16 th Lomonosov conference on elementary particle physics

MSU, August 22-28, 2013

GERDA experiment – results and status.

Leonid Bezrukov (INR)

On behalf GERDA Collaboration

The GERDA collaboration

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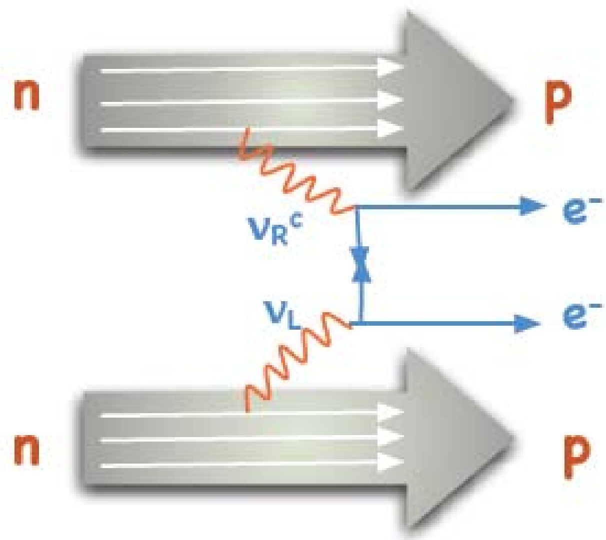
~ 100 members
19 institutions
6 countries

0νββ decay and neutrino mass



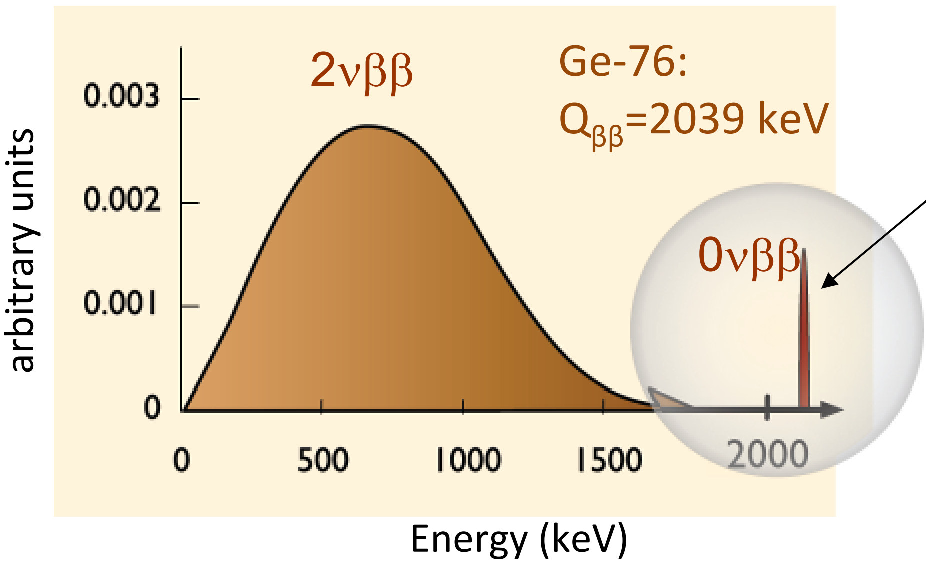
Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral — Nuclear matrix element

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

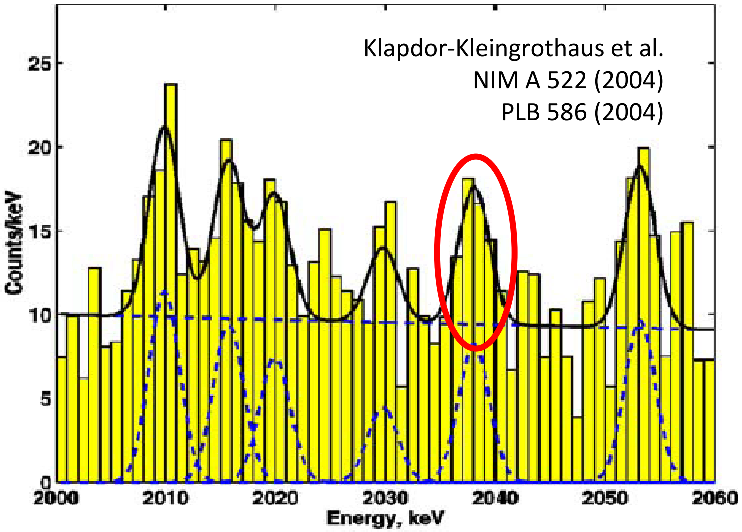
U_{ei} Elements of (complex) PMNS mixing matrix



Experimental signatures:
- peak at $Q_{\beta\beta} = m(A,Z)-m(A,Z+2)-2m_e$
- two electrons from vertex

Discovery would imply:
- lepton number violation $\Delta L = 2$
- ν's have Majorana character
- mass scale & hierarchy
- physics beyond the standard model

^{76}Ge 0νββ search: the claim



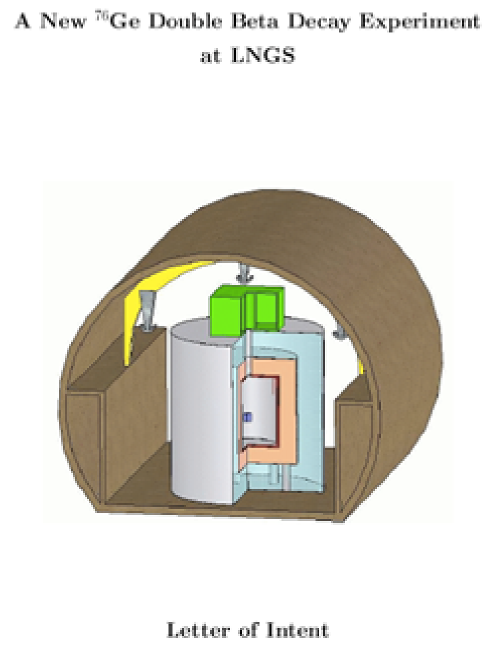
Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

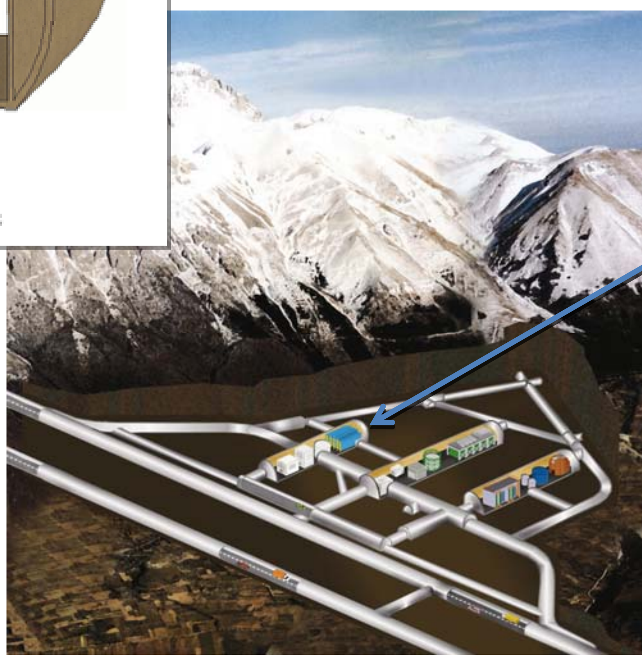
N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr $T_{1/}$after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

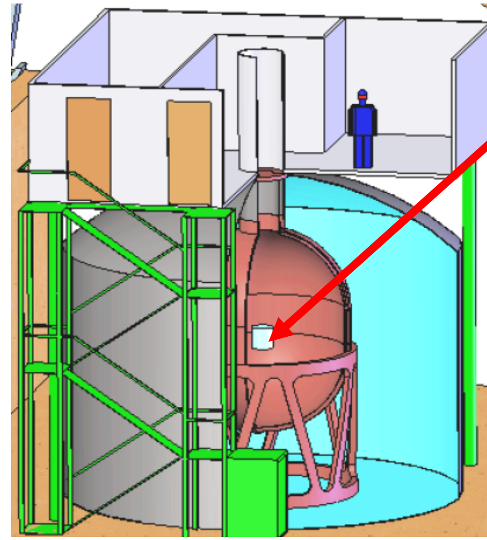
- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx$ 0.6)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):


A New ^{76}Ge Double Beta Decay Experiment at LNGS

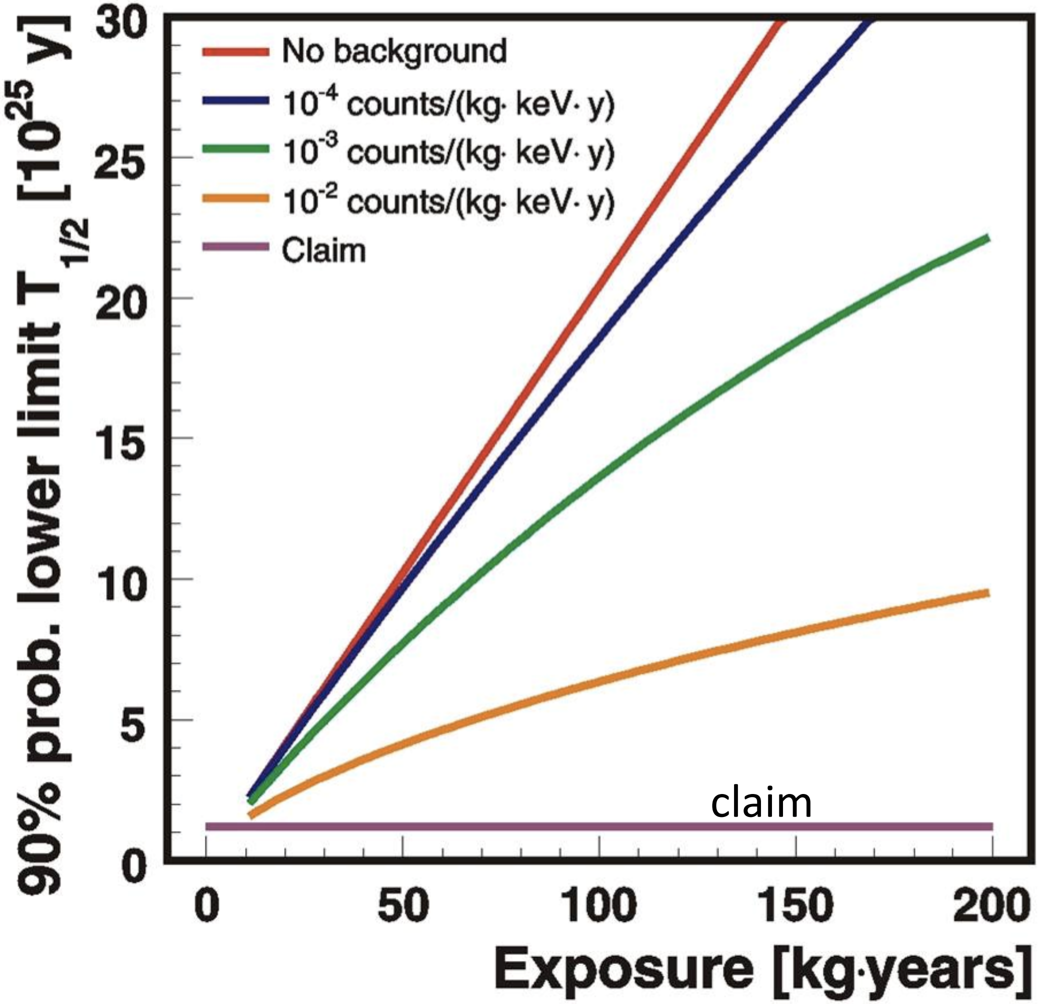
Letter of Intent

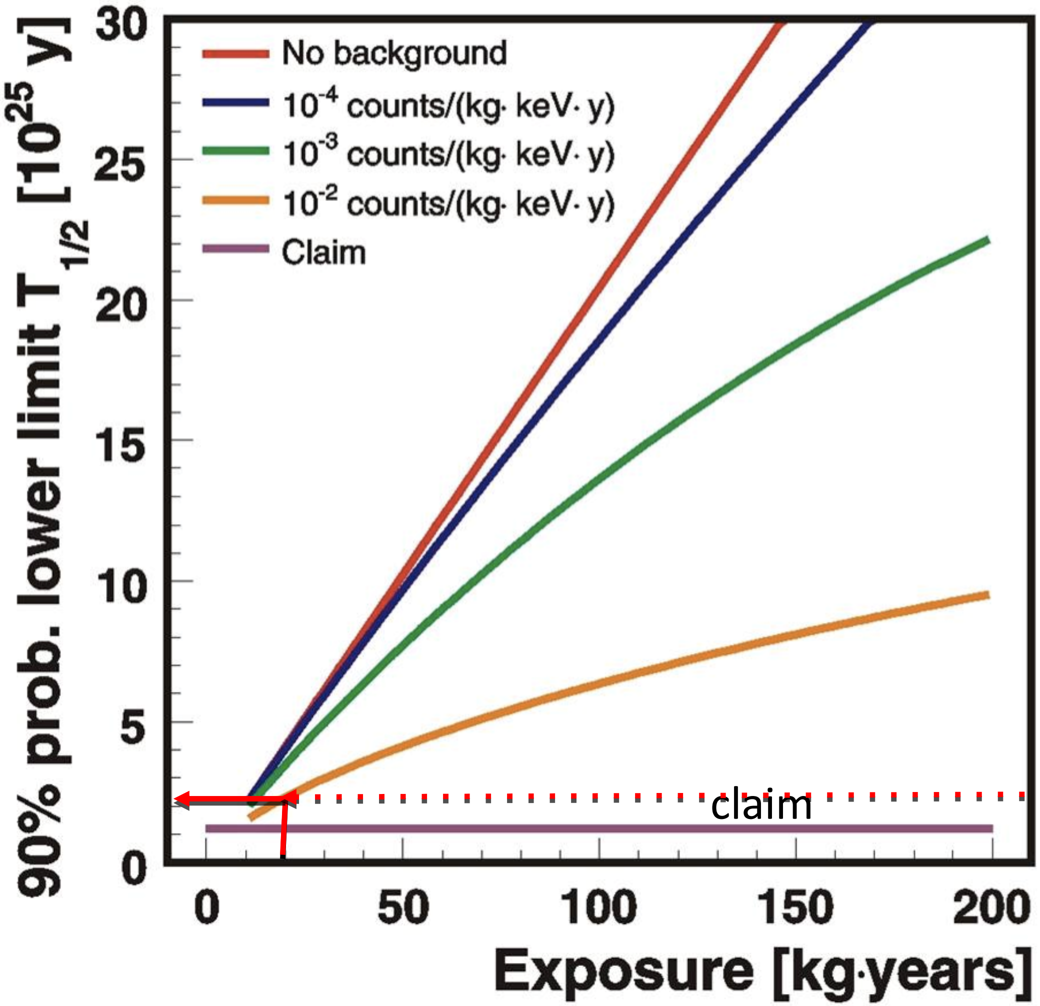




- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

GERDA Phases



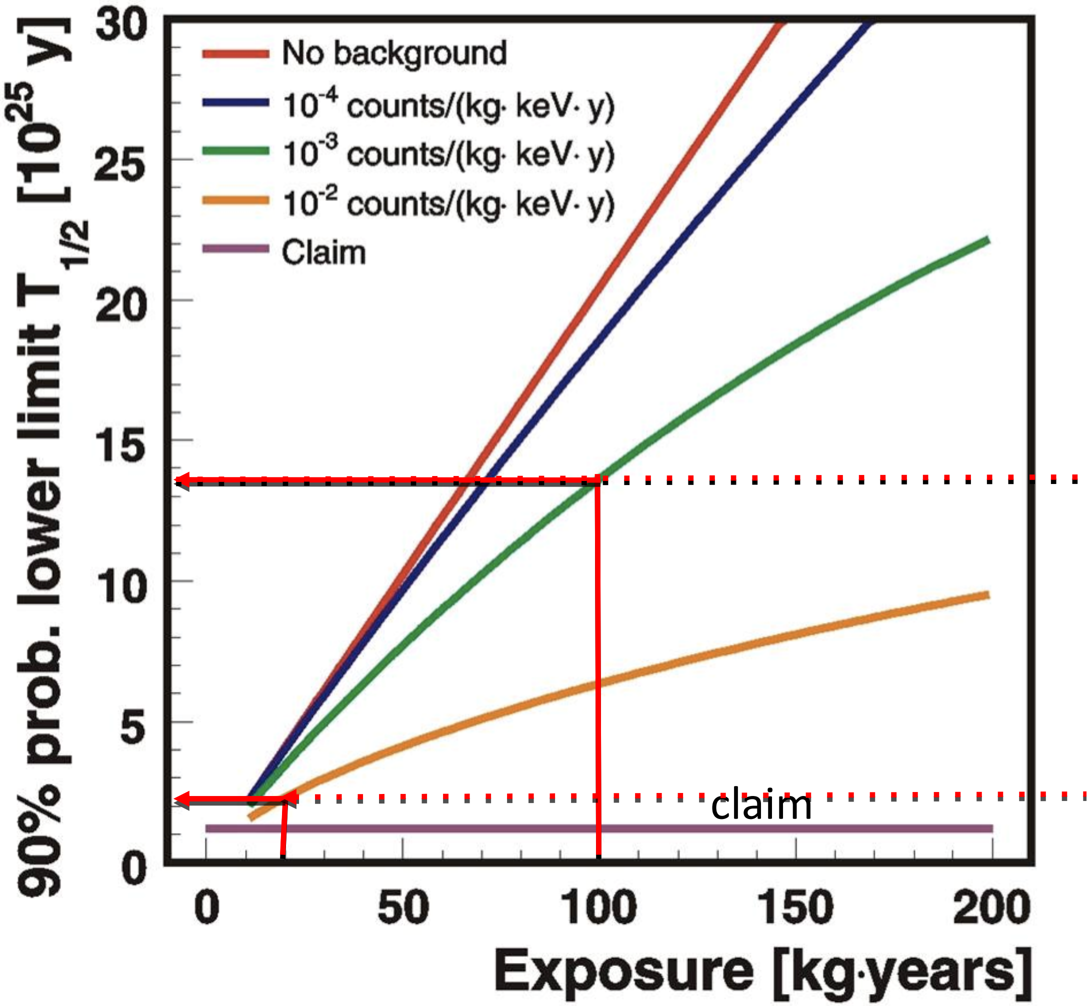


Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr



Phase II:

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

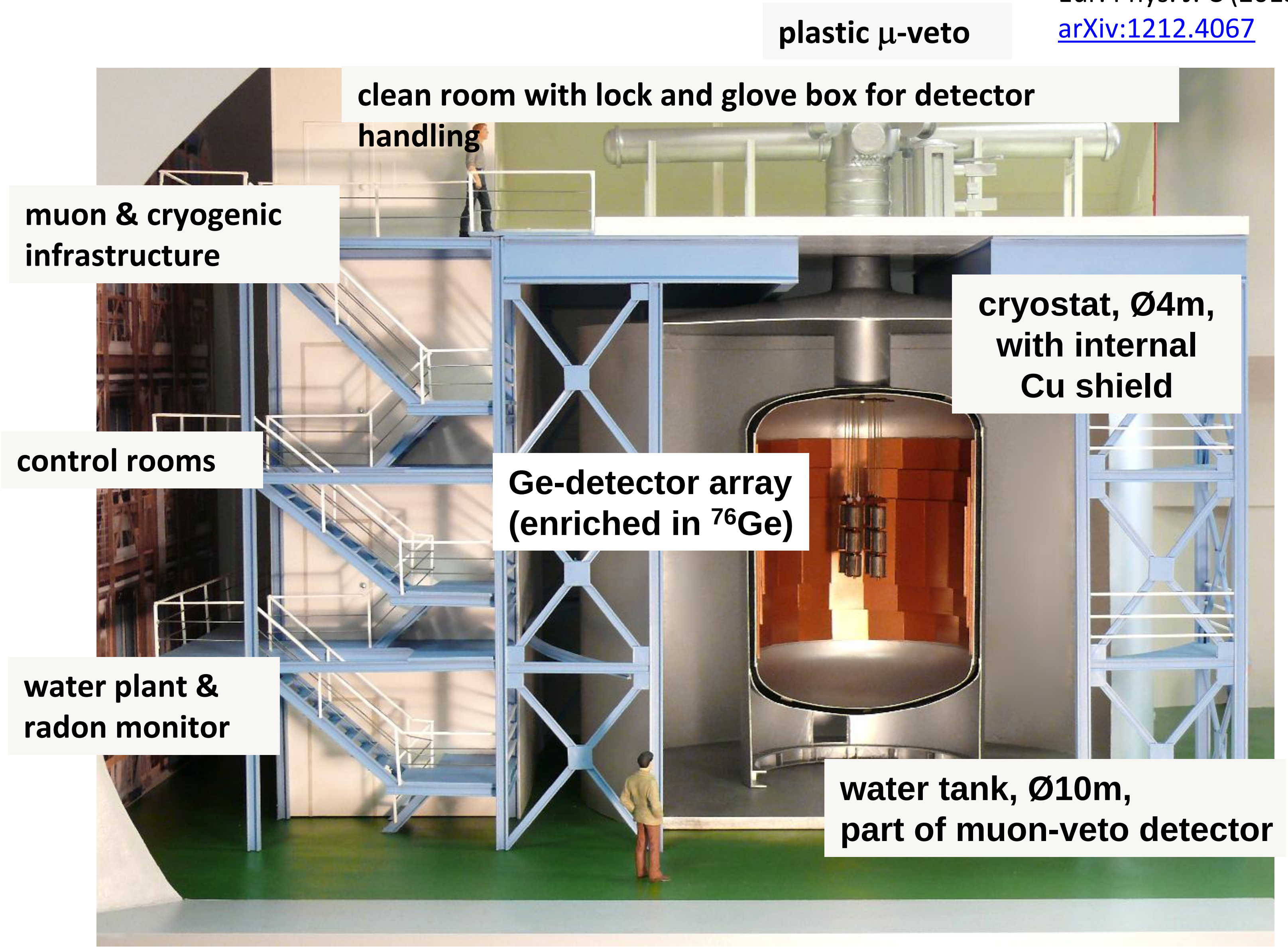
Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

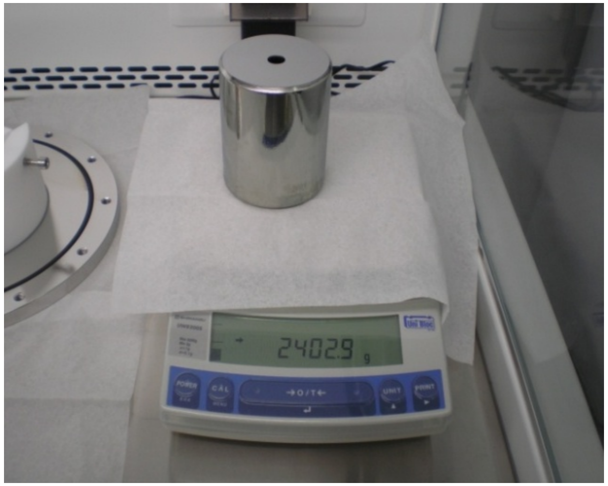
Sensitivity after 20 kg yr

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



Phase I detectors: semi-coaxial detectors

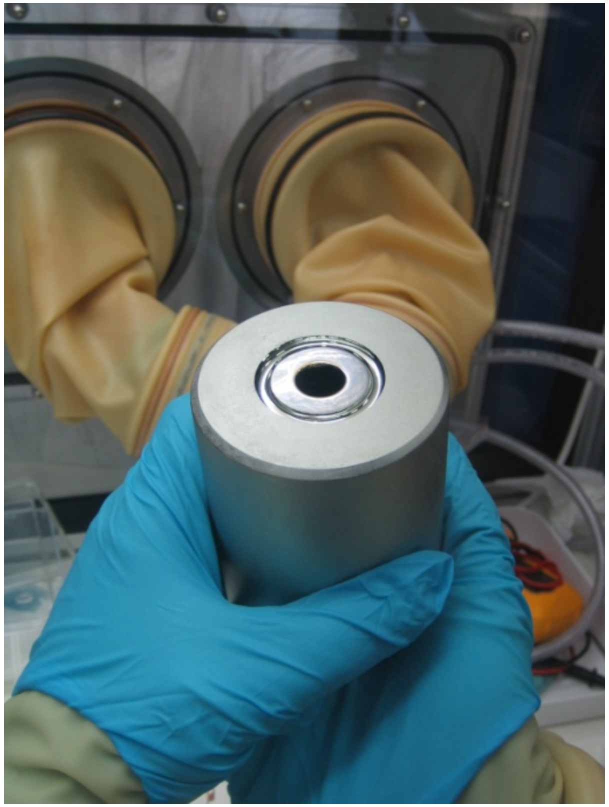
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



- HdM & IGEX diodes reprocessed at Canberra, Olen
- Long term stability in LAr w/o passivation layer
- Energy resolution in LAr: ~2.5 keV (FWHM) @1.3 MeV

8 diodes (from HdM, IGEX):

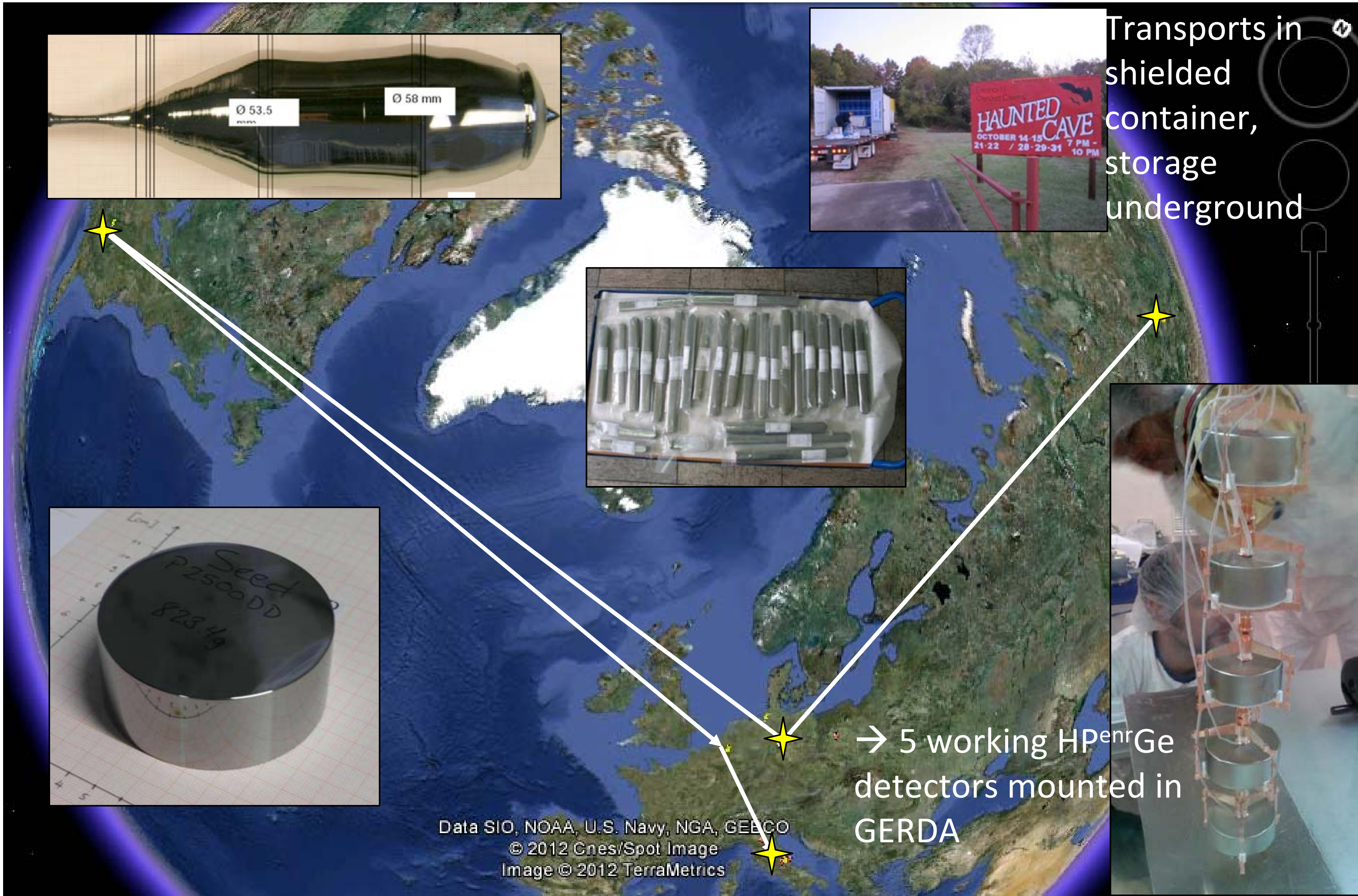
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



6 diodes from Genius-TF:

- ^{nat}Ge
- Total mass: 15.60 kg

Production of ^{enr}Ge Phase II detectors

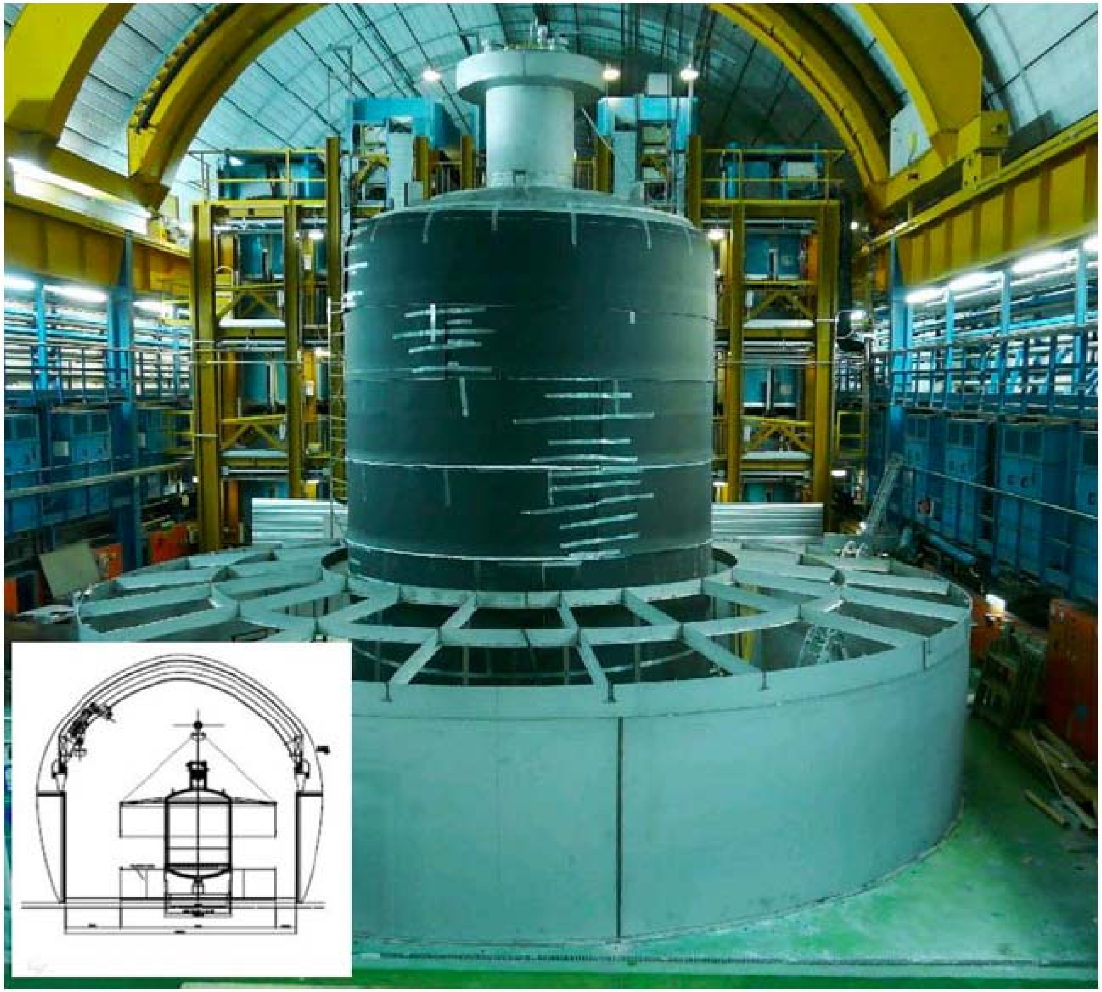


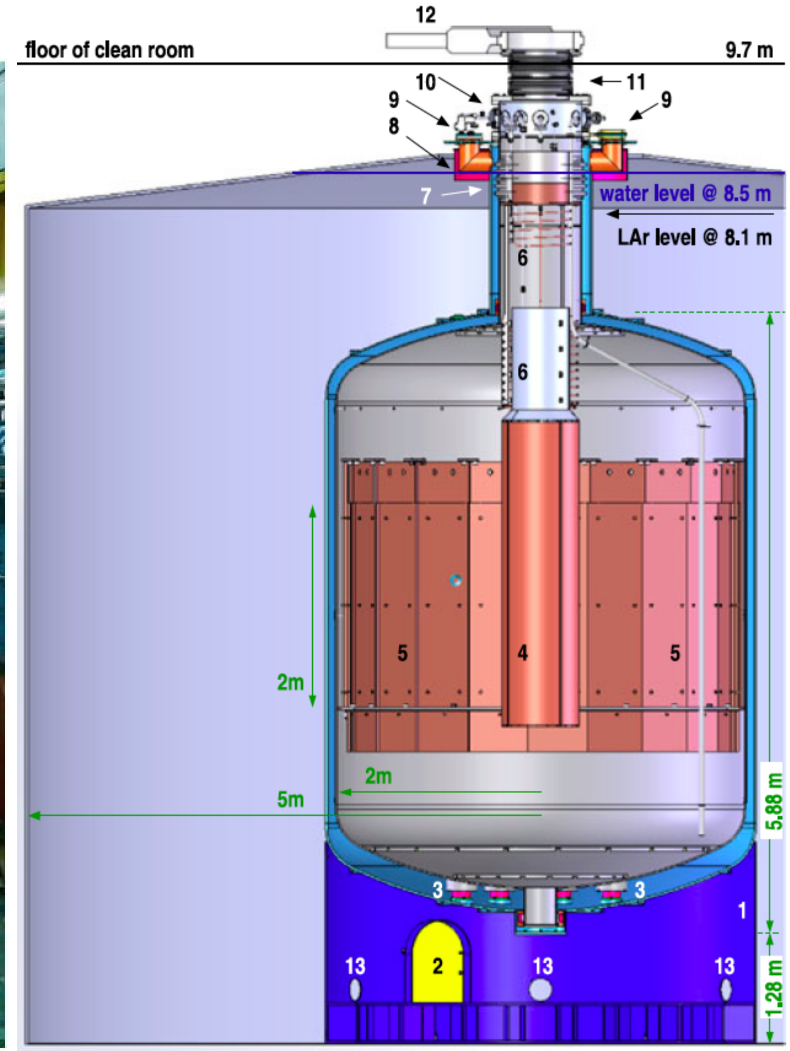
Transports in shielded container, storage underground

→ 5 working HP^{enr}Ge detectors mounted in GERDA

Water tank and cryostat

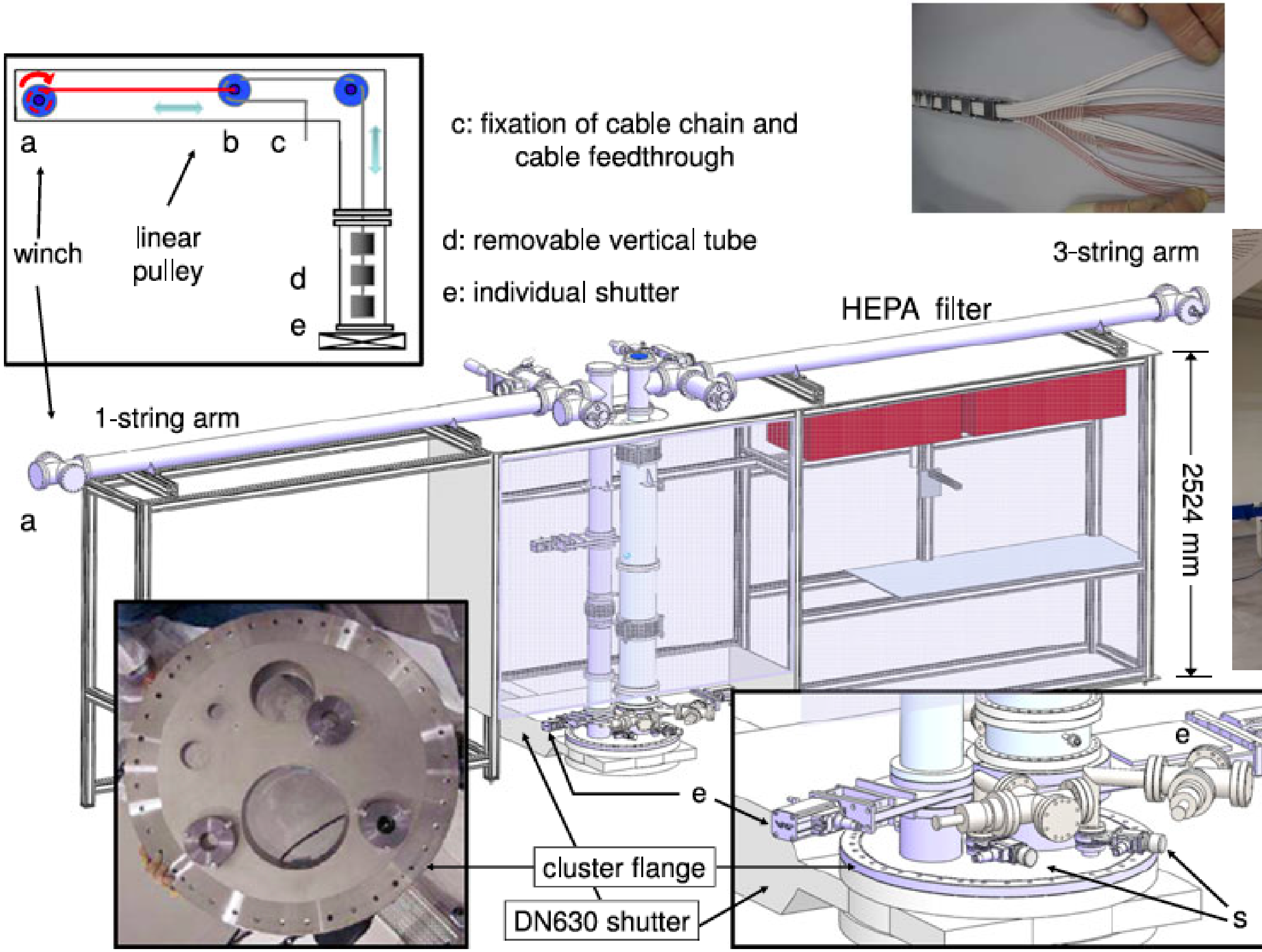
Eur. Phys. J. C (2013) 73:2330
[arXiv:1212.4067](https://arxiv.org/abs/1212.4067)

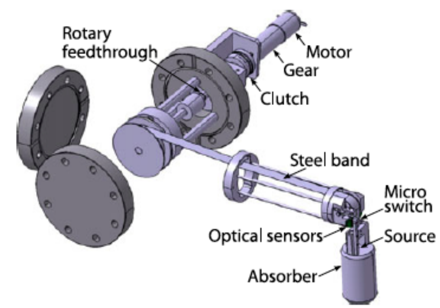




Clean room with Lock system, glove box and calibration devices

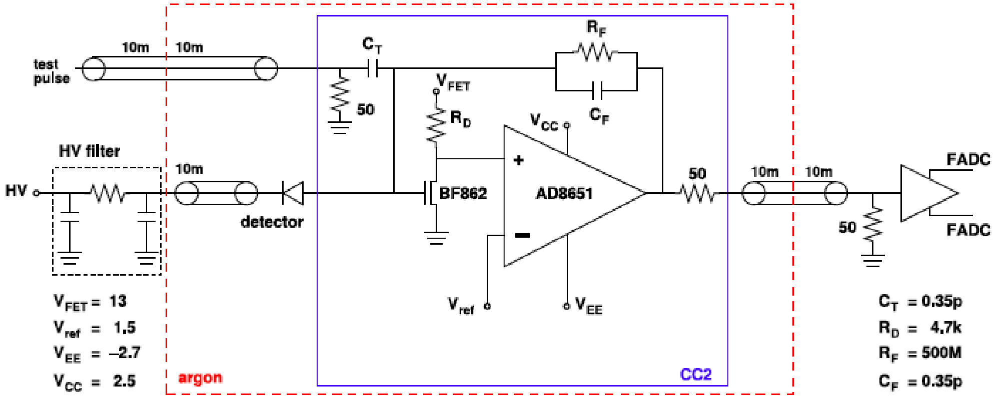
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

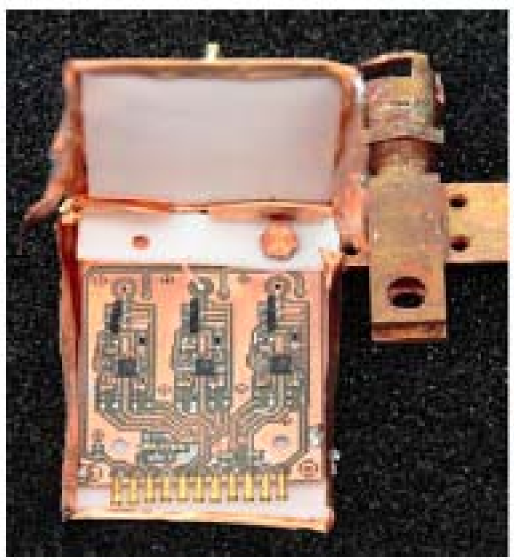


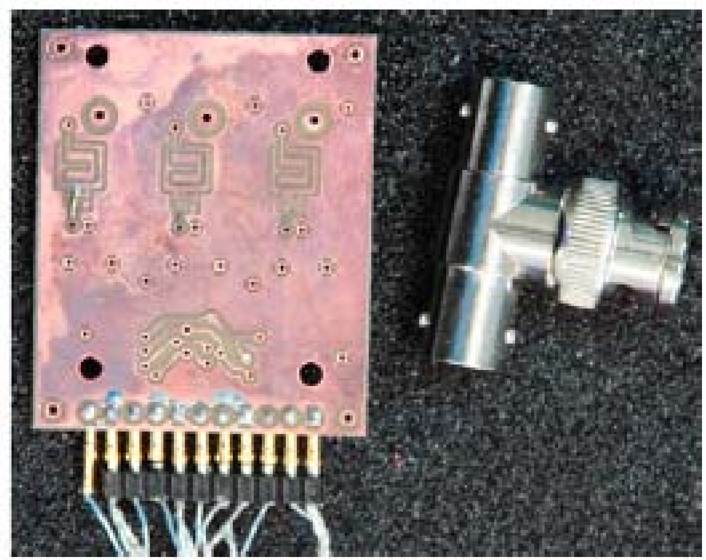


Front-end electronics

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



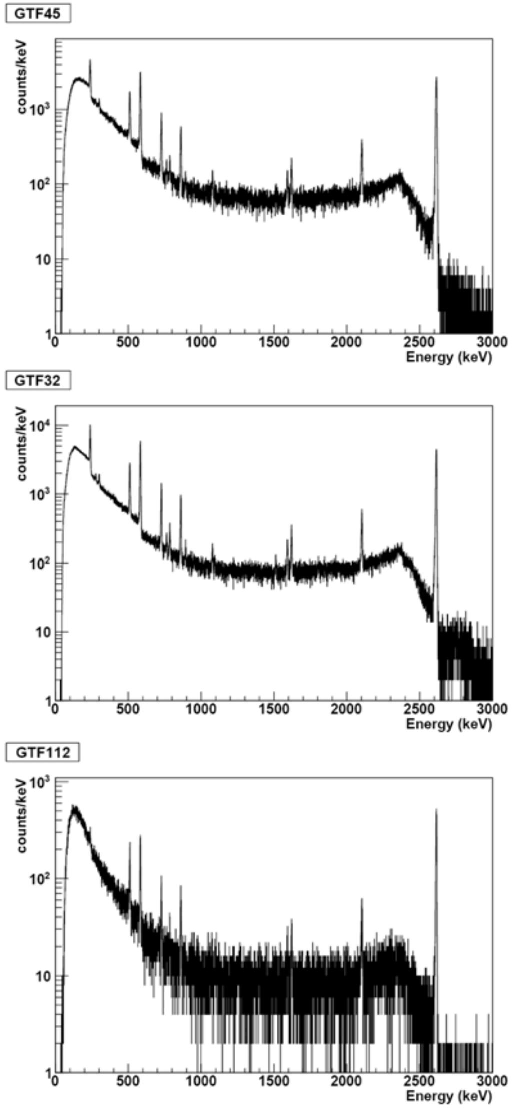




Commissioning with 1-string assembly

65µm Cu cylinder ('mini-shroud') to shield E-field

Calibration with ^{228}Th:

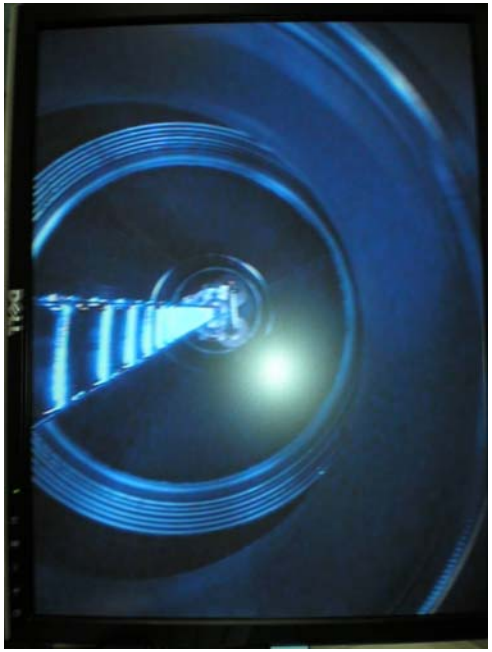


Commissioning runs with **non-enriched low-background detectors** to study performance and backgrounds (June 2010 – Mai 2011)

Energy resolutions during commissioning: dependent on chosen detector configuration:

- Coaxial (Phase I): 4.5-5.keV (*FWHM*) @ 2.6 MeV
- BEGe (Phase II): 2.8 keV (*FWHM*) @ 2.6 MeV

Nov 2011: deployment of 3-string & start of phase I physics runs

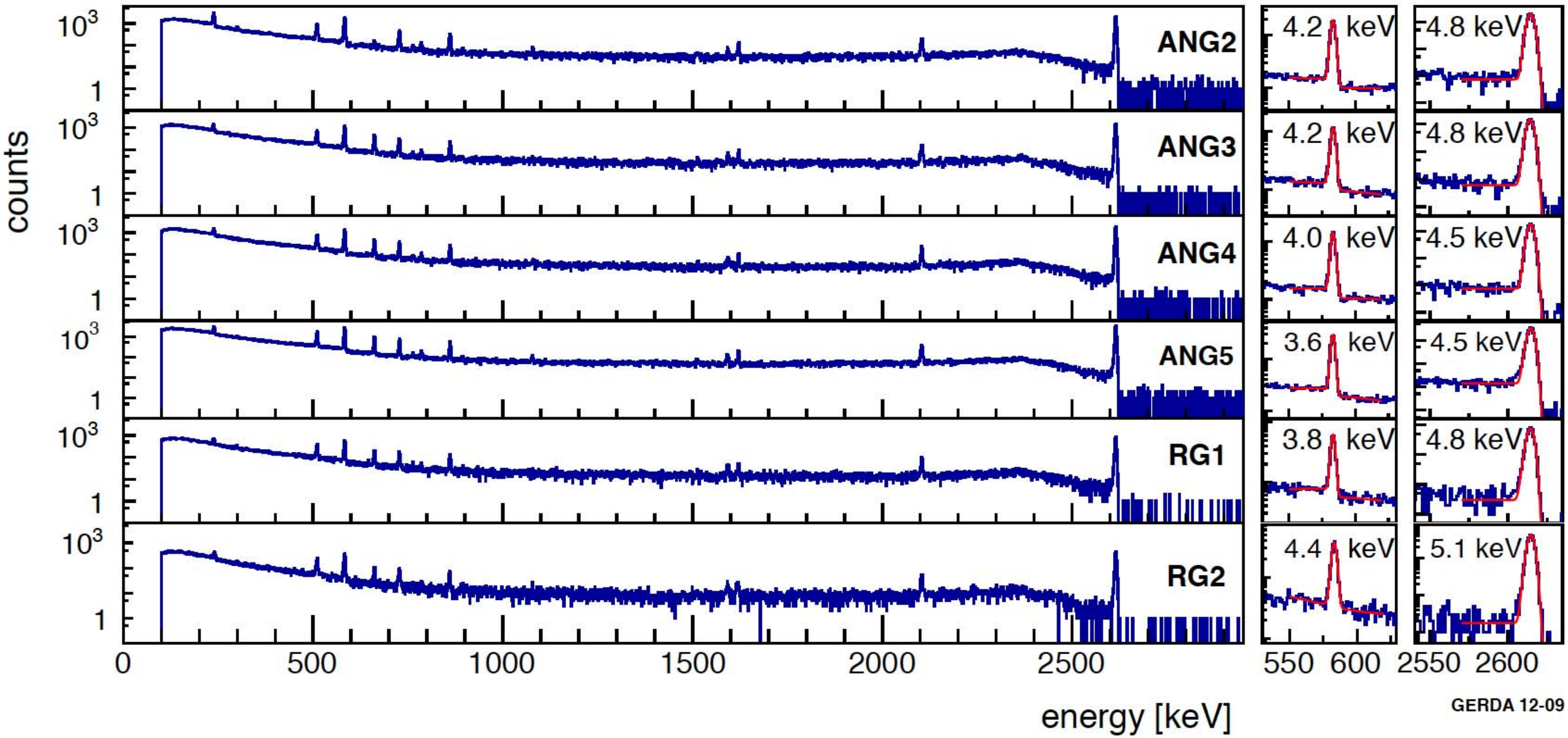


8 refurbished enriched diodes from HdM & IGEX
•86% isotopically enriched in Ge-76
•17.66 kg total mass
•plus 1 natural Ge diode from GTF

2 diodes shut off because leakage current high:
•total enriched enriched detector mass 14.6 kg

First calibration spectra

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

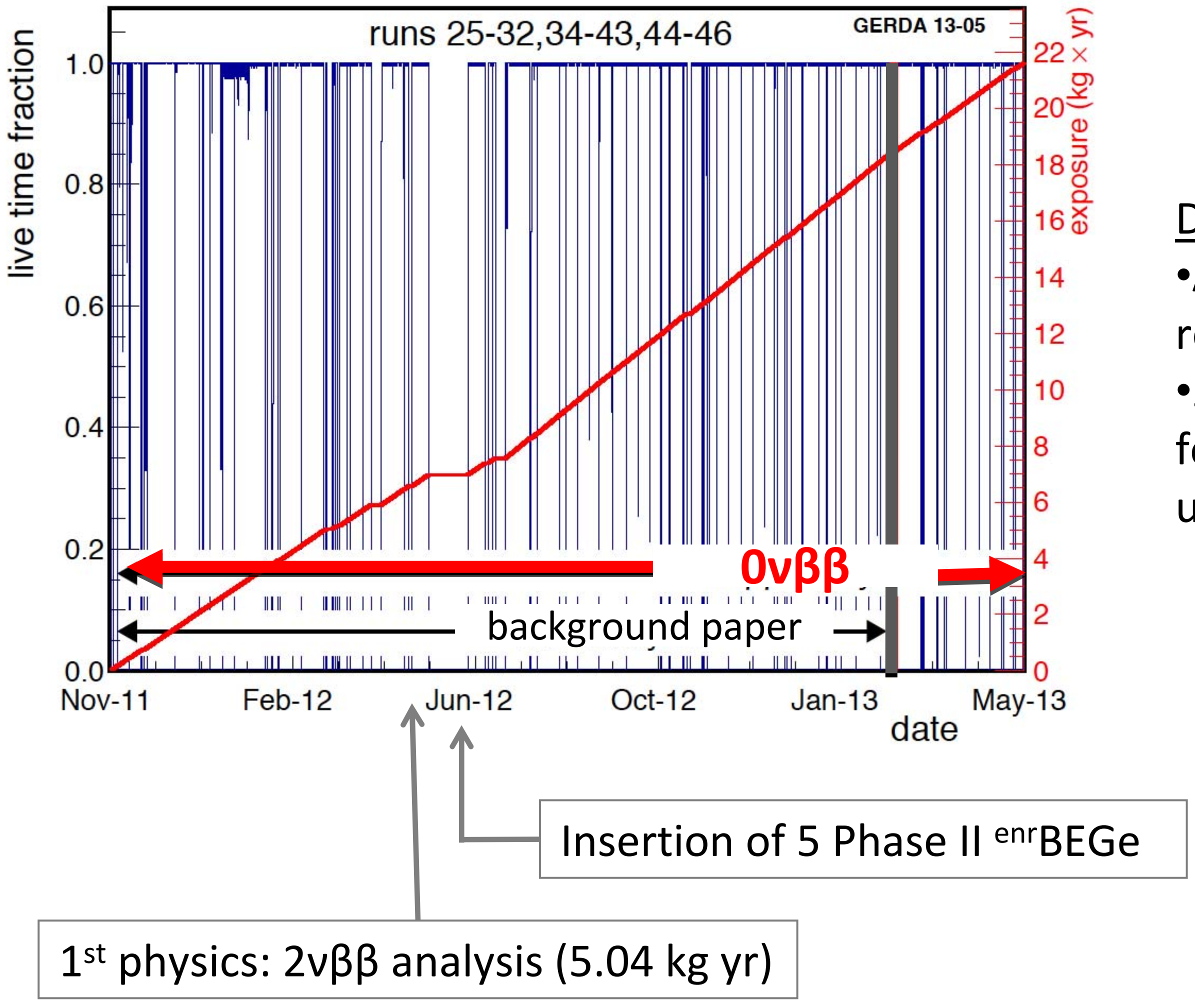


^{228}Th calibration once every one to two weeks; stability continuously monitored with pulser

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

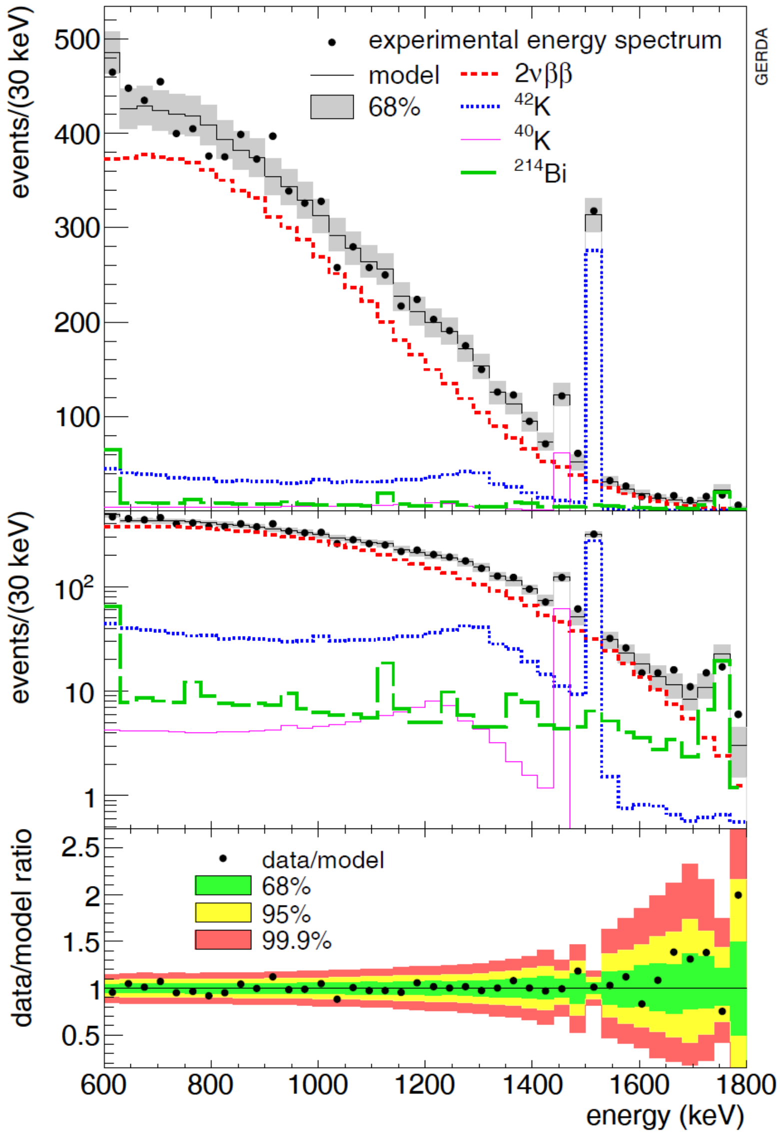
Total exposure for 0νββ analysis: 21.6 kg yr

(bi-)weekly calibration runs ('spikes')



Data blinding:

- All events in $Q_{\beta\beta}\pm20$ keV removed in Tier 1
- 2 copies of raw data kept for processing after unblinding

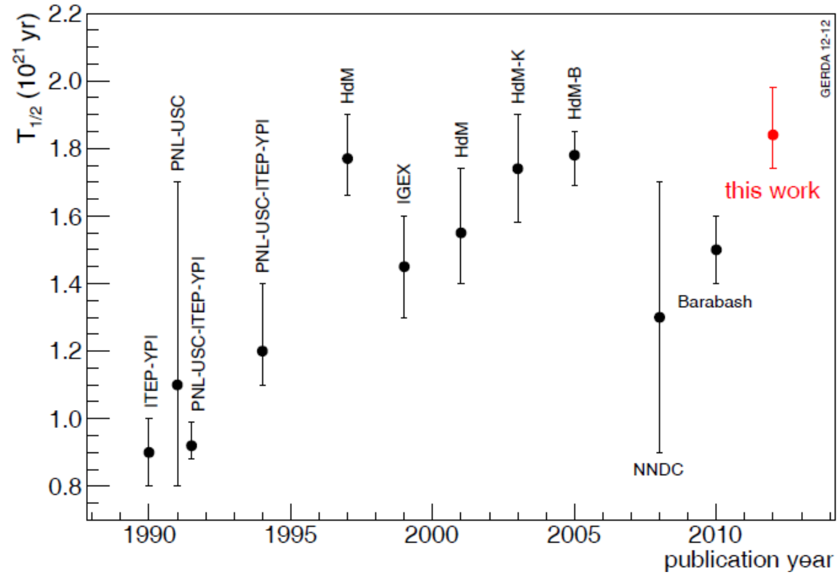


IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp) doi:10.1088/0954-3899/40/3/035110

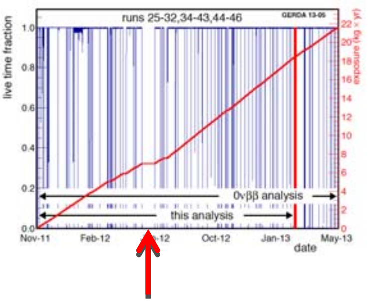
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

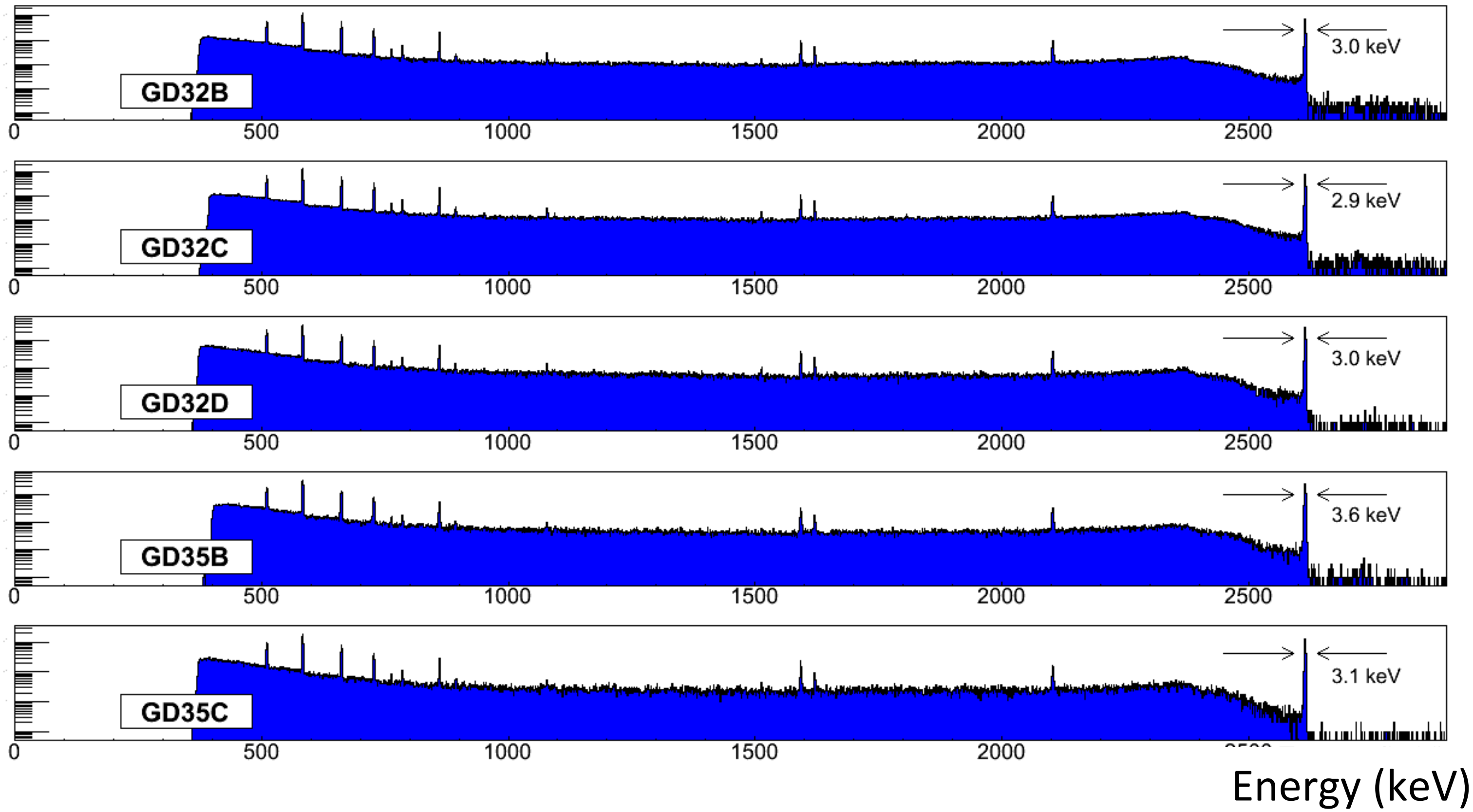
$T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



LAB Talk of J. Phys. G Feb. 2013 issue:
http://iopscience.iop.org/0954-3899/labtalk-article/52398

June 2012: 5 ^{enr}BEGe Phase II detectors deployed in GERDA

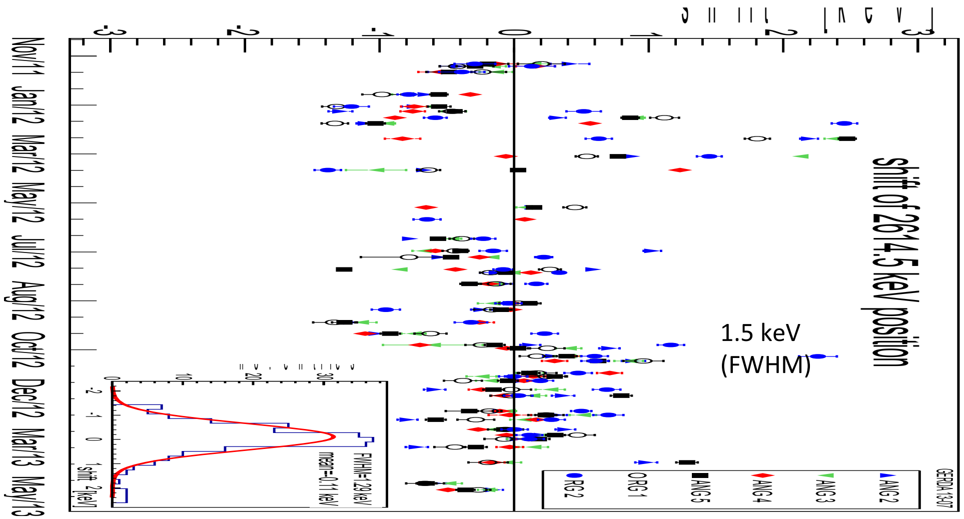


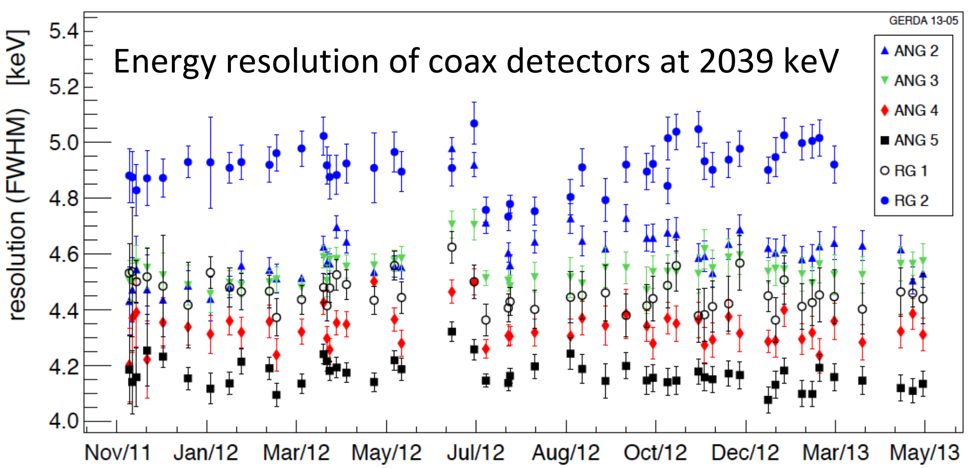


Calibration: stability of HPGe detectors

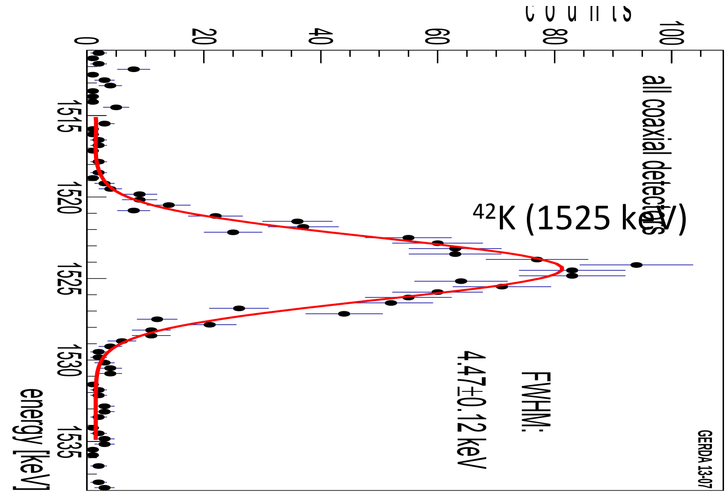
arXiv:1306.5084

Peak position stability of 2614.5 keV calibration line:
coax: 1.5 keV / BEGe: 1.0 keV (FWHM)





Summing all runs:



Mean energy resolution at $Q_{\beta\beta}$ =2039 keV:

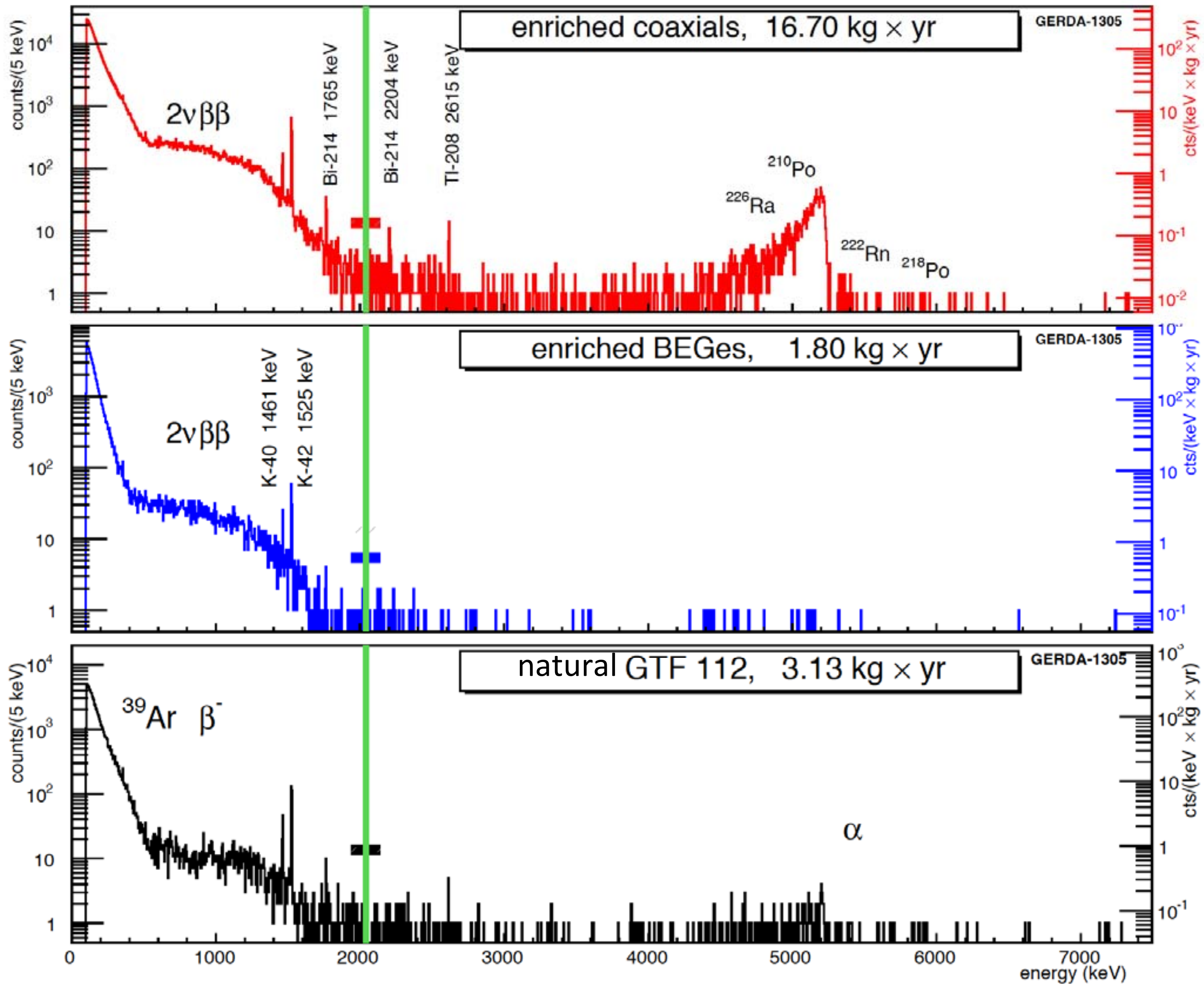
- Coax: 4.8 keV (FHWM)
- BEGe: 3.2 keV (FWHM)

detector	FWHM [keV]	detector	FWHM [keV]
SUM-coax		*SUM-bege*	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)

Physics run: energy spectra

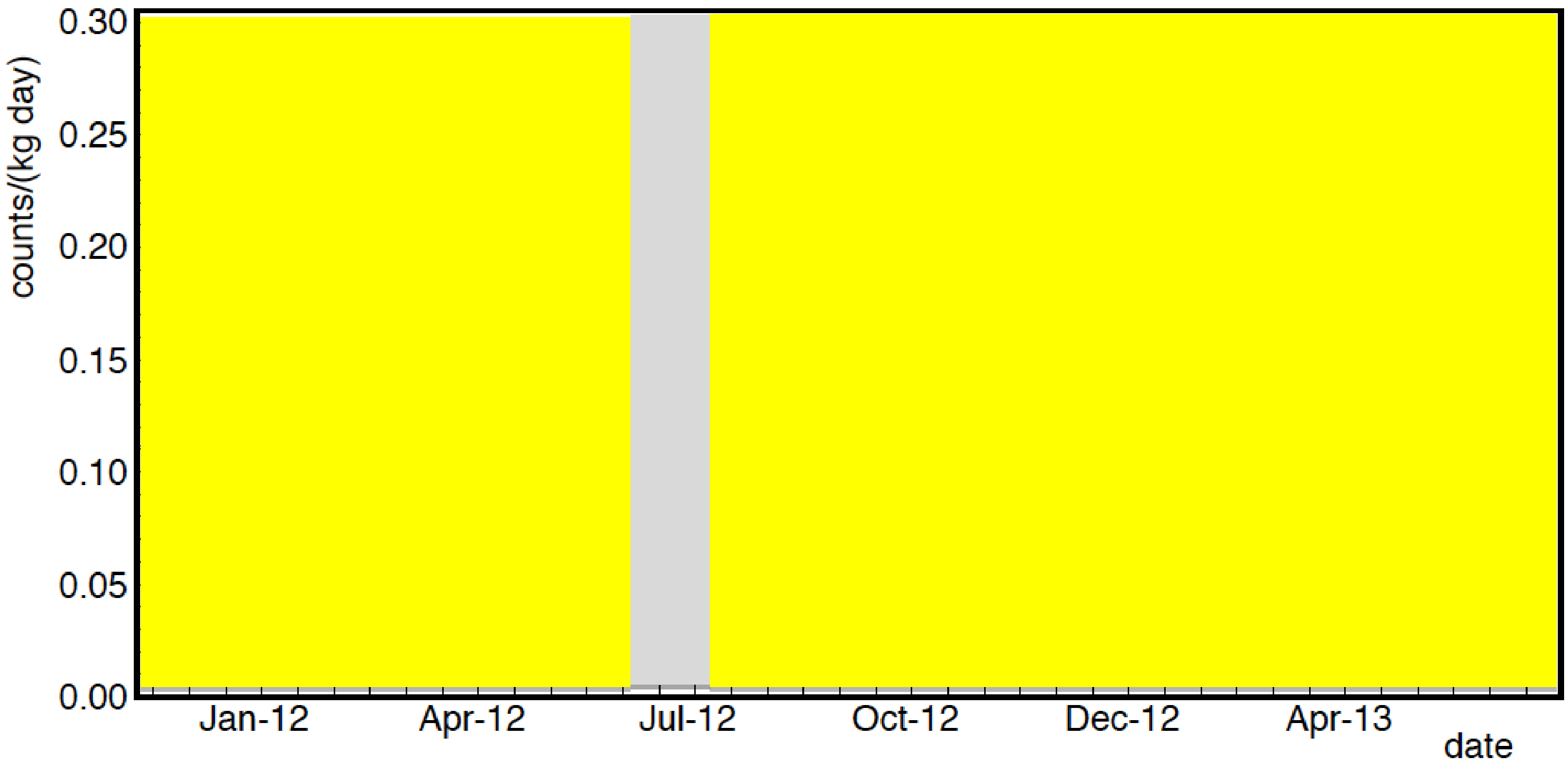
arXiv:1306.5084

Submitted to EPJ A
Data for background model



Physics run: background rate as function of time

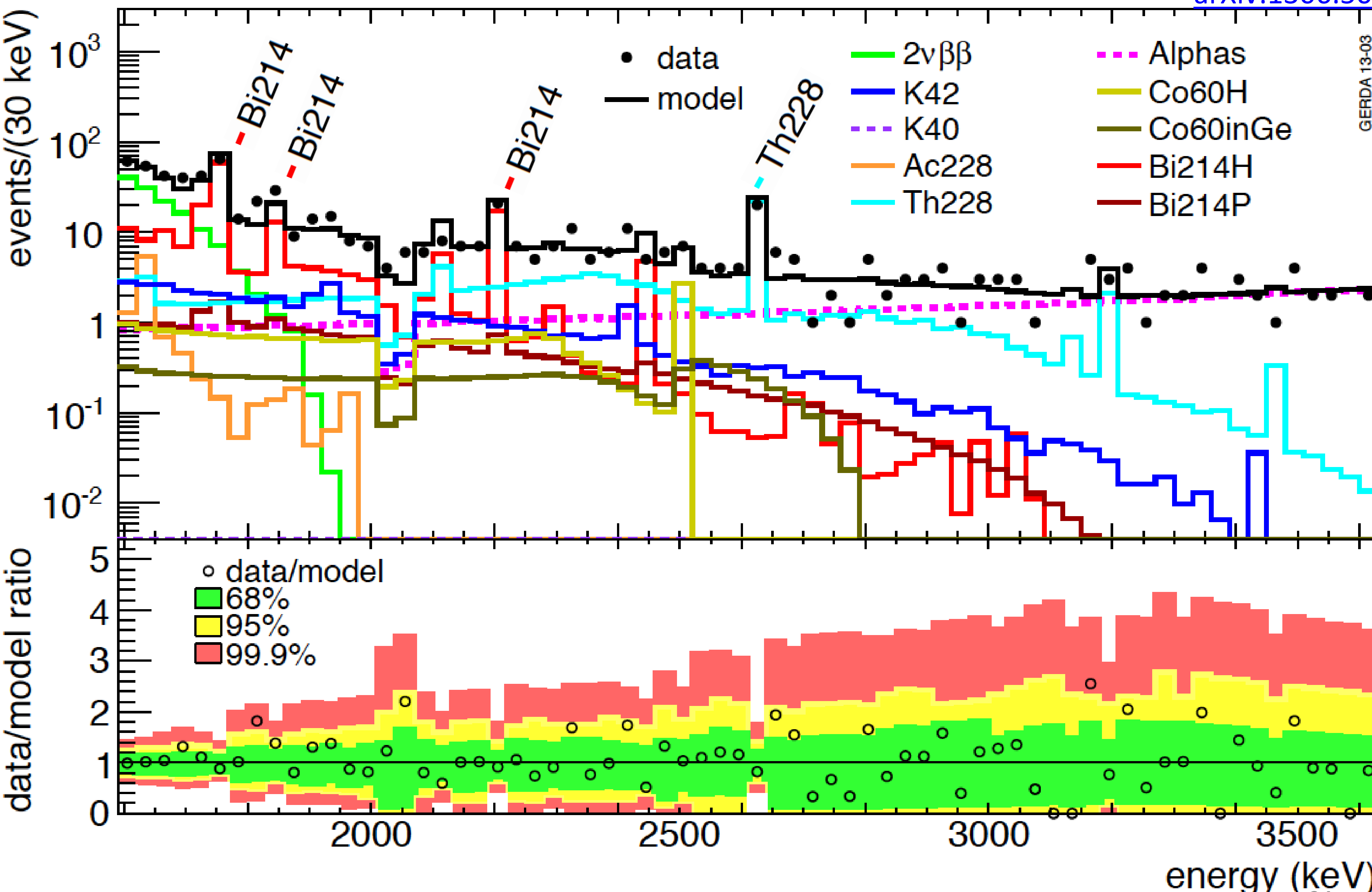
arXiv:1306.5084



Coax-detector data set split in and

Physics data: high-energy alpha

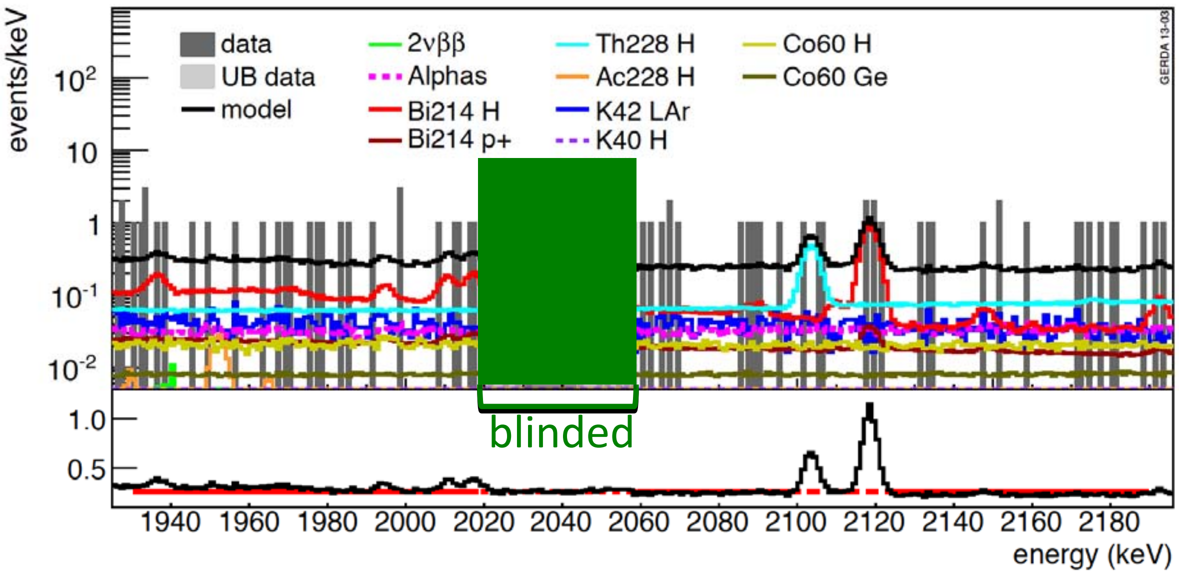
arXiv:1306.5084



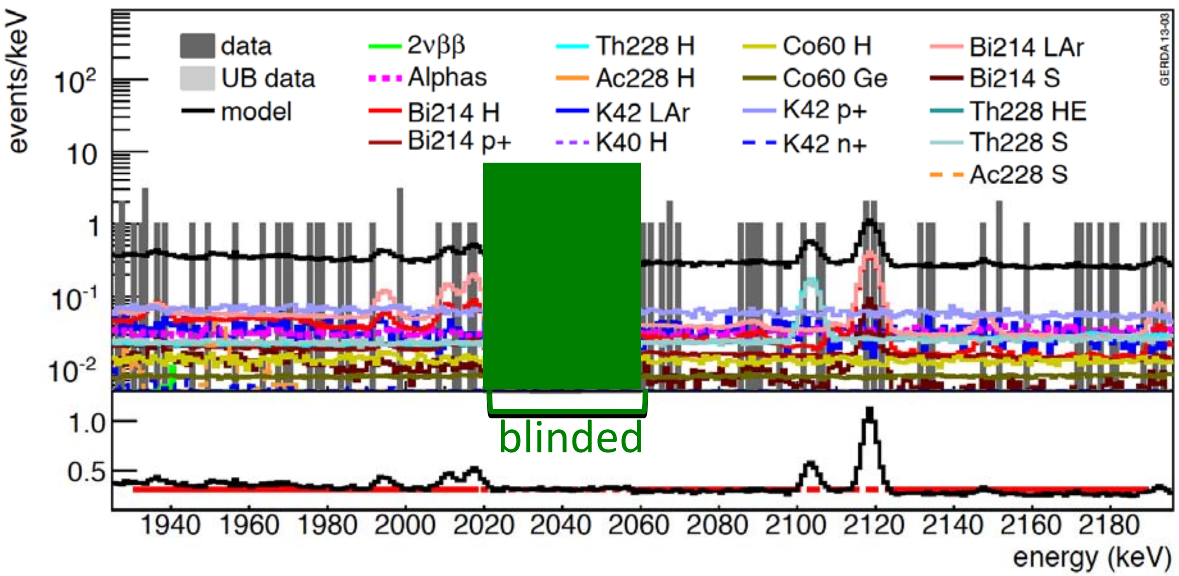
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

arXiv:1306.5084

Minimal model



Maximum model



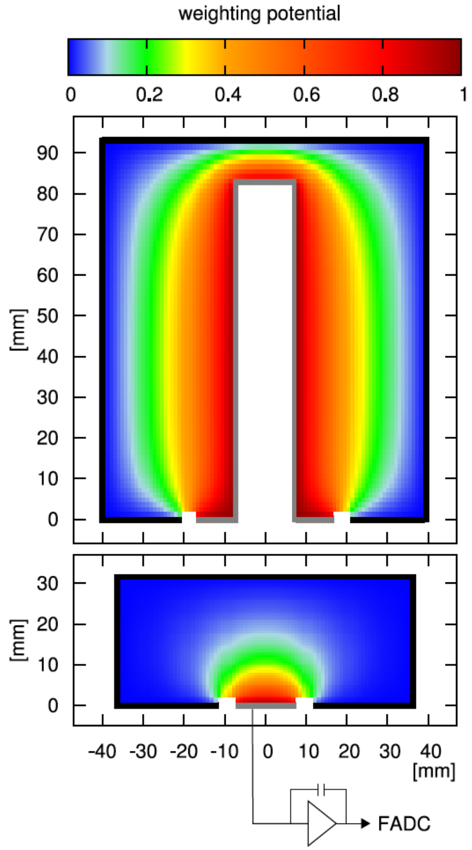
Background model:

- No background peak expected around $Q_{\beta\beta}$
- Spectrum can be modeled with flat background (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- Background index (BI) at $Q_{\beta\beta}$ (17.6-23.8) 10^{-3} cts/(keV kg yr) depending on assumptions for location of sources
- Statistical uncertainty of BI from interpolation coincides numerically with systematic uncertainty from model
- Prediction for 30 keV BW:
  - Min./Max Mod: 8.2-9.1 / 9.7-11.1
  - observed.: 13

➔linear fit with flat background 1930-2190 keV excluding peaks arXiv:1307.2610

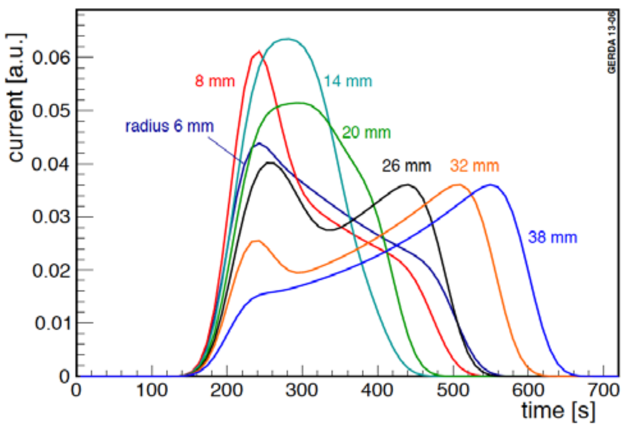
Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

Weighting potential for coax and BEGe detectors are different

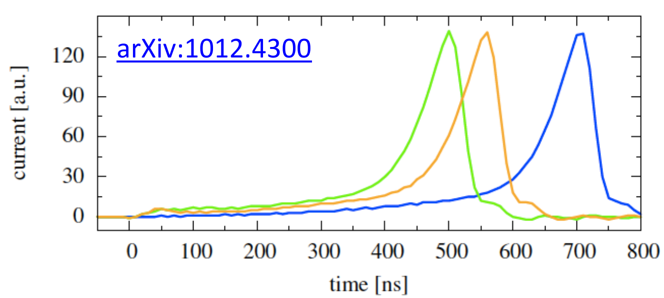


Current pulses of simulated SSE signals

Coax

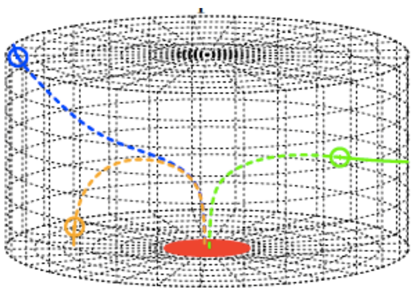


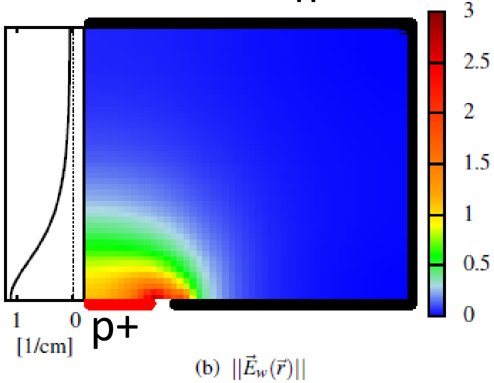
BEGe



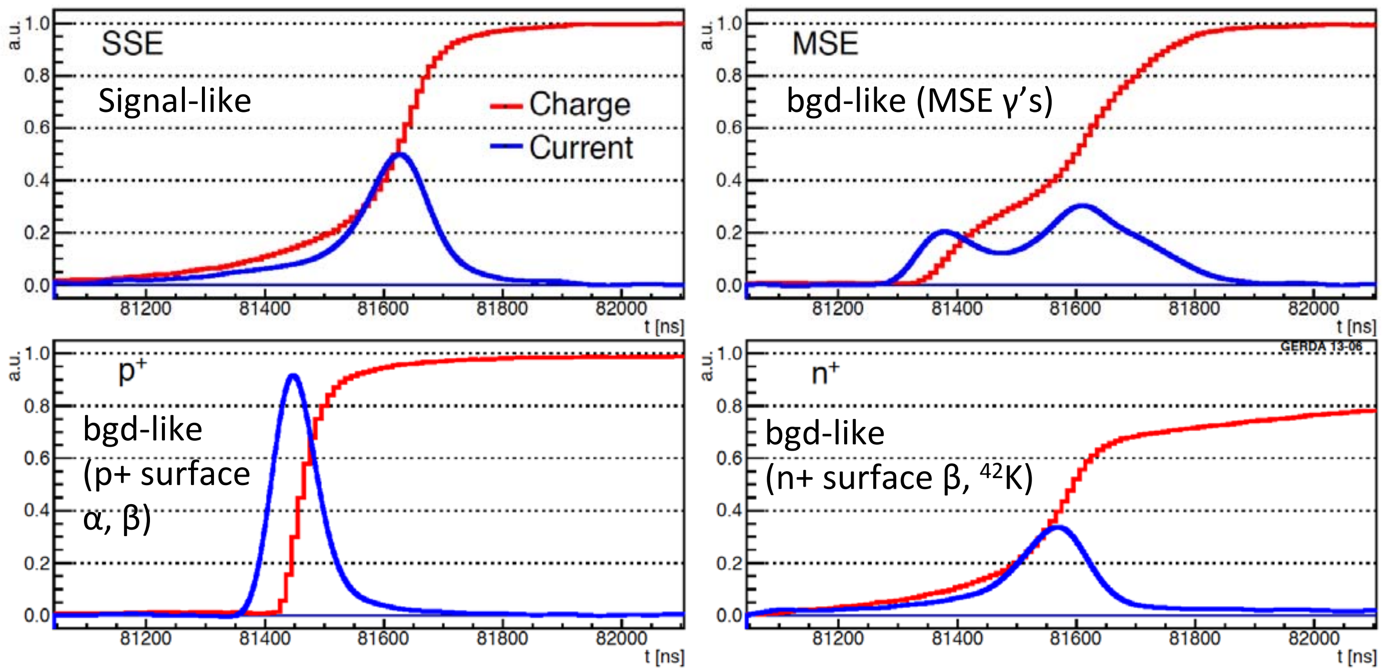
Pulse shape discrimination: BEGe

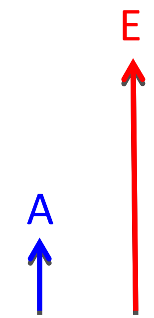
[arXiv:1307.2610](https://arxiv.org/abs/1307.2610)





PSD discrimination parameter: A/E

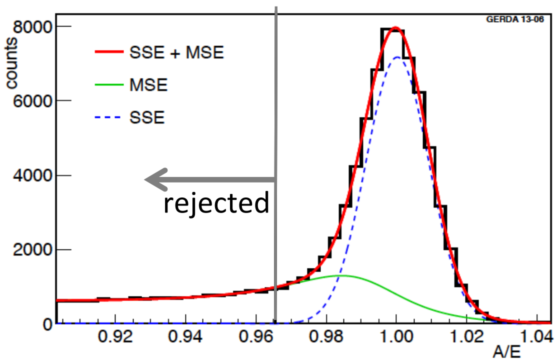




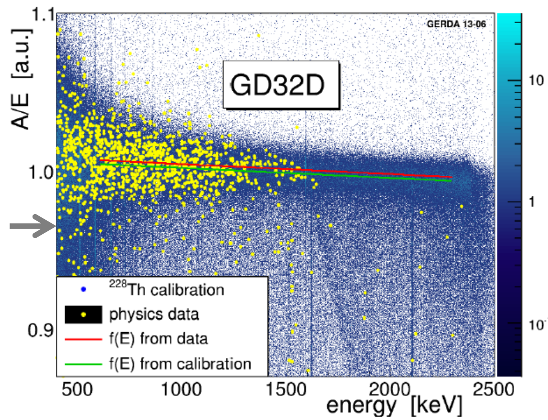
Pulse shape discrimination: BEGe

arXiv:1307.2610

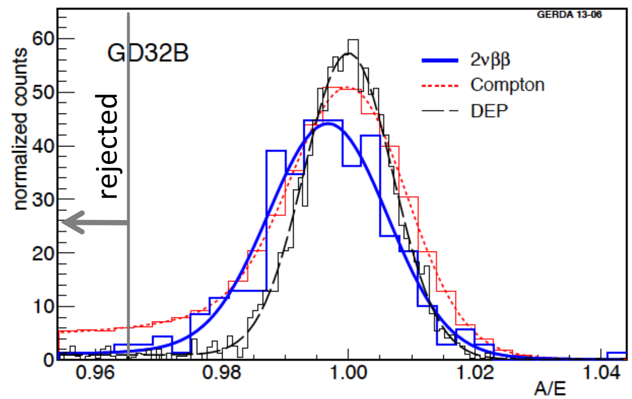
A/E of Compton continuum from calibration



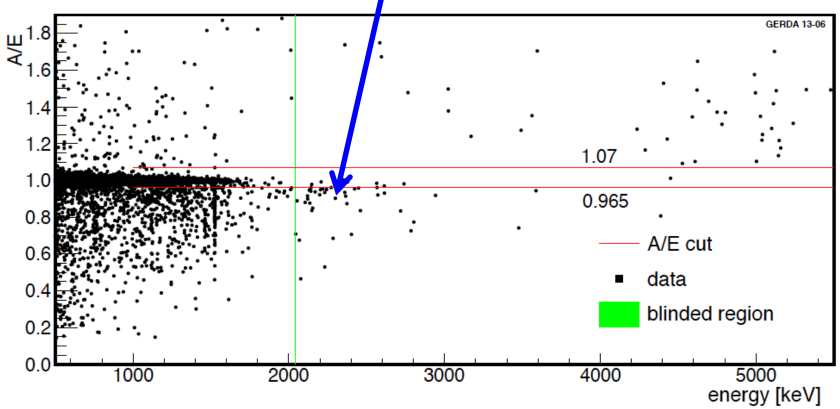
Energy dependence of A/E



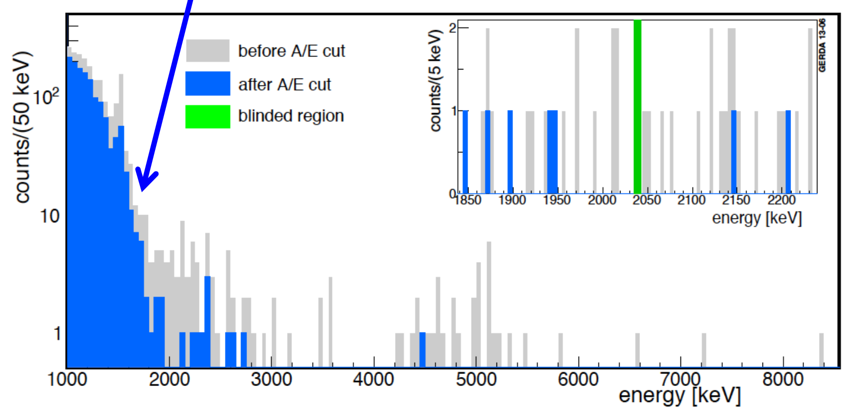
A/E for 2νββ, Compton (1-1.4 MeV), DEP (1592 keV)



^{42}K-β n+ surface dominated



2νββ acceptance: 0.91±0.05

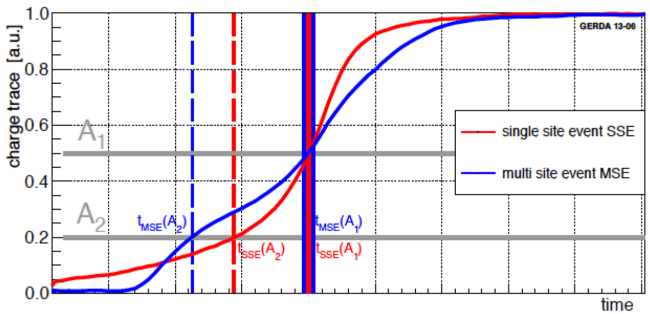


0νββ acceptance: 0.92±0.02

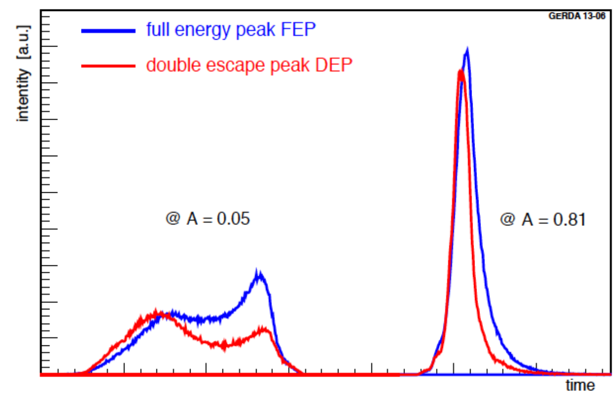
Pulse shape discrimination: Coax

arXiv:1307.2610

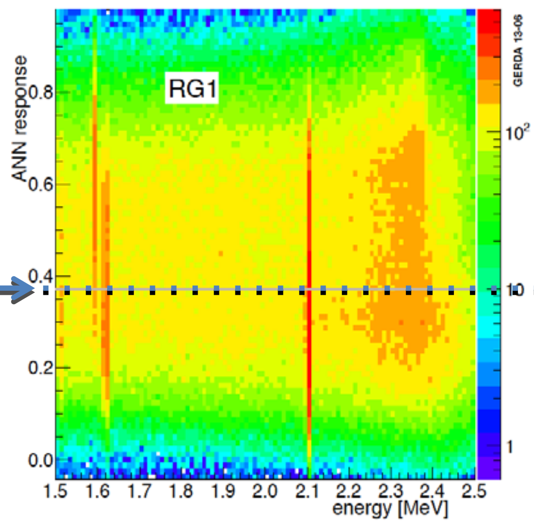
ANN analysis of 50 rise time info (1,3,5,…99%) with TMVA / TMlpANN
- SSE training with signal-like ^{208}Tl DEP events (1592 keV)
- MSE training with background-like ^{212}Bi FEP (1621 keV)



Distribution for 5 and 81% rise time

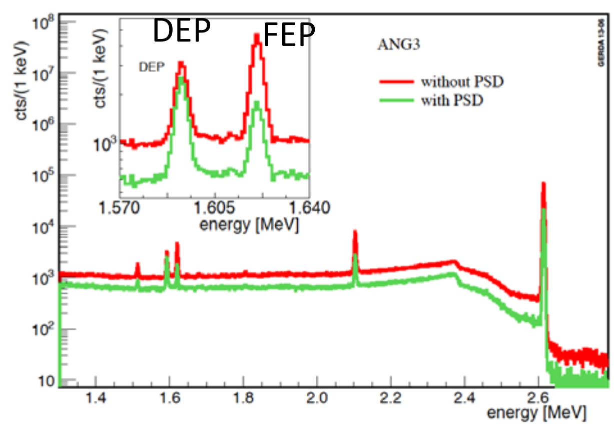


Cut adjusted for each detector to 90% DEP survival



SSE-like

MSE-like

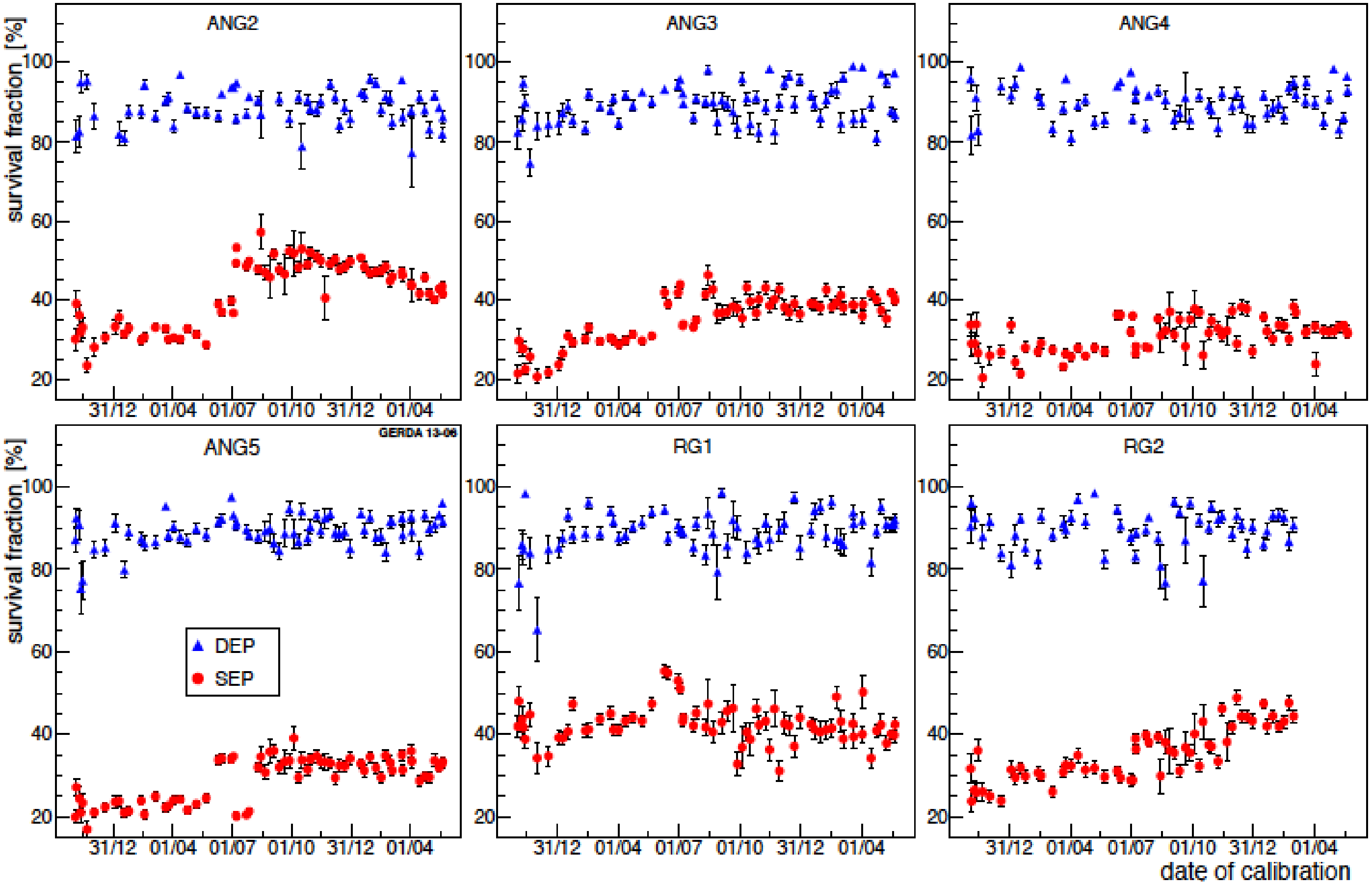


Pulse shape discrimination: Coax – survival fraction for Phase I

arXiv:1307.2610

Stability of survival fraction from calibration data

Y-axis suppressed:



DEP

SEP

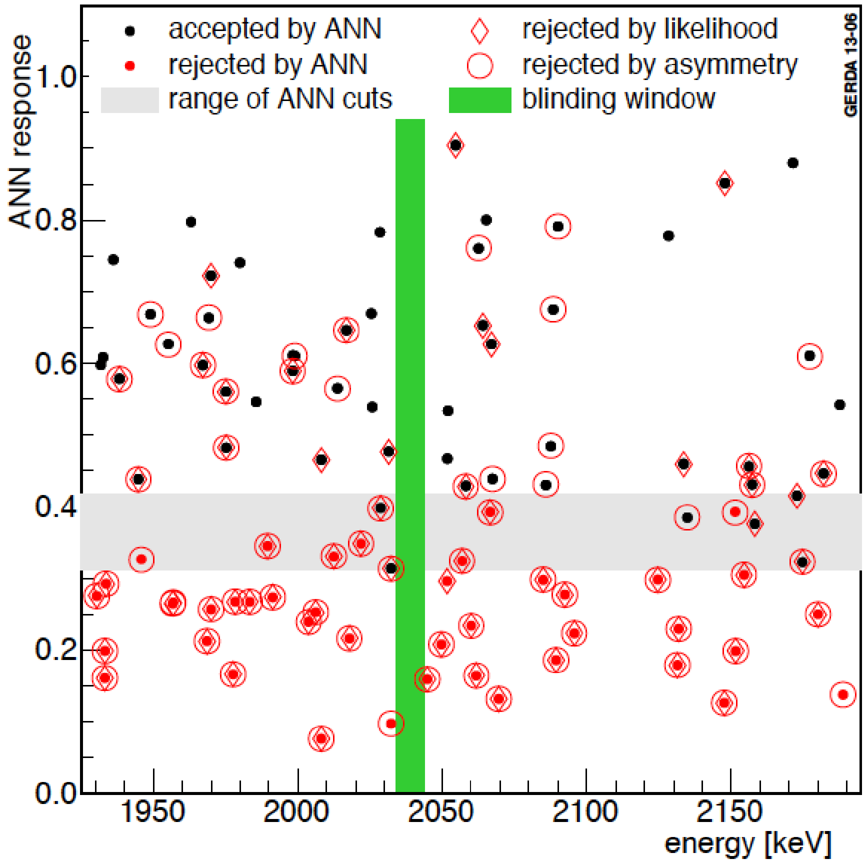
DEP

SEP

Data split in 3 periods: p1: Nov 11 – July 12, p2: July/Aug 12, p3: Aug 12-May 13

Pulse shape discrimination: Cross check w. independent methods

arXiv:1307.2610



- 90% of ANN signal-like events are also classified by both alternative methods
- 3% are only classified by ANN as background in the 1.5-2.5 MeV range

Alternative methods use different training/optimization event classes and aim at stronger bgd suppression than ANN

PSD method based on likelihood method

Training:

•Signal-like: ^{208}Tl Compton-edge 2350-2370 keV

•Bgd-like:^{208}Tl above Compton-edge 2450-2570 keV

•DEP survival: 0.8

•Bgd survival (230 keV): 0.45

PSD based on pulse asymmetry

q_{AS}=A/E (c+A_s)

Optimization of DEP and bgd (1700-2200 keV) for each detector separately

•DEP survival: 0.7-0.9

•Bgd survival: 0.25

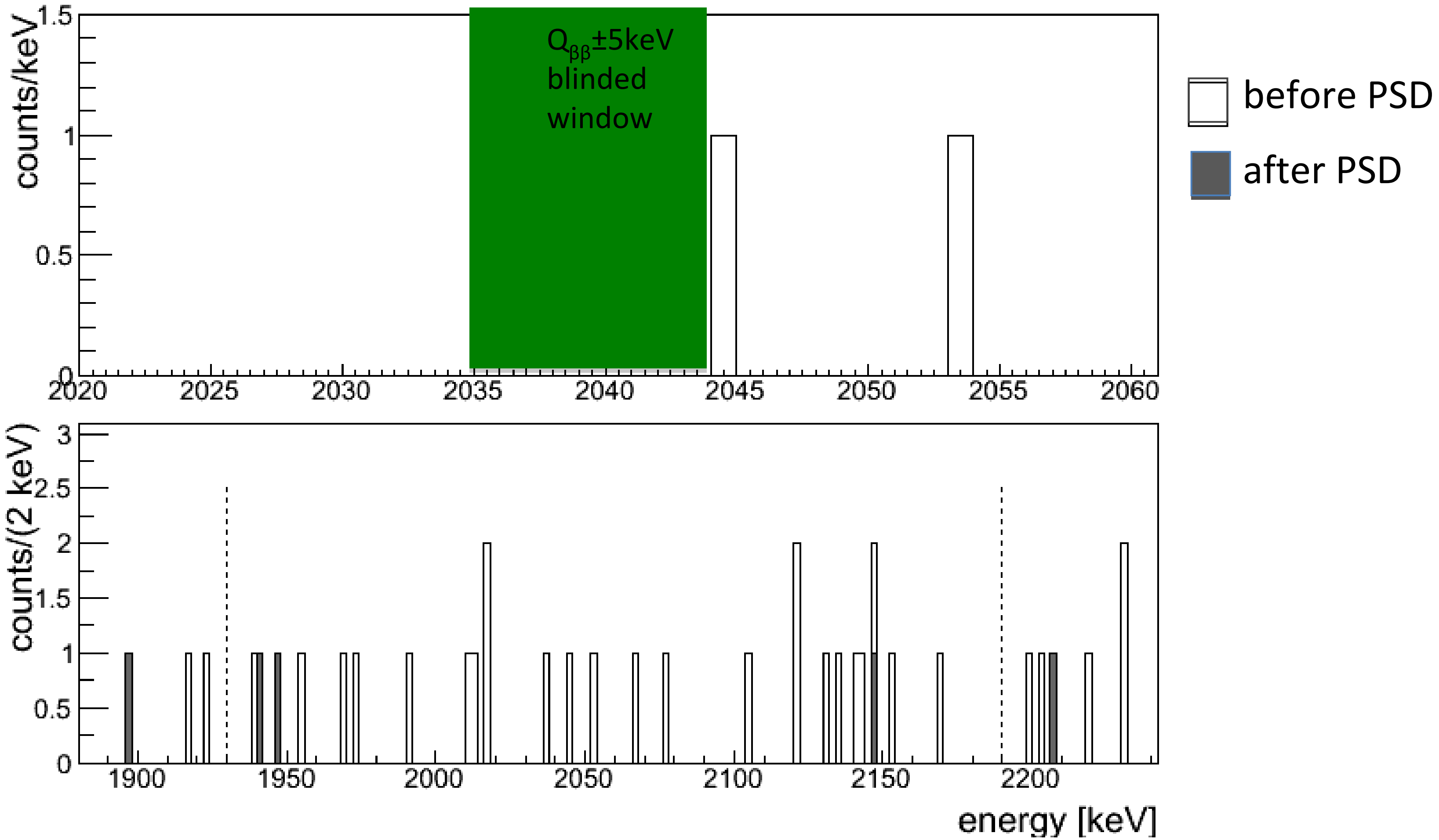
ANN selected for 0νββ analysis and cuts fixed prior to unblinding

Unblinding at GERDA collaboration meeting in Dubna, June 12-14

Discussion and freezing of all parameters and methods prior to un-blinding:

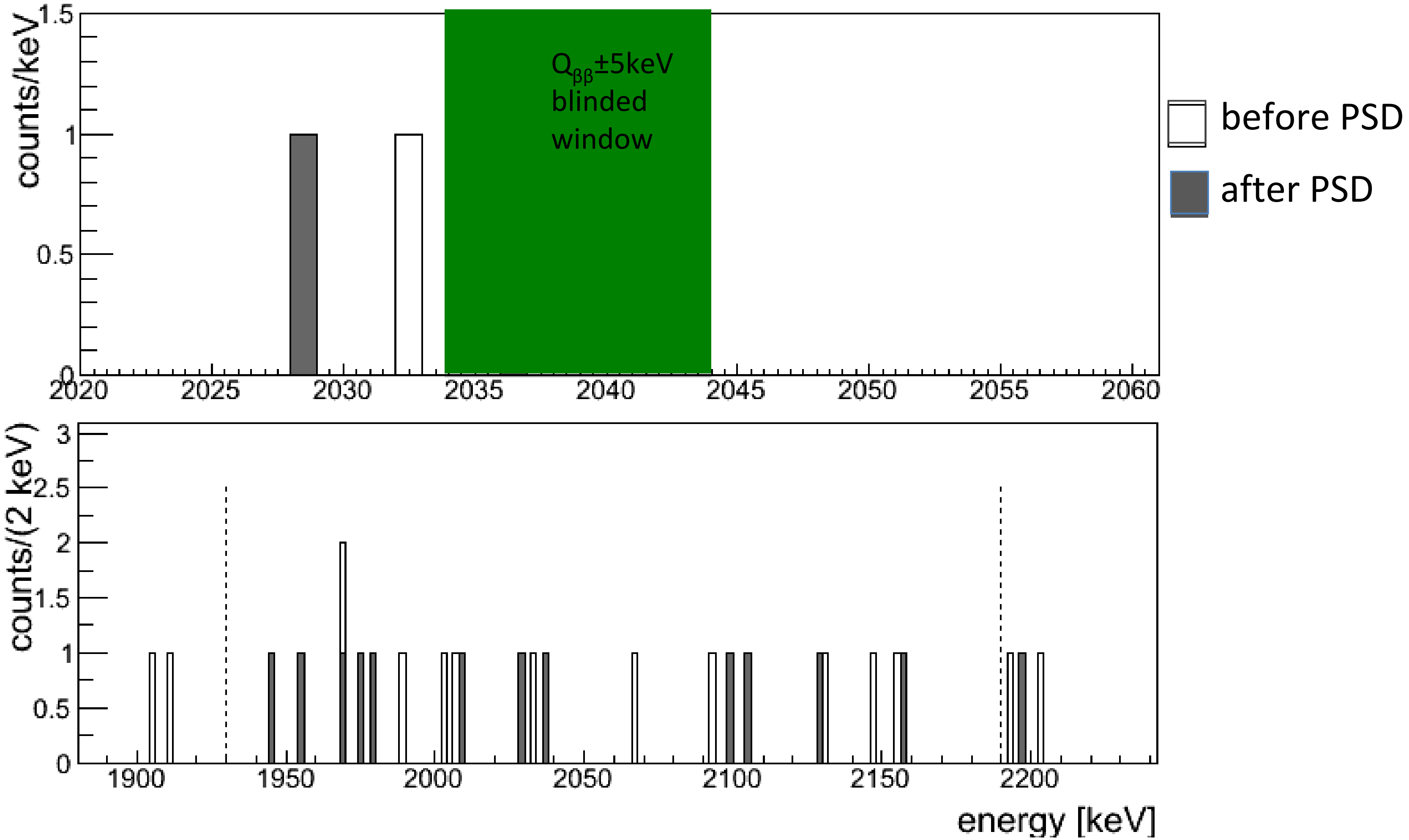
- 3 Data sets: golden, silver, BEGe
- Energy calibration method and parameters
- Unblind traces for PSD
- PSD method and cuts

- Statistical treatment of results:
- Likelihood fit of 3 indep. data sets ('global fit')
- Frequentist (constraint profile likelihood)
- Bayesian
- …….

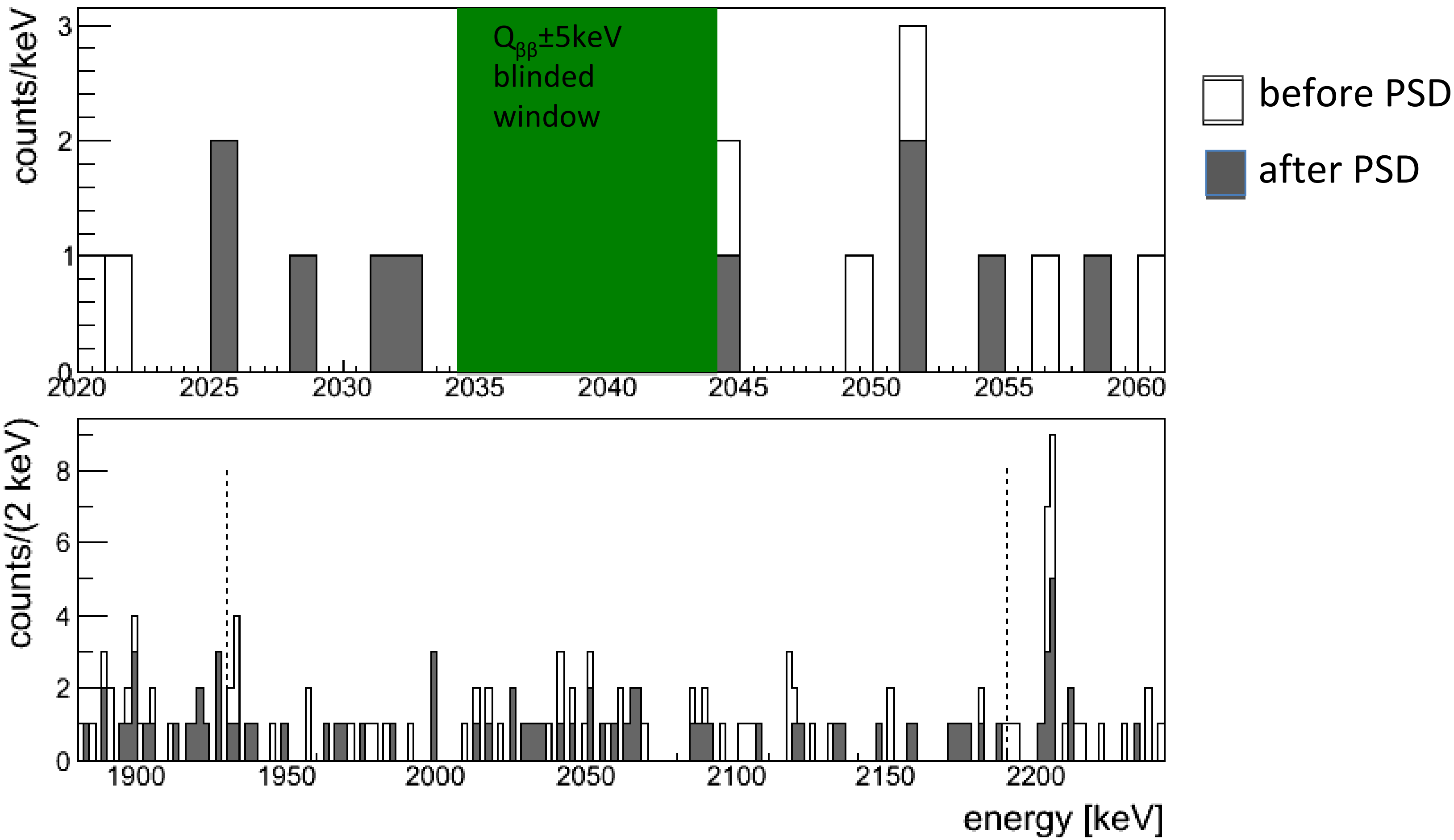


BEGe data set: 1 event in blinded window
0 event survive PSD cut

Unblinding: silver-coax data set (1.3 kg yr)



Silver data set:	1 event in blinded window
	1 event survives PSD cut



Golden data set: 5 event in blinded window
2 event survive PSD cut

Parameters of 3 data sets and counts in blinded window

data set	$\mathcal{E}$[kg·yr]	$\langle\epsilon\rangle$	bkg (in 230 keV)	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).

Counts in blinded window (BW)

Total counts in BW	Expected (bgd only)	Observed
without PSD	5.1	7
with PSD	2.5	3

From counts to half-life

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} \cdot \mathcal{E} \cdot \epsilon$$

$$\epsilon = f_{76} \cdot f_{av} \cdot \varepsilon_{fep} \cdot \varepsilon_{psd}$$

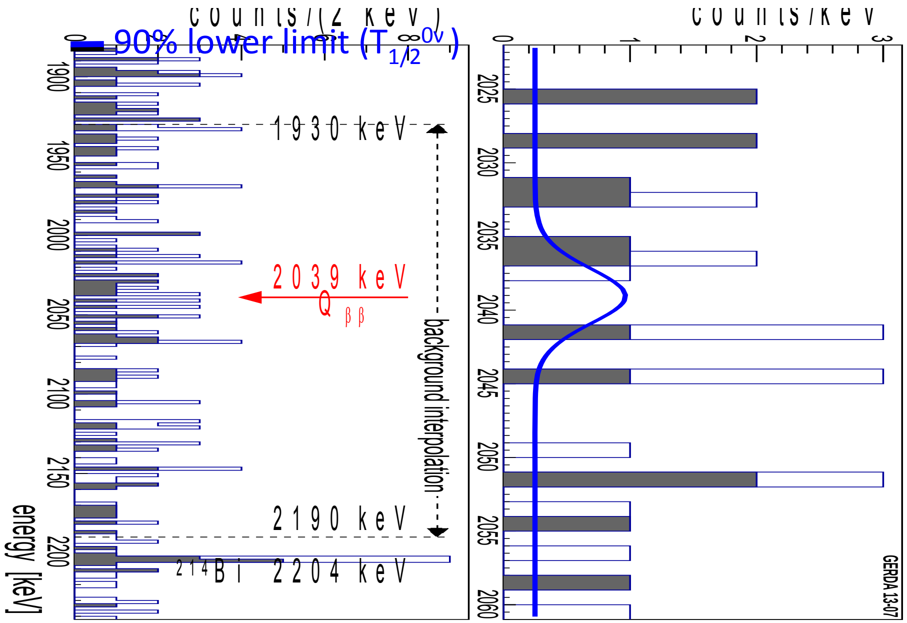
N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficieny for 0νββ
ε_{psd}: signal acceptance

Data set	**Exposure (kg yr)**
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$\langle f_{76} \rangle$	$\langle f_{av} \rangle$	$\langle \varepsilon_{fep} \rangle$	$\langle \varepsilon_{psd} \rangle$	$\langle \varepsilon \rangle$
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ±0.02	0.663 ±0.022

Frequentist and Bayesian limits & median sensitivities



Systematics:

Parameter	Det./Set	Value	Uncertainty
<ε> w/o PSD	Coax	0.688	0.031
	BEGe	0.720	0.018
Energy res.	Golden	4.83 keV	0.19 keV
	Silver	4.63 keV	0.14 keV
	BEGe	3.24 keV	0.14 keV
Energy scale (keV)		N.A.	0.2 keV
ε_{PSD}	Coax	0.90	0.10
	BEGe	0.92	0.02

Frequentist limit:

- 90% lower limit derived from profile likelihood fit to 3 data sets (constraint to physical 1/T range; excluding known γ-lines from bgd model at 2104±5 and 2119±5 keV)
- Best fit: **$N^{0\nu}$=0**
- **No excess** of signal counts above the background
- 90% C.L. lower limit:

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

- Limit on half-life c s
- Median sensitivity (90% C.L.): >2.4×10^{25} yr

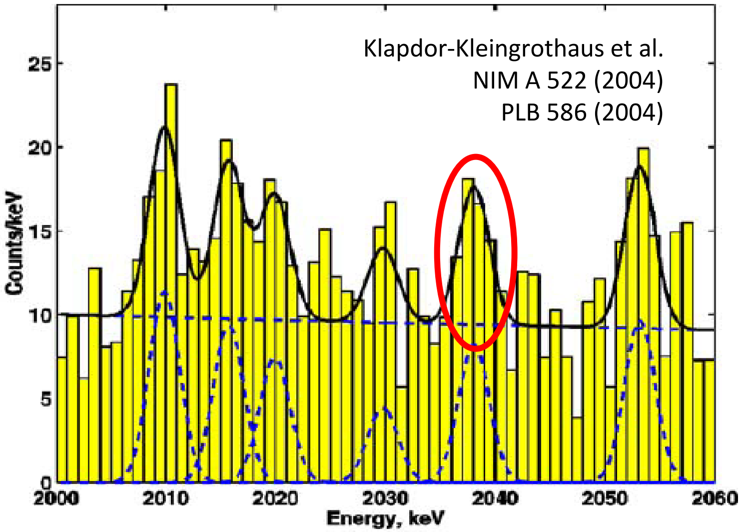
Bayesian:

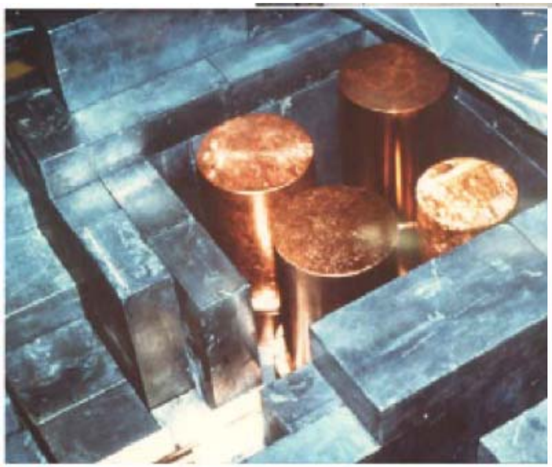
- Flat prior for 1/T
- Posterior distribution for $T_{1/2}^{0\nu}$
- Best fit: **$N^{0\nu}$=0**
- 90% credibile interval:
- Median sensitivity: (90% C

$$T_{1/2}^{0\nu} > 1.9 \cdot 10^{25} \text{ yr}$$

Systematics folded: limit weakened by 1.5%

^{76}Ge 0νββ search: the claim





Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

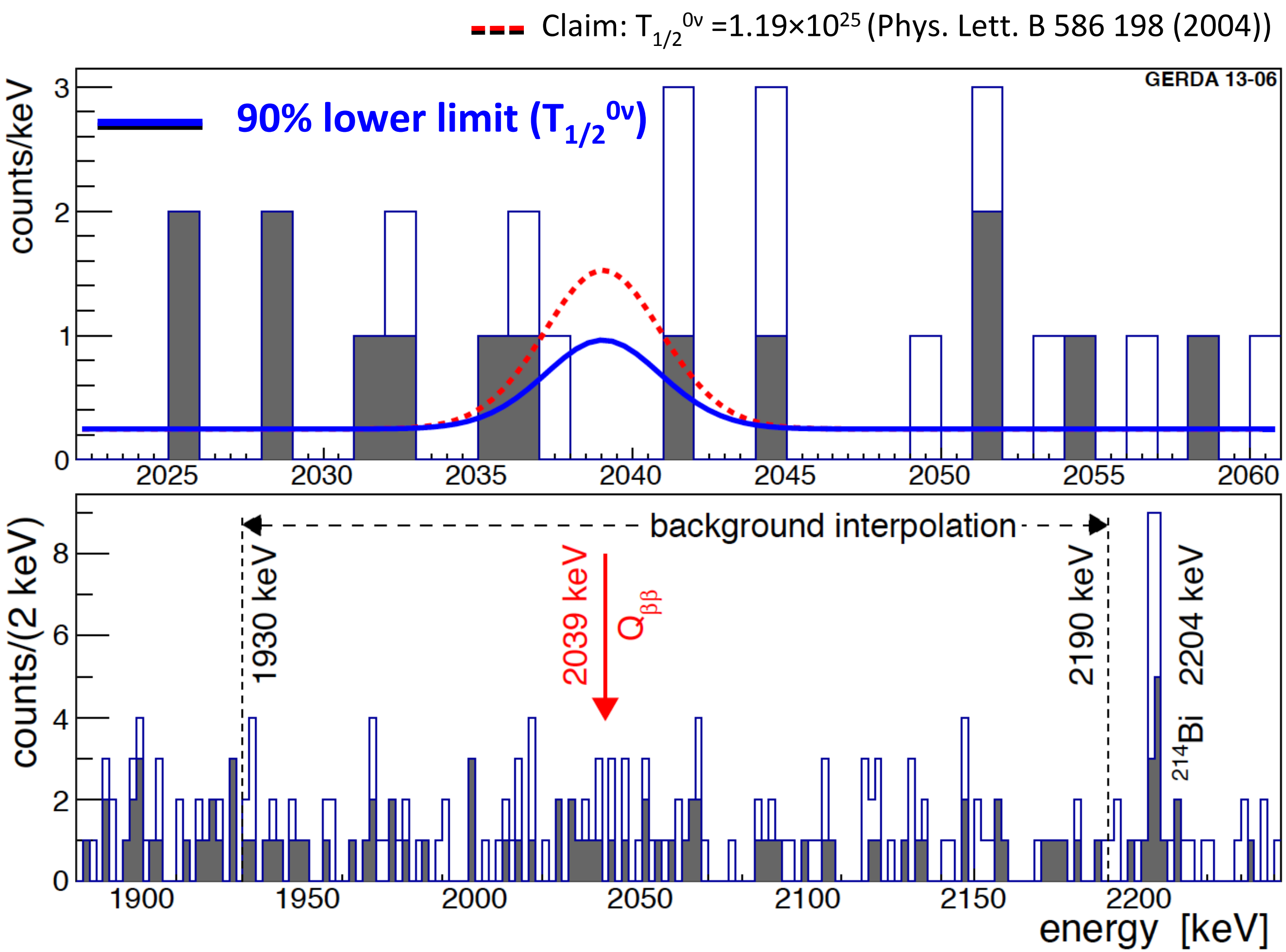
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr $T_{1/}$after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis ε_{psd} ≈ 0.6)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004)) (GERDA value for same detectors: ε_{fep} = 0.9)

(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

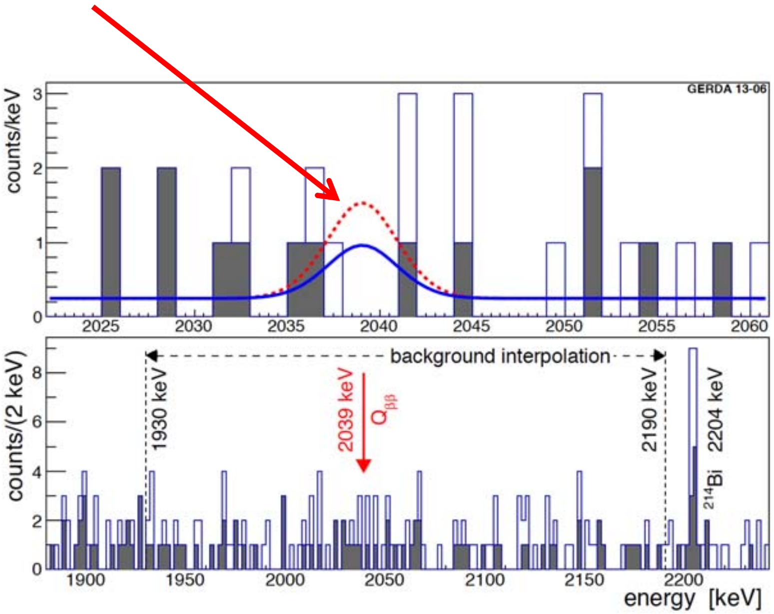
Comparison with Phys. Lett. B 586 198 (2004) claim

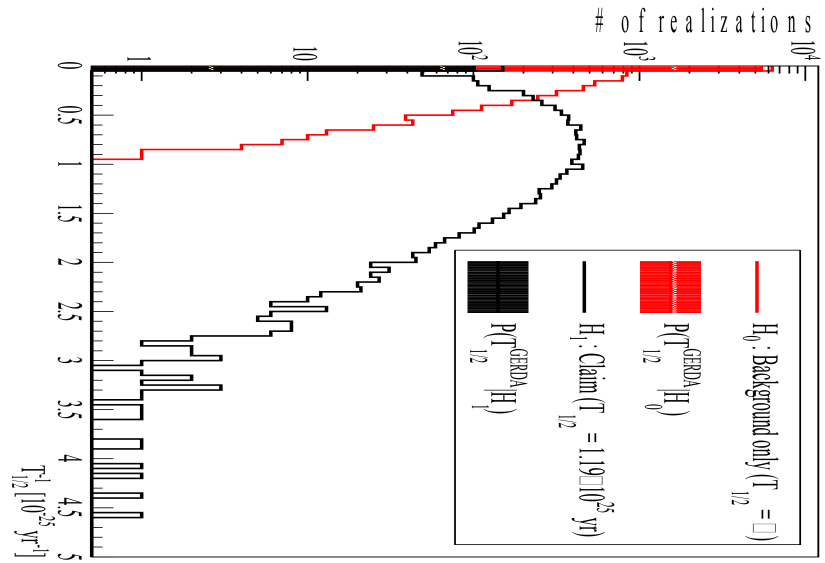


Comparison with Phys. Lett. B 586 198 (2004) claim

Expectation for claimed $T_{1/2}^{0\nu}$ =1.19×10^{25} yr (Phys. Lett. B 586 198 (2004)):

5.9±1.4 signal over 2.0±0.3 bgd in ±2σ energy window to be compared with 3 cts (0 in ±1σ)





H1: claimed signal: 5.9±1.4

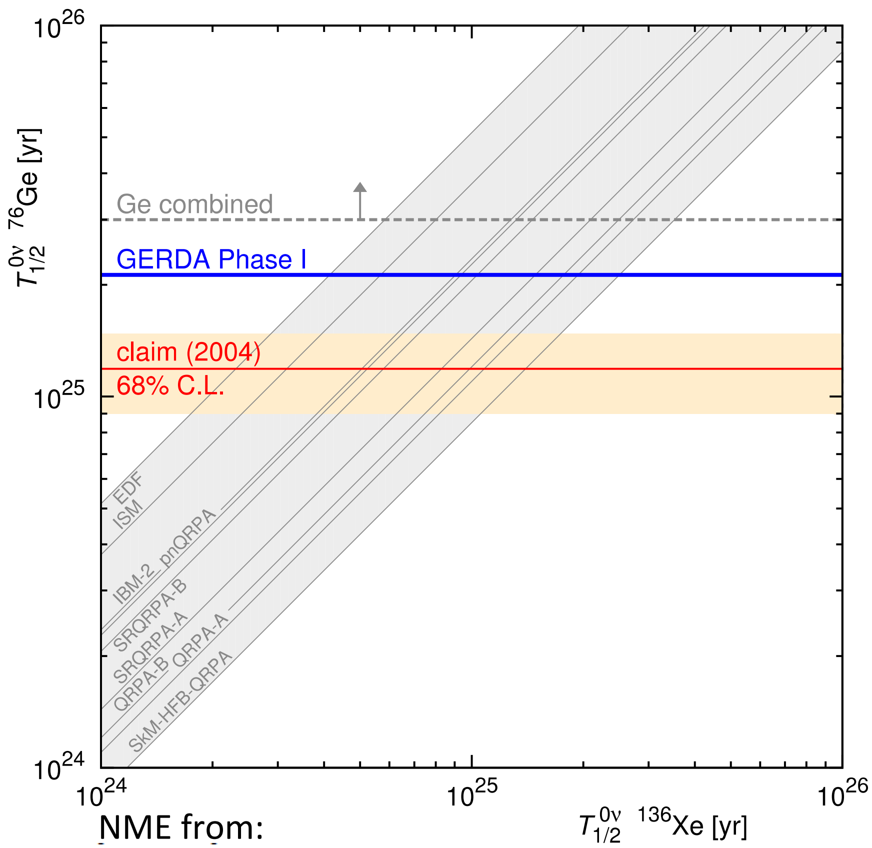
H0: background only

Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood

P(N=0 = 0|H1) = 0. 01 (0.006 if 1/T unconstrained)

➔Claim refuted with high probability

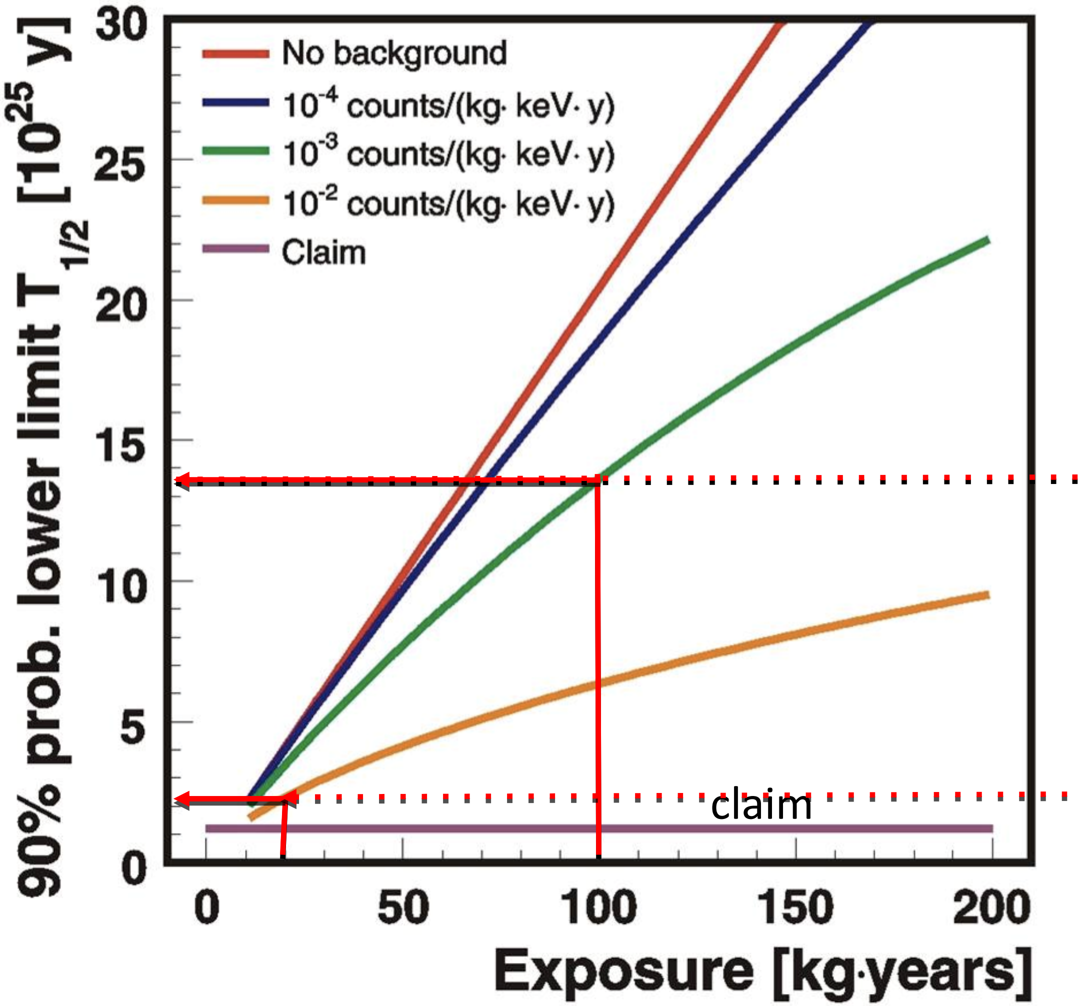


NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Ge combined: <m_{ee}> < 0.2-0.4 eV

H1: signal with $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr
H0: background only

	Isotope	$P(H_1)/P(H_0)$	Comment
GERDA	^{76}Ge	0.024	Model independent
GERDA+HdM+IGEX	^{76}Ge	0.0002	Model independent



Phase II:
Add new enr. BEGe detectors (20 kg)
BI ≈ 0.001 cts / (keV kg yr)
Sensitivity after 100 kg yr

Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

- **GERDA Phase I design goals reached:**
    - Background index after PSD: 0.01 cts / (keV kg yr)
    - Exposure 21.6 kg yr

- **No 0νββ-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu}$=0**
    - Background-only hypothesis H_0 strongly favored
    - Claim strongly disfavored (independent of NME and of leading term)

- **Bayes Factor / p-value:**

GERDA:	2.4×10^{-2} / 1.0×10^{-2}
GERDA+IGEX+HdM:	2×10^{-4} / -

- **Limit on half-life:**

GERDA:	$T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)
GERDA+IGEX+HdM:	$T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($<m_{ee}> < 0.2$-0.4 eV)

- Results reached after only 21.6 kg yr exposure because of **unprecedented low background:** bgd counts in ±2σ after analysis cuts:
  0.01 cts /(mol yr) (cf. EXO: 0.07, KL: 0.67)

- **Getting ready for Phase II…..**

Recent GERDA publications: http://www.mpi-hd.mpg.de/gerda/public

the draft pdf submitted on July 16, 2013
the presentation at LNGS by S. Schönert

GERDA publications before unblinding:
pulse shape analysis: **Pulse shape discrimination for GERDA Phase I data** submitted to EPJC; on arXiv:1307.2610 [physics.ins-det] the plot release
the background: **The background in the neutrinoless double beta decay experiment GERDA** submitted to EPJC; on arXiv:1306.5084 [physics.ins-det] the plot release
2νββ decay: Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110 DOI: 10.1088/0954-3899/40/3/035110 the plot release
the experiment: **The GERDA experiment for the search of 0νββ decay in ^{76}Ge**
Eur. Phys. J. C 73 (2013) 2330 DOI: 10.1140/epjc/s10052-013-2330-0 the plot release