Recherche de la double désintégration bêta sans émission de neutrinos par l'expérience GERDA: résultats et perspectives futures

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LAPP Annecy 20.02.15

Je me présente

- 2010: PhD at Università degli Studi dell'Aquila - INFN.
  Title of the thesis: *Search for anisotropies in the arrival directions of UHECRs detected by the Pierre Auger Observatory*.
  Study of anisotropy patterns in the arrival directions of Auger data.

- 2010-2012: Postdoc (CDD chercheur) at LPNHE-Paris, working in the Pierre Auger experiment.
  Study of the mass composition and radio detection of UHECRs (EASIER R&D).

- 2012-2014: Postdoc at LNGS (INFN), working in the GERDA experiment for the search for $0\nu\beta\beta$ decay.

- 2014-today: Postdoc at GSSI and LNGS (INFN), working in the GERDA experiment for the search for $0\nu\beta\beta$ decay.
  Search for $0\nu\beta\beta$ decay, $2\nu\beta\beta$ decay to excited states, 0νECEC of ^{36}Ar, data reconstruction, study of GERDA background.

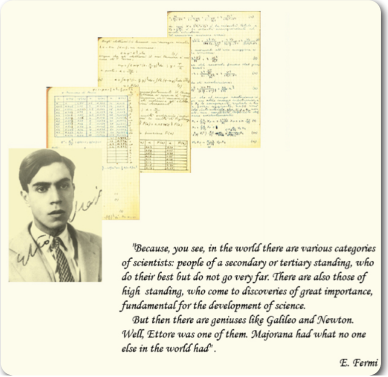
In total: 8 years of research activities in neutrino and astroparticle physics

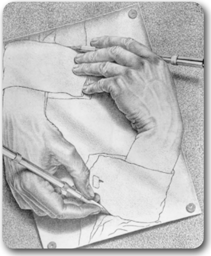
Outline

- 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
  - Half-life of $2\nu\beta\beta$ decay
  - Half-life of $0\nu\beta\beta$ decay with Majorons
  - The Pulse Shape Discrimination of GERDA events
  - Half-life of $0\nu\beta\beta$ decay
- On the way to GERDA Phase II
- Future perspectives for $0\nu\beta\beta$ decay search

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

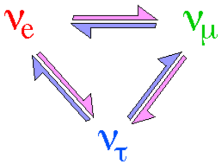
- **$0\nu\beta\beta$ decay probes fundamental questions:**
  - Neutrino properties: the only practical technique to determine if neutrinos are their own anti-particles (Majorana or Dirac neutrino)
  - Lepton number violation: might leptogenesis be the explanation for the observed matter - antimatter asymmetry?
  - Smallness of neutrino mass could be naturally explained by requiring physics beyond Standard Model: see-saw mechanism,...



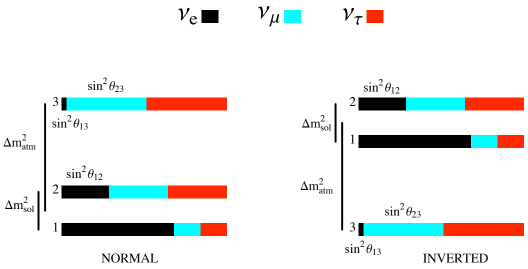


Investigate existence of $0\nu\beta\beta$

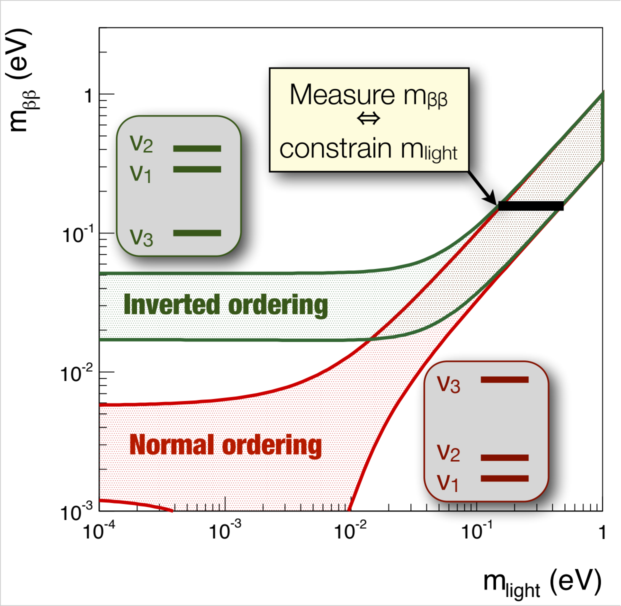
- **If $0\nu\beta\beta$ is observed:**
  - Measurements in a series of different isotopes can reveal the interaction process
  - It is possible determine the absolute neutrino mass complementary to other techniques
  - It is possible to shed lights on the neutrino mass hierarchy
  - It is possible to probe beyond Standard Model theories



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, ...) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



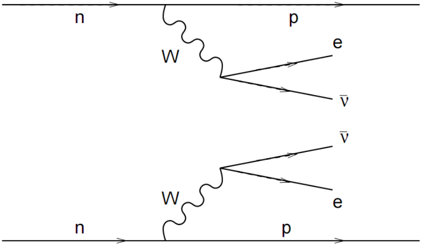
Investigate existence of $0\nu\beta\beta$



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

$2\nu\beta\beta$

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



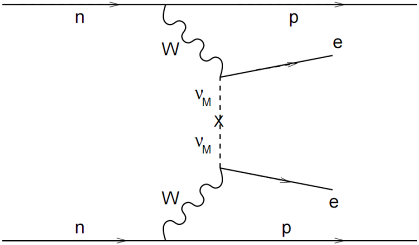
$\Delta L = 0$

2-nd order process

predicted by the Standard Model

$0\nu\beta\beta$

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



$\Delta L = 2$

$\boldsymbol{Q = M_i - M_f - 2m_e}$

not allowed within the Standard Model

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

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

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

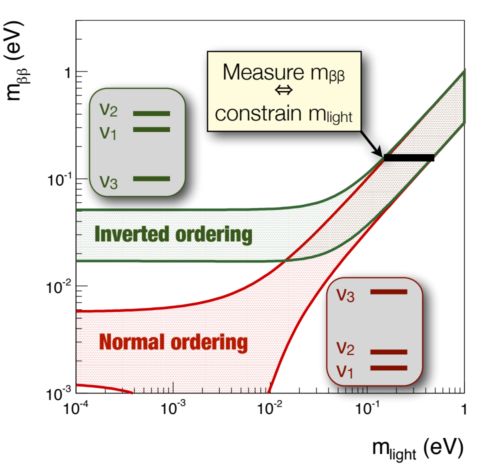
If light Majorana neutrino exchange is the dominant mechanism and no further sterile neutrino exists:

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

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

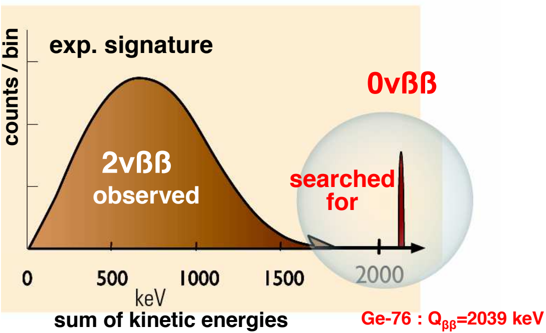
m_i=masses of the neutrino mass eigenstates
U_{ei}=elements of the neutrino mixing matrix
$e^{i\phi_2}$ and $e^{i\phi_3}$=Majorana CP phases

→ information on the absolute mass scale!



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

Clear experimental signature in the energy spectrum of the two emitted electrons

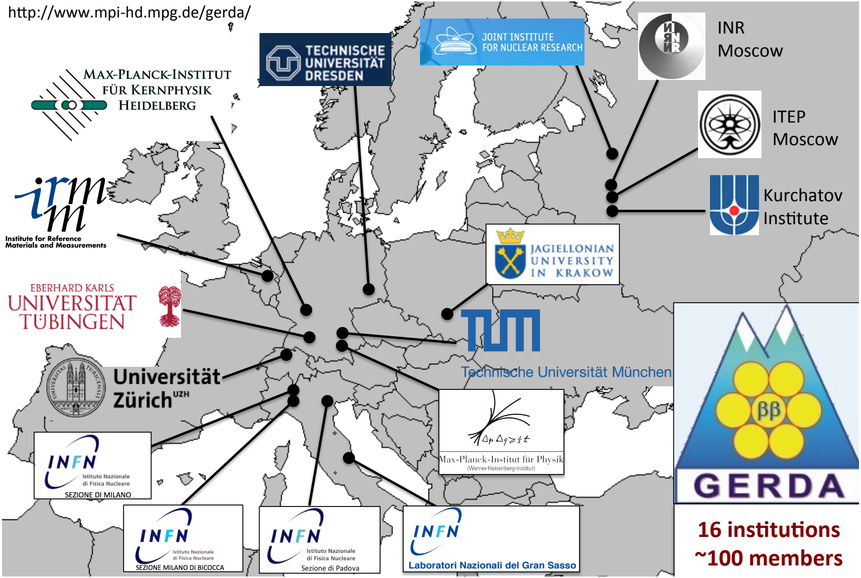


For ^{76}Ge $Q_{\beta\beta} = 2039$ keV

- Observe the monochromatic line at $Q_{\beta\beta}$
- Reduce background as much as possible
- Estimate half-life of the decay ($> 10^{25}$ yr)
- What is the mechanism beyond ? (light Majorana neutrino exchange or other?)

The GERDA collaboration

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



112 physicists, 16 institutions, 7 countries

GERDA @ LNGS

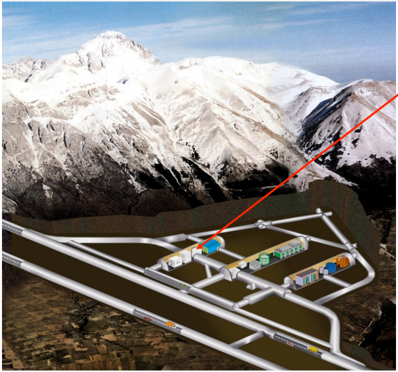
Construction completed in 2009 - Inauguration 9 Nov. 2010

GERDA @ LNGS

GERDA Building

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

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

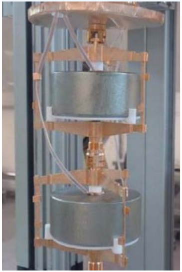
Internal:

- 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 or active shield (H_2O - LAr - Cu)
- Muon veto
- Detector anticoincidence
- Pulse-shape analysis

The GERDA detectors in Phase I



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

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:

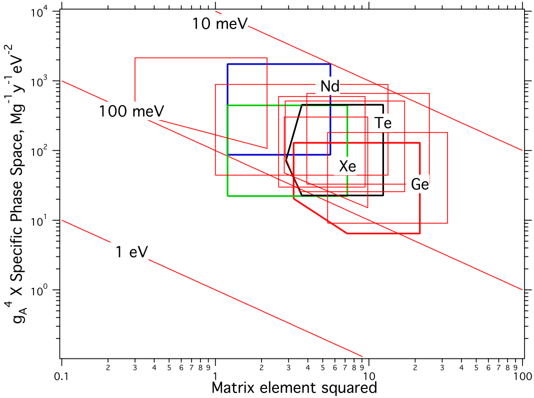
- high enrichment of isotope material
- M and T large
- **very good energy resolution**
  For GERDA $\Delta E < 0.2\%$
- **very good detection efficiency** because GERDA detector $\equiv$ source, $\epsilon \sim 1$
- **high-purity detectors $\rightarrow$ low background**
  For GERDA $b < 10^{-2}$ cts/(keV 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

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



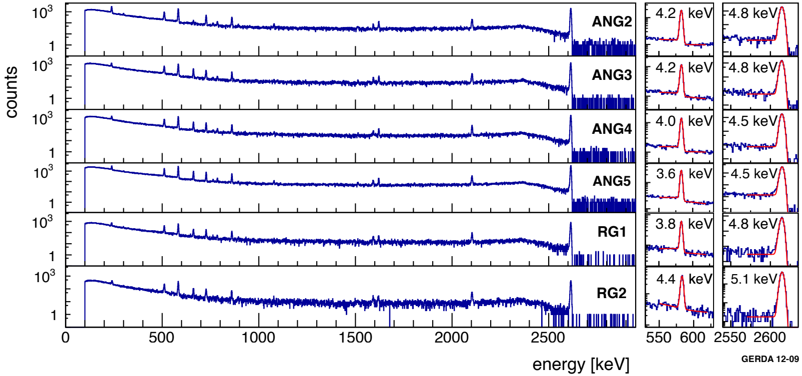
Plot by R. G. H. Robertson, arXiv:1301.1323v1

- 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

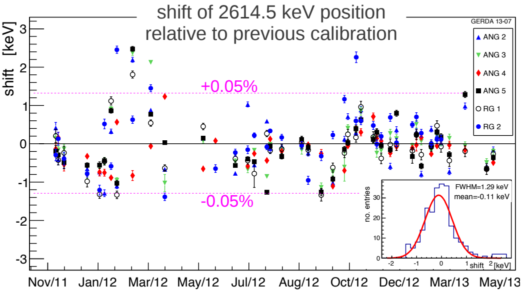
Data processing and Energy calibrations

Analysis

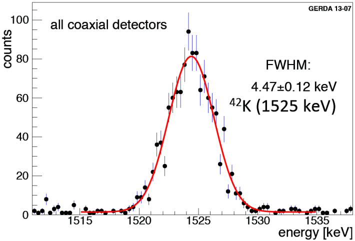
- Processing: diode → amplifier → FADC → digital filter → energy/pulse shape/etc...
- Selection: anti-coincidence muon/2nd Ge (20% rejected at $Q_{\beta\beta}$), quality cuts (9% rej.), pulse-shape discrimination ($\sim$ 50% rej.)
- Calibration: ^{228}Th (bi)weekly and pulser every 20 seconds for short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



Data processing and Energy calibrations



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

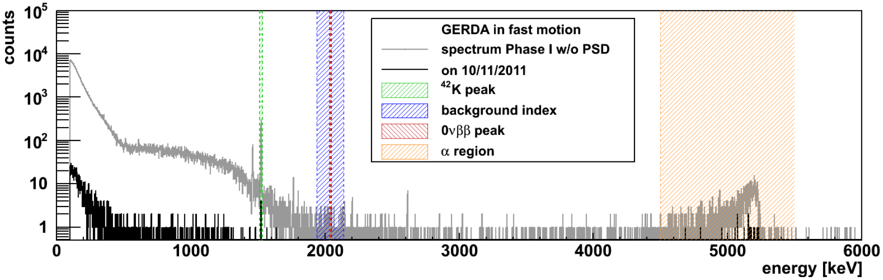


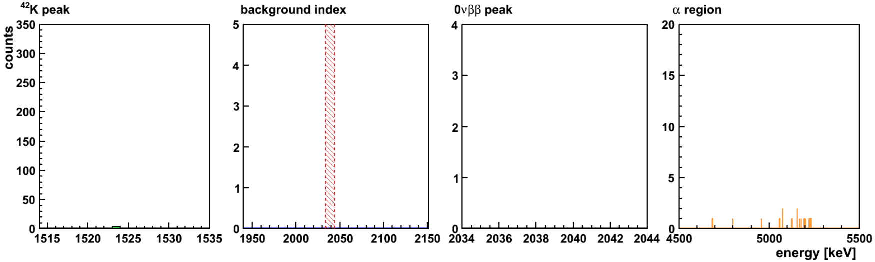
Results

- peak pos. within 0.3 keV at correct position (from ^{42}K peak)
- FWHM $\sim$ 4% larger than expected from calibration data
- exposure-weighted FWHM at $Q_{\beta\beta}$ is:

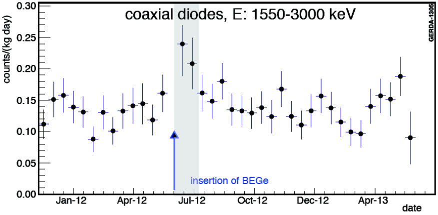
  4.8 keV for coaxials (0.23%)
  3.2 keV for BEGes (0.16%)

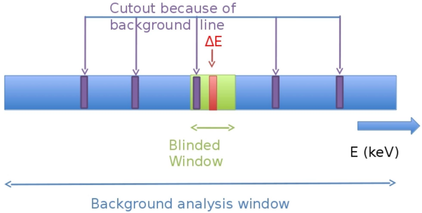
GERDA spectrum in fast motion





Energy spectra





Phase I data divided in three subsets:

- *Golden coax*: 17.9 kg yr
- *Silver coax*: 1.3 kg yr
- *BEGe*: 2.4 kg yr

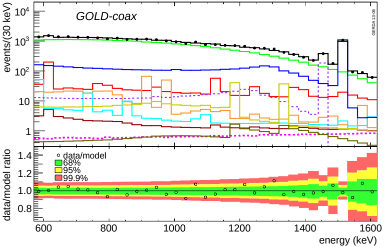
Silver coax: data from coaxial detectors during BEGe deployment (higher BI)
Golden coax: data from coaxial detectors except Silver coax
BEGe: data from BEGe detectors

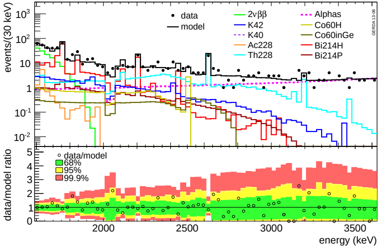
- Events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- **Background level before PSD at $Q_{\beta\beta}$ for Golden coax**: 0.018±0.002 cts/(keV kg yr)

Background ∼10× lower than previous Ge experiments!!

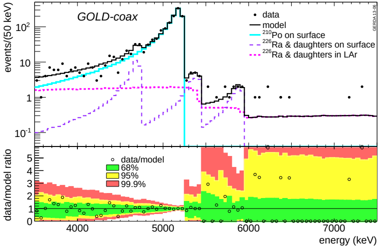
The Background Model of GERDA Phase I

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





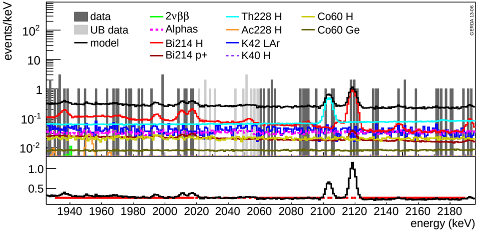
- Simulation of known and observed background
- Fit combination of MC spectra to data from 570 keV to 7500 keV
- Different combinations of positions and contributions tested



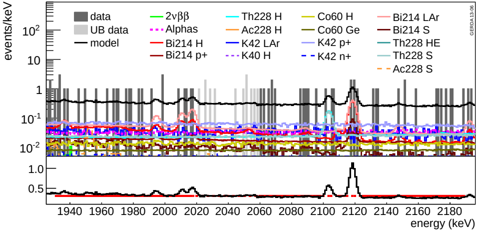
Main contribution from close sources: ^{228}Th and ^{226}Ra in holders, ^{42}Ar α on detector surface

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)

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

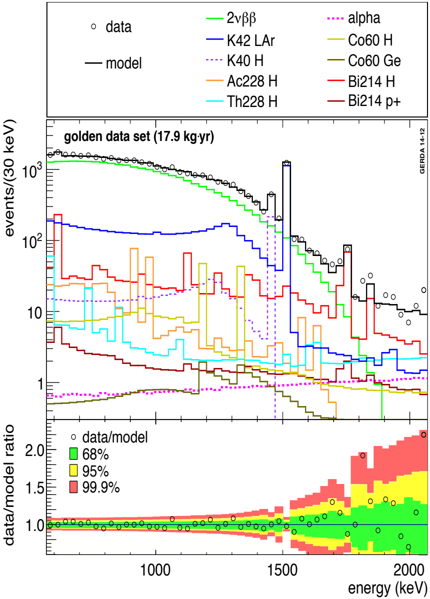
Consider the minimum background model to estimate the $2\nu\beta\beta$ half-life of ^{76}Ge

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

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:

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

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

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

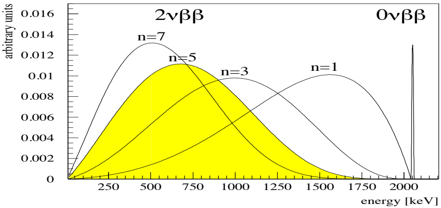
The GERDA collaboration
J. Phys. G: Nucl. Part. Phys. 40 (2013)

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

arXiv:1501.02345

$0\nu\beta\beta\chi$ 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

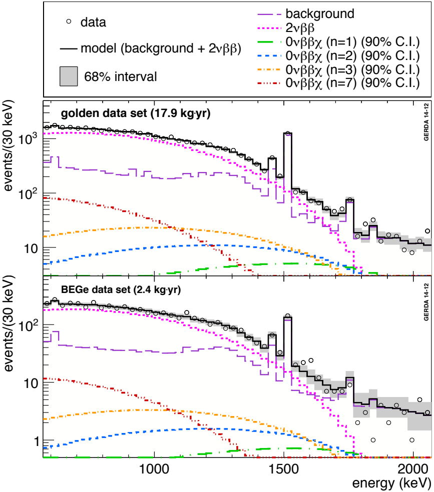
$$\frac{dN}{dK} \sim G \sim (Q_{\beta\beta} - K)^n$$

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

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

Golden coax + BEGe: total exposure 20.3 kg

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



Model	n	Mode	Goldstone boson	L	$T^{0\nu\chi}_{1/2}$ [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

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

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

and

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

Results from GERDA Phase I

Model	n	Mode	Goldstone boson	L	$T^{0\nu\chi}_{1/2}$ [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	$2.07 \cdot 10^{-19}$	$< 4.7 \cdot 10^{-2}$

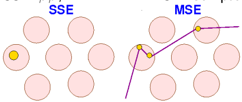
The coupling constants allow a comparison with other isotopes

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

arXiv:1501.02345

Pulse shape discrimination of GERDA Phase I data

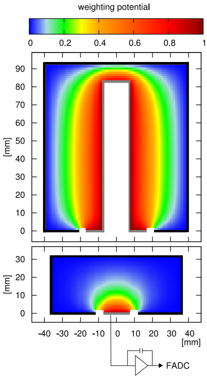
SSE: $\beta\beta$, DEP   MSE: Compton



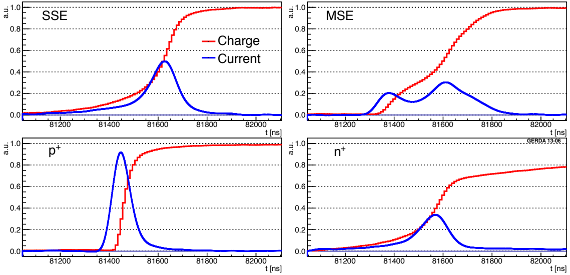
Pulse-shape analysis

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)

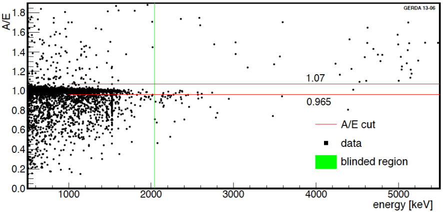
Surface events: only electron or hole drift

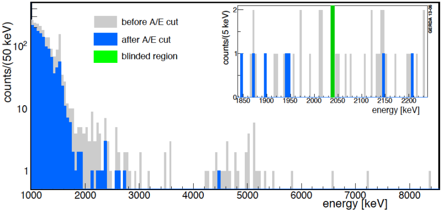
Pulse shape discrimination of GERDA Phase I data

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
- 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$\pm$0.02 efficiency for $0\nu\beta\beta$ - 7/40 events kept in 400 keV window



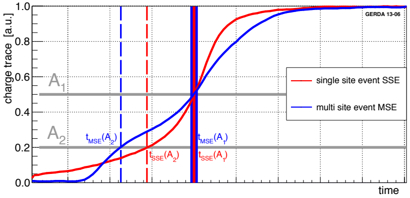


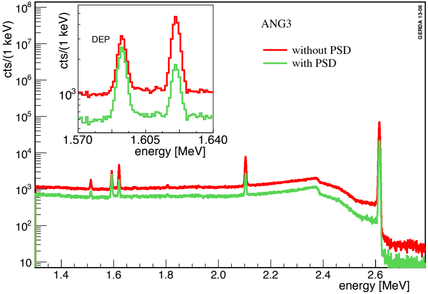
Pulse shape discrimination of GERDA Phase I data

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

PSD for coaxial detectors:

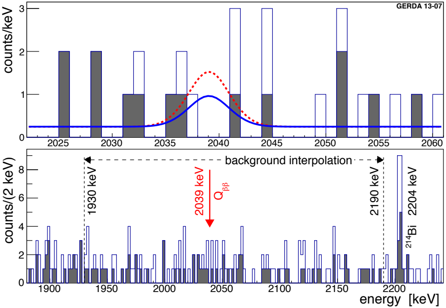
- Artificial Neural Network **ANN**
- ANN analysis of 50 rise-time info (1,3,5,...,99%) with TMVA/TMlpANN
- trained on signal SSE: ^{208}Tl (2614 keV) DEP at 1592 keV
- MSE training with background-like ^{212}Bi FEP at 1621 keV





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

- 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

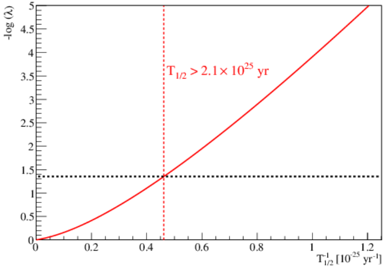
†) in units of 10^{-3} cts/(keV·kg·yr).

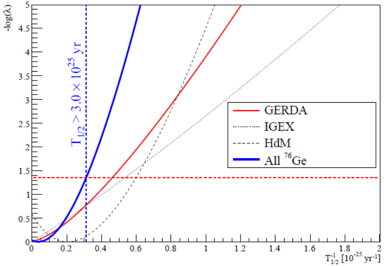
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG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

- **Profile likelihood result**:
  $\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr at 90% C.L.**
- $N^{0\nu} < 3.5$ Best fit: $N^{0\nu} = 0$

- **Combine with HdM and IGEX**:
  $\mathbf{T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}}$ **yr at 90% C.L.**
- independent of NME and physical mechanism for $0\nu\beta\beta$

↓

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

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

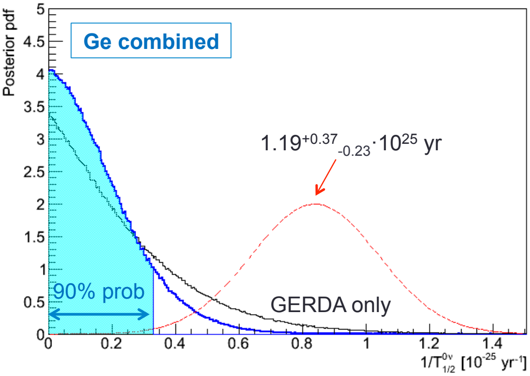
$$P(D|\vec{\lambda}, T_{1/2}, \bar{H}) = \prod_i \frac{e^{-(\lambda_i+\nu_i)}(\lambda_i+\nu_i)_i^n}{n_i!}$$

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

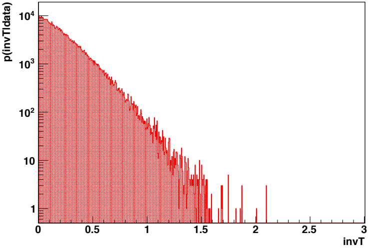
Comparison with claim from Phys. Lett. B 586 198 (2004)

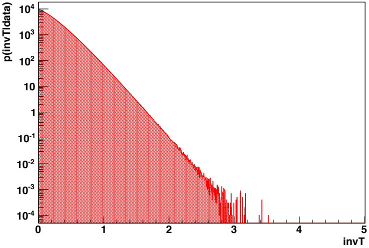


- **Bayesian result (GERDA only)**
- $T^{0\nu}_{1/2} > \mathbf{1.9{\cdot}10^{25}}$ **yr at 90% C.redibility Interval**
- Best fit $N^{0\nu}$=0
- MC Median Sensitivity: $T^{0\nu}_{1/2} > 2.0{\cdot}10^{25}$ yr at 90% C.I.

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%

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

Compare two hypotheses:

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

Bayes factor:

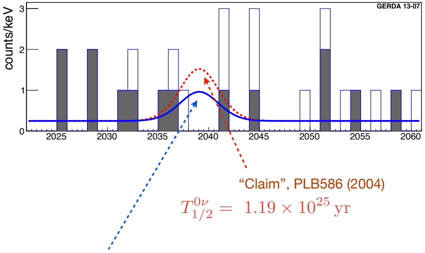
$$BF(n, T_{1/2}) = \frac{P(\text{signal+background} | n, T_{1/2})}{P(\text{background})}$$

$$= \frac{1}{\nu_{max}} \int_0^{\nu_{max}} \exp(-\nu) \left(\frac{\lambda+\nu}{\lambda}\right)^n d\nu$$

Bayes factor for GERDA only

$P(H_1)/P(H_0) = 0.024$

$P(N^{0\nu}{=}0|H_1){=}0.01$



Compatible with no signal events

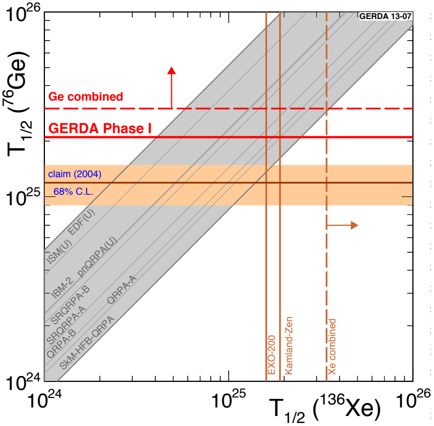
$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr

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
C. Macolino and the GERDA collab., Mod. Phys. Lett. A29 (2014) 1430001

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

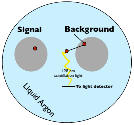
Strategy:

- 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
- First data in these days

Liquid Argon instrumentation for Phase II

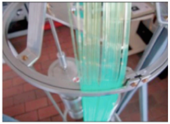
LAr scintillation veto in GERDA Phase II

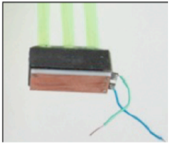
- **SiPM fiber curtain**
- **PMTs on top and bottom of the array**



Top/bottom: PMTs

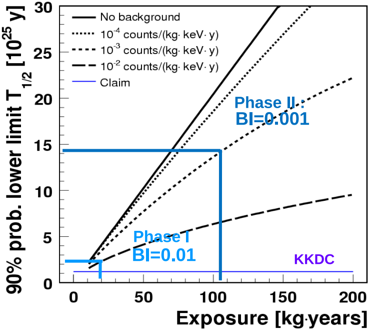
Central cylinder:
SiPM/Fiber readout

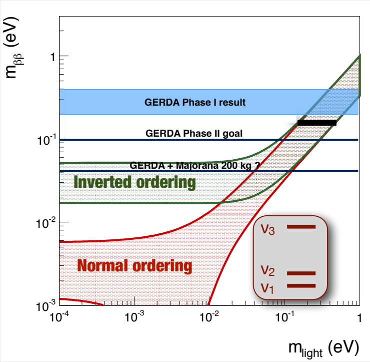




LAr veto + PSA allows a strong reduction of the background at $Q_{\beta\beta}$!

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

Latest results

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	6.6×10^{24} 1×10^{26}	$0.2 \div 0.5$ $0.04 \div 0.11$	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	1000	5×10^{26}	$0.03 \div 0.07$	in progress
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
- 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
- this translates in a limit on the effective neutrino mass: $\boldsymbol{m_{\beta\beta}}$ between **0.2 eV** and **0.4 eV**
- probability that the signal from the previous claim produces the GERDA outcome is 1%
- starting Phase II with improved sensitivity
- **exciting results to come from different experiments!**

Merci de votre attention!!

GERDA Collaboration Meeting in MPI Heidelberg, Germany
June 2014