Search of Neutrinoless Double Beta Decay with the GERDA Experiment

Giovanni Benato for the GERDA Collaboration

University of Zurich

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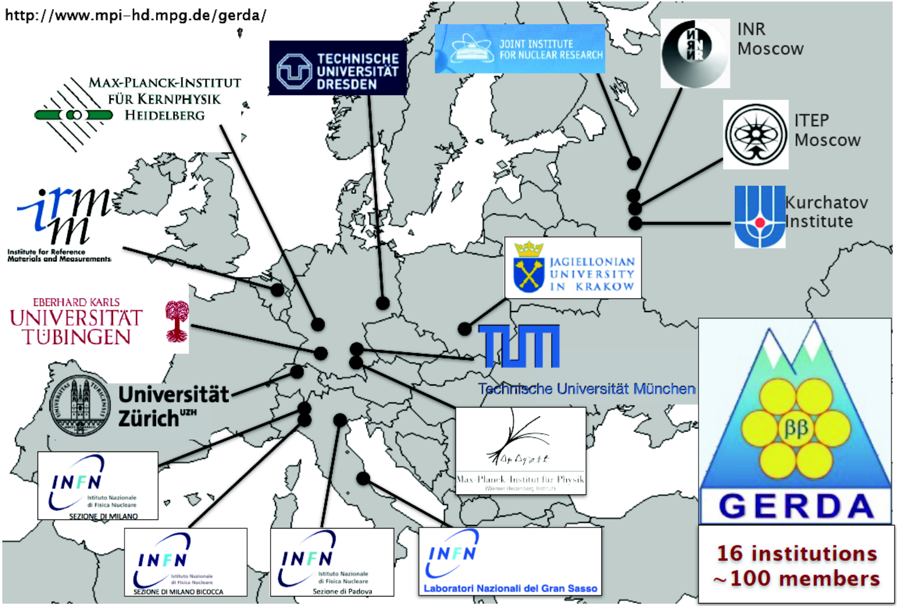
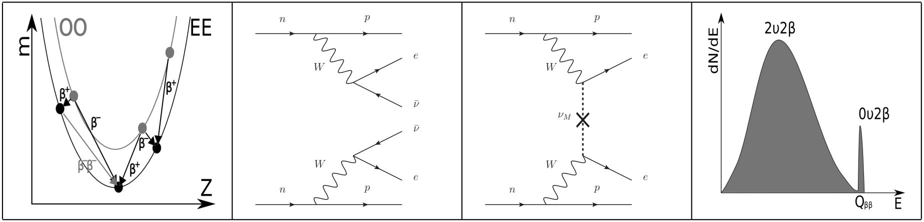
The GERDA Collaboration



Two neutrino double beta decay ($2\nu\beta\beta$)

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



Neutrinoless double beta decay ($0\nu\beta\beta$)

- Violates lepton number conservation ($\Delta L = 2$)
- Possible only if ν's have Majorana mass component
- Could enlighten the neutrino mass hierarchy

Experimental signatures

- $2\nu\beta\beta$: continuum
- $0\nu\beta\beta$: peak at $Q_{\beta\beta}$ (2039 keV for ^{76}Ge)

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

The mass mechanism

Expected decay rate (for light ν exchange):

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

where:

- $G^{0\nu}(Q,Z)$ = Phase Space integral
- $\left|M^{0\nu}\right|^2$ = nuclear matrix element
- $\langle m_{ee}\rangle^2 = \sum_i U^2_{ei} m_i$ = effective ν mass
- U_{ei} = elements of the PMNS mixing matrix

Space for competing technologies!

Experimental Sensitivity

Sensitivity on $T^{0\nu}_{1/2}$ for exclusion limit at n_σ CL with non null background is given by:

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

where:

f = enrichment fraction

N_A = Avogadro number

m_A = atomic mass

ε = total efficiency

M = detector mass

t = livetime

$M \cdot t$ = exposure

BI = Background Index

ΔE = energy resolution

Why using germanium?

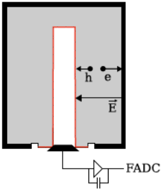
- High total efficiency ($\varepsilon \sim 0.75$)
- Best energy resolution on the market ($\sim 1.5\%$ FWHM at $Q_{\beta\beta}$)
- Can be enriched to 86% in ^{76}Ge

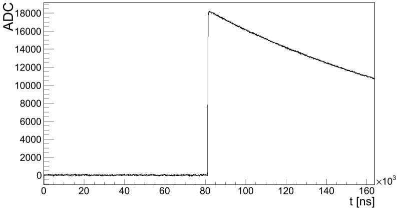
How to reduce the background?

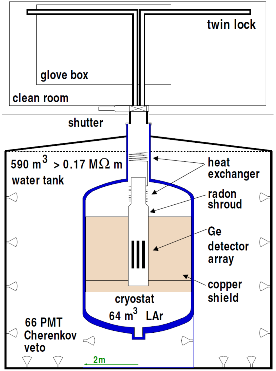
- Operate the experiment underground
- Use active veto for cosmic muons and external backgrounds
- Minimize radioactive contaminations in the materials close to the detectors
- Current pulse is different for single site events (like $0\nu\beta\beta$ signal) versus multi site events (like Compton scattered γ) or surface events $\rightarrow$ Pulse Shape Discrimination (PSD)

Ge detector readout

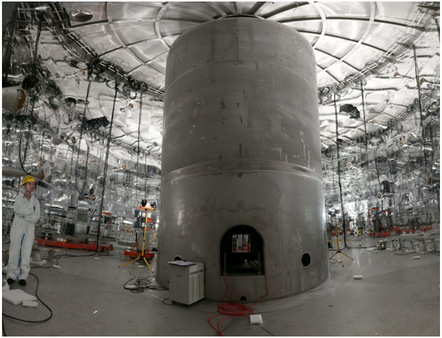
- Ge diode in reverse bias $\rightarrow$ measurement of ionization energy
- FADC allows offline analysis of recorded signals (energy, rise time, PSD parameters, ...)







- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden
- Array of bare Ge detectors 86% enriched in ^{76}Ge directly inserted in liquid argon (LAr)
- Minimal amount of material in proximity of the diodes



Why Liquid Argon + Water?

Material	^{208}Tl Activity [μBq/Kg]
Rock, concrete	3000000
Stainless steel	~ 5000
Cu (NOSV), Pb	< 20
Purified water	< 1
LN_2, LAr	~ 0

The two phases of GERDA

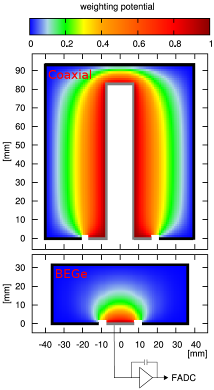
	Mass [kg]	BI [counts/(keV·kg·yr)]	Livetime [yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
Phase I	15	10^{-2}	1	$2.4 \cdot 10^{25}$
Phase II	35	10^{-3}	3	$1.4 \cdot 10^{26}$

Coaxial detectors

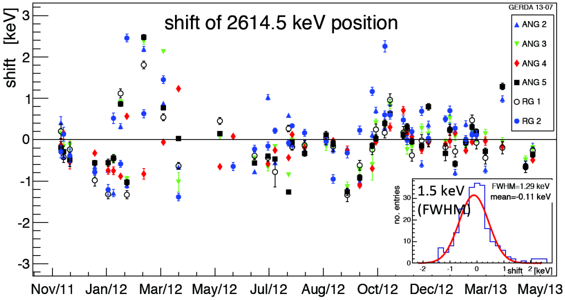
- Inherited from HdM and IGEX experiments
- 2.4‰ FWHM at $Q_{\beta\beta}$ (1.7‰ reachable with better cables & shaping)
- Total enriched mass: 17.7 kg (14.6 kg used for analysis)

BEGe detectors (design for Phase II)

- BEGe = Broad Energy Germanium
- 1.6‰ FWHM at $Q_{\beta\beta}$ (1.2‰ reachable)
- $\sim$ 20 kg of BEGe's produced and tested in 2012
- 5 BEGe's inserted in GERDA in July 2012

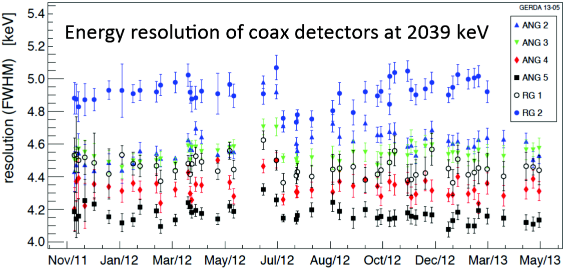


Time Stability and Energy Resolution

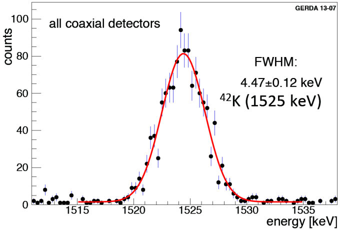


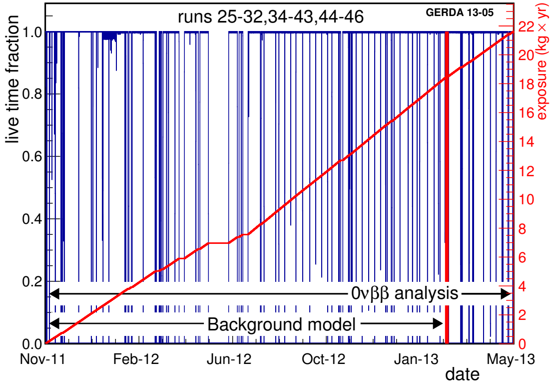
FWHM at $Q_{\beta\beta}$

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)



FWHM at ^{42}K peak

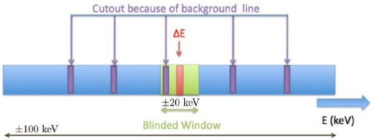


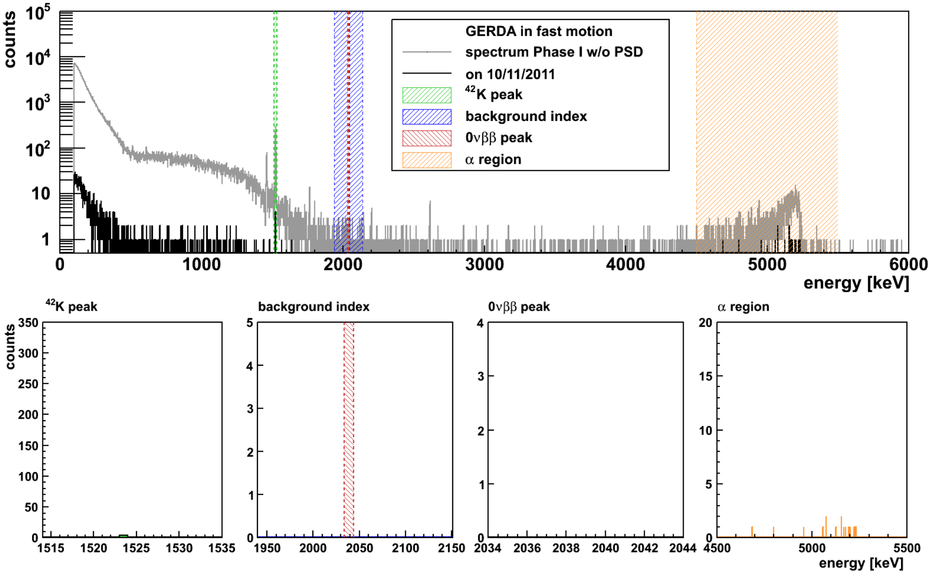


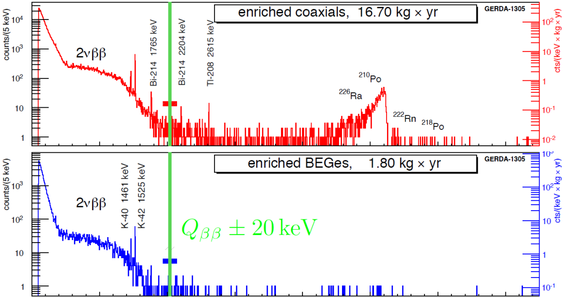
- Spikes: calibration runs
- Flat parts: BEGe's insertion (June 2012), maintenance
- Total livetime: 492.3 days
- Exposure: 21.6 kg·yr
- Used 6 coaxial (14.6 kg) and 4 BEGe (3.0 kg)

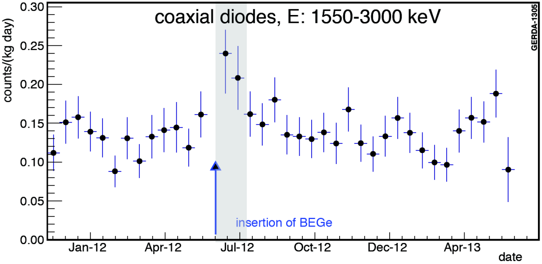
Blind analysis and unblinding procedure

- 40 keV blind region around $Q_{\beta\beta}$
- Background model published before unblinding (EPJC 74 (2014) 2764)
- Fixed data processing procedure, quality cuts, PSD methods and statistical analysis




counts
energy [keV]
GERDA in fast motion
spectrum Phase I w/o PSD
on 10/11/2011
42K peak
background index
0νββ peak
α region
42K peak
background index
0νββ peak
α region
counts
energy [keV]





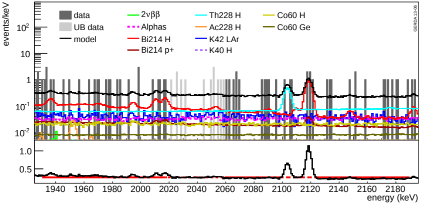
- Split coaxial data in two sets (Golden and Silver), according to the BI
- BEGe data kept separated, due to different resolution and background

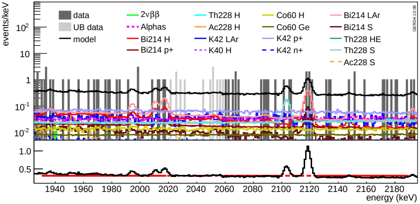
dataset	exposure [kg·yr]	FWHM @ $Q_{\beta\beta}$ [keV]
Golden	17.90	4.8 ± 0.2
Silver	1.30	4.6 ± 0.2
BEGe	2.40	3.2 ± 0.2

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 $Q_{\beta\beta}$

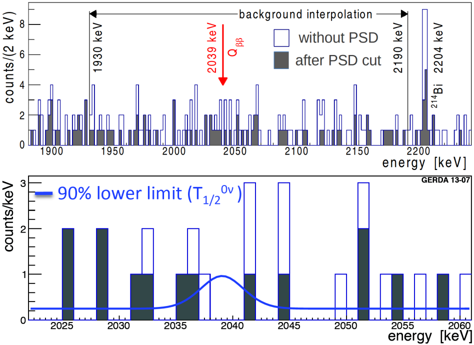




Analysis recipe:

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

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



Profile Likelihood Method

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

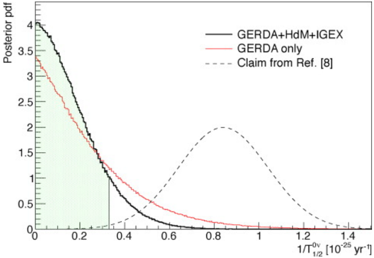
$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\ \text{yr}$$

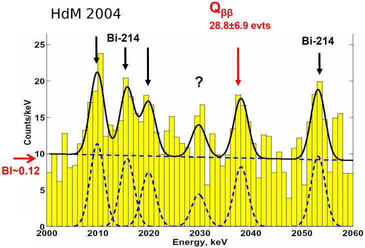
- Median sensitivity: $2.4 \cdot 10^{25}$ yr

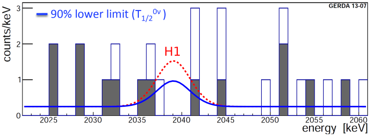
Bayesian Approach

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]$ yr^{-1}
- best fit $N^{0\nu} = 0$
- 90% credibility interval: $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: $2.0 \cdot 10^{25}$ yr

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







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 PL and Bayesian approach

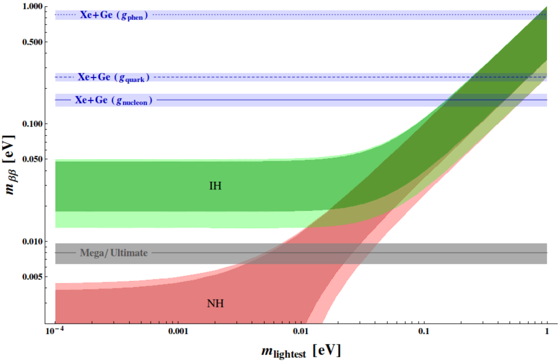
$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90%) C.L.

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

- Claimed signal with $T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr
- H1: claimed signal (expected 5.9 ± 1.4 events)
- P-value from PL: $P(N^{0\nu} = 0|H1) = 0.01$
- Comparison independent of NME and physical mechanism generating $0\nu2\beta$

Claim strongly disfavored

From arXiv:1404.2616v1:



- GERDA, KamLAND-Zen and EXO-200 succesfully completed their first phase
- Klapdor's claim strongly disfavoured
- The field of research is open again to search for $0\nu\beta\beta$ decay

(Near) future experiments:

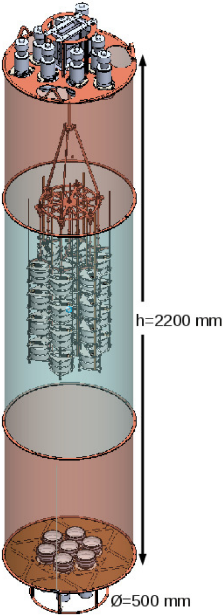
- ^{76}Ge: GERDA Phase II, Majorana, GERDA+Majorana
- ^{136}Xe: Exo-200, nEXO, KamLAND2-Zen, NEXT-100, MAGIX/GraXe
- Bolometers: CUORE, AMoRE, LUCIFER
- Other technologies: SNO+, CANDLES, SuperNEMO, DCBA
- Plus many others...

Summary

- GERDA Phase I data taking successfully completed
- $2\nu\beta\beta$ decay: $T_{1/2}^{2\nu} = 1.84^{+0.14}_{-0.10} \cdot 10^{21}$ yr
- $0\nu\beta\beta$ decay: $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% CL)

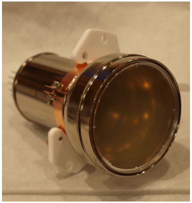
Outlook

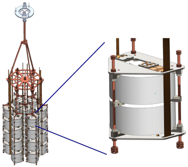
- Upgrade for GERDA Phase II is ongoing
- Aimed sensitivity: $1.4 \cdot 10^{26}$ yr
- Slowly approaching the inverted hierarchy land...

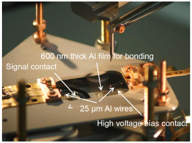


Goal: reach 10^{26} yr sensitivity in $T^{0\nu}_{1/2}$

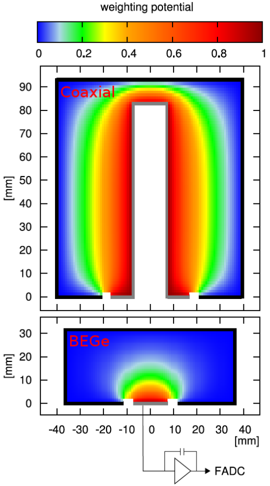
- Increase the statistics
  - More active mass (new BEGe detectors)
  - Longer data taking
- Improve energy resolution
  - Use BEGe detectors
  - Improve shaping filter
- Reduce Background
  - Cleaner cables and electronics
  - Lighter detector holders
  - Special care in crystal production
  - Reject residual background radiation
    - Improve PSD (BEGe detectors)
    - Read LAr scintillation light

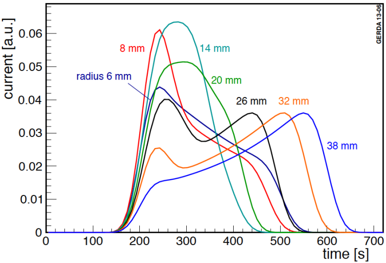




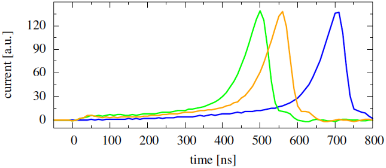


- PSD: distinguish between ($0\nu2\beta$) signal-like events (SSE) and background-like events (MSE, p^+, n^+)
- Different PSD needed for coaxial and BEGe detectors





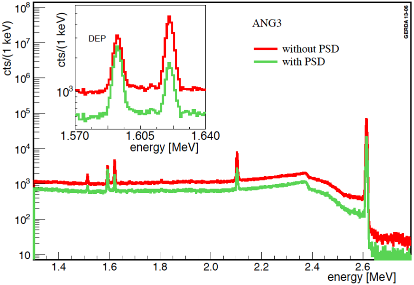
- Simulated current pulse in coaxial detector



- Simulated current pulse in BEGe

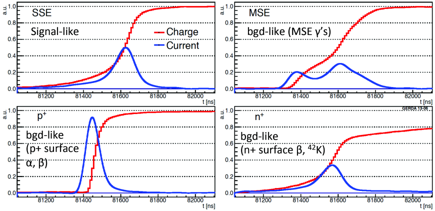
Coaxial: Artificial Neural Network (ANN)

- TMVA/TMlpANN applied to time when the pulse reaches 1, 3, . . . , 99%
- SSE training with signal-like ^{208}Tl DEP at 1592 keV
- MSE training with background-like ^{212}Bi FEP at 1621 keV
- Cut adjusted for each detector to have 90% survival probability on DEP



BEGe: A/E

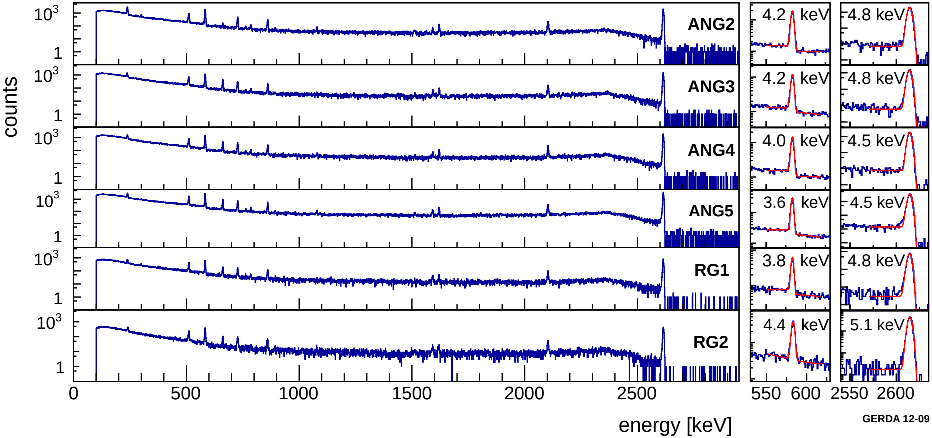
- A = amplitude of current pulse
- E = energy
- High capability of distinguishing SSE from MSE, p^+ and n^+ events
- Well tested and documented method*



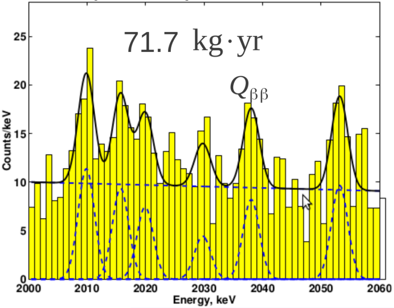
- Acceptance for $2\nu2\beta$: 0.91 ± 0.05
- Acceptance for $0\nu2\beta$: 0.92 ± 0.02

[a] JINST 4 (2009) P10007; JINST 3 (2011) P03005; EPJC 73 (2013) 2583

- Spectra calibrated (bi)-weekly with ^{228}Th sources
- Data useful also for monitoring the resolution and gain stability over time



a) 2004 publications: NIM A522 371 & PL B586 198



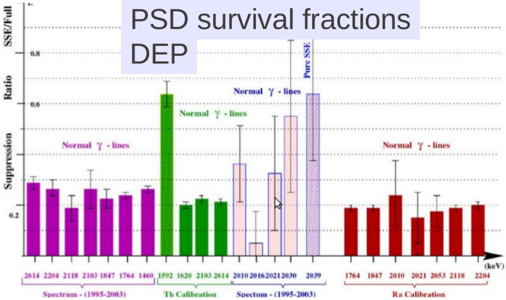
entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events

$$T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right)\cdot 10^{25}\ \mathrm{yr}$$

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events

$$T^{0\nu}_{1/2} = \left(1.25^{+0.49}_{-0.27}\right)\cdot 10^{25}\ \mathrm{yr}$$

PSD survival fractions
DEP



with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%

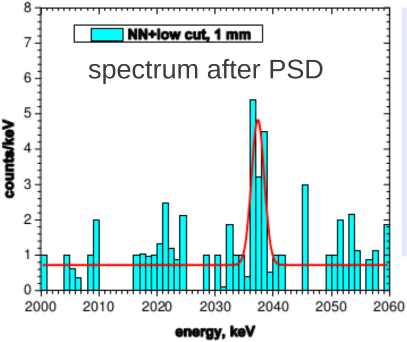
$$\rightarrow \quad T^{0\nu}_{1/2} = 1.23\cdot 10^{25}\ \mathrm{yr}$$

Without efficiency correction:

$$T^{0\nu}_{1/2} = 1.98\cdot 10^{25}\ \mathrm{yr}$$

No efficiency correction is applied in any publication!

b) 2006 publication: Mod Phys Lett A21 p. 1547-1566



fit gives 11.32±1.75 signal events

$\rightarrow T^{0\nu}_{1/2} = \left(2.23^{+0.44}_{-0.31}\right) \cdot 10^{25}\,\text{yr}$

error on signal count not correct
since smaller than Poisson error

PSD based on 3 previous methods
(2 neural networks + pulse boardness)
& library of SSE pulses:
Event accepted IF pulse in library OR
found by neural network of Ref. 16 but
not by the other two neural networks

NO event overlap between the 2 sets!?

statement of publication:
- "multi site events are suppressed
by 100%",
– $0\nu\beta\beta$ efficiency = 1 used for $T^{0\nu}_{1/2}$

efficiency factor not considered
→ calculation of $T^{0\nu}_{1/2}$ not correct
→ GERDA does not use this result