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

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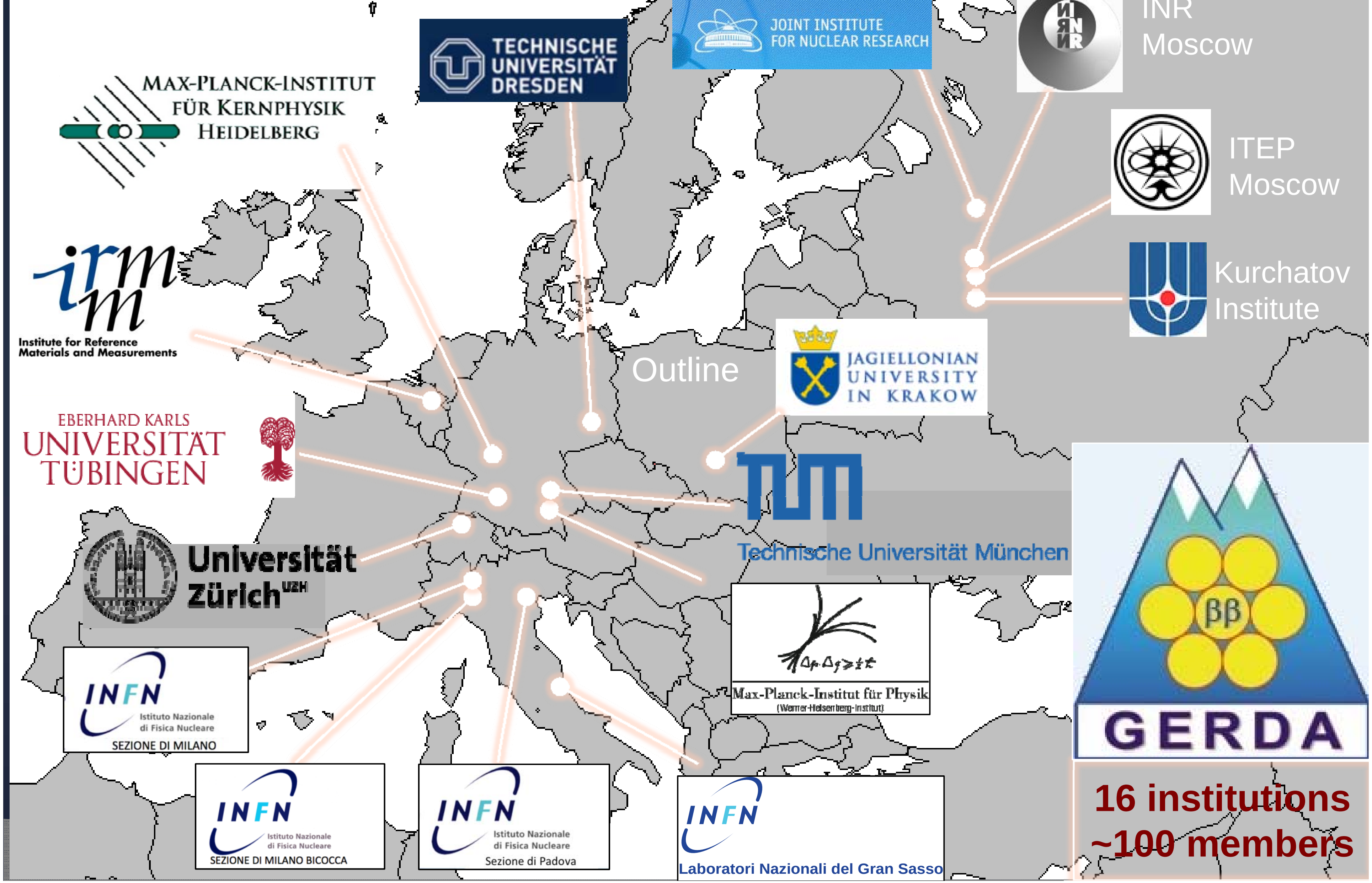
on behalf of the GERDA Collaboration

EPS 2013, 18-24 July 2013

Greetings from Dubna!

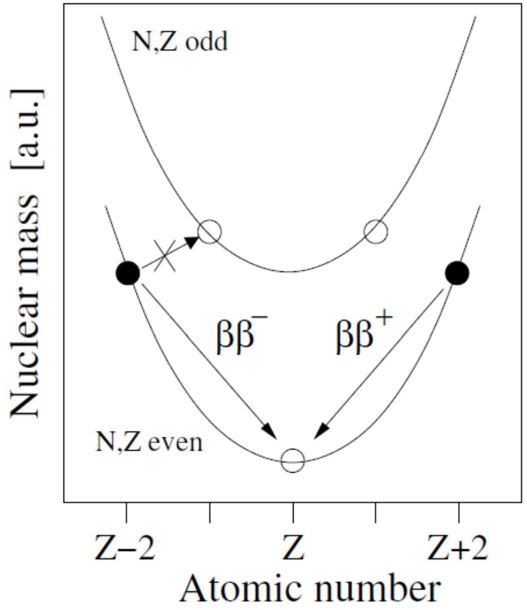
# The GERDA Collaboration

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



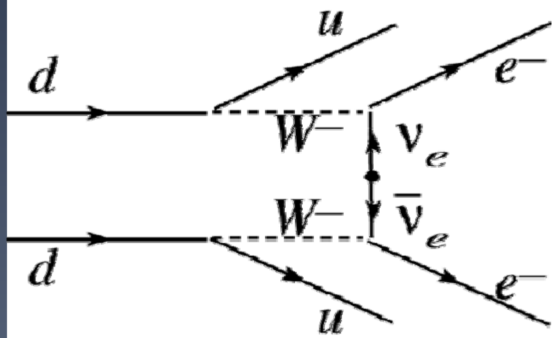
# Outline


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

Experimental sensitivity on T1/2

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

Ideal case: no bckgd

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

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

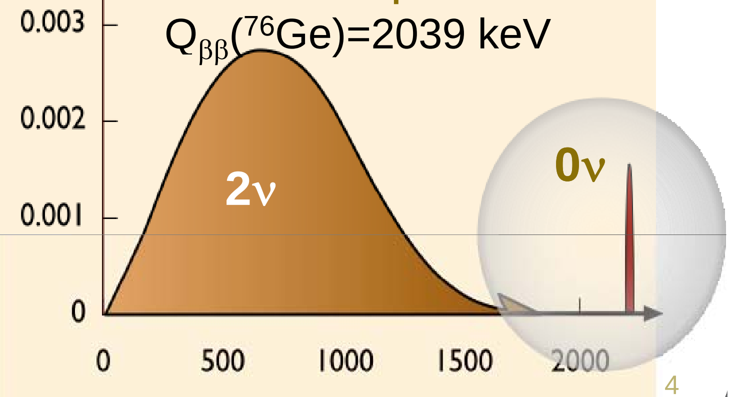
$< m_{\beta\beta} > =$ *effective ν mass*

$M_\nu =$ *Nuclear Matrix Element*

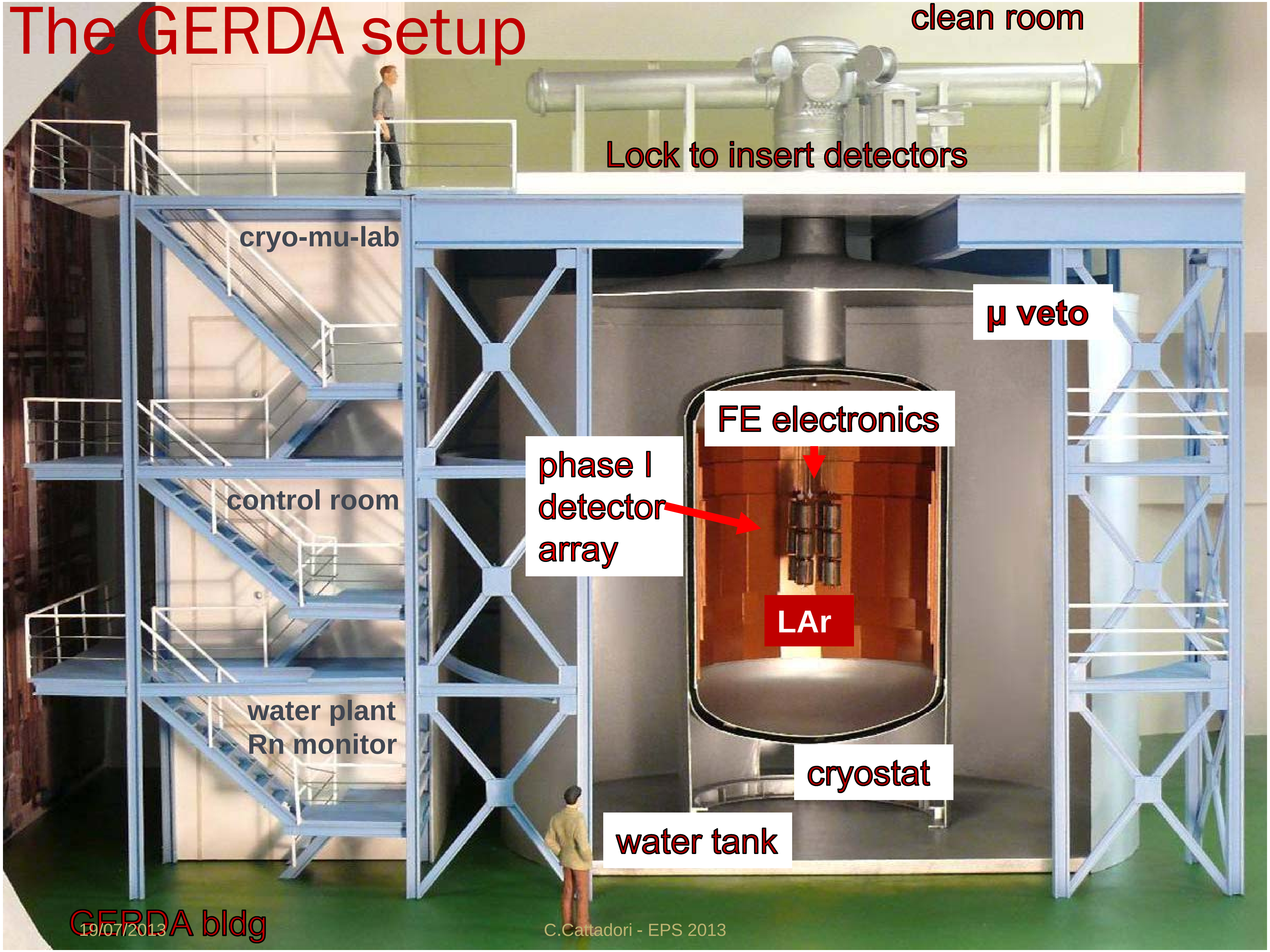
$G_{0\nu} =$ *Phase Space Factor*

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

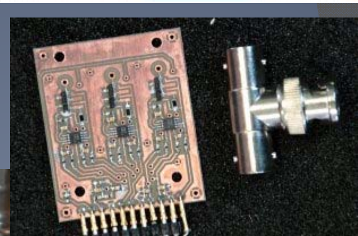
Electron spectrum



# The GERDA setup

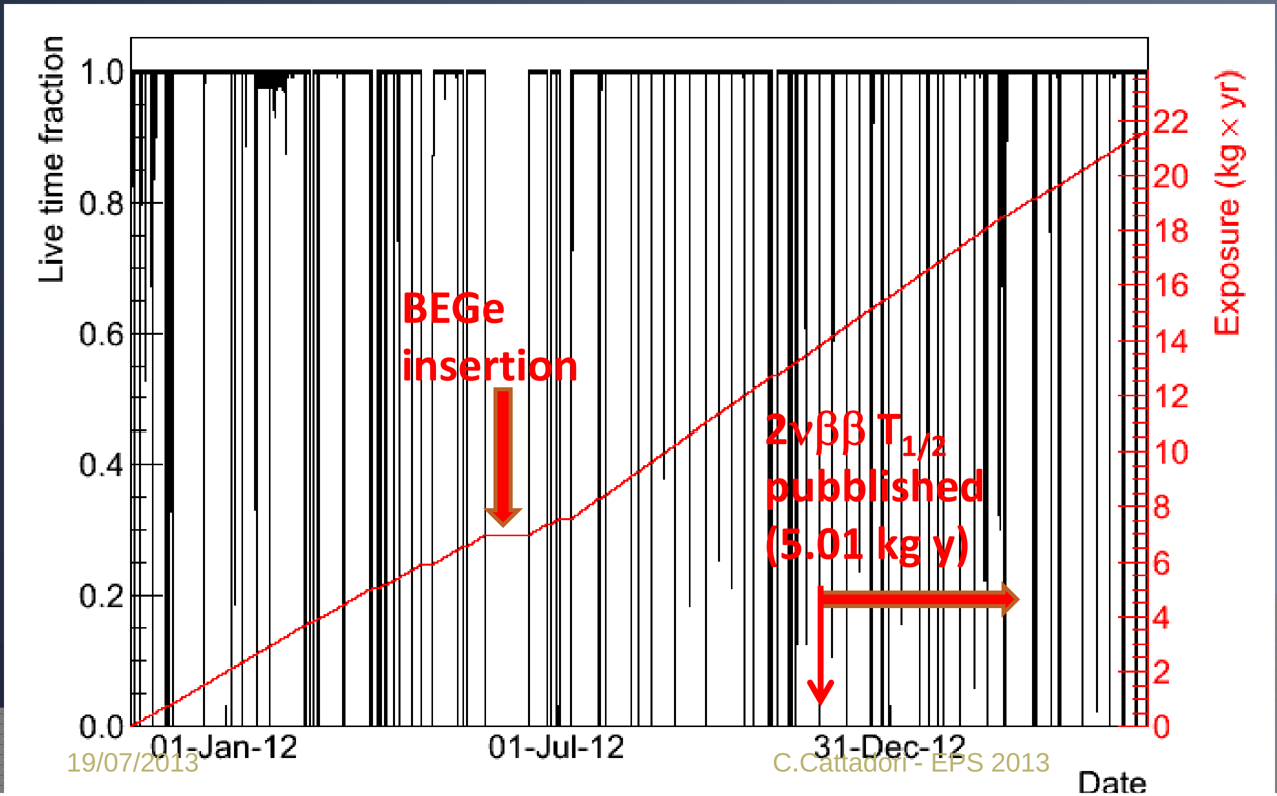



# A tour in GERDA



# 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

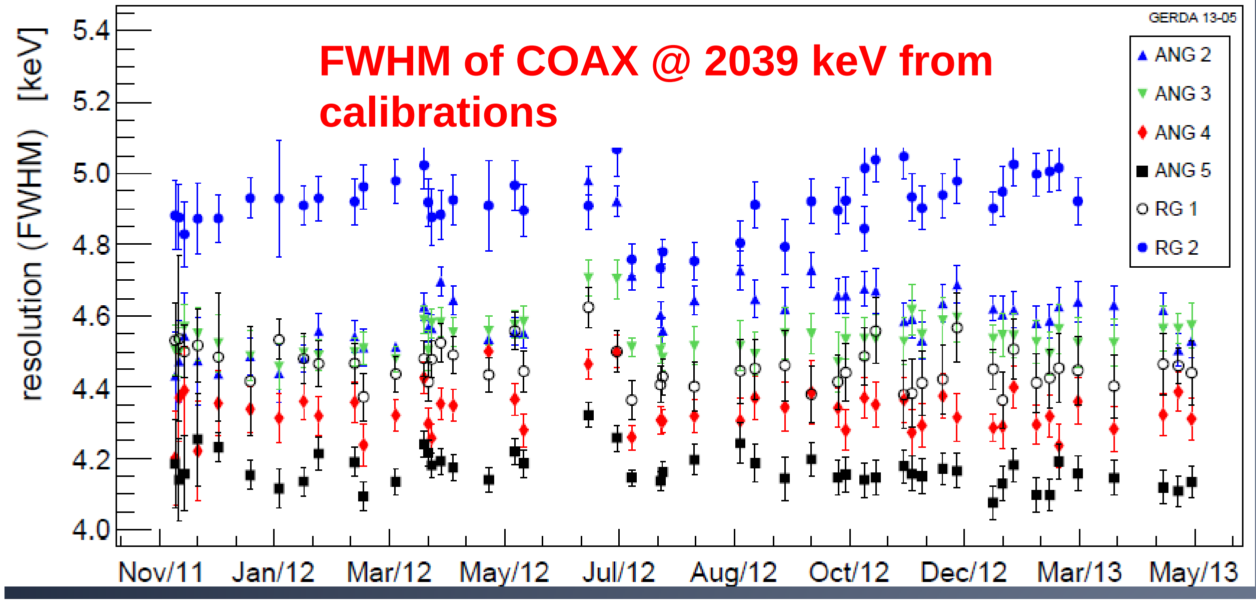
ICPMS

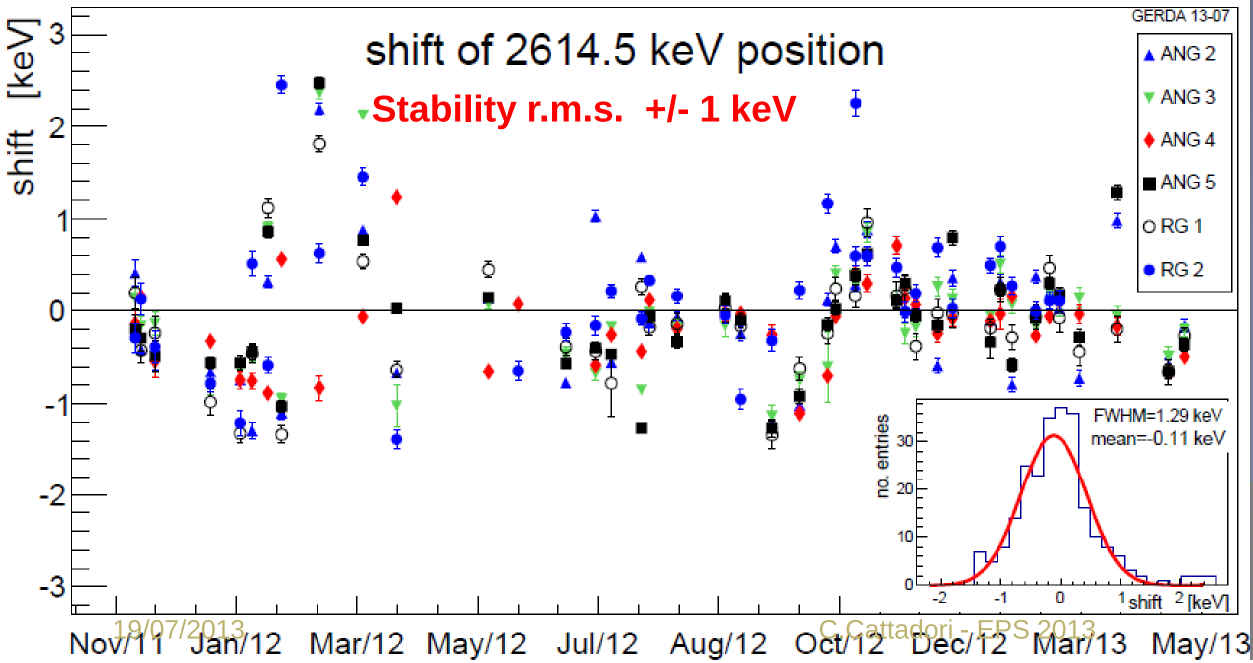
Low E $\gamma$-sources

| 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 | | | |

# The Energy Scale: COAX

arXiv: 1306.5084v1




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

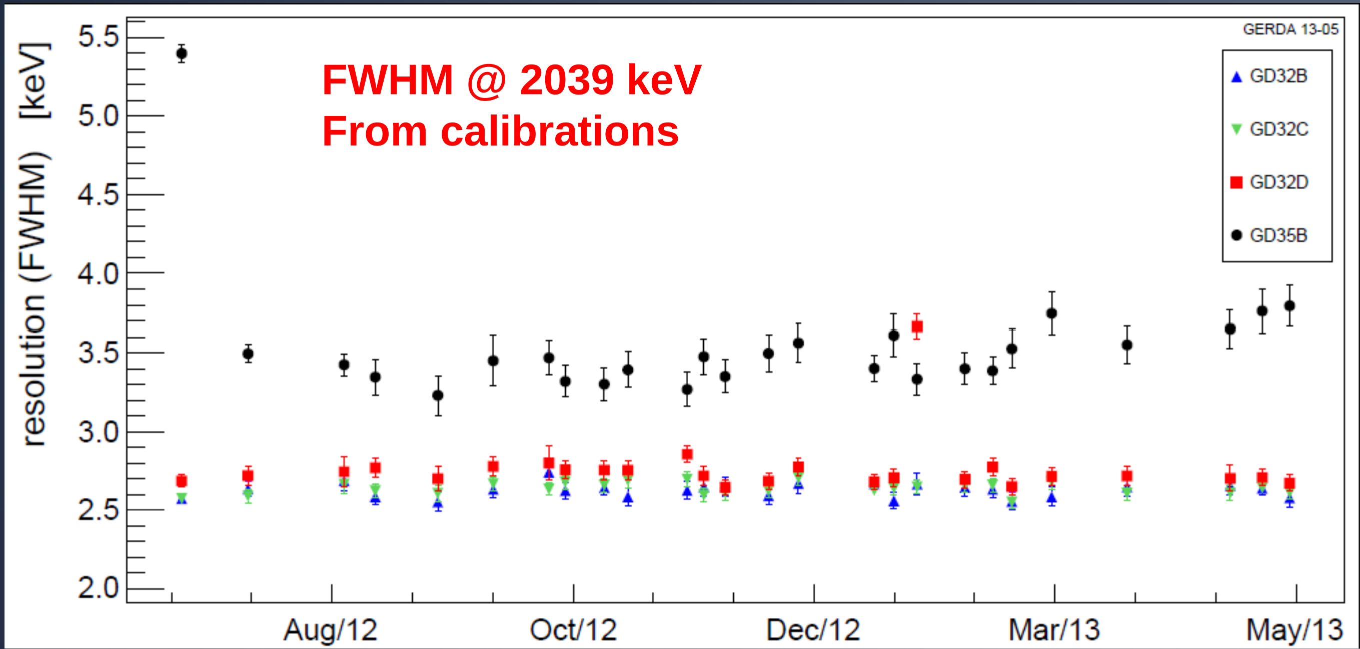
| detector | FWHM @ 2039 keV |
|---|---|
| ANG2 | 5.8 ± 0.3 |
| ANG3 | 4.5 ± 0.1 |
| ANG4 | 4.9 ± 0.3 |
| ANG5 | 4.2 ± 0.1 |
| RG1 | 4.5 ± 0.3 |
| RG2 | 4.9 ± 0.3 |
| Mean COAX | 4.8 ± 0.2 |

**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



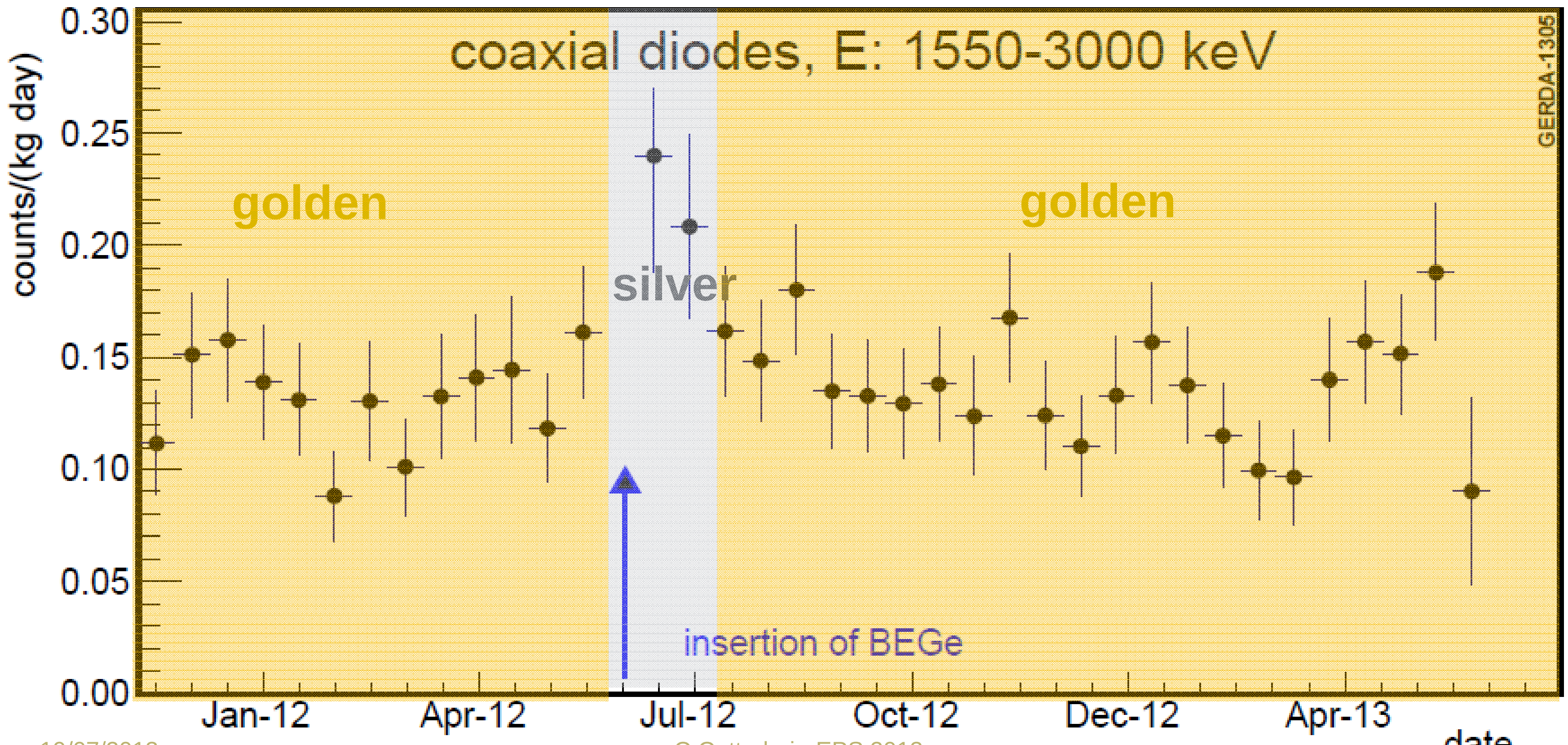

**From 1525 keV $^{42}$K $\gamma$-line summed BEGe spectra**

| 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 |

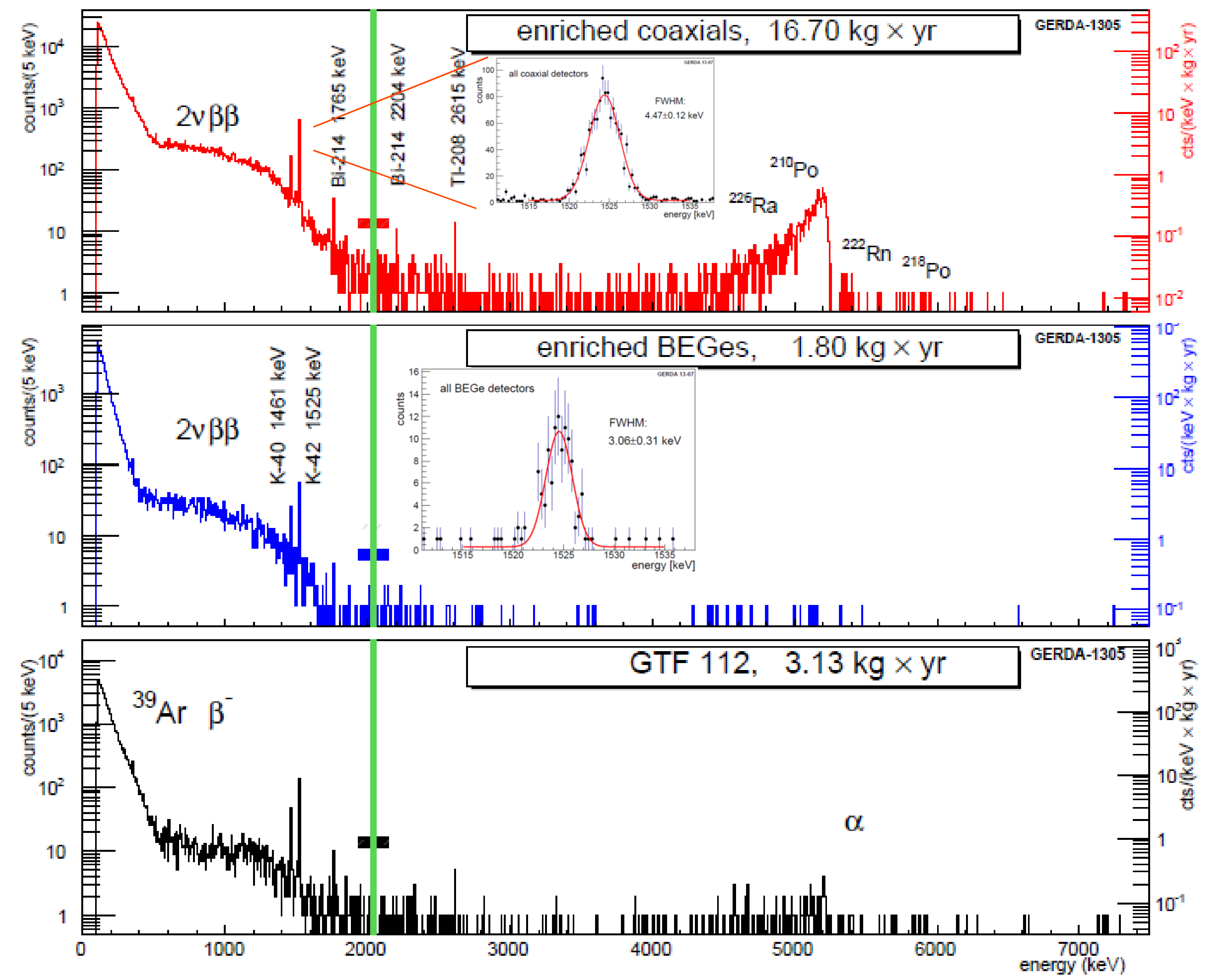
1 $^{enr}$BEGe not used in the $0\nu\beta\beta$ data sets because of instabilities

# GERDA Data Sets

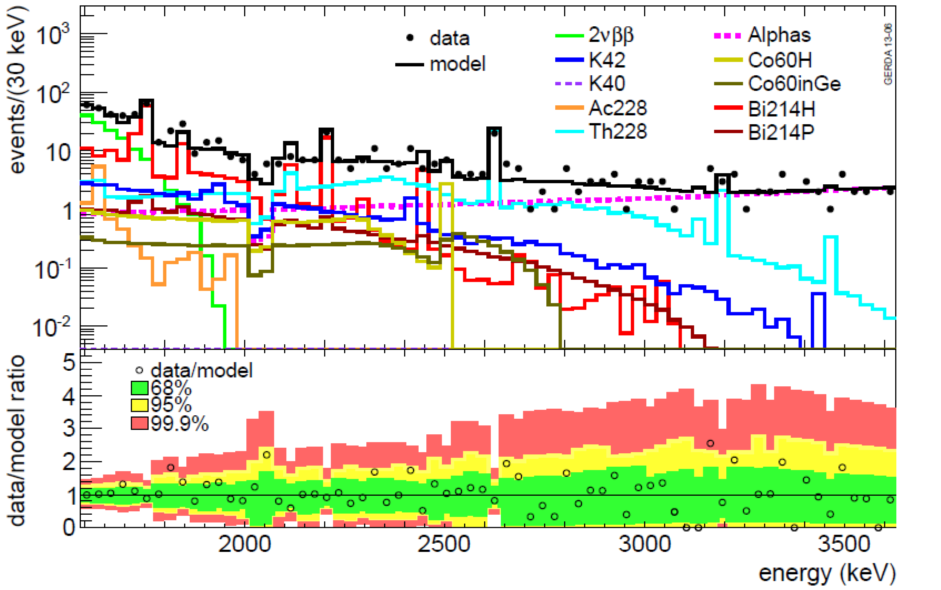
- Golden coax: all the coax runs apart from 30 days just after the BEGe insertion in june 2012
- Silver coax: The coax data collected in the 30 days following the BEGe insertion
- BEGe: Treated separately because of intrinsic differences (better FWHM, intrinsic PSD, lower alfa contamination)



# The energy spectra

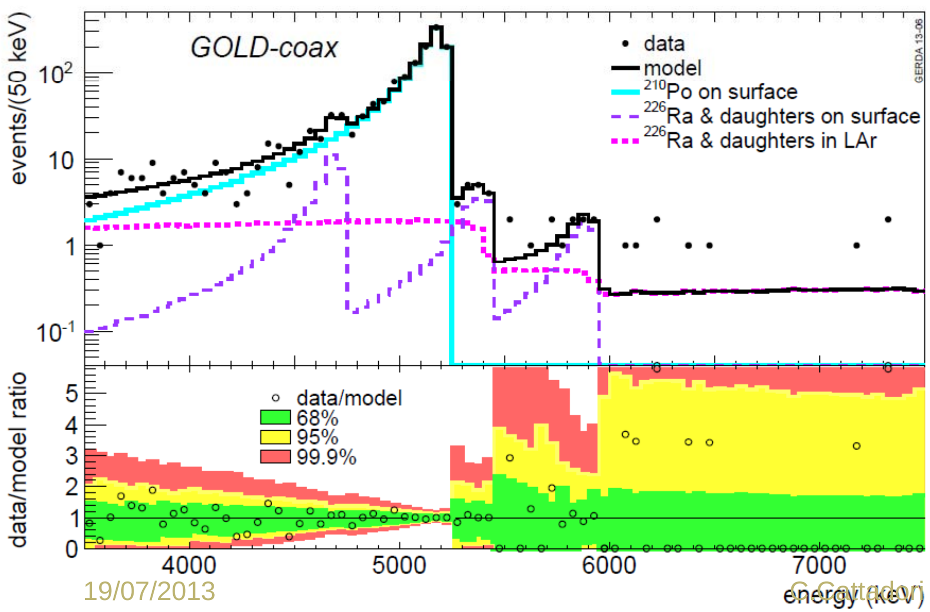


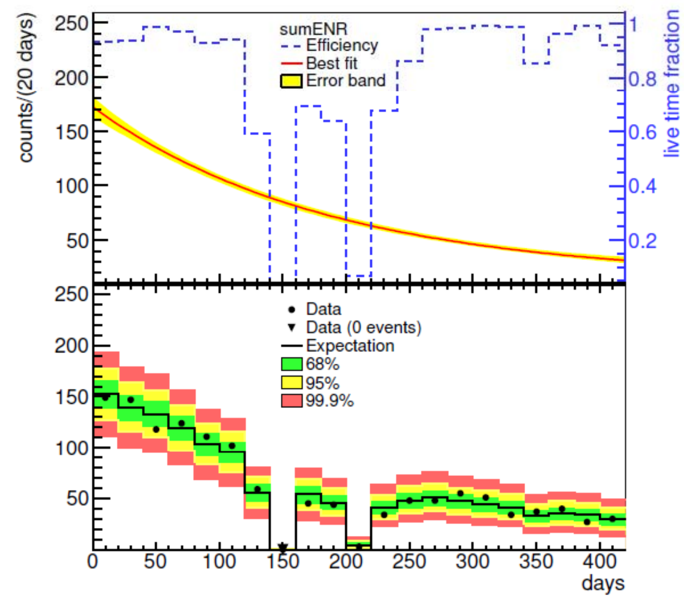
# Identification of Background Components




arXiv: 1306.5084v1

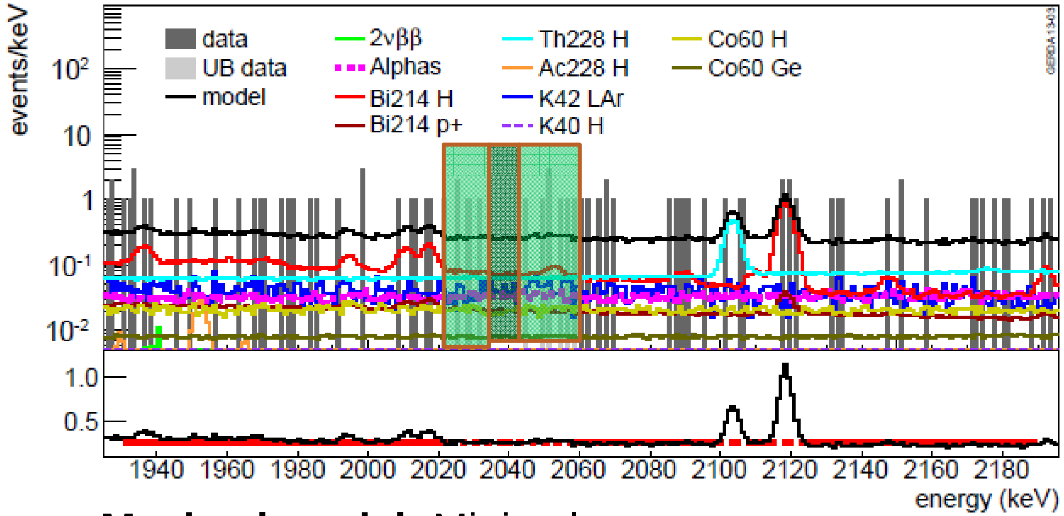
- α contamination from $^{210}$Po.
- contamination at time of refurbishment mostly on thin p+ contact
- $^{210}$Po decaying away ($t_{1/2}$=138 d)
- Large differences among detectors
- BEGes much cleaner (> factor 10)



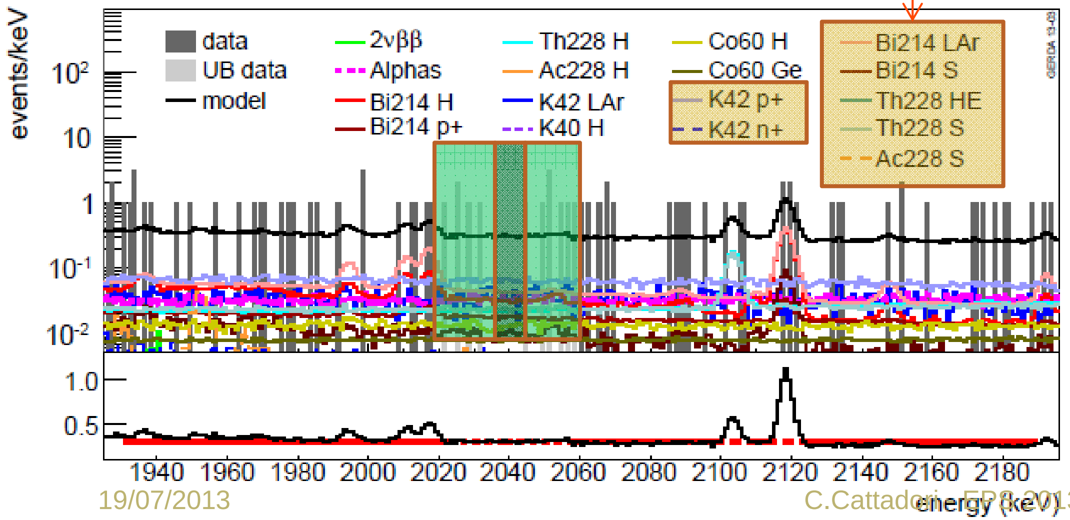



# Background model predictions vs data in 260 keV range around Q_ββ

**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

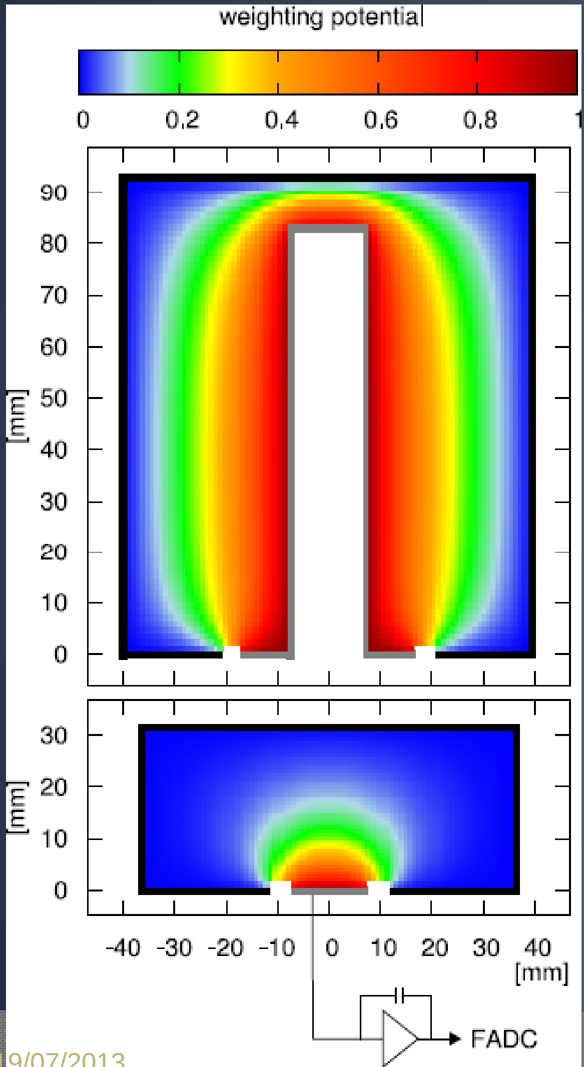
→ spectra can be fitted with a flat background apart from $^{214}$Bi lines @ 2104 keV and 2119 keV

arXiv: 1306.5084v1

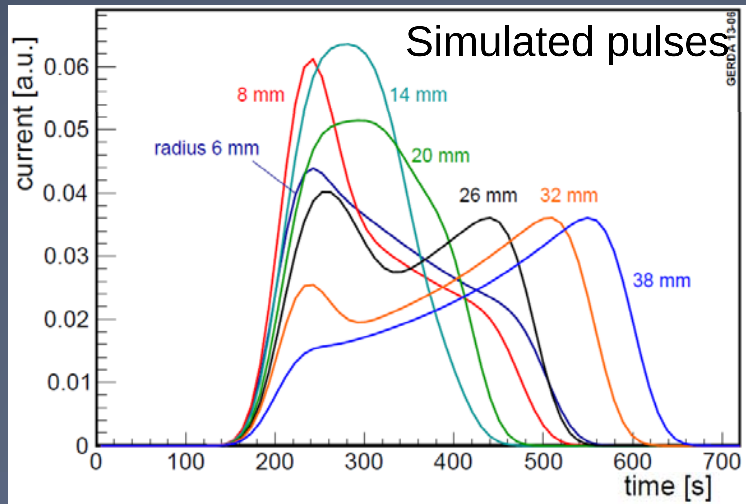
# PSD to discriminate ββ-like (SSE) to γ-like (MSE) events

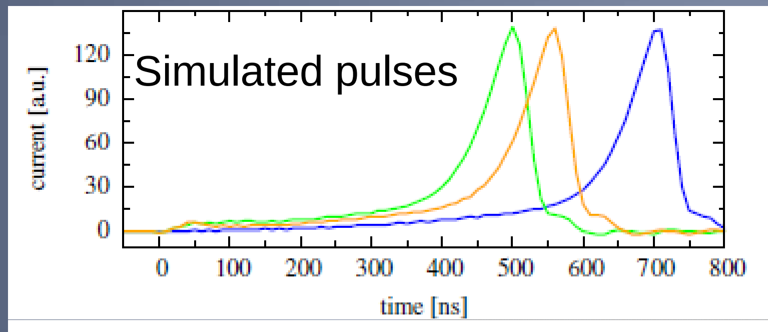
arXiv: 1307.2610

Different weighting potentials for Coax and BEGe




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



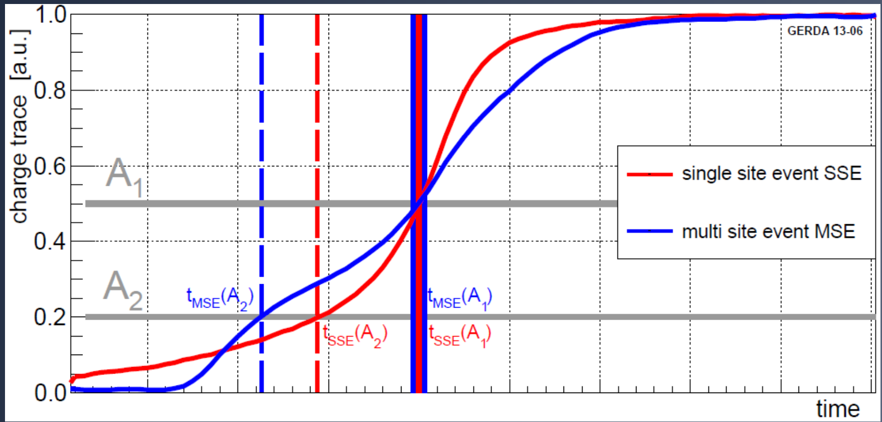




BEGe: Amplitude of Current/Amplitude of Charge Pulse (A/E) is the PSD parameter

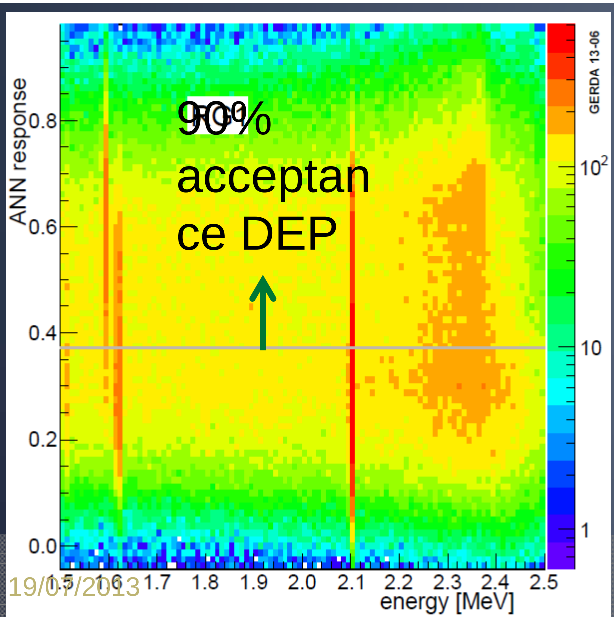
# PSD for coax

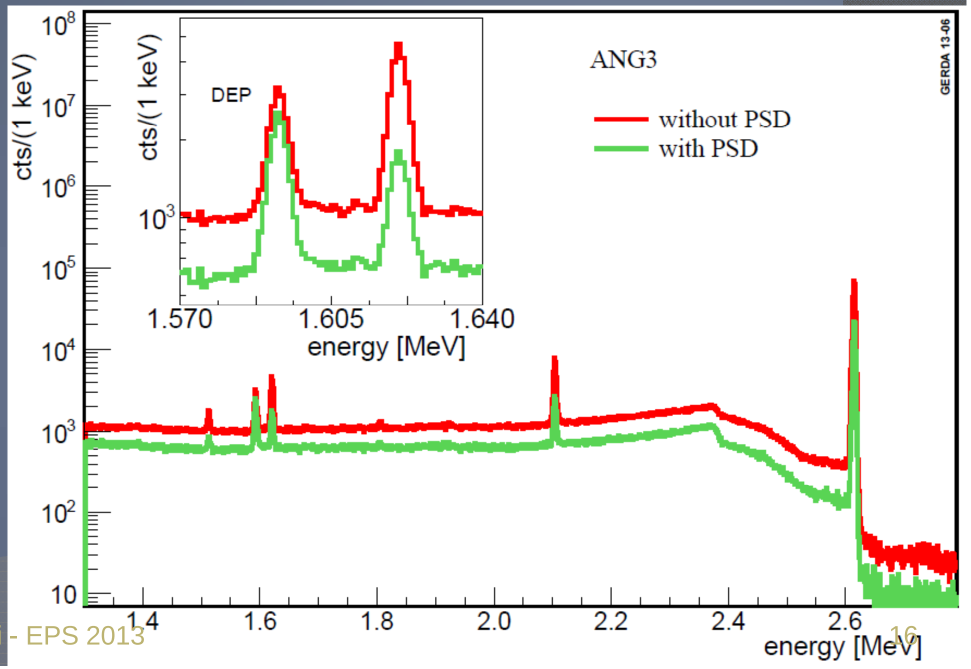
arXiv: 1307.2610

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



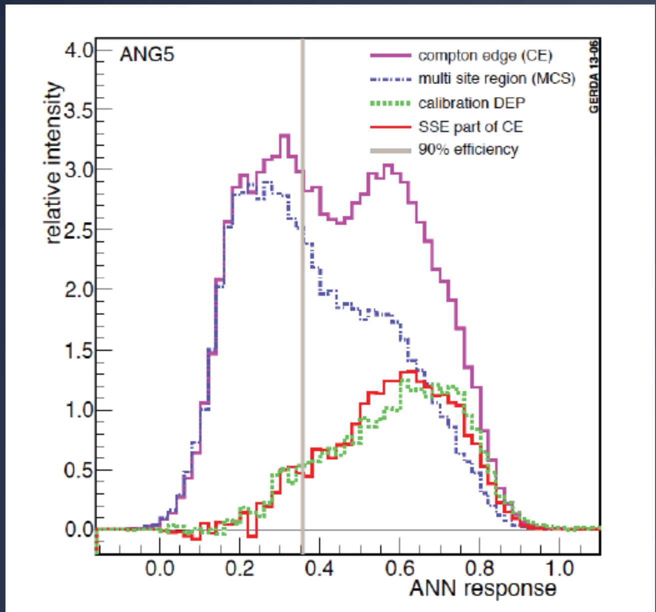

- Required 90% acceptance of DEP
- ε for other classes of events derived
- acceptance of SSE verified on Compton edges (CE) and $2\nu\beta\beta$

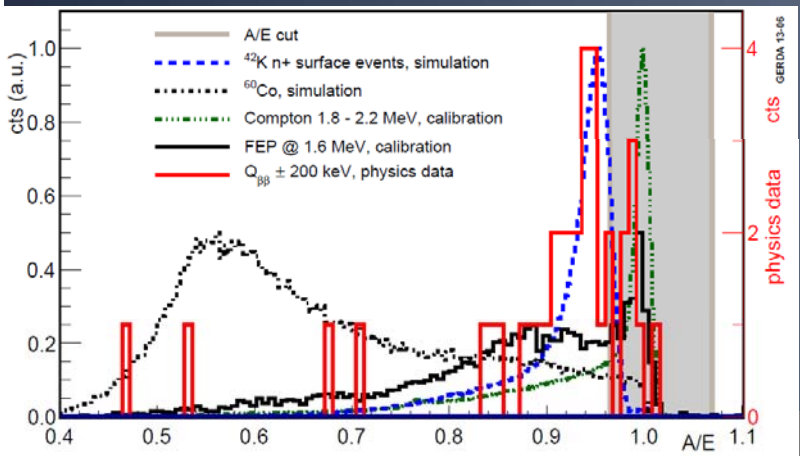


# ..to conclude PSD efficiencies and their systematics are evaluated

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 relevant to $T_{1/2}^{0\nu}$

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

76Ge fraction → $\langle f_{76} \rangle$

Active volume fraction → $\langle f_{av} \rangle$

$\beta\beta$ FEP efficiency → $\langle \varepsilon_{fep} \rangle$

PSD efficiency → $\langle \varepsilon_{PSD} \rangle$

Total efficiency → $\langle \varepsilon \rangle$

| 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 |

Systematics:

| Parameter | Det./Set | Value | Uncertainty |
|---|---|---|---|
| $\langle \varepsilon \rangle$ w/o PSD | Coax | 0.688 | 0.031 |
| | BEGe | 0.720 | 0.018 |
| Energy res. | Golden | 4.83 keV | 0.19 keV |
| | Silver | 4.63 keV | 0.14 keV |
| | BEGe | 3.24 keV | 0.14 keV |
| Energy scale (keV) | | N.A. | 0.2 keV |
| $\varepsilon_{PSD}$ | Coax | 0.90 | 0.10 |
| | BEGe | 0.92 | 0.02 |

# 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 @ $Q_{\beta\beta}$

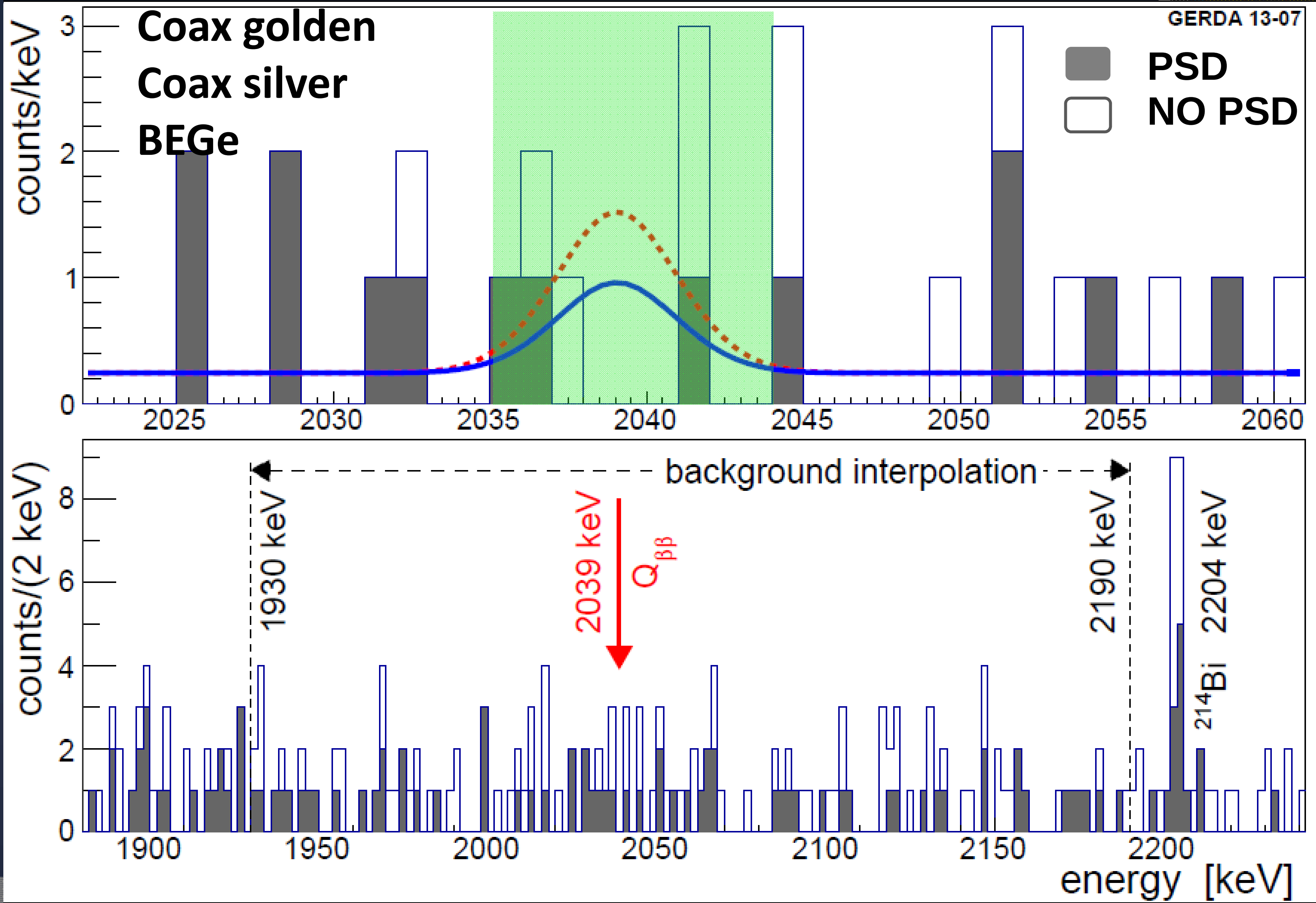
arXiv: 1307.4720v1

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

GERDA

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

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

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 | $0.688 \pm 0.031$ | 76 | $18 \pm 2$ | 5 | |
| *silver* | 1.3 | $0.688 \pm 0.031$ | 19 | $63^{+16}_{-14}$ | 1 | 5.1 |
| *BEGe* | 2.4 | $0.720 \pm 0.018$ | 23 | $42^{+10}_{-8}$ | 1 | |
| with PSD | | | | | | |
| *golden* | 17.9 | $0.619^{+0.044}_{-0.070}$ | 45 | $11 \pm 2$ | 2 | |
| *silver* | 1.3 | $0.619^{+0.044}_{-0.070}$ | 9 | $30^{+11}_{-9}$ | 1 | 2.5 |
| *BEGe* | 2.4 | $0.663 \pm 0.022$ | 3 | $5^{+4}_{-3}$ | 0 | |

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

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

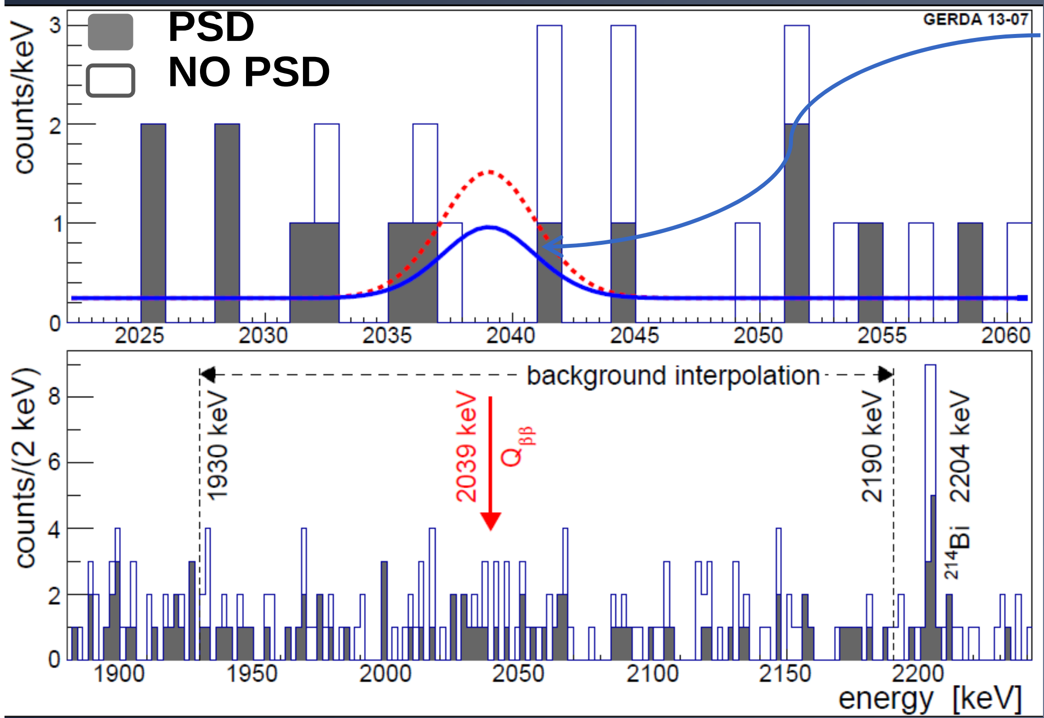
**BI Rej $_{PSD}$ $^{BEGe}$ ~ 87%**

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

arXiv: 1307.2610

Performed Profile Likelihood fit of the 3 data sets

- B+S: described by constant term + Gaus($Q_{\beta\beta}$,$\sigma_E$)
- 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:

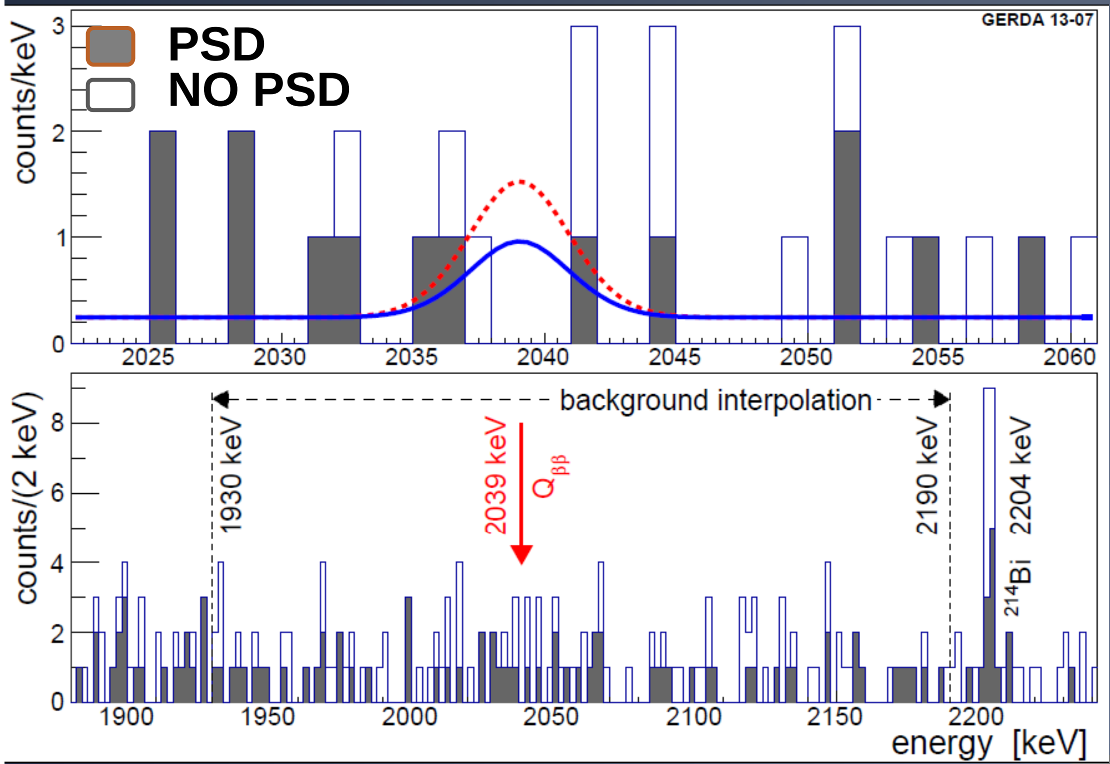
$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr

# 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)



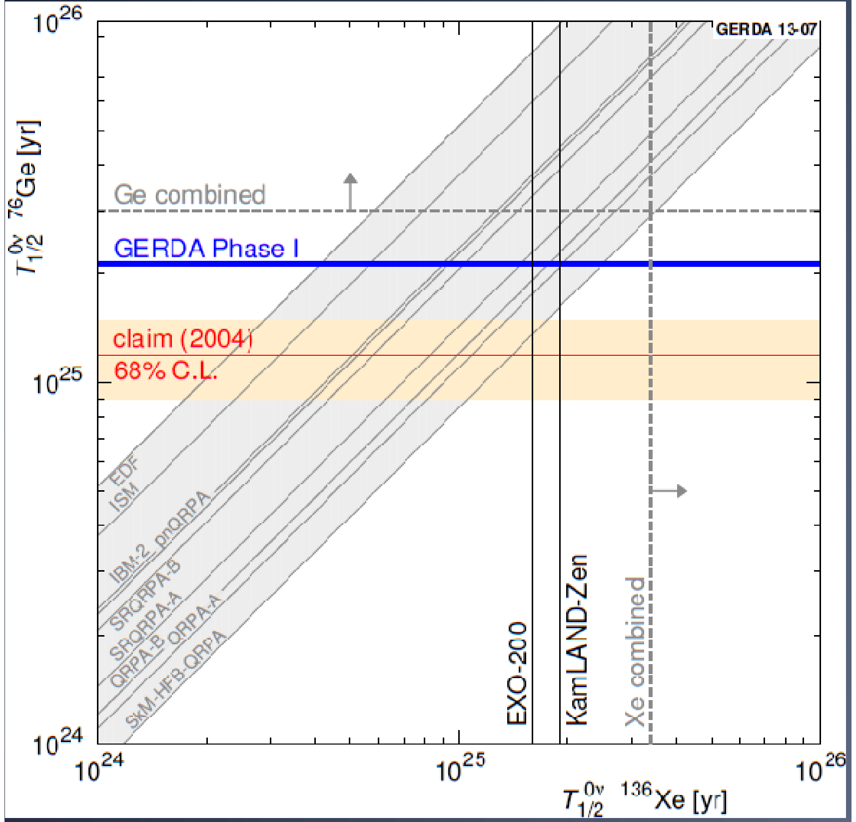

Comparing
H1: Claimed signal
H0: Background only

Bayes factor
P(H1)/P(H0)=0.024
Claim poorly credible

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

# Combining GERDA, HdM, IGEX & Xe

arXiv: 1307.2610




**H1**: signal with $T_{1/2}^{0\nu} = 1.19\times10^{25}$ 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

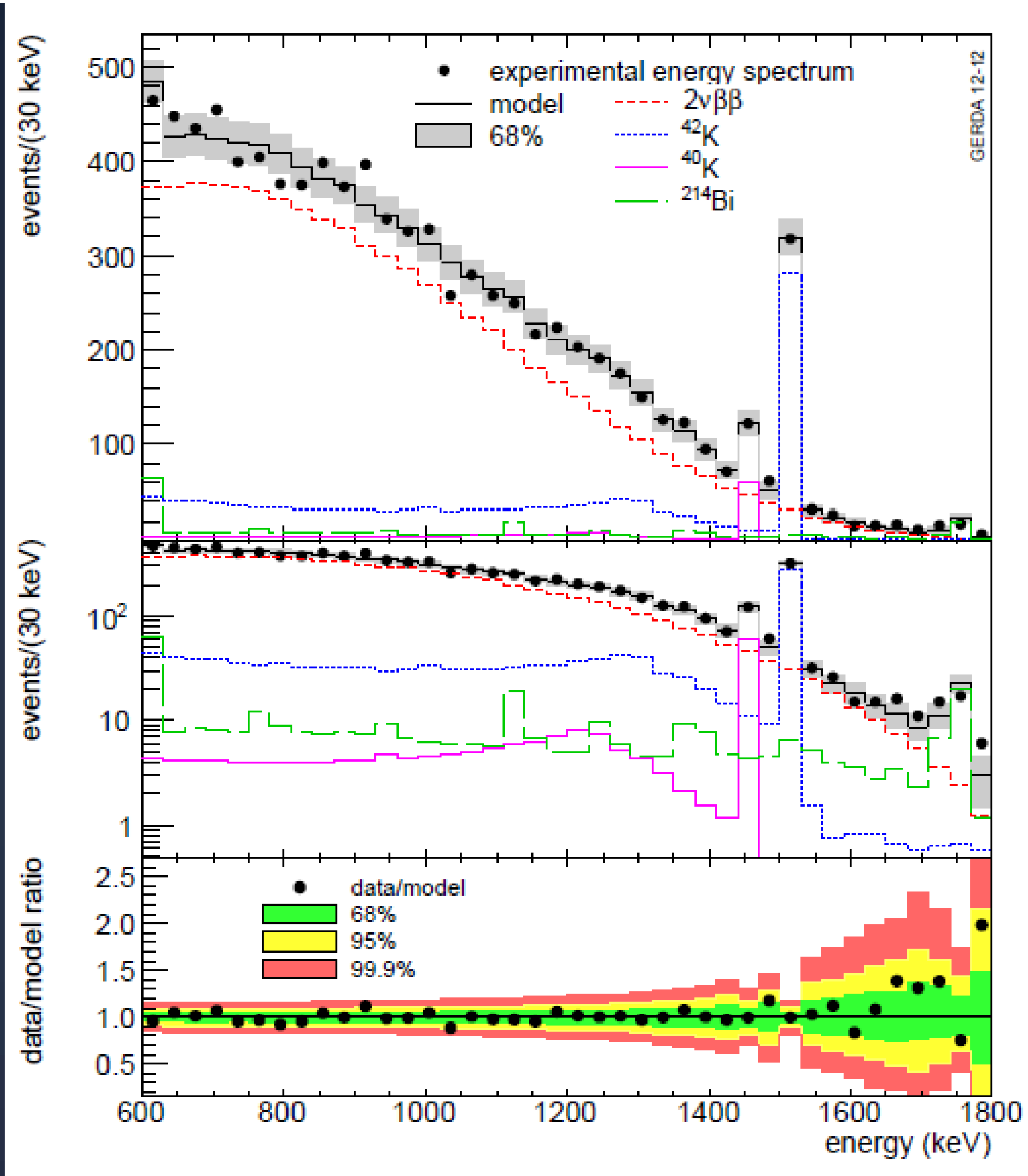
- GERDA achieved its design goals
  - Phase I Exposure: 21.6 kg yr
  - Background Index: ~$10^{-2}$ cts / (Kev kg y) Unprecedent value!
  - Scrutinize the KK claim in 1.5 yr data taking
- No excess of counts above background is found @ $Q_{\beta\beta}$ after unblinding: 7 (3 after PSD) cts in ± 5keV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

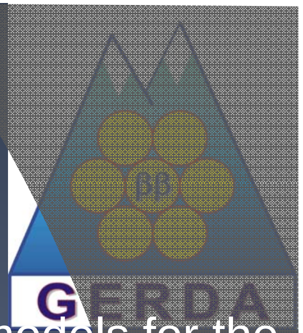
- PSD works well mainly for BEGEs
- Phase II challenge: achieve another factor 10 in BI and sensitivity

……….. *who will live will see it.*

# EXTRA slides




- 2νββ spectrum generated by DECAY0 (V.Tetryak)



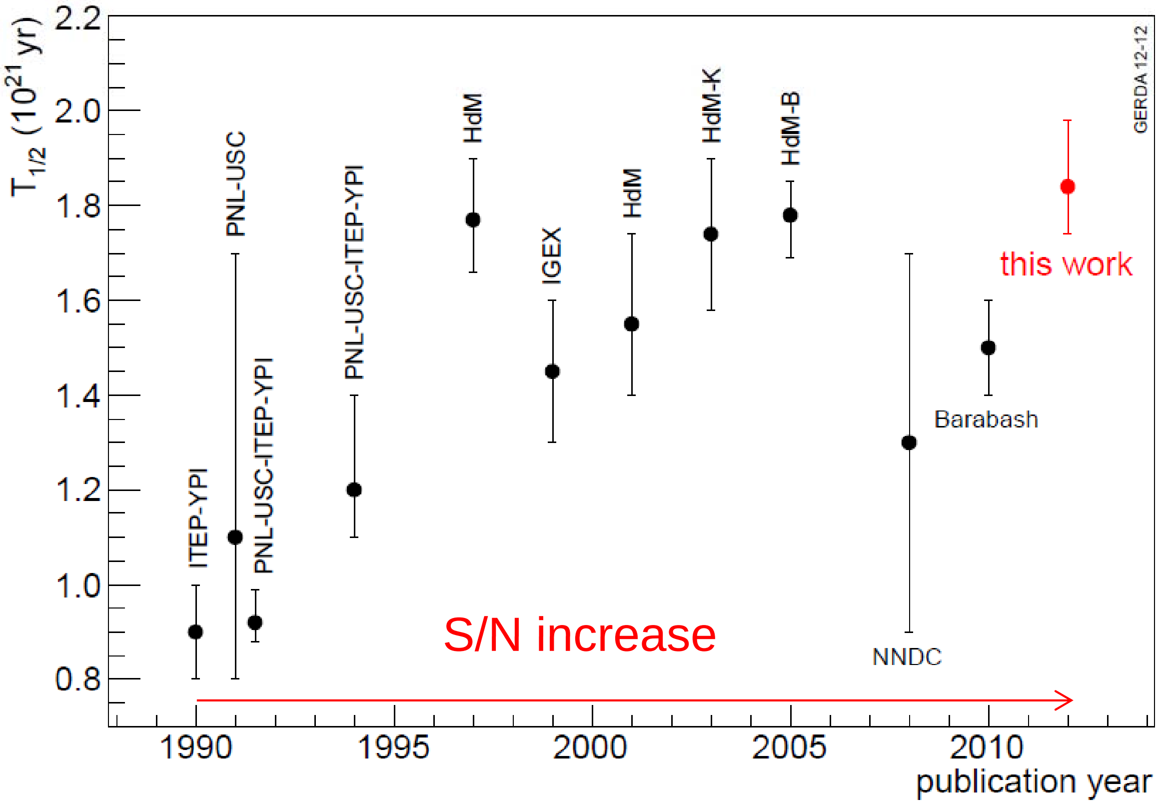

- 6 independent models for the 6 detectors (5 x 6=30 detector parameters)
- $T^{2\nu}_{1/2}$ common in 6 detectors
- Background from 3 sources: $^{42}K$, $^{40}K$, $^{214}Bi$ (γ-lines used for normalization)
  - $^{42}K$: homogeneusly distributed
  - $^{40}K$ & $^{214}Bi$: close sources
- Detectors active 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% $^{40}K$,

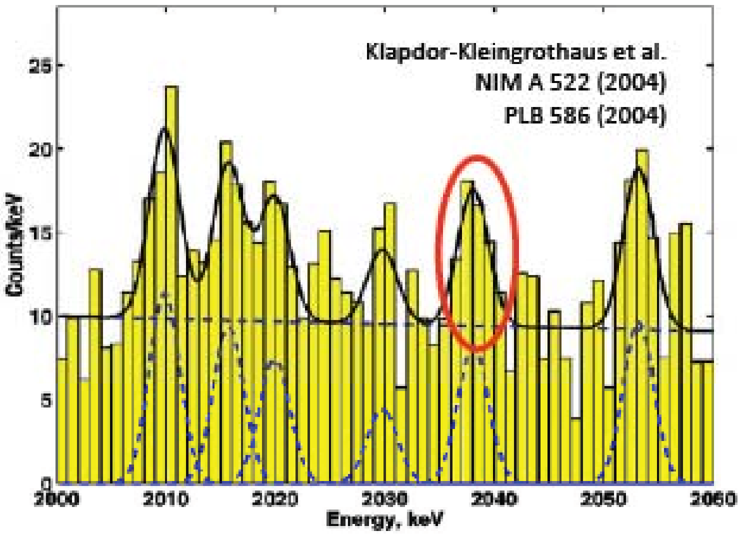
# GERDA vs previous measurements of $T^{2\nu}_{1/2}$

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




- GERDA is consistent with HdM $T^{2\nu}_{1/2} = 1.78^{+0.07}_{-0.09}$
- Thanks to our BI comparable $\sigma_{stat}$ 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):

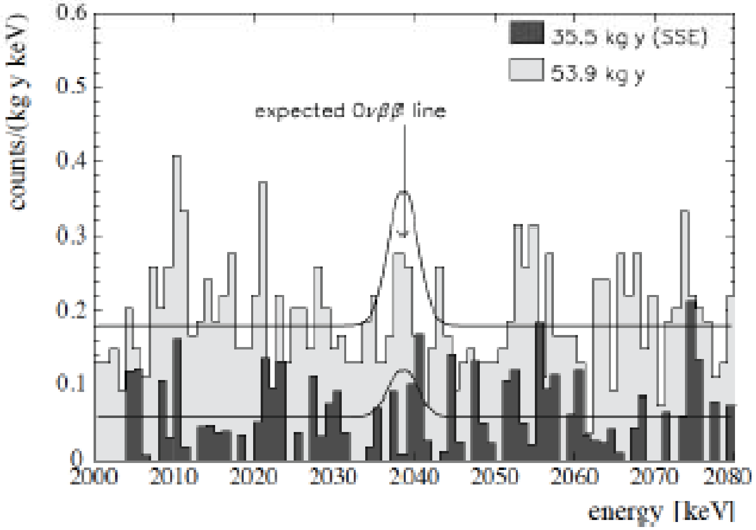
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x$10^{25}$ yr

N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x$10^{25}$ 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 $\varepsilon_{psd}$ = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- $\varepsilon_{fep}$ = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\varepsilon_{fep}$ = 0.9)

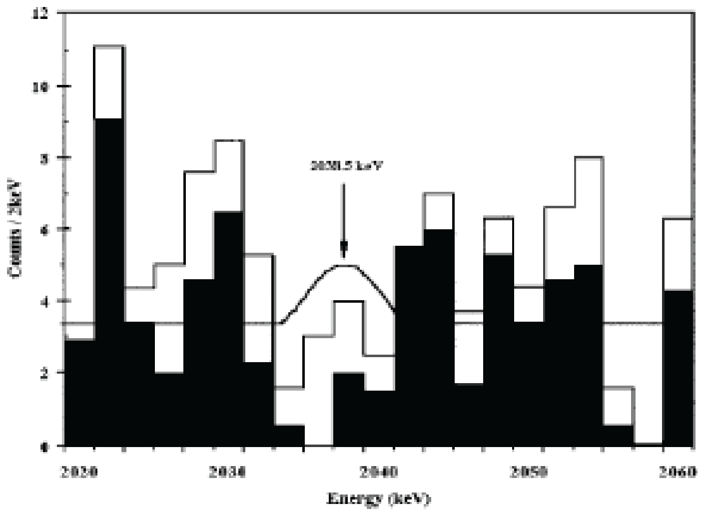
(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

# 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 ($1.9 \times 10^{25}$ 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 | | | | |
| $\alpha$ 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