

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



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



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. Budjás,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. Lubsandorzhiyev,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. Zuzel²

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*

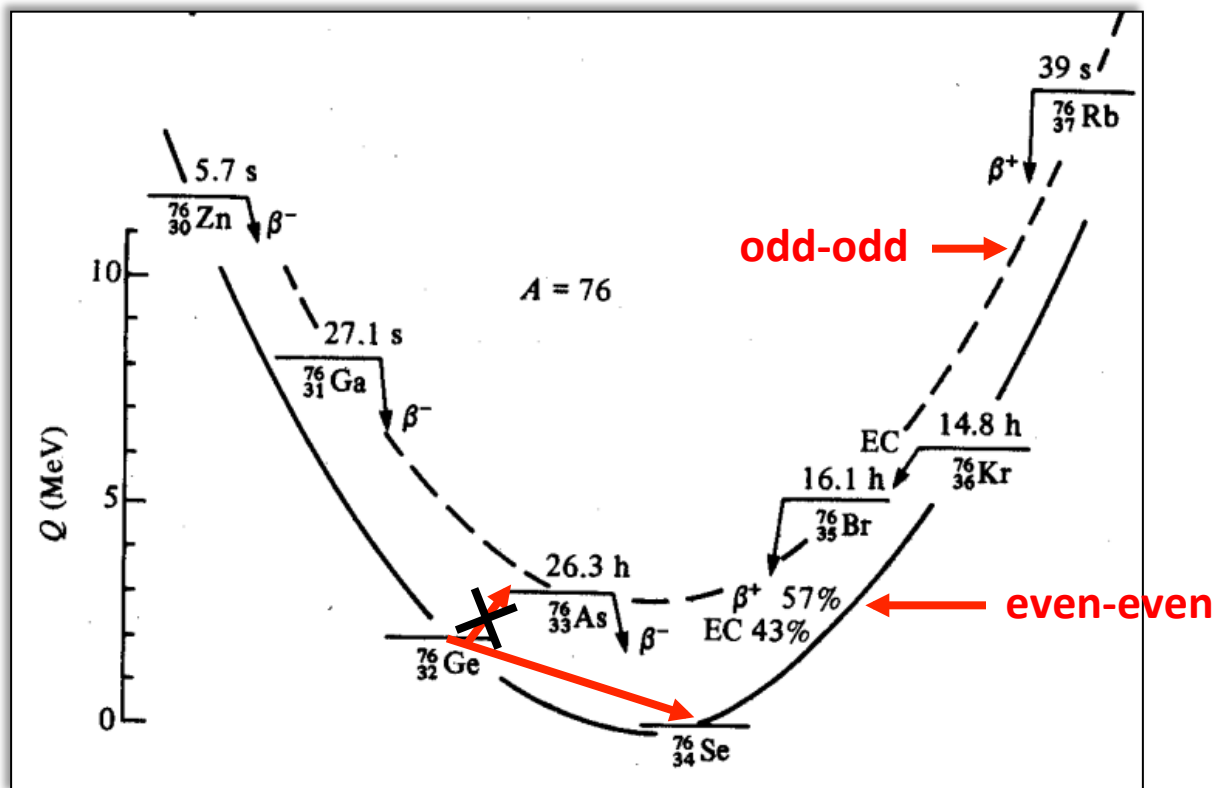
¹⁵*Dipartimento di Fisica e Astronomia dell'Università di Padova, Padova, Italy*

¹⁶*INFN Padova, Padova, Italy*

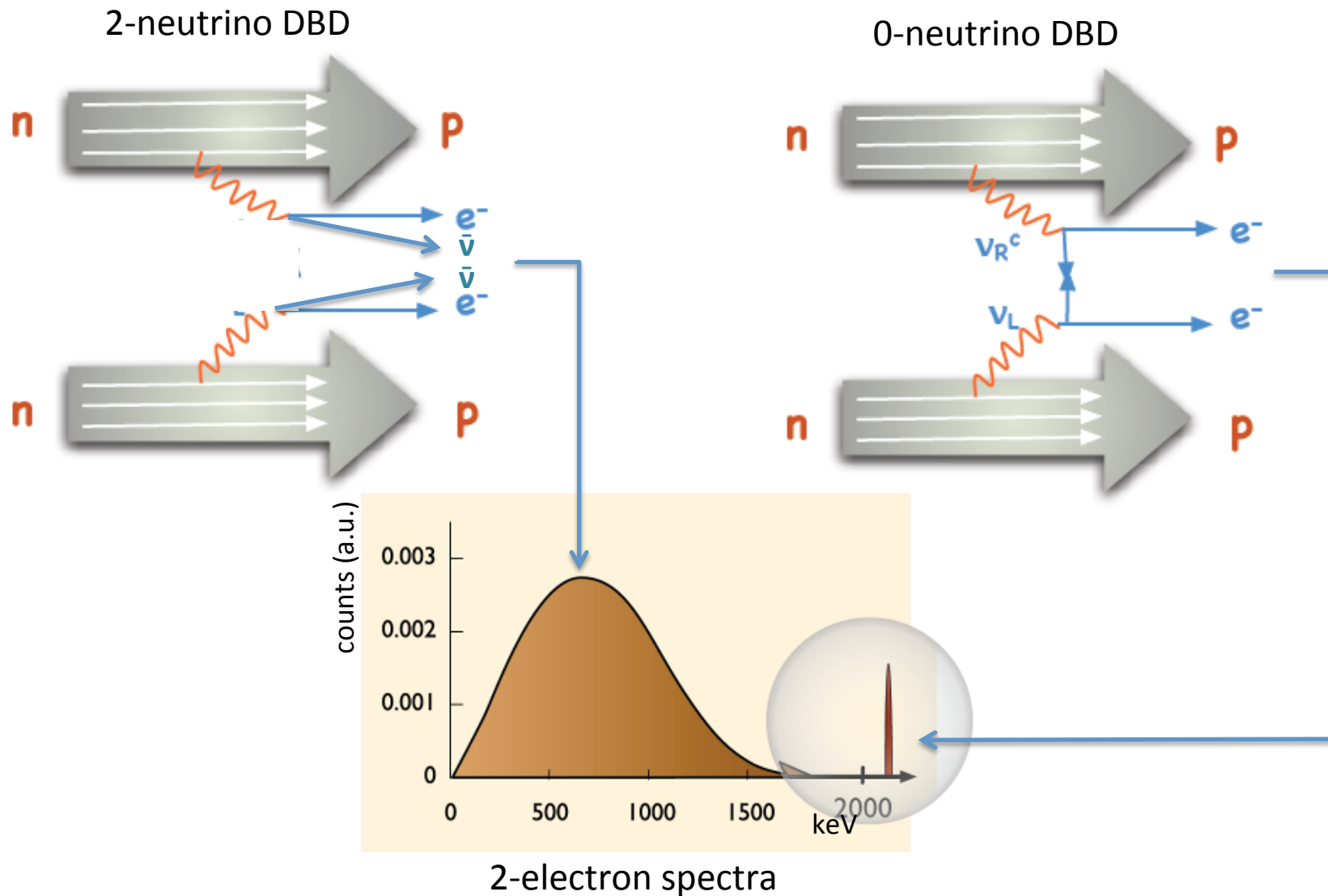
¹⁷*Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany*

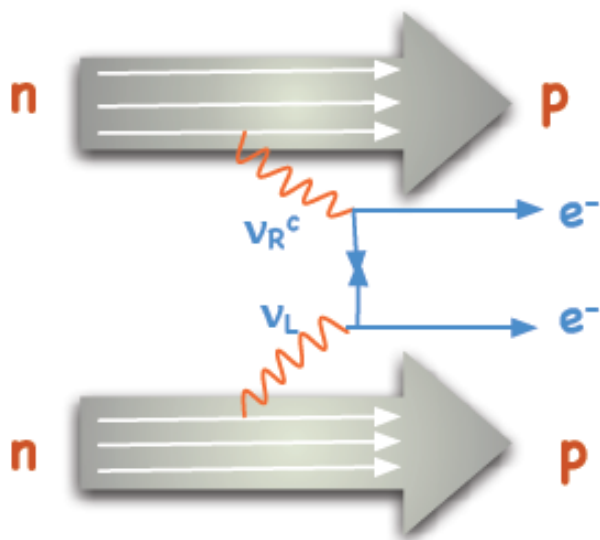
¹⁸*Physik Institut der Universität Zürich, Zürich, Switzerland*

~ 100 members
19 institutions
6 countries



$$Q_{\beta\beta} = 2039.01(5) \text{ keV}$$





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

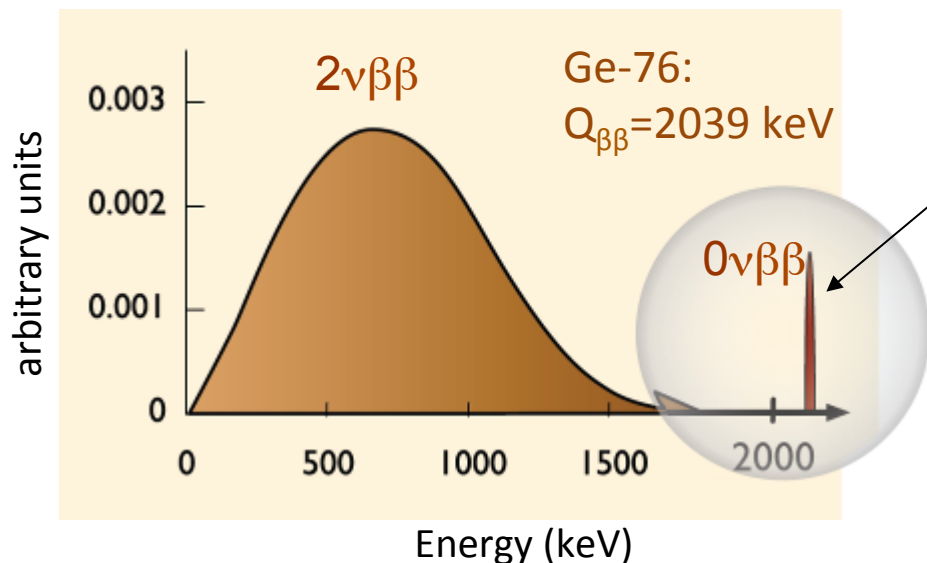
Nuclear matrix element

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

Effective neutrino mass

U_{ei}

Elements of (complex) PMNS mixing matrix

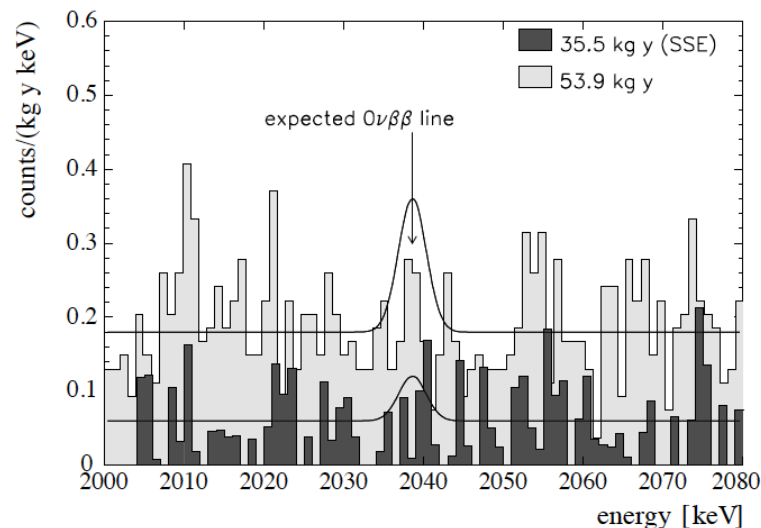


Experimental signatures:

- 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

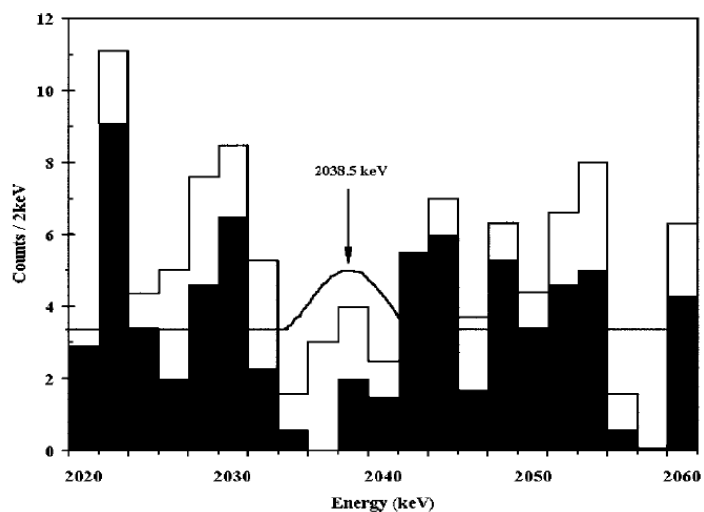


Heidelberg-Moscow

(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.)

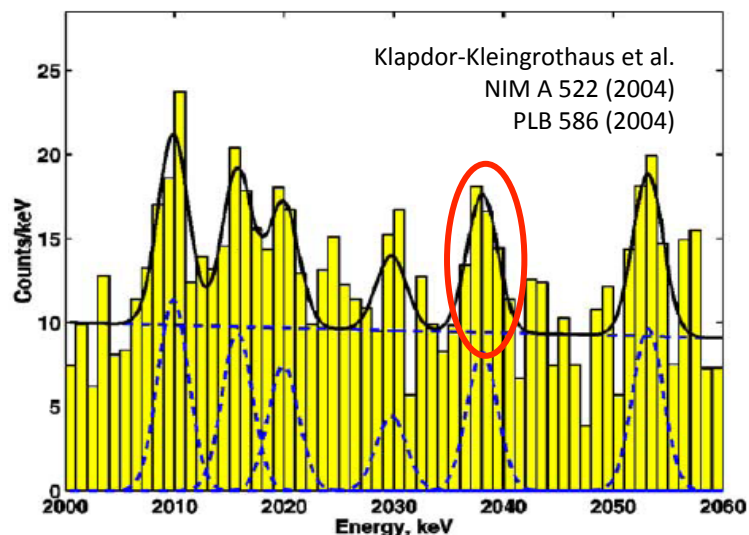


IGEX

(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.)



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 $0\nu\beta\beta$
- reported $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

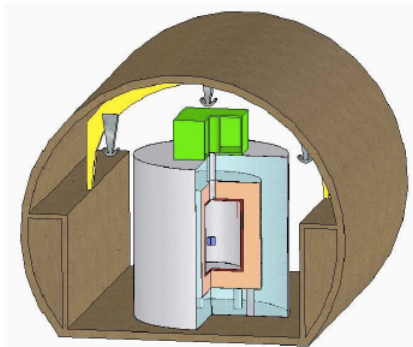


N.B. Half-life $T_{1/2}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/2}$ after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

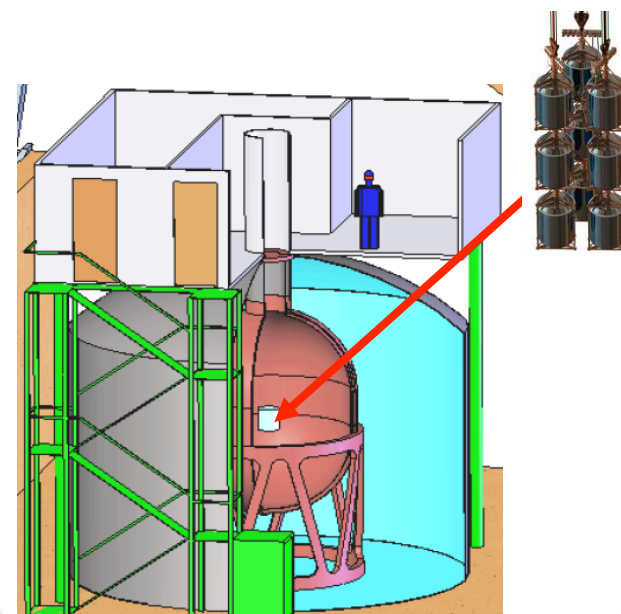
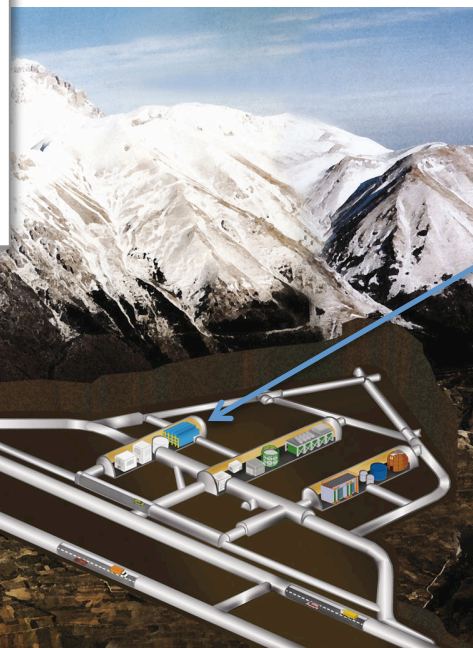
- reported half-life can be reconstructed only (Ref. 1) with $\epsilon_{\text{psd}} = 1$ (previous similar analysis $\epsilon_{\text{psd}} \approx 0.6$)
- $\epsilon_{\text{fep}} = 1$ (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\epsilon_{\text{fep}} = 0.9$))

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

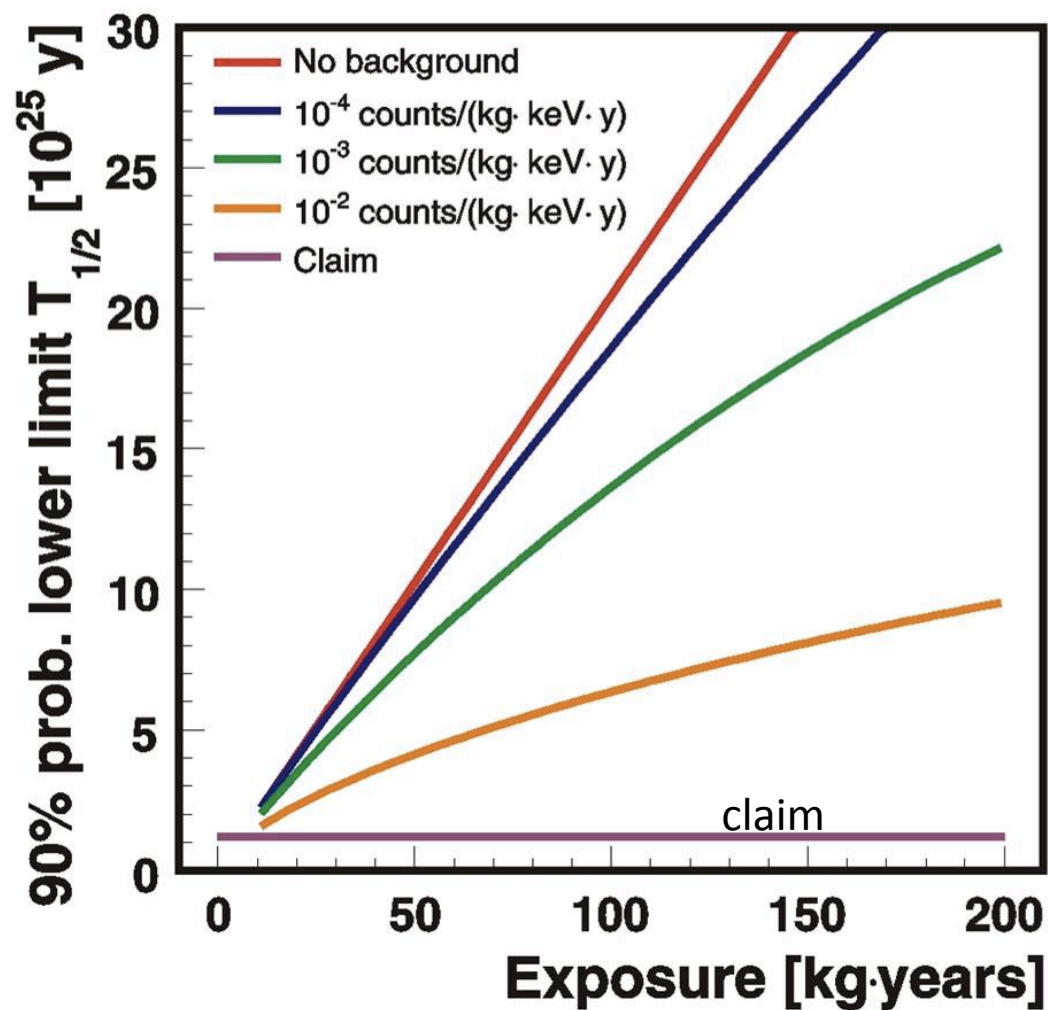
A New ^{70}Ge Double Beta Decay Experiment at LNGS

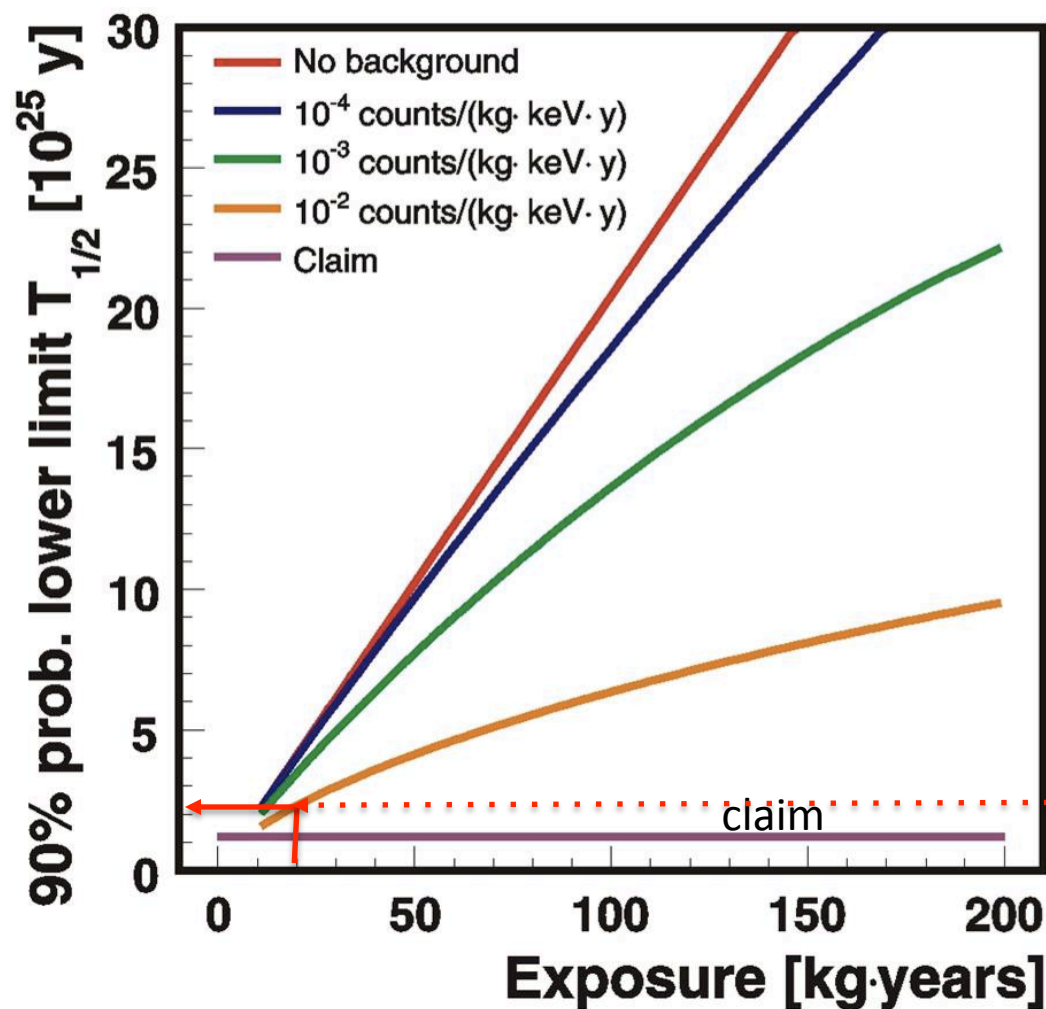


Letter of Intent



- 'Bare' ^{70}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



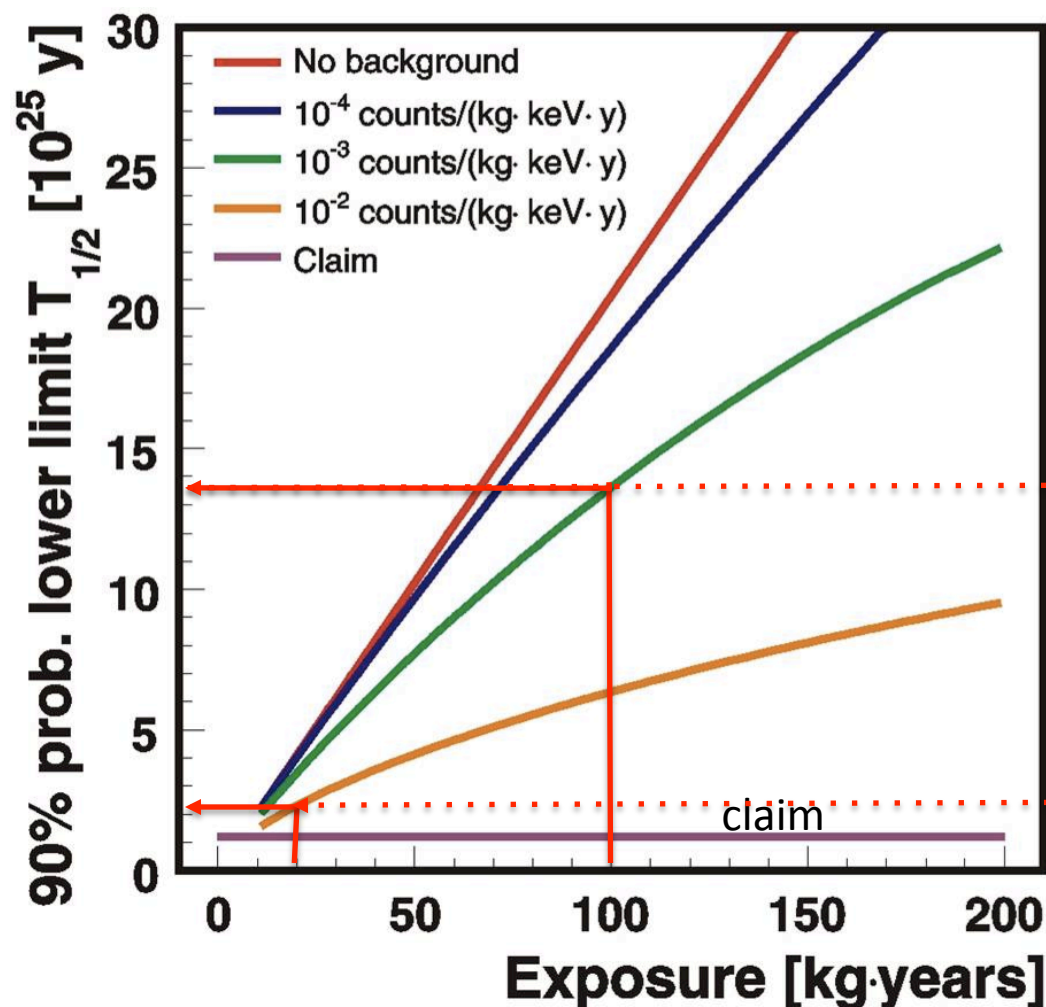


Phase I:

Use refurbished HdM & IGEX (18 kg)

BI $\approx$ 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

plastic μ -veto

clean room with lock

muon & cryogenic
infrastructure

cryostat, Ø4m,
with internal
Cu shield

control rooms

Ge-detector array
(enriched in ^{76}Ge)

water plant &
radon monitor

water tank, Ø10m,
part of muon-veto detector

Phase I detectors: semi-coaxial detectors

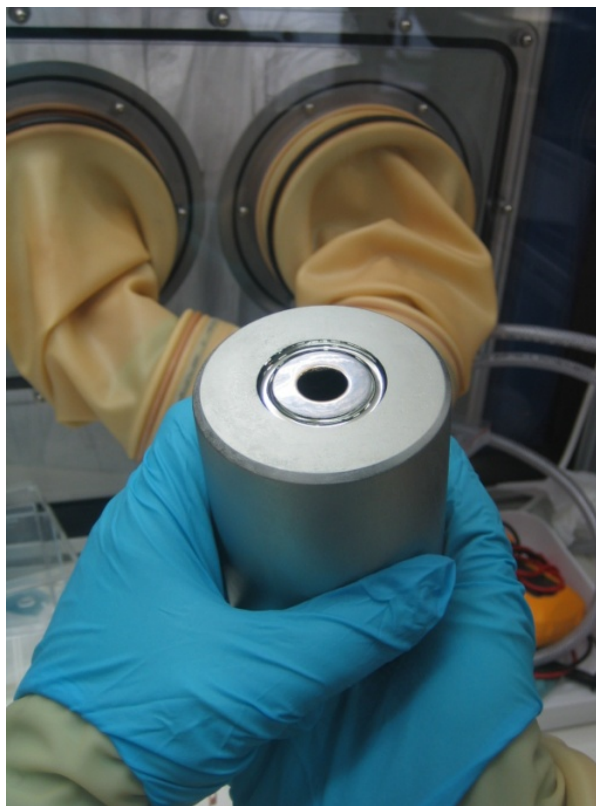
Eur. Phys. J. C (2013) 73:2330
[arXiv:1212.4067](https://arxiv.org/abs/1212.4067)



- 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):

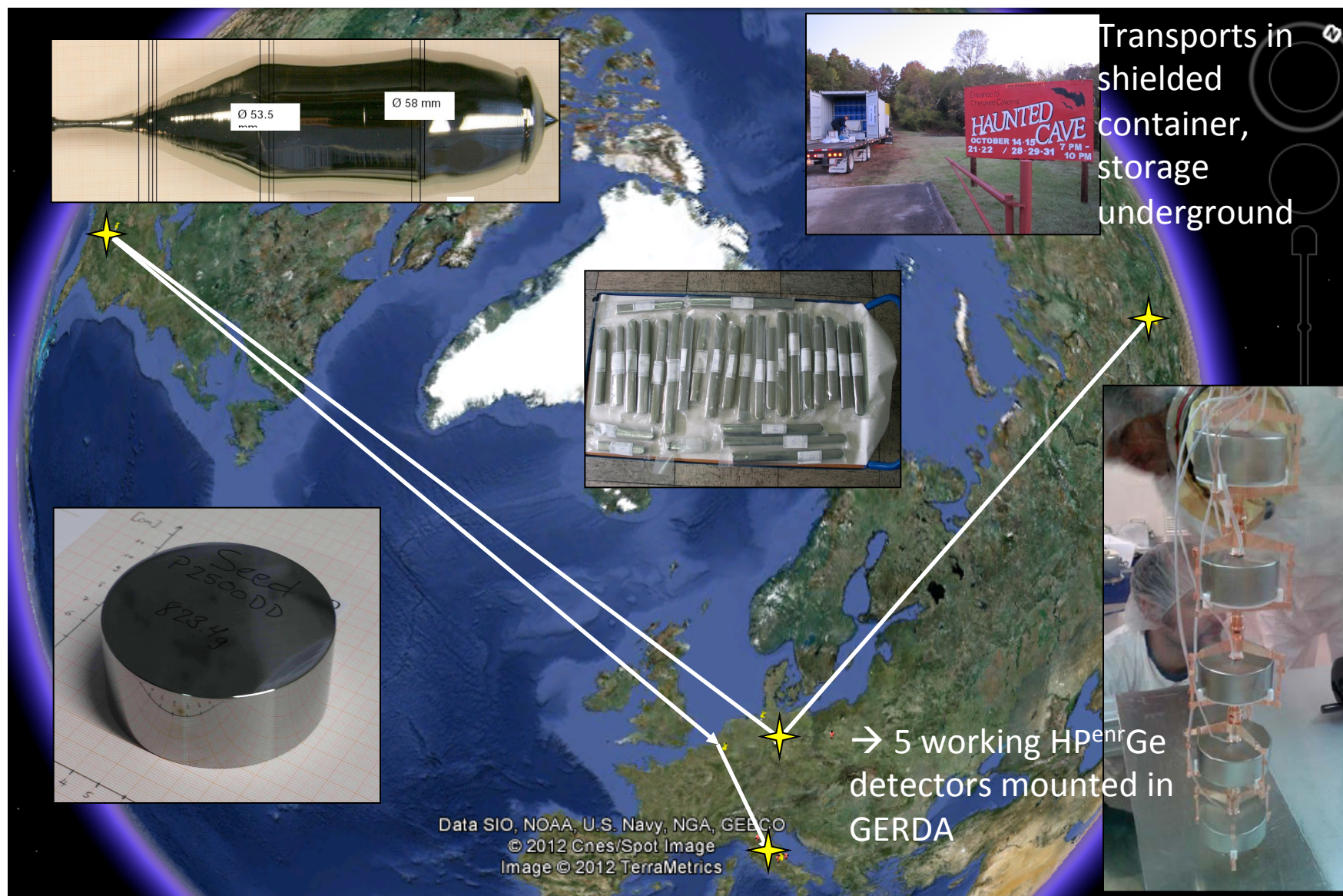
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



6 diodes from Genius-TF:

- natGe
- Total mass: 15.60 kg

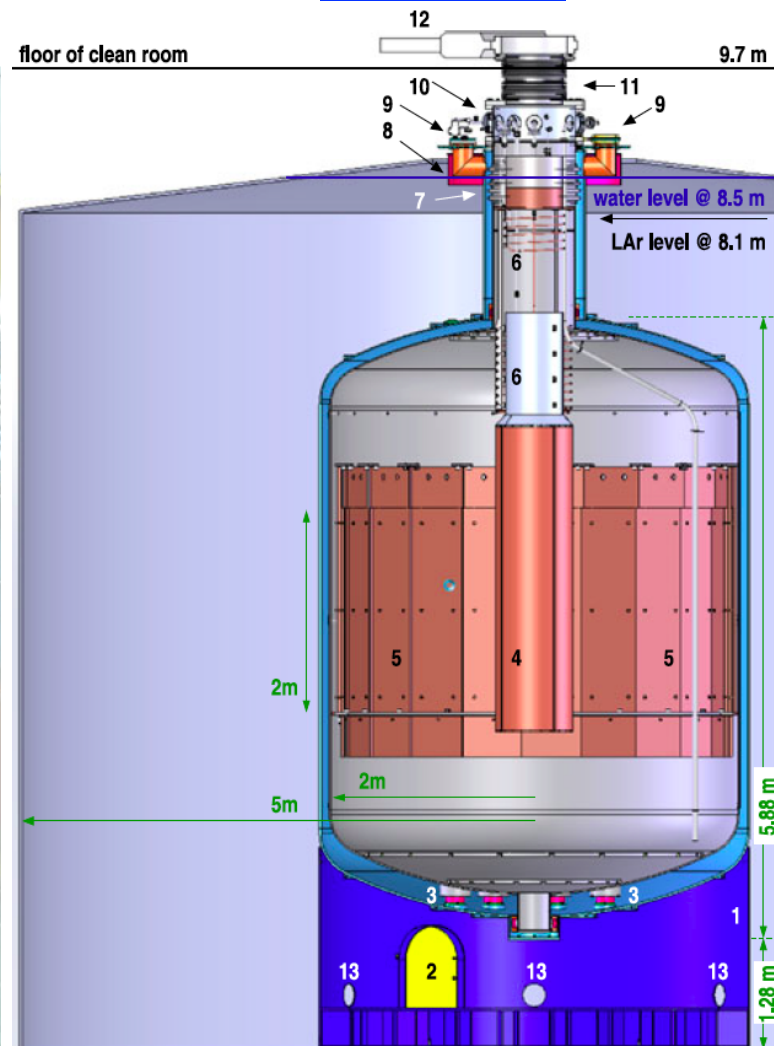
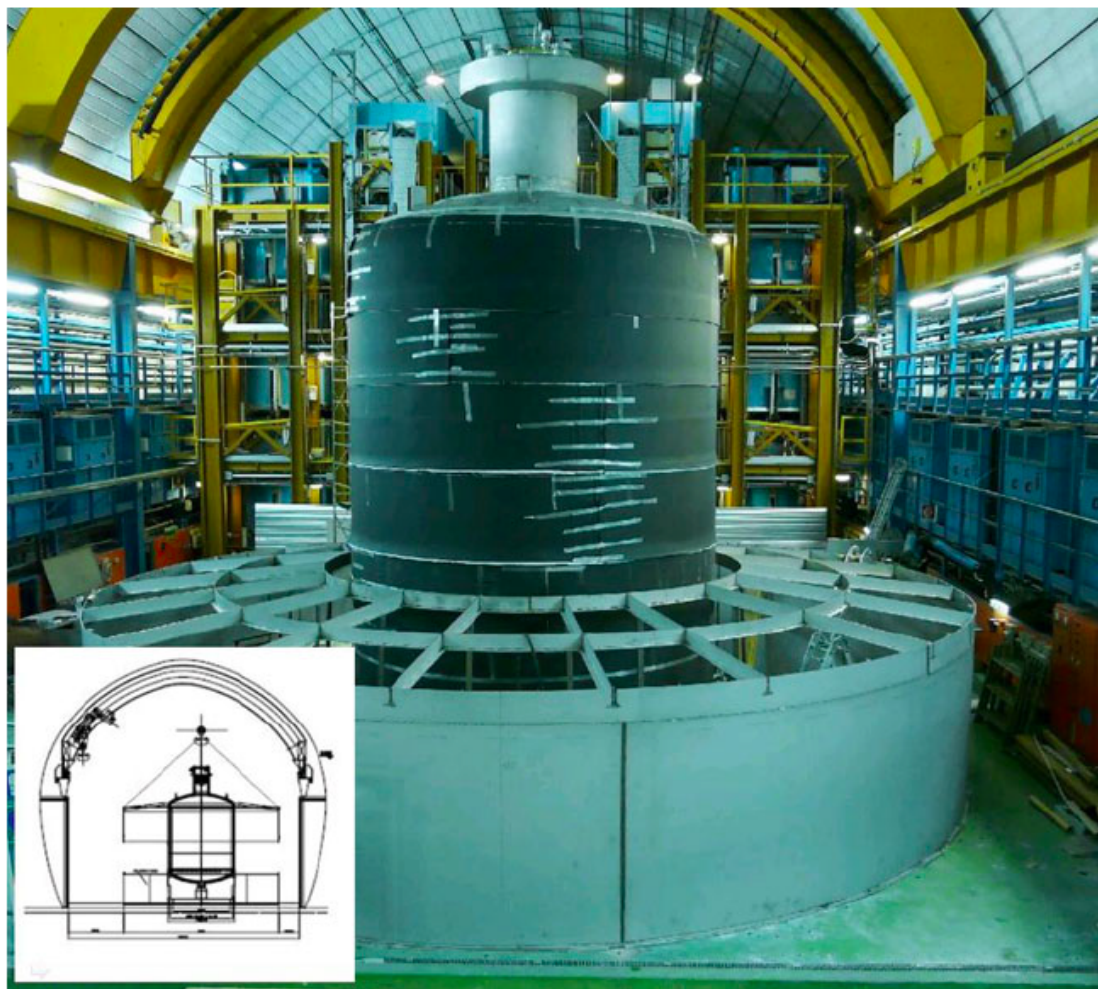
Production of ^{enr}Ge Phase II detectors

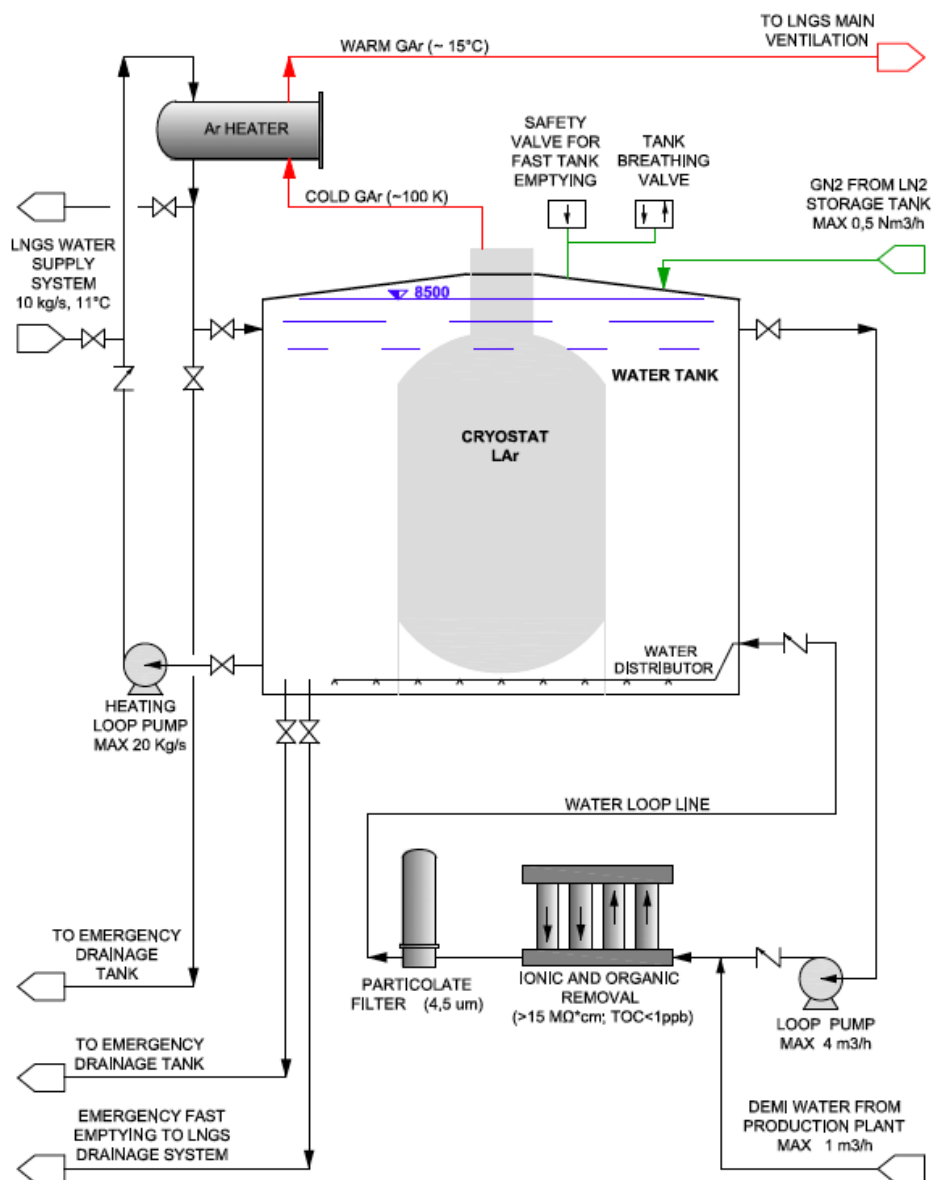


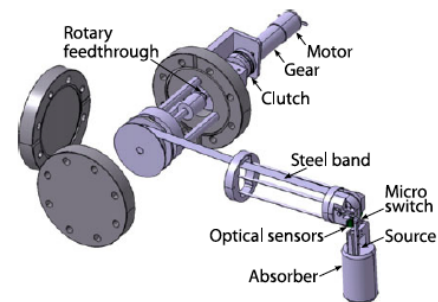
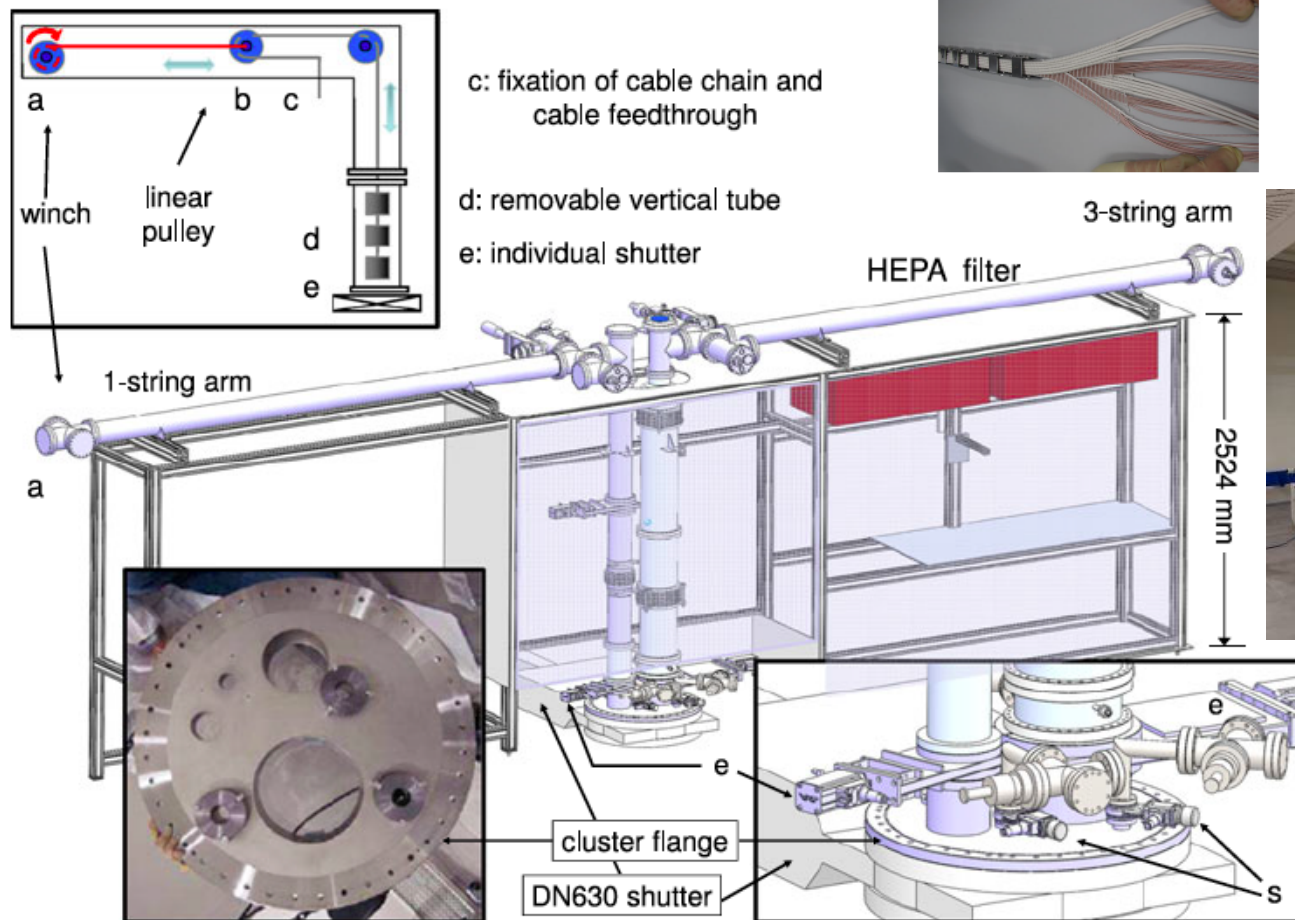
Water tank and cryostat

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

[arXiv:1212.4067](https://arxiv.org/abs/1212.4067)

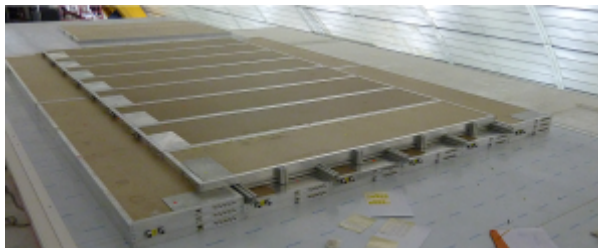


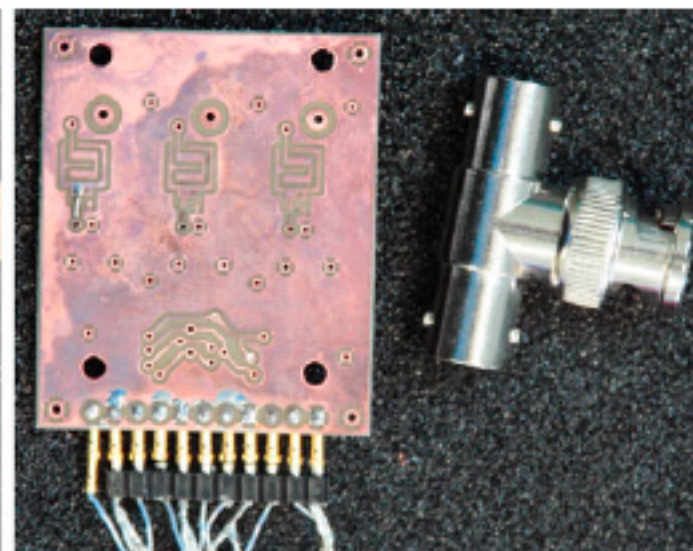
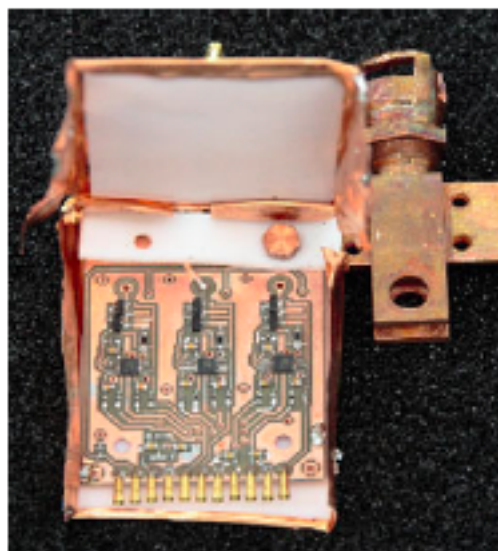
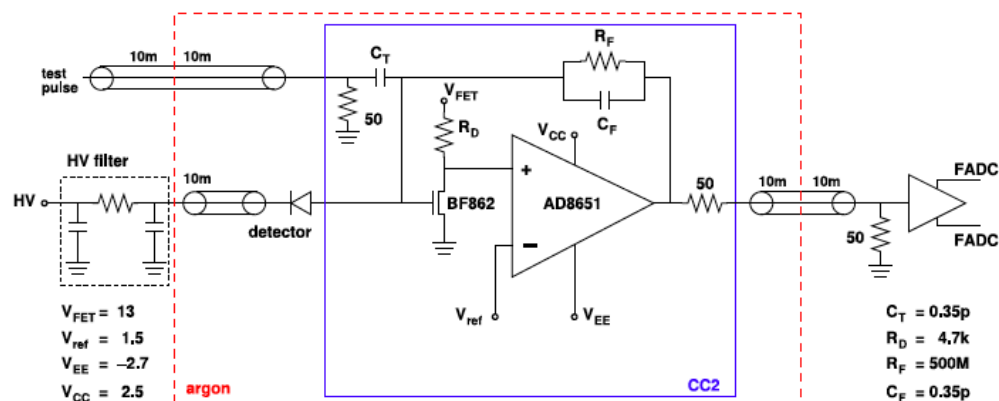




Water Cherenkov detector and plastic scintillator muon veto

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





The GERDA construction 2008-2010



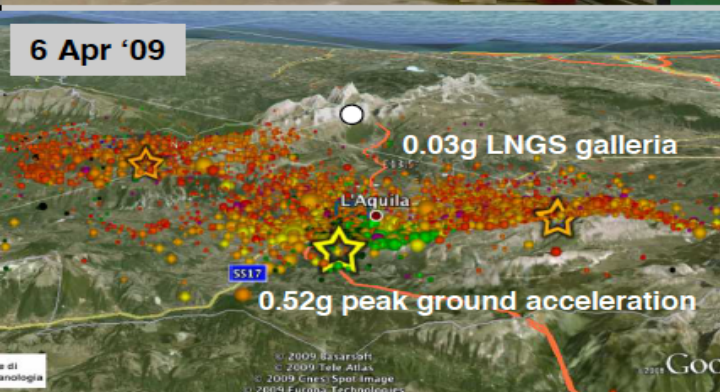
6 Mar '08



5 May '08

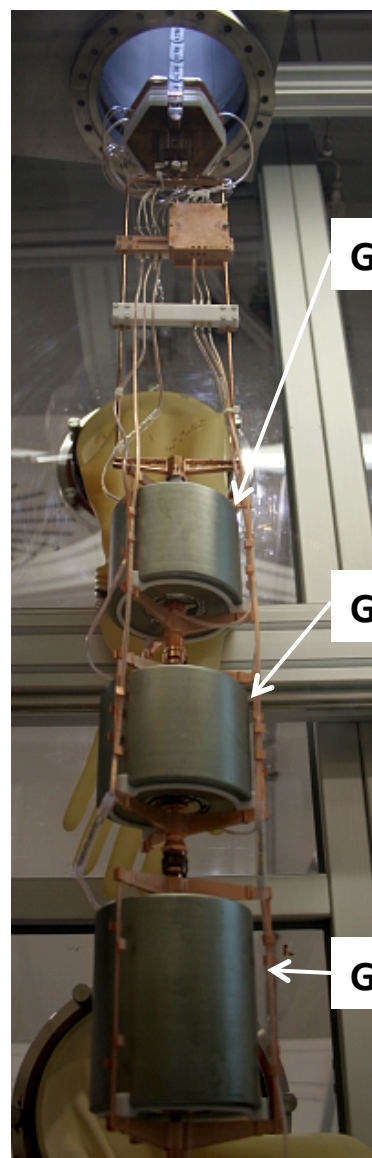


29 feb '09



Cryostat filled since December 2009

Commissioning with 1-string assembly

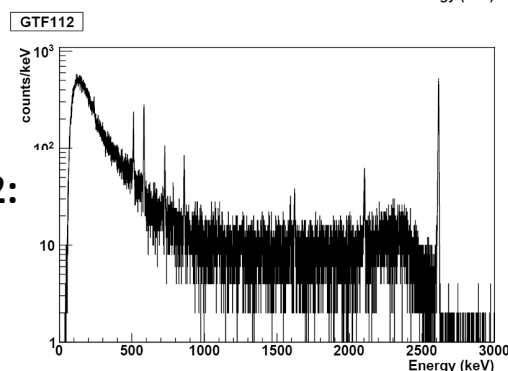
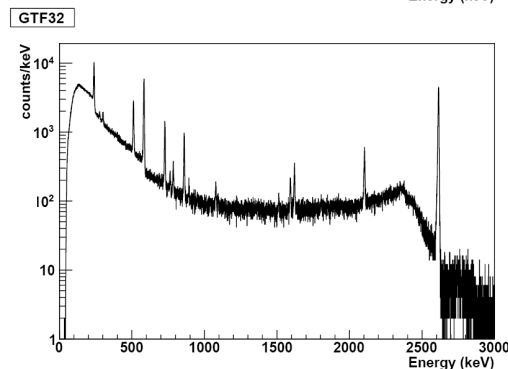
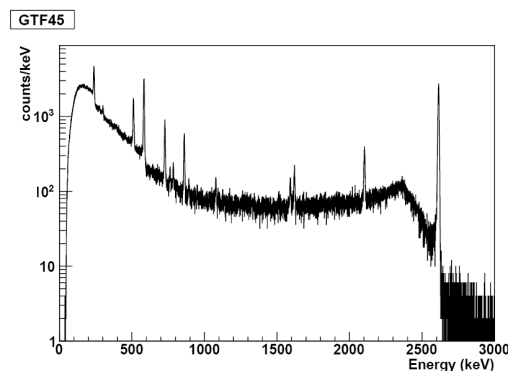


GTF 45:

GTF 32:

GTF 112:

Calibration with ^{228}Th :



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



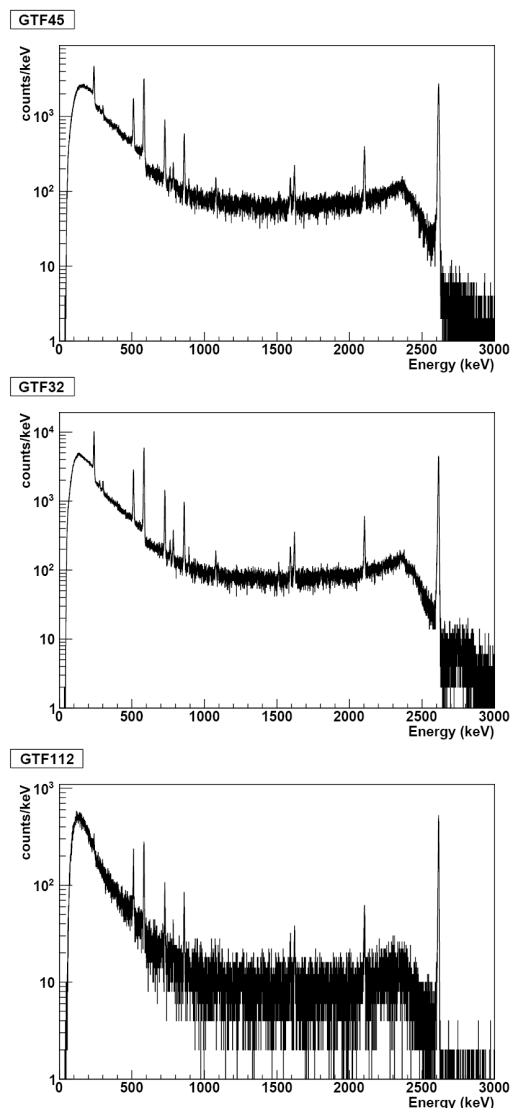
Energy resolutions during commissioning:

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

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)

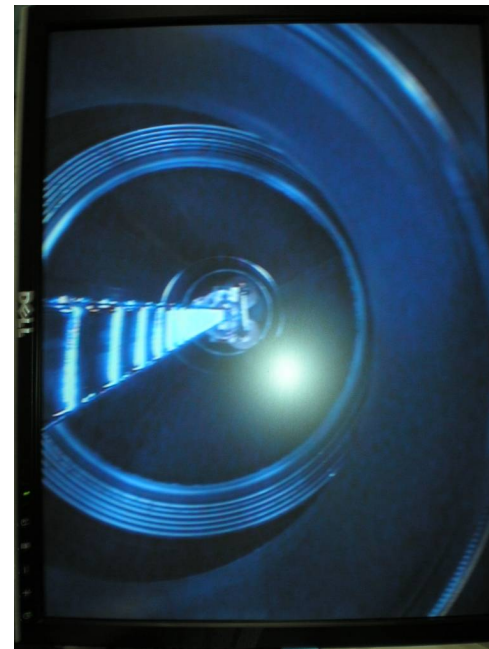


65μm Cu cylinder
(‘mini-shroud’) to
shield E-field

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



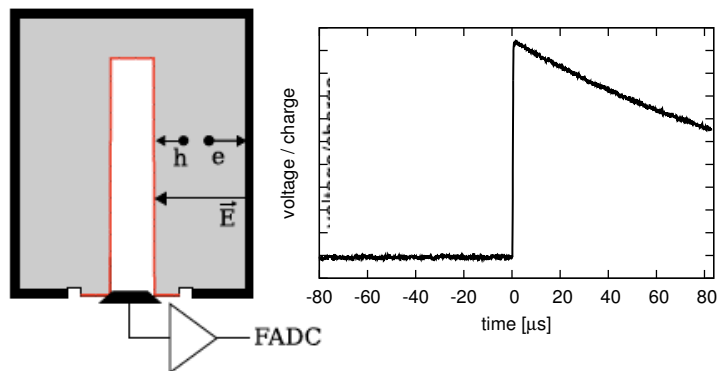
8 refurbished enriched diodes from HdM & IGEX

- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

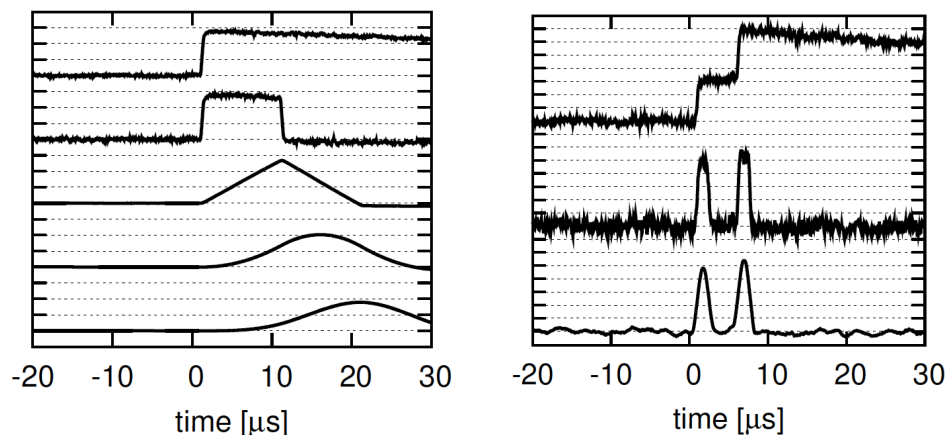
2 diodes shut off because leakage current high:

- total enriched detector mass 14.6 kg

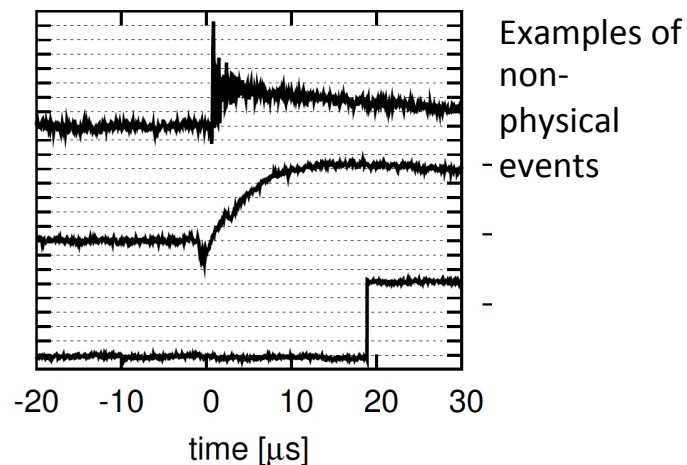
Read-out and signal structure



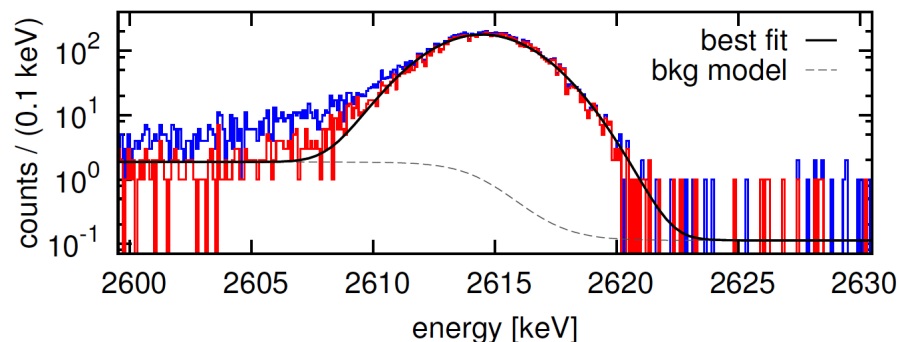
Digital signal processing to extract amplitude, rise time, etc.



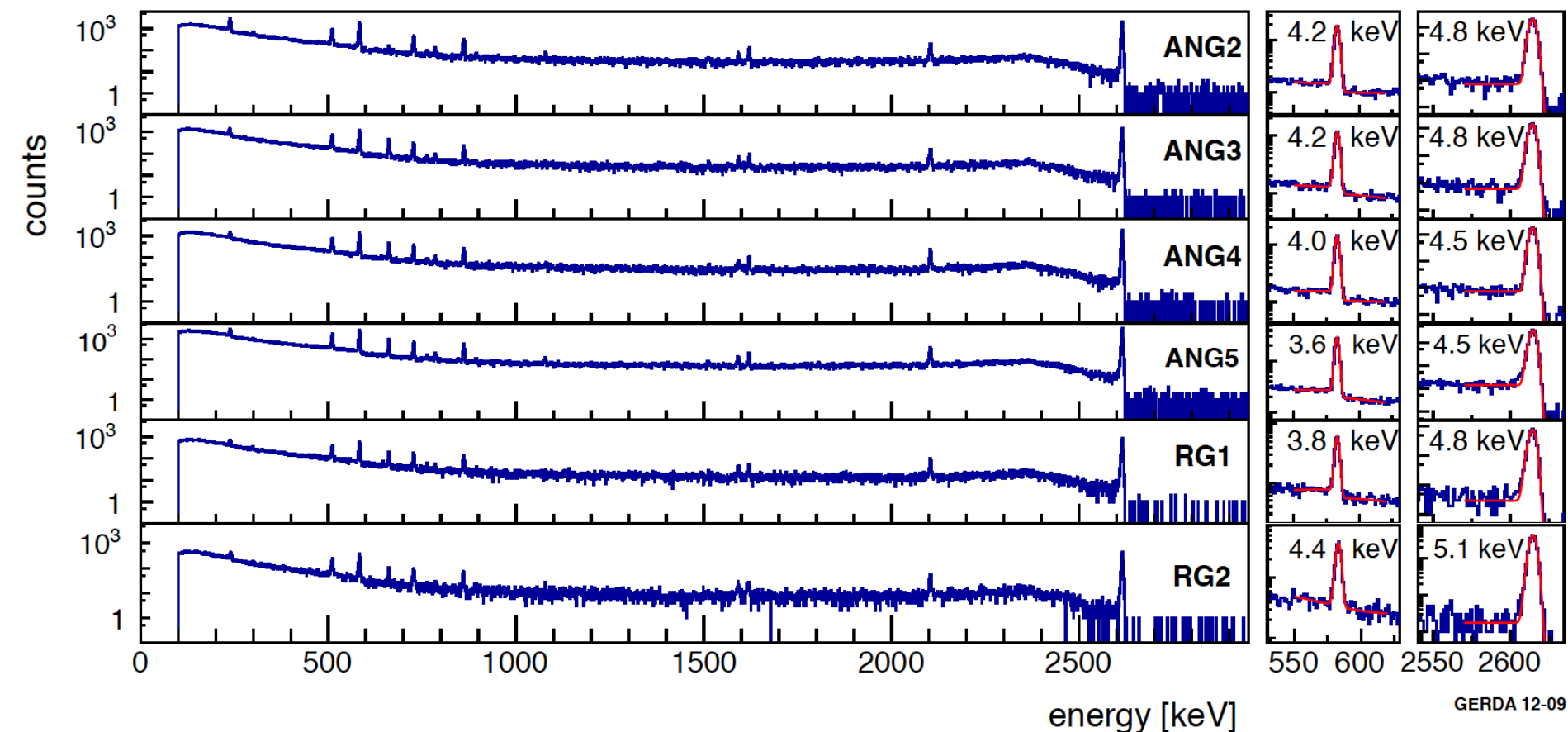
Data selection and quality monitoring



Calibration of energy scale (^{228}Th)

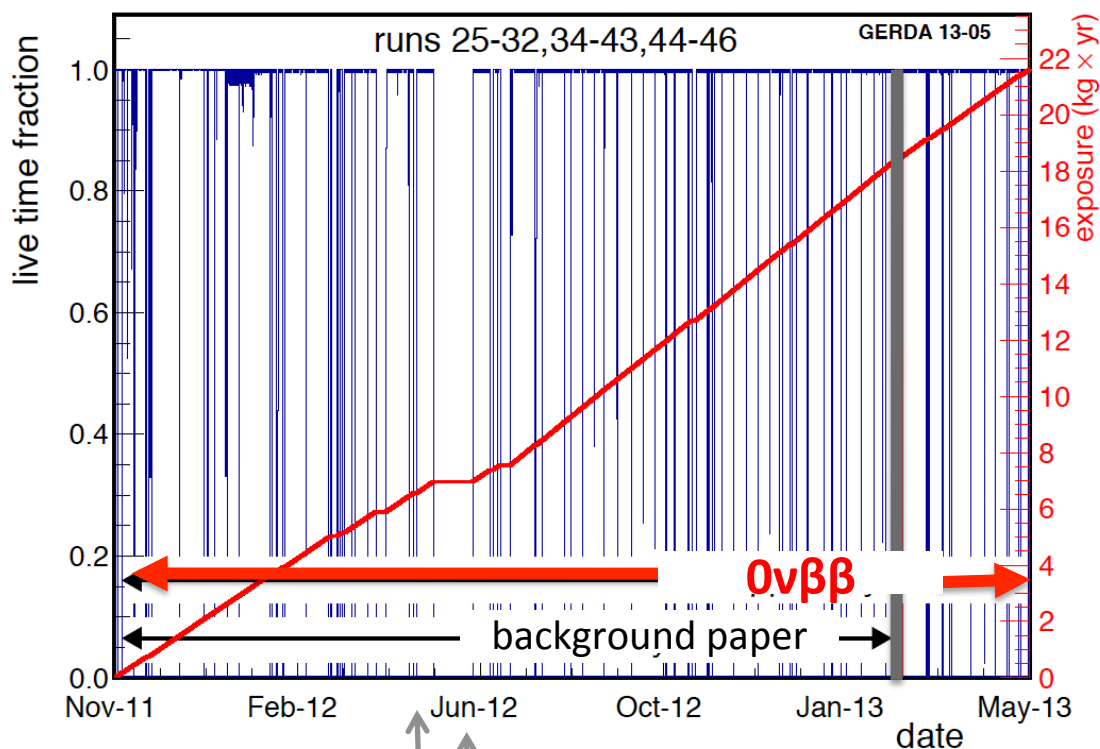


- Data processing frame work 'Gelatio'
- 2nd independent data processing software for cross check



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

Total exposure for $0\nu\beta\beta$ analysis: **21.6 kg yr**
(bi-)weekly calibration runs ('spikes')

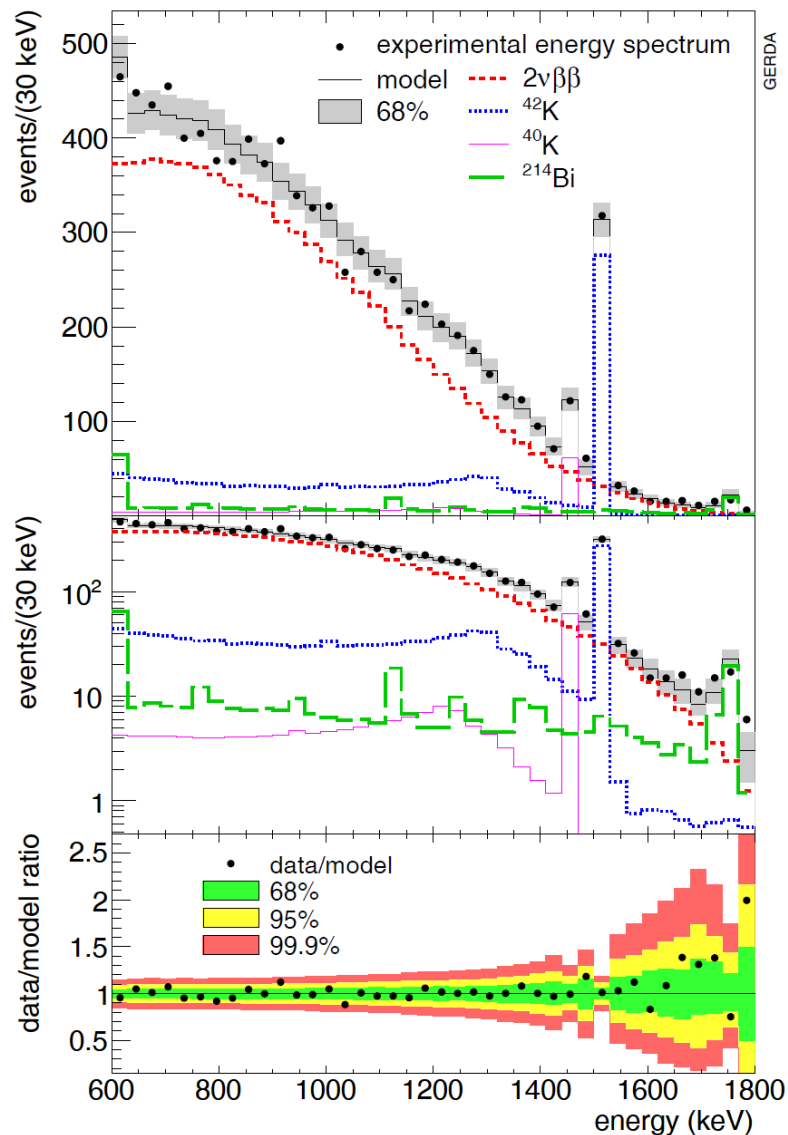


Data blinding:

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

Insertion of 5 Phase II $^{\text{enr}}$ BEGe

1st physics: $2\nu\beta\beta$ analysis (5.04 kg yr)



IOP PUBLISHING

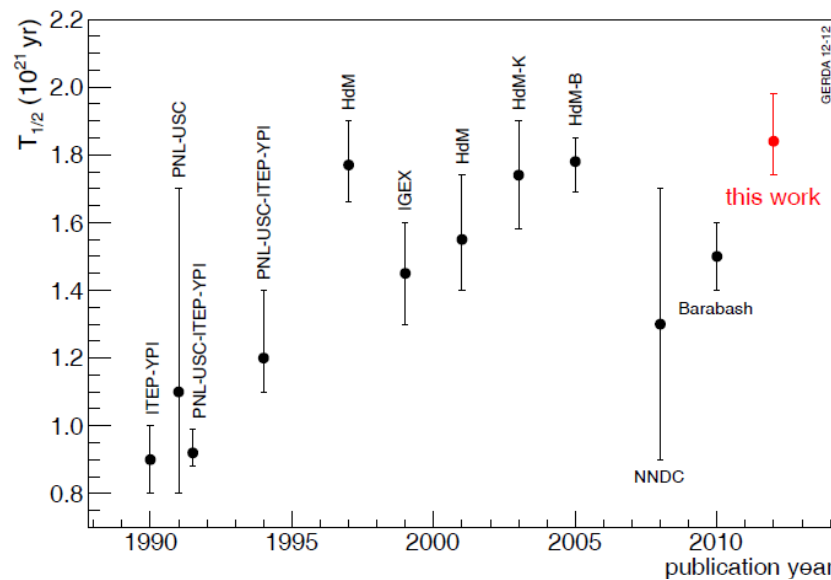
JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **40** (2013) 035110 (13pp)

doi:10.1088/0954-3899/40/3/035110

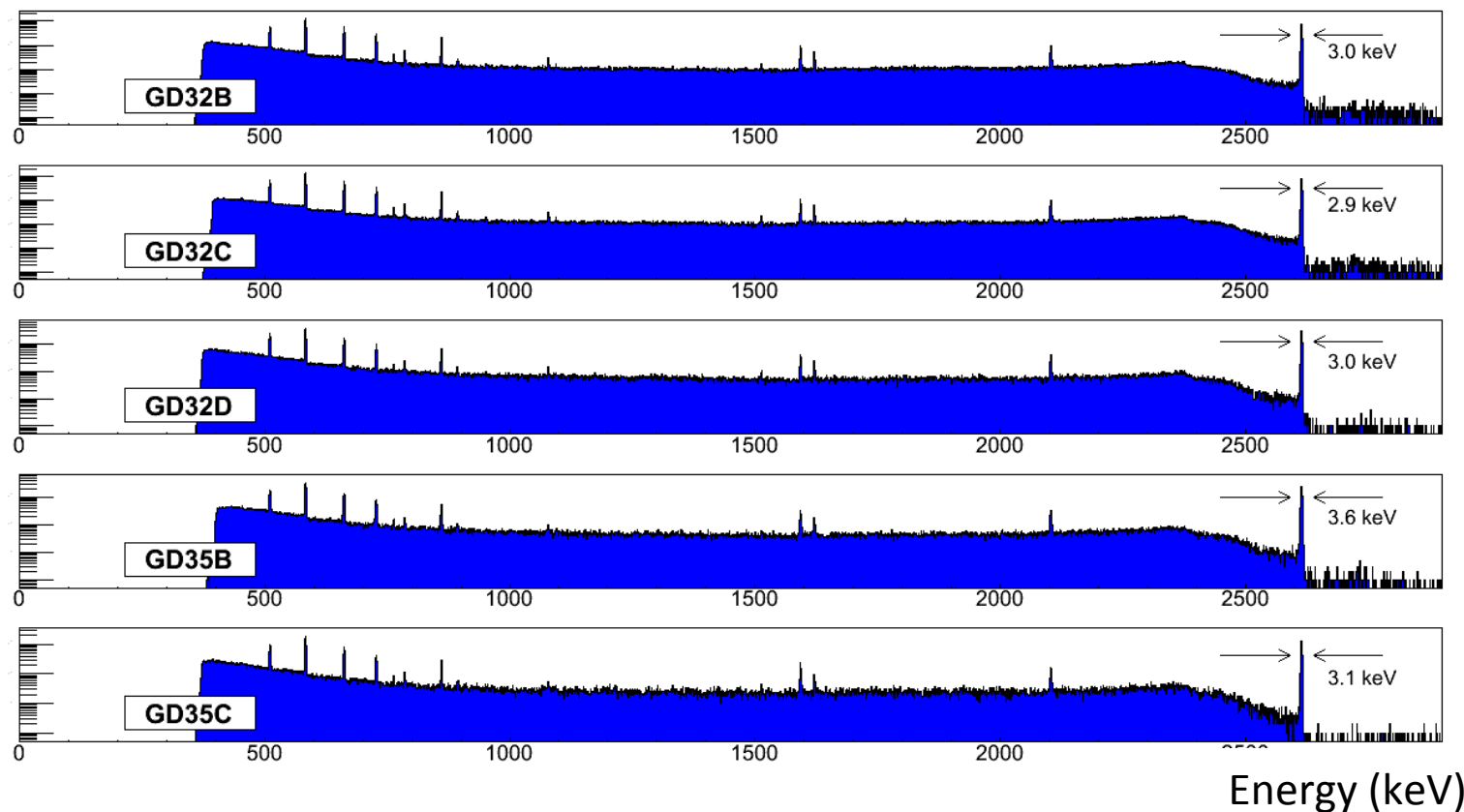
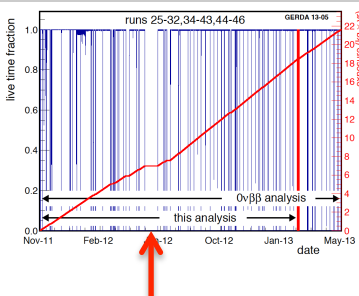
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

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

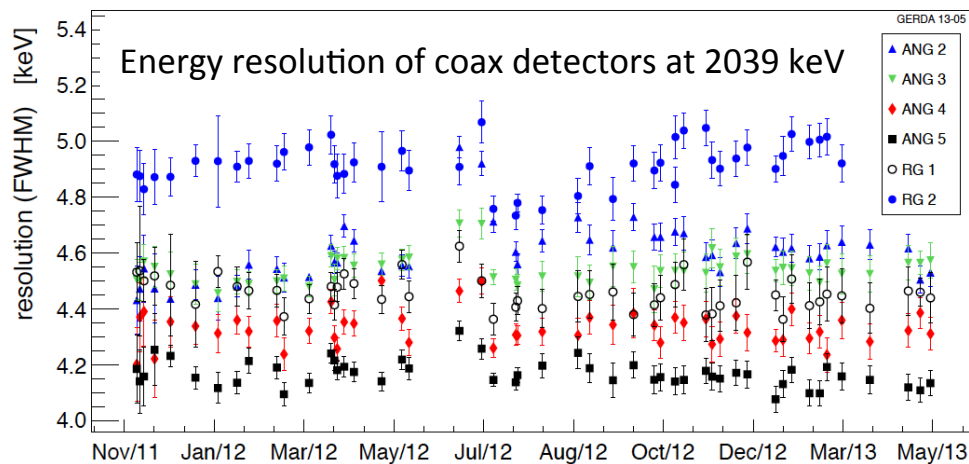
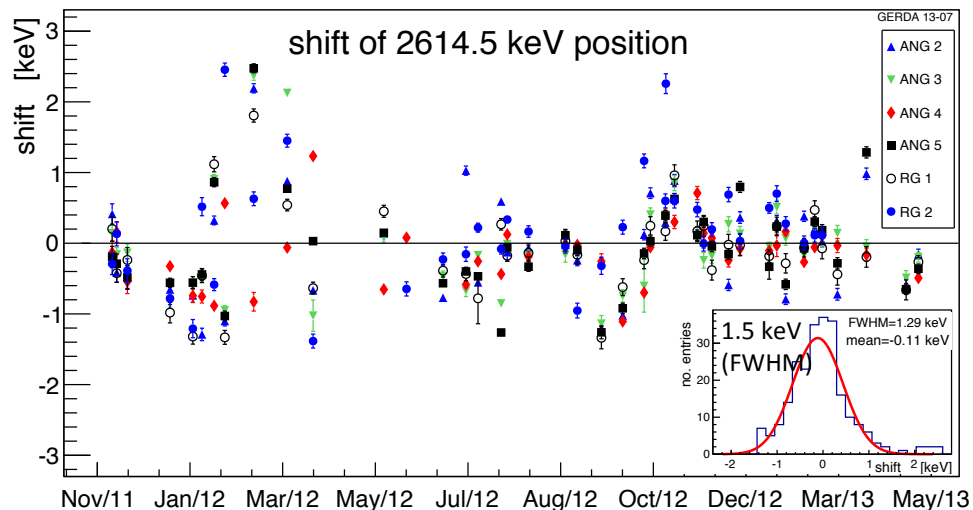


LAB Talk of J. Phys. G Feb. 2013 issue:
<http://iopscience.iop.org/0954-3899/labtalk-article/52398>

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

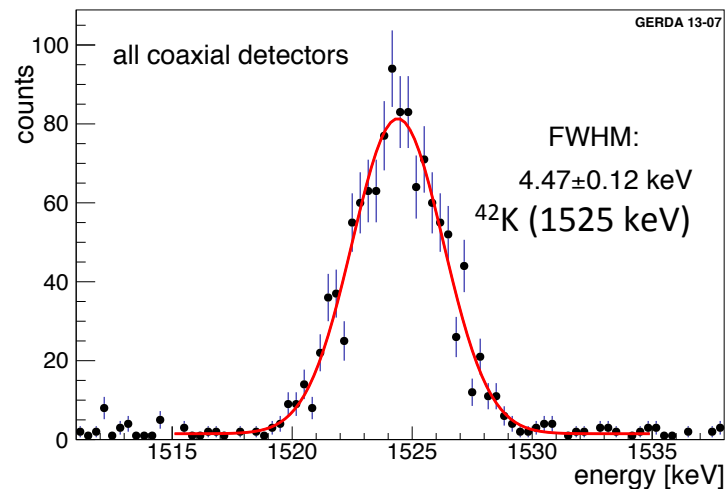


Peak position stability of 2614.5 keV calibration line:
coax: 1.5 keV / BEGe: 1.0 keV (FWHM)



Summing all runs:

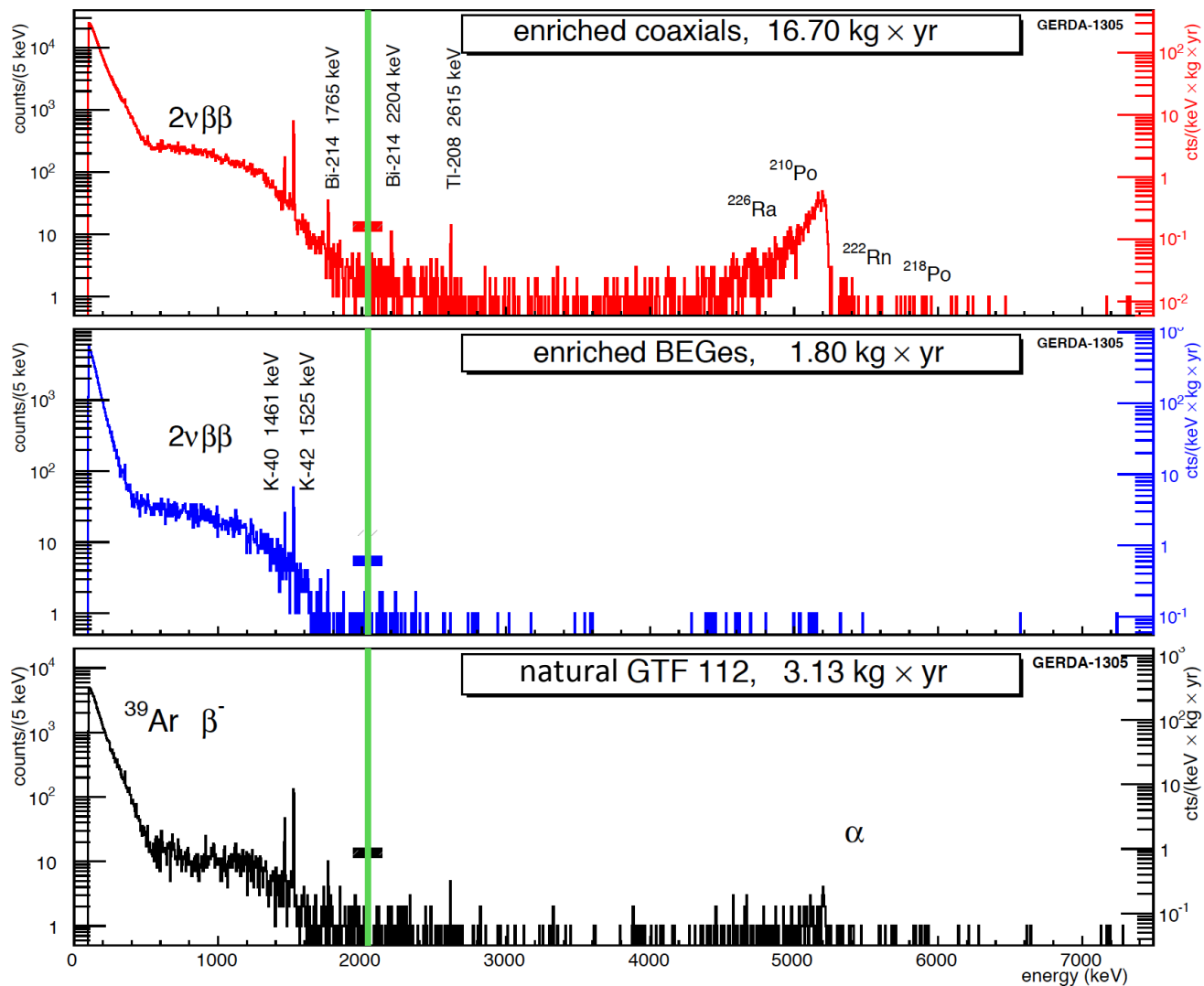
[arXiv:1306.5084](https://arxiv.org/abs/1306.5084)

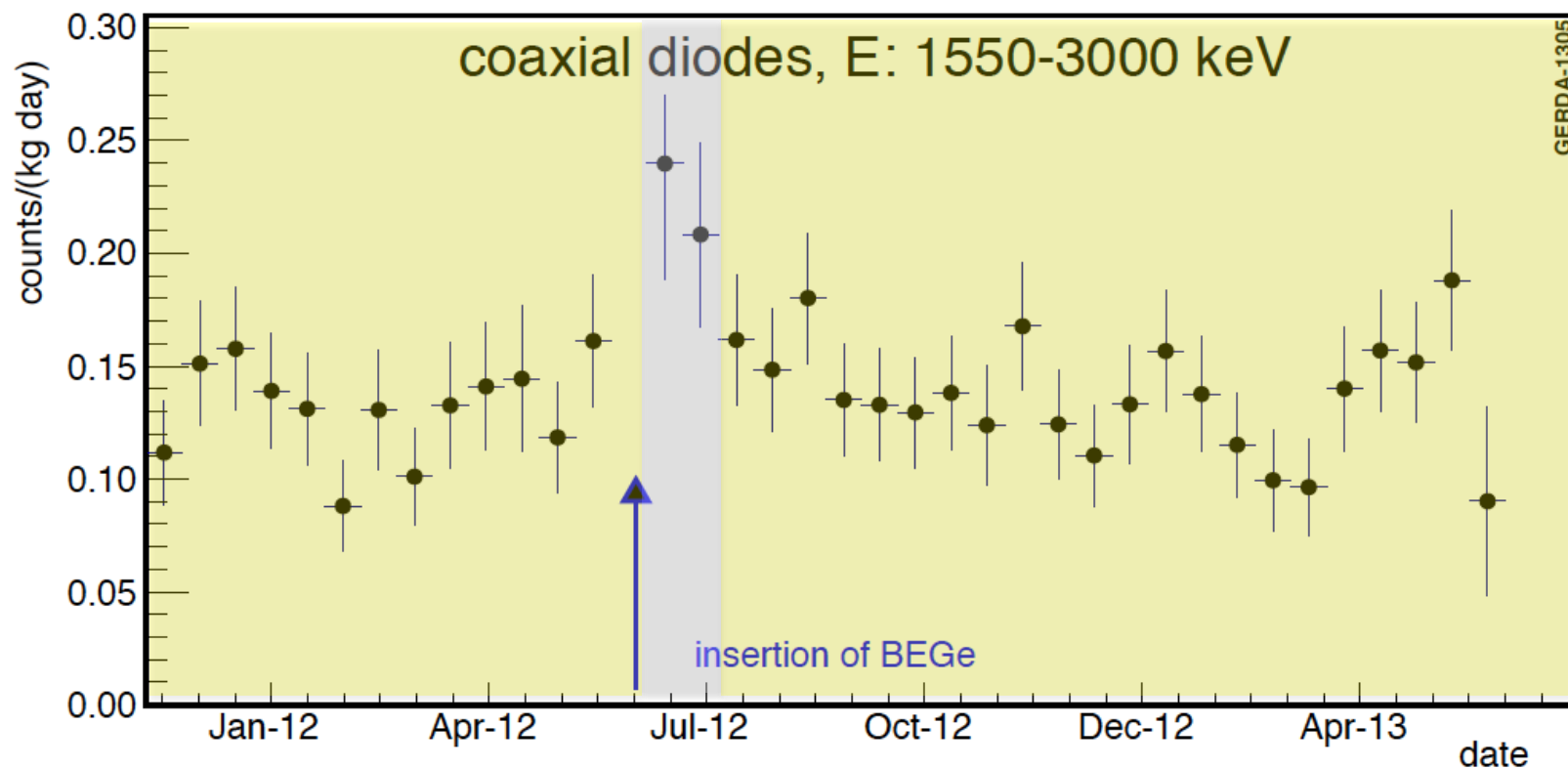


Mean energy resolution at $Q_{\beta\beta} = 2039$ keV:

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

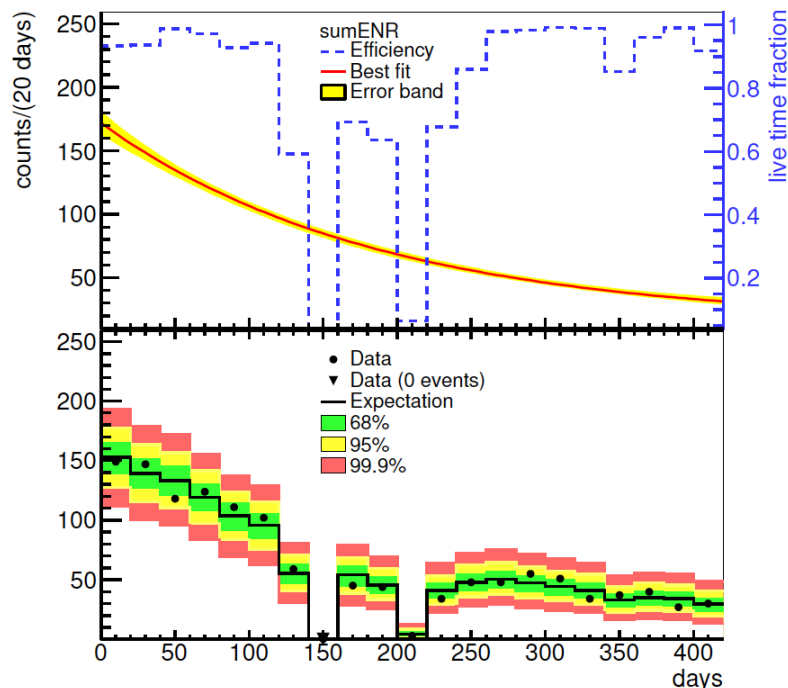
detector	FWHM [keV]	detector	FWHM [keV]
<i>SUM-coax</i>		<i>SUM-bege</i>	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)



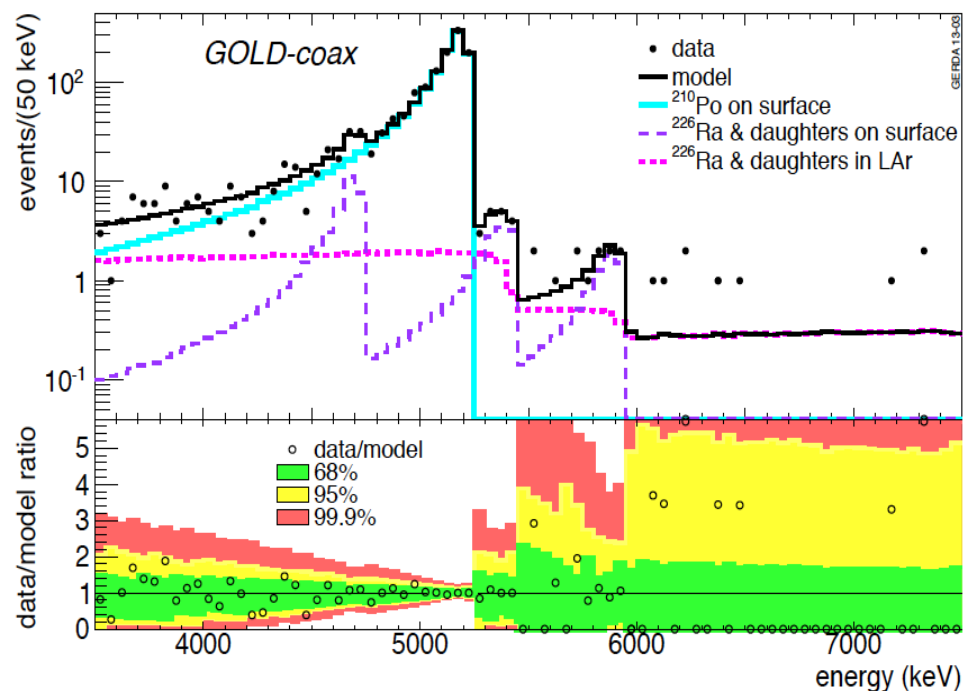


Coax-detector data set split in 'Gold' and 'Silver' (30 d)

Time distribution (3.5-5.3 MeV)

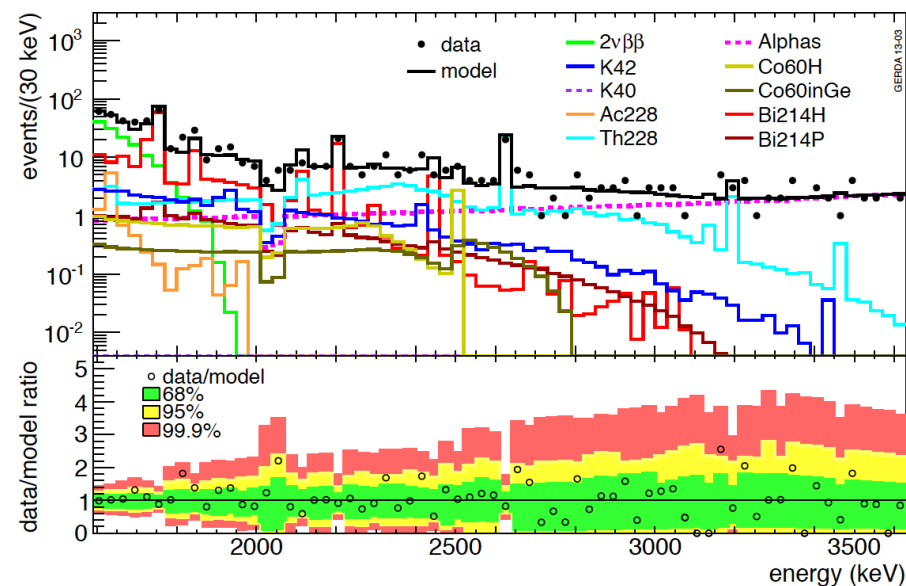
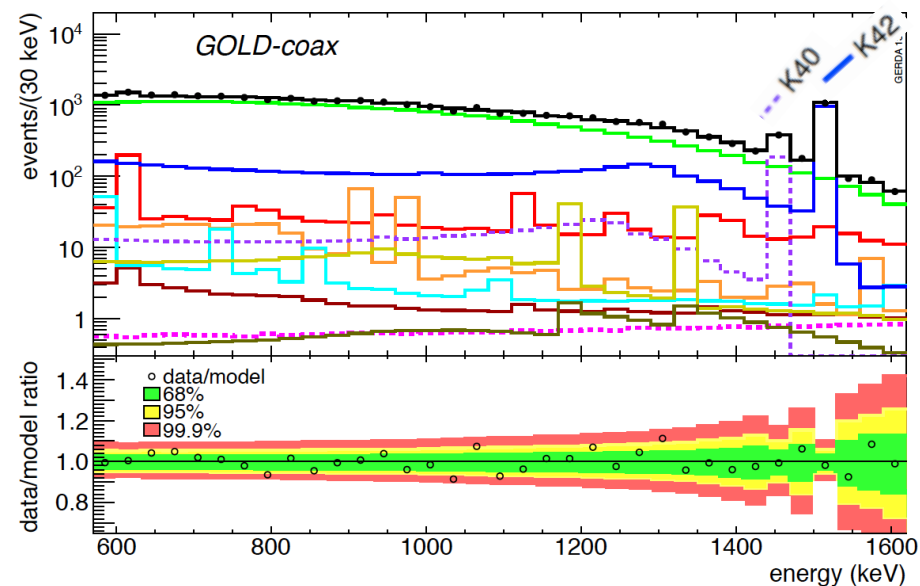


Energy spectrum

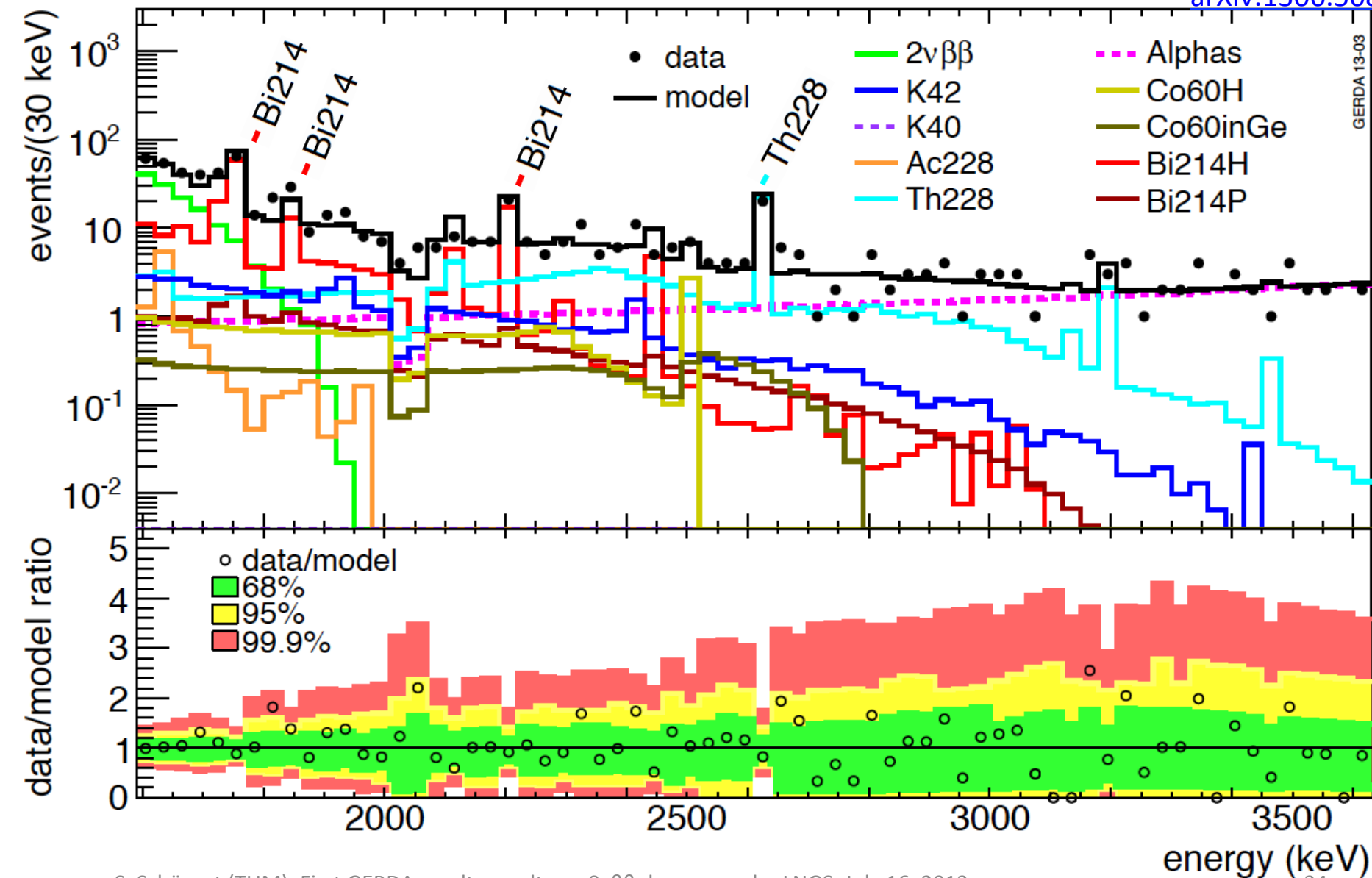


- ^{210}Po ($T_{1/2}=138$ d) dominated
- Contributions also from ^{226}Ra & progenies
- Located on (thin) p+ surface contact (also confirmed by pulse shape analysis)
- Background model only with Gold-coax; same sources in Silver-coax, but limited statistics does not allow quantitative background decomposition

Fit of minimal background model to complete energy spectrum



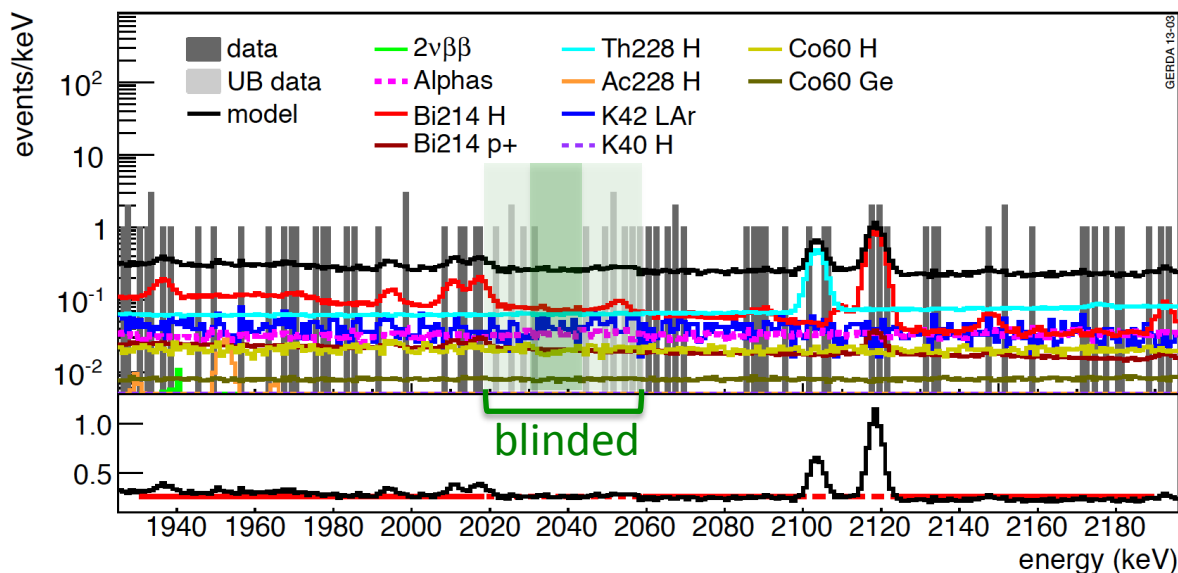
- Minimal Model is sufficient to describe data well
- Maximum Model includes ^{42}K on p+ and n+ contacts, ^{214}Bi in LAr & far sources



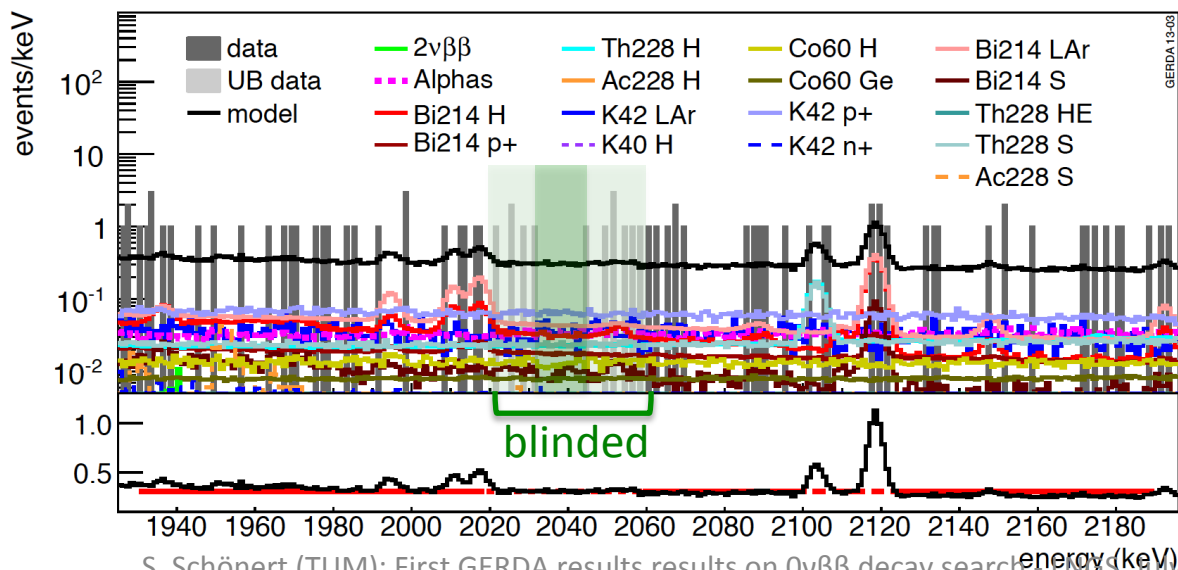
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

[arXiv:1306.5084](https://arxiv.org/abs/1306.5084)

Minimal model



Maximum model

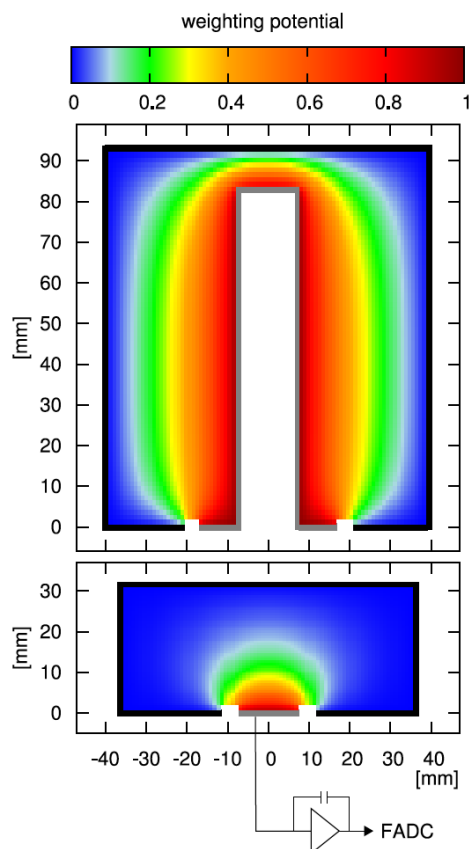


Background model:

- 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

Classification of $(0\nu\beta\beta)$ signal-like (SSE) or background-like (MSE, p^+) events

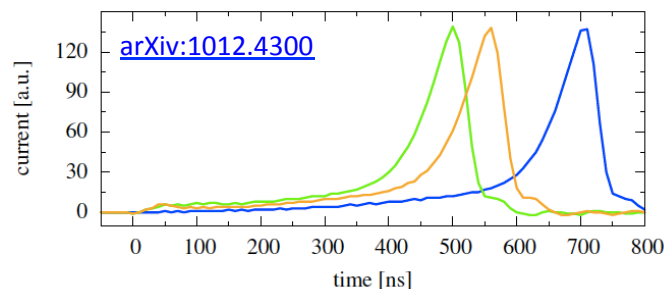
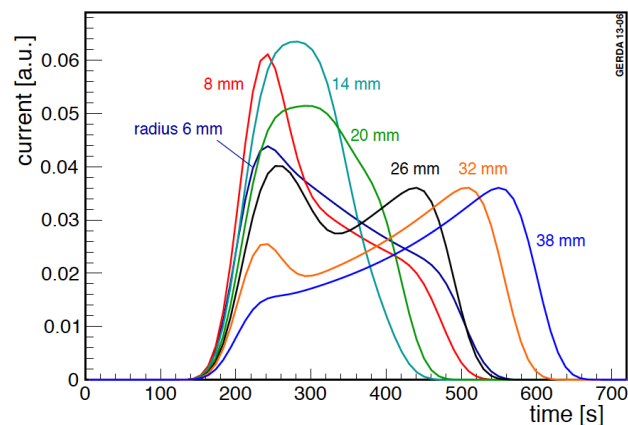
Weighting potential for coax and BEGe detectors are different

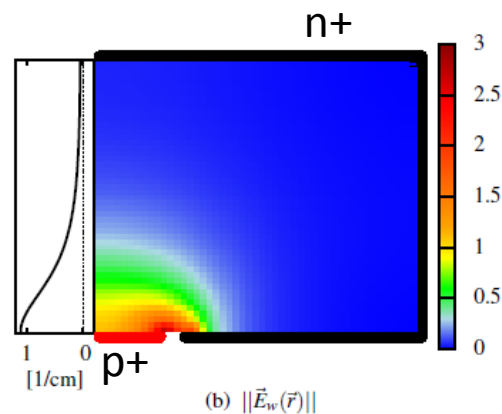
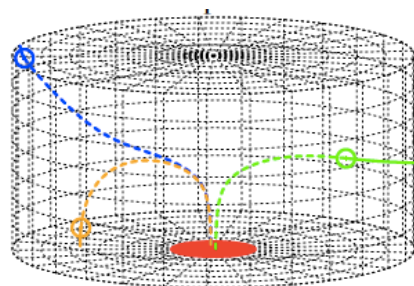


Coax

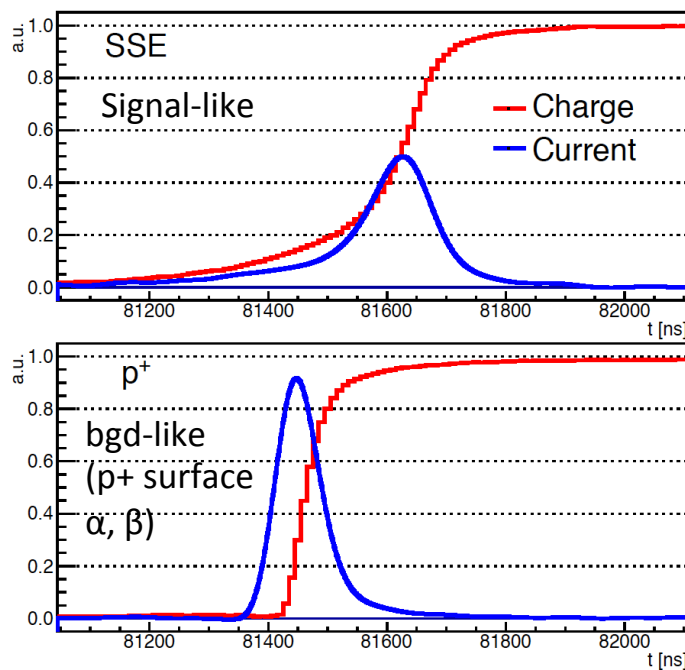
BEGe

Current pulses of simulated SSE signals

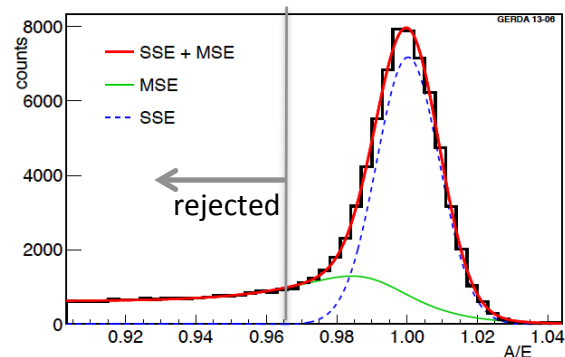




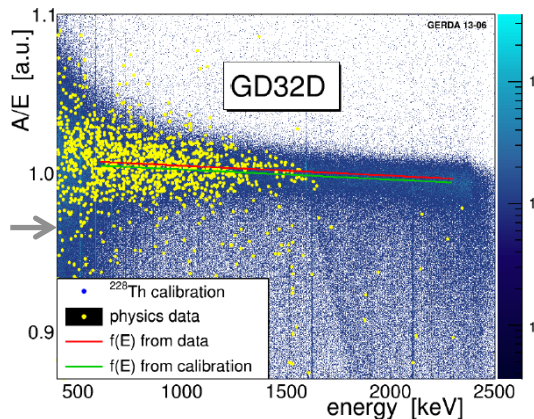
PSD discrimination
parameter: A/E



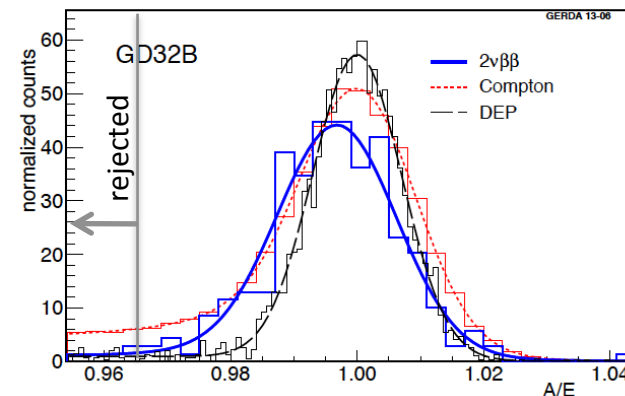
A/E of Compton continuum from calibration



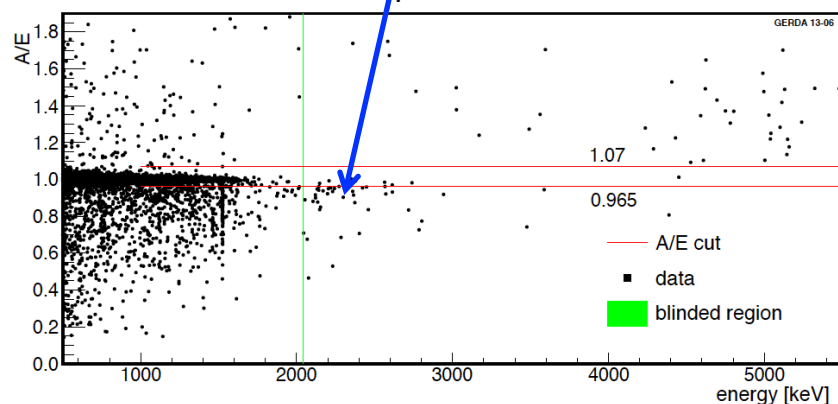
Energy dependence of A/E



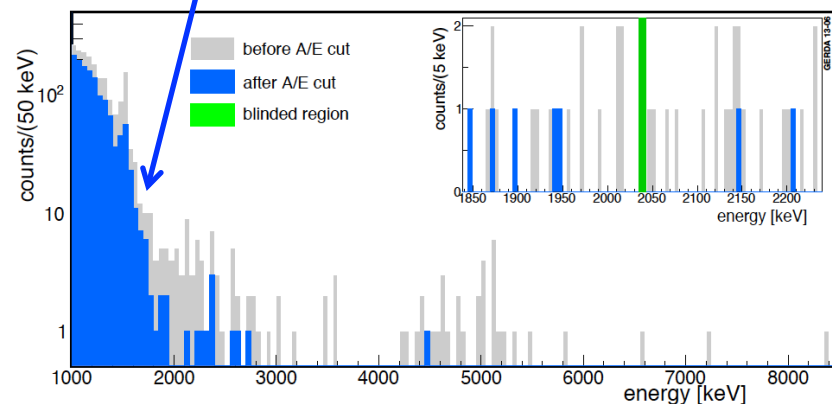
A/E for $2\nu\beta\beta$, Compton (1-1.4 MeV), DEP (1592 keV)



$^{42}\text{K-}\beta$ n+ surface dominated



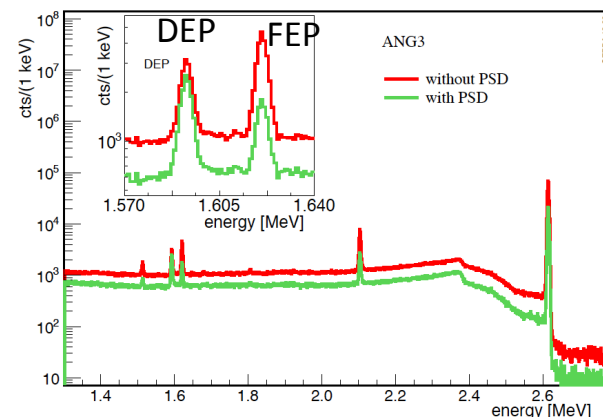
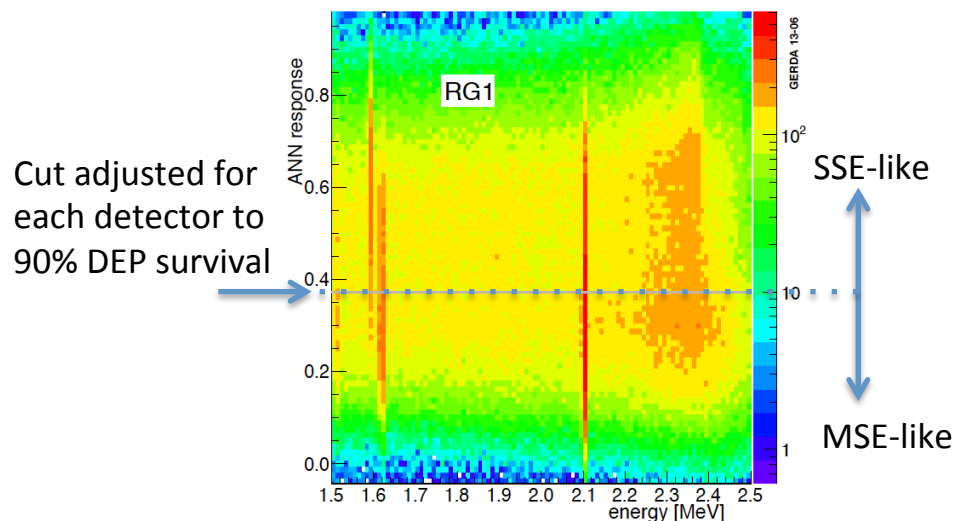
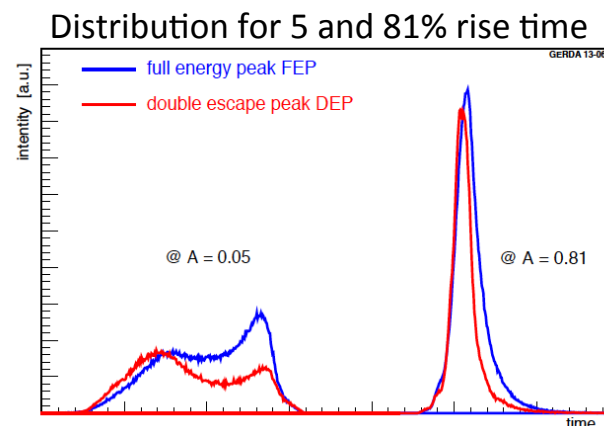
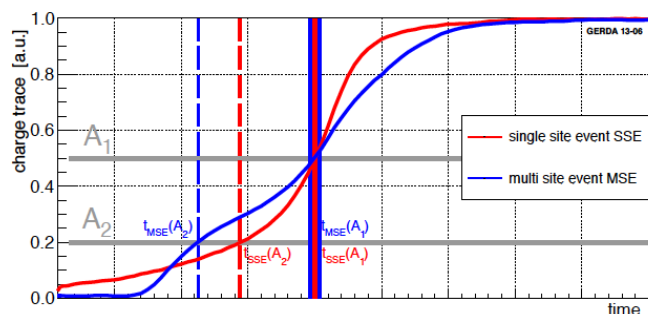
$2\nu\beta\beta$ acceptance: 0.91 ± 0.05



$0\nu\beta\beta$ acceptance: 0.92 ± 0.02

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

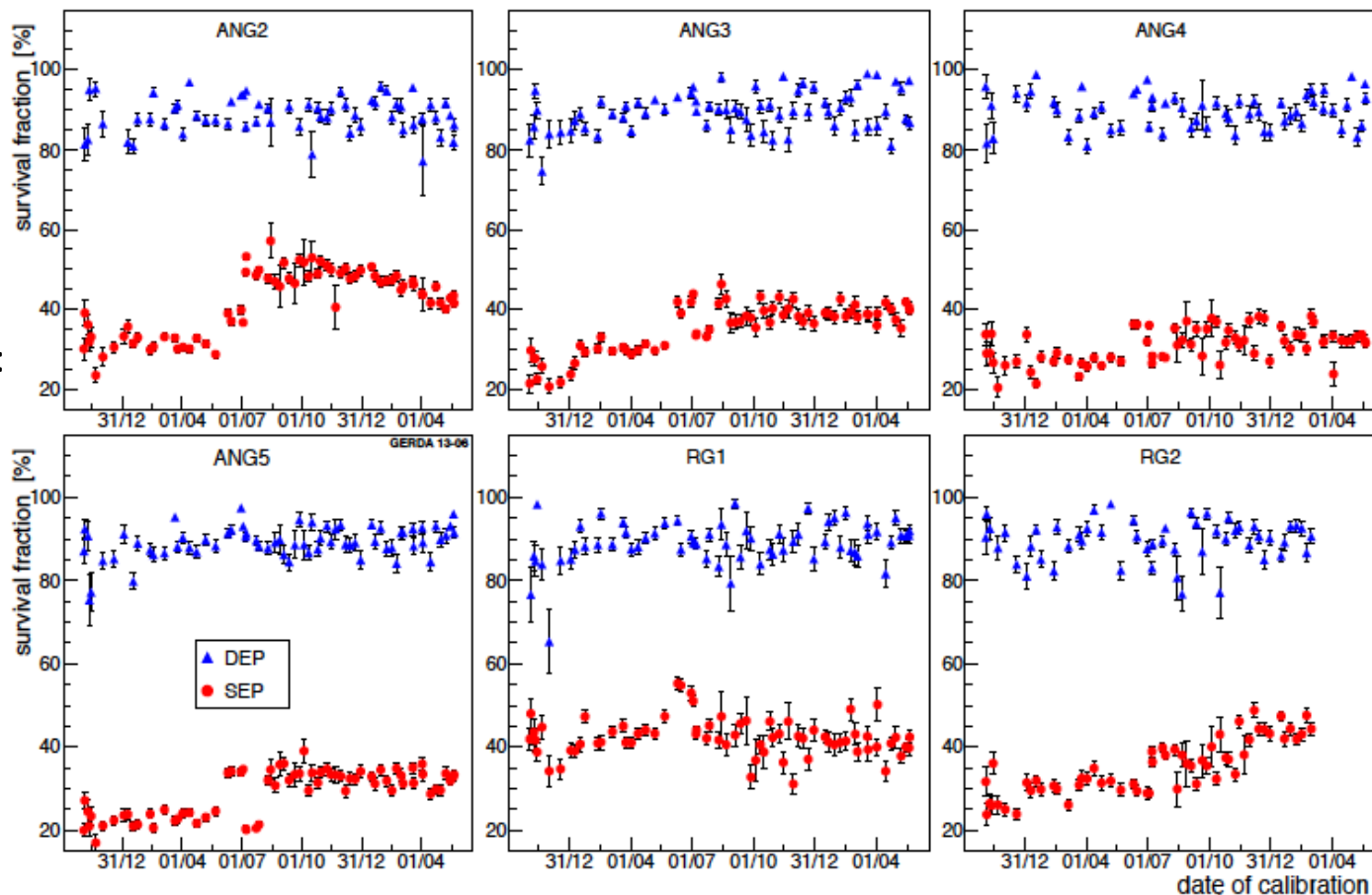
- SSE training with signal-like ^{208}Tl DEP events (1592 keV)
- MSE training with background-like ^{212}Bi FEP (1621 keV)



Pulse shape discrimination: Coax – survival fraction for Phase I

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

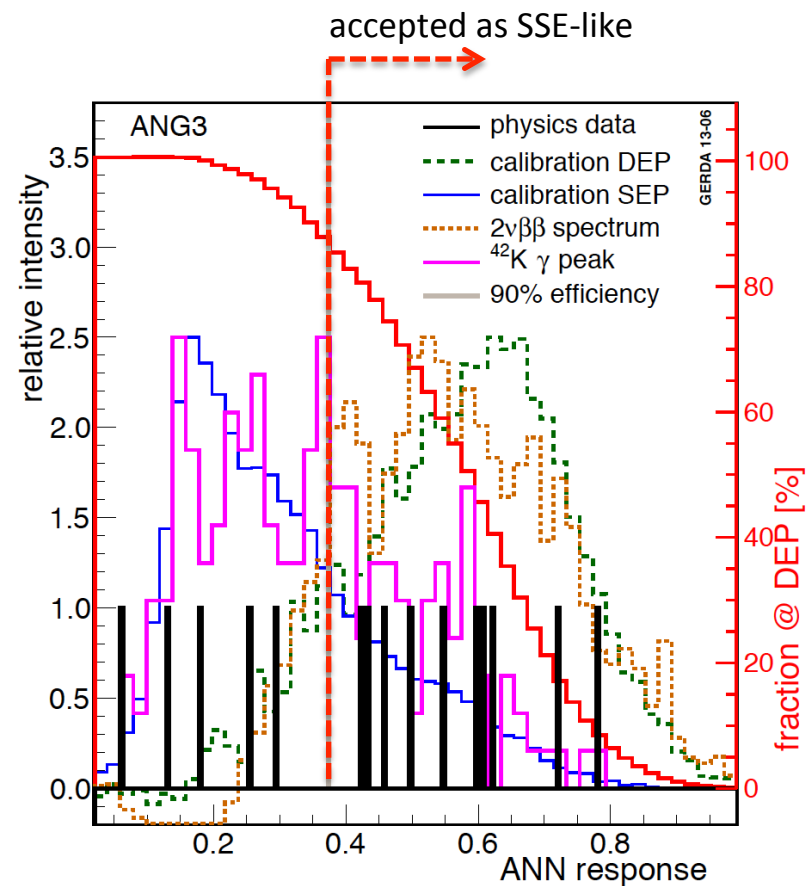
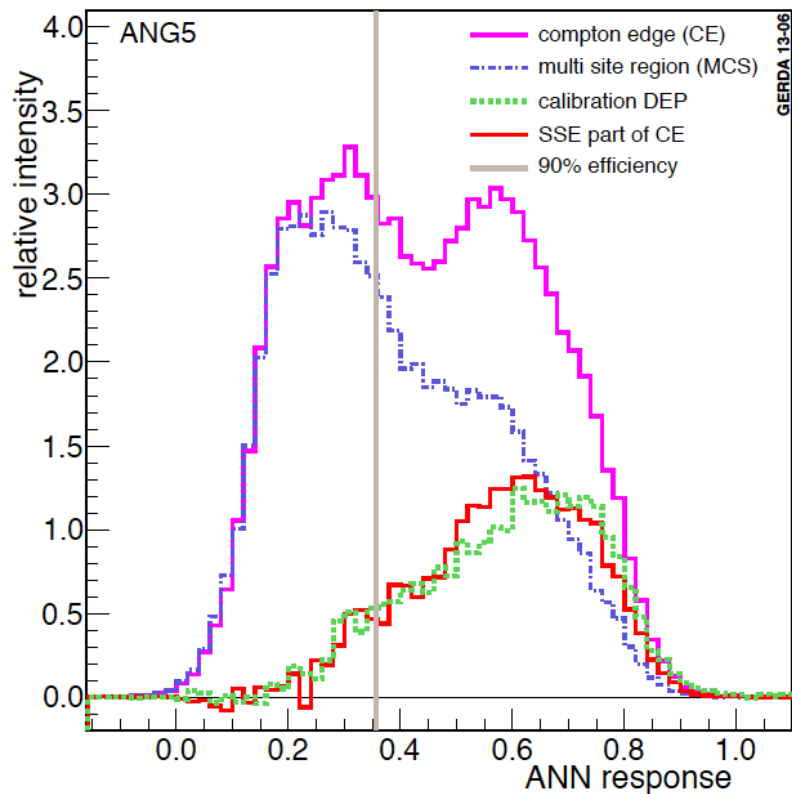
Stability of survival fraction from calibration data



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

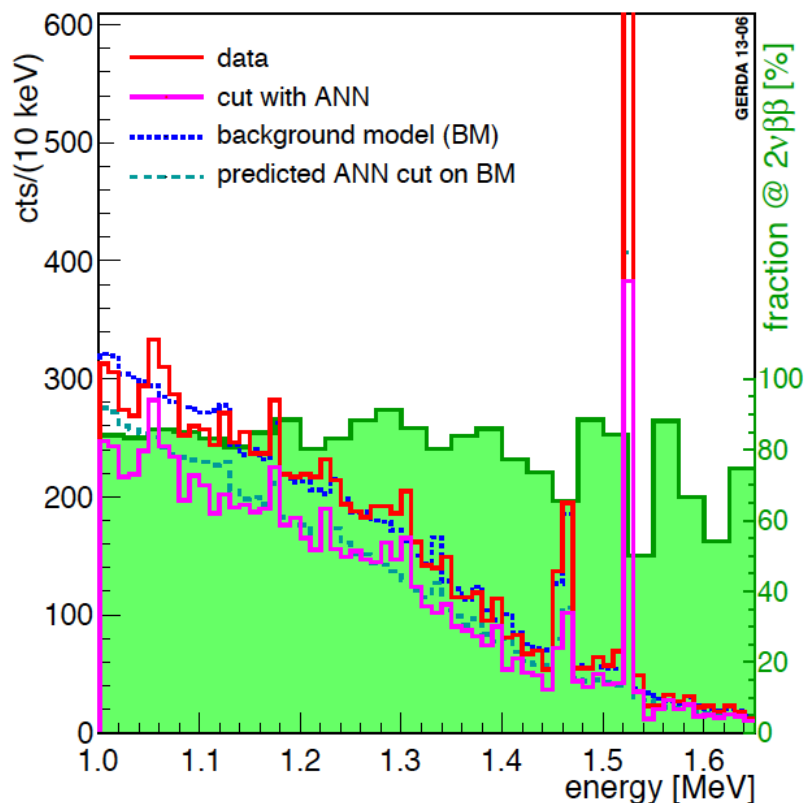
[arXiv:1307.2610](https://arxiv.org/abs/1307.2610)



Pulse shape discrimination: Coax – survival fraction for Phase I

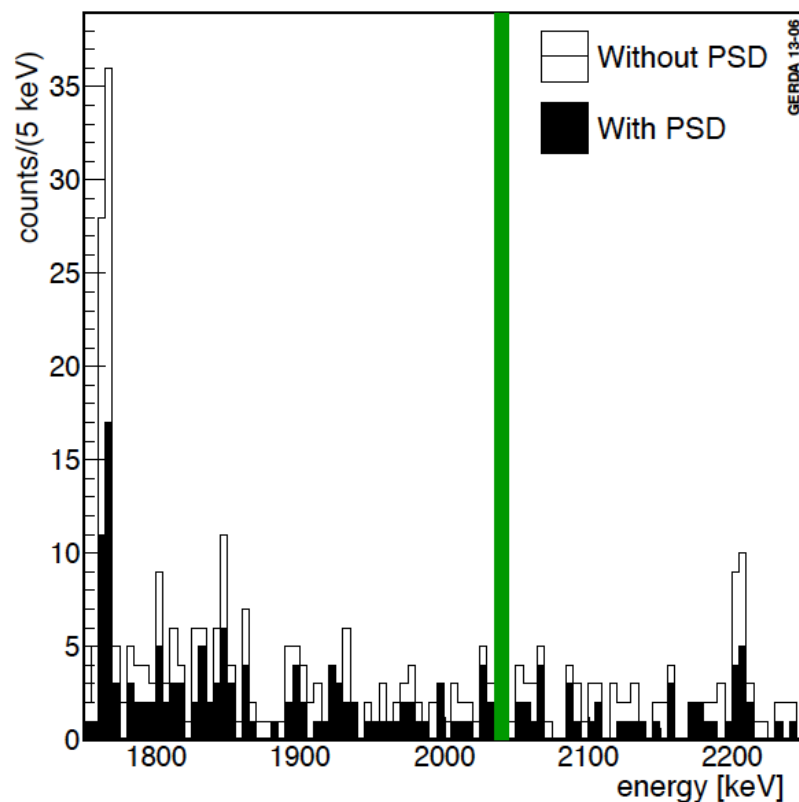
[arXiv:1307.2610](https://arxiv.org/abs/1307.2610)

PSD selection in $2\nu\beta\beta$ energy range



Measured $2\nu\beta\beta$ ANN survival: 0.85 ± 0.02

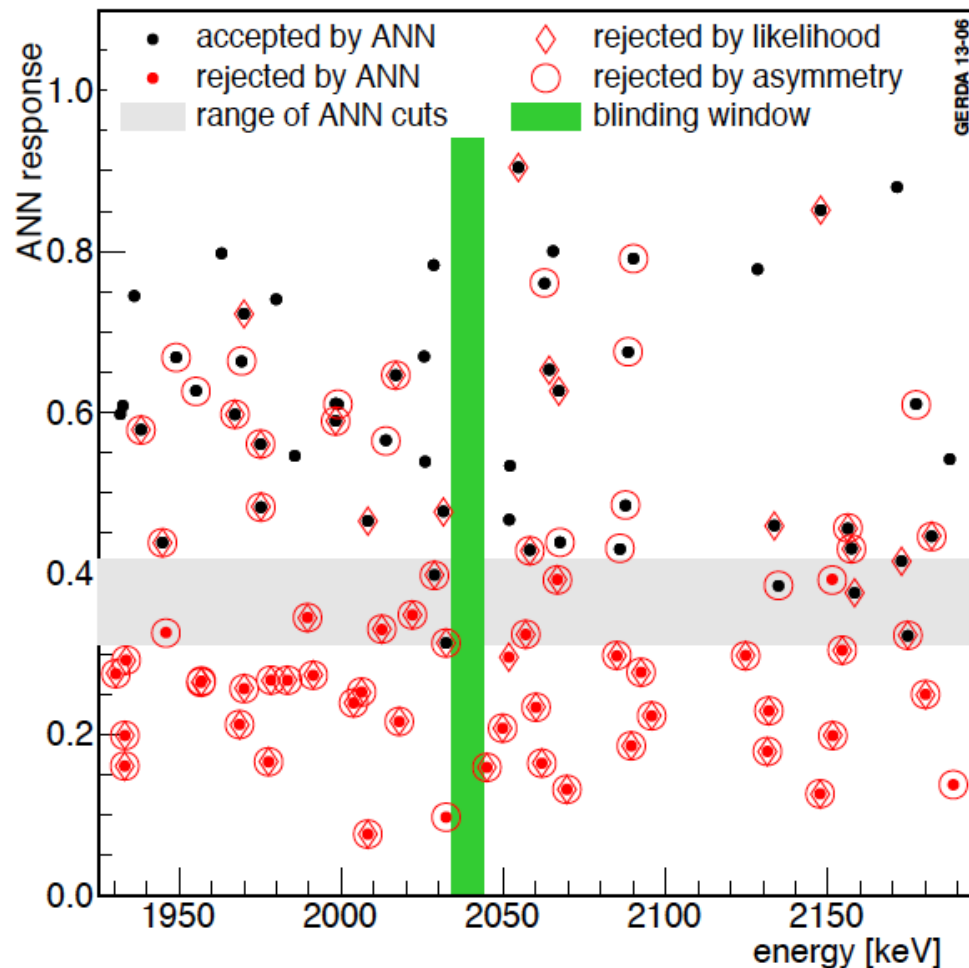
PSD selection in $0\nu\beta\beta$ energy range



Estimated $0\nu\beta\beta$ ANN survival: $0.90^{+0.05}_{-0.09}$

Pulse shape discrimination: Cross check w. independent methods

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



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

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 $0\nu\beta\beta$ analysis and cuts fixed prior unblinding

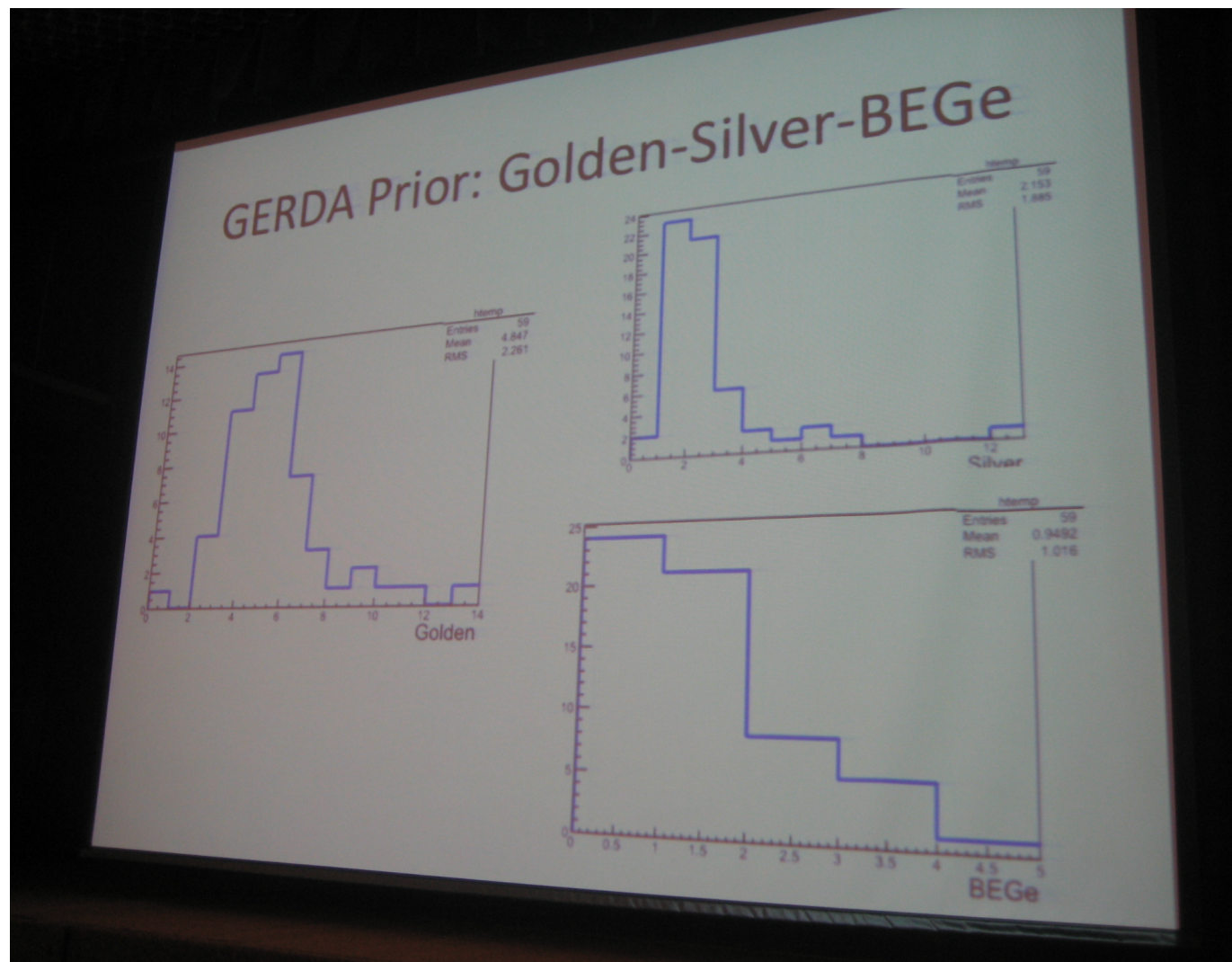
Unblinding at GERDA collaboration meeting in Dubna, June 12-14



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

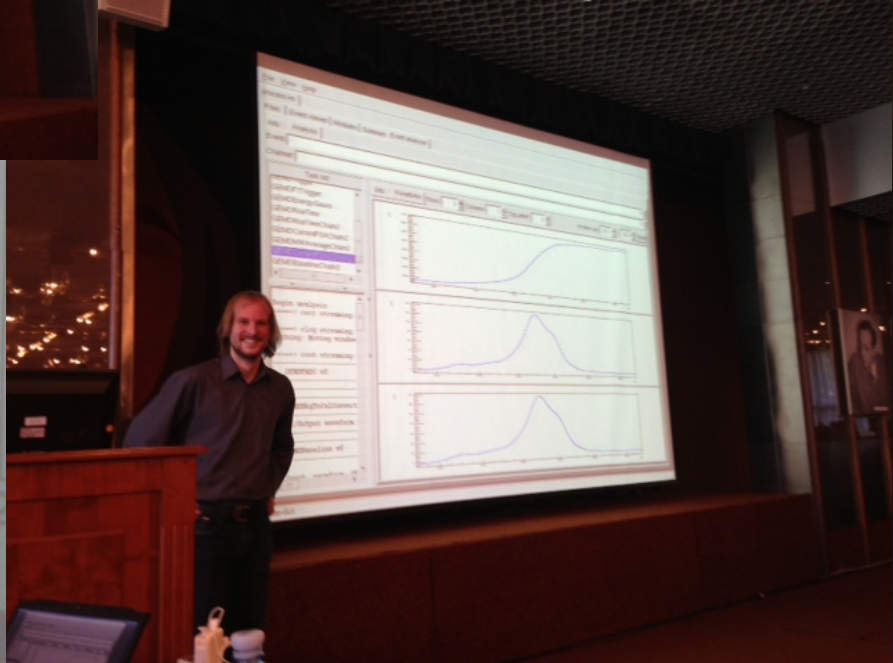
- 3 Data sets: golden, silver, BEGe
- Energy calibration method and parameters
- Unblind traces for PSD
- PSD method and cuts
- Statistical treatment of results:
- Likelihood fit of 3 indep. data sets ('global fit')
- Frequentist (constraint profile likelihood)
- Bayesian
-

Unblinding at Dubna: the bets of the collaboration

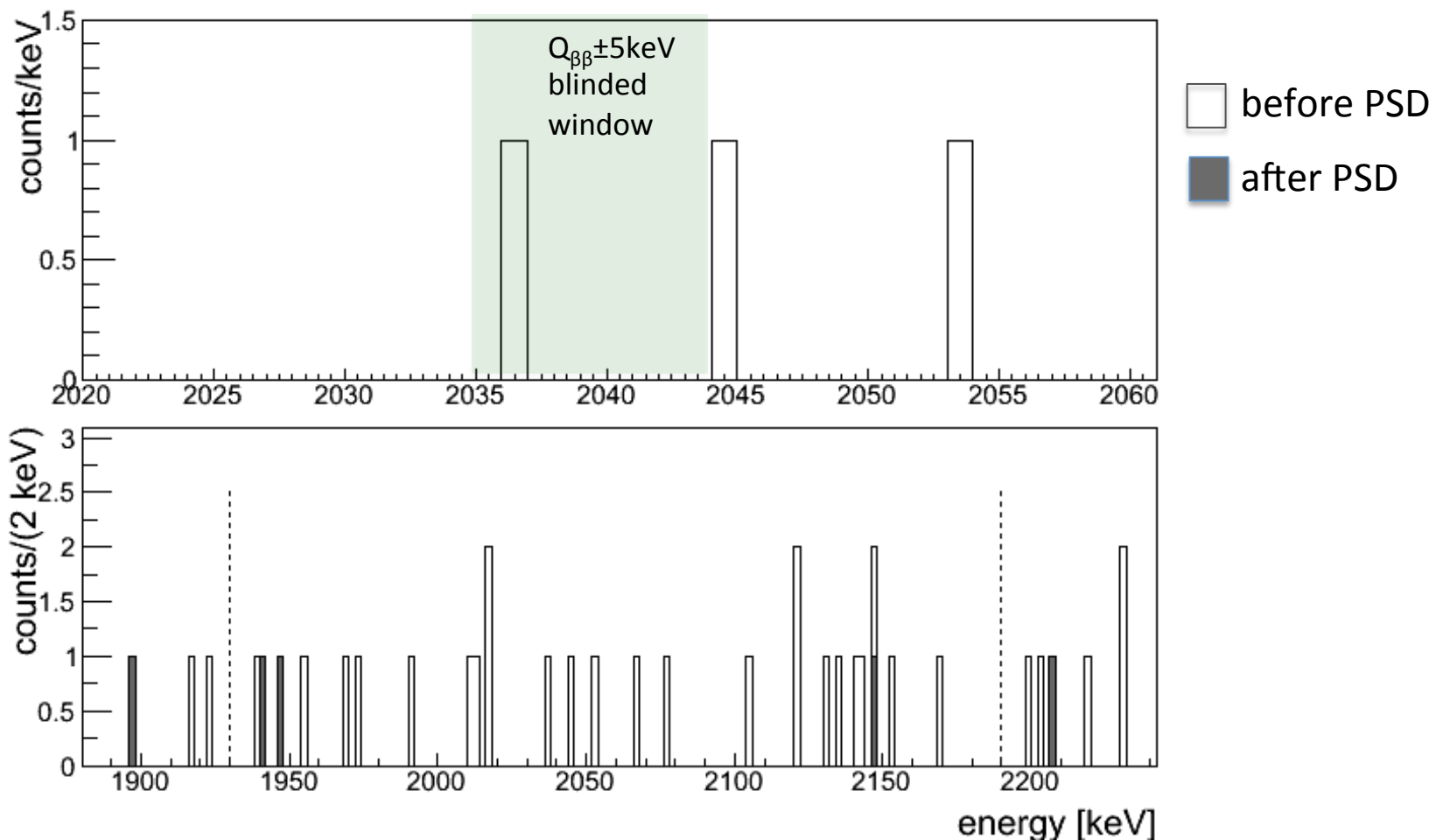




hsub_0	
Entries	664070
Mean	2042
RMS	12.87

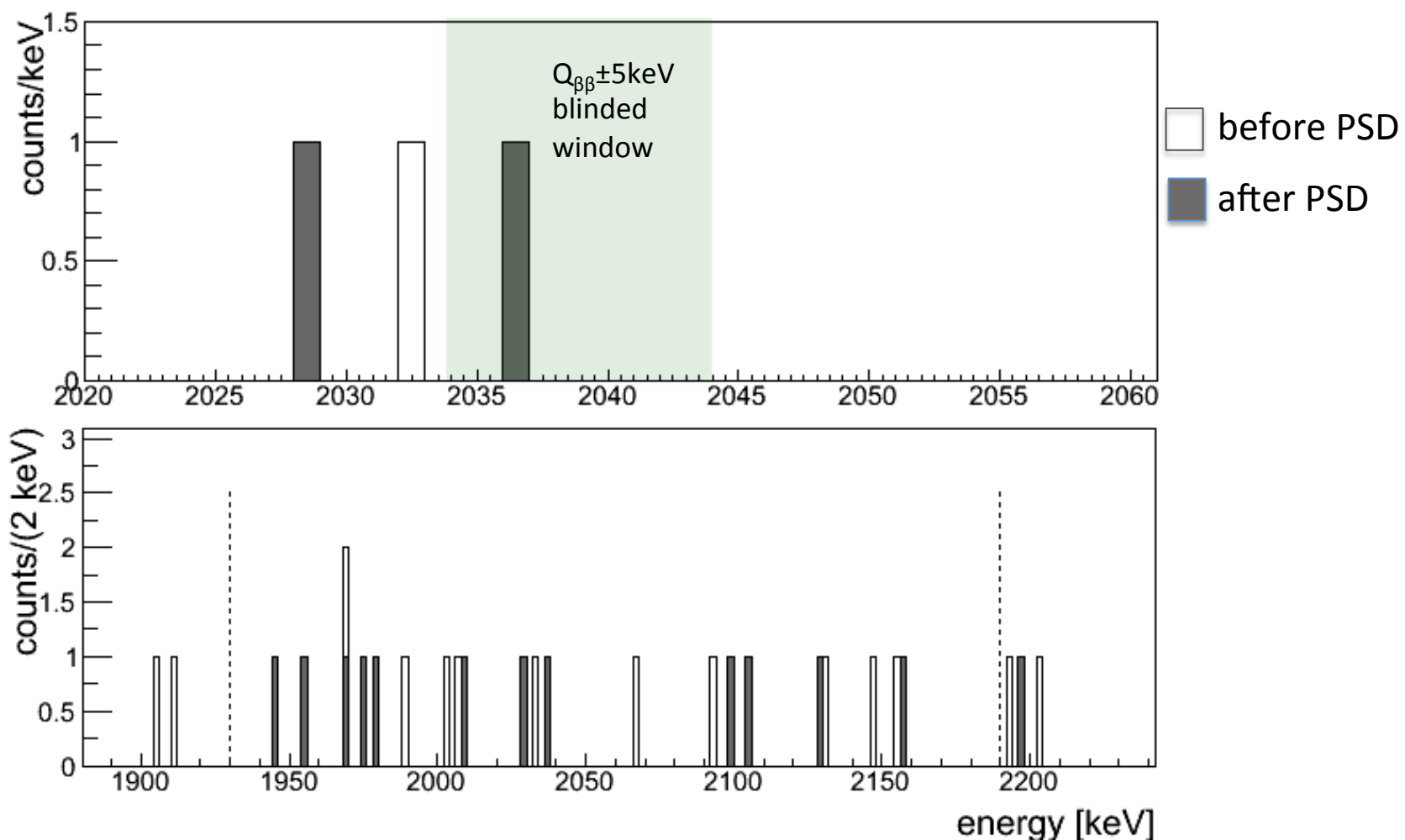


Unblinding: BEGe data set (2.4 kg yr)



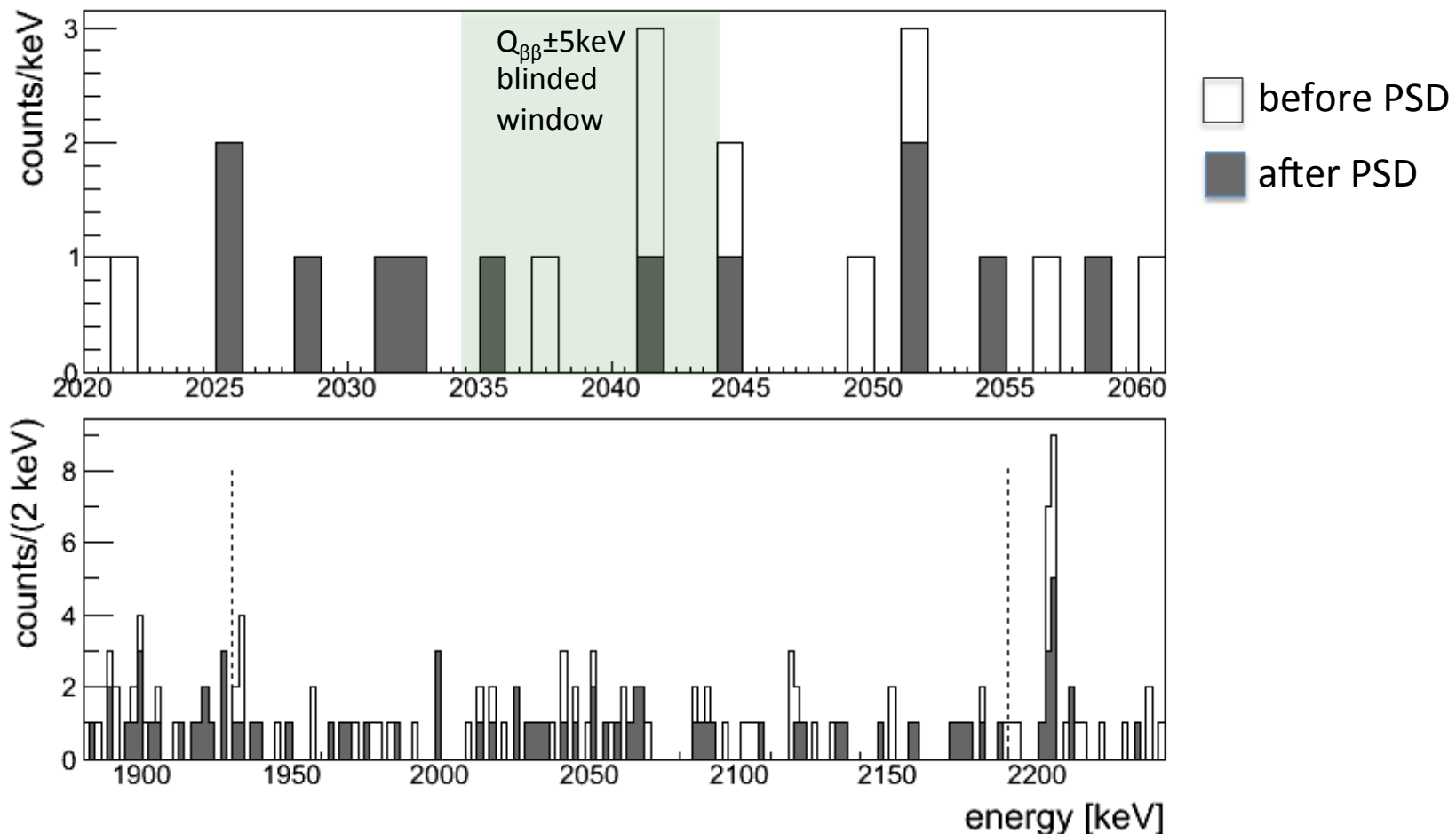
BEGe data set: 1 event in blinded window
0 event survive PSD cut

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



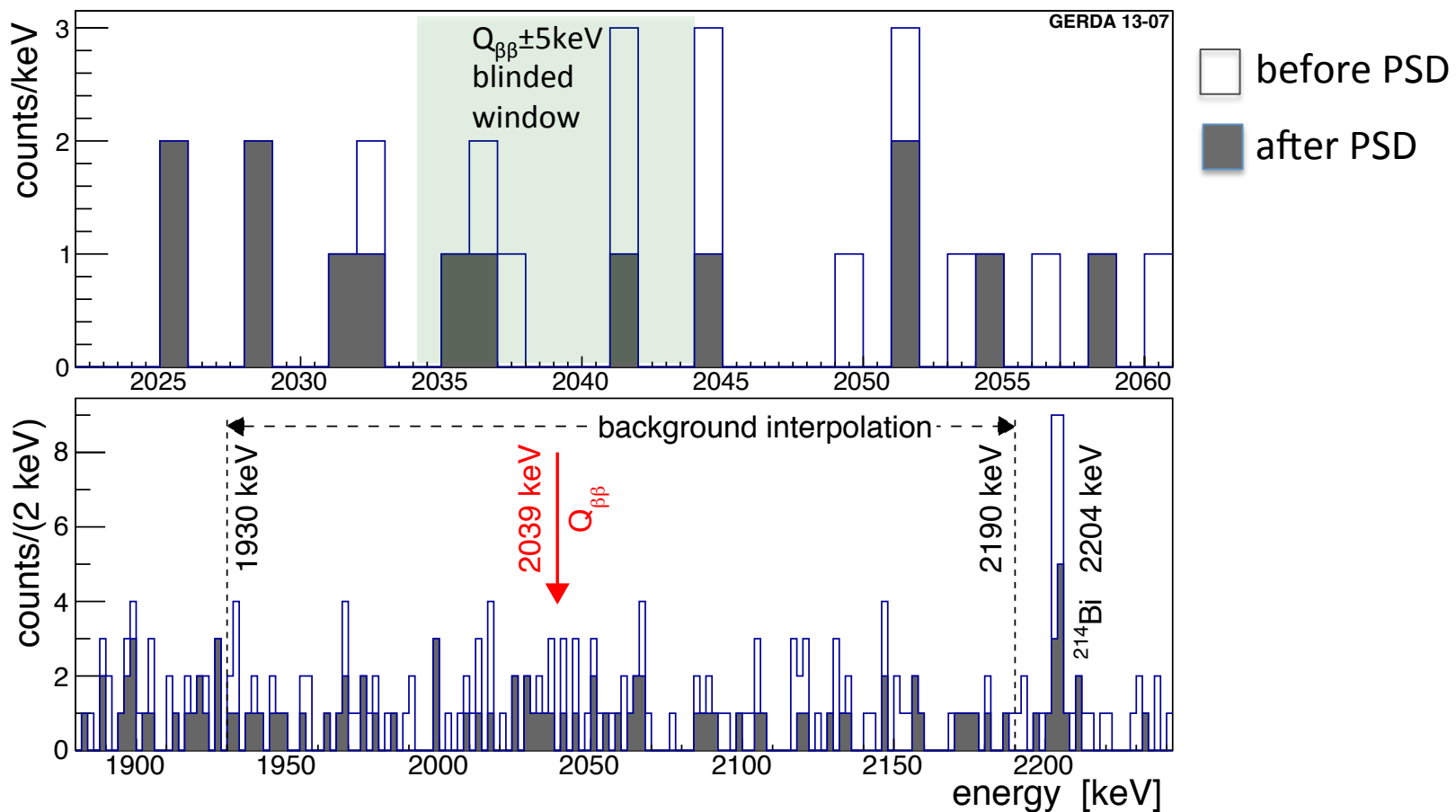
Silver data set: 1 event in blinded window
1 event survives PSD cut

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

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
<i>golden</i>	ANG 5	2041.8	18-Nov-2011 22:52	no	0.344		0.366
<i>silver</i>	ANG 5	2036.9	23-Jun-2012 23:02	yes	0.518		0.366
<i>golden</i>	RG 2	2041.3	16-Dec-2012 00:09	yes	0.682		0.364
<i>BEGe</i>	GD32B	2036.6	28-Dec-2012 09:50	no		0.067	0.965÷1.070
<i>golden</i>	RG 1	2035.5	29-Jan-2013 03:35	yes	0.713		0.372
<i>golden</i>	ANG 3	2037.4	02-Mar-2013 08:08	no	0.205		0.345
<i>golden</i>	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	$\mathcal{E}[\text{kg}\cdot\text{yr}]$	$\langle\epsilon\rangle$	bkg	BI [†])	cts
without PSD			(in 230 keV)		
<i>golden</i>	17.9	0.688 ± 0.031	76	18 ± 2	5
<i>silver</i>	1.3	0.688 ± 0.031	19	63^{+16}_{-14}	1
<i>BEGe</i>	2.4	0.720 ± 0.018	23	42^{+10}_{-8}	1
with PSD					
<i>golden</i>	17.9	$0.619^{+0.044}_{-0.070}$	45	11 ± 2	2
<i>silver</i>	1.3	$0.619^{+0.044}_{-0.070}$	9	30^{+11}_{-9}	1
<i>BEGe</i>	2.4	0.663 ± 0.022	3	5^{+4}_{-3}	0

Counts
in blinded
window
(BW)

[†]) in units of 10^{-3} cts/(keV·kg·yr).

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

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

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

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

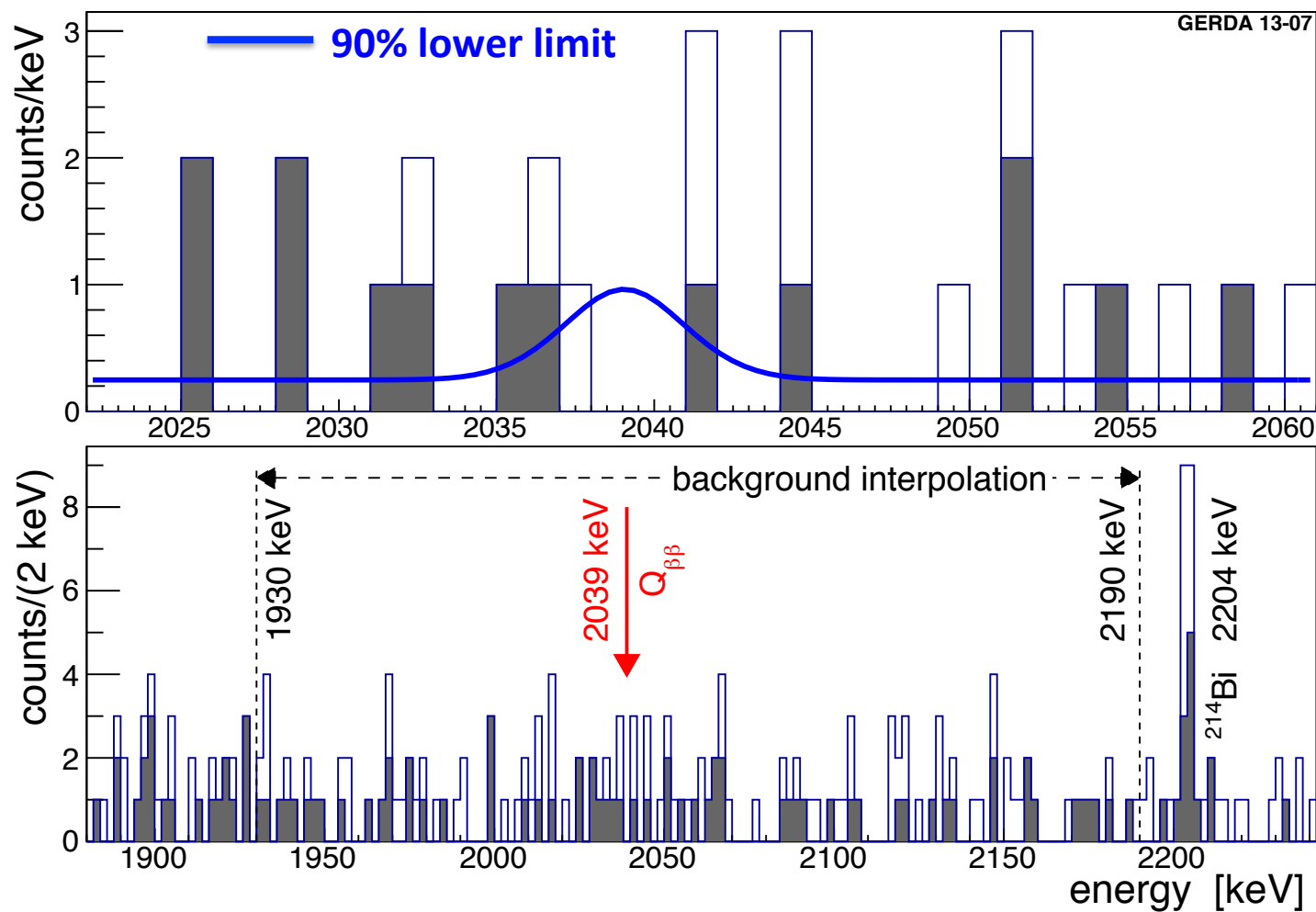
ϵ_{fep} : full energy peak efficiency for $0\nu\beta\beta$

ϵ_{psd} : signal acceptance

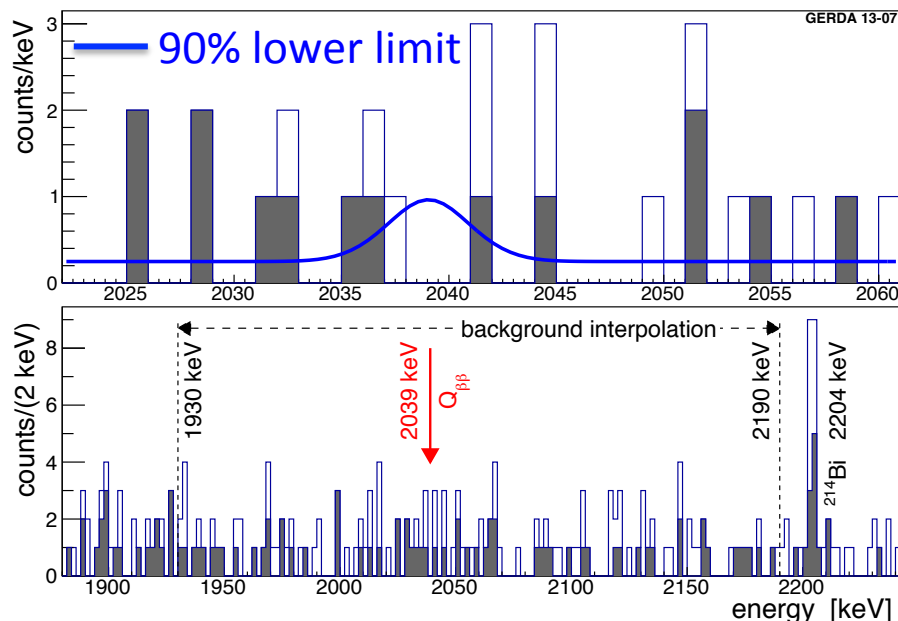
Data set	Exposure (kg yr)
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

	$\langle f_{76} \rangle$	$\langle f_{\text{av}} \rangle$	$\langle \epsilon_{\text{fep}} \rangle$	$\langle \epsilon_{\text{psd}} \rangle$	$\langle \epsilon \rangle$
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	0.10
	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^{0ν}=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 corresponds to N^{0ν}<3.5 cts
- Median sensitivity (90% C.L.): >2.4×10²⁵ yr

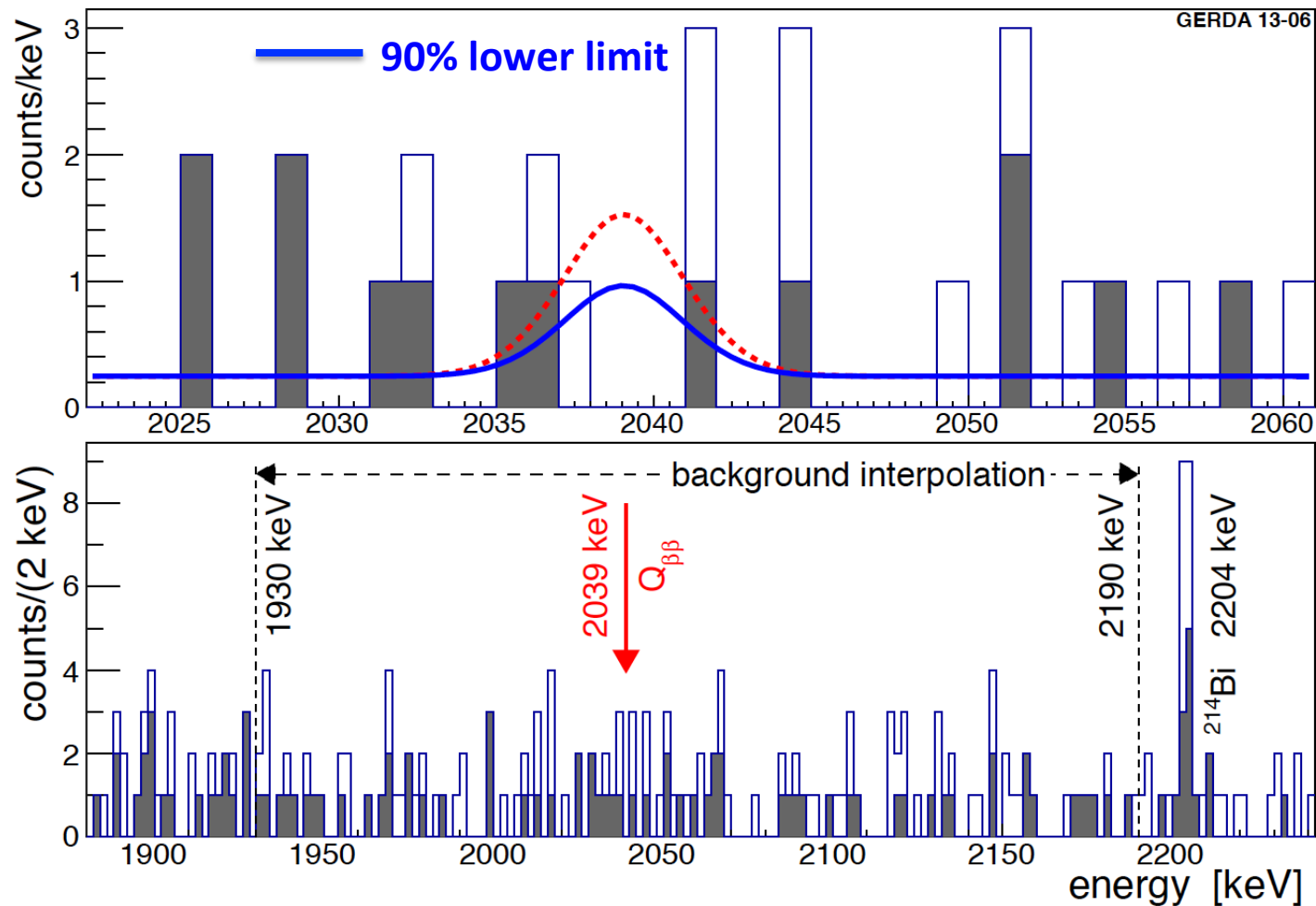
Bayesian:

- Flat prior for 1/T
- Posterior distribution for T_{1/2}^{0ν}
- Best fit: **N^{0ν}=0**
- 90% credible interval:
- Median sensitivity: (90% C.I.): >2.0×10²⁵ yr

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

Systematics folded: limit weakened by 1.5%

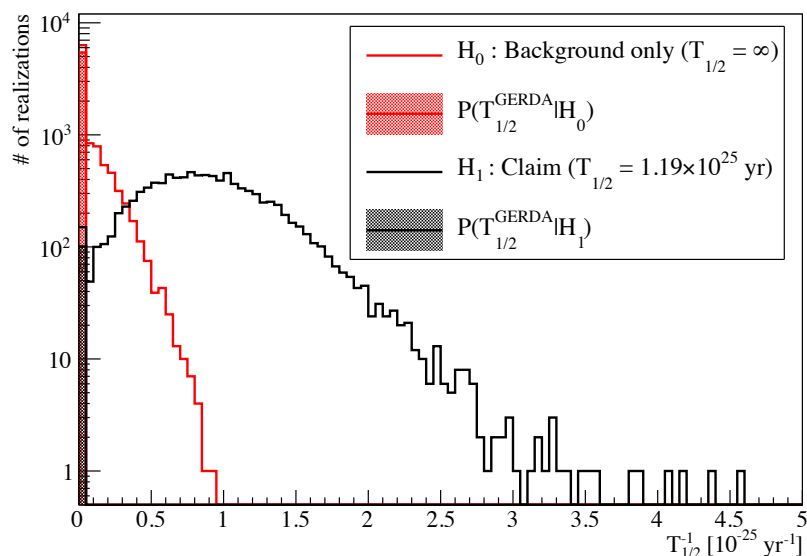
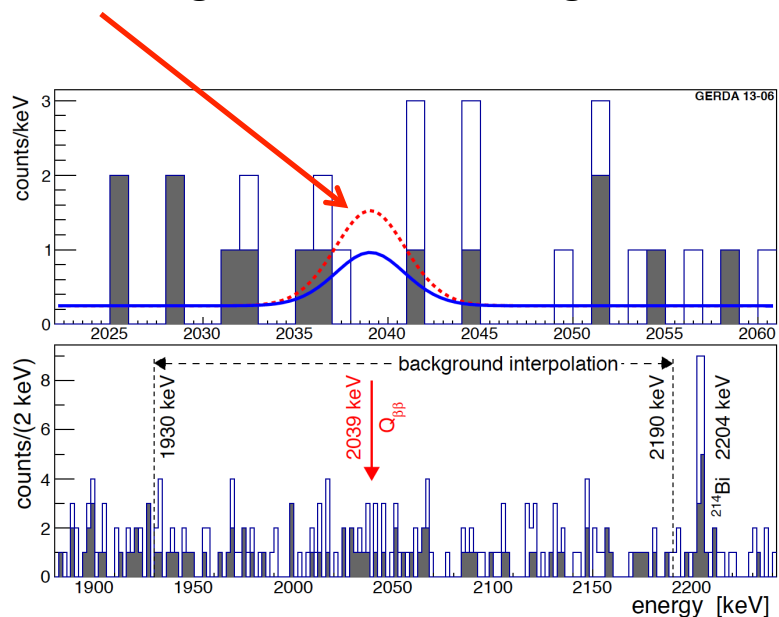
Comparison with Phys. Lett. B 586 198 (2004) claim



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

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

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



H1: claimed signal: 5.9 ± 1.4

H0: background only

Bayes factor: $P(H1)/P(H0) = 0.024$

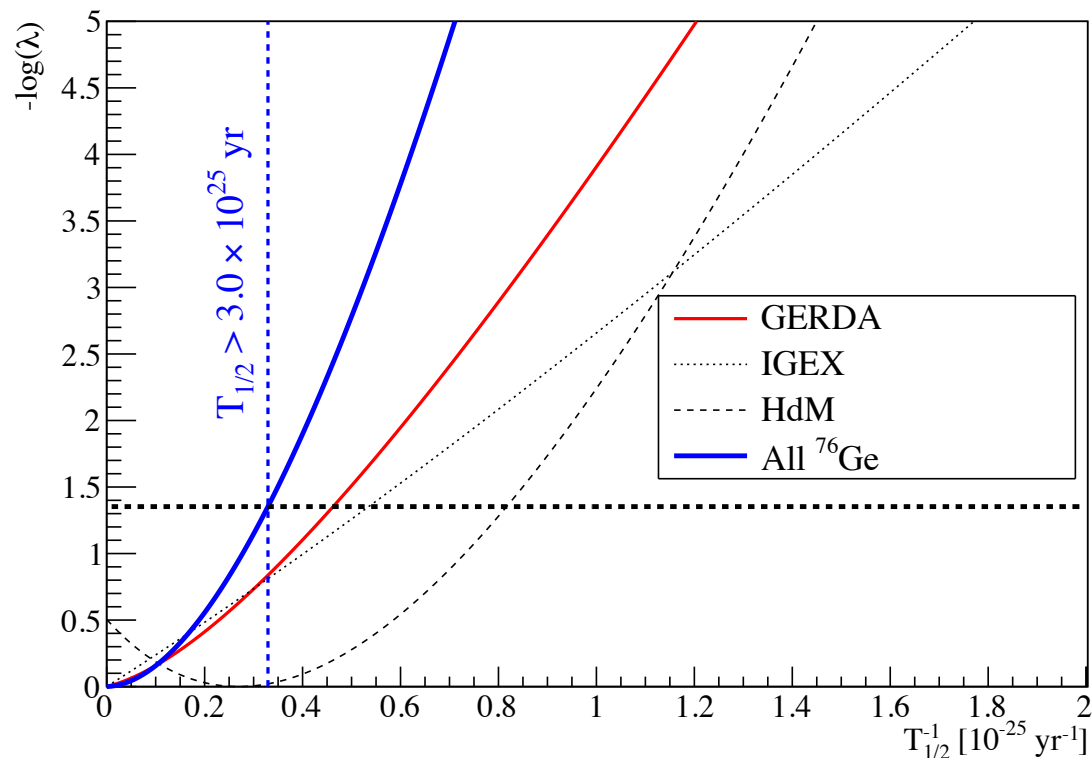
p-value from profile likelihood

$P(N=0 = 0 | H1) = 0.01$ (0.006 if $1/T$ unconstrained)

→ Claim refuted with high probability

Combined analysis with HdM and IGEX experiments

Profile Likelihood - All ^{76}Ge data



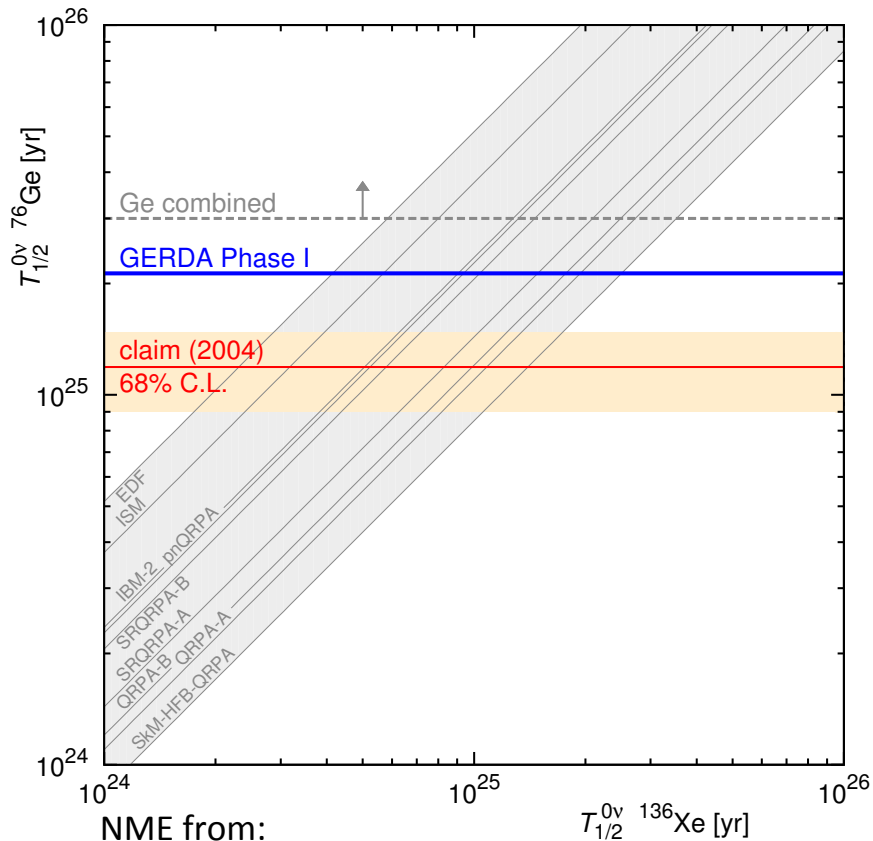
HdM: Eur. Phys. J. A 12, 147 (2001)
 IGEX: Phys. Rev. D 65, 092007 (2002),
 Phys. Rev. D 70 078302 (2004)

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

Identical limits with
 Frequentists & Bayesian analysis

Bayes factor: $P(H1)/P(H0) = 2 \times 10^{-4}$ strongly disfavors claim

Comparison is independent of NME and of physical mechanism which generates $0\nu\beta\beta$



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

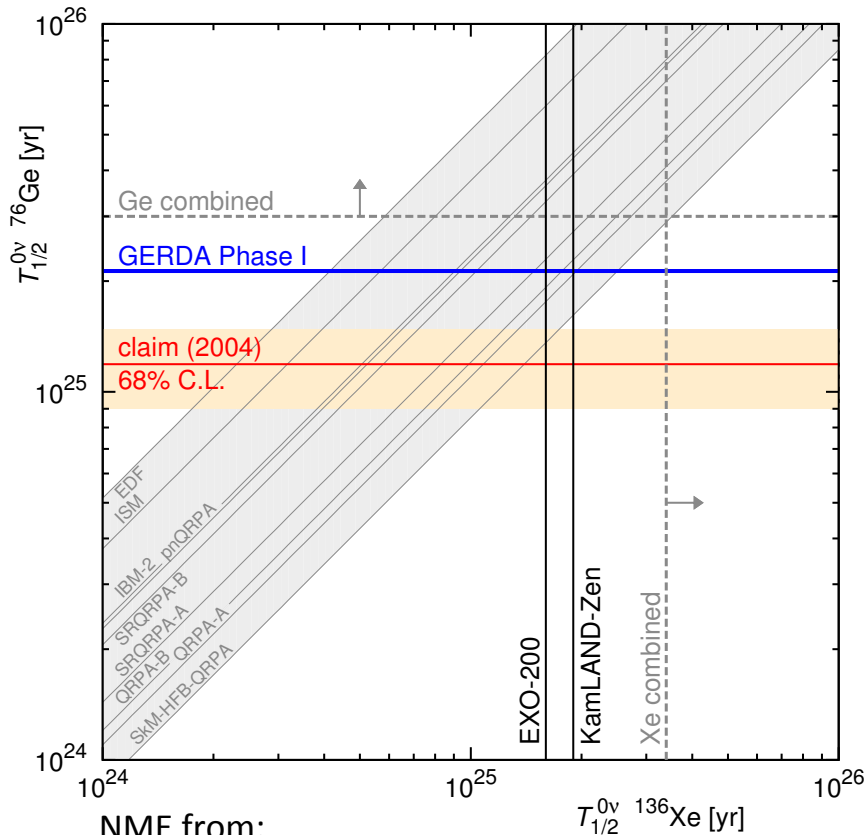
H0: background only

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

NME from:

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

Ge combined: $\langle m_{ee} \rangle < 0.2-0.4$



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

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
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*	$^{76}\text{Ge} + ^{136}\text{Xe}$	0.002	Model dependent: NME, leading term

*: with conservative NME ratio $M_{0\nu}(^{136}\text{Xe})/M_{0\nu}(^{76}\text{Ge}) \approx 0.4$ 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 $0\nu\beta\beta$ -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:	10^{-2}
GERDA+IGEX+HdM:	10^{-4}
- **Limit on half-life:**

GERDA:	$T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yr (90% C.L.)
GERDA+IGEX+HdM:	$T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yr (90% C.L.) ($\langle m_{ee} \rangle < 0.2-0.4$)
- Results reached after only 21.6 kg yr exposure because of **unprecedented low background**: bgd counts in $\pm 2\sigma$ after analysis cuts:
0.01 cts / (mol yr) (cf. EXO: 0.07, KL: 0.67)
- **Getting ready for Phase II.....**

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](#)

$2\nu\beta\beta$ 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 $0\nu\beta\beta$ decay in ^{76}Ge**

[Eur. Phys. J. C 73 \(2013\) 2330 DOI: 10.1140/epjc/s10052-013-2330-0](#)

[the plot release](#)