Results on neutrinoless double beta decay of ^{76}Ge from GERDA Phase I

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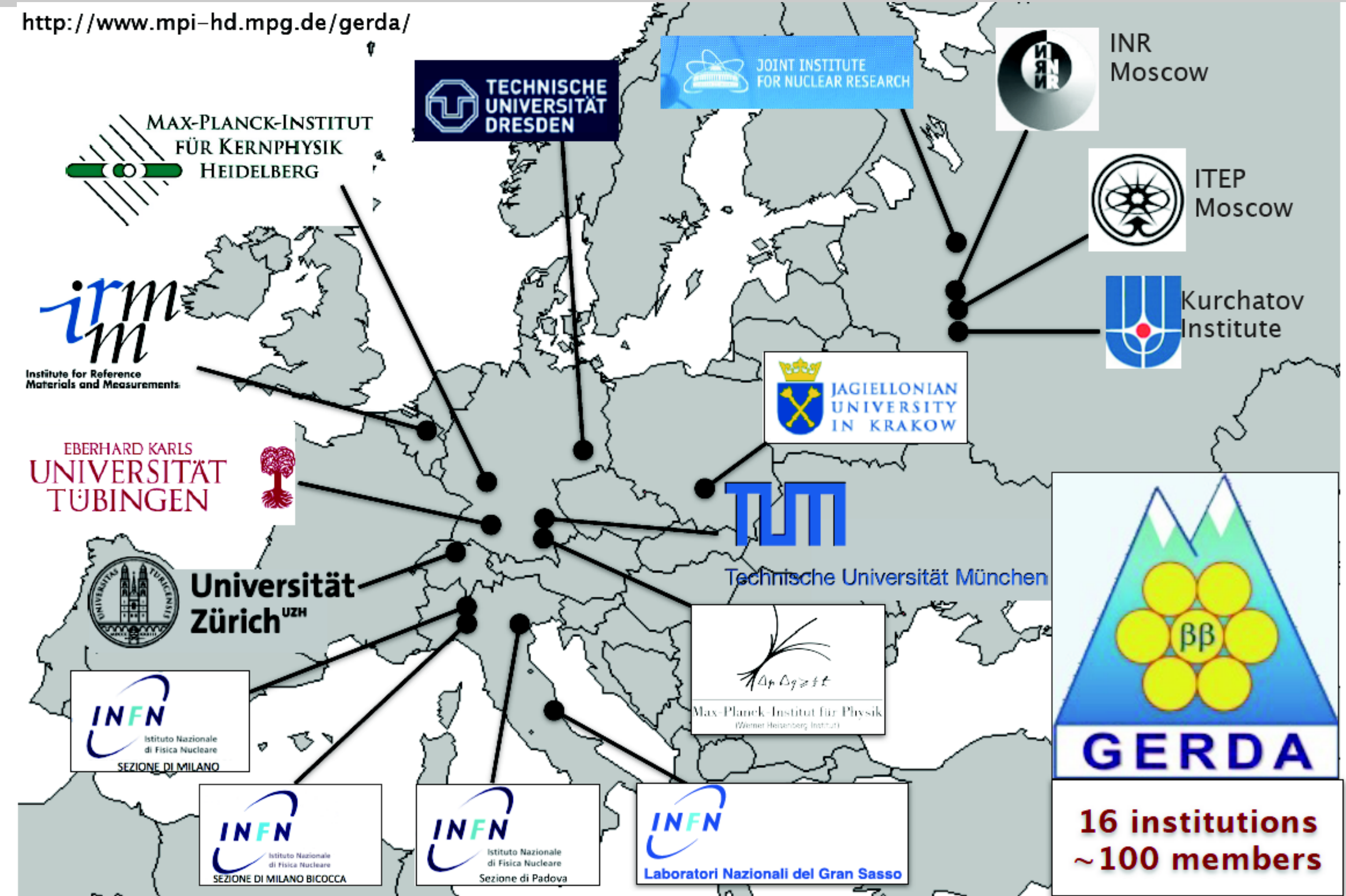
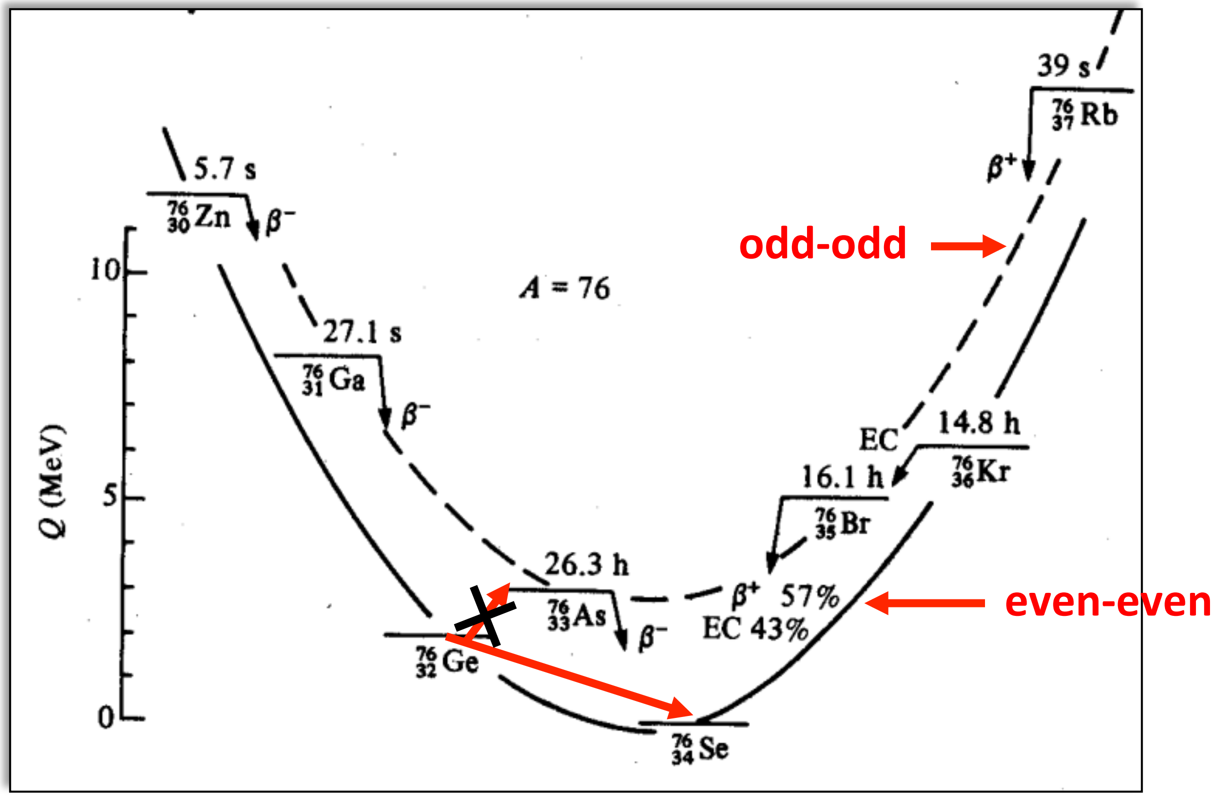
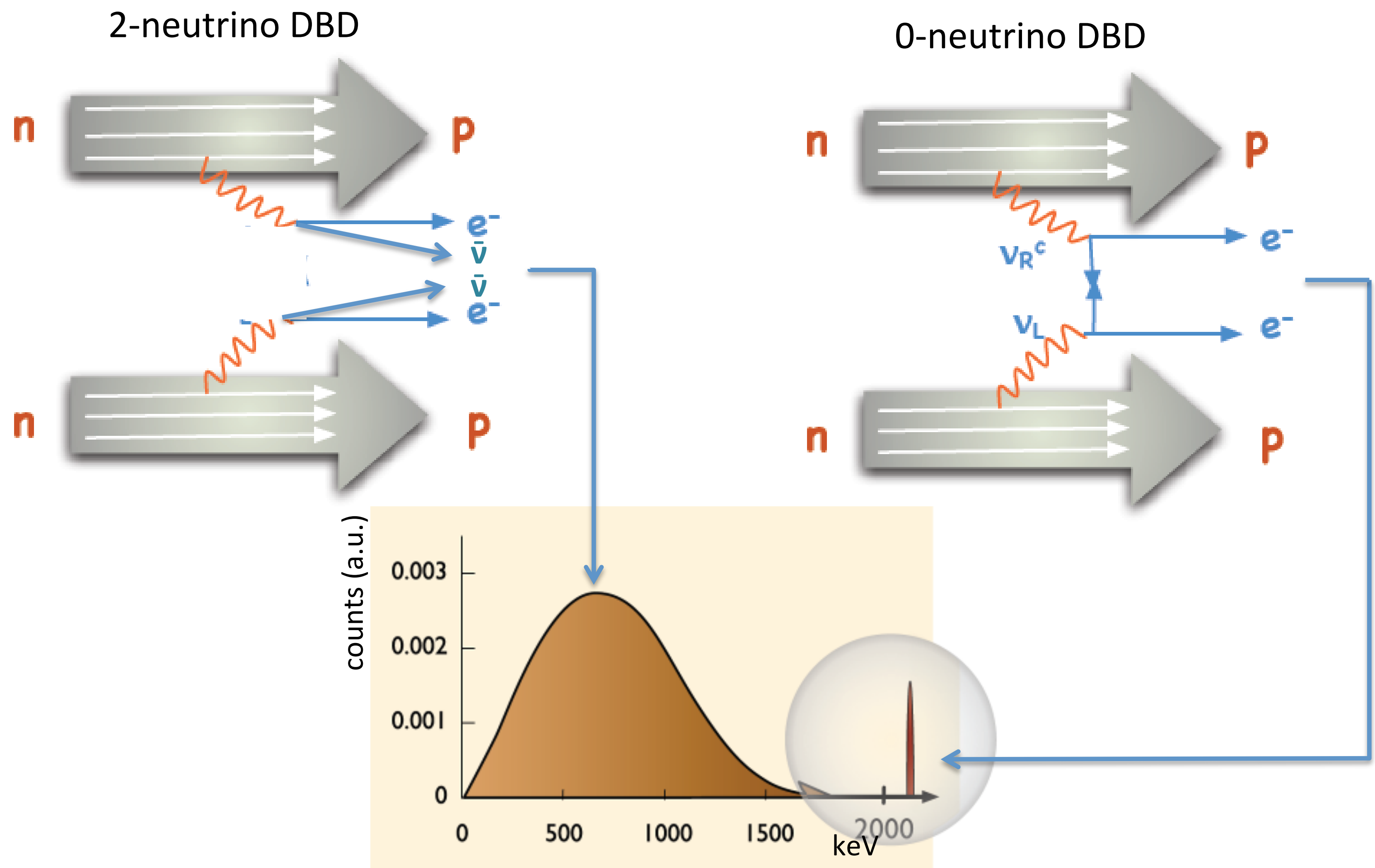
Lake Louise Winter Institute
February, 21, 2014

The GERDA collaboration

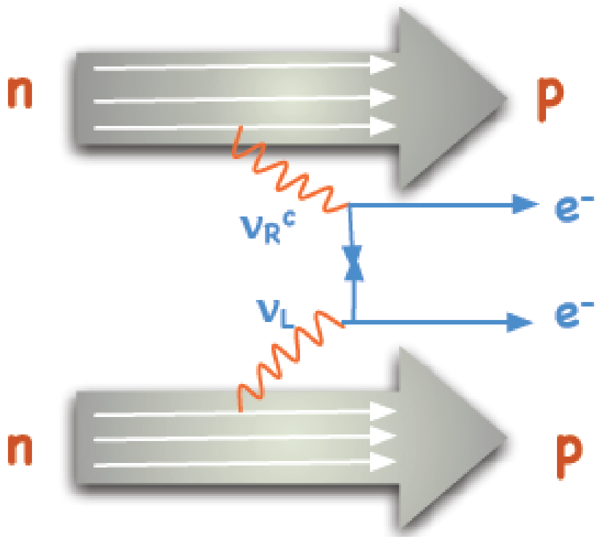




$Q_{\beta\beta}$ = (2039.061±0.007) keV B. J. Mount et al., Phys.Rev. 401 C81, 032501 (2010)



2-electron spectra



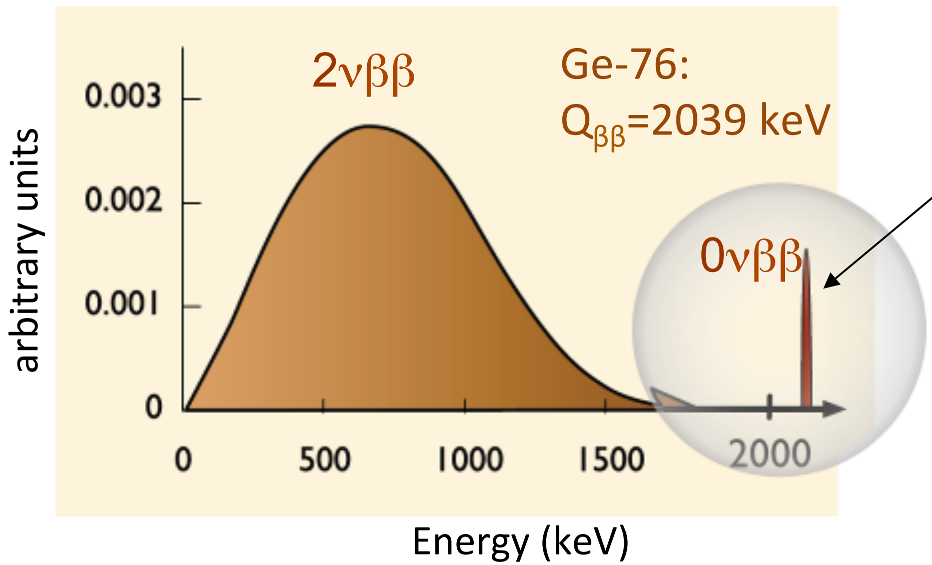
Expected decay rate:

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

Phase space integral — Nuclear matrix element

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

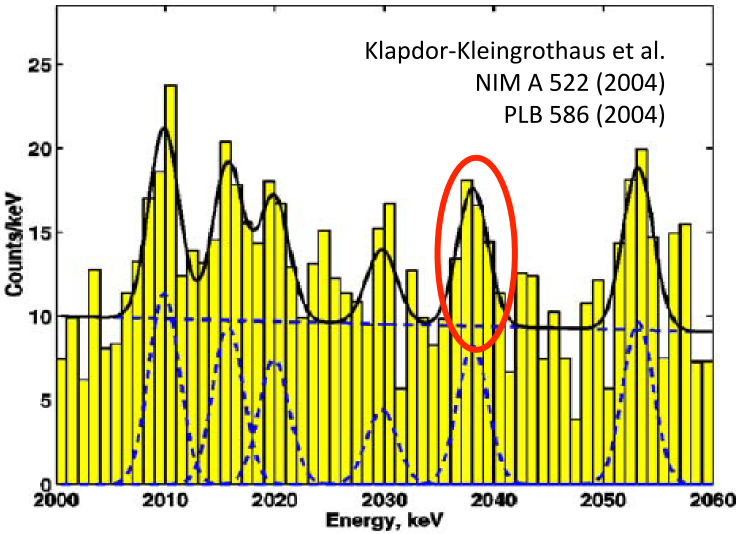
U_{ei} Elements of (complex) PMNS mixing matrix



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

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

^{76}Ge 0νββ search: the claim



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

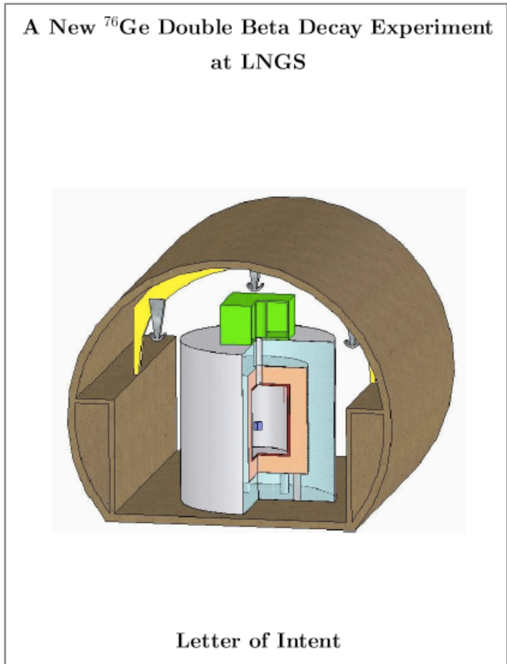
- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for 0νββ
- reported $T_{1/2}^{0\nu}$ = 1.19 x10^{25} yr

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:

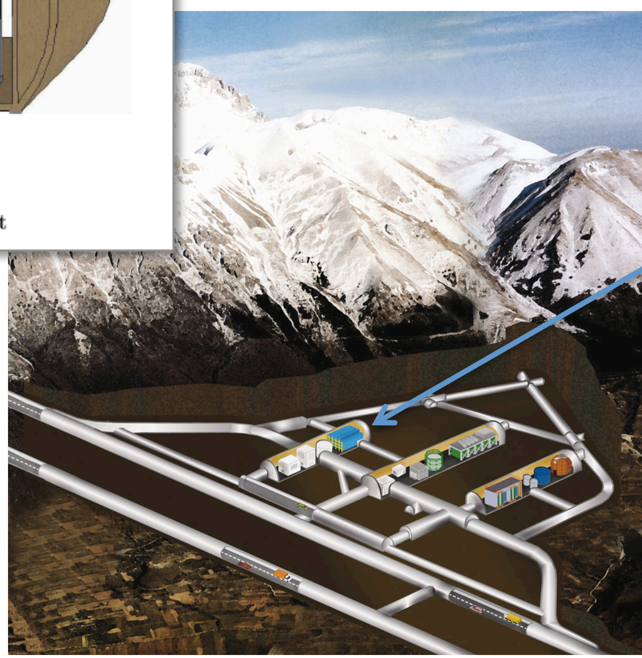
- reported half-life can be reconstructed only (Ref. 1) with ε_{psd} = 1 (previous similar analysis ε_{psd} ≈ 0.6)
- ε_{fep} = 1 (also in NIM A 522, PLB 586, 198 (2004) (GERDA value for same detectors: ε_{fep} = 0.9)

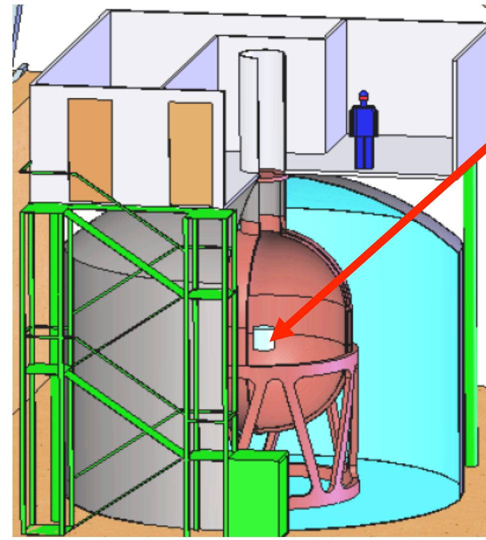
(1) B. Schwingenheuer in Ann. Phys. 525, 269 (2013)

GERDA @ LNGS

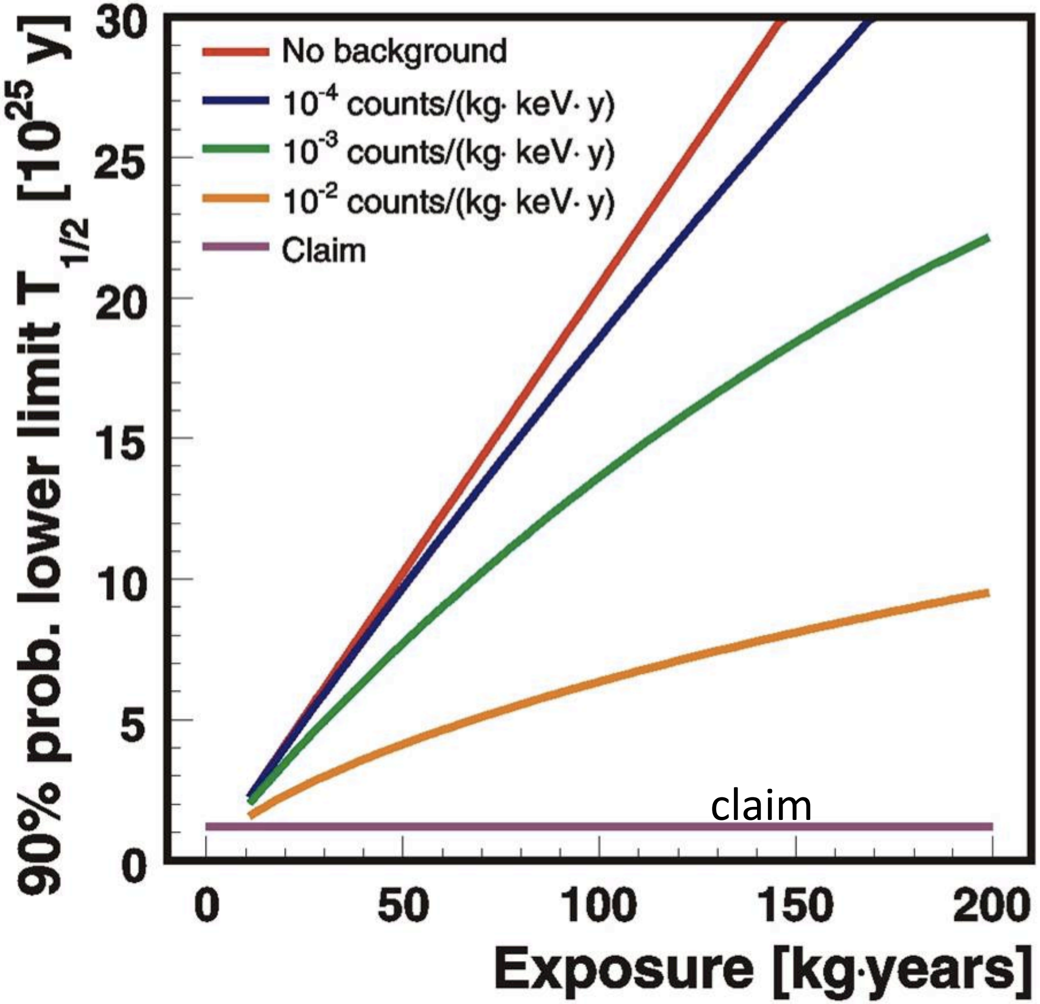

A New ^{76}Ge Double Beta Decay Experiment at LNGS

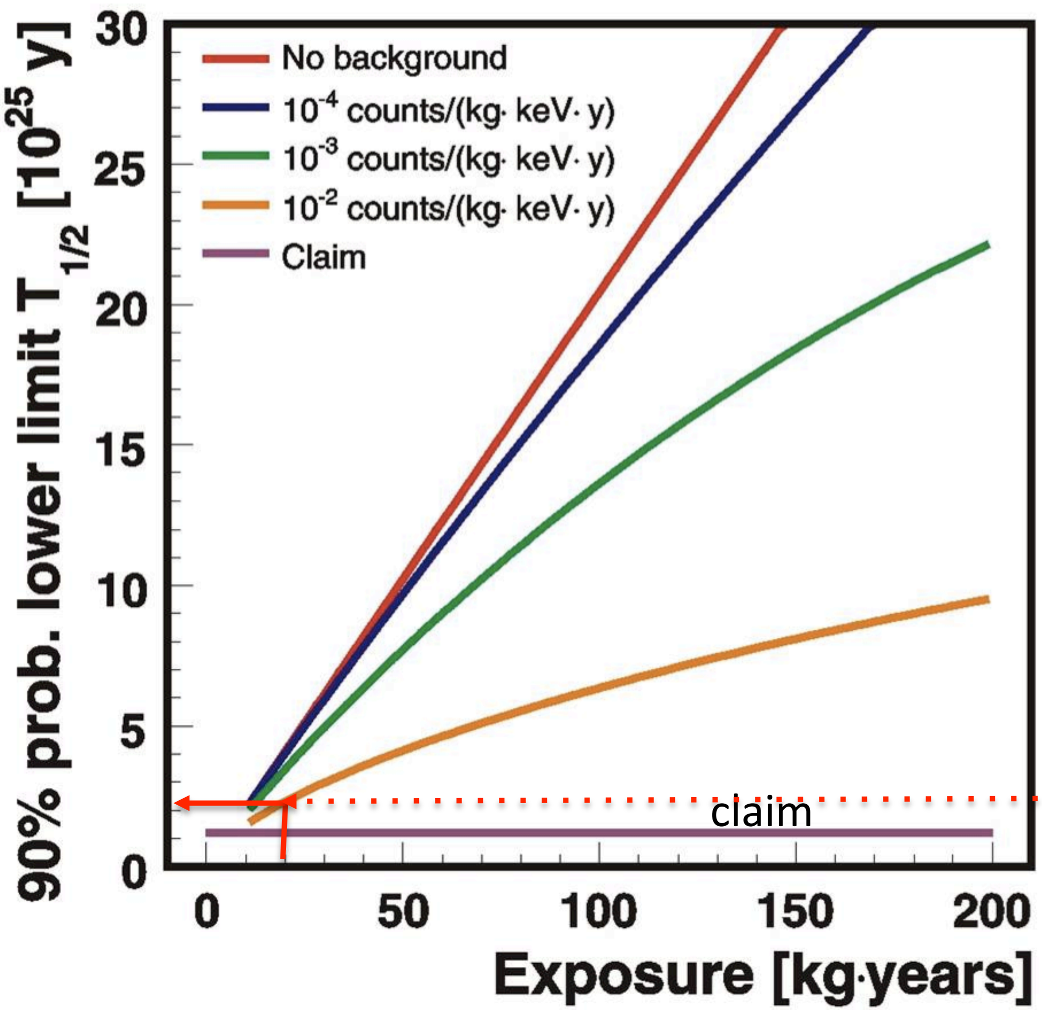
Letter of Intent





- ‘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


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

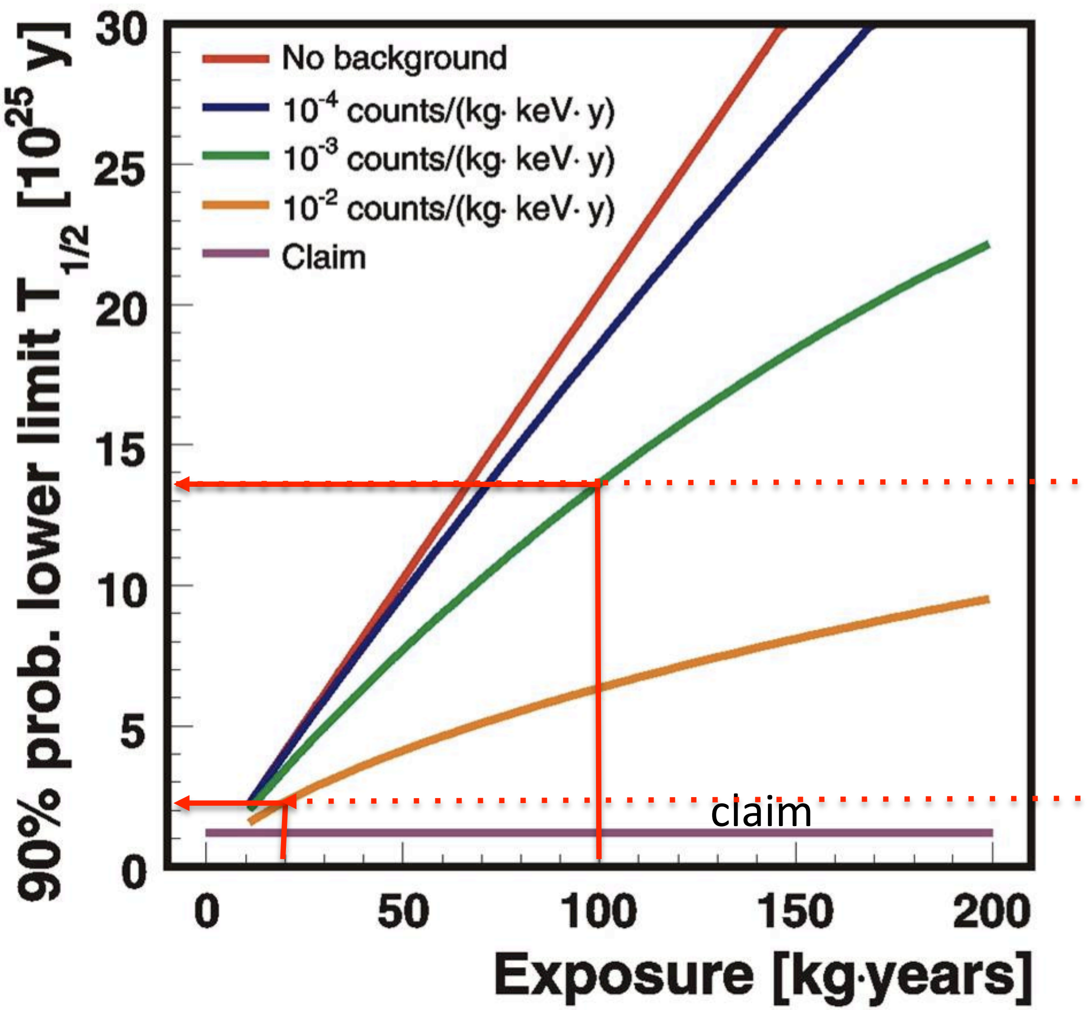


<u>Phase I:</u>

Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

Sensitivity after 20 kg yr



Phase II:

Add new enr. BEGe detectors (20 kg)

BI ≈ 0.001 cts / (keV kg yr)

Sensitivity after 100 kg yr

Phase I:

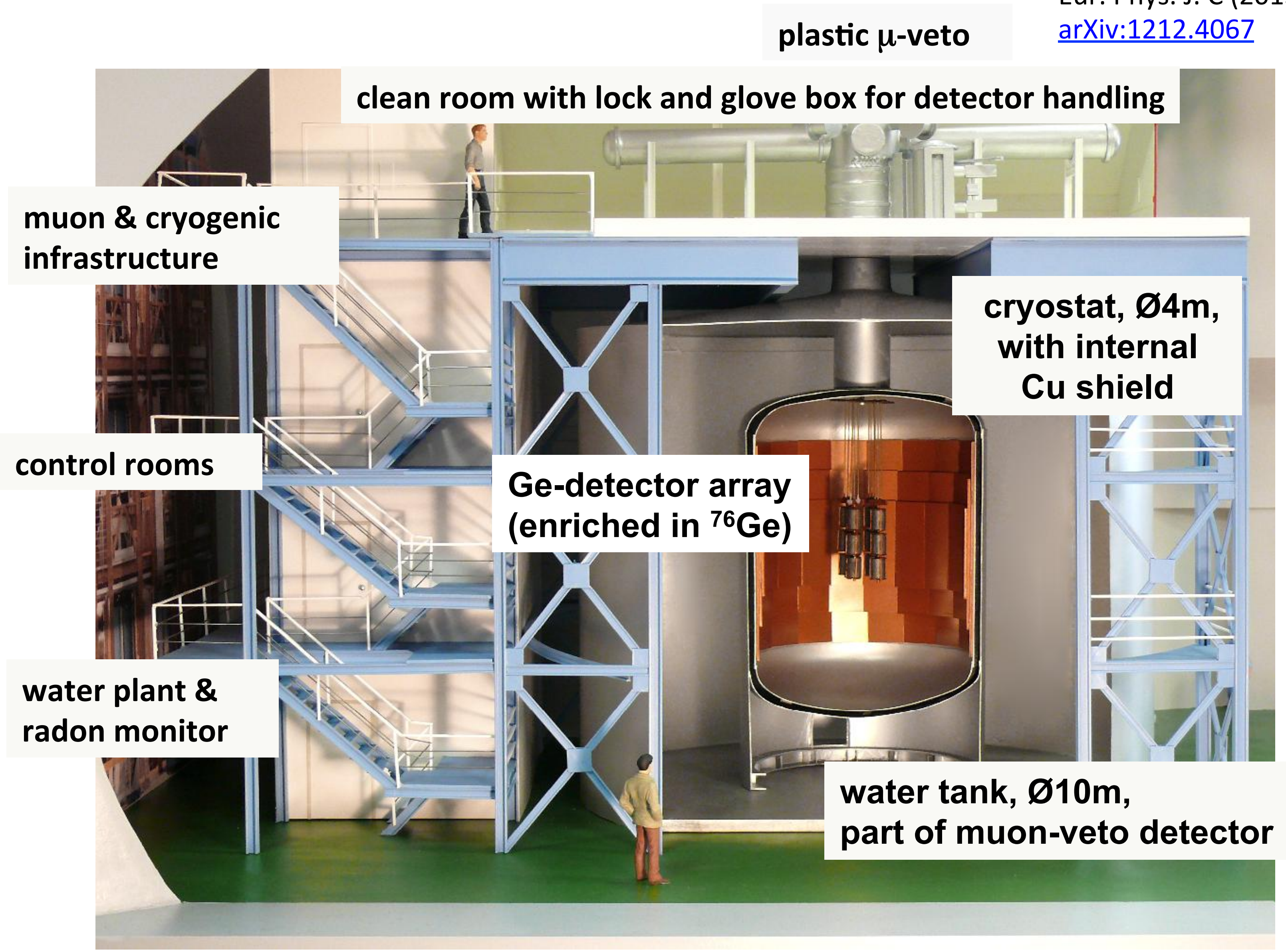
Use refurbished HdM & IGEX (18 kg)

BI ≈ 0.01 cts / (keV kg yr)

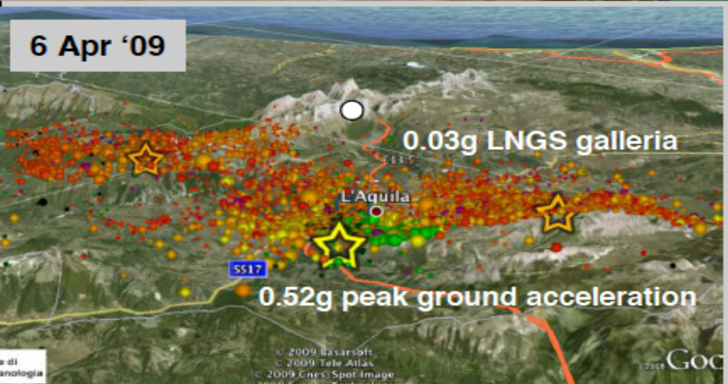
Sensitivity after 20 kg yr

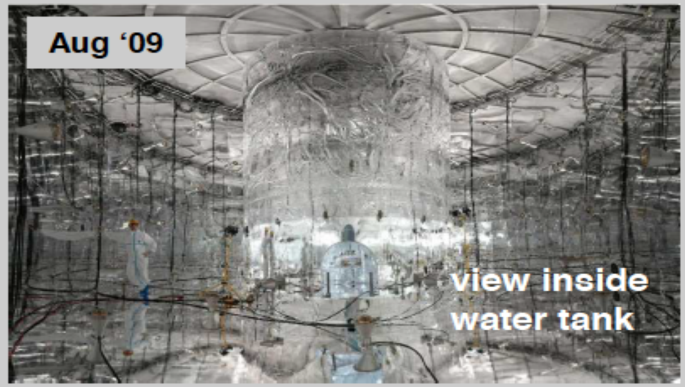
The GERDA experiment

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



The GERDA construction 2008-2010

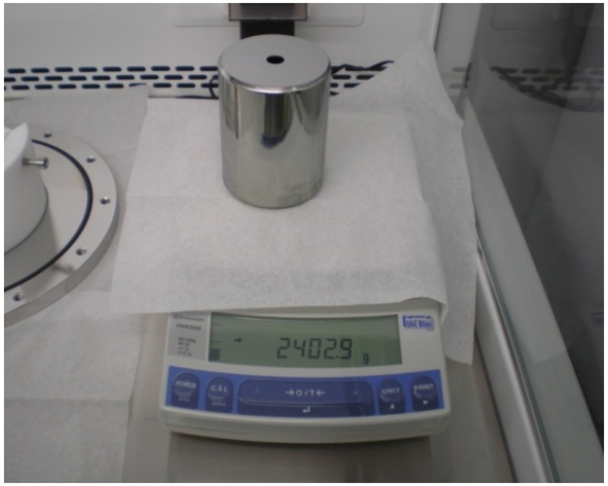




Cryostat filled since December 2009

Phase I detectors: semi-coaxial detectors

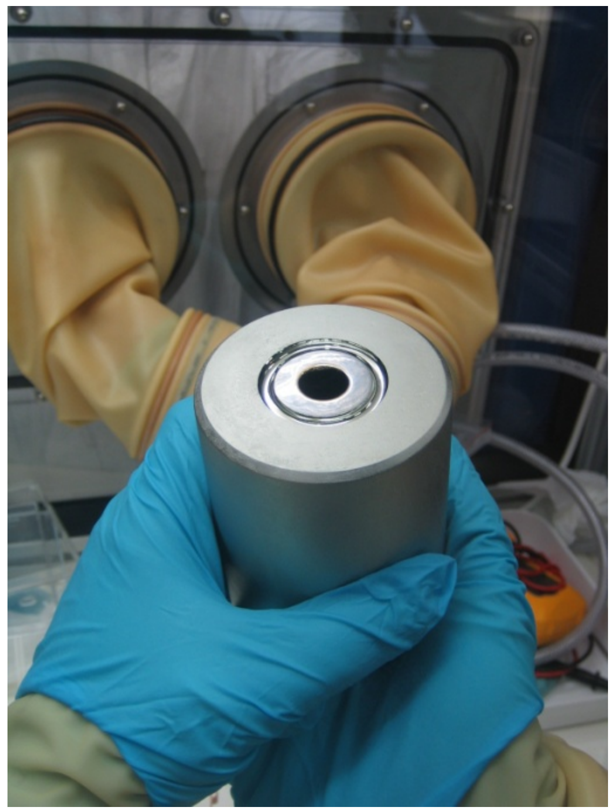
Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



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

8 diodes (from HdM, IGEX):

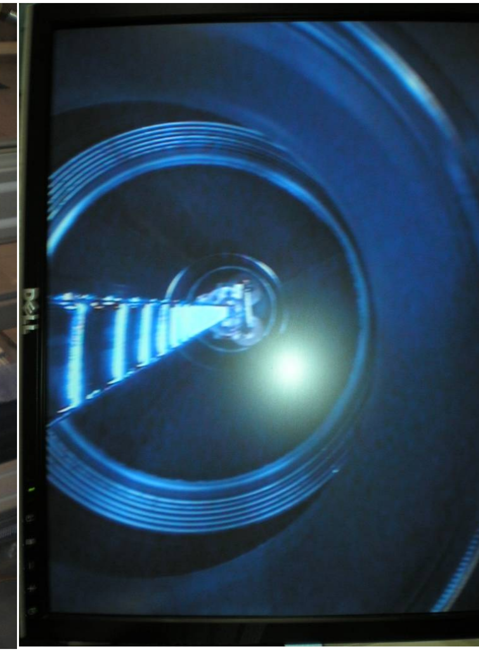
- Enriched 86% in ^{76}Ge
- Total mass 17.66 kg
- Diodes fully refurbished



6 diodes from Genius-TF:

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

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

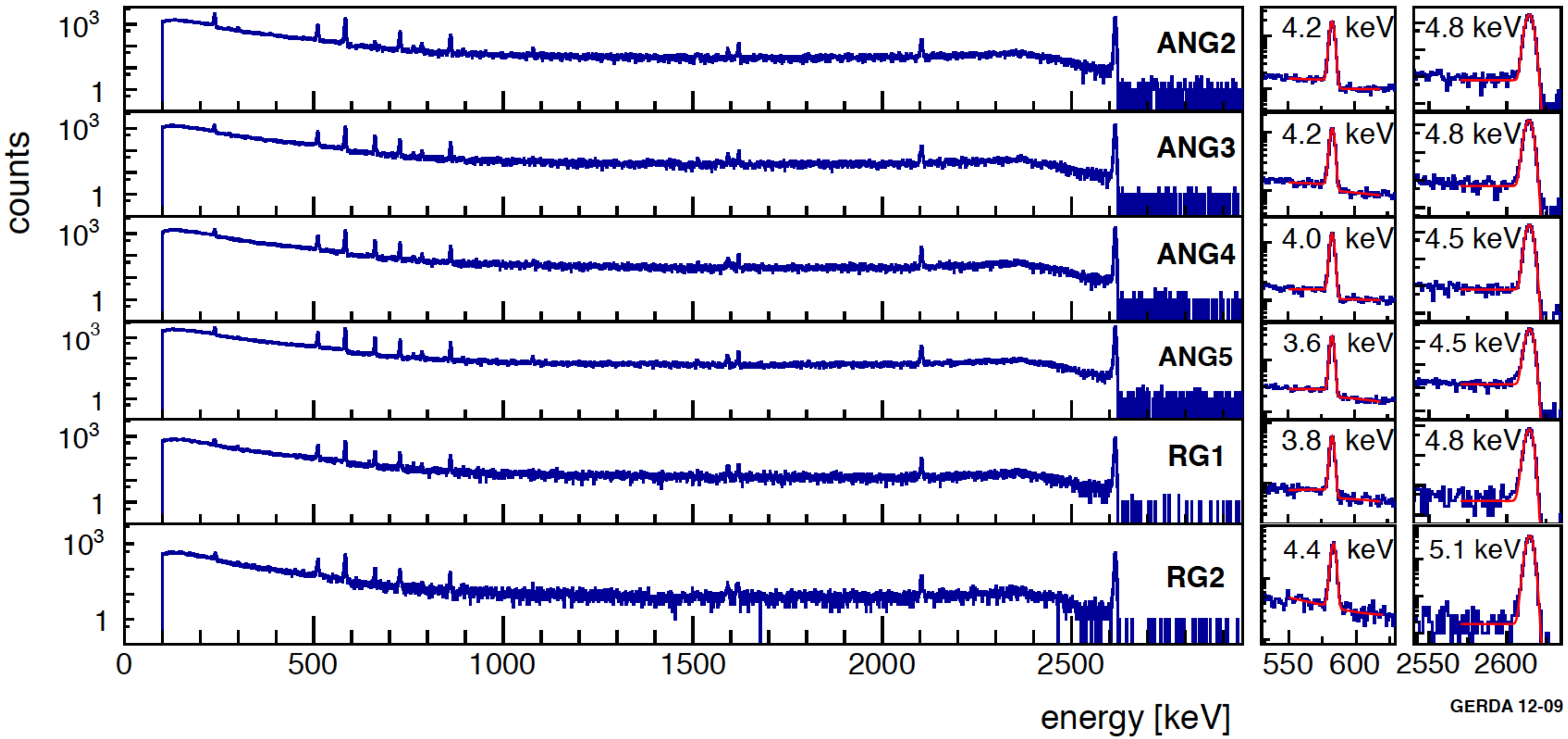


8 refurbished enriched diodes from HdM & IGEX
- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

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

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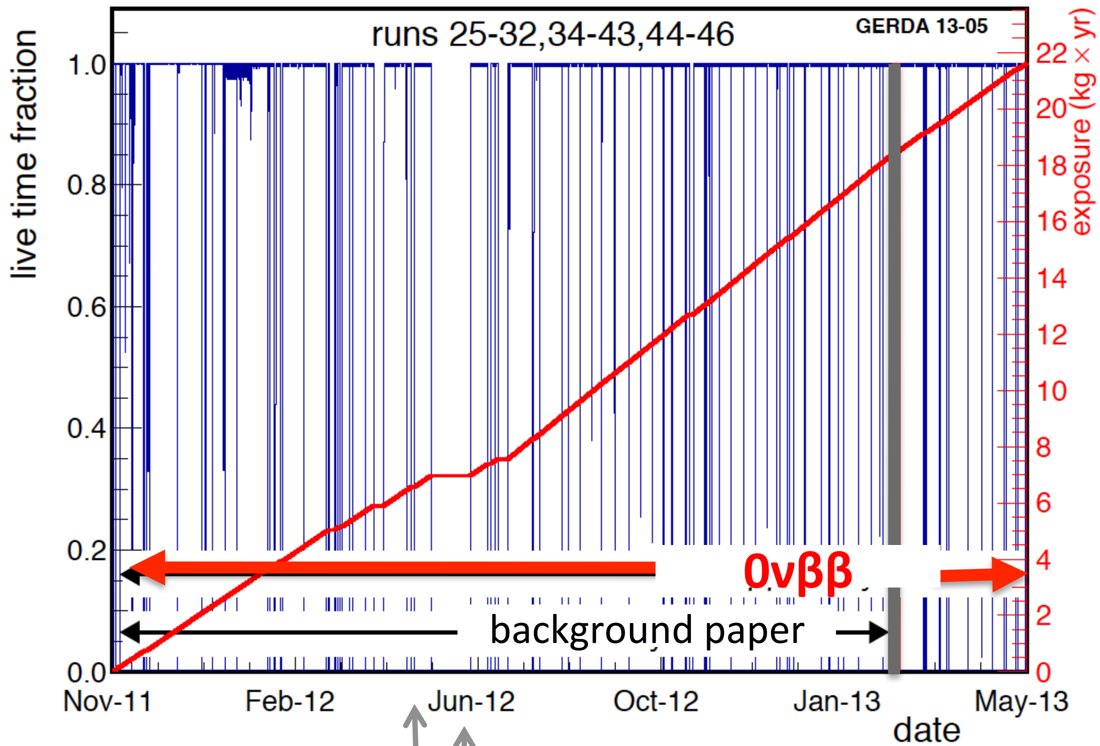
arXiv:1212.4067

Total exposure for 0νββ analysis: 21.6 kg yr

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



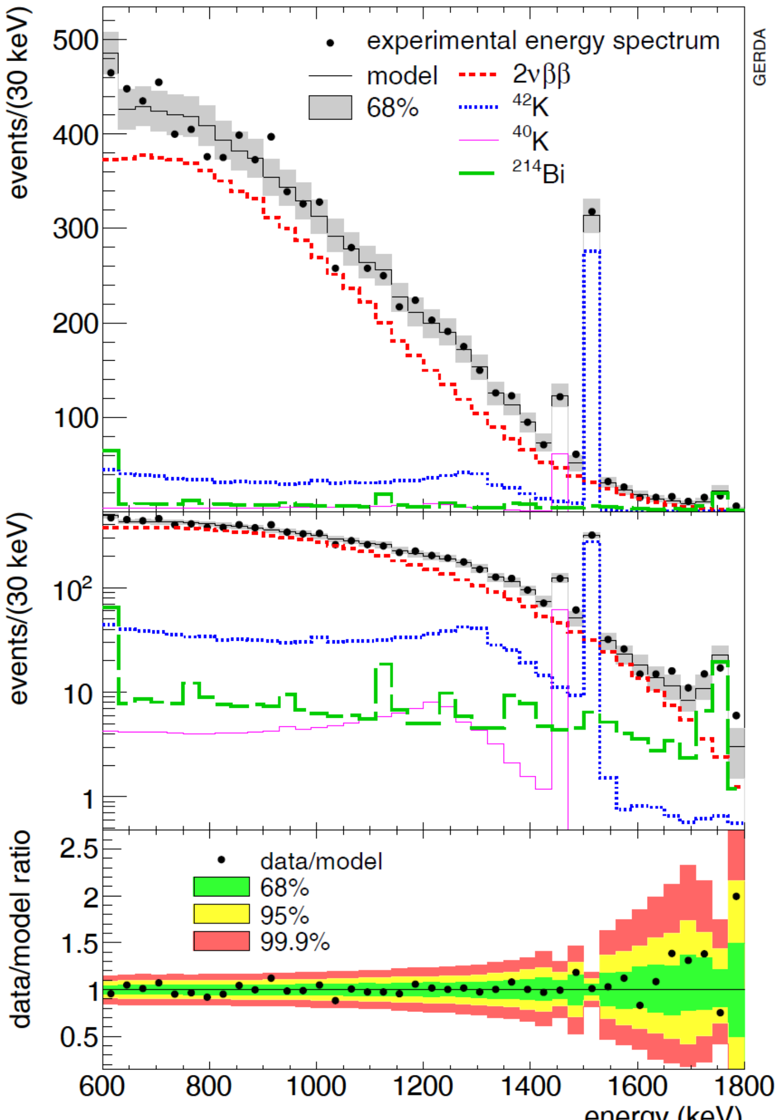
Insertion of 5 Phase II ^{enr}BEGe

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

Data blinding:

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

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

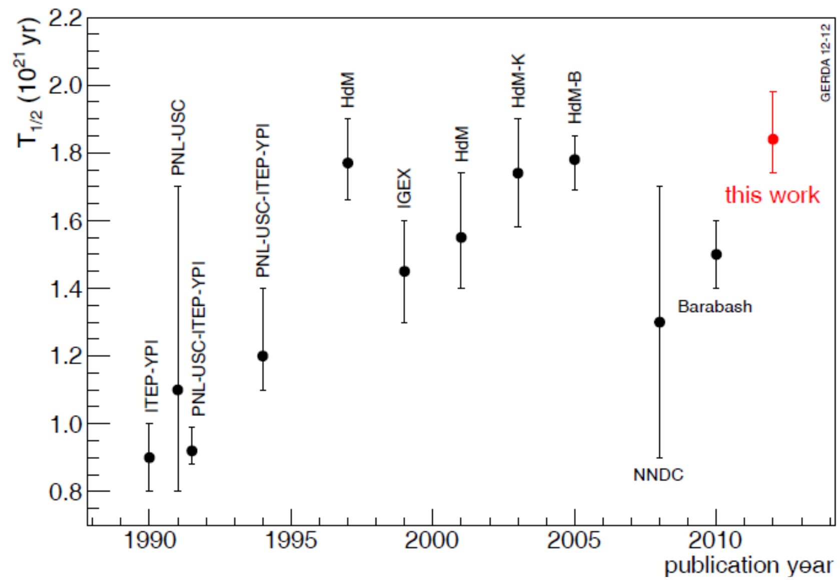


IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

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

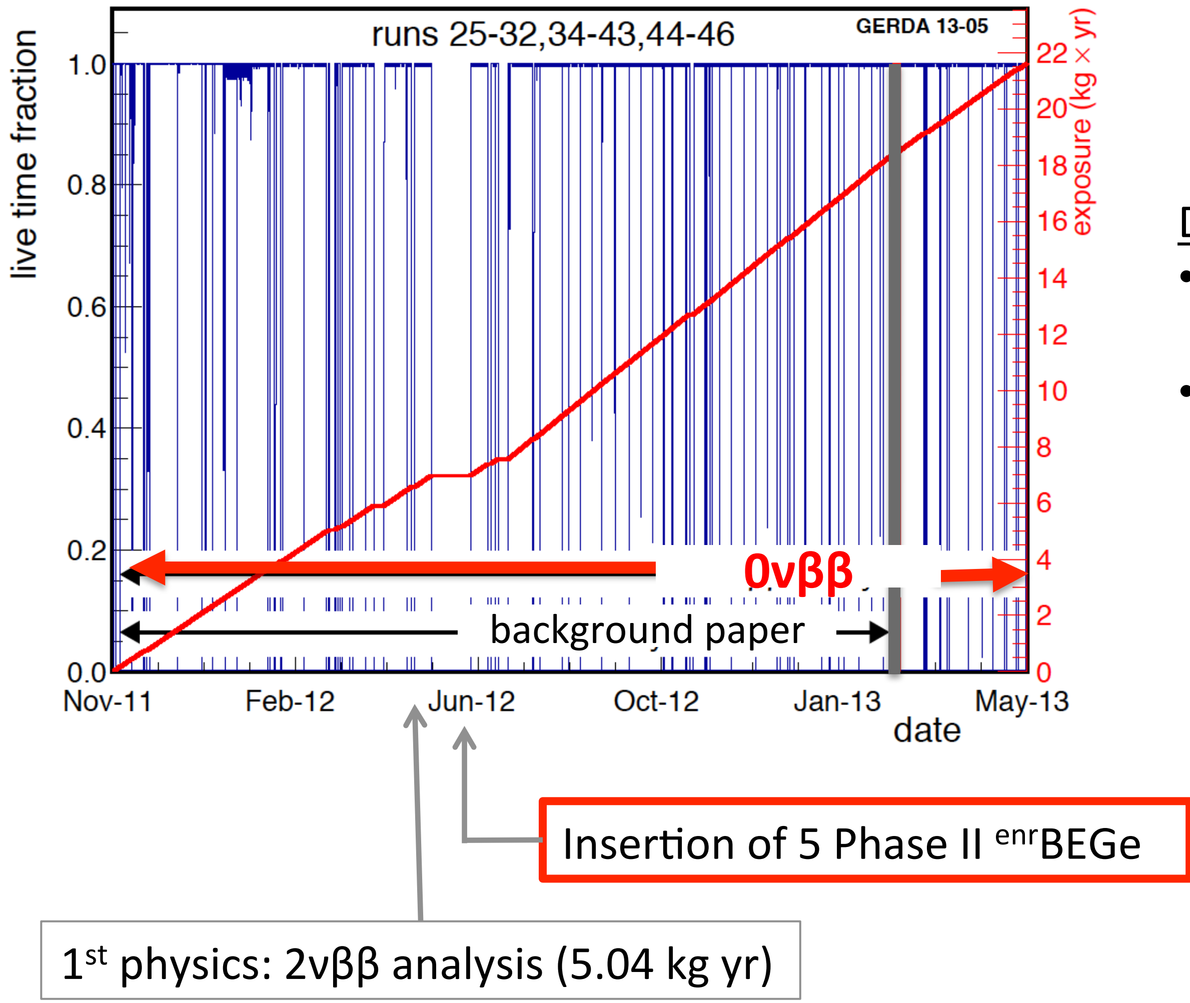


LAB Talk of J. Phys. G Feb. 2013 issue:
http://iopscience.iop.org/0954-3899/labtalk-article/52398

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

Total exposure for 0νββ analysis: 21.6 kg yr

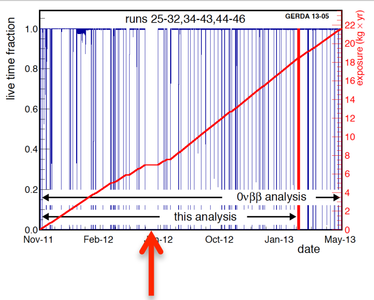
(bi-)weekly calibration runs ('spikes')

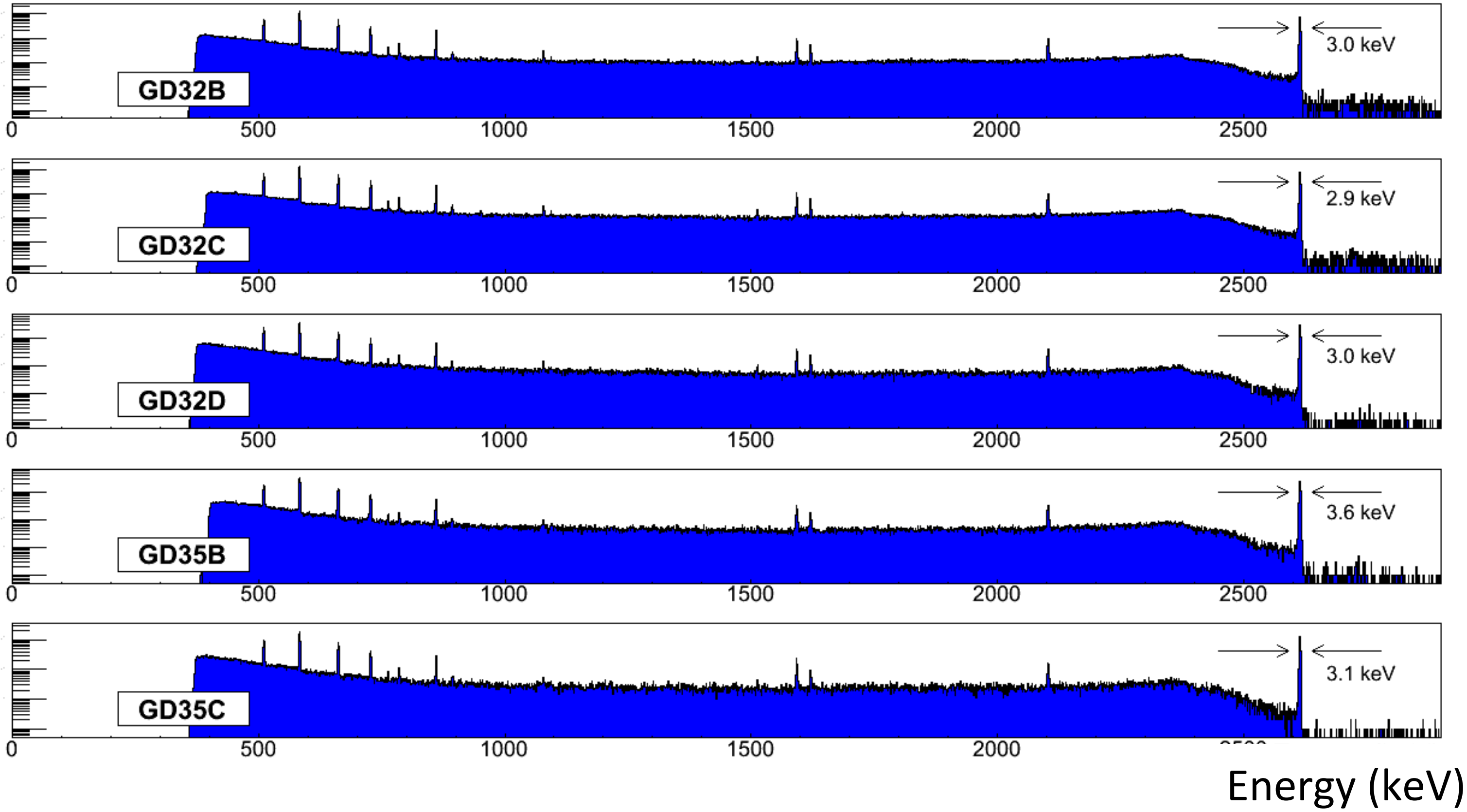


Data blinding:

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

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

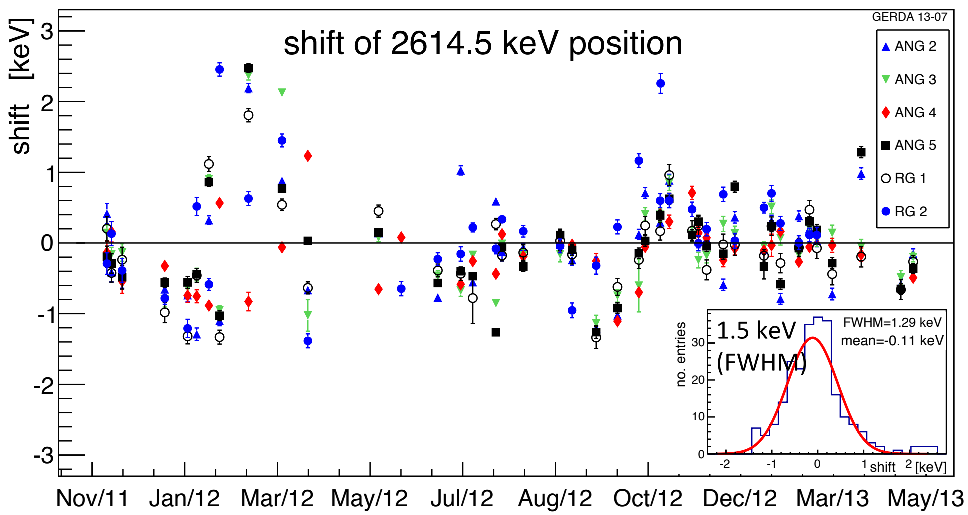


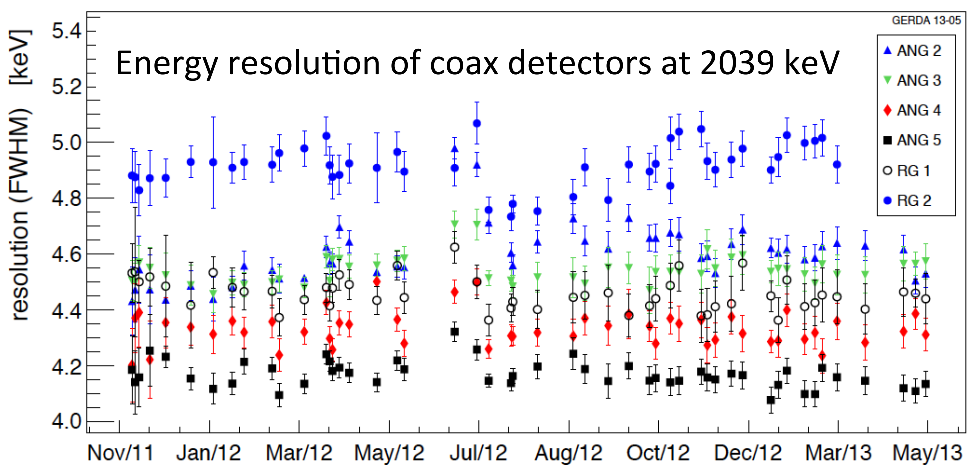


Calibration: stability of HPGe detectors

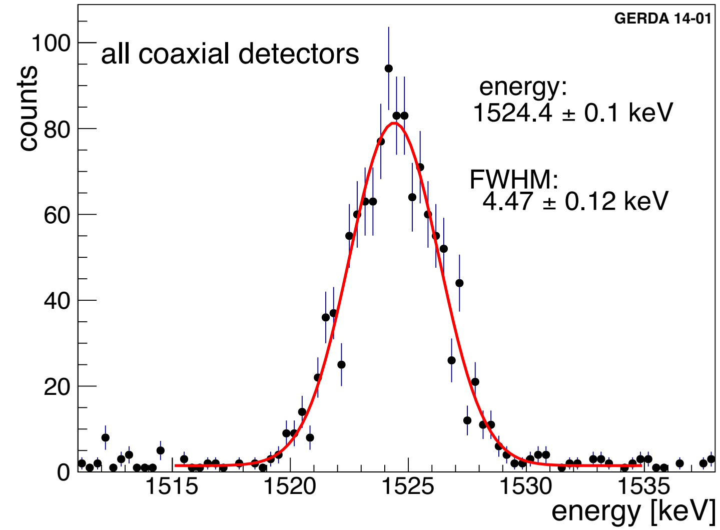
arXiv:1306.5084

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





Summing all runs:



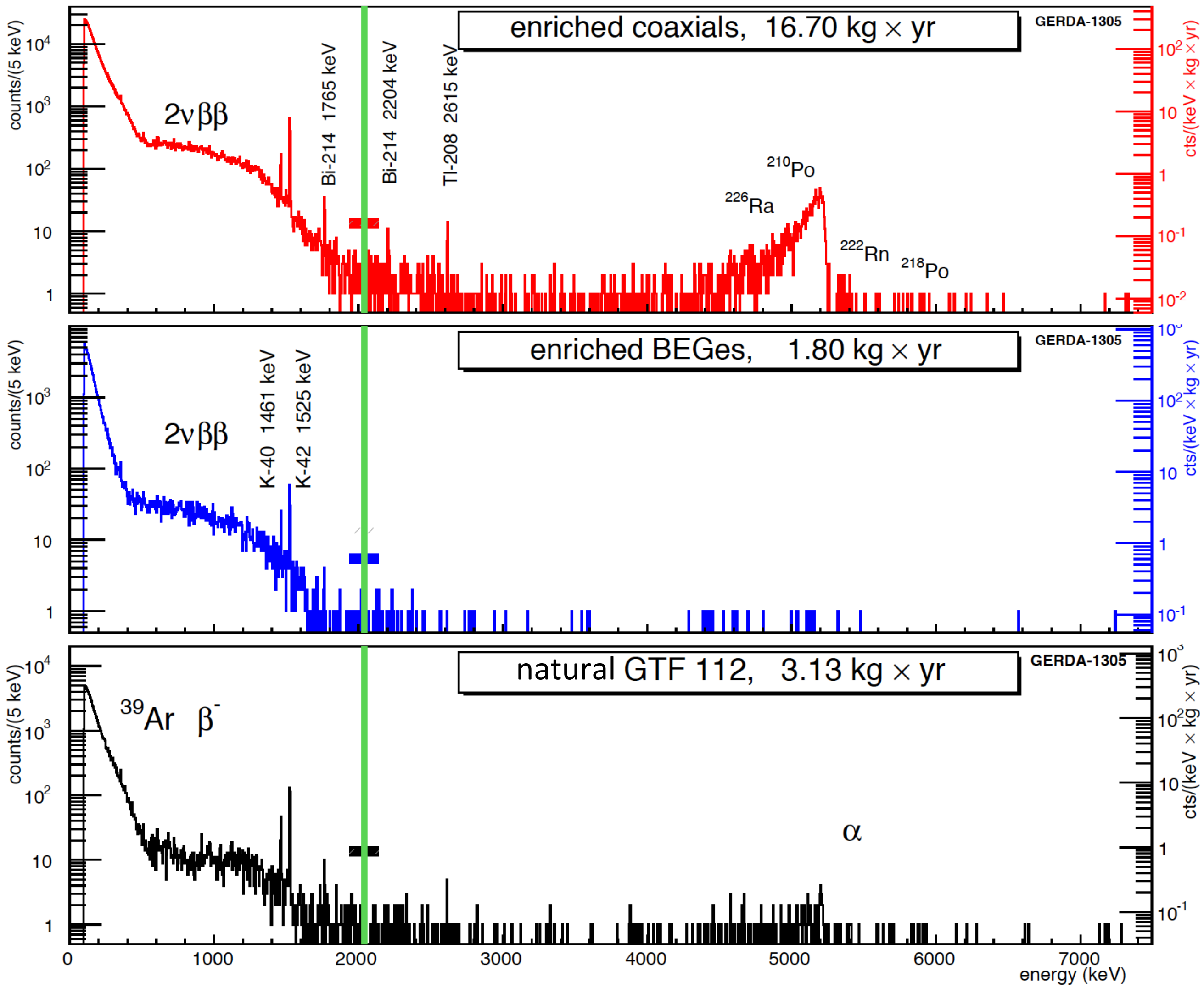
Mean energy resolution at $Q_{\beta\beta}$ =2039 keV:

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

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

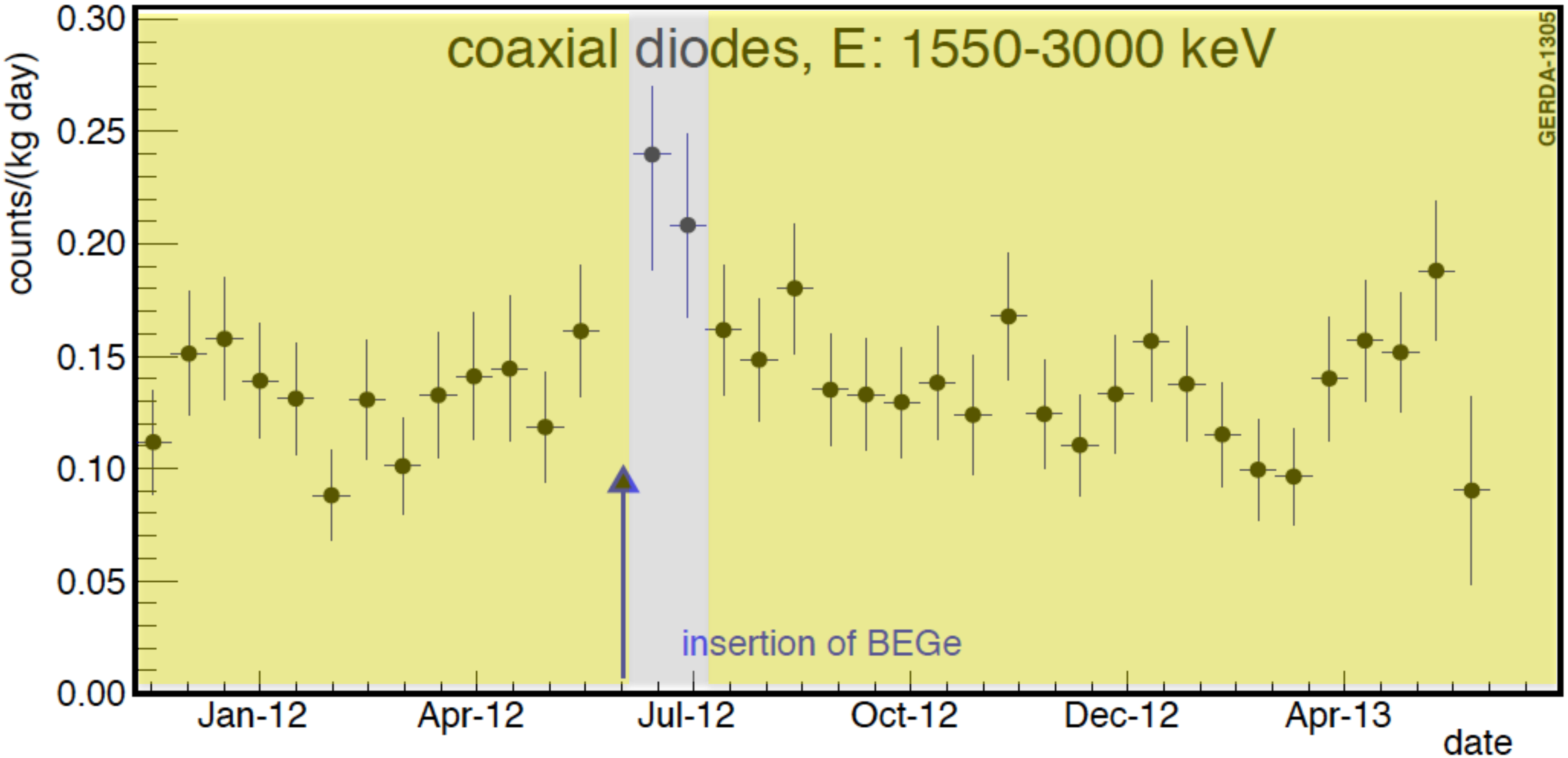
arXiv:1306.5084

Submitted to EPJ A
Data for background model



Physics run: background rate as function of time

arXiv:1306.5084

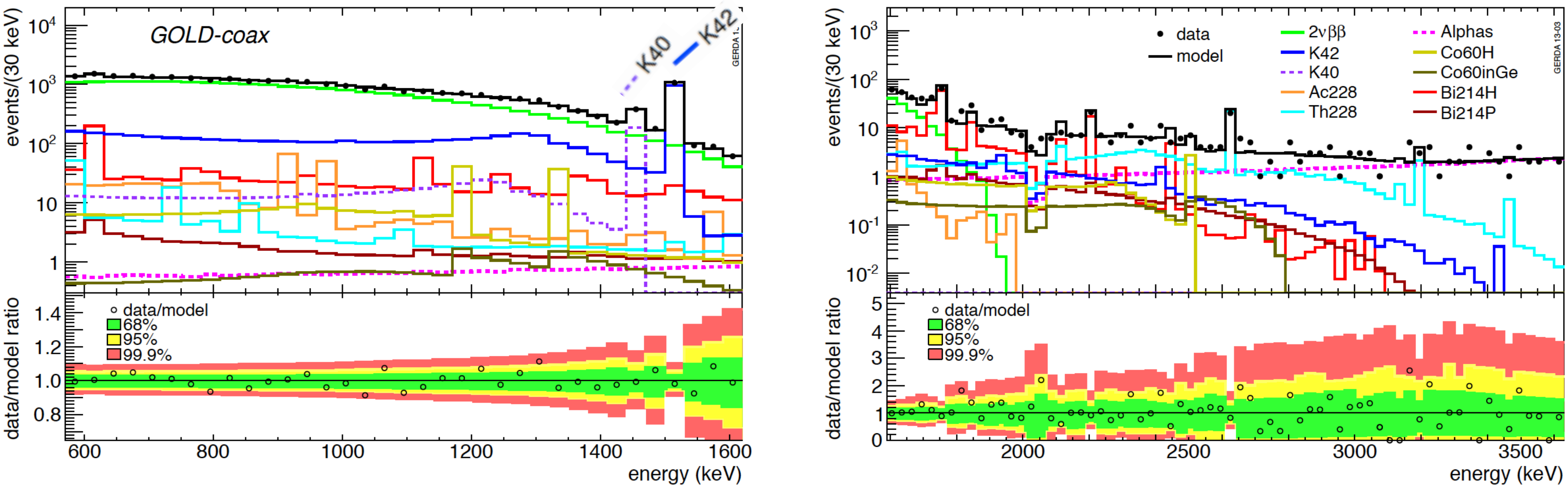


Coax-detector data set split in 'Gold' and 'Silver' (30 d)

Physics run: background decomposition

arXiv:1306.5084

Fit of minimal background model to complete energy spectrum

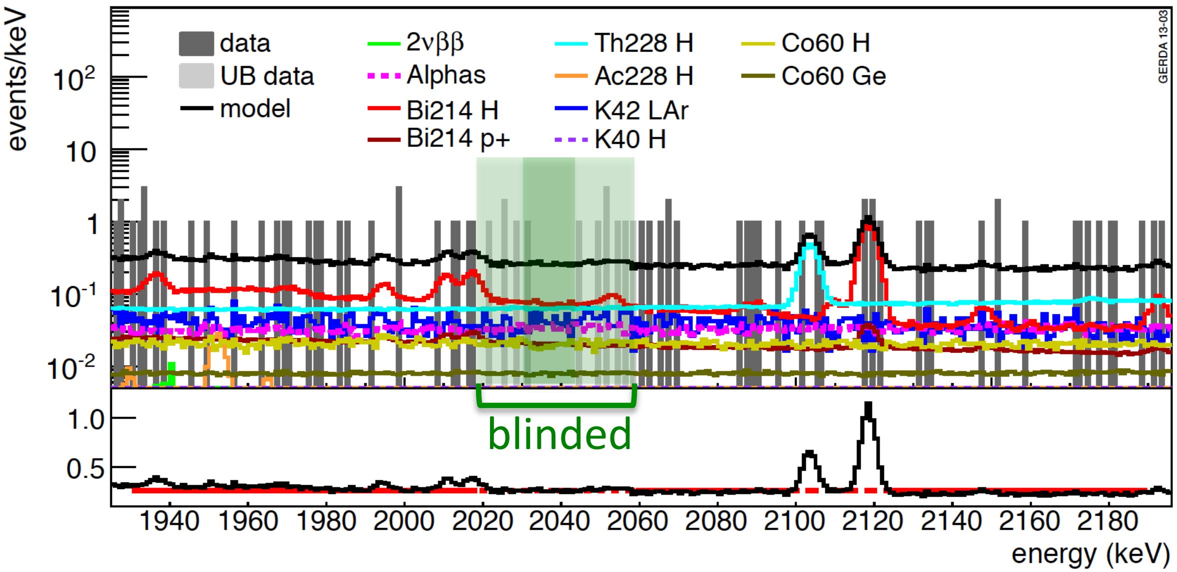


- "Minimal Model" is sufficient to describe data well
- "Maximum Model" includes ^{42}K on p+ and n+ contacts, ^{214}Bi in LAr & far sources

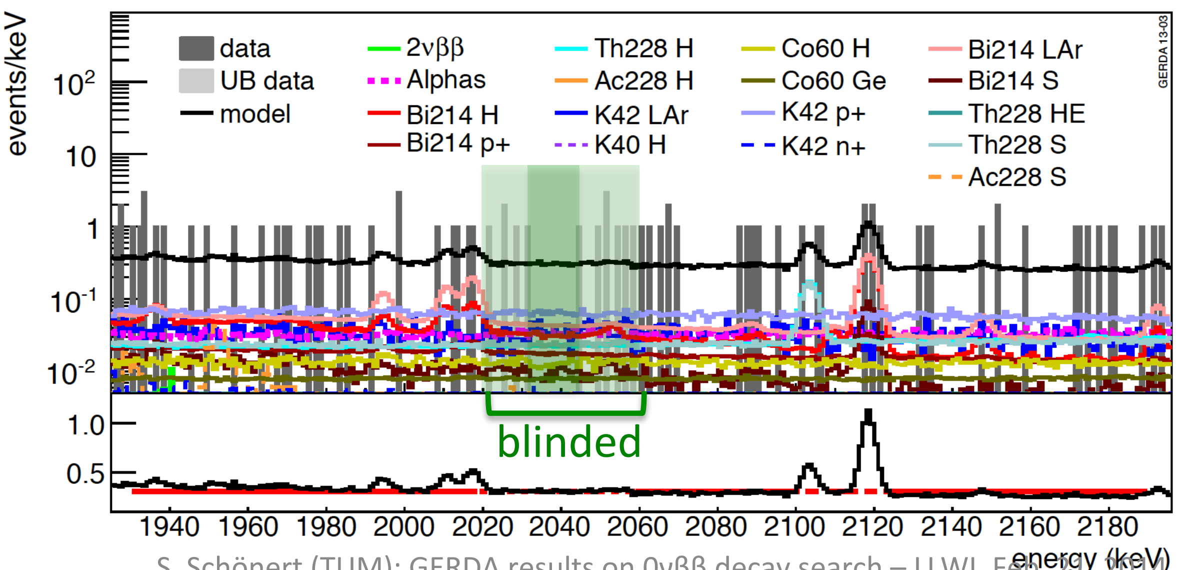
Physics run: background model and prediction of BI at $Q_{\beta\beta}$

arXiv:1306.5084

Minimal model



Maximum model

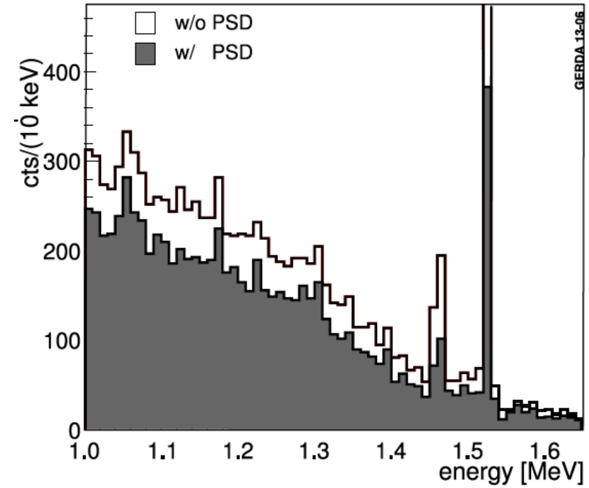


Background model:

- 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

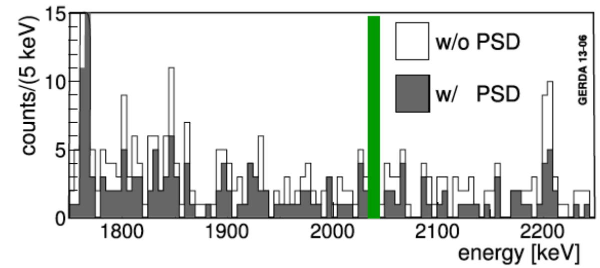
➔ fit with constant background 1930-2190 keV excluding peaks

Pulse shape discrimination: method and cuts fixed prior unblinding



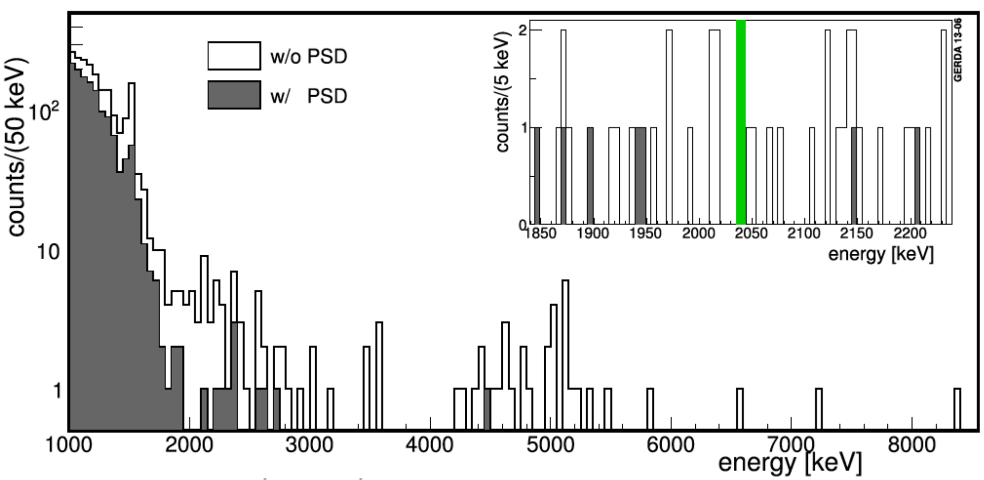
Coaxial detectors:

- artificial neural network TMlpANN
- cut defined using ^{228}Th calibration data
  cut fixed to 90% acceptance of 2.6 MeV DEP
- cross checks:
  - $2\nu\beta\beta$ acc. = (85±2)%
  - 2.6 MeV γ-line compton-edge acc. = 85-94%
  - Co-56 DEP (1576 & 2231 keV) acc. = 83-95%



$0\nu\beta\beta$ acceptance $= 90^{+5}_{-9}\%$

background acc at $Q_{\beta\beta} = \sim 45\%$



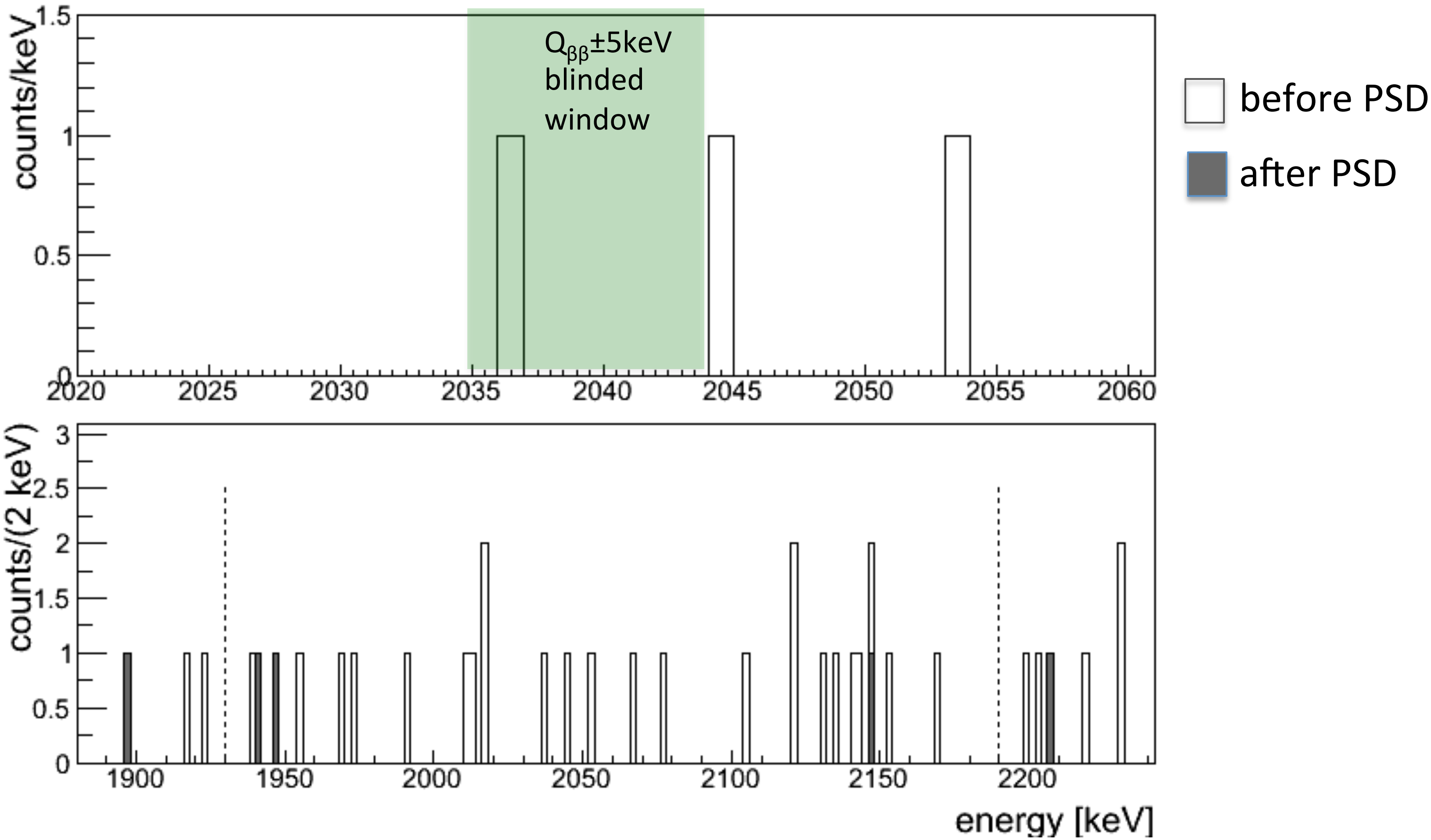
BEGe detectors:

- A/E method (mono-parametric PSD)
- $0\nu\beta\beta$ acc (DEP and simulations) (92±2)%
- $2\nu\beta\beta$ acc (91±5)%
- background acc at $Q_{\beta\beta} \leq 20\%$

more details in [Eur.Phys.J C73 (2013) 2583]

Unblinding: BEGe data set (2.4 kg yr)

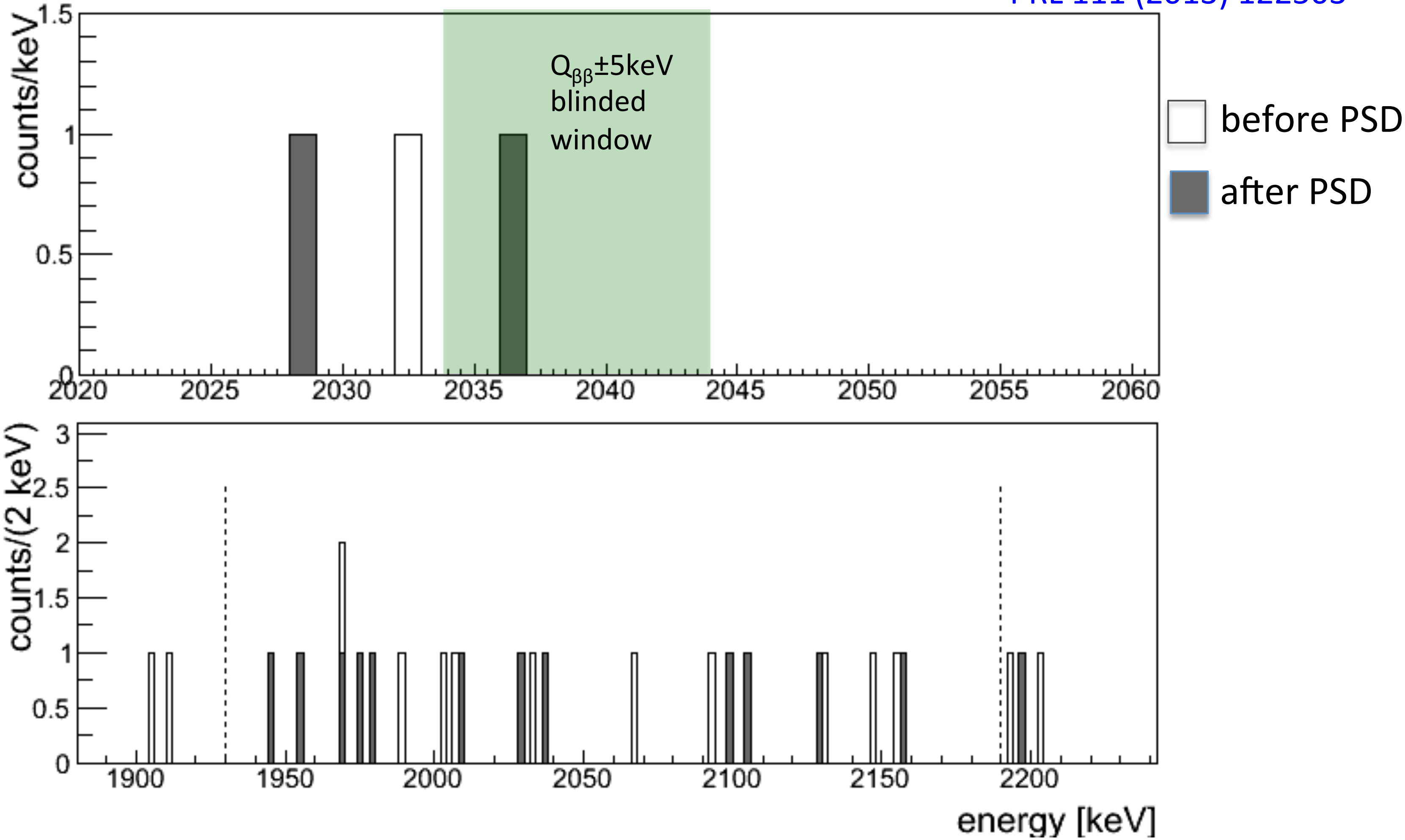
PRL 111 (2013) 122503



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

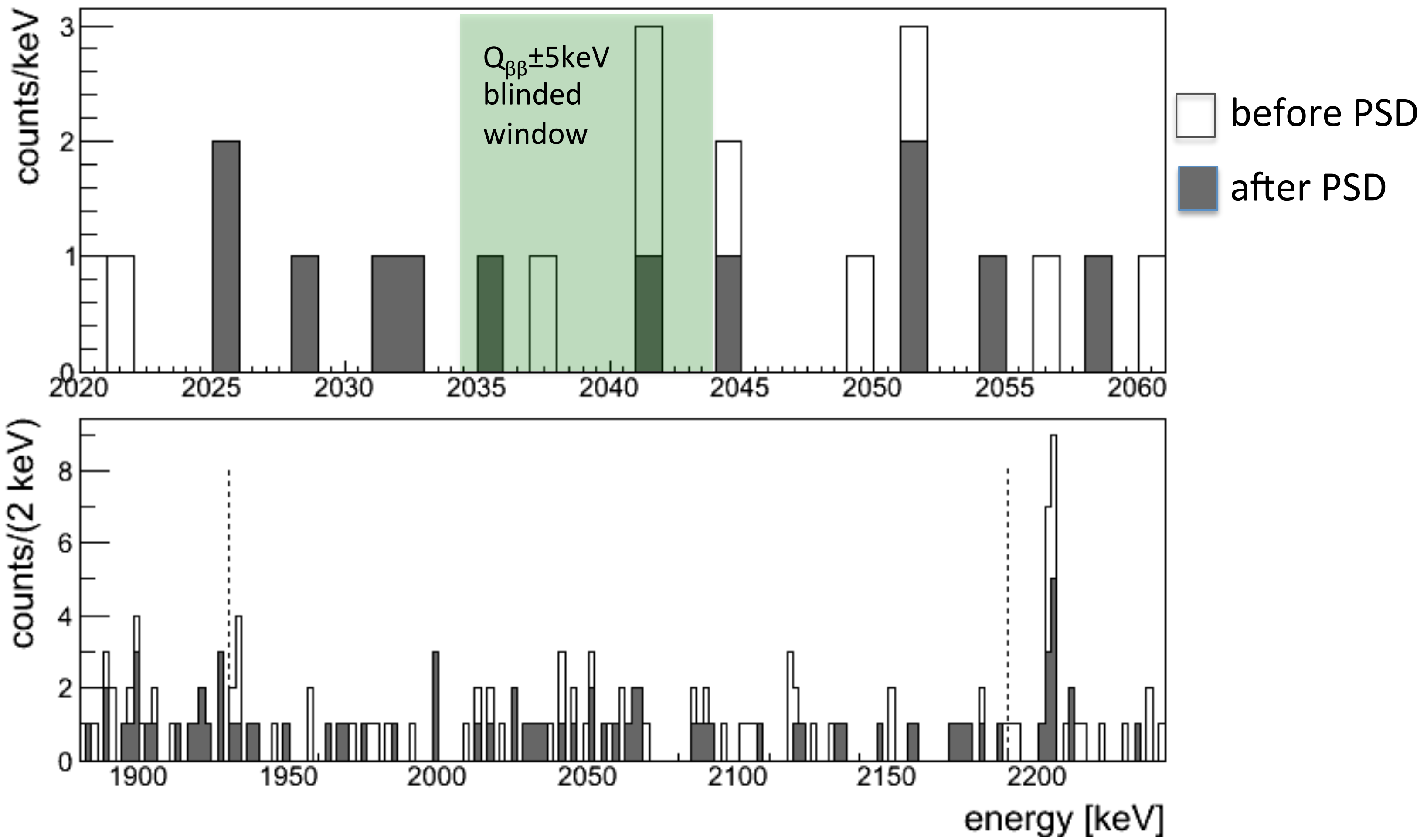
Unblinding: silver-coax data set (1.3 kg yr)

PRL 111 (2013) 122503



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

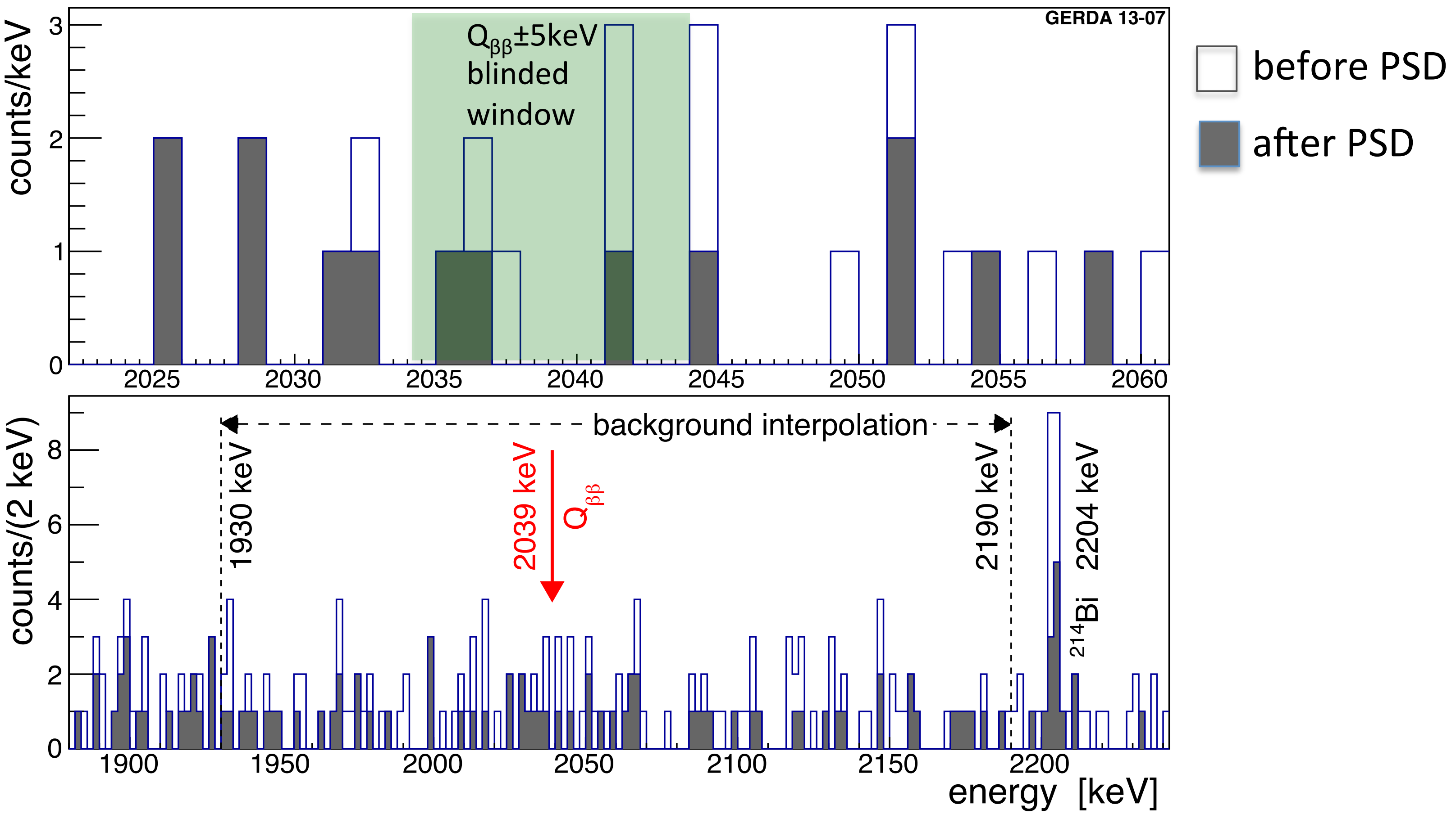
PRL 111 (2013) 122503



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

Unblinding: full data set (21.6 kg yr)

PRL 111 (2013) 122503



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

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

PRL 111 (2013) 122503

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

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

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

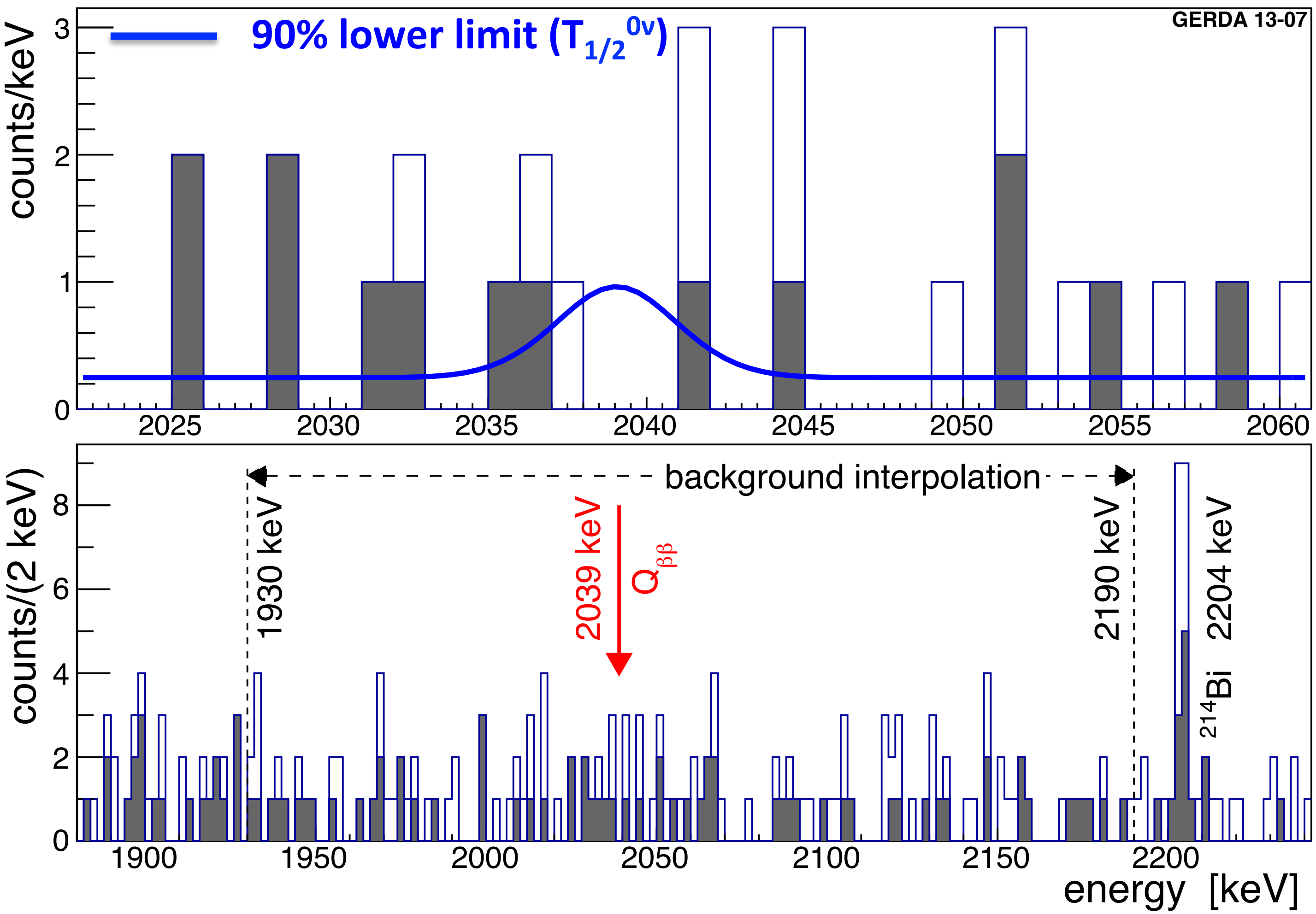
f_{76}: enrichment fraction
f_{av}: fraction of active detector volume
ε_{fep}: full energy peak efficieny for 0νββ
ε_{psd}: signal acceptance

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

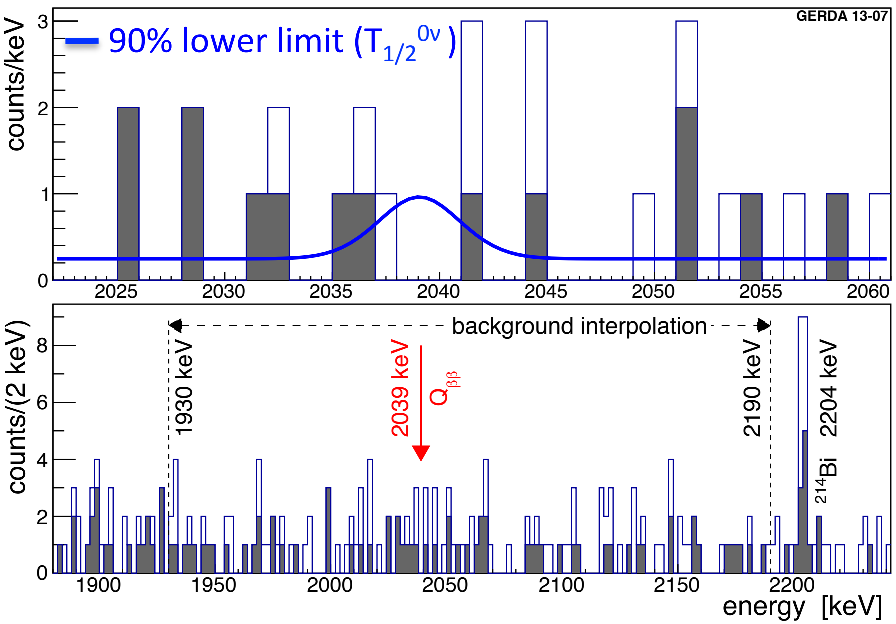
	$\langle f_{76} \rangle$	**$\langle f_{av} \rangle$**	**$\langle \varepsilon_{fep} \rangle$**	**$\langle \varepsilon_{psd} \rangle$**	**$\langle \varepsilon \rangle$**
Coax	0.86	0.87	0.92	0.90 +0.05/ -0.09	0.619 +0.044/-0.070
BEGe	0.88	0.92	0.90	0.92 ±0.02	0.663 ±0.022

Profile likelihood fit to 3 data set (21.6 kg yr)

PRL 111 (2013) 122503



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

PRL 111 (2013) 122503

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.): $>2.4\times10^{25}$ yr

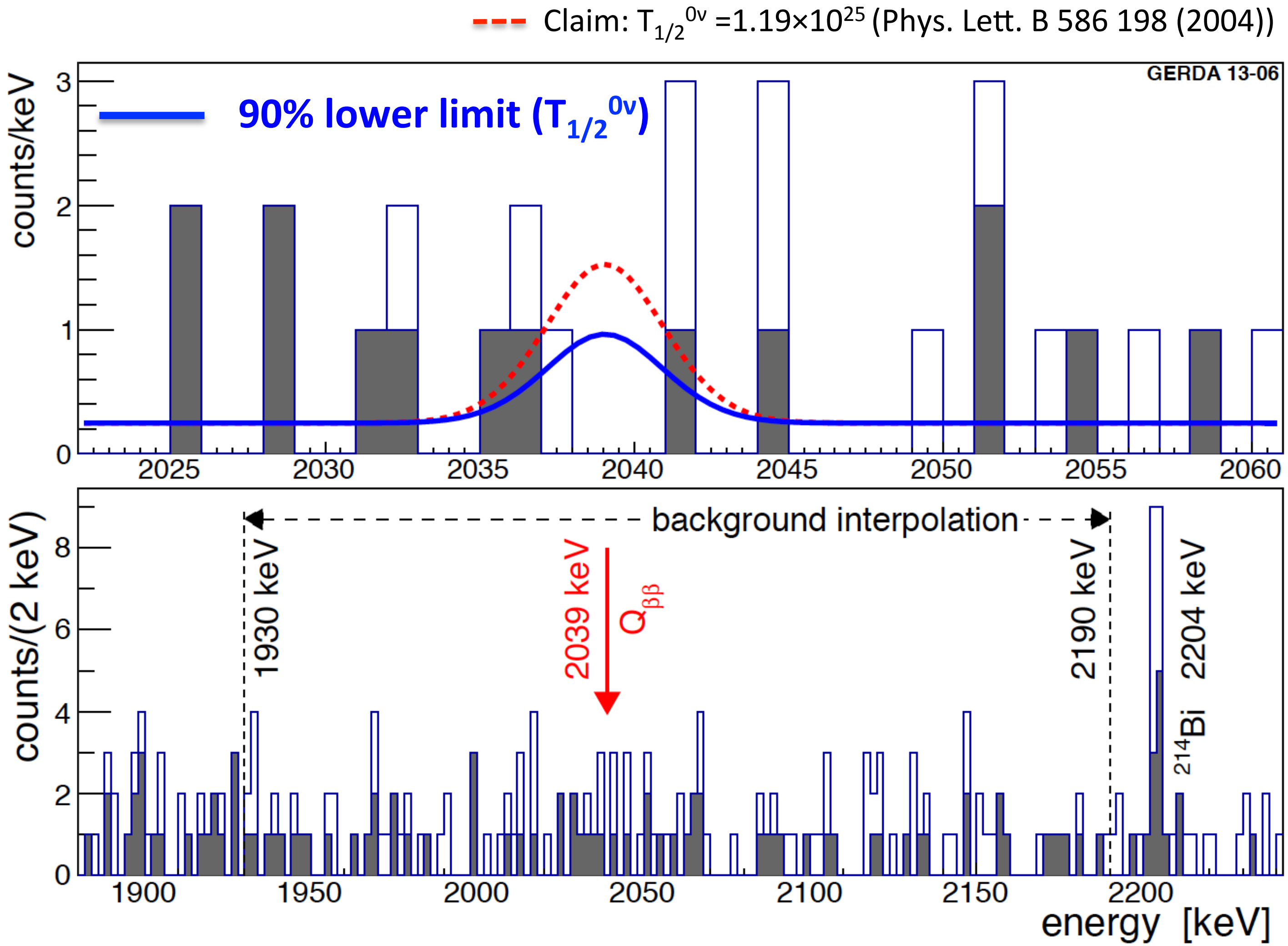
Bayesian:

- 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.): $>2.0\times10^{25}$ yr

Systematics folded: limit weakened by 1.5%

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

PRL 111 (2013) 122503

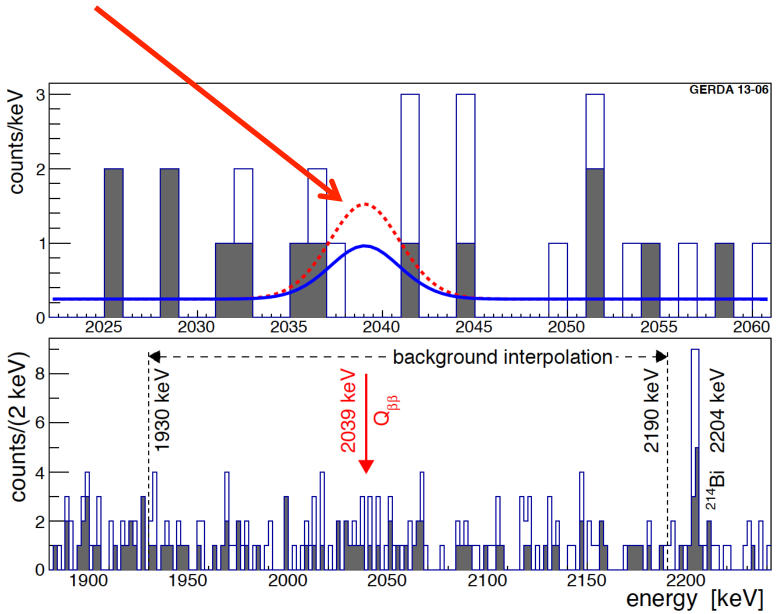


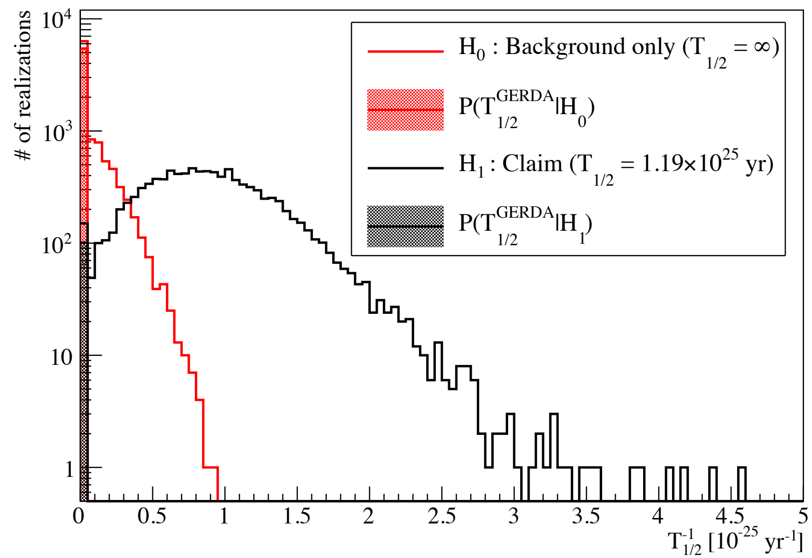
Comparison with Phys. Lett. B 586 198 (2004) claim

PRL 111 (2013) 122503

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)





H0: background only

H1: claimed signal plus background

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

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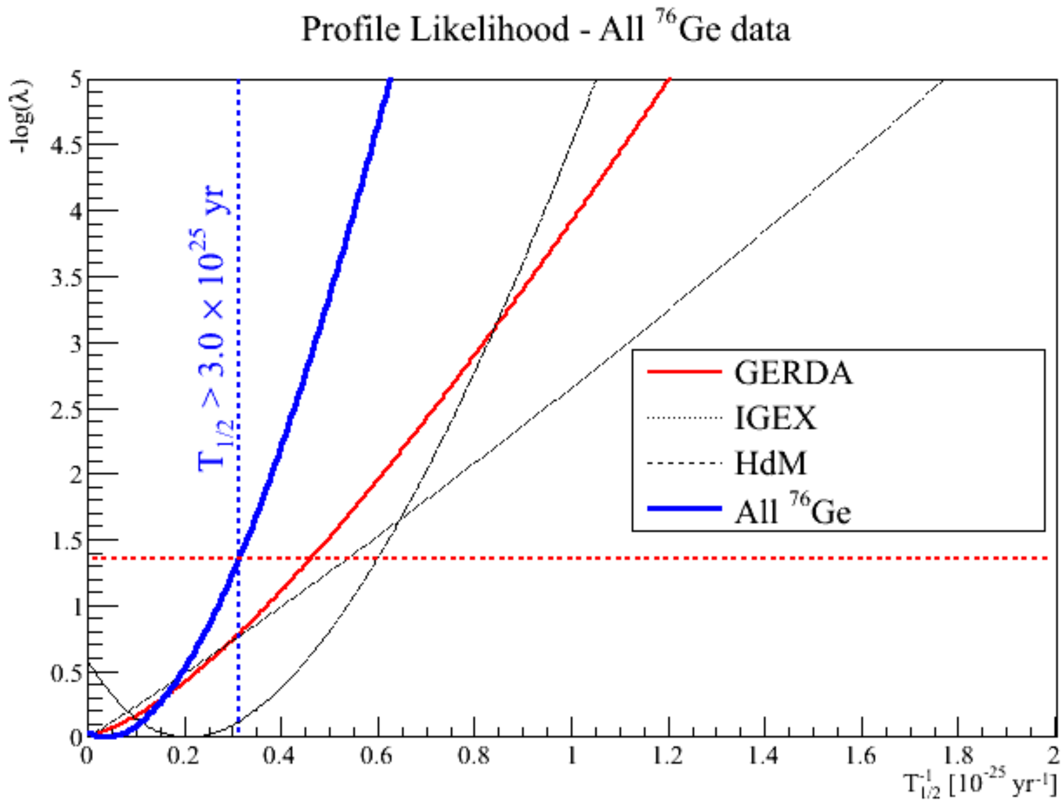


HdM: Eur. Phys. J. A 12, 147 (2001)
IGEX: Phys. Rev. D 65, 092007 (2002),
Phys. Rev. D 70 078302 (2004)

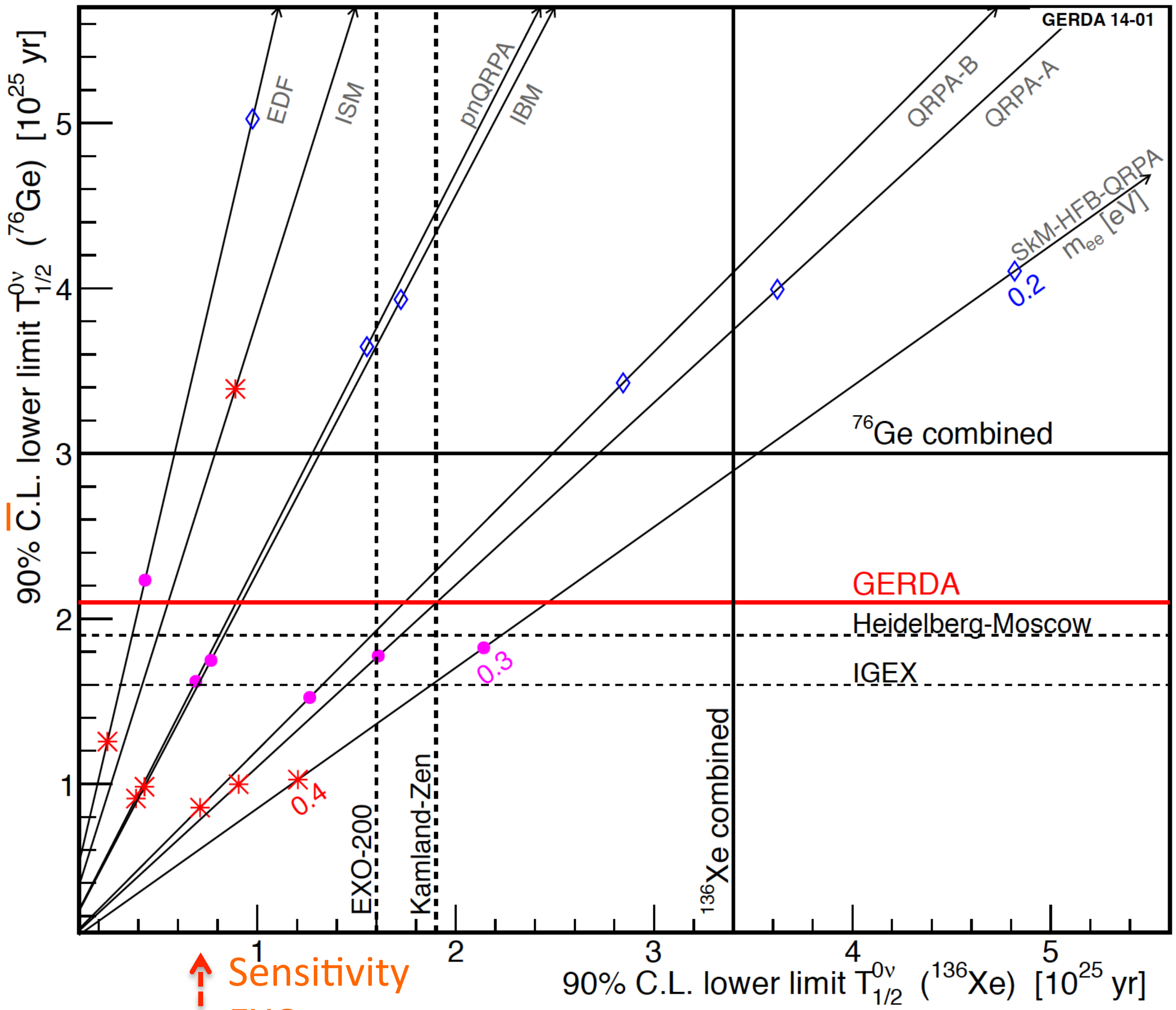
$$T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}\ \text{yr} \quad (90\,\%\ \ \text{C.L.})$$

- Coverage verified with toy MC
- 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

Comparison with the Xenon DBD experiments



Sensitivity GERDA Phase I

Sensitivity EXO

Summary

- **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 after analysis cuts and correcting for efficiencies:
  0.006 cts /(mol yr FWHM) (cf. EXO: 0.044, KL: 0.19)

Transition to Phase II ongoing:

- Increase of target mass (+20 kg; total ≈40 kg of Ge detectors)
- New custom made BEGe detectors with enhance pulse shape discrimination
- Liquid argon instrumentation (anti-coincidence veto)
- Background ≤ 10^{-3} cts /(keV kg yr)
- Explore $T_{1/2}(0\nu)$ values in the 10^{26} yr range

Beyond Phase II:

- Common 1t experiment with Majorana to cover 'inverse mass hierarchy' mass range conceived