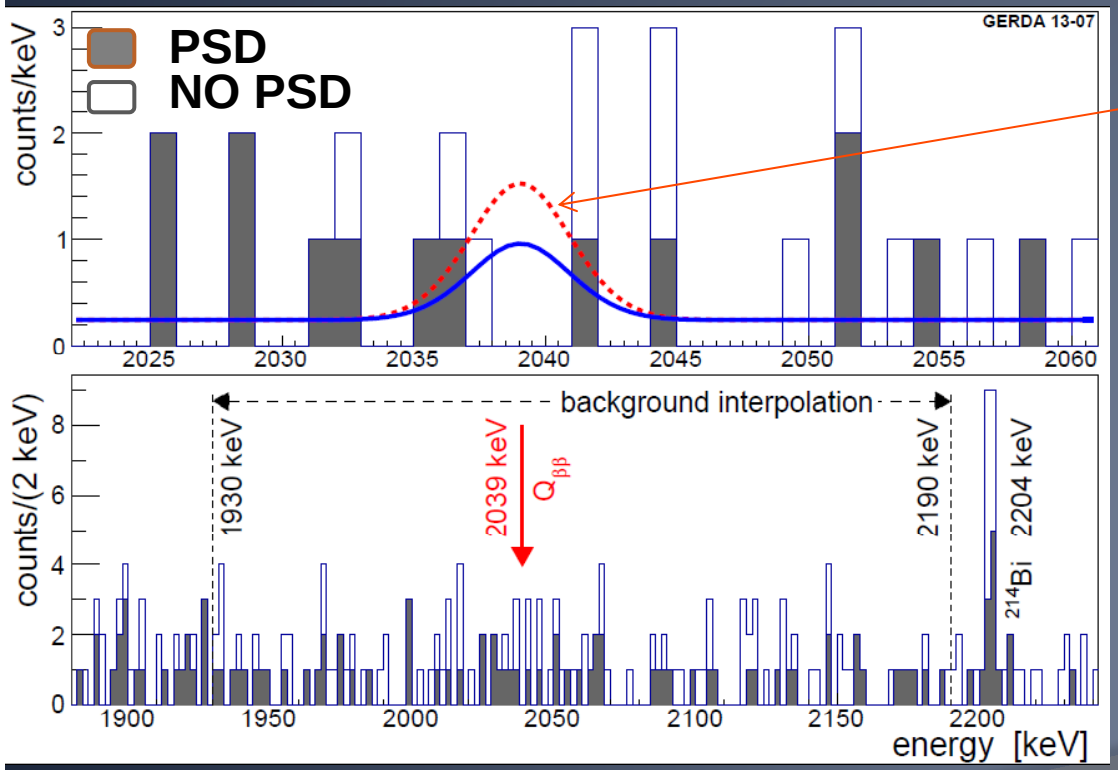
arXiv: 1307.2610

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

Expected Signal (after PSD): 5.9 ± 1.4 cts in ±2σ

Expected Bckgd (after PSD): 2.0 ± 0.3 cts in ±2σ

Observed: 3.0 (0 in ±1σ)



From profile likelihood
Assuming H1,
P ($N^{0\nu}$=0 for H1)=1%

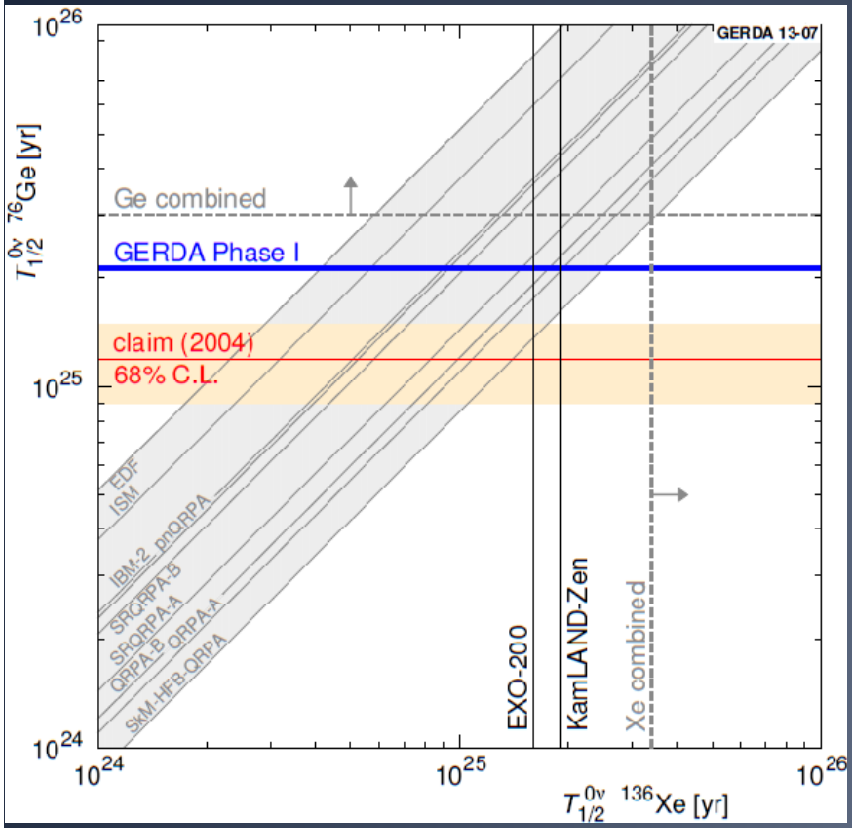
Comparing
H1: Claimed signal
H0: Background only

Bayes factor
P(H1)/P(H0)=0.024
(uncertainties on claim included)

Claim poorly credible

Combining GERDA, HdM, IGEX & Xe

arXiv: 1307.2610



H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

H0: background only

	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

*:with conservative NME ratio $M_{0\nu}(^{136}Xe)/M_{0\nu}(^{76}Ge) \approx 0.4$ from:

NME from P.S. Bhupal DeV et al (2103), arXiV:1305.0056

Combining GERDA, HdM,IGEX

3 GERDA Data sets, 1 HdM, 1 IGEX

Profile likelihood function w. 5 independent bckgds

$T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr @ 90% CL

Conclusions and outlooks

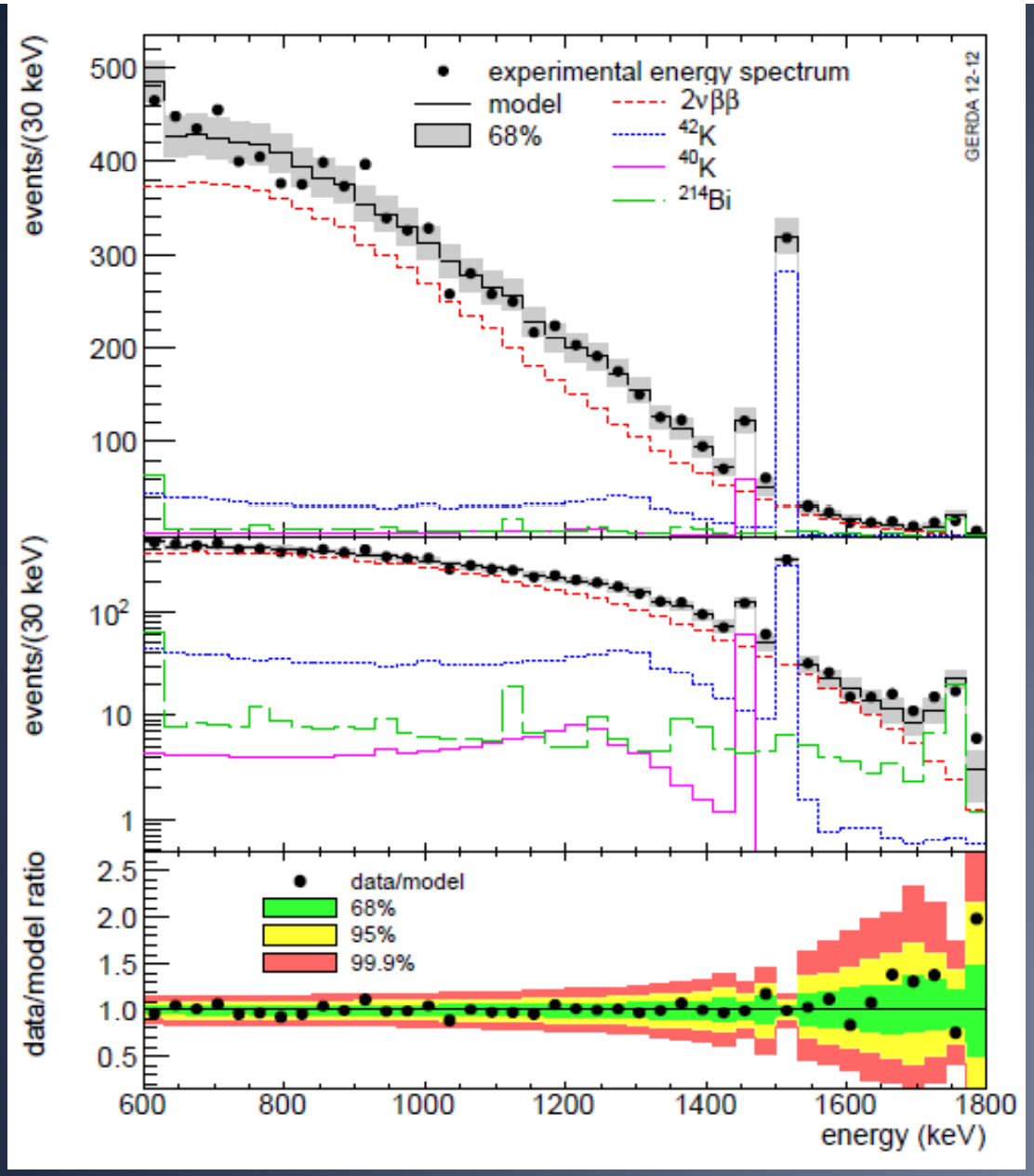
- GERDA achieved its design goals
  - Phase I Exposure: 21.6 kg yr
  - Background Index: ~10^{-2} cts / (Kev kg y) Unprecedent value!
  - Scrutinize the KK claim in 1.5 yr data taking
- No excess of counts above background is found @ $Q_{\beta\beta}$ after unblinding: 7 (3 after PSD) cts in ± 5keV region

- GERDA : $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr @ 90% CL
- GERDA combined w. IGEX & HdM $T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr @ 90% CL
- $m_{\beta\beta} < (0.2 – 0.4)$ eV depending on NME and Phase Space Factors

- PSD works well mainly for BEGEs
- Phase II challenge: achieve another factor 10 in BI and sensitivity

…….. *who will live will see it.*

EXTRA slides

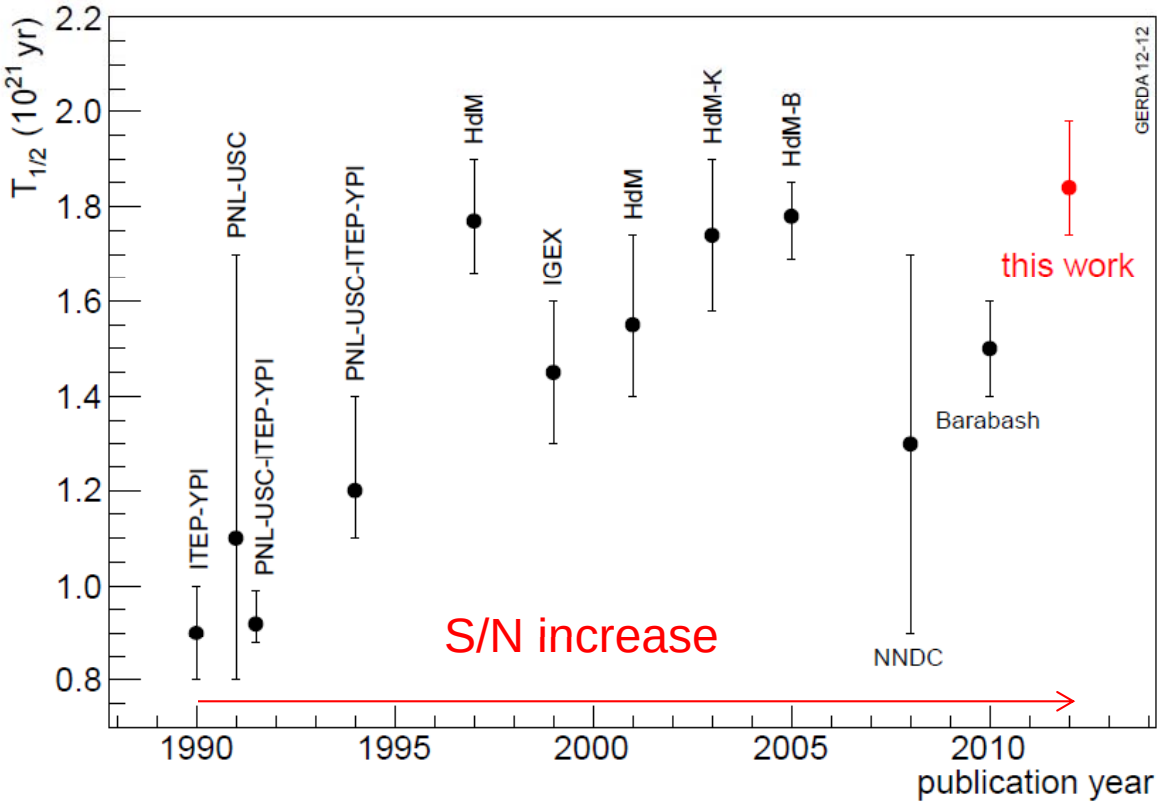


- 2νββ spectrum generated by DECAY0 (V.Tetryak)
- 6 independent models for the 6 detectors (5 x 6=30 detector parameters)
- $T^{2\nu}_{1/2}$ common in 6 detectors
- Background from 3 sources: ^{42}K, ^{40}K, ^{214}Bi (γ-lines used for normalization)
  - ^{42}K: homogeneusly distributed
  - ^{40}K & ^{214}Bi: close sources
- Detectors active masses and enr. factors are nuisance parameters in the fit.
- $T^{2\nu}_{1/2}$ *pdf is quasi-gaussan*

ββ spectrum: 8796 events:
Model of the residual background: 80% 2νββ, 14% ^{42}K, 3.8% ^{214}Bi, 2% ^{40}K,

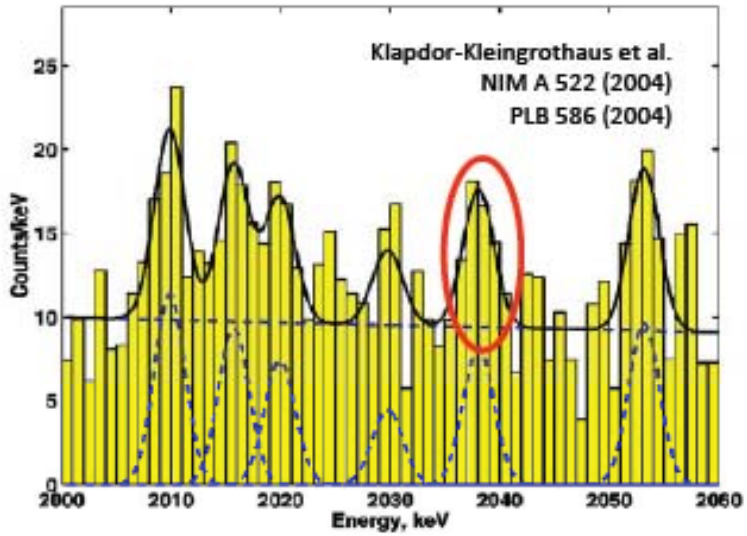
GERDA vs previous measurements of $T^{2\nu}_{1/2}$

$$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}\ {}_{\text{fit}}\ {}^{+0.11}_{-0.06}\ {}_{\text{syst}}) \cdot 10^{21}\ \text{yr} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}\ \text{yr}, \quad (2)$$



- GERDA is consistent with HdM $T^{2\nu}_{1/2} = 1.78^{+0.07}_{-0.09}$
- Thanks to our BI comparable σ_{stat} with ~1/10 exposure
- GERDA results can improve by
  - New measurement of coax active volumes
  - &
  - Increased statistics (already available)

The KK 2006 claim



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

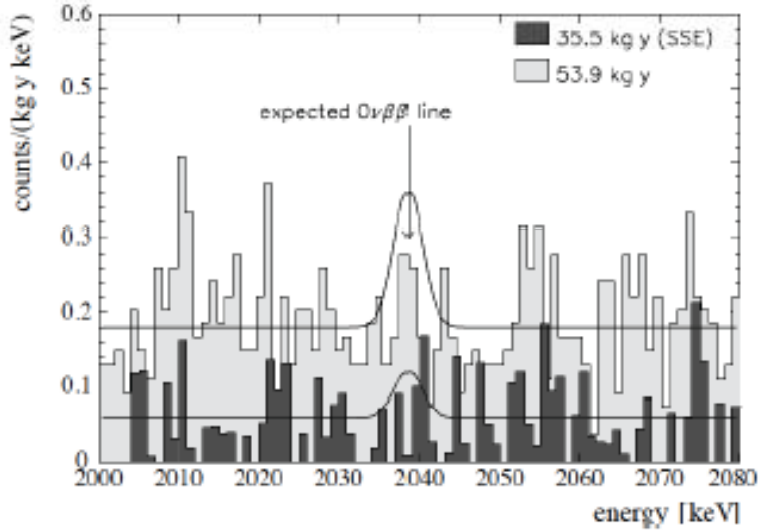
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr $T_{1/}$after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

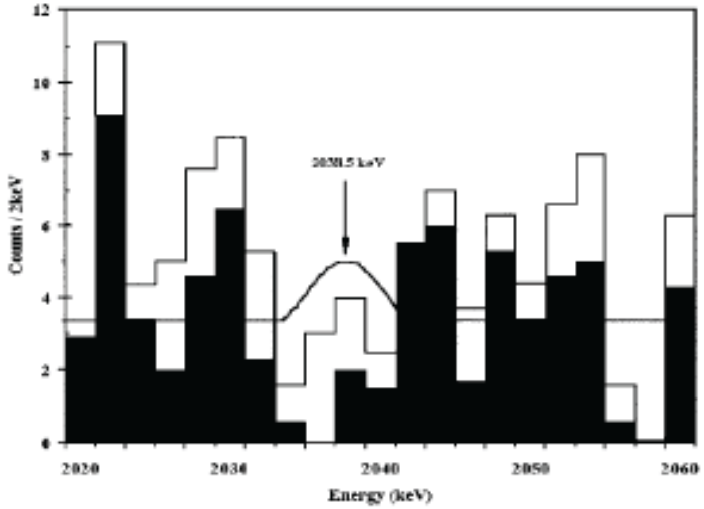
(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

Precursor Ge experiments



Heidelberg-Moscow
(H.V. Klapdor-Kleingrothaus et al.)
(Eur. Phys. J. A 12, 147-154 (2001)):

53.9 kg y (35.5 kg y): $T_{1/2}^{0\nu} > 1.3 \times 10^{25}$ yr (1.9×10^{25} yr)
(90% C.L.)



IGEX
(Aalseth et al.)
Phys. Rev. D 65 (2002) 092007

8.8 kg y: $T_{1/2}^{0\nu} > 1.6 \times 10^{25}$ yr (90%C.L.)

	Golden Coax	BEGe
	BI[10^{-3}] in 10 keV	BI[10^{-3}] in 10 keV
Interpolation	17.5 [15-20]	36.1 [26-49]
Minimal	18.5 [17.6- 19.3]	38.1 [37.5 – 38.7]
Maximal	21.9 [20.7– 23.8]	
	Cts in 40 keV	Cts in 32 keV
data	13	
Minimal	8.6 [8.2-9.1]	2.2 [2.1 – 2.2]
Maximal	10.3 [9.7-11.1]	

The background index evaluated in the 230 keV region centered at Q_bb

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* minimum model		*GOLD-coax* maximum model		*GOLD-nat* minimum model		*SUM-bege* 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]

†) prior: discussed in sec. 5