Results from GERDA Phase I

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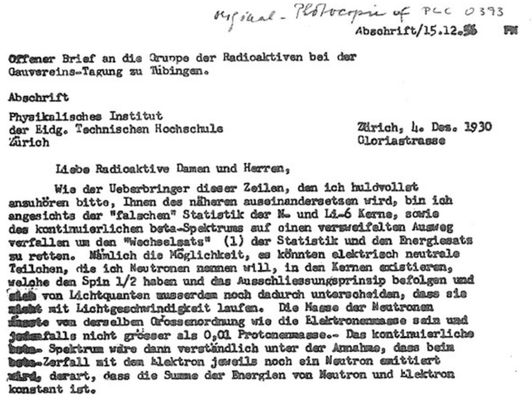
LAPP, Annecy, January 10, 2014

Outline

- Neutrinoless double beta decay - theory and experiement
- The Gerda experiment
- Data taking and data processing
- Background models and $2\nu\beta\beta$ analysis
- Background reduction methods
- $0\nu\beta\beta$ results
- Outlooks

Neutrinoless double beta decay

Postulation of the neutrino - single beta decay


Original - Photocopie of PLC 0393
Abschrift/15.12.56

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

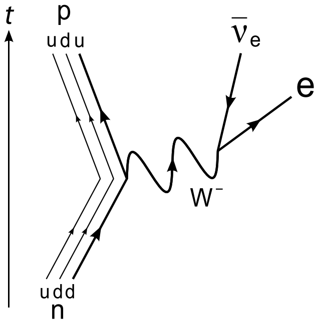
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

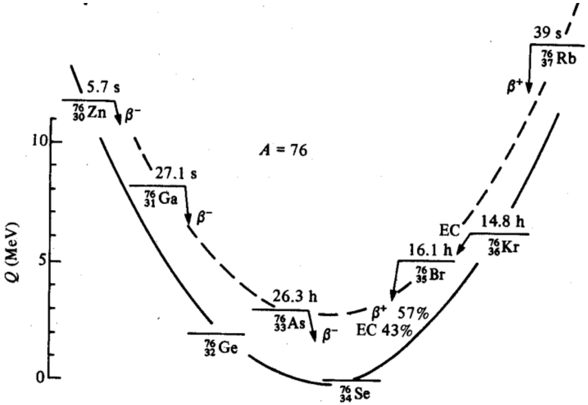
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



Neutrinoless double beta decay

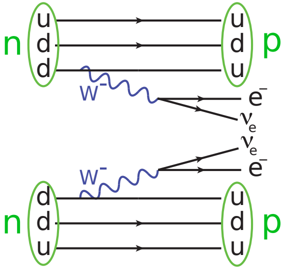
Mass parabolas of odd-odd, even-even nuclei



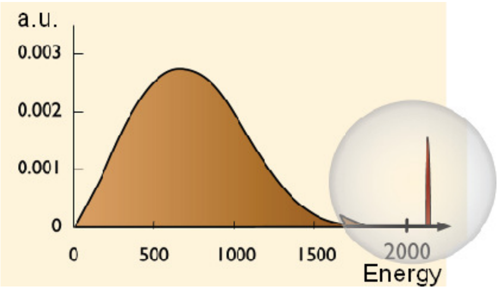
- Even-even nuclides are more stable (smaller binding energy)
- Beta decay transforms even-even nuclides into odd-odd nuclides
- For a few isotopes the next odd-odd nuclide can have higher binding energy
  ⇒ In such a case single beta decay is forbidden:
  ⇒ Double beta decay is allowed $2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$

Neutrinoless double beta decay

Double beta decay spectrum

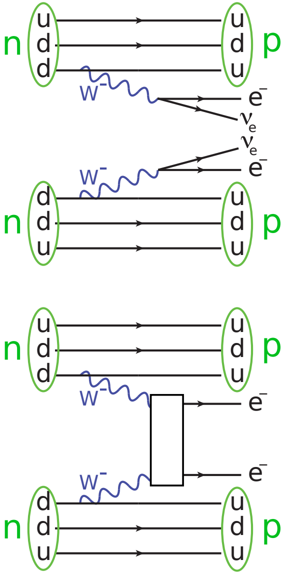


- Standard Model - two neutrino double beta decay:
  - Emission of two neutrinos and two electrons
  - Continuous spectrum (neutrinos usually escape)
  - Has been observed for 11 isotopes

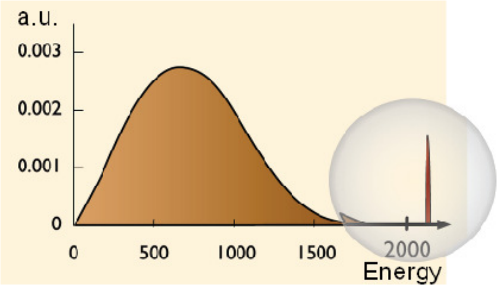


Neutrinoless double beta decay

Double beta decay spectrum

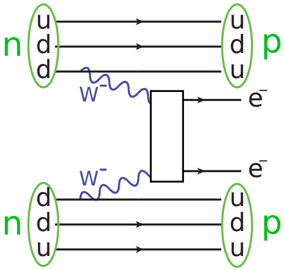


- Standard Model - two neutrino double beta decay:
  - Emission of two neutrinos and two electrons
  - Continuous spectrum (neutrinos usually escape)
  - Has been observed for 11 isotopes
- Neutrinoless double beta decay:
  - Emission of only two electrons
  - Peak at $Q_{\beta\beta} = 2039$keV (for ^{76}Ge)



Neutrinoless double beta decay

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



- Process of form: $(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+2) + 2\mathrm{e}^-$
- It violates Lepton number conservation by two units
- Implies physics beyond the standard model
- Schechter-Valle theorem: All realizations of $0\nu\beta\beta$ are connected to a Majorana neutrino mass

Neutrinoless double beta decay

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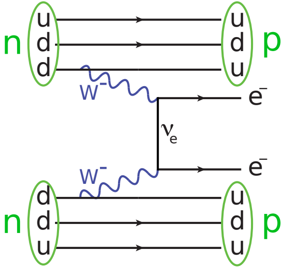

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Neutrinoless double beta decay

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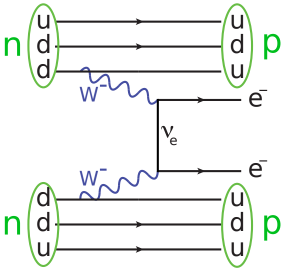

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- Implies physics beyond the standard model
- Schechter-Valle theorem: All realizations of $0\nu\beta\beta$ are connected to a Majorana neutrino mass
- Simplest case: Annihilation of neutrino and anti-neutrino.
- Any $\Delta L = 2$ process possible
- Higgs triplet, SUSY,...: Important connections to high energy particle physics
- sub eV Majorana mass $\leftrightarrow$ TeV scale physics

Neutrinoless double beta decay

Neutrino mass formula

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 m_{\beta\beta}^2$$

- $(T_{1/2}^{0\nu})^{-1}$: Half life of isotope, measured
- $G_{0\nu}(Q_{\beta\beta}, Z)$ phase space
- $M_{0\nu}$: nuclear matrix element, calculated
- $m_{\beta\beta}$: effective Majorana mass: $m_{\beta\beta} = |\sum_{i=0}^{3} U_{ei}^2 m_i|$
- U: PMNS matrix (measured in neutrino oscillation experiments)
- m_i: mass eigenvalue

Experimental limits

Isotope	$Q_{\beta\beta}$, keV	$T_{1/2}^{0\nu}$, yr	$m_{\beta\beta}$, eV
^{48}Ca	4272	$> 5.8 \times 10^{22}$	< 14
^{76}Ge	2039.0	$> 1.9 \times 10^{25}$	$< 0.2 - 0.7$
^{82}Se	2996	$> 3.6 \times 10^{23}$	$< 0.8 - 2.4$
^{96}Zr	3350	$> 9.2 \times 10^{21}$	$< 3.9 - 13.7$
^{100}Mo	3034.4	$> 1.1 \times 10^{24}$	$< 0.3 - 0.7$
^{116}Cd	2813.5	$> 1.7 \times 10^{23}$	$< 1.2 - 2.2$
^{128}Te	867	$> 1.5 \times 10^{24}$	$< 1.8 - 4.2$
^{130}Te	2527.5	$> 2.8 \times 10^{24}$	$< 0.4 - 0.8$
^{136}Xe	2458.7	$> 1.6 \times 10^{25}$	$< 0.1 - 0.4$
^{150}Nd	3371.4	$> 1.8 \times 10^{22}$	$< 2.2 - 7.5$

A. S. Barabash, http://arxiv.org/abs/1209.4241

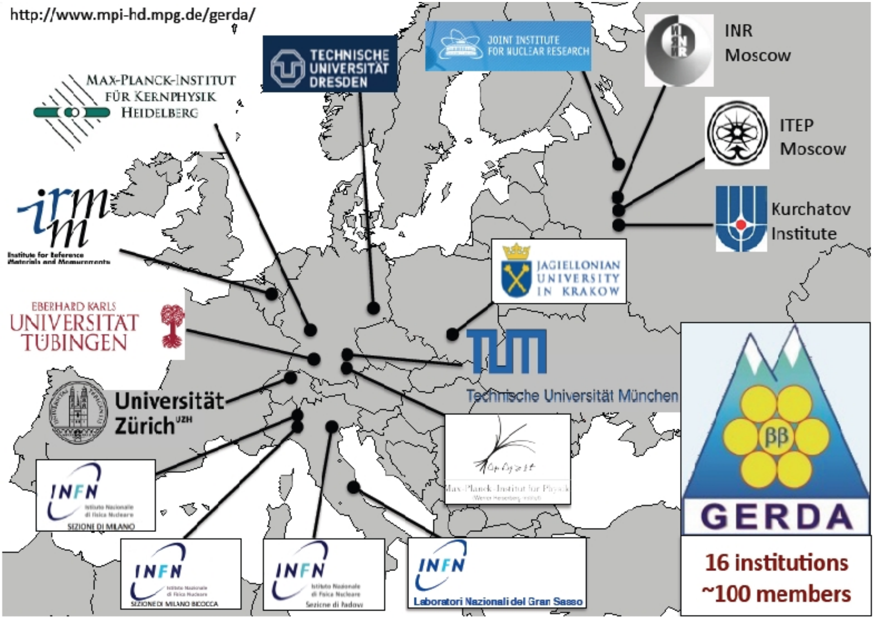
Claim of observation: KKDC: 71.7 kg · yr: $T_{1/2}^{0\nu} = 1.2(0.7\text{-}4.2)\cdot 10^{25}$ yr (Phys Lett B586 (2004) 198)

Sensitivity of an experiment:

$$T_{1/2}^{0\nu}(n_\sigma) = \frac{4.16\times 10^{26} yr}{n_\sigma}\left(\frac{\epsilon a}{W}\right)\sqrt{\frac{Mt}{b\Delta(E)}}$$

- ϵ detection efficiency
- a abundance of isotope
- W molecular weight of source
- Mt exposure [kg yr]
- b background index (BI)
- $\Delta(E)$ instrumental spectral width

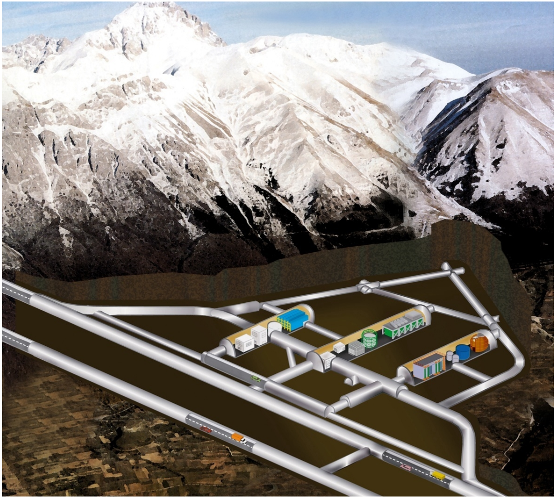
The GERDA experiment - collaboration



The GERDA experiment - millestones and location

GErmanium Detector Array

- 2004: Letter of Intent
- R&D: material selection and screening, tests of bare diodes in LAr
- 2008-2010: construction at LNGS (Laboratori Nazionali del Gran Sasso, Italy, 3400mwe)
- 2010-2011: commissioning



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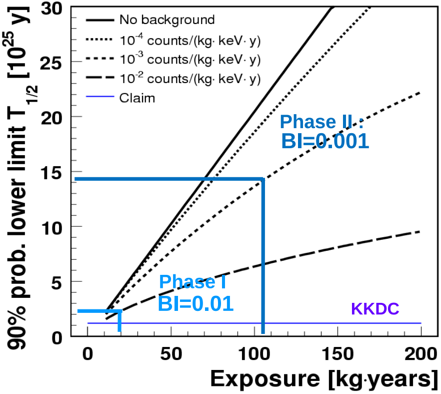
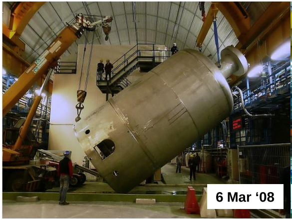
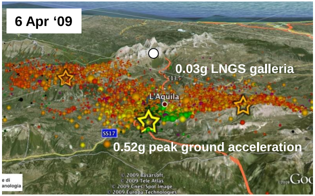
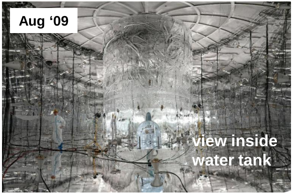
- Nov. 2011 - May 2013: data taking Phase I data
- Change to Phase II presently ongoing

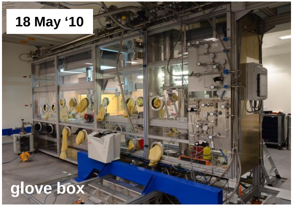


The GERDA experiment - construction



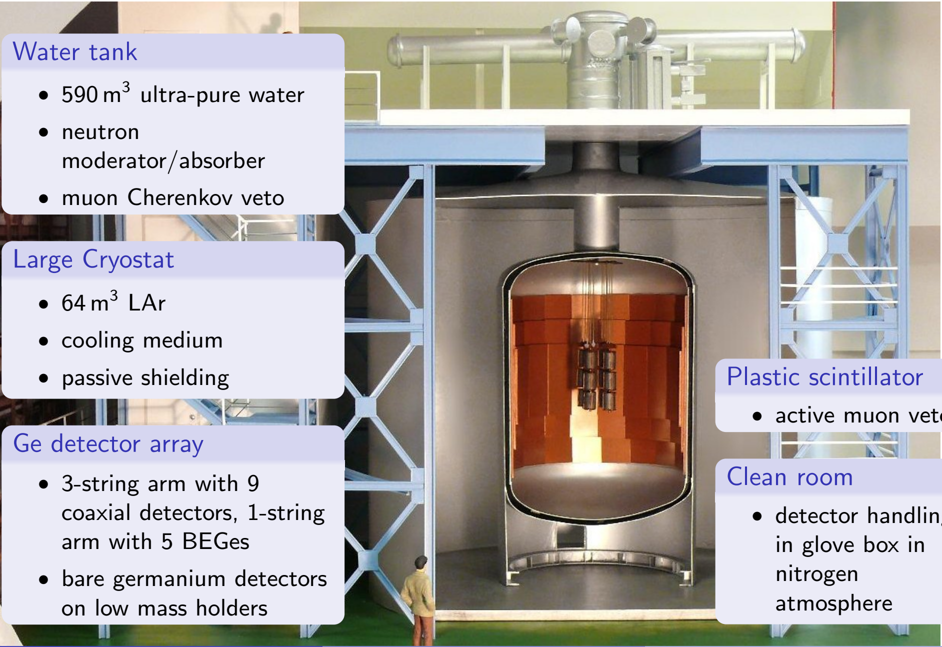






Cryostat filled since December 2009

The GERDA experiment - setup



Water tank

- $590\,m^3$ ultra-pure water
- neutron moderator/absorber
- muon Cherenkov veto

Large Cryostat

- $64\,m^3$ LAr
- cooling medium
- passive shielding

Ge detector array

- 3-string arm with 9 coaxial detectors, 1-string arm with 5 BEGes
- bare germanium detectors on low mass holders

Plastic scintillator

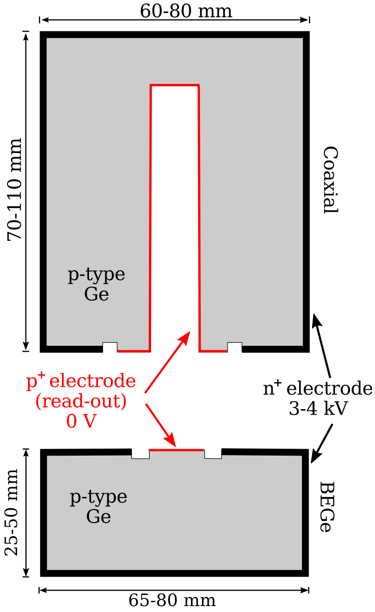
- active muon veto

Clean room

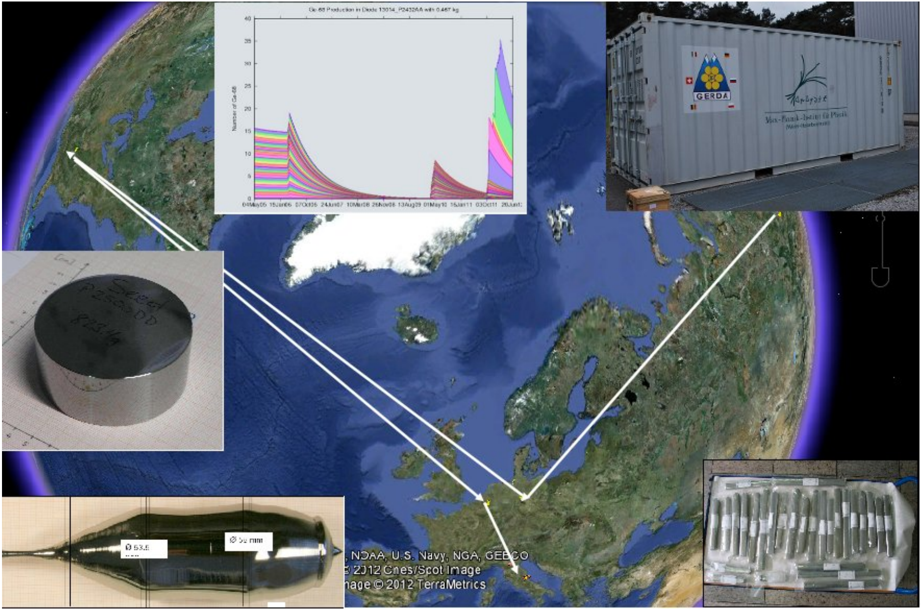
- detector handling in glove box in nitrogen atmosphere

The GERDA experiment - detectors

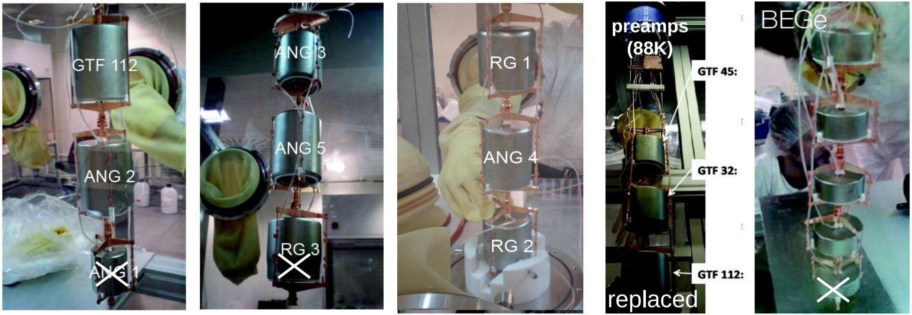
- Why germanium?
  - Solid even at room temperature
  - Very good energy resolution
  - Detector material = source material
- Deployed detectors:
  - Refurbished semi-coaxial detectors from HdM and IGEX experiments
  - n+ conductive Li layer, separated by a groove from the boron implanted p+ contact
  - Phase II detector type, already used: BEGe - broad energy Ge detector
  - Semi-coaxial detectors: 2 - 2.8kg, BEGe ∼0.7kg



The GERDA experiment - production of new diodes



The GERDA experiment - strings

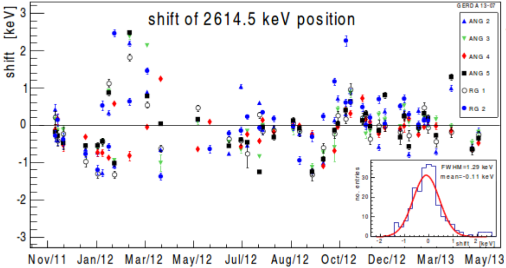


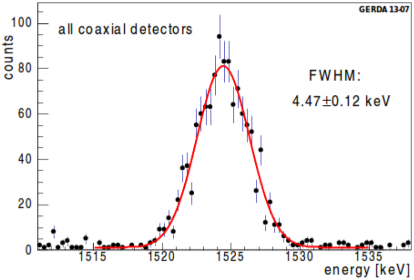
- Used in this analysis:

since Nov. 11:	6 enriched semi-coaxial : ANG2,3,4,5, RG1,2	14.63kg
	1 natural semi-coaxial: GTF112	2.96kg
since Jul. 12:	4 enriched BEGe : GD32B,C,D, GD35B	3.00kg

- Enrichment of ^{76}Ge: 86-87%

The GERDA experiment - calibration and data processing





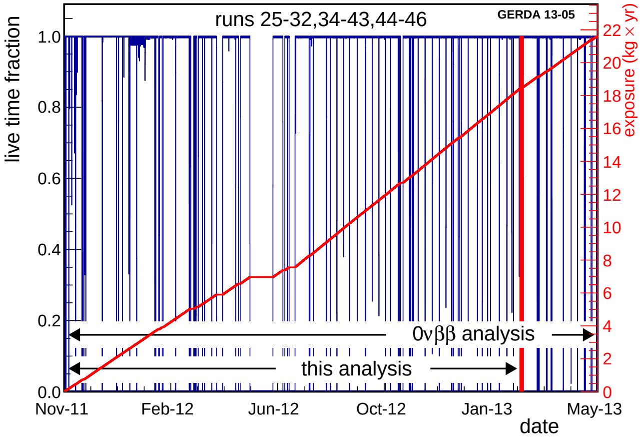
Analysis

- Processing: diode → amplifier → FADC → digital filter → energy/pulse shape/etc
- Selection: anti-coincidence muon / 2nd Ge (∼20% rejected at $Q_{\beta\beta}$), quality cuts (∼9% rej.), pulse shape discrimination (∼50% rej.)
- Calibration: ^{228}Th (bi)weekly and pulser every 20 seconds for short term drifts

Results

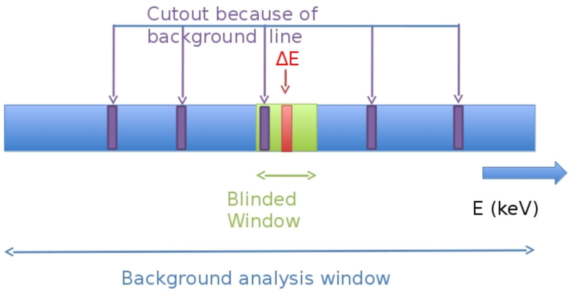
- shifts are small compared to FWHM ∼0.2% $Q_{\beta\beta}$
- peak pos. within 0.3keV at correct position (here for ^{42}K)
- FWHM ∼4% larger than expected from calibration data

The GERDA experiment - data taking



- Stable data taking during most of the time (492 d, duty cycle 88%)
- total exposure: 21.6 kg·yr
- Blue spikes indicate calibration measurements
- Break during deployment of BEGe detectors

The GERDA experiment - data blinding



- Blinding is done for avoiding biases (due to low statistics)
- During data taking: All events in $Q_{\beta\beta} \pm 20$keV removed
- May 2013: All events up to $Q_{\beta\beta} \pm 5$keV unblinded $\Rightarrow$ additional check
- 2 copies of raw data kept for processing after unblinding

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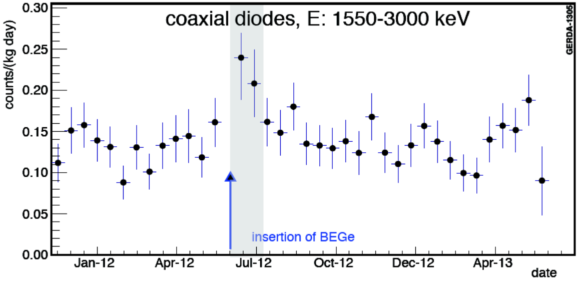

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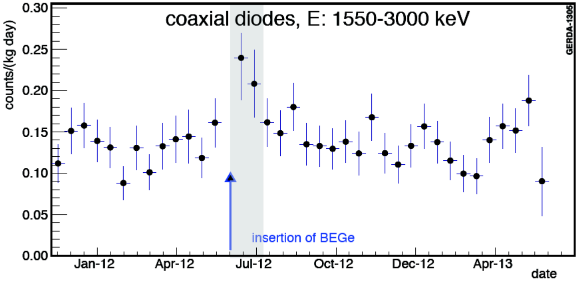
- Data processing details fixed before unblinding:
  - quality cuts
  - pulse shape discrimination parameters
  - analysis method: three data sets

golden coaxial	=	17.9 kg·yr
silver coaxial	=	1.3 kg·yr
BEGe	=	2.4 kg·yr

The GERDA experiment - data blinding



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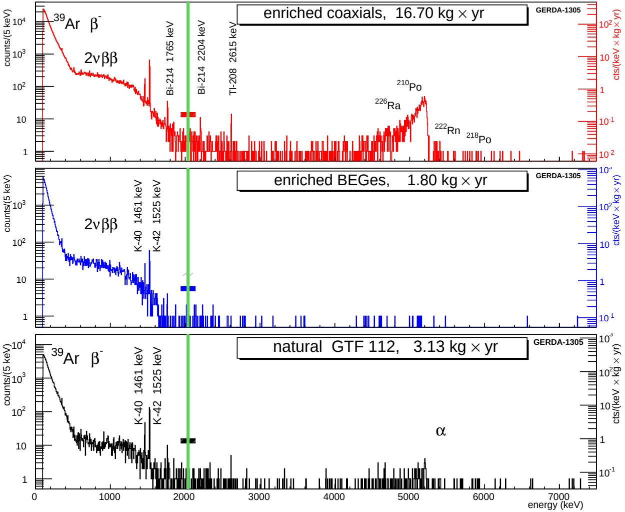
- Date unblinded in June 2013

The GERDA experiment - spectrum

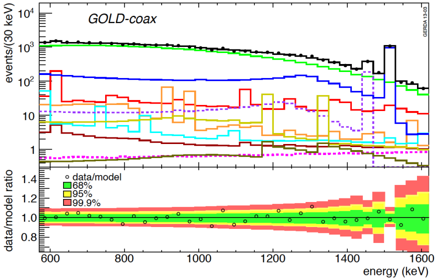


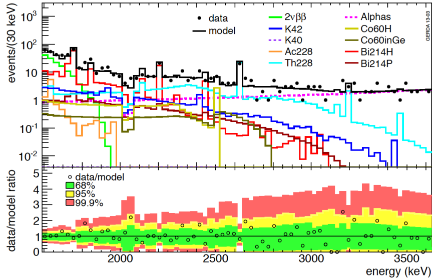
http://arxiv.org/abs/1306.5084 (accepted by EPJC)

Visible backgrounds:

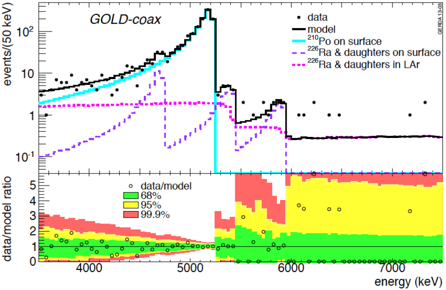
- Double beta decay of ^{76}Ge
- β decay of cosmogenic ^{39}Ar
- Alphas (decay on p+ surface, ^{226}Ra, ^{222}Rn ^{210}Po)
- Decay of ^{42}K on the surface or close to the detector from ^{42}Ar (mini shroud was deployed to reduce this background)

The GERDA experiment - background model





- Fit of combination of MC spectra to data between 570 keV and 7500 keV
- Good fits, however not unique (different models possible)
- Close background sources dominate: ^{42}Ar, ^{228}Th, ^{226}Ra in holders, α particles on detector surfaces.



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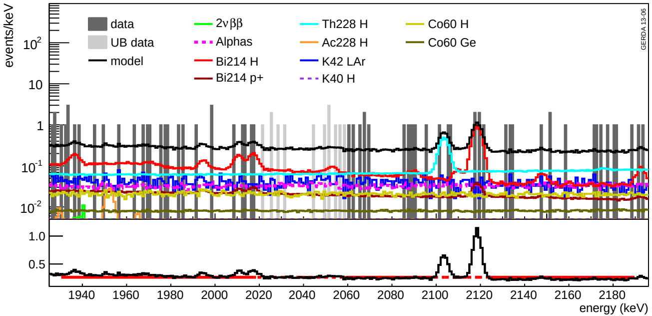
The GERDA experiment - background model



- Background flat between 1930 keV - 2190 keV w/o 2104 keV and 2119 keV peaks
- No line expected in the blinded window
- Linear fit with flat background excluding 2104 $\pm$ 5 keV and 2119 $\pm$ 5 keV peak regions
- For $0\nu\beta\beta$ analysis a flat background around $Q_{\beta\beta}$ can be used

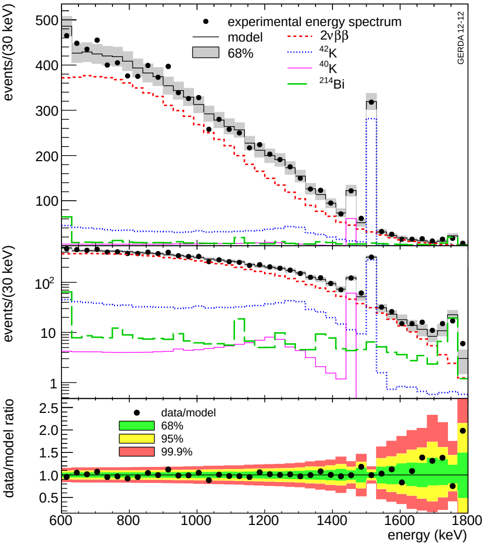
http://arxiv.org/abs/1306.5084 (accepted by EPJC)

The GERDA experiment - $2\nu\beta\beta$

- Region between 600 keV and 1400 keV dominated by $2\nu\beta\beta$ decay
- Global fit of background model contains this distribution
- It is possible to extract $2\nu\beta\beta$ half-life

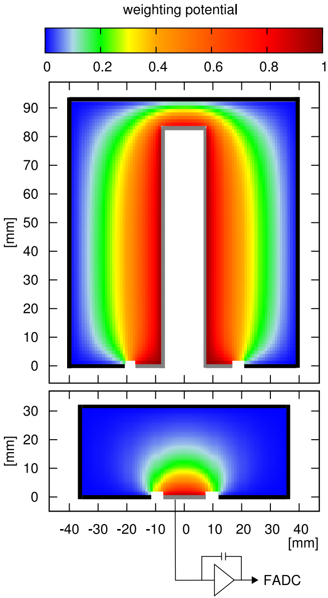
$$T_{1/2}^{2\nu} = (1.84 + 0.14) \cdot 10^{21} \text{ yr}$$

- This is the best current limit for this decay



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

The GERDA experiment - pulse shape discrimination



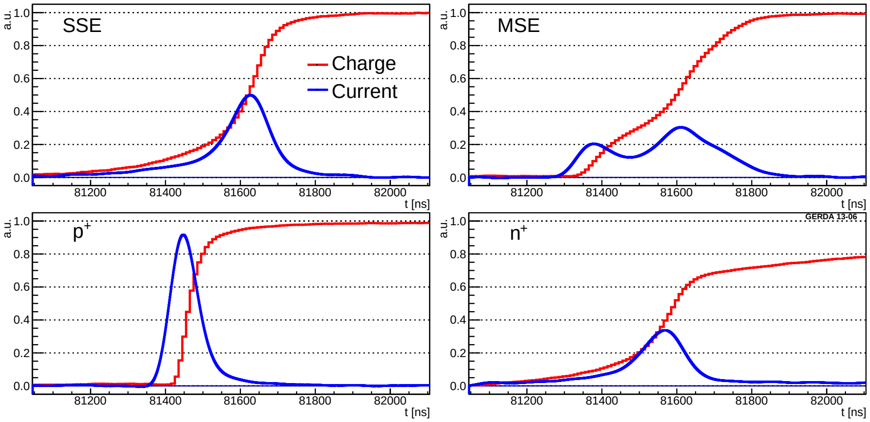
- Exploit different pulse structure of
  - single-site events (SSE)
  - multi-site events (MSE).
- $0\nu\beta\beta$ events are SSE: (1 MeV electron has range of $\sim$1mm)
- Compton scatted MeV γ's more than 10$\times$ larger range $\Rightarrow$ MSE
- Surface events: only electrons or holes drift $\Rightarrow$ characteristic pulse shape
- Coaxial and BEGe diodes have very different E-fields $\Rightarrow$ different PSD properties and algorithms
- PSD developed with calibration and physics data: ^{228}Th spectrum, certain features used as proxies for signal-like (DEP,Compton Edge,$2\beta\beta$) and background-like events (FEP).

http://arxiv.org/abs/1307.2610 (accepted by EPJC)

The GERDA experiment - pulse shape discrimination

BEGe detectors:

- A = Amplitude of current pulse
- E = energy reconstructed with shaping filter
- A / E is a robust, simple and well understood cut parameter



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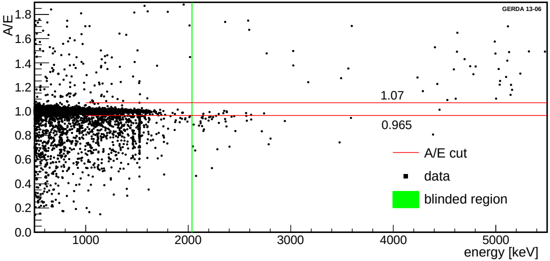

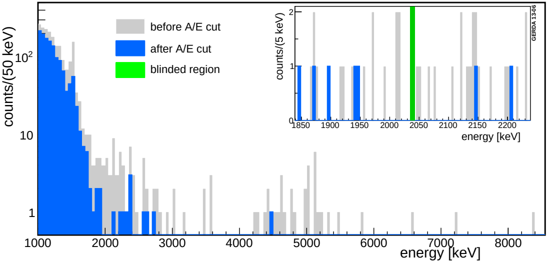

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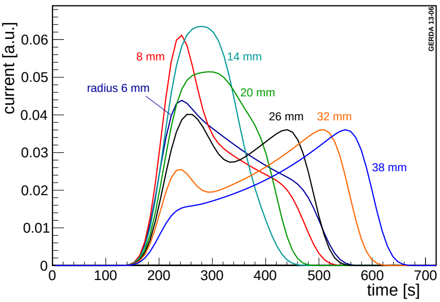
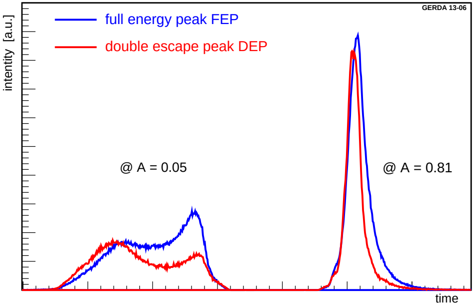
- SSE accepted for 0.965 $<$ A/E $<$ 1.07
- $0\nu\beta\beta$ efficiency = (92 $\pm$ 2) % (from DEP efficiency and simulation)
- $2\nu\beta\beta$ efficiency = (91 $\pm$ 5) % (good agreement with DEP eff.
- 80% of background events rejected around $Q_{\beta\beta}$

The GERDA experiment - pulse shape discrimination

Coaxial detectors:





- Artificial neural network (ANN) : TMlpANN implemented in TMVA (ROOT)
- Input: time when charge signal reaches 1%, 3%, ..., 99% of maximum amplitude
- $0\nu\beta\beta$ efficiency (from DEP and simulation): (90 +0.05/-0.09) %
- About 45% events rejected around $Q_{\beta\beta}$
- Cross checks:
  - $2\nu\beta\beta$ eff $= (85 \pm 2)$ %
  - 2.6 MeV γ Compton edge eff. $=$ 85 - 94 %
  - Co-56 DEP (1576 and 2231 keV) eff. $=$ 83 - 93 %
  - Simulations

http://arxiv.org/abs/1307.2610 (accepted by EPJC)

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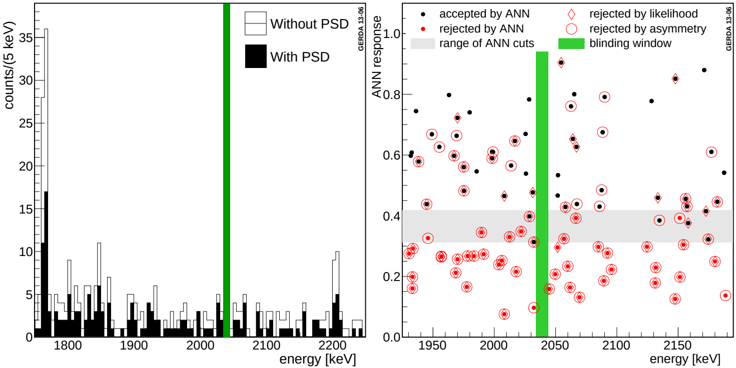
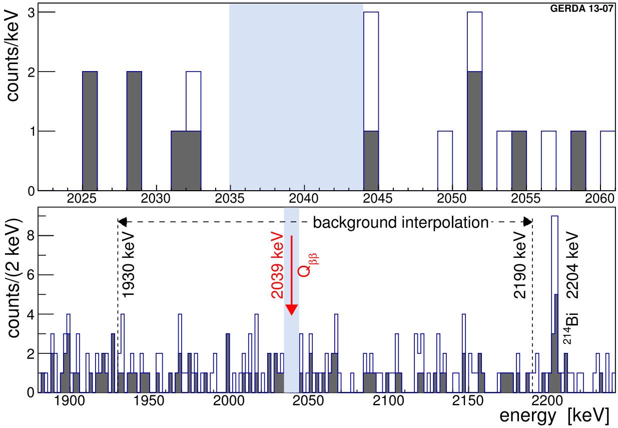


Cross check ANN classification with 2 other methods:

- Projective likelihood trained with Compton edge events
- Current pulse asymmetry $\times$ A/E
- 90% of ANN rejected events also rejected by both, 3% only rejected by ANN
  $\Rightarrow$ Classification of background like events meaningful

http://arxiv.org/abs/1307.2610 (accepted by EPJC)

$0\nu\beta\beta$ analysis - unblinding

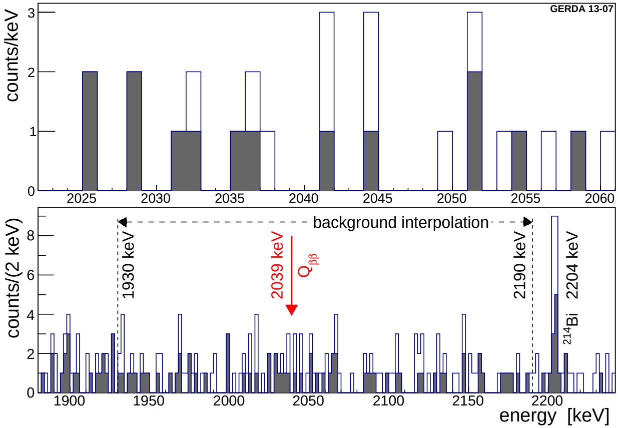


open box = w/o PSD
grey box = with PSD

Expected background from interpolation:
5.1 events w/o PSD
2.5 events with PSD

Phys. Rev. Lett 111 (2013) 122503

$0\nu\beta\beta$ analysis - unblinding



open box = w/o PSD
grey box = with PSD

Expected background from interpolation:	**observed:**
5.1 events w/o PSD	7 events w/o PSD
2.5 events with PSD	3 events with PSD

Phys. Rev. Lett 111 (2013) 122503

$0\nu\beta\beta$ analysis - calculating the half life

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

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

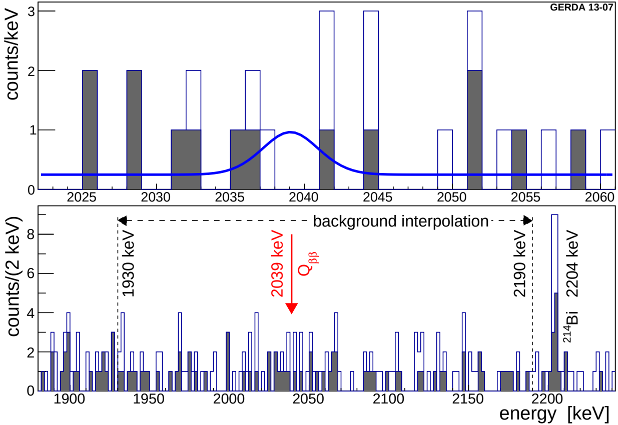
N_A	Avogadro number,
m_{enr}	molar mass of enriched Ge,
$N^{0\nu}$	signal counts/limit,
$\mathcal{E}$	total exposure,
ε	exposure averaged efficiency
f_{76}	enrichment fraction,
f_{av}	fraction of active detector volume,
ε_{fep}	full energy peak efficiency for $0\nu\beta\beta$,
ε_{psd}	signal acceptance

Data set	Exposure (kg·yr)
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$< f_{76} >$	$< f_{av} >$	$< \varepsilon_{fep} >$	$< \varepsilon_{psd} >$	$< \varepsilon >$
Coax	0.86	0.87	0.92	$0.90^{+0.05}_{-0.09}$	$0.619^{+0.044}_{-0.070}$
BEGe	0.88	0.92	0.90	0.92 ± 0.02	0.663 ± 0.022

Phys. Rev. Lett 111 (2013) 122503

$0\nu\beta\beta$ analysis - unblinding



open box = w/o PSD
grey box = with PSD

Profile likelihood fit to the 3 data sets: constant (bgnd) + gaussian

- Given param.: $\mu = (2039.06 \pm 0.2)$keV, $\sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)$ keV coax/BEGe

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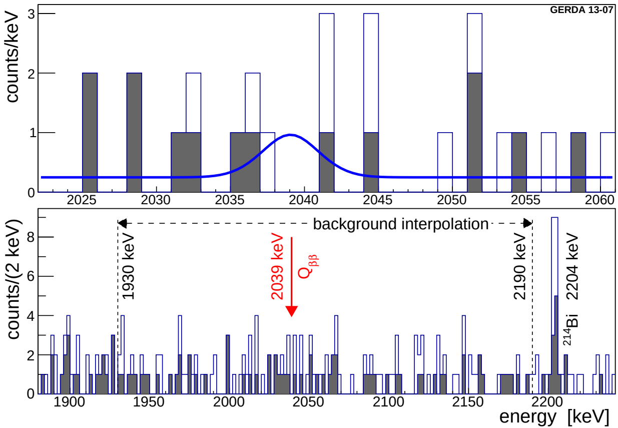

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Profile likelihood fit to the 3 data sets: constant (bgnd) + gaussian

- Given param.: $\mu = (2039.06 \pm 0.2)$keV, $\sigma = (2.0 \pm 0.1)/(1.4 \pm 0.1)$ keV coax/BEGe
- Frequentist: best fit $N^{0\nu} = 0 \quad \Rightarrow \quad \mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$yr (90% C.L.)
- Bayes: best fit $N^{0\nu} = 0 \quad \Rightarrow \quad \mathbf{T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}}$yr (90% C.I., flat 1/T prior)

$0\nu\beta\beta$ analysis - other ^{76}Ge experiments

- This can be combined with previous ^{76}Ge experiments (IGEX and HdM)
- Almost identical limits with Frequentist and Bayes approach

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

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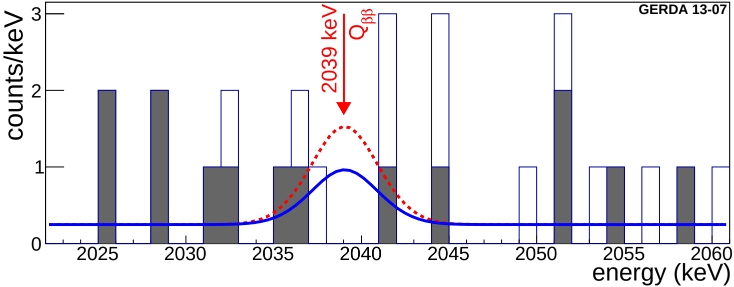
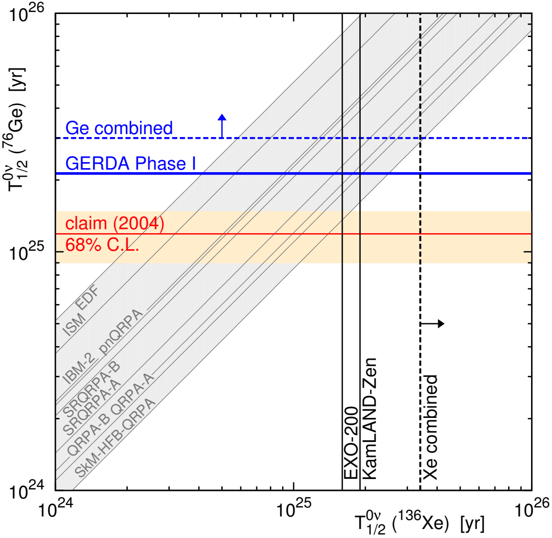


- KK claim (observation with $T_{1/2}^{0\nu} = 1.2 \cdot 10^{25}$yr) strongly disfavoured
- Assuming the KK claimed signal, GERDA should see 5.9 ± 1.4 $0\nu\beta\beta$ events in $\pm 2\sigma$ interval above bkg $= 2.0 \pm 0.3$
- probability $p(N_{0\nu} = 0 | H1 = signal + bkg) = 1\%$, claim ruled out at 99%
- Bayes factor $H1(= signal + bkg)/H0(= bkg\ only) = 0.024$

$0\nu\beta\beta$ analysis - limit from ^{136}Xe

Coaxial detectors:



Bayes factors:

- EXO 0.23
- KamLAND-Zen 0.40
- GERDA
- 0.024
- All combined 0.002

HdM claim even stronger disfavoured
$\Rightarrow$ the quest for $0\nu\beta\beta$ decay is open again!

Outlook - Gerda Phase II

sensitivity $T^{0\nu}_{1/2}(^{76}Ge) \sim 1.4 \cdot 10^{26}$ yr at 100 kg·yr

- Reduce BI by another order of magnitude to 0.001 cts/(keV·kg·yr)
- more BEGe detectors with better PSD and resolution
- instrumentation of LAr to veto specific backgrounds
- less and cleaner material in detector holders, cables, ..
- double detector mass (15 kg coaxial + 20 kg BEGe)
- new readout electronics, radio-purer + better resolution
- get exposure of ∼100 kg·yr within 3 years

Outlook - The next generation of $0\nu\beta\beta$ experiments

Experiments	Isotope	Mass of Isotope (kg)	Sensitivity of $T_{1/2}$ (years)	Sensitivity of $m_{\beta\beta}$ (meV)
CUORE (2013)	^{130}Te	200	6.5×10^{26} 2.1×10^{26}	20 - 50 35 - 90
GERDA (2011)	^{76}Ge	40 1000	2×10^{26} 6×10^{27}	70 - 300 10 - 40
MAJORANA (2013)	^{76}Ge	30-60 1000	$1 - 2 \times 10^{26}$ 6×10^{27}	70 - 300 10 - 40
EXO (2011)	^{136}Xe	200 1000	6.4×10^{25} 8×10^{26}	95 - 220 27 - 63
SuperNEMO (Proposal)	^{82}Se	100-200	$1 - 2 \times 10^{26}$	40 - 100

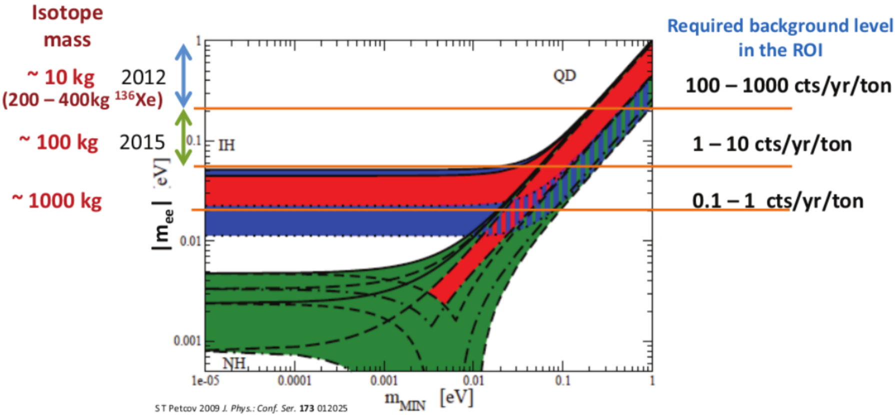
(A.S.Barabash **arXiv:0807.2948**)

(S.R.Elliott **arXiv:1203.1070**)

All sensitivities beyond 10^{26} yr !

Outlook - Aims of $0\nu\beta\beta$ research

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 m^2_{\beta\beta} \quad \Rightarrow \quad m_{\beta\beta} < 0.2\text{–}0.4 eV$$



- 1T scale experiments are required

Conclusion

GERDA Phase I results:

- unprecedented BI of 0.011 ± 0.002 cts/(keV $\cdot$ kg $\cdot$ yr) with PSD
- no indication of peak at 2039 keV
- half life limit for $0\nu\beta\beta$ decay of Ge-76:

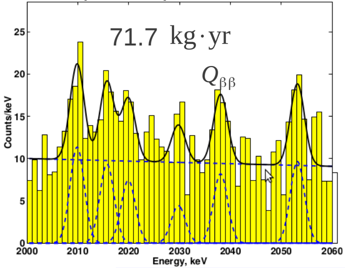
$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25} \text{ yr (90\% C.L.)}$$
$$T_{1/2}^{0\nu} > 3.0 \cdot 10^{25} \text{ yr (90\% C.L.) with HdM + IGEX}$$

- The HdM claim is strongly disfavoured
- The quest for $0\nu\beta\beta$ decay is open again!
- The next years will see a variety of experiments searching for $0\nu\beta\beta$ decay of ^{76}Ge, ^{130}Te and ^{136}Xe with largely improved sensitivities.

Backup

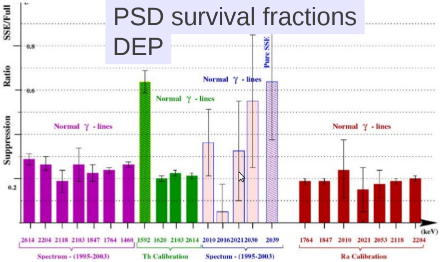
What HdM value to compare with?

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



entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events
$T^{0\nu}_{1/2} = (1.19^{+0.37}_{-0.23}) \cdot 10^{25}$ yr

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events
$T^{0\nu}_{1/2} = (1.25^{+0.49}_{-0.27}) \cdot 10^{25}$ yr



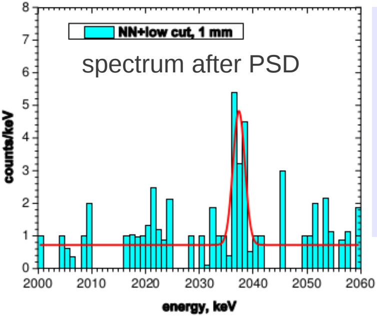
with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%
→ $T^{0\nu}_{1/2} = 1.23 \cdot 10^{25}$ yr

Without efficiency correction:
$T^{0\nu}_{1/2} = 1.98 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!

Backup

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



fit gives 11.32±1.75 signal events

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

error on signal count not correct since smaller than Poisson error

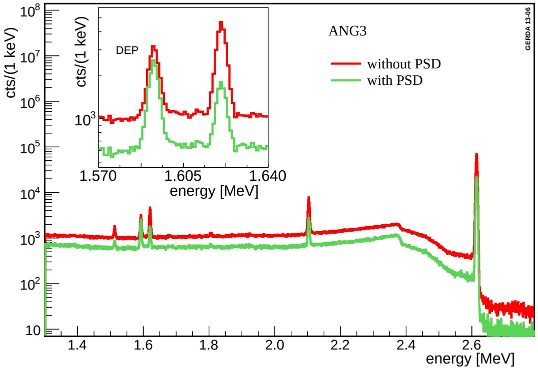
PSD based on 3 previous methods (2 neural networks + pulse boardness) & library of SSE pulses:
Event accepted IF pulse in library OR found by neural network of Ref. 16 but not by the other two neural networks

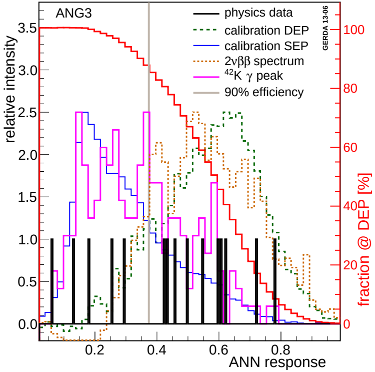
NO event overlap between the 2 sets!?

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

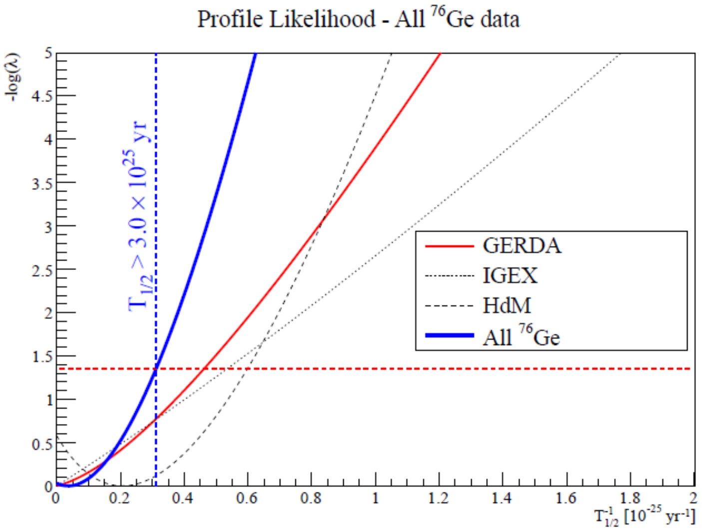
efficiency factor not considered
→ calculation of $T_{1/2}^{0\nu}$ not correct
→ GERDA does not use this result

Backup


cts/(1 keV)
ANG3
without PSD
with PSD
DEP
energy [MeV]
GERDA 13-06

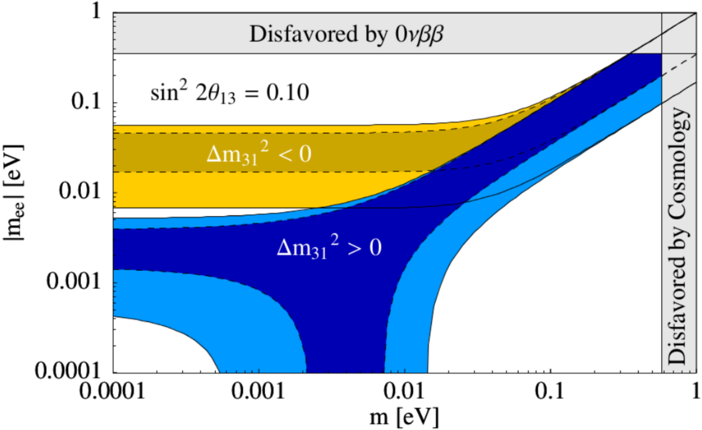

ANG3
physics data
calibration DEP
calibration SEP
2νββ spectrum
42K γ peak
90% efficiency
GERDA 13-06
relative intensity
fraction @ DEP [%]
ANN response

Backup



Profile Likelihood - All 76Ge data
-log(λ)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
T-1 1/2 [10-25 yr-1]
T1/2 > 3.0 × 10^25 yr
GERDA
IGEX
HdM
All 76Ge

Backup



Disfavored by 0νββ
sin² 2θ₁₃ = 0.10
Δm₃₁² < 0
Δm₃₁² > 0
Disfavored by Cosmology
|m_ee| [eV]
m [eV]
1
0.1
0.01
0.001
0.0001
0.0001
0.001
0.01
0.1
1