Search for neutrinoless double beta decay with the GERDA experiment

Carla Macolino on behalf of the GERDA collaboration

INFN, Laboratori Nazionali del Gran Sasso ITALY

BEACH 2014 - Birmingham
25.07.2014

INFN
Laboratori Nazionali del Gran Sasso

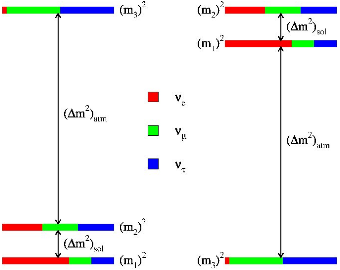
ββ
GERDA

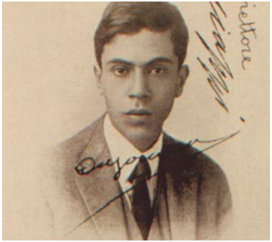
Outline

- 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

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
- CP violation phases

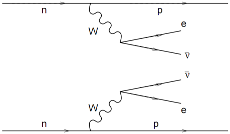




Search for $0\nu\beta\beta$ decay

$2\nu\beta\beta$

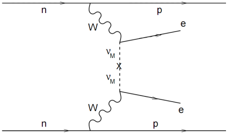
$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$



$\Delta L = 0 \Longrightarrow$ Predicted by SM

$0\nu\beta\beta$

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

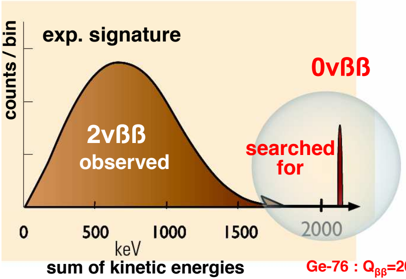


$\Delta L = 2 \Longrightarrow$ Prohibited by SM (no RHν)

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

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

Most stringent limits on $0\nu\beta\beta$ decay

Isotope	Experiment	$T_{1/2}^{0\nu}$ at 90% CL [yr]	Ref.
^{76}Ge	Heidelberg-Moscow	$1.9 \cdot 10^{25}$ yr	(1)
^{76}Ge	IGEX	$1.6 \cdot 10^{25}$ yr	(2)
^{136}Xe	EXO	$1.1 \cdot 10^{25}$ yr	(3)
^{136}Xe	KamLAND-Zen	$1.9 \cdot 10^{25}$ yr	(4)

Claim of observation of the decay:

$T_{1/2}^{0\nu}$ (^{76}Ge) $= 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr (5)

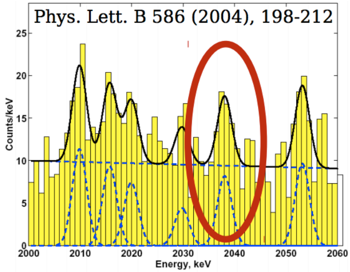
(1): Eur. Phys. J. A12 (2001), 147-154

(2): Phys. Rev. D 65 (2002), 092007

(3): Nature 510 (2014), 229-234

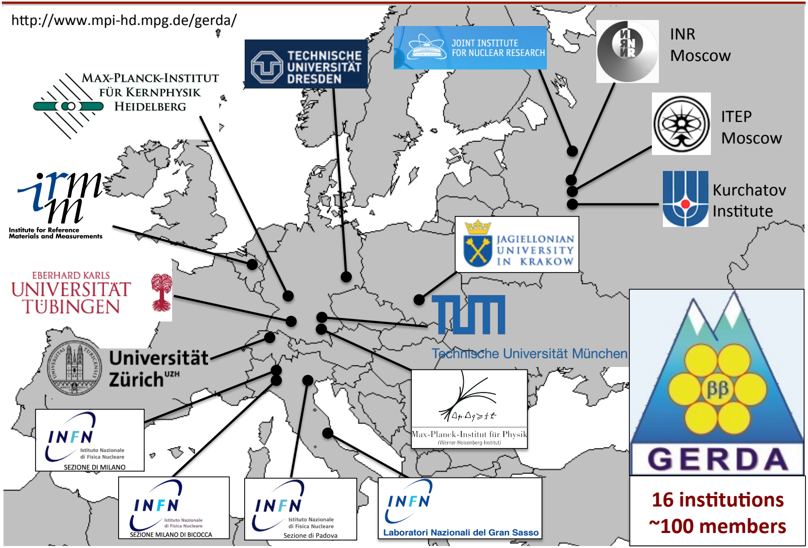
(4): Phys. Rev. Lett. 110 (2013), 062502

(5): Phys. Lett. B 586 (2004), 198-212



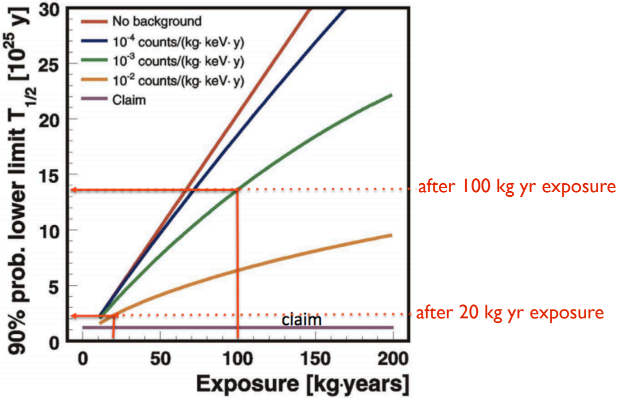
The GERDA collaboration

The GERDA Collaboration



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

GERDA Sensitivity on half-life of the decay



- **GERDA 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
- **GERDA 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)

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

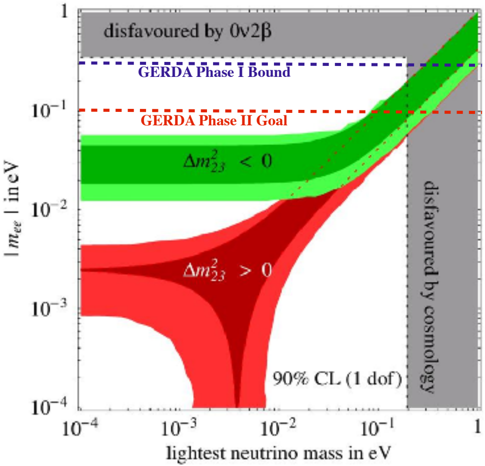
If light Majorana neutrino exchange is the dominant mechanism and no further sterile neutrino exists:

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

$\langle m_{\beta\beta}\rangle \equiv$ 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!



- **GERDA Phase I result**: Upper limit on $m_{\beta\beta}$: between 0.2 and 0.4 eV
- **GERDA Phase II goal**: reach sensitivity on $m_{\beta\beta} \sim 10^{-1}$ eV

Ge detectors

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

ϵ	detection efficiency	$\gtrsim$ 85%
f_A	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

Ge semiconductor detectors

Advantages:

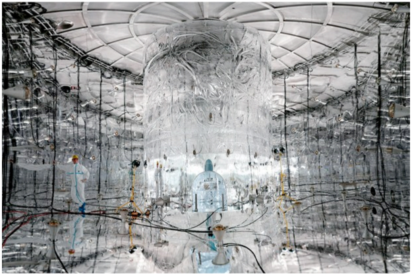
- well established enrichment technique $f_A = f_{76} = 86\%$ for ^{76}Ge
- M and T expandable
- very good energy resolution $\Delta E \sim 0.1\%$ - 0.2%
- very good detection efficiency $\epsilon \sim 1$ (Ge as source and detector)
- high-purity detectors → low background b

Disadvantages:

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

GERDA @ LNGS

Construction completed in 2009 - Inauguration 9 Nov. 2010



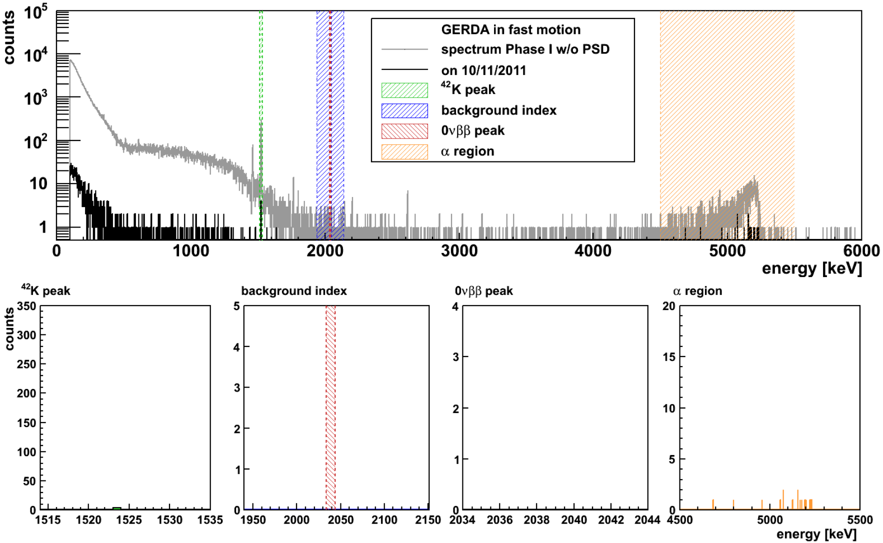
GERDA @ LNGS

GERDA Building

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

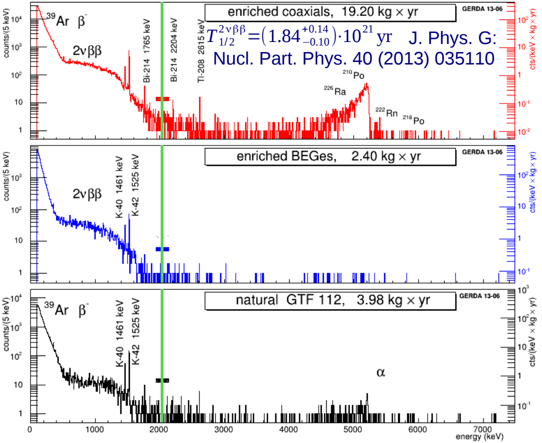
- 8 enriched Coaxial detectors: working mass 14.6 kg - **avg energy resolution 4.8 keV** (2 of them are not working due to high leakage current)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: working mass 3.0 kg - **avg energy resolution 3.2 keV** (testing Phase II concept)

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



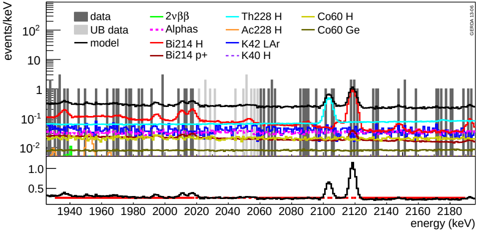
- Events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- Phase I data divided in three subsets:
  - *Golden coax*: 17.9 kg yr
  - *Silver coax*: 1.3 kg yr
  - *BEGe*: 2.4 kg yr
- **Background level before PSD at $Q_{\beta\beta}$ for Golden coax**: 0.018±0.002 cts/(keV kg yr)

Background ∼10× lower than previous Ge experiments!!

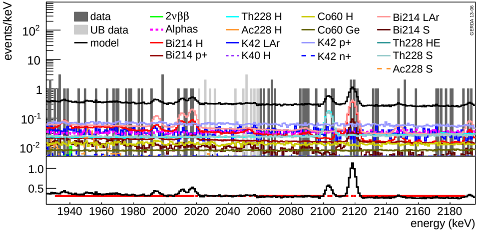
The Background Model of GERDA Phase I

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

Minimum model fit



Maximum model fit



- 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:

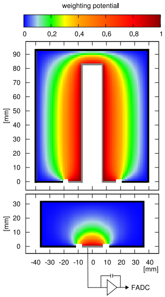
$$\mathrm{BI} = 1.75^{+0.26}_{-0.24} \cdot 10^{-2}\ \mathrm{cts/(keV\ kg\ yr)}$$

BEGe:

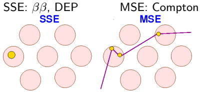
$$\mathrm{BI} = 3.6^{+1.3}_{-1.0} \cdot 10^{-2}\ \mathrm{cts/(keV\ kg\ yr)}$$

Pulse shape discrimination of GERDA Phase I data

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



Current signal = q v ΔΦ

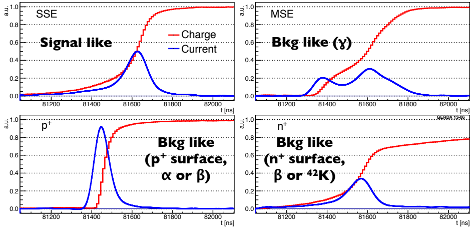


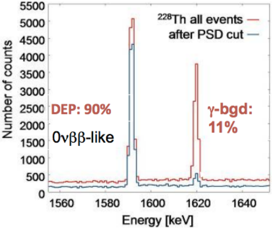
Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition

Different energy deposition between gamma and electron
Different recorded pulses



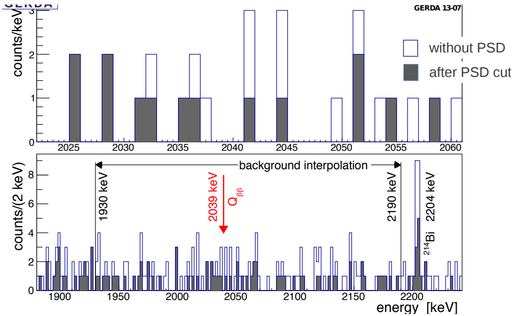


Efficiency on signal events: about 90%
Efficiency of background rejection: about 50%

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**
- 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

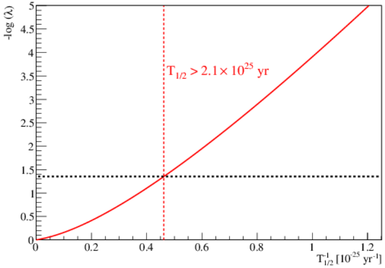
†) in units of 10^{-3} cts/(keV·kg·yr).

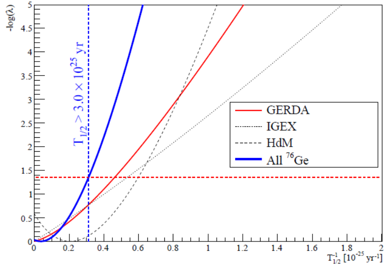
data set	detector	energy [keV]	date	PSD passed
golden	ANG 5	2041.8	18-Nov-2011 22:52	no
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes
golden	RG 2	2041.3	16-Dec-2012 00:09	yes
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no
golden	RG 1	2035.5	29-Jan-2013 03:35	yes
golden	ANG 3	2037.4	02-Mar-2013 08:08	no
golden	RG 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:
  $T^{0\nu}_{1/2}$ >2.4·10^{25} yr at 90% C.L.
- Maximum likelihood spectral fit
  (3 subsets, $1/T_{1/2}$ common)
- Bayesian analysis also available
  Median sensitivity:
  $T^{0\nu}_{1/2}$>2.0·10^{25} yr at 90% C.L.

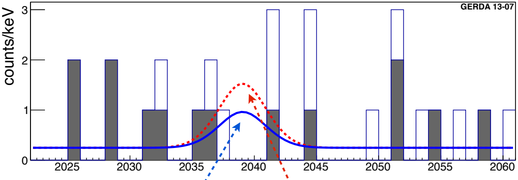
- **Profile likelihood result**:
  $T^{0\nu}_{1/2}$ >2.1 · 10^{25} yr at 90% C.L.
- **Bayesian analysis result**:
  $T^{0\nu}_{1/2}$ >1.9 · 10^{25} yr at 90% C.I.
- Best fit: $N^{0\nu}$=0

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

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

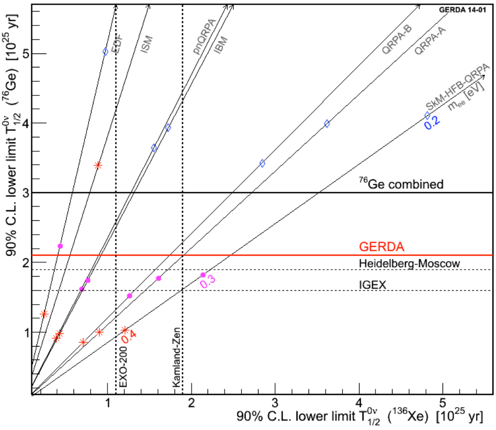
Claim strongly disfavoured!

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

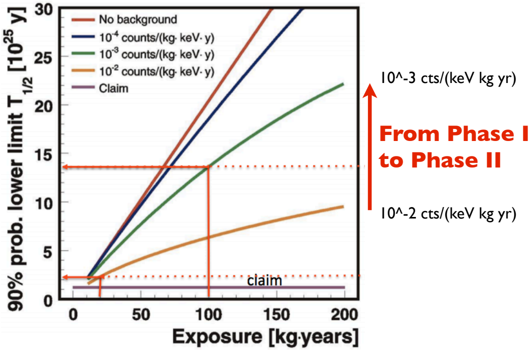


(from B. Schwingenheuer TAUP 2013)

GERDA+HdM+IGEX:

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

On the way to GERDA Phase II



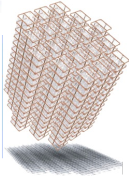
How to get a higher sensitivity for the Phase II:

- 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 for high background recognition efficiency
  2. by LAr scintillation light for background recognition and rejection

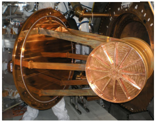
Present and future perspectives

An explosion of technology and exciting results to come!

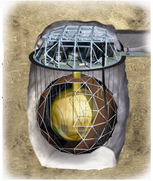
CUORE



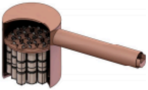
EXO



SNO+



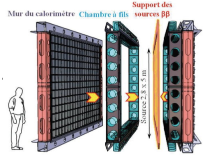
MAJORANA

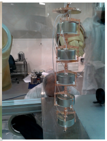


Future perspectives

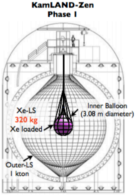
Isotope	Experiment	Mass [kg]	Sensitivity $T_{1/2}^{0\nu}$ [yr]	Sensitivity $\langle m_{\beta\beta} \rangle$ [meV]	Status
^{130}Te	CUORE	11	$5 \cdot 10^{24}$	230-570	in progress
^{130}Te	CUORE	200	$1 \cdot 10^{26}$	50-130	in progress
^{76}Ge	GERDA	40	$1.4 \cdot 10^{26}$	80-190	in progress
^{76}Ge	GERDA	1000	$6 \cdot 10^{27}$	15-35	R&D
^{76}Ge	MAJORANA	40	$1.5 \cdot 10^{26}$	90-200	in progress
^{76}Ge	MAJORANA	40	$6 \cdot 10^{27}$	15-35	R&D
^{136}Xe	EXO	200	$4 \cdot 10^{25}$	100-240	in progress
^{136}Xe	EXO	5000	$2 \cdot 10^{27}$	14-33	R&D
^{136}Xe	SNO+	800	$1 \cdot 10^{26}$	50-130	in progress
^{136}Xe	SNO+	8000	$1 \cdot 10^{27}$	16-40	R&D
^{136}Xe	KamLAND-Zen	320	$3 \cdot 10^{25}$	140-280	in progress
^{136}Xe	KamLAND-Zen	700	$1 \cdot 10^{26}$	95-190	R&D
^{136}Xe	KamLAND-Zen	1000	$6 \cdot 10^{26}$	25-60	R&D
^{82}Xe	SuperNEMO	7	$6.5 \cdot 10^{24}$	240-560	in progress
^{82}Xe	SuperNEMO	100-200	$1\text{-}2 \cdot 10^{26}$	44-140	R&D

SuperNEMO





KamLAND-Zen



Conclusions

- Phase I data taking successful!! Phase I ended Sept.,30th 2013
- very low background 0.01 cts/(keV kg yr) after PSD
- **half-life of $0\nu\beta\beta$:**
  $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge
- probability that the signal from the previous claim produces the actual GERDA outcome is 1%
- **Limit on effective neutrino mass $\langle m_{\beta\beta} \rangle$:**
  $0.2 \div 0.4$ eV
- starting the Phase II to improve sensitivity on half-life of a factor of 10

Thanks

Thank you for your attention!!

GERDA Collaboration Meeting in Heidelberg, Germany
June 2014