GERDA presents the first results on neutrinoless double beta decay of ^{76}Ge from Phase I

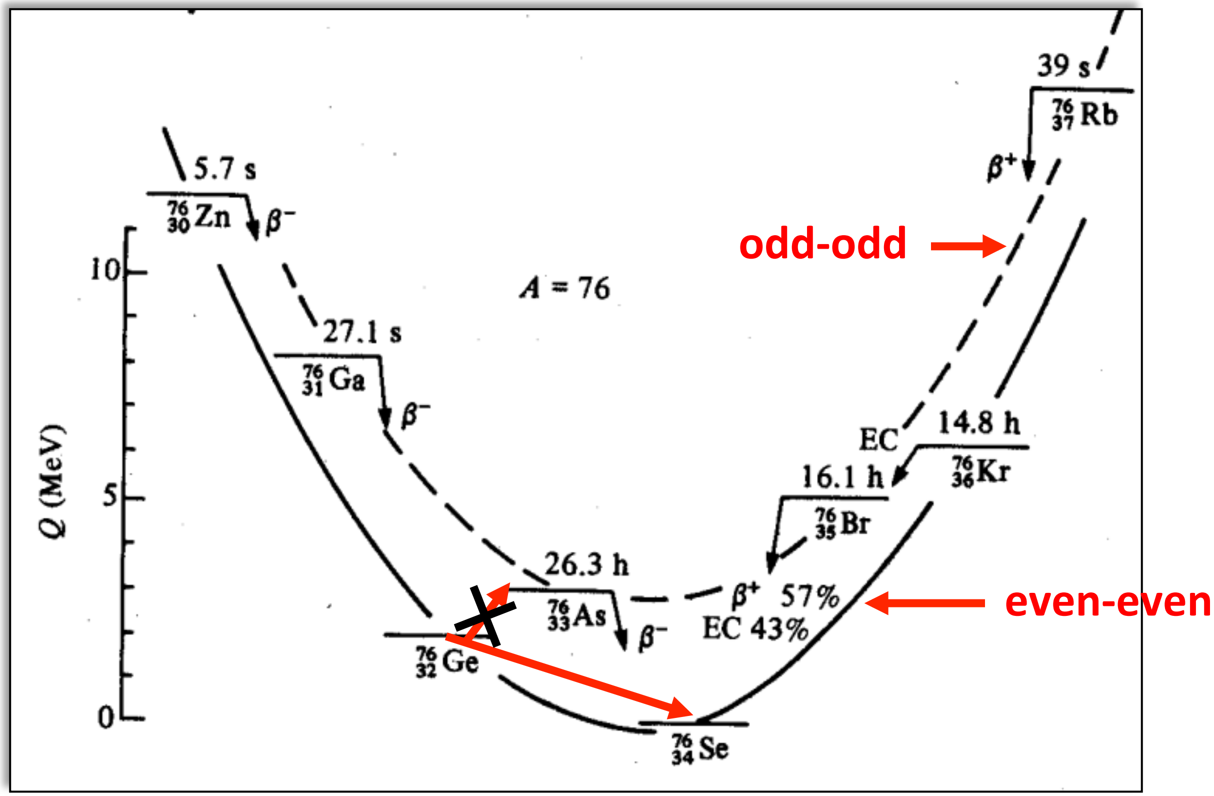
Stefan Schönert (TUM)
for the GERDA collaboration
LNGS Seminar
July 16, 2013

The GERDA collaboration

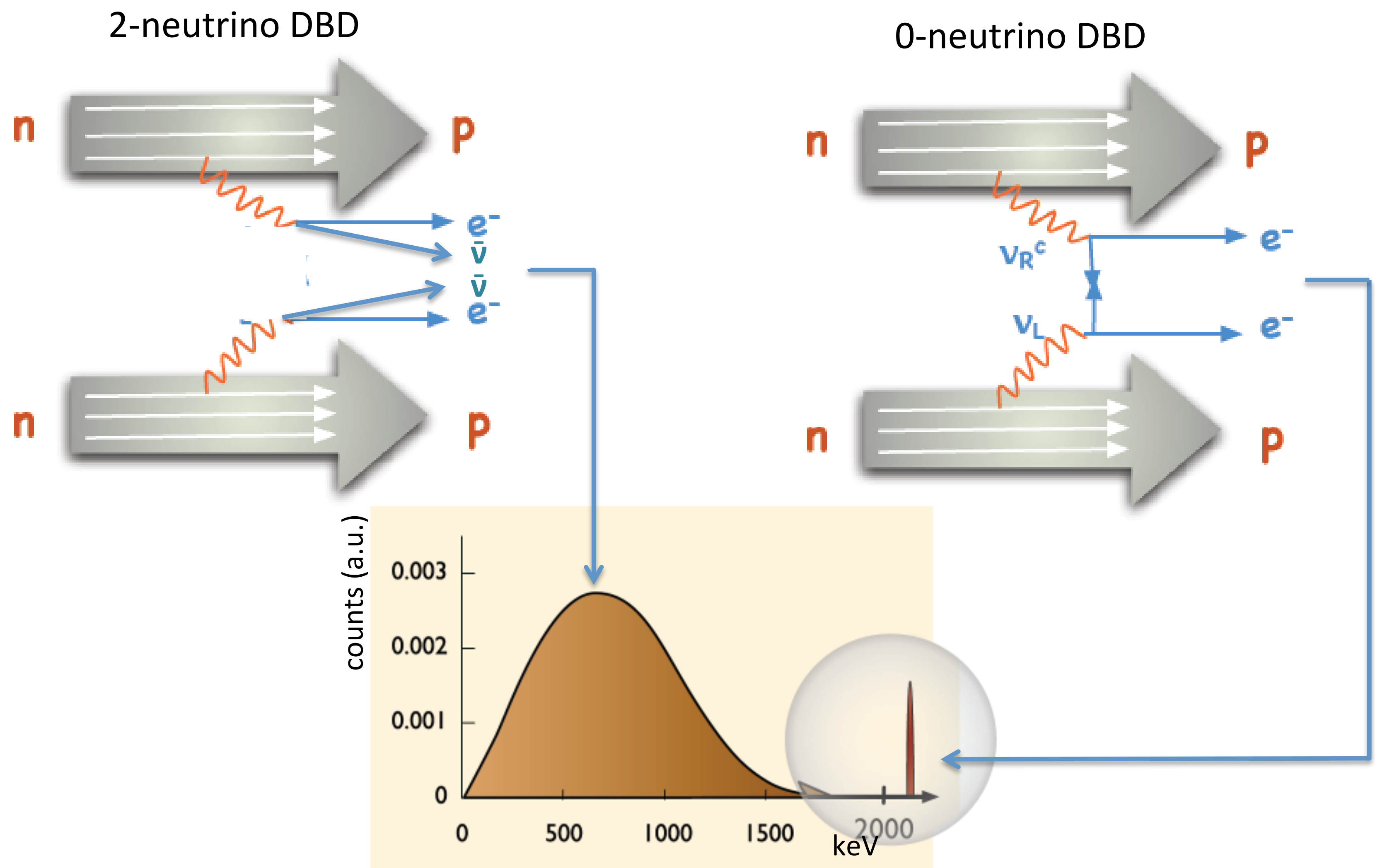
M. Agostini,[14] M. Allardt,[3] E. Andreotti,[17,5] A.M. Bakalyarov,[12] M. Balata,[1] I. Barabanov,[10] M. Barnabè Heider,[6,14,a] N. Barros,[3] L. Baudis,[18] C. Bauer,[6] N. Becerici-Schmidt,[13] E. Bellotti,[7,8] S. Belogurov,[11,10] S.T. Belyaev,[12] G. Benato,[18] A. Bettini,[15,16] L. Bezrukov,[10] T. Bode,[14] V. Brudanin,[4] R. Brugnera,[15,16] D. Budjáš,[14] A. Caldwell,[13] C. Cattadori,[8] A. Chernogorov,[11] F. Cossavella,[13] E.V. Demidova,[11] A. Domula,[3] V. Egorov,[4] R. Falkenstein,[17] A. Ferella,[18,b] K. Freund,[17] N. Frodyma,[2] A. Gangapshev,[10,6] A. Garfagnini,[15,16] C. Gotti,[8,c] P. Grabmayr,[17] V. Gurentsov,[10] K. Gusev,[12,4,14] K.K. Guthikonda,[18] W. Hampel,[6] A. Hegai,[17] M. Heisel,[6] S. Hemmer,[15,16] G. Heusser,[6] W. Hofmann,[6] M. Hult,[5] L.V. Inzhechik,[10,d] L. Ioannucci,[1] J. Janicskó Csáthy,[14] J. Jochum,[17] M. Junker,[1] T. Kihm,[6] I.V. Kirpichnikov,[11] A. Kirsch,[6] A. Klimenko,[4,6,e] K.T. Knöpfle,[6] O. Kochetov,[4] V.N. Kornoukhov,[11,10] V.V. Kuzminov,[10] M. Laubenstein,[1] A. Lazzaro,[14] V.I. Lebedev,[12] B. Lehnert,[3] H.Y. Liao,[13] M. Lindner,[6] I. Lippi,[16] X. Liu,[13,f] A. Lubashevskiy,[6] B. Lubsandorzhiev,[10] G. Lutter,[5] C. Macolino,[1] A.A. Machado,[6] B. Majorovits,[13] W. Maneschg,[6] M. Misiaszek,[2] I. Nemchenok,[4] S. Nisi,[1] C. O'Shaughnessy,[13,g] L. Pandola,[1] K. Pelczar,[2] G. Pessina,[8,7] A. Pullia,[9] S. Riboldi,[9] C. Sada,[15,16] M. Salathe,[6] C. Schmitt,[17] J. Schreiner,[6] O. Schulz,[13] B. Schwingenheuer,[6] S. Schönert,[14] E. Shevchik,[4] M. Shirchenko,[12,4] H. Simgen,[6] A. Smolnikov,[6] L. Stanco,[16] H. Strecker,[6] M. Tarka,[18] C.A. Ur,[16] A.A. Vasenko,[11] O. Volynets,[13] K. von Sturm,[17,15,16] V. Wagner,[6] M. Walter,[18] A. Wegmann,[6] T. Wester,[3] M. Wojcik,[2] E. Yanovich,[10] P. Zavarise,[1,h] I. Zhitnikov,[4] S.V. Zhukov,[12] D. Zinatulina,[4] K. Zuber,[3] and G. Zuzel[2]

[1] *INFN Laboratori Nazionali del Gran Sasso, LNGS, Assergi, Italy*
[2] *Institute of Physics, Jagiellonian University, Cracow, Poland*
[3] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[4] *Joint Institute for Nuclear Research, Dubna, Russia*
[5] *Institute for Reference Materials and Measurements, Geel, Belgium*
[6] *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[7] *Dipartimento di Fisica, Università Milano Bicocca, Milano, Italy*
[8] *INFN Milano Bicocca, Milano, Italy*
[9] *Dipartimento di Fisica, Università degli Studi di Milano e INFN Milano, Milano, Italy*
[10] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[11] *Institute for Theoretical and Experimental Physics, Moscow, Russia*
[12] *National Research Centre "Kurchatov Institute", Moscow, Russia*
[13] *Max-Planck-Institut für Physik, München, Germany*
[14] *Physik Department and Excellence Cluster Universe, Technische Universität München, Germany*
[15] *Dipartimento di Fisica e Astronomia dell'Università di Padova, Padova, Italy*
[16] *INFN Padova, Padova, Italy*
[17] *Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany*
[18] *Physik Institut der Universität Zürich, Zürich, Switzerland*

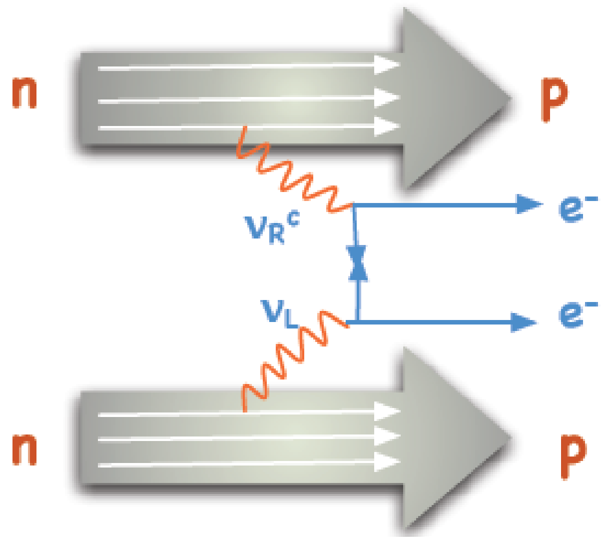
~ 100 members
19 institutions
6 countries



$Q_{\beta\beta}$ = (2039.061±0.007) keV B. J. Mount et al., Phys.Rev. 401 C81, 032501 (2010)



2-electron spectra



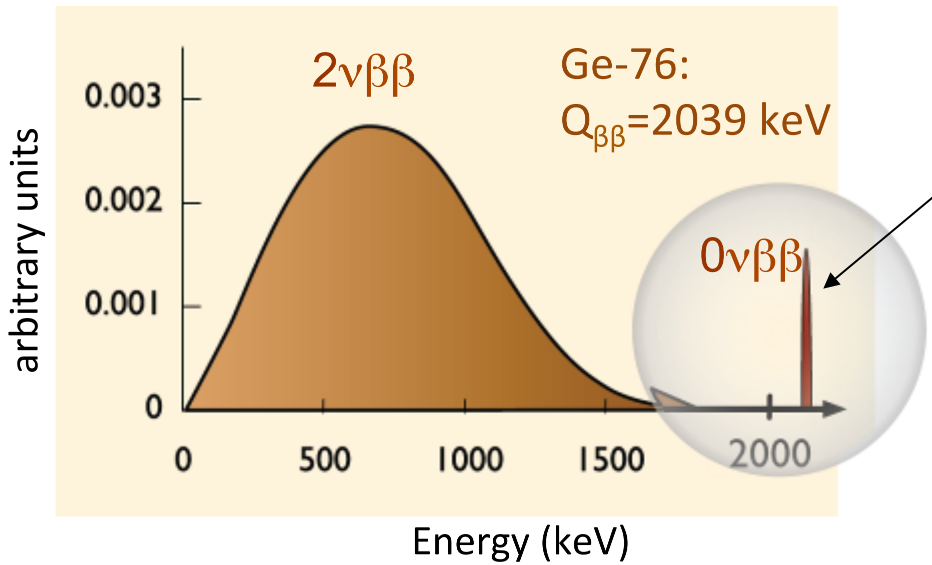
Expected decay rate:

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

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

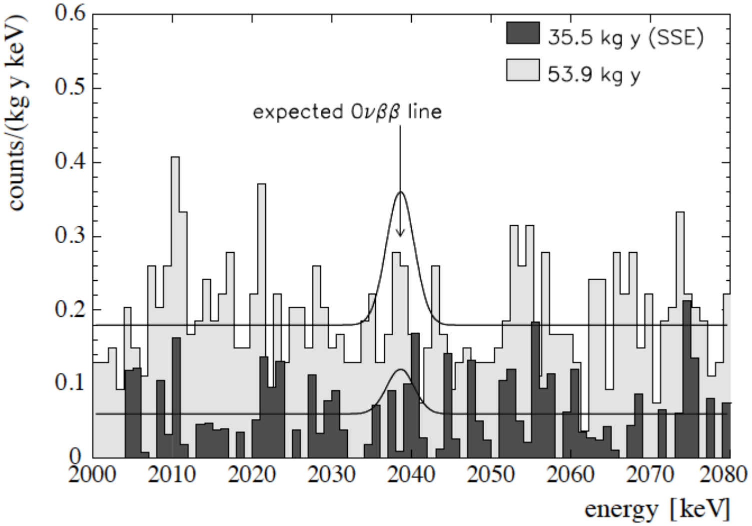


Experimental signatures:

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

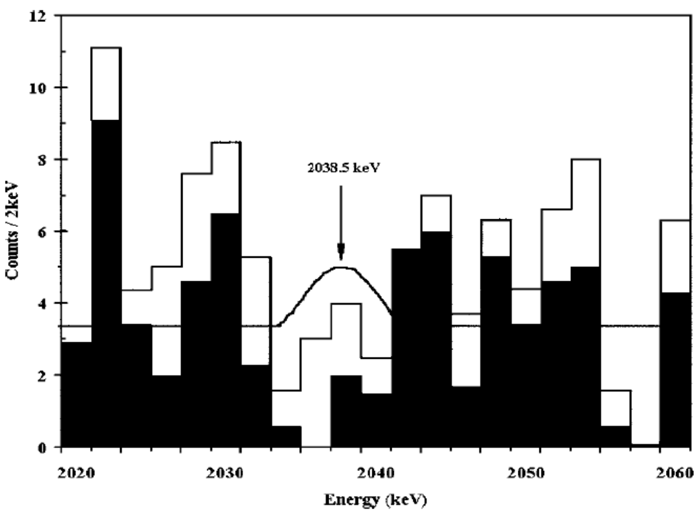
Discovery would imply:

- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale & hierarchy
- physics beyond the standard model



Heidelberg-Moscow
(H.V. Klapdor-Kleingrothaus et al.)
(Eur. Phys. J. A 12, 147-154 (2001)):

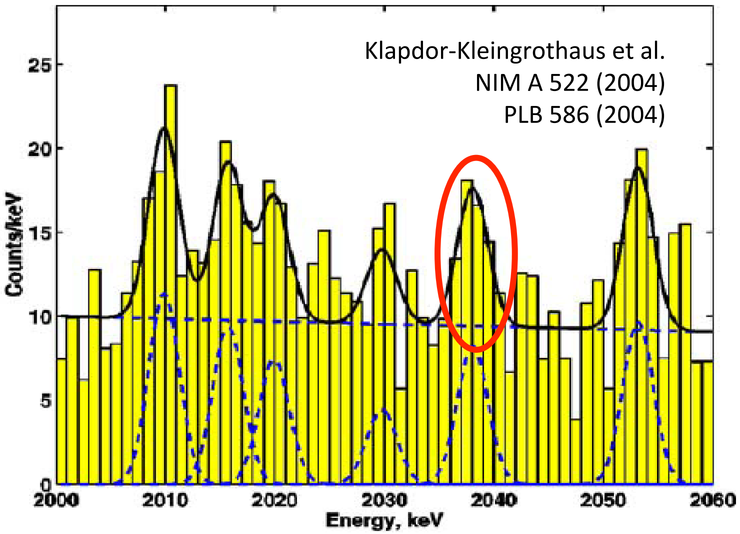
53.9 kg y (35.5 kg y): $T_{1/2}^{0\nu} > 1.3 \times 10^{25}$ yr (1.9×10^{25} yr)
(90% C.L.)



IGEX
(Aalseth et al.)
Phys. Rev. D 65 (2002) 092007

8.8 kg y: $T_{1/2}^{0\nu} > 1.6 \times 10^{25}$ yr (90%C.L.)

^{76}Ge 0νββ search: the claim



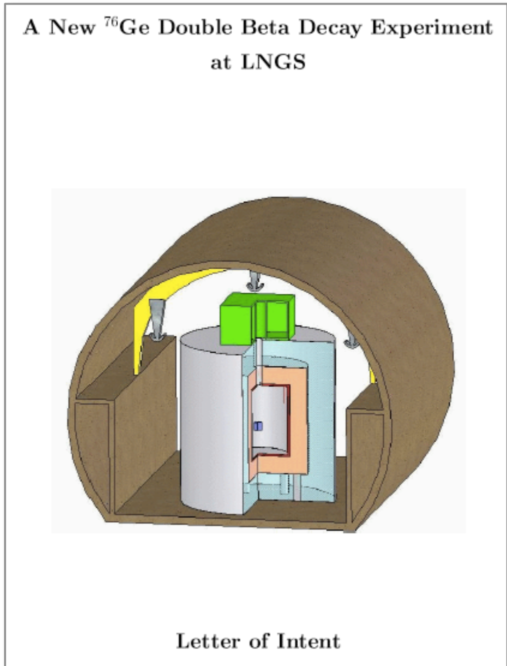
Klapdor-Kleingrothaus et al., NIM A 522 371 (2004), PLB 586 198 (2004):

- 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

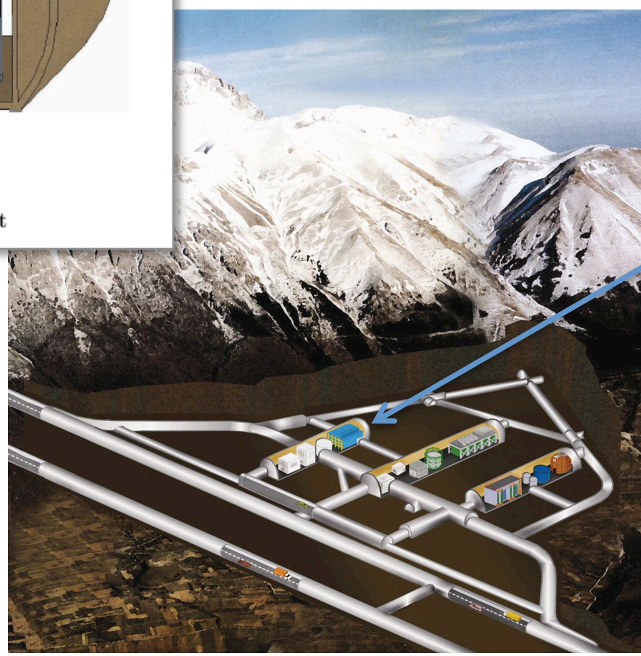
N.B. Half-life $T_{1/2}^{0\nu}$ = 2.23 x10^{25} yr after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

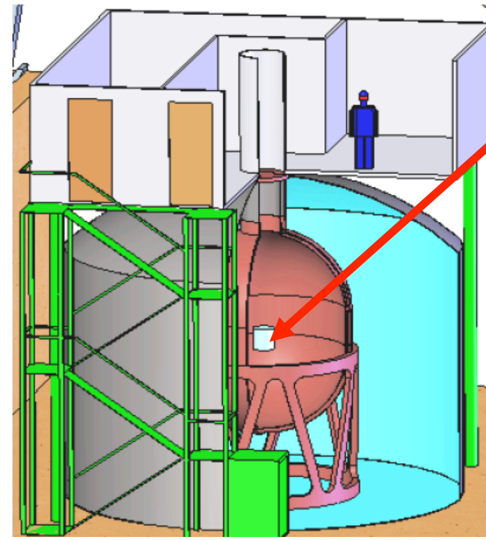
- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx$ 0.6)
- ε_{fep} = 1 (also in NIM A 522, PLB 586, 198 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

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


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

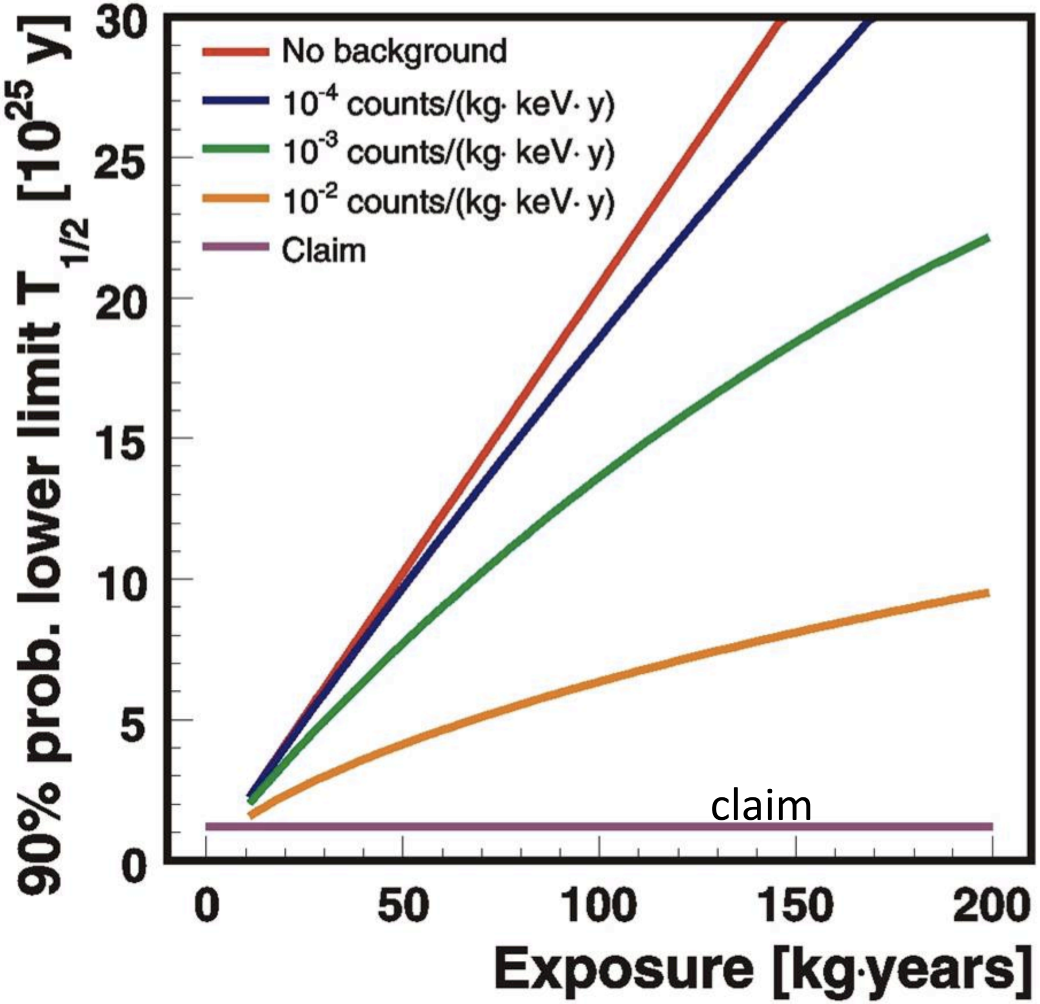
Letter of Intent

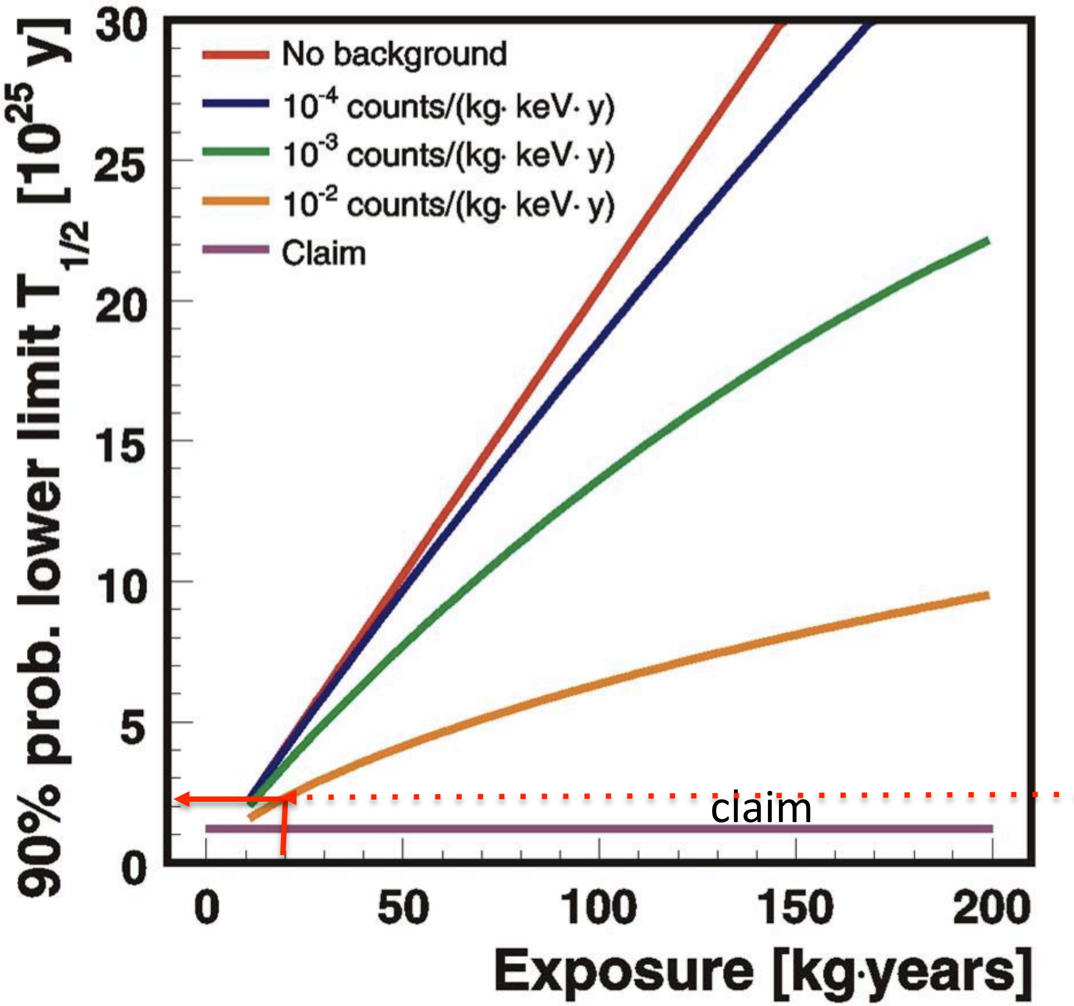




- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

GERDA Phases



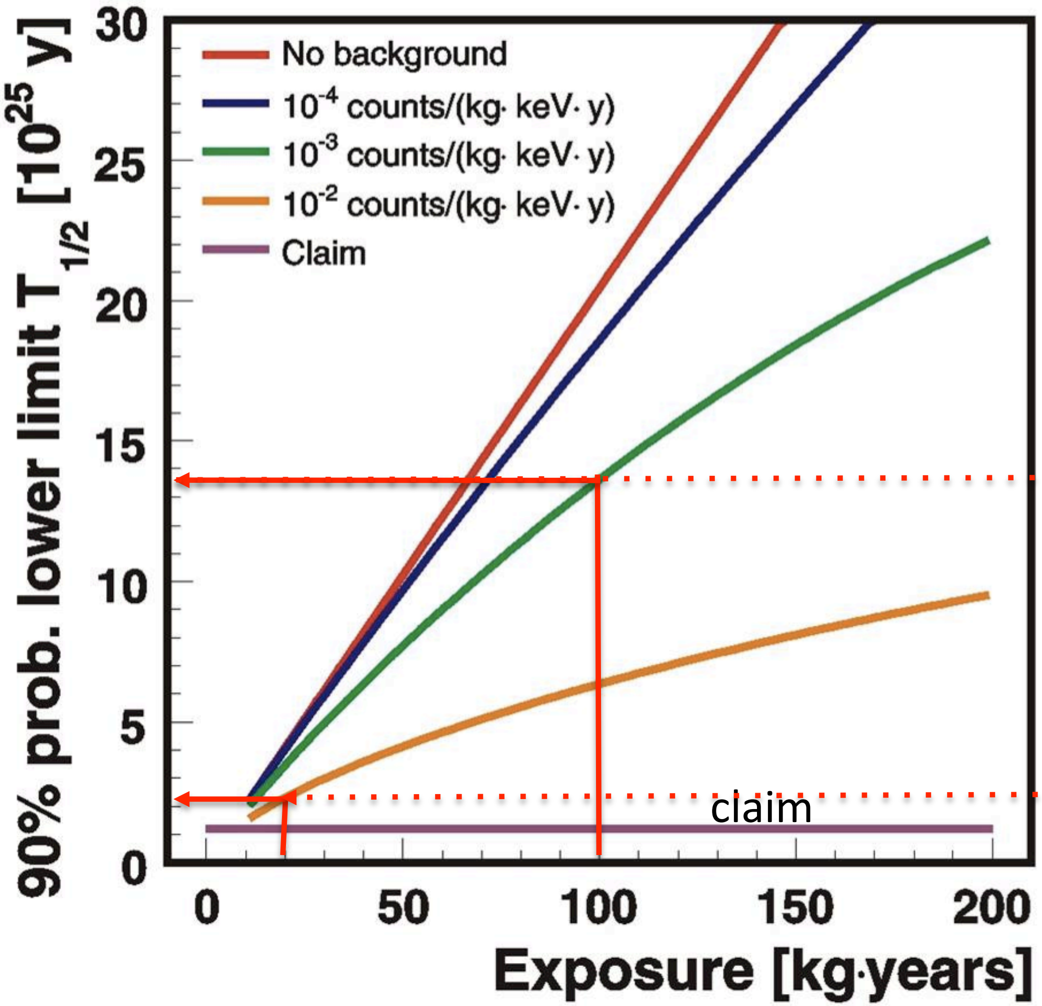


Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr



<u>Phase II:</u>

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

<u>Phase I:</u>

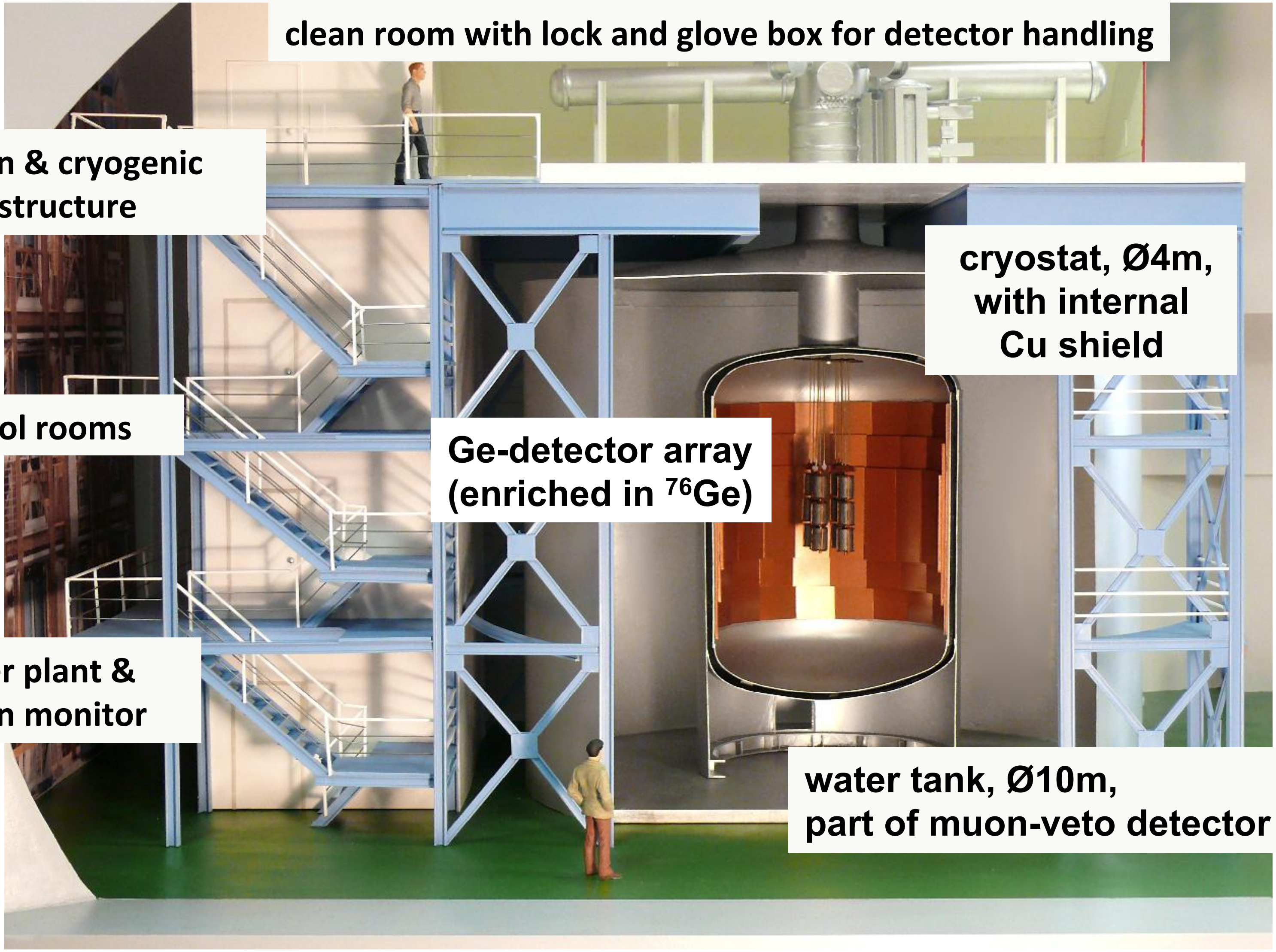
Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

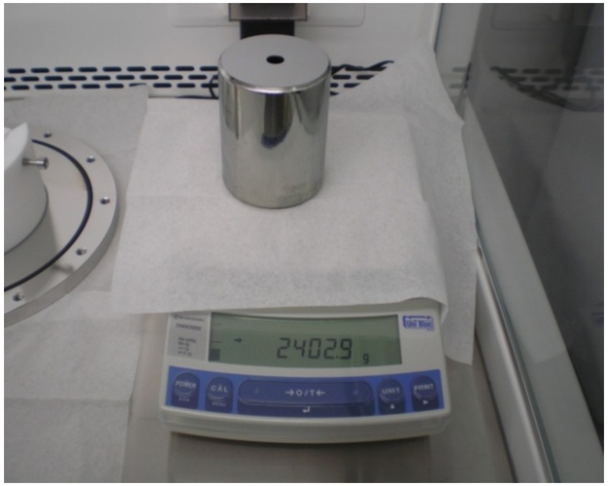
The GERDA experiment

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



Phase I detectors: semi-coaxial detectors

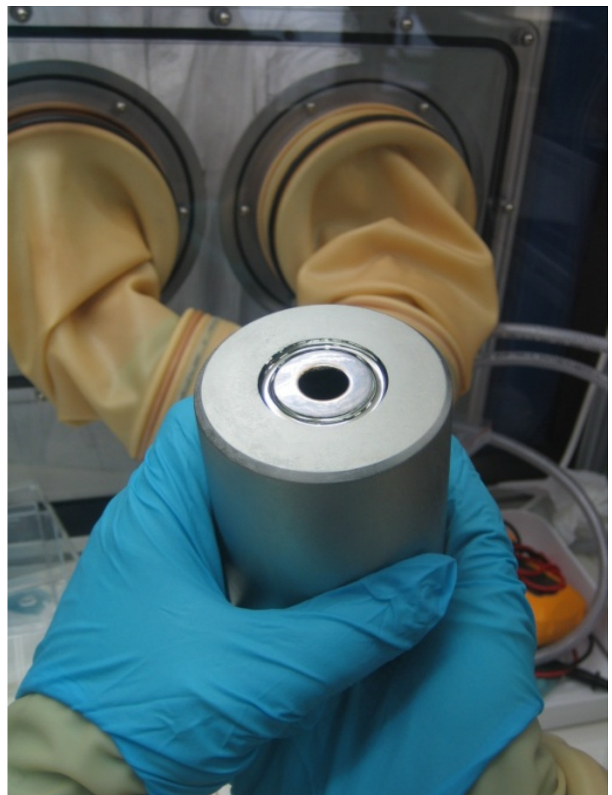
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



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

8 diodes (from HdM, IGEX):

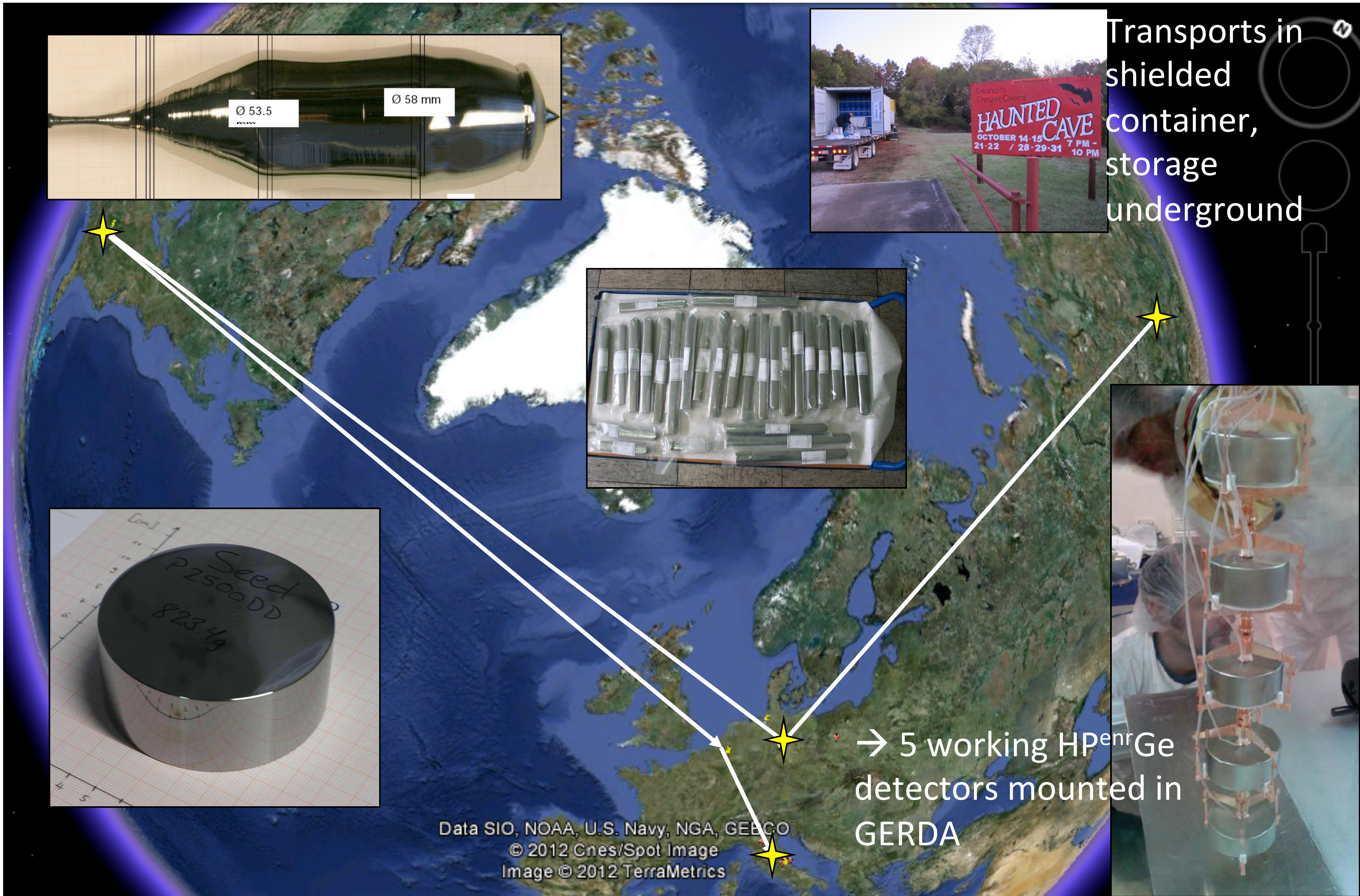
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



6 diodes from Genius-TF:

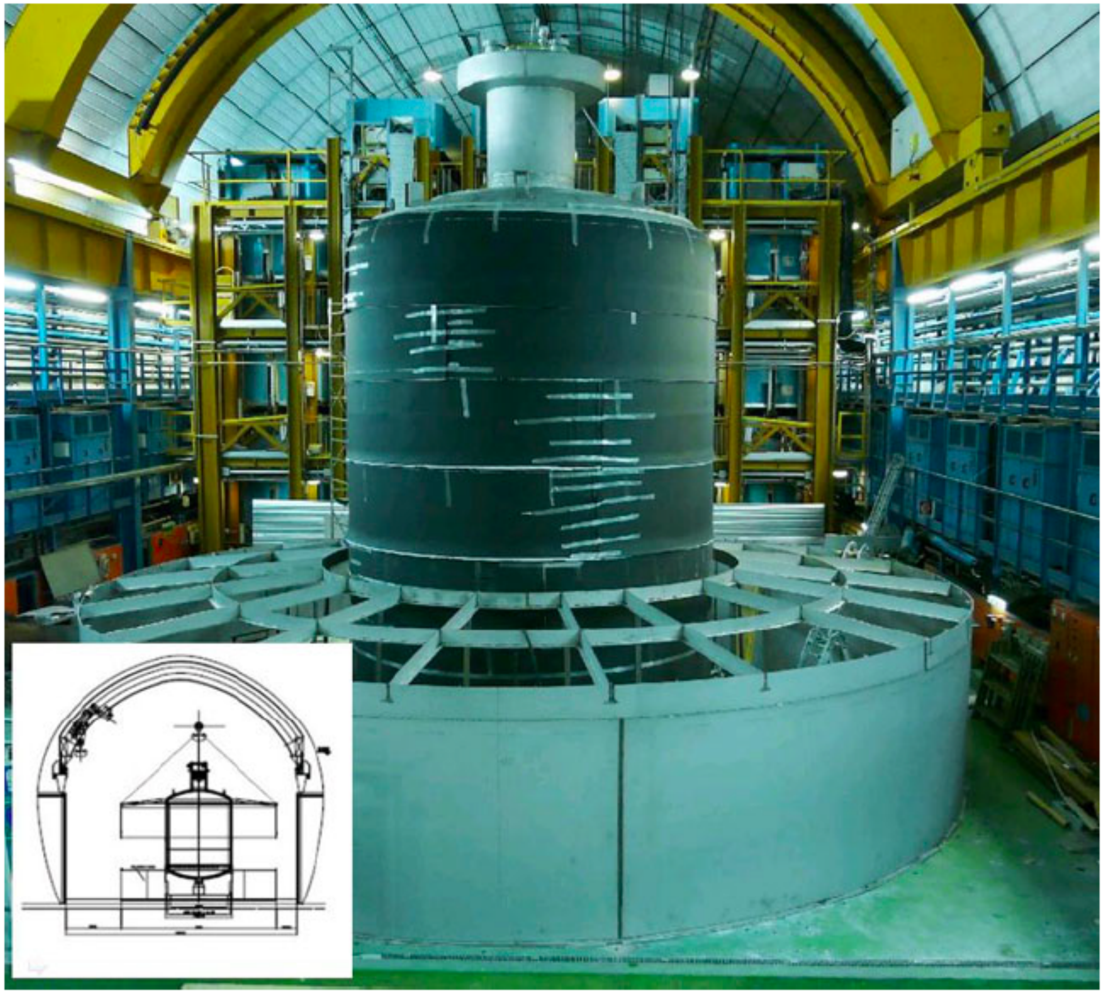
- ^{nat}Ge
- Total mass: 15.60 kg

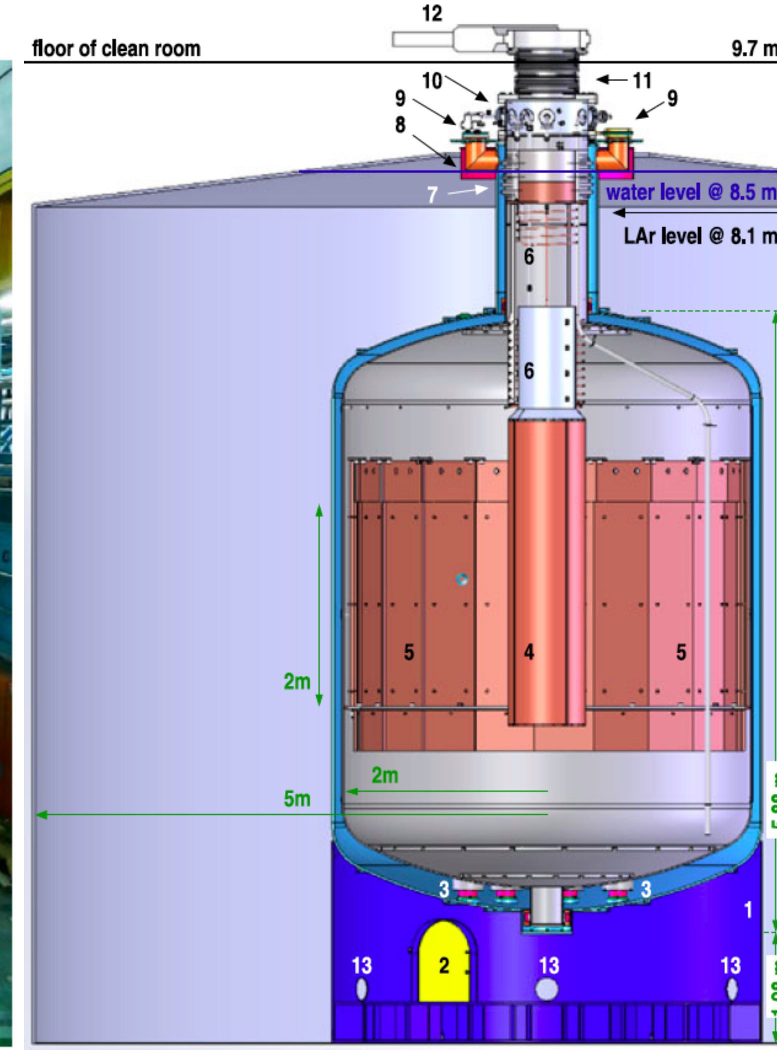
Production of ^{enr}Ge Phase II detectors



Water tank and cryostat

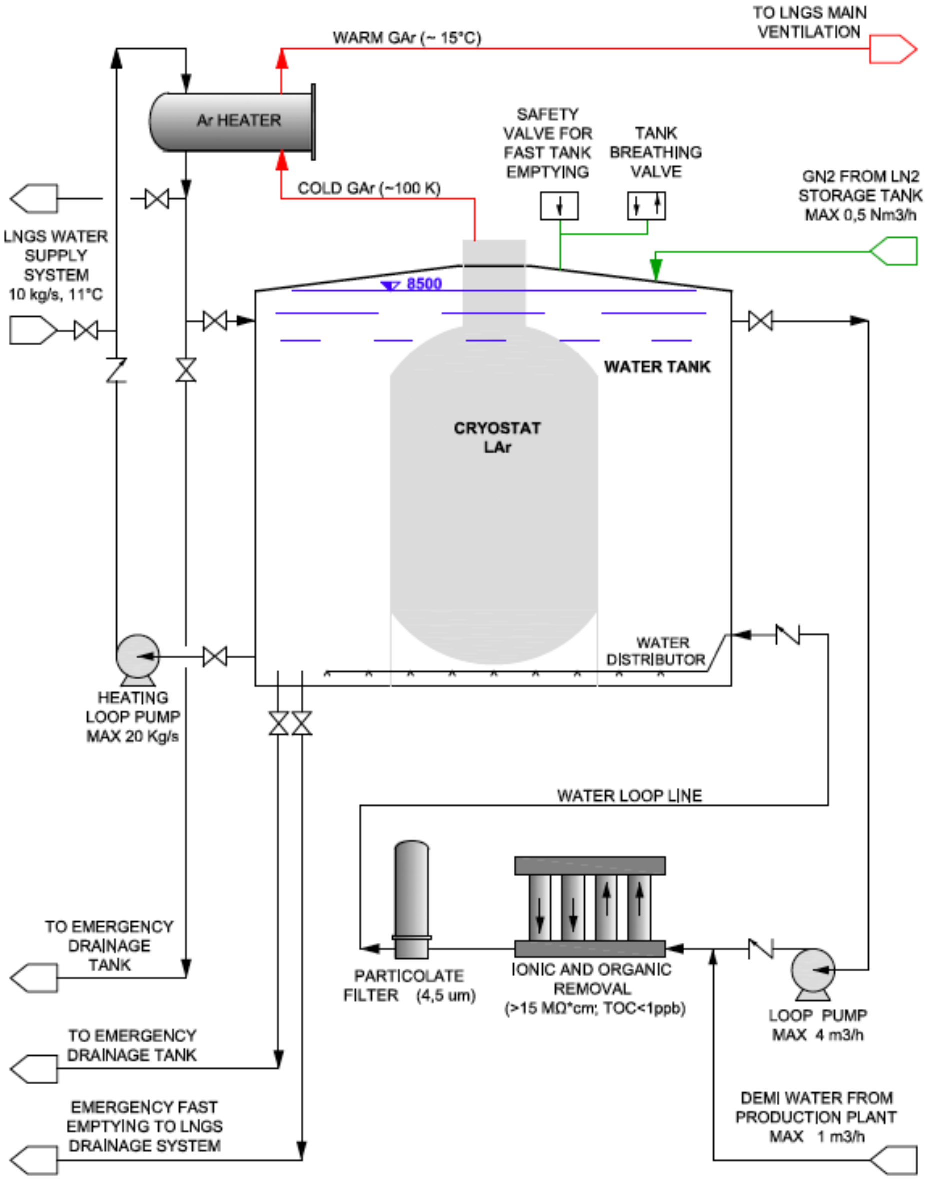
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067





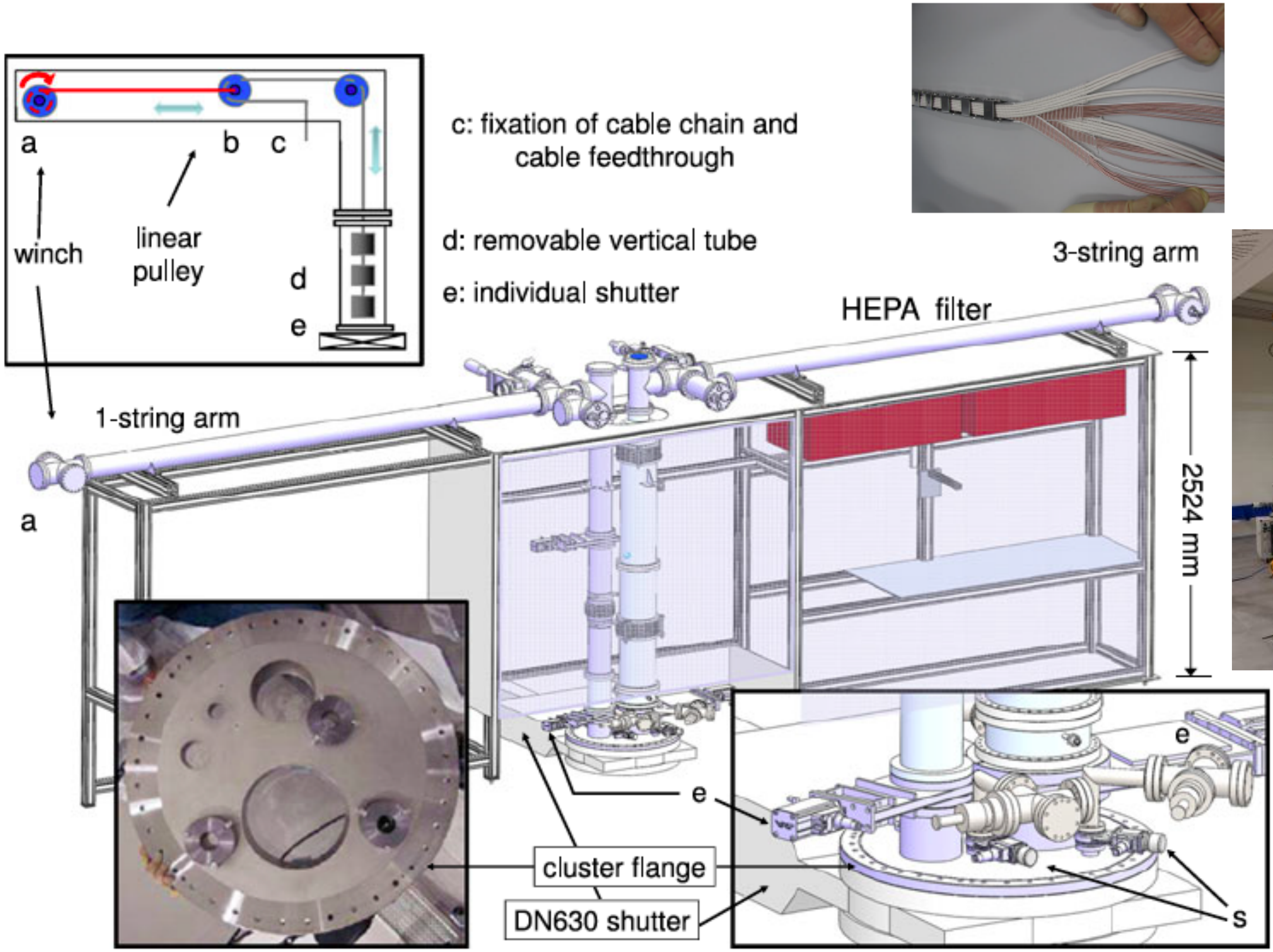
Water purification system

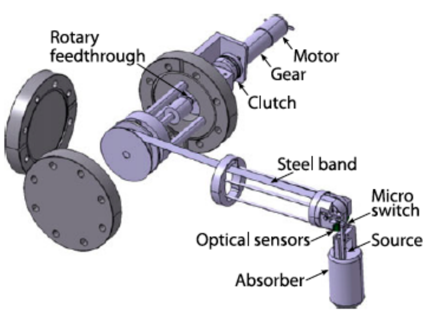
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



Clean room with Lock system, glove box and calibration devices

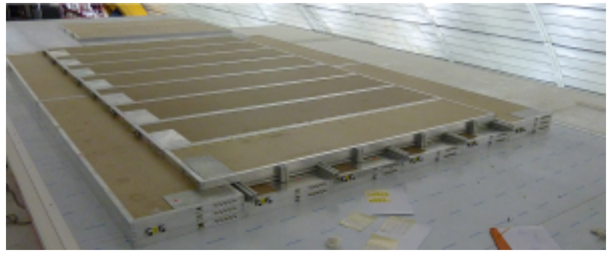
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

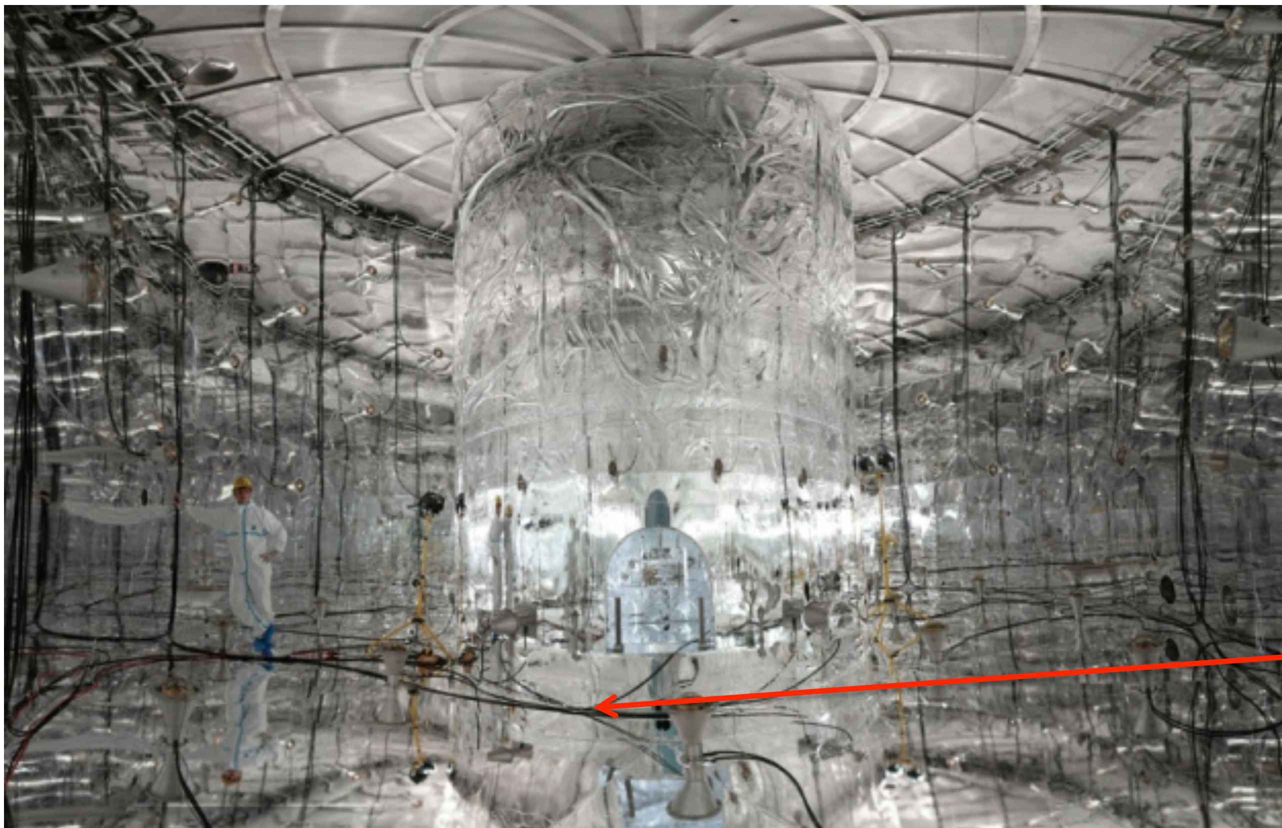


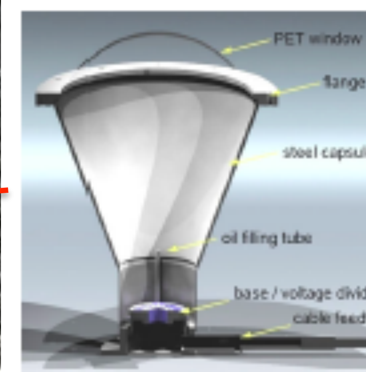


Water Cherenkov detector and plastic scintillator muon veto

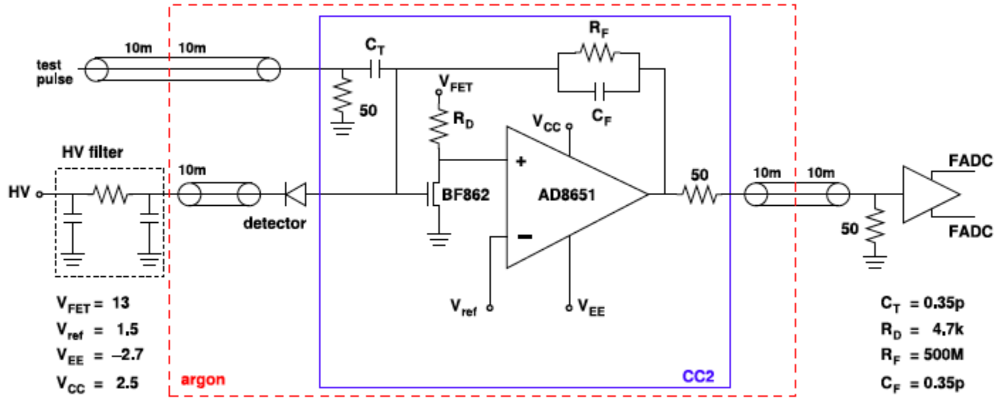
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

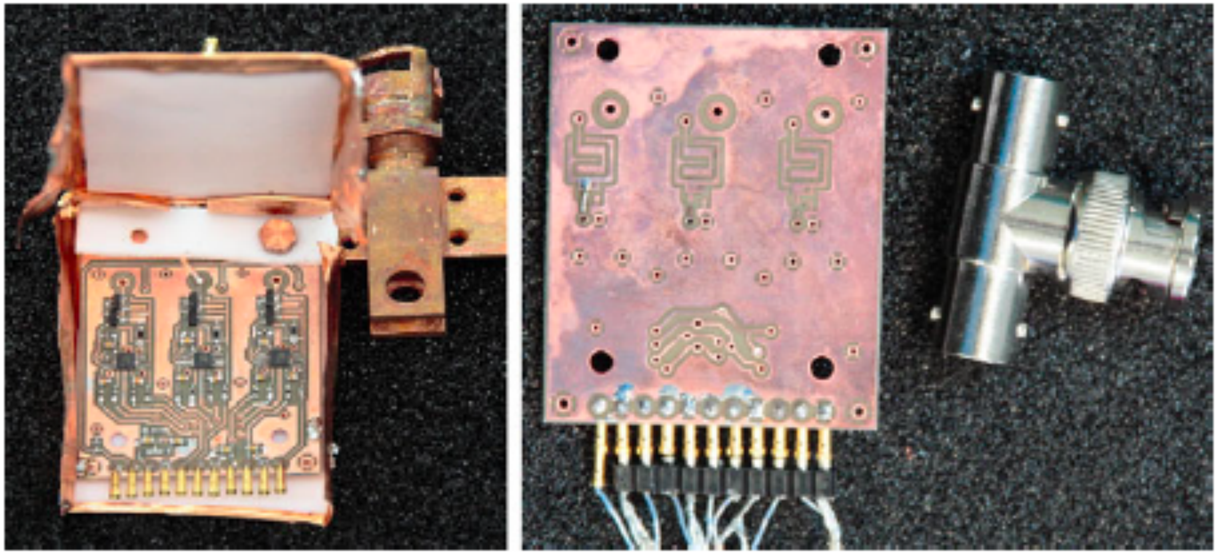




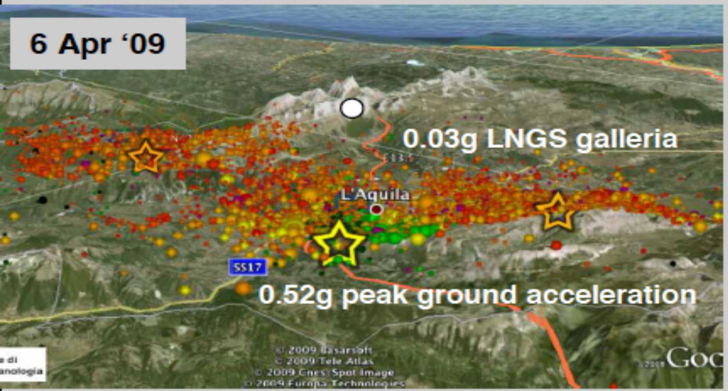


Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



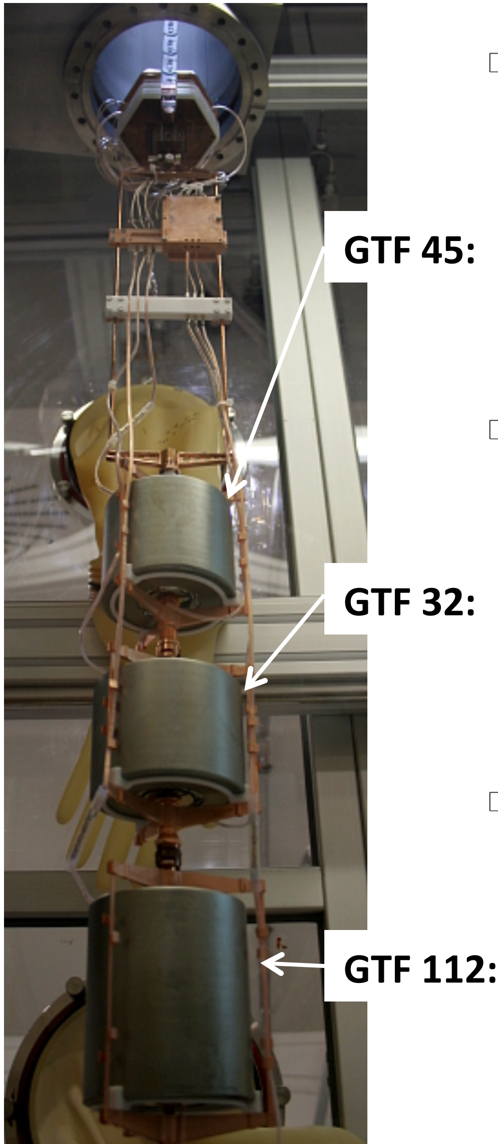


The GERDA construction 2008-2010

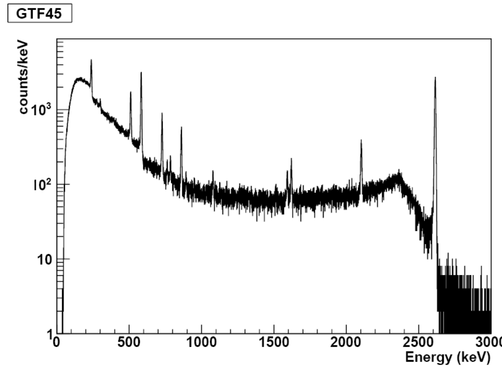


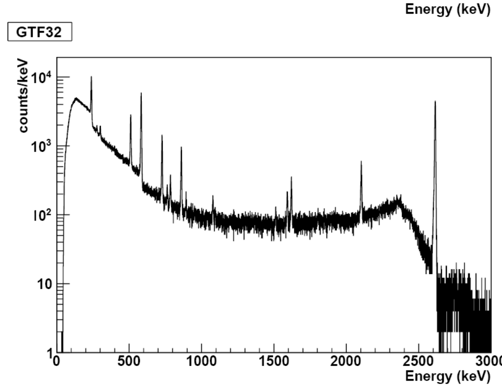
Cryostat filled since December 2009

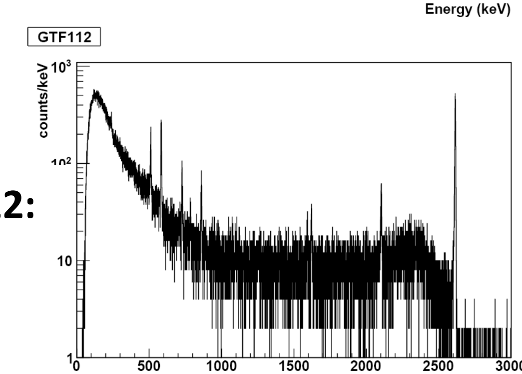
Commissioning with 1-string assembly



Calibration with ^{228}Th:







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

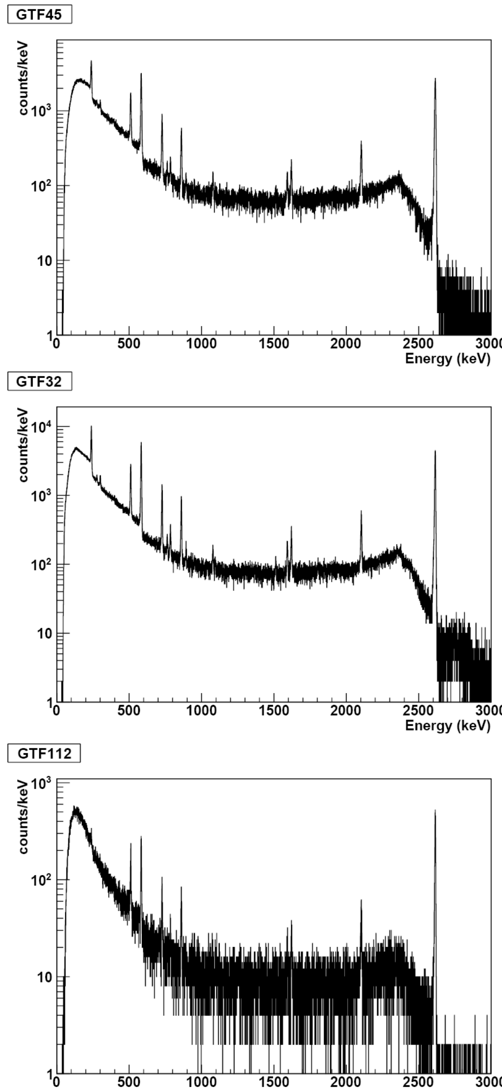
Energy resolutions during commissioning: dependent on chosen detector configuration:

- Coaxial (Phase I): 3.4-5 keV (*FWHM*) @ 2.6 MeV
- BEGe (Phase II): 2.8 keV (*FWHM*) @ 2.6 MeV

Commissioning with 1-string assembly

60 µm 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

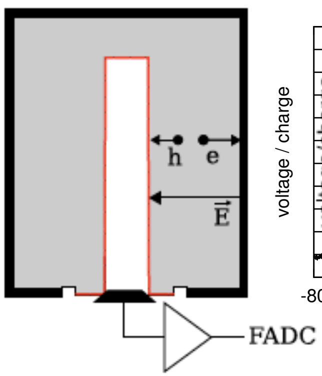
2 diodes shut off because leakage current high:

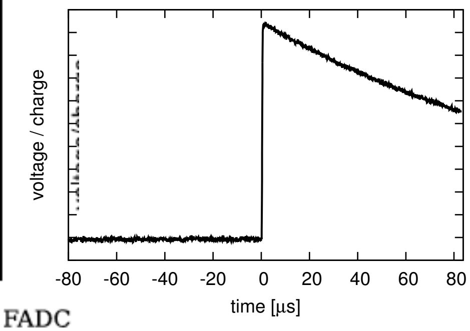
- total enriched enriched detector mass 14.6 kg

Data processing and selection

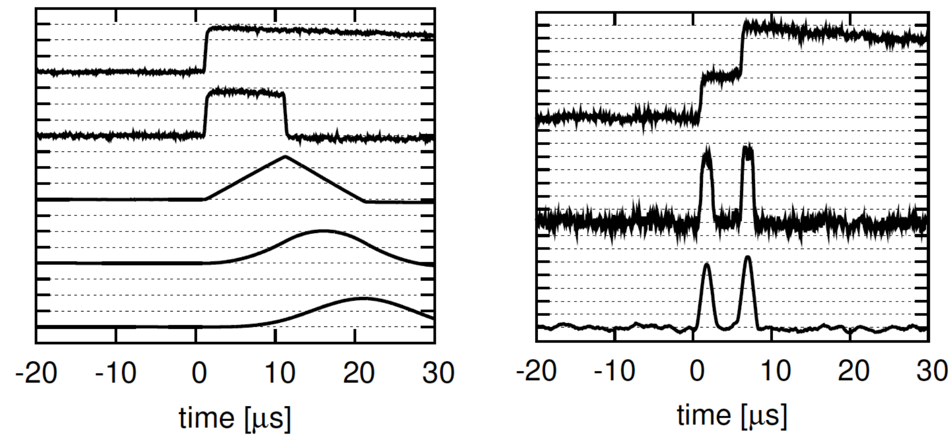
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

Read-out and signal structure

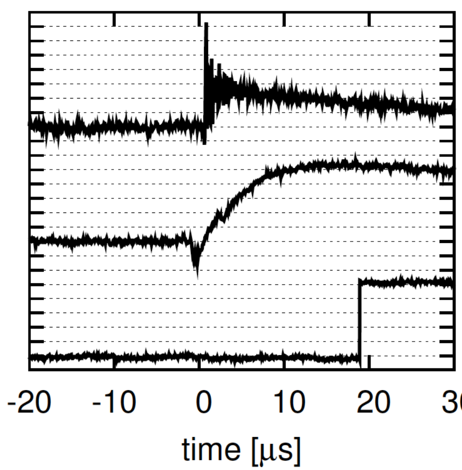




Digital signal processing to extract amplitude, rise time, etc.

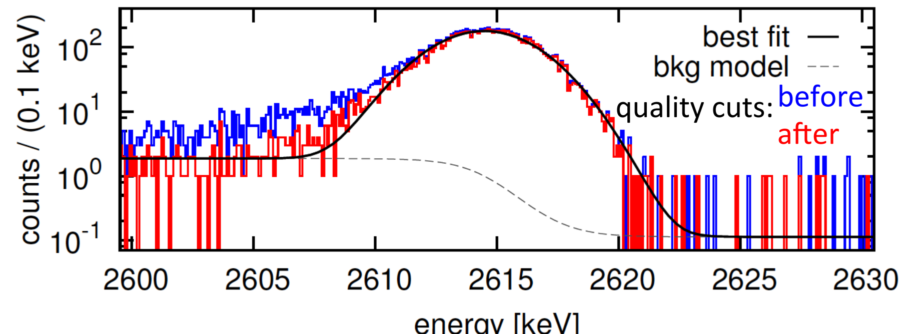


Data selection and quality monitoring



Examples of non-physical events

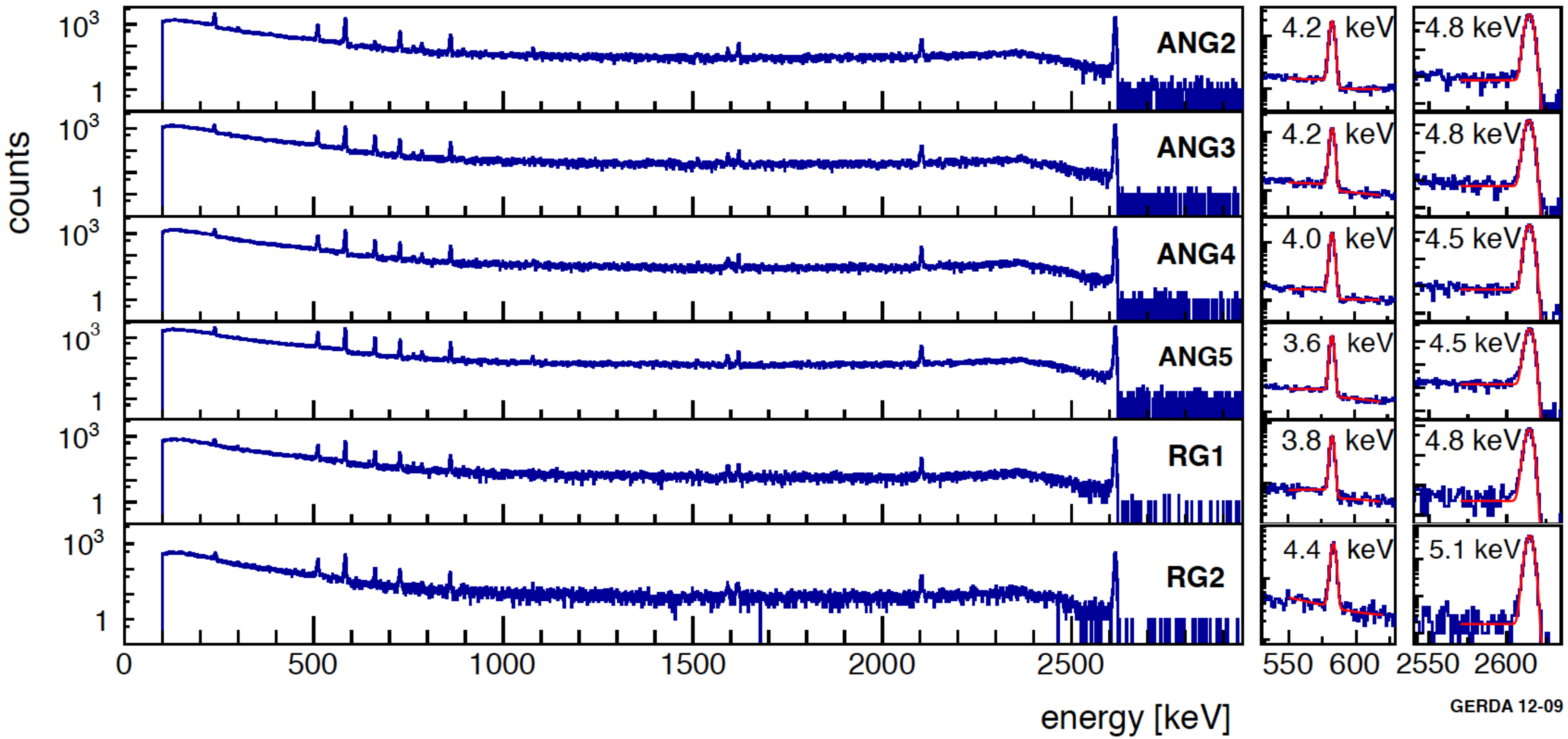
Calibration of energy scale (^{228}Th)



- Data processing frame work 'Gelatio'
- 2nd independent data processing software for cross check

First calibration spectra

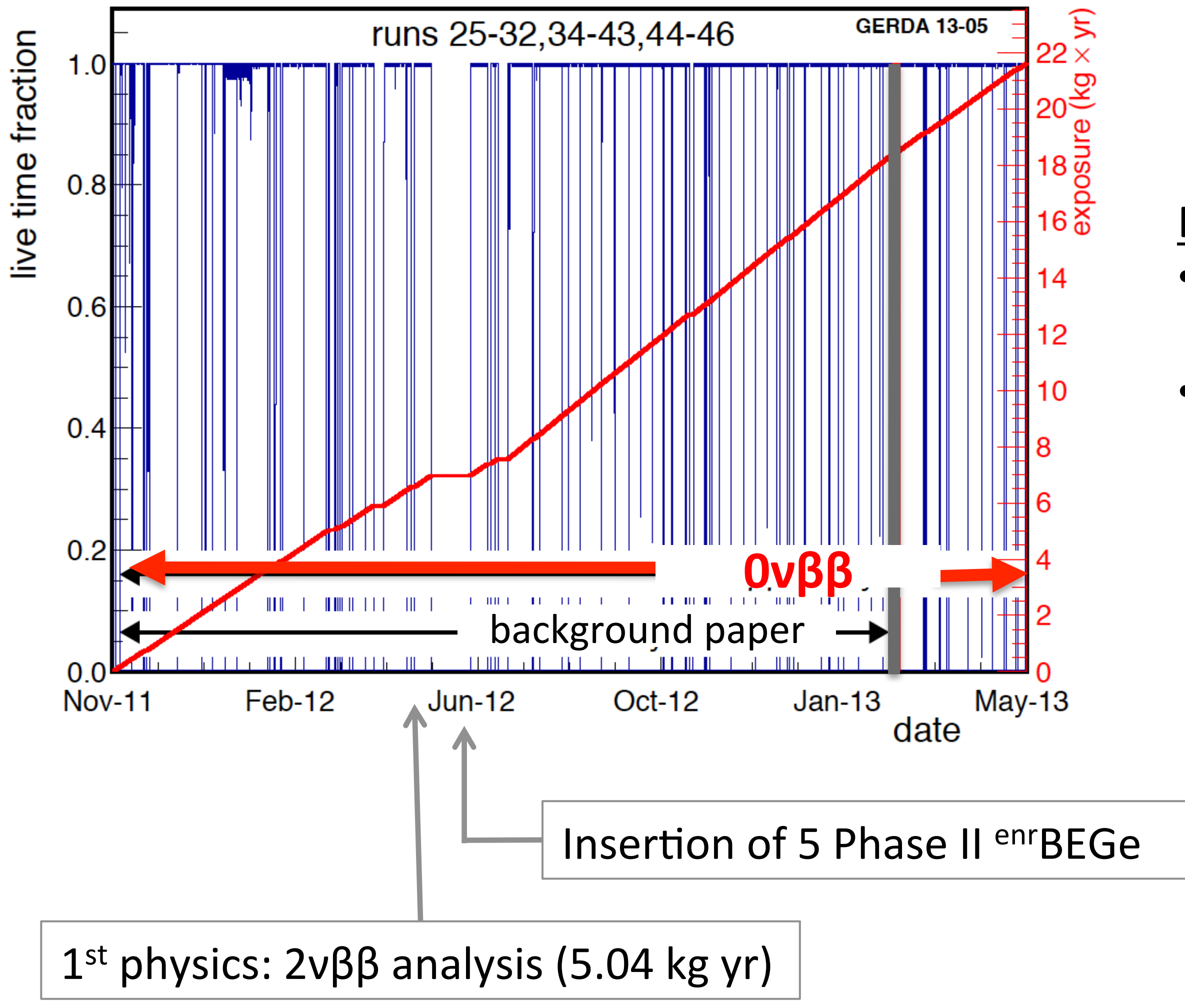
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



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

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

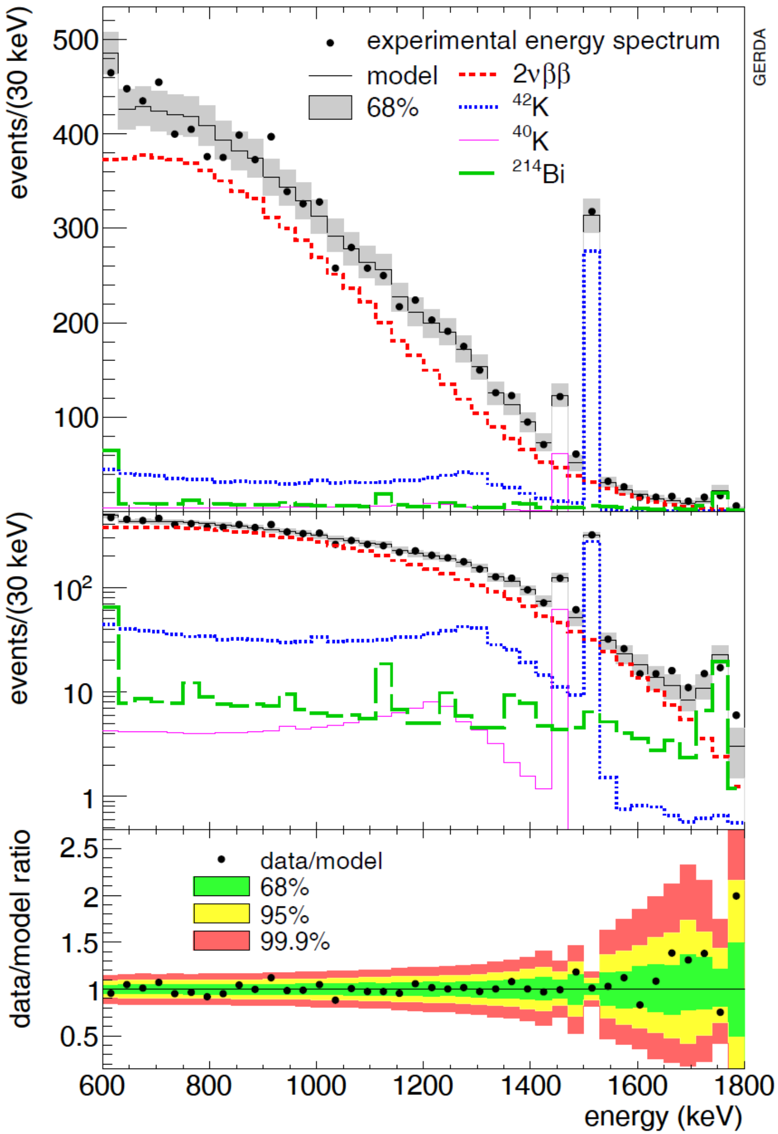
Total exposure for 0νββ analysis: 21.6 kg yr
(bi-)weekly calibration runs (‘spikes’)



Data blinding:

- All events in $Q_{\beta\beta}\pm 20$ keV removed in Tier 1
- 2 copies of raw data kept for processing after unblinding

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

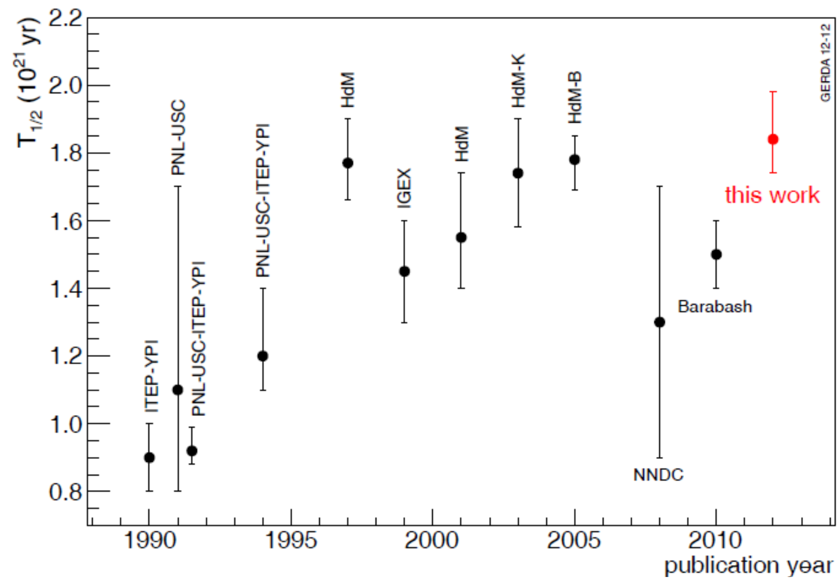


IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

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

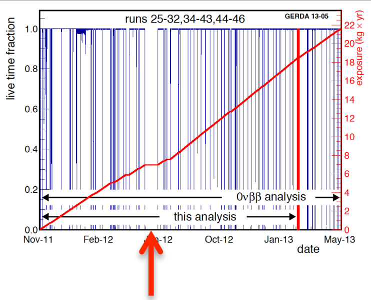
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

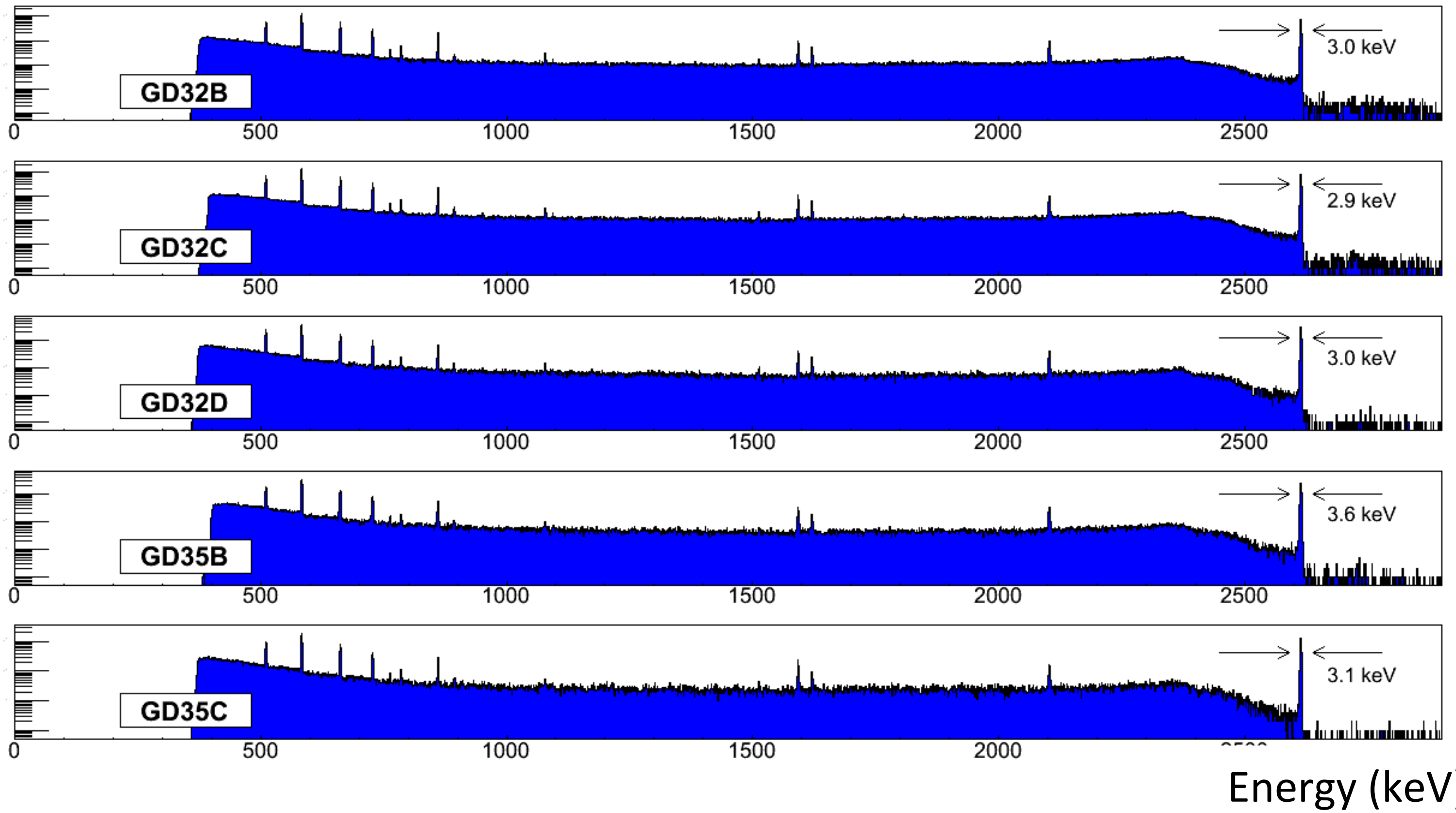
$T^{2\nu}_{1/2}(^{76}\text{Ge}) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



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

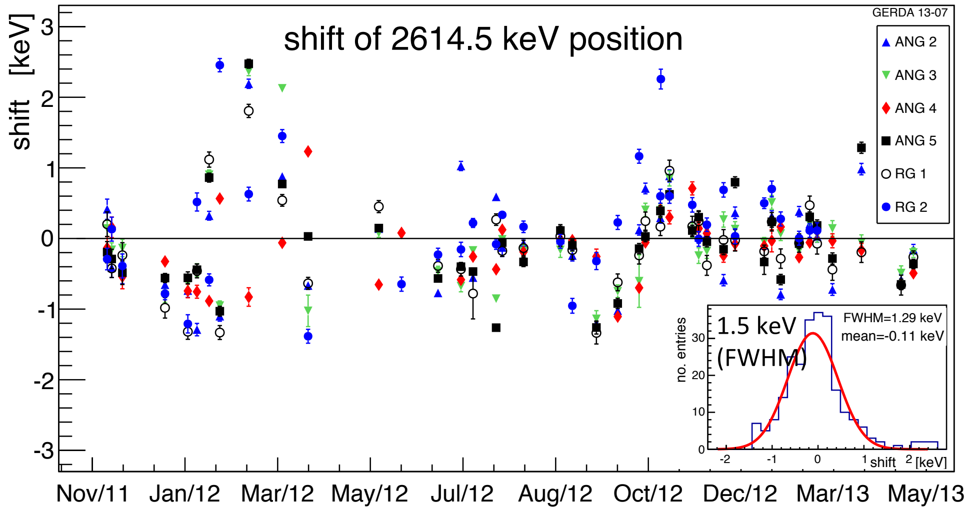


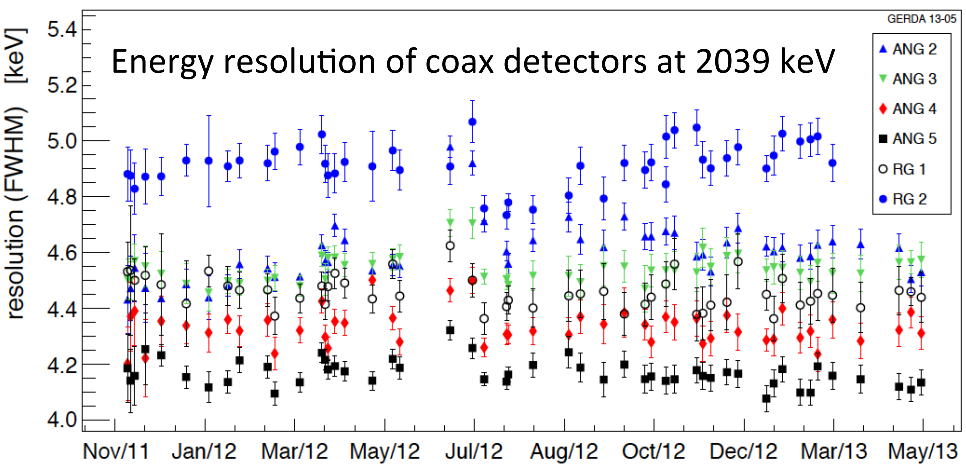


Calibration: stability of HPGe detectors

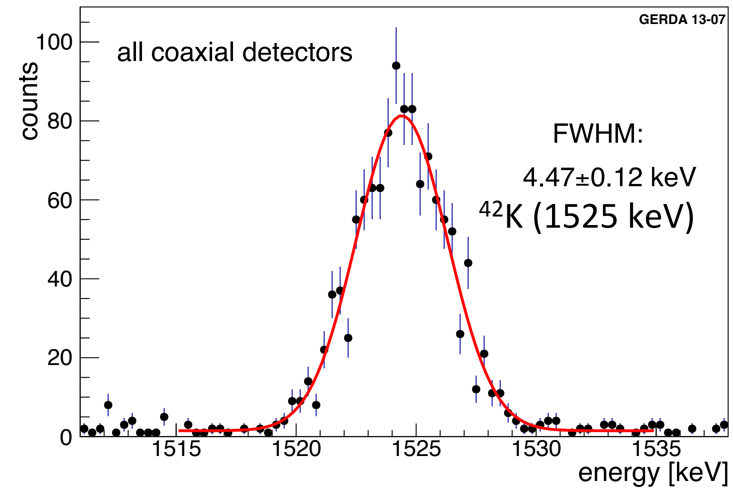
[arXiv:1306.5084]

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:

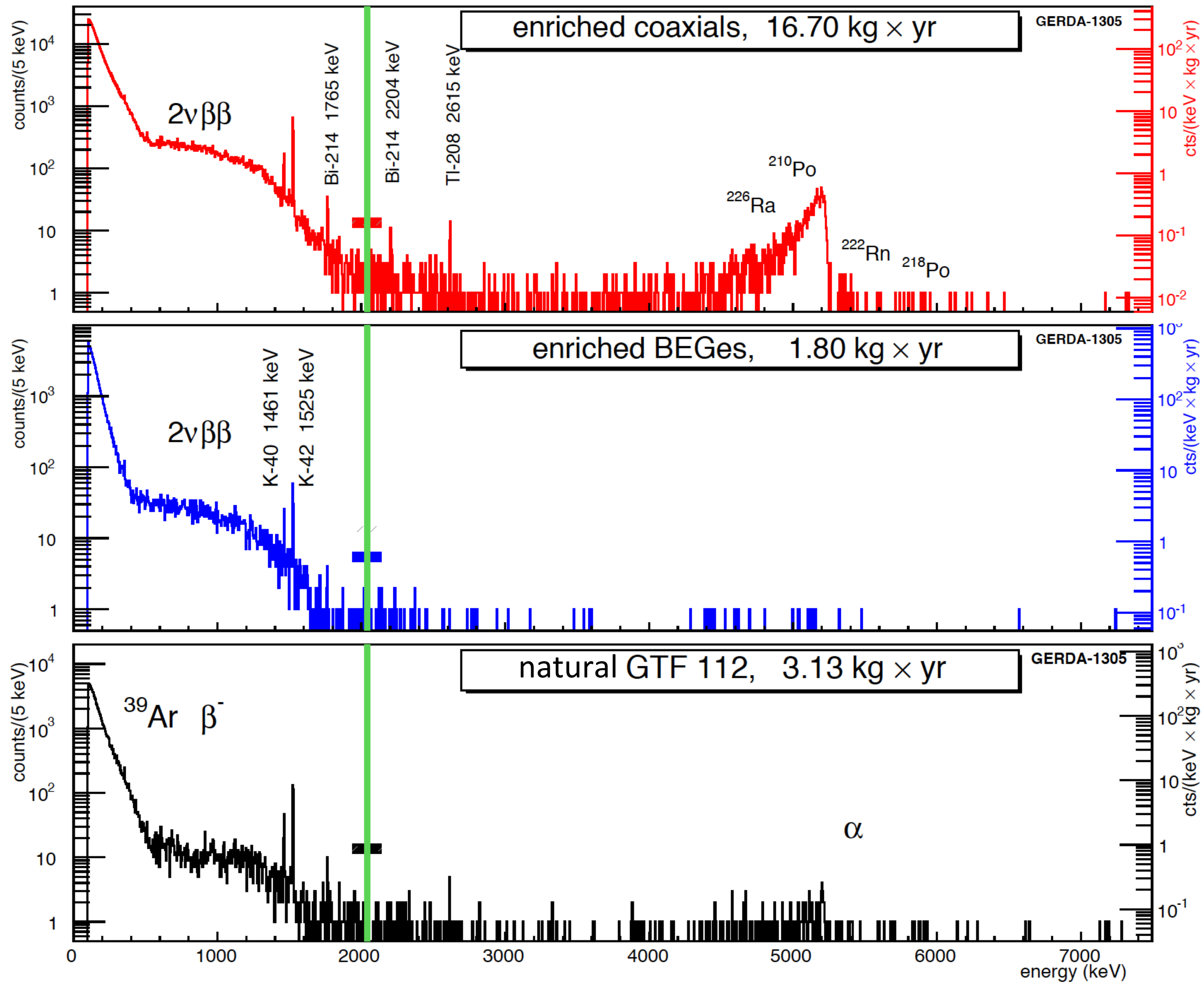
- Coax: 4.8 keV (FHWM)
- BEGe: 3.2 keV (FWHM)

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)

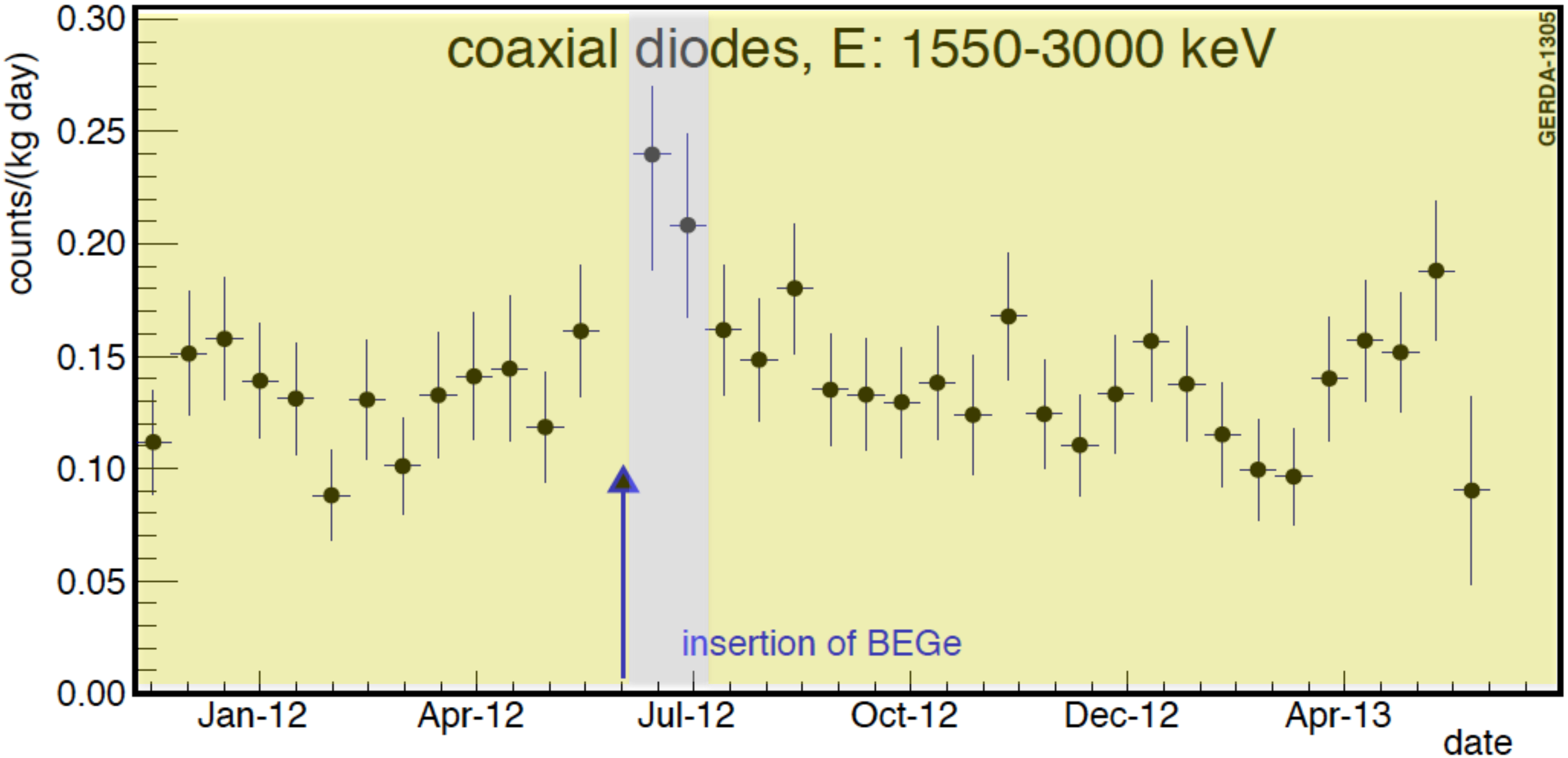
Physics run: energy spectra

arXiv:1306.5084

Submitted to EPJ A
Data for background model



arXiv:1306.5084

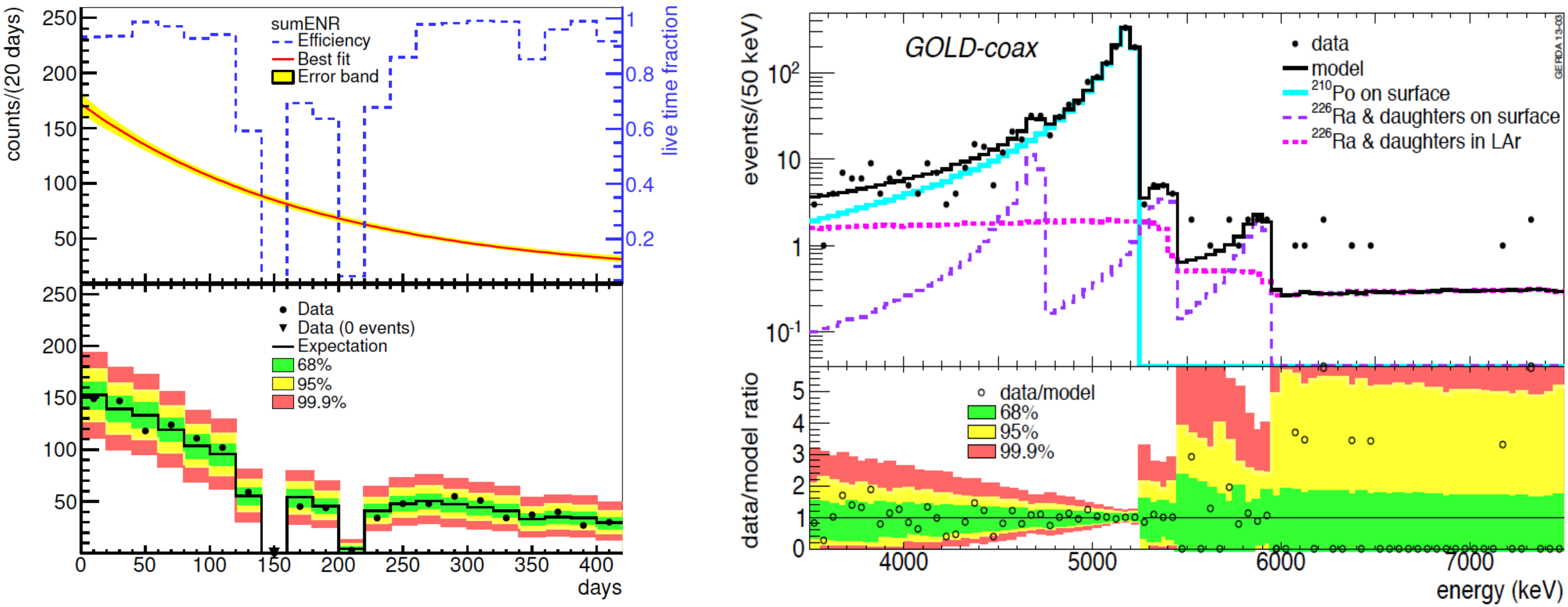


Coax-detector data set split in 'Gold' and 'Silver' (30 d)

Physics run: background model at **high energy**

arXiv:1306.5084

Time distribution (3.5-5.3 MeV) Energy spectrum

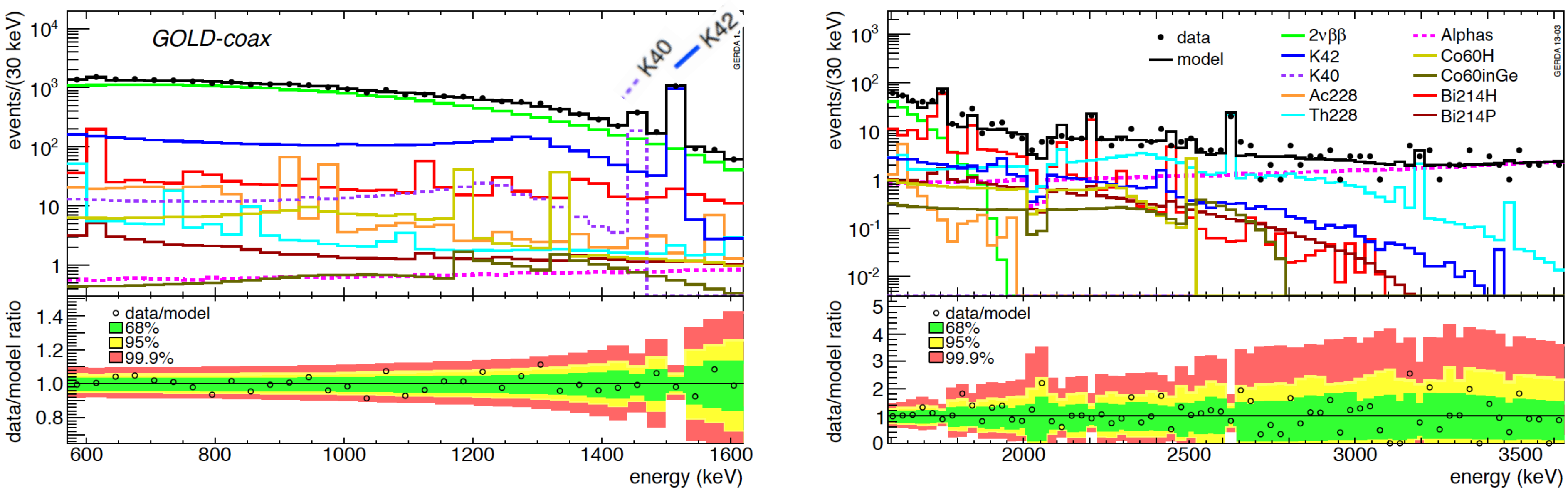


- ^{210}Po ($T_{1/2}$=138 d) dominated
- Contributions also from ^{226}Ra & progenies
- Located on (thin) p+ surface contact (also confirmed by pulse shape analysis)
- Background model only with Gold-coax; same sources in Silver-coax, but limited statistics does not allow quantitative background decomposition

Physics run: background model **full energy**

arXiv:1306.5084

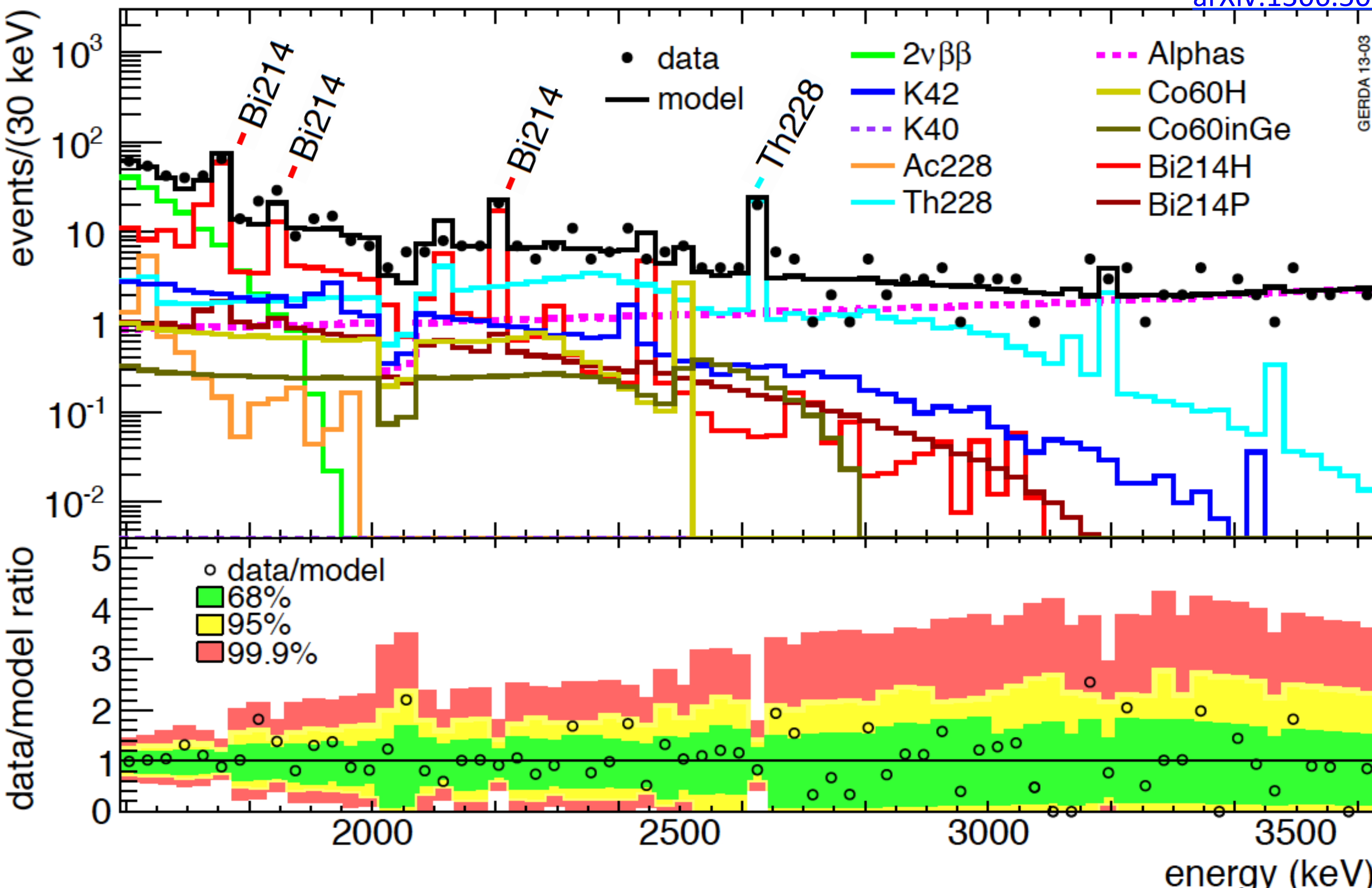
Fit of minimal background model to complete energy spectrum



- “Minimal Model” is sufficient to describe data well
- “Maximum Model” includes ^{42}K on p+ and n+ contacts, ^{214}Bi in LAr & far sources

Physics data: high-energy alpha

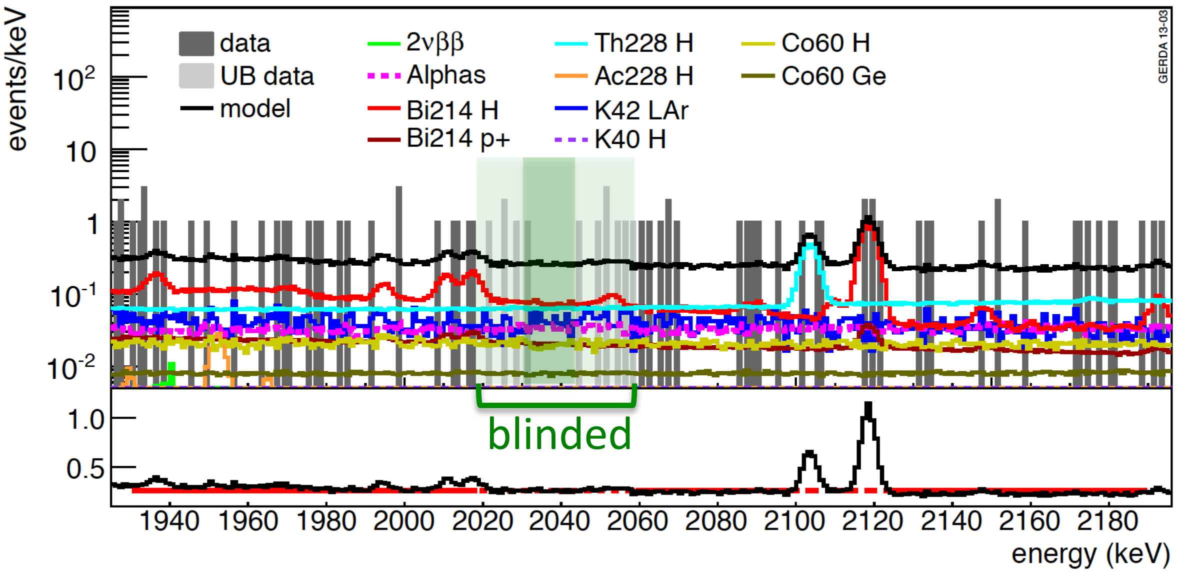
arXiv:1306.5084



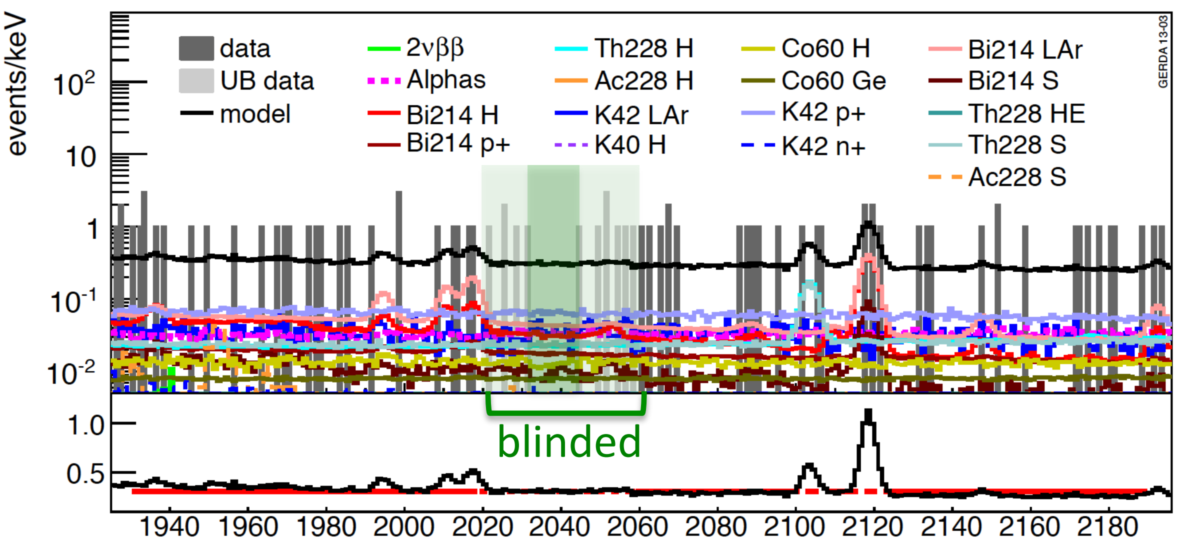
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

arXiv:1306.5084

Minimal model



Maximum model



Background model:

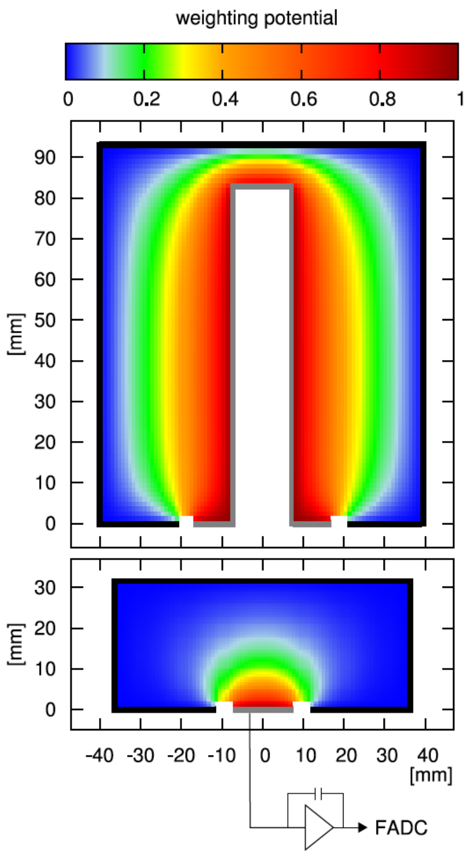
- No background peak expected around $Q_{\beta\beta}$
- Spectrum can be modeled with flat background (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- Background index (BI) at $Q_{\beta\beta}$ (17.6-23.8) 10^{-3} cts/(keV kg yr) depending on assumptions for location of sources
- 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

➔ fit with constant background 1930-2190 keV excluding peaks

arXiv:1307.2610

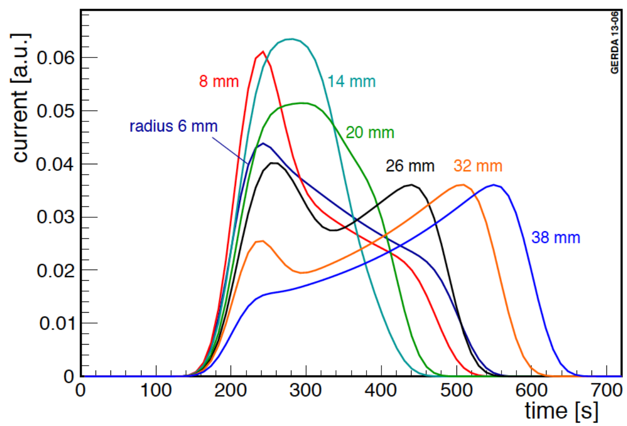
Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

Weighting potential for coax and BEGe detectors are different

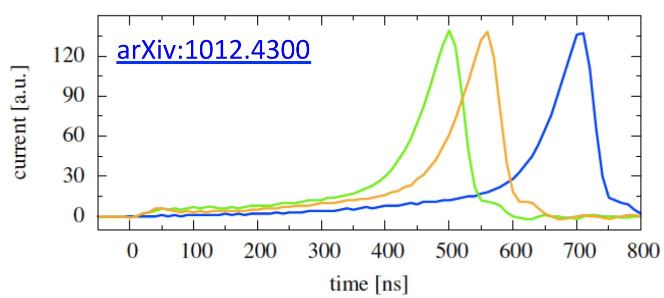


Current pulses of simulated SSE signals

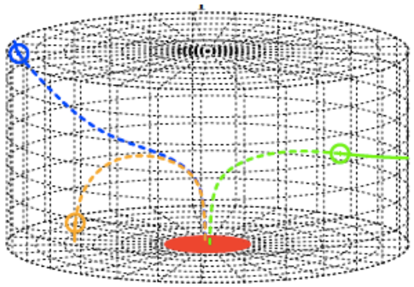
Coax

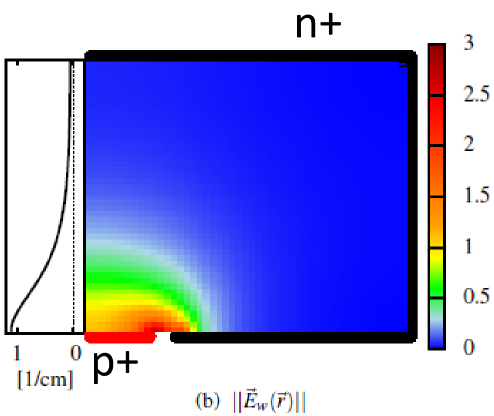


BEGe



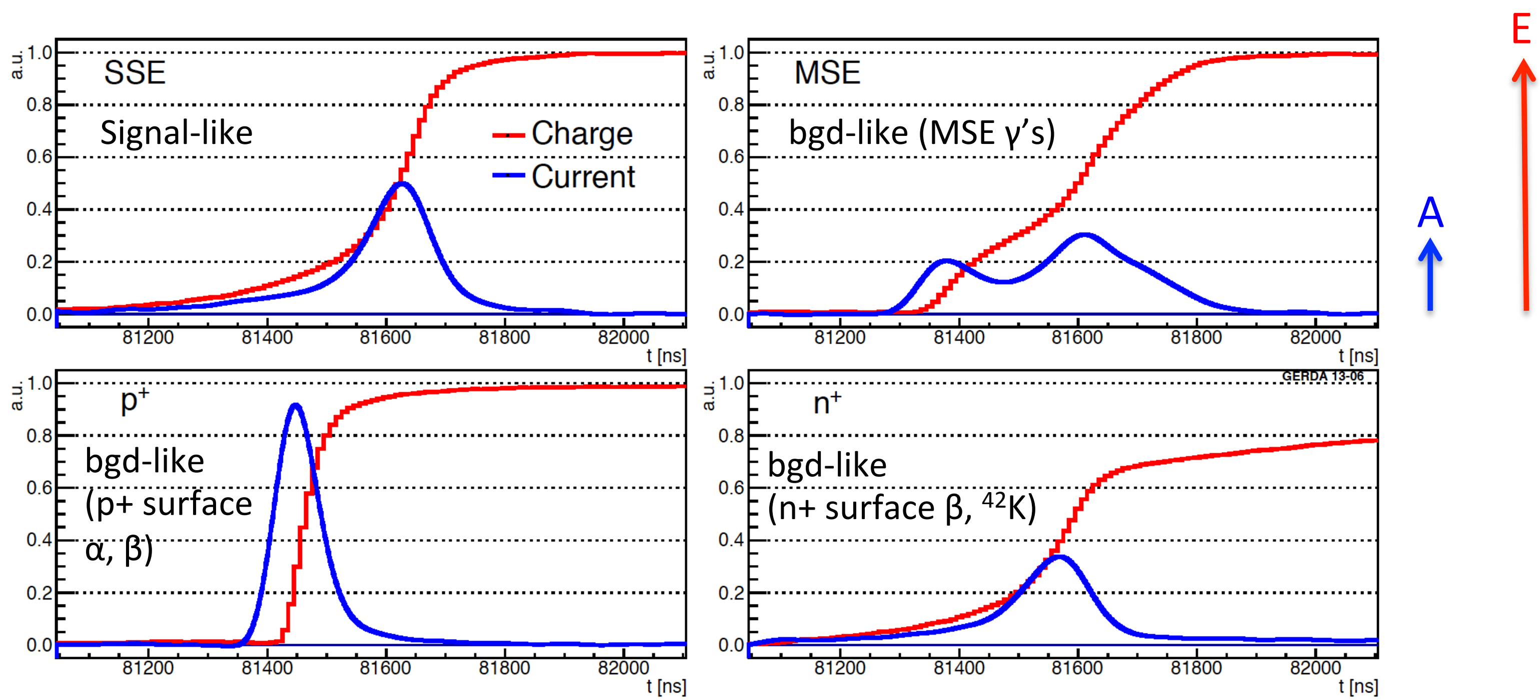
arXiv:1307.2610





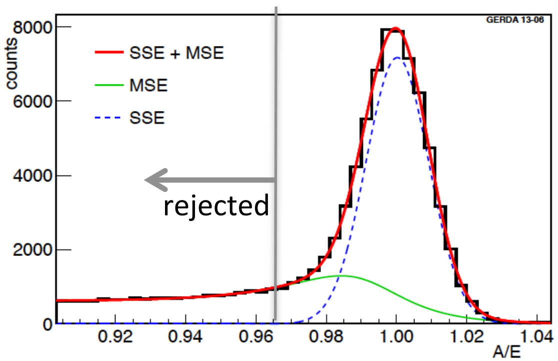
(b) $||\vec{E}_w(\vec{r})||$

PSD discrimination parameter: A/E

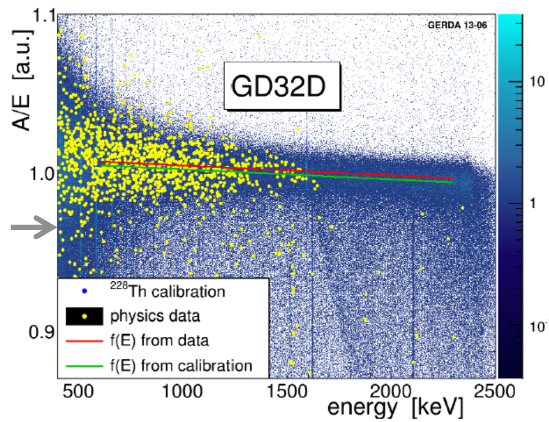


arXiv:1307.2610

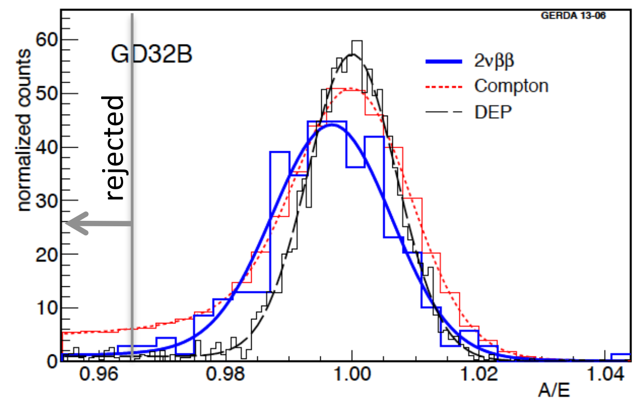
A/E of Compton continuum from calibration



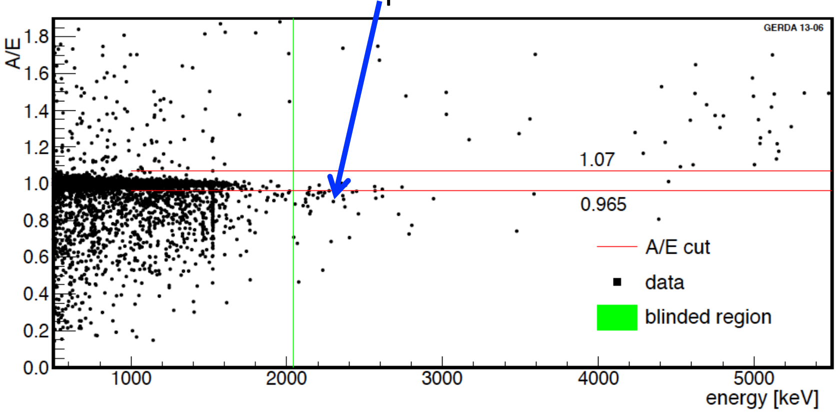
Energy dependence of A/E



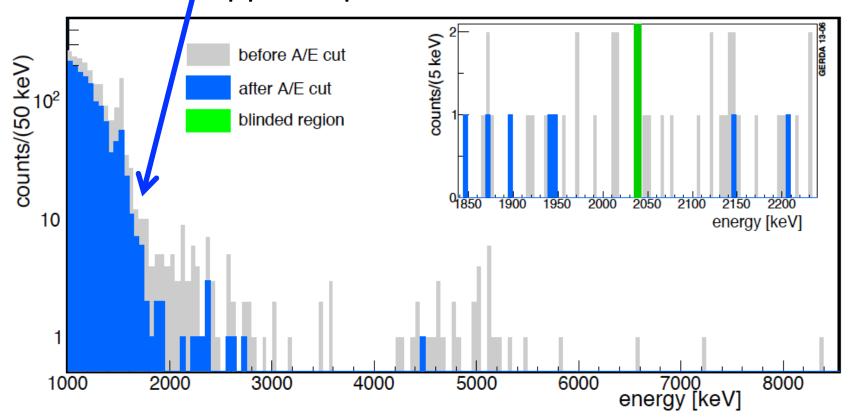
A/E for 2νββ, Compton (1-1.4 MeV), DEP (1592 keV)



^{42}K-β n+ surface dominated



2νββ acceptance: 0.91±0.05



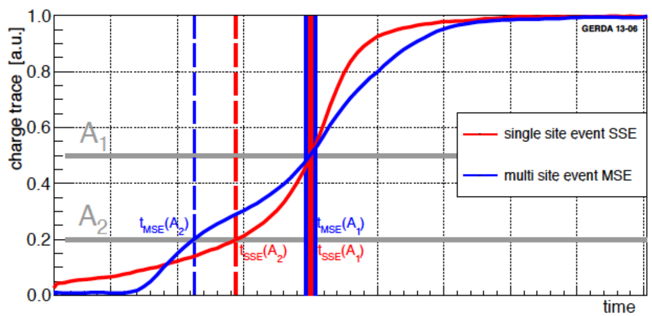
0νββ acceptance: 0.92±0.02

Pulse shape discrimination: Coax

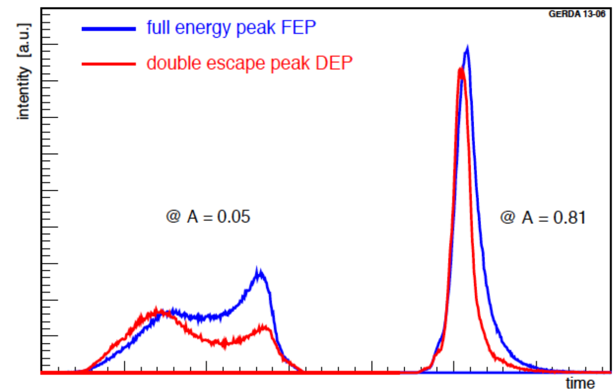
arXiv:1307.2610

ANN analysis of 50 rise time info (1,3,5,…99%) with TMVA / TMlpANN

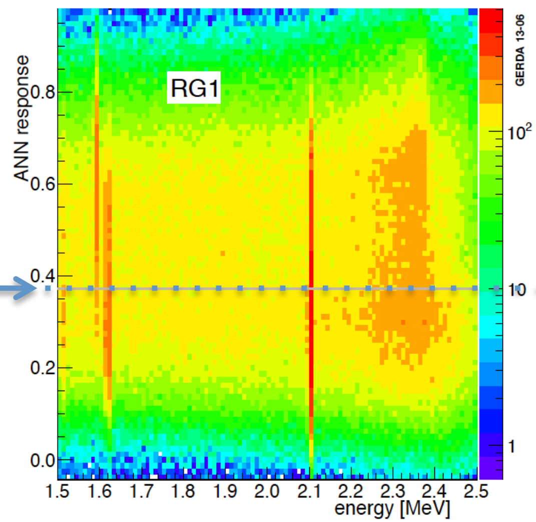
- SSE training with signal-like ^{208}Tl DEP events (1592 keV)
- MSE training with background-like ^{212}Bi FEP (1621 keV)



Distribution for 5 and 81% rise time

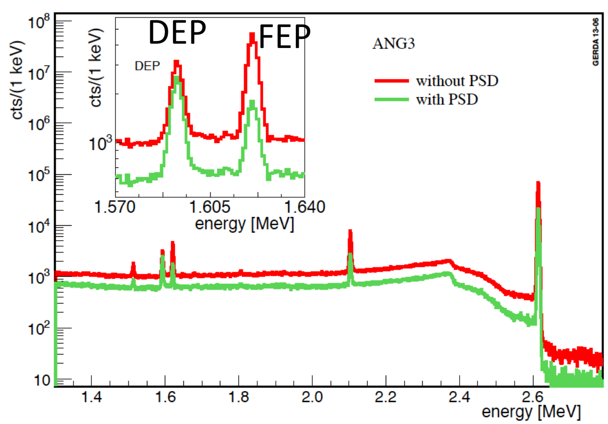


Cut adjusted for each detector to 90% DEP survival



SSE-like

MSE-like

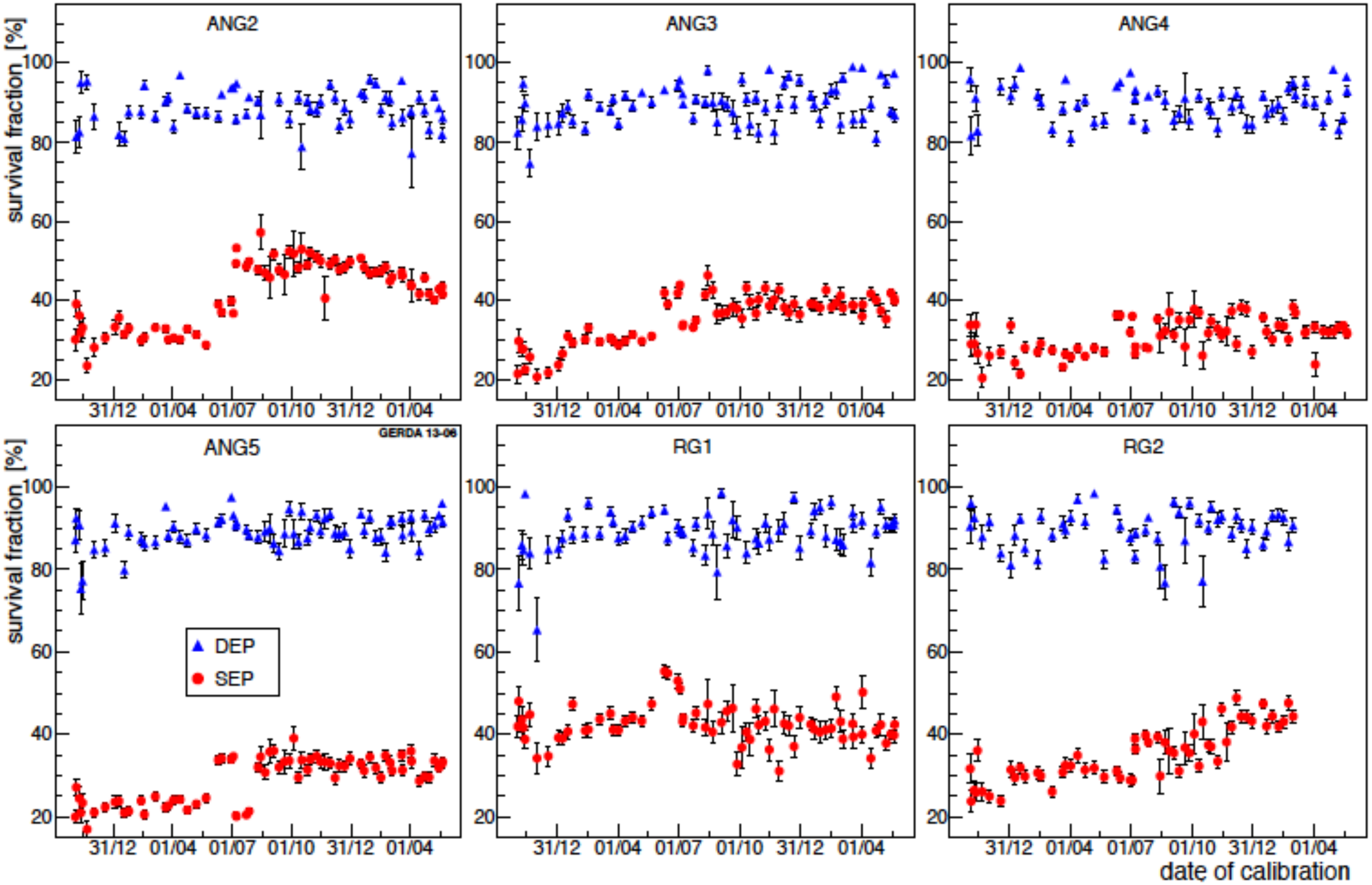


Pulse shape discrimination: Coax – survival fraction for Phase I

arXiv:1307.2610

Stability of survival fraction from calibration data

Y-axis suppressed:



DEP

SEP

DEP

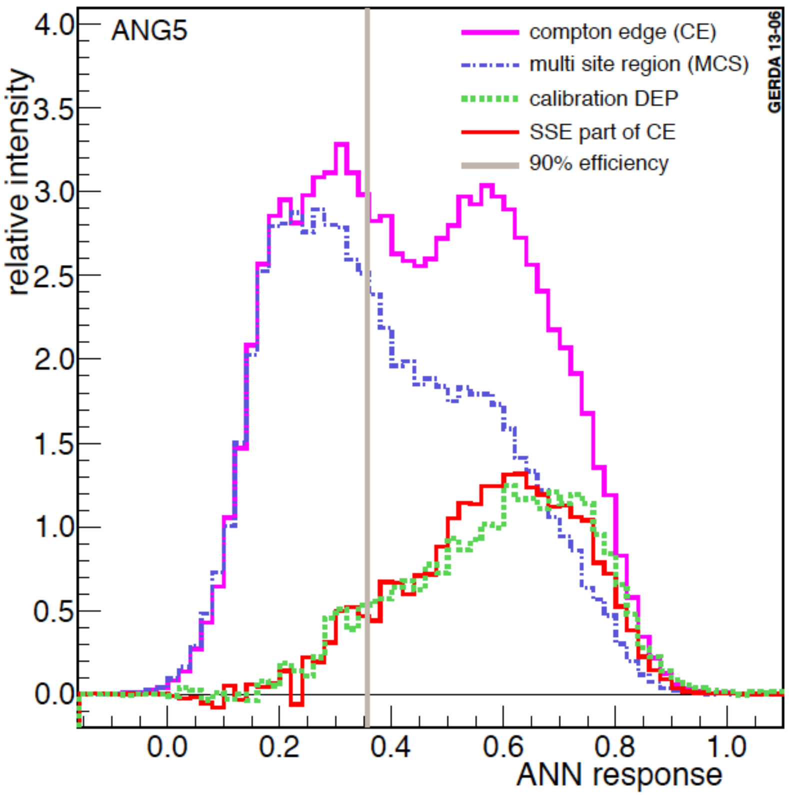
SEP

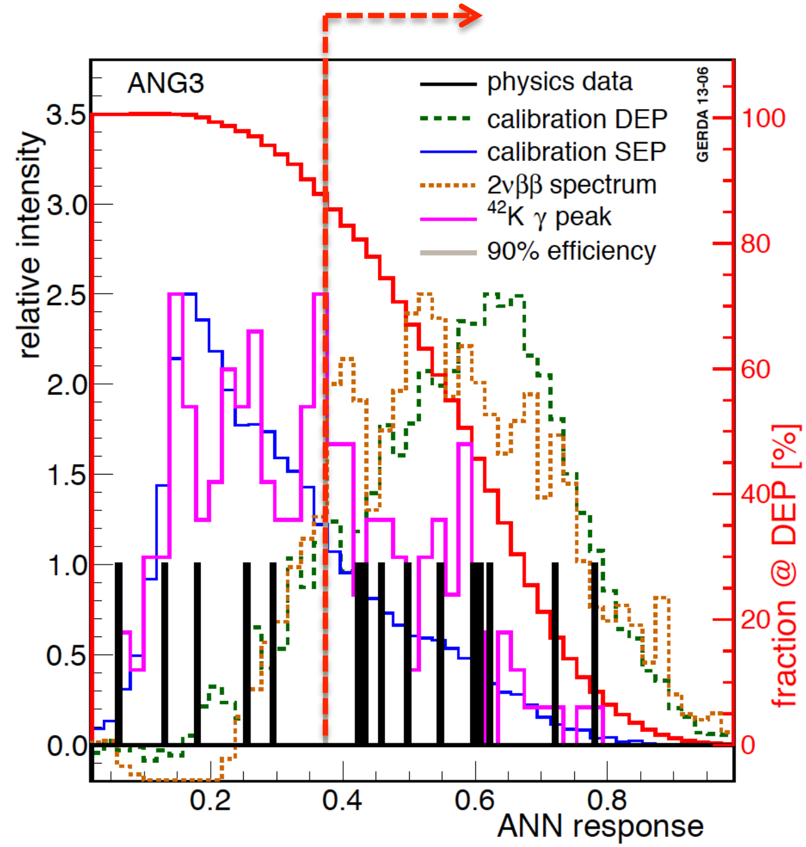
Data split in 3 periods: p1: Nov 11 – July 12, p2: July/Aug 12, p3: Aug 12-May 13

Pulse shape discrimination: Coax survival fraction for Phase I

arXiv:1307.2610

accepted as SSE-like

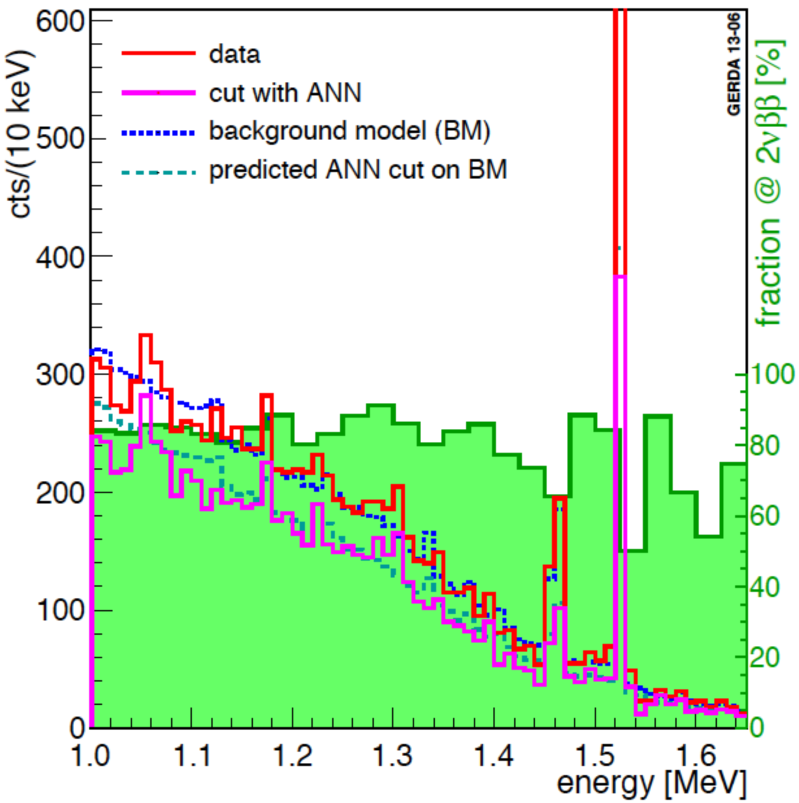




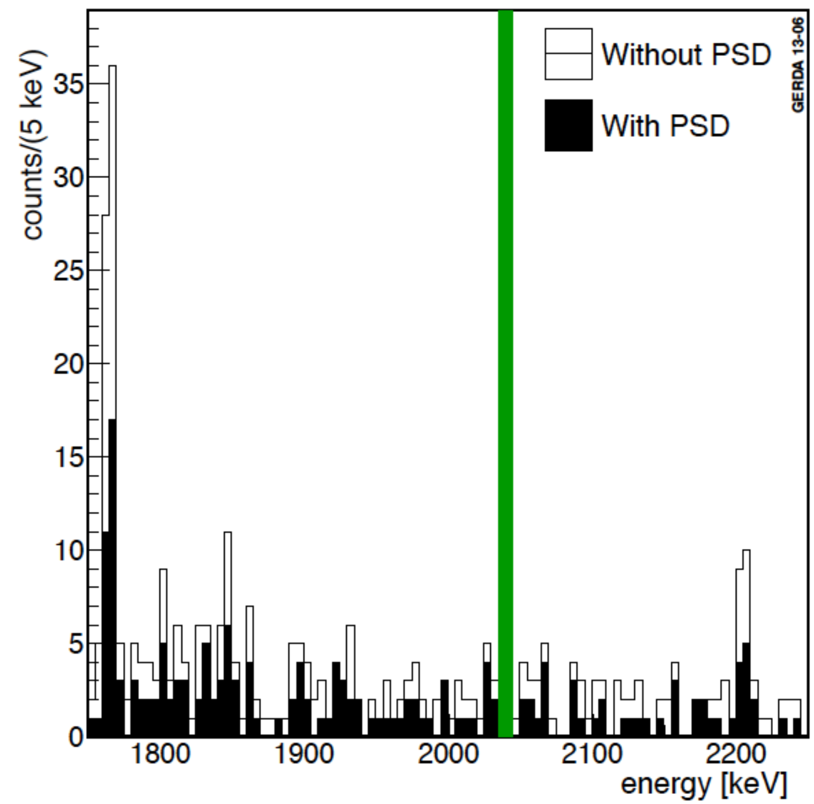
Pulse shape discrimination: Coax – survival fraction for Phase I

arXiv:1307.2610

PSD selection in 2νββ energy range



PSD selection in 0νββ energy range

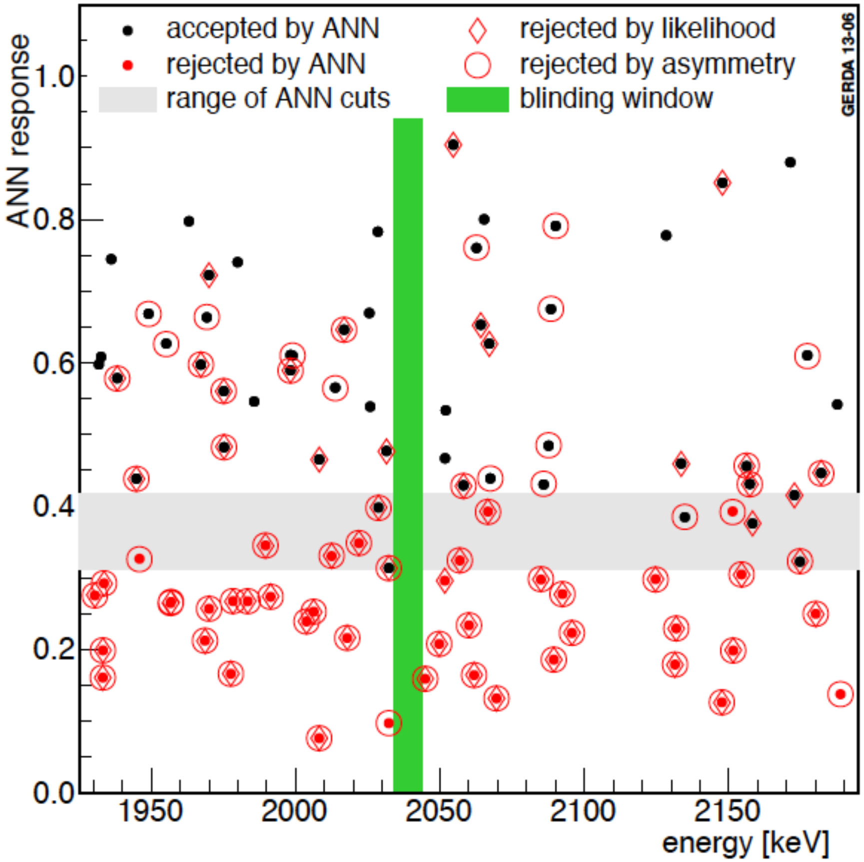


Measured 2νββ ANN survival: 0.85±0.02

Estimated 0νββ ANN survival: $0.90^{+0.05}_{-0.09}$

Pulse shape discrimination: Cross check w. independent methods

arXiv:1307.2610



- 90% of ANN signal-like events are also classified by both alternative methods as MSE
- 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

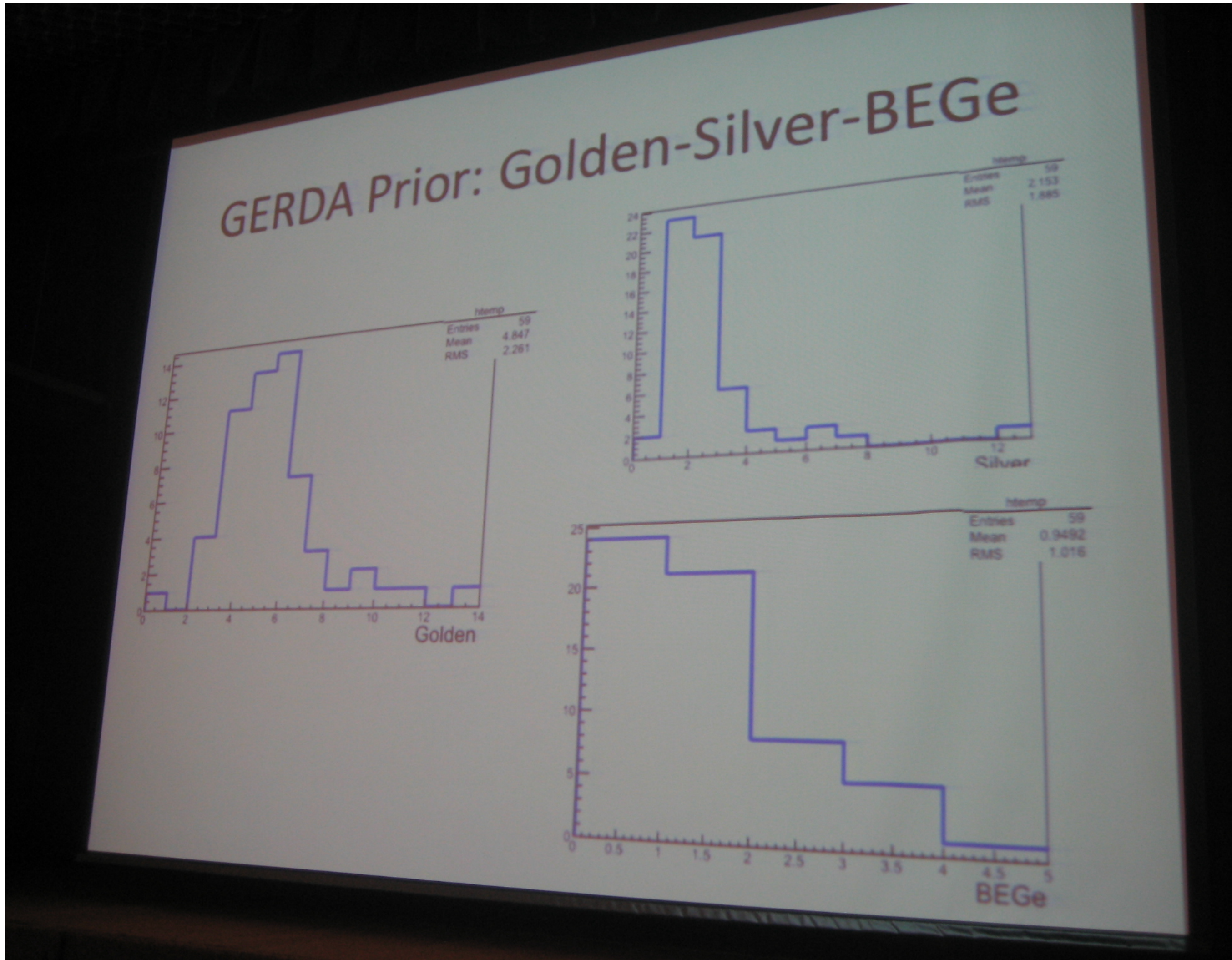
ANN selected for 0νββ analysis and cuts fixed prior to unblinding

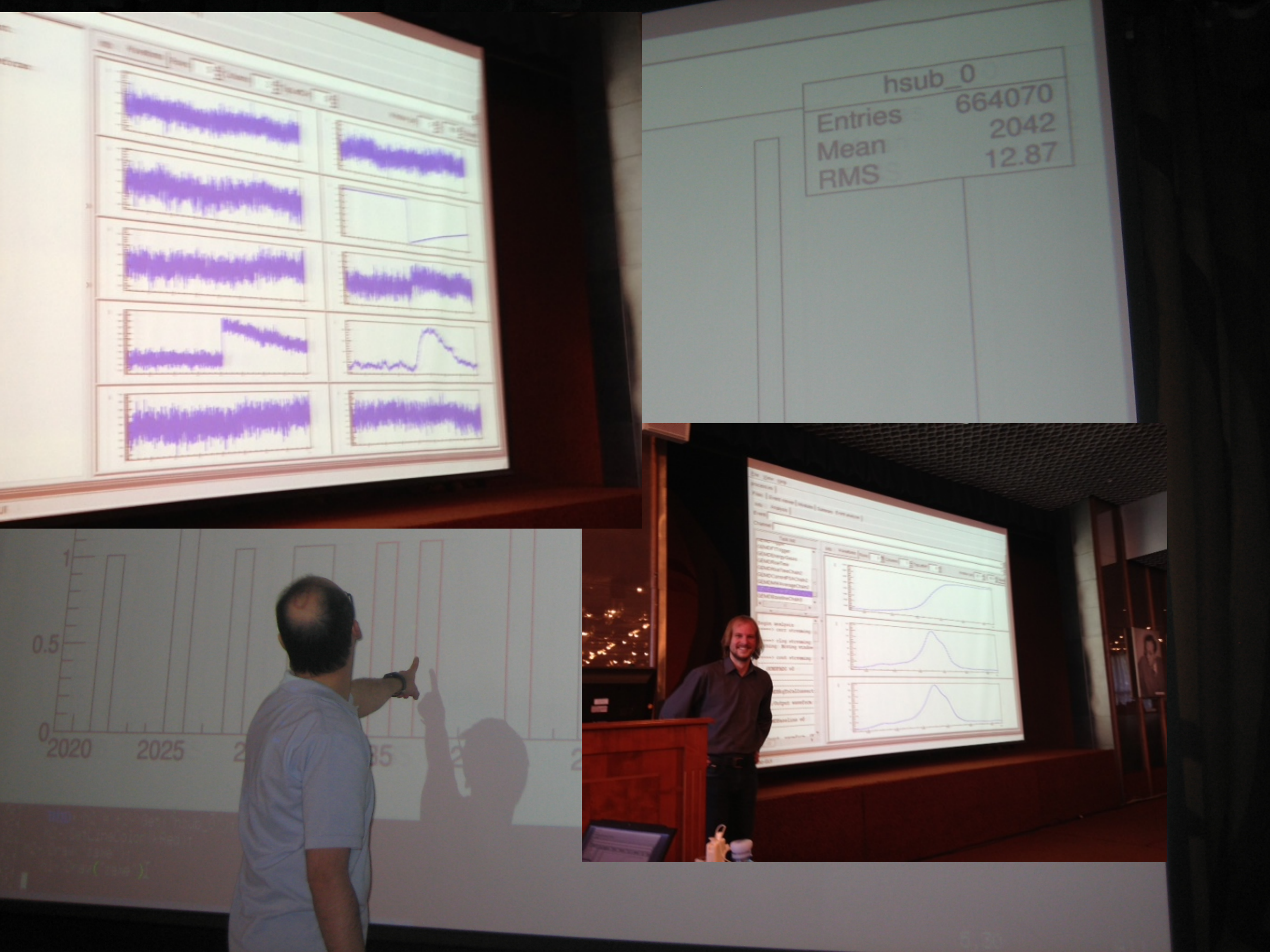
Unblinding at GERDA collaboration meeting in Dubna, June 12-14

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

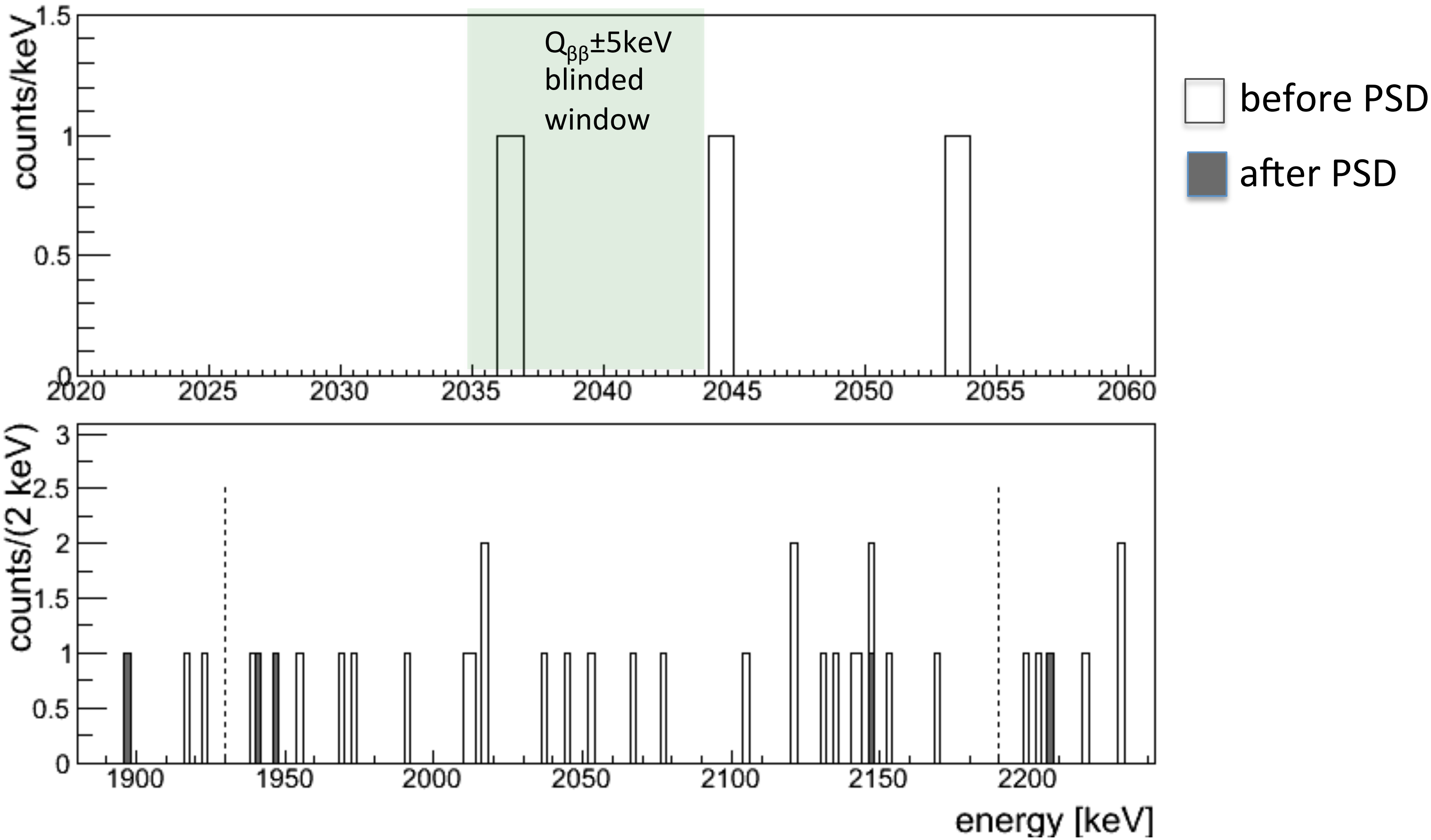
- 3 Data sets: golden, silver, BEGe
- Energy calibration method and parameters
- Unblind traces for PSD
- PSD method and cuts
- Statistical treatment of results:
- Likelihood fit of 3 indep. data sets ('global fit')
- Frequentist (constraint profile likelihood)
- Bayesian
- ....

Unblinding at Dubna: the bets of the collaboration



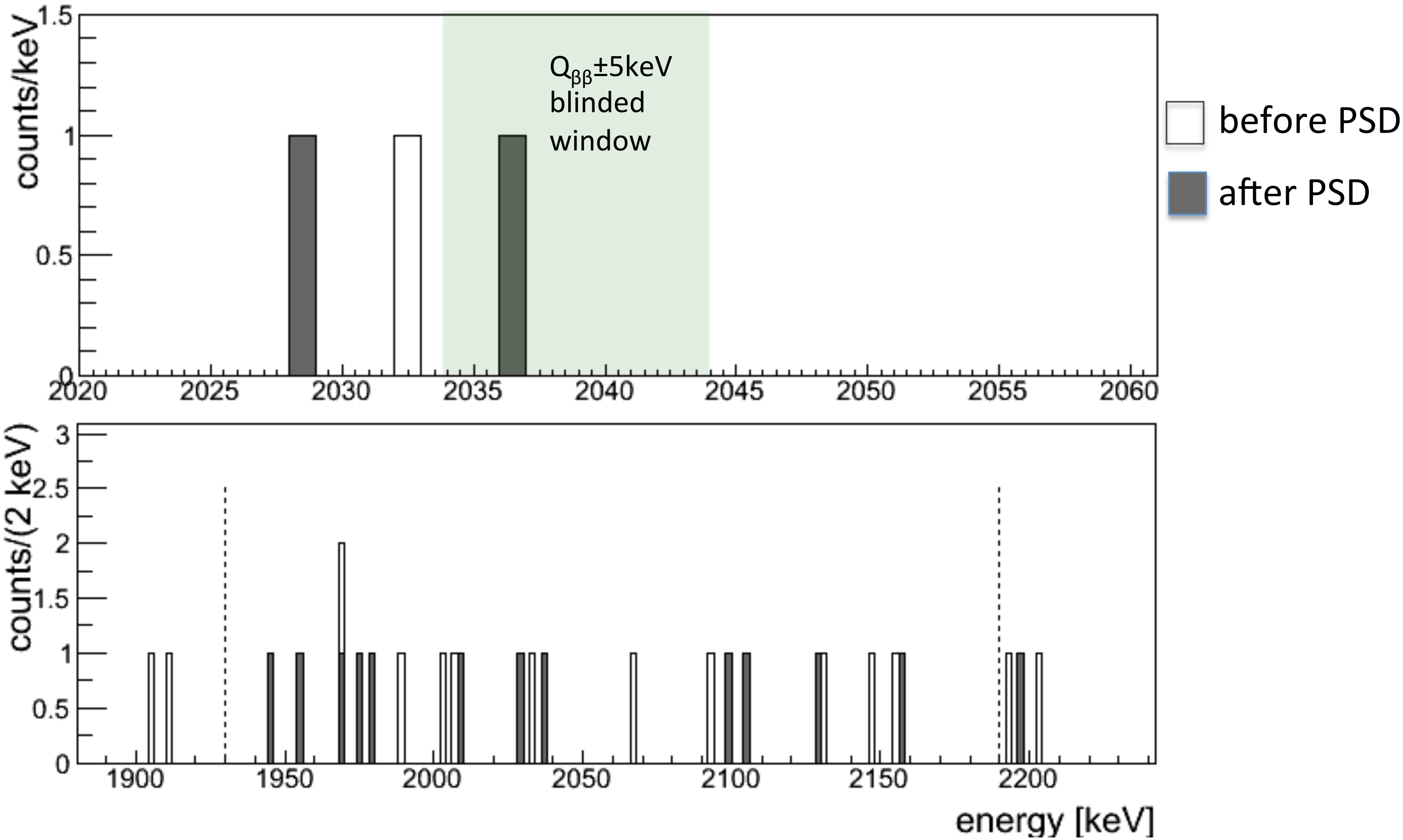

hsub_0
Entries 664070
Mean 2042
RMS 12.87
1
0.5
0
2020
2025

Unblinding: BEGe data set (2.4 kg yr)



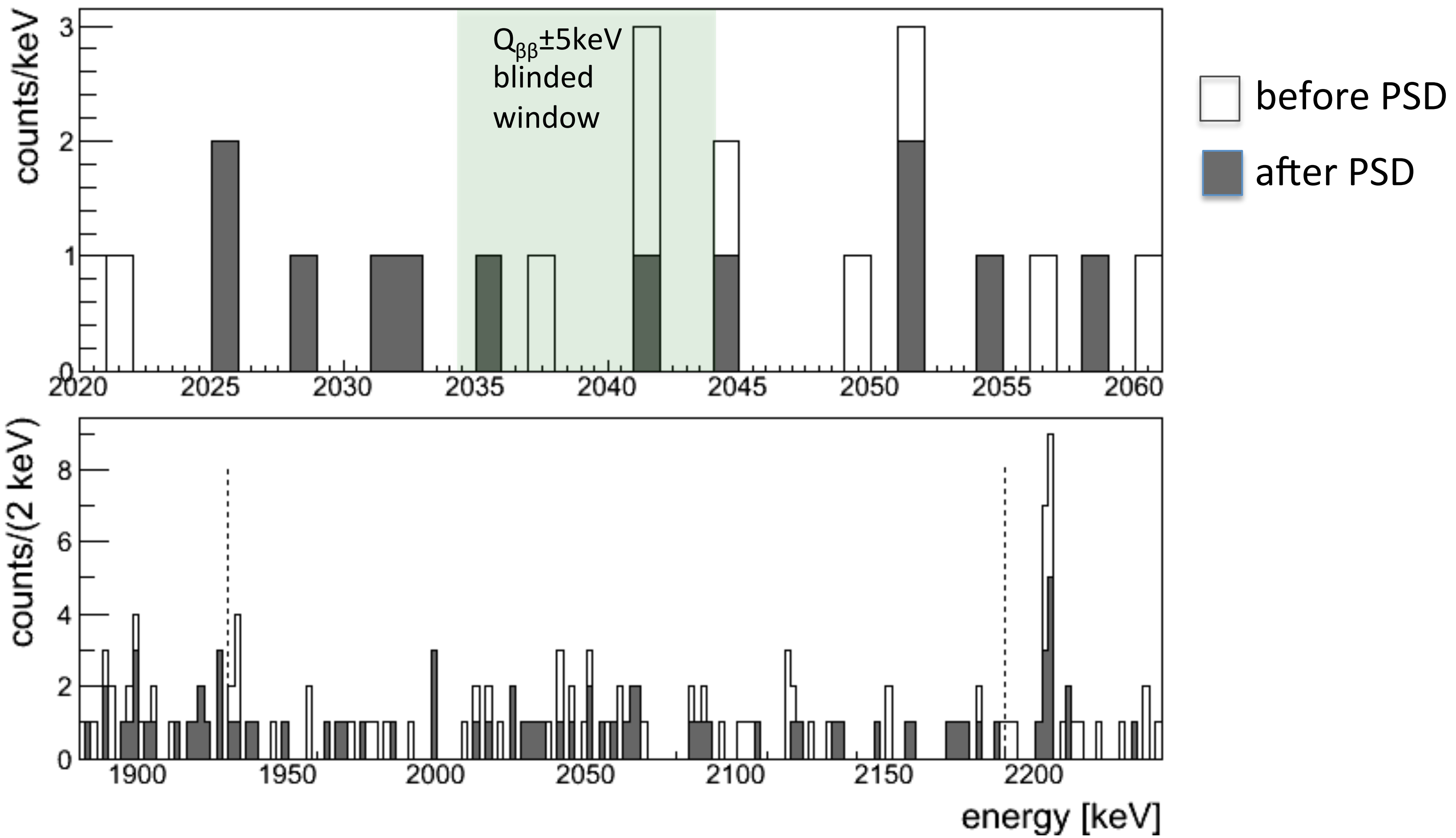
BEGe data set: 1 event in blinded window
0 event survive PSD cut

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



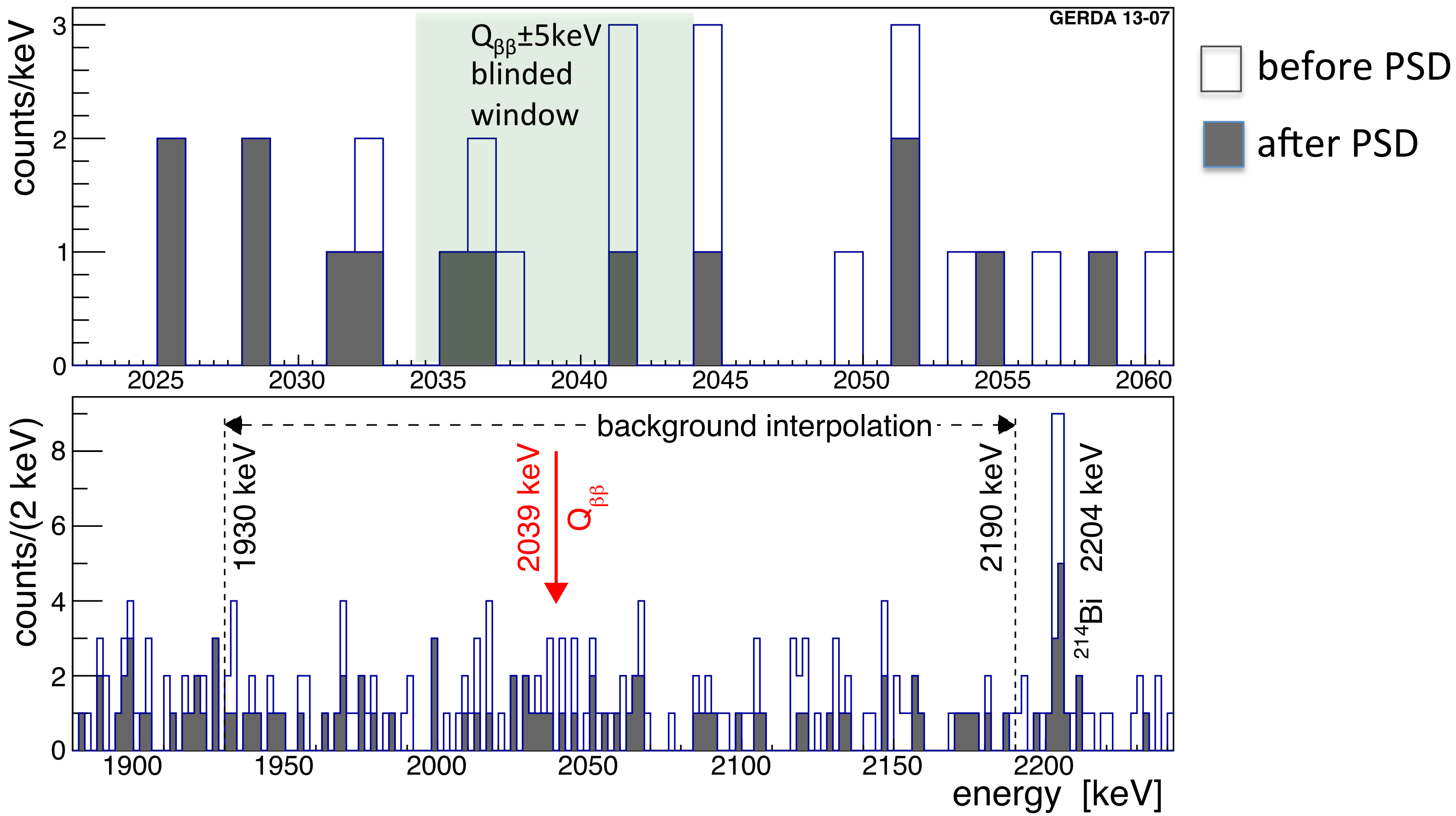
Silver data set: 1 event in blinded window
1 event survives PSD cut

Unblinding: golden-coax data set (17.9 kg yr)



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

Unblinding: full data set (21.6 kg yr)



Full data set:	7 event in blinded window
	3 event survive PSD cut

List of events in blinded window

Table 1: List of all events within $Q_{\beta\beta} \pm 5$ keV

data set	detector	energy [keV]	date	PSD passed	ANN	A/E	Cut Threshold
golden	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
silver	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
golden	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
BEGe	GD32B	2036.6	28-Dec-2012 09:50	no		0.750	0.965÷1.070
golden	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
golden	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
golden	RG 1	2041.7	27-Apr-2013 22:21	no	0.369		0.372

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	$18{\pm}2$	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	$11{\pm}2$	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

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

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

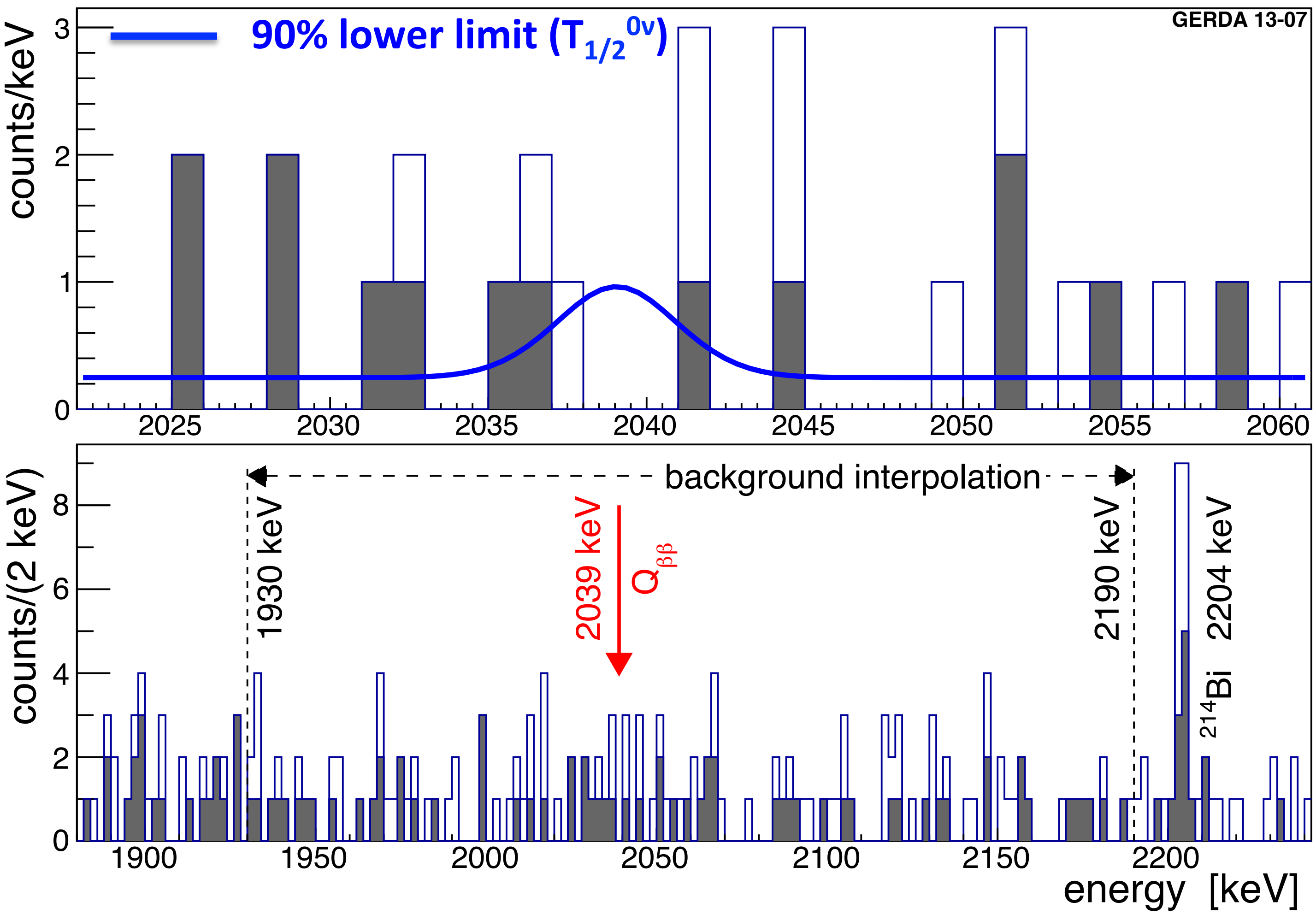
N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

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

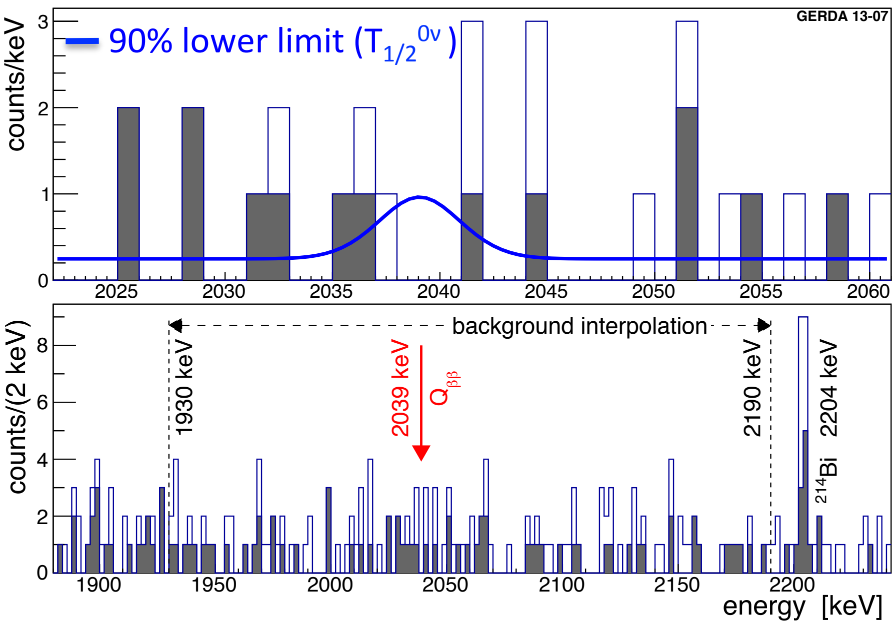
Data set	**Exposure (kg yr)**
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$\langle f_{76} \rangle$	$\langle f_{av} \rangle$	$\langle \varepsilon_{fep} \rangle$	$\langle \varepsilon_{psd} \rangle$	$\langle \varepsilon \rangle$
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

Profile likelihood fit to full data set (21.6 kg yr)



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	+0.05/-0.09
	BEGe	0.92	0.02

Frequentist limit:

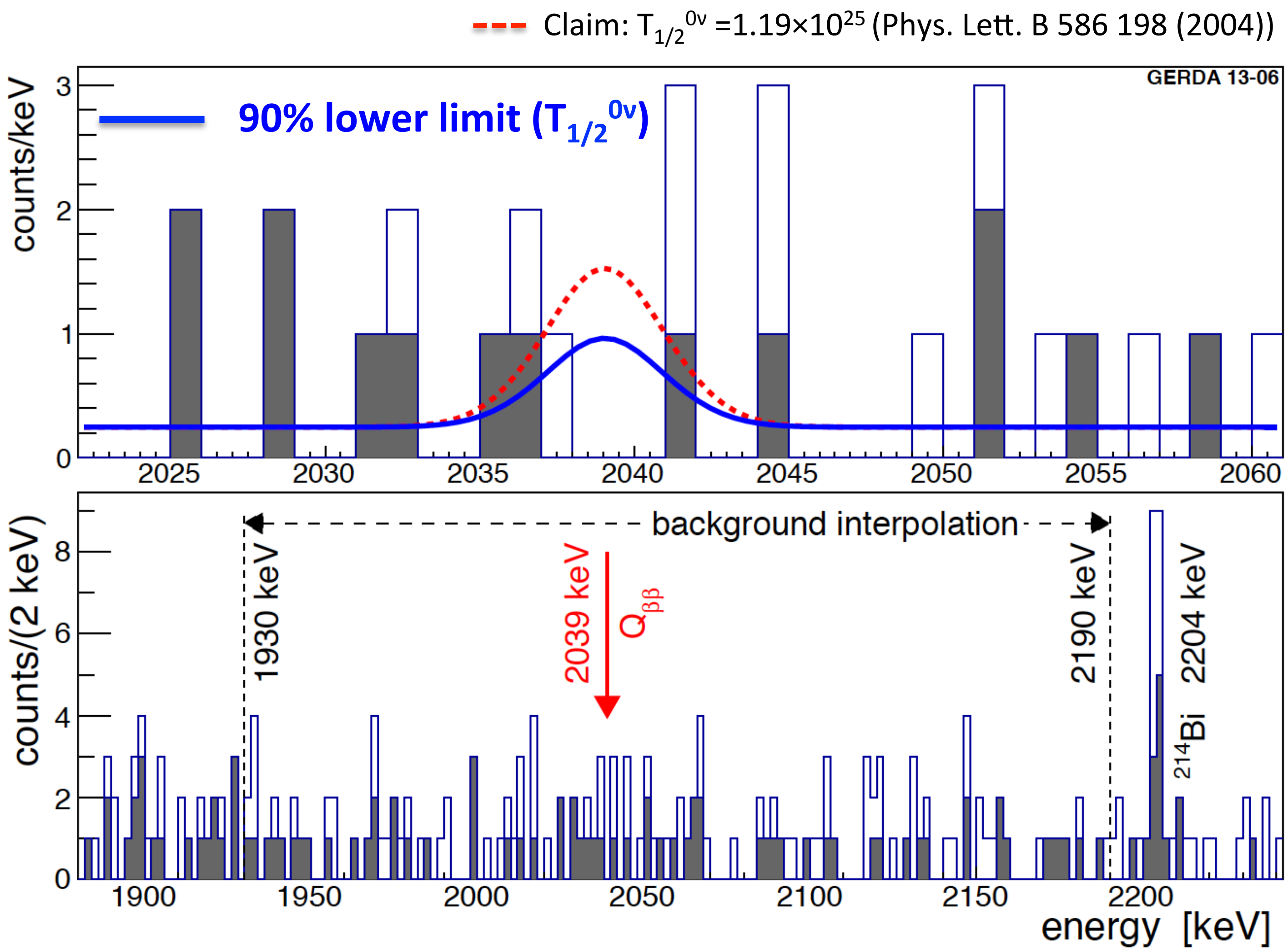
- 90% lower limit derived from profile likelihood fit to 3 data sets (constraint to physical 1/T range; excluding known γ-lines from bgd model at 2104±5 and 2119±5 keV)
- Best fit: **$N^{0\nu}$=0**
- **No excess** of signal counts above the background
- 90% C.L. lower l $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr
- Limit on half-life corresponds to $N^{0\nu}$<3.5 cts
- 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: $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: (90% C.I.): >2.0×10^{25} yr

Systematics folded: limit weakened by 1.5%

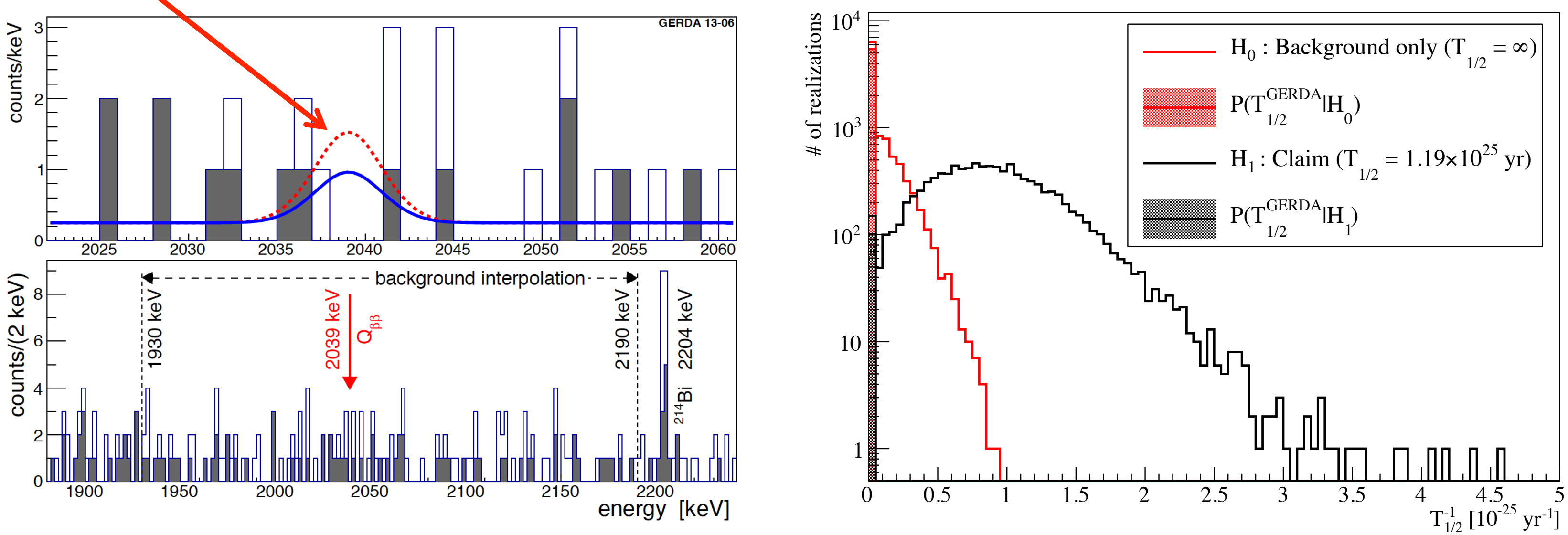
Comparison with Phys. Lett. B 586 198 (2004) claim



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 plus background

H0: background only

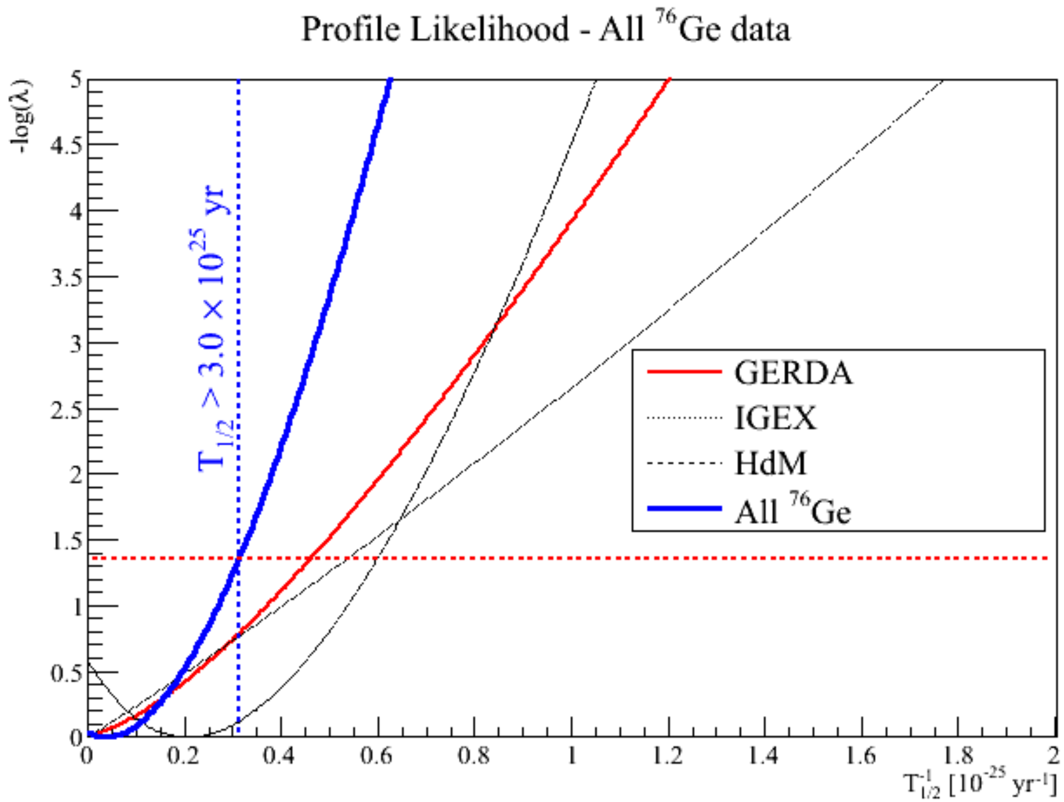
Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood

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

➔Claim refuted with high probability

Combined analysis with HdM and IGEX experiments



HdM: Eur. Phys. J. A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002), Phys. Rev. D 70 078302 (2004)

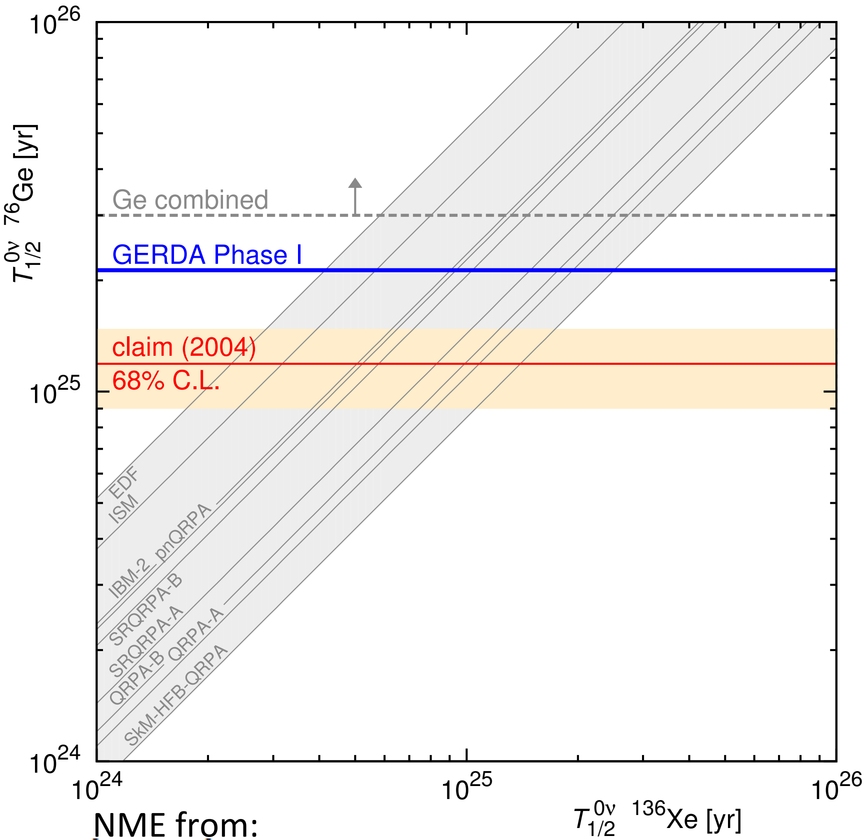
$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25} \text{ yr} \quad (90\,\% \text{ C.L.})$$

Identical limits with Frequentists & Bayesian analysis

Bayes Factor: P(H1)/P(H0)=2×10^{-4} strongly disfavors claim

Comparison is independent of NME and of physical mechanism which generates 0νββ

The claim: global picture

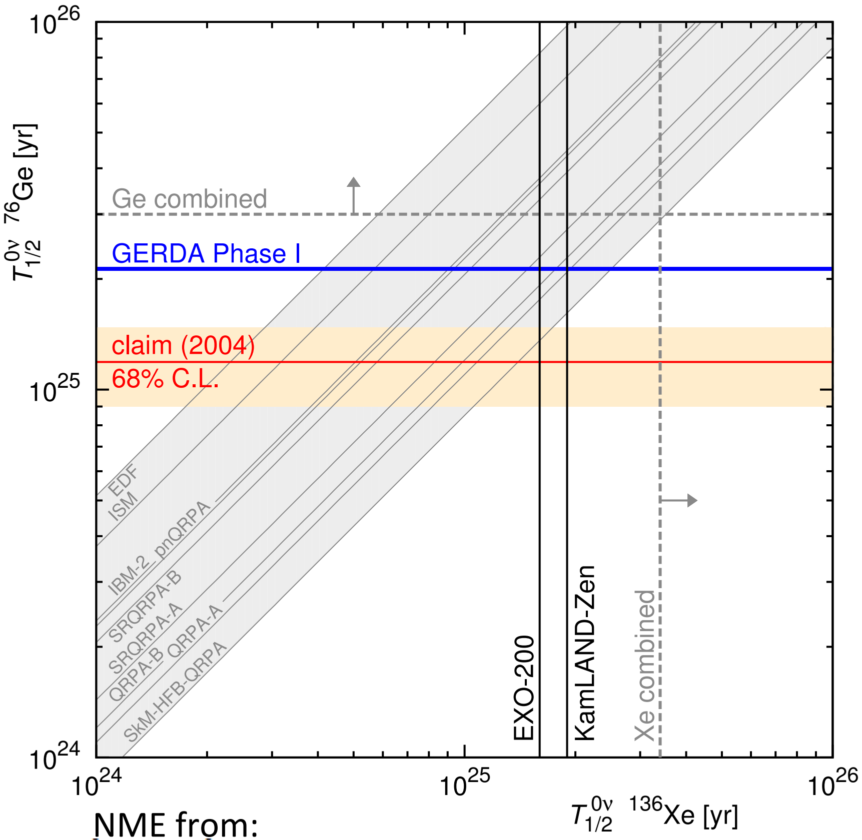


NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

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

H1: signal with $T_{1/2}^{0\nu} = 1.19\times10^{25}$ 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



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

H1: signal with $T_{1/2}^{0\nu}$ =1.19×10^{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
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

*:weakest exclusion using smallest NME ratio $M_{0\nu}(^{136}Xe)/M_{0\nu}(^{76}Ge)$ ≈0.4 from:

F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C. **87**, 045501 (2013).
M. T. Mustonen and J. Engel, (2013), arXiv:1301.6997 [nucl-th].
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056 [hep-ph].

- **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.) ($\langle m_{ee}\rangle < 0.2$-$0.4$ eV)

- Results reached after only 21.6 kg yr exposure because of **unprecedented low background:** bgd expectations in ±2σ after analysis cuts and correcting for efficiencies: 0.01 cts /(mol yr) (cf. EXO: 0.07, KL: 0.2)

- **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