First results from the GERDA experiment

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LNGS seminar,
21 February 2013

Outline

- Double beta decay: $2\nu\beta\beta$ and $0\nu\beta\beta$
- The GERDA experiment
- First results: The $2\nu\beta\beta$ half-life of ^{76}Ge
- A look into the future

Unveil the nature of the neutrino

Majorana
$\nu = \bar{\nu}$

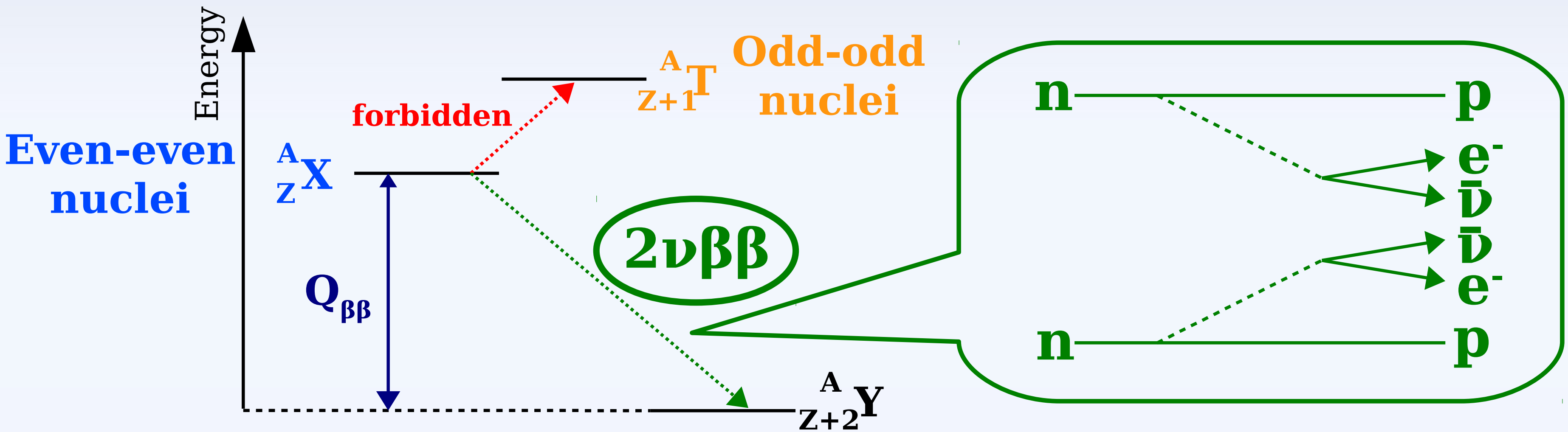
or

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

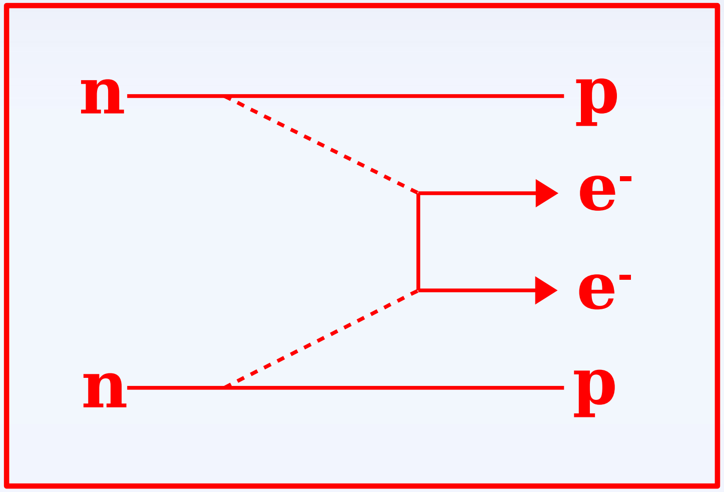
2νββ



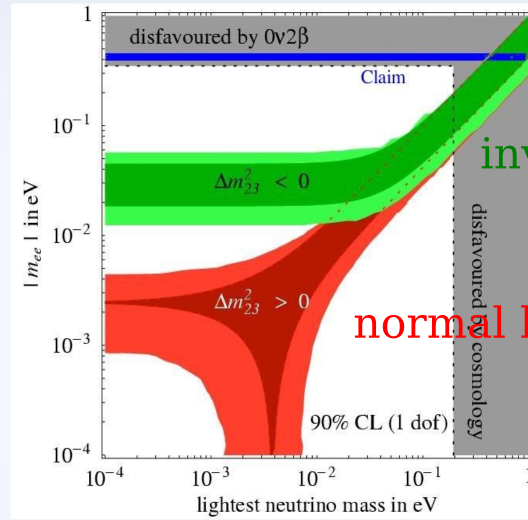
- allowed by SM
- $\Delta L=0$
- observed in many isotopes
- $T^{2\nu}_{1/2} \sim 10^{19}\text{-}10^{21}\text{yr}$
- $(T^{2\nu}_{1/2})^{-1} = G^{2\nu}(Q_{\beta\beta},Z) \cdot |M^{2\nu}|^2$

Phase space *nuclear matrix element*

0νββ



$|m_{\beta\beta}|$



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inverted hierarchy

normal hierarchy

Lightest neutrino mass

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

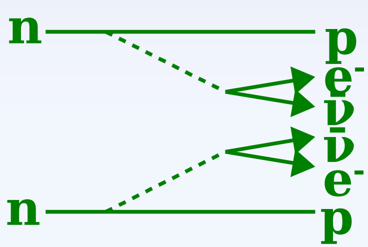
Phase space ($\sim Q_{\beta\beta}^5$)

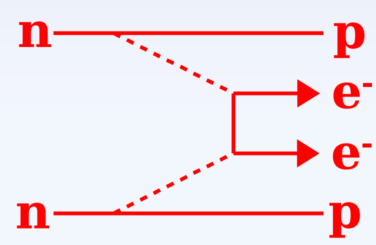
nuclear matrix element

$<m_{\beta\beta}>^2 = |\sum_i |U_{ei}|^2 e^{i\alpha} m_i|^2$

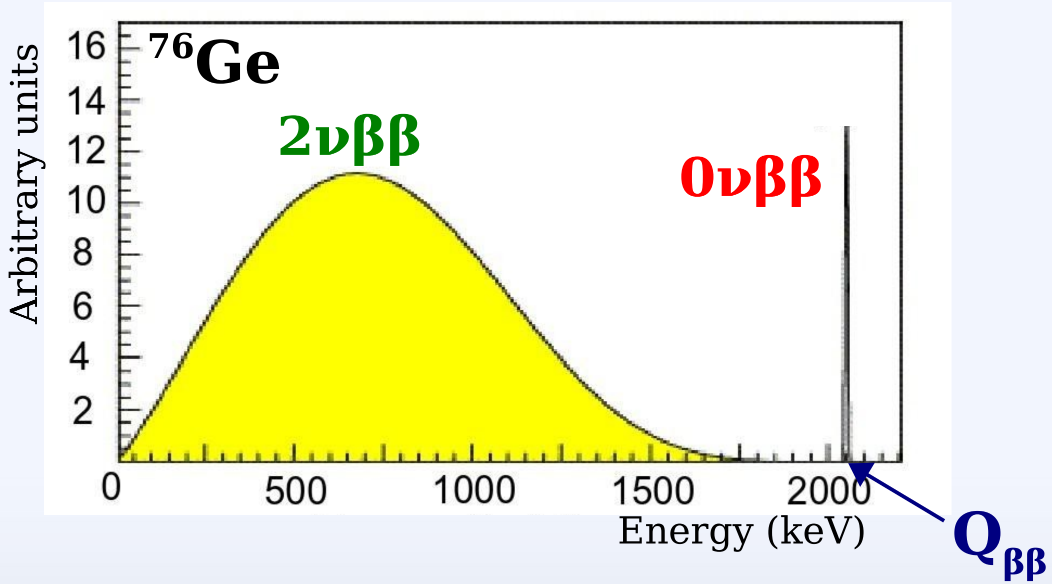
Majorana neutrino mass

Experimental signature



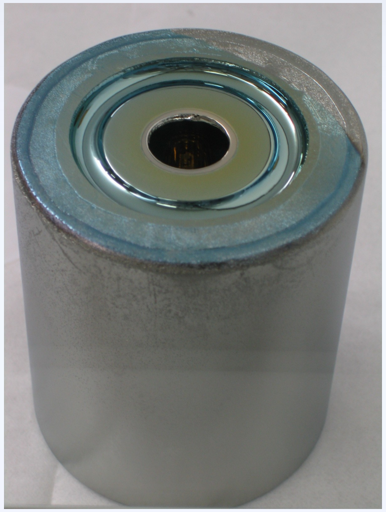


➡ **Measure electron energy spectrum:**



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 $G^{0\nu}(Q_{\beta\beta},Z)$

Previous ^{76}Ge experiments

	HdM	IGEX
Location	LNGS	Homestake, Baksan, Canfranc
Exposure [kg·yr]	71.1	8.9
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:

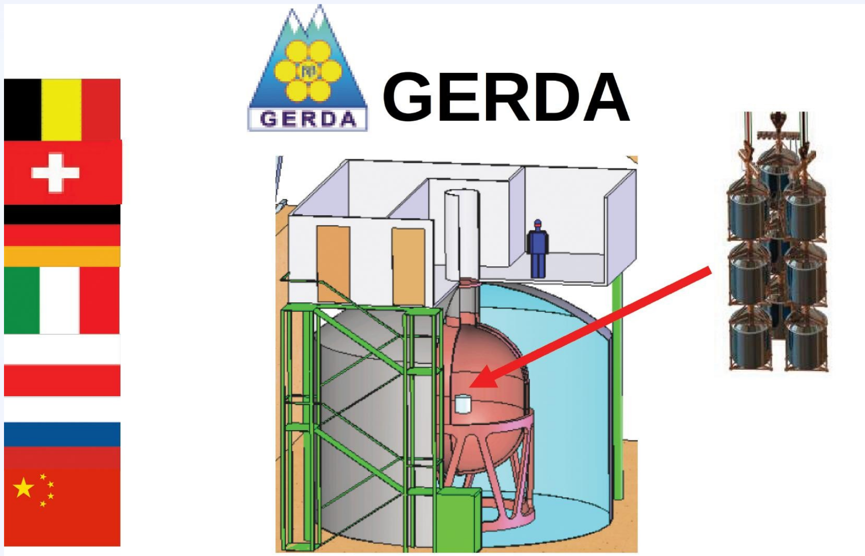
$T_{1/2}$ (^{76}Ge) = $(0.69 – 4.18) \cdot 10^{25}$ yr (3σ) (Best fit: $T_{1/2}$ (^{76}Ge) = $1.19 \cdot 10^{25}$ yr)

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

GERmanium Detector Array (GERDA)

The GERDA collaboration

112 members, 19 institutes, 7 countries



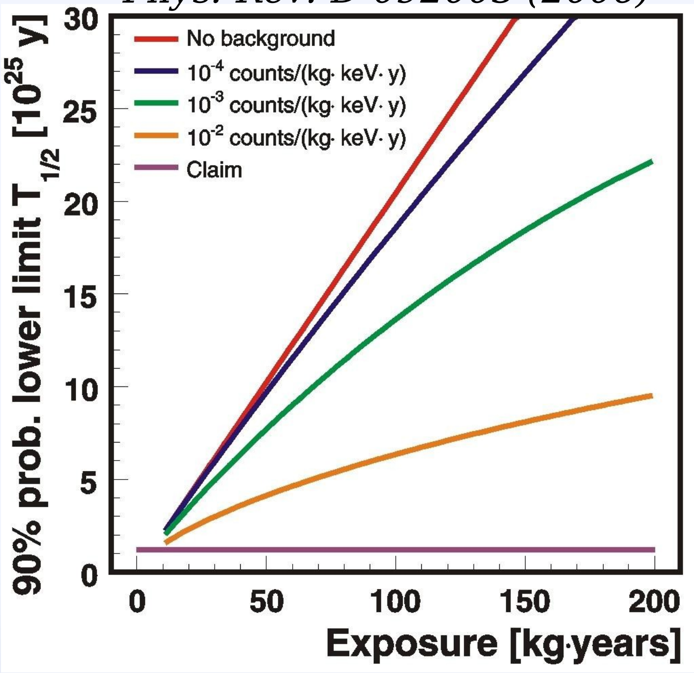
- Bare ^{enr}Ge array in liquid Argon
- Shield: high-purity liquid Argon / H_2O
- **Phase I:** 18 kg enriched coaxial detectors (~86%)(HdM/IGEX)
- **Phase II:** add ~20 kg new enriched BEGe detectors
- For future ton scale experiment: Merge with Majorana collaboration (already open exchange of knowledge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

GERDA physics goal

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

Phys. Rev. D 092003 (2006)



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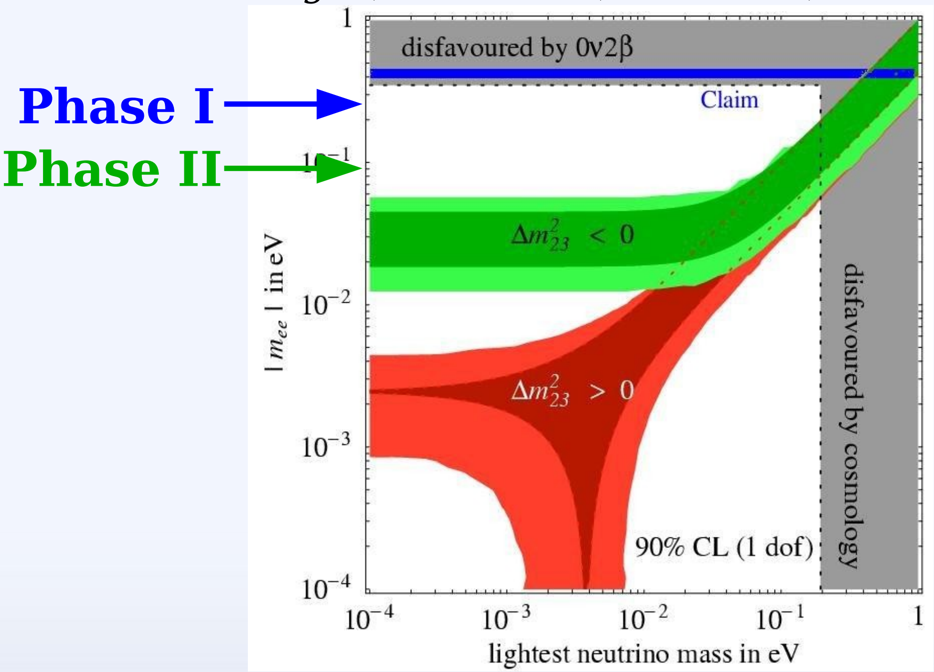


Background reduction

Key issue: Low background rate

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

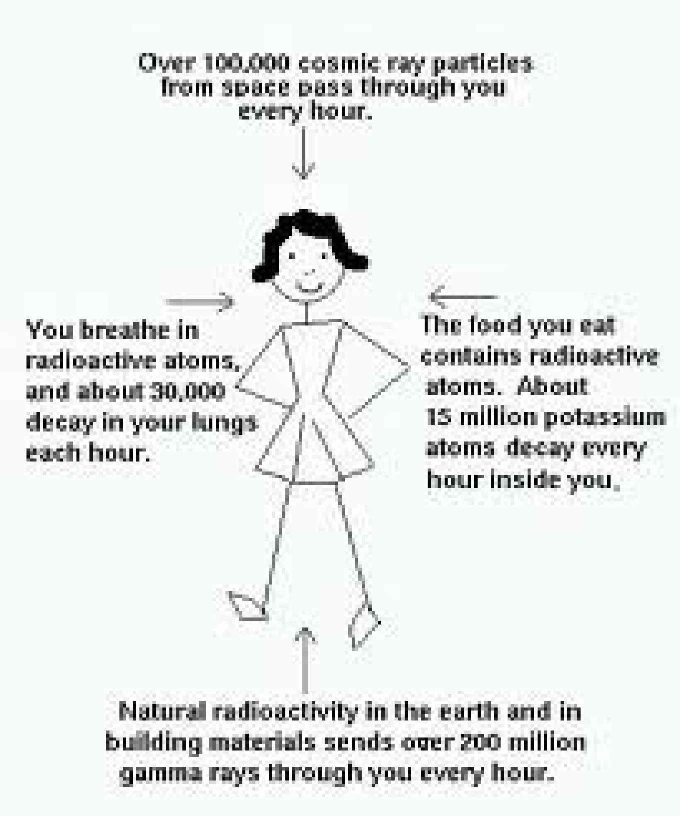
Possible backgrounds:

External:

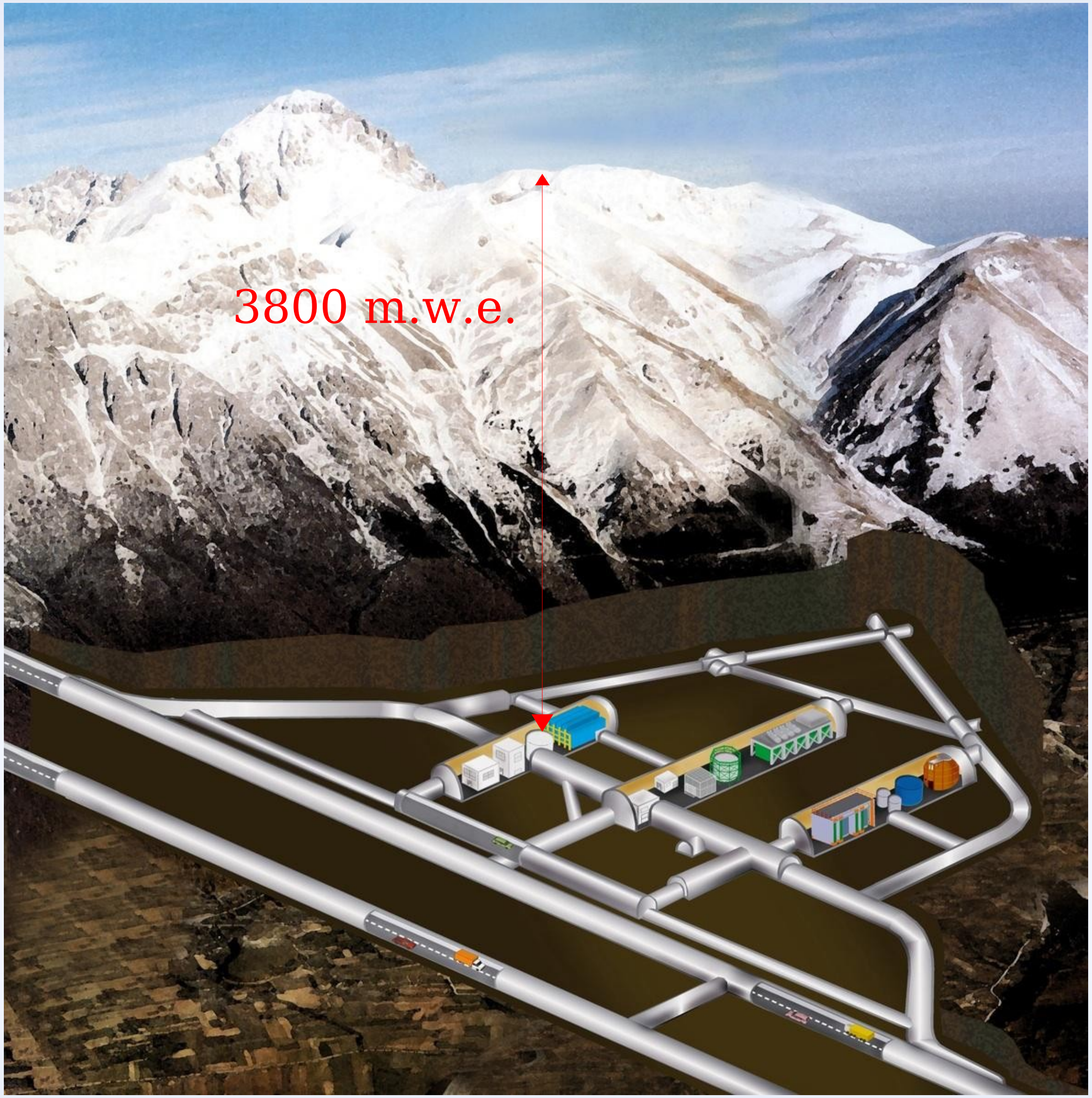
- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

Internal:

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



Background reduction



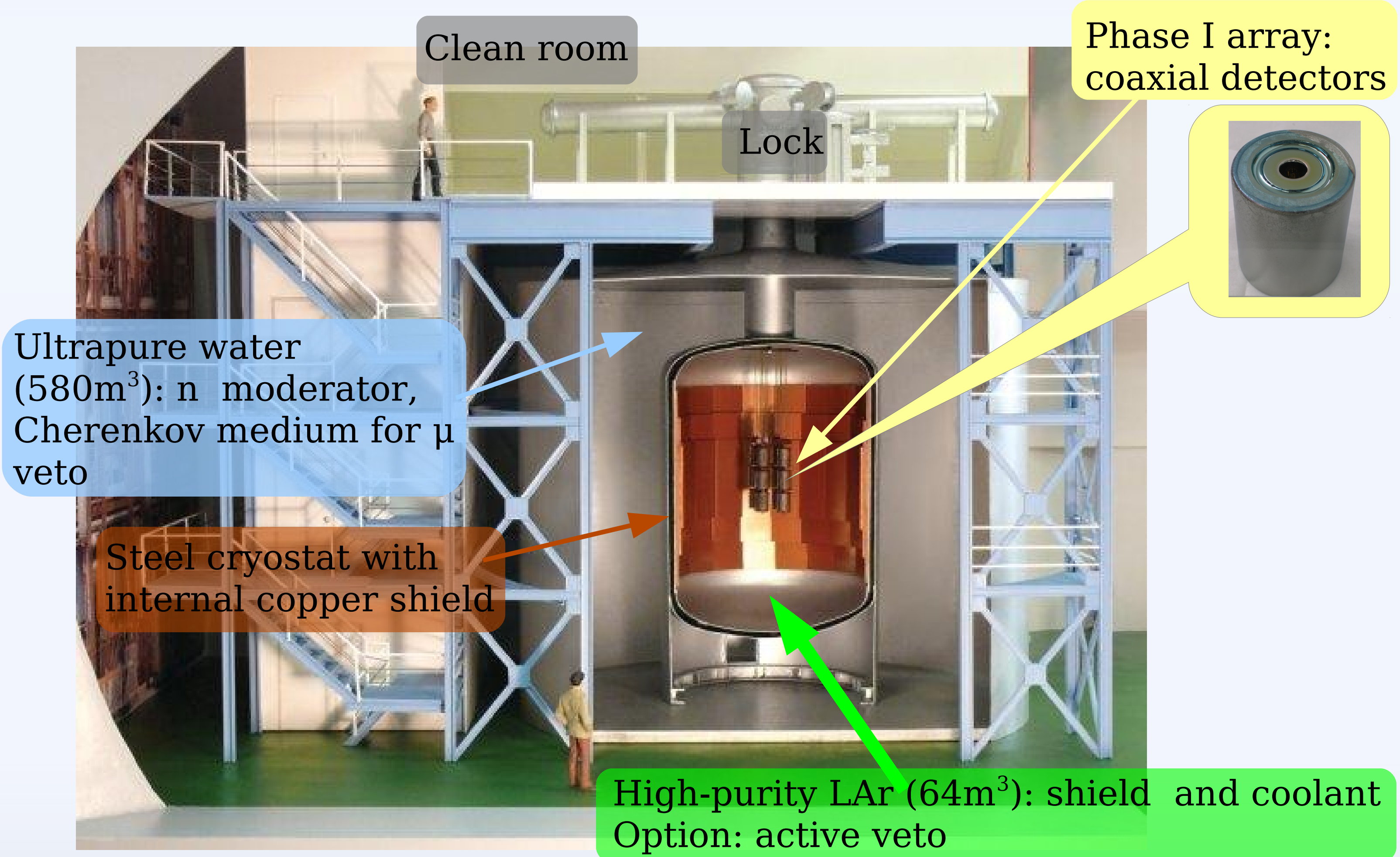
GERDA situtated in LNGS underground laboratories

➡ suppression of cosmic ray muons by factor 10^6 by overlaying rock

➡ hadronic components of cosmic rays removed

Background reduction

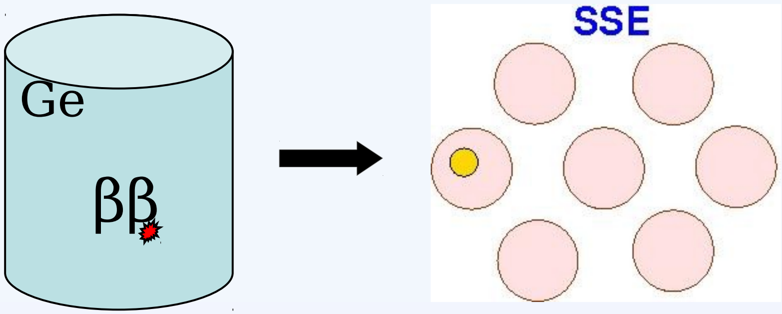
- Graded shielding against ambient radiation
- Rigorous material selection, avoid exposure above ground for detectors



arXiv: 1212.4067

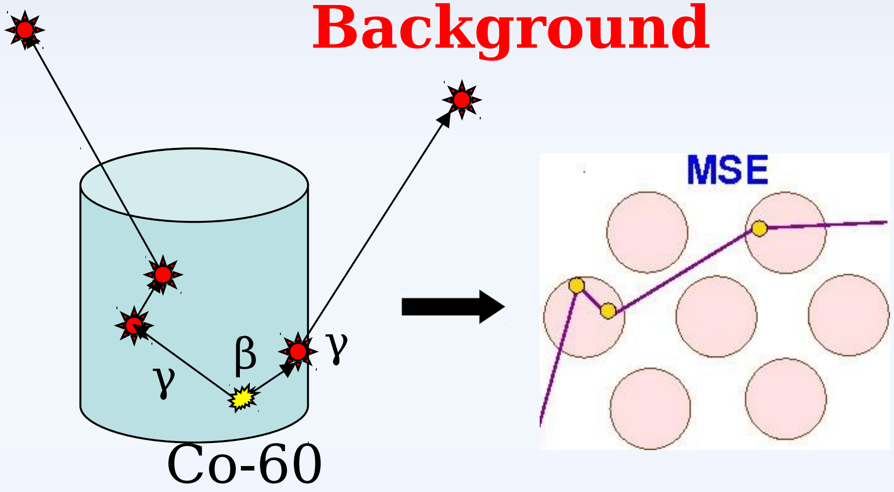
Background reduction

Signal



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

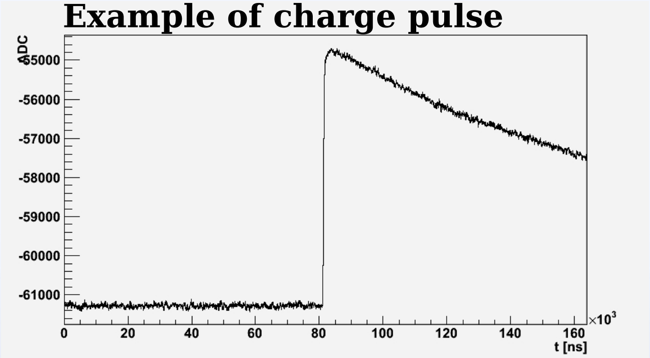
Background



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

Signal analysis:

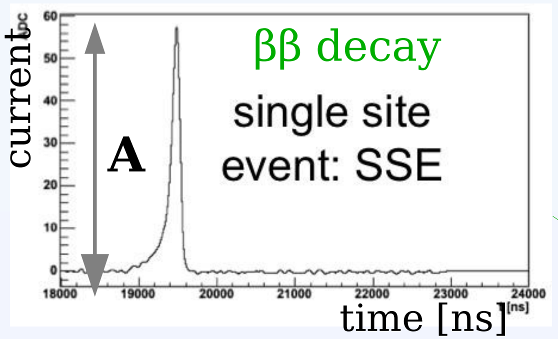
- anti-coincidence between detectors
- pulse shape analysis (PSA)

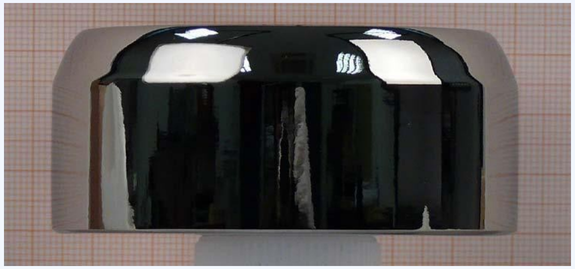


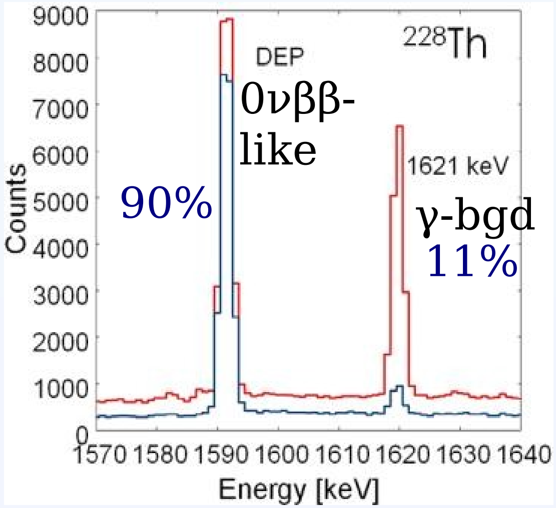
Background reduction Phase II

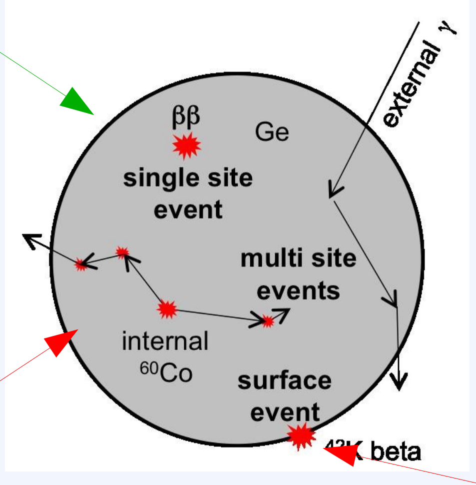
BEGe detectors: strongly non-linear field allows improved PSA

ACCEPT









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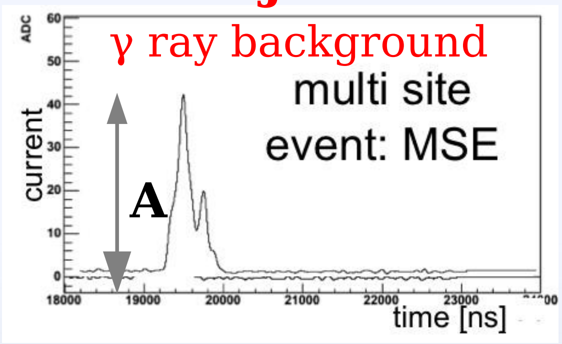

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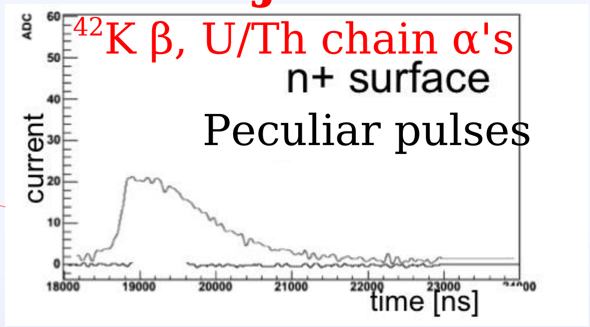
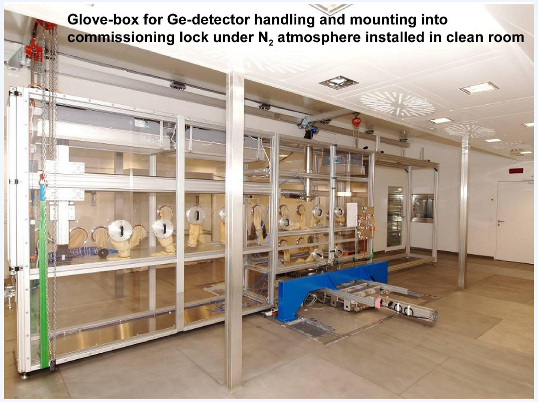
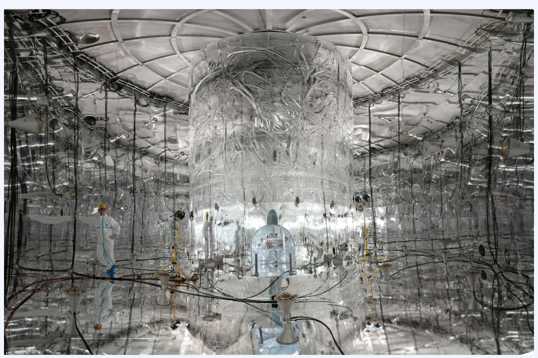
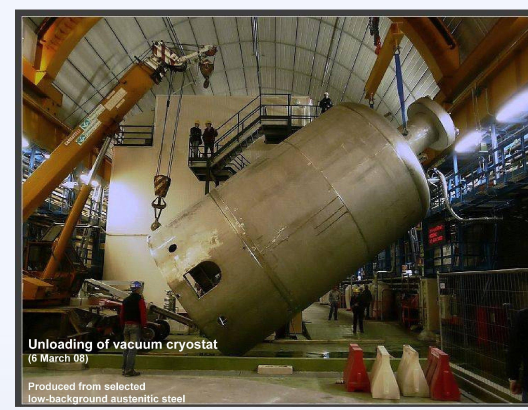


The GERDA experiment





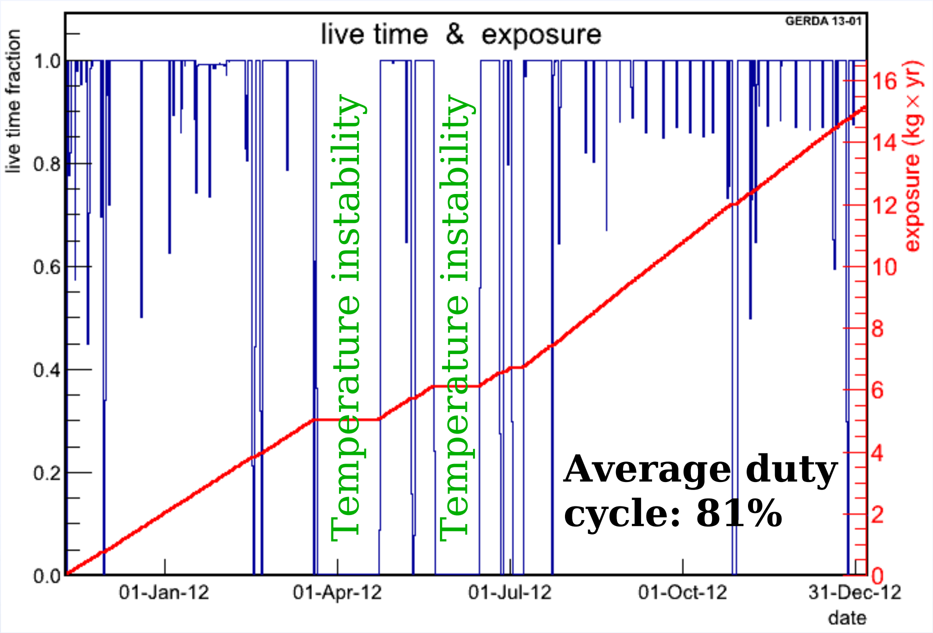


Data taking

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)

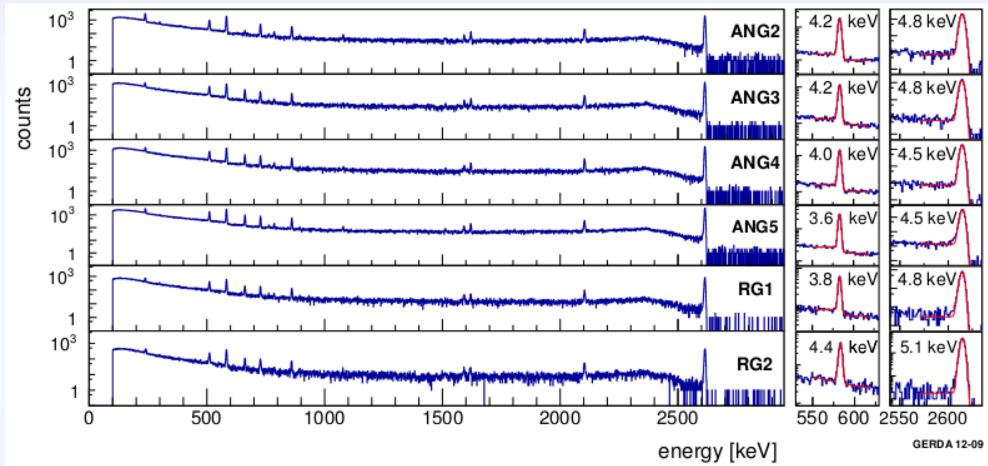
7 July 2012: Insert **5 ^{enr}Ge BEGe** detectors
(Remove 2 ^{nat}Ge detectors)

9 Nov 2011 – 5 Jan 2013:
341 live days / 15.16 kg·yr enr exposure



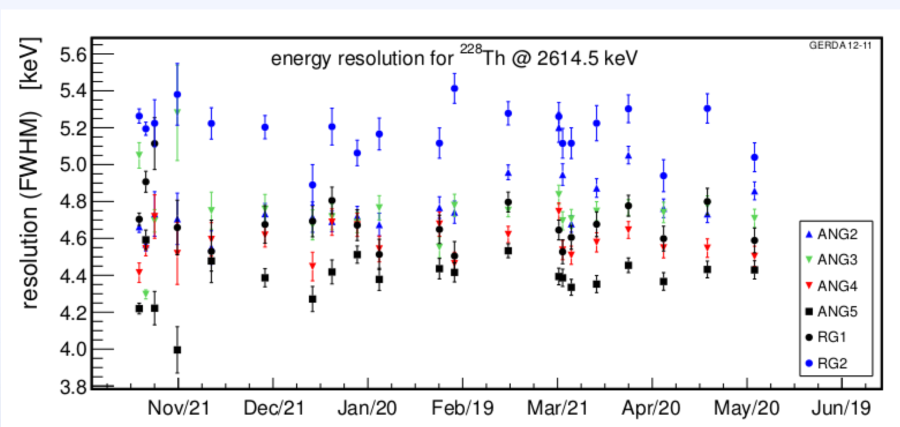
Energy resolution

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

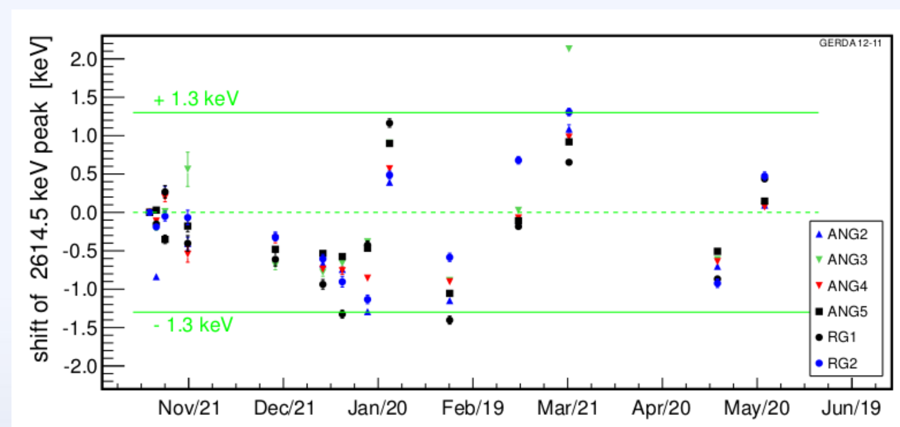


Mass weighted average for **FWHM at $Q_{\beta\beta}$= 4.5 keV**

Stability of the resolution

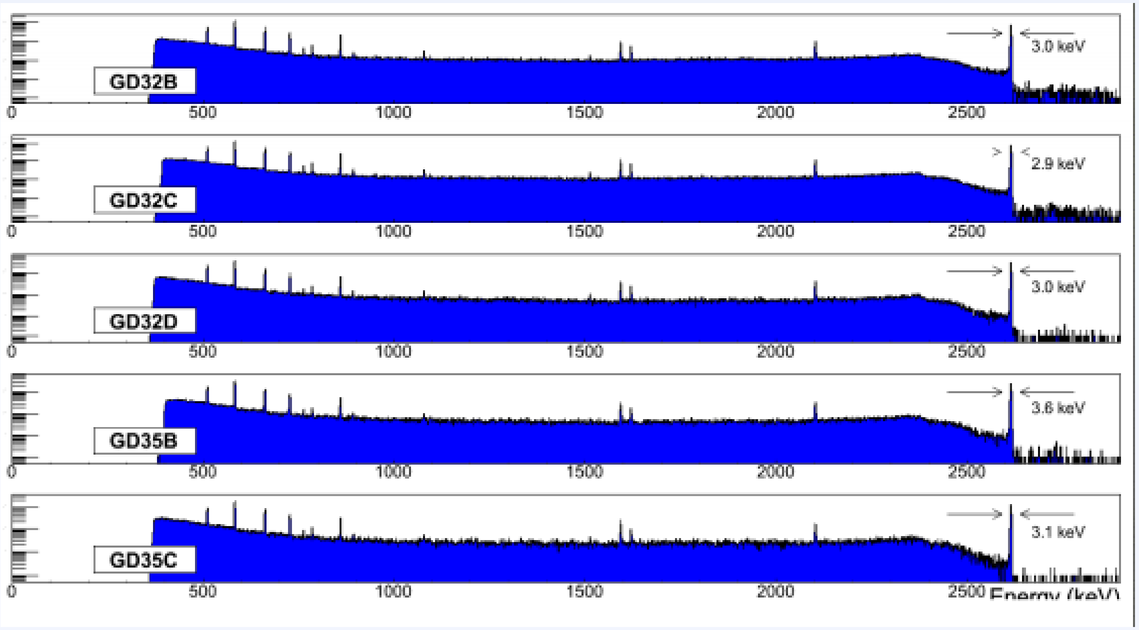


Stability of the energy scale



First BEGe's in GERDA

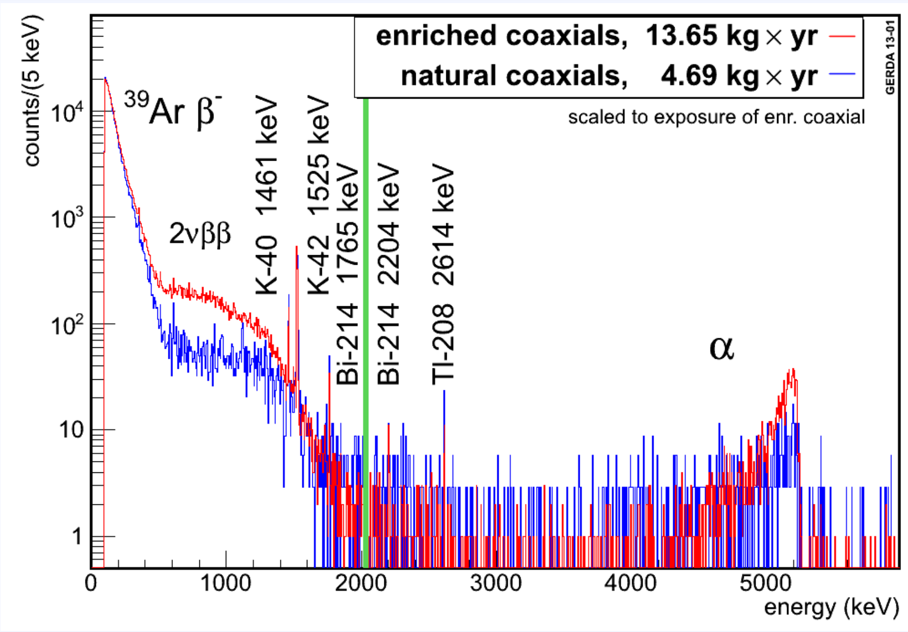
Calibration spectra

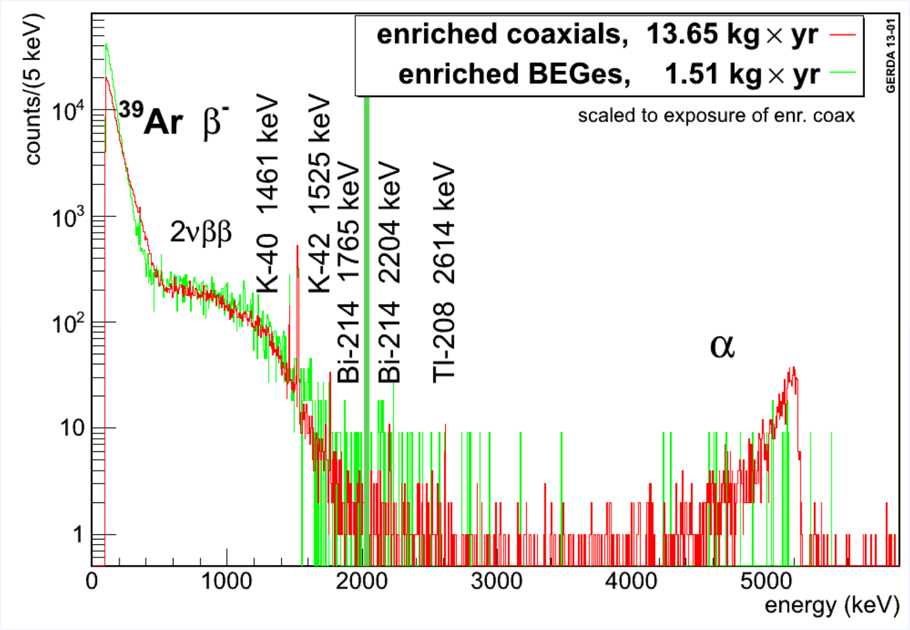


Energy resolution and PSA properties

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





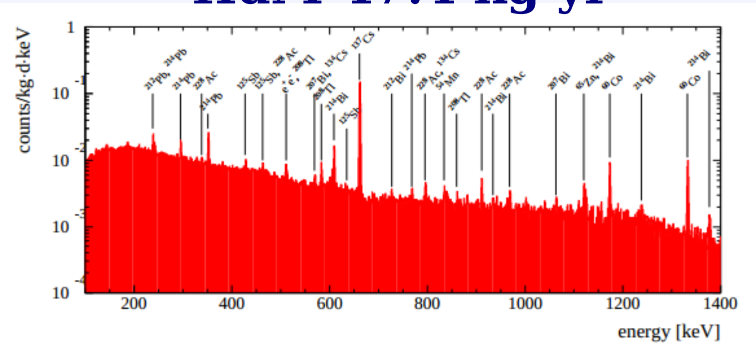
Data blinded between 2019 keV and 2059 keV

Background lines

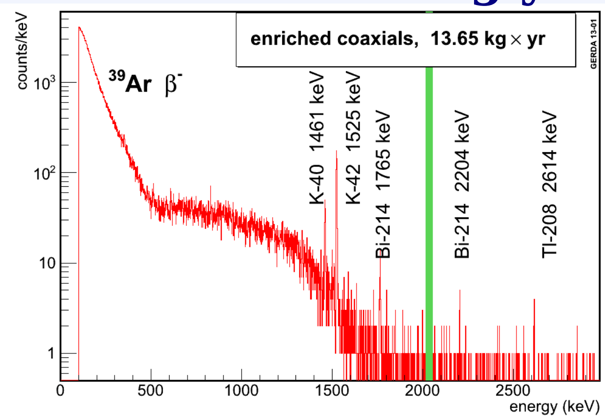
isotope	energy [keV]	^{nat}Ge (3.17 kg·yr) tot/bck [cts]	^{nat}Ge rate [cts/(kg·yr)]	^{enr}Ge (6.10 kg·yr) * tot/bck [cts]	^{enr}Ge rate [cts/(kg·yr)]	HdM (71.7 kg·yr) rate [cts/(kg·yr)]	Rate HdM/ ^{enr}coaxial
^{40}K	1460.8	85 / 15	$21.7^{+3.4}_{-3.0}$	125 / 42	$13.5^{+2.2}_{-2.1}$	181 ± 2	13
^{60}Co	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	~10
	1764.5	23 / 5	$5.4^{+1.9}_{-1.5}$	24 / 1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7	
	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



GERDA 13.65 kg·yr

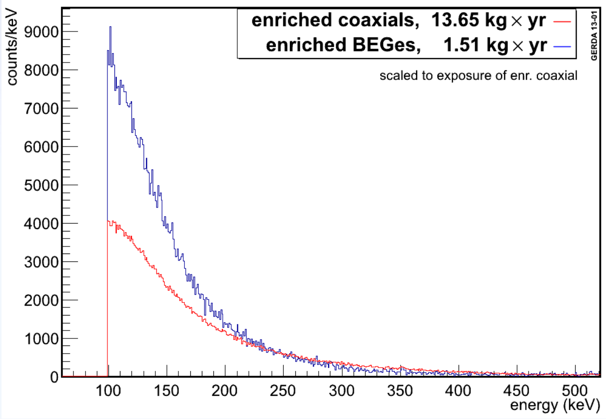


taken from Eur. Phys. J. A12, 147-154 (2001)

Background from Argon

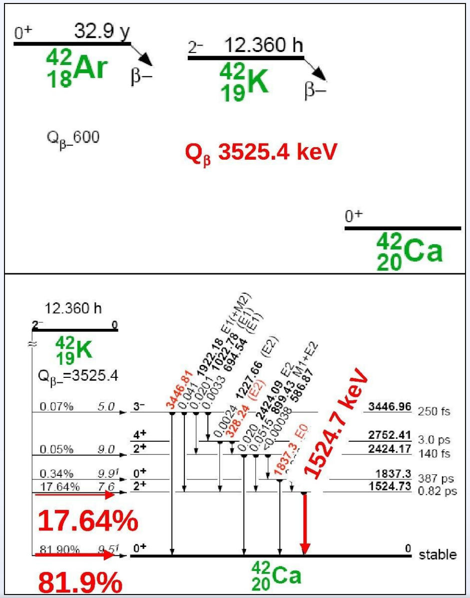
^{39}Ar

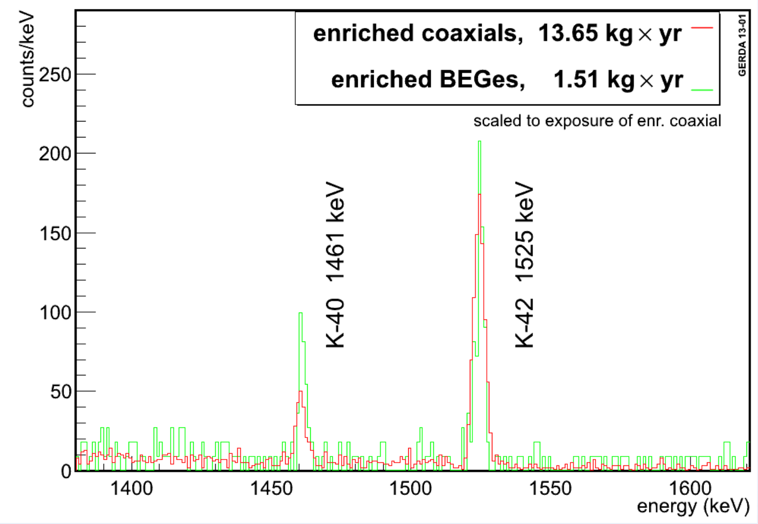
- 1.01 Bq/kg, $T_{1/2}$=269 yr
- pure β emitter, Q-value=565 keV
  → **below region of interest**



^{42}Ar

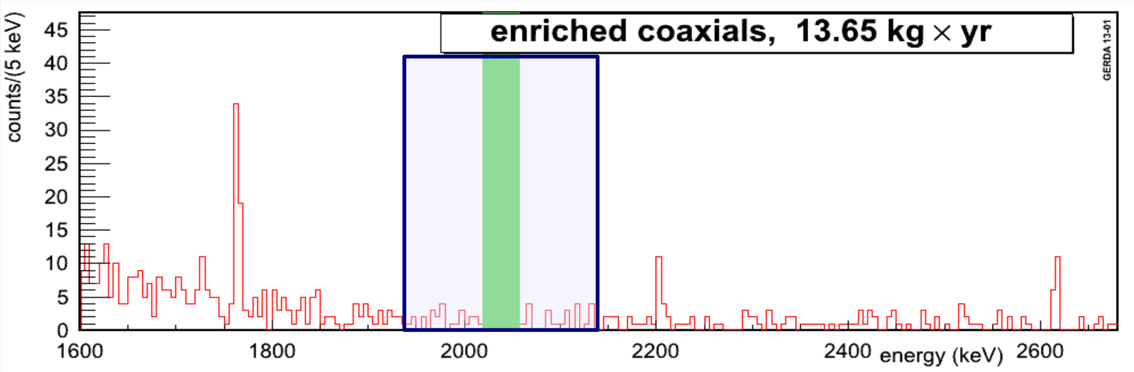
GERDA proposal: ^{42}Ar/^{nat}Ar < 3 x 10^{-21} (*Barabash et al. 2002)*
GERDA measurement: Count rate at 1525 keV ~ 2 times expectation





Region of Interest

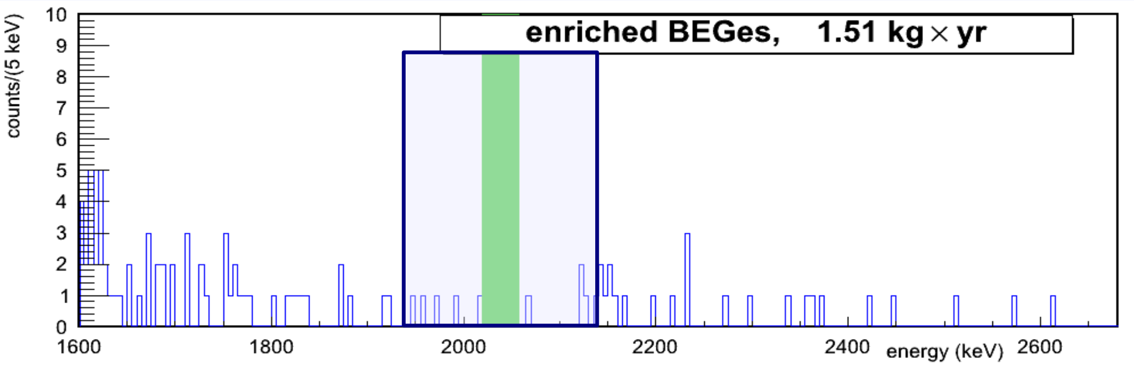
Background rate in ROI ($Q_{\beta\beta}$±100 keV, blinded window excluded)



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 ~6-8 lower than previous experiments (HdM, IGEX)**

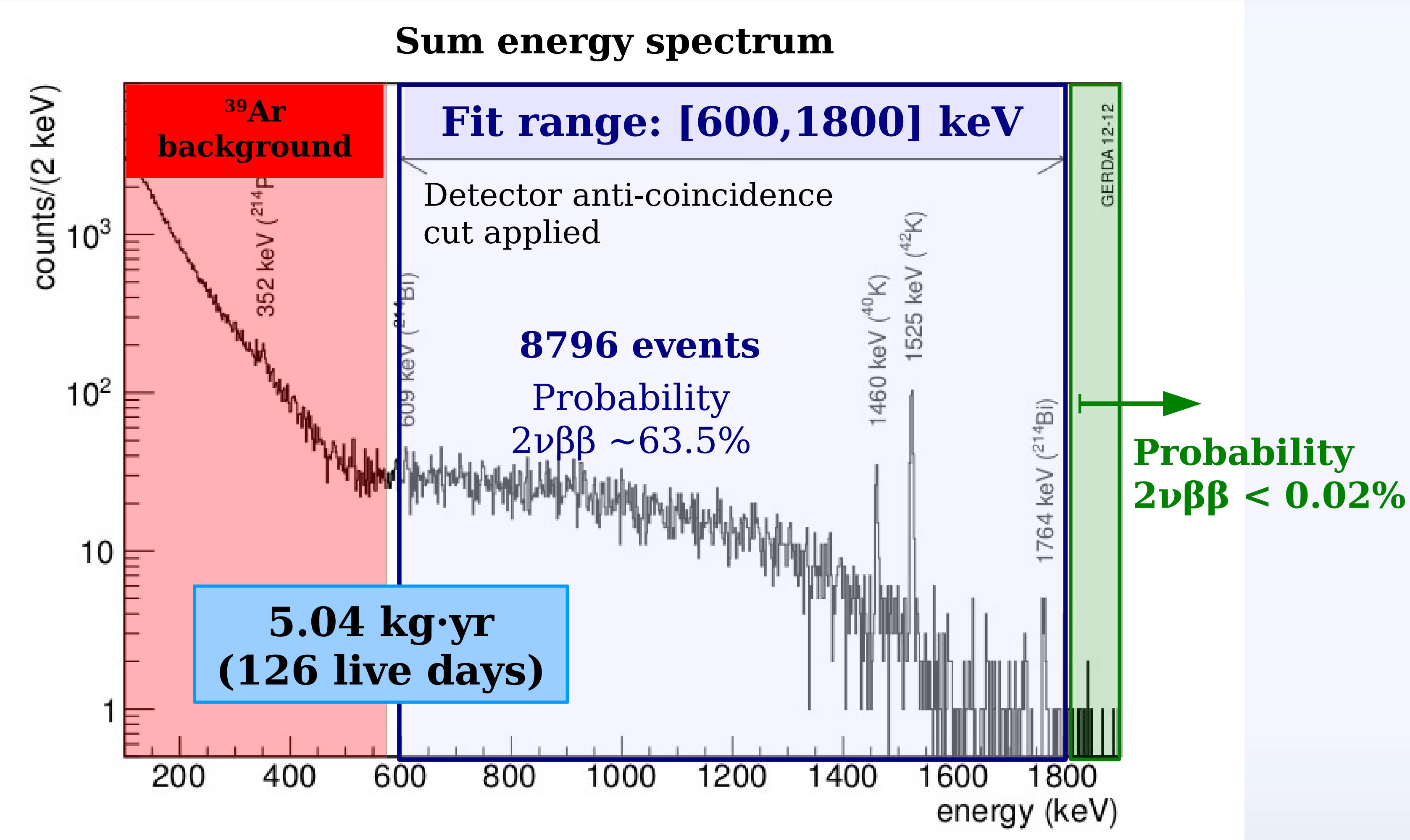


Enriched BEGes: $0.041^{+0.015}_{-0.012}$ cts/(keV·kg·yr)

(No pulse shape analysis applied yet)

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

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



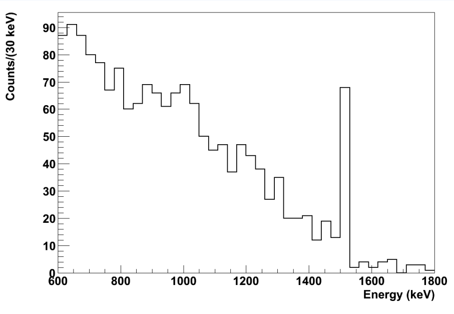
Measurement of $T^{2\nu}_{1/2}$: Fit

Binned maximum likelihood approach

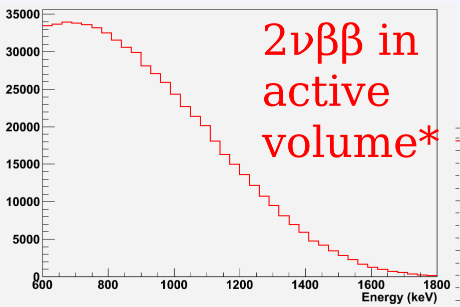
Ingredients:

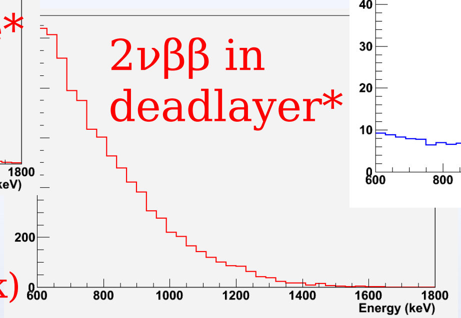
- 6 energy spectra from ^{enr}Ge detectors (30 keV bins)

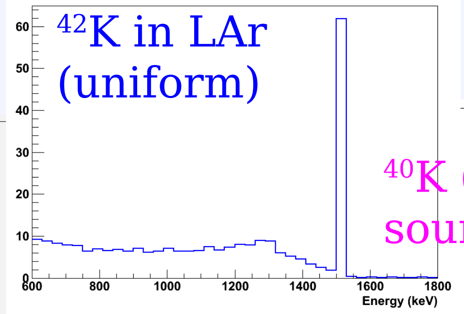
Single detector energy spectrum:

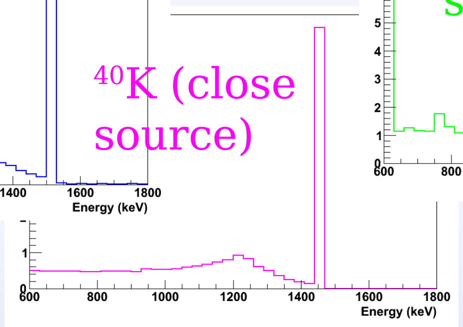


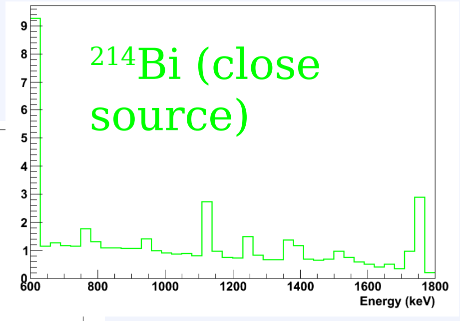
- Model: Simulated spectra of $2\nu\beta\beta$, ^{42}K, ^{40}K, ^{214}Bi for each detector











*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. Phys. 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

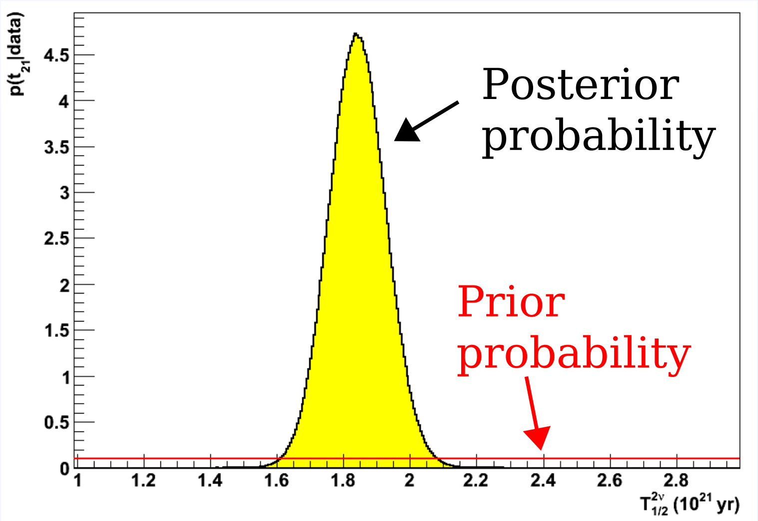
- Run the fit

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

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

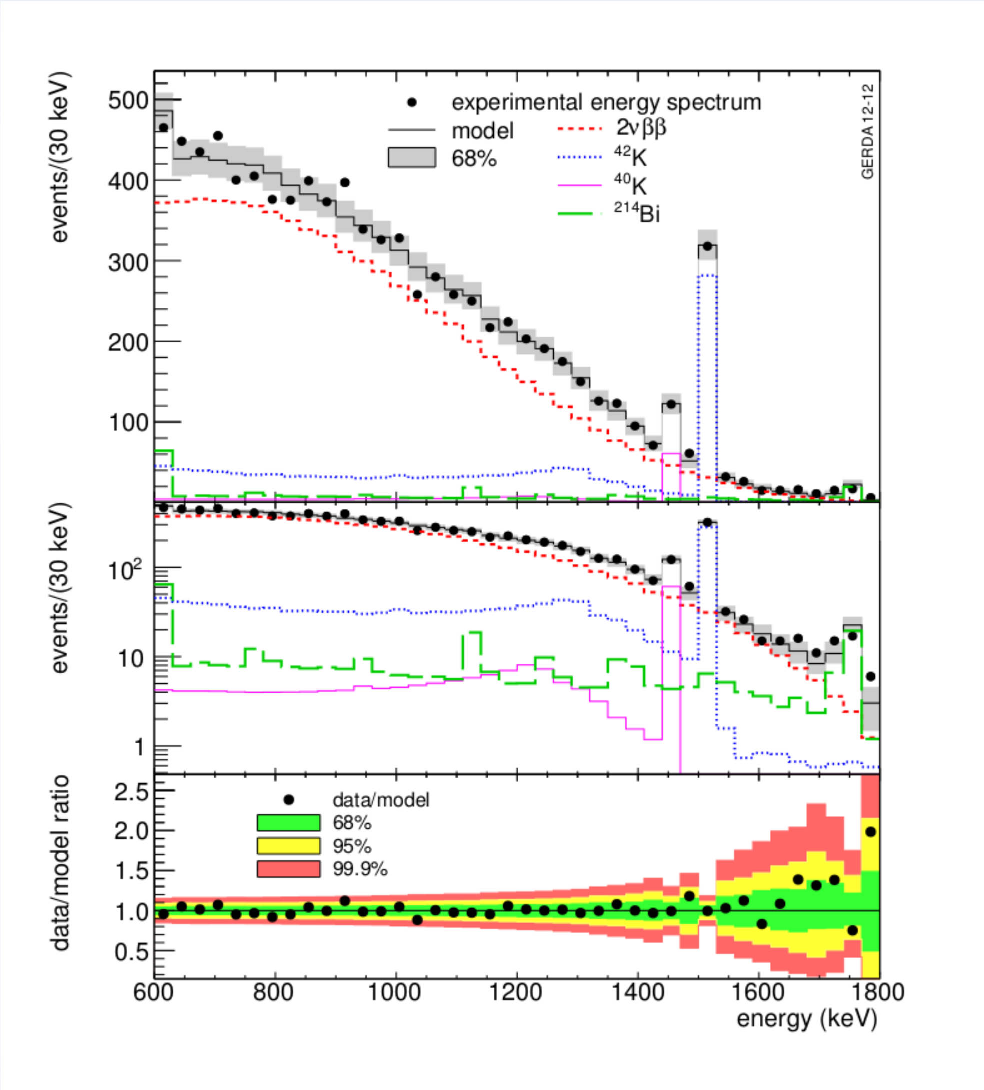
$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08}) \cdot 10^{21}$ yr (smallest interval 68%)

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)

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



Data: 8796 events

Best fit model: 8797.0 events
2νββ: 80%
^{42}K: 14%
^{214}Bi: 4%
^{40}K: 2%

Signal to background: 4:1

p-value: 0.77

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

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

Source positions

Decay distribution model

Dimensions, materials, ...

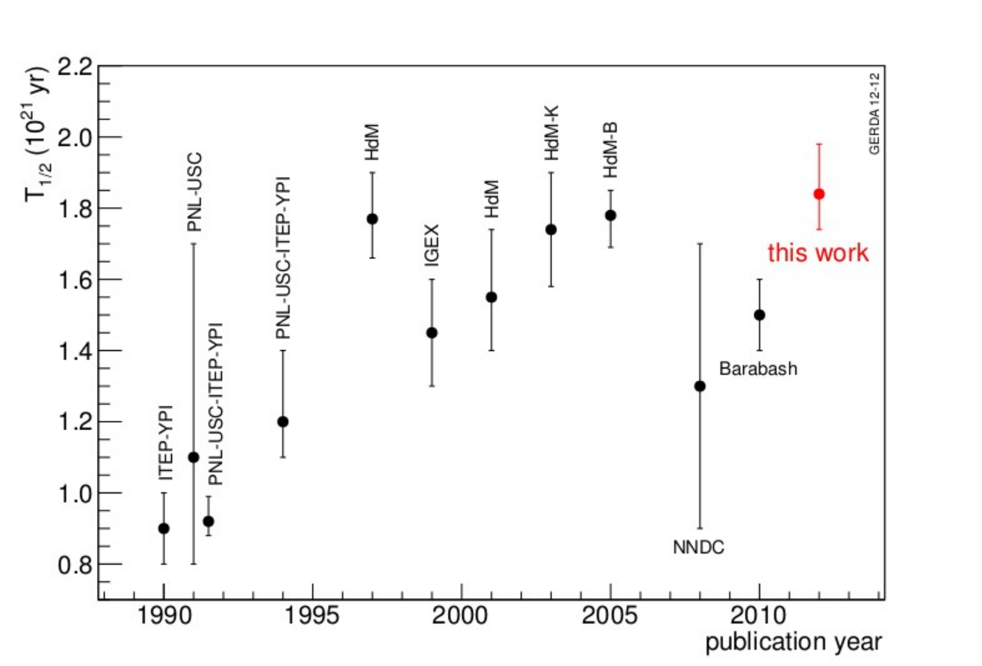
Validation of GEANT4 processes

Source of uncertainty	Uncertainty on $T^{2\nu}_{1/2}$ [%]
Non-identified background components	+5.3
Energy spectra from ^{42}K, ^{40}K, ^{214}Bi	±2.1
Shape of the 2νββ 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**

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

Final result:

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



- 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 $\mathbf{M^{2\nu}}$

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

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

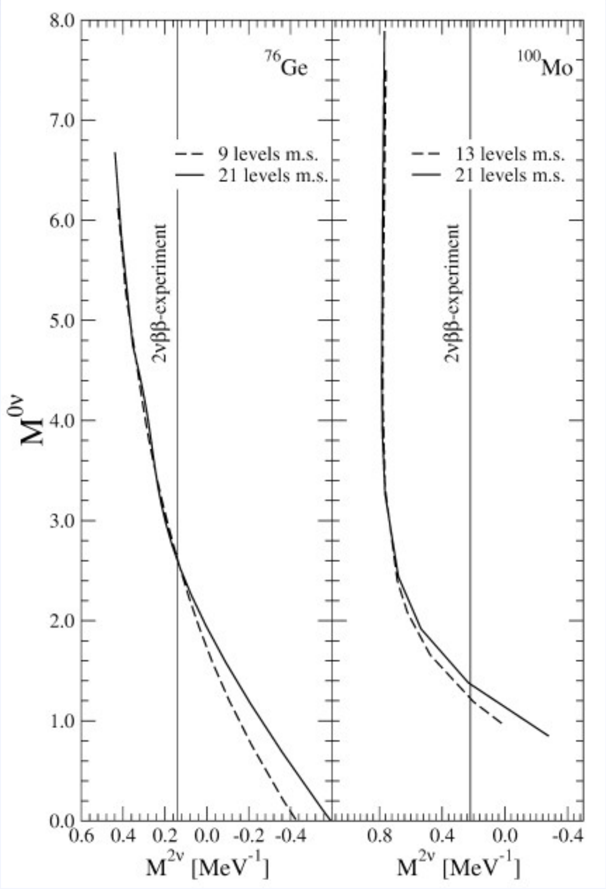
→ decrease by 11% compared to *[2]*

→ 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%



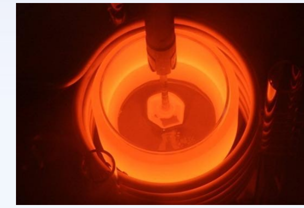
Relation between $M^{2\nu}$ and $M^{0\nu}$ (taken from *[2]*)

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

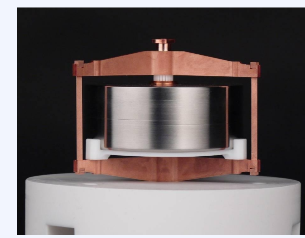
[2] Rodin V. A., Fässler A., Šimkovic F. and Vogel P. 2006 Nucl. Phys. A 766 107; erratum: 793 (2007) 213

Phase II detector production

Production of 30 new ^{enr}Ge BEGe detectors (~20 kg):



- ✓ Crystal pulling at Canberra: Oak Ridge, TN, USA
- ✓ Transport to Mol, Belgium

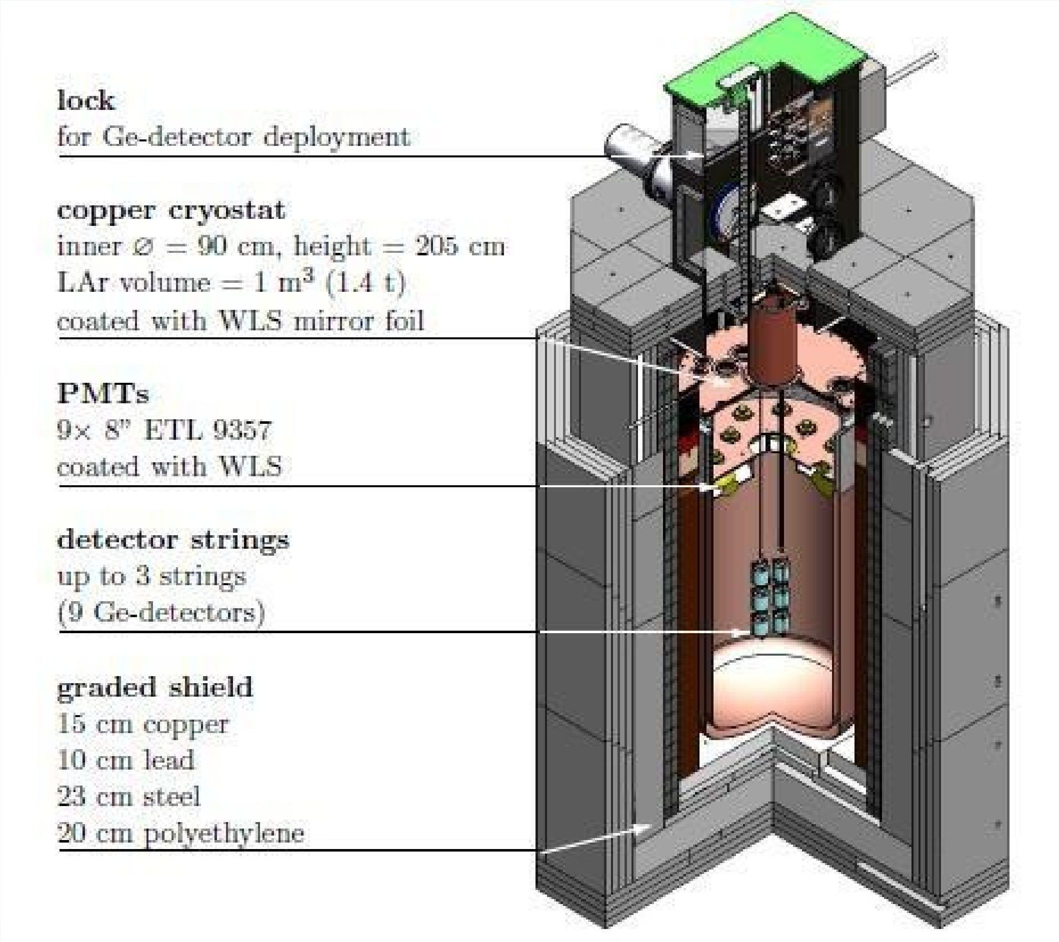


- ✓ BEGe detector diode production: Olen, Belgium
- ✓ BEGe acceptance tests: Hades, Belgium
  (Tests of detector performance and properties)

- ✗ Electrical contacting : Olen, Belgium

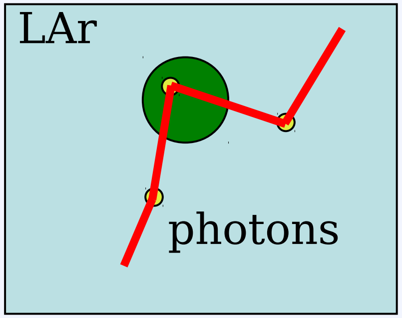
→ **Phase II detectors almost ready!**

Liquid Argon readout

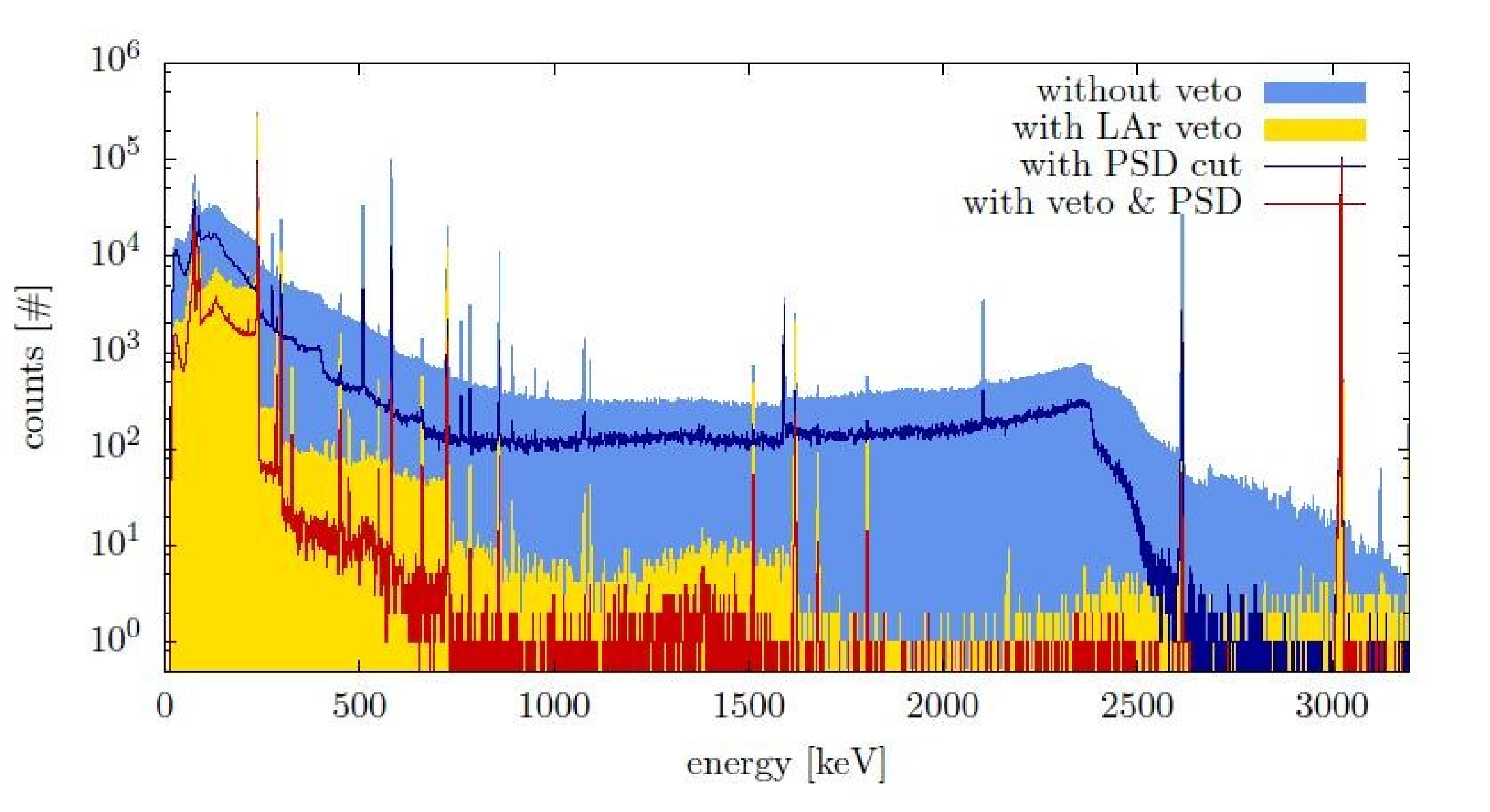


LArGe: Low-background test facility at LNGS

Detection of coincident LAr scintillation light to discriminate background



Phase II background reduction



Operation of Phase II proto-type detector in LArGe:
Combining **PSD of BEGe detector and LAr veto**:
Measured suppression factor for a ^{228}Th source at $Q_{\beta\beta}$: **~ 5·10^3**

Also other designs using SiPM's investigated
→ **avoid additional background!**

Conclusions

- **GERDA Phase I collected about 15 kg·yr of enr data so far**
- **Background in ROI about factor 1/10 compared to previous experiments**
- **First result using 5 kg·yr of data: $T^{2\nu}_{1/2} = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr**
  The GERDA Collaboration, J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110
- **Phase II detectors produced and tested**

2013 will be very exciting year:

- **Unblinding**
- **$T^{0\nu}_{1/2}$ results**
- **Transition to Phase II**

Additional material

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)

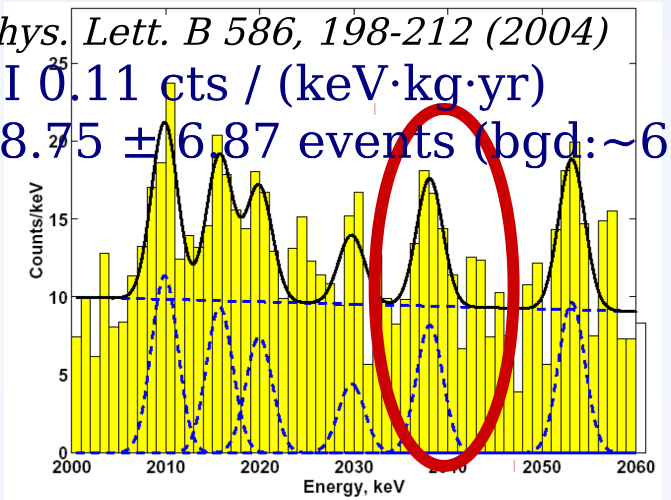
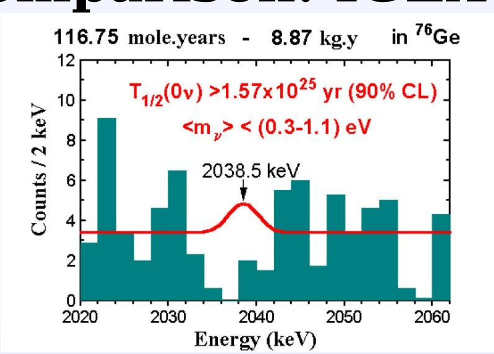


Fig. 17. The total sum spectrum of all five detectors (in total 10.96 kg enriched in ^{76}Ge), for the period November 1990–May 2003 (71.7 kg year) in the range 2000–2060 keV and its fit (see Section 3.2).

Comparison: IGEX



- Nov 1990 - May 2003
- 71.7 kg·yr
- 4.2σ/6σ evidence for 0νββ

- (0.69 – 4.18)·10^{25} yr (3σ)
  Best fit: 1.19·10^{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 *arXiv: 1210.7432*

- $m_{\beta\beta}$ = (0.24-0.58) eV (best fit 0.44 eV) / 0.32±0.03 eV

Note: statistical significance depends on background model!

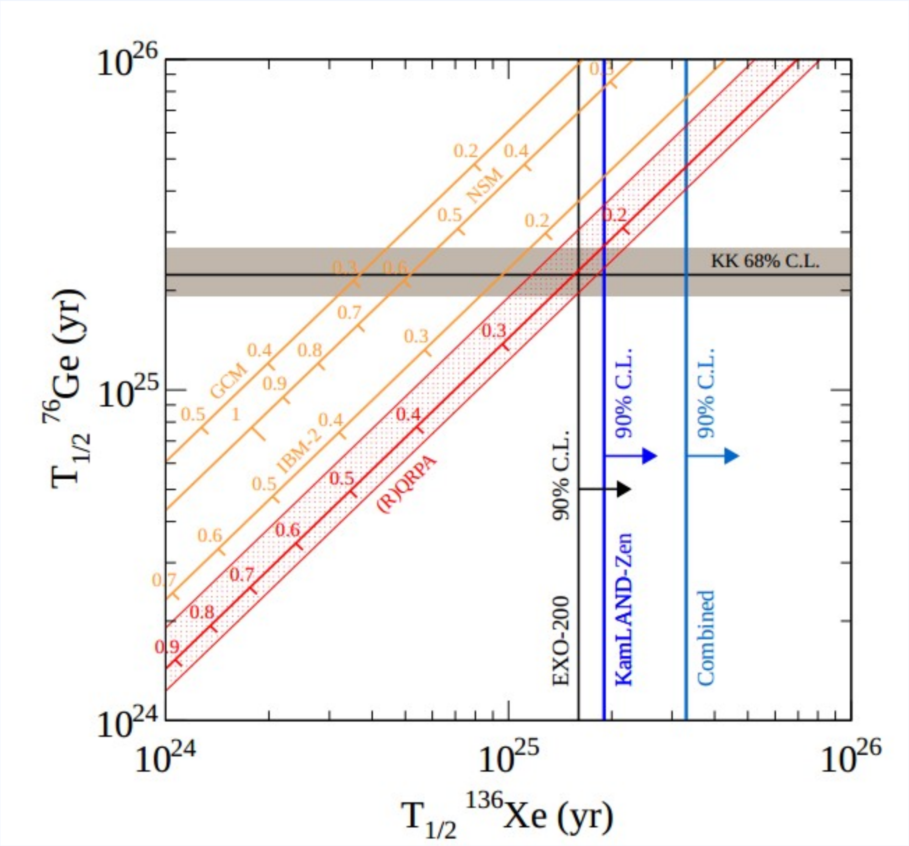
Detector parameters

detector	total mass (g)	active mass (g)	^{76}Ge isotopic abundance (%)	$T^{2\nu}_{1/2}$ (10^{21} yr)
ANG2	2833	2468±121±89	86.6±2.5	$1.99^{+0.14}_{-0.15}$
ANG3	2391	2070±118±77	88.3±2.6	$1.69^{+0.15}_{-0.14}$
ANG4	2372	2136±116±79	86.3±1.3	$1.94^{+0.14}_{-0.15}$
ANG5	2746	2281±109±82	85.6±1.3	$1.79^{+0.12}_{-0.14}$
RG1	2110	1908±109±72	85.5±2.0	$1.94^{+0.18}_{-0.14}$
RG2	2166	1800±99±65	85.5±2.0	$1.93^{+0.16}_{-0.16}$

$\chi^2/\nu=3.02/5$

KamLAND-Zen and EXO-200

From arXiv:1211.3863v1 [hep-ex] (2012):



“Combined result for ^{136}Xe refutes the 0νββ detection claim in ^{76}Ge at > 97.5%”

Comparison depends on matrix calculations
→ GERDA will check claim independently from calculations

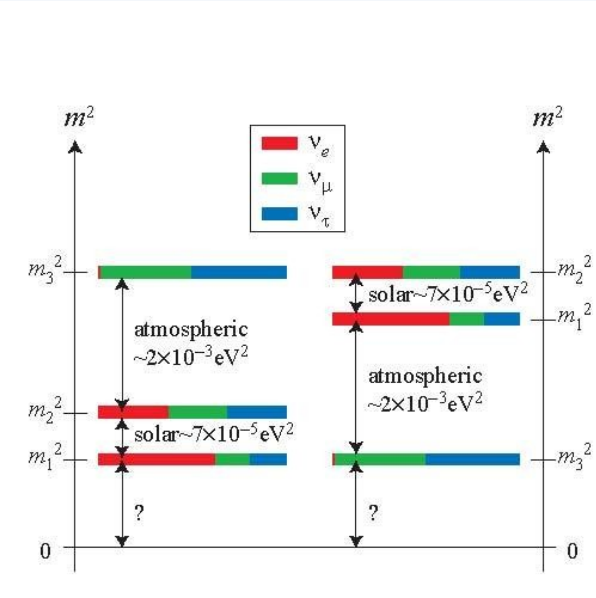
Neutrino properties

Neutrino Mixings

Weakly interacting and mass eigenstates are independant basis

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

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



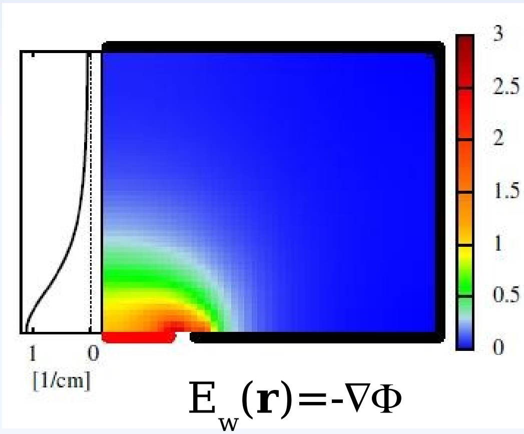
What we know:

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

What we do not know:

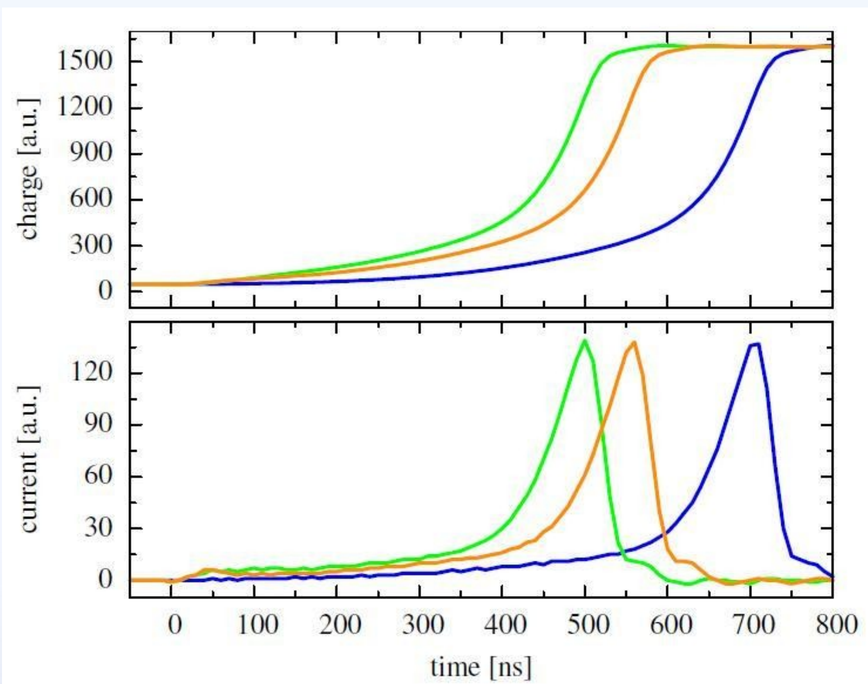
- Absolute mass scale
- Mass hierarchy
- Phases (δ_{13}, α_{21}, α_{31})
- Nature of the neutrino mass (Dirac or Majorana)

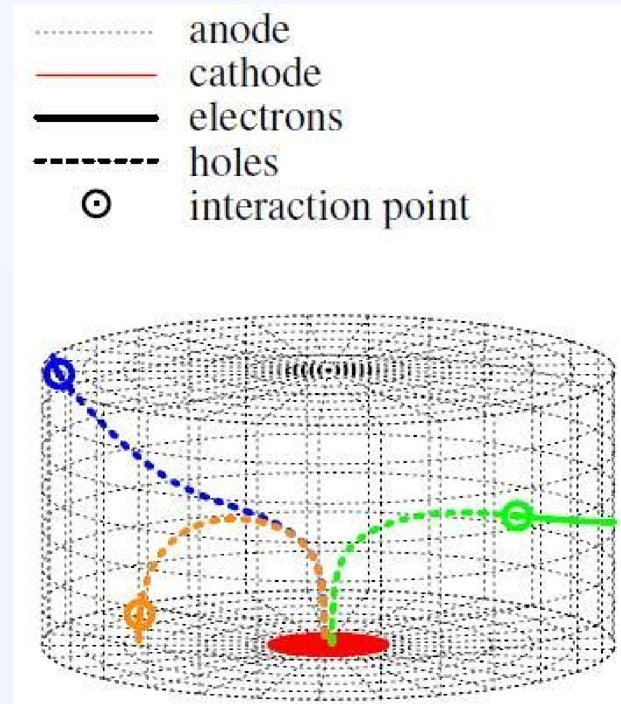
Phase II detectors



Shockley-Ramo Theorem:

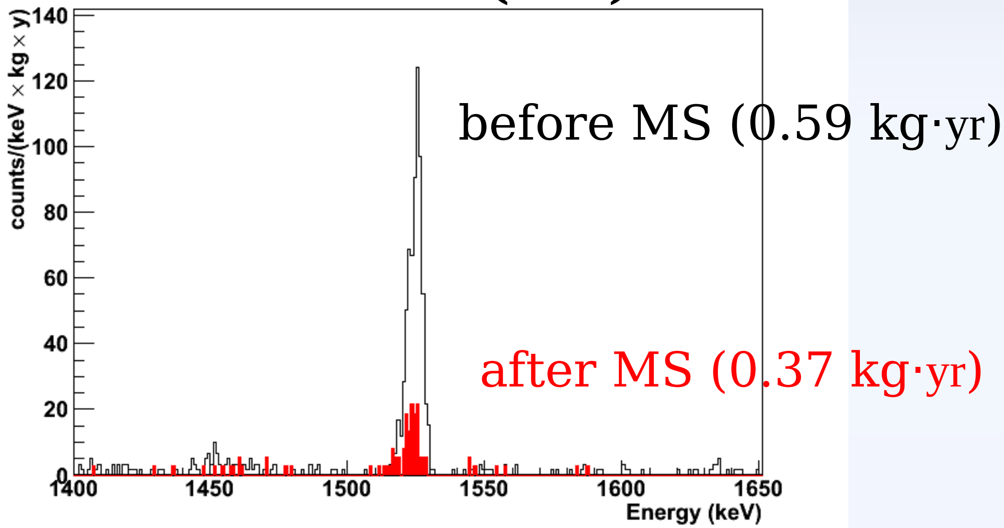
$Q(t)=-q\cdot\Phi_w(\mathbf{r}(t))$

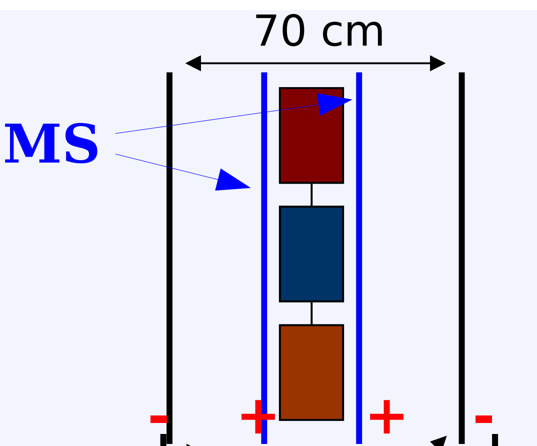




Background from Argon

Add a mini-shroud (MS):





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