Search of Neutrinoless Double Beta Decay with the GERDA Experiment

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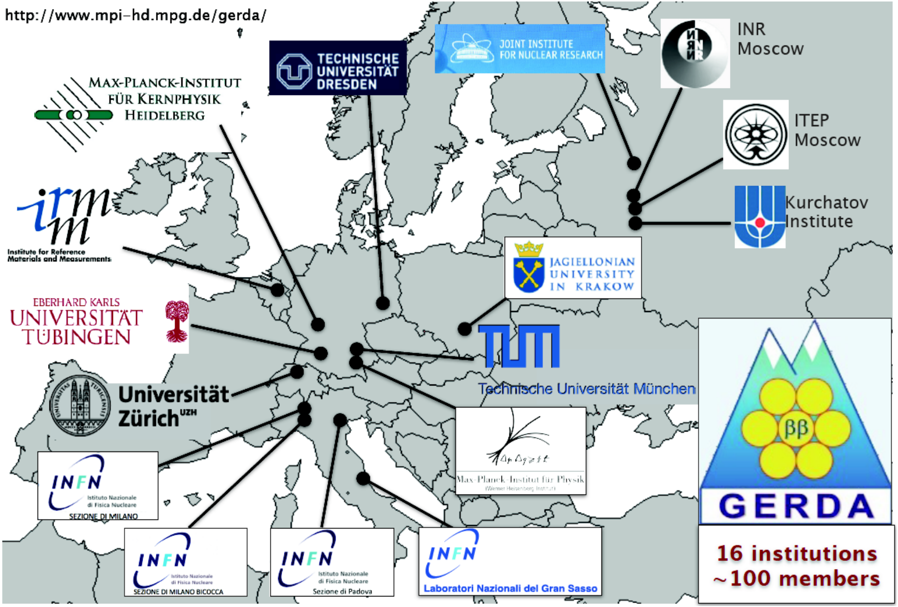
University of Zurich

New Haven, 29 May 2015



http://www.mpi-hd.mpg.de/gerda/
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ββ
GERDA
16 institutions
~100 members

What will I talk about?

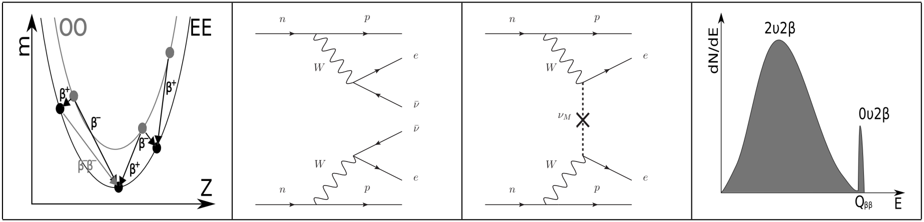
- GERDA experimental setup
- GERDA Phase I data analysis
- GERDA Phase II preparation
- My contribution: signal processing and production of calibration sources

Open questions

- Is lepton number conservation violated?
- Is the neutrino a Majorana particle?
- What's the absolute neutrino mass scale?
- What's the neutrino mass hierarchy?

Possible answer: double beta decay

- Occurs in even-even isobars
- Measurable if single β decay energetically forbidden
- Rare process $\rightarrow$ ultra-low bkg required!



$2\nu\beta\beta$ decay

- Allowed in the SM, ΔL=0
- Signature: continuum from 0 to $Q_{\beta\beta}$
- Half life: $T^{2\nu}_{1/2} \sim (10^{18}\text{-}10^{24})$ yr
- $T^{2\nu}_{1/2}(^{76}\text{Ge}) = \left(1.926 \pm 0.095\right) \cdot 10^{21}$ yr
  ArXiV:1501.02345

$0\nu\beta\beta$ decay

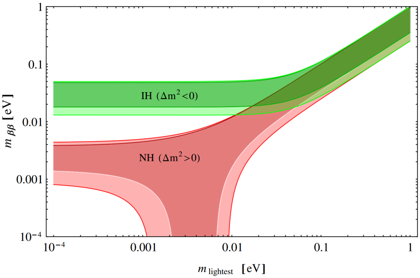
- Non-SM process, ΔL=2
- Possible only if neutrinos have Majorana mass component
- Signature: peak at $Q_{\beta\beta}$(^{76}Ge: 2039 keV)

The mass mechanism

- For light Majorana ν exchange:

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

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



Phys. Rev. D90 (2014) 033005

Experimental sensitivity:

- Number of signal events:

$$n_S = \frac{1}{T^{0\nu}_{1/2}} \cdot \frac{\ln 2 \cdot N_A}{m_A} \cdot f_{76} \cdot \varepsilon \cdot M \cdot t$$

- Number of background events:

$$n_B = BI \cdot \Delta E \cdot M \cdot t$$

where:
f = enrichment fraction
N_A = Avogadro number
m_A = atomic mass
ε = total efficiency
M = detector mass
t = live time
$M \cdot t$ = exposure
BI = Background Index
ΔE = Region Of Interest (ROI)

Why using germanium?

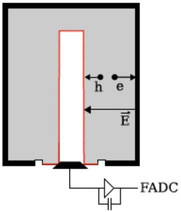
- High total efficiency: $\varepsilon \sim 0.75$
- Best energy resolution on the market: $\sim 1.5‰$ Full Width at Half Maximum (FWHM) at $Q_{\beta\beta}$
- Can be enriched to 86% in ^{76}Ge

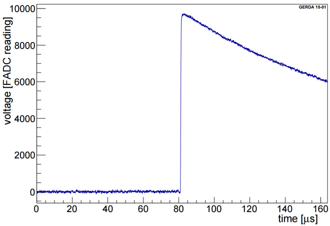
How to reduce the background?

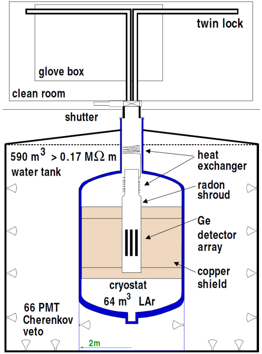
- Operate the experiment underground
- Use active veto for cosmic muons and external radiation
- Minimize radioactive contamination in the materials close to the detectors
- Current pulse is different for single site events (like $0\nu\beta\beta$ signal) versus multi-site events (like Compton scattered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

Ge detector readout

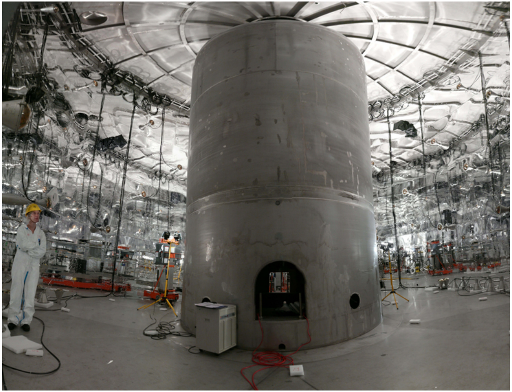
- Ge diode in reverse bias
  $\rightarrow$ measurement of ionization energy
- FADC allows offline analysis of recorded signals (energy, rise time, PSD parameters, ...)







- Located in Hall A at Laboratori Nazionali del Gran Sasso of INFN
- 3800 mwe overburden (μ flux $\sim 1\ m^{-2}h^{-1}$))
- Array of bare Ge detectors 86% enriched in ^{76}Ge directly inserted in liquid argon (LAr)



Why Liquid Argon + Water?

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

The two phases of GERDA

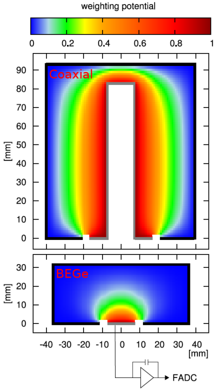
	Mass [kg]	Expected BI [counts/(keV·kg·yr)]	Live time [yr]	Expected $T^{0\nu}_{1/2}$ Sensitivity [yr]
Phase I	15	10^{-2}	1	$2.4 \cdot 10^{25}$
Phase II	35	10^{-3}	3	$1.4 \cdot 10^{26}$

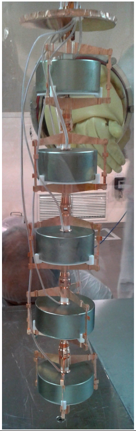
Coaxial detectors

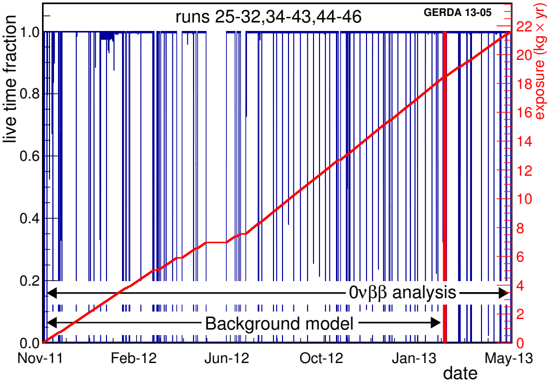
- Inherited from HdM and IGEX experiments
- 2.4‰ FWHM at $Q_{\beta\beta}$ (1.7‰ reachable with better cables & improved signal shaping)
- Total enriched mass: 17.7 kg (analysis on 14.6 kg)

BEGe detectors (design for Phase II)

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



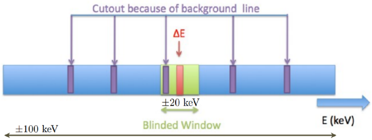


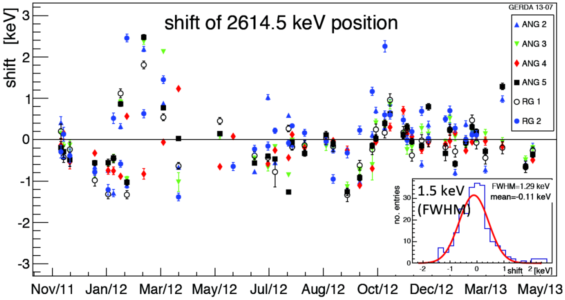


- Spikes: calibration runs
- Flat parts: BEGe's insertion (June 2012), maintenance
- Total livetime: 492.3 days
- Exposure: 21.6 kg·yr
- Used 6 coaxial (14.6 kg) and 4 BEGe (3.0 kg)

Blind analysis and unblinding procedure

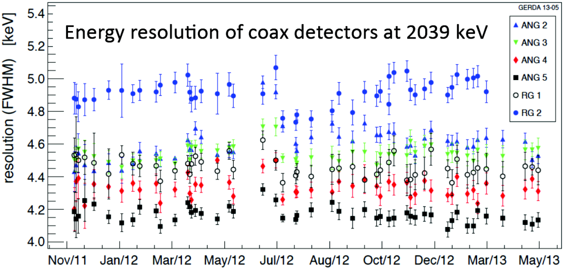
- 40 keV blind region around $Q_{\beta\beta}$
- Background model published before unblinding (EPJC 74 (2014) 2764)
- Fixed data processing procedure, quality cuts, PSD methods and statistical analysis



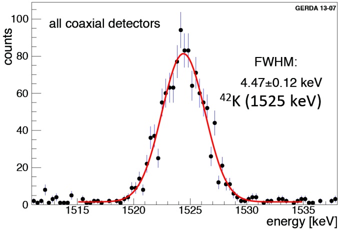


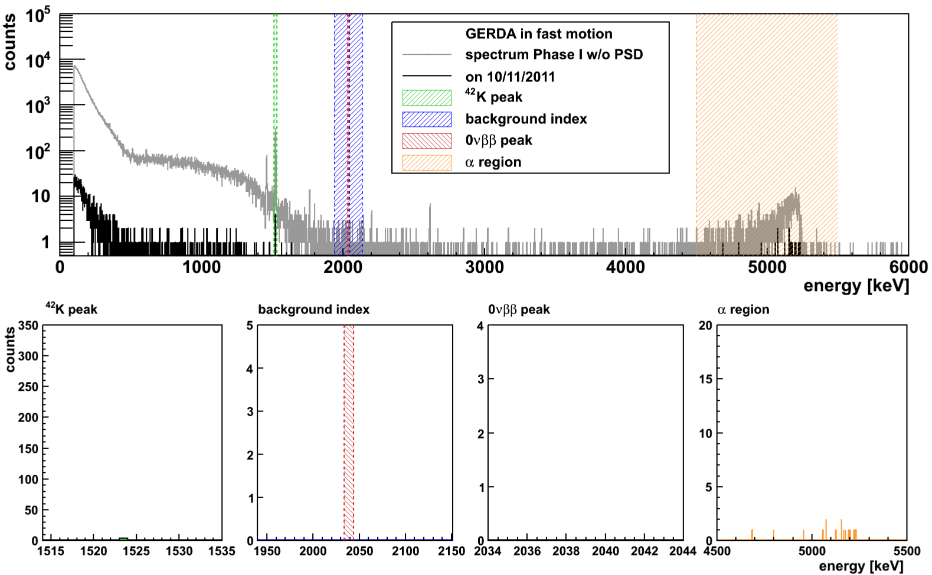
FWHM at $Q_{\beta\beta}$

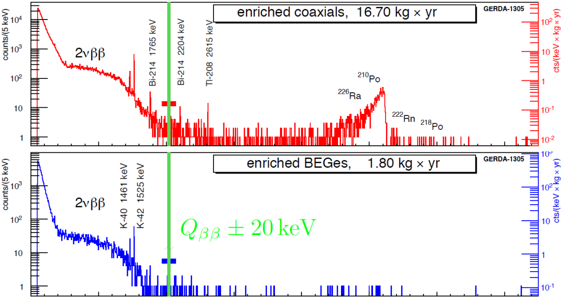
detector	FWHM [keV]
SUM-coax	
ANG2	5.8 (3)
ANG3	4.5 (1)
ANG4	4.9 (3)
ANG5	4.2 (1)
RG1	4.5 (3)
RG2	4.9 (3)
mean coax	4.8 (2)
SUM-BEGe	
GD32B	2.6 (1)
GD32C	2.6 (1)
GD32D	3.7 (5)
GD35B	4.0 (1)
mean BEGe	3.2(2)

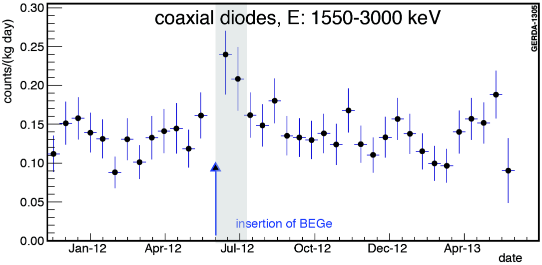


FWHM at ^{42}K peak



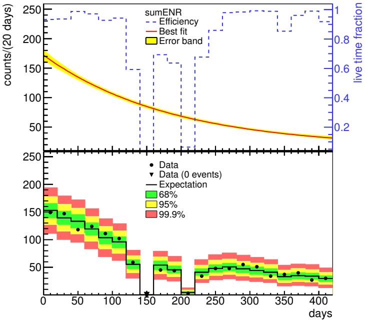

counts
energy [keV]
GERDA in fast motion
spectrum Phase I w/o PSD
on 10/11/2011
^{42}K peak
background index
$0\nu\beta\beta$ peak
α region
^{42}K peak
background index
$0\nu\beta\beta$ peak
α region
counts
energy [keV]

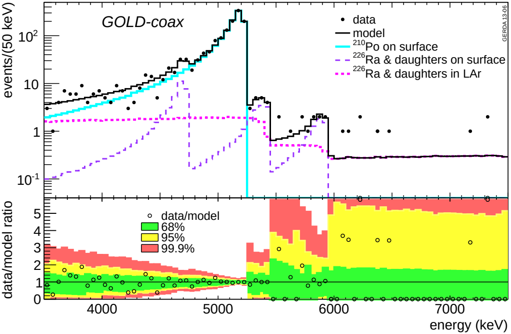




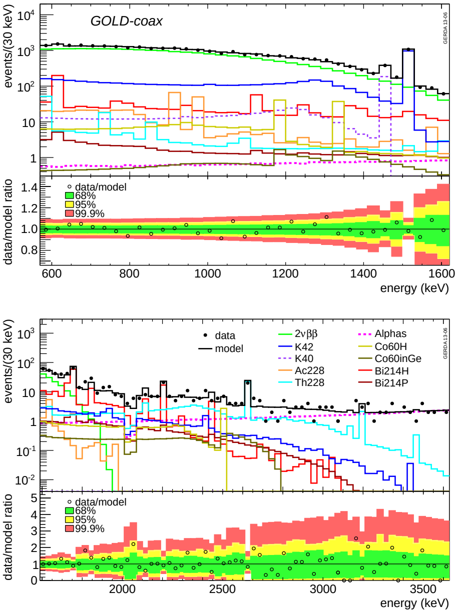
- Split coaxial data in two sets (Golden and Silver), according to the BI
- Golden: all the coax data, but July 2012
- Silver: coax data taken in June and July 2012 (removal of two nat-coaxial and insertion of BEGe's)
- BEGe data kept separated, due to different resolution and background

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



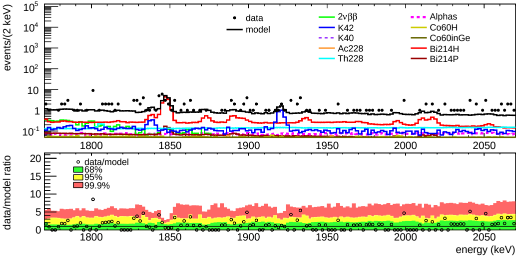


- Duty-factor corrected time distribution of events in the 3.5-5.3 MeV compatible with ^{210}Po half-life ($T_{1/2} = 138$ d)
- Contribution from ^{226}Ra and daughters also visible
- α-emitter mostly located on p^{+} surface (also confirmed by PSD)
- α events account for $\sim$ 10% of the BI at Q$_{\beta\beta}$ for coaxial detectors and $\sim$ 5% for BEGe's.



Minimum model for Golden dataset

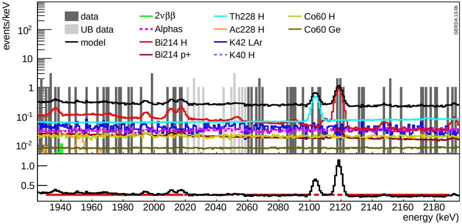
- Only known and visible contributions considered
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- No hint for any different behavior in the last 3 months of data taking
- Official result found with 30 keV binning, crosschecks performed with thinner binnings
- Background Model published: EPJC 74 (2014) 2764

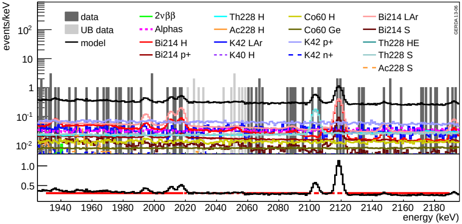


iso-tope	energy [keV]	GOLD-coax rate [cts/(kg·yr)]		
		Global analysis (min. fit)	Global analysis (max. fit)	Fit to data
^{40}K	1460.8	11.9[10.8, 13.0]	11.9[10.8, 13.0]	13.9[12.8, 15.0]
^{60}Co	1173.2	2.5[1.4, 4.2]	$<$ 3.0	3.4[2.2, 5.2]
	1332.3	2.5[0.9, 4.1]	1.6[0.5, 2.7]	2.3[1.5, 3.1]
^{228}Ac	910.8	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 → 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

- Both min and max model predict a flat bkg at $Q_{\beta\beta}$ $\rightarrow$ unblind side-bands!
- BI predicted form bkg models and fitted from data are in agreement



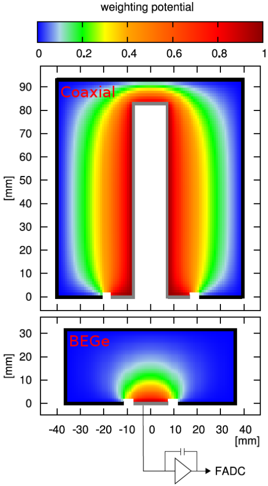


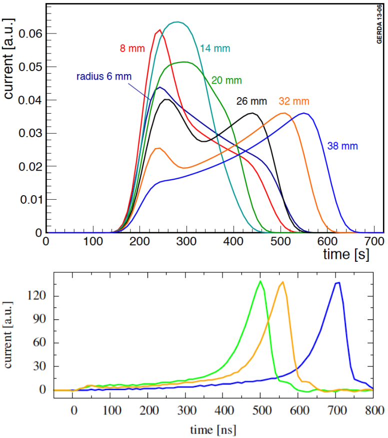
BI before PSD interpolated in the Region of Interest:

	GOLD-coax	SUM-BEGe
	BI in ROI before PSD (10 keV for coaxial, 8 keV for BEGe) $[10^{-3}$cts/(keV·kg·yr)]	
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]	-

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

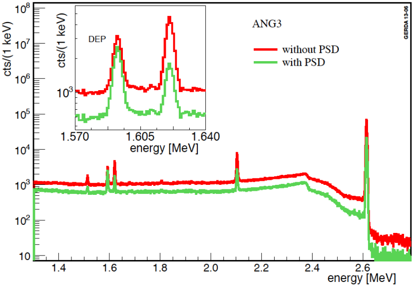




- Simulated current pulse in coaxial detector
- Simulated current pulse in BEGe

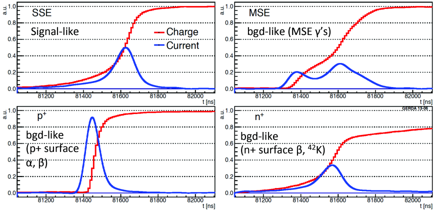
Coaxial: Artificial Neural Network (ANN)

- 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

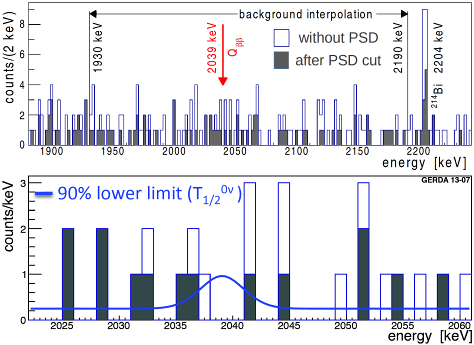
- A = amplitude of current pulse
- E = energy
- High capability of distinguishing SSE from MSE, p$^+$ and n$^+$ events
- Well tested and documented method*



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

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

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:

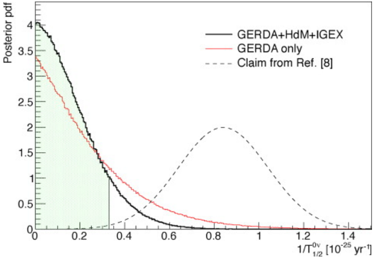
$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25} \text{ yr}$$

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

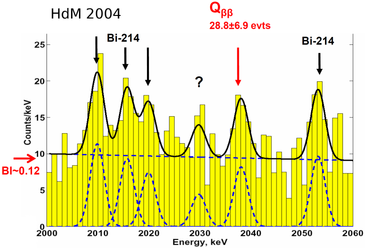
Bayesian Approach

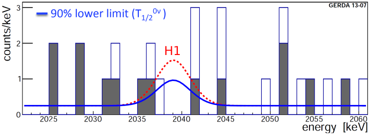
- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]$ yr^{-1}
- best fit $N^{0\nu} = 0$
- 90% credibility interval: $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: $2.0 \cdot 10^{25}$ yr

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



HdM 2004





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

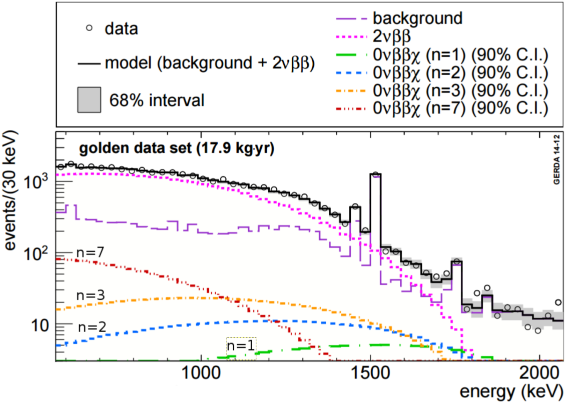
- Same result with PL and Bayesian approach

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

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



$2\nu\beta\beta$ decay search

- Updated $2\nu\beta\beta$ decay analysis using 17.9(2.4) kg·yr from the coaxial (BEGe) detectors
- Measured half life: $T^{2\nu}_{1/2} = (1.926 \pm 0.095) \cdot 10^{21}$ yr
- Agrees with J. Phys. G40 (2013) 035110

Majoron search

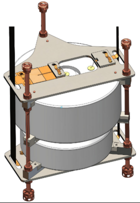
- Search for $0\nu\beta\beta$ decay with Majoron(s) emission performed for spectral index $n = 1, 2, 3, 7$
- Same dataset as for $2\nu\beta\beta$ analysis
- No signal found, limits of $O(10^{23})$ yr on half-lives

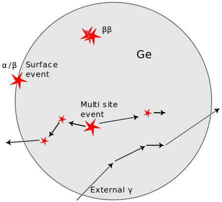
How to improve sensitivity?

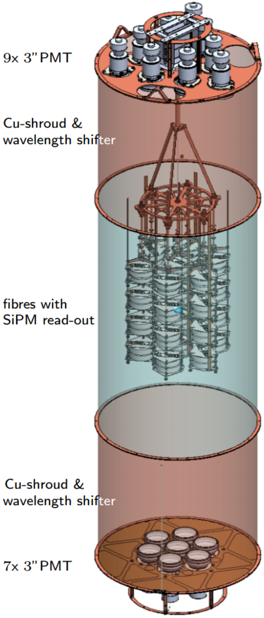
- $n_S = \frac{1}{T^{0\nu}_{1/2}} \cdot \frac{\ln 2 \cdot N_A}{m_A} \cdot f_{76} \cdot \varepsilon \cdot M \cdot t$
- $n_B = BI \cdot \Delta E \cdot M \cdot t$
- Maximize n_S and minimize n_B using BI, M, t, ΔE, ε

Minimization of the BI at $Q_{\beta\beta}$

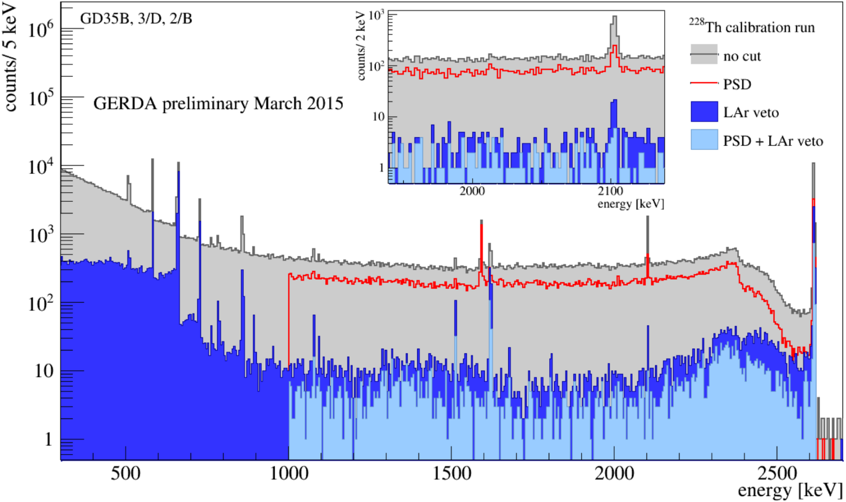
- Reduce close background sources: cleaner signal and HV cables, reduce materials for detector holders
- Special care in crystal production and handling
- BEGe detectors for enhanced PSD
- Install PMTs and SiPMs to detect LAr scintillation light and reject external background







First GERDA Phase II Data



- Spectrum from ^{228}Th calibration source
- 3 BEGe detectors (2 depleted, 1 enriched), 15 hours live time
- 15/16 PMTs and 7/16 SiPM working
- Background from ^{228}Th at $Q_{\beta\beta}$ suppressed by a factor ~ 100

Sensitivity and energy resolution

$n_B \propto \Delta E \propto FWHM_{Q_{\beta\beta}} \rightarrow$ Need to minimize FWHM for a lower background

$$FWHM(E) = 2.355 \cdot \sqrt{ENC^2 + \eta\, F\, E + c^2\, E^2}$$

where: ENC = Electronic Noise Charge

η = average electron-hole pair creation energy (2.96 eV in Ge)

F = Fano factor (~ 0.11 in Ge)

c = charge collection and integration term

Shaping filters and ENC

$$ENC^2 = \alpha \frac{2kT}{g_m \tau_s} C_T^2 + \beta C_T^2 + \gamma \left(e(I_G + I_L) + \frac{2kT}{R_f} \right) \tau_s$$

where: C_T = total capacitance (detector, feedback, preamplifier input)

τ_s = filter shaping time

I_G = gate current

I_L = leakage current

R_F = feedback resistance

g_m = JFET trasconductance

α, β, σ = normalization constants related to filter's shape

GERDA energy reconstruction

- Full traces digitized with FADC
- Digital pseudo-Gaussian filter ($25 \times 5\ \mu$s moving average)
- Same filter parameters for all detectors and all Phase I data

Possible improvements

- Stability of energy scale
- "Intrinsic" energy resolution of calibration data
- "Effective" energy resolution of physics data at $Q_{\beta\beta}$

Strategy

- Develop a new digital shaping filter tuned on the experimental noise figure
  $\rightarrow$ Enhanced noise whitening, less sensitive to 1/f noise
- Correct preamplifier response function
- Tune the filter separately for each detector
- Split the Phase I data in different data sets, according to the detector configurations and the noise conditions

The ZAC filter

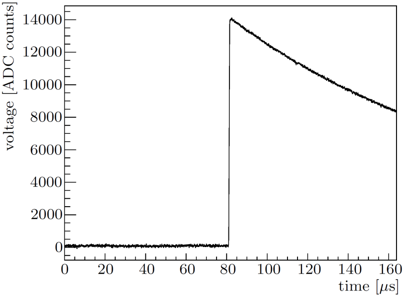
- Sinh-like cusp $\rightarrow$ optimal shaping filter for δ-like traces of finite length
- Central flat top (FT) $\rightarrow$ maximize charge integration
- Total zero-area $\rightarrow$ filter out 1/f noise
- Baseline subtraction best performed with parabolic filters

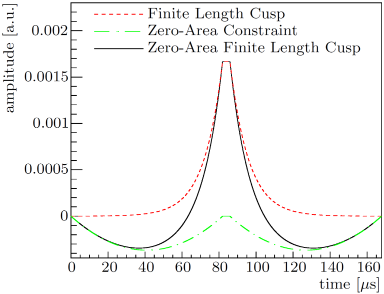
$$ZAC(t) = \begin{cases} \sinh\left(\frac{t}{\tau_s}\right) + A\left[\left(t - \frac{L}{2}\right)^2 - \frac{L}{2}^2\right] & 0 < t < L \\ \sinh\left(\frac{L}{\tau_s}\right) & L < t < L + FT \\ \sinh\left(\frac{2L+FT-t}{\tau_s}\right) + A\left[\left(\frac{3}{2}L + FT - t\right)^2 - \left(\frac{L}{2}\right)^2\right] & L + FT < t < 2L + FT \end{cases}$$

Final filter

- Deconvolution of the preamplifier response function: $f_\tau = \{1, -\exp\left(-\Delta t/\tau\right)\}$
- Final filter through convolution of ZAC with f_τ: $FF(t) = ZAC(t) * f_\tau(t)$

The **Z**ero-**A**rea Finite-Length **C**usp Filter (ZAC)

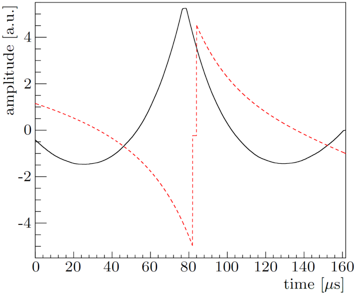




Original waveform

ZAC filter

Final filter FF (dashed red) and filtered waveform (black)



Optimization of the ZAC filter

- Phase I data divided in 5 periods according to detector configuration
- Filter optimization performed for 2-3 calibration runs of each period
- Scan parameter space, fit ^{208}Tl peak at 2614.5 keV, compute FWHM

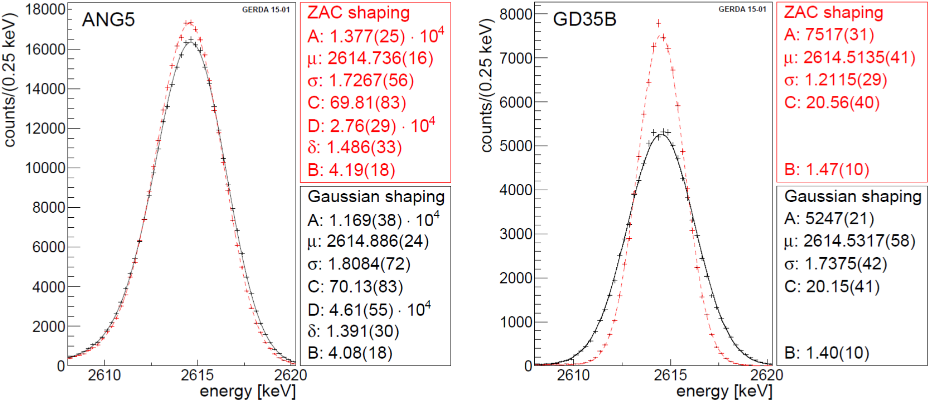
$$f(E) = A\exp\left(-\frac{(E-\mu)^2}{2\sigma^2}\right) + B + \frac{C}{2}\operatorname{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma}\right) + \frac{D}{2}\exp\left(\frac{E-\mu}{\delta}\right)\operatorname{erfc}\left(\frac{E-\mu}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}\delta}\right)$$

- The optimal parameters are stable within each period

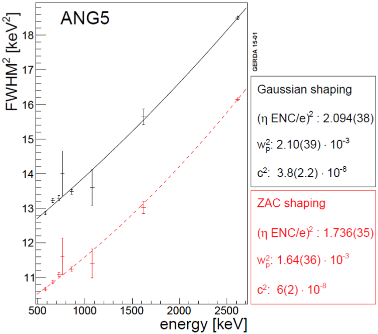
Reprocessing of calibration and physics Phase I data

- Create tier2 (uncalibrated spectra) of calibration data using optimized ZAC filter
  → Extract calibration curves, produce stability plots (e.g. FWHM vs time)
- Create tier3 (calibrated spectra) of calibration data
  → Further stability plots (deviations from literature, ...)
- Produce tier2 and tier3 of physics data using optimized ZAC filter

Comparison of the 2614.5 keV Peak

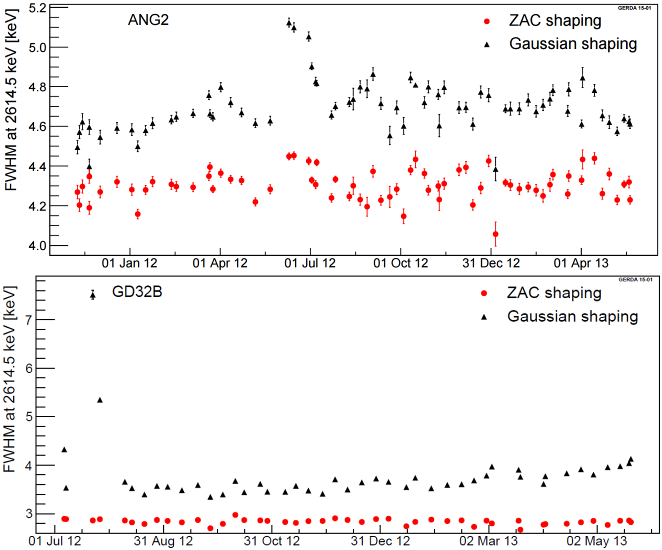


- All Phase I calibration spectra summed-up, same events considered in both cases
- Energy resolution improved in all cases
- Low-energy tail reduced thanks to better charge integration



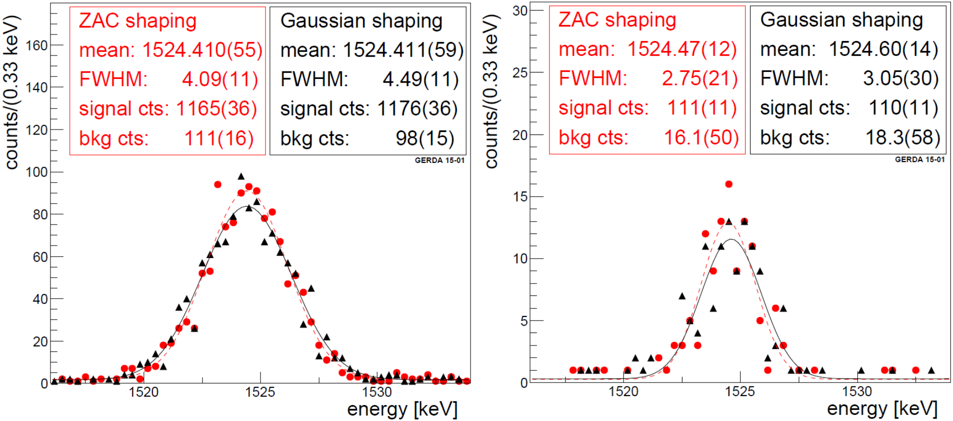
Detector	FWHM at 2614.5 keV Gaussian	ZAC	Improvement [keV]
ANG2	4.712(3)	4.314(3)	0.398(4)
ANG3	4.658(3)	4.390(3)	0.268(4)
ANG4	4.458(3)	4.151(3)	0.307(4)
ANG5	4.323(3)	4.022(3)	0.301(4)
RG1	4.595(4)	4.365(4)	0.230(6)
RG2	5.036(5)	4.707(4)	0.329(6)
GD32B	2.816(4)	2.699(3)	0.117(5)
GD32C	2.833(3)	2.702(3)	0.131(4)
GD32D	2.959(4)	2.807(3)	0.152(5)
GD35B	3.700(5)	2.836(3)	0.864(6)

- Greatest improvement obtained on ENC^2
- Average improvement in FWHM at 2614.5 keV on all Phase I calibration data is 0.30 keV for coaxial and 0.13 keV for BEGes (GD35B excluded)
- Higher improvement for GD35B due to better treatment of low-frequency disturbance by the ZAC filter

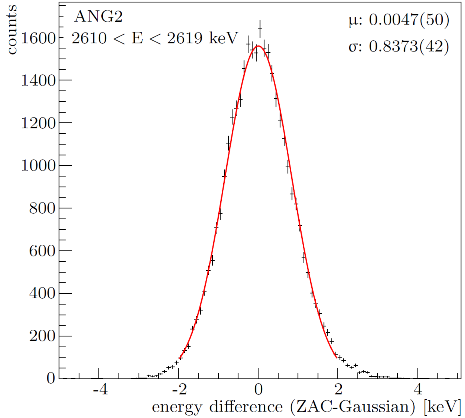


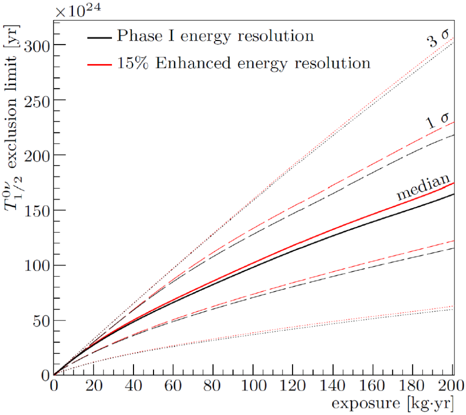
- ZAC filter insensitive to microphonic disturbance of ANG2 (June 2012)
- FWHM brought to nominal for GD35B for all Phase I duration

Comparison of Energy Resolution for Physics Data



- ^{42}K peak at 1524.6 keV is the only spectral line in the physics spectrum
- Improvement of $\sim$ 0.4 keV, about 0.1 keV larger than expected for calibration data due to higher precision in the estimation of the calibration curves and lower sensitivity to time evolution of microphonics during physics run
- FWHM improvement at $Q_{\beta\beta}$ estimated to be $\sim$ 0.5 keV for both coaxial and BEGe detectors





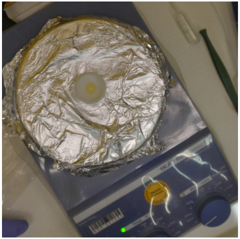
- No surprise in the event-by-event energy difference (verified on physics data, too)
- Phase II $0\nu\beta\beta$ median sensitivity increased by $\sim 5\%$
- Same recipe for filter optimization will be used in Phase II
- Reprocessed Phase I data will be combined with Phase II data for $0\nu\beta\beta$ decay analysis
- GERDA collaboration paper accepted by Eur. Phys. J. C (ArXiV:1502.0392)

Requirements for calibration sources

- Half life comparable with live time of GERDA Phase II
- Good precision of energy estimation at $Q_{\beta\beta} \rightarrow \geq$10 peaks in [0; 2.5] MeV range
- Presence of a high statistic double escape peak not too far from $Q_{\beta\beta}$
- Solution: ^{228}Th

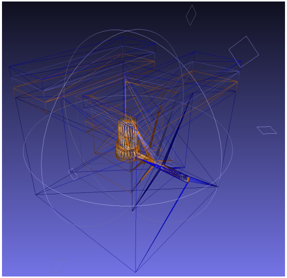
Drawbacks of ^{228}Th

- Several members of the ^{228}Th radioactive chain emit α-particles with few MeV
- Need to avoid (α; n) reaction in the source support material
- Solution: embed ^{228}Th in a material with high enough threshold, e.g. gold



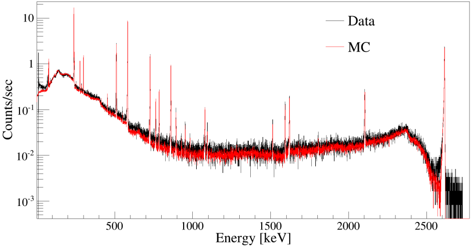

Data

- 20 min long measurement with the underground low-background Ge detector Gator at LNGS
- Source ∼ 12 cm above the detector's cryostat
- Dead time: 1.7-2.8% (depending on the source activity)



MC

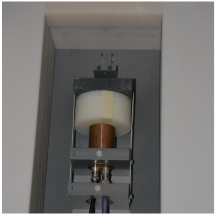
- 10^9 events simulated with Geant4.9.6
- Simulation repeated with source at ±2 mm, and with ±5% on cross sections for PE, Compton and PP processes

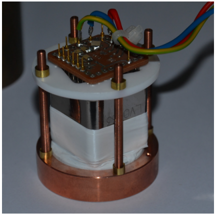


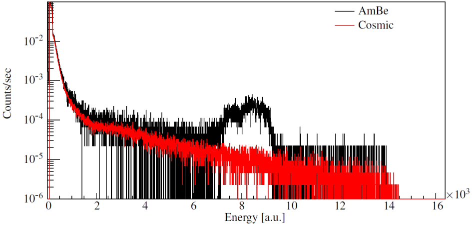
- Analysis: Maximum likelihood in 200-2617 keV range

Source	Activity [kBq]
9854	$24.21^{+0.05}_{-0.06}$
9855	$34.20^{+0.06}_{-0.07}$
9856	$30.75^{+0.08}_{-0.05}$
9857	$41.28^{+0.08}_{-0.07}$

Effect	Systematic [%]
Geometry	$^{+2.5}_{-2.1}$
Photoelectric	$^{+0.2}_{-0.4}$
Compton	$^{+1.7}_{-1.2}$
Pair	< 0.1%
Fit range	±2.5%





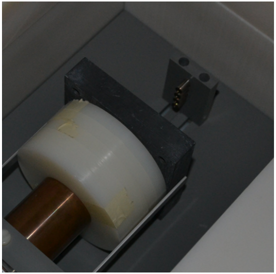


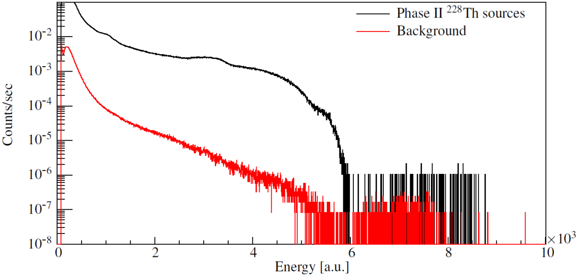
LiI(Eu) thermal neutron detector

- LiI(Eu) crystal, coupled to Hamamatsu R8520 low-bkg PMT
- Operated underground at LNGS with borated polyethylene shielding
- Physics process: ${}^6_3Li + n \rightarrow {}^7_3\, Li^* \rightarrow {}^3_1\, H + {}^4_2\, He + 4.78\ MeV$
- Crystal+PMT wrapped with PTFE tape to improve light collection $\rightarrow \sim 30\%$ better energy resolution

Measurement campaign

- Calibration with AmBe (160 ± 4 n/s) to determine ROI and efficiency
- Total efficiency: $\varepsilon = (5.32 \pm 0.33) \cdot 10^{-4}$
- 3 months long background measurement performed underground at LNGS





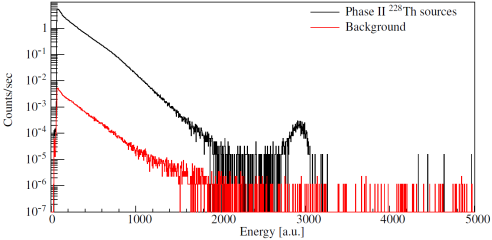
Data taking and analysis

- 4 Phase II sources screened for 11 days underground at LNGS
- Analysis: count events in 7000-9500 bin range; combined maximum likelihood fit of source and background data together
- Priors on total activity and efficiency

Results

- Neutron source strength: $\left(8.2^{+1.7}_{-1.2}(\text{stat}) \pm 1.1(\text{fit}) \pm 1.0(\text{shape})\right) \cdot 10^{-7}$ n/(s·Bq)
- $O(10)$ reduction with respect to commercial sources
- For a commercial ^{228}Th source: S$= 7.5^{+2.5}_{-1.3} \cdot 10^{-6}$ n/(s·Bq)

Measurement of Neutron Strength of Phase II Sources with ^{3}He Detector



^{3}He Detector

- Standard ^{3}He proportional counter in borated paraffin shielding
- Physics: $^{3}He + n \rightarrow ^{1} H + ^{3} H + 764\ keV$

Data taking and analysis

- 15 days long background measurement, 4 Phase II sources screened for 17.5 hours
- Analysis: same recipe as for LiI(Eu)
- Efficiency: $\varepsilon = 0.0713 \pm 0.0085$ [E. Bellotti et al., GERDA internal note GSTR-10-001]

Results

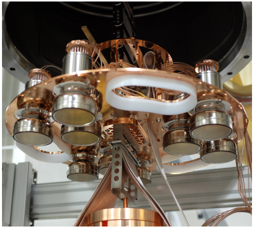
- Neutron source strength: $\left(9.4^{+2.0}_{-0.8}(\text{stat}) \pm 0.4(\text{fit}) \pm 1.1(\text{shape})\right) \cdot 10^{-7}$ n/(s·Bq)
- ^{3}He and LiI(Eu) results are compatible
- Ready for submission to JINST!

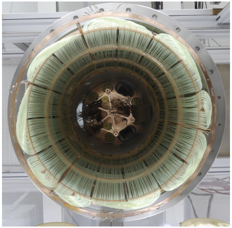
GERDA Phase I

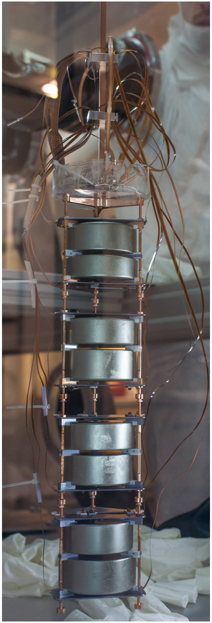
- Limit on $0\nu\beta\beta$ decay half life: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- Limit on effective neutrino mass: $m_{\beta\beta} < 0.2\text{-}0.4$ eV (90% C.L.)
- Signal from previous claim disfavored with 99% probability

GERDA Phase II

- Expected background at $Q_{\beta\beta}$: 10^{-3} counts/(keV·kg·yr)
- Expected sensitivity: $\hat{T}^{0\nu}_{1/2} \sim 1.4 \cdot 10^{26}$ yr, $m_{\beta\beta} \sim 0.1$ eV
- First GERDA Phase II data with LAr veto and PSD applied: ~ 100 suppression factor for external ^{228}Th
- Start of Phase II in 2015, commissioning ongoing. Stay tuned!

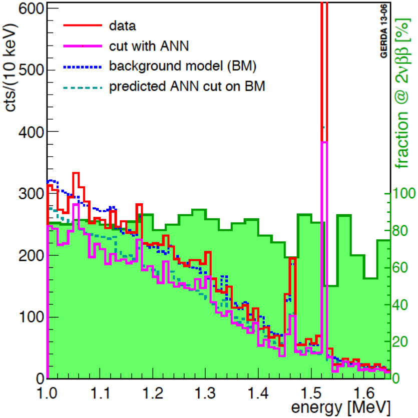


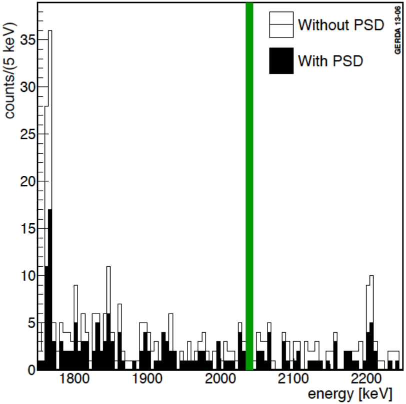




PSD selection in $2\nu2\beta$ and $0\nu2\beta$ energy ranges

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





- Estimated survival fraction for $0\nu2\beta$ event: $0.90^{+0.05}_{-0.09}$

A bit of chemistry [M. Tarka, PhD thesis, UZH]

- Subfix s=solid, g=gaseous
- $3ThCl_4 + 16HNO_3 \rightarrow 200^oC \rightarrow [3Th(NO_3)_4]_s + [(4NOCl + 8H_2O + 4Cl_2)]_g$
- Only $Th(NO_3)_4$ remainin on PTFE crucible
- Add again HNO_3 to dissolve $Th(NO_3)_4$, transfer solution to gold crucible
- Heat to $\sim 750^oC$
- $3Th(NO_3)_4 \rightarrow 750^oC \rightarrow [3ThO_2]_s + [12NO_2 + 3O_2]_g$
- Only ThO_2 on gold foil
- Close and wrap with second gold foil
- Ship to Eckert & Ziegler for encapsulation

Source Encapsulation at Eckert & Ziegler

- Gold foils further wrapped and inserted in PO2 capsule
- PO2 capsule: two stainless steel capsules, TIG welded
- Leak test at room temperature successfully performed by E&Z
- Leak test after insertion in acetone and liquid nitrogen performed at INMRI-ENEA