Results on neutrinoless double beta decay from GERDA Phase I

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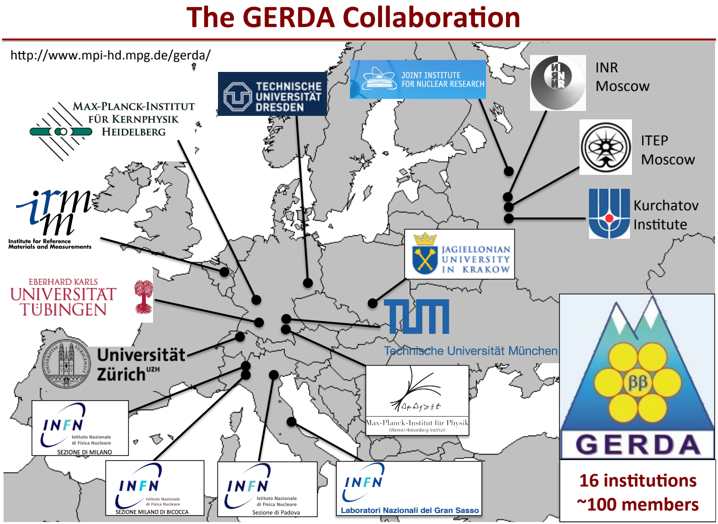
INFN, Laboratori Nazionali del Gran Sasso

CPPM Marseille
25.11.2013

Outline

- Probing the nature of neutrino with neutrinoless double-beta decay
- The GERDA experiment
- The GERDA energy spectra
- The GERDA physics results:
    - Measurement of the half-life of $2\nu\beta\beta$ decay of ^{76}Ge
    - The background models for GERDA Phase I
    - The Pulse Shape Discrimination of GERDA events
    - Result on $0\nu\beta\beta$ half-life
- On the way to GERDA Phase II

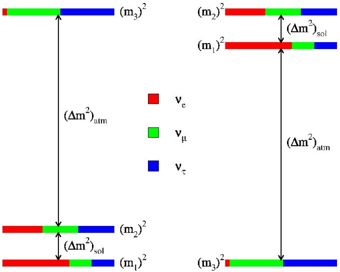
The GERDA collaboration



112 physicists, 16 institutions, 7 countries

Investigate existence of $0\nu\beta\beta$

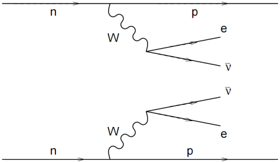
- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- Lepton number violation
- physics beyond Standard Model
- Shed light on effective neutrino mass
- Shed light on neutrino mass hierarchy



Search for $0\nu\beta\beta$ decay

$2\nu\beta\beta$

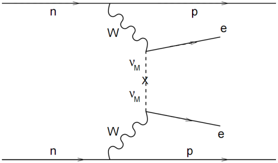
$$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\overline{\nu}_e$$



$\Delta L = 0 \Longrightarrow$ Predicted by s.m.

$0\nu\beta\beta$

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$



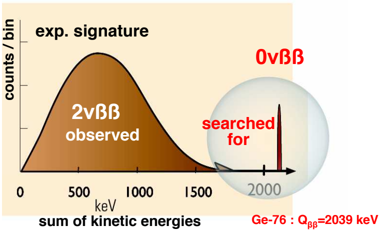
$\Delta L = 2 \Longrightarrow$ Prohibited by s.m.

Light Majorana neutrino exchange ?

$$Q = M_i - M_f - 2m_e$$

The GERmanium Detector Array

experiment is an ultra-low background experiment designed to search for ^{76}Ge $0\nu\beta\beta$ decay.



$Q_{\beta\beta} = 2039$ keV

Search for $0\nu\beta\beta$ decay

If light Majorana neutrino exchange is the dominant mechanism:

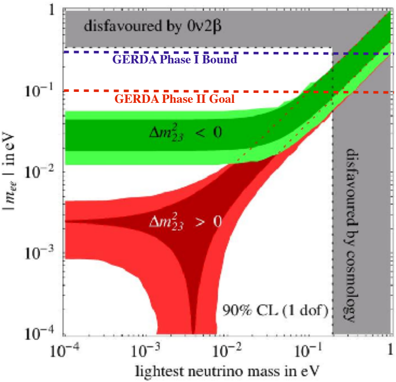
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

with $\langle m_{\beta\beta}\rangle$ = effective electron neutrino mass

$$\langle m_{\beta\beta}\rangle \equiv |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$$

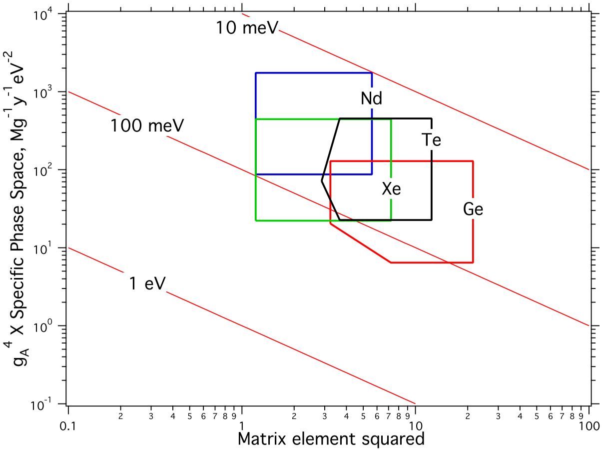
m_i=masses of the neutrino mass eigenstates
U_{ei}=elements of the neutrino mixing matrix
$e^{i\phi_2}$ and $e^{i\phi_3}$=Majorana CP phases

→ information on the absolute mass scale!



- **Phase I result**: BI ∼ 10^{-2} cts/(keV kg yr) and ∼ 20 kg yr exposure
  Claim from *Phys. Lett. B 586 (2004) 198* rejected with high probability
- **Phase II goal**: BI ∼ 10^{-3} cts/(keV kg yr) and 100 kg yr exposure
  sensitivity on $T^{0\nu}_{1/2} \sim 1.4 \cdot 10^{26}$ yr (factor 7 better than Phase I)

Ge detectors w.r.t. other isotopes



Plot by R. G. H. Robertson, arXiv:1301.1323v1

- plot corresponding to $0\nu\beta\beta$ rate of 1 count/(ton·yr)
- no clear golden candidate
- similar specific rates within a factor of 2
- ^{76}Ge important for historical reasons too

Ge detectors

Sensitivity $T_{1/2} \propto \epsilon \cdot \frac{\varepsilon}{A} \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ϵ	detection efficiency	$\gtrsim$ 85%
ε	enrichment fraction	high natural or enrichment
M	active target mass	increase mass
T	measuring time	
b	background rate (cts/(keV kg yr))	minimize & select radio-pure material
ΔE	energy resolution	use high resolution spectroscopy

Very low background High-Purity Germanium Detectors (HPGe)

Advantages:

- well established enrichment technique $\varepsilon = 86\%$ for ^{76}Ge
- M and T expandable
- very good energy resolution $\Delta E \sim 0.1\%$ - 0.2%
- very good detection efficiency $\epsilon \sim 1$ (Ge as source and detector)
- high-purity detectors $\rightarrow$ low background b

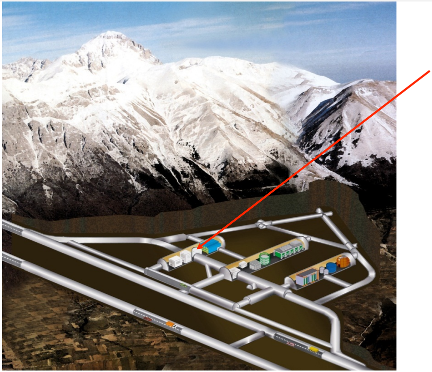
Disadvantages:

- Low $Q_{\beta\beta}$ value (lower than ^{208}Tl 2614 keV) $\rightarrow$ background
- Need enrichment from 7% to 86% $\rightarrow$ it is expensive

GERDA @ LNGS

Construction completed in 2009 - Inauguration 9 Nov. 2010

GERDA @ LNGS



- Hall A of Gran Sasso Laboratory (INFN)
- 3800 m.w.e.

Background from:

External:

- γ's from Th and Ra chain
- neutrons
- cosmic-ray muons

Internal:

- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

Background reduction and events identification

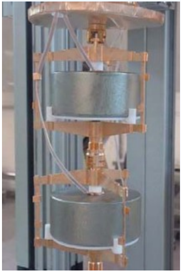
- Gran Sasso suppression of μ flux (10^6)
- Material selection
- Passive shield (H_2O - LAr - Cu)
- Muon veto
- Detector anticoincidence
- Pulse-shape analysis

GERDA @ LNGS

GERDA Building

The GERDA collaboration, Eur. Phys. Journ. C 73 (2013)

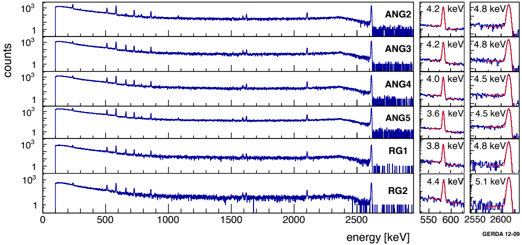
The GERDA detectors

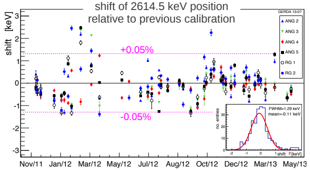


- 3 + 1 strings
- 8 enriched Coaxial detectors: working mass 14.6 kg
  (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg
  (testing Phase II concept in the real environment)

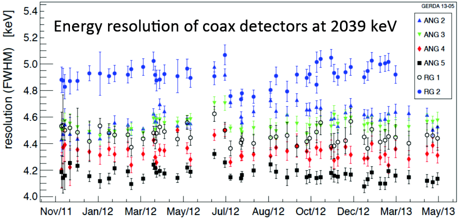
Energy calibrations and data processing

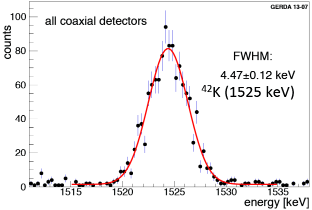
- weekly calibrated spectra with ^{228}Th sources and pulser with 0.05 Hz frequency
- data useful for monitoring of resolution and stability over time
- exposure-weighted FWHM at $Q_{\beta\beta}$ is about 4.8 keV for Coaxials (0.23%) and 3.2 keV (0.16%) for BEGes



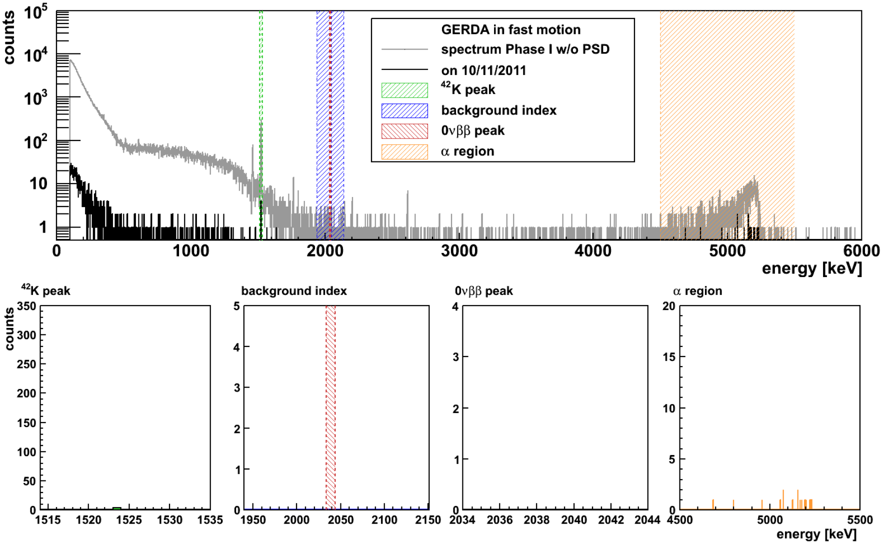


shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$



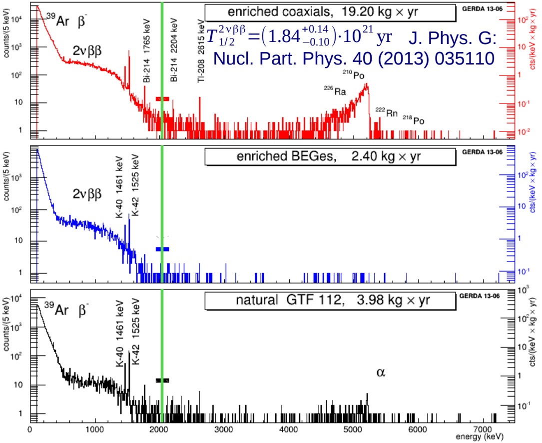


GERDA spectrum in fast motion



Energy spectra

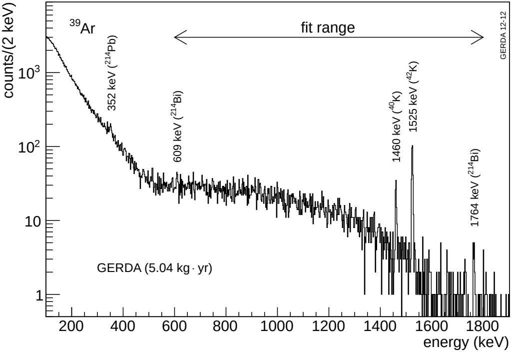
- *Silver coax*: data from coaxial detectors during BEGe deployment (higher BI)
- *Golden coax*: data from coaxial detectors except Silver coax
- *BEGe*: data from BEGe detectors



- Events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- Phase I data divided in three subsets:
  - *Golden coax*: 17.9 kg yr
  - *Silver coax*: 1.3 kg yr
  - *BEGe*: 2.4 kg yr
- **Background level before PSD at $Q_{\beta\beta}$ for Golden coax**: 0.018±0.002 cts/(keV kg yr)

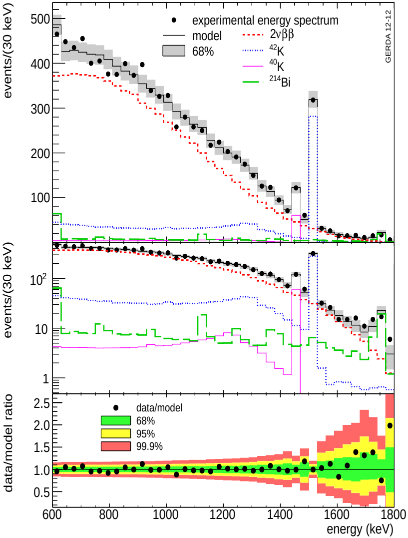
Background ∼10× lower than previous Ge experiments!!

Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



- Data: 8796 events
- Fit range: 600-1800 keV
- 5.04 kg · yr exposure
- Avg. active mass fraction: $(86.7 \pm 4.6(\text{uncorr.}) \pm 3.2(\text{corr.}))\%$
- Avg. enrichment fraction: $(86.3 \pm 2)\%$

Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



Binned maximum likelihood

Parameters:

- Active detector masses (6+1) *nuisance parameter*
- Fraction enrichment in ^{76}Ge (6) *nuisance parameter*
- Background contributions (3x6) *nuisance parameter*
- $T_{1/2}^{2\nu}$ common to all the detectors (1)

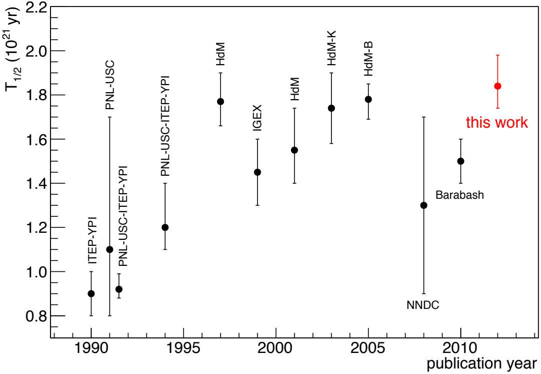
Derive $T_{1/2}^{2\nu}$ after the fit integrating over nuisance parameters

$2\nu\beta\beta$ (80%) ^{42}K (14%)
^{214}Bi (4%) ^{40}K (2%)

$$\mathbf{T_{1/2}^{2\nu} = (1.84^{+0.09+0.11 syst}_{-0.08-0.06 syst}) \cdot 10^{21}\ yr}$$

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

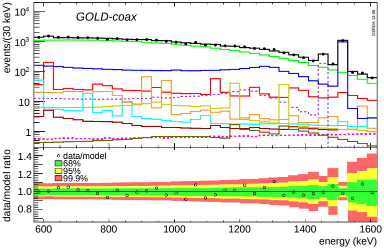
Half-life of $2\nu\beta\beta$ decay of ^{76}Ge

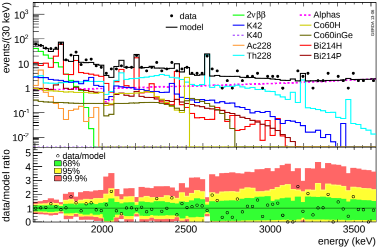


- Uncertainty comparable to best previous experiment (even with lower exposure).
- Such a careful systematic error analysis never done in the past.
- Good agreement with re-analysis of HdM data
  HdM-K: *Nucl. Instr. Meth. A 513, 596 (2003)*
  HdM-B: *Phys. Part. Nucl. Lett. 2, 77/ Pisma Fiz. Elem. Chast. Atom. Yadra 2, 21 (2005)*

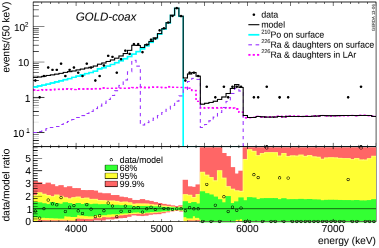
The Background Model of GERDA Phase I

The GERDA collaboration, submitted to Eur. Phys. J. C arXiv:1306.5084





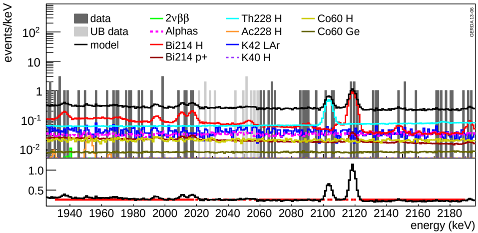
- Simulation of known and observed background
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested



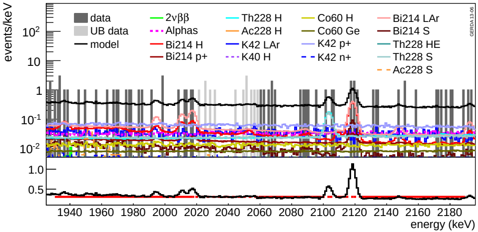
Main contribution from close background sources: ^{228}Th and ^{226}Ra in holders, ^{42}Ar α on detector surface

The Background Model of GERDA Phase I

Minimum model fit



Maximum model fit



- No line expected in the blinded window
- Background flat between 1930 and 2190 keV
- 2104±5 keV and 2119±5 keV excluded
- Partial unblinding after fixing calibration and background model

In 30 keV window:

- expected events: 8.6 (minimum model) or 10.3 (maximum model)
- observed events: 13

Golden coax:

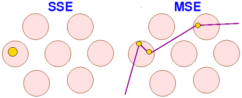
BI $= 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)

BEGe:

BI $= 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)

Pulse shape discrimination of GERDA Phase I data

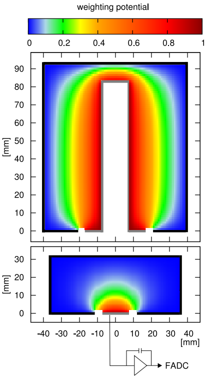
SSE: $\beta\beta$, DEP   MSE: Compton

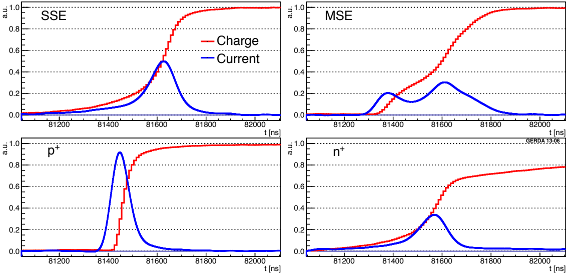


Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition





Current signal = q · v · ΔΦ
q=charge, v=velocity
(Schockley-Ramo theorem)

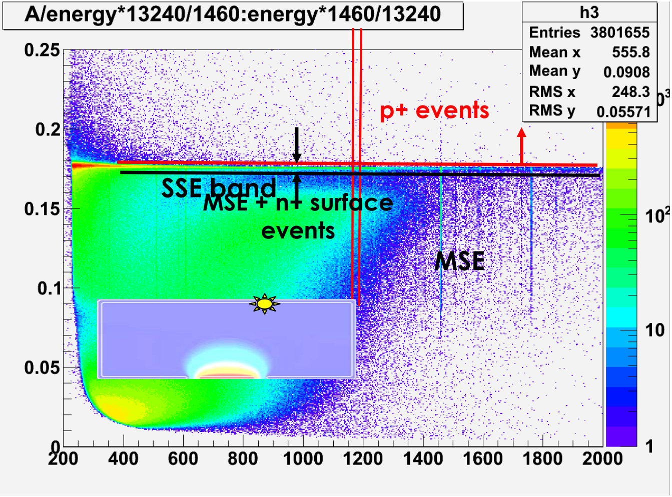
$0\nu\beta\beta$ events: 1 MeV electrons in Ge ∼ 1mm range one drift of electrons and holes SINGLE SITE EVENTS (SSE)

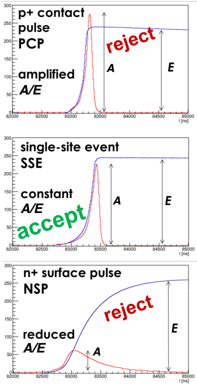
Background from γ's: MeV γ in Ge ∼ cm range several electron/holes drifts MULTI SITE EVENTS (MSE)

Surface events: only electron or hole drift

Pulse shape discrimination for BEGEs

A/E parameter allows to separate SSE events from MSE, n^+ and p^+ events





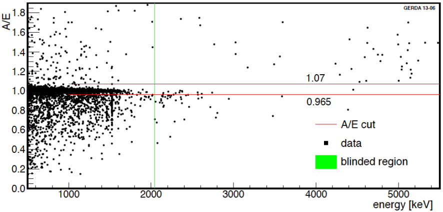
D. Budjas et al, JINST 4 P10007 (2009)
M. Agostini et al., JINST 6P03005 (2011)

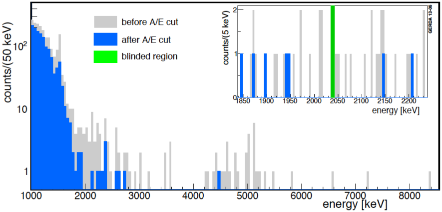
Pulse shape discrimination of GERDA Phase I data

The GERDA collaboration, Eur. Phys. J. C 73, 2583 (2013)

PSD for BEGe:

- A over E parameter (A/E) between 0.965 and 1.07
- Double Escape Peak of 2615 keV γ in ^{228}Th from calibrations (1593 keV) $\rightarrow$ SSE for $0\nu\beta\beta$
- FEP at 1621 keV or SEP at 2104 keV are MSE
- 80% background rejection at $Q_{\beta\beta}$
- 0.92±0.02 efficiency for $0\nu\beta\beta$ - 7/40 events kept in 400 keV window



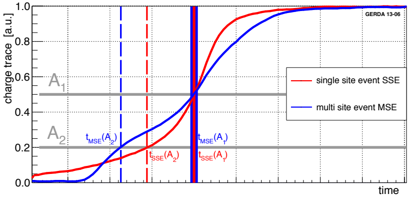


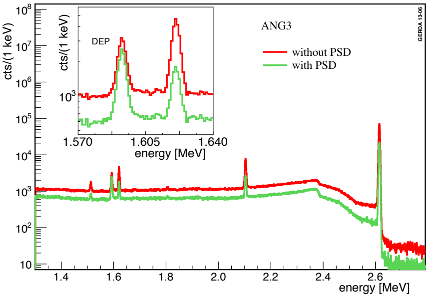
Pulse shape discrimination of GERDA Phase I data

The GERDA collaboration, Eur. Phys. J. C 73, 2583 (2013)

PSD for Coaxials:

- Artificial Neural Network **ANN**
- ANN analysis of 50 rise-time info (1,3,5,...,99%) with TMVA/TMlpANN
- trained on signal SSE: ^{208}Tl (2614 keV) DEP at 1592 keV
- MSE training with background-like ^{212}Bi FEP at 1621 keV

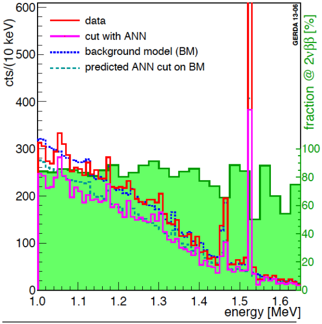


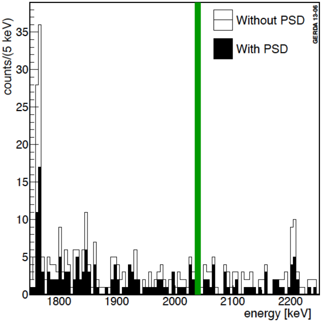


Pulse shape discrimination of GERDA Phase I data

The GERDA collaboration, Eur. Phys. J. C 73, 2583 (2013)

PSD for Coaxials

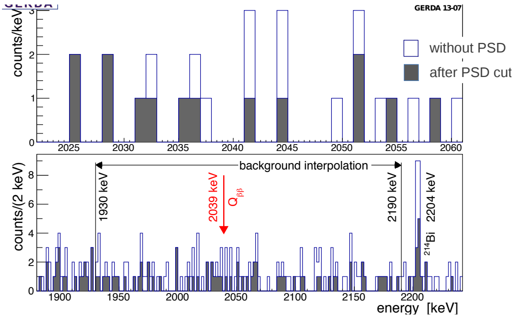




- Good agreement between model and data for $2\nu\beta\beta$
- $2\nu\beta\beta$ survival fraction: 0.85 ± 0.02
- Estimated survival fraction for $0\nu\beta\beta$ events: $0.90^{+0.05}_{-0.09}$
- Other 2 methods for PSD considered for cross-check: 90% of the events rejected by ANN are also rejected by the others 2 methods

Results on $0\nu\beta\beta$ decay

- Summed exposure: **21.6 kg yr**
- Unblinding after calibration finished, data selection frozen, analysis method fixed and PSD selection fixed
- Consider the 3 data sets separately in the analysis
- BI $=$ 0.01 cts/(keV kg yr) after PSD
- No events in $\pm\sigma_E$ after PSD
- 3 events in $\pm 2\sigma_E$ after PSD



data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg	BI †)	cts
without PSD					
golden	17.9	0.688 ± 0.031	76	18 ± 2	5
silver	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
BEGe	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
golden	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
silver	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
BEGe	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

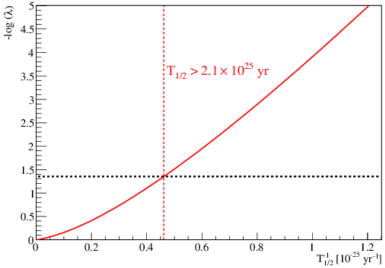
†) in units of 10^{-3} cts/(keV·kg·yr).

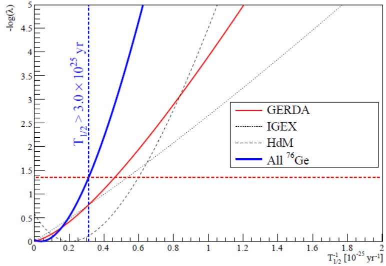
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 1	2041.7	27-Apr-2013 22:21	no

No peak in spectrum observed, number of events consistent with expectation from background → GERDA sets a limit on the half-life of the decay!

Results on $0\nu\beta\beta$ decay

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503





- Frequentist analysis
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.4 \cdot 10^{25}$ yr at 90% C.L.
- Maximum likelihood spectral fit
  (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available
  Median sensitivity:
  $T^{0\nu}_{1/2} > 2.0 \cdot 10^{25}$ yr at 90% C.L.

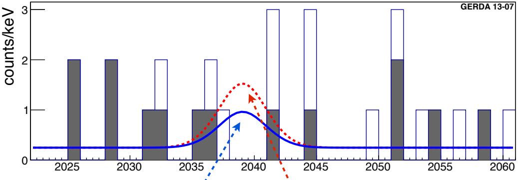
- **Profile likelihood result**:
  $\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr at 90% C.L.**
- **Bayesian analysis result**:
  $\mathbf{T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}}$ **yr at 90% C.I.**
- Best fit: $N^{0\nu} = 0$

Results on $0\nu\beta\beta$ decay

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

Compare two hypotheses:

- H_1: $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr
- H_0: background only



"Claim", PLB586 (2004)

$T^{0\nu}_{1/2} = \ 1.19 \times 10^{25}\,\mathrm{yr}$

GERDA only:

- Profile likelihood
  $P(N^{0\nu}{=}0|H_1) = 0.01$
- Bayes factor
  $P(H_1)/P(H_0) = 0.024$

Compatible with no signal events
$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr

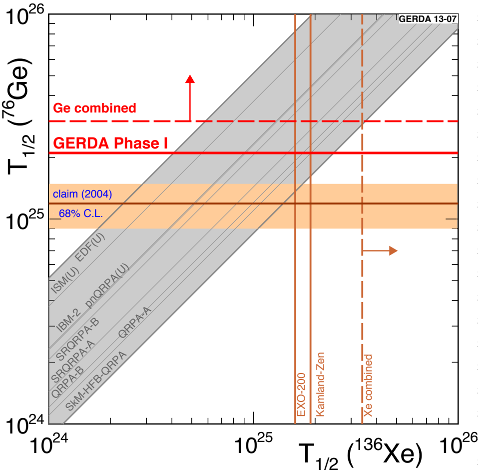
Claim strongly disfavoured!

N.B.: $T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2006) 157 not considered because of inconsistencies (missing efficiency factors) pointed out in Ann. Phys. 525 (2013) 259 by B. Schwingenheuer.

Combining with Ge and Xe previous results

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503

Comparison with previous half-life limits from Ge and Xe experiments



- **GERDA+HdM+IGEX:**
  - $T^{0\nu}_{1/2}$ >3.0 $\cdot$ 10^{25} yr at 90% C.I.
  - Bayes factor $P(H_1)/P(H_0) = 0.0002$
  - best fit: $N^{0\nu}$=0
- **GERDA+KamLAND+EXO**:
  - Bayes factor $P(H_1)/P(H_0) = 0.0022$

On the way to GERDA Phase II

How to get a higher sensitivity for the Phase II:

- reduce radiation sources and understand background sources
- improve background rejection
- increase mass and improve energy resolution

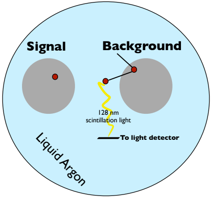
Strategy:

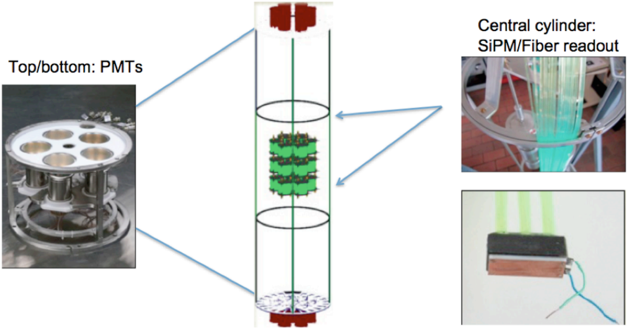
- Phase I ended on Sept. 30th 2013. Phase II transition currently ongoing at LNGS
- increase mass: additional 30 enriched BEGe detectors (about 20 kg)
- **reduce background** by a factor of 10 w.r.t. GERDA Phase I:
  1. make things cleaner:
     - use lower background Signal and HV cables w.r.t. Phase I
     - reduce material for holders and special care in crystal production
  2. reject residual background radiation:
     - by Pulse Shape Analysis for high background recognition efficiency
     - by LAr scintillation light for background recognition and rejection
- start commissioning in Early 2014

Liquid Argon instrumentation for Phase II

PMT LAr instrumentation studies for Phase II in LArGe (a smaller GERDA facility)

- **SiPM fiber curtain**
- **PMTs on top and bottom of the array**
  - Hamamatsu PMTs showed flashing problems in LAr
  - Hamamatsu sent us modified versions of PMTs with problem solved
  - Currently under test in Heidelberg





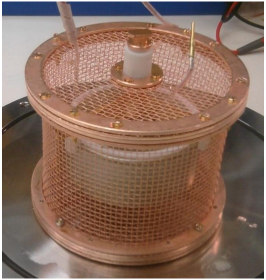
Liquid Argon instrumentation for Phase II

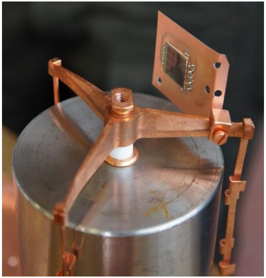
Background	rate without cuts (10^{-3} cts/(keV·kg·yr))
^{228}Th (near)	**$\leq$5**
^{228}Th (1m away)	**$<$3**
^{228}Th (distant)	**$<$3**
^{214}Bi (holder/MS)	**$\leq$5**
^{214}Bi (near p^+)	**$<$6**
^{214}Bi (n^+)	**$<$7**
^{214}Bi (1m away)	**$<$3**
^{60}Co (near)	**1**
^{60}Co (in Ge)	**$\leq$0.3**
^{68}Ga (in Ge)	**$\leq$2.3**
^{226}Ra (α near p^+)	**1.5**
^{42}K (β on n^+)	**$\sim$20**
unknown (n?)	**?**

- Phase II background based on Phase I
- background decomposition from coaxial detectors compatible with BEGe spectral decomposition
- ^{42}K dominant background source
- ^{42}K with Cu MS
- holder and MS contamination expected to be reduced by a factor of 10
- ^{226}Ra contamination dominated by ^{226}Ra in LAr near p^+

Liquid Argon instrumentation for Phase II

^{42}K mitigation by different Mini-Shroud configurations





- Phase I configuration: Copper +PSA Mini-Shroud
- Option 1: Copper-meshed Mini-Shroud
- Option 2: Nylon Mini-Shroud with WLS
- Option 3: Copper Mini-Shroud but SiPMs inside

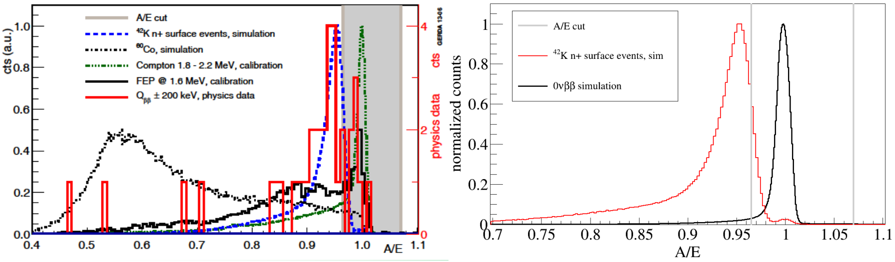
^{42}K mitigation

Expected background contributions from MC simulations
with background rejection from PSD and LAr veto

Background	without cuts (10^{-3} cts/(keV·kg·yr))	after PSD + Veto (10^{-3} cts/(keV·kg·yr))
^{228}Th (near)	**$\leq$5**	**$\leq$0.01**
^{228}Th (1m away)	**$<$3**	**$<$0.01**
^{228}Th (distant)	**$<$3**	**$<$0.1**
^{214}Bi (holder/MS)	**$\leq$5**	**$\leq$0.13**
^{214}Bi (near p^+)	**$<$6**	**$<$0.03**
^{214}Bi (n^+)	**$<$7**	**$<$0.15**
^{214}Bi (1m away)	**$<$3**	**$<$0.08**
^{60}Co (near)	**1**	**0.001**
^{60}Co (in Ge)	**$\leq$0.3**	**$\leq$0.0004**
^{68}Ga (in Ge)	**$\leq$2.3**	**$\leq$0.04**
^{226}Ra (α near p^+)	**1.5**	**$<$0.03**
^{42}K (β on n^+)	**$\sim$20**	**$<$0.86**
unknown (n?)	**?**	**?**

PSD and ^{42}K mitigation

Experimental evidence of efficient ^{42}K rejection by PSD on GERDA Phase I data
The GERDA collaboration, Eur. Phys. J. C 73, 2583 (2013)



- surface β rejection can be traded against $0\nu\beta\beta$ acceptance
- final cut level will be optimised for optimal sensitivity
- better signal noise/stability directly translates in better rejection
- We are confident to reach 0.001 cts/(keV kg yr) given NO additional background components

Conclusions

- Phase I data taking successful!! Phase I ended Sept.,30th 2013
- **5 publications in the first 9 months of 2013**
- total exposure of GERDA Phase I is 21.6 kg yr
- very low background 0.01 cts/(keV kg yr) after PSD
- **half-life of $0\nu\beta\beta$:**
  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge
- probability that the signal from the previous claim produces the actual GERDA outcome is 1%
- starting the Phase II to improve sensitivity
- **Phase II commissioning in Early 2014**

Merci de votre attention!!

GERDA Collaboration Meeting in Dubna, Russia
June 2013