XV International Workshop on Neutrino Telescopes

Venice, 11 -15 March 2013

Riccardo Brugnera

Padova University and INFN

on behalf of the

GERDA Collaboration

Status of the GERDA experiment

Outline:

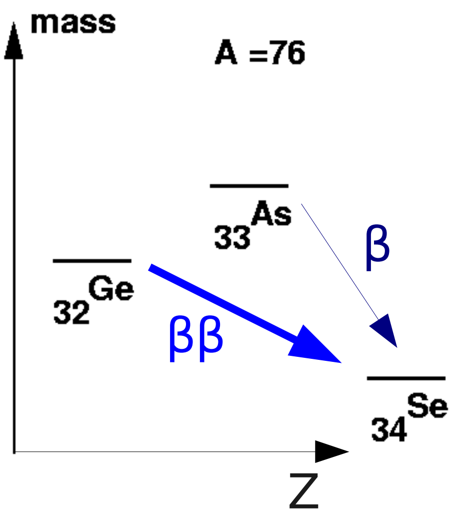
- Double Beta Decay
- GERDA design
- Status of Phase I
- First results from Phase I
- Status of Phase II
- Summary

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays

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

2^{nd} order process, observed, $T_{1/2} \sim 10^{19}$-10^{24} yrs

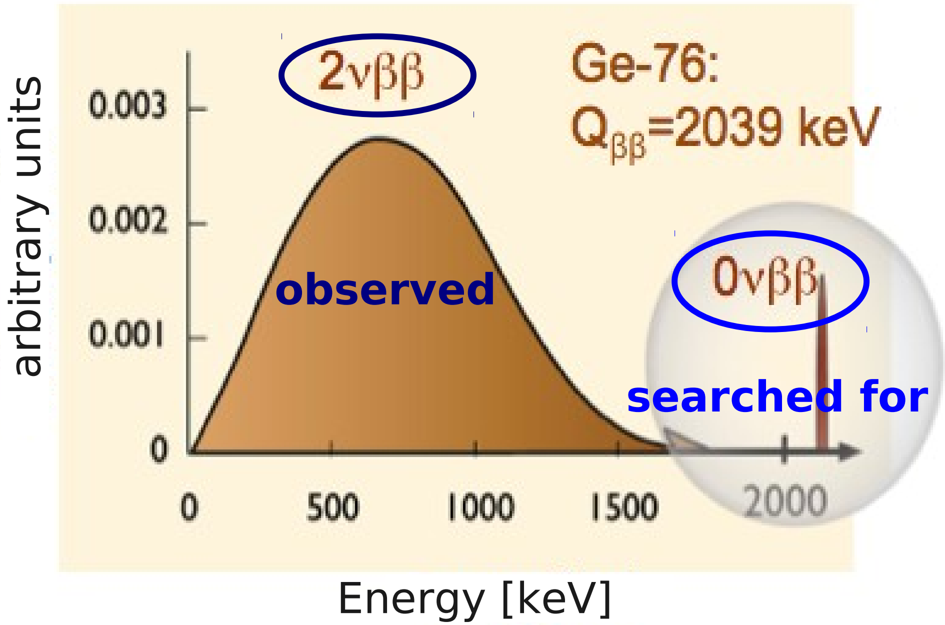
^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs



$$0\nu\beta\beta : (A,Z) \rightarrow (A,Z+2) + 2e^-$$

new physics, $T_{1/2} > 10^{25}$ yrs

Signature for $0\nu\beta\beta$ decays:

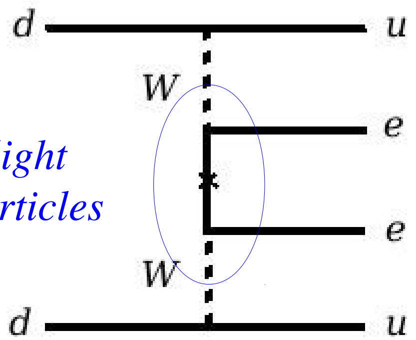


motivation for $0\nu\beta\beta$ decay searches

- would establish ***lepton number violation*** $\Delta L = 2$
- more ***physics beyond standard model***
- Only way to determine if neutrino is its own antiparticle:

$$\nu = \bar{\nu}$$ ⇨ ***Majorana particle***

exchange of light Majorana particles



If YES:

- would provide access to ***absolute neutrino mass scale***

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

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

nuclear matrix element

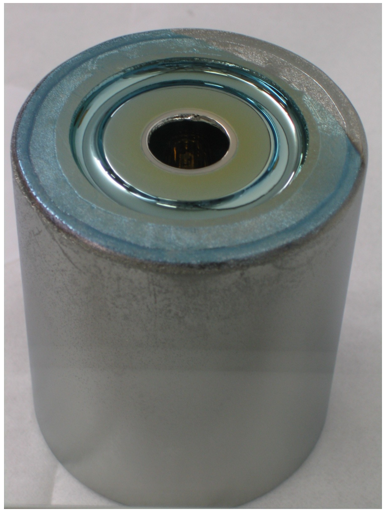
phase space factor

effective Majorana neutrino mass

- would provide ***important input to cosmology***

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:

- at $Q_{\beta\beta}$= 2039keV more challenging to reach **low enough background**
- **Small f of ^{76}Ge:** 7.8% → Enrichment needed!
- Limited sources of crystal & detector manufacturers
- Small $G^{0\nu}(Q_{\beta\beta},Z)$

Previous ^{76}Ge experiments

	HdM	IGEX
Location	LNGS	Homestake, Baksan, Canfranc
Exposure [kg·yr]	71.1	8.9
BI [cts/(keV·kg·yr)]	0.16	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) = $(0.69 – 4.18) \cdot 10^{25}$ yr (3σ) (Best fit: $T_{1/2}$ (^{76}Ge) = $1.19 \cdot 10^{25}$ yr)
Phys. Lett. B 586, 198-212 (2004)

GERmanium Detector Array (GERDA)

a) INFN Laboratori Nazionali del Gran Sasso, LNGS, Assergi, Italy
b) Institute of Physics, Jagiellonian University, Cracow, Poland
c) Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
d) Joint Institute for Nuclear Research, Dubna, Russia
e) Institute for Reference Materials and Measurements, Geel, Belgium
f) Max Planck Institut für Kernphysik, Heidelberg, Germany
g) Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy
h) INFN Milano Bicocca, Milano, Italy
i) Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy
j) Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
k) Institute for Theoretical and Experimental Physics, Moscow, Russia
l) National Research Centre "Kurchatov Institute", Moscow, Russia
m) Max-Planck-Institut für Physik, München, Germany
n) Physik Department and Excellence Cluster Universe, Technische Universität München, Germany
o) Dipartimento di Fisica e Astronomia dell'Università di Padova, Padova, Italy
p) INFN Padova, Padova, Italy
q) Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
r) Physik Institut der Universität Zürich, Zürich, Switzerland

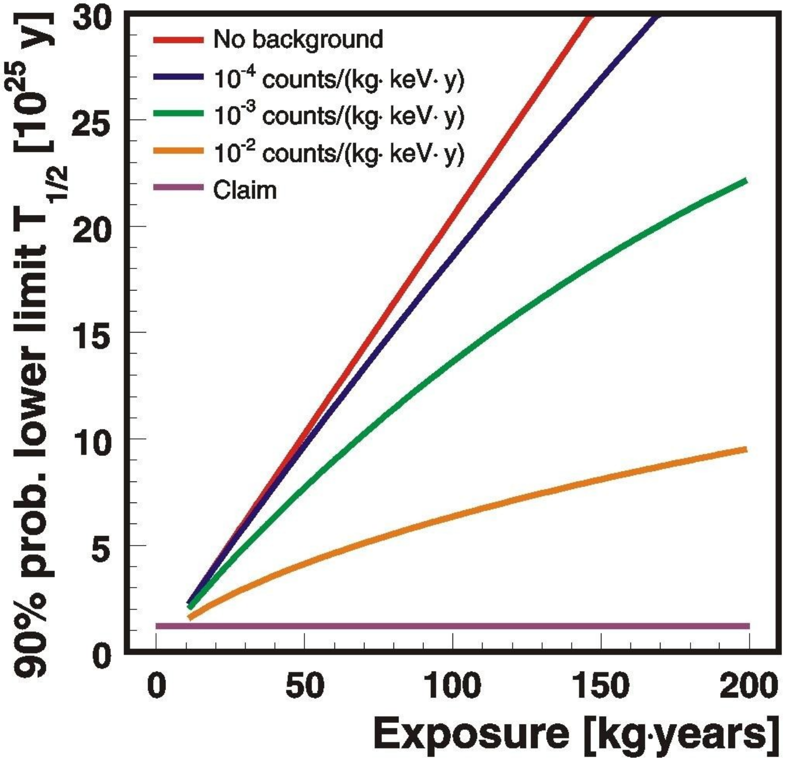
The GERDA collaboration

111 members, 18 institutes, 6 countries

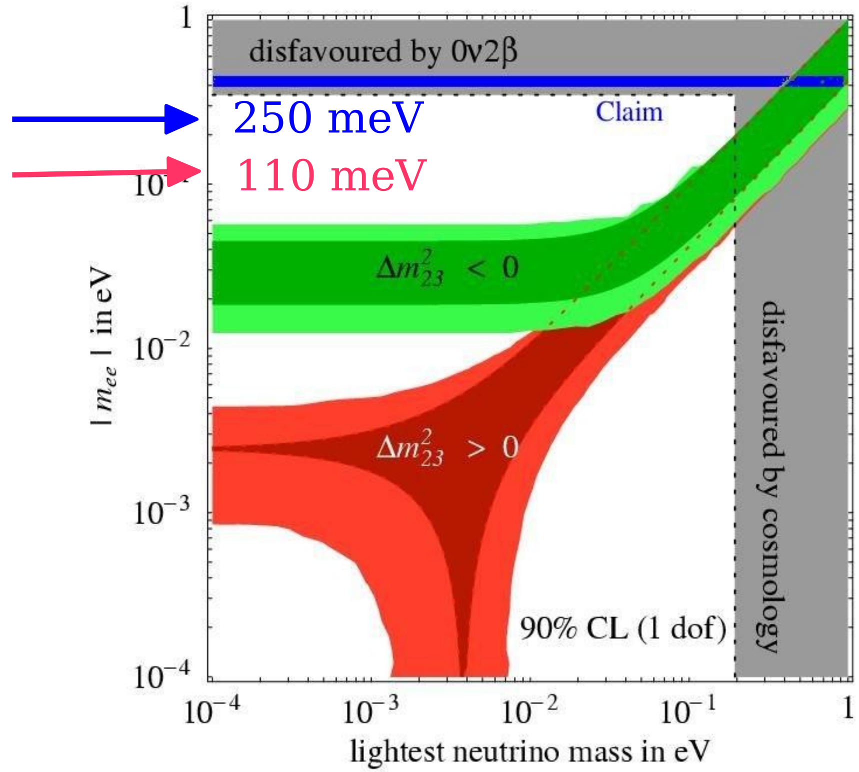
- Bare ^{enr}Ge array in liquid Argon
- Shield: high-purity liquid Argon / H_2O
- **Phase I:** 18 kg enriched coaxial detectors (~86%)(HdM/IGEX)
- **Phase II:** add ~20 kg new enriched BEGe detectors
- For future ton scale experiment: Merge with Majorana collaboration (already open exchange of knowledge and technologies)

GERDA physics goal

Phys. Rev. D 092003 (2006)



F. Feruglio, A. Strumia, F. Vissani, NPB 659



Phase I:

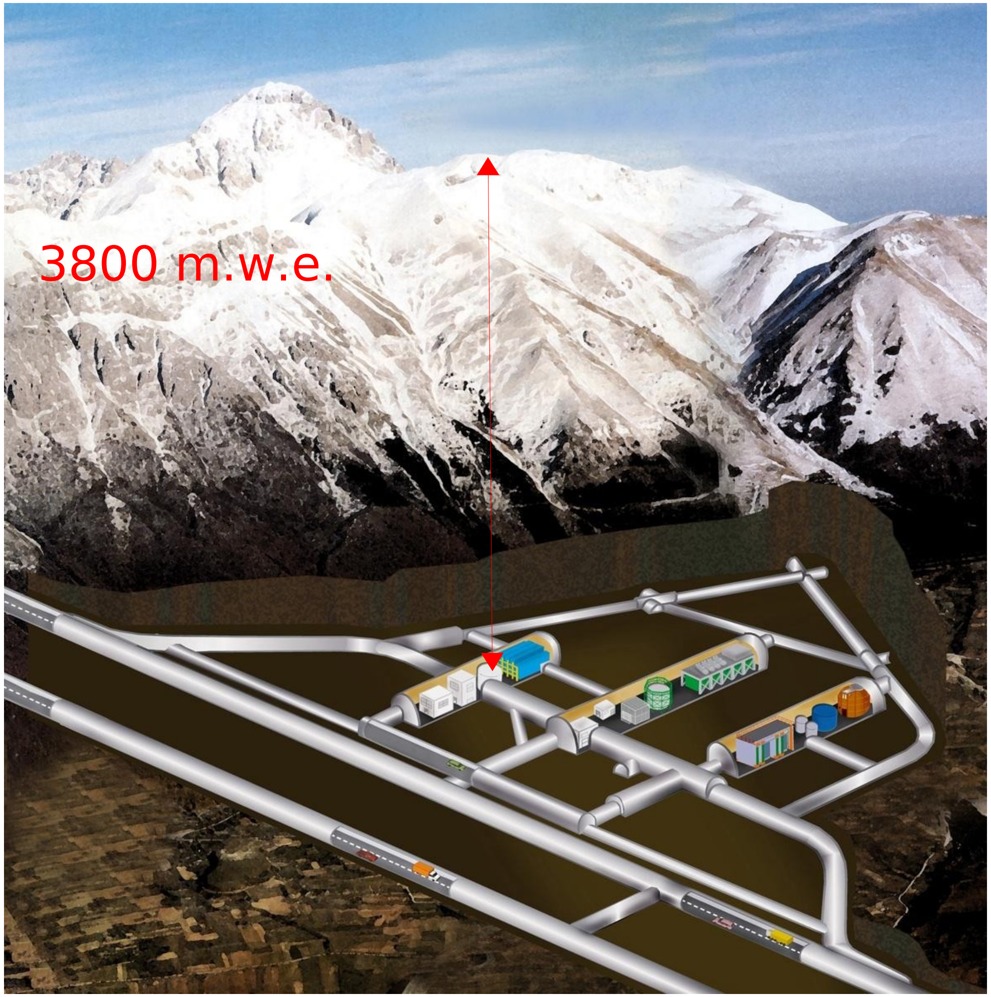
- reach sensitivity of $T_{1/2} = 2\cdot10^{25}$ yr at 90% C.L.
- $<m_{\beta\beta}> \leq$ 0.23-0.39 eV
- → **check claim!**

Phase II:

- reach background of **10^{-3} cts/(keV·kg·yr)**
- Exposure of 100 kg·yr → $T_{1/2}$ > $1.35\cdot10^{26}$ yr
- $<m_{\beta\beta}> \leq$ 0.09-0.15 eV

Gerda @ LNGS: Background reduction

- **GERDA situated in LNGS underground laboratories**
- 3800 m.w.e.



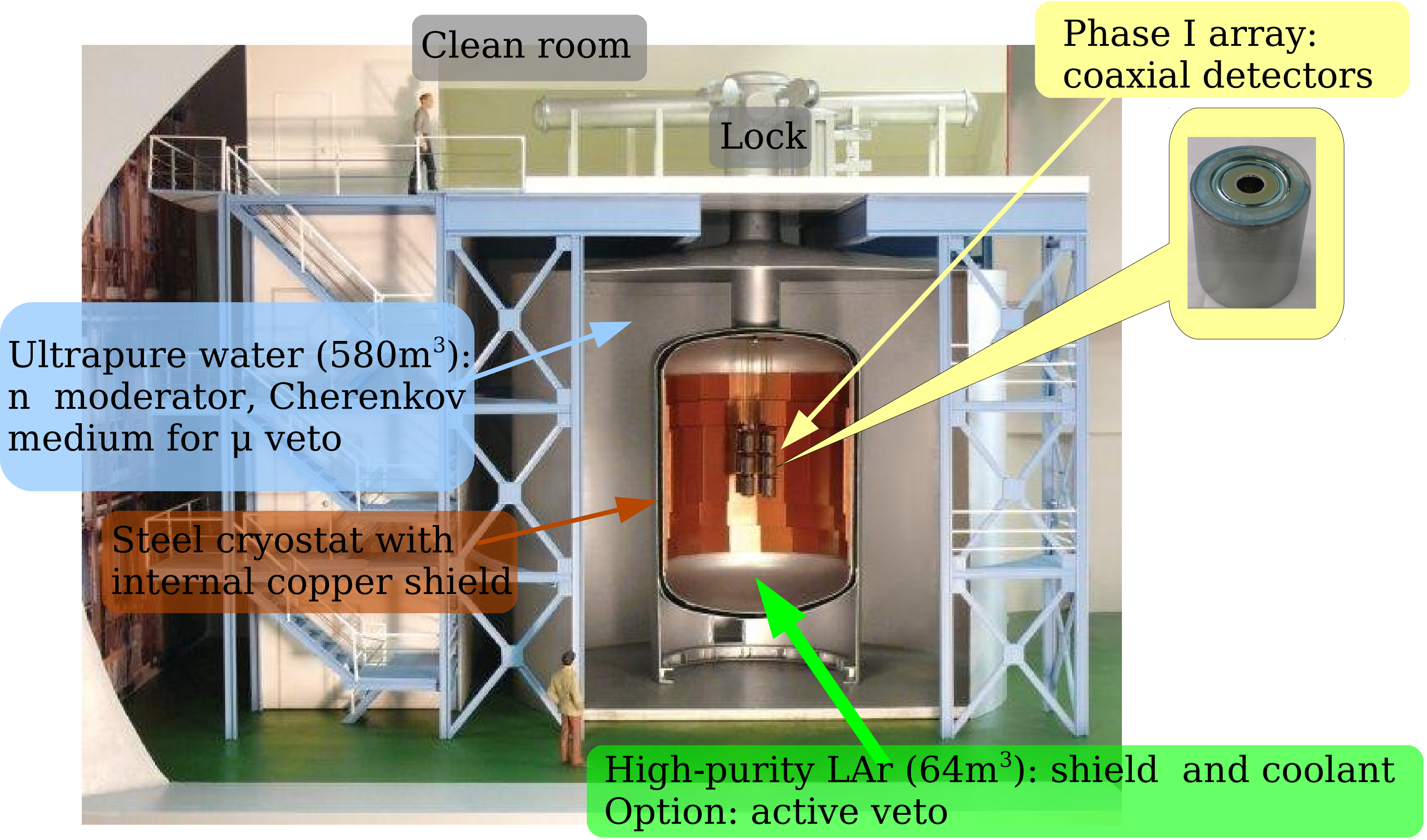
Possible **backgrounds** from:

External:
- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

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

Gerda @ LNGS: Background reduction

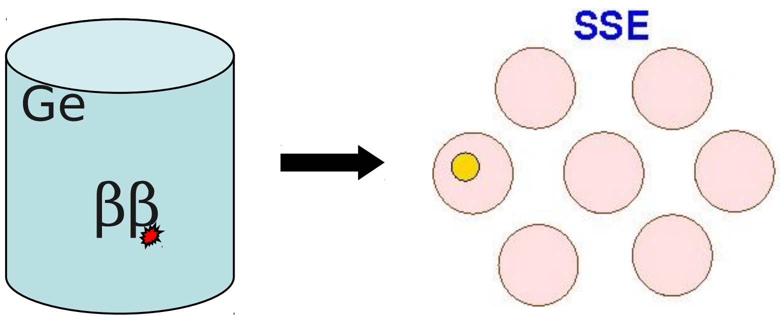
- Graded shielding against ambient radiation
- Rigorous material selection, avoid exposure above ground for detectors



The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge
Eur. Phys. J. C (2013) 73:2330

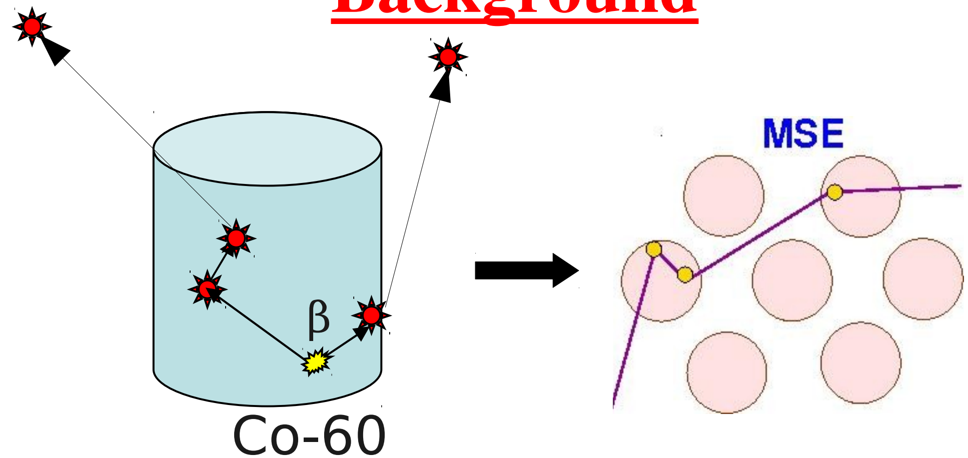
Background reduction

Signal



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

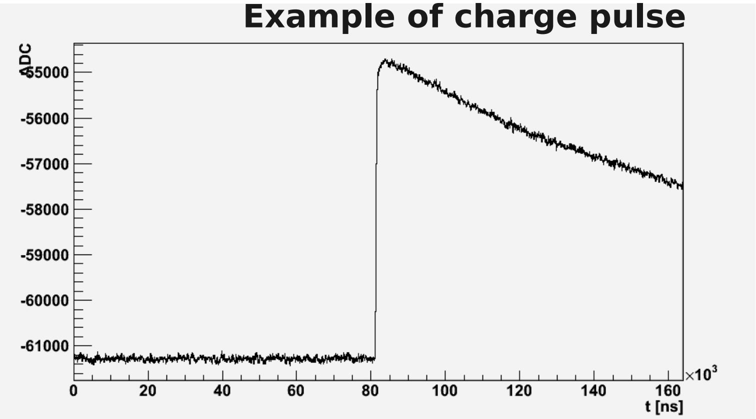
Background



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

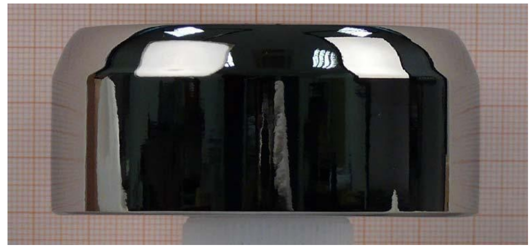
Signal analysis:

- anti-coincidence between detectors
- pulse shape analysis (PSA) with Phase II BEGe detectors

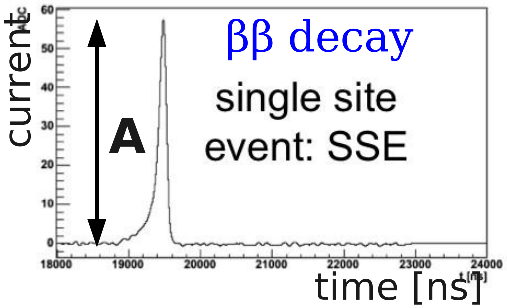


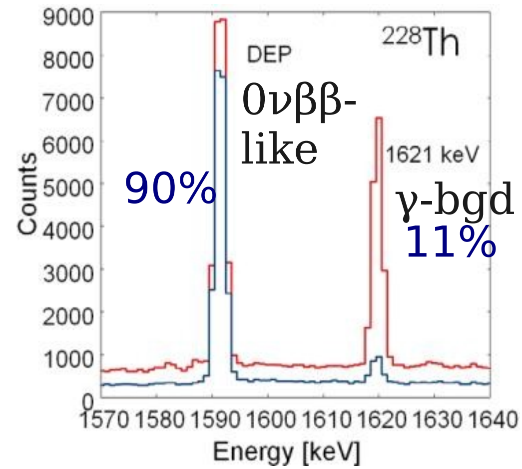
Background reduction Phase II

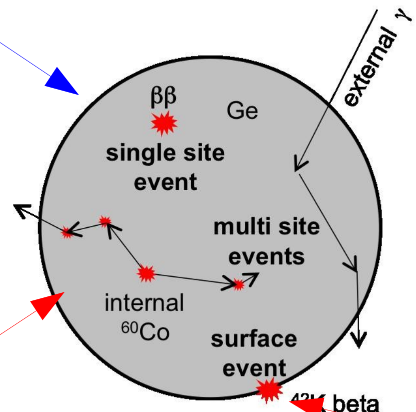
BEGe detectors: strongly non-linear field allows improved PSA



ACCEPT







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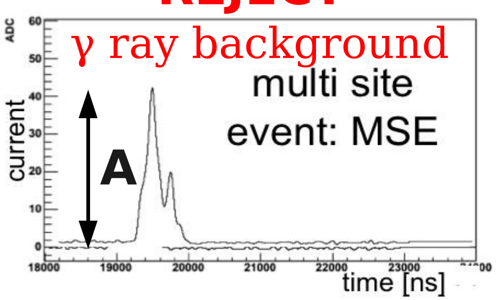
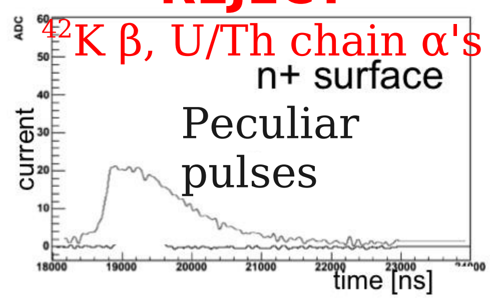


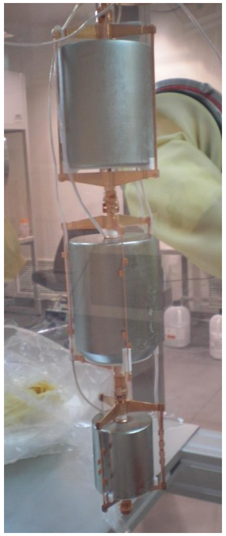
REJECT

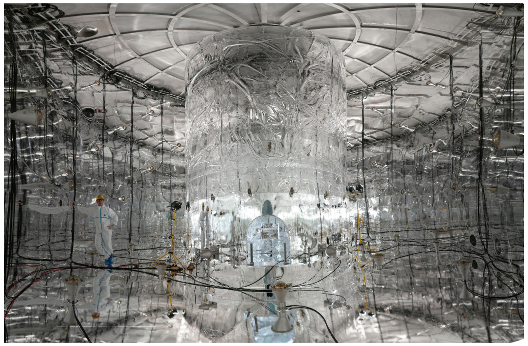


D. Budjas et al., NPB Procs. Suppl. 229-232 (2012) 489
M. Agostini et al., JINST 6 (2011) P04005
M. Agostini et al., JINST 6 (2011) P03005
M. Barnabe Heider et al., JINST 5 (2010) P10007
D. Budjas et al., JINST 4 (2009) P10007

→ **see S. Hemmer's poster**

The GERDA experiment



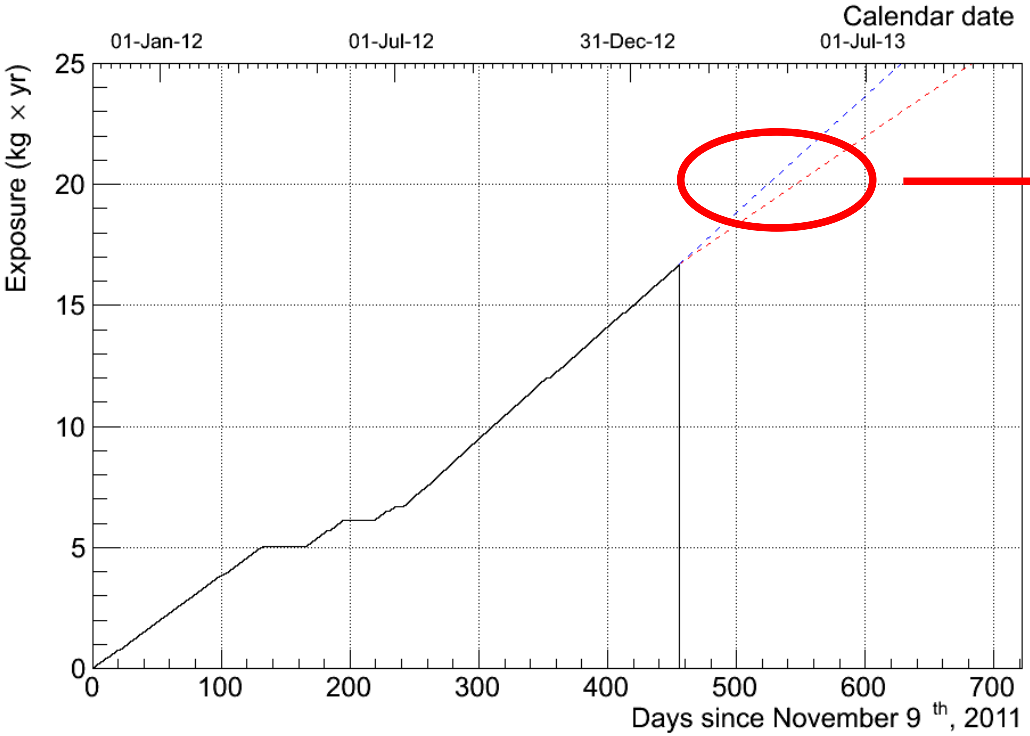


Data taking

9 November 2011: Start of Phase I
All **8 ^{enr}Ge + 3 ^{nat}Ge coaxial detectors** deployed in GERDA
(2 ^{enr}Ge detectors cannot be used for analysis due to high leakage current)

7 July 2012: Insert **5 ^{enr}Ge BEGe** detectors
(Remove 2 ^{nat}Ge detectors)

9 Nov 2011 – 7 Feb 2013:
372.8 live days / 16.71 kg·yr enr exposure



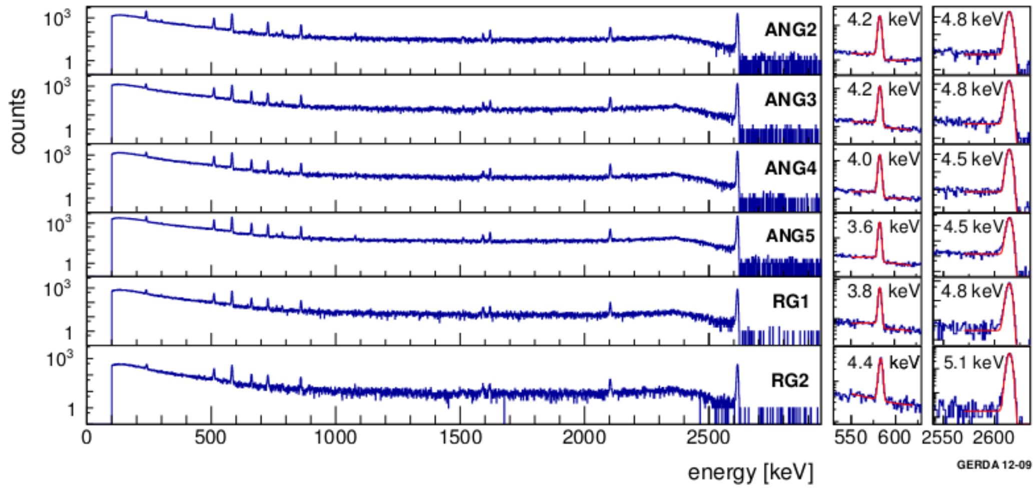
The **Phase I** *data taking will last up to the collection of an exposure of* **20 kg.yr**

… then in summer the modification of the detector for **Phase II** will start

Energy resolution

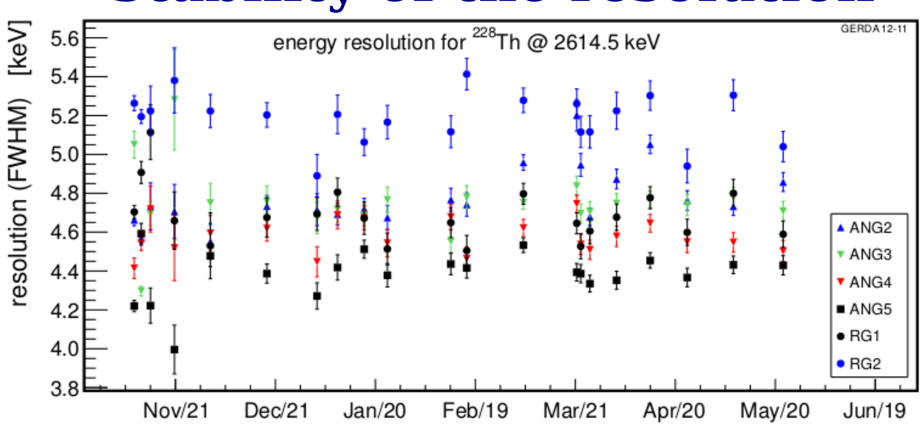
The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge
Eur. Phys. J. C (2013) 73:2330

Calibration spectra for ^{enr}Ge detectors with ^{228}Th source

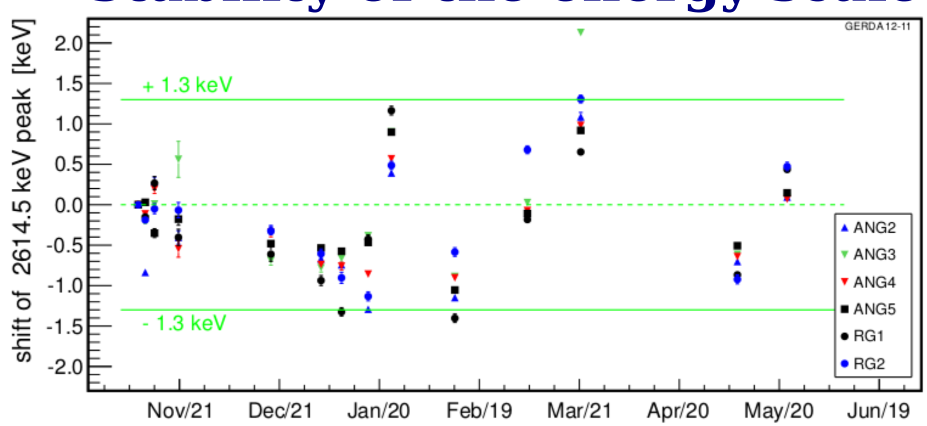


Mass weighted average for **FWHM at $Q_{\beta\beta}$ = 4.5 keV**

Stability of the resolution

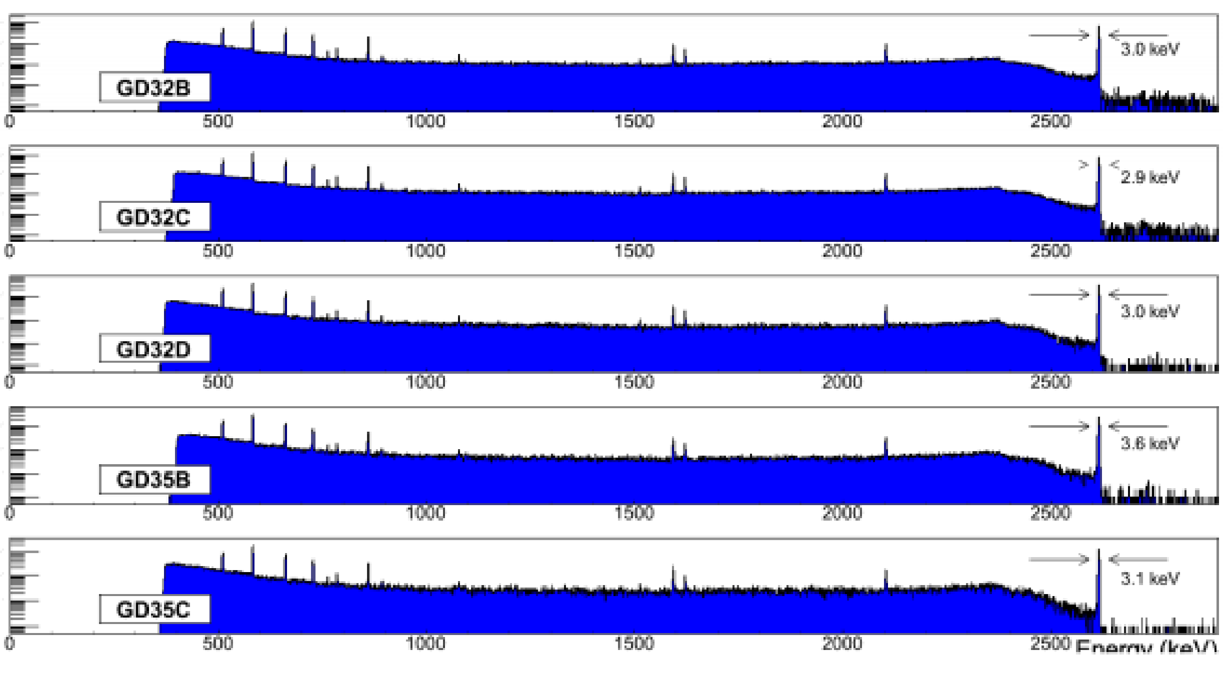


Stability of the energy scale



First BEGe's in GERDA

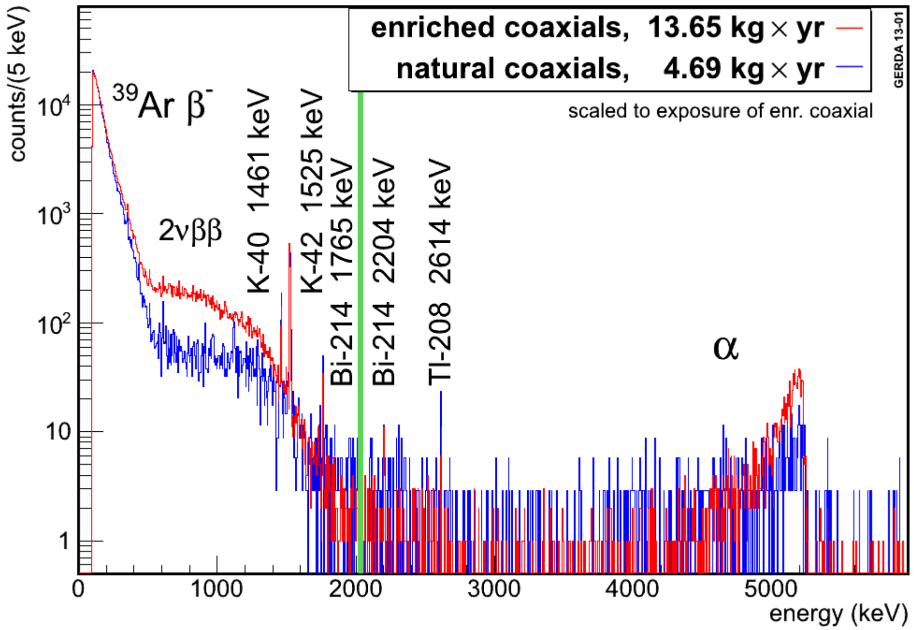
Calibration spectra

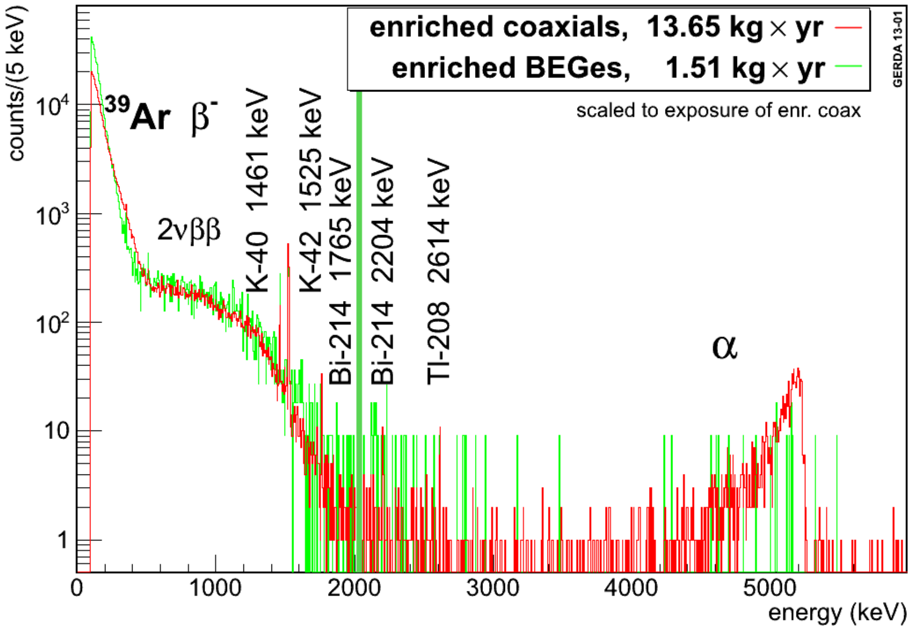


Energy resolution and PSA properties

Detector	E resolution [keV]	A/E res.	A/E res. HADES
Agamennone (GD32B)	*2.88 ± 0.02*	*1.5%*	*0.8%*
Andromeda (GD32C	*2.84 ± 0.02*	*1.7%*	*1.3%*
Anubis (GD32D)	*2.96 ± 0.04*	*1.7%*	*1.6%*
Achilles(GD35B)	*3.61 ± 0.05*	*1.9%*	*0.6%*
Aristoteles(GD35C)	*3.09 ± 0.06*	*1.7%*	*1.7%*

Energy spectra





Data blinded between 2019 keV and 2059 keV

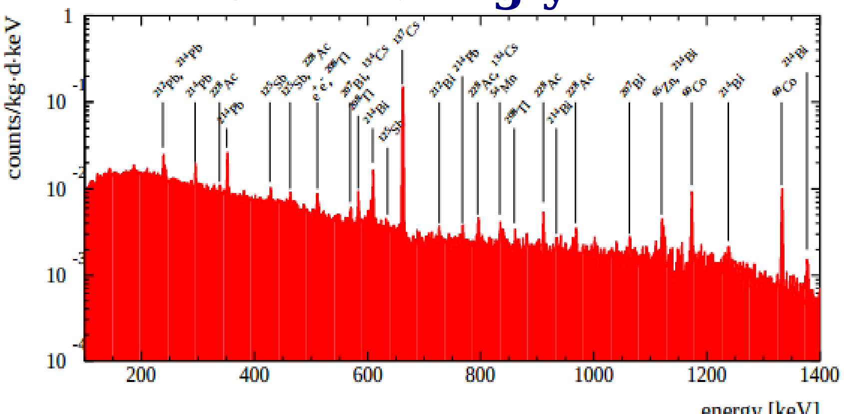
Background lines

The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge
Eur. Phys. J. C (2013) 73:2330

isotope	energy [keV]	^{nat}Ge (3.17 kg·yr) tot/bck [cts]	^{nat}Ge (3.17 kg·yr) rate [cts/(kg·yr)]	^{enr}Ge (6.10 kg·yr) * tot/bck [cts]	^{enr}Ge (6.10 kg·yr) * rate [cts/(kg·yr)]	HdM (71.7 kg·yr) rate [cts/(kg·yr)]	Rate HdM/ ^{enr}coaxial
^{40}K	1460.8	85 / 15	$21.7^{+3.4}_{-3.0}$	125 / 42	$13.5^{+2.2}_{-2.1}$	181 ± 2	13
^{60}Co	1173.2	43 / 38	< 5.8	182 / 152	$4.8^{+2.8}_{-2.8}$	55 ± 1	11
	1332.3	31 / 33	< 3.8	93 / 101	< 3.1	51 ± 1	
^{137}Cs	661.6	46 / 62	< 3.2	335 / 348	< 5.9	282 ± 2	>48
^{228}Ac	910.8	54 / 38	$5.1^{+2.8}_{-2.9}$	294 / 303	< 5.8	29.8 ± 1.6	
	968.9	64 / 42	$6.9^{+3.2}_{-3.2}$	247 / 230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1	
^{208}Tl	583.2	56 / 51	< 6.5	333 / 327	< 7.6	36 ± 3	
	2614.5	9 / 2	$2.1^{+1.1}_{-1.1}$	10 / 0	$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5	11
^{214}Pb	352	740 / 630	$34.1^{+12.4}_{-11.0}$	1770 / 1688	$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8	11
^{214}Bi	609.3	99 / 51	$15.1^{+3.9}_{-3.9}$	351 / 311	$6.8^{+3.7}_{-4.1}$	105 ± 1	
	1120.3	71 / 44	$8.4^{+3.5}_{-3.3}$	194 / 186	< 6.1	26.9 ± 1.2	
	1764.5	23 / 5	$5.4^{+1.9}_{-1.5}$	24 / 1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7	~10
	2204.2	5 / 2	$0.8^{+0.8}_{-0.7}$	6 / 3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5	

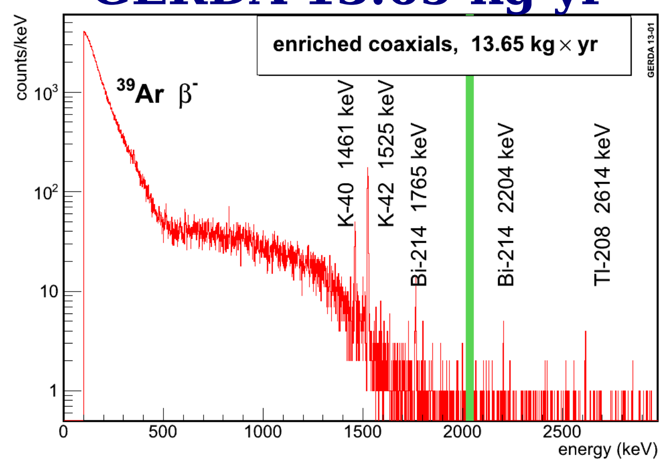
* only coaxial detectors

HdM 47.4 kg·yr



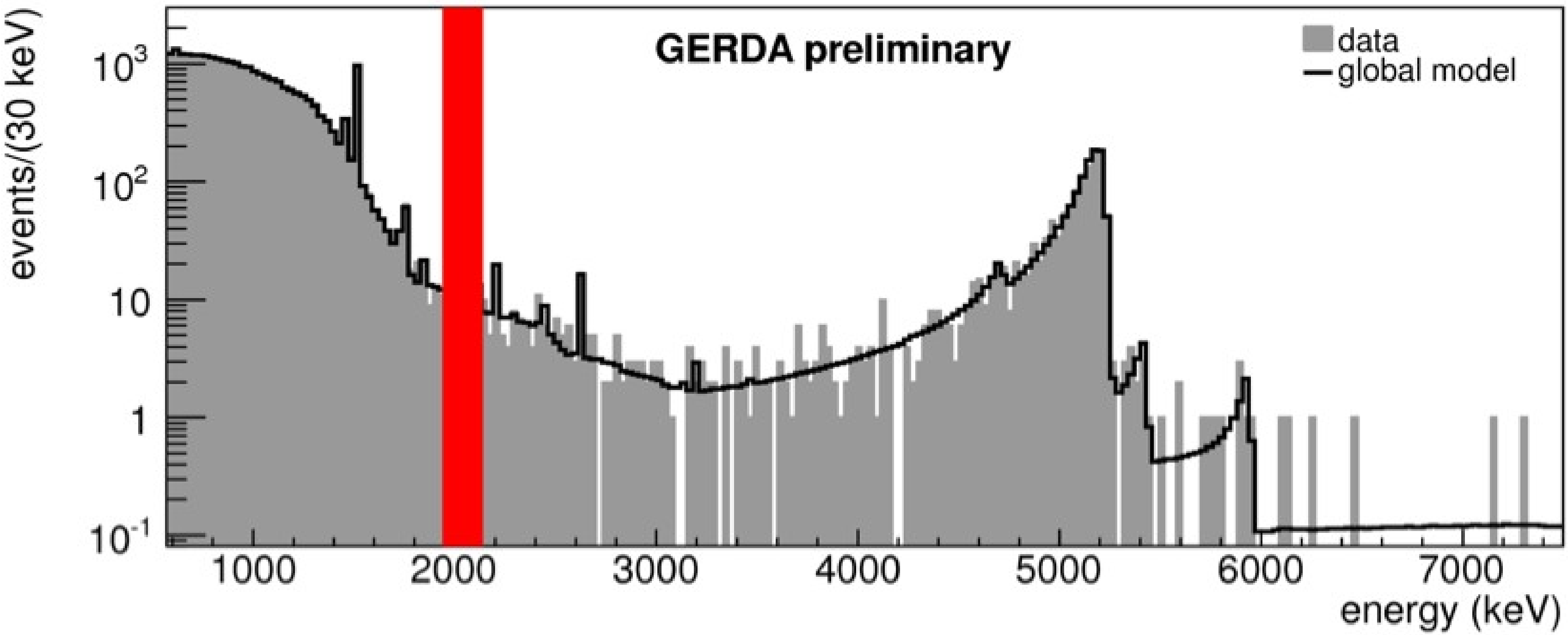
taken from Eur. Phys. J. A12, 147-154 (2001)

GERDA 13.65 kg·yr



Decomposition of the Background Spectrum

- Fit to the sum enrGe-coax spectrum in (570 – 7500) keV window
- background components considered in the global fit:
  ^{42}K, ^{40}K, ^{214}Bi, ^{228}Ac & ^{228}Th (β - γ induced events)
  and α induced events (from ^{210}Po, ^{226}Ra, ^{222}Rn & daughters)

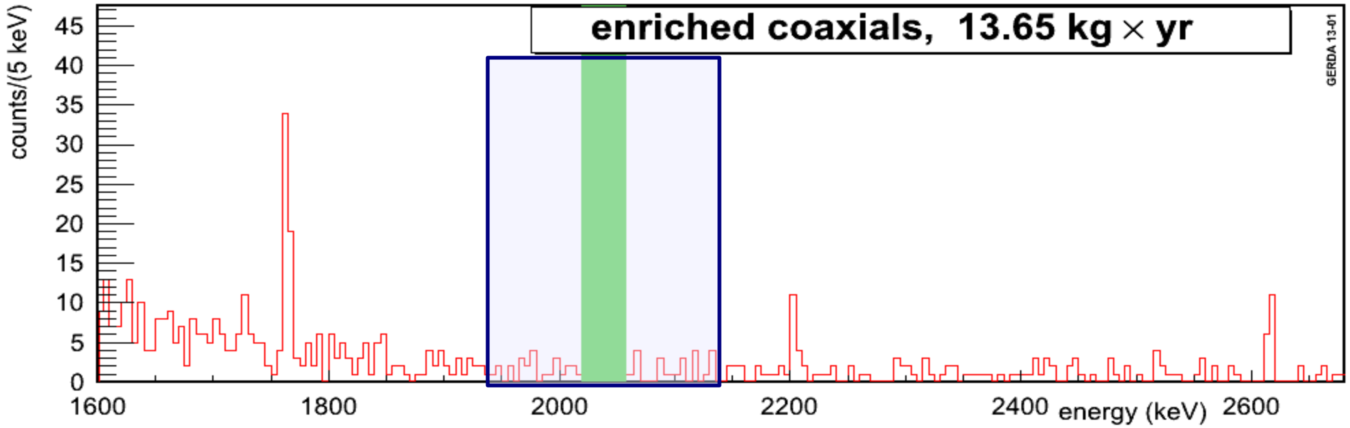


Main background contributions around $Q_{\beta\beta}$

→ ^{42}K, ^{214}Bi, ^{228}Th and α events.

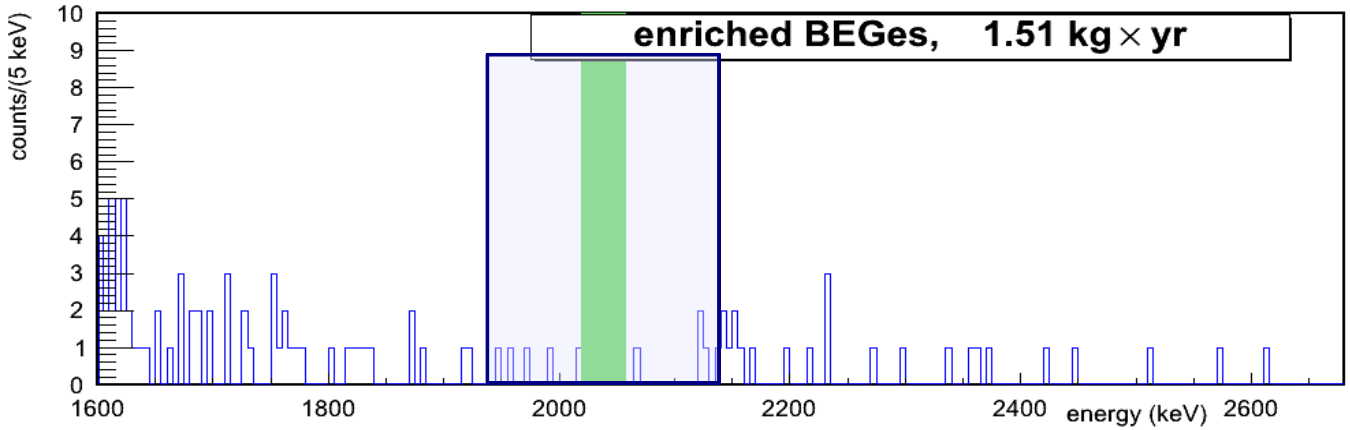
Region of Interest

Background rate in ROI ($Q_{\beta\beta}$±100 keV, blinded window excluded)



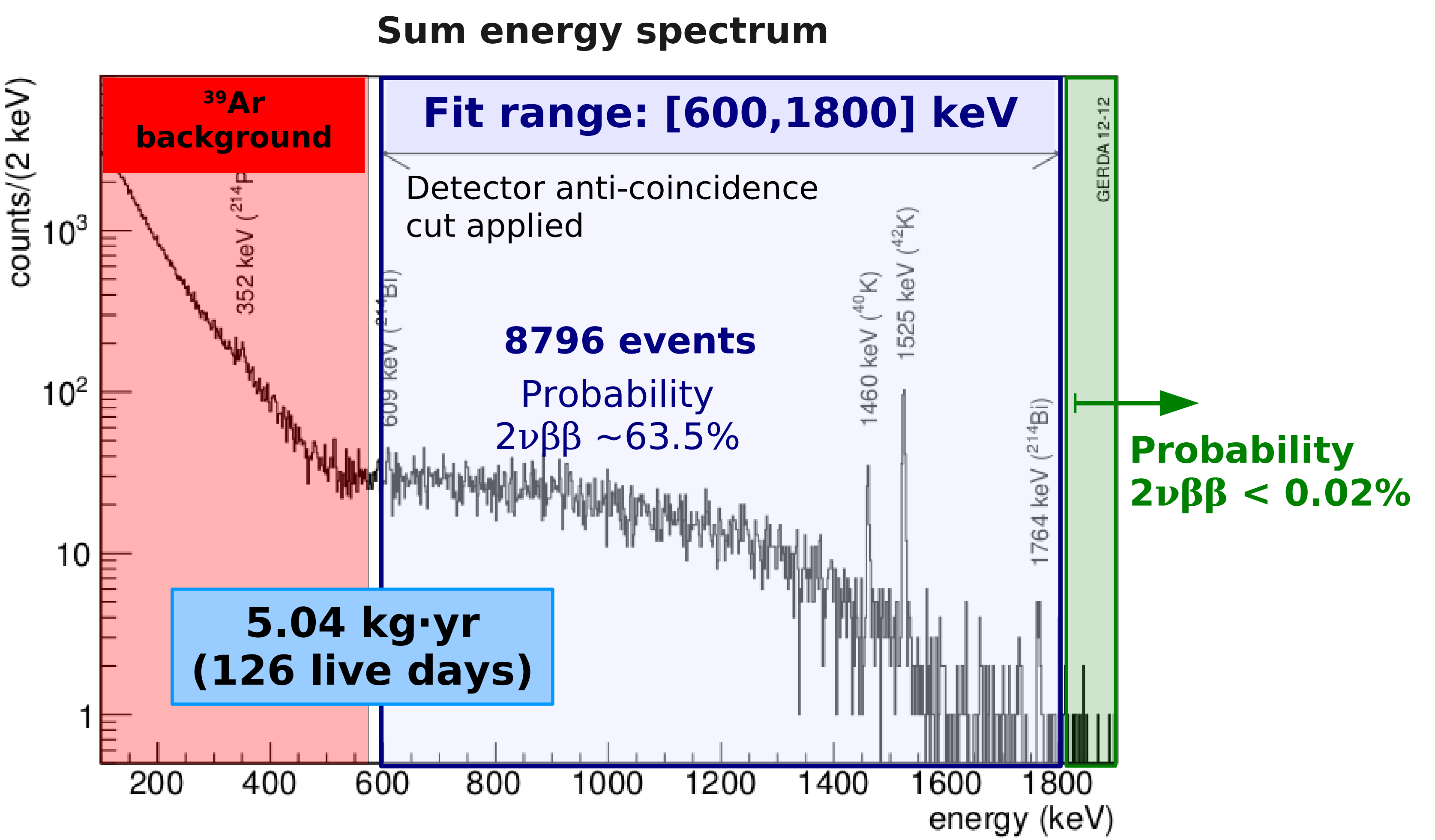
Enriched coaxials: 0.022±0.003 cts/(keV·kg·yr)
(0.017±0.003 cts/(keV·kg·yr) excluding 1.30 kg·yr period with higher background following detector substitutions in July)

➡ **factor ~10 lower than previous experiments (HdM, IGEX)**

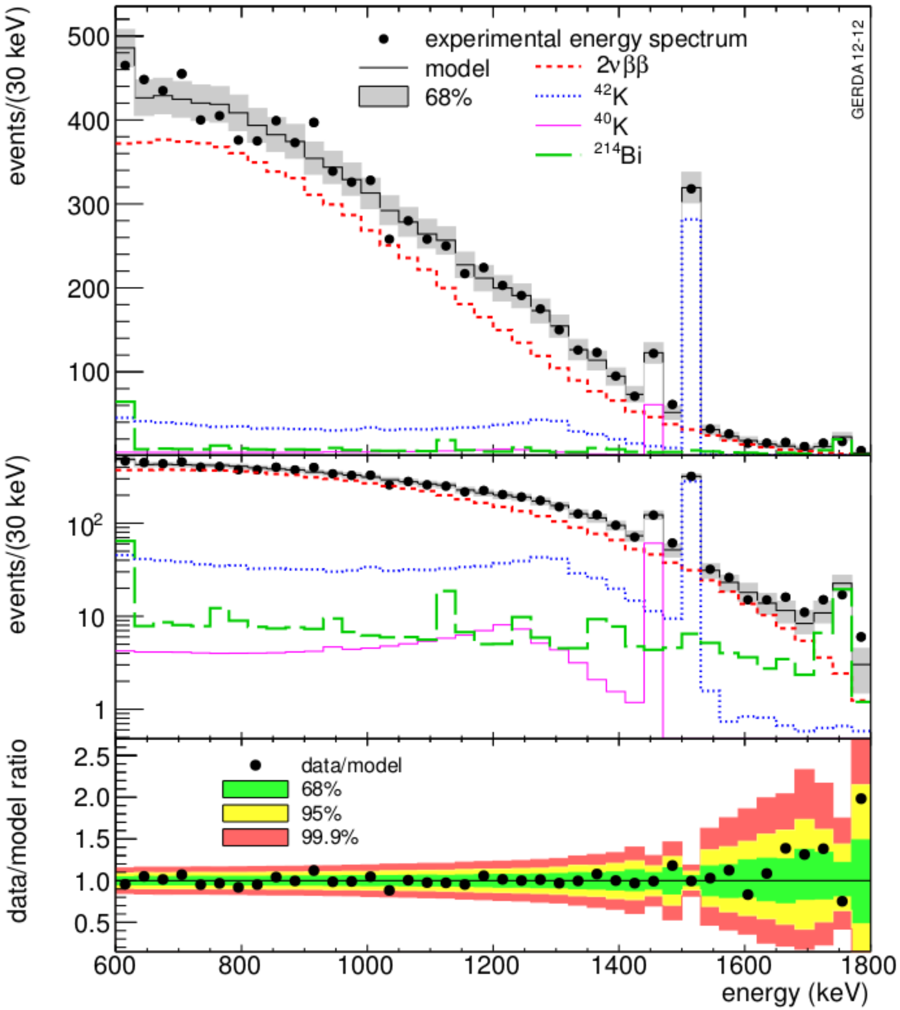


Measurement of $T^{2\nu}_{1/2}$: Data set

First 126 live days of the 6 ^{enr}Ge detectors:



Measurement of $T^{2\nu}_{1/2}$: Result



Signal to background: 4:1

Binned maximum likelihood

Parameters:

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

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

$2\nu\beta\beta$ (80%) ^{42}K (14%)

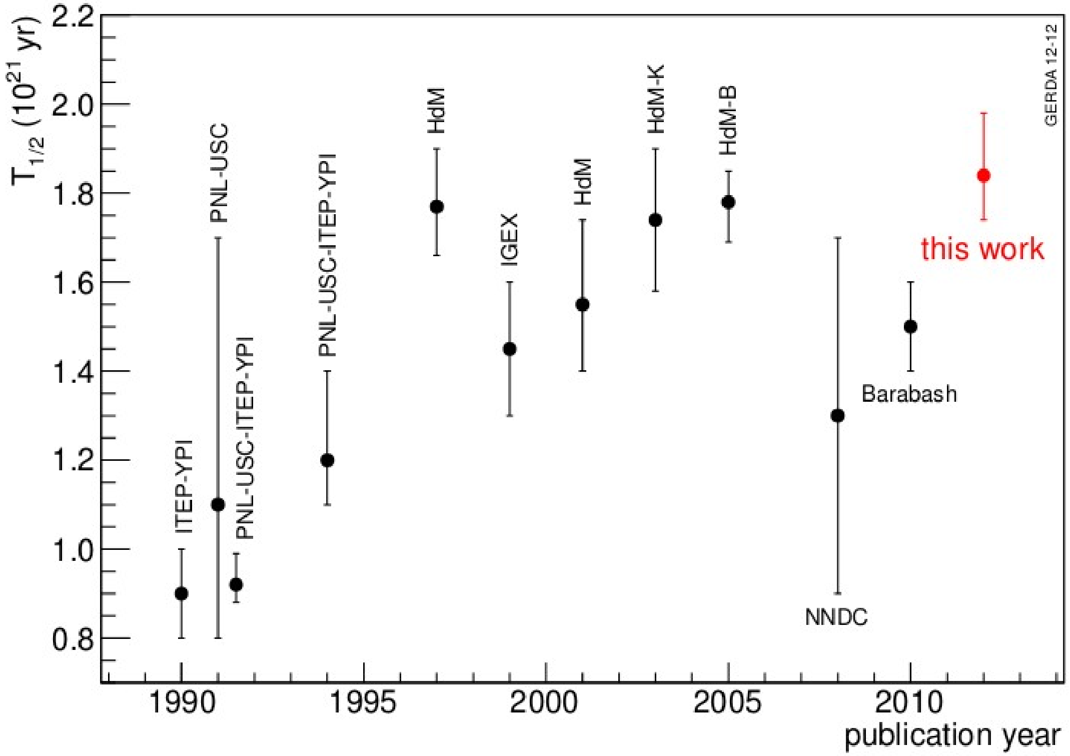
^{214}Bi (4%) ^{40}K (2%)

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

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

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

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



- **Superior signal-to-background ratio**
  → uncertainty comparable to previous measurements despite much smaller exposure
- **Good agreement with re-analysis of HdM data**
  HdM-K: Nucl. Instrum. Methods A 513, 596 (2003)
  HdM-B: Phys. Part. Nucl. Lett. 2, 77 / Pisma Fiz. Elem. Chast. Atom. Yadra 2, 21 (2005)

Measurement of $T^{2\nu}_{1/2}$: Matrix element

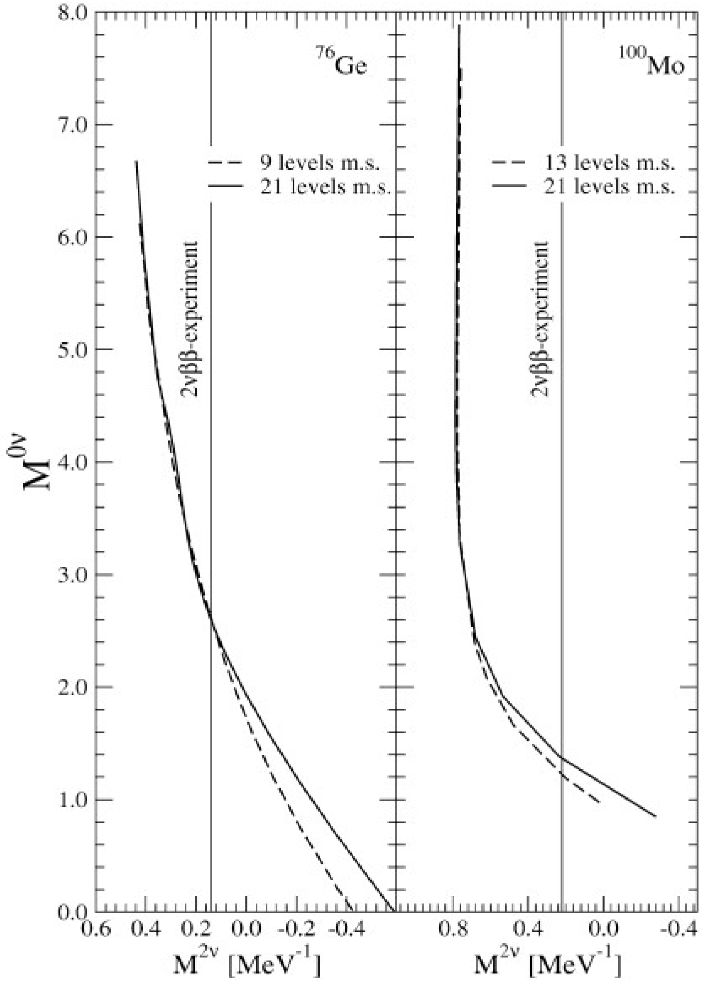
Calculate $\mathbf{M^{2\nu}}$: $\left(T^{2\nu}_{1/2}\right)^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)\ \left|M^{2\nu}\right|^2$

(with phase space factor from *[1]*):

$0.133^{+0.004}_{-0.005}$ MeV^{-1}

➜ decrease by 11% compared to *[2]*

➜ well consistent with $M^{2\nu}$ derived from (d,^{2}He) and (^{3}He,t) charge exchange reactions



Relation between $M^{2\nu}$ and $M^{0\nu}$ *[2]* :

☞ **Decreasing $M^{2\nu}$ decreasing $M^{0\nu}$**

Increase of predicted $T^{0\nu}_{1/2}$ by 15%

[1] Kotila J., and Iachello F. 2012 Phys. Rev. C 85 034316

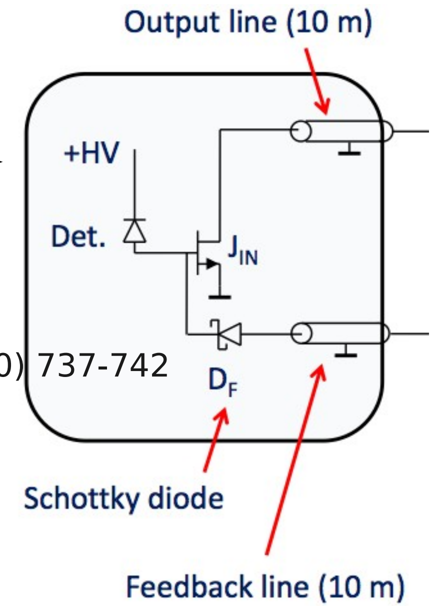
[2] Rodin V. A., Fässler A., Šimkovic F. and Vogel P. 2006 Nucl. Phys. A 766 107; erratum: 793 (2007) 213

Status of the Phase II

- **increase mass**: up to additional 30 enriched BEGe detectors (**~ 20 kg**)
  - already produced by Canberra Olen
  - completely tested at Hades (Belgium)
  - first BEGe sample already in the data chain of the Phase I

→ **see S. Hemmer's poster**

- **reduce background by factor > 10 with respect to Phase I**
  - new signal and HV cables with lower background budget
  - new FE cards with lower background budget and optimized characteristics for the new detectors →
  - PSA discrimination with the BEGe's
  - **liquid argon veto instrumentation**

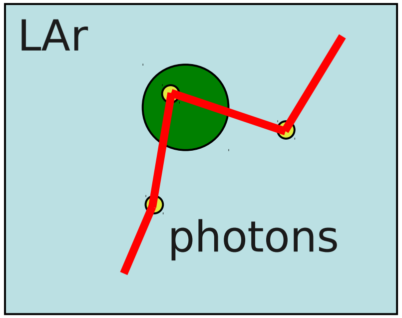


Cattadori C. et al.
JINST 6 (2011) P05006
Pullia A. et al.
IEEE Trans. N.S. 57 (2010) 737-742

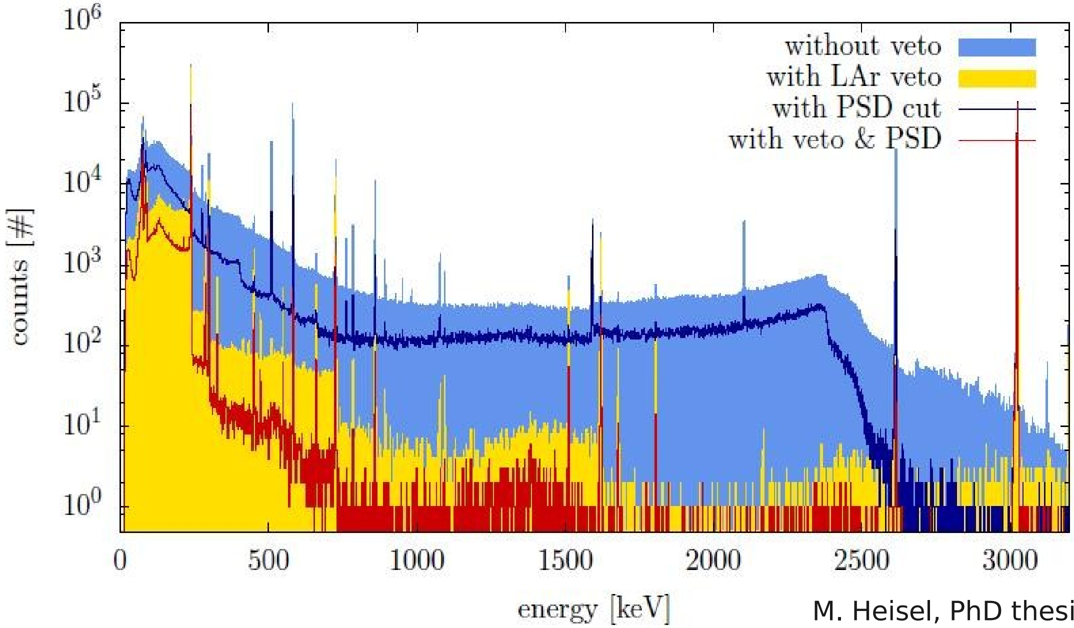
- **new lock system** for the deployment of the detectors into the cryostat

Status of the Phase II: LAr veto instrumentation

Detection of coincident LAr scintillation light to discriminate background



data from LARGE: a test facility at LNGS



M. Heisel, PhD thesis
M. Agostini et al., J. Phys.: Conf. Ser. 375 (2012) 042009

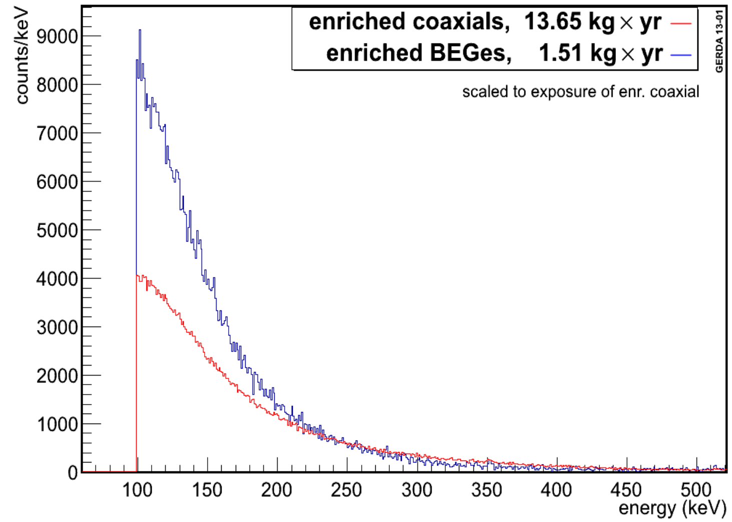
Combining PSD of BEGe detector and LAr veto: measured suppression factor at $Q_{\beta\beta}$, e.g. $\approx 10^3$ for a ^{228}Th calibration source inside cryostat.

summary

- **Phase I data taking started on 11.2011**
- Data acquisition ongoing
- **Background much lower** than in previous experiments (HdM & IGEX)
- Progress in the understanding of the Background composition
- **Determination of the $T^{2\nu}_{1/2}$** with the first 5.04 kg·yr
- **Phase I completed (20 kg·yr) in June/July**: data unblinding
- **Phase II** roadmap to get a **background 10× lower than Phase I**

backup slides

Background from Argon



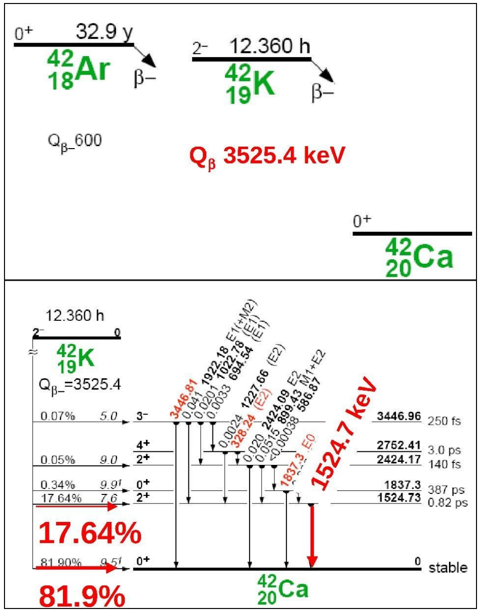
^{39}Ar

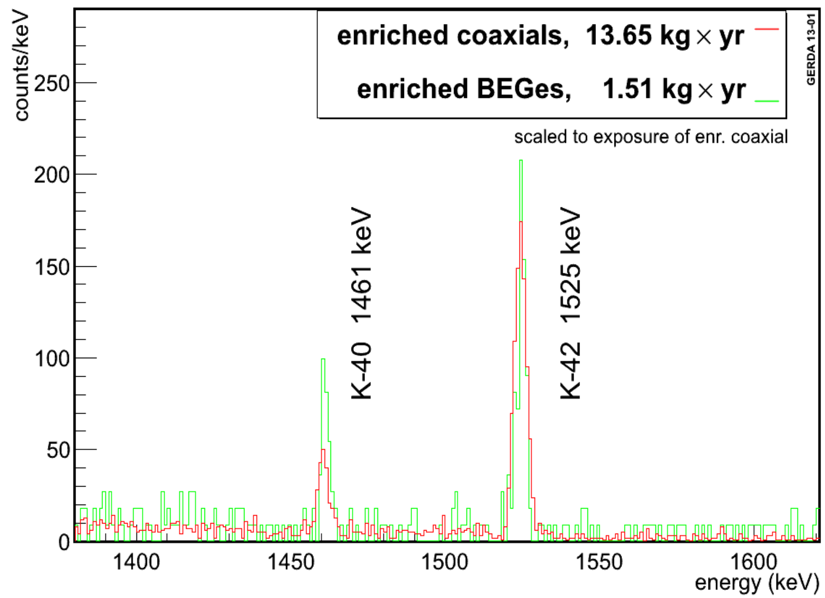
- 1.01 Bq/kg, $T_{1/2}$=269 yr
- pure β emitter, Q-value=565 keV
  → **below region of interest**

^{42}Ar

GERDA proposal: $^{42}Ar/^{nat}Ar < 3 \times 10^{-21}$ (*Barabash et al. 2002)*

GERDA measurement: Count rate at 1525 keV ~ 2× expectation ⇒ lower limit





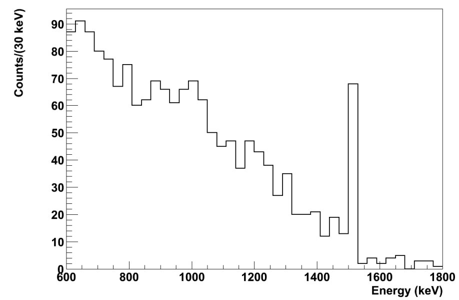
Measurement of $T^{2\nu}_{1/2}$: Fit

Binned maximum likelihood approach

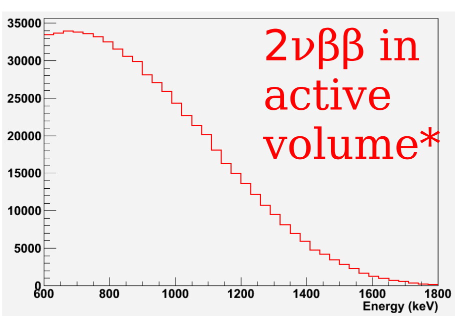
Ingredients:

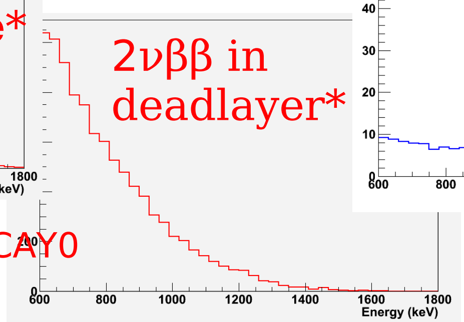
- 6 energy spectra from ^{enr}Ge detectors (30 keV bins)

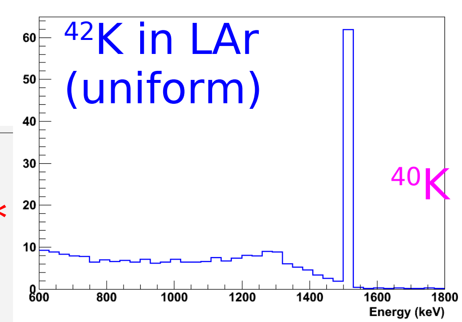
Single detector energy spectrum:

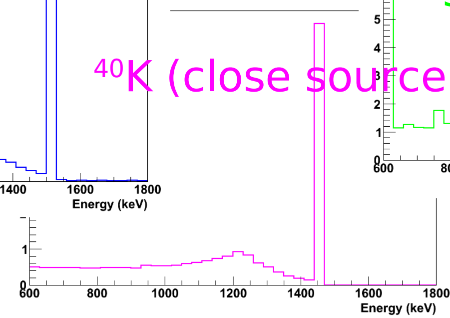


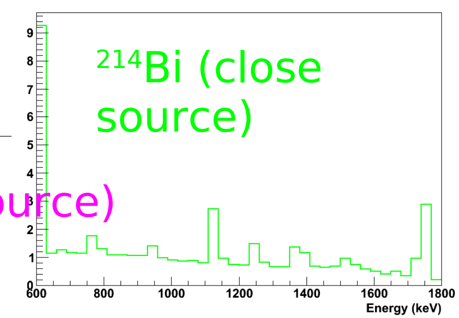
- Model: Simulated spectra of $2\nu\beta\beta$, ^{42}K, ^{40}K, ^{214}Bi for each detector











*Distribution from DECAY0 (V. I. Tretyak)

Measurement of $T^{2\nu}_{1/2}$: Fit

Binned maximum likelihood approach

Ingredients:

- Information on active masses and enrichment fractions:

detector	total mass (g)	active mass (g)	^{76}Ge isotopic abundance (%)
ANG2	2833	2468±121±89	86.6±2.5
ANG3	2391	2070±118±77	88.3±2.6
ANG4	2372	2136±116±79	86.3±1.3
ANG5	2746	2281±109±82	85.6±1.3
RG1	2110	1908±109±72	85.5±2.0
RG2	2166	1800±99±65	85.5±2.0

uncorrelated   correlated

Average active mass fraction: (86.7±4.6(uncorr.)±3.2(corr.))%

Average enrichment fraction: (86.3±2)%

Measurement of $T^{2\nu}_{1/2}$: Fit

Binned maximum likelihood approach

Tool:

- Bayesian Analysis Toolkit BAT
  Caldwell A., Kollar D., and Kröninger K. 2009 Comput. Phts. Comm. 180 2197

Directions:

- Define the parameters:
  - Active detector masses (6+1)
  - Fraction of enrichment in ^{76}Ge (6)
  - Background contributions (3x6)
  - $T^{2\nu}_{1/2}$ common to all detectors (1)

  } nuisance parameters

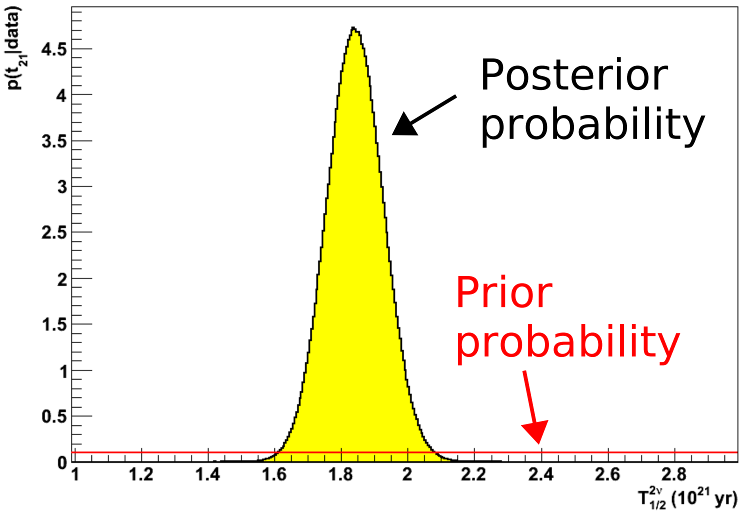
- Run the fit

- Integrate over all nuisance parameters to derive posterior for $T^{2\nu}_{1/2}$

Measurement of $T^{2\nu}_{1/2}$: Fit result

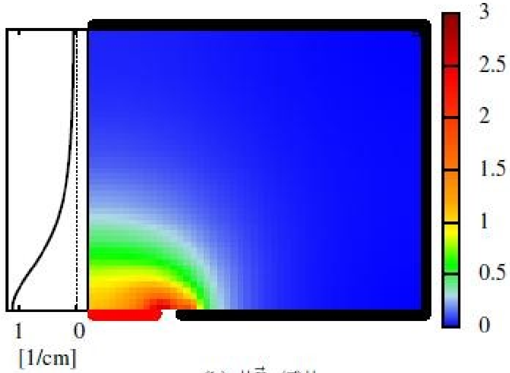
$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}) \cdot 10^{21}$ yr (smallest interval 68%)

Uncertainty includes uncertainties on nuisance parameters, especially on active masses and enrichment fractions



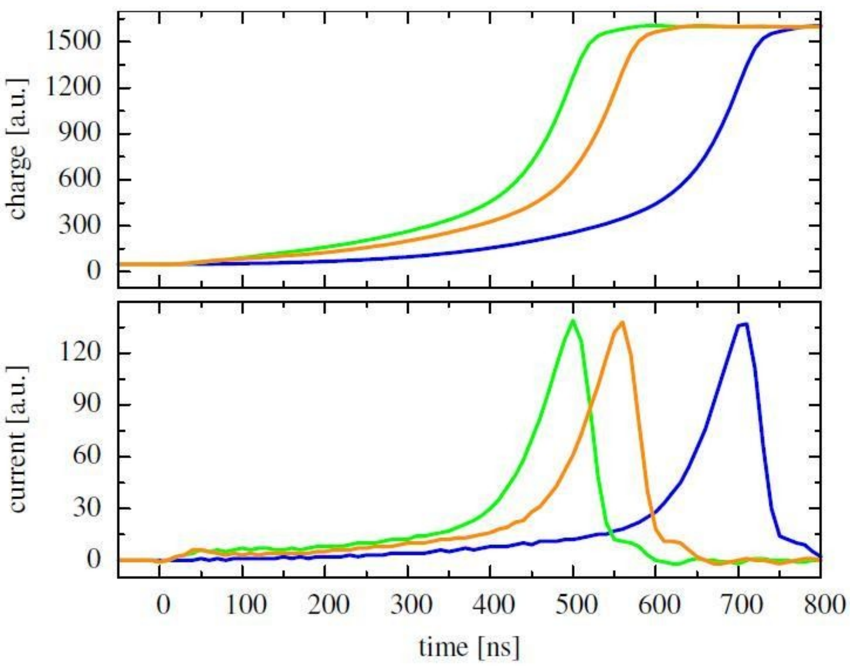
Crosscheck:
Fit each detector separately → results mutually consistent (χ^2/ν=3.02/5)

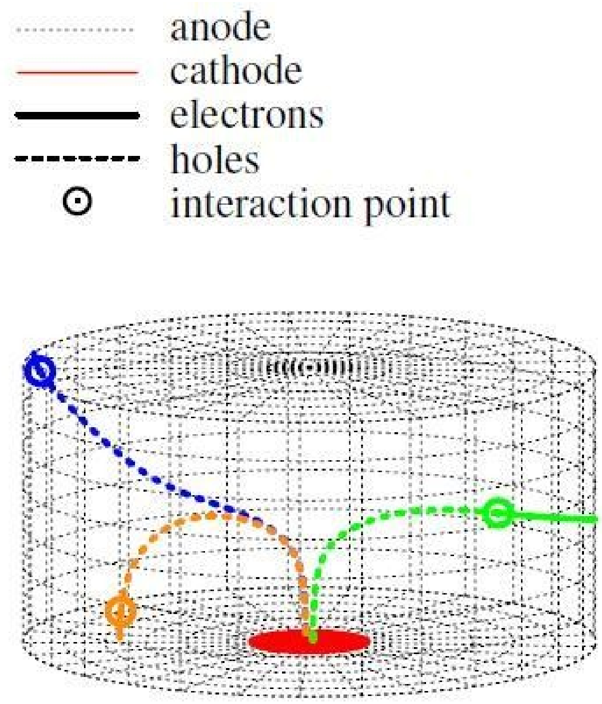
Phase II detectors



(b) $||\vec{E}_w(\vec{r})||$

Shockley-Ramo Theorem:
$Q(t) = -q \cdot \Phi_w(\mathbf{r}(t))$





Measurement of $T^{2\nu}_{1/2}$: Systematics

^{60}Co, ^{228}Ac, ^{208}Tl ???

Source positions

Decay distribution model

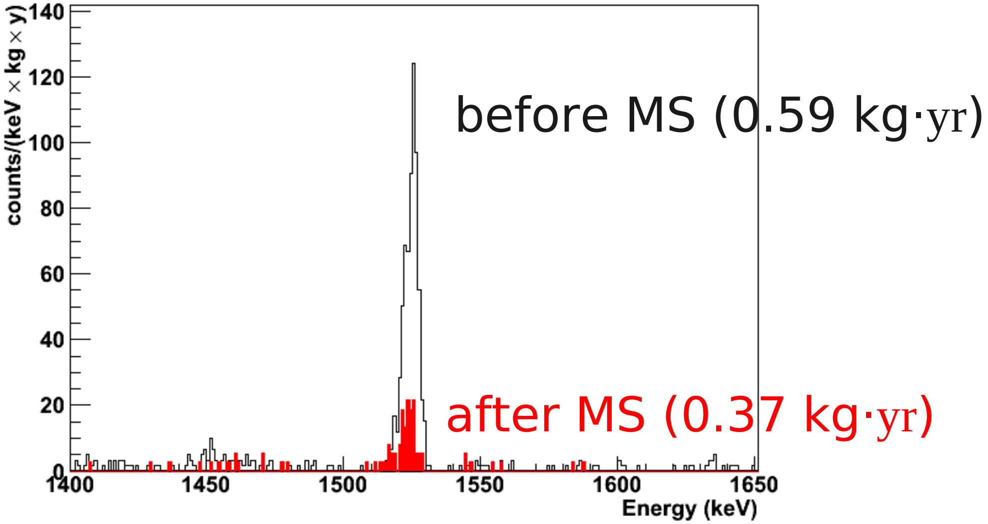
Dimensions, materials, ...

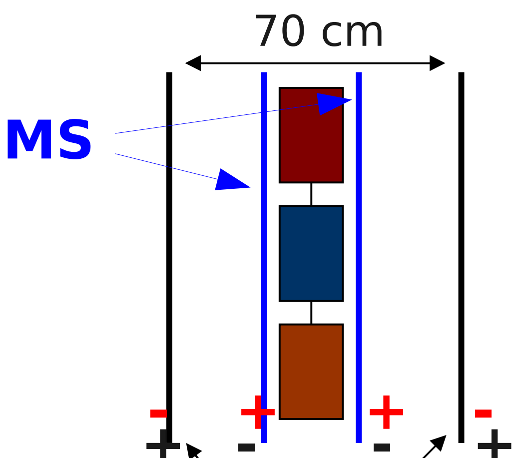
Validation of GEANT4 processes

Source of uncertainty	
Non-identified background components	+5.3
Energy spectra from ^{42}K, ^{40}K, ^{214}Bi	±2.1
Shape of the $2\nu\beta\beta$ decay spectrum	±1
Precision of the Monte Carlo geometry model	±1
Accuracy of the Monte Carlo tracking	±2
Data acquisition and selection	±0.5
Total	**+6.2 -3.3**

Background from Argon

Add a mini-shroud (MS):





Shroud (already installed to prevent ^{222}Rn concentration)