The GERDA Experiment
for the Search of Neutrinoless Double Beta Decay

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Seminar on Particle and Astrophysics
Universität Zürich
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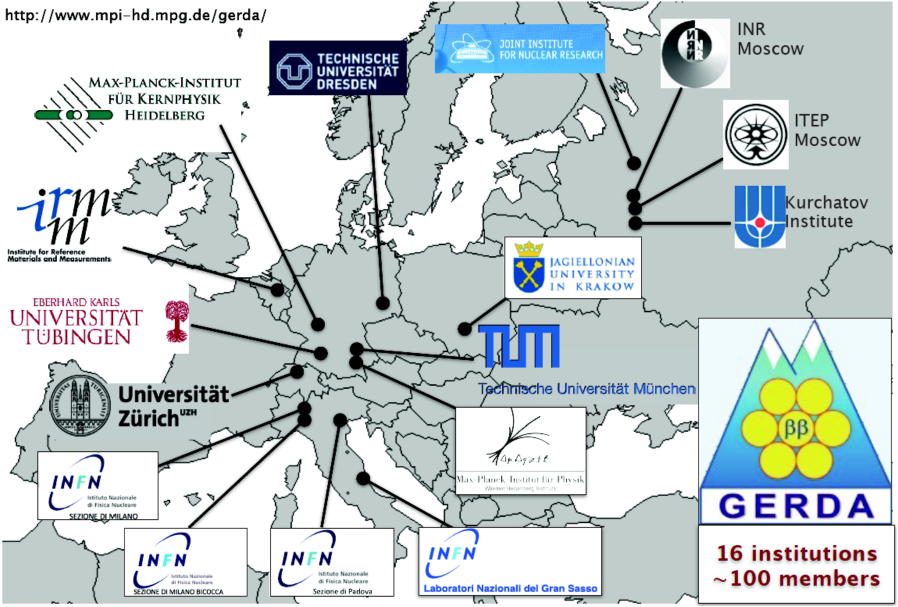
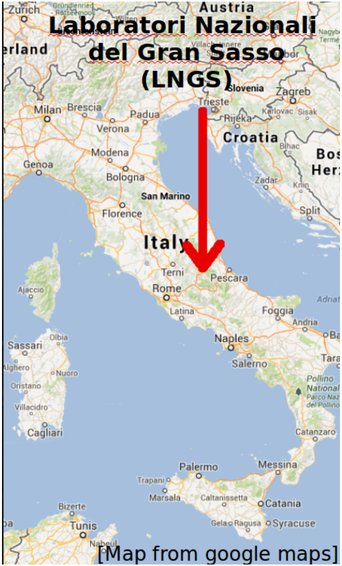
The GERDA Collaboration



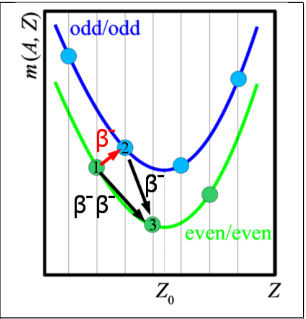
Situated in Hall A of LNGS

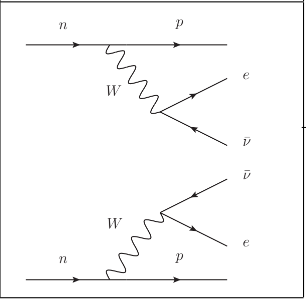


[Map from google maps]

[Image from LNGS]

The Double Beta Decay

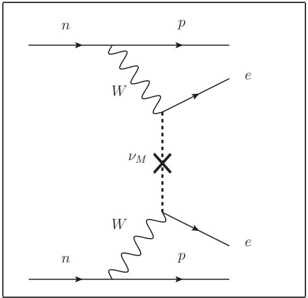


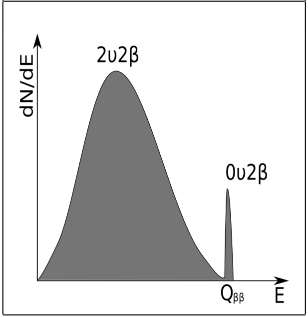


- $2\nu 2\beta$ decay introduced by Maria Goeppert-Mayer in 1935
- Discovered in 1950 by Inghram and Reynolds
- It is a standard model process known for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{130}Ba, ^{136}Xe
- $T^{2\nu}_{1/2}$ in the range of $10^{18\text{–}24}$ yr
- For ^{76}Ge: $T^{2\nu}_{1/2} = \left(1.84^{+0.14}_{-0.10}\right) \cdot 10^{21}$ yr[a]

[a] J. GERDA Collaboration, Phys. G: Nucl. Part. Phys. 40 (2013) 035110

The Neutrinoless Double Beta Decay





If $0\nu2\beta$ decay is discovered:

- Lepton number is violated ($\Delta L = 2$)
- Requires physics beyond the Standard Model
- Most likely mechanism is "massive Majorana neutrino exchange"

Experimental signature:

- Peak at $Q_{\beta\beta} = m(A, Z) - m(A, Z-2) - 2m_e$ (2039 keV for ^{76}Ge)
- Expected decay rate:

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

$G^{0\nu}(Q, Z) =$ 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

Experimental Aspects

Number of signal events:

$$N_{sig}^{0\nu} = \frac{f_{76} \cdot N_A}{m_A} \frac{\ln 2}{T_{1/2}^{0\nu}} \varepsilon \cdot M \cdot t$$

Number of background events:

$$N_{bkg} = M \cdot t \cdot BI \cdot \Delta E$$

Experimental sensitivity:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{\ln 2 \cdot N_A}{n_\sigma \sqrt{2}} \frac{f_{76} \cdot \varepsilon}{m_A} \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}}$$

f_{76} = enrichment fraction

N_A = Avogadro number

m_A = atomic mass

ε = efficiency

M = detector mass

t = livetime

BI = Background Index

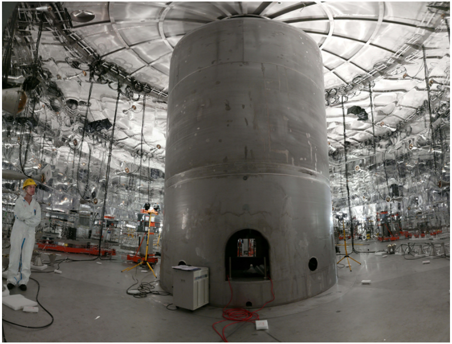
ΔE = energy resolution

n_σ = Confidence Level

Advantages of Ge

Disadvantages of Ge

The GERDA Experiment



Experiment structure

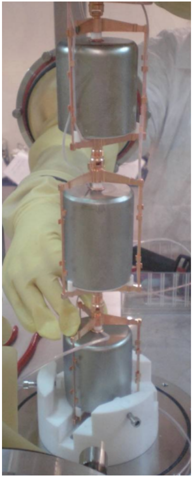
- Bare Ge diodes enriched to 86 % of ^{76}Ge directly immersed in a 5.5 m high 64 m^3 liquid Ar cryostat for cooling and shielding (and vetoing).
- Water Cherenkov detector (590 m^3) to veto cosmic muons and absorb neutrons
- Plastic scintillators above the cryostat to further veto cosmic muons

GERDA Collaboration, arXiv:1212.4067[physics.ins-det] (2013)

The GERDA Detectors

Coaxial detectors (Phase I)

- 5 enr-Ge ("ANG") detectors from Heidelberg-Moscow (HdM), 3 enr-Ge ("RG") from IGEX, 3 nat-Ge from Genius Test Facility (GTF)
- Detectors reprocessed at Canberra before being used
- Two detectors turned off because of high leakage current $\Rightarrow$ total mass of remaining enriched detectors: 14.6 kg
- $\sim 2‰$ FWHM at 2.6 MeV



BEGe detectors (design for Phase II)

- BEGe = Broad Energy Germanium
- $\sim 1‰$ FWHM at 2.6 MeV
- Enhanced Pulse Shape Discrimination (PSD)
- $\sim$ 20 kg of BEGe's successfully produced and tested in 2012
- 5 BEGe's inserted in GERDA in July 2012
- One showed instabilities in the energy calibration and was not used

GERDA Time-line

The time-line of GERDA:

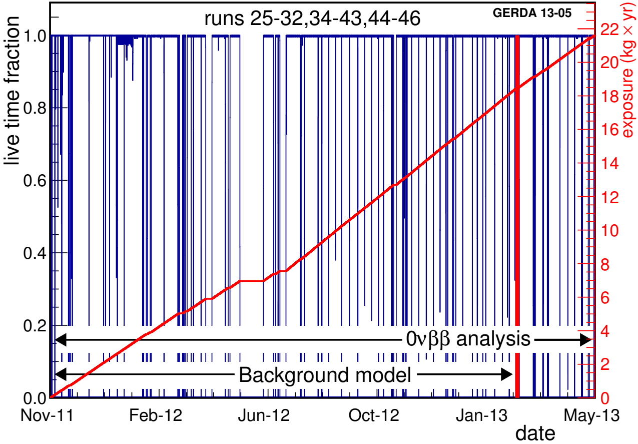
- Mar. 2008: cryostat installation
- May 2010: start of commissioning
- Nov. 2011 - May 2013: Phase I data taking
- Now: preparing Phase II
- Early 2014: Start of Phase II

Two Phases:

	Mass [kg]	BI [counts/(keV·kg·yr)]	Exposure [kg·yr]	Expected $T_{1/2}^{0\nu}$ Sensitivity [yr]
Phase I	18	10^{-2}	21.6	$2 \cdot 10^{25}$
Phase II (preparing)	38	10^{-3}	100	$2 \cdot 10^{26}$

GERDA Phase I Data Taking

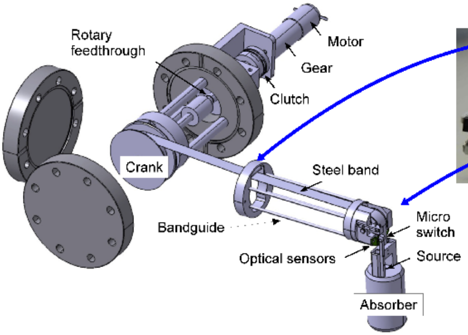
- Total livetime of 492.3 days with 88% duty factor
- 5% of data not used due to temperature originating electronics instabilities

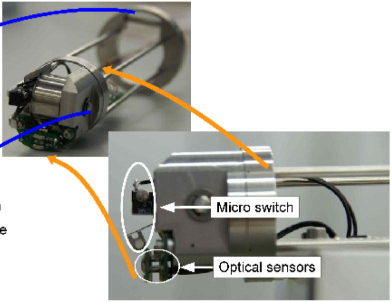


- Spikes: (Bi)-weekly calibration runs
- June 2012: Insertion of BEGe detectors
- Dataset for background model: Nov 2011 - March 2013
- Dataset for $0\nu2\beta$ analysis: Nov 2011 - May 2013 (21.6 kg·yr)

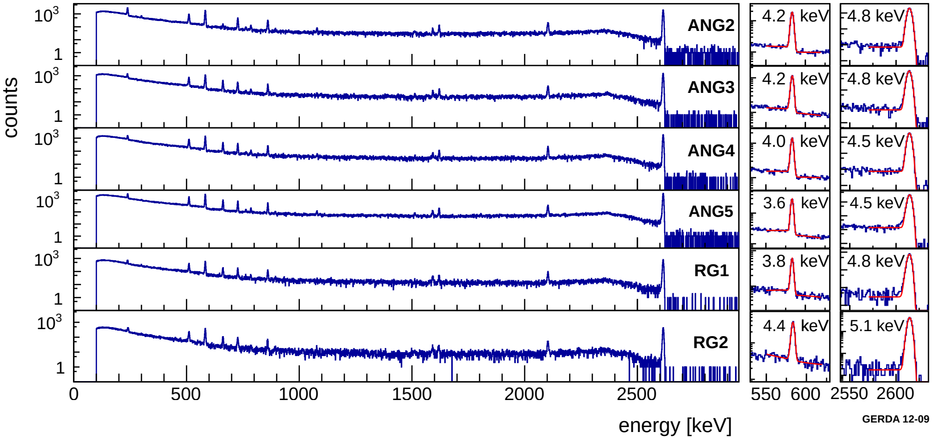
Calibration of the GERDA Data

- (Bi)-weekly calibrations with three ^{228}Th sources (use $\approx$ 10 peaks, depending on statistics)
- Sources are lowered into the cryostat with a systems build at UZH:
  Two independent position measurements
  Friction clutch to prevent over-forcing of steel band
- Neutron background induced by (α,n) reactions in commercial sources just acceptable for Phase I $\Rightarrow$ produce custom low n-flux ^{228}Th sources in collaboration with PSI and University of Mainz for Phase II



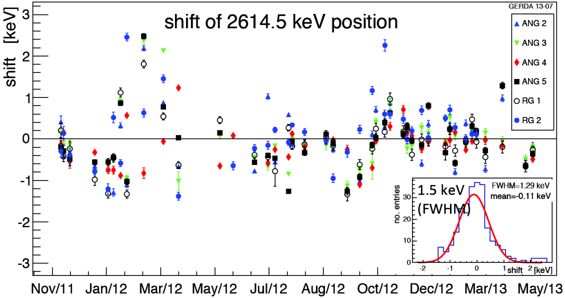


Calibration of the GERDA Data



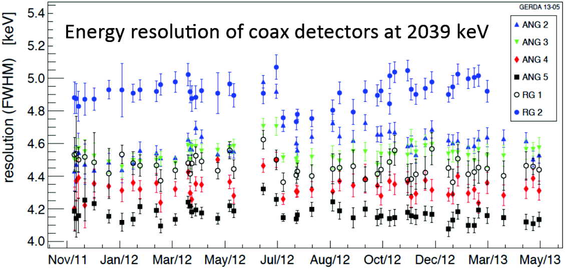
- Used also for monitoring the resolution and gain stability over time
- FWHM at $Q_{\beta\beta}$: 4.8 keV for the coaxial detectors, 3.2 keV for the BEGe's (space for $\sim$ 10% improvement with better filtering)

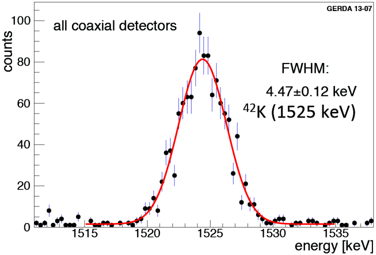
Time Stability and Energy Resolution



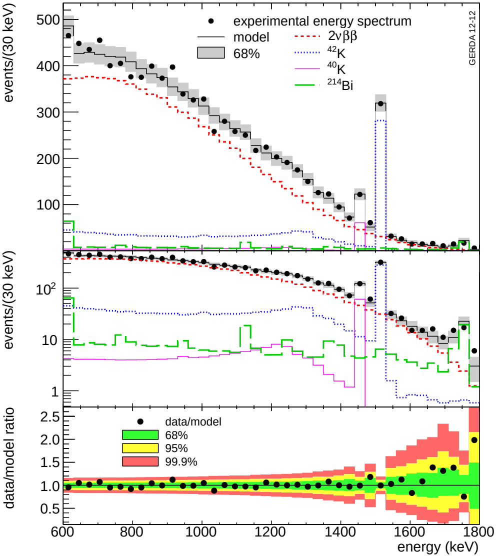
detector	FWHM [keV]
SUM-coax	
ANG2	5.8 (3)
ANG3	4.5 (1)
ANG4	4.9 (3)
ANG5	4.2 (1)
RG1	4.5 (3)
RG2	4.9 (3)
mean coax	4.8 (2)
SUM-BEGe	
GD32B	2.6 (1)
GD32C	2.6 (1)
GD32D	3.7 (5)
GD35B	4.0 (1)
mean BEGe	3.2(2)

- If needed, correction term applied to FWHM to account for instabilities

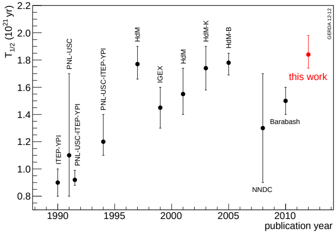




$2\nu2\beta$ Measurement

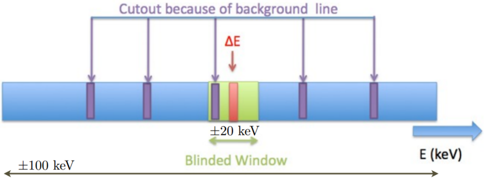


- Measured by GERDA with 5.04 kg·yr exposure
- Very simple background model due to high signal-to-background ratio
- $T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



GERDA Collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

Blinding



Before unblinding

- Reach sensitivity of $2 \cdot 10^{25}$ yr on $T^{0\nu}_{1/2}$
- Have (and publish: arXiv:1306.5084) a good background model
- Be able to predict a reliable BI at $Q_{\beta\beta}$ (intensity and shape)
- Fix the data selection and the partition
- Fix the data processing procedure, PSD methods and cuts
- Fix the statistical analysis

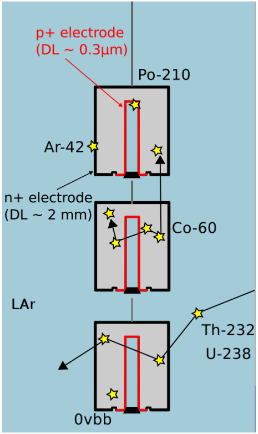
Unblinding

- Once the background model is fixed, open 15 keV side-bands
- If no surprise is found, apply unchanged analysis

Phase I Background

Background sources

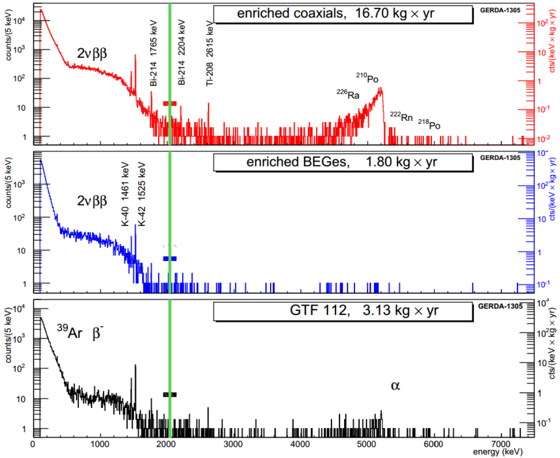
- The outer most, so called Dead Layer, of the detectors is not active.
- α decays on the p+ surface
- β decay of ^{42}K on the surface or close to the detector which comes from ^{42}Ar (contribution a factor ≈ 10 higher than expected!)
- β decay of ^{60}Co inside the detectors
- γ from ^{208}Tl, ^{214}Bi from various set-up components.

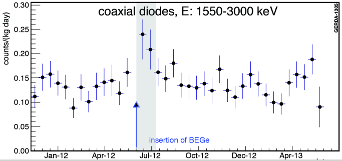


Phase I background reduction

- Cut detector coincidences
- Prevent ^{42}K ions from drifting to the detectors using minishrouds
- Use pulse shape discrimination to remove MSE

Phase I Background



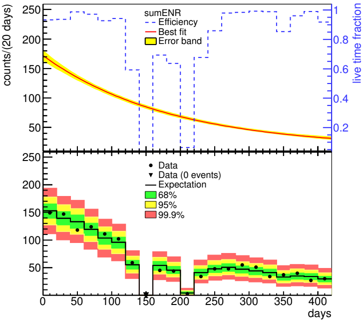


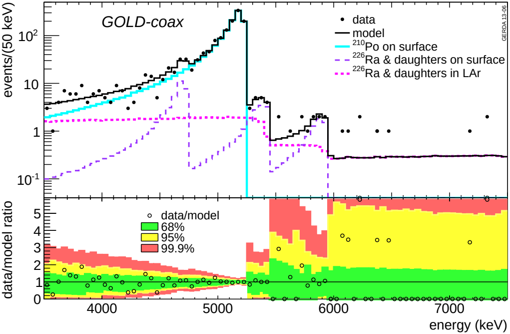
Datasets

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

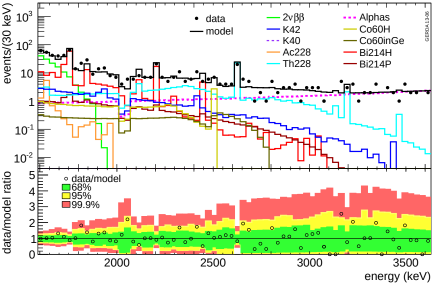
dataset	exposure [kg·yr]
Golden	17.90
Silver	1.30
BEGe	2.40

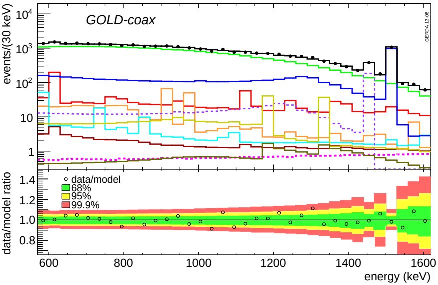
The Background Model at High Energy





- Duty-factor corrected time distribution of events in the 3.5-5.3 MeV compatible with ^{210}Po half-life ($T_{1/2} = 138\,\mathrm{d}$) plus constant.
- Contribution from ^{226}Ra and daughters also visible
- α-emitter mostly located on p^{+} surface



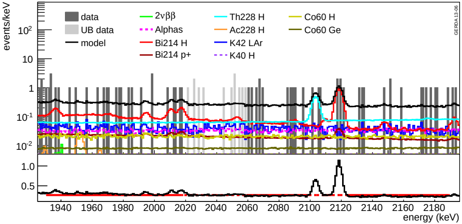


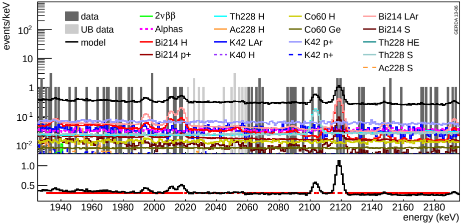
Minimum model for Golden dataset

- Simulate spectral shape of individual background sources.
- Add up minimal number of well motivated sources
- Data used: 09.11.2011-03.03.2013 in order to be in time for the unblinding
- Fit range: 570-7500 keV
- 30 keV binning crosschecked with finer binnings
- Background Model published: arXiv:1306.5084v1
- $T_{1/2}(2\nu 2\beta)$ from model consistent with previously published value

Background prediction at $Q_{\beta\beta}$

- Maximum Model: Use same isotopes as for the Minimal Model but more possible source positions to fit the background
- Both min and max model predict a flat background at $Q_{\beta\beta}$





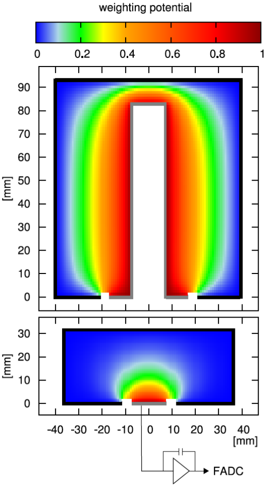
- Compare to interpolation of the background by a constant excluding known γ peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi)
- BI (before PSD) in the ROI [10^{-3}cts/(keV·kg·yr)]:

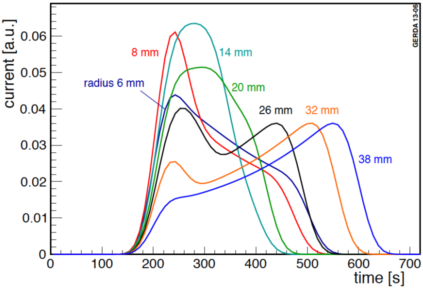
	GOLD-coax	SUM-BEGe
interpolation	17.5[15.1, 20.1]	36.1[26.4, 49.3]
minimum	18.5[17.6, 19.3]	38.1[37.5, 38.7]
maximum	21.9[20.7, 23.8]	-

- Model predictions of BI consistent with interpolation from a constant background, which will be used for the $0\nu2\beta$ analysis

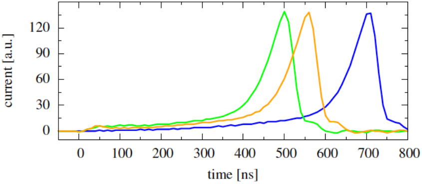
Pulse Shape Discrimination

- PSD: distinguish between SSE (like many $0\nu2\beta$ events) and MSE and surface events (like many background events)
- Different PSD needed for coaxial and BEGe detectors





- Simulated SSE current pulse in coaxial detector

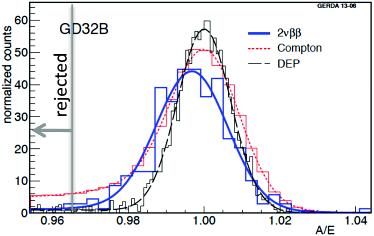


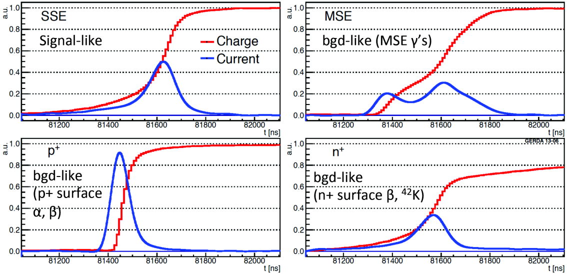
- Simulated SSE current pulse in BEGe

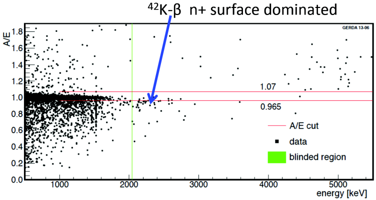
Pulse Shape Discrimination for BEGe

PSD discrimination parameter: 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*







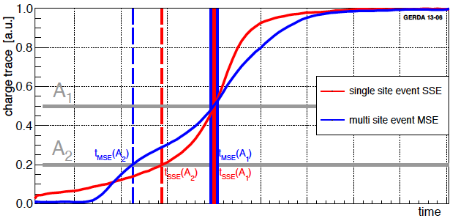
- Acceptance for $0\nu 2\beta$: 0.92 ± 0.02

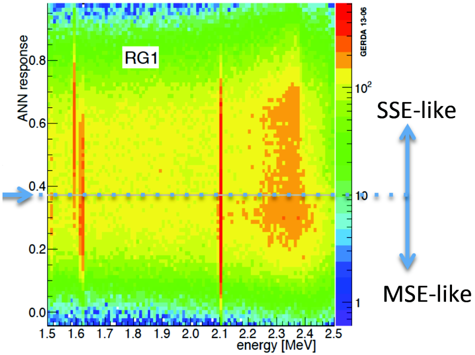
JINST 4 (2009) P10007; JINST 3 (2011) P03005; arXiv:1307.2610

Pulse Shape Discrimination for Coaxial Detectors

PSD discrimination method: Artificial Neural Network (ANN)

- ANN analysis of 50 rise-time info (1,3,5,. . . ,99%) using TMVA/TMlpANN
- 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% acceptance of the DEP

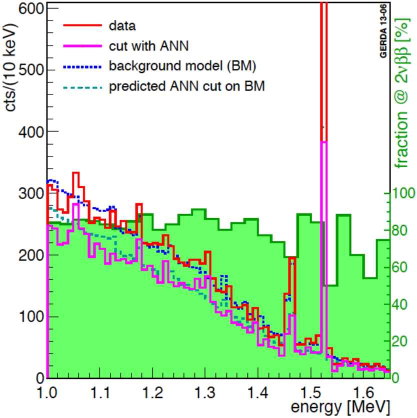




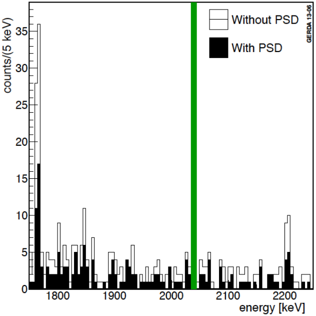
Pulse Shape Discrimination for Coaxial Detectors

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

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



arXiv:1307.2610

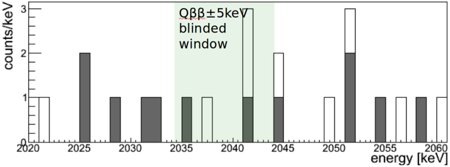


- Estimated survival fraction for $0\nu2\beta$ event: $0.90^{+0.05}_{-0.09}$
- BI after PSD in the ROI $[10^{-3}$cts/(keV·kg·yr)]:

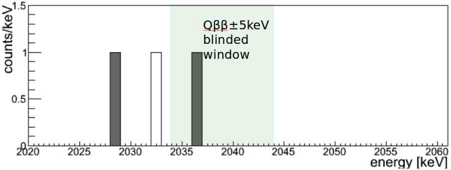
	GOLD-coax	SUM-BEGe
interpolated	11[9, 13]	5[2, 9]

Unblinded ROI

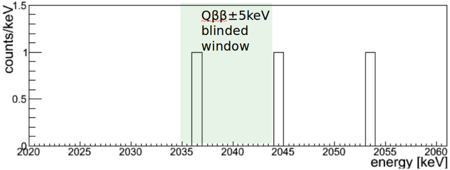
Golden dataset



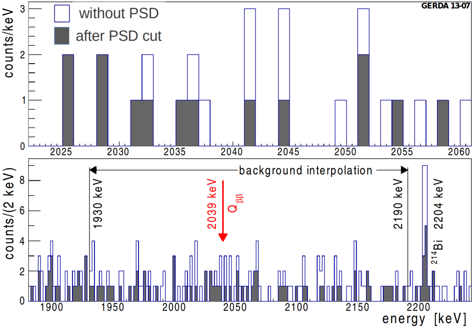
Silver dataset



BEGe dataset



All datasets

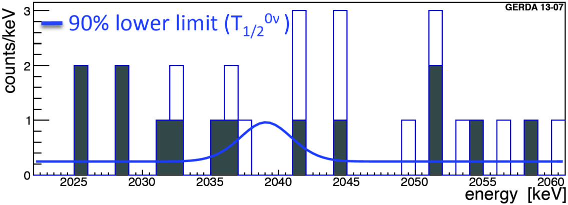


data set	detector	energy [keV]	date	PSD passed
golden	ANG5	2041.8	18-Nov-2011 22:52	no
silver	ANG5	2036.9	23-Jun-2012 23:02	yes
golden	RG2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG1	2035.5	29-Jan-2013 03:35	yes
golden	ANG3	2037.4	02-Mar-2013 08:08	no
golden	RG1	2041.7	27-Apr-2013 22:21	no

GERDA Phase I Results

Events at $Q_{\beta\beta} \pm 5$ keV

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:

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

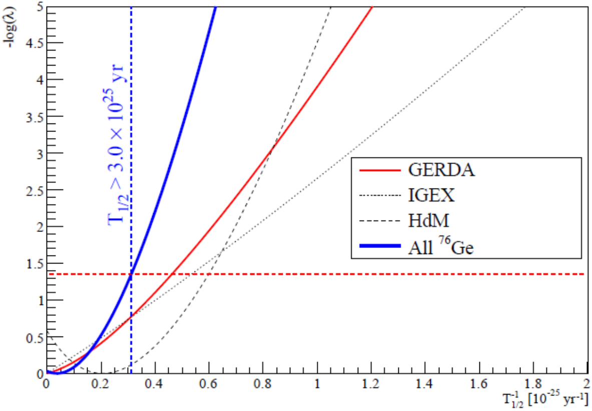
Bayesian Approach

- Flat prior for $1/T^{0\nu}_{1/2}$ in $[0; 10^{-24}]$ yr^{-1}
- Best fit $N^{0\nu} = 0$
- 90% credibility interval:

$$T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}\ \text{yr}$$

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

Combination with HdM 2001 and IGEX



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 Profile Likelihood and Bayesian approach

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

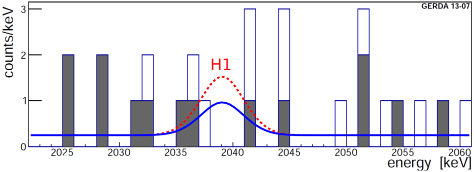
Comparison with Claim from 2004

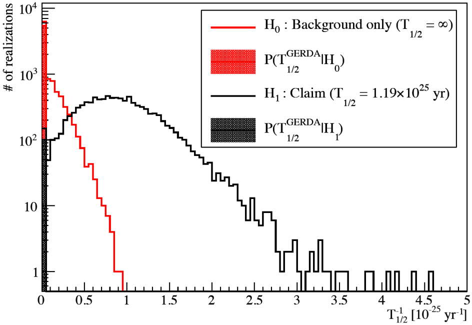
- Phys. Lett. B 586 198 (2004): $T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr
- Expected 5.9 ± 1.4 signal events over 2.0 ± 0.3 bkg events in a $\pm 2\sigma$ region
- Found 3 counts in $\pm 2\sigma$ region (0 in $\pm 1\sigma$)

Hypothesis comparison

- H1: claimed signal (5.9 ± 1.4)
- H0: background only
- Bayes factor: $P(H1)/P(H0) = 0.024$
- P-value from profile likelihood: $P(N^{0\nu} = 0 | H1) = 0.01$
- Bayes factor lowered to $2 \cdot 10^{-4}$ when combining with IGEX and HdM 2001
- Comparison independent of NME and physical mechanism generating $0\nu 2\beta$

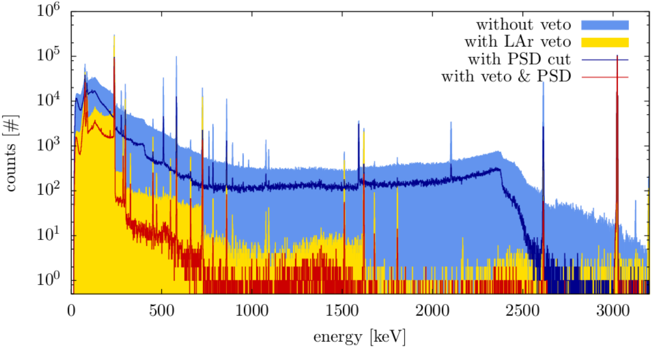
Claim strongly disfavored





Phase II upgrade: Liquid Ar Veto

- Many background events at $Q_{\beta\beta}$ are in coincidence with an energy deposition in LAr
- Ar is a scintillator $\Rightarrow$ can be used to efficiently suppress background
- Background suppression of a LAr veto and pulse shape discrimination was measured for a close ^{228}Th source (in a test set-up): Typical suppression factors in the ROI: ^{208}Tl: 1180, ^{214}Bi: 4.6 [1]



- Representative for impurities in holders, pre-amplifiers and other close objects
- Peak at 3 MeV from pulser

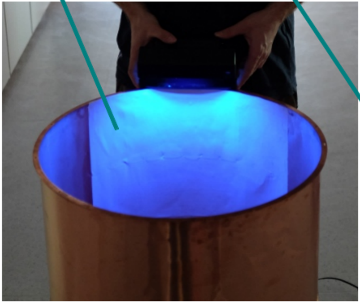
[1] "A liquid argon scintillation veto for Gerda", PhD thesis, M. Heisel, 2011

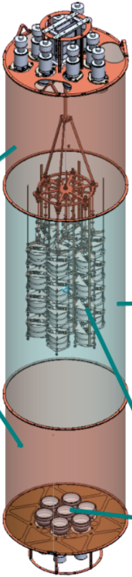
Phase II upgrade: Liquid Ar Veto

Scintillation light has 128 nm
⇒ needs to be converted to longer wavelength before detection

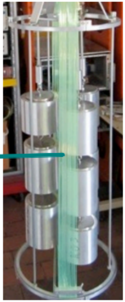
Performed by Tetraphenyl butadiene (TPB) coated onto Tetratex (a PTFE fabric), developed at UZH

Tetratex is fixed to Cu shrouds





Middle part surrounded by ≈ 1000 m of wavelength shifting fibres equipped with Si-photomultiplier

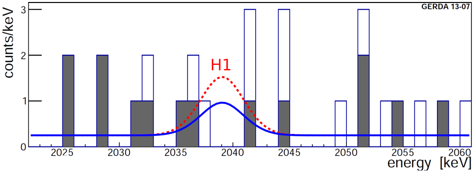


Allows to detect light from outside of the cylinder

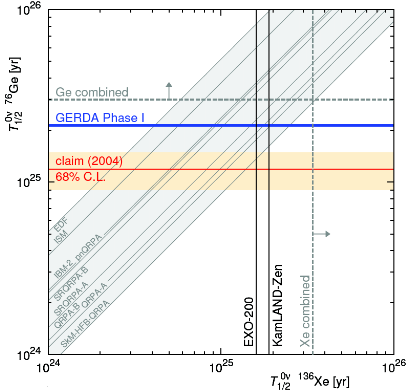
Ge detector array

Low radioactivity Photomultiplier tubes (PMTs) R11065-20

Conclusion



- Best fit gives 0 counts both for PL and BA
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- 2004 claim predicted 5.9 ± 1.4 signal events over 2.0 ± 0.3 bkg events in $Q_{\beta\beta} \pm 2\sigma$, GERDA observed 3 events in $Q_{\beta\beta} \pm 2\sigma$, 0 in $Q_{\beta\beta} \pm \sigma \Rightarrow$ claim disfavored with high probability
- Combining with HdM 2001 and IGEX 2002: $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90%) C.L. (same with Bayesian approach)
- Limit on effective Majorana neutrino mass: $m_{ee} < 0.2$-0.4 eV



Outlook

GERDA Phase II is under preparation:

- BEGe detectors
- Liquid Ar veto
- Custom low n-flux ^{228}Th sources
- Exposure goal 100 kg·yr
- Background Rate: $1 \cdot 10^{-3}$cts/(keV·kg·yr)
- Design sensitivity $T_{1/2} \approx 2 \cdot 10^{26}$ yr