Results on $0\nu\beta\beta$ of ^{76}Ge from GERDA Phase I

Sabine Hemmer for the GERDA collaboration

Università di Padova, INFN Padova

Warsaw, 23 June 2014

Outline

- **Neutrinos and Double Beta Decay**
- **The GERDA experiment**
- **GERDA Phase I data taking**
- **GERDA Phase I analysis**
- **Outlook on GERDA Phase II**

Unveil the nature of the neutrino

Majorana

$\nu = \bar{\nu}$

or

Dirac

$\nu \neq \bar{\nu}$

If $0\nu\beta\beta$ is observed:

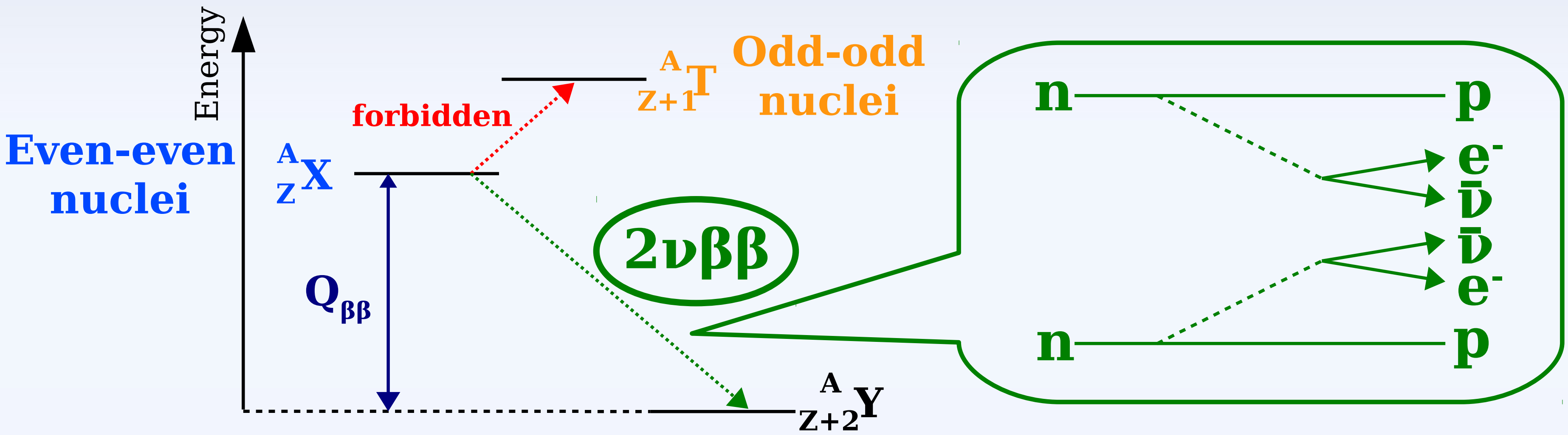
Lepton number violation $\Delta L=2$

Neutrino has a Majorana mass term

Sheds light on absolute neutrino mass scale

Sheds light on neutrino mass hierarchy

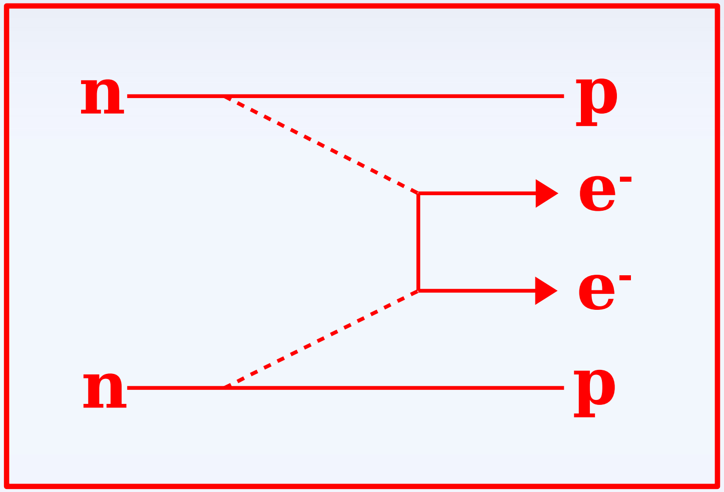
2νββ

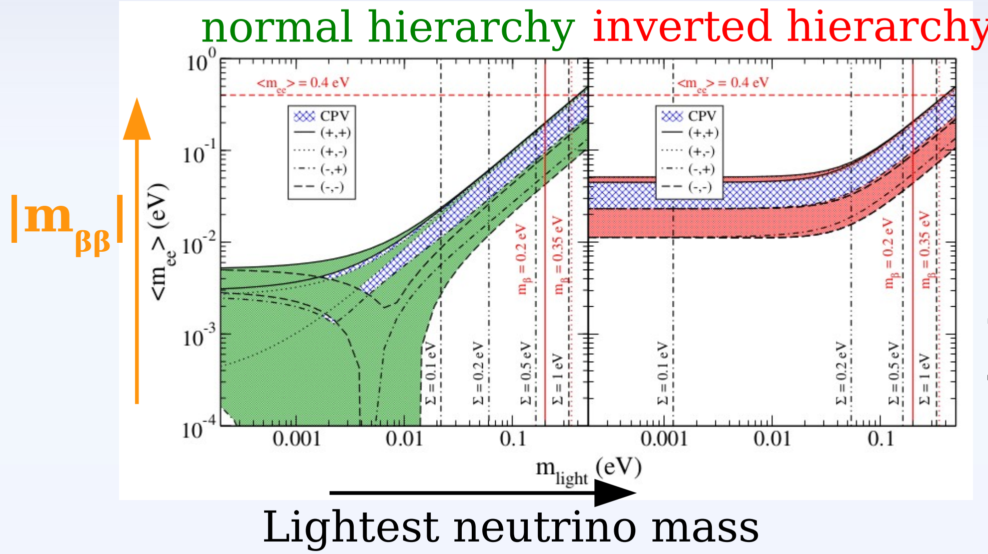


- allowed by SM
- $\Delta L=0$
- observed in many isotopes
- $T^{2\nu}_{1/2} \sim 10^{19}\text{-}10^{21}$ yr
- $(T^{2\nu}_{1/2})^{-1} = G^{2\nu}(Q_{\beta\beta},Z) \cdot |M^{2\nu}|^2$

Phase space *nuclear matrix element*

0νββ





W. Rodejohann,
J. Phys. G39 (2012), 124008

- **forbidden process in SM, needs Majorana neutrino**
- **$\Delta L = 2$**
- $(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z) \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$ *

Phase space $(\sim Q_{\beta\beta}^{5})$

nuclear matrix element

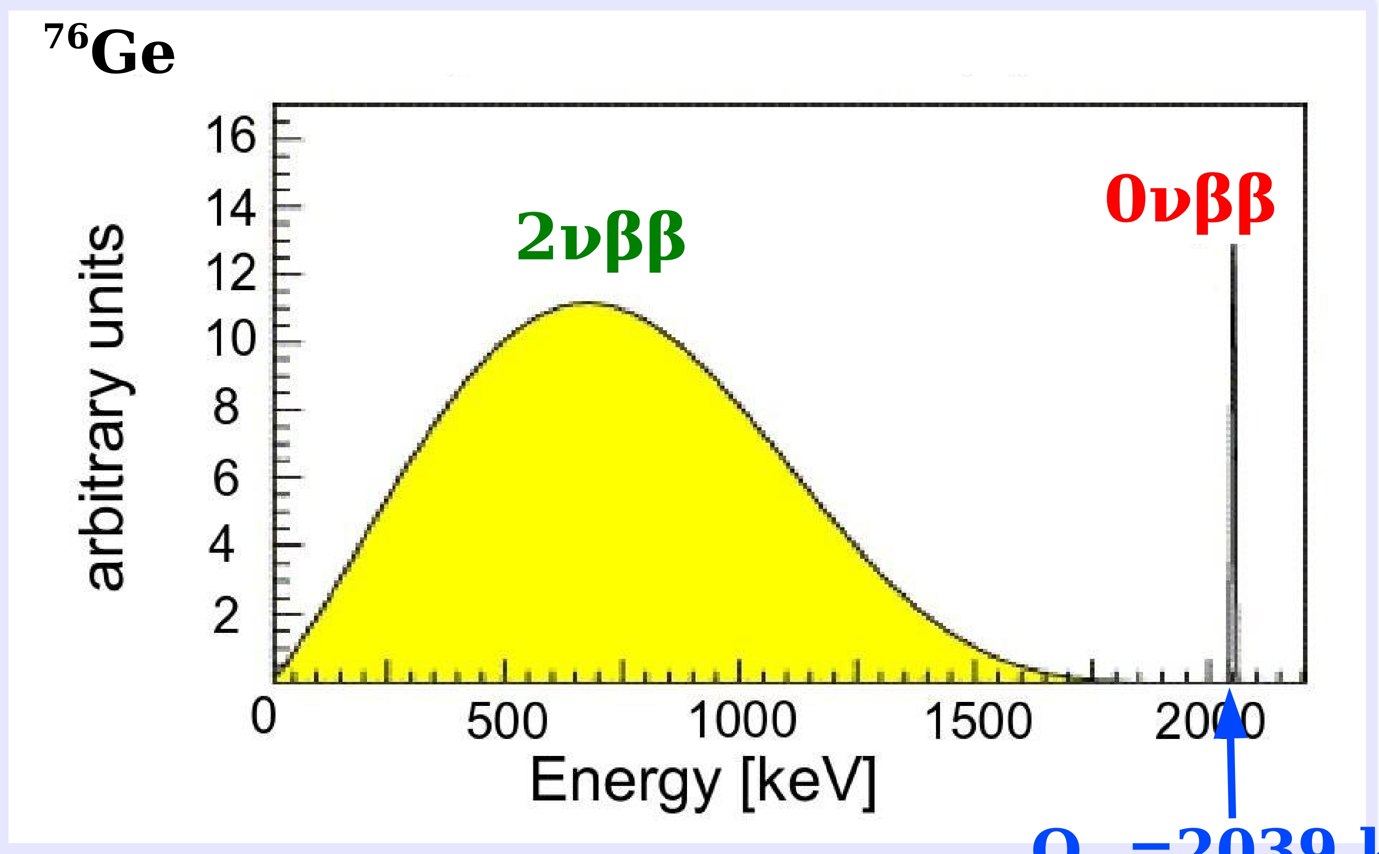
$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_i|^2$

Majorana neutrino mass

* assuming exchange of light Majorana neutrino

Experimental signatures

➡ **Measure summed electron energy spectrum E:**



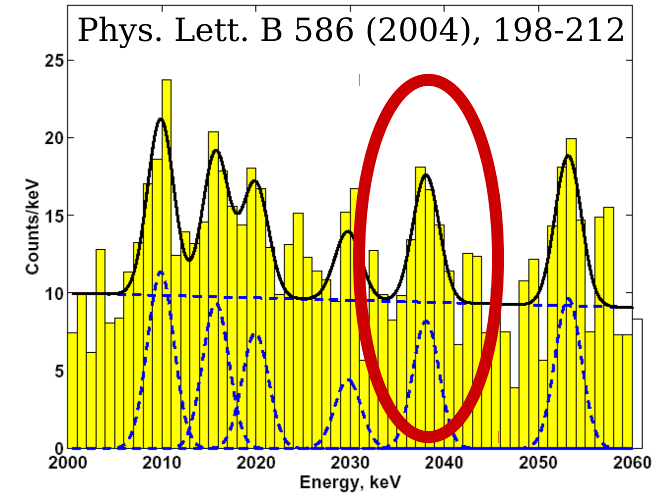
$Q_{\beta\beta}$=2039 keV

Most stringent limits on 0νββ

Isotope	Experiment	$T^{0\nu}_{1/2}$ (yr) (90% C.L.)
^{76}Ge	HdM collaboration	$1.9\cdot10^{25}$ [1]
	IGEX collaboration	$1.6\cdot10^{25}$ [2]
^{136}Xe	EXO collaboration	$1.1\cdot10^{25}$ [3]
	KamLAND-Zen collaboration	$1.9\cdot10^{25}$ [4]

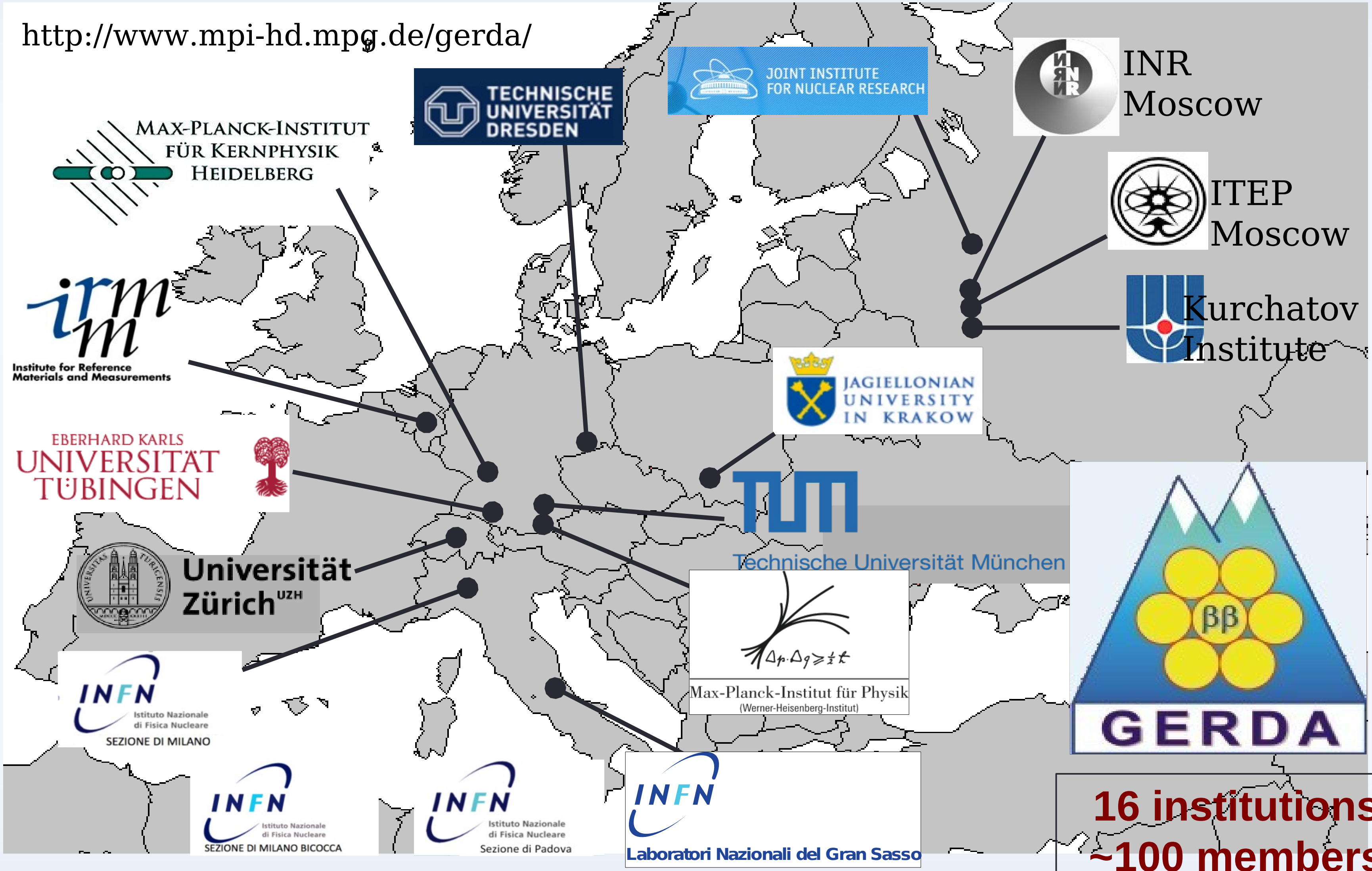
Claim of signal for 0νββ:

$T^{0\nu}_{1/2}\ (^{76}\mathrm{Ge}) = 1.19^{+0.37}_{-0.23}\cdot10^{25}$ 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

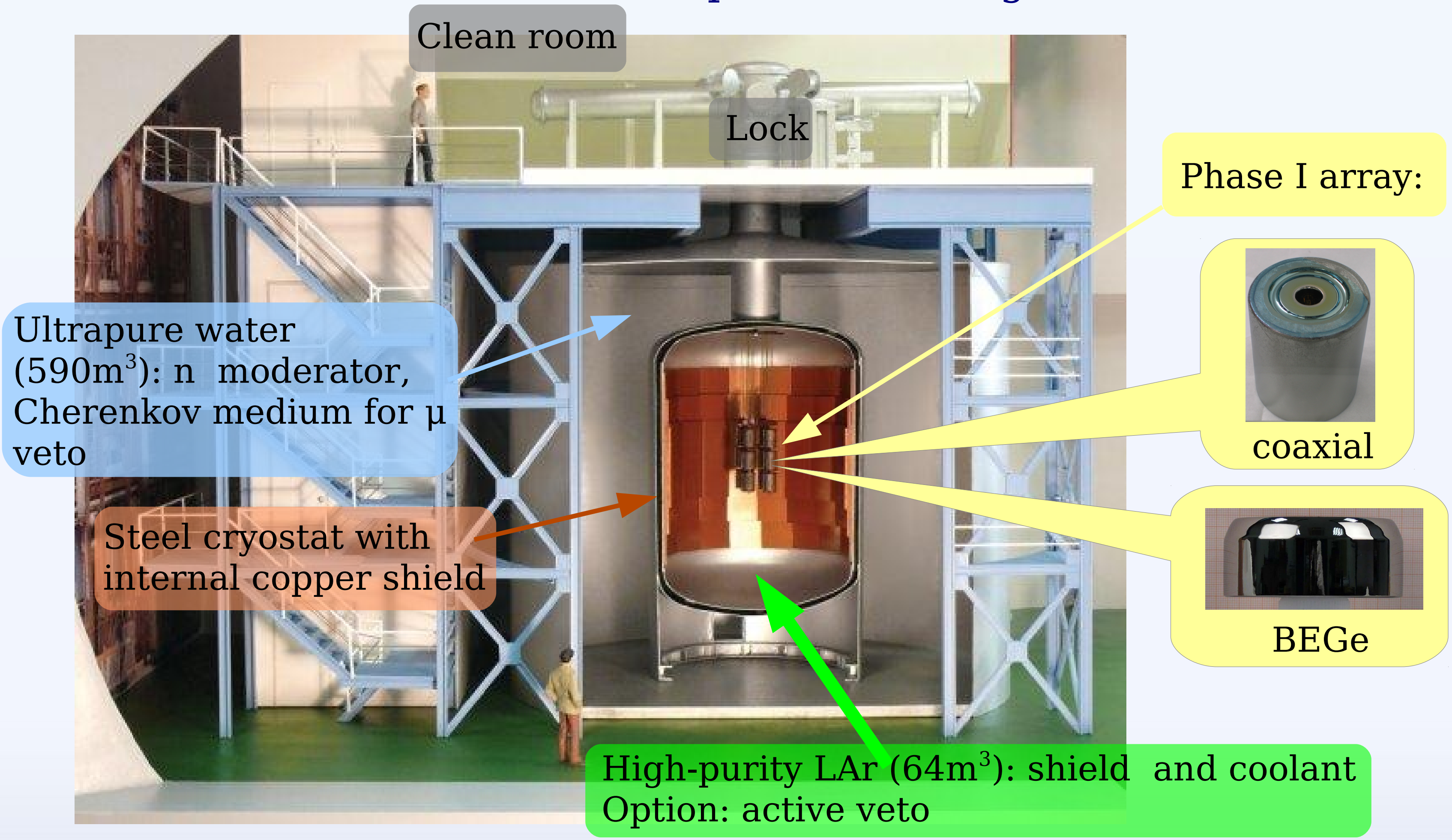
The GERDA experiment



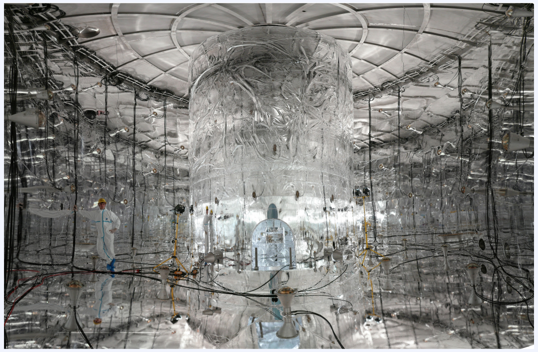
16 institutions
~100 members

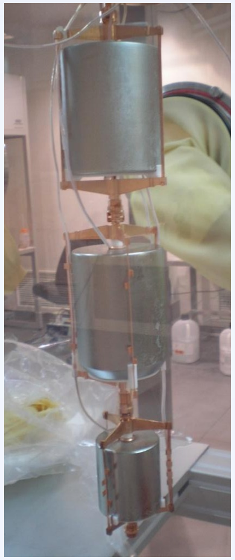
Experimental setup

- situtated in LNGS underground laboratories (3500 m w.e. shielding)
- graded shielding against ambient radiation
- rigorous material selection, avoid exposure above ground for detectors



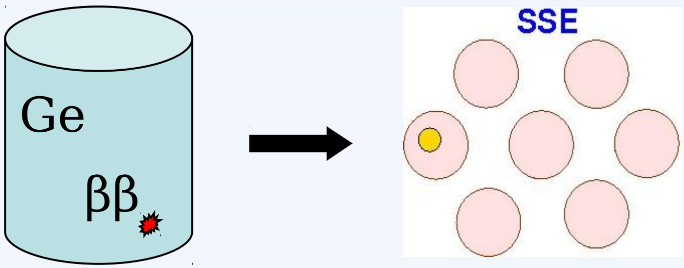
Experimental setup





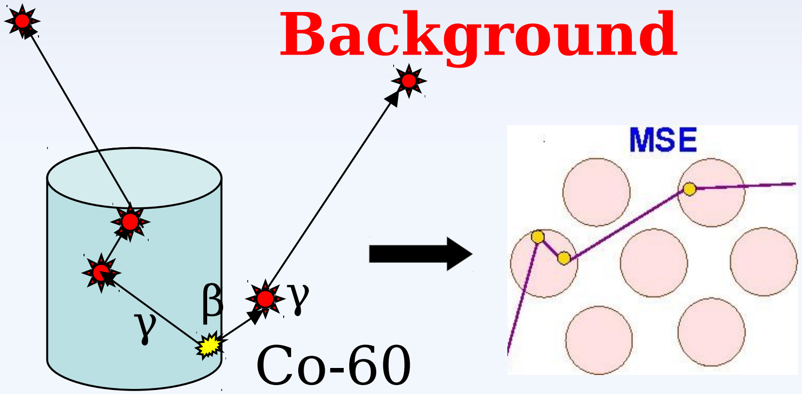
Additional background reduction

Signal



Point-like (single-site) energy deposition inside one HP-Ge diode (Range: ~ 1 mm)

Background

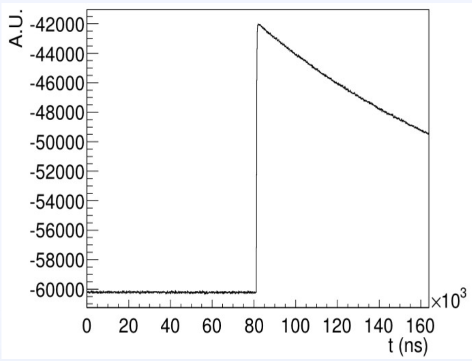


Multi-site energy deposition inside HP-Ge diode (Compton scattering)

Signal analysis:

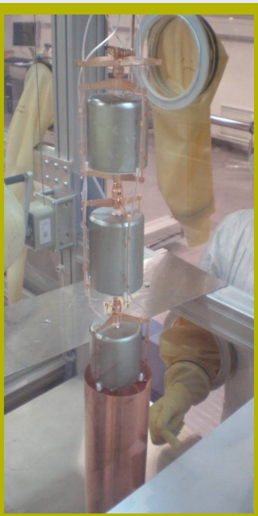
- anti-coincidence between detectors
- pulse shape analysis (PSA)
- time-coincidence (Bi-Po)

Example of charge pulse



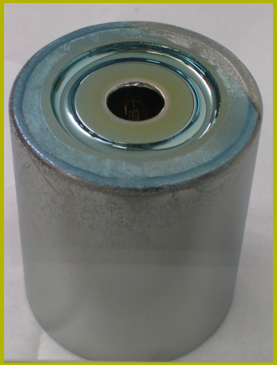
Ge diode with HV in blocking direction → leakage current very small
Energy deposition → e⁻h-pair drift in E-field to electrodes
Readout with charge-sensitive preamplifier with R-feedback

GERDA Phase I data



8 semi-coaxial p-type detectors
(reprocessed HdM and IGEX detectors)
(2 detectors not considered for analysis)
Enrichment fraction of ^{76}Ge: ~86%
Data taking: November 2011 – May 2013

Total mass: 14.6 kg



5 p-type BEGe detectors
(newly processed Phase II detectors)
(1 detector not considered for analysis)
Enrichment fraction of ^{76}Ge:: ~88%
Data taking: July 2012 – May 2013

Total mass: 3.0 kg

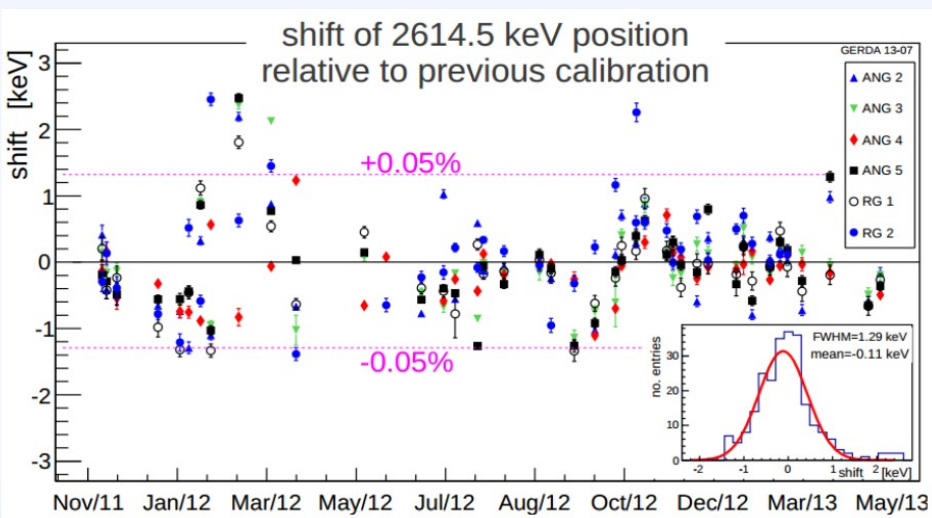
GERDA Phase I data

Calibration and energy resolution

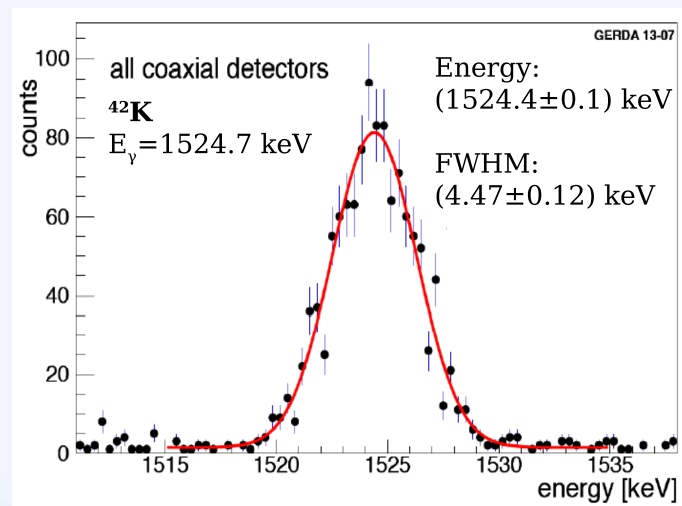
- (bi-) weekly calibration with ^{228}Th source
- offline energy reconstruction (semi-Gaussian filter)
- stability monitored with test pulses

Mean FWHM @ $Q_{\beta\beta}$:
Semi-coaxial detectors: (4.8 ± 0.2) keV
BEGe detectors: (3.2 ± 0.2) keV

Stable over the entire data taking period!



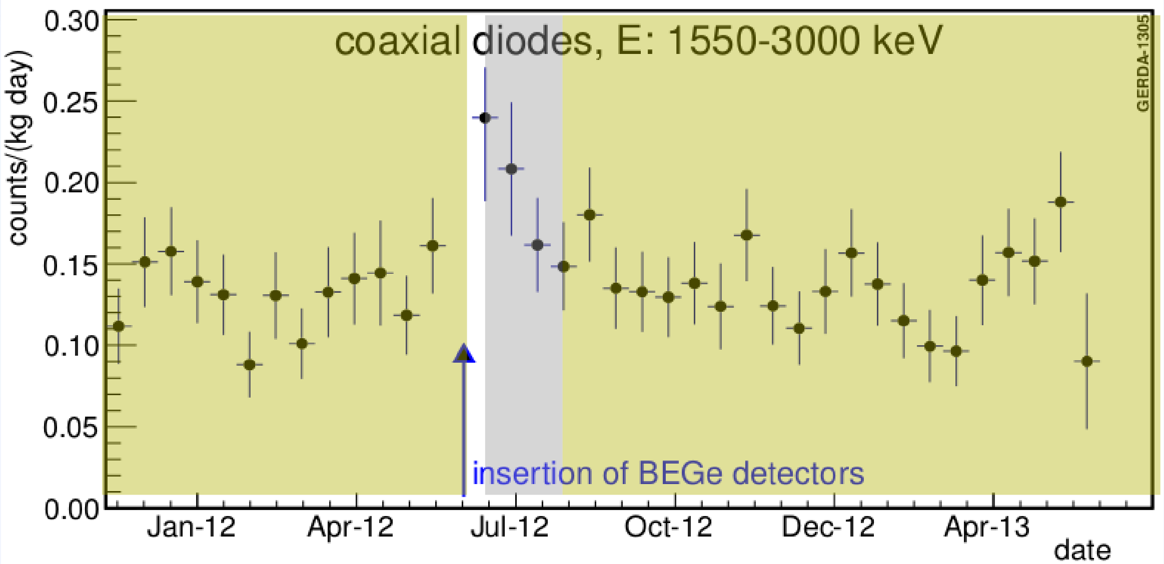
Shifts small compared to FWHM (~0.2% $Q_{\beta\beta}$)

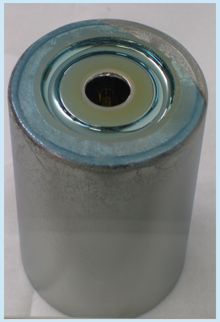


Peak position within 0.3 keV of correct position

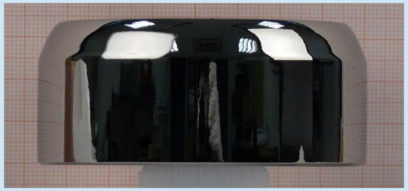
GERDA Phase I data

Group data according to energy resolution and background level:



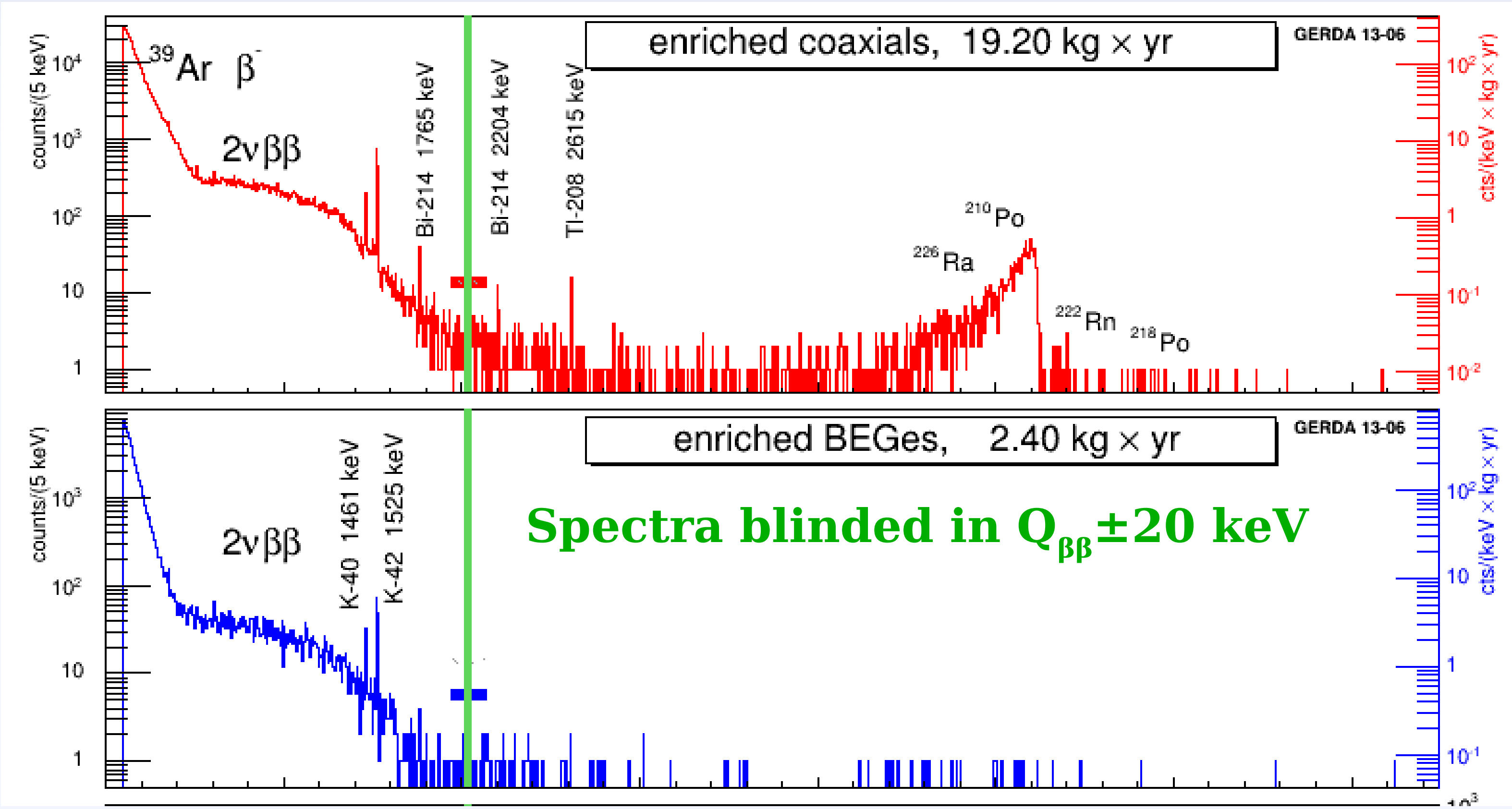


Golden data set: 17.9 kg·yr
Silver data set: 1.3 kg·yr



BEGe data set: 2.4 kg·yr

GERDA Phase I data

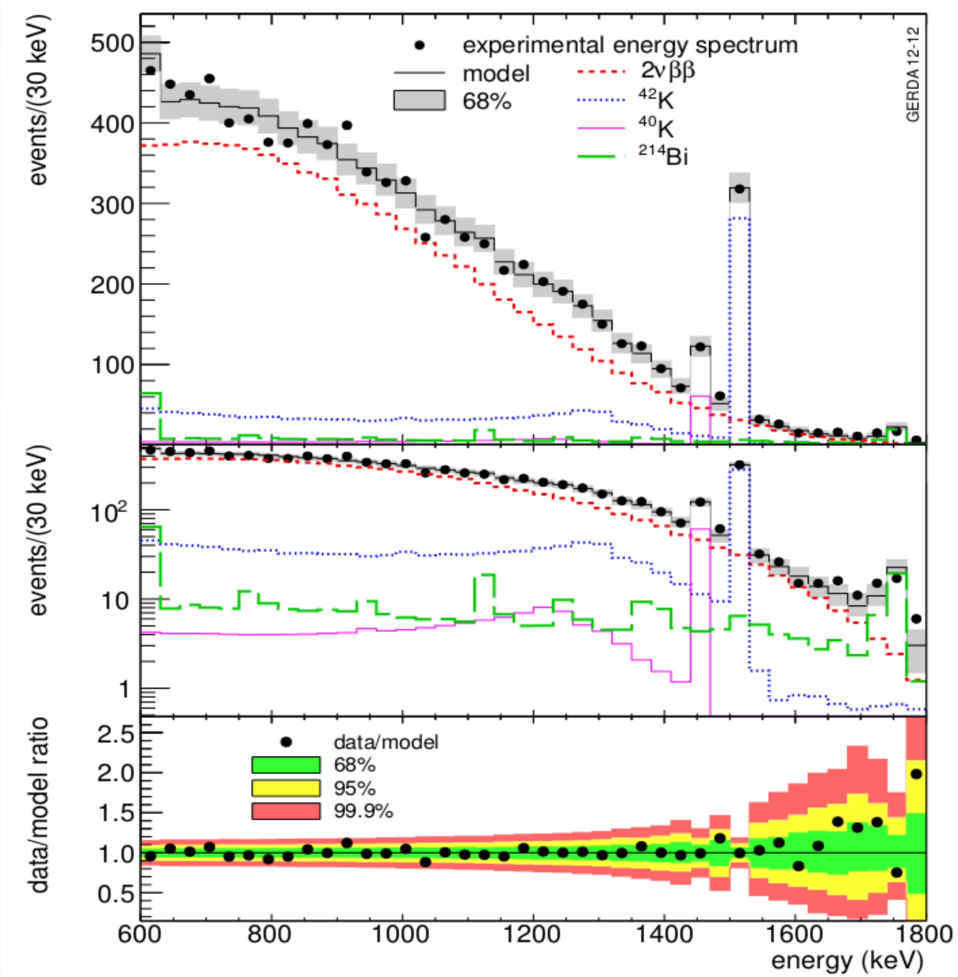


Dominating background sources:

- β-spectrum of ^{39}Ar (Q=565 keV)
- α-spectrum of ^{238}U chain (in coaxial detectors)
- γ-lines from ^{42}K, ^{40}K, ^{214}Pb/^{214}Bi, ^{208}Tl, ^{228}Ac

Measurement of $T^{2\nu}_{1/2}$ of ^{76}Ge

Binned maximum likelihood approach

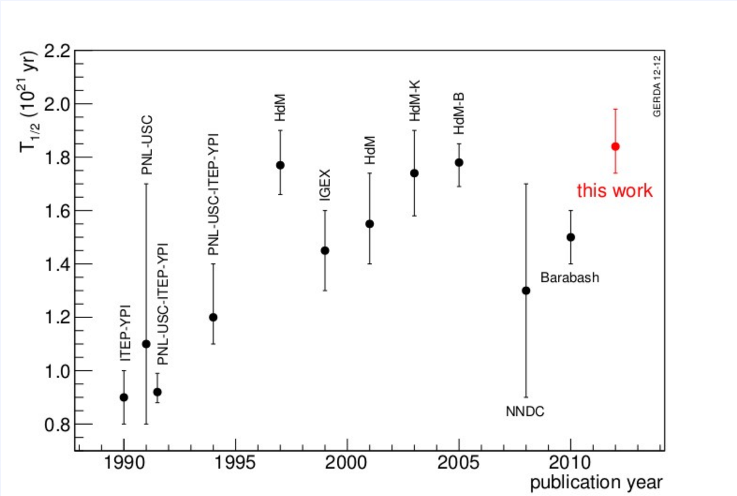


Data set: 5.04 kg·yr subset of golden data set

Fit window: [600;1800] keV

Model: Simulated spectra of 2νββ, ^{42}K, ^{40}K, ^{214}Bi

Fit parameters: active det. masses, enrichment fractions, bkg contributions, common $T^{2\nu}_{1/2}$



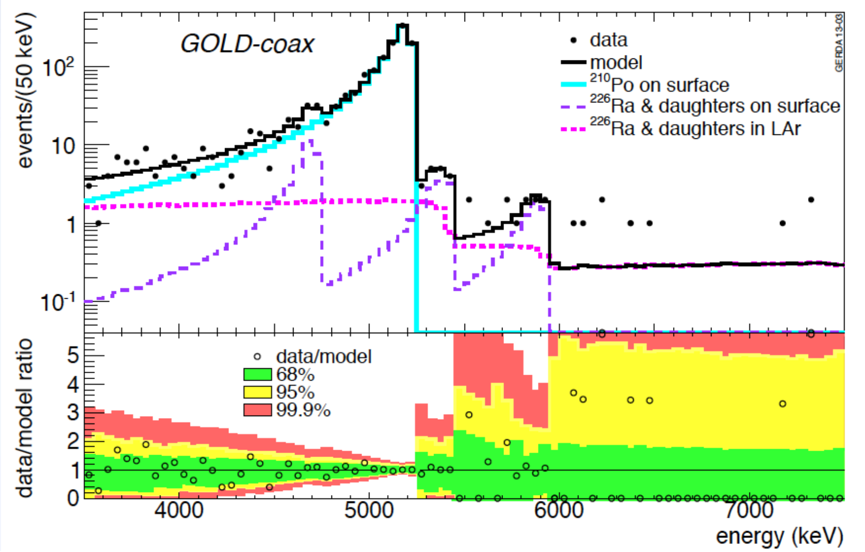
Final result: $(1.84^{+0.09}_{-0.08\ fit}\ {}^{+0.11}_{-0.06\ syst}) \cdot 10^{21}$ yr = $(1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr

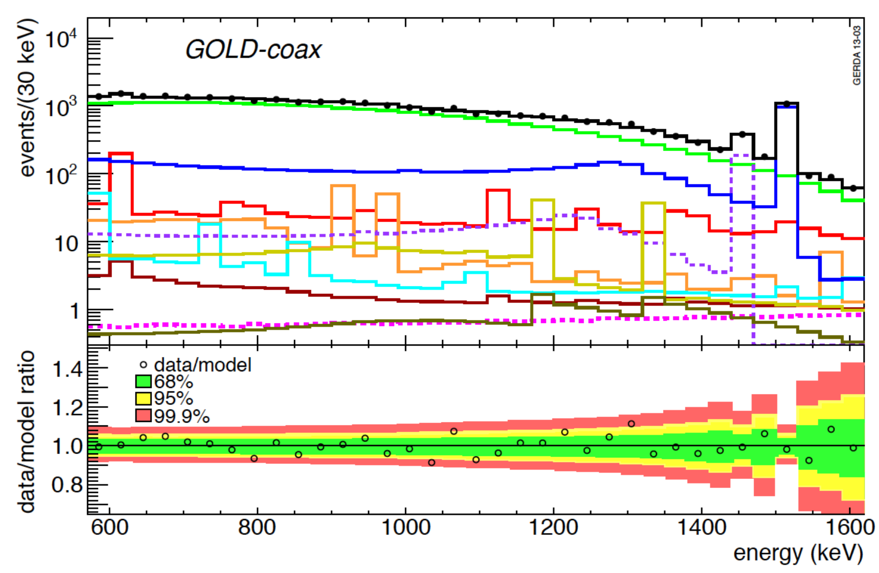
Background model

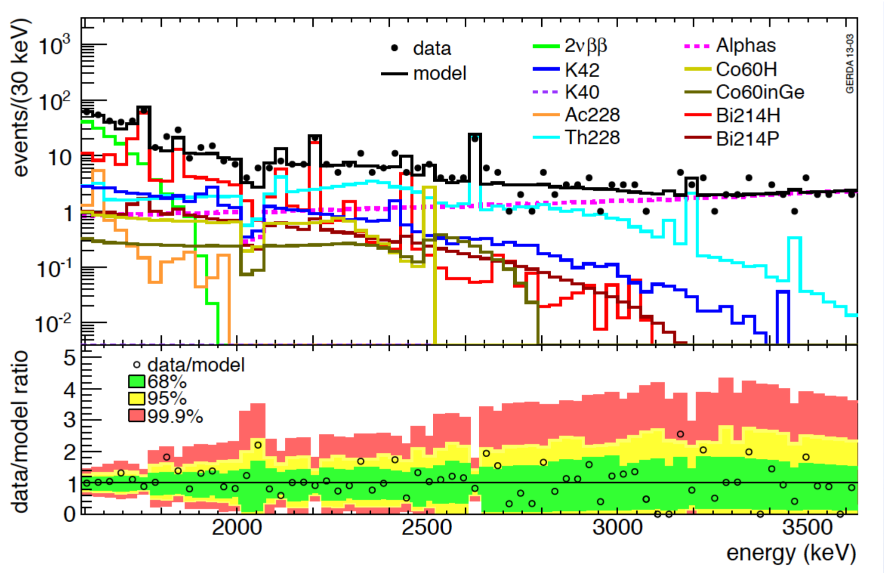
- simulate spectra of known and observed background sources

- spectral fit with combination of simulated spectra in [570;7500] keV (excluding blinded window)

EPJC 74 (2014) 2764

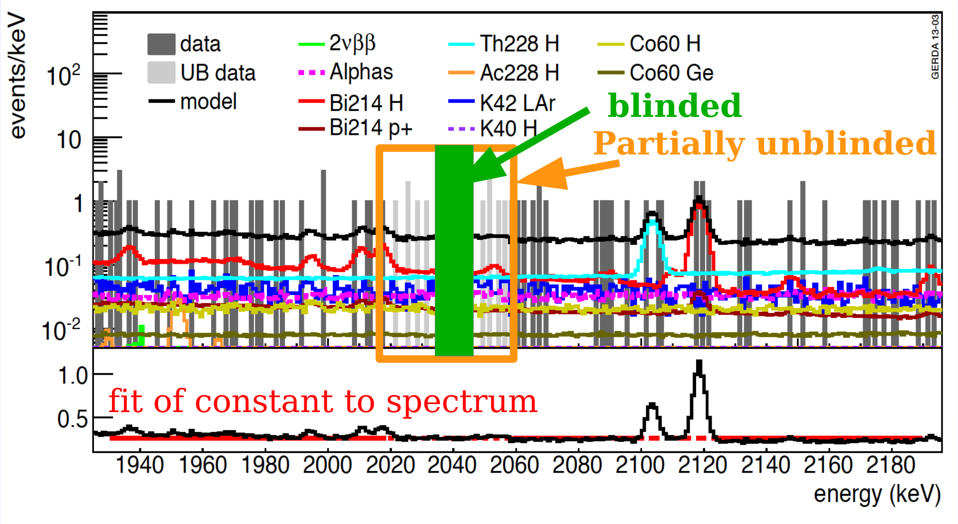




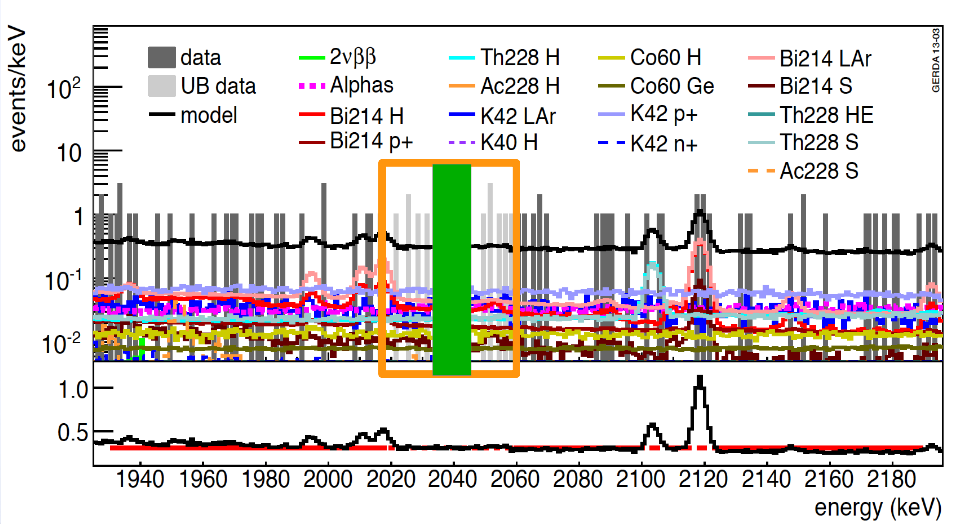


Background model

"Minimal" model (all known contributions)



"Maximum" model (addit. contributions)



Dominating contributions at $Q_{\beta\beta}$:

- β/γ events from ^{42}K, ^{60}Co, ^{214}Bi, ^{208}Tl
- α events from ^{238}U chain

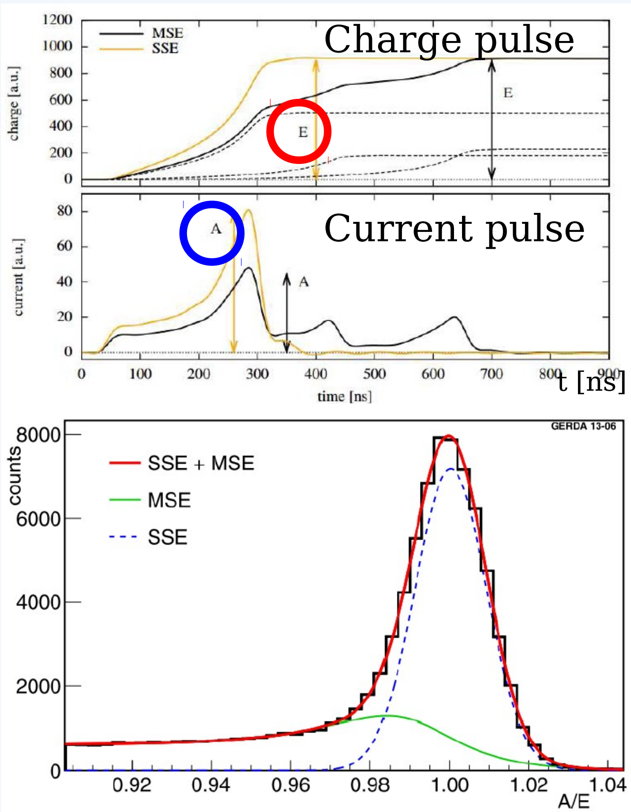
No γ-line expected in the blinded window!

Flat background between 1930 and 2190 keV
excluding known γ-lines:
(2104±5) keV (^{214}Bi)
(2119±5) keV (^{208}Tl SEP)
(valid for all data sets)

Partial unblinding after calibration & background model fixed:
→ no line observed
→ expected: 8.6-10.3 events
observed: 13 events

Pulse shape analysis (PSA)

BEGe detectors



BEGe detectors:

- cut based on **A**/**E**
- tuned using double escape peak of ^{208}Tl, compton continuum and $2\nu\beta\beta$ events
- background acceptance at $Q_{\beta\beta} \leq 20\%$

$$\varepsilon_{PSA} = 0.92 \pm 0.02 \text{ for SSE}$$

Semi-coaxial detectors:

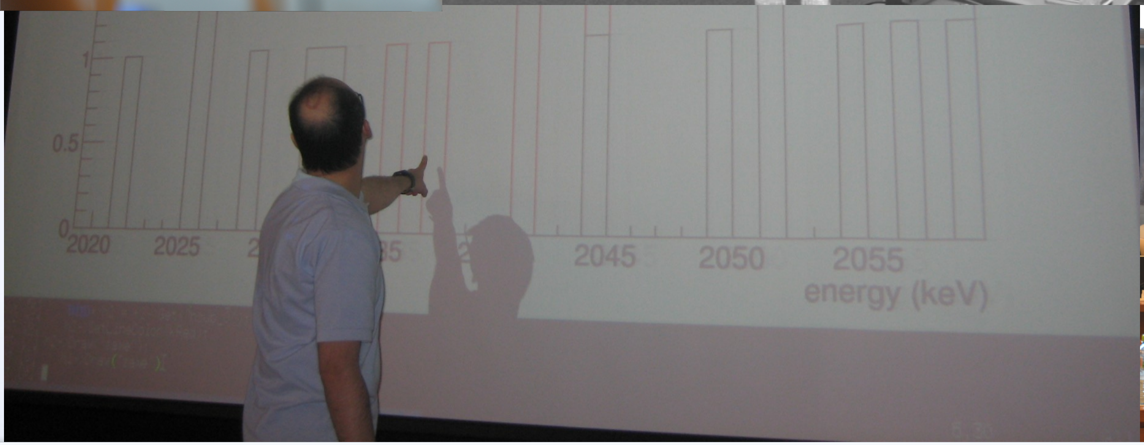
- **c**ut based on ANN using rising part of charge pulse
- tuned using double escape peak of ^{208}Tl, $2\nu\beta\beta$, compton edge events
- background acceptance at $Q_{\beta\beta} \sim 45\%$

$$\varepsilon_{PSA} = 0.90^{+0.05}_{-0.09} \text{ for SSE}$$

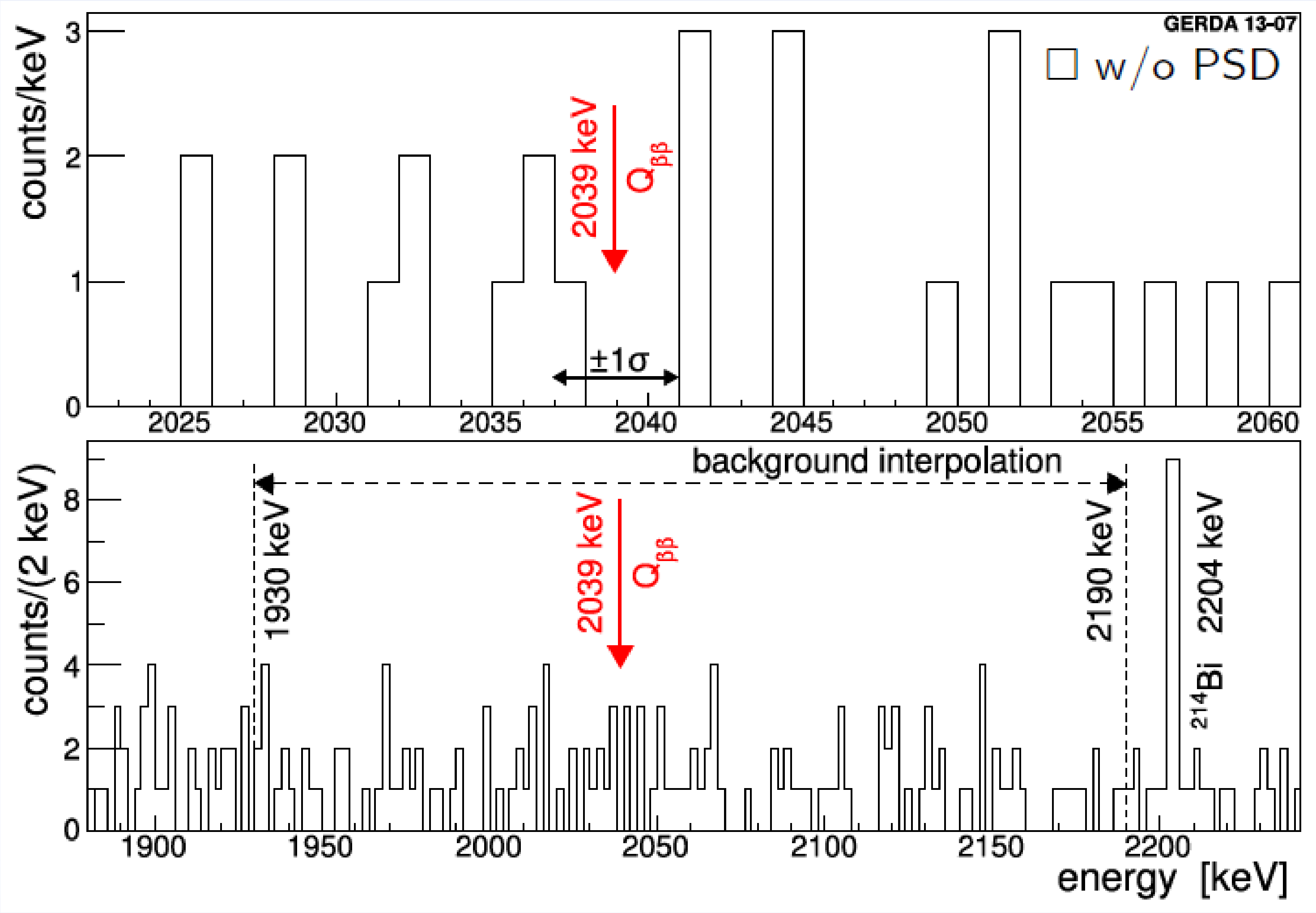
Eur.Phys.J C73 (2013) 2583

Unblinding Phase I data

At the GERDA collaboration meeting in Dubna, 12 June 2013

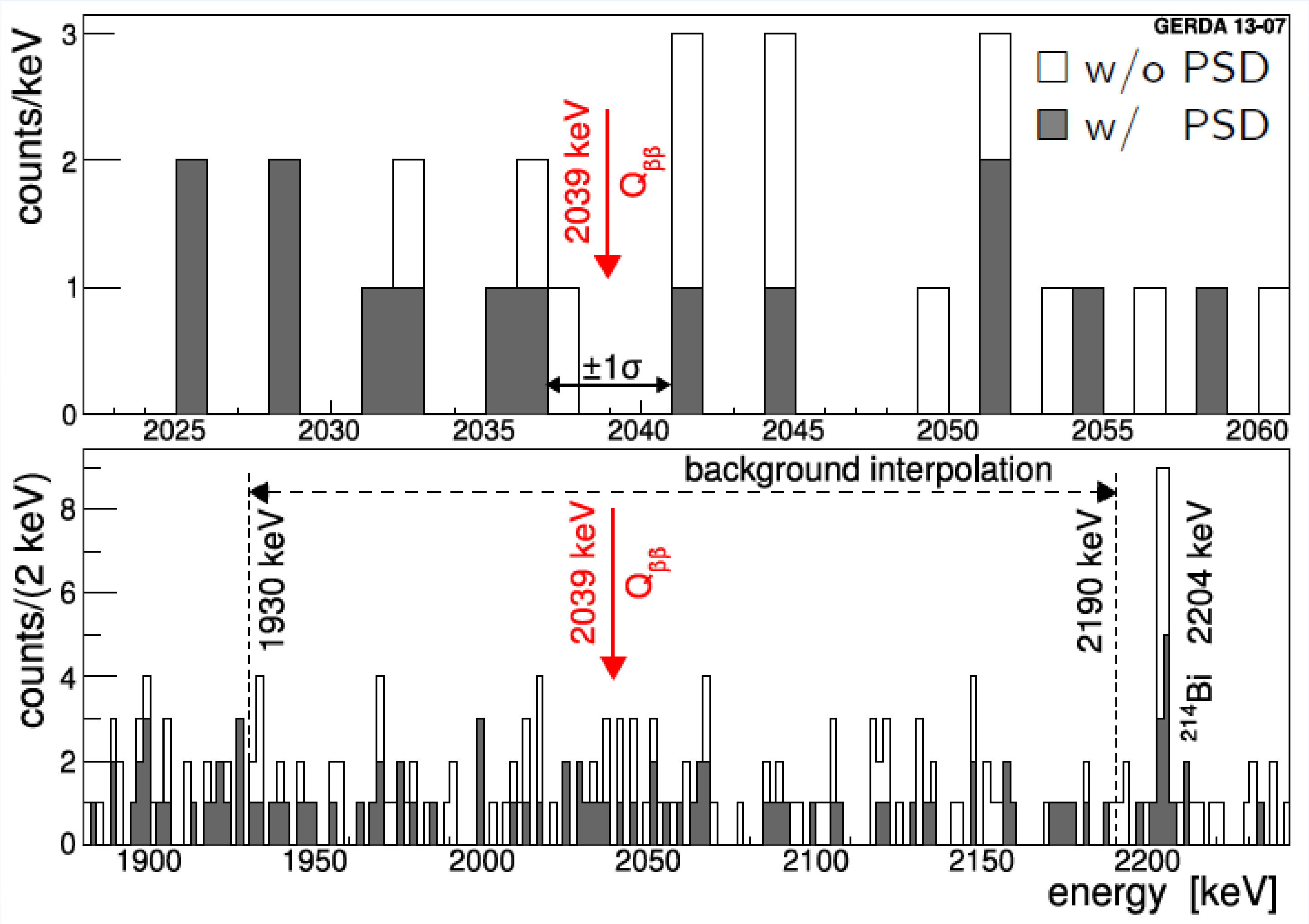


The unblinded energy spectrum



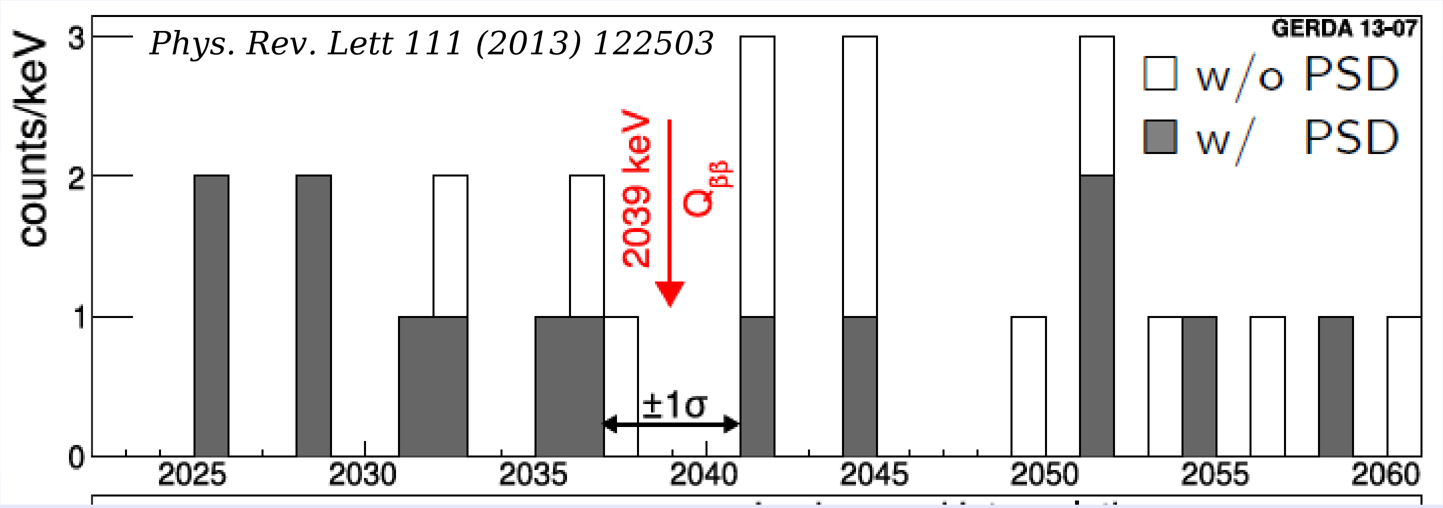
Phys. Rev. Lett 111 (2013) 122503

The unblinded energy spectrum



Phys. Rev. Lett 111 (2013) 122503

The unblinded energy spectrum

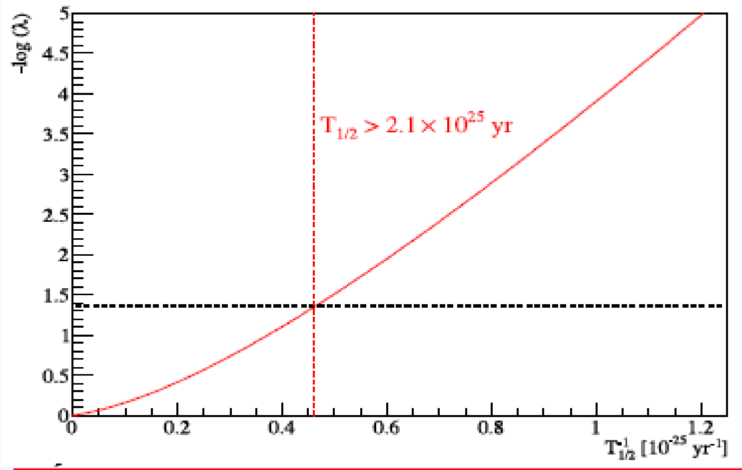


Data set	Exposure [kg·yr]	FWHM [keV]	Efficiency	BI [10^{-3} cts/(keV·kg·yr)]	Exp. counts in ($Q_{\beta\beta}$±5 keV)	Obs. counts in ($Q_{\beta\beta}$±5 keV)
Golden	17.3	4.8±0.2	0.688±0.031	18±2	3.3	5
Silver	1.3	4.8±0.2	0.688±0.031	63^{+15}_{-14}	0.8	1
BEGe	2.4	3.2±0.2	0.720±0.018	42^{+10}_{-8}	1.0	1
Golden	17.3	4.8±0.2	$0.619^{+0.044}_{-0.070}$	11±2	2.0	2
Silver	1.3	4.8±0.2	$0.619^{+0.044}_{-0.070}$	30^{+11}_{-9}	0.4	1
BEGe	2.4	3.2±0.2	0.663±0.022	5^{+4}_{-3}	0.1	0

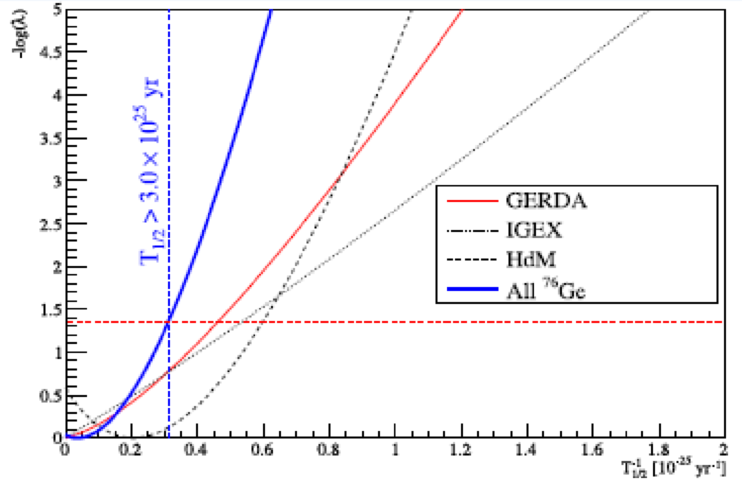
Data analysis

Baseline analysis with frequentist approach (profile likelihood)

Phys. Rev. Lett 111 (2013) 122503



- maximum likelihood spectral fit (constant+Gauss in [1930;2190] keV)
- 3 datasets
- 4 free parameters (3 constant background contributions, 1 common $T^{0\nu}_{1/2}$)
- systematic uncertainties in fit



GERDA only

Best fit: $N^{0\nu} = 0$

$N^{0\nu} < 3.5$ counts (90% C.L.)

→ $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

MC Median sensitivity (for no signal):

$T^{0n}_{1/2} > 2.4 \cdot 10^{25}$ yr (90% C.L.)

GERDA+IGEX[1]+HdM[2]

Best fit: $N^{0\nu} = 0$

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

[1] Eur. Phys. J. A 12, 147 (2001)
[2] Phys. Rev. D 65, 092007 (2002)

Hypothesis test for claimed signal

Claim: $T^{0\nu}_{1/2}=1.19^{+0.37}_{-0.23}\cdot 10^{25}$ yr [*Phys. Lett. B 586 (2004) 198*]

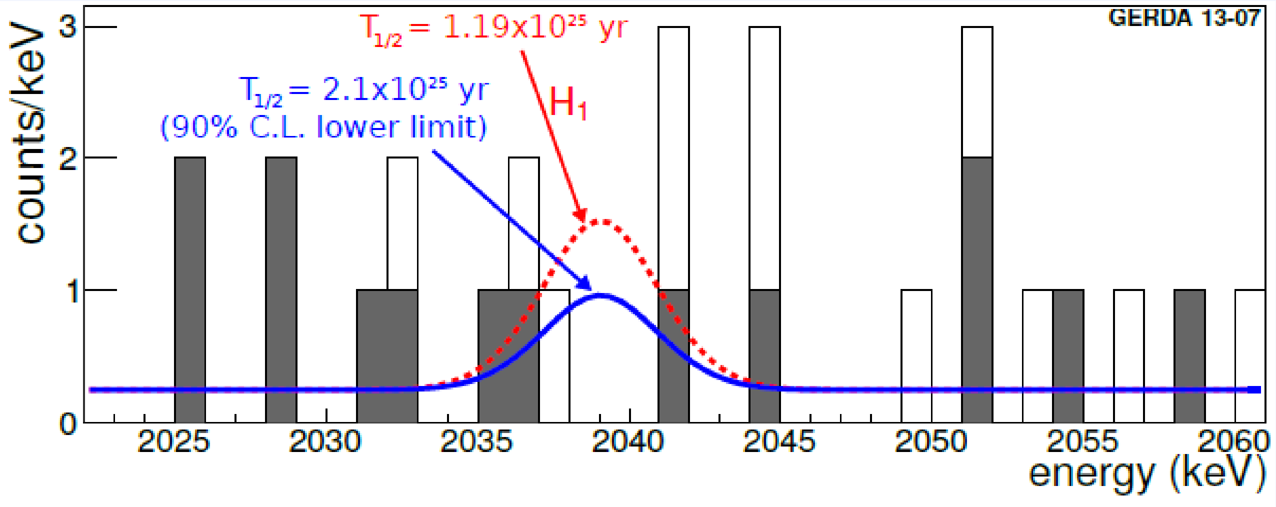
H_0: background only

Expected:
2.0±0.3 background counts
in $Q_{\beta\beta}\pm 2\sigma_E$

H_1: background + signal (claim)

Expected:
2.0±0.3 background counts
+ 5.9±1.4 signal counts in $Q_{\beta\beta}\pm 2\sigma_E$

Observed: 3 counts in $Q_{\beta\beta}\pm 2\sigma_E$



Phys. Rev. Lett 111 (2013) 122503

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

GERDA+IGEX+HdM
Bayes factor
$P(H_1)/P(H_0)=0.0002$

Hypothesis test for claimed signal

Claim: $T^{0\nu}_{1/2}=1.19^{+0.37}_{-0.23}\cdot 10^{25}$ yr [*Phys. Lett. B 586 (2004) 198*]

Claim strongly disfavoured!

H_0: background only

Expected:

2.0±0.3 background counts in $Q_{\beta\beta}\pm 2\sigma_E$

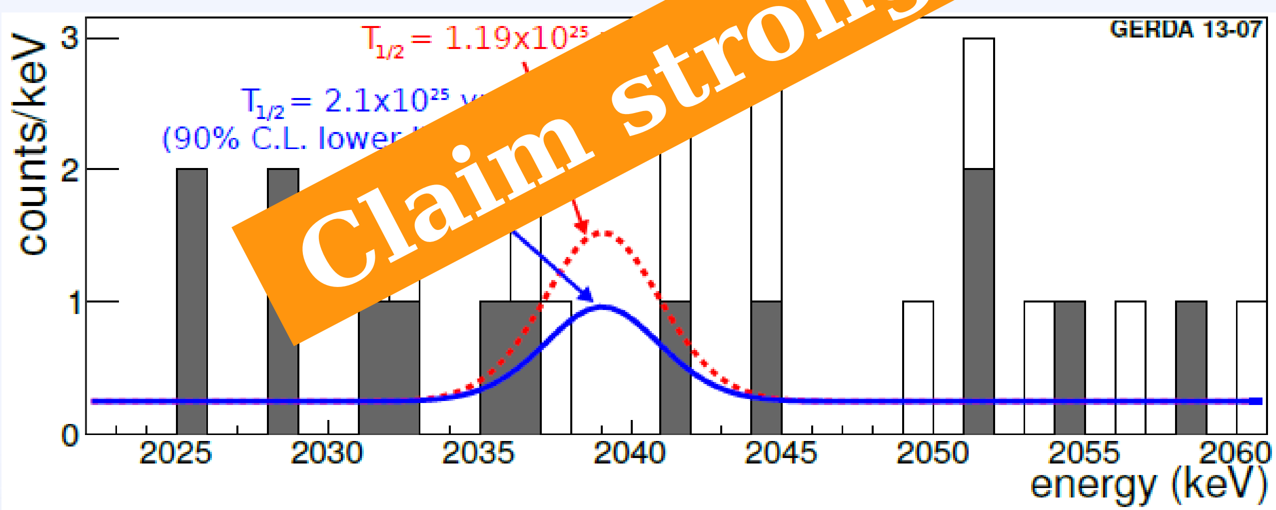
H_1: backgroun[illegible] (claim)

Expected[illegible]

2.0±0.[illegible]und counts

+ [illegible]ignal counts in $Q_{\beta\beta}\pm 2\sigma_E$

Observed: 3 c[illegible] $Q_{\beta\beta}\pm 2\sigma_E$



Phys. Rev. Lett 111 (2013) 122503

GERDA only

Profile likelihood:

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

Bayes factor

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

GERDA+IGEX+HdM

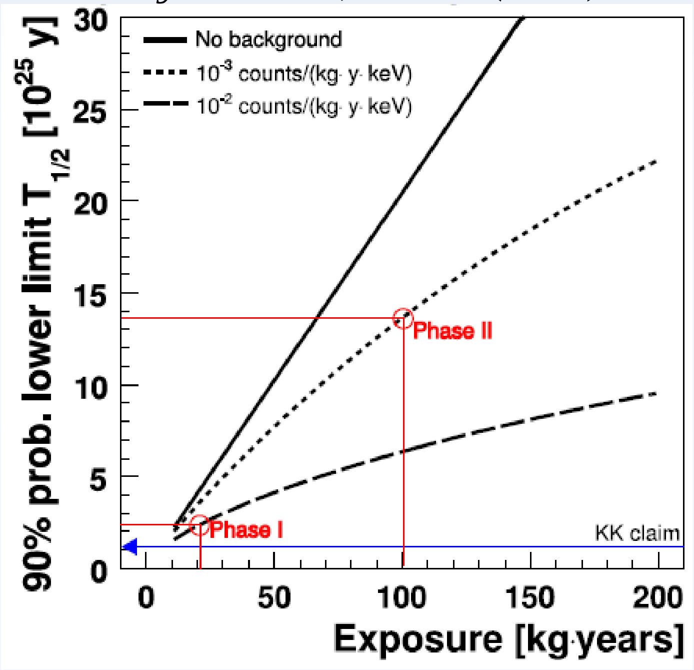
Bayes factor

$P(H_1)/P(H_0)=0.0002$

Transition to Phase II

- new BEGe detectors
  → increase mass by 20 kg
- enhanced energy resolution
- enhanced background suppression
  - good PSA performance of BEGe detectors
  - detection of coincident LAr scintillation light

Phys.Rev.D75, 092003 (2006)



~35 kg of detector mass

BI ≤10^{-3} cts/(keV·kg·yr)

Improve sensitivity by one order of magnitude within 5 years

Conclusions

- GERDA Phase I collected 21.6 kg·yr of exposure
- Measurement of $2\nu\beta\beta$ with ~5 kg·yr: $\mathbf{T^{2\nu}_{1/2}=(1.84^{+0.14}_{-0.10}) \cdot 10^{21}}$ **yr**
- Background at $Q_{\beta\beta}$ order of magnitude lower than previous experiments: $\mathbf{10^{-2}}$ **cts/(keV·kg·yr) after PSA**
- Blind analysis results in **no positive $0\nu\beta\beta$ signal**:
  $\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr (90% C.L.) with GERDA data**
  $\mathbf{T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}}$ **yr (90% C.L.) with GERDA+IGEX+HdM data**
- **Claim from *Phys. Lett. B 586 (2004) 198* strongly disfavored**, in a model–independent way

Additional material

Previous measurements and claim

Previous 0νββ experiments

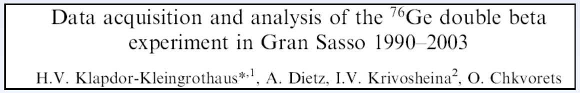
	HdM	IGEX
Location	LNGS	Homestake, Baksan, Canfranc
Exposure [kg·yr]	71.1	8.8
Bg [cts/(keV·kg·yr)]	≥ 0.11	0.17
$T_{1/2}$ limit (90% CL) [yr]	$1.9 \cdot 10^{25}$ [1]	$1.6 \cdot 10^{25}$ [2]

[1] *Eur. Phys. J. A12, 147-154 (2001)*
[2] *Phys. Rev. D 65, 092007 (2002)*

Claim of signal from part of HdM:

$T_{1/2}$ (^{76}Ge) = $1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr *Phys. Lett. B 586, 198-212 (2004)*

HdM claim


Data acquisition and analysis of the ^{76}Ge double beta experiment in Gran Sasso 1990–2003

H.V. Klapdor-Kleingrothaus*[,1], A. Dietz, I.V. Krivosheina[2], O. Chkvorets

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

BI 0.11 cts / (keV·kg·yr)

28.75 ± 6.87 events (bgd:~60)

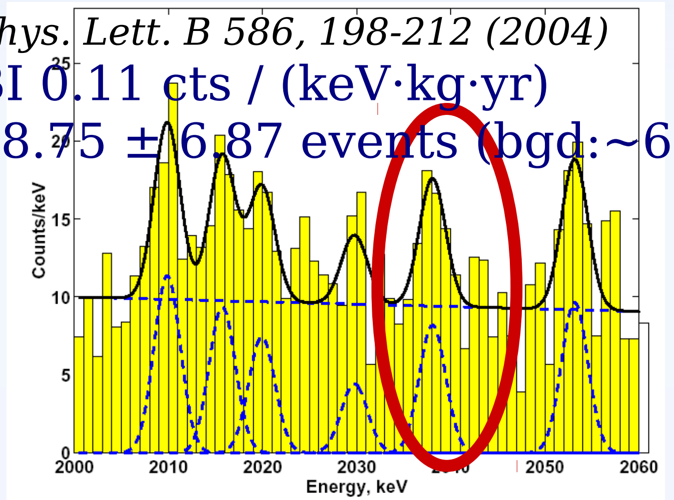
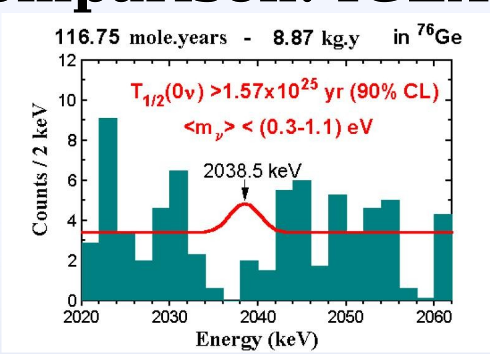


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

Comparison: IGEX



- Nov 1990 - May 2003
- 71.7 kg·yr
- 4.2σ/6σ evidence for $0\nu\beta\beta$

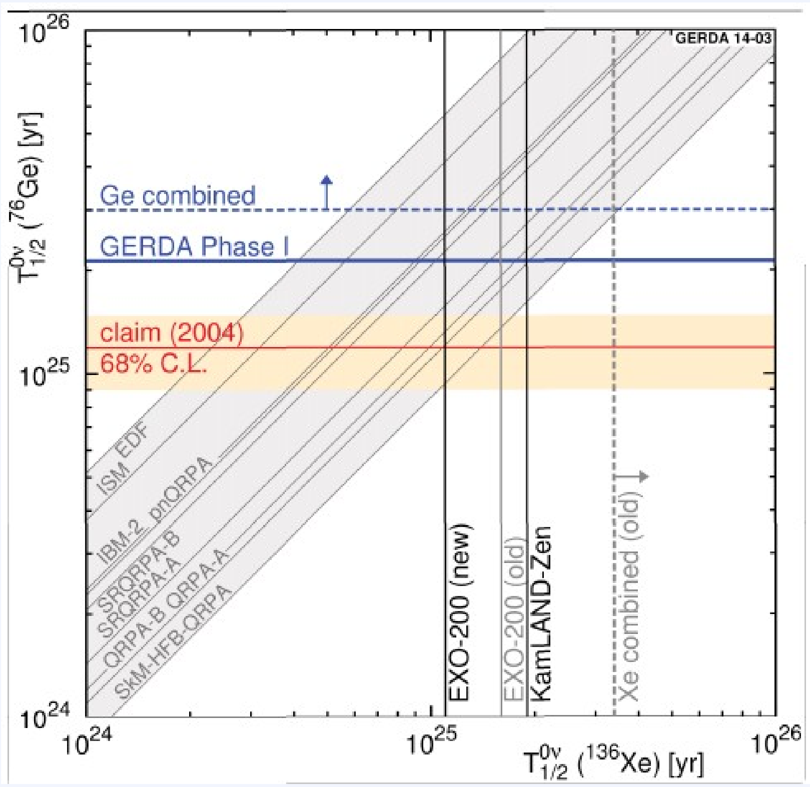
- $(0.69 – 4.18)\cdot 10^{25}$ yr (3σ)
  Best fit: $1.19\cdot 10^{25}$ yr
  Phys. Lett. B 586, 198-212 (2004)

  $2.23^{+0.44}_{-0.31}\cdot 10^{25}$ yr
  Mod. Phys. Lett. A 21, 1547-1566 (2006)
  Criticism in *Ann. Phys. 525, 269-280 (2013)*:
  Mainly: missing efficiency correction, uncertainty on signal counts smaller than Poissonian
- $m_{\beta\beta}$ = (0.24-0.58) eV
  (best fit 0.44 eV) /
  0.32±0.03 eV

Note: statistical significance depends on background model!

Comparison with ^{136}Xe experiments

Phys. Rev. Lett 111 (2013) 122503



Premise: leading mechanism is exchange of light neutrino

NME calculations:
Phys. Rev. D 88 (2013) 091301

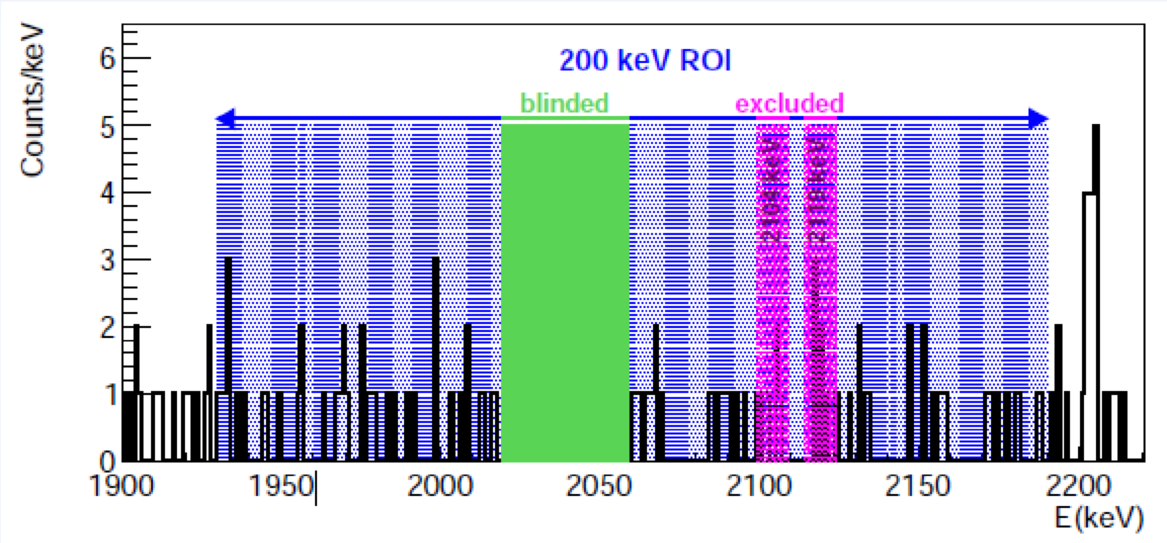
EXO-200 (new):
Nature 510 (2014) 229

KamLAND-Zen:
Phys. Rev. Lett. 110 (2013), 062502

^{136}Xe combined using the latest results (not shown on the plot):
$\mathbf{T^{0\nu}_{1/2} > 2.2 \cdot 10^{25}}$ **yr (90% C.L.)**
arXiv:1404.2616

BI definition

Definition of BI



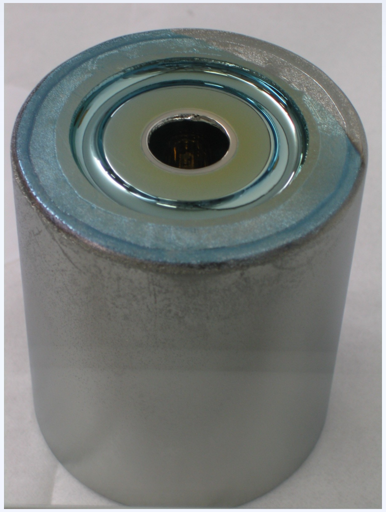
BI (10^{-3} cts/(keV·kg·yr)) after partial unblinding:

	Before PSA	After PSA
Golden:	$18.5^{+2.3}_{-2.2}$	$10.9^{+1.9}_{-1.6}$
Silver:	$63.4^{+18.0}_{-14.3}$	$30.1^{+13.7}_{-9.8}$
BEGe sum:	$41.3^{+10.4}_{-8.4}$	$5.4^{+5.2}_{-2.9}$

Germanium for the search of $0\nu\beta\beta$

Searching in ^{76}Ge

$$S \sim \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t_{run}}{BI \cdot \Delta E}}$$



Germanium detector

S: sensitivity
ε: efficiency
f: abundance of 0νββ isotope
M: detector mass

t_{run}: measurement time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Advantages of Germanium:

- **High ε**: Source = Detector
- **Small instrinsic BI**: High purity Ge
- **Excellent ΔE**: FWHM ~ (0.1-0.2)%
- Well-established technology

Disadvantages of Germanium:

- **High external BI:** $Q_{\beta\beta}$=2039keV
- **Small f of ^{76}Ge:** 7.8% → Enrichment needed!
- Limited sources of crystal & detector manufacturers
- Small $G^{0\nu}(Q_{\beta\beta},Z)$

Pulse Shape Analysis

Pulse shape analysis in ROI

Data set	Detector	E (keV)	Date	Passed PSA
golden	ANG5	2041.8	Nov 18, 2011 22:52	–
silver	ANG5	2036.9	Jun 23, 2012 23:02	√
golden	RG2	2041.3	Dec 16, 2012 00:09	√
BEGe	GD32B	2036.6	Dec 28, 2012 09:50	–
golden	RG1	2035.5	Jan 29, 2013 03:35	√
golden	ANG3	2037.4	Mar 2, 2013 08:08	–
golden	RG1	2041.7	Apr 27, 2013 22:21	–

Decays

Decay chains

^{238}U chain

Nuclide	mode	$T_{1/2}$	Q-value (keV)	decay product	E_γ (keV)
^{238}U	α	$4.5 \cdot 10^9$ yr	4270.0	^{234}Th	–
^{234}Th	β	24.1 d	273.0	^{234m}Pa	–
^{234m}Pa	β	1.2 min	2195.0	^{234}U	–
^{234}U	α	$2.5 \cdot 10^5$ yr	4858.5	^{230}Th	–
^{230}Th	α	$7.5 \cdot 10^4$ yr	2770.0	^{226}Ra	–
^{226}Ra	α	$1.6 \cdot 10^3$ yr	4870.6	^{222}Rn	–
^{222}Rn	α	3.8 d	5590.3	^{218}Po	–
^{218}Po	α	3.1 min	6114.7	^{214}Pb	–
^{214}Pb	β	26.8 min	1024.0	^{214}Bi	351.9
^{214}Bi	β	19.9 min	3272.0	^{214}Po	609.3
					768.4
					1120.3
					1238.1
					1764.5
					2204.2
^{214}Po	α	164.3 μs	7833.5	^{210}Pb	–
^{210}Pb	β	22.3 yr	63.5	^{210}Bi	–
^{210}Bi	β	5.0 d	1162.1	^{210}Po	–
^{210}Po	α	138.4 d	5407.5	^{206}Pb	–

^{232}Th chain

Nuclide	mode	$T_{1/2}$	Q-value (keV)	decay product	E_γ (keV)
^{232}Th	α	$1.4 \cdot 10^{10}$ yr	4082.8	^{228}Ra	–
^{228}Ra	β	5.8 yr	45.9	^{228}Ac	–
^{228}Ac	β	6.2 h	2127.0	^{228}Th	911.2
					969.0
^{228}Th	α	1.9 yr	5520.1	^{224}Ra	–
^{224}Ra	α	3.7 d	5788.9	^{220}Rn	–
^{220}Rn	α	55.6 s	6404.7	^{216}Po	–
^{216}Po	α	0.1 s	6906.5	^{212}Pb	–
^{212}Pb	β	10.6 h	573.8	^{212}Bi	–
^{212}Bi	β /	60.6 min	2254.0 /	^{212}Po /	727.3
	α		6207.1	^{208}Tl	
^{212}Po	α	0.3 μs	8954.1	^{208}Pb	–
^{208}Tl	β	3.1 min	5001.0	^{208}Pb	510.8
					583.2
					860.6
					2614.5

^{42}Ar: β (599 keV, 33 yr) → ^{42}K: β (3525.4 keV, 1524.7 keV photon, 12 h)
^{40}K: β/β^++ec (1311.1/1504.9 keV, 1460.8 keV photon, $1.3 \cdot 10^9$ yr)
^{60}Co: β (2823.9 keV, 1173.3 keV & 1332.5 keV photon, 5.3 yr)
^{68}Ge: ec (106.0 keV, 270 d) → ^{68}Ga: ec+β^+ (2921.1 keV, 1077.4 keV photon, 67.6 min)

Neutrino properties

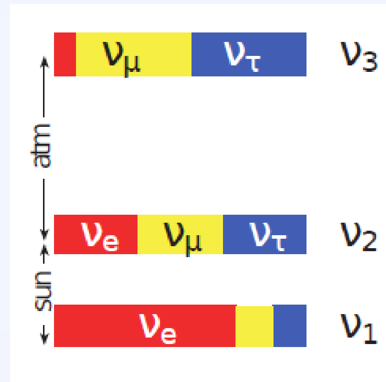
Neutrino properties

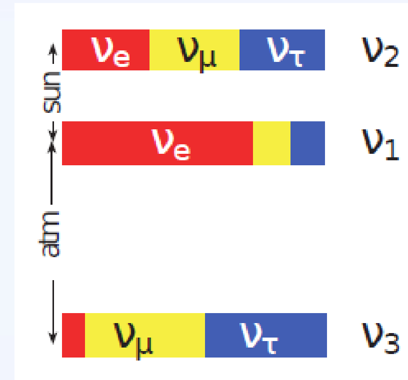
Neutrino Mixings

Weakly interacting and mass eigenstates are independant basis

$$\begin{bmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} |m_1\rangle \\ |m_2\rangle \\ |m_3\rangle \end{bmatrix}$$

$$U_{\nu i} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{bmatrix}$$





What we know:

- $m_2^2 - m_1^2 = \Delta m_{sun}^2$
- $m_2^2 - m_1^2 = \Delta m_{atm}^2$
- $\theta_{12} = \theta_{sun}$
- $\theta_{23} = \theta_{atm}$
- θ_{13}

What we do not know:

- Absolute mass scale
- Mass hierarchy
- Phases (δ_{13}, α_{21}, α_{31})
- Nature of the neutrino mass (Dirac or Majorana)
- CP violation in lepton sector?

parameter	best fit [1σ range]
$\Delta m^2_{21} (10^{-5} eV^2)$	7.62 [7.43, 7.81]
$\Delta m^2_{31} (10^{-3} eV^2)$	2.55 [2.46, 2.61]
	−2.43 [−2.37, −2.50]
$\sin^2\theta_{12}$	0.320 [0.303, 0.336]
$\sin^2\theta_{23}$	0.613 [0.573, 0.635]
	0.600 [0.569, 0.626]
$\sin^2\theta_{13}$	0.0246 [0.0218, 0.0275]
	0.0250 [0.0223, 0.0276]