The GERDA experiment: results and perspectives for neutrinoless double beta decay

Carla Macolino for the GERDA collab.
(GSSI/LNGS)

NeuTel15 Venezia 05.03.15

INFN Laboratori Nazionali del Gran Sasso

GERDA

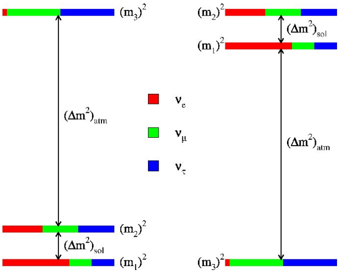
GSSI GRAN SASSO SCIENCE INSTITUTE CENTER FOR ADVANCED STUDIES Istituto Nazionale di Fisica Nucleare

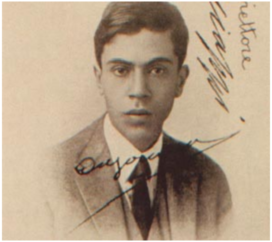
Outline

- Probing the nature of neutrino with neutrinoless double-beta decay
- The GERDA experiment
- The GERDA energy spectra
- The GERDA physics results from Phase I:
  - The background model for GERDA Phase I
  - The Pulse Shape Discrimination of GERDA events
  - Half-life of $0\nu\beta\beta$ decay
  - Half-life of $0\nu\beta\beta$ decay with Majorons
- On the way to GERDA Phase II: first Phase II commissioning data!
- Future perspectives for $0\nu\beta\beta$ decay search

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

- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- lepton number violation
- physics beyond Standard Model
- shed lights on absolute neutrino mass
- shed lights on neutrino mass hierarchy
- Reveal the interaction process from different isotopes

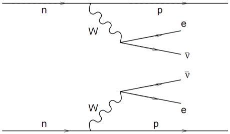




Search for $0\nu\beta\beta$ decay

$2\nu\beta\beta$

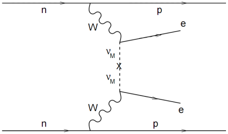
$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$



$\Delta L = 0 \rightarrow$ Described by SM

$0\nu\beta\beta$

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

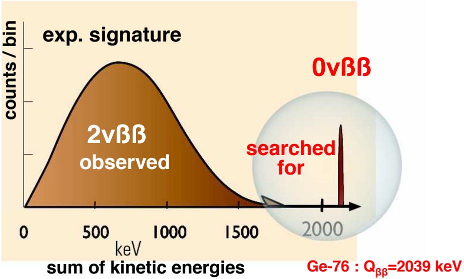


$\Delta L = 2 \rightarrow$ Not present in SM

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

Light Majorana neutrino exchange?

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

- Observe the monochromatic line at $Q_{\beta\beta}$
- Reduce background as much as possible
- Estimate half-life of the decay ($> 10^{25}$ yr)

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

There are many possible underlying mechanisms for $0\nu\beta\beta$ decay and in general:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}|M^{0\nu}|^2\eta^2$$

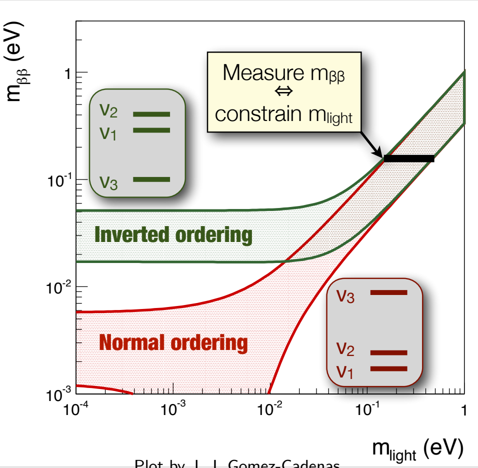
If light Majorana neutrino exchange is the dominant mechanism and no further sterile neutrino exists:

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

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

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

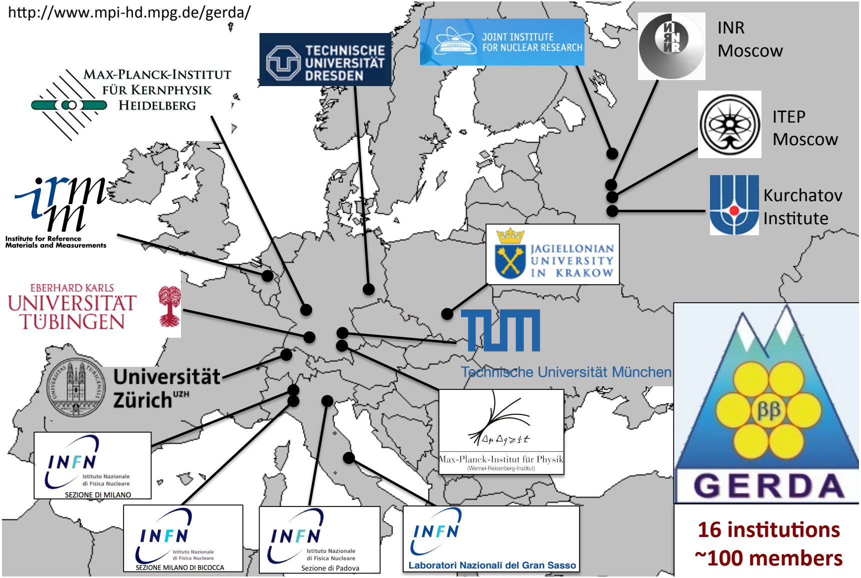
→ **information on the absolute mass scale!**



Plot by J. J. Gomez-Cadenas
see also Strumia,Vissani (arXiv:0606054)

The GERDA collaboration

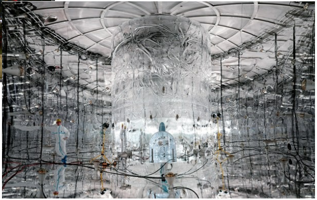
http://www.mpi-hd.mpg.de/gerda/



123 physicists, 16 institutions, 7 countries

GERDA @ LNGS

GERDA at Laboratori Nazionali del Gran Sasso (LNGS) - 3800 m.w.e.
Construction completed in 2009 - Inauguration 9 Nov. 2010



GERDA @ LNGS

GERDA Building

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

- 8 enriched Coaxial detectors: working mass 14.6 kg - **avg energy resolution 4.8 keV** (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 - **avg energy resolution 3.2 keV** (testing Phase II concept)

Experimental Sensitivity

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

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

Requirements:

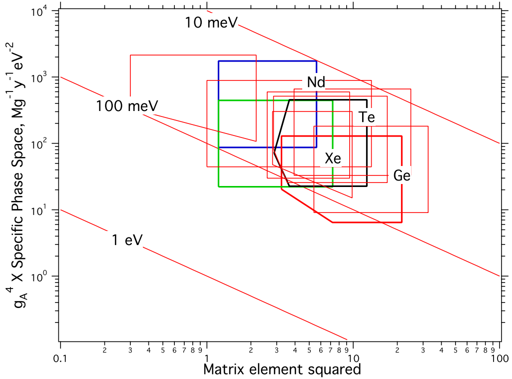
- high enrichment of isotope material
- M and T large
- **very good energy resolution**
  For GERDA $\Delta E < 0.2\%$
- **very good detection efficiency** because GERDA detector $\equiv$ source, $\epsilon \sim 1$
- **high-purity detectors → low background**
  For GERDA $b < 10^{-2}$ cts/(keV kg yr)
- higher $M^{0\nu}$ w.r.t. other isotopes

Additional tools to distinguish from background:

- Angular distribution
- Single electron spectrum
- Decay to excited states (gamma-rays)
- Identification of daughter nucleus

Ge isotope w.r.t. other isotopes

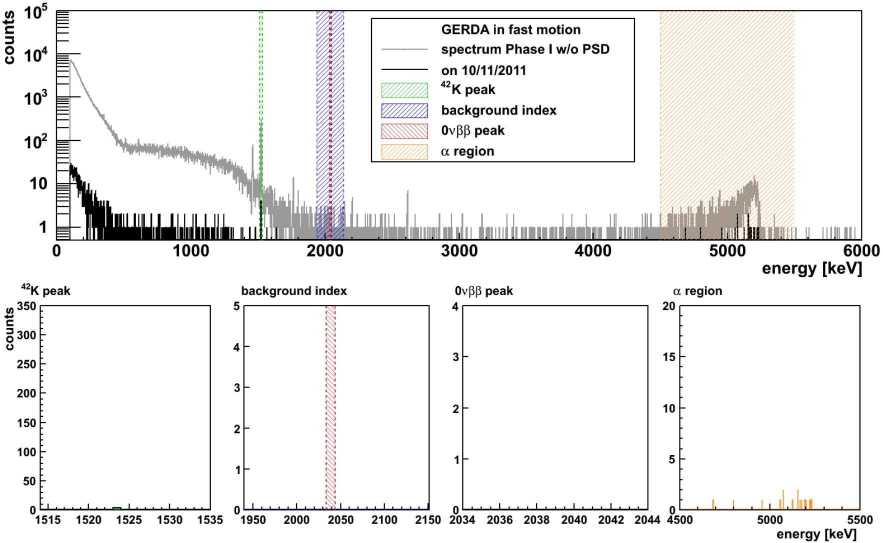
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$



Plot by R. G. H. Robertson, arXiv:1301.1323v1
see also Dell'Oro, Marcocci, Vissani arXiv:1404.2616

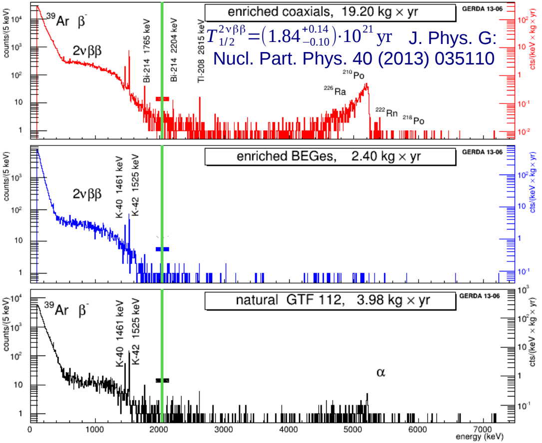
- plot corresponding to $0\nu\beta\beta$ rate of 1 count/(ton·yr)
- no clear golden candidate
- similar specific rates within a factor of 2
- ^{76}Ge important for historical reasons too: claim of $0\nu\beta\beta$ observation with $T^{0\nu}_{1/2}$=1.19·10^{25} yr (90% CL) by Klapdor et al. Phys. Lett. B 586 (2004) 198

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



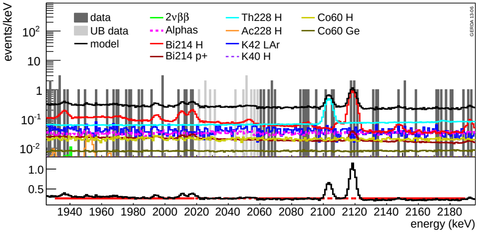
- Events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- Phase I data divided in three subsets:
  - *Golden coax*: 17.9 kg yr
  - *Silver coax*: 1.3 kg yr
  - *BEGe*: 2.4 kg yr
- **Background level before PSD at $Q_{\beta\beta}$ for Golden coax**: 0.018±0.002 cts/(keV kg yr)

Background ∼10× lower than previous Ge experiments!!

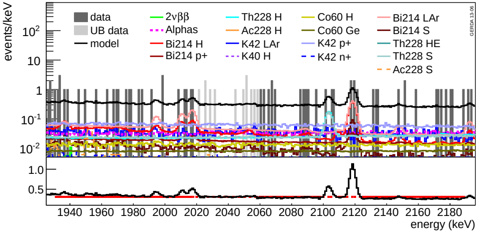
The Background Model of GERDA Phase I

The GERDA collaboration, Eur. Phys. J. C 74 (2014) 2764

Minimum model fit



Maximum model fit



- Main contributions: ^{228}Th and ^{226}Ra on holders, ^{42}Ar, α on surface
- No line expected in the ROI
- 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:

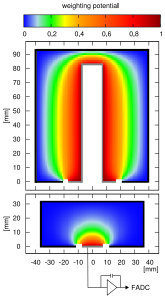
$$\text{BI} = 1.75^{+0.26}_{-0.24} \cdot 10^{-2} \text{ cts/(keV kg yr)}$$

BEGe:

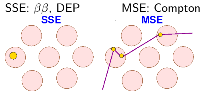
$$\text{BI} = 3.6^{+1.3}_{-1.0} \cdot 10^{-2} \text{ cts/(keV kg yr)}$$

Pulse shape discrimination of GERDA Phase I data

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



Current signal = q v ΔΦ

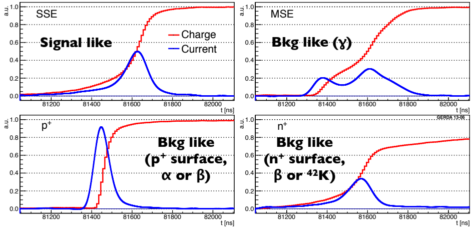


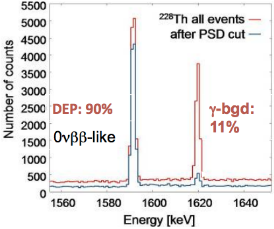
Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition

Different energy deposition between gamma and electron
Different recorded pulses



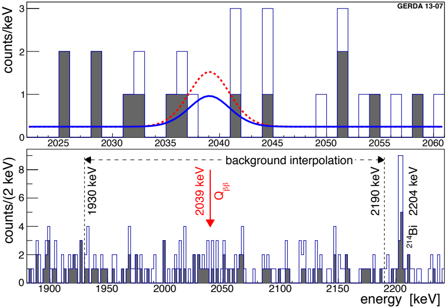


Efficiency on signal events: about 90%
Efficiency of background rejection: about 50%

Method based on Pulse Shape applied
to GERDA Phase I data to reject background

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

- Summed exposure: **21.6 kg yr**
- After calibration finished + data selection frozen + analysis method fixed + PSD selection fixed → Unblinding
- 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

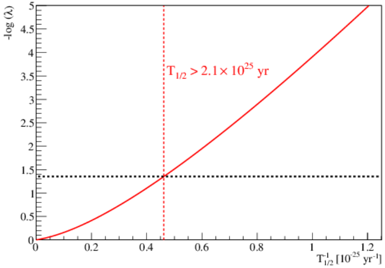
†) in units of 10^{-3} cts/(keV·kg·yr).

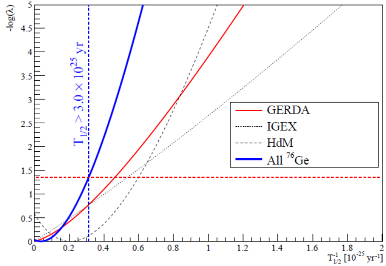
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 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**:
  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
- **Bayesian analysis result**:
  $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr at 90% C.I.
- Best fit: $N^{0\nu} = 0$

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

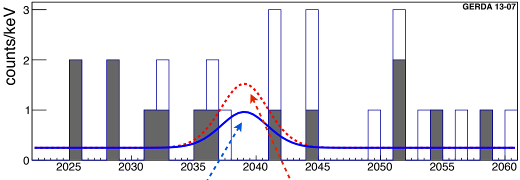
The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503
Comparison with claim from Phys. Lett. B 586 (2004) 198

Compare two hypotheses:

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

GERDA only:

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



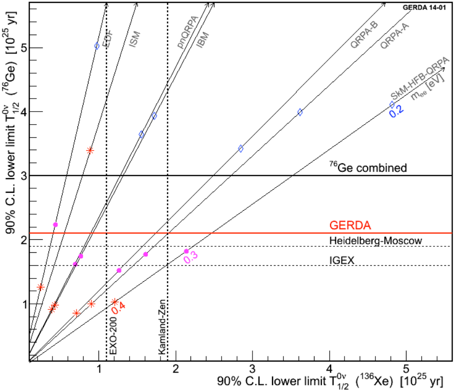
"Claim", PLB586 (2004)
$T^{0\nu}_{1/2} = 1.19 \times 10^{25}\,\mathrm{yr}$

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.

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503
Comparison with previous half-life limits from Ge and Xe experiments



Combine with HdM and IGEX

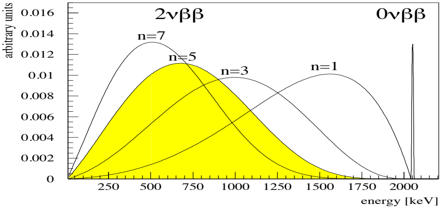
- $\mathbf{T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}}$ **yr (90% C.L.)**
- Bayes factor
  $P(H_1)/P(H_0) = 0.0002$
- best fit: $N^{0\nu}$=0

↓

Effective neutrino mass: upper limit between 0.2 eV and 0.4 eV

$0\nu\beta\beta\chi$ decays

Search for Majoron accompanied $0\nu\beta\beta$ decay of ^{76}Ge



Model	n	Mode	Goldstone boson	L
IB	1	χ	no	0
IC	1	χ	yes	0
ID	3	$\chi\chi$	no	0
IE	3	$\chi\chi$	yes	0
IF	2	χ	bulk field	0
IIB	1	χ	no	-2
IIC	3	χ	yes	-2
IID	3	$\chi\chi$	no	-1
IIE	7	$\chi\chi$	yes	-1
IIF	3	χ	gauge boson	-2

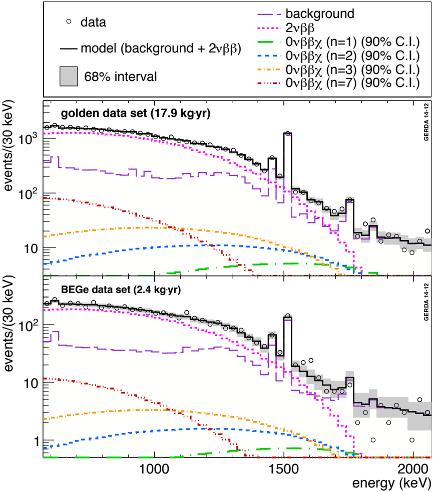
$$\frac{dN}{dK} \sim G \sim (Q_{\beta\beta} - K)^n$$

$$\lambda_i^{\alpha,0\nu\chi} = \frac{(\ln 2)\ N_A}{m_{\mathrm{enr}}\, T_{1/2}^{0\nu\chi}} M_\alpha\, f_{76,\alpha} \cdot \left[f_{AV,\alpha} \sum_{j=1}^{N_{det}} t_j \varepsilon_{AV,j}^{\alpha} \Phi_{AV,i,j}^{\alpha,0\nu\chi} + (1 - f_{AV,\alpha}) \sum_{j=1}^{N_{det}} t_j \varepsilon_{DL,j}^{\alpha} \Phi_{DL,i,j}^{\alpha,0\nu\chi} \right]$$

$$\lambda_i^{0\nu\chi} = \sum_{\alpha=1}^{N_{det}} \lambda_i^{\alpha,0\nu\chi}$$

Golden coax + BEGe: total exposure 20.3 kg

$0\nu\beta\beta\chi$ decays



Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ [10^{23}yr]
IB	1	χ	no	0	> 4.2
IC	1	χ	yes	0	> 4.2
ID	3	$\chi\chi$	no	0	> 0.8
IE	3	$\chi\chi$	yes	0	> 0.8
IF	2	χ	bulk field	0	> 1.8
IIB	1	χ	no	-2	> 4.2
IIC	3	χ	yes	-2	> 0.8
IID	3	$\chi\chi$	no	-1	> 0.8
IIE	7	$\chi\chi$	yes	-1	> 0.3
IIF	3	χ	gauge boson	-2	> 0.8

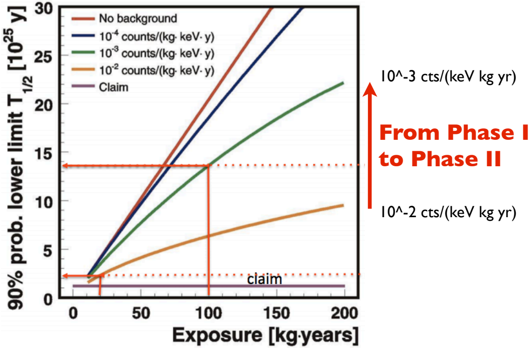
Most stringest limits obtained for ^{76}Ge

- for n=1 and n=3 limits improved by a factor 6
- for n=7 limit improved by a factor 5
- for n=2 limit reported for the first time

The GERDA collaboration, submitted to Eur. Phys. J. C

arXiv:1501.02345

On the way to GERDA Phase II



How to get a higher sensitivity for the Phase II:

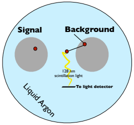
- Phase II transition currently ongoing at LNGS
- increase mass: additional 30 enriched BEGe detectors (about 20 kg)
- **reduce background** by a factor of 10 w.r.t. GERDA Phase I:
  1. by Pulse Shape Analysis (BEGe improved performance)
  2. by LAr scintillation light for background recognition and rejection

First commissioning data from Phase II in these days!

Liquid Argon instrumentation for Phase II

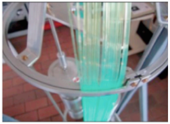
LAr scintillation veto in GERDA Phase II

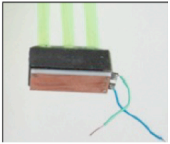
- **SiPM fiber curtain**
- **PMTs on top and bottom of the array**



Top/bottom: PMTs

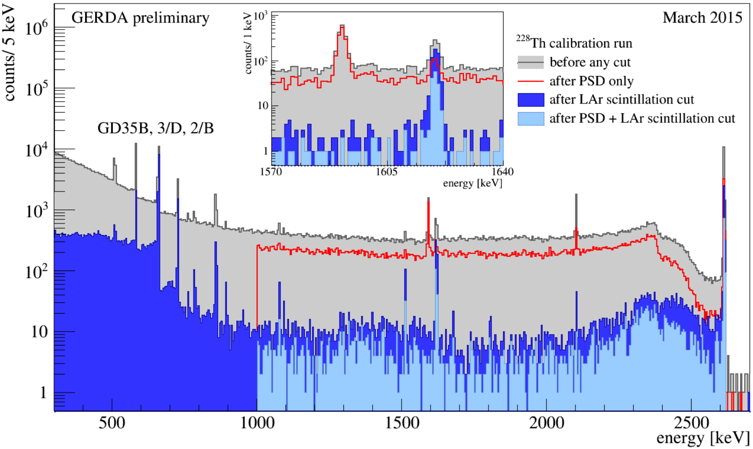
Central cylinder:
SiPM/Fiber readout





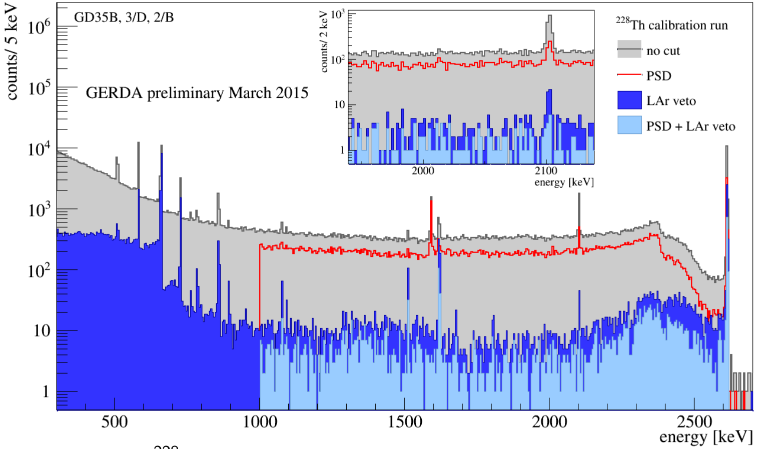
LAr veto + PSA allows a strong reduction of the background at $Q_{\beta\beta}$!

First data from Phase II: LAr veto + PSD



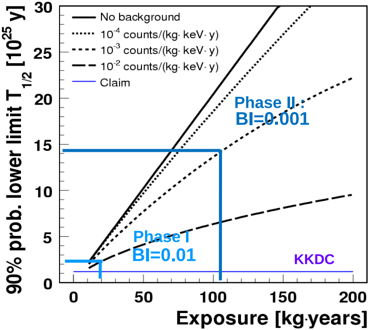
- Spectrum from ^{228}Th source
- 15 hours data - 3 BEGe det. (2 depleted, 1 enriched)
- 16/16 PMTs and 7/15 SiPM running

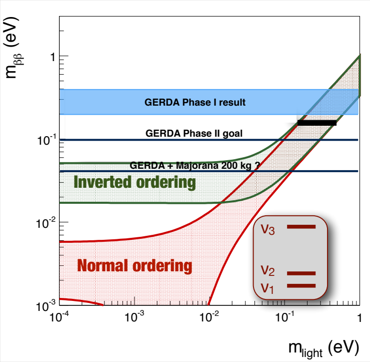
First data from Phase II: LAr veto + PSD



- Spectrum from ^{228}Th source
- 15 hours data - 3 BEGe det. (2 depleted, 1 enriched)
- 15 PMTs and 7 SiPM running
- **Background from external Th suppressed by a factor 100!** **(even higher with full equipment)**

Experimental scenario





- **Phase I result**: BI $\sim 10^{-2}$ cts/(keV kg yr) and $\sim$ 20 kg·yr exposure
  Claim from *Phys. Lett. B 586 (2004) 198* rejected with high probability
- **Phase II goal**: BI $\sim 10^{-3}$ 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)
- **GERDA + Majorana**: discussion on possible 200 kg (1 ton) experiment

Present knowledge scenario

Present knowledge scenario:
most stringent limits on $0\nu\beta\beta$ decay

Isotope	Experiment	$T^{0\nu}_{1/2}$ at 90% CL [yr]	$\langle m_{\beta\beta} \rangle$ [eV]	Ref.
^{76}Ge	GERDA Phase I	$2.1 \cdot 10^{25}$ yr	0.25 - 0.42	(1)
^{136}Xe	EXO	$1.1 \cdot 10^{25}$ yr	0.19 - 0.45	(2)
^{136}Xe	KamLAND-Zen	$1.9 \cdot 10^{25}$ yr	0.14 - 0.34	(3)
^{130}Te	CUORICINO	$2.8 \cdot 10^{24}$ yr	0.31 - 0.76	(4)
^{100}Mo	NEMO-3	$1.1 \cdot 10^{25}$ yr	0.34 - 0.87	(5)

(1): Phys. Rev. Lett 111 (2013), 122503
(2): Nature 510 (2014), 229-234
(3): Phys. Rev. Lett. 110 (2013), 062502
(4): Astropart. Phys. 34 (2011) 822-831
(5): Phys. Rev. D 89, 111101 (2014)

In summary: $\langle m_{\beta\beta} \rangle < 0.4$ eV (90% CL)

Experimental scenario

Exciting time with running and upcoming experiments!!!

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yr]	Sensitivity $m_{\beta\beta}$ [eV]	Status
GERDA	^{76}Ge	18 40 1000	3×10^{25} 2×10^{26} 6×10^{27}	$0.2 \div 0.4$ 0.1 0.03	running in progress R&D
CUORE	^{130}Te	200	1×10^{26}	$0.04 \div 0.1$	in progress
MAJORANA	^{76}Ge	40 1000	2×10^{26} 6×10^{27}	0.1 0.03	in progress R&D
EXO	^{136}Xe	200 1000	5×10^{25} 8×10^{26}	$0.08 \div 0.3$ $0.01 \div 0.03$	in progress R&D
SuperNEMO	^{82}Se	7 100	6.5 ‘ $\times 10^{24}$ 1×10^{26}	$0.2 \div 0.4$ $0.04 \div 0.10$	in progress R&D
KamLAND-Zen	^{136}Xe	400 1000	4×10^{26} 1×10^{27}	0.06 0.02	in progress R&D
NEXT	^{136}Xe	100 1000	5×10^{25} 5×10^{26}	$0.08 \div 0.13$ $0.03 \div 0.07$	in progress R&D
SNO+	^{130}Te	200 800	1×10^{26} 1×10^{27}	$0.06 \div 0.1$ $0.02 \div 0.06$	in progress R&D

Conclusions

- Phase I data taking successful! Phase II ongoing
- **half-life of $0\nu\beta\beta$**: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge
- this translates in a limit on the effective neutrino mass: $m_{\beta\beta}$ between **0.2 eV** and **0.4 eV**
- Signal from the previous claim disfavoured by GERDA with 99% probability
- **First data from Phase II with improved sensitivity** (background reduced by a factor 100!)
- **exciting results to come!**

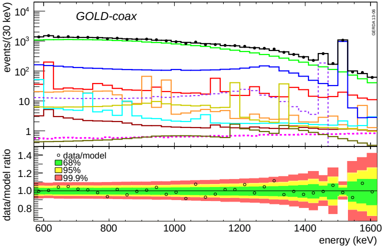
Grazie della vostra attenzione!!

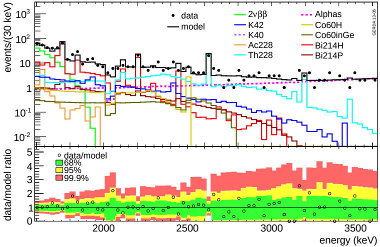
GERDA Collaboration Meeting in MPI Heidelberg, Germany
June 2014

BACKUP SLIDES

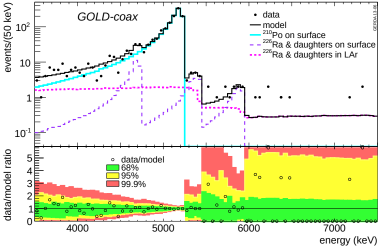
The Background Model of GERDA Phase I

The GERDA collaboration, Eur. Phys. J. C 74 (2014) 2764





- 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 sources: ^{228}Th and ^{226}Ra in holders, ^{42}Ar α on detector surface

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

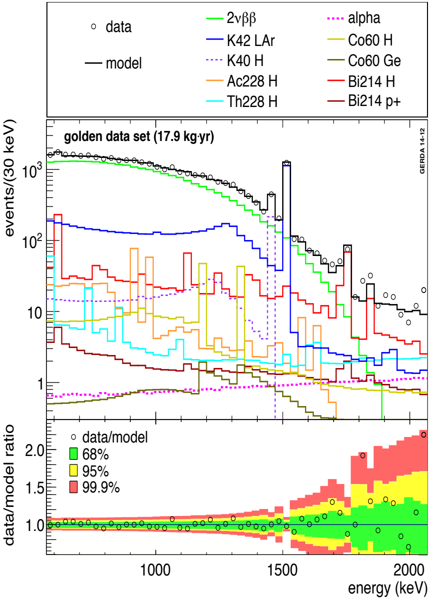
Consider the minimum background model to estimate the $2\nu\beta\beta$ half-life of ^{76}Ge

$$T_{1/2}^{2\nu} = \frac{(\ln 2)\; N_A}{m_{\text{enr}}\; N_{2\nu}^{\text{fit}}} \sum_{i=1}^{N_{det}} M_i\, t_i\, f_{76,i} \left[f_{AV,i}\; \varepsilon_{AV,i}^{\text{fit}} + (1 - f_{AV,i})\; \varepsilon_{DL,i}^{\text{fit}} \right]$$

detectors	t [days]	M [kg]	f_{76} [%]	f_{AV} [%]
enriched coaxial detectors				
ANG2	485.5	2.833	86.6 ± 2.5	$87.1 \pm 4.3 \pm 2.8$
ANG3	485.5	2.391	88.3 ± 2.6	$86.6 \pm 4.9 \pm 2.8$
ANG4	485.5	2.372	86.3 ± 1.3	$90.1 \pm 4.9 \pm 2.9$
ANG5	485.5	2.746	85.6 ± 1.3	$83.1 \pm 4.0 \pm 2.7$
RG1	485.5	2.110	85.5 ± 1.5	$90.4 \pm 5.2 \pm 2.9$
RG2	384.8	2.166	85.5 ± 1.5	$83.1 \pm 4.6 \pm 2.7$
enriched BEGe detectors				
GD32B	280.0	0.717	87.7 ± 1.3	89.0 ± 2.7
GD32C	304.6	0.743	87.7 ± 1.3	91.1 ± 3.0
GD32D	282.7	0.723	87.7 ± 1.3	92.3 ± 2.6
GD35B	301.2	0.812	87.7 ± 1.3	91.4 ± 2.9

- golden coaxial data
- Fit range: 570-7500 keV
- 17.9 kg·yr exposure
- 30 keV energy bin

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



Binned maximum likelihood

Best fit result:

$$N_{2\nu}^{fit} = 25690^{+310}_{-330}$$

$$\mathbf{T^{2\nu}_{1/2} = (1.926^{+0.025}_{-0.022}{}_{stat}{}^{+0.092}_{-0.092}{}_{syst}) \cdot 10^{21}\ yr}$$

Signal to background ratio 3:1 between 570 and 2039 keV.

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

The GERDA collaboration
submitted to Eur. Phys. J. C
arXiv:1501.02345

Systematic uncertainties on $T^{2\nu}_{1/2}$

Table 2 Contributions to the systematic uncertainty on $T^{2\nu}_{1/2}$ taken into account in this work. The total systematic uncertainty is obtained by combining the individual contributions in quadrature.

Item	Uncertainty on $T^{2\nu}_{1/2}$ [%]	
Active ^{76}Ge exposure	± 4	
Background model components	$^{+1.4}_{-1.2}$	
Binning	± 0.5	
Shape of the $2\nu\beta\beta$ spectrum	< 0.1	
Subtotal fit model		± 4.3
Precision of the Monte Carlo geometry model	± 1	
Accuracy of the Monte Carlo tracking	± 2	
Subtotal Monte Carlo simulation		± 2.2
Data acquisition and handling		< 0.1
Total		± 4.8

$0\nu\beta\beta\chi$ decays

$$1/T_{1/2}^{0\nu\chi} = |\langle g\rangle|^2 \cdot G^{0\nu\chi}(Q_{\beta\beta}, Z) \cdot |M^{0\nu\chi}|^2$$

and

$$1/T_{1/2}^{0\nu\chi} = |\langle g\rangle|^4 \cdot G^{0\nu\chi\chi}(Q_{\beta\beta}, Z) \cdot |M^{0\nu\chi\chi}|^2$$

Results from GERDA Phase I

Model	n	Mode	Goldstone boson	L	$T_{1/2}^{0\nu\chi}$ [10^{23}yr]	$\mathcal{M}^{0\nu\chi}$	$G^{0\nu\chi}$ [yr^{-1}]	$\langle g\rangle$
IB	1	χ	no	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IC	1	χ	yes	0	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
ID	3	$\chi\chi$	no	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IE	3	$\chi\chi$	yes	0	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IF	2	χ	bulk field	0	> 1.8	–	–	–
IIB	1	χ	no	-2	> 4.2	$(2.30 - 5.82)$	$5.86 \cdot 10^{-17}$	$< (3.4 - 8.7) \cdot 10^{-5}$
IIC	3	χ	yes	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$
IID	3	$\chi\chi$	no	-1	> 0.8	$10^{-3\pm1}$	$6.32 \cdot 10^{-19}$	$< 2.1^{+4.5}_{-1.4}$
IIE	7	$\chi\chi$	yes	-1	> 0.3	$10^{-3\pm1}$	$1.21 \cdot 10^{-18}$	$< 2.2^{+4.9}_{-1.4}$
IIF	3	χ	gauge boson	-2	> 0.8	0.16	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$

The coupling constants allow a comparison with other isotopes

The GERDA collaboration, submitted to Eur. Phys. J. C

arXiv:1501.02345

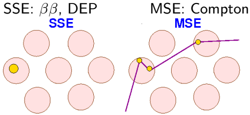
Systematic uncertainties on Majoron accompanied emissions

- **Detector parameters and fit model**
  - minimum number of events expected from ^{214}Bi and ^{228}Th decays
  - energy binning (from 10 to 50 keV)
  - uncertainties on the active volume fractions
  - uncertainties on enrichment in ^{76}Ge
  - uncertainty on exact position of medium and near sources
  - uncertainty on transition layer thickness in BEGes
- **MC simulation**: total 2.2% uncertainty on Monte Carlo due to effects related to geometry implementation and particle tracking, weakly affecting the limit
- **Data acquisition and selection**: estimated to be below 0.1%, it does not affect the limit

In total, limit is weakened by:

- 2.8% (n=1)
- 5.8% (n=2)
- 10.6% (n=3)
- 5.7% (n=7)

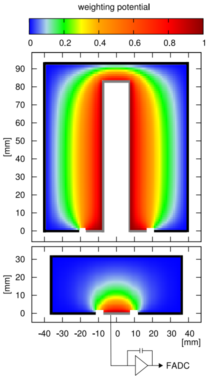
Pulse shape discrimination of GERDA Phase I data

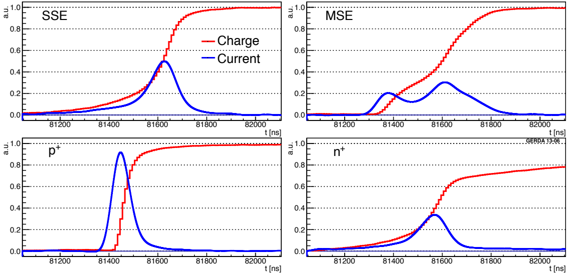


Pulse-shape analysis

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)

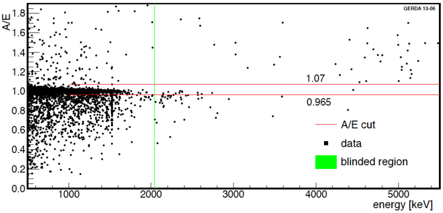
Surface events: only electron or hole drift

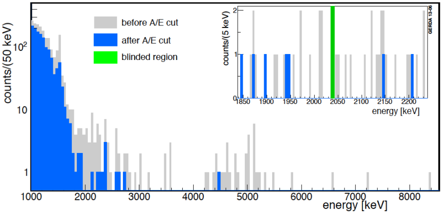
Pulse shape discrimination of GERDA Phase I data

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

PSD for BEGe detectors:

- A over E parameter (A/E) between 0.965 and 1.07
- Compton and Double Escape Peak of 2615 keV γ in ^{228}Th from calibrations (1593 keV) $\rightarrow$ SSE
- Events in the $2\nu\beta\beta$ range and simulations to validate PSD cut efficiency
- FEP at 1621 keV or SEP at 2104 keV are MSE
- 80% background rejection at $Q_{\beta\beta}$
- 0.92$\pm$0.02 efficiency for $0\nu\beta\beta$ - 7/40 events kept in 400 keV window



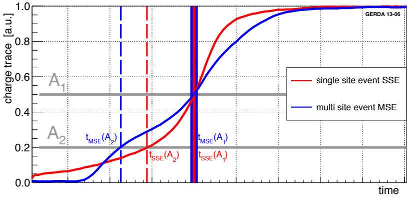


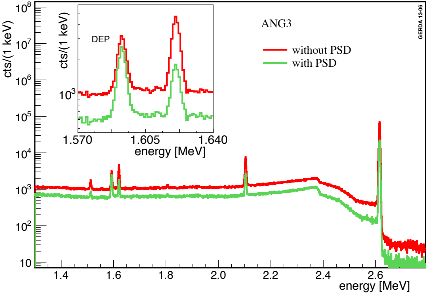
Pulse shape discrimination of GERDA Phase I data

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

PSD for coaxial detectors:

- 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





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

Bayesian analysis based on Bayes theorem:

$$P(H|D) = \frac{P(D|H) \cdot P(H)}{P(D)}$$

$\mu = \lambda + \nu$ Background (λ) + Signal(ν)
n_i = number of observed events in dataset i, D = total number of measured events

1. H = data fully explained by background processes
2. $\bar{H}$ = data explained by background plus signal

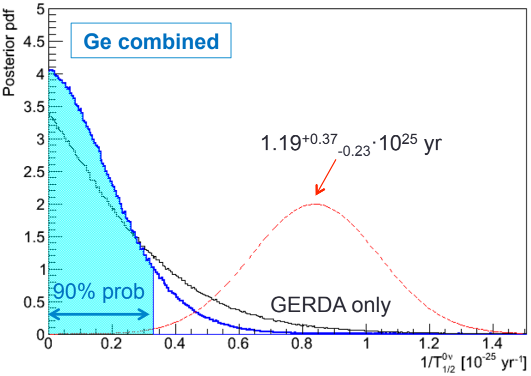
$$P(D|\vec{\lambda}, T_{1/2}, \bar{H}) = \prod_i \frac{e^{-(\lambda_i+\nu_i)}(\lambda_i+\nu_i)_i^n}{n_i!}$$

Power of Bayesian statistical method

the limit at 90% Credibility Interval, statistically means that $T_{1/2}$ is greater than T_{lim} with 90% probability.
In the frequentist approach one can only state that, assuming $0\nu\beta\beta$ exists, the value of T_{lim} derived will cover the true value of $T_{1/2}$ in 90% of repetitions of similar experiment.

- Counting number of signal events
- Fitting signal + background

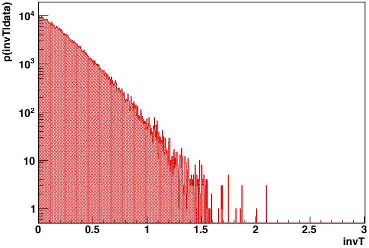
Comparison with claim from Phys. Lett. B 586 198 (2004)

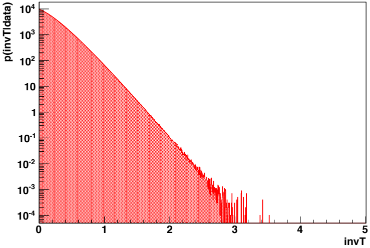


- **Bayesian result (GERDA only)**
- $T_{1/2}^{0\nu} >$ **1.9·10^25 yr at 90% C.redibility Interval**
- Best fit $N^{0\nu}=0$
- MC Median Sensitivity: $T_{1/2}^{0\nu} > 2.0\cdot 10^{25}$ yr at 90% C.I.

Systematical uncertainties

Influence of the systematical uncertainty on the estimation of the 90% C.I. limit on the half-life.

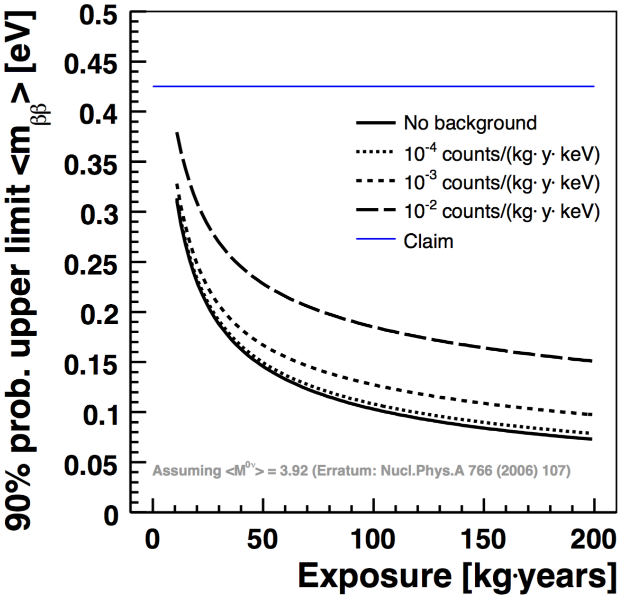




- Uncertainty on energy resolution (FWHM at $Q_{\beta\beta}$)
- Uncertainty on the total efficiency
- Error on the optimal window
- Uncertainty on ϵ_{res}: this is the effciency for a signal event to fall within the energy window
- Systematic shift of the energy scale
- Uncertainty on PSD efficiency

The limit is weakened by a factor $< 1.5\%$

Expected sensitivity



Background lines in GERDA Phase I

	Energy (keV)	GERDA arXiv: 1306.5084v1 counts/(kg yr)	Heidelberg-Moscow O. Chvorets, PhD thesis counts/(kg yr)
^{40}K	1460.8	13.9[12.8,15.0]	181 ± 2
^{60}Co	1173.2	3.4 [2.2, 5.2]	55 ± 1
	1332.3	2.3 [1.5, 3.1]	51 ± 1
^{228}Ac	910.8	2.3 [0.5, 4.6]	29.8 ± 1.6
	968.9	<3.9	17.6 ± 1.1
^{208}Tl	583.2	6.3 [4.5, 8.4]	36 ± 3
	2614.5	1.1 [0.8, 1.4]	16.5 ± 0.5
^{214}Pb	352	17.6 [13.8,21.4]	138.7 ± 4.8
^{214}Bi	609.3	13.7 [9.6, 17.8]	105 ± 1
	1120.3	<1.9	26.9 ± 1.2
	1764.5	3.3 [2.8, 3.8]	30.7 ± 0.7
	2204.2	0.8 [0.5, 1.1]	8.1 ± 0.5
^{212}Bi	727	< 4.0	8.1 ± 1.2
^{137}Cs	662	< 4.8	282 ± 2
e+	511	9±3	30 ± 3
^{42}K	1525	60.5 ± 2.1	N.A.

From counts to half-life

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \varepsilon \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{AV} \cdot \varepsilon_{FEP} \cdot \varepsilon_{PSD}$$

Dataset	Exposure [kg·yr]
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

$N_A =$ Avogado Number
$E =$ Exposure
$\varepsilon =$ Exposure averaged efficiency
$m_{enr} =$ Molar mass of enriched Ge
$N^{0\nu} =$ Signal counts /limit

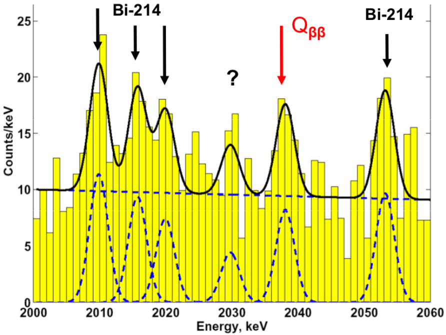
$f_{76} =$ Enrichment fraction
$f_{AV} =$ Active Volume detector fraction
$\varepsilon_{FEP} =$ Full Energy Peak efficiency for $0\nu 2\beta$
$\varepsilon_{PSD} =$ Signal acceptance

	$\langle f_{76} \rangle$	$\langle f_{AV} \rangle$	$\langle \varepsilon_{FEP} \rangle$	$\langle \varepsilon_{PSD} \rangle$	ε
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

The Heidelberg-Moscow claim

HPGe detectors enriched at 86% in ^{76}Ge

Exposure: 71.7 kg yr
Background: 0.11 counts/(keV kg yr) (without pulse shape)

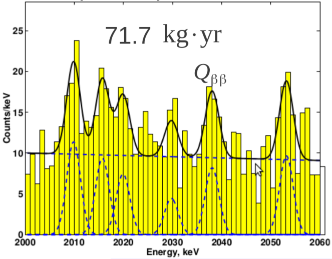


- $T^{0\nu}_{1/2} = 1.2(0.69 - 4.18) \times 10^{25}$ yr
  Phys. Lett. B 586, 198 (2004)
  3σ range
  4.2σ C.L. evidence for $0\nu\beta\beta$
- $T^{0\nu}_{1/2} = 2.23(1.92 - 2.67) \times 10^{25}$ yr
  Mod. Phys. Lett. A 21, 1547 (2006)
  Critized in arXiv:1210.7432
- $m_{\beta\beta}$=(0.24-0.58) eV / (0.29-0.35) eV

IGEX: $T^{0\nu}_{1/2} = 1.57 \times 10^{25}$ yr (90% C.L.)

Why GERDA does not use KK 2006 result?

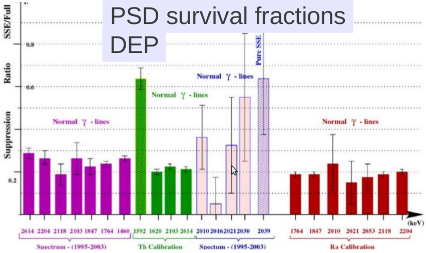
a) 2004 publications: NIM A522 371 & PL B586 198



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

PSD survival fractions
DEP



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

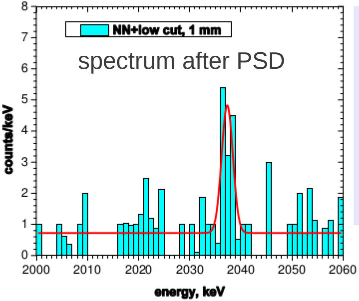
Without efficiency correction:
$T^{0\nu}_{1/2} = 1.98 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!

see B. Schwingenheuer, Ann. Phys. 525, 269 (2013) arXiv:1210.7432

Why GERDA does not use KK 2006 result?

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



fit gives 11.32±1.75 signal events

$\rightarrow T^{0\nu}_{1/2} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ 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%",
– $0\nu\beta\beta$ efficiency = 1 used for $T^{0\nu}_{1/2}$

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

see B. Schwingenheuer, Ann. Phys. 525, 269 (2013) arXiv:1210.7432

Comparison with claim from Mod. Phys. Lett. A 21 1547 (2006)

Compare **two hypotheses**

- **H_2**: $T_{1/2}^{0\nu} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}$ yr vs. **H_0**: background only

Expected Signal (w/ PSD): (3.1 ± 0.8) cts in ±2σ

Expected Bckgd (w/ PSD): (2.0 ± 0.3) cts in ±2σ

Observed: **3.0** in ±2σ (0 in ±1σ)

GERDA only:

Profile likelihood:

$P(N^{0\nu}=0|H_2)=5\%$

Bayes factor

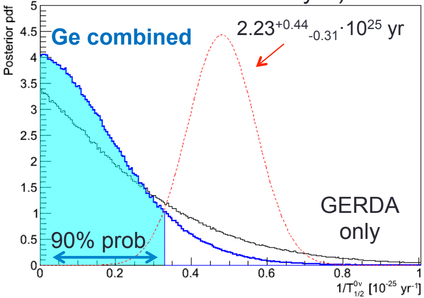
$P(H_2)/P(H_0)=0.052$

GERDA+HdM+IGEX:

Bayes factor **$P(H_2)/P(H_0)=0.027$**

Still disfavoured

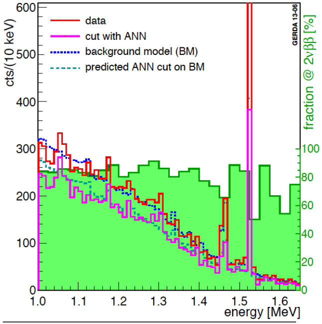
Bayesian posterior pdf (flat prior on $1/T_{1/2}$ between 0 and 10^{-24} yr^{-1})

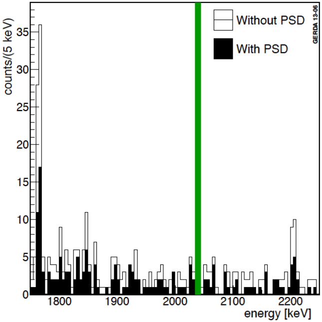


Pulse shape discrimination of GERDA Phase I data

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

PSD for Coaxials

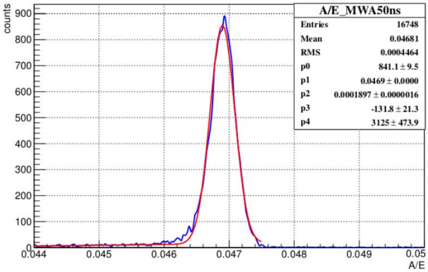


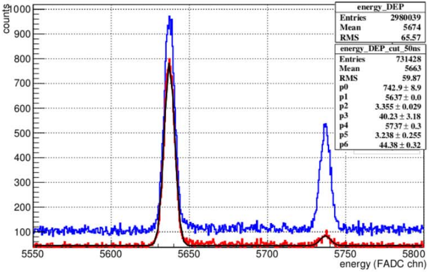


- Good agreement between model and data for $2\nu\beta\beta$
- $2\nu\beta\beta$ survival fraction: 0.85 ± 0.02
- Estimated survival fraction for $0\nu\beta\beta$ events: $0.90^{+0.05}_{-0.09}$
- Other 2 methods for PSD considered for cross-check: 90% of the events rejected by ANN are also rejected by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

PSD for Phase II

PSD in Phase II



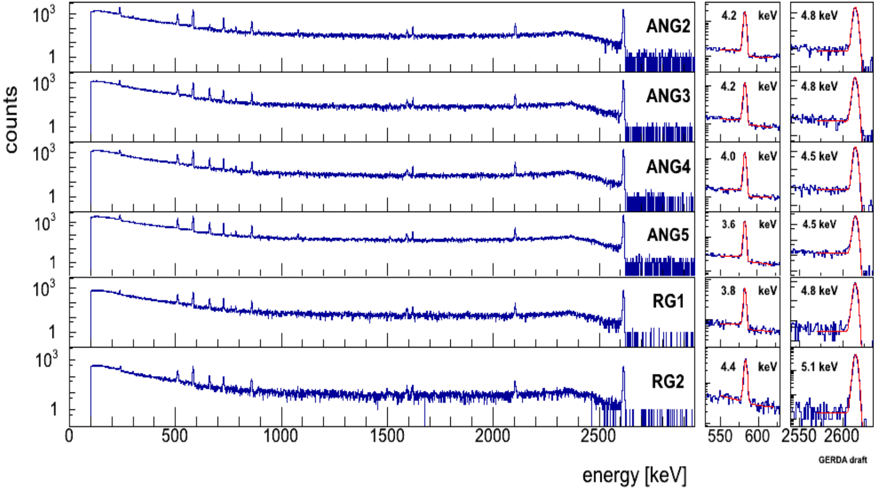


A/E resolution (FWHM): < 1%

Acceptance: ~ 90% at DEP of 2614 keV ^{208}Tl line

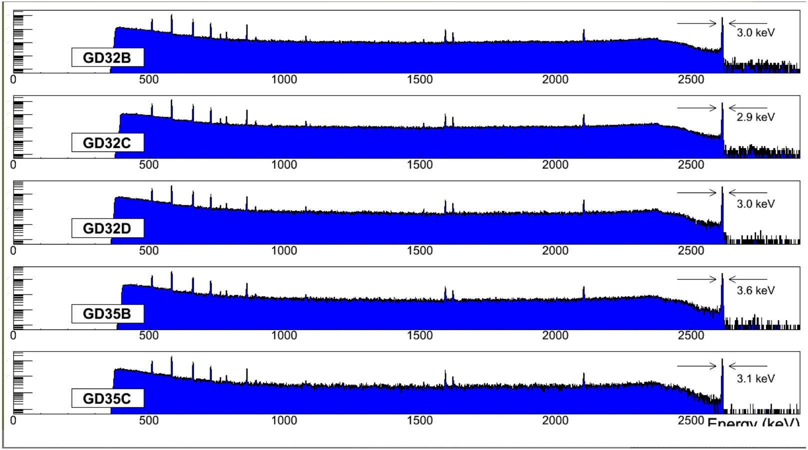
~11% at 1620 keV ^{212}Bi line

Energy calibration - ^{228}Th sources



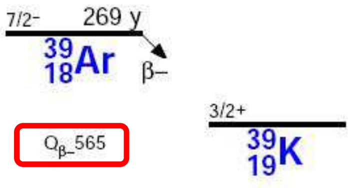
Coaxials: **Exposure-weighted average for FWHM at $Q_{\beta\beta} \simeq 4.8 \pm 0.2$ keV**

Energy calibration - ^{228}Th sources



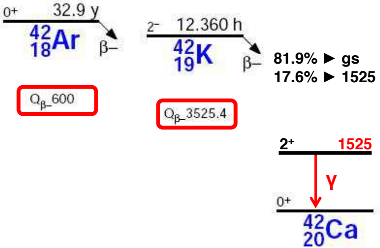
BEGe: **Exposure weighted average for FWHM at $Q_{\beta\beta} \simeq 3.2 \pm 0.2$ keV**

Background from Argon



- ^{39}**Ar**

Published activity of (1.01 ± 0.08) Bq/kg (Benetti et al., *NIM A547 (2007)* 83) fully compatible with our data
Not relevant for BI at $Q_{\beta\beta}$



- ^{42}**Ar**

Lower limit of 41 μBq/kg (90% C.L.) (Ashitkov et al., arXiv:nucl-ex:0309001)
Count rate at 1525 keV about 2 times expectation

Convincing evidence that charged ^{42}K ions drift in the E field of Ge-diodes
$\rightarrow$ thin Cu foil (mini-shroud) as electrostatic and physical shield