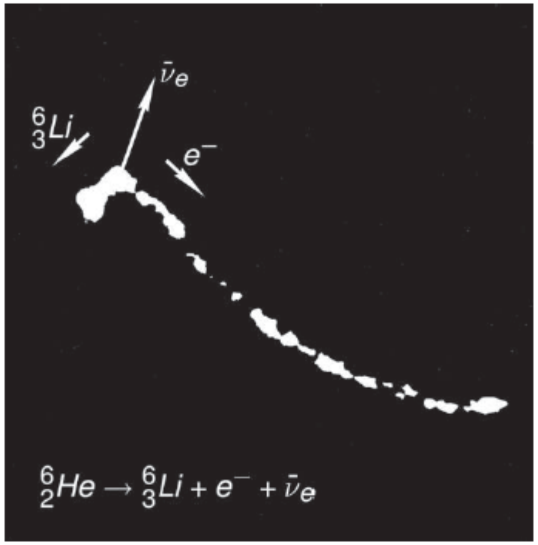


European Physical Society – EPS Historic Site
The neutrino experiment at MTA Atomki

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.

Európai Fizikai Társulat – EPS történelmi emlékhely
A neutrínókísérlet, MTA Atomki

1956-ban Csikai Gyula és Szalay Sándor ebben az épületben béta-bomlási eseményeket fényképezett le egy ködkamrában. Az elektron és a maradékmag pályájának szöge azt mutatja, hogy a bomlásban keletkezik egy nem detektált harmadik részecske is. A neutrínó létezését így megerősítve, a kísérlet hozzájárult a modern fizika megalapozásához.

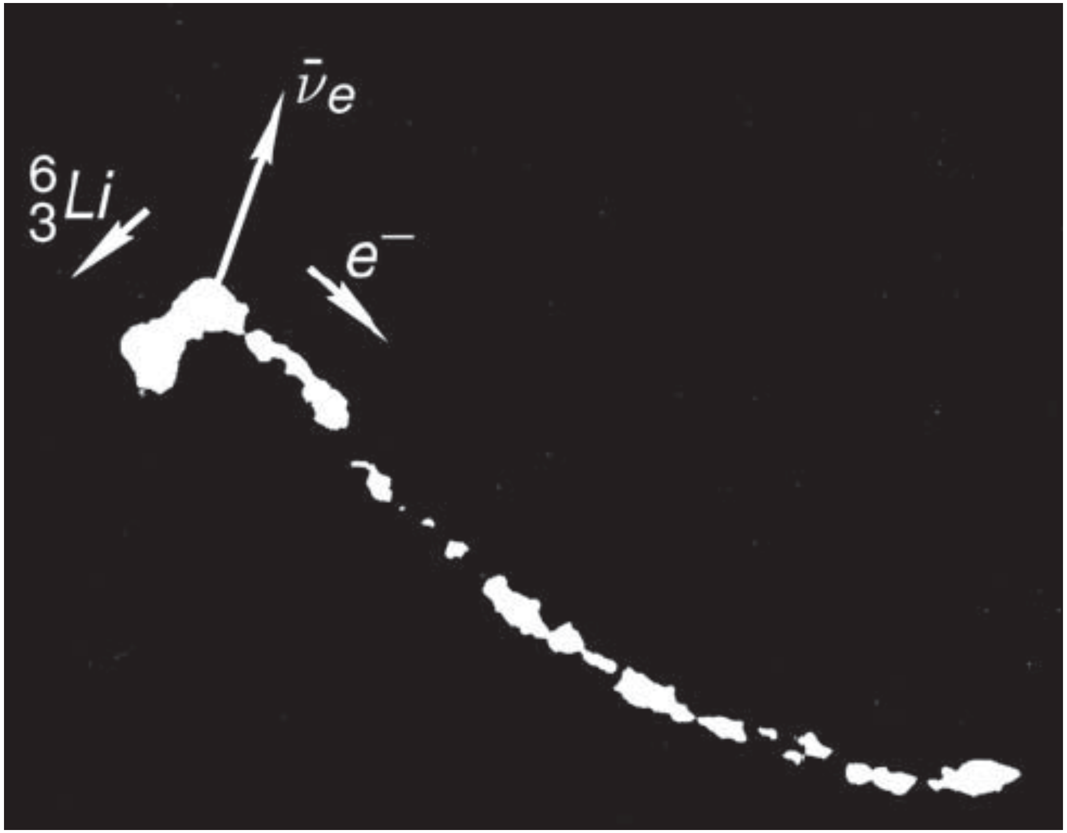
Debrecen
2013

From beta-decay to neutrino-less double beta decay:
The quest for Majorana neutrinos

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

Stefan Schönert
Physik-Department, TU München

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



Reconstruction of neutrino energy and momentum event-by-event

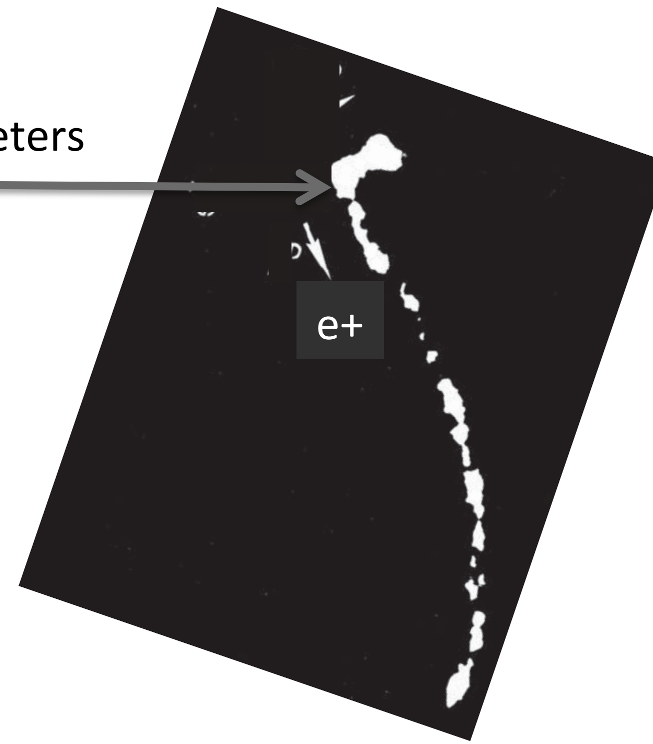
1956: The Reines-Cowan experimental concept

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



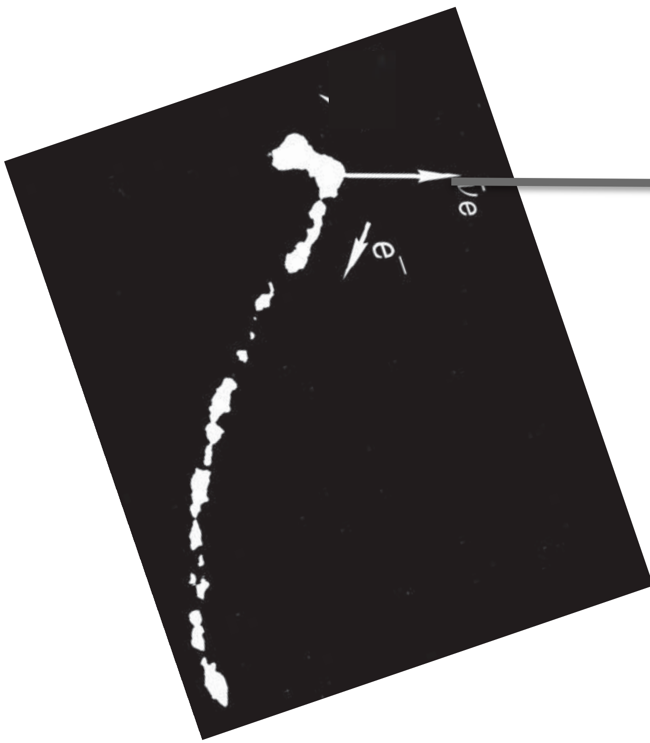
Beta-decays of neutron rich
fission products

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

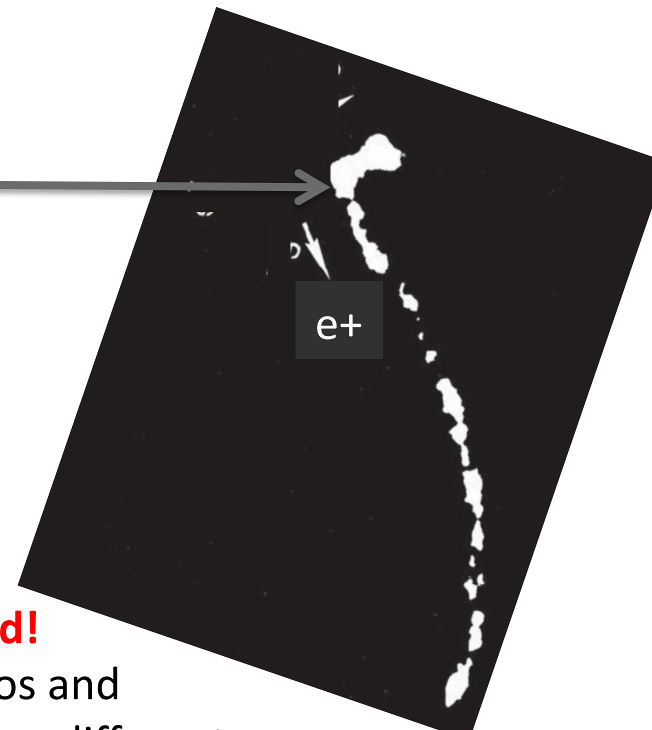
Source: Anti-Neutrinos
from nuclear reactor core

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

ν_e + „**n**“ ➔ „p“ + e^+



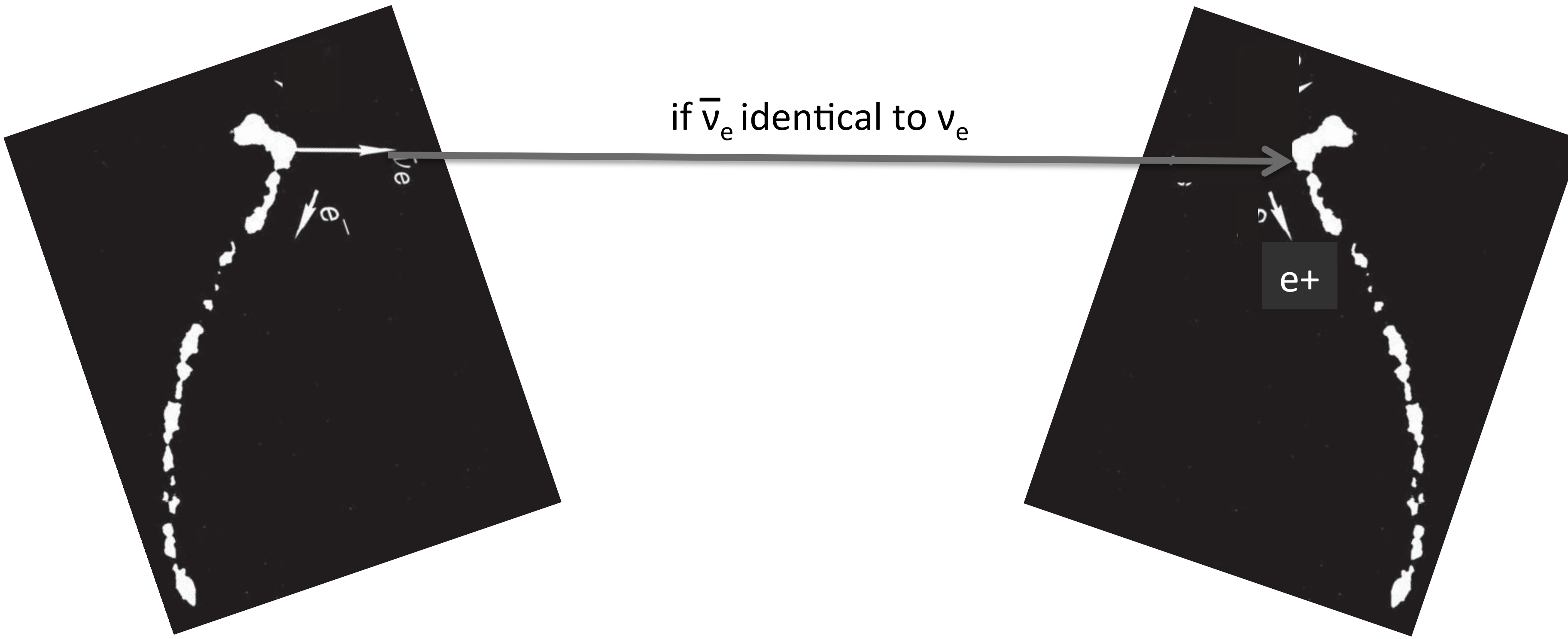
if $\bar{\nu}_e$ identical to ν_e



Not observed!
Anti-neutrinos and
neutrinos have different
helicities

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

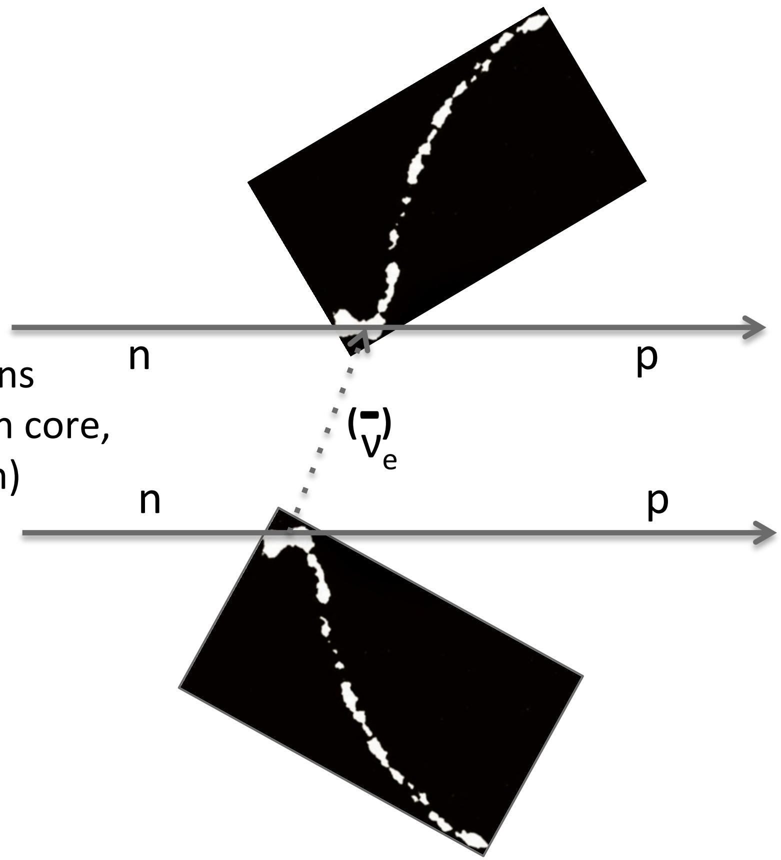


Neutrinoless Double Beta Decay (0νββ)

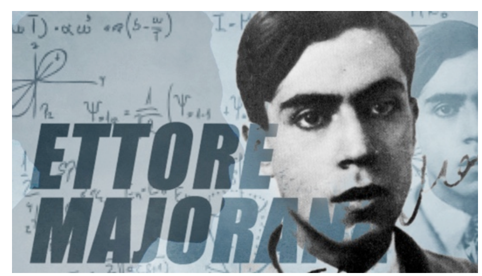
Today we know that

- 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

(Nukleons bound in core, $\approx 10^{-15}$ m)



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



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)

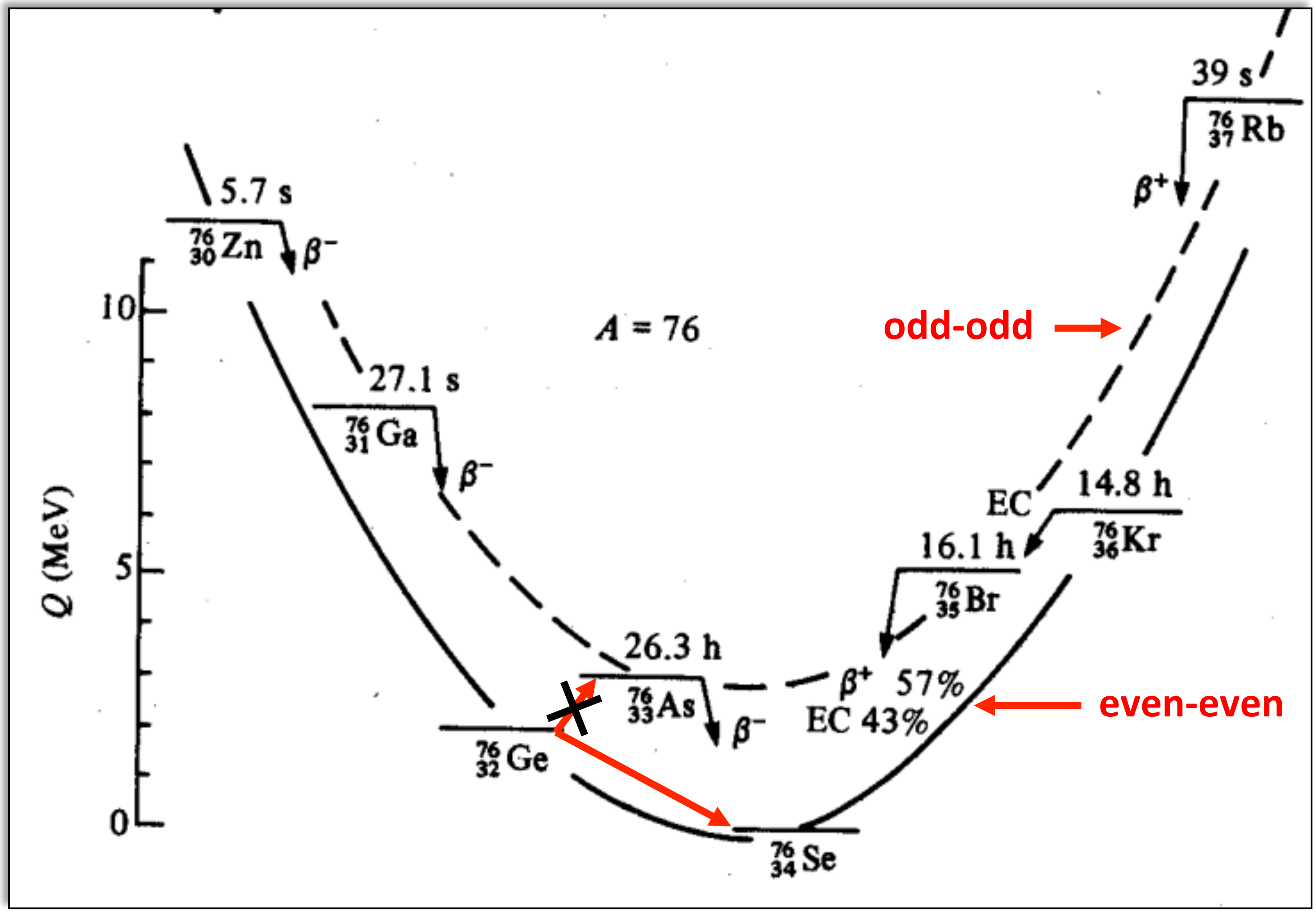
Are neutrinos Majorana fermions ?

Chi l'ha visto ?

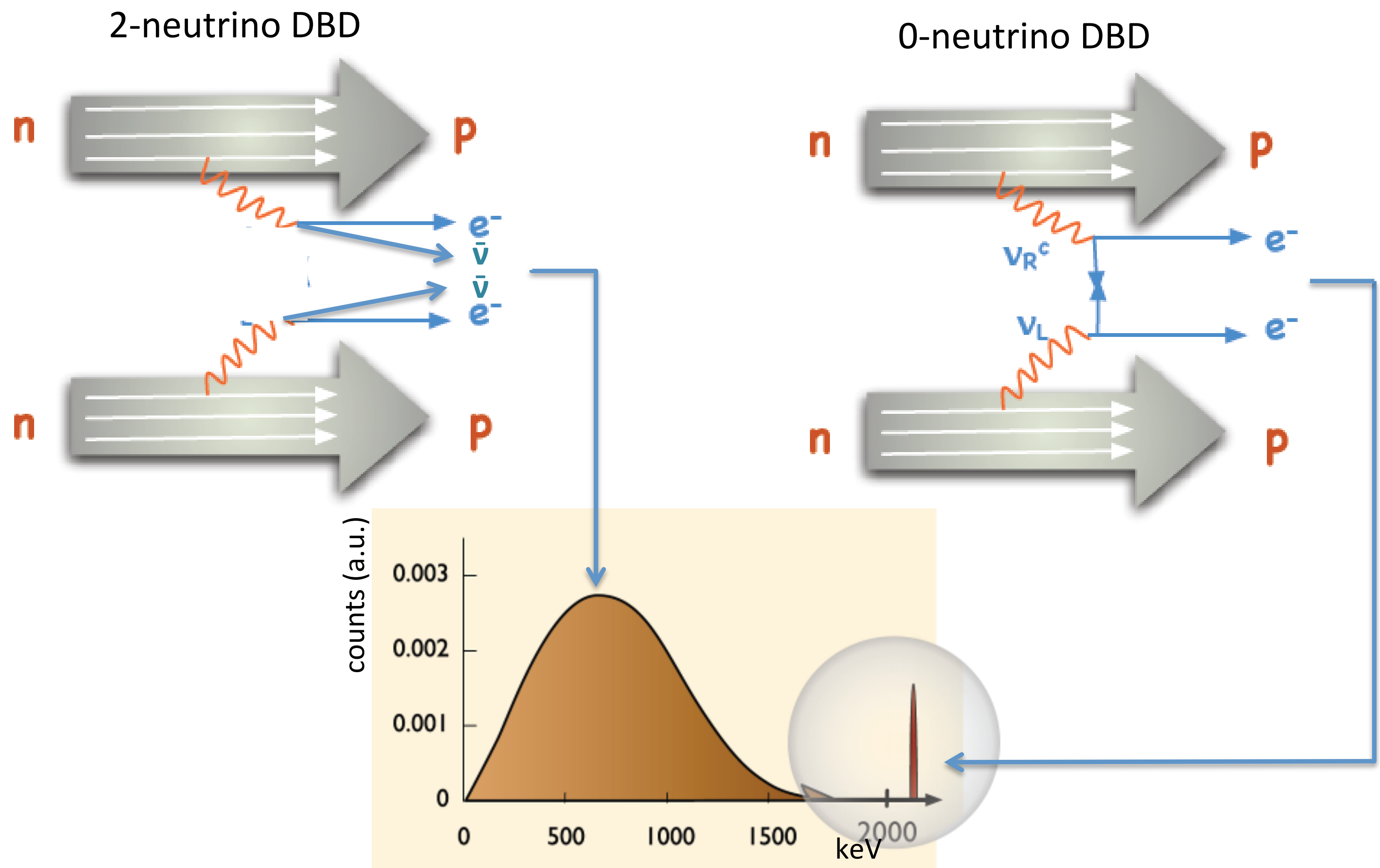
Ettore Majorana, ordinario di fisica teorica all' Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Marianecci,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

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

Double beta decay

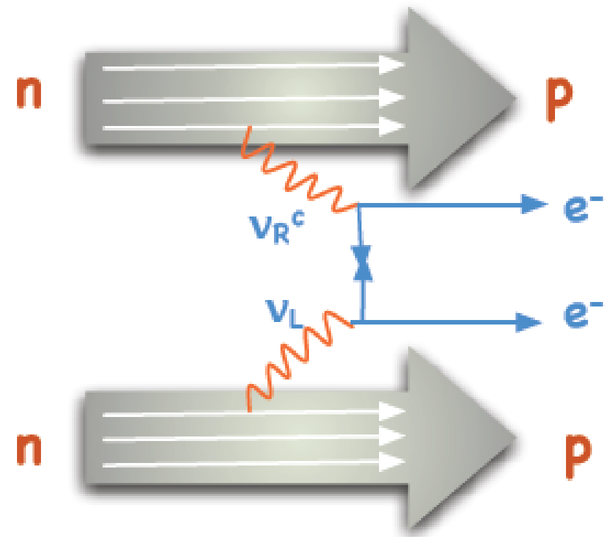


2νββ vs 0νββ decay



2-electron spectra

0νββ decay and neutrino mass



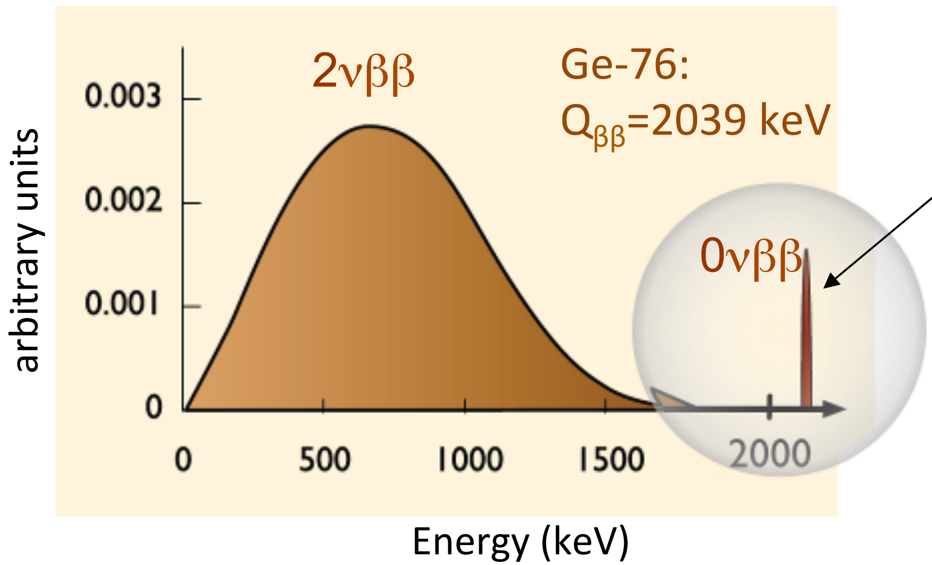
Expected decay rate:

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

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

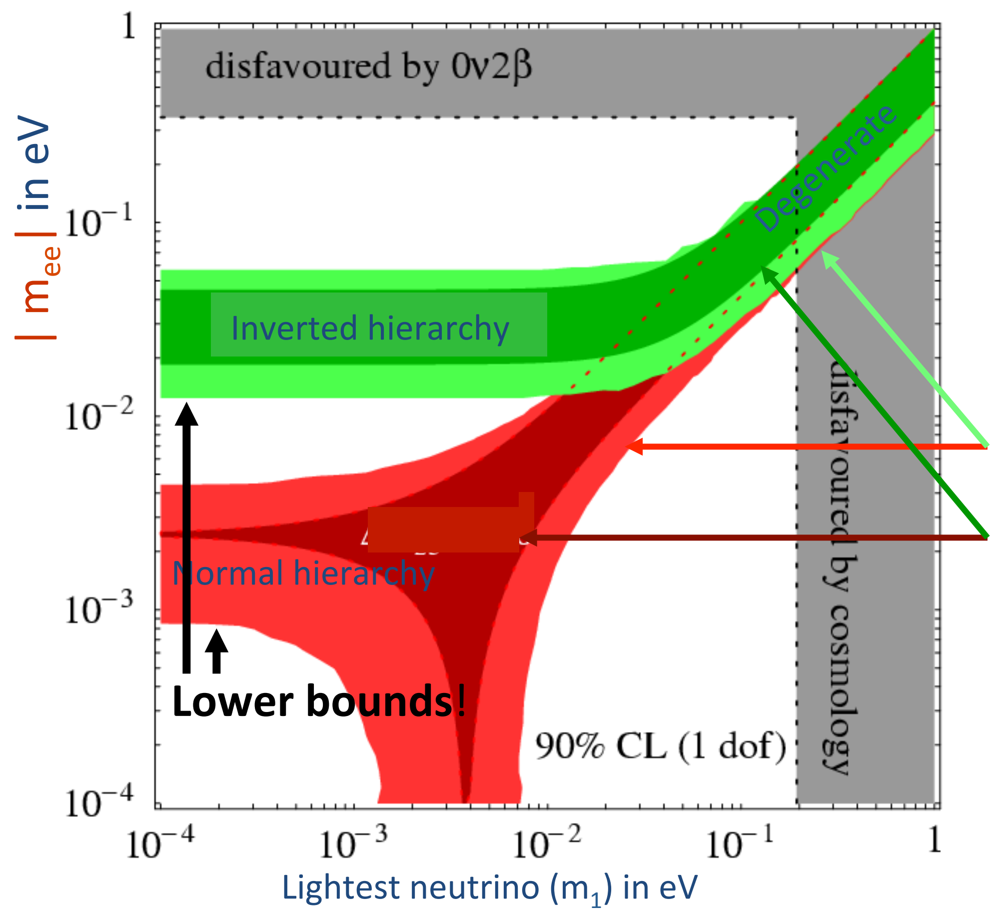
Discovery would imply:

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

$0\nu\beta\beta$: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha\text{-}\beta}_{\text{from oscillation experiments}})$$

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



F.Feruglio,
A. Strumia,
F. Vissani,
NPB 637

90% CL

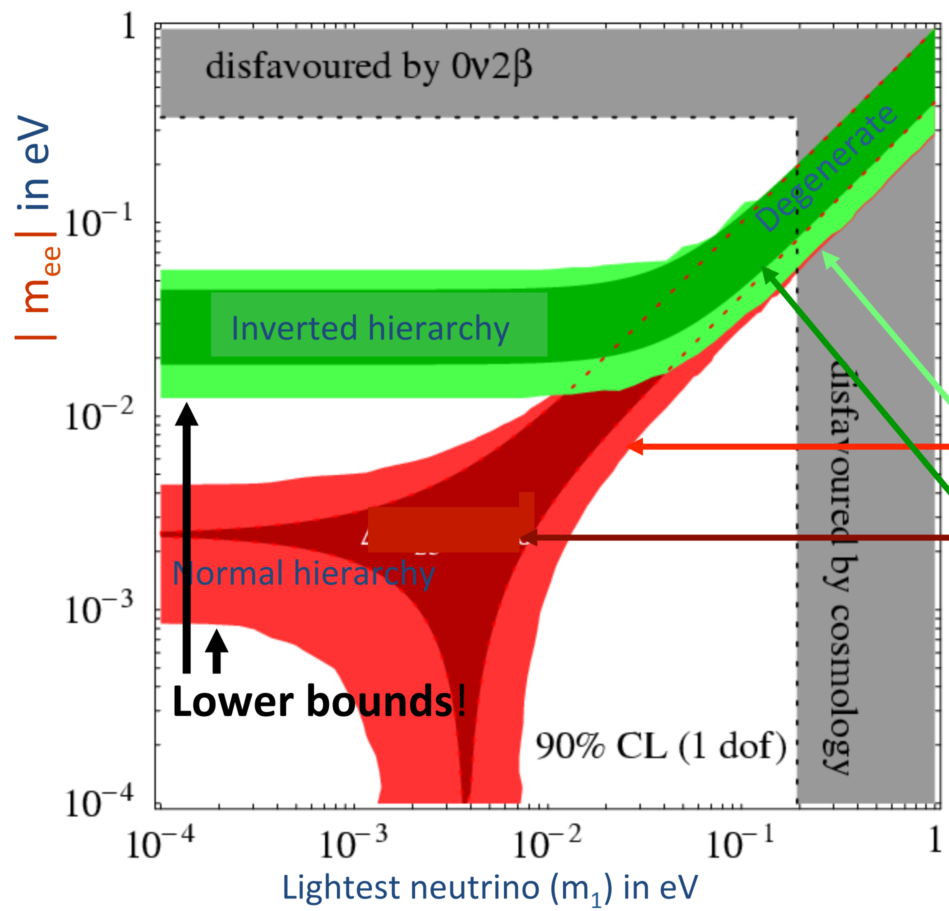
Negligible errors from oscillations; width due to CP phases

$0\nu\beta\beta$: Range of m_{ee} derived from solar and atmospheric oscillation experiments

$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}, \alpha\text{-}\beta}_{\text{from oscillation experiments}})$$

KDKC claim: 0.44 eV

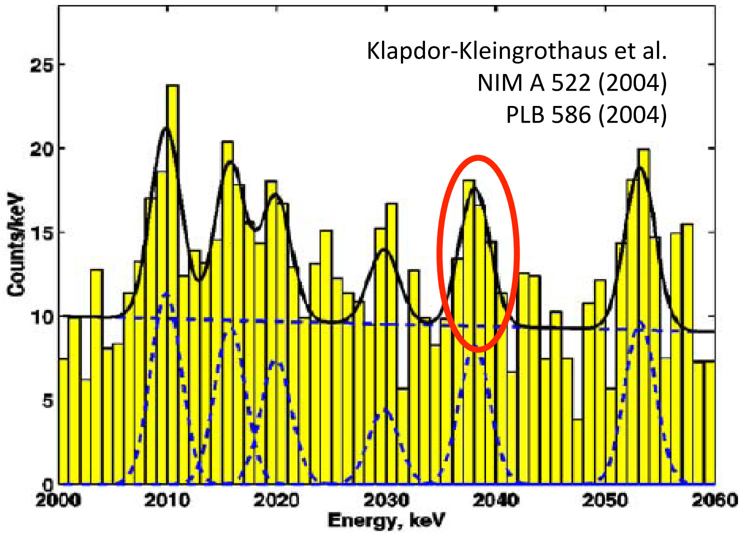
Goal of next generation experiments: ~10 meV



90% CL

Negligible errors from oscillations; width due to CP phases

F.Feruglio, A. Strumia, F. Vissani, NPB 637



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

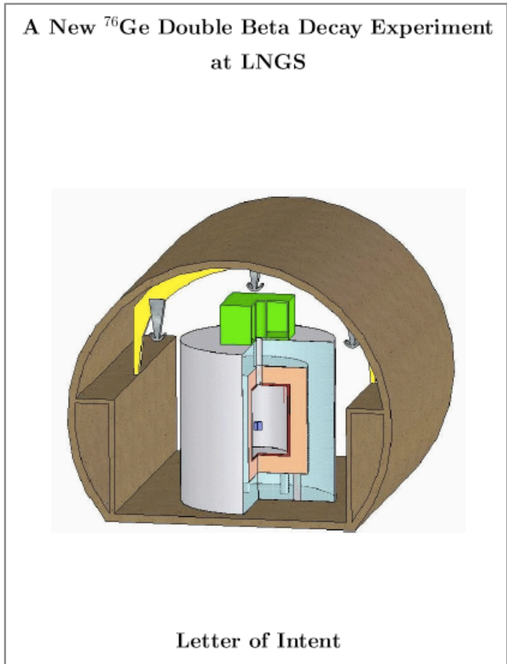
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for $0\nu\beta\beta$
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

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

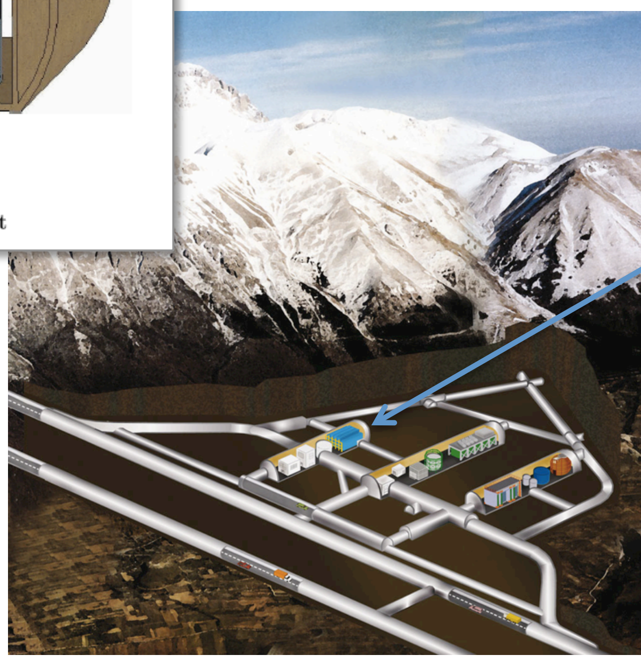
- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- ε_{fep} = 1 (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

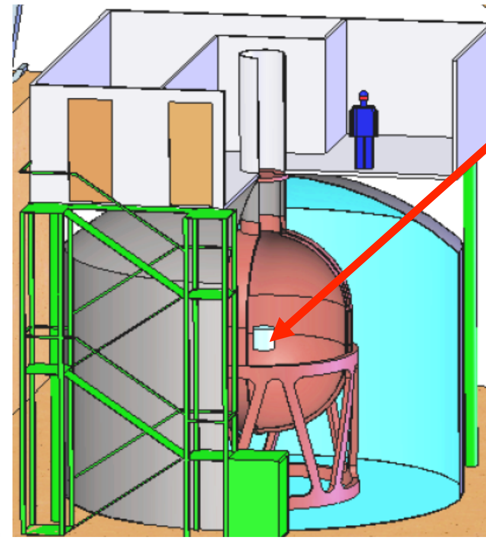
(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013):

GERDA @ LNGS


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

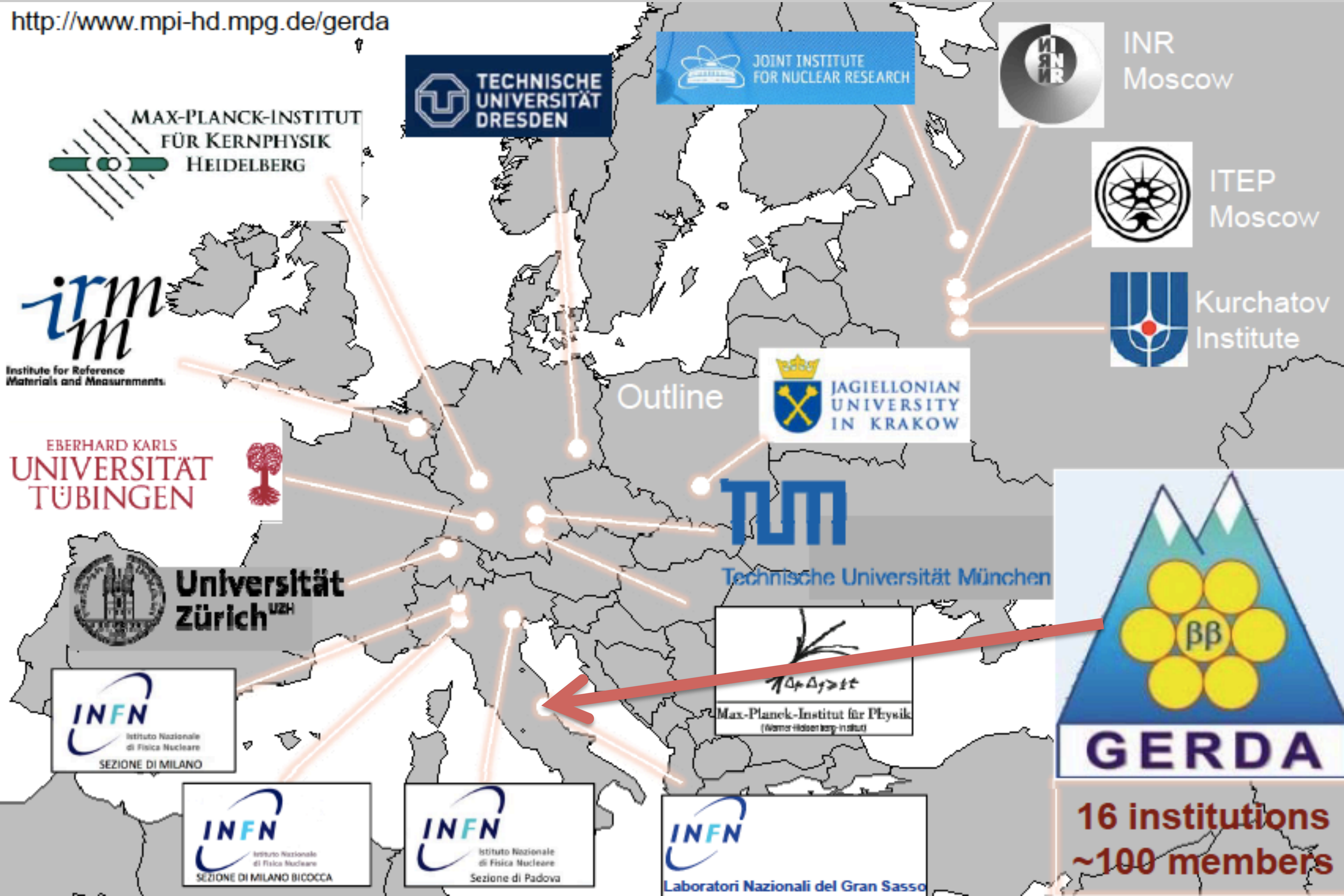
Letter of Intent

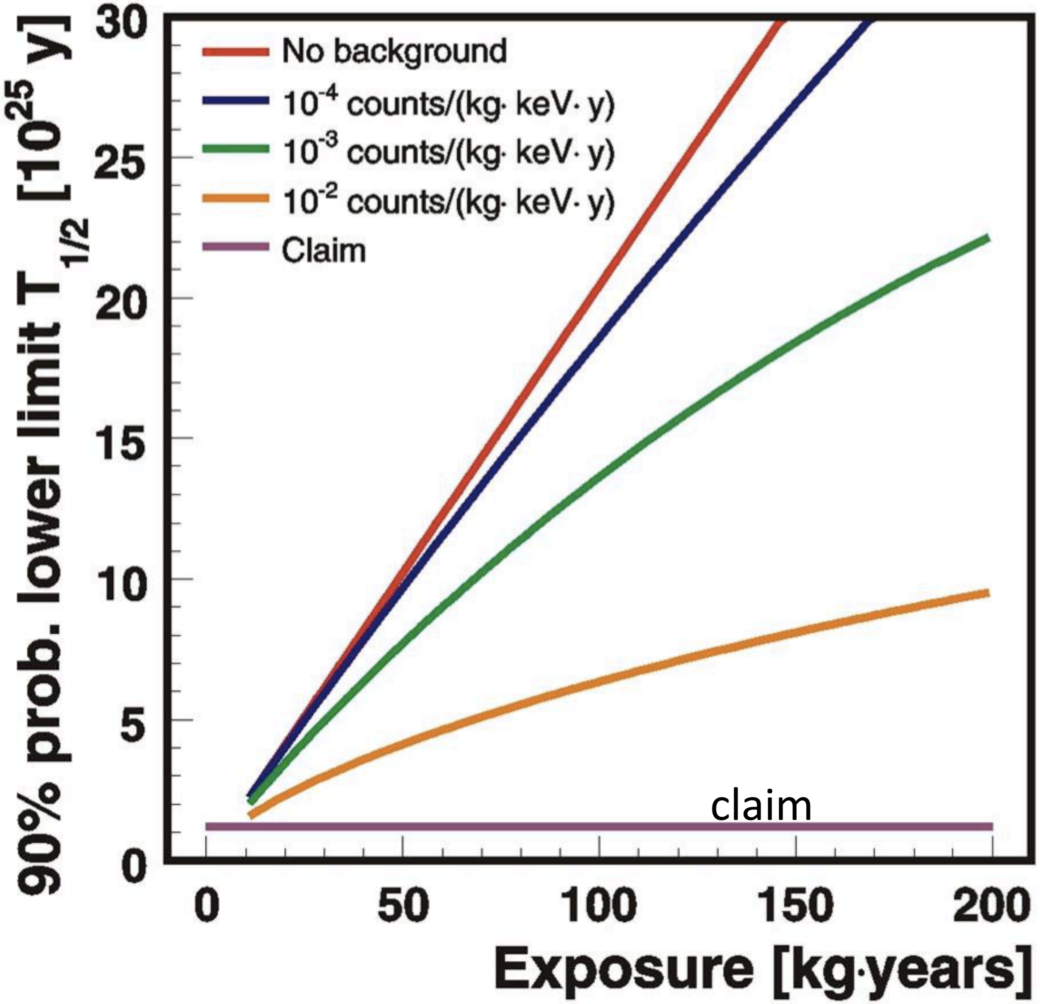


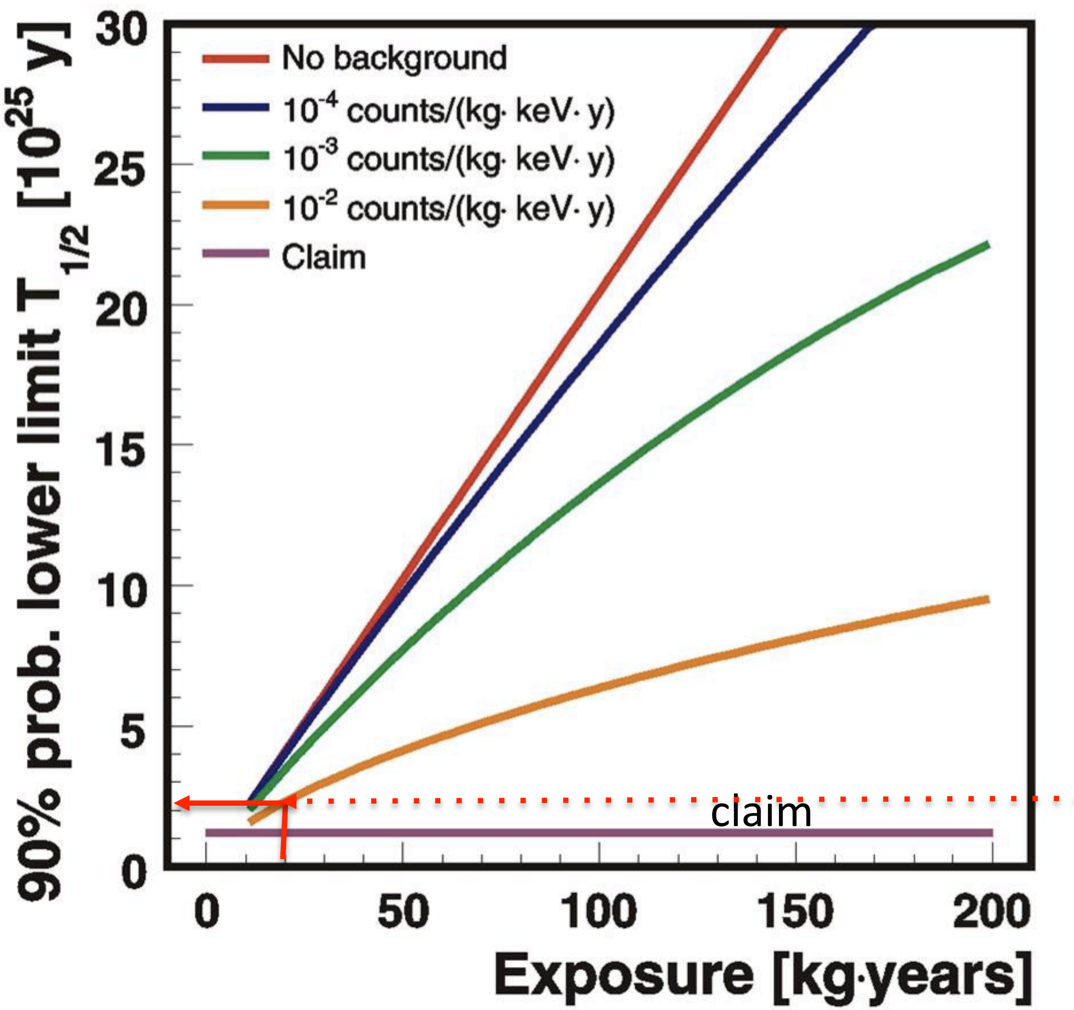


- ‘Bare’ ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX)
- Phase II: add ~20 kg new enriched detectors

The GERDA collaboration




90% prob. lower limit $T_{1/2}$ [10^{25} y]
30
25
20
15
10
5
0
No background
10^{-4} counts/(kg· keV· y)
10^{-3} counts/(kg· keV· y)
10^{-2} counts/(kg· keV· y)
Claim
claim
0
50
100
150
200
Exposure [kg·years]

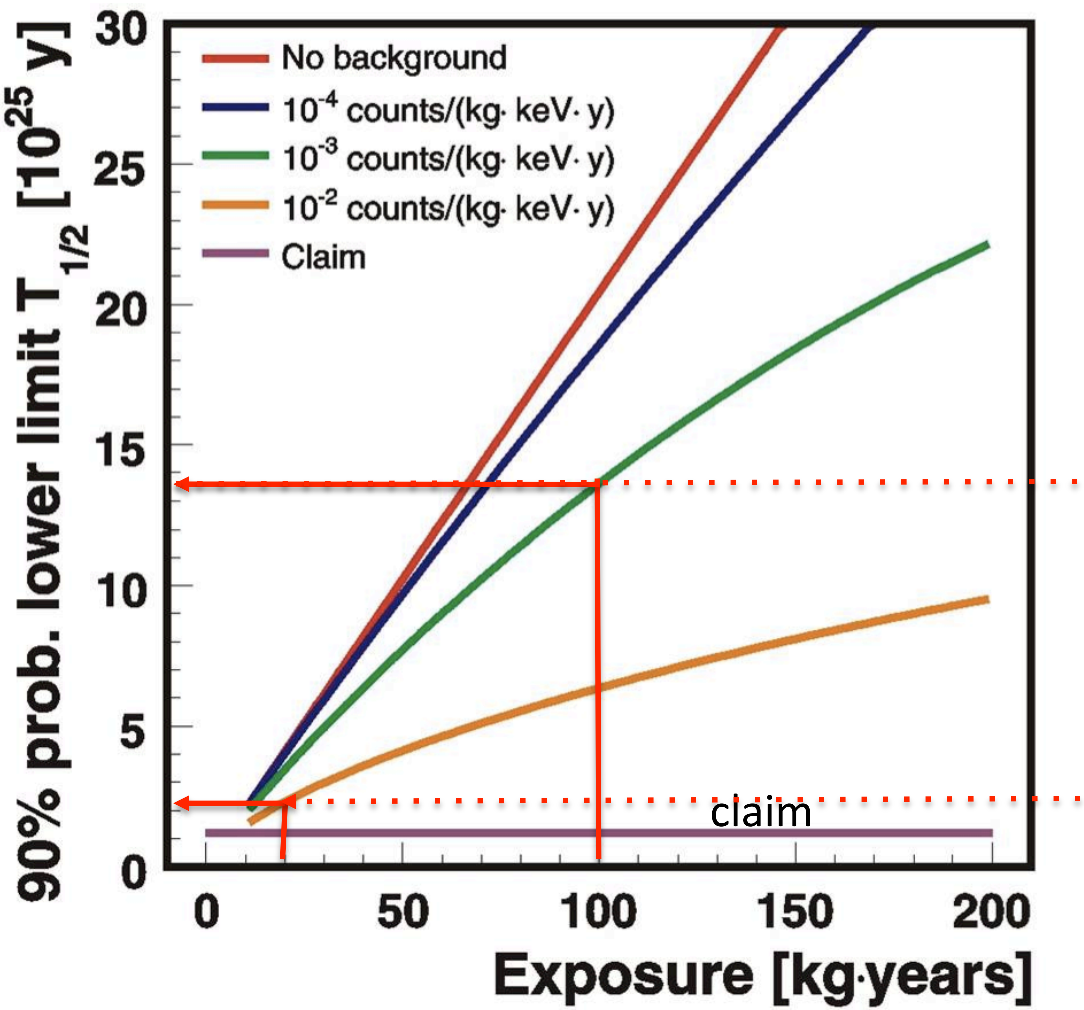


<u>Phase I:</u>

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr



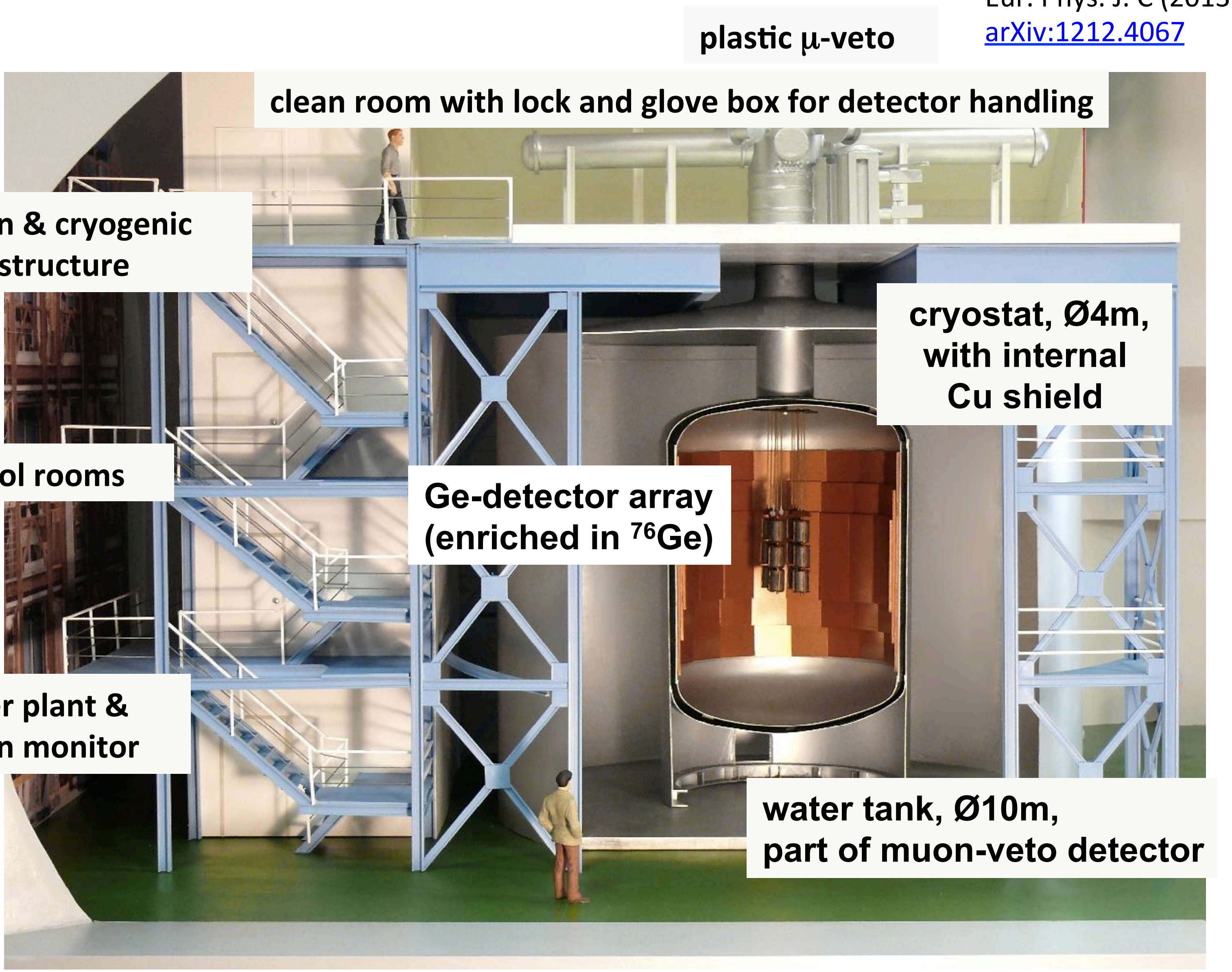
<u>Phase III (LoI):</u>
GERDA & Majorana
BI ≈ 0.0001 cts / (keV kg yr)
Sensitivity after several 1000 kg yr

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

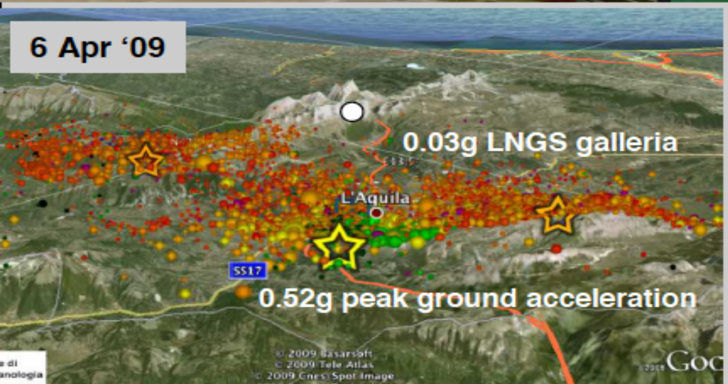
<u>Phase I:</u>
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr)
Sensitivity after 20 kg yr

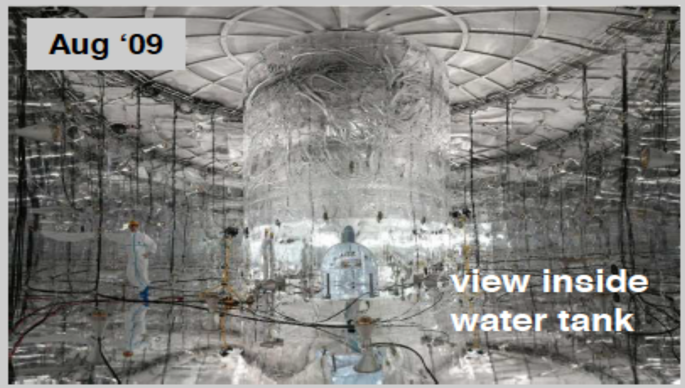
The GERDA experiment

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



The GERDA construction 2008-2010

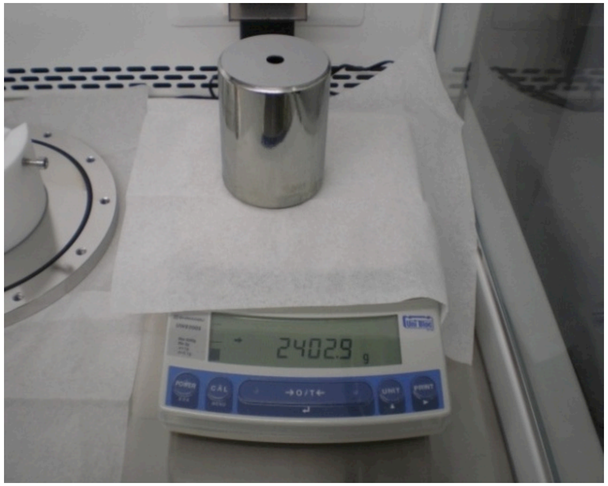




Cryostat filled since December 2009

Phase I detectors: semi-coaxial detectors

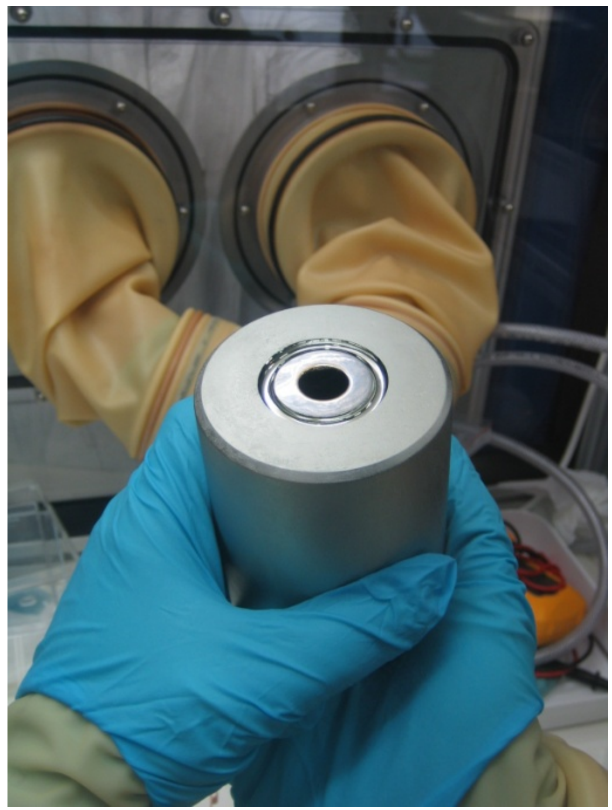
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



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

8 diodes (from HdM, IGEX):

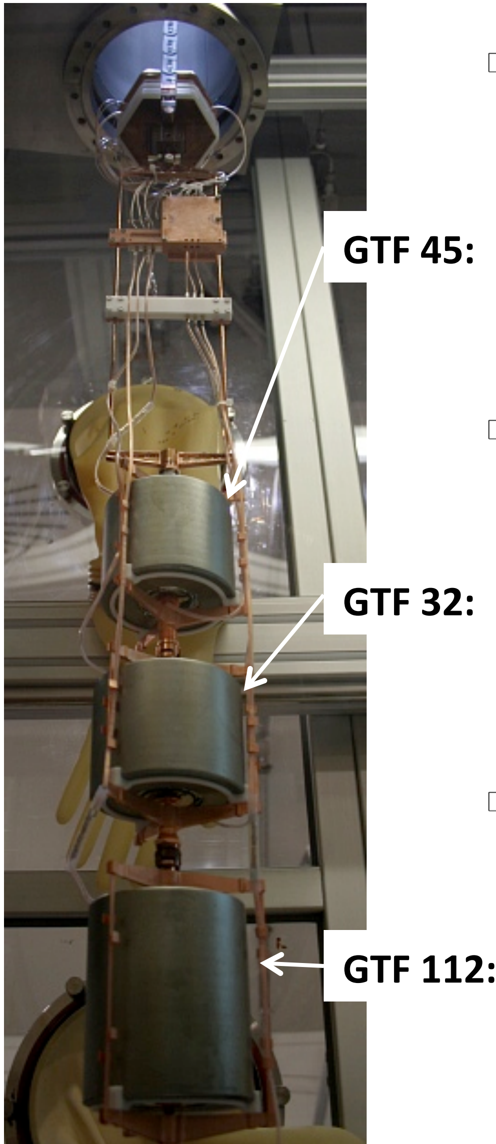
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg



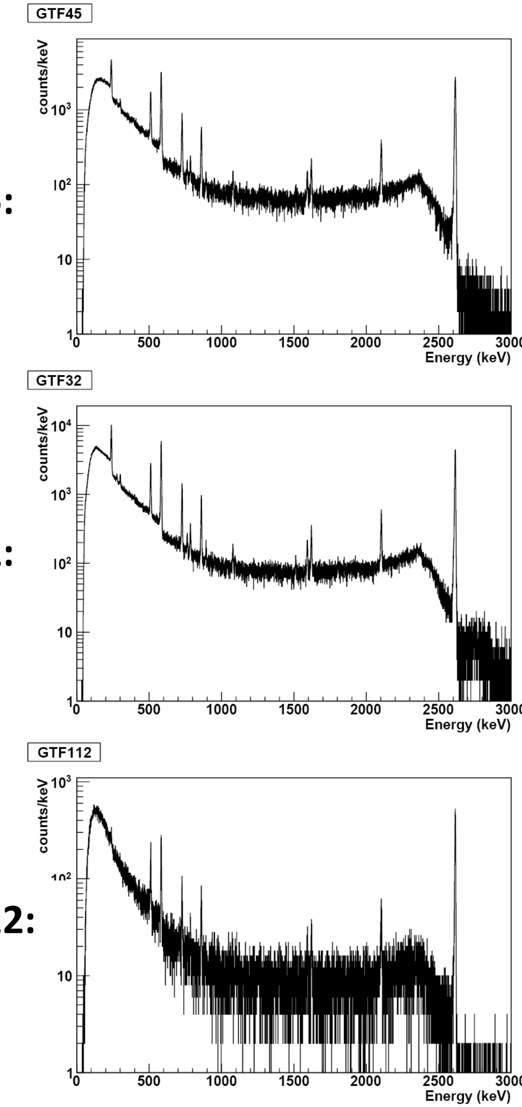
6 diodes from Genius-TF:

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

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:

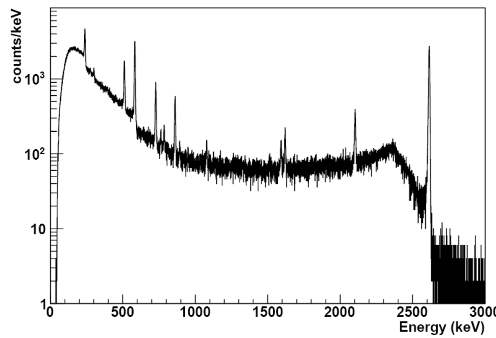
- Coaxial (Phase I): 4.5-5.keV (*FWHM*) @ 2.6 MeV
- BEGe (Phase II): 2.8 keV (*FWHM*) @ 2.6 MeV

Commissioning with 1-string assembly

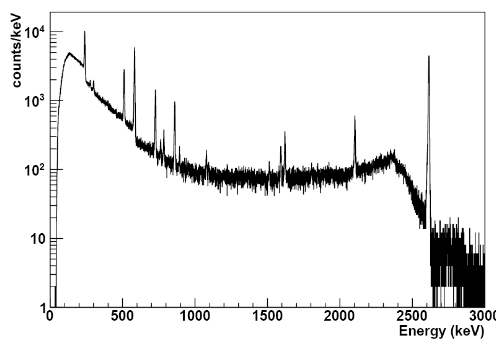
65µm Cu cylinder ('mini-shroud') to shield E-field

Calibration with ^{228}Th:

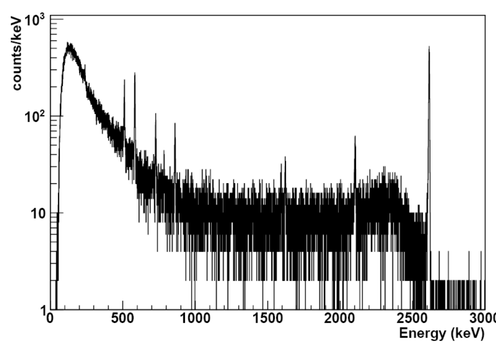
GTF45



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

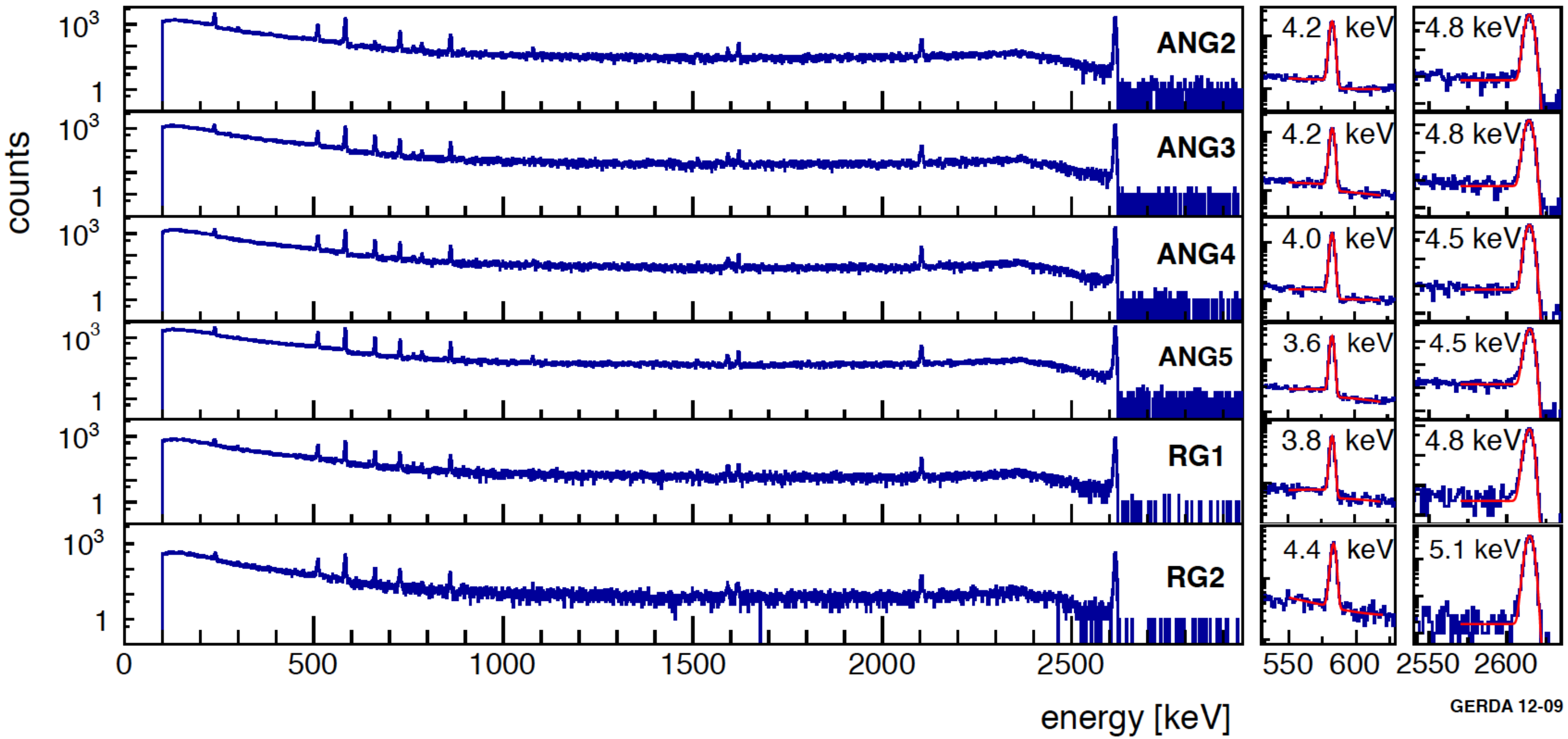
- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

2 diodes shut off because leakage current high:

- total enriched enriched detector mass 14.6 kg

First calibration spectra

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

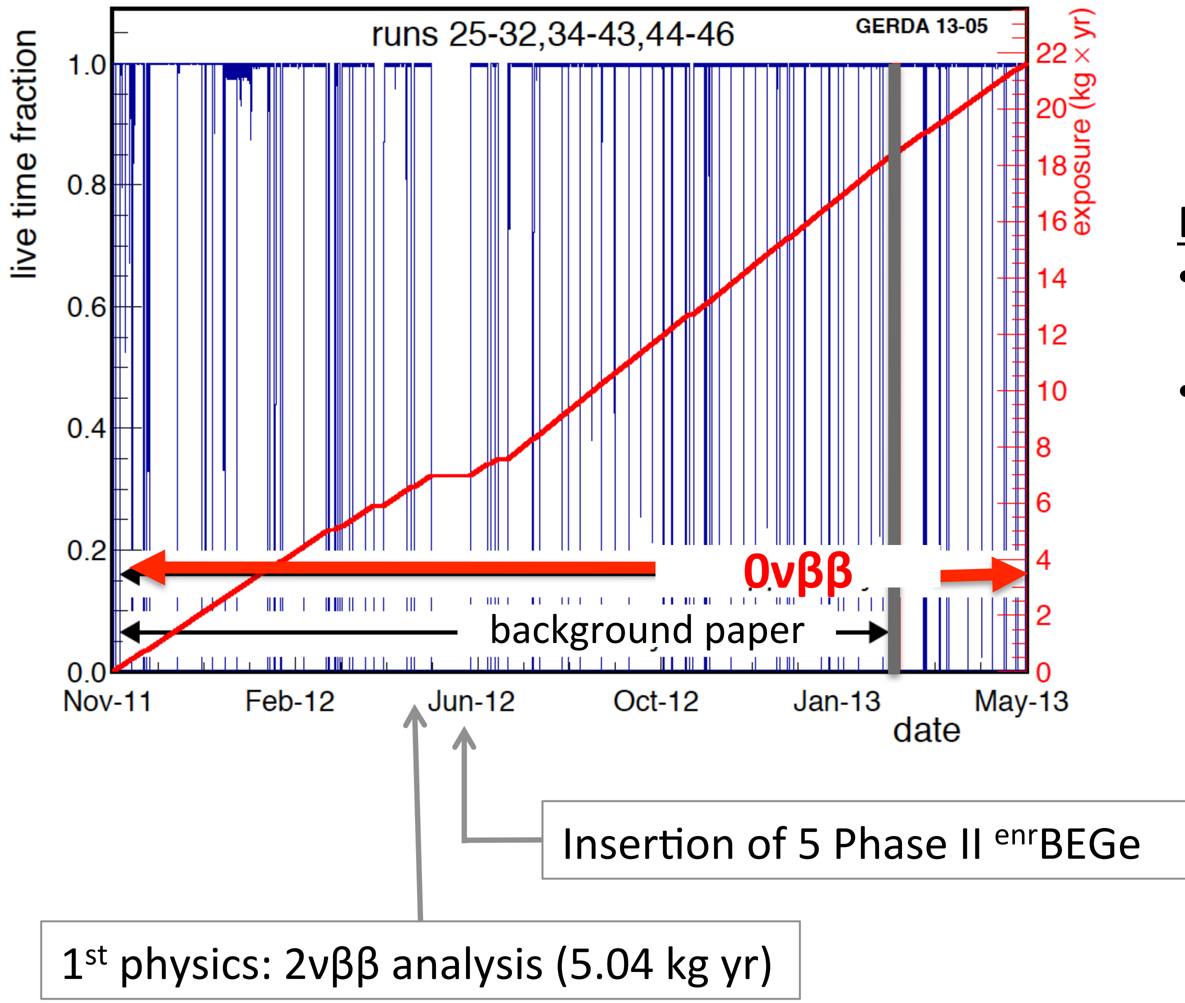


^{228}Th calibration once every one to two weeks; stability continuously monitored with pulser

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

Total exposure for 0νββ analysis: 21.6 kg yr

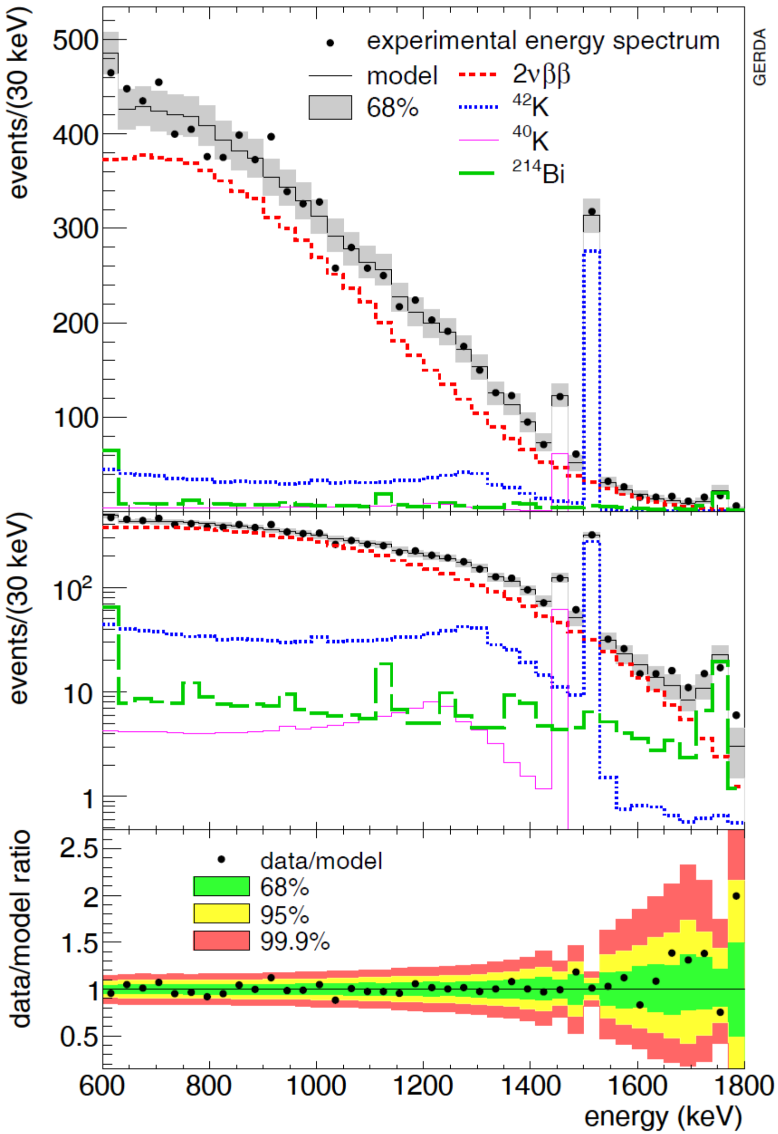
(bi-)weekly calibration runs ('spikes')



Data blinding:

- All events in $Q_{\beta\beta}$±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)

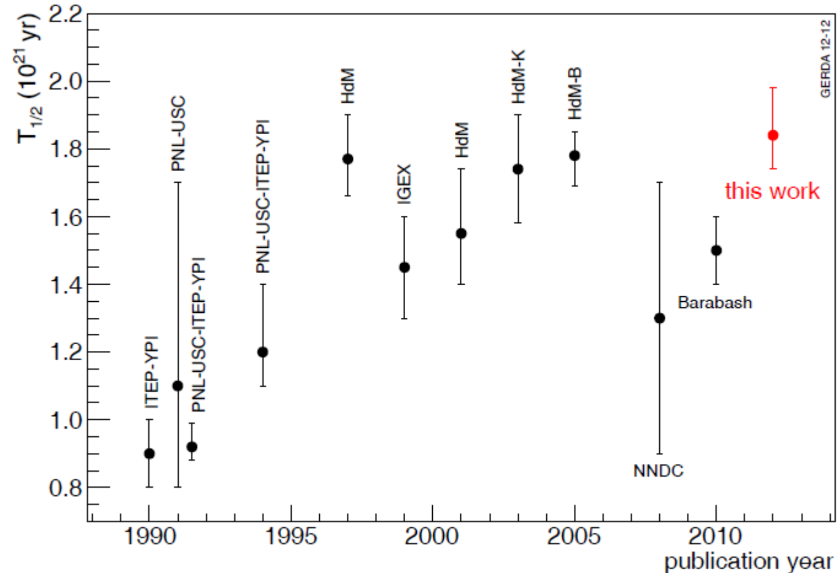


IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

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)

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

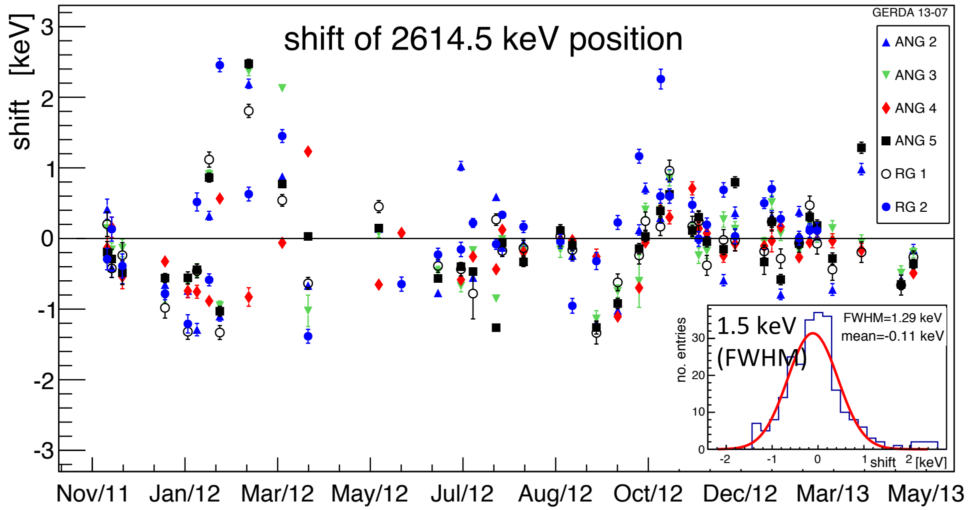


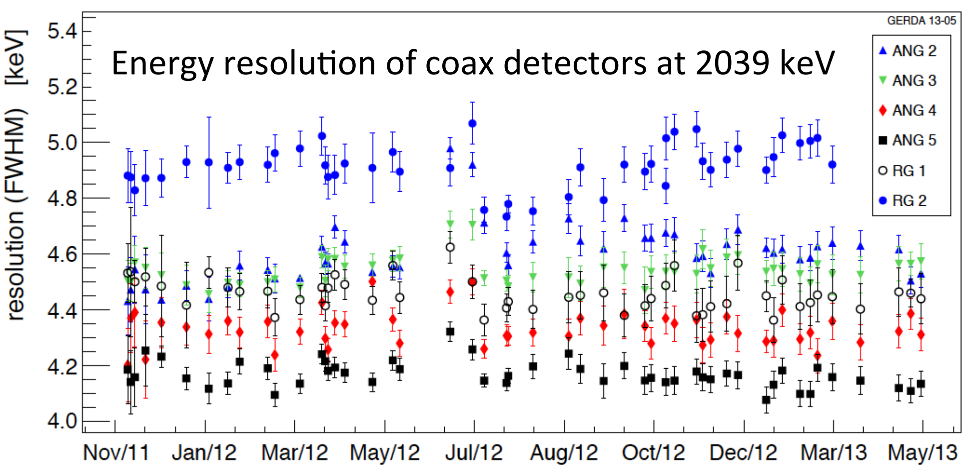
LAB Talk of J. Phys. G Feb. 2013 issue:
http://iopscience.iop.org/0954-3899/labtalk-article/52398

Calibration: stability of HPGe detectors

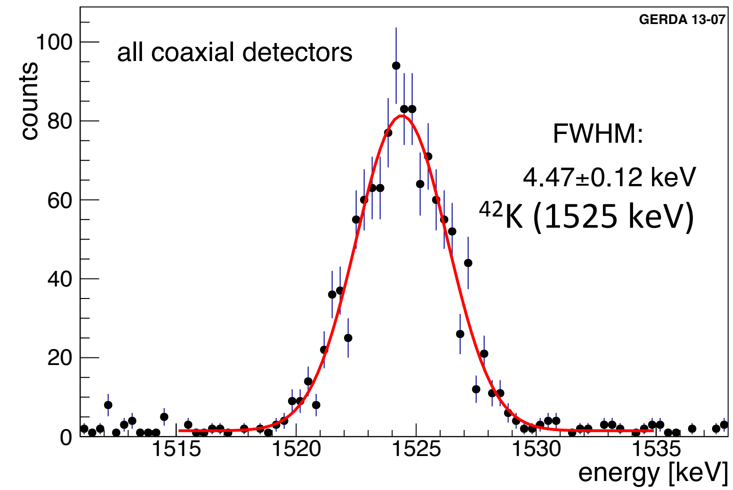
arXiv:1306.5084

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:

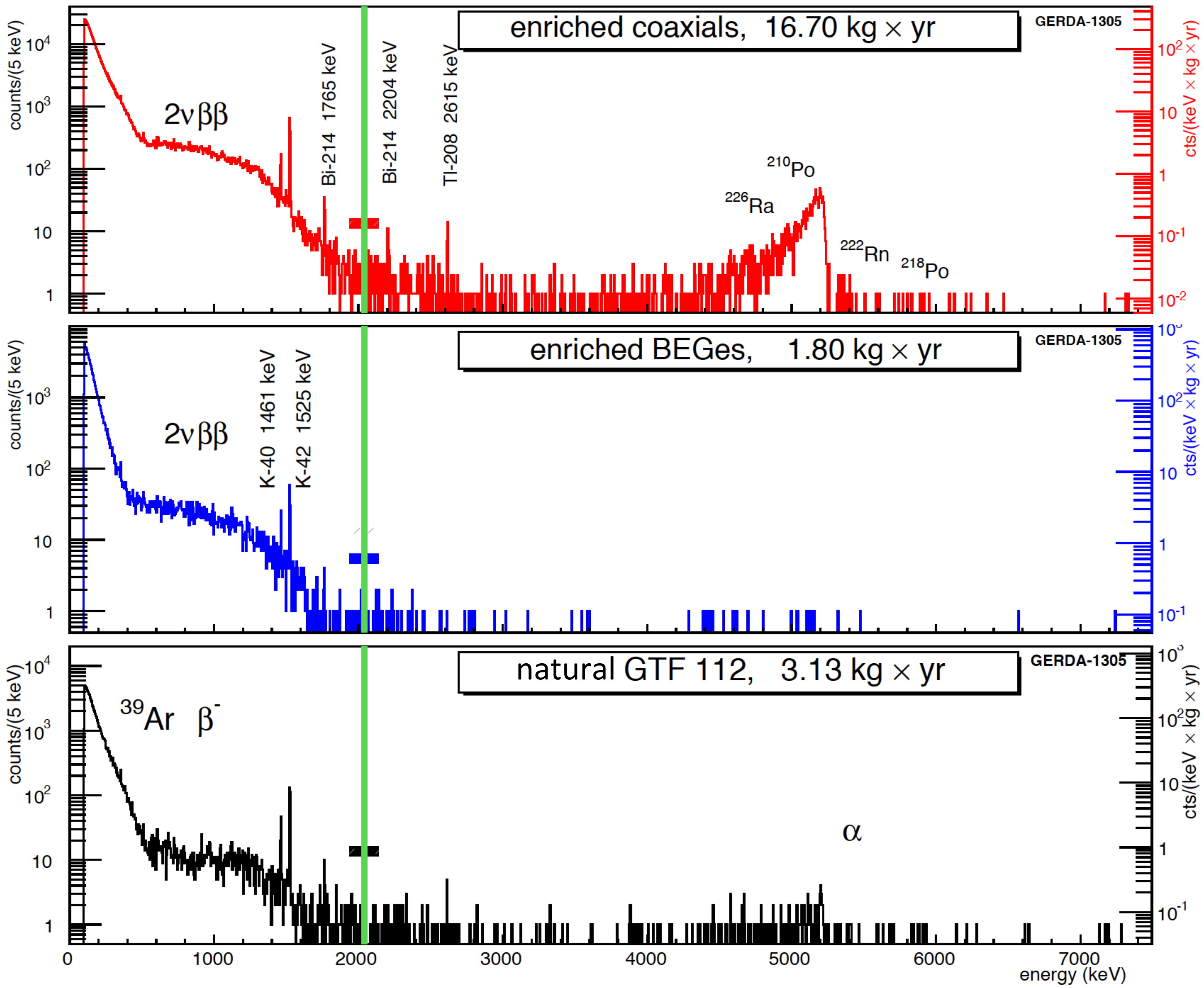
- Coax: 4.8 keV (FHWM)
- BEGe: 3.2 keV (FWHM)

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

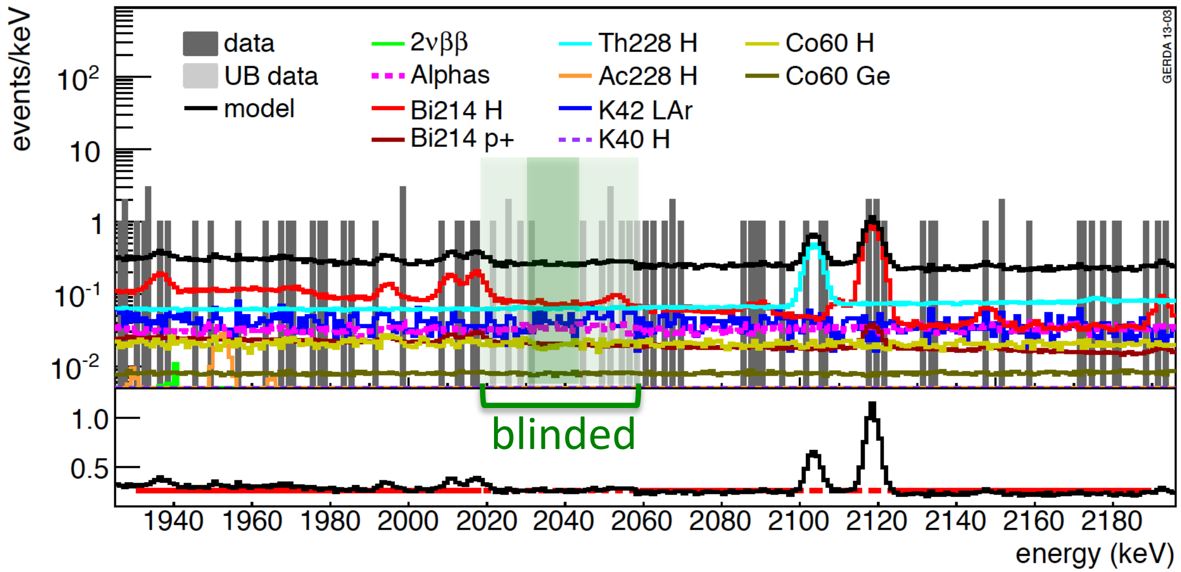
Submitted to EPJ A
Data for background model



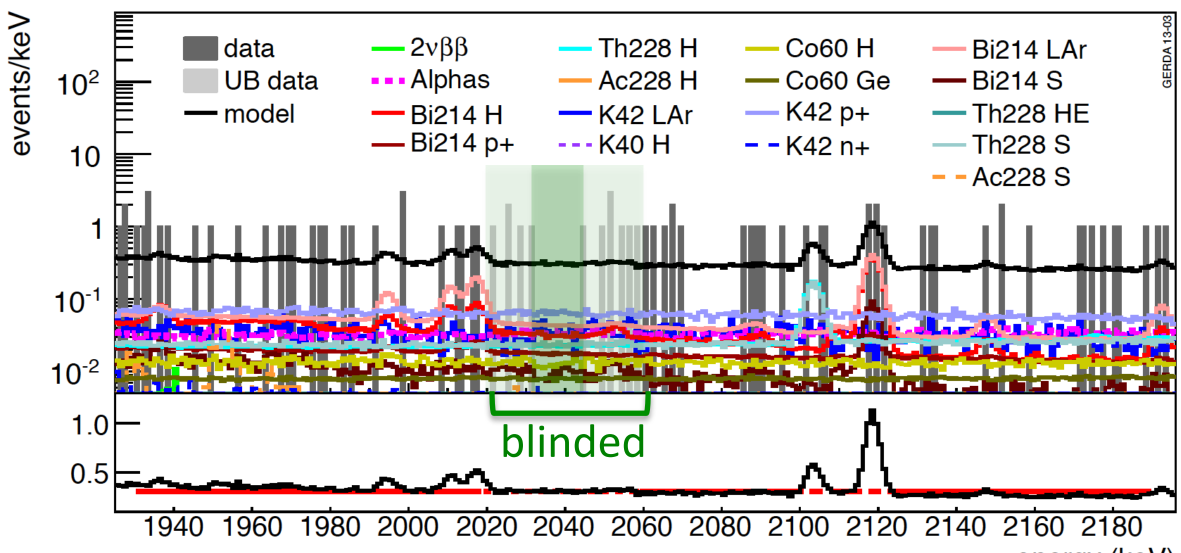
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

arXiv:1306.5084

Minimal model



Maximum model



Background model:

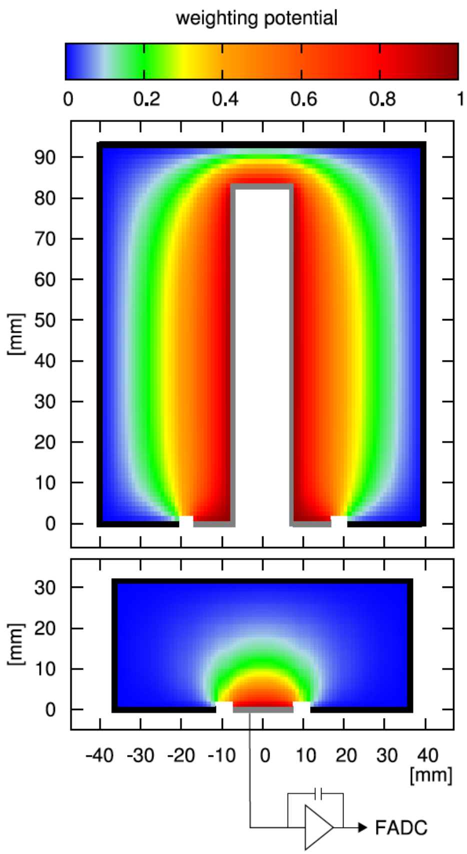
- No background peak expected around $Q_{\beta\beta}$
- Spectrum can be modeled with flat background (red line) in 1930-2190 keV excluding known peaks at 2104 and 2119 keV
- Background index (BI) at $Q_{\beta\beta}$ (17.6-23.8) 10^{-3} cts/(keV kg yr) depending on assumptions for location of sources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

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

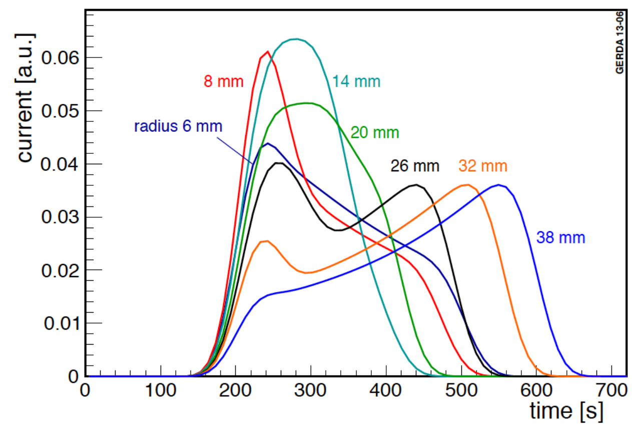
Classification of (0νββ) signal-like (SSE) or background-like (MSE, p+) events

Weighting potential for coax and BEGe detectors are different

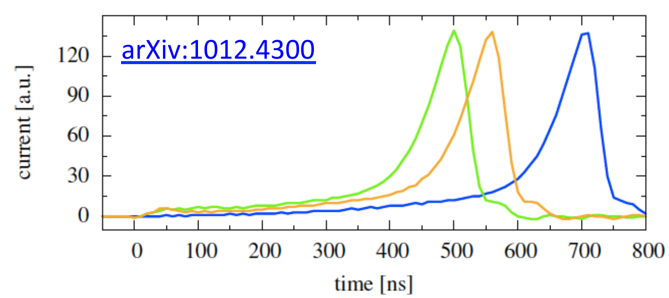
Current pulses of simulated SSE signals



Coax



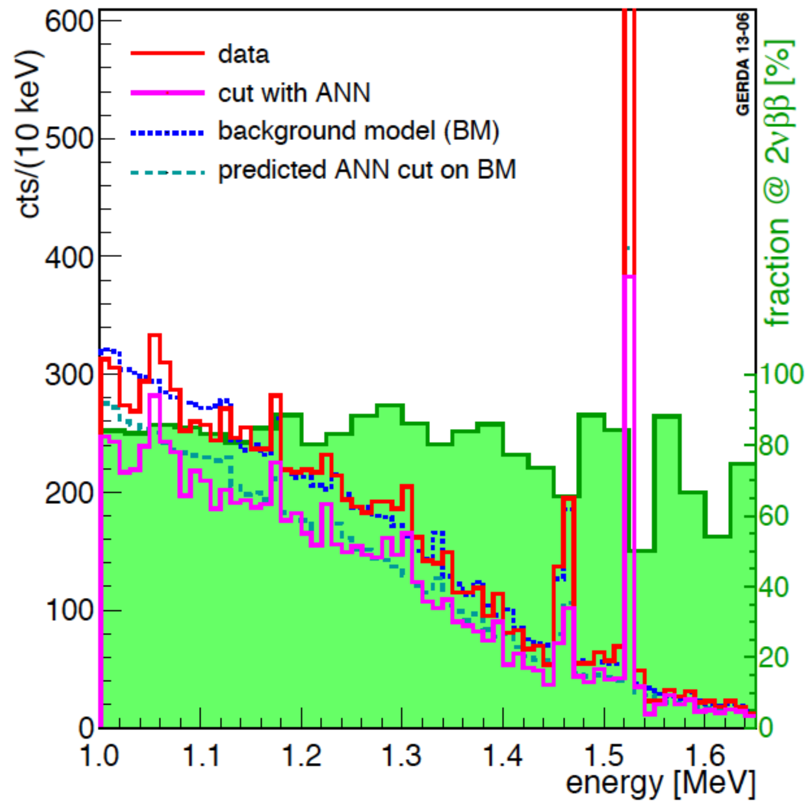
BEGe



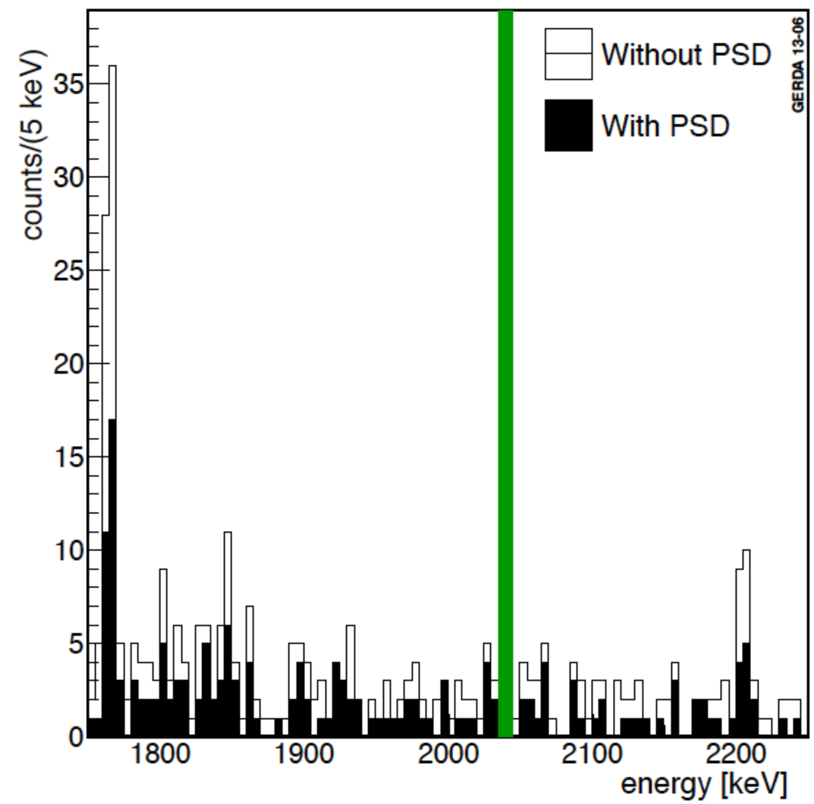
Pulse shape discrimination: Coax – survival fraction for Phase I

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: $0.90^{+0.05}_{-0.09}$

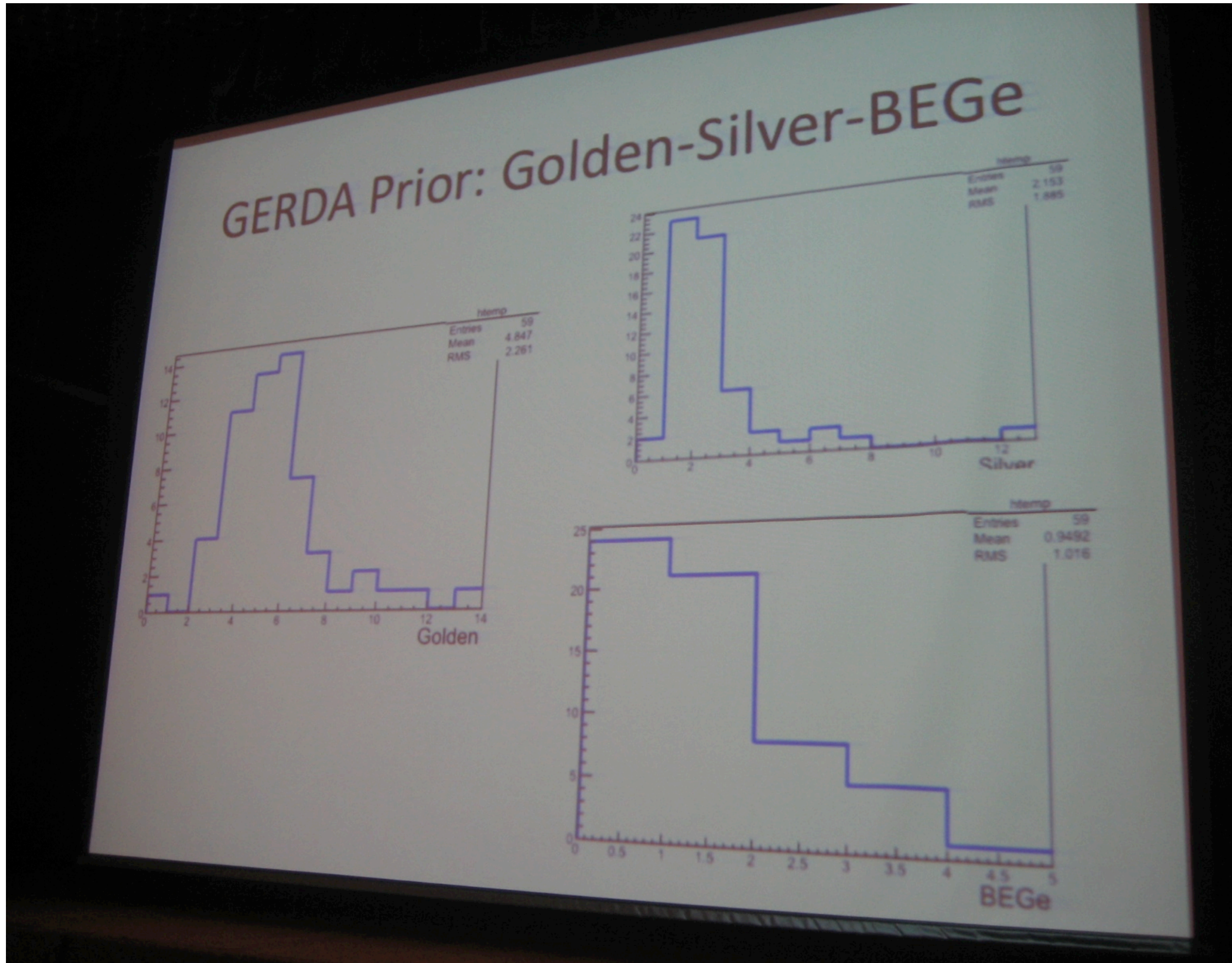
Unblinding at GERDA collaboration meeting in Dubna, June 12-14

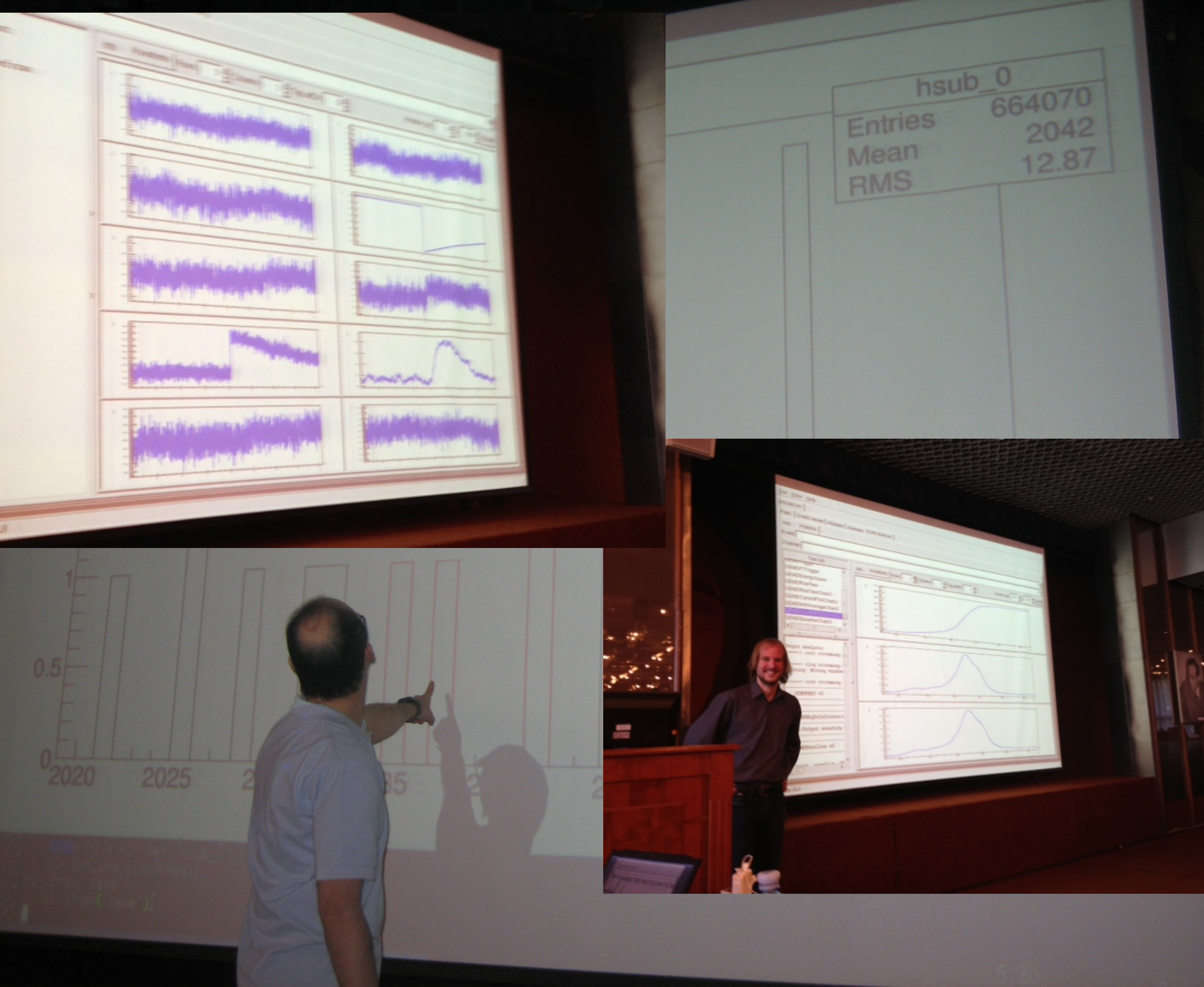
Discussion and freezing of all parameters and methods prior to un-blinding:

- 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
- ....

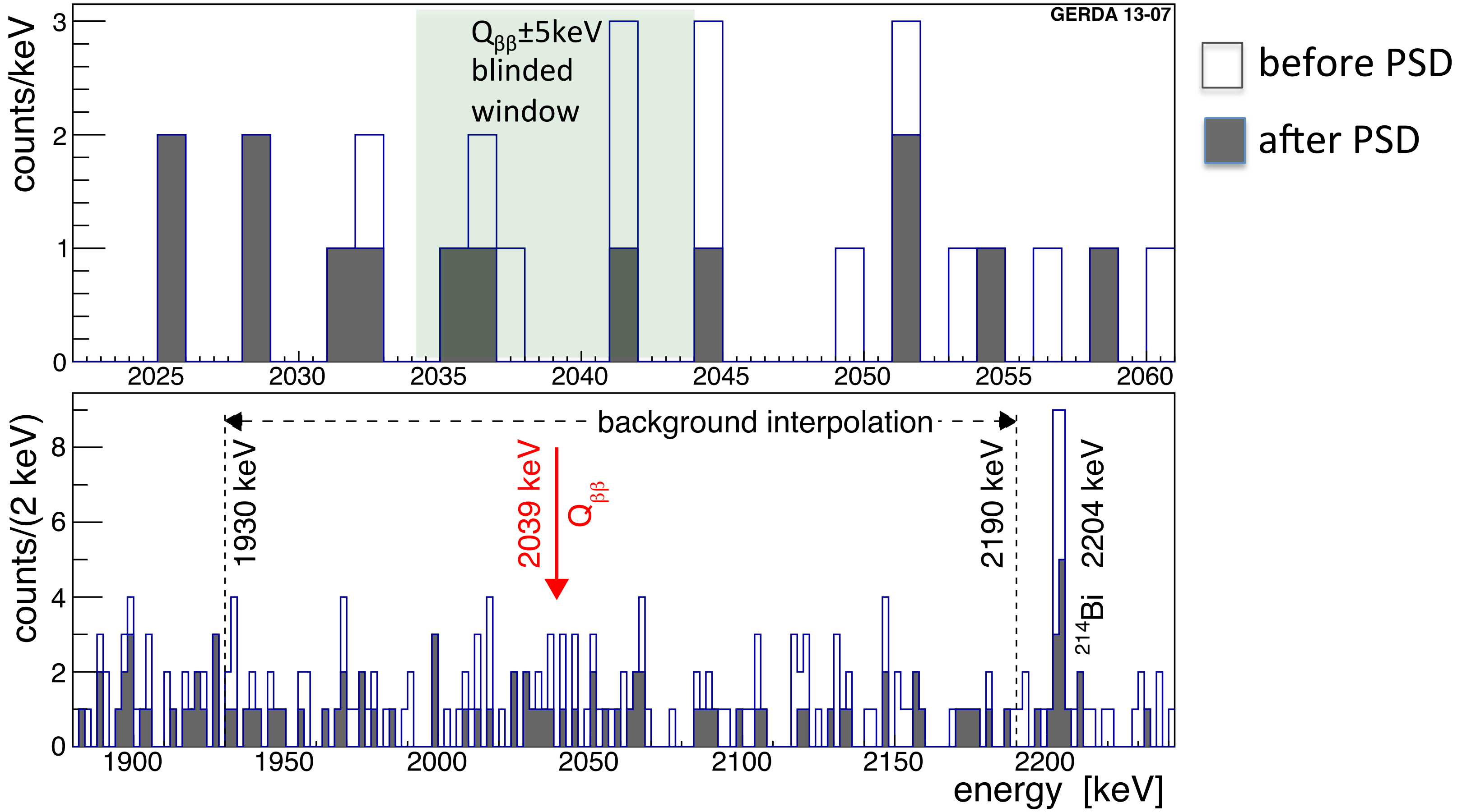
Unblinding at Dubna: the bets of the collaboration




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

Unblinding: full data set (21.6 kg yr)

PRL 111 (2013) 122503
arXiv:1307.4720



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

Parameters of 3 data sets and counts in blinded window

PRL 111 (2013) 122503
arXiv:1307.4720

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

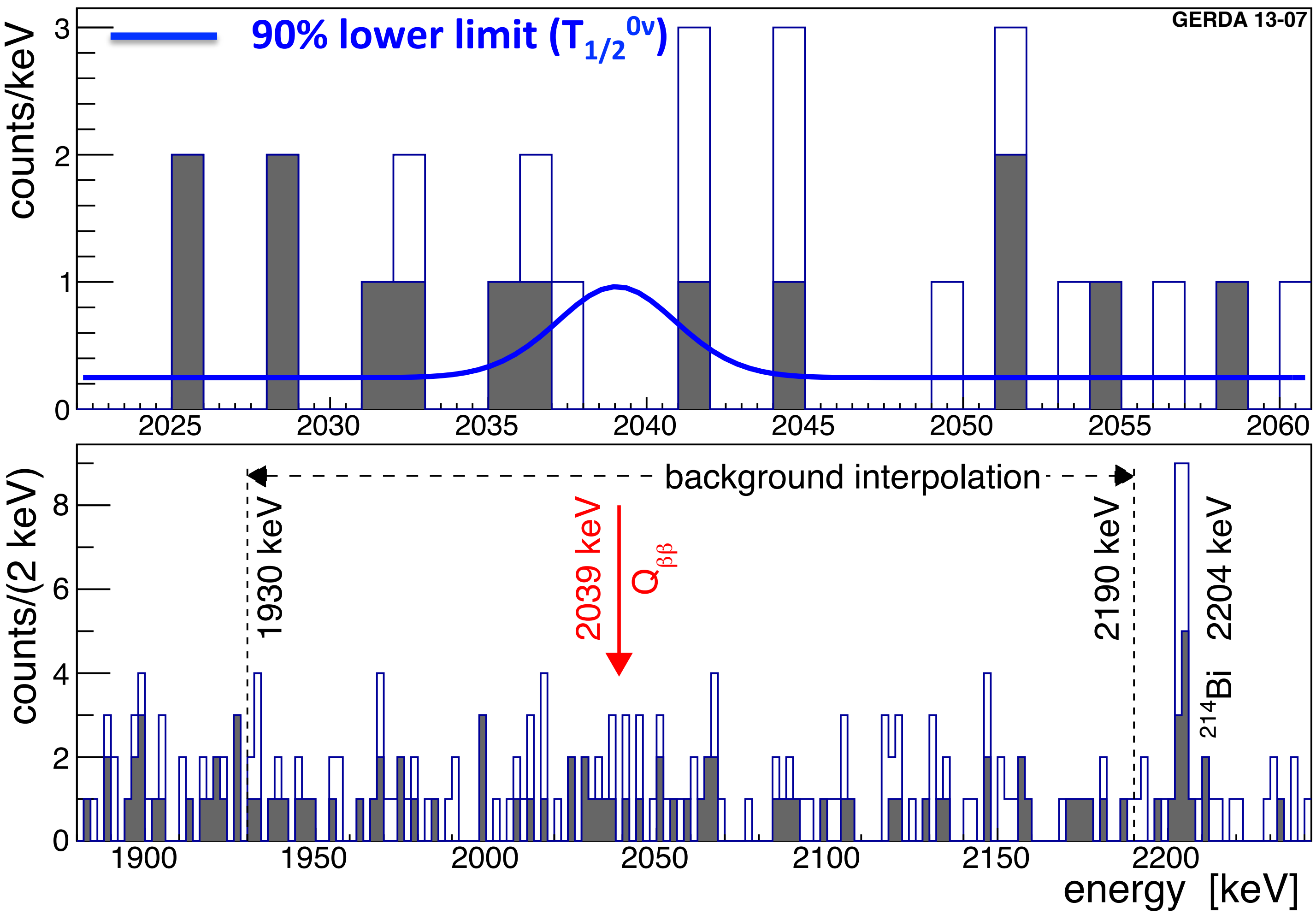
†) in units of 10^{-3} cts/(keV·kg·yr).

Counts in blinded window (BW)

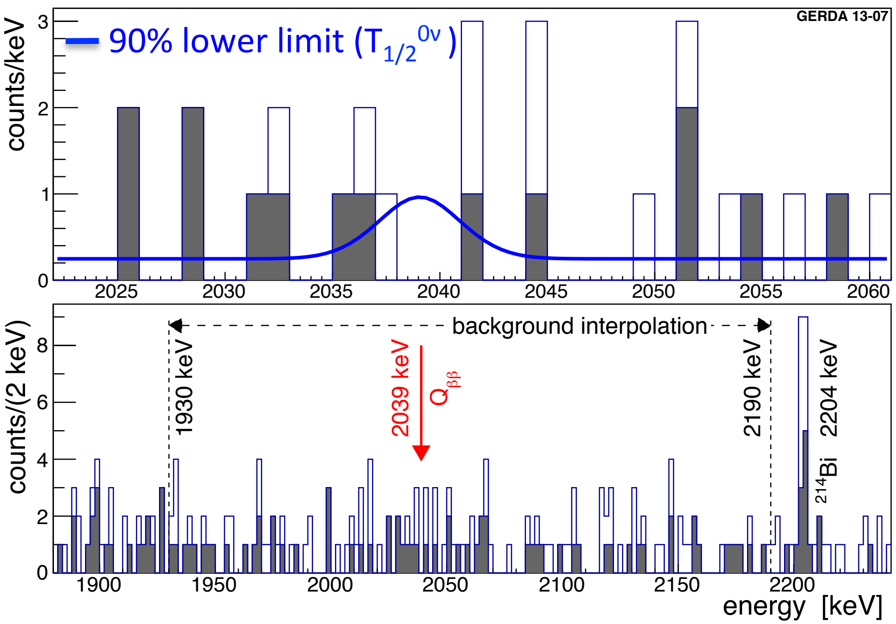
Total counts in BW	Expected (bgd only)	Observed
without PSD	5.1	7
with PSD	2.5	3

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

PRL 111 (2013) 122503
arXiv:1307.4720



Frequentist and Bayesian limits & median sensitivities



arXiv:1307.4720

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%

Systematics:

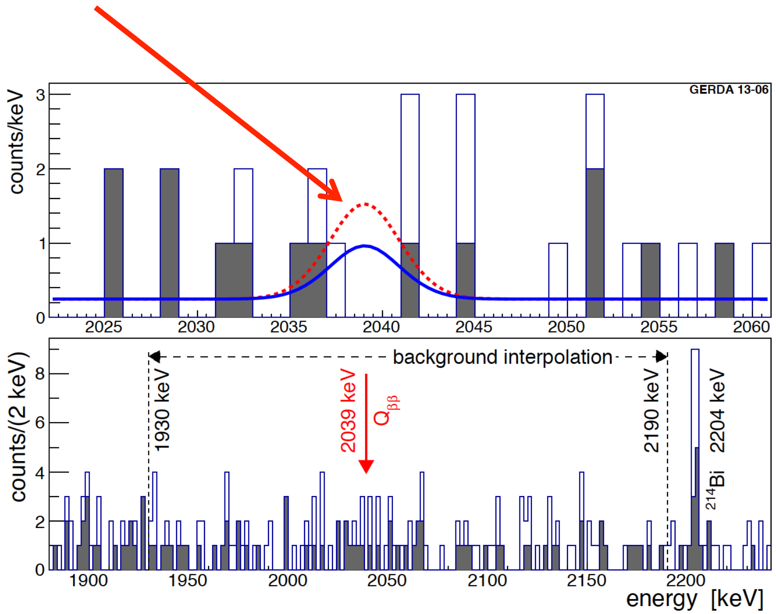
Parameter	Det./Set	Value	Uncertainty
<ε> w/o PSD	Coax	0.688	0.031
	BEGe	0.720	0.018
Energy res.	Golden	4.83 keV	0.19 keV
	Silver	4.63 keV	0.14 keV
	BEGe	3.24 keV	0.14 keV
Energy scale (keV)		N.A.	0.2 keV
ε_{PSD}	Coax	0.90	0.10
	BEGe	0.92	0.02

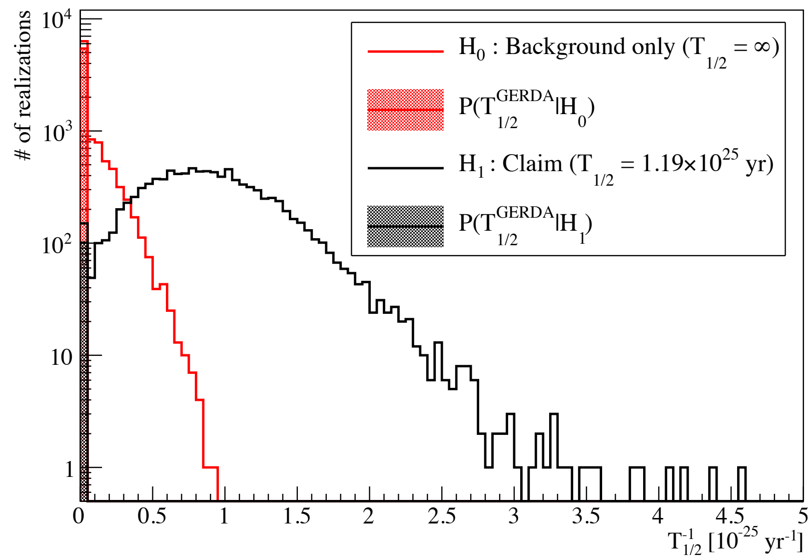
Comparison with Phys. Lett. B 586 198 (2004) claim

PRL 111 (2013) 122503
arXiv:1307.4720

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 ±2σ energy window to be compared with 3 cts (0 in ±1σ)





H1: claimed signal: 5.9±1.4
H0: background only

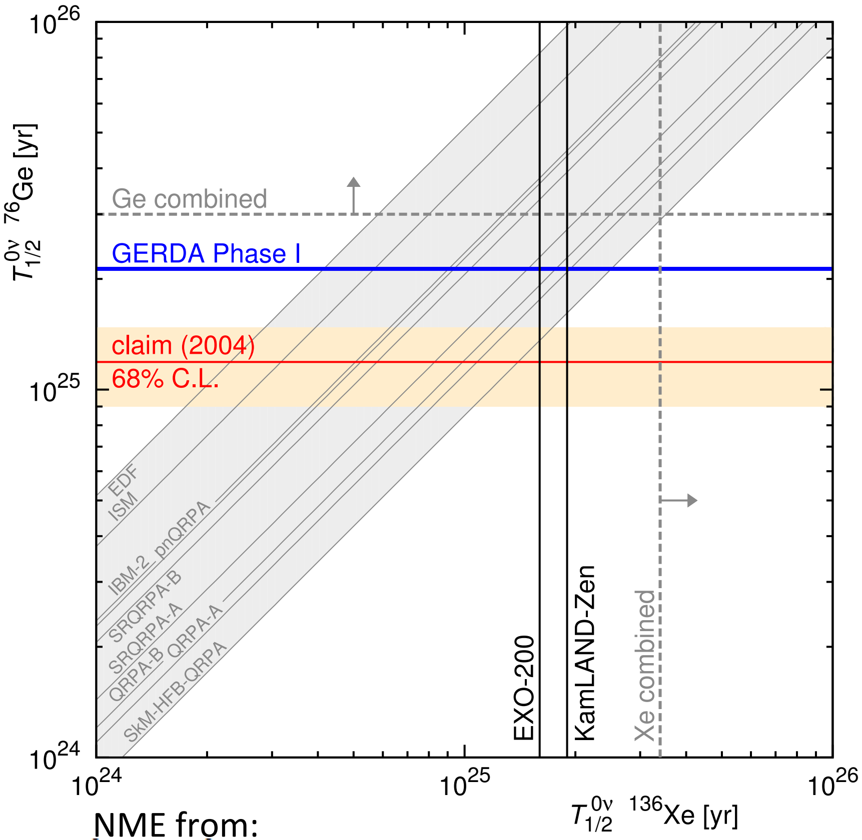
Bayes factor: P(H1)/P(H0)=0. 024

p-value from profile likelihood
P(N=0 = 0|H1) = 0. 01 (0.006 if 1/T unconstrained)

➔Claim refuted with high probability

The claim: global picture

PRL 111 (2013) 122503
arXiv:1307.4720



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

*:with conservative 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].

- **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 counts in ±2σ after analysis cuts:
  0.01 cts /(mol yr)

- **Getting ready for Phase II & discussing a Phase III (1 ton) experiment**

The search goes on…..

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.

The quest whether neutrinos are **Majorana particles** and whether there are **sterile neutrinos** are among the most fundamental questions today ...

.... ATOMKI could connect to its (neutrino) history

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

GERDA publications before unblinding:

pulse shape analysis: **Pulse shape discrimination for GERDA Phase I data**
EPJC 73 (2013) 2583; 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

GERDA publications after unblinding:

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