The quest for Majorana neutrinos:

Results from the GERDA search for 0νββ decay

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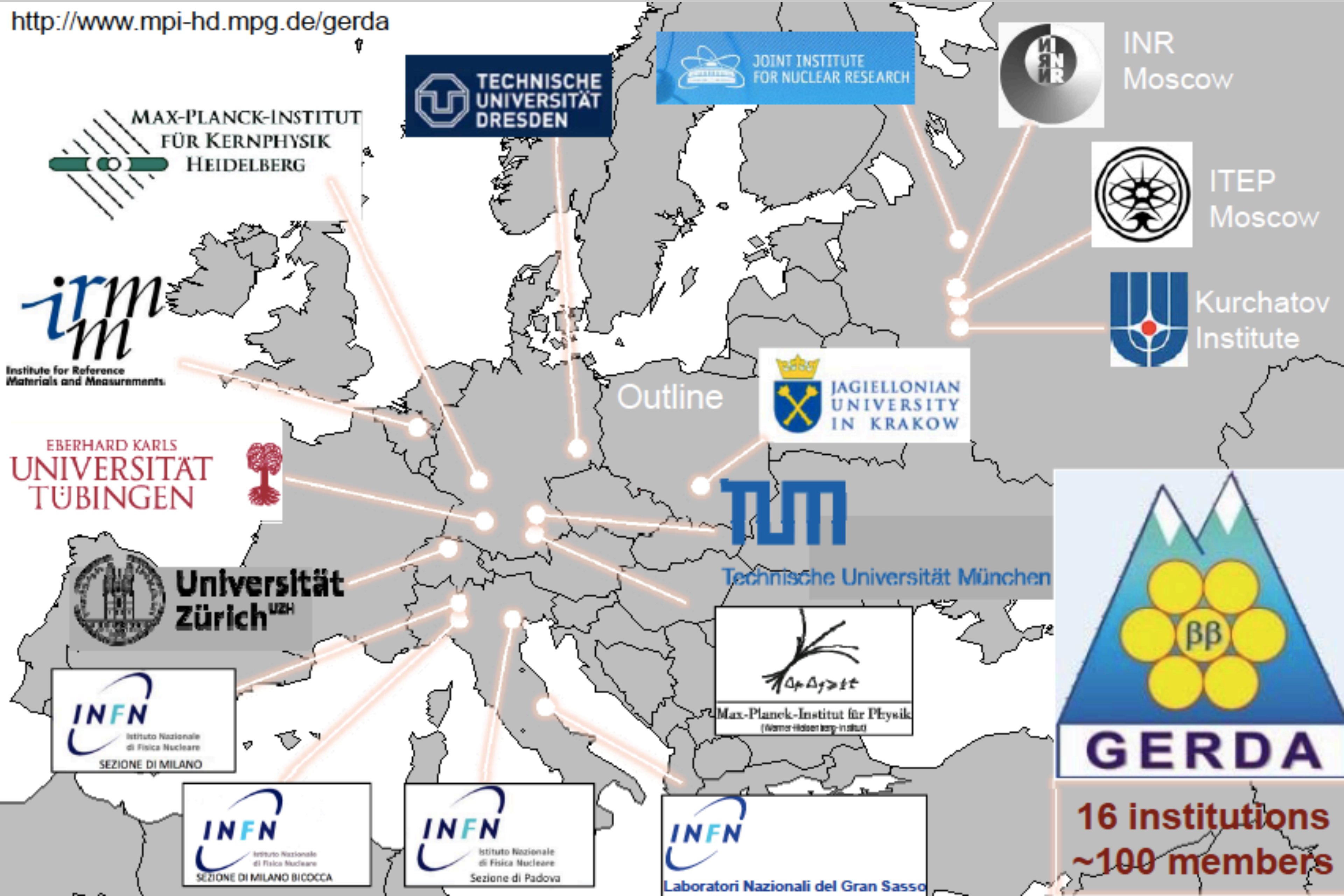
Seminar am Zentrum für Teilchen- und Astroteilchenphysik Karlsruhe KIT)

Januar 21, 2014

The GERDA collaboration

http://www.mpi-hd.mpg.de/gerda



Max-Planck-Institut für Kernphysik Heidelberg

Technische Universität Dresden

Joint Institute for Nuclear Research

INR Moscow

ITEP Moscow

Kurchatov Institute

irmm Institute for Reference Materials and Measurements

Jagiellonian University in Krakow

Eberhard Karls Universität Tübingen

TUM Technische Universität München

Universität Zürich UZH

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

INFN Istituto Nazionale di Fisica Nucleare Sezione di Milano

INFN Istituto Nazionale di Fisica Nucleare Sezione di Milano Bicocca

INFN Istituto Nazionale di Fisica Nucleare Sezione di Padova

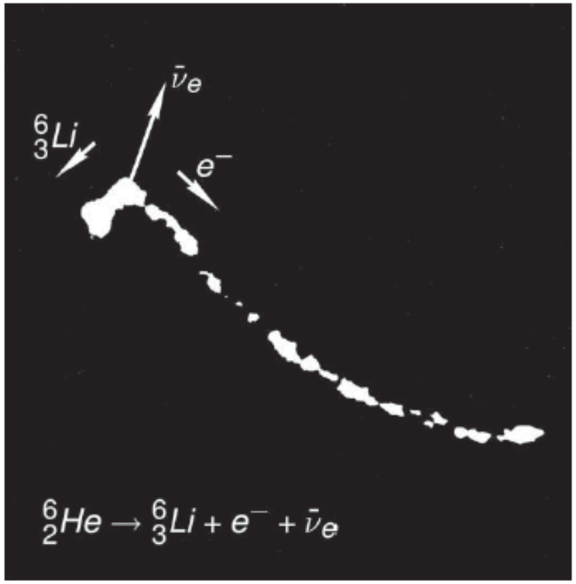
INFN Laboratori Nazionali del Gran Sasso

16 institutions
~100 members

1956: The Neutrino Experiment at Debrecen by J. Csikai and A. Szalay

Reconstruction of neutrino energy and momentum event-by-event

EPS Historic Site: The Neutrino Experiment at Debrecen
by J. Csikai and A. Szalay
Debrecen, Hungary
October 25, 2013



European Physical Society – EPS Historic Site

The Neutrino Experiment at MTA Atomki

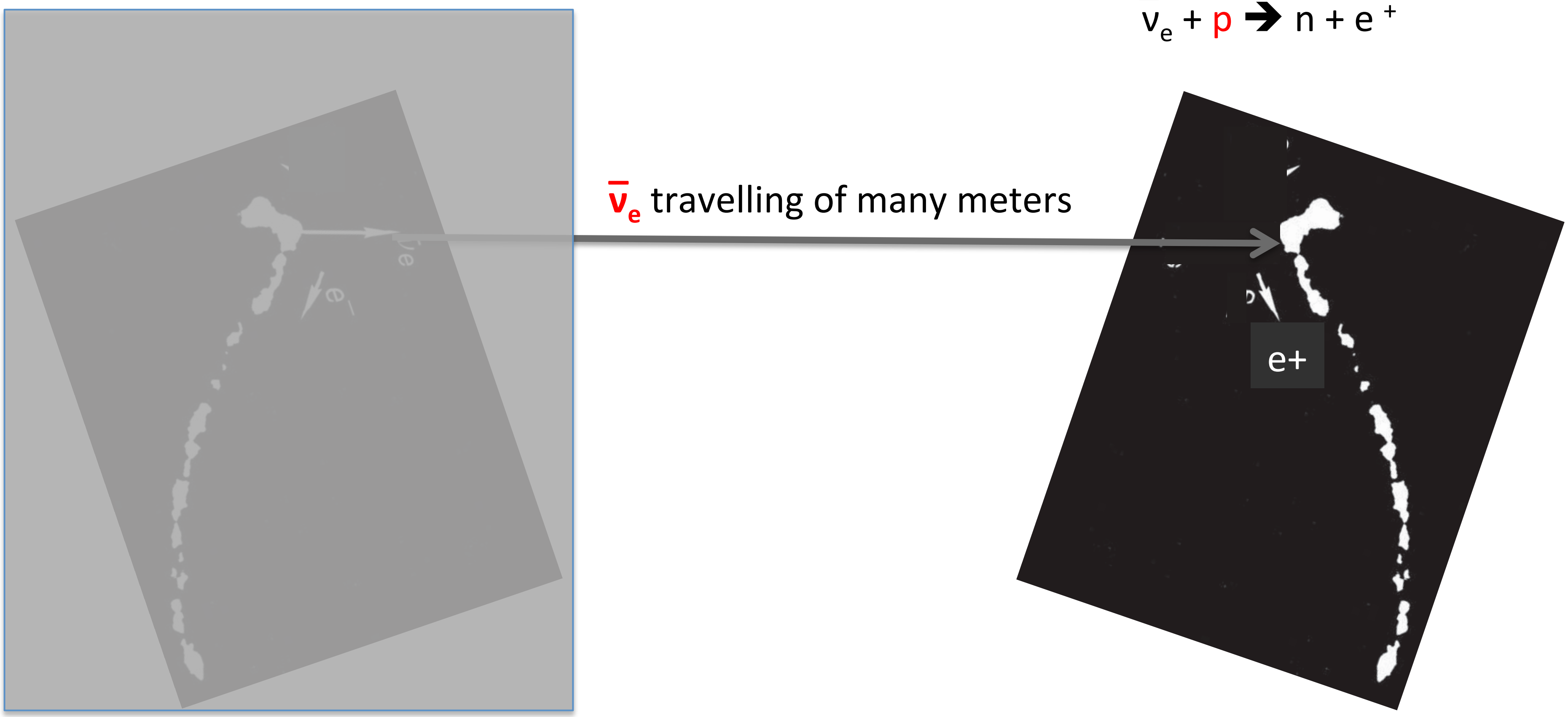
USING A CLOUD CHAMBER LOCATED IN THIS BUILDING, IN 1956 J. CSIKAI AND A. SZALAY PHOTOGRAPHED BETA-DECAY EVENTS. IN SOME CASES THE ANGLE BETWEEN THE TRACKS OF THE ELECTRON AND THE RESIDUAL NUCLEUS IMPLIED THE EMERGENCE OF AN UNDETECTED THIRD PARTICLE IN THE DECAY. THUS CONFIRMING THE EXISTENCE OF THE NEUTRINO, THE DEBRECEN NEUTRINO EXPERIMENT LAID A BRICK OF THE FOUNDATION OF MODERN PHYSICS.

1956: The Reines-Cowan experimental concept

Source: Anti-Neutrinos
from nuclear reactor core

Detection via capture on
protons (H_2O):

$\bar{\nu}_e + p \rightarrow n + e^+$



$\bar{\nu}_e$ travelling of many meters

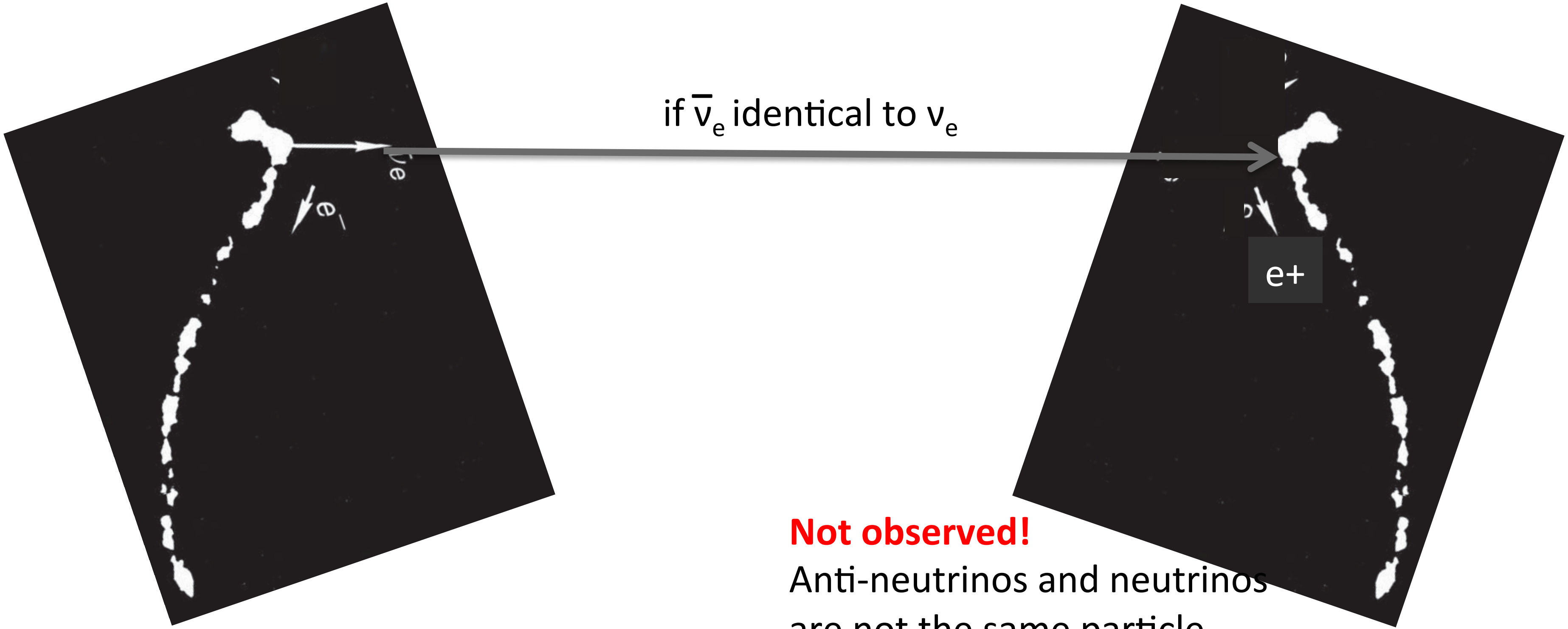
Beta-decays of neutron rich
fission products

1955 Ray Davis: are neutrinos and anti-neutrinos identical particles?

Source: Anti-Neutrinos
from nuclear reactor core

Detection via capture on
bound **neutrons** (Cl)

ν_e + „**n**“ → „p“ + e^-

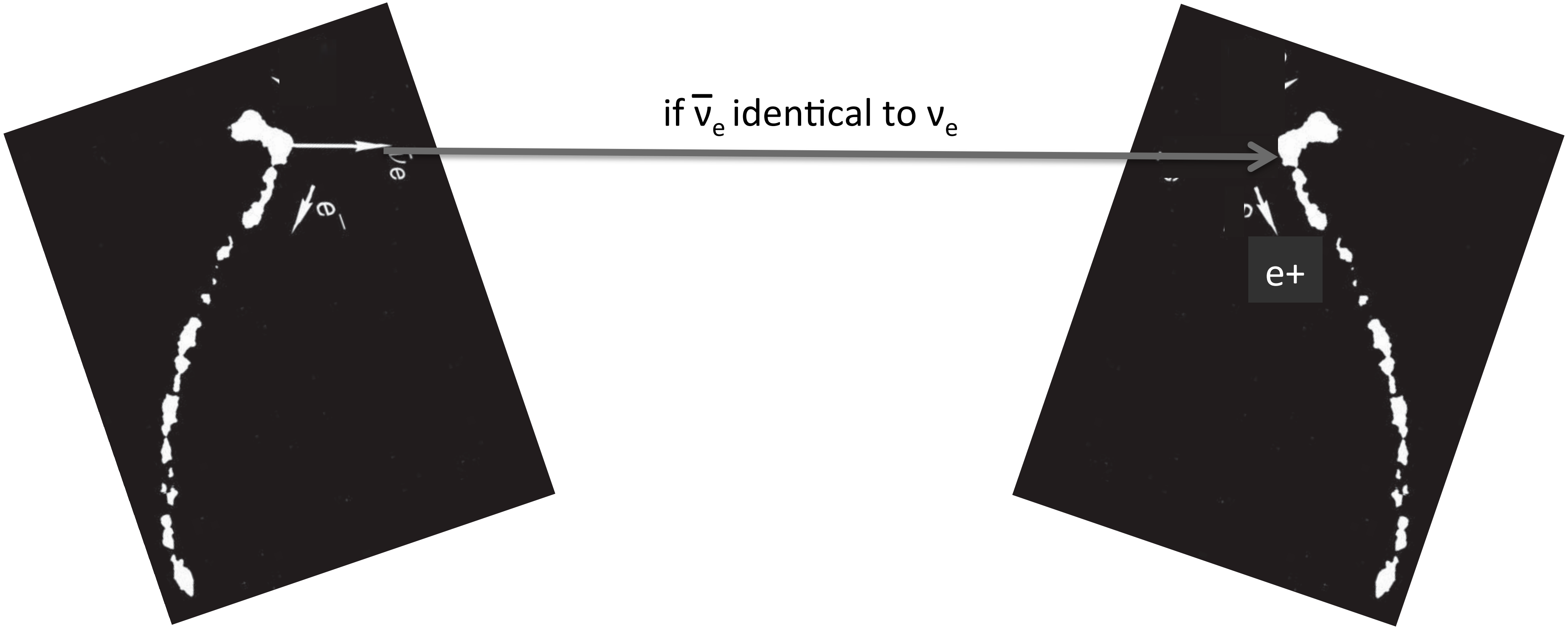


Not observed!
Anti-neutrinos and neutrinos
are not the same particle
(neutrinos are left handed
Goldhaber 1957)

Are neutrinos and anti-neutrinos identical particles?

Today we know that

- neutrinos are massive particles, thus helicity is not a good quantum number
- therefore, emission of anti-neutrinos with „wrong“ helicity state possible (prop. m/E) possible

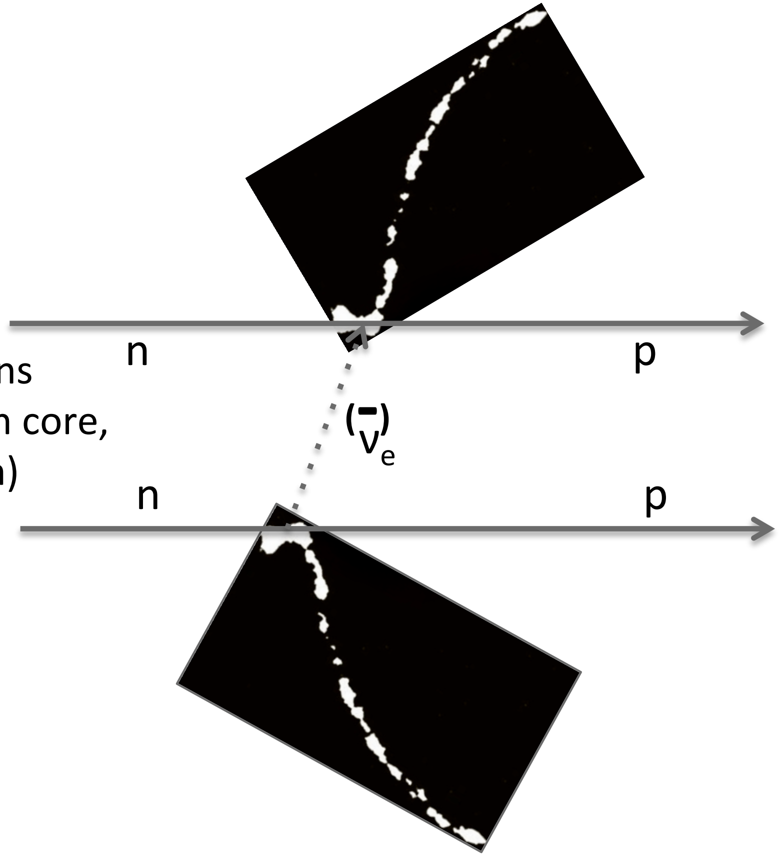


if $\bar{\nu}_e$ identical to ν_e

Neutrinoless Double Beta Decay (0νββ)

Today we know that

- Neutrinos are massive particles, thus helicity is not a good quantum number
- Therefore, emission of anti-neutrinos with „wrong“ helicity state possible (prop. m/E) possible


n

p

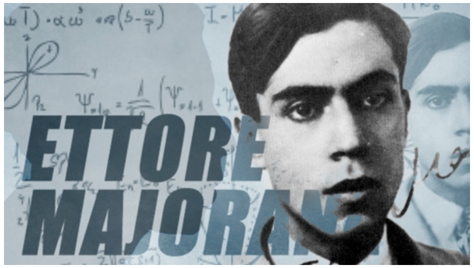
$\overset{(-)}{\nu}_e$

n

p

(Nukleons bound in core, ≈10^{-15} m)

0νββ-decay would imply that neutrinos are **Majorana particle**



The quest(s)

A **Majorana fermion** is a fermion that is its own antiparticle

(N.B.: so far, no elementary fermions are known to be their own antiparticle)

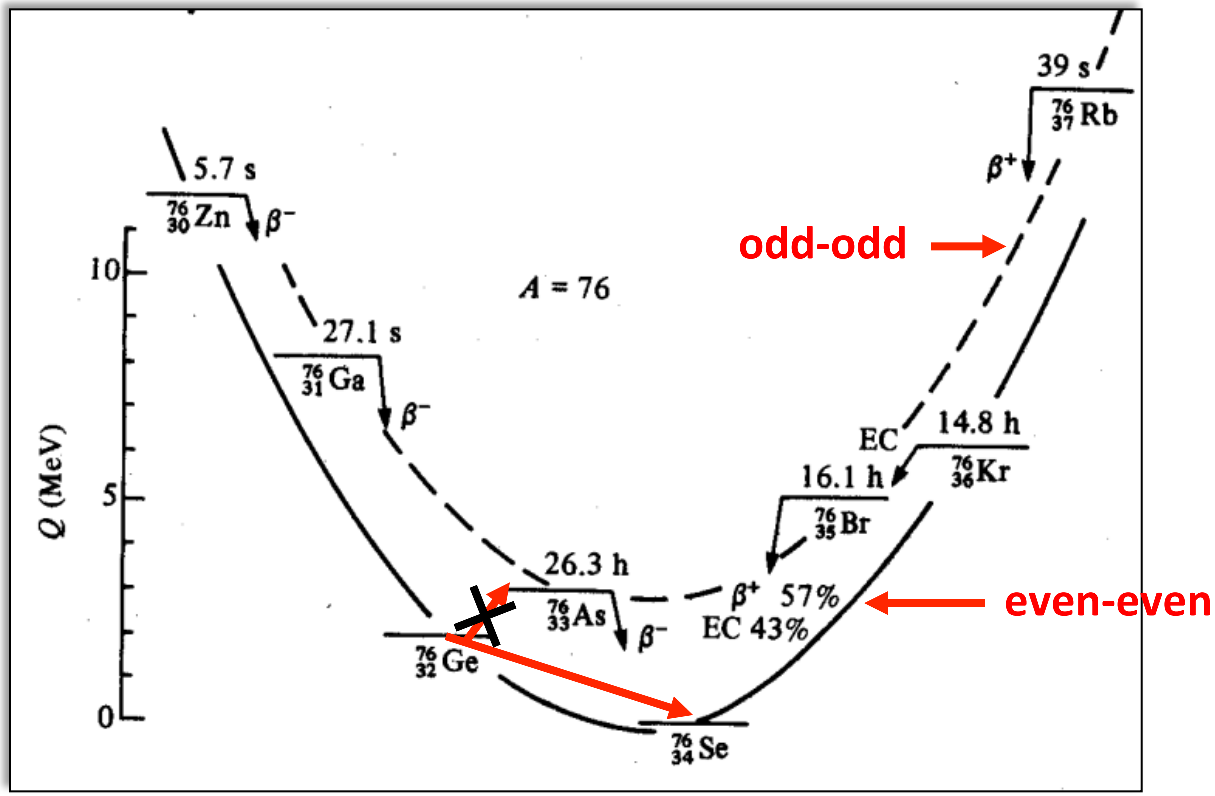
Are neutrinos Majorana fermions ?

Chi l'ha visto ?

Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci, Viale Regina Margherita 66 - Roma.

Ettore Majorana - Questo annuncio della famiglia Majorana apparve sulla «Domenica del Corriere» del 17 luglio 1938.

Double beta decay (DBD)

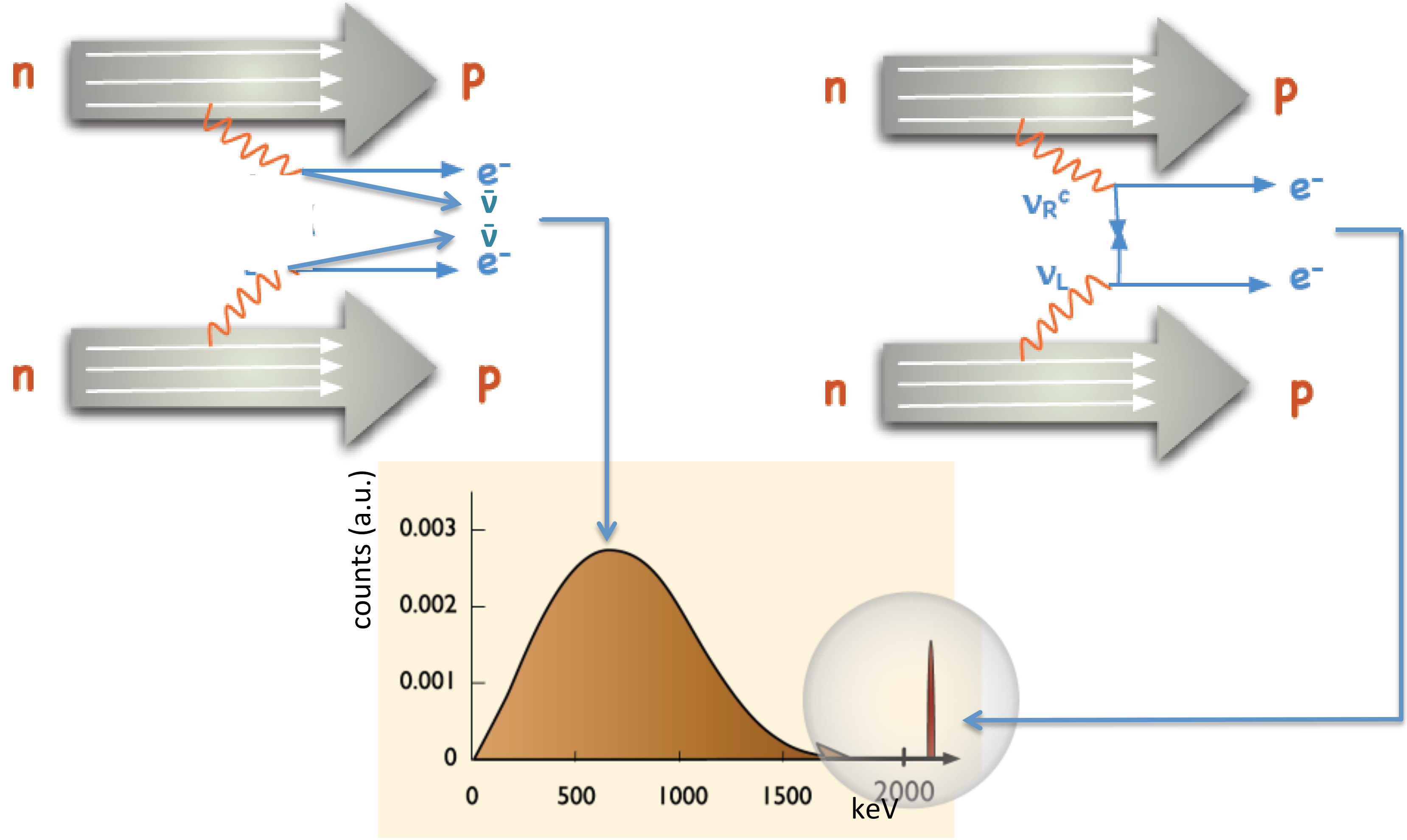


$Q_{\beta\beta}$ = (2039.061±0.007) keV B. J. Mount et al., Phys.Rev. 401 C81, 032501 (2010)

2νββ vs. 0νββ decay

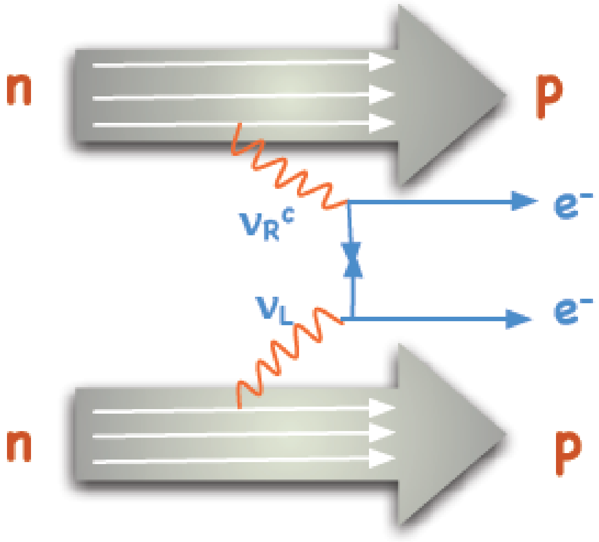
2-neutrino DBD

0-neutrino DBD



2-electron spectra

0νββ decay and neutrino mass



Expected decay rate:

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

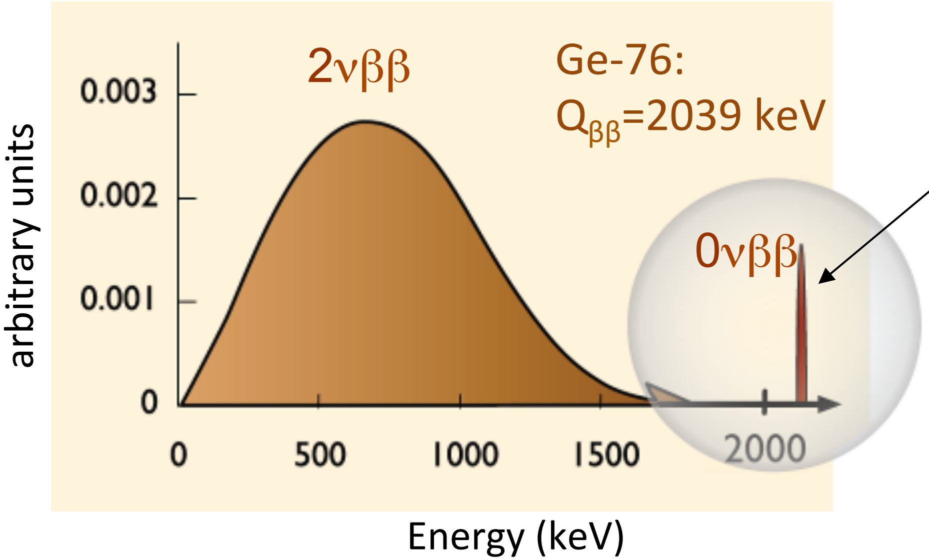
Phase space integral

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



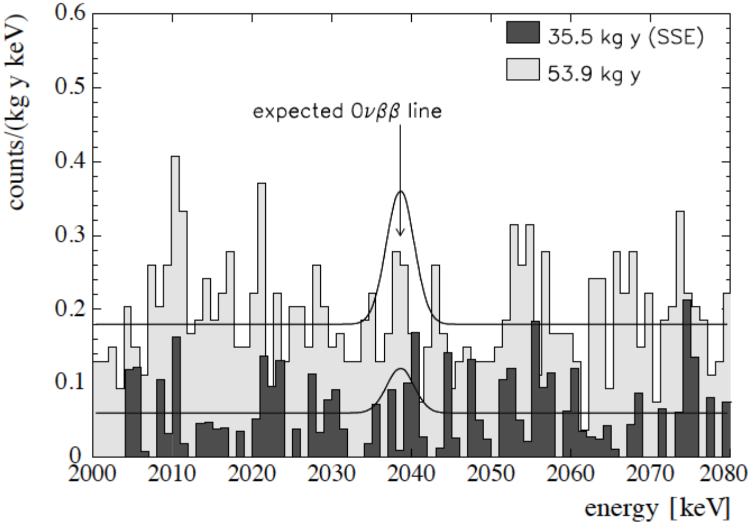
Experimental signatures:

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

Discovery would imply:

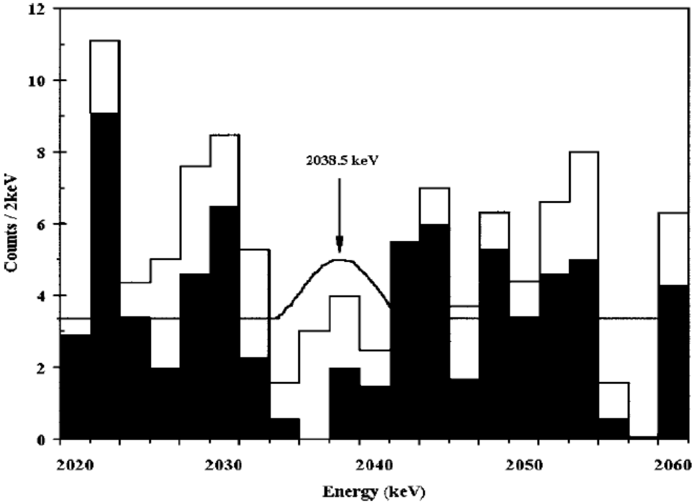
- lepton number violation ΔL = 2
- ν's have Majorana character
- mass scale & hierarchy
- physics beyond the standard model

^{76}Ge 0νββ search: state-of-the-art



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

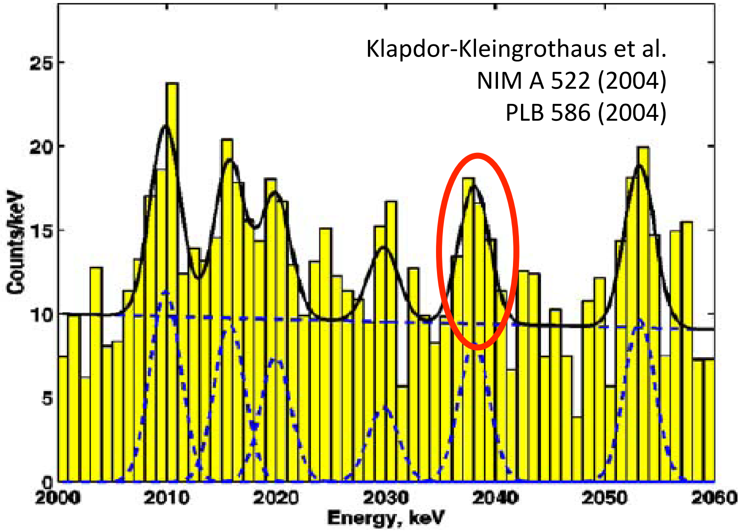
53.9 kg y (35.5 kg y): $T_{1/2}^{0\nu}$ >1.3 ×10^{25} yr (1.9 ×10^{25} yr)
(90% C.L.)



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

8.8 kg y: $T_{1/2}^{0\nu}$ >1.6 ×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):

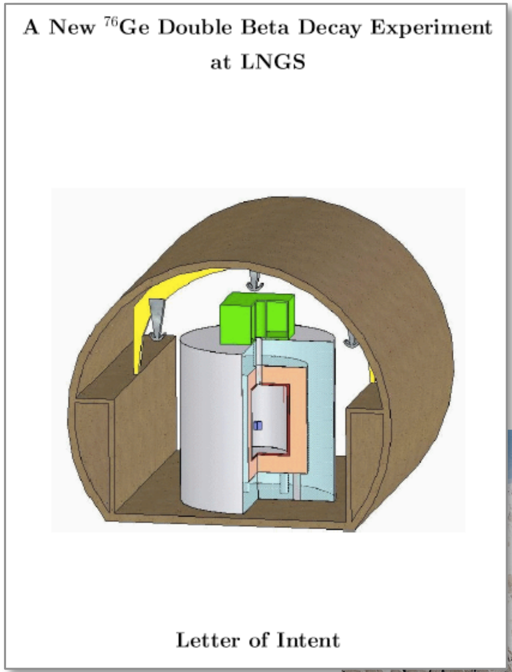
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

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)

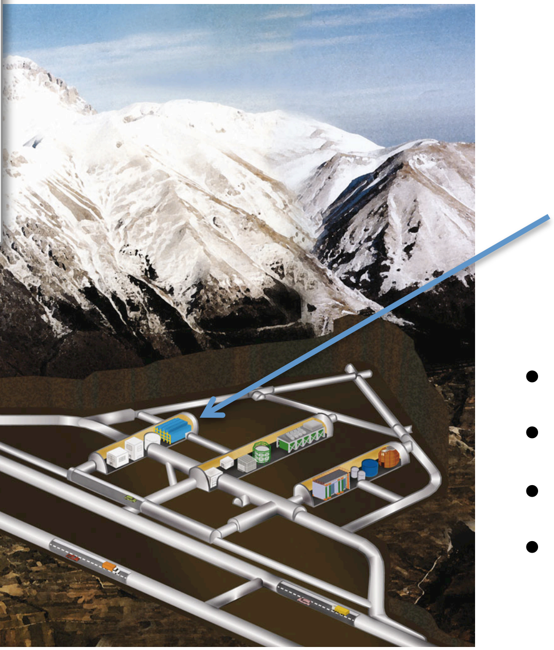
(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013)

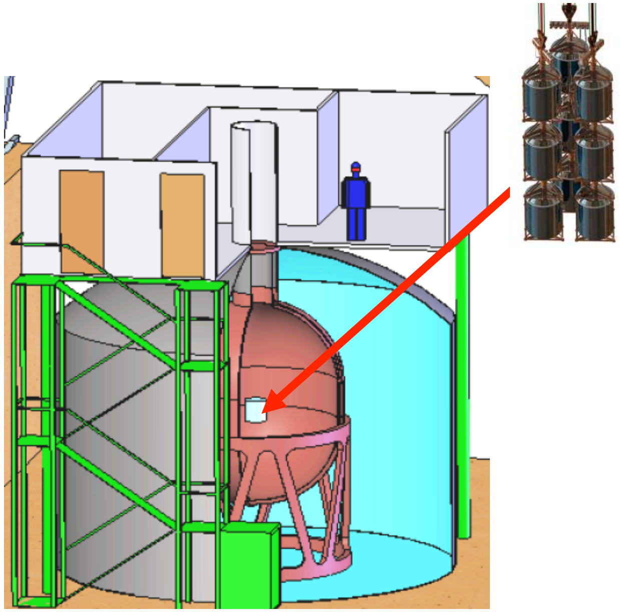
GERDA @ LNGS



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

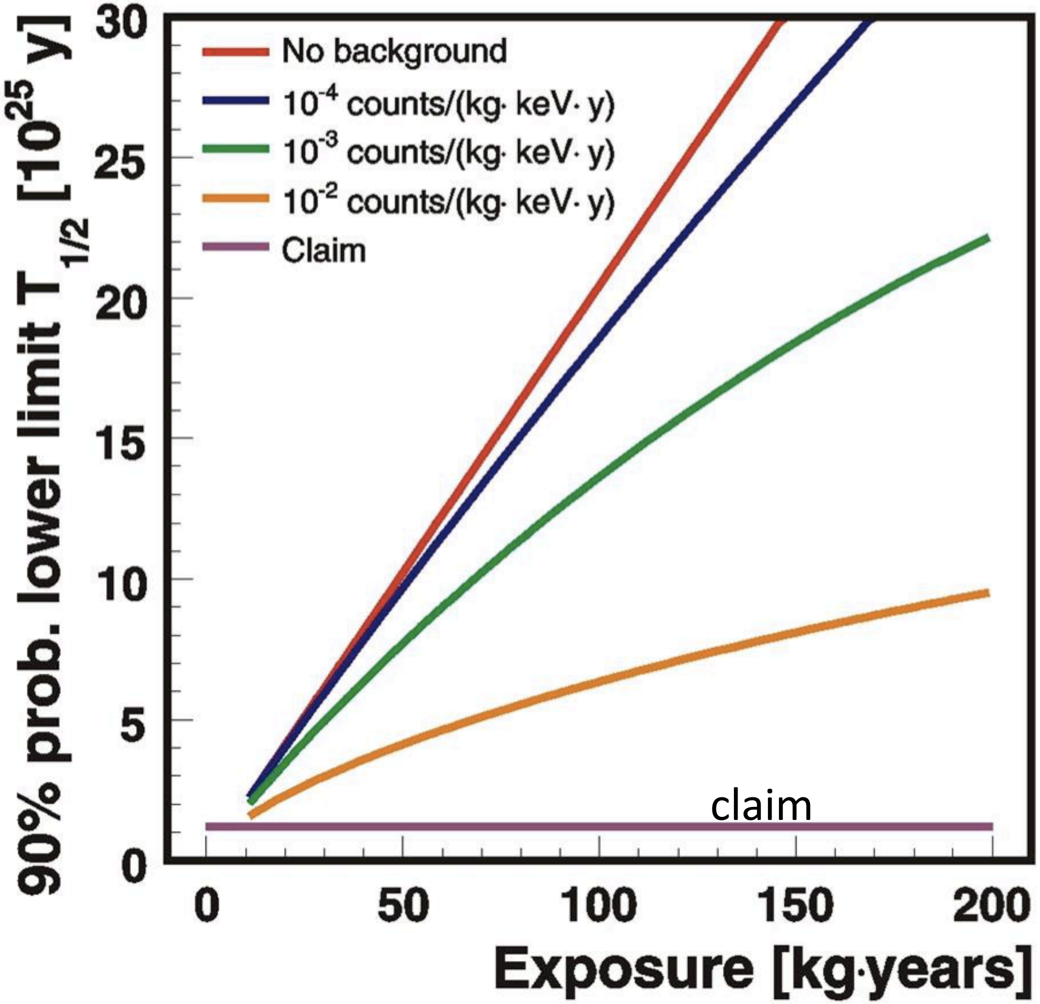
Letter of Intent



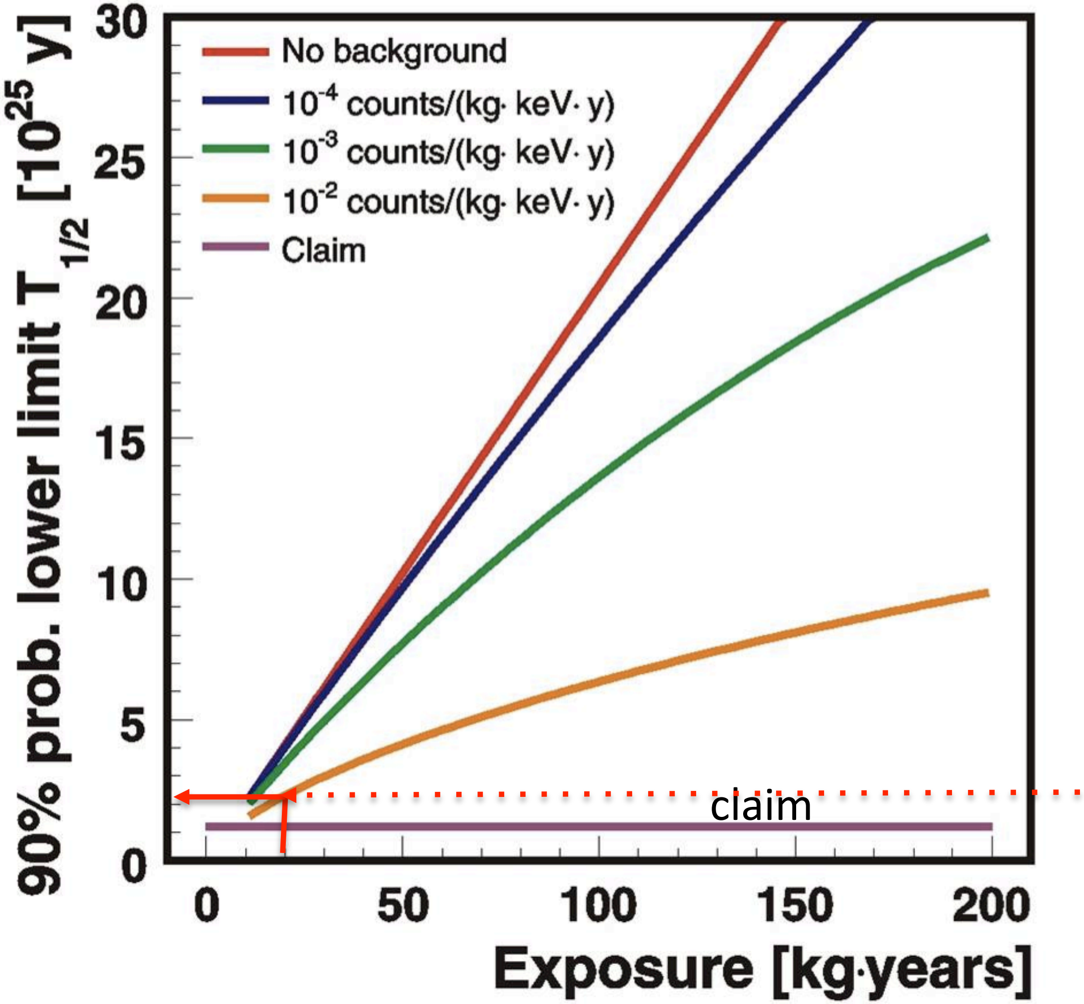


- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

GERDA Phases



GERDA Phases



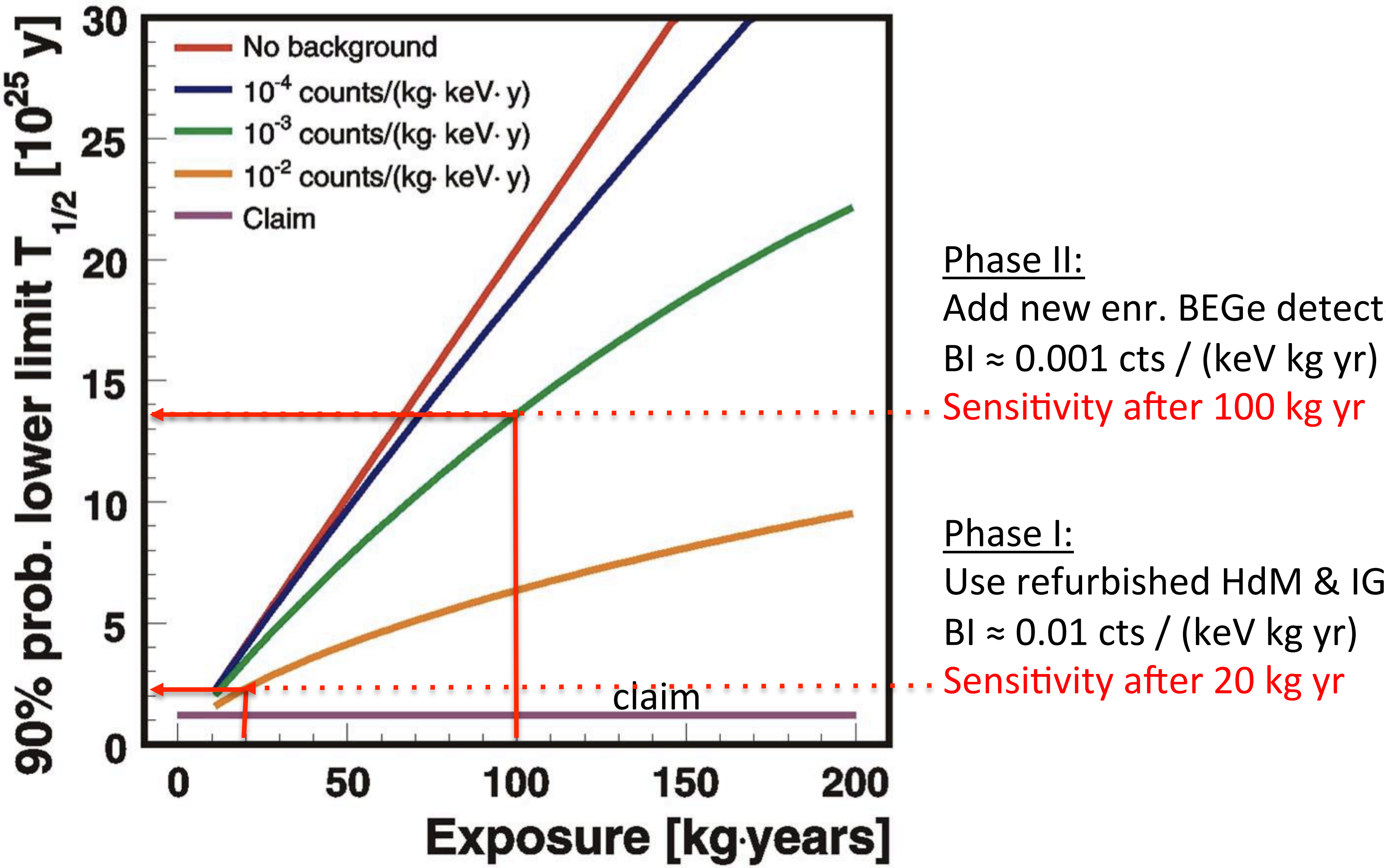
Phase I:

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

GERDA Phases



Phase II:

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

Phase I:

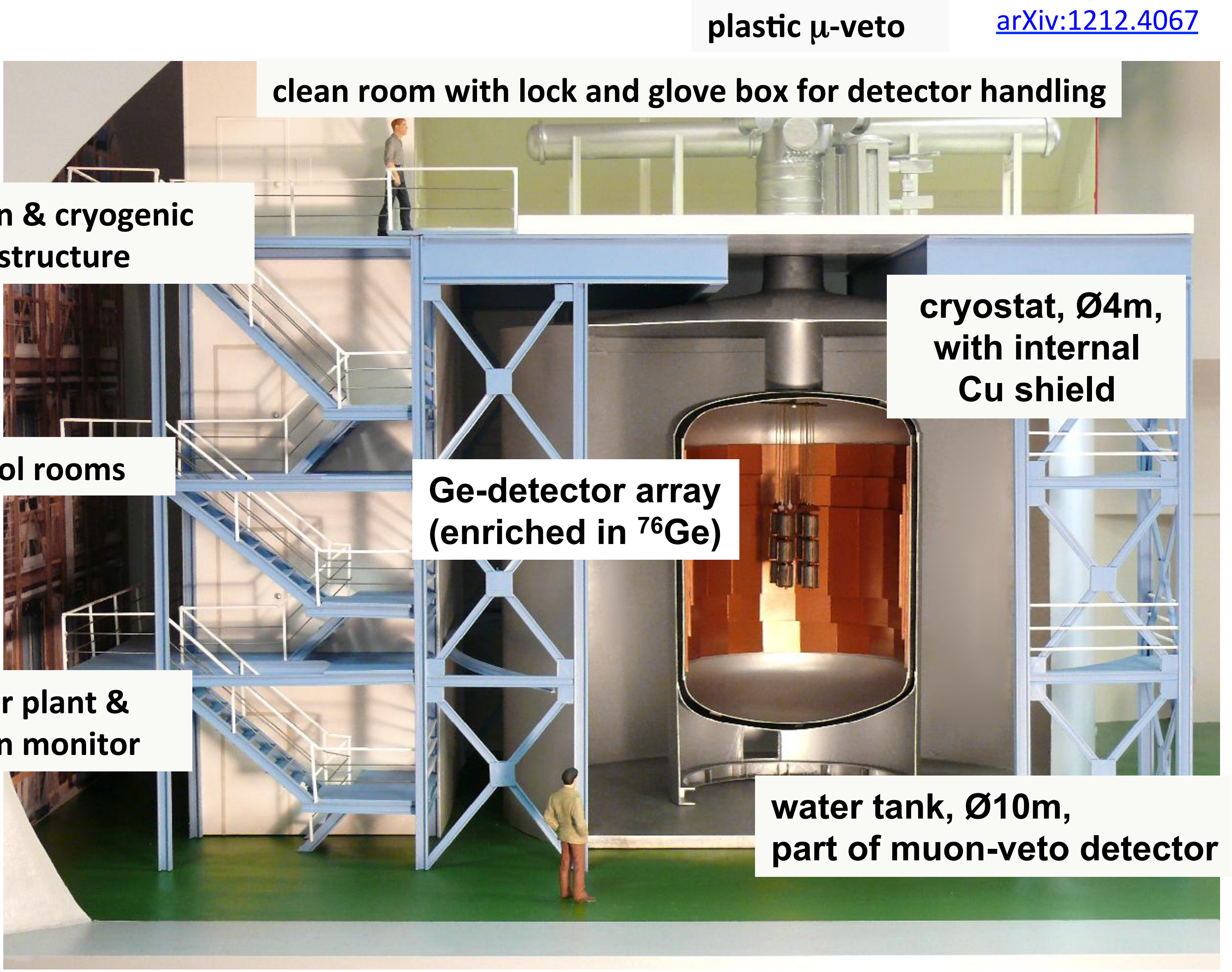
Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr

The GERDA experiment

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



plastic μ-veto

clean room with lock and glove box for detector handling

muon & cryogenic infrastructure

control rooms

water plant & radon monitor

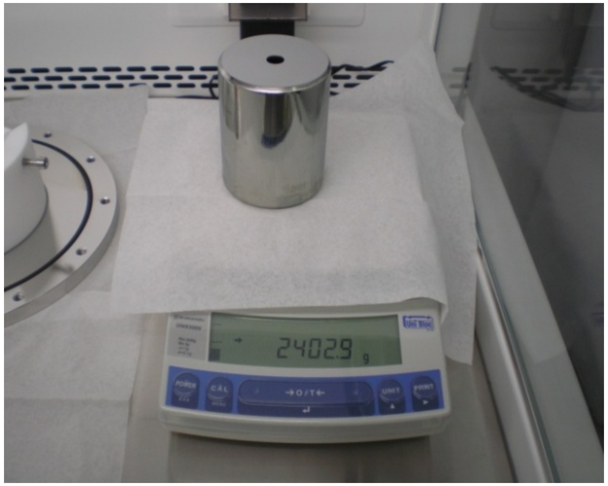
Ge-detector array (enriched in ^{76}Ge)

cryostat, Ø4m, with internal Cu shield

water tank, Ø10m, part of muon-veto detector

Phase I detectors: semi-coaxial detectors

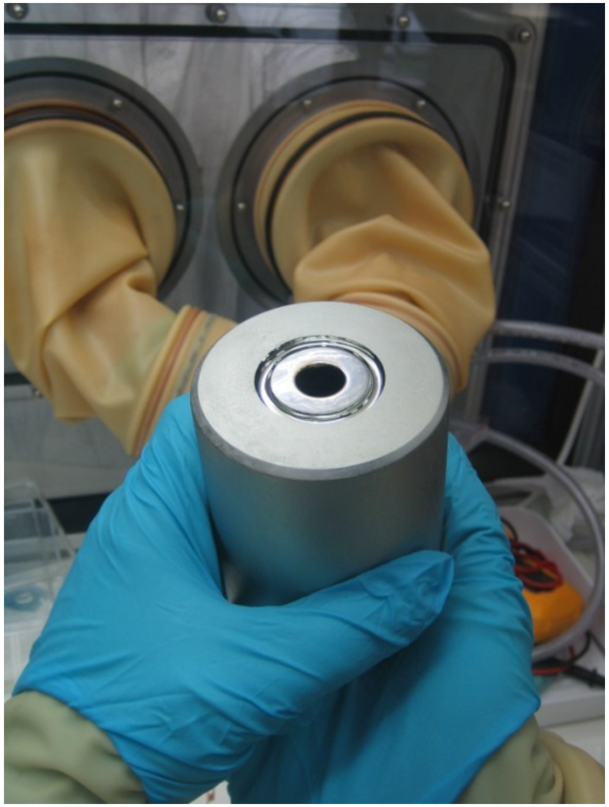
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

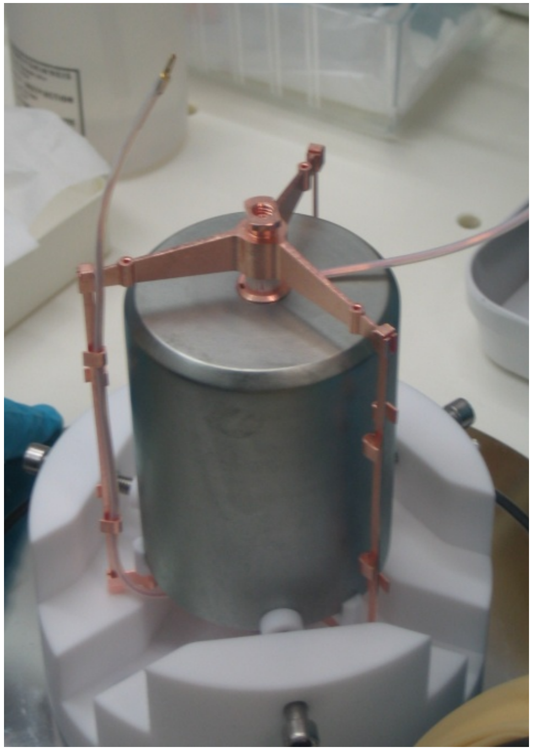


- HdM & IGEX diodes reprocessed at Canberra, Olen
- Long term stability in LAr w/o passivation layer
- Energy resolution in LAr test stand: 2.5 keV (FWHM) @1.3 MeV

8 diodes (from HdM, IGEX):

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

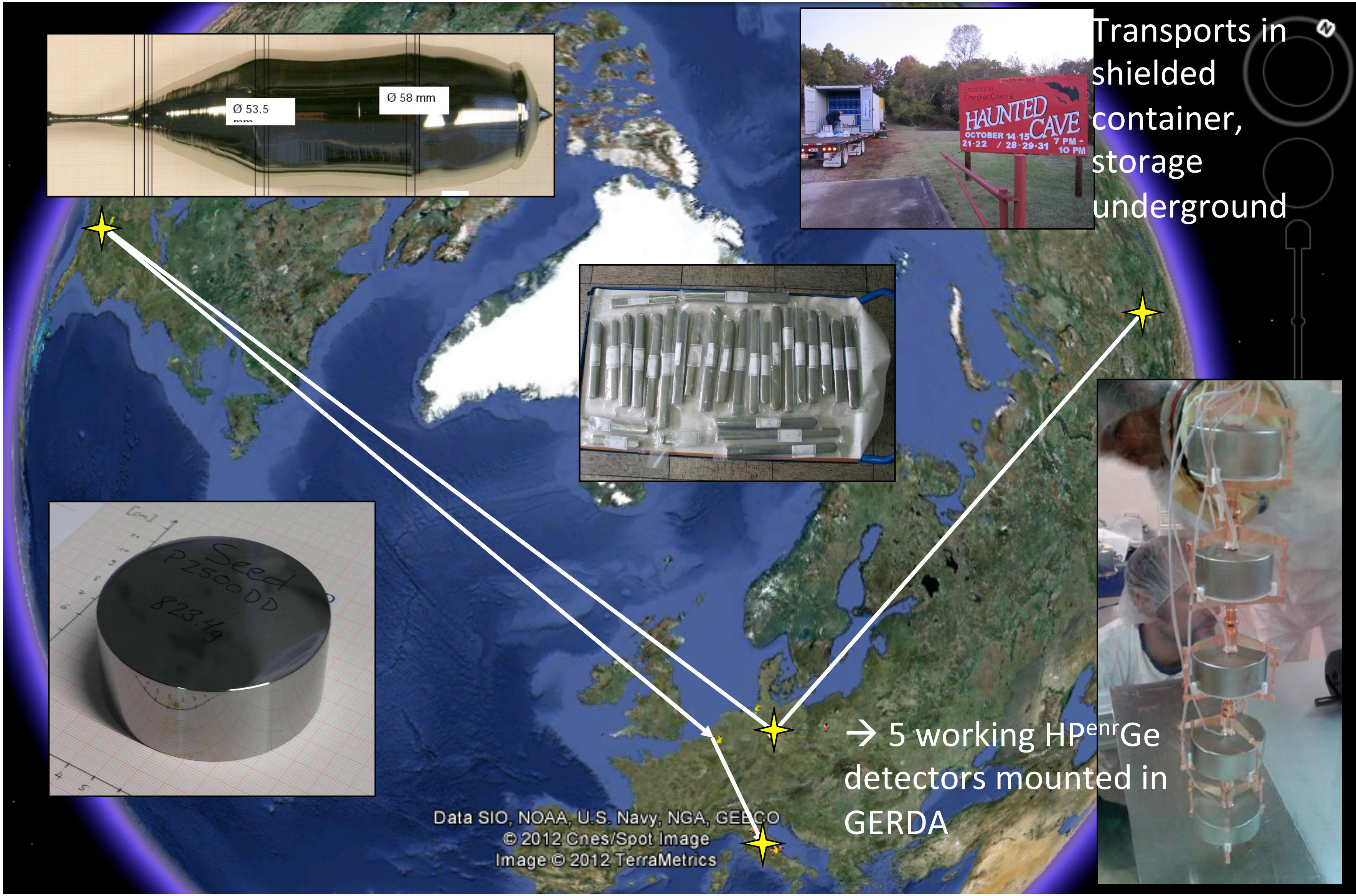




6 diodes from Genius-TF:

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

Production of ^{enr}Ge Phase II detectors



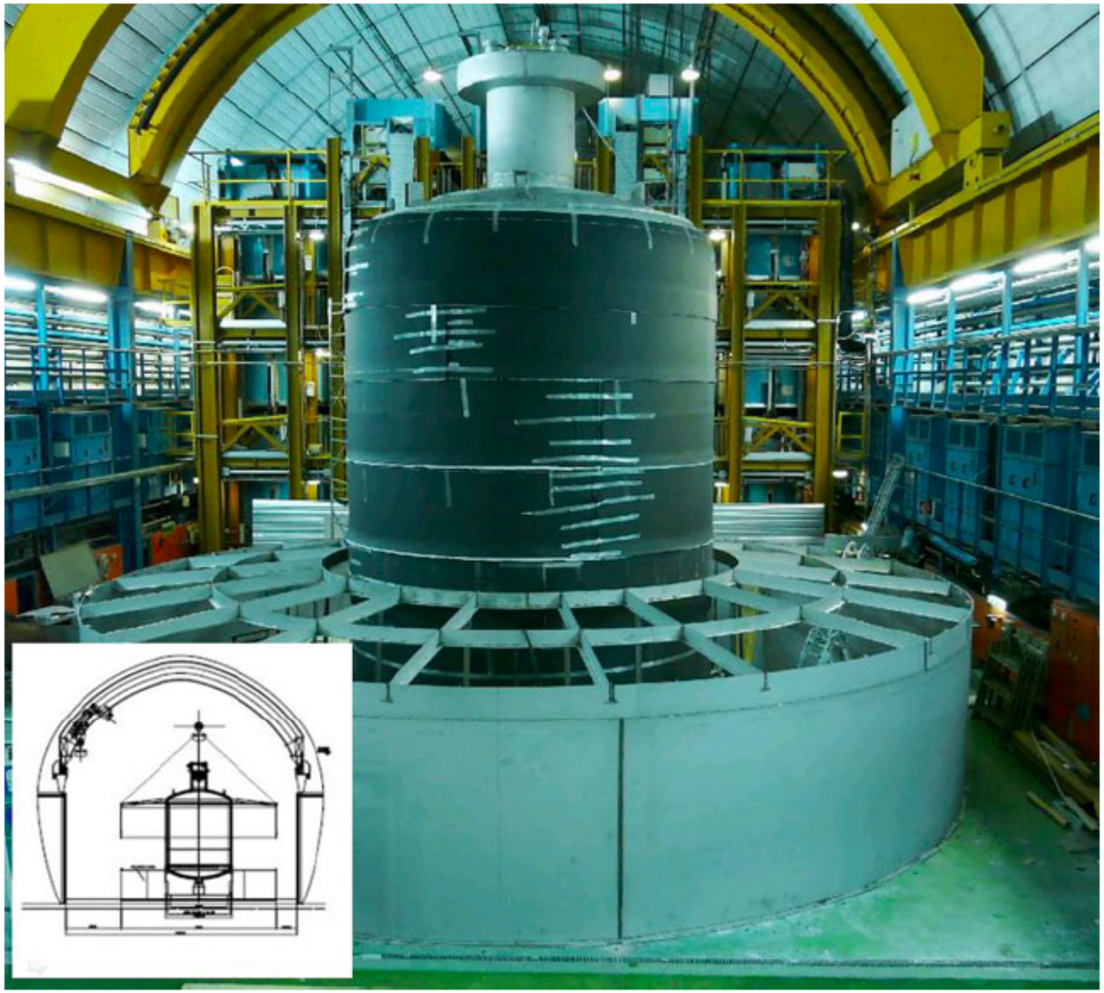
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2012 Cnes/Spot Image
Image © 2012 TerraMetrics

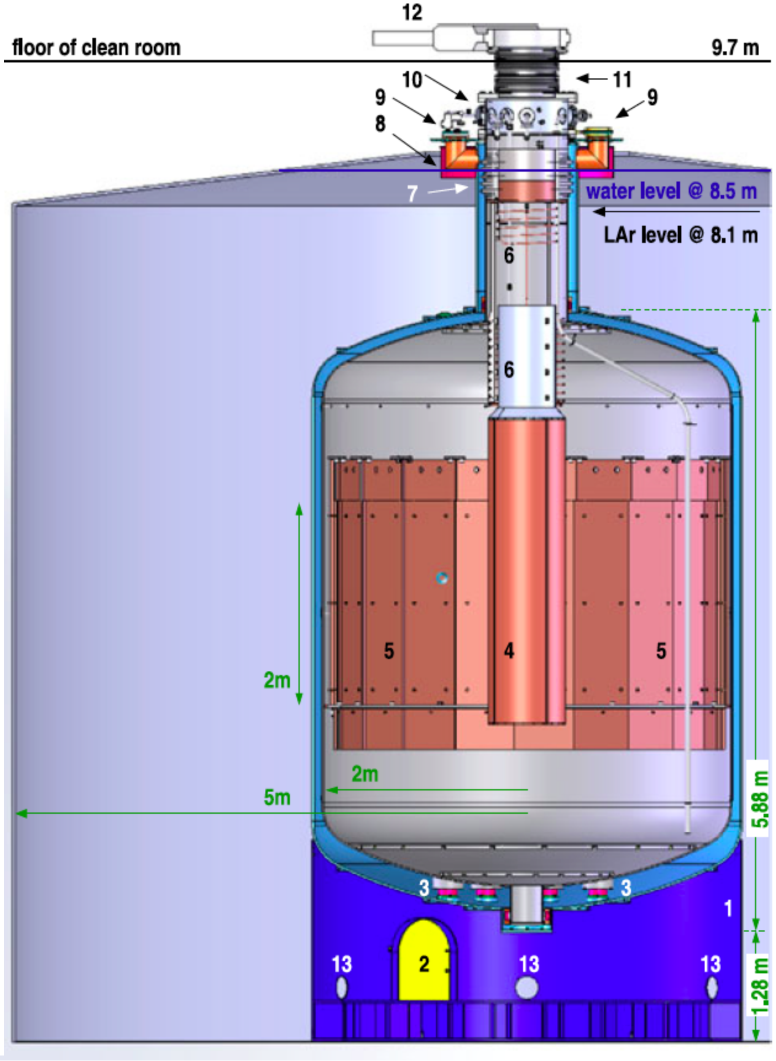
Transports in shielded container, storage underground

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

Water tank and cryostat

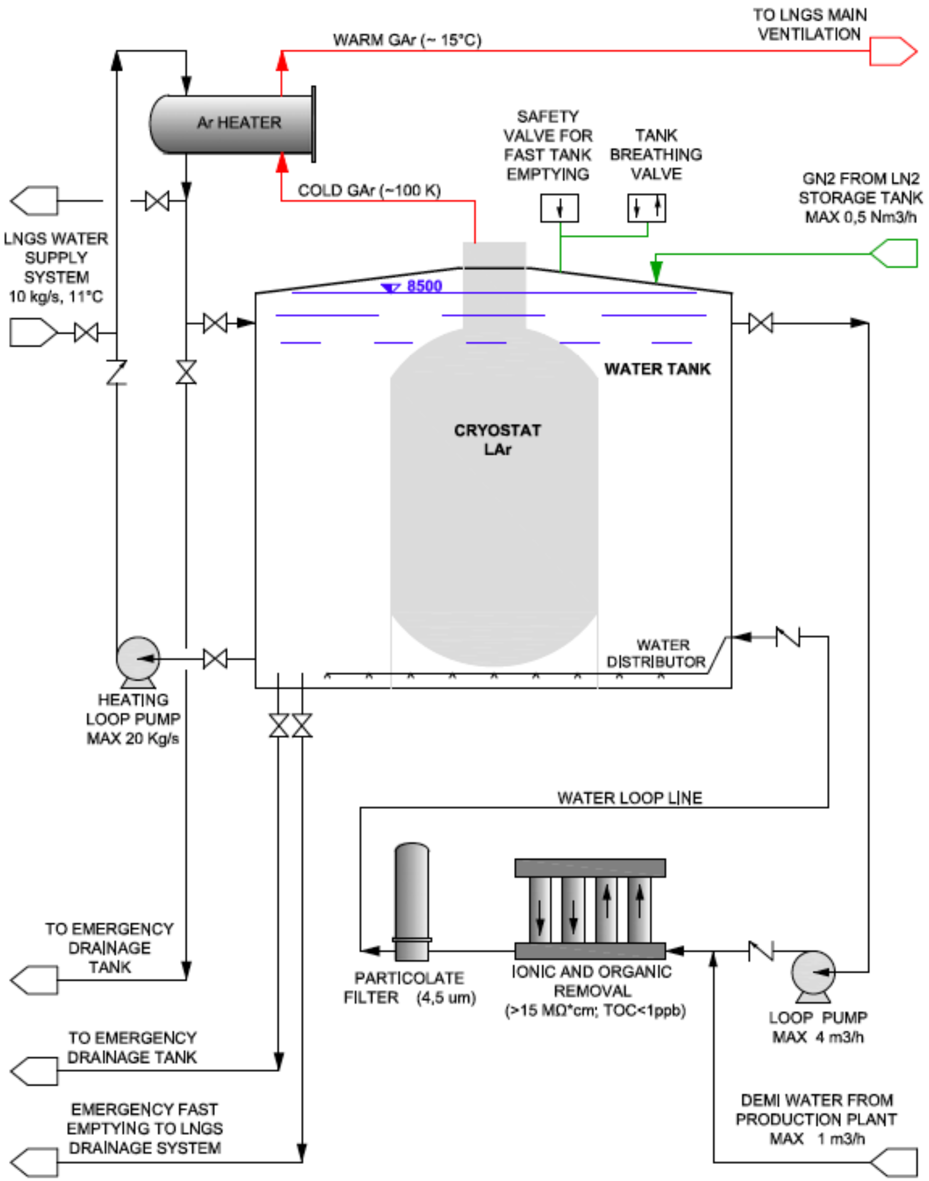
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067





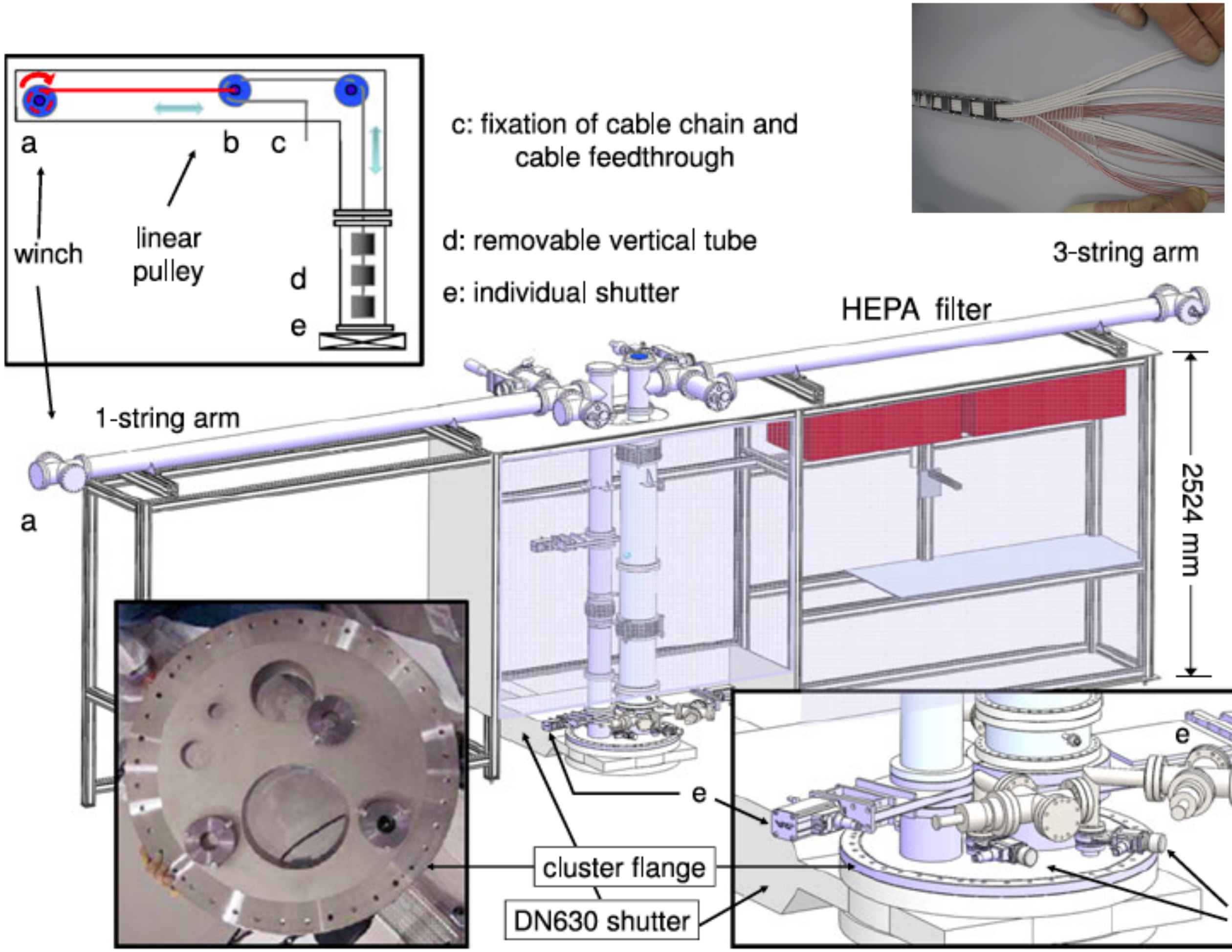
Water purification system

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



Clean room with Lock system, glove box and calibration devices

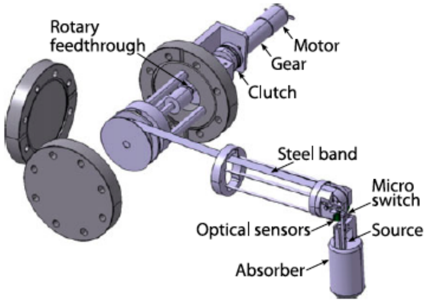
Eur. Phys. J. C (2013) 73:2330
[arXiv:1212.4067](https://arxiv.org/abs/1212.4067)



c: fixation of cable chain and cable feedthrough

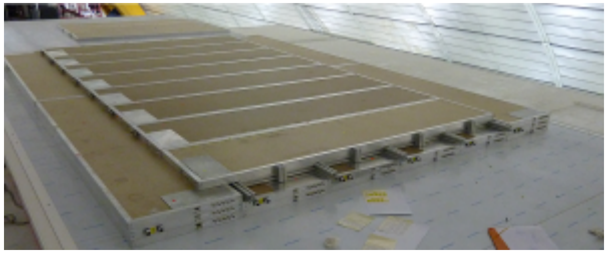
d: removable vertical tube

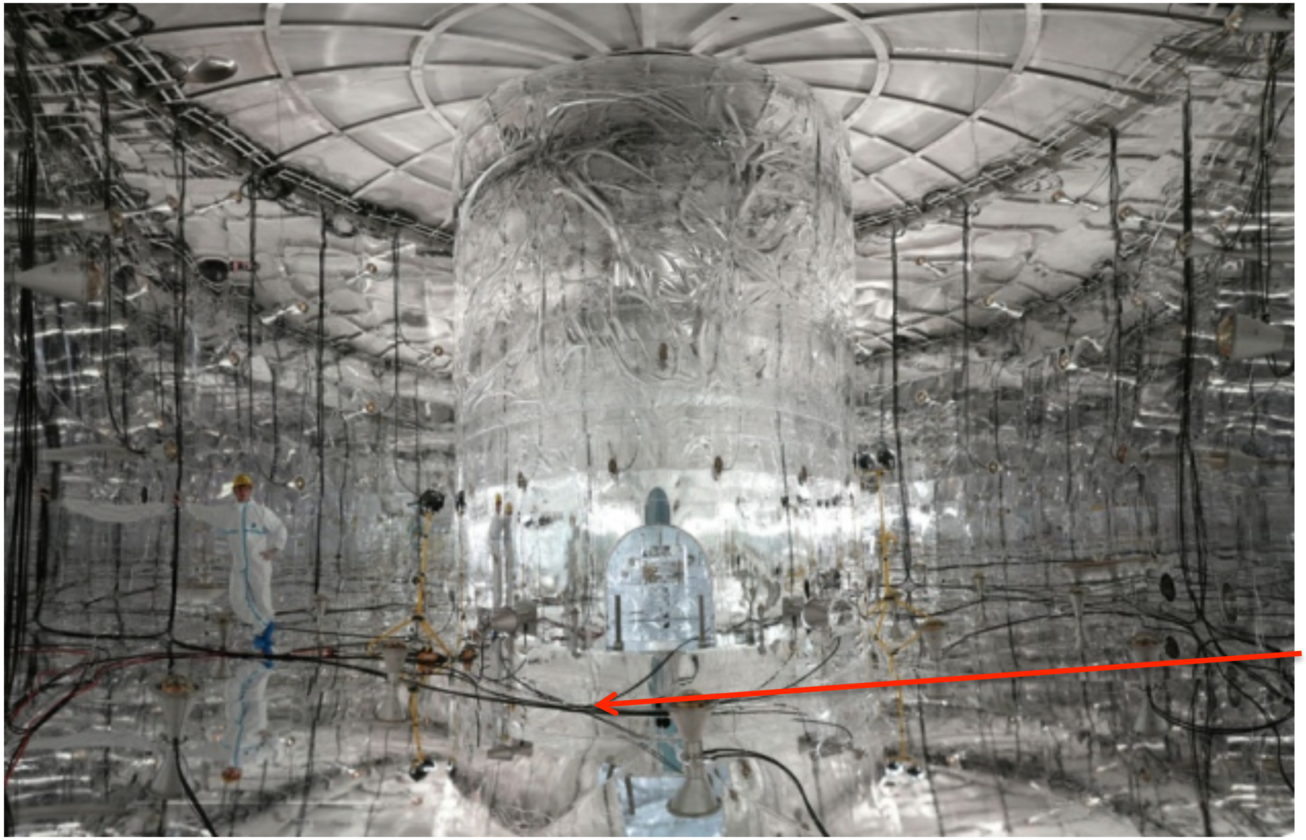
e: individual shutter

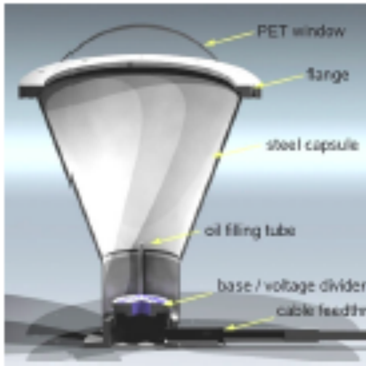


Water Cherenkov detector and plastic scintillator muon veto

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

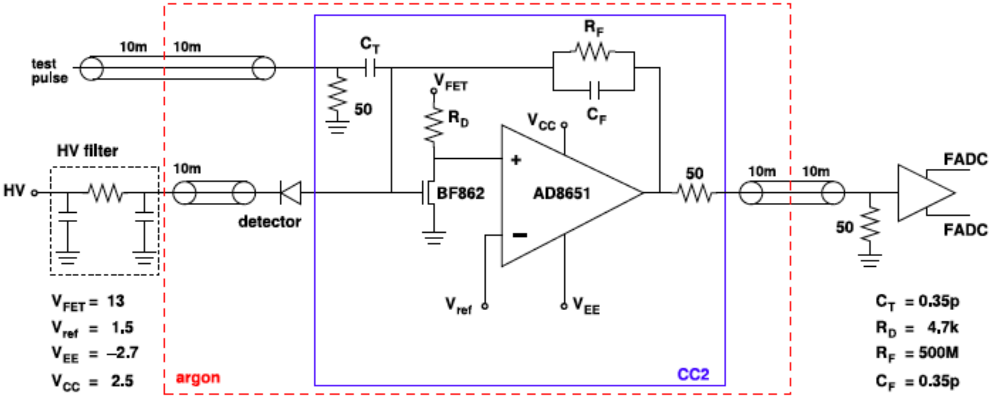


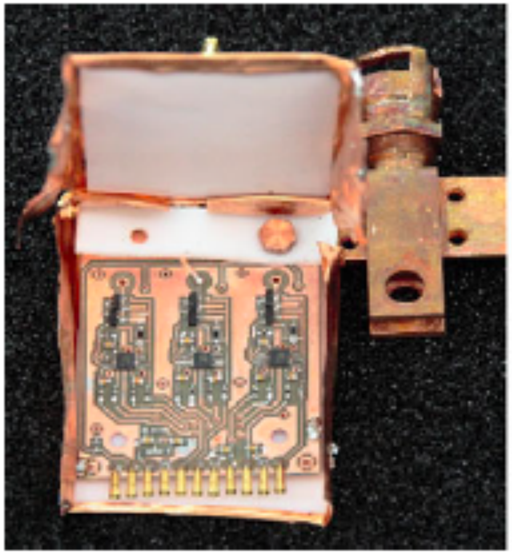


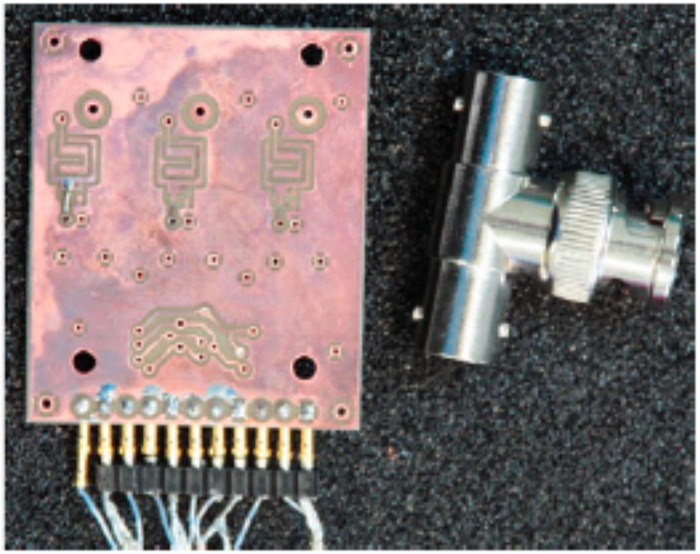


Front-end electronics

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





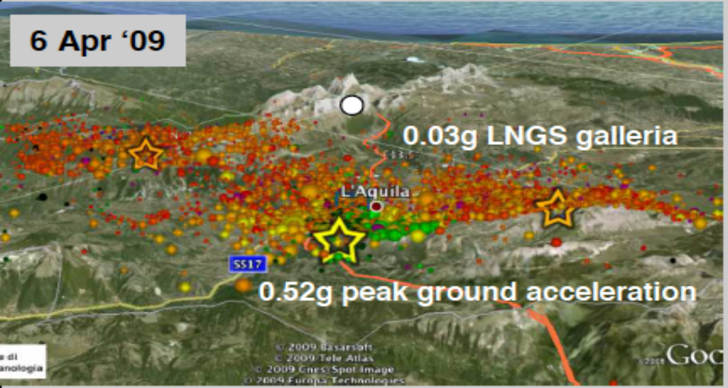


The GERDA construction 2008-2010


6 Mar '08


5 May '08


29 feb '09



6 Apr '09

0.03g LNGS galleria

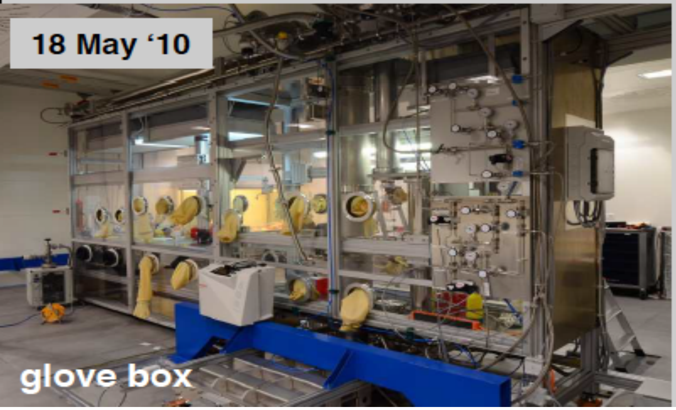
0.52g peak ground acceleration


Aug '09

view inside water tank


active cooling system inst.

18 Jul '09

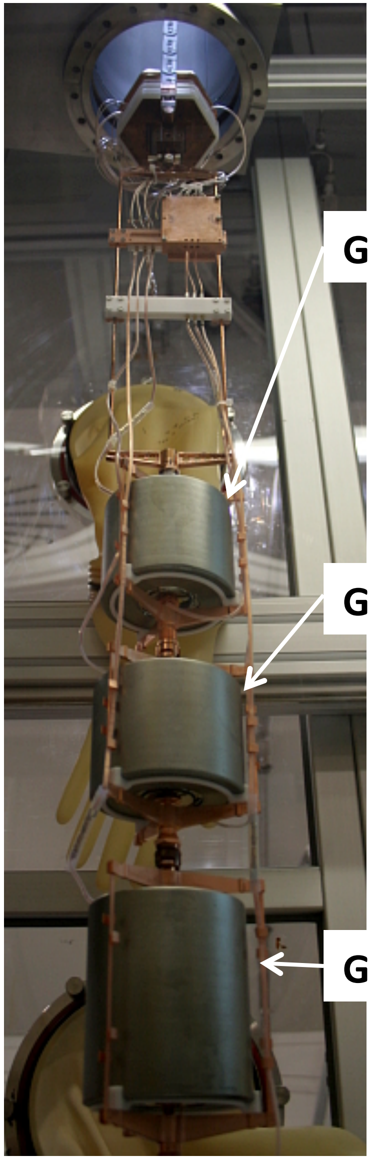

18 May '10

glove box

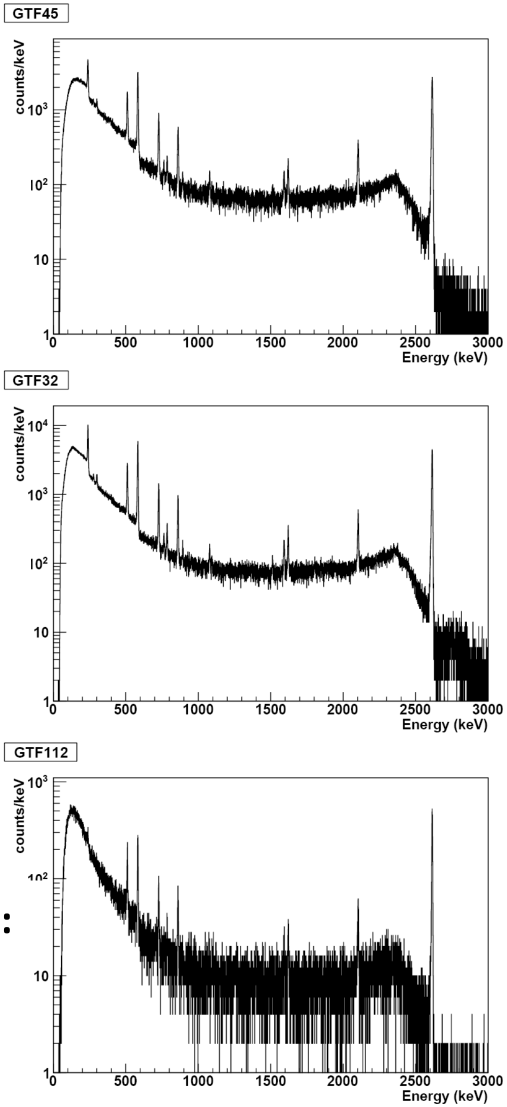

inauguration 9 Nov 2010

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:

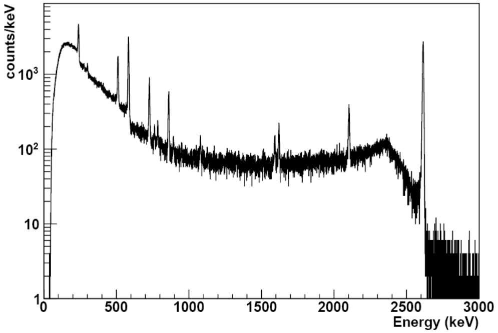
- Coaxial (Phase I): 3.4-5 keV (*FWHM*) @ 2.6 MeV
- BEGe (Phase II): 2.8 keV (*FWHM*) @ 2.6 MeV

Commissioning with 1-string assembly

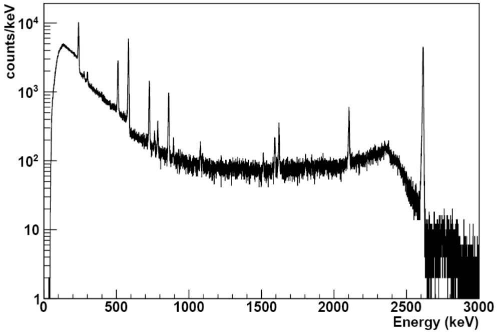
60 µm Cu cylinder
(‘mini-shroud’) to
shield E-field

Calibration with ^{228}Th:

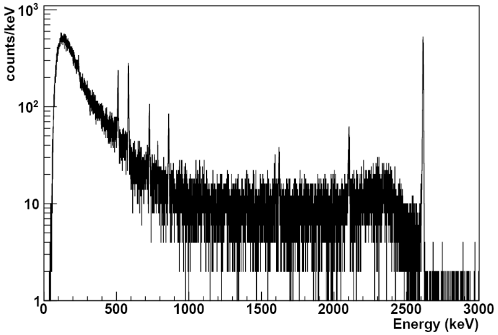
GTF45



GTF32



GTF112



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

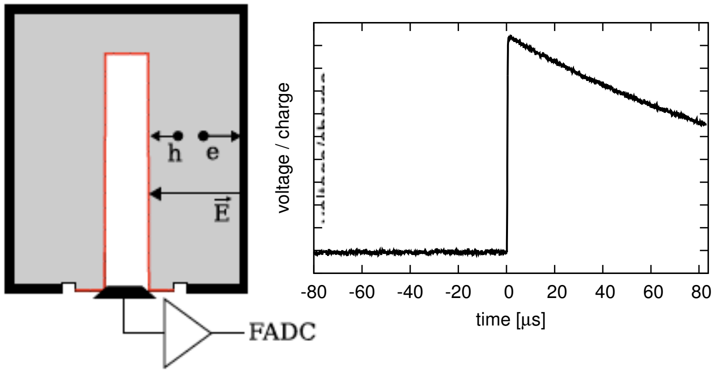
2 diodes shut off because leakage current high:

- total enriched enriched detector mass 14.6 kg

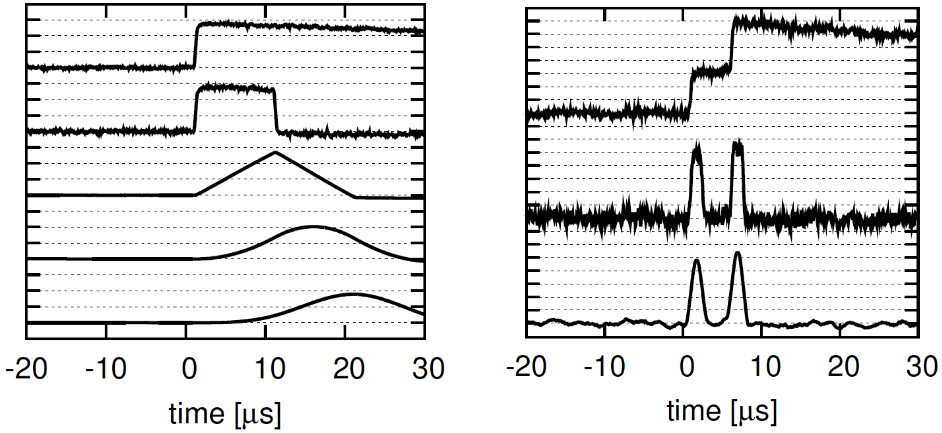
Data processing and selection

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

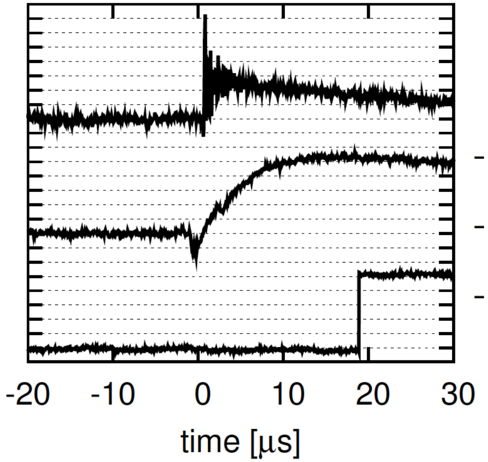
Read-out and signal structure



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

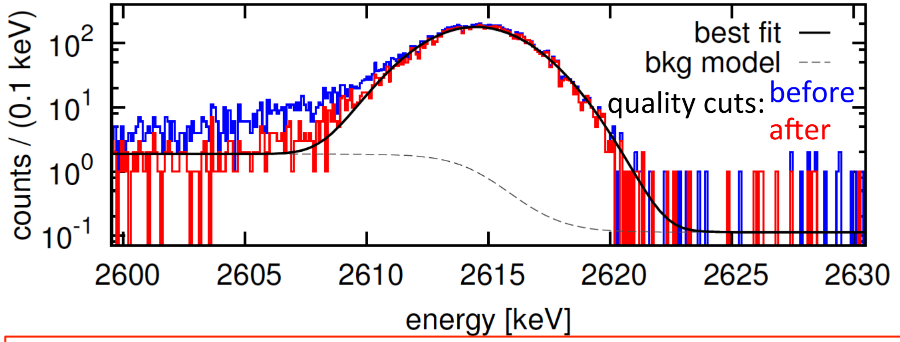


Data selection and quality monitoring



Examples of non-physical events

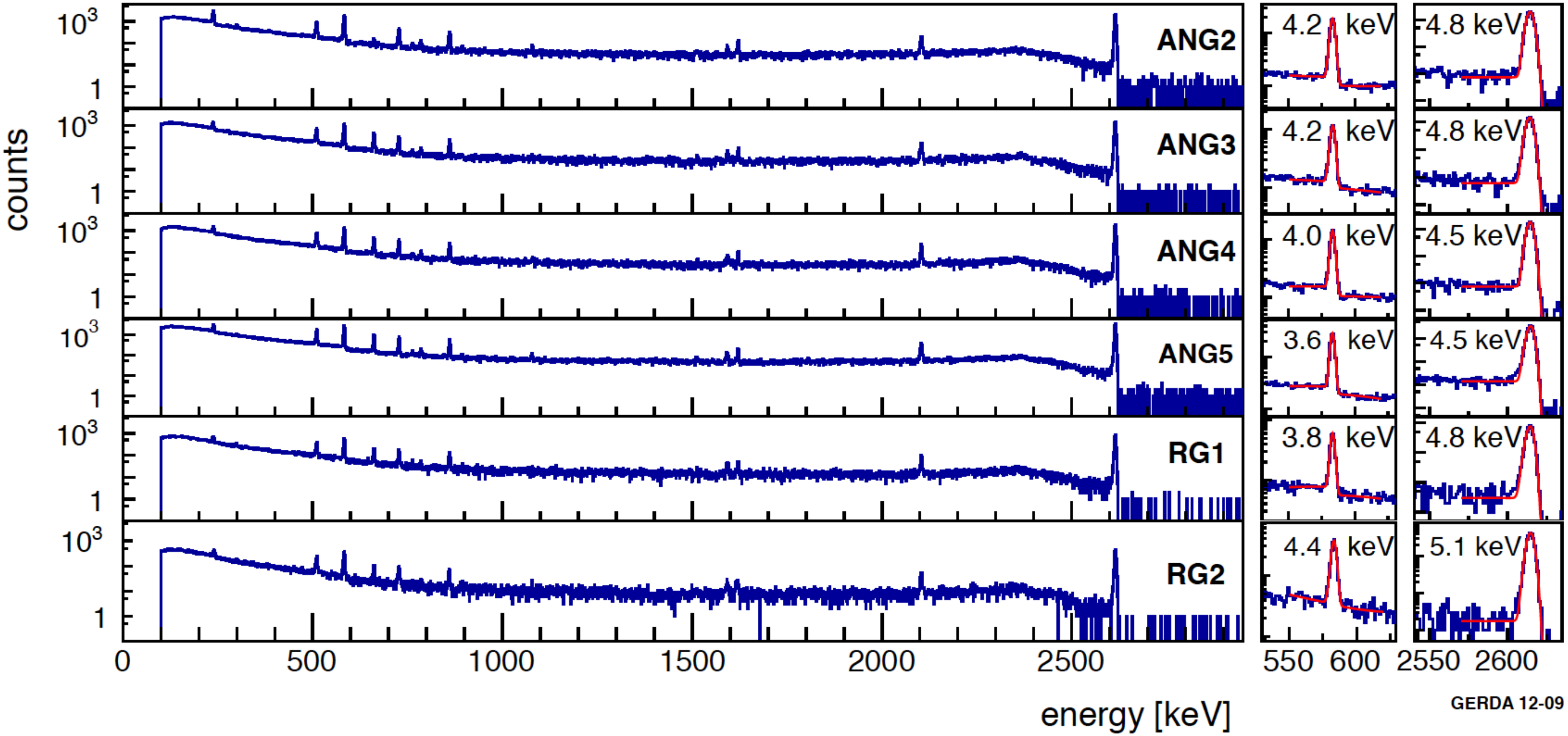
Calibration of energy scale (^{228}Th)



- 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



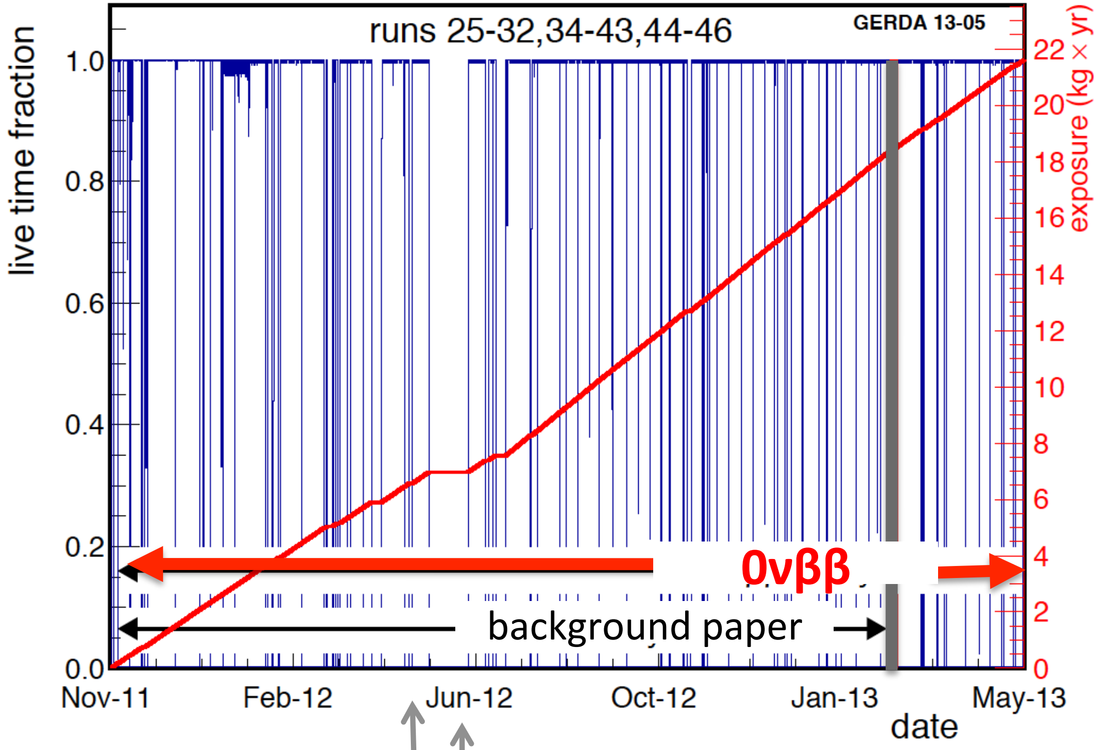
^{228}Th calibration once every one to two weeks; stability continuously monitored with pulser

Overview of data taking

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

Total exposure for 0νββ analysis: 21.6 kg yr

(bi-)weekly calibration runs (‘spikes’)



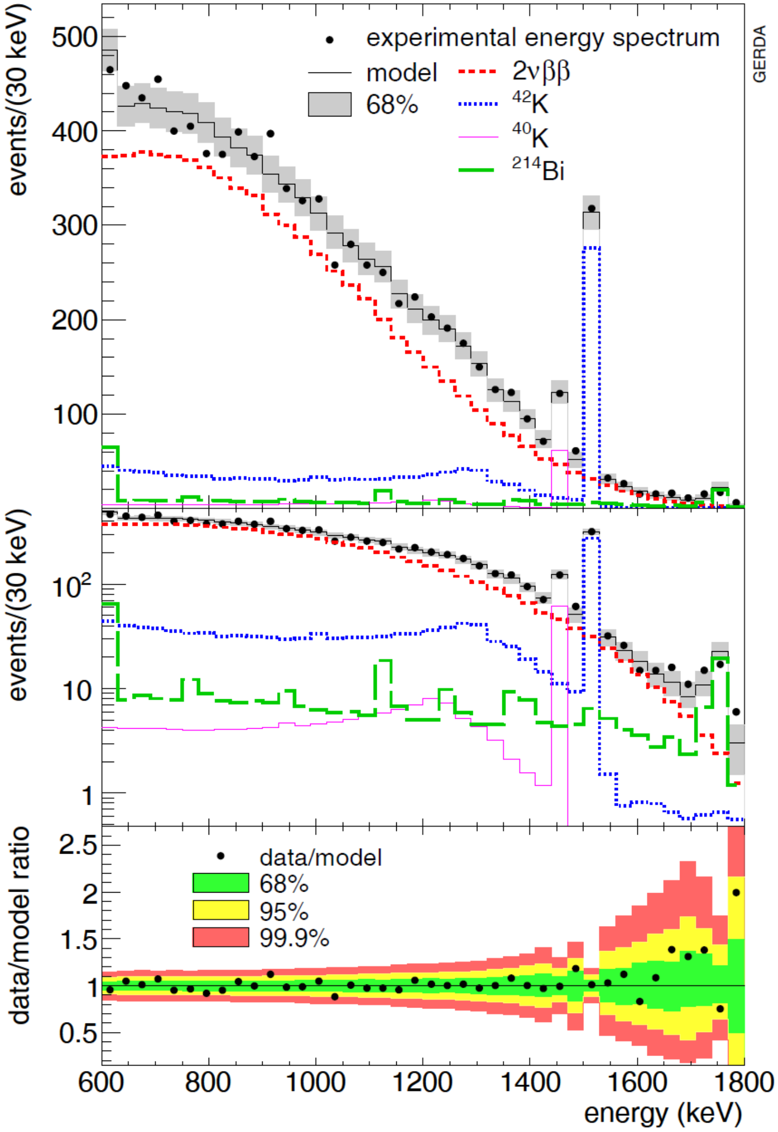
Insertion of 5 Phase II ^{enr}BEGe

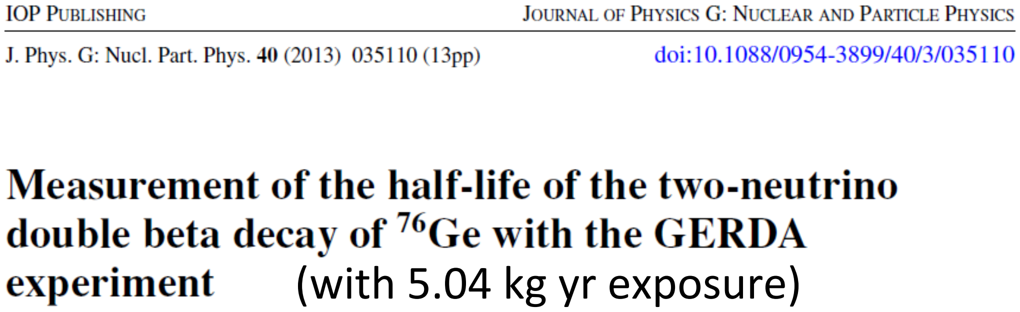
1st physics: 2νββ analysis (5.04 kg yr)

Data blinding:

- All events in $Q_{\beta\beta}$±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)



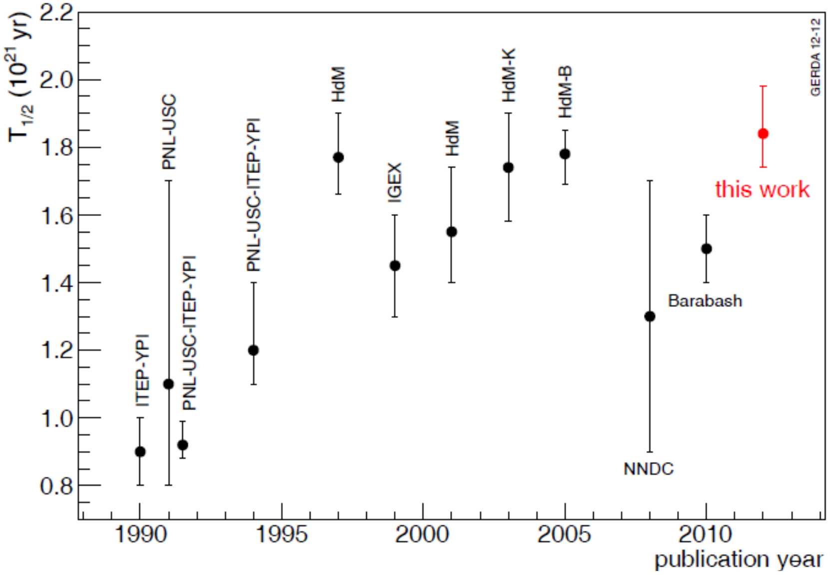


IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

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

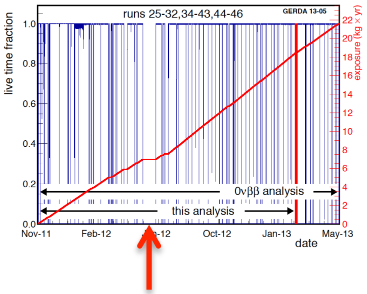
Measurement of the half-life of the two-neutrino double beta decay of ^{76}Ge with the GERDA experiment (with 5.04 kg yr exposure)

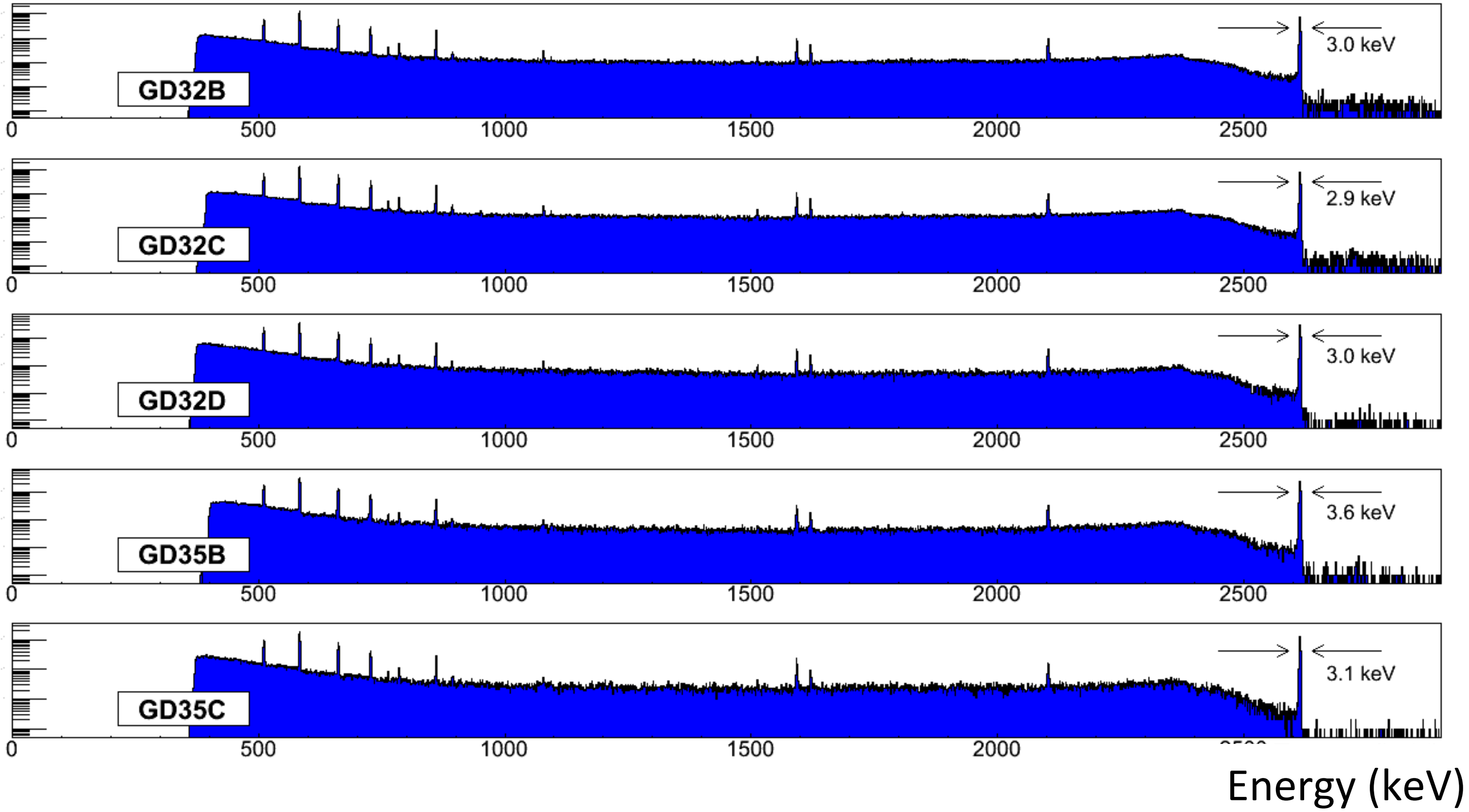
$T^{2\nu}_{1/2}(^{76}\text{Ge}) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr



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

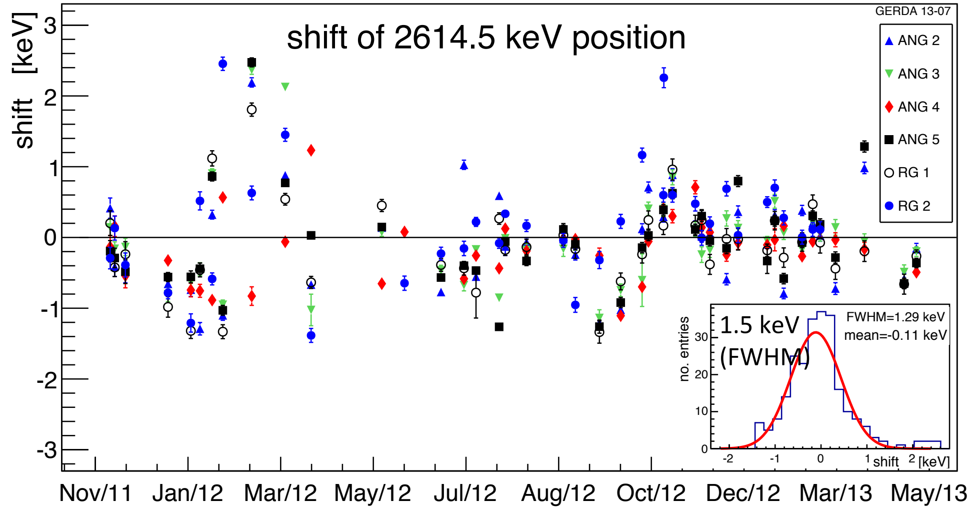
June 2012: 5 ^{enr}BEGe Phase II detectors deployed in GERDA

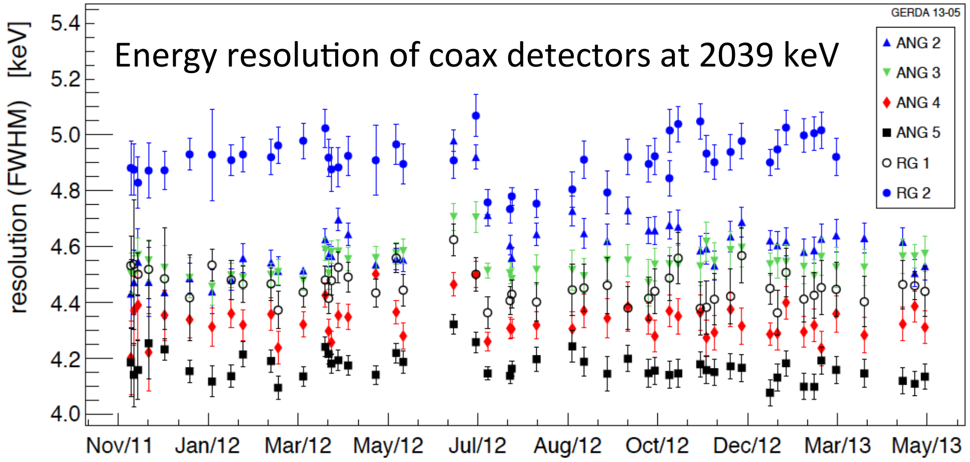




Calibration: stability of HPGe detectors

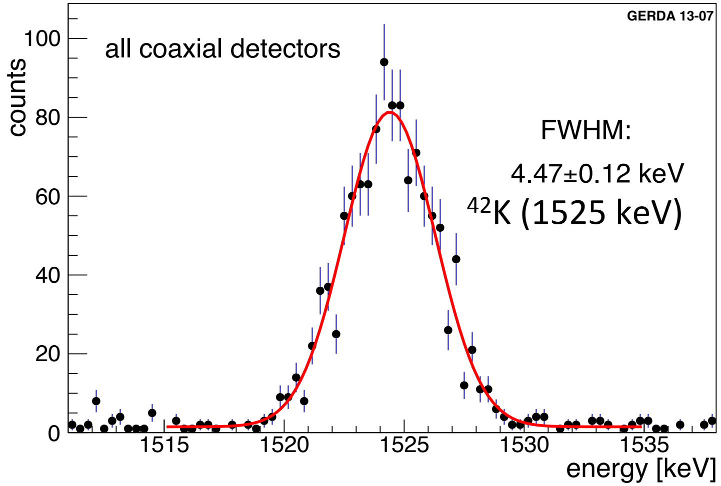
Peak position stability of 2614.5 keV calibration line:
coax: 1.5 keV / BEGe: 1.0 keV (FWHM)





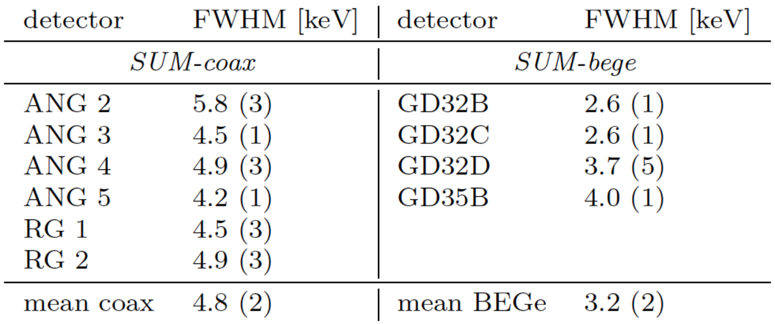
[arXiv:1306.5084](https://arxiv.org/abs/1306.5084)

Summing all runs:



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

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

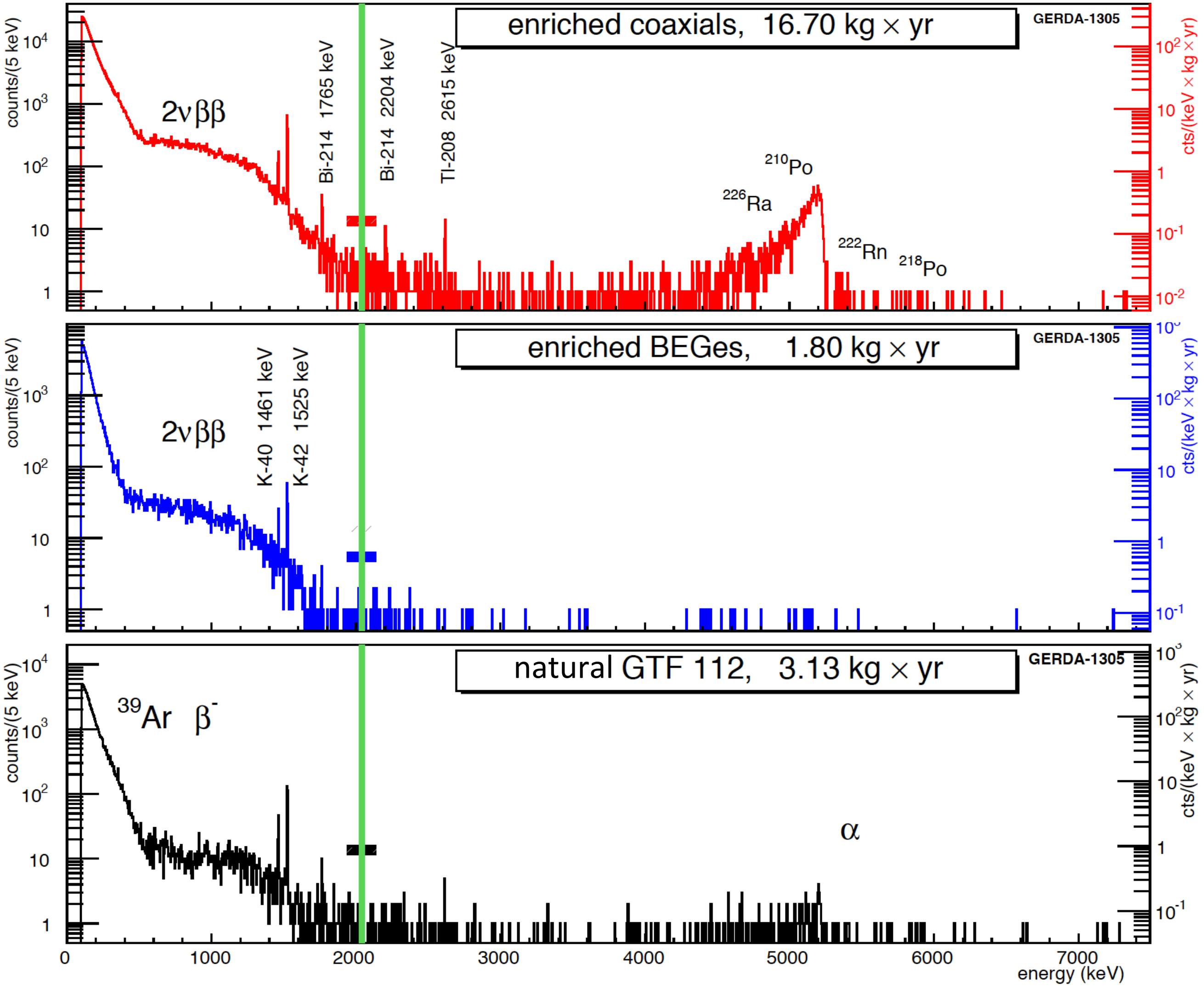


detector	FWHM [keV]	detector	FWHM [keV]
SUM-coax		*SUM-bege*	
ANG 2	5.8 (3)	GD32B	2.6 (1)
ANG 3	4.5 (1)	GD32C	2.6 (1)
ANG 4	4.9 (3)	GD32D	3.7 (5)
ANG 5	4.2 (1)	GD35B	4.0 (1)
RG 1	4.5 (3)		
RG 2	4.9 (3)		
mean coax	4.8 (2)	mean BEGe	3.2 (2)

Physics run: energy spectra

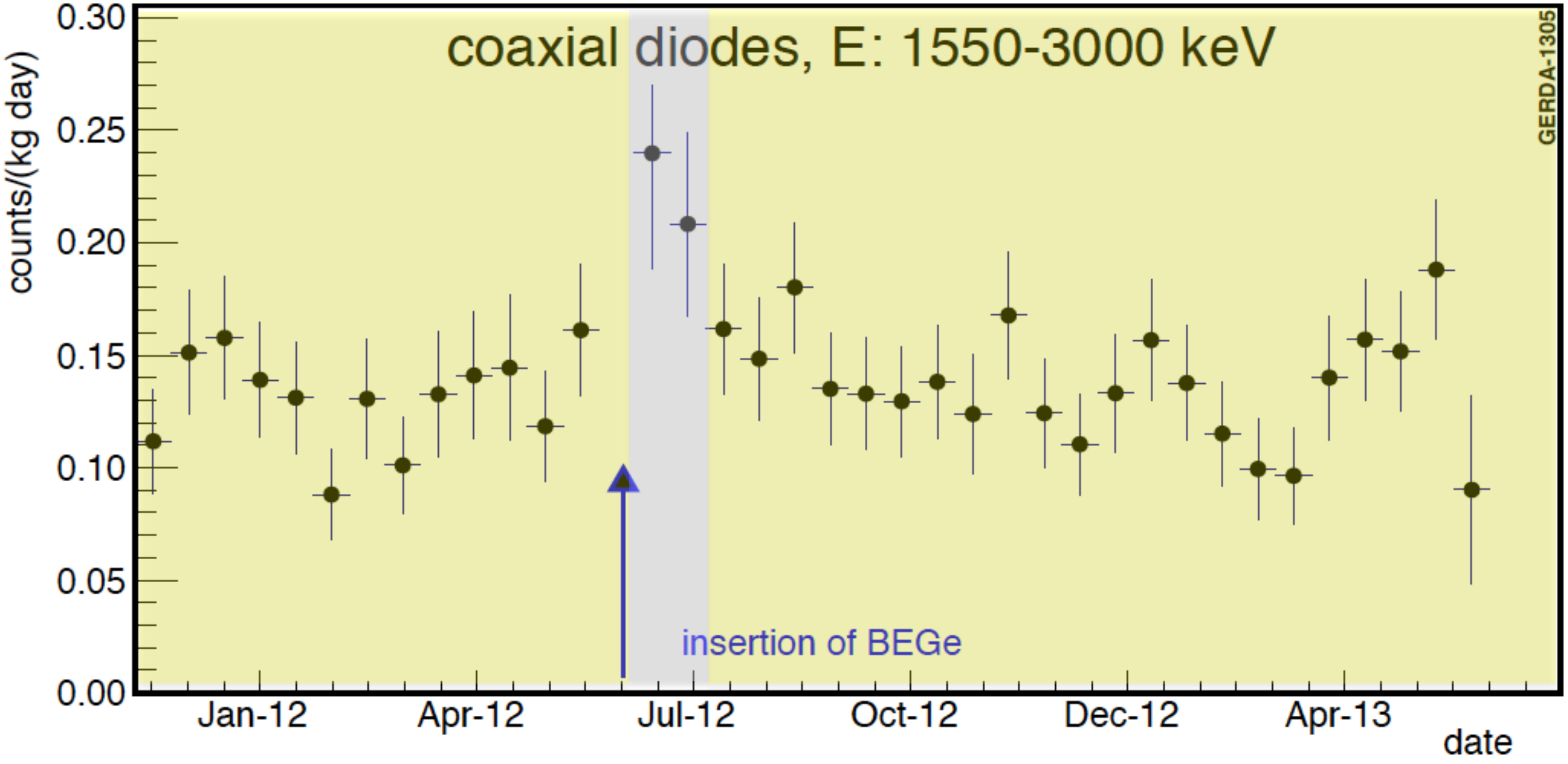
[arXiv:1306.5084](https://arxiv.org/abs/1306.5084)

Submitted to EPJ A
Data for
background model



Physics run: background rate as function of time

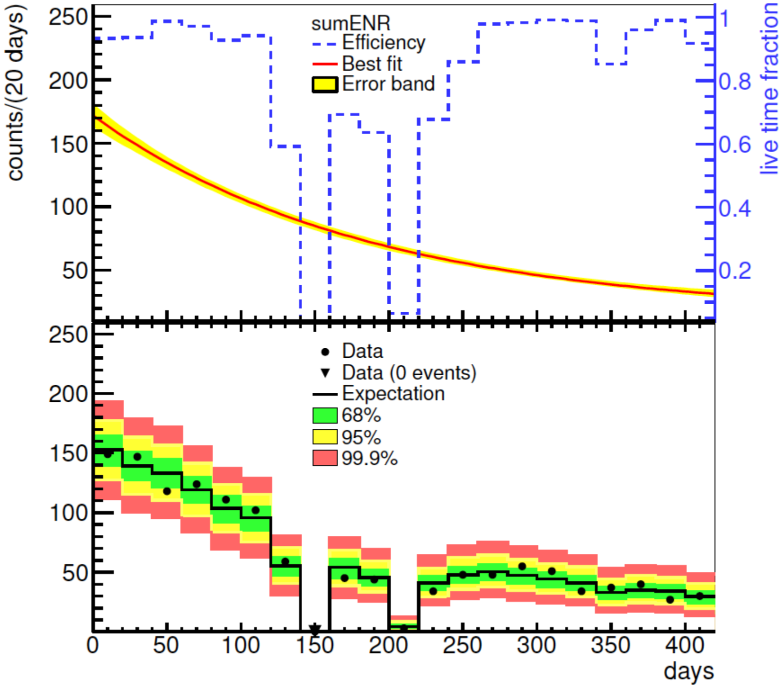
arXiv:1306.5084



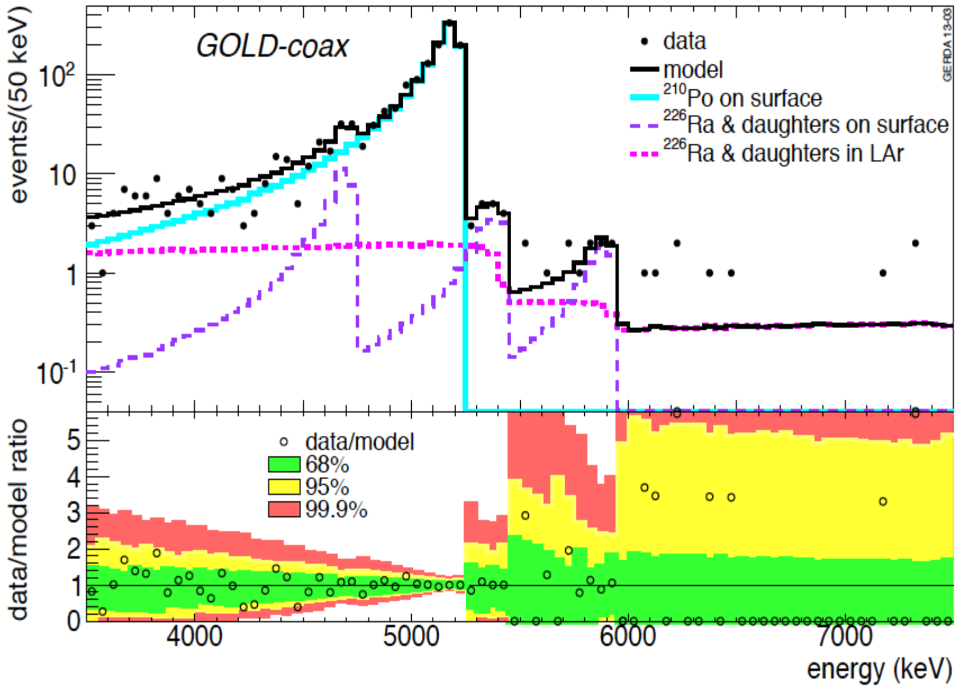
Coax-detector data set split in ‘Gold’ and ‘Silver’ (30 d)

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

arXiv:1306.5084



Time distribution (3.5-5.3 MeV)



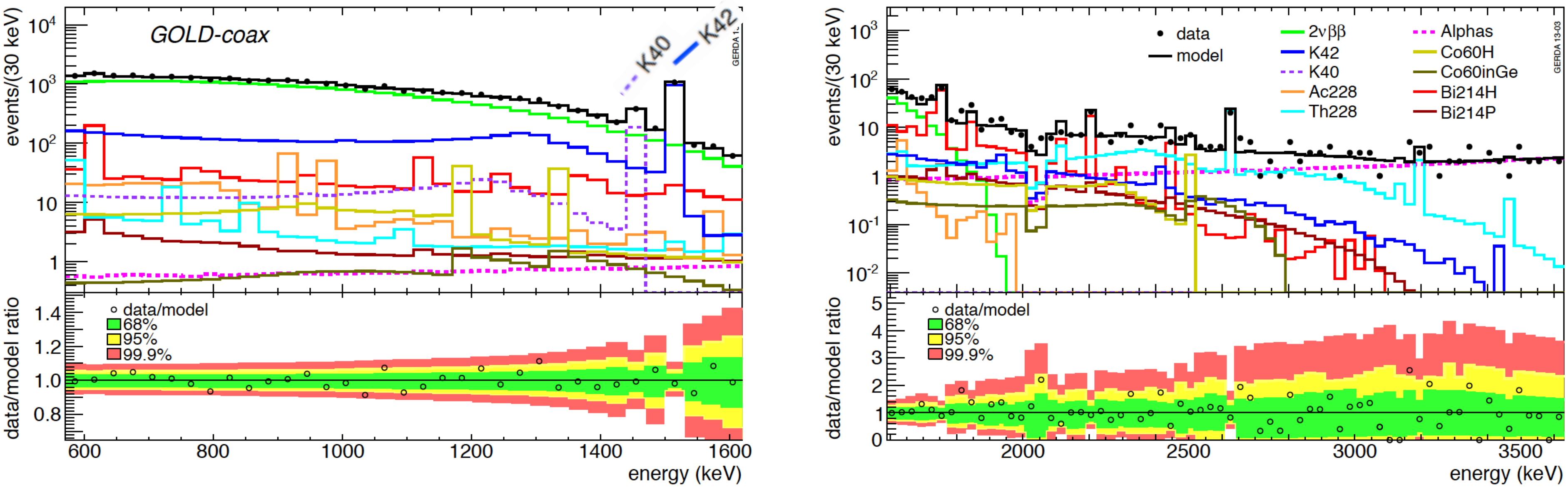
Energy spectrum

- ^{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

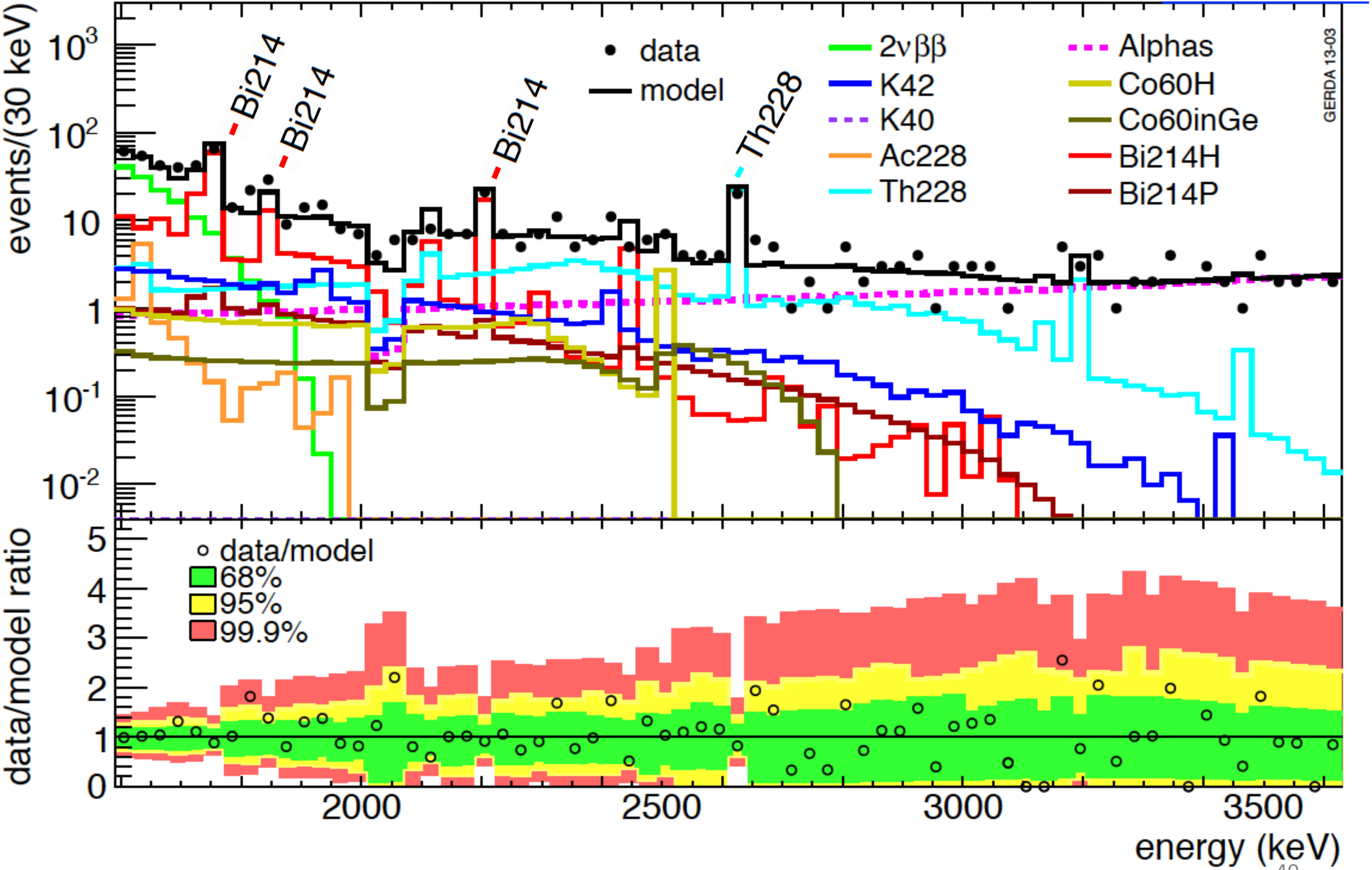
Fit of minimal background model to complete energy spectrum



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

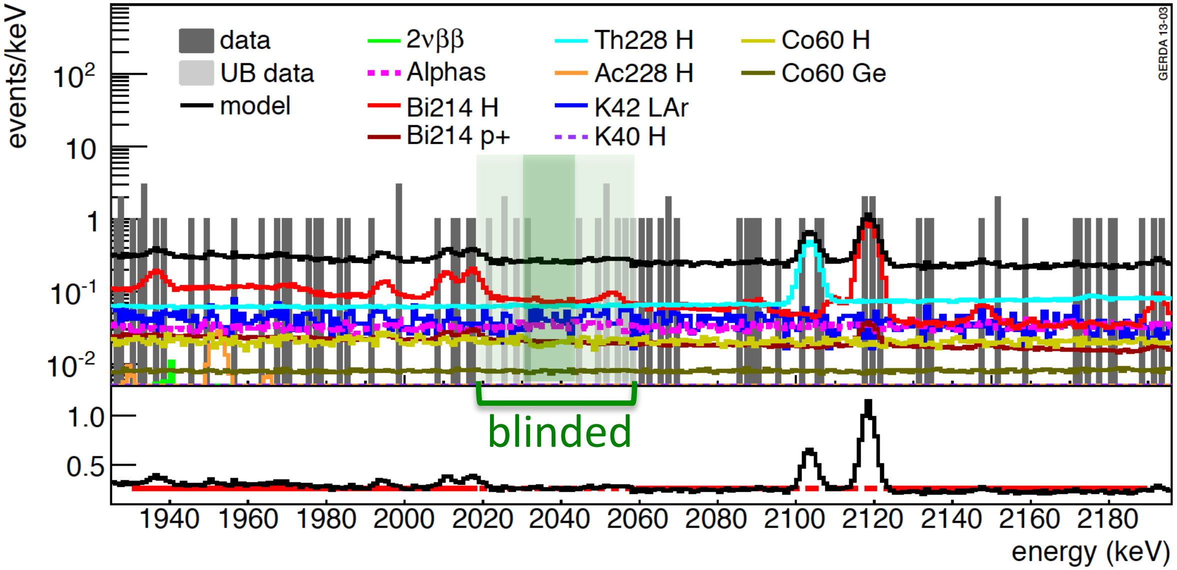
Physics data: high-energy alpha

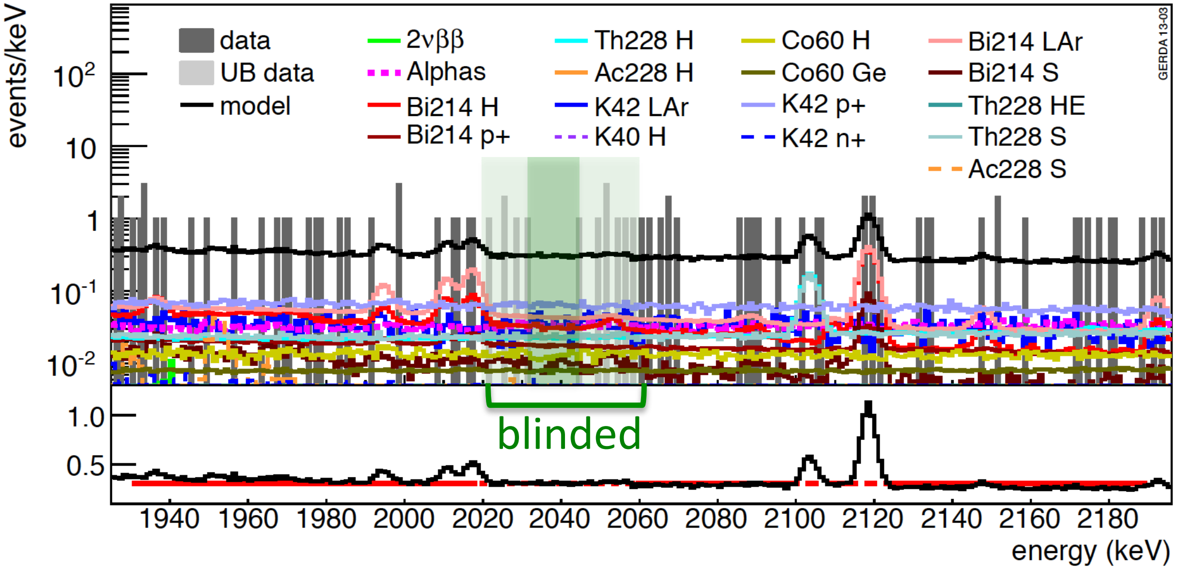
arXiv:1306.5084



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

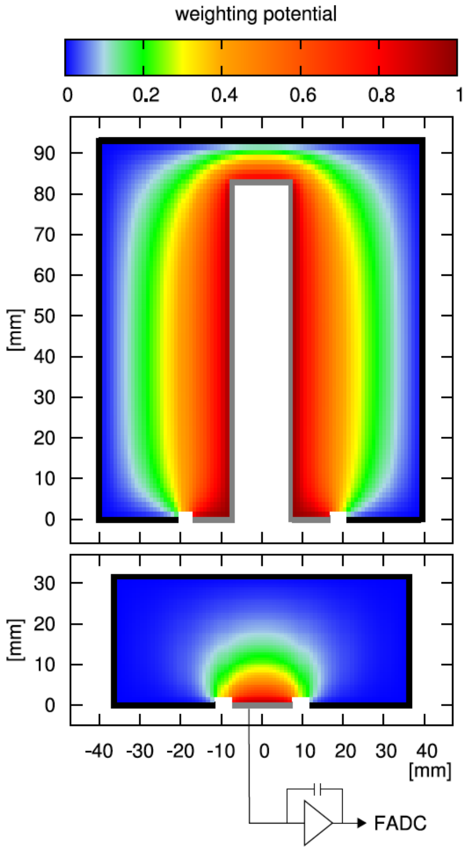
Pulse shape discrimination

arXiv:1307.2610

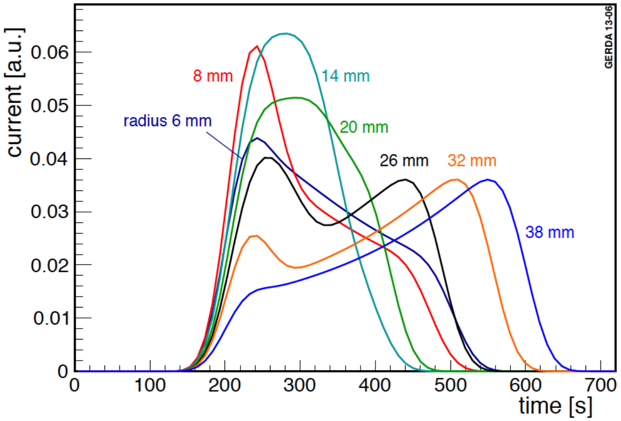
Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

Weighting potential for coax and BEGe detectors are different

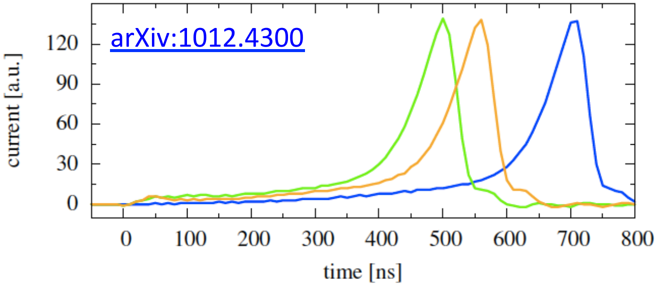
Current pulses of simulated SSE signals



Coax



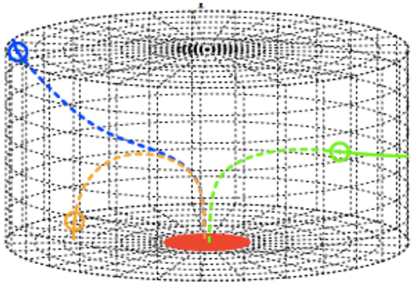
BEGe

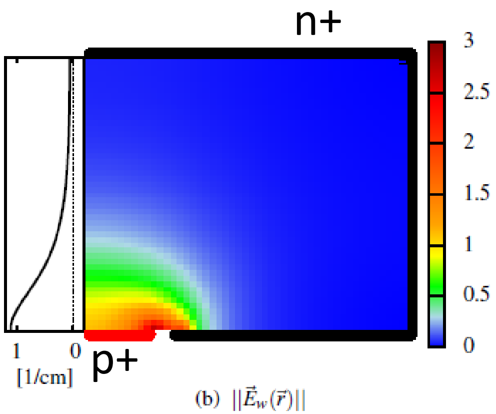


arXiv:1012.4300

Pulse shape discrimination: BEGe

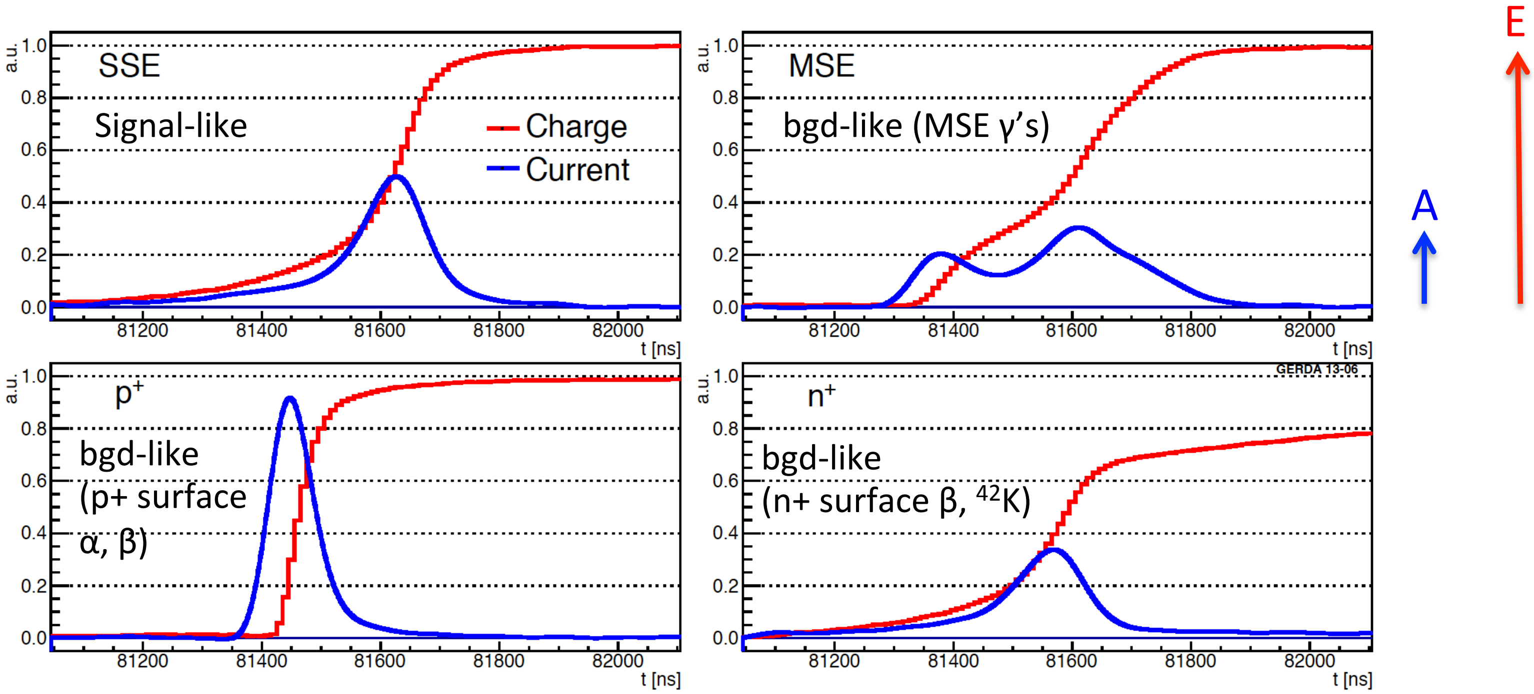
arXiv:1307.2610





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

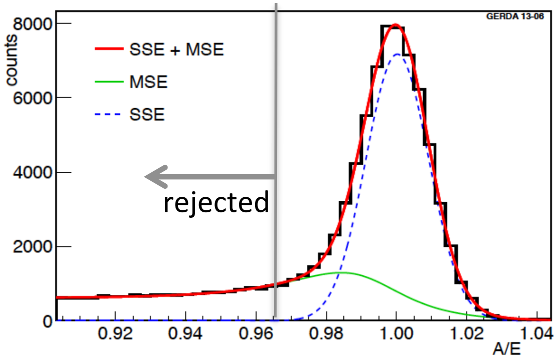
PSD discrimination parameter: A/E



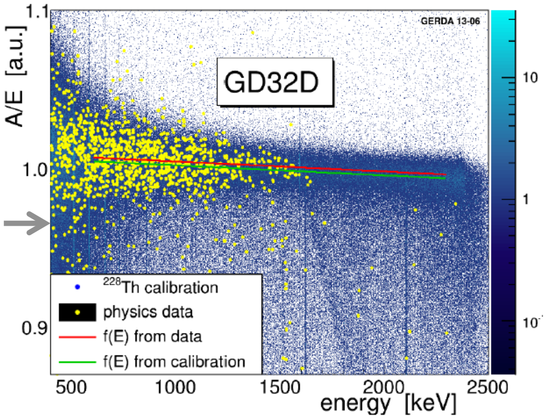
Pulse shape discrimination: BEGe

arXiv:1307.2610

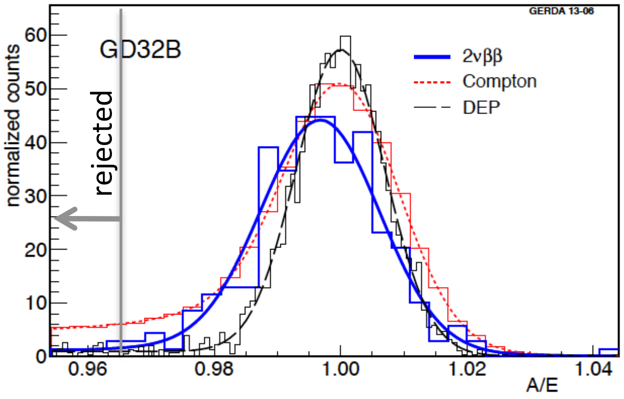
A/E of Compton continuum from calibration



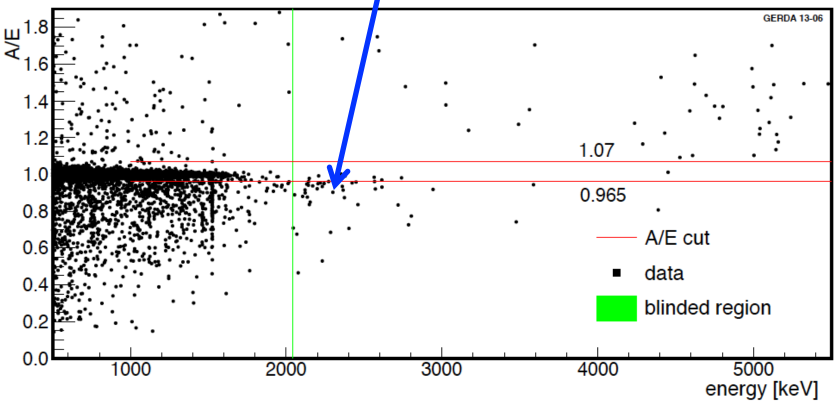
Energy dependence of A/E



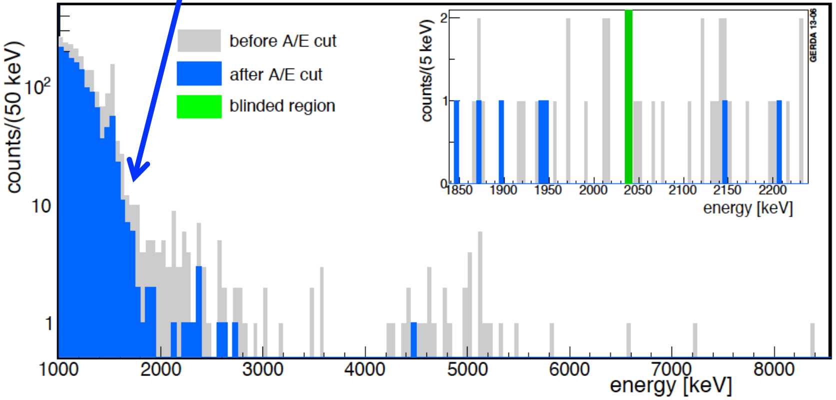
A/E for 2νββ, Compton (1-1.4 MeV), DEP (1592 keV)



^{42}K-β n+ surface dominated



2νββ acceptance: 0.91±0.05



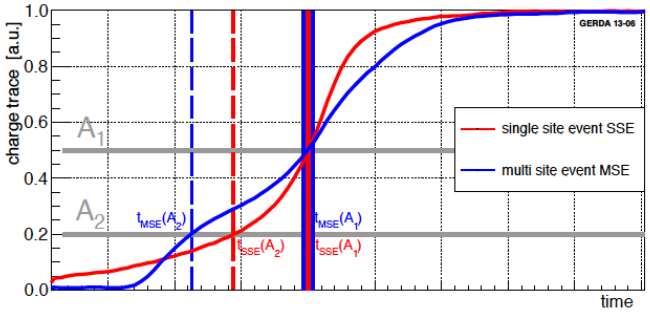
0νββ acceptance: 0.92±0.02

Pulse shape discrimination: Coax

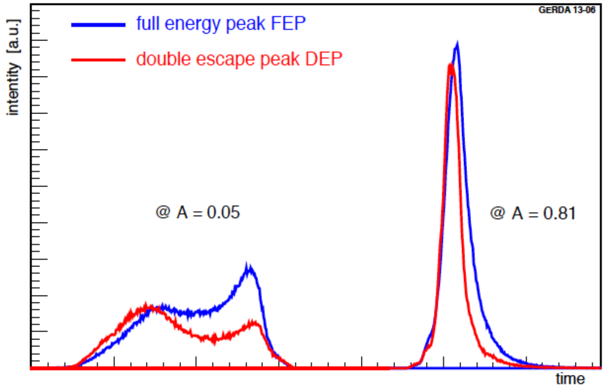
arXiv:1307.2610

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

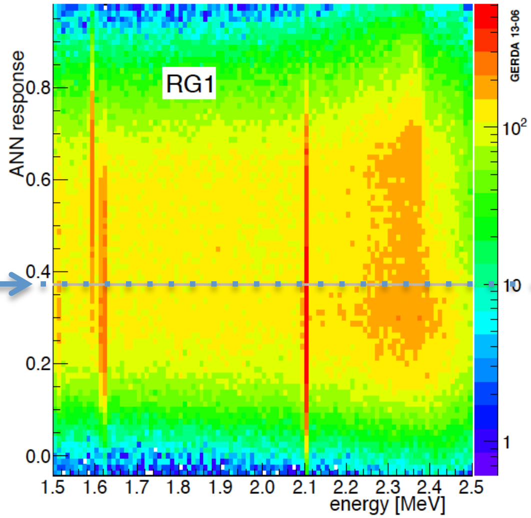
- SSE training with signal-like ^{208}Tl DEP events (1592 keV)
- MSE training with background-like ^{212}Bi FEP (1621 keV)



Distribution for 5 and 81% rise time

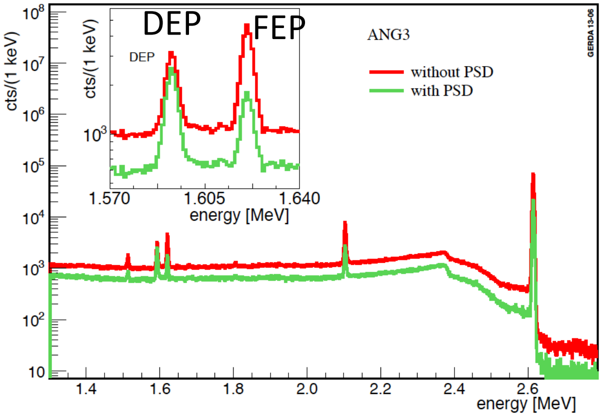


Cut adjusted for each detector to 90% DEP survival



SSE-like

MSE-like

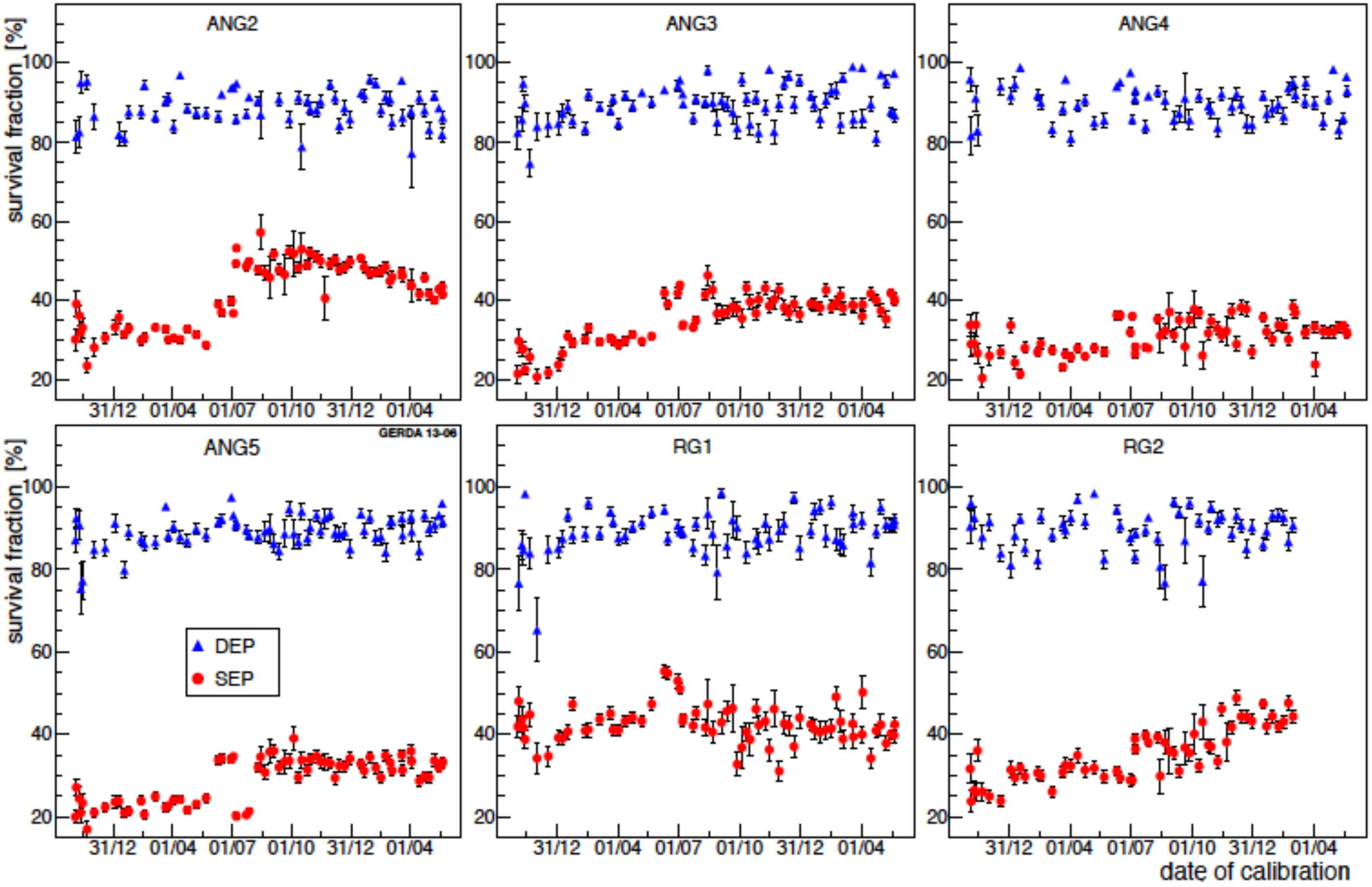


Pulse shape discrimination: Coax – survival fraction for Phase I

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

Stability of survival fraction from calibration data

Y-axis suppressed:



DEP

SEP

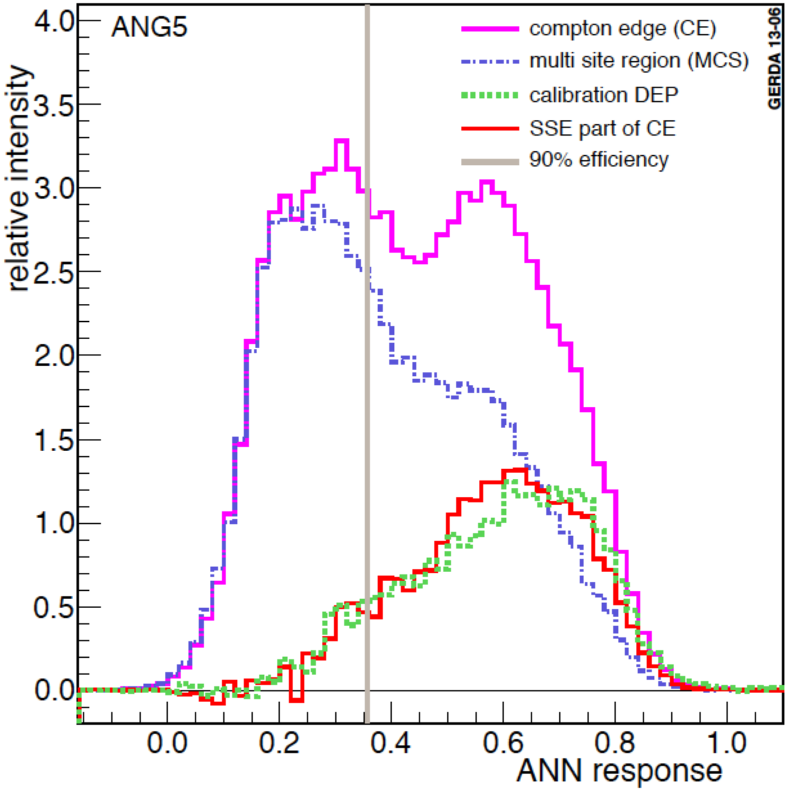
DEP

SEP

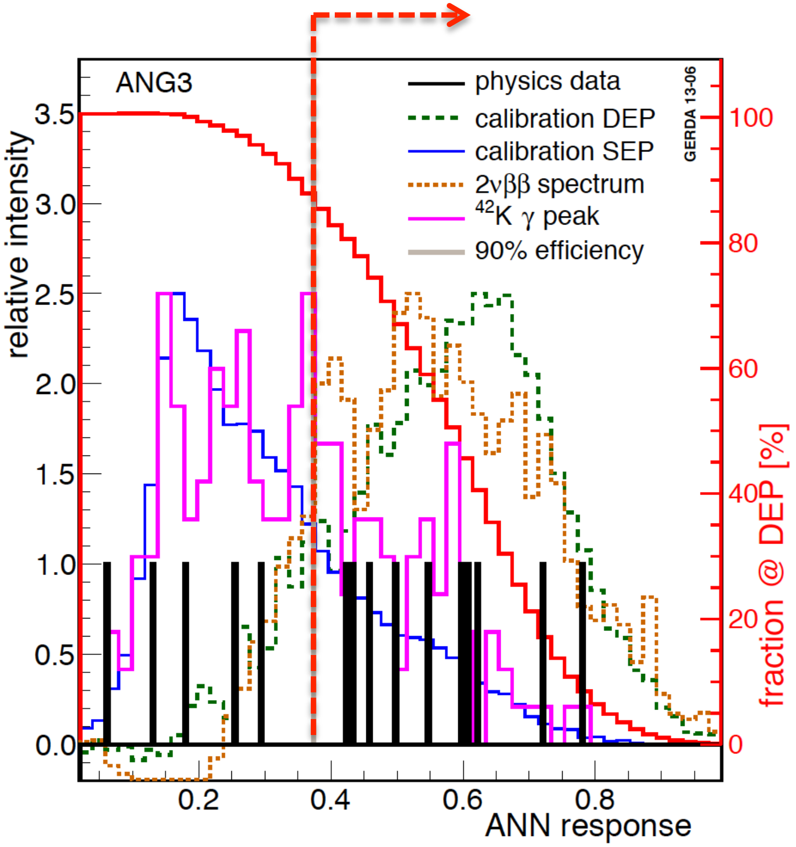
Data split in 3 periods: p1: Nov 11 – July 12, p2: July/Aug 12, p3: Aug 12-May 13

Pulse shape discrimination: Coax survival fraction for Phase I

arXiv:1307.2610



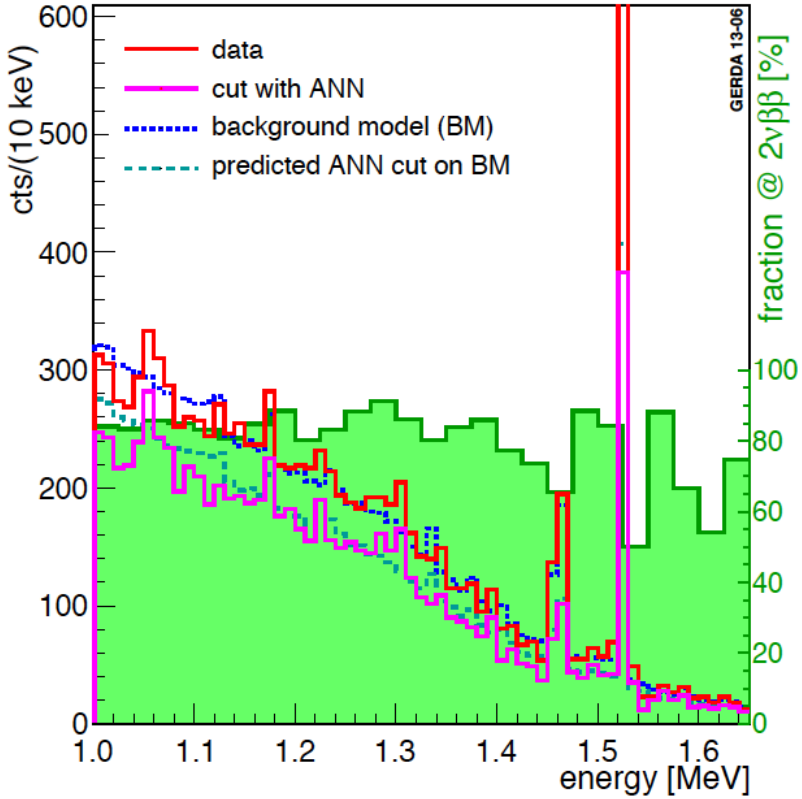
accepted as SSE-like



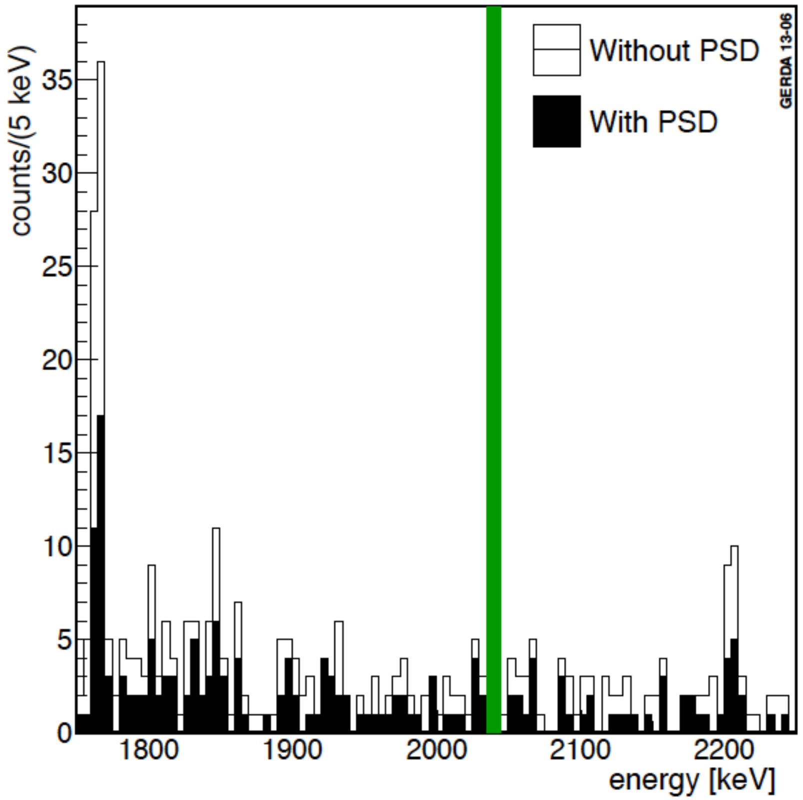
Pulse shape discrimination: Coax – survival fraction for Phase I

arXiv:1307.2610

PSD selection in 2νββ energy range



PSD selection in 0νββ energy range

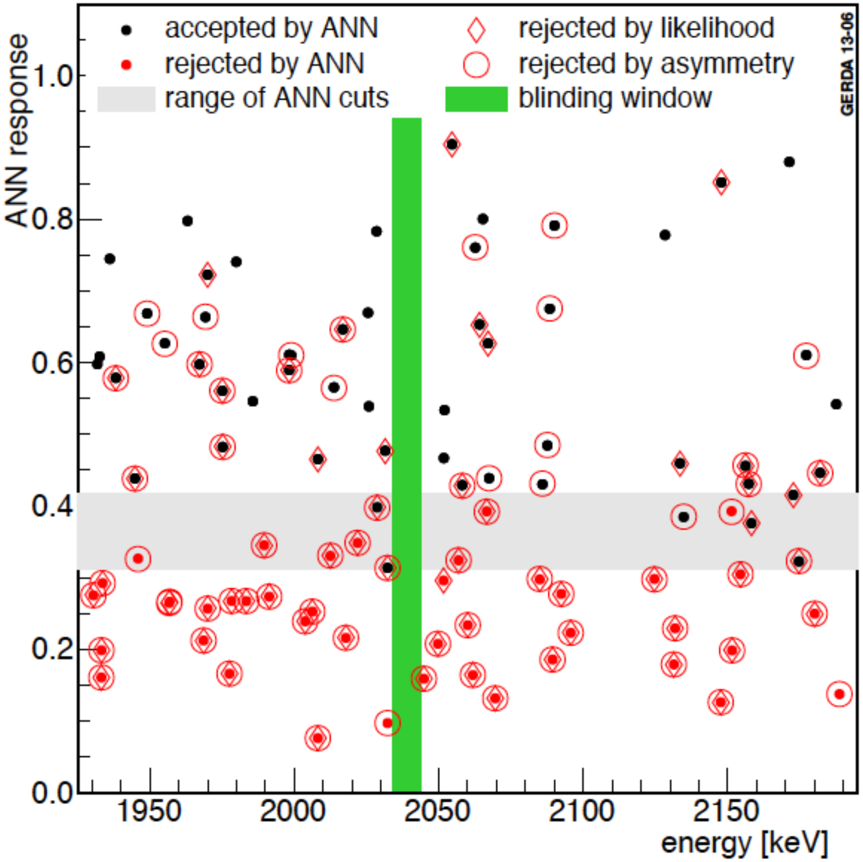


Measured 2νββ ANN survival: 0.85±0.02

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

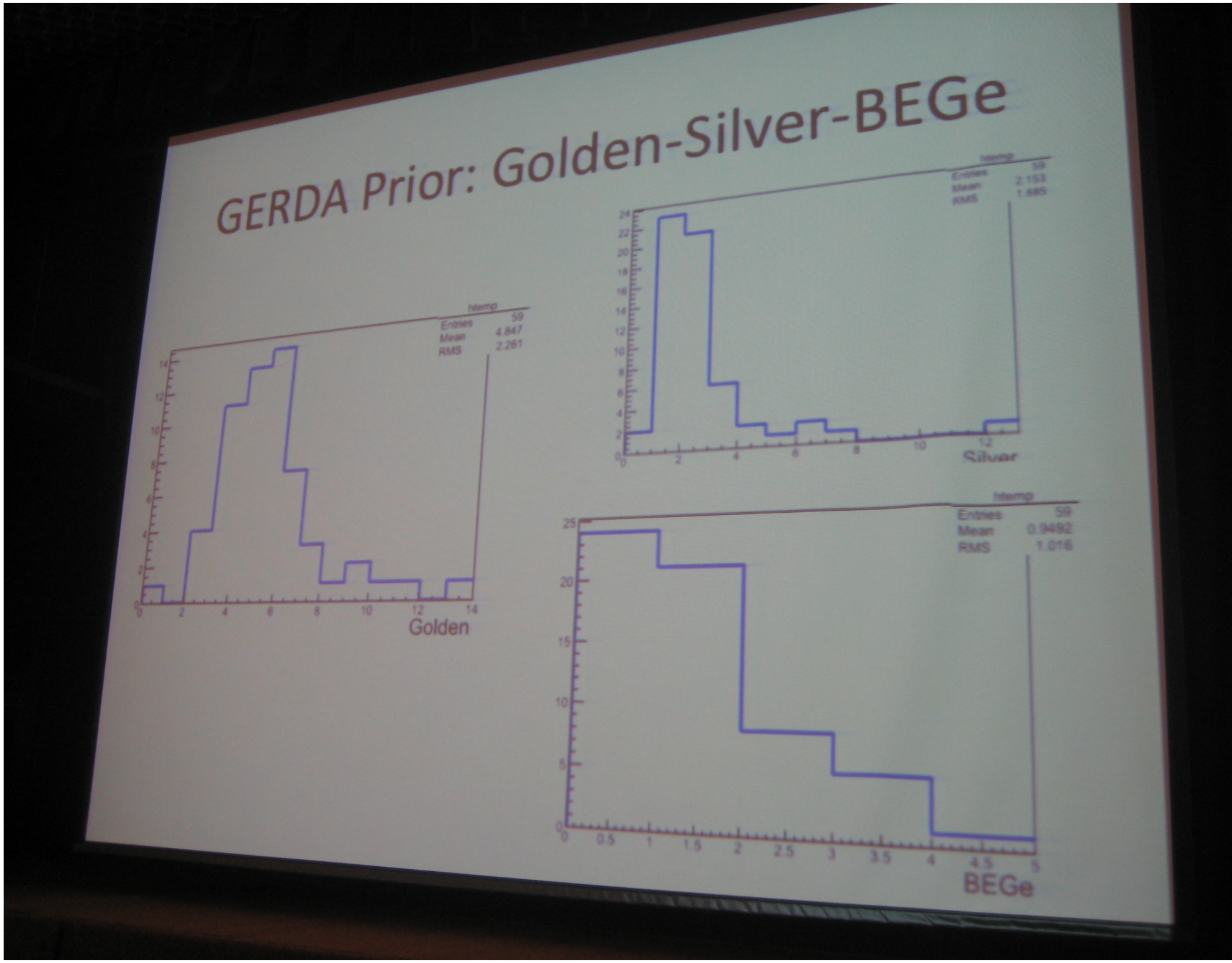
Unblinding at GERDA collaboration meeting in Dubna, June 12-14

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

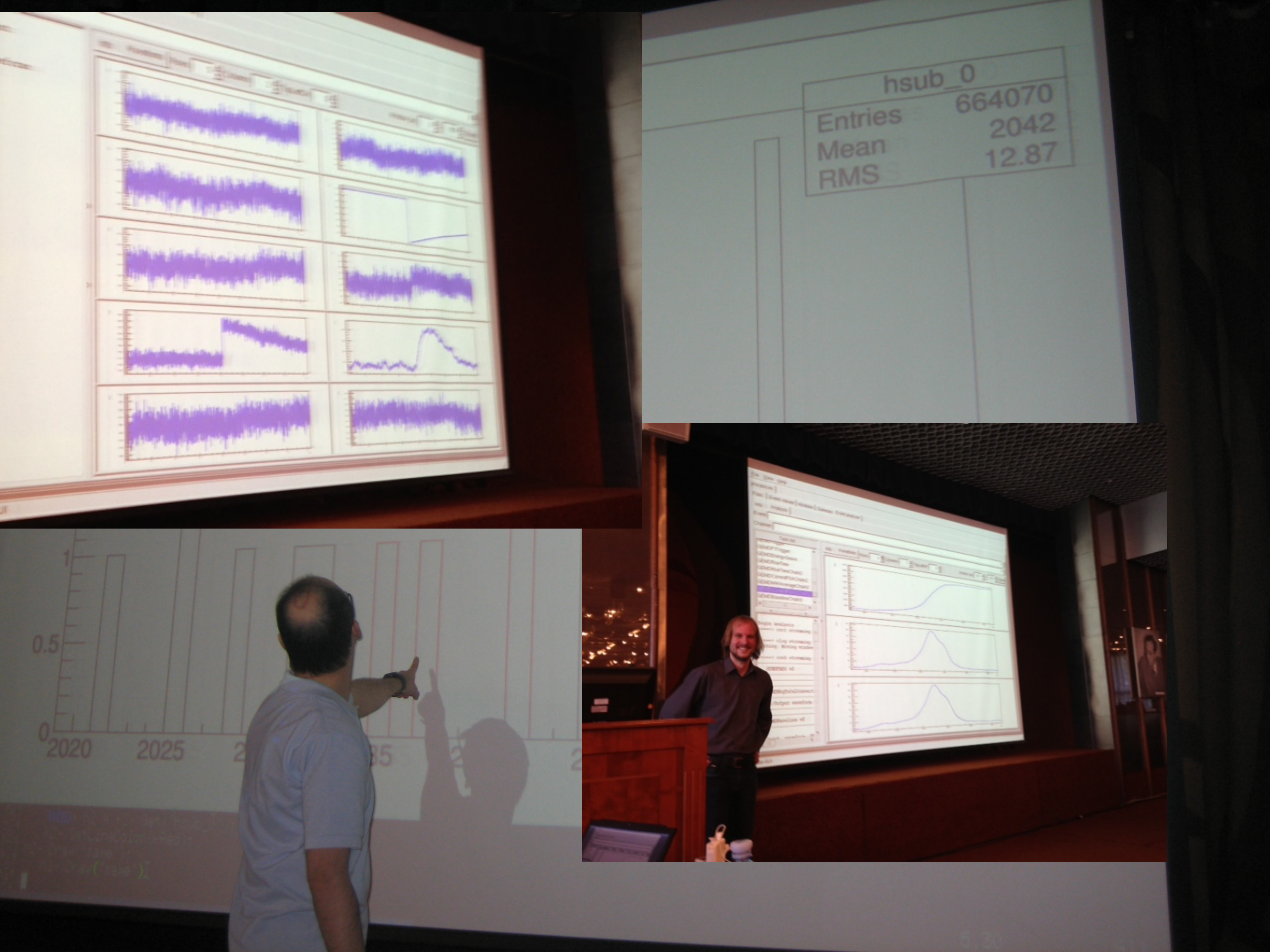
- 3 Data sets: golden, silver, BEGe
- Energy calibration method and parameters
- Unblind traces for PSD
- PSD method and cuts

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

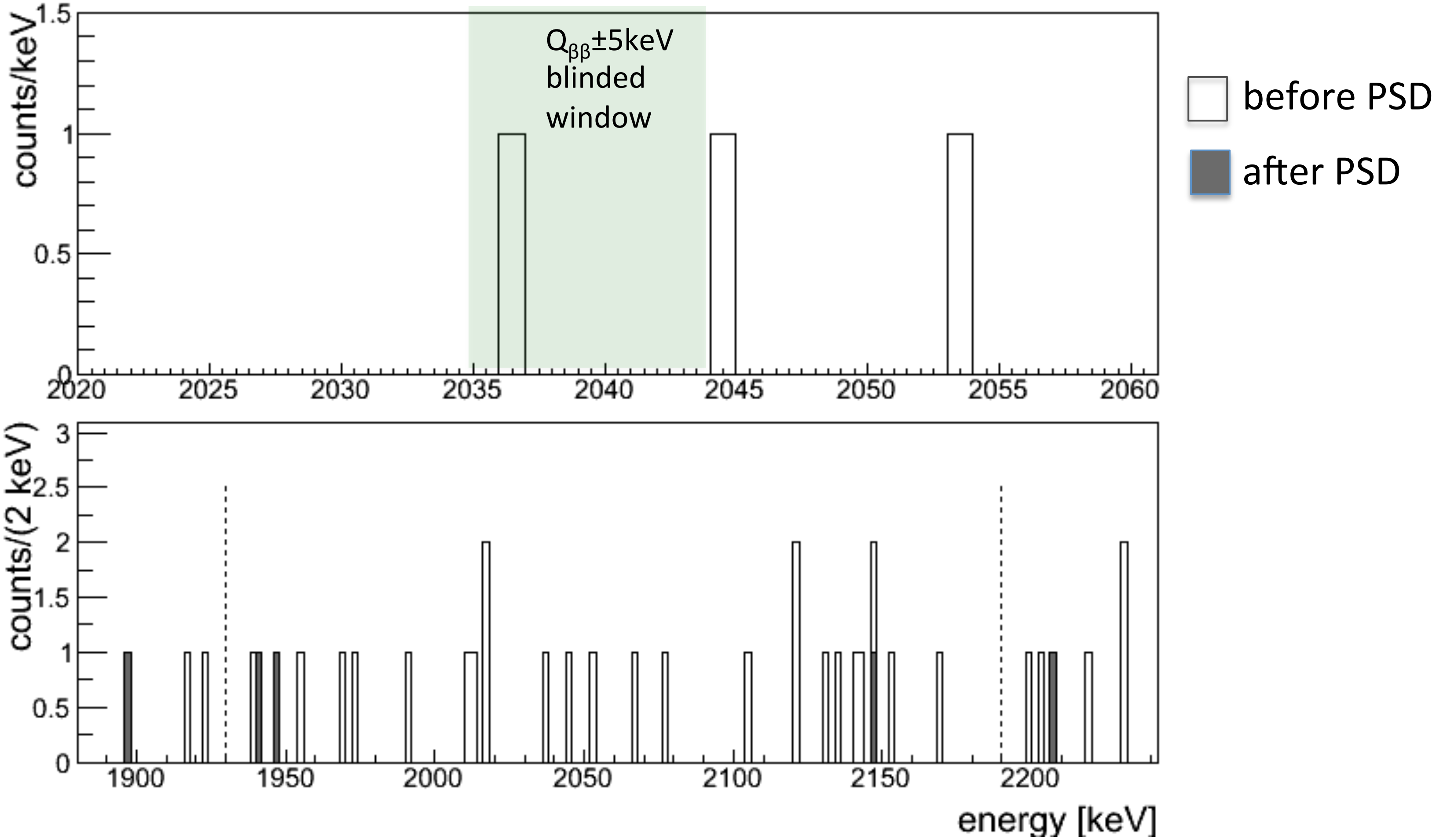
Unblinding at Dubna: the bets of the collaboration



GERDA Prior: Golden-Silver-BEGe

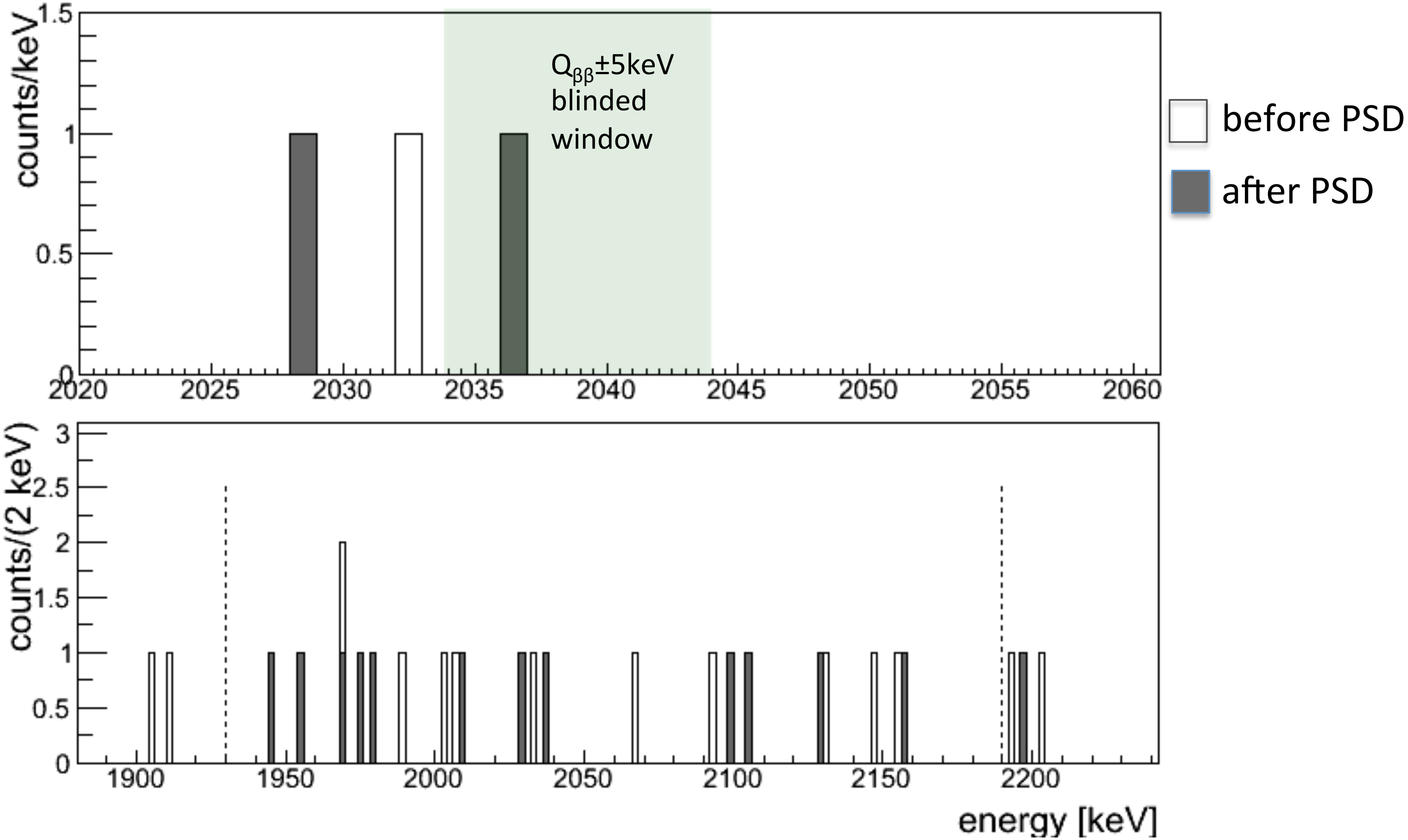

hsub_0
Entries 664070
Mean 2042
RMS 12.87
1
0.5
0
2020
2025

Unblinding: BEGe data set (2.4 kg yr)



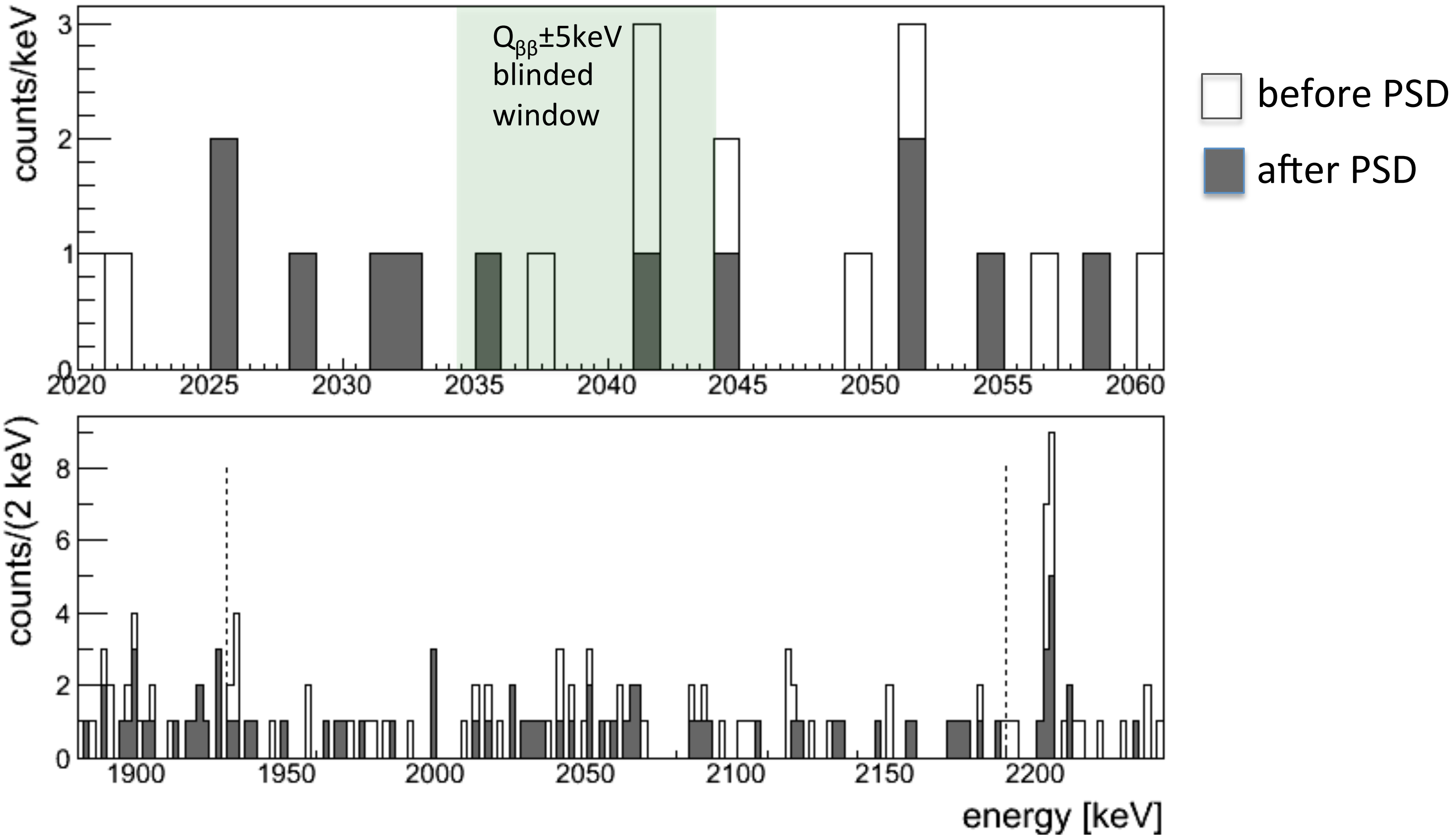
BEGe data set: 1 event in blinded window
0 event survive PSD cut

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



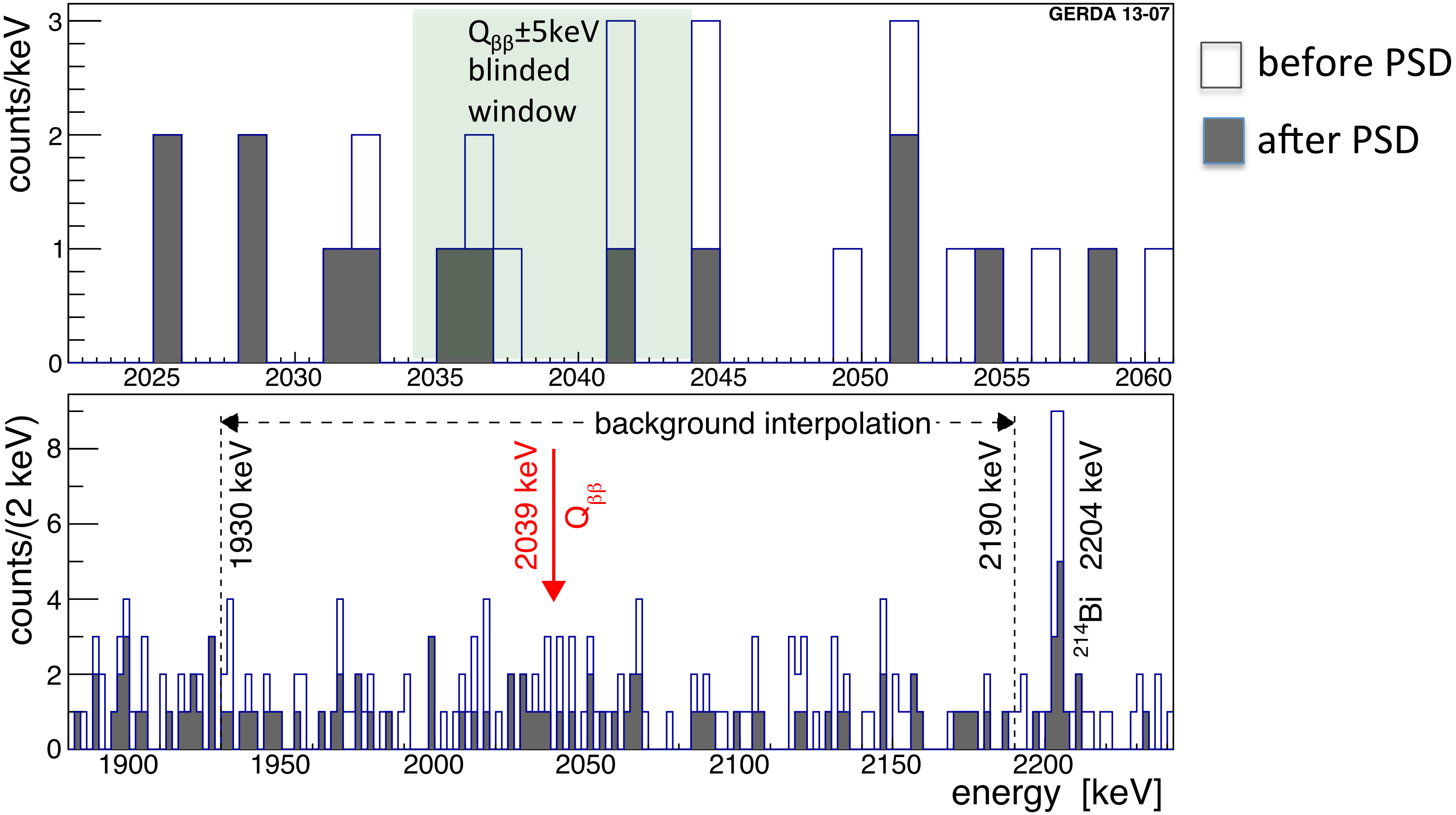
Silver data set: 1 event in blinded window
1 event survives PSD cut

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

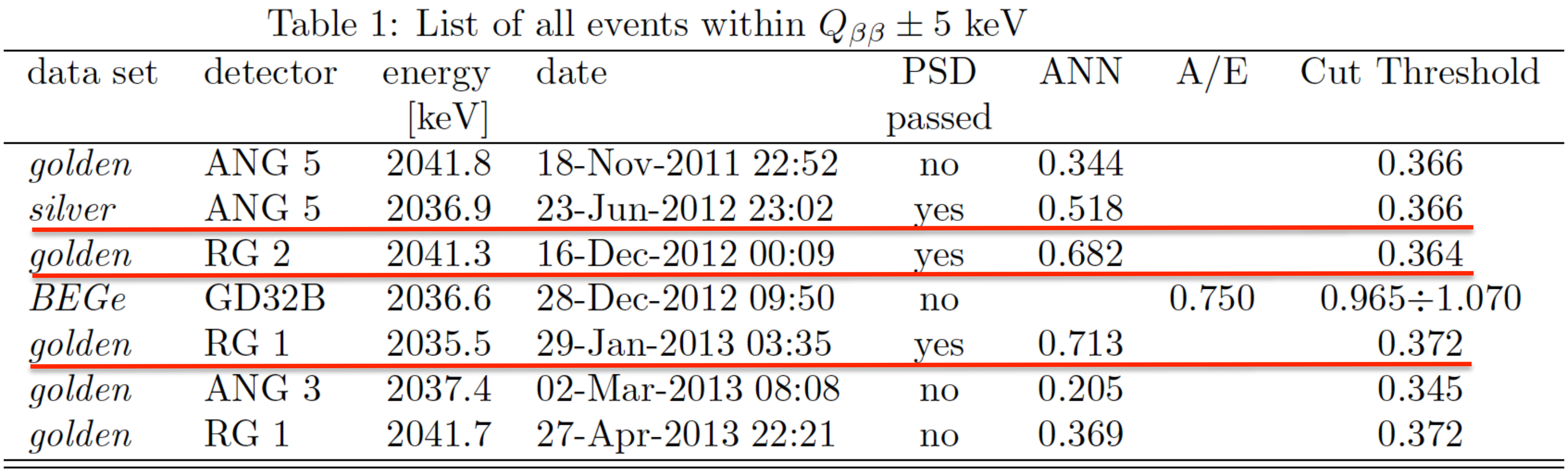
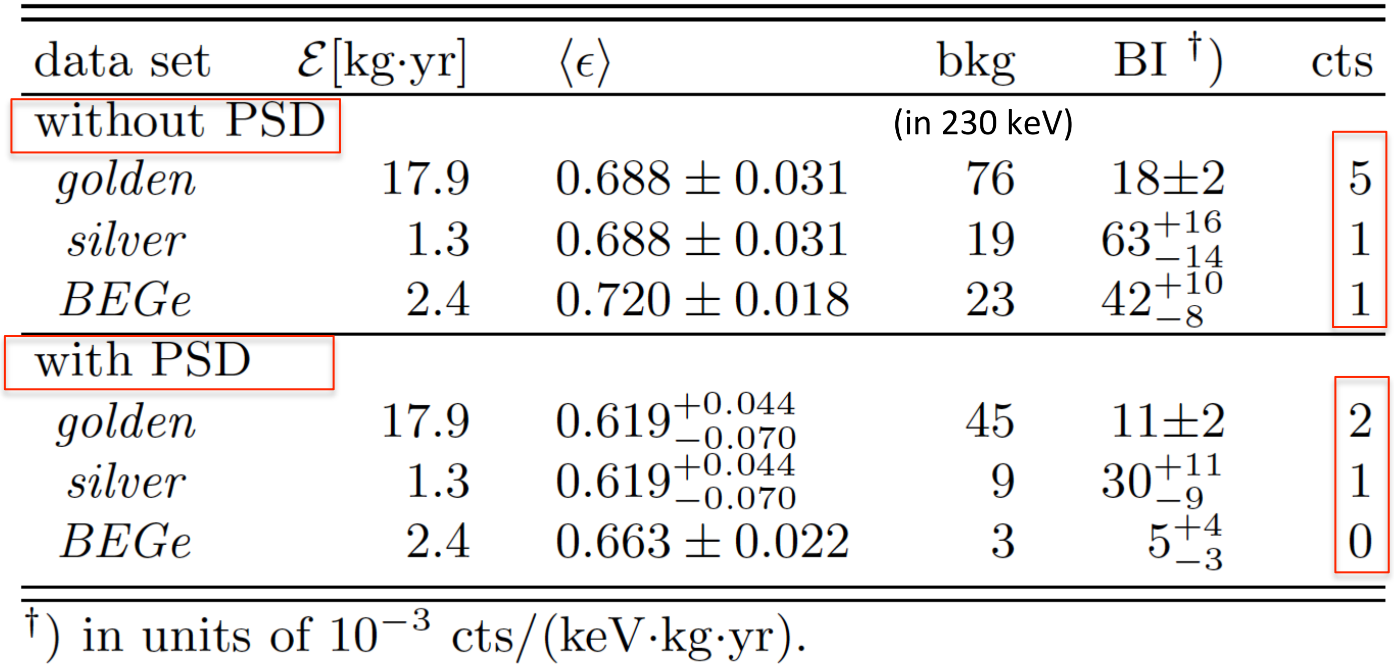


Table 1: List of all events within $Q_{\beta\beta} \pm 5$ keV

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 ± 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

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

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

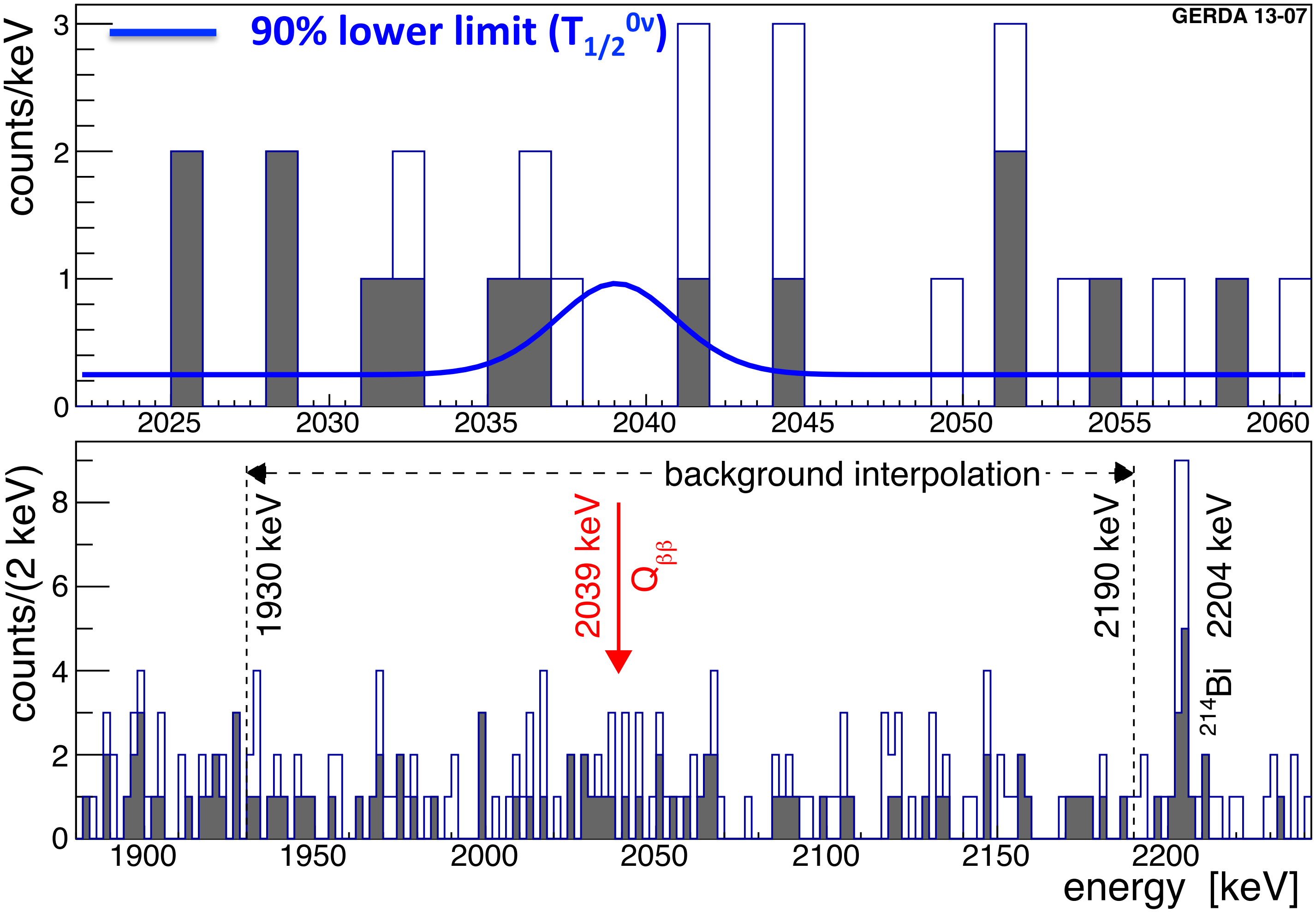
N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

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

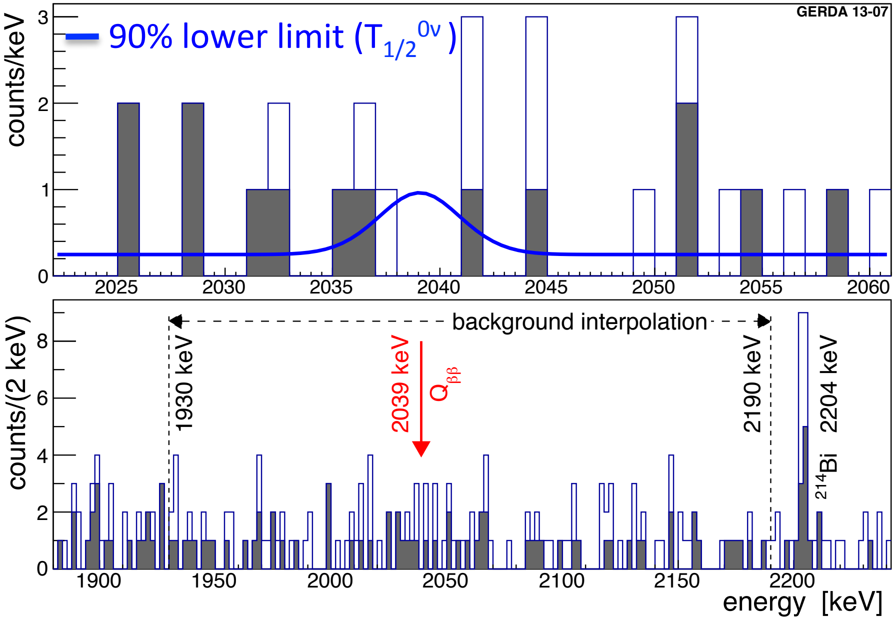
Data set	**Exposure (kg yr)**
Golden-coax	17.9
Silver-coax	1.3
BEGe	2.4

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

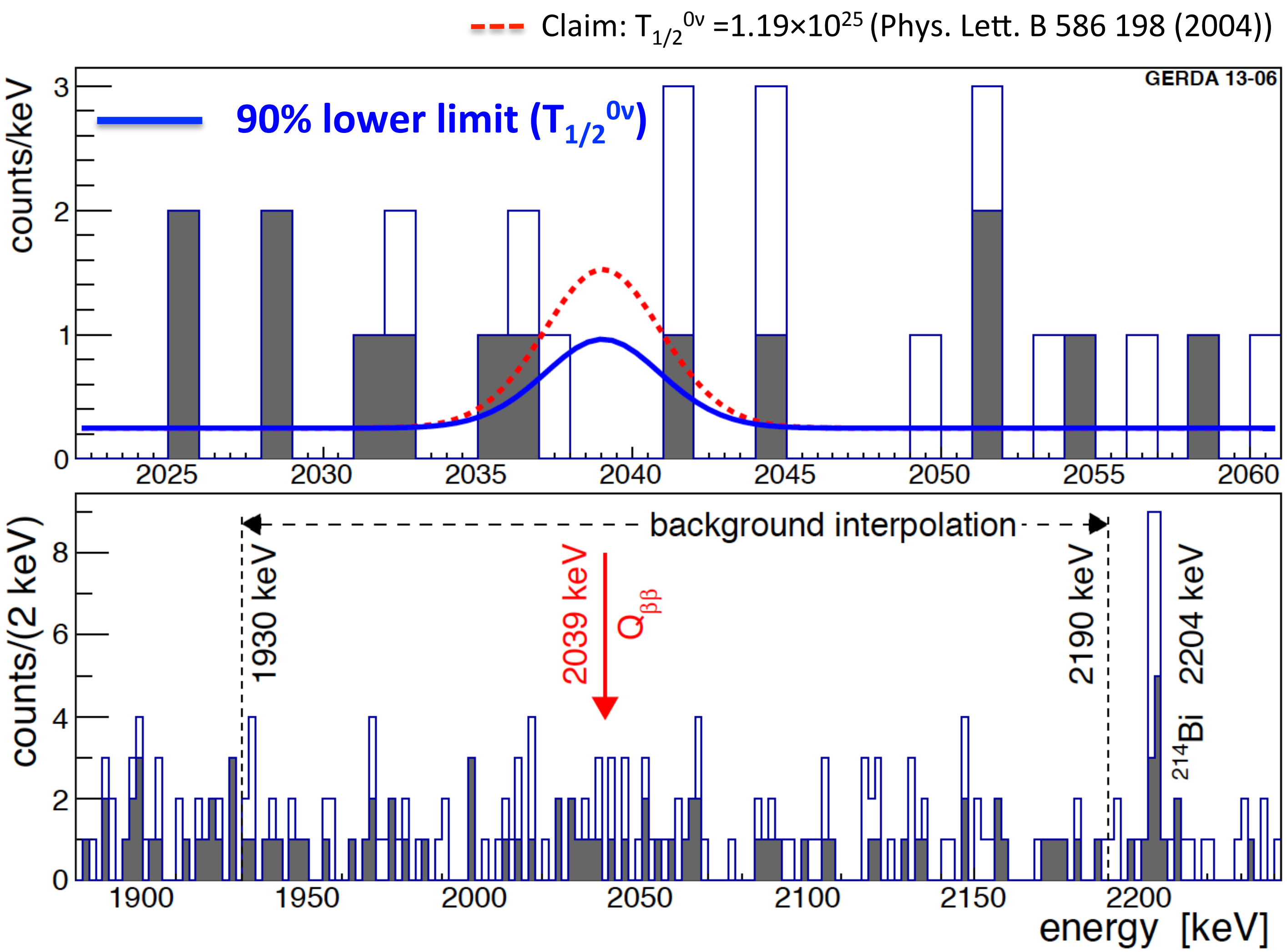
- 90% lower limit derived from profile likelihood fit to 3 data sets (constraint to physical 1/T range; excluding known γ-lines from bgd model at 2104±5 and 2119±5 keV)
- Best fit: **$N^{0\nu}$=0**
- **No excess** of signal counts above the background
- 90% C.L. lower l $\boxed{T_{1/2}^{0\nu} > 2.1 \cdot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

Systematics folded: limit weakened by 1.5%

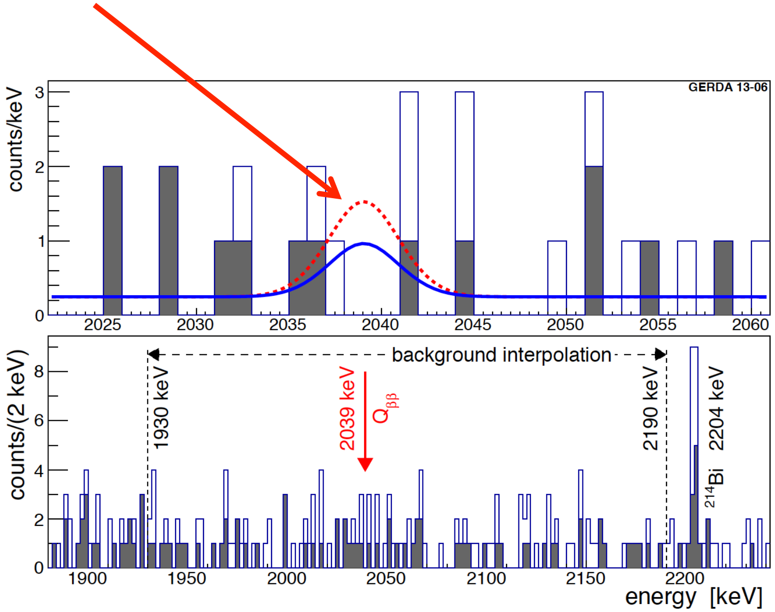
Comparison with Phys. Lett. B 586 198 (2004) claim

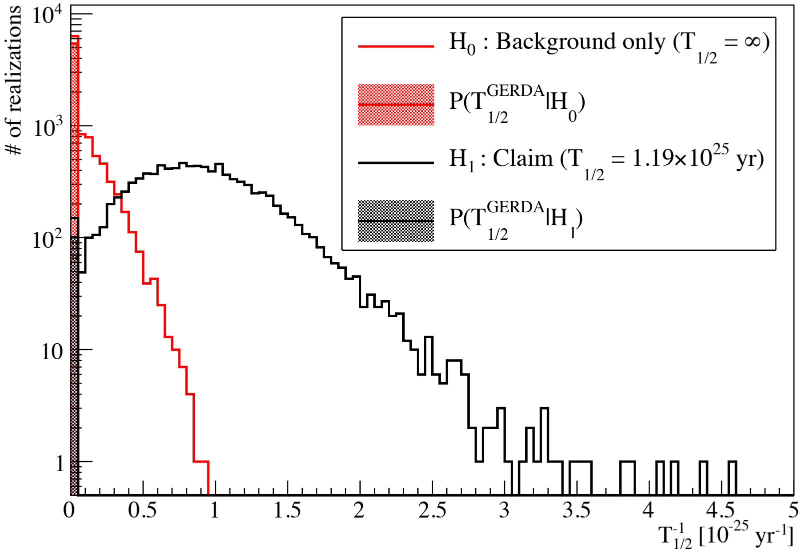


Comparison with Phys. Lett. B 586 198 (2004) claim

Expectation for claimed $T_{1/2}^{0\nu} = 1.19\times10^{25}$ 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

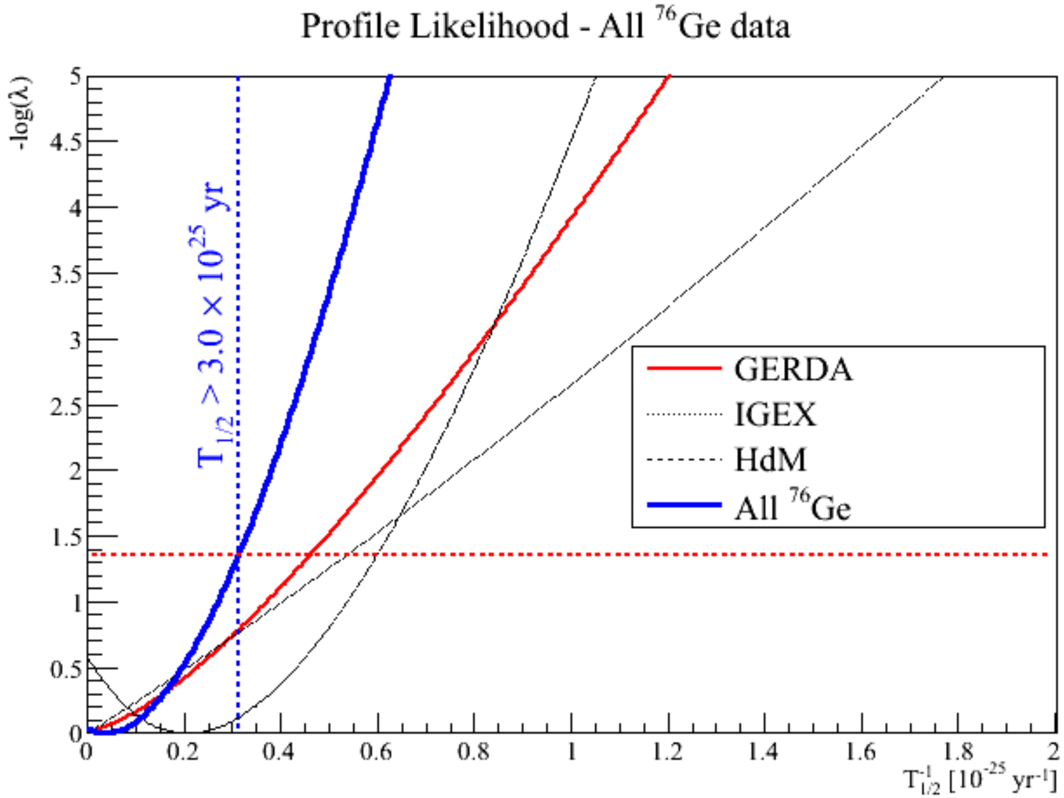
Bayes factor: P(H1)/P(H0)=0. 024

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)

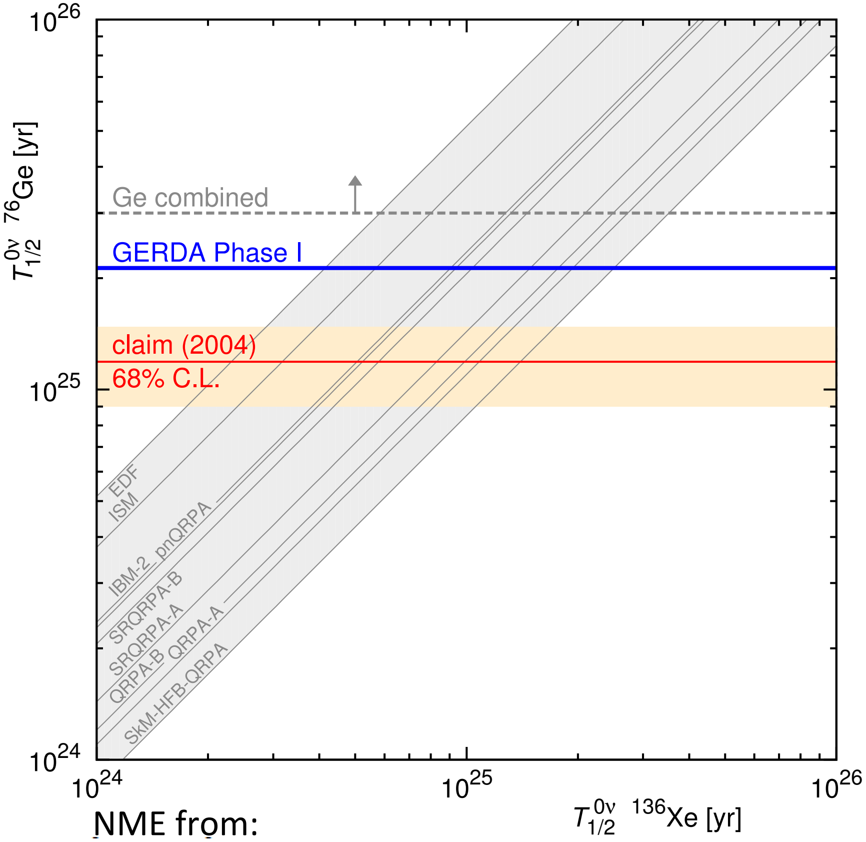
$$T_{1/2}^{0\nu} > 3.0 \cdot 10^{25}\ \mathrm{yr} \quad (90\,\%\ \ \mathrm{C.L.})$$

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



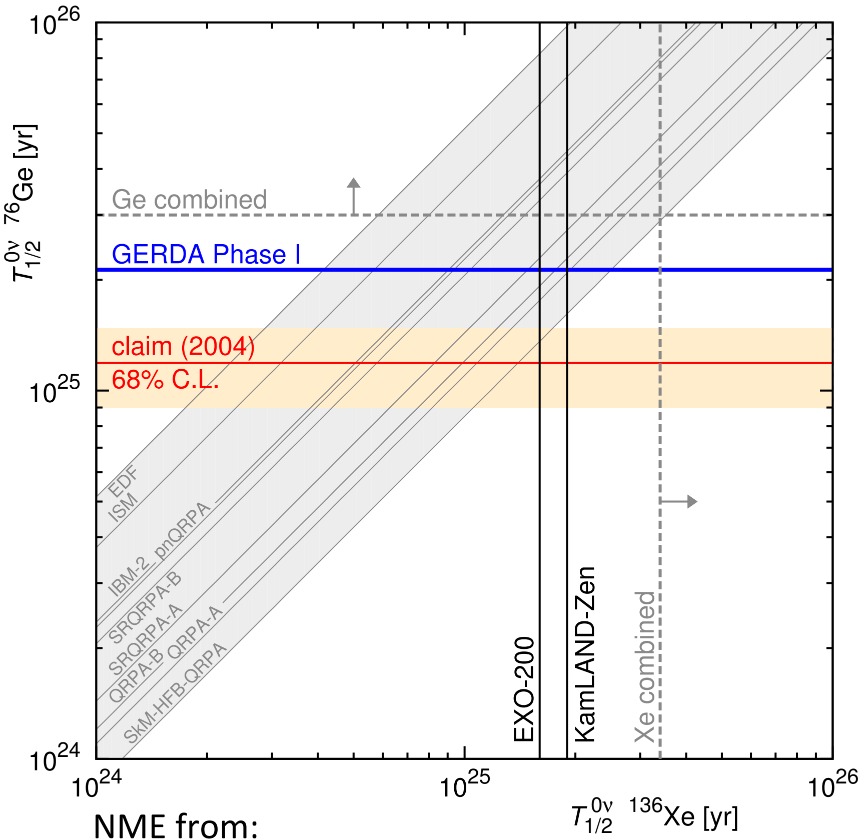
NME from:
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056

Ge combined: $<m_{ee}> < 0.2\text{-}0.4$ 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

The claim: global picture



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

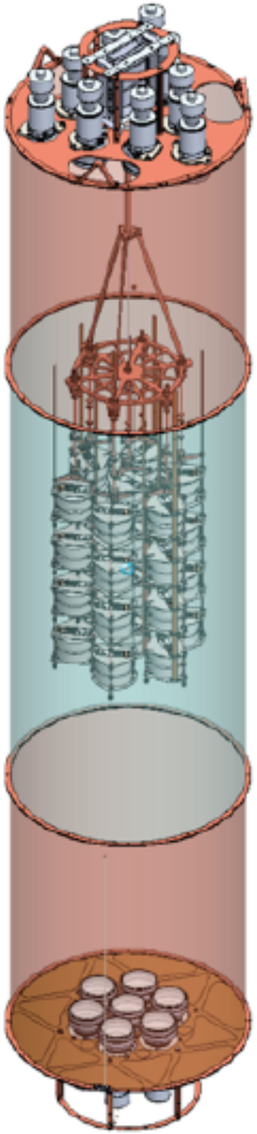
H1: signal with $T_{1/2}^{0\nu} = 1.19\times10^{25}$ yr
H0: background only

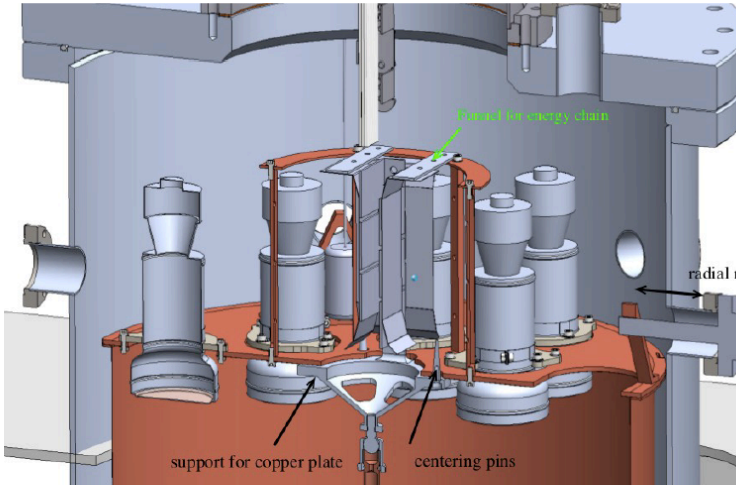
	Isotope	**$P(H_1)/P(H_0)$**	**Comment**
GERDA	^{76}Ge	0.024	Model independent
GERDA +HdM+IGEX	^{76}Ge	0.0002	Model independent
KamLAND-Zen*	^{136}Xe	0.40	Model dependent: NME, leading term
EXO-200*	^{136}Xe	0.23	Model dependent: NME, leading term
GERDA+KLZ* +EXO*	^{76}Ge + ^{136}Xe	0.002	Model dependent: NME, leading term

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

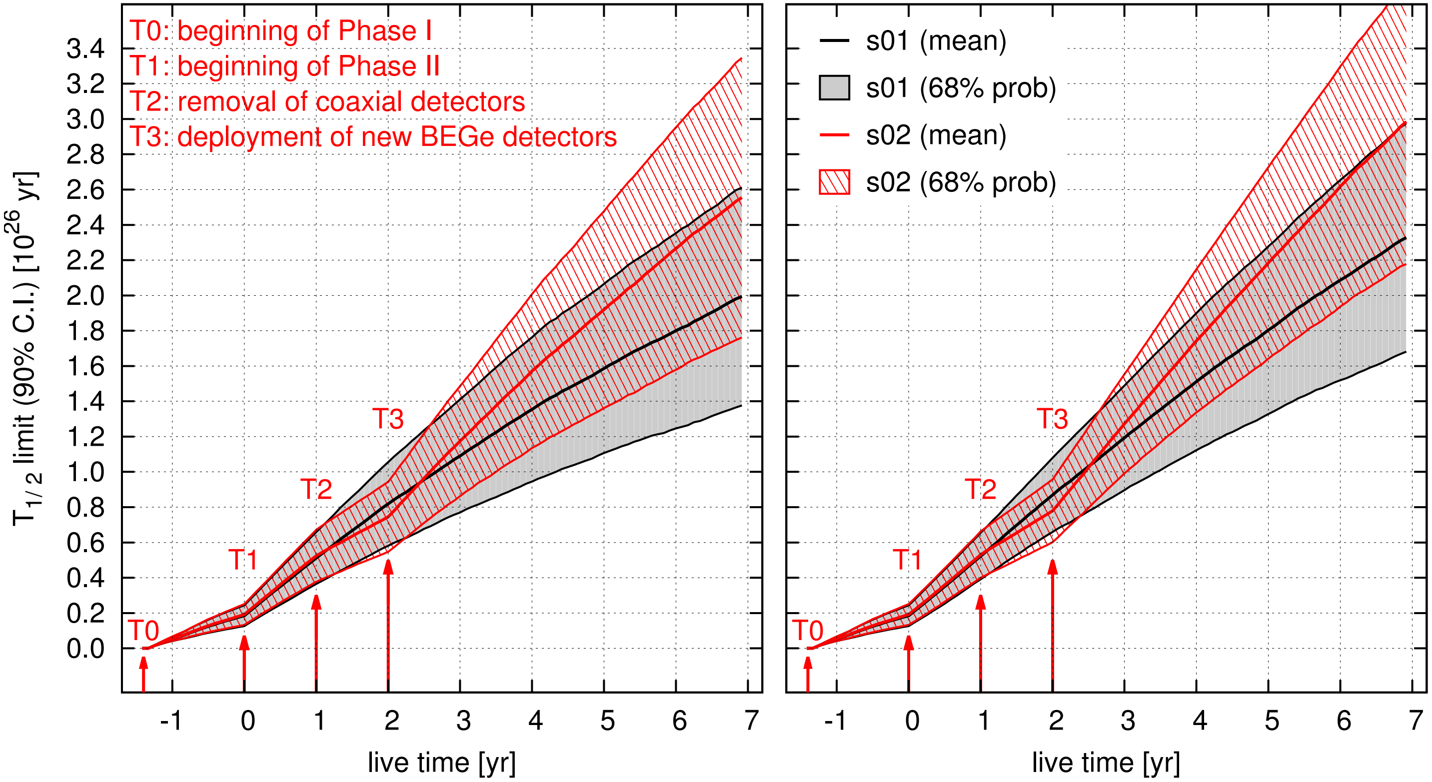
F. Simkovic, V. Rodin, A. Faessler, and P. Vogel, Phys. Rev. C. **87**, 045501 (2013).
M. T. Mustonen and J. Engel, (2013), arXiv:1301.6997 [nucl-th].
P. S. Bhupal Dev *et al.*, (2013), arXiv:1305.0056 [hep-ph].

Liquid argon instrumentation: PMTs & WLS fibers/SiPM





Expected sensitivity: Phase II/II+ (preliminary)



Summary & Outlook

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

GERDA publications & dissemination of results 2013

GERDA publications before unblinding:

1. *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
2. *$2\nu\beta\beta$ 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
3. *Pulse shape analysis:* **Pulse shape discrimination for GERDA Phase I data**
   EPJC 73 (2013) 2583; on arXiv:1307.2610 [physics.ins-det]
4. *The background:* **The background in the neutrinoless double beta decay experiment GERDA**
   Under review at EPJC; on arXiv:1306.5084 [physics.ins-det]

GERDA publications after unblinding:

GERDA Phase I results (Data release seminar at LNGS on July 16)
https://agenda.infn.it/conferenceDisplay.py?confId=6641

5. **Results on neutrinoless double beta decay of 76Ge from GERDA Phase I**
   Phys. Rev. Lett. 111 (2013) 122503, arXiv:1307.4720