Results from Phase I of the GERDA experiment and outlook to Phase II

K.T.Knöpfle for the GERDA collaboration
MPI Kernphysik, Heidelberg
ktkno@mpi-hd.mpg.de

HEP2013, Dec 16 - 20, Valparaiso, Chile

GERDA : The GERmanium Detector Array

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

Search for neutrinoless double beta decay of Ge-76

Introduction

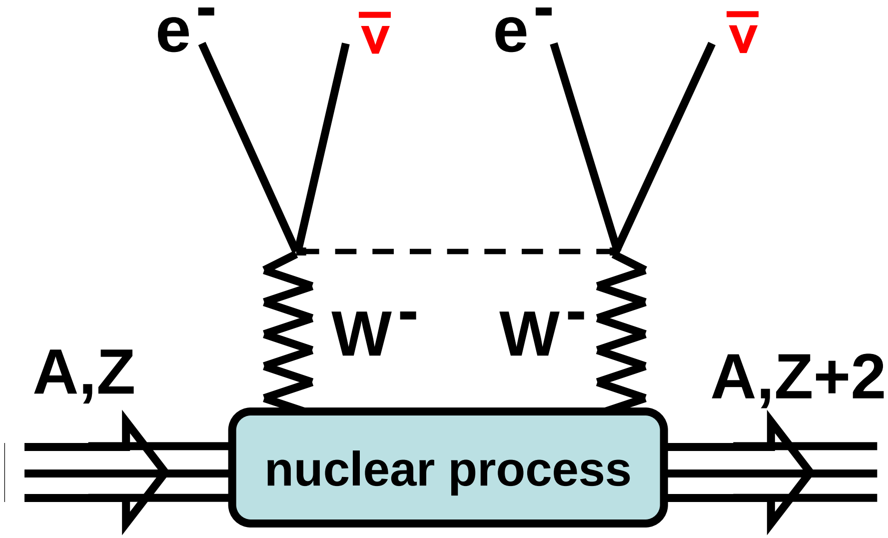
Experimental setup

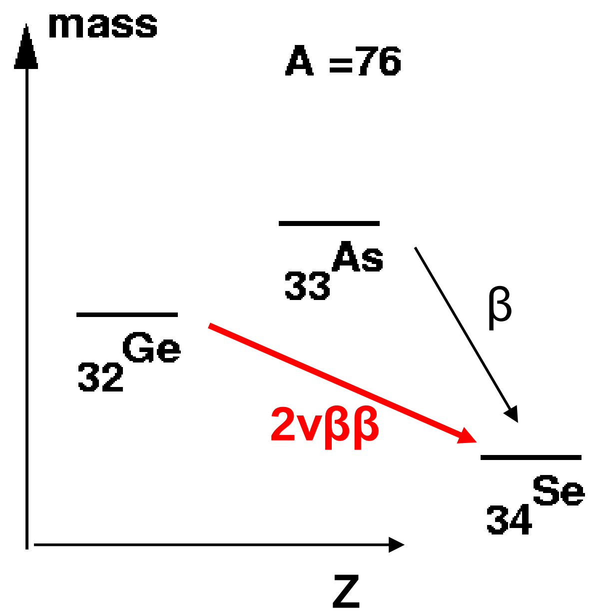
Results from Phase I

Phase II

- Preparations
- Competitors

2νββ





$T_{1/2} = 1.8 \cdot 10^{21}$ yr

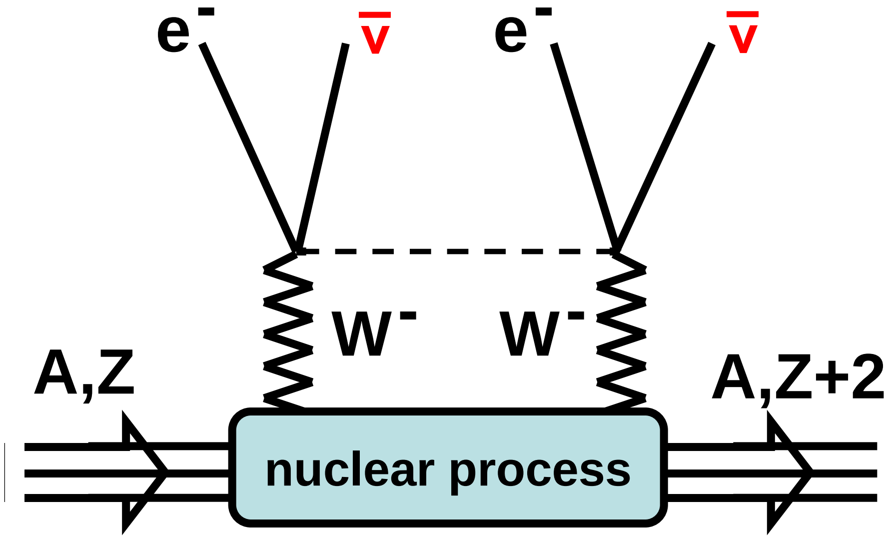
conventional 2nd order process

observed in various nuclei

$T_{1/2} \sim 10^{19} – 10^{21}$ yr

	$Q_{\beta\beta}$/keV	nat. abund. (%)
Ge- 76	2039	7.6
Te-130	2527	33.8
Xe-136	2458	8.9

2νßß

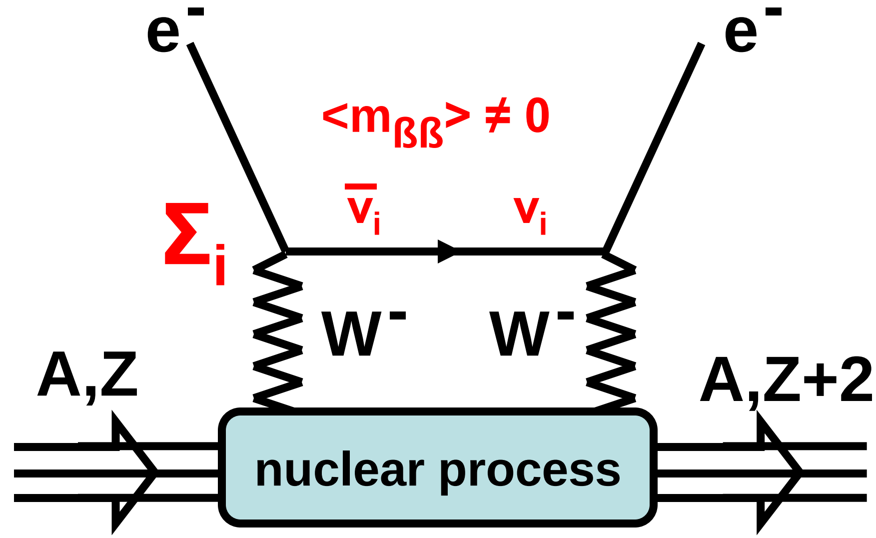


conventional 2nd order process

observed in various nuclei

$T_{1/2} \sim 10^{19} - 10^{21}$ yr

0νßß



hypothetical process , $T_{1/2} > 10^{25}$ yr,

only possible if

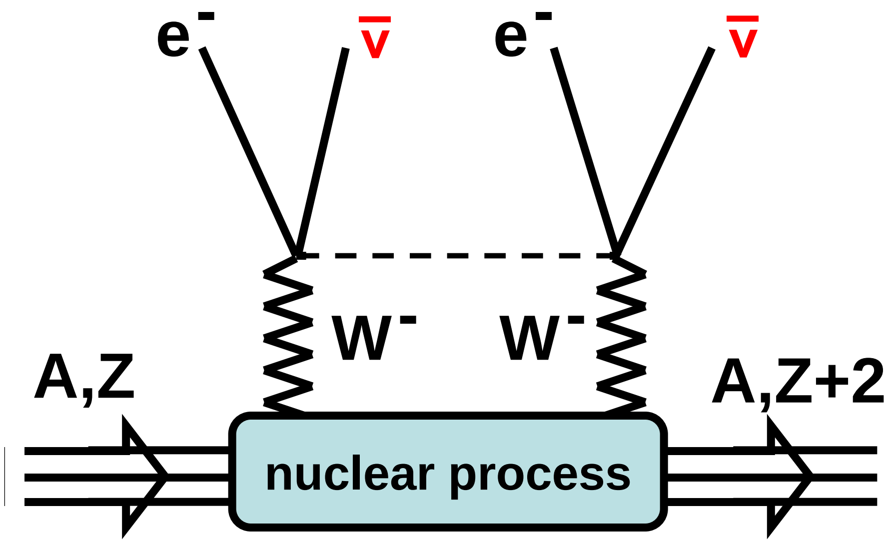
neutrino is massive Majorana particle

► lepton number violation ΔL=2

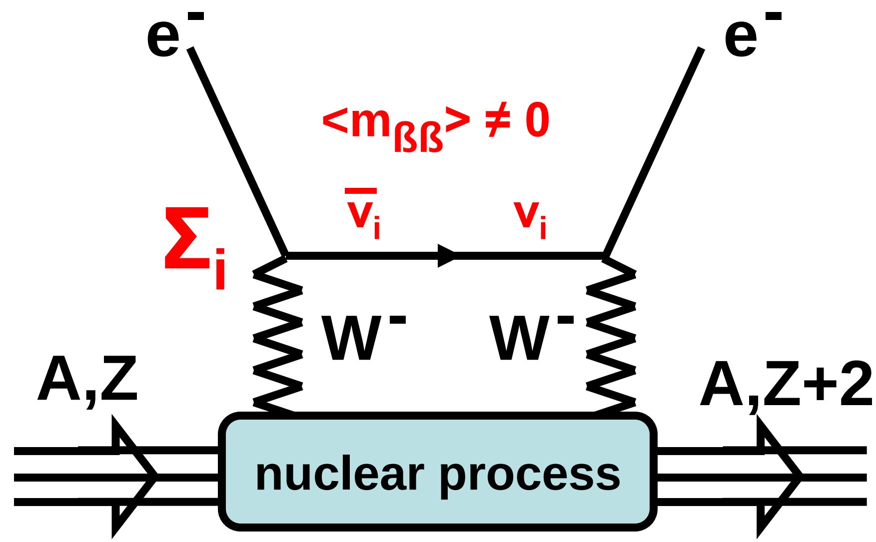
► access to absolute ν mass scale

► physics beyond s.m.

2νßß



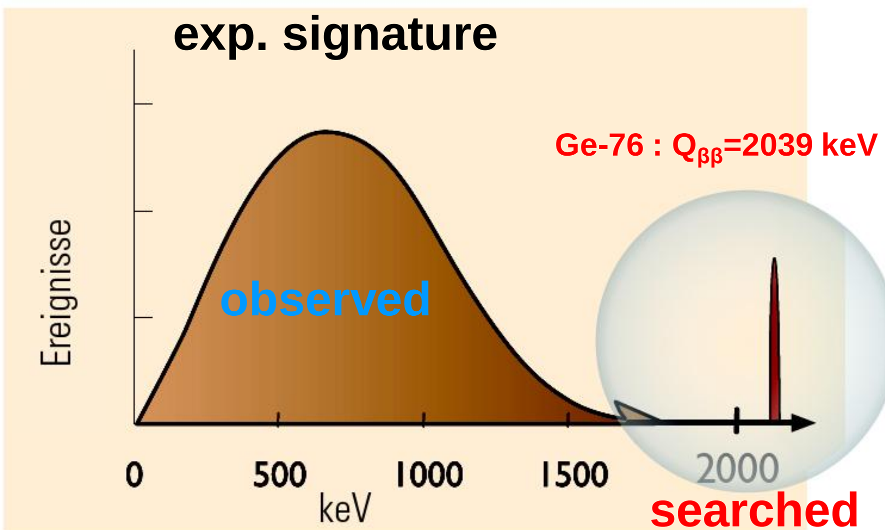
0νßß



conventional 2n

observed in vari

$T_{1/2} \sim 10^{19} – 10^{2}$



ss , $T_{1/2} > 10^{25}$ yr,

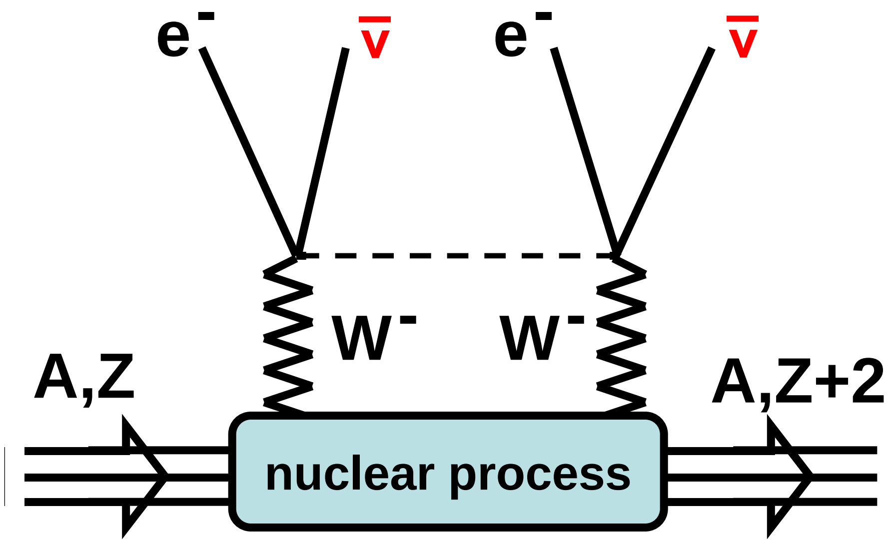
e Majorana particle

iolation ΔL=2

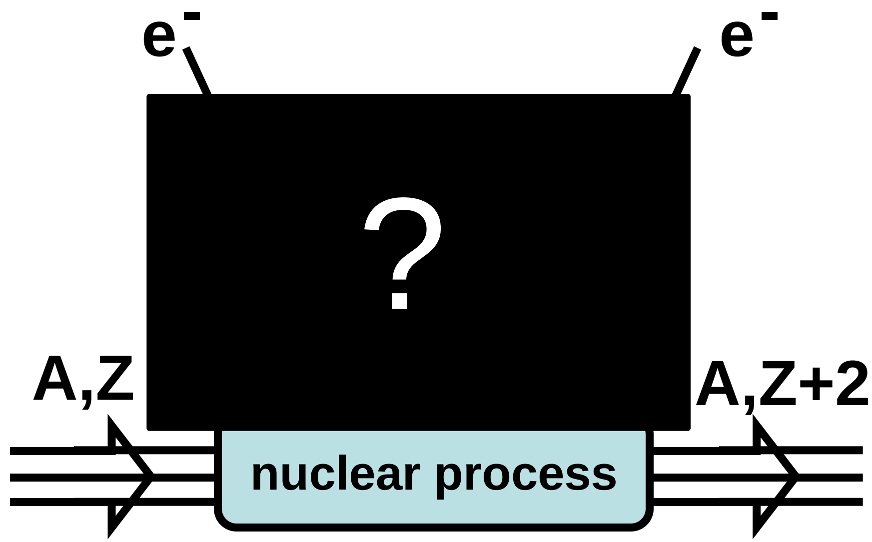
te ν mass scale

s.m.

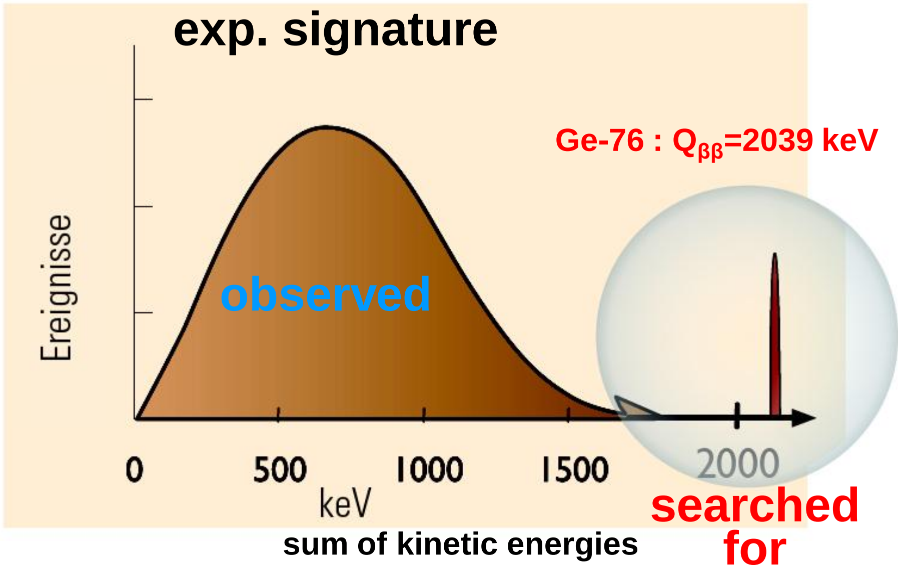
2vßß



0vßß



conventional 2n
observed in vari
$T_{1/2}$ ~ 10^{19} – 10^{2}



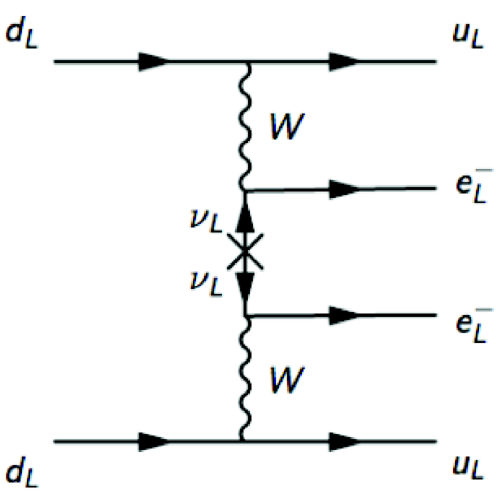
ss , $T_{1/2} > 10^{25}$ yr,

e Majorana particle
iolation ΔL=2
te ν mass scale
s.m.

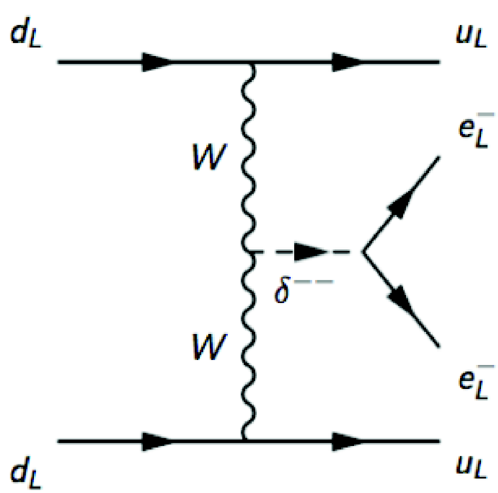
0νßß

$$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$$

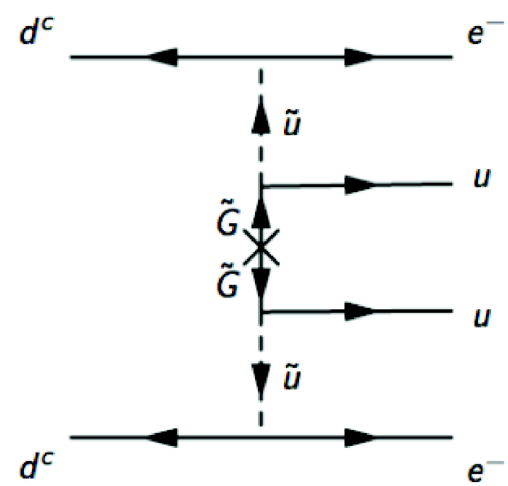
ΔL = 2



light Majorana neutrino



SM + Higgs triplet

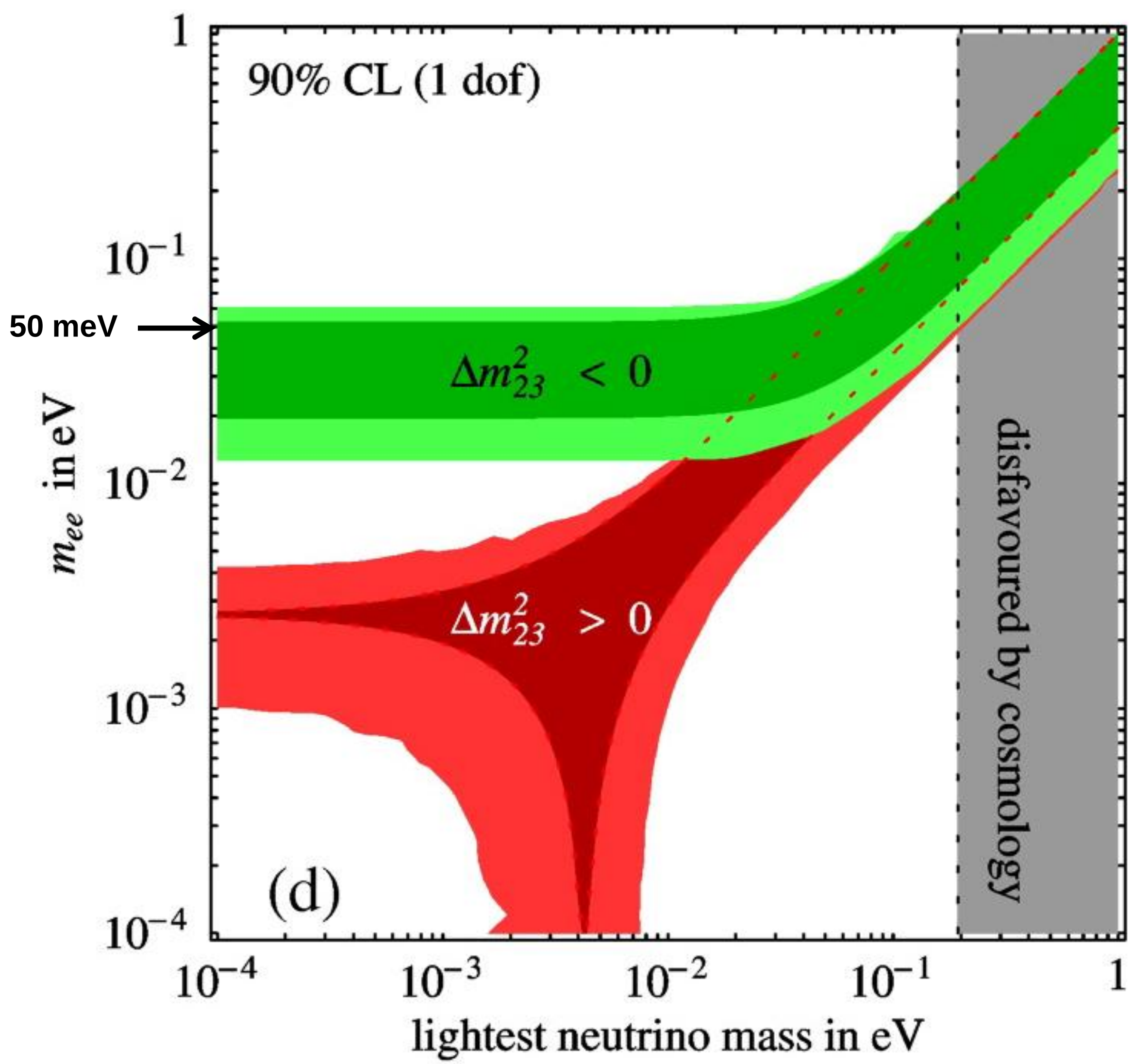


SUSY

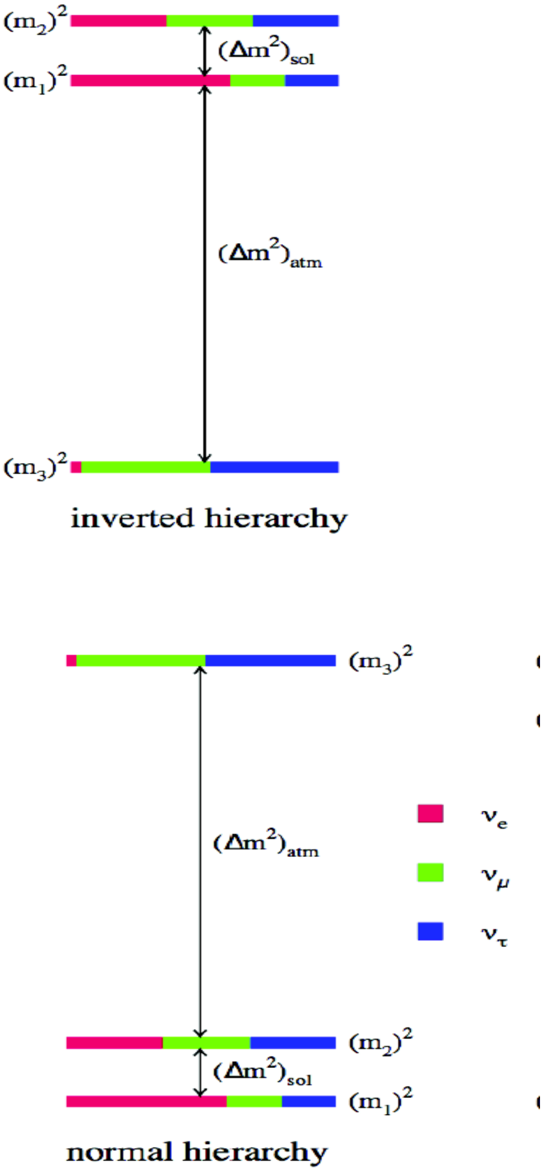
►LHC physics

see talk by J.C. Helo, Wednesday 16:15

Majorana neutrino mass range

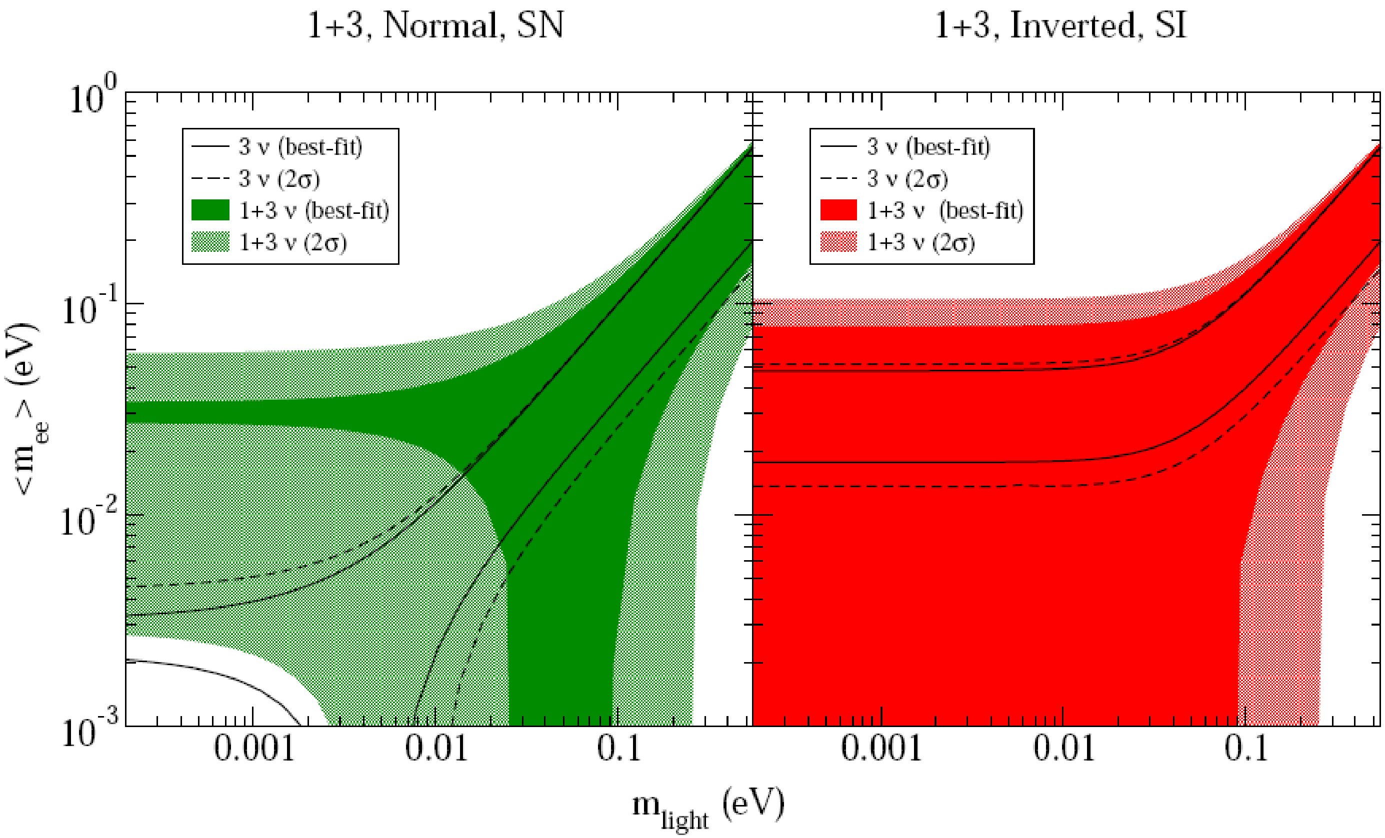


Nucl.Phys. B659 (2003) 359



Majorana neutrino mass range

Including additional sterile neutrino …



Rodejohann 2012

… no lower bounds !

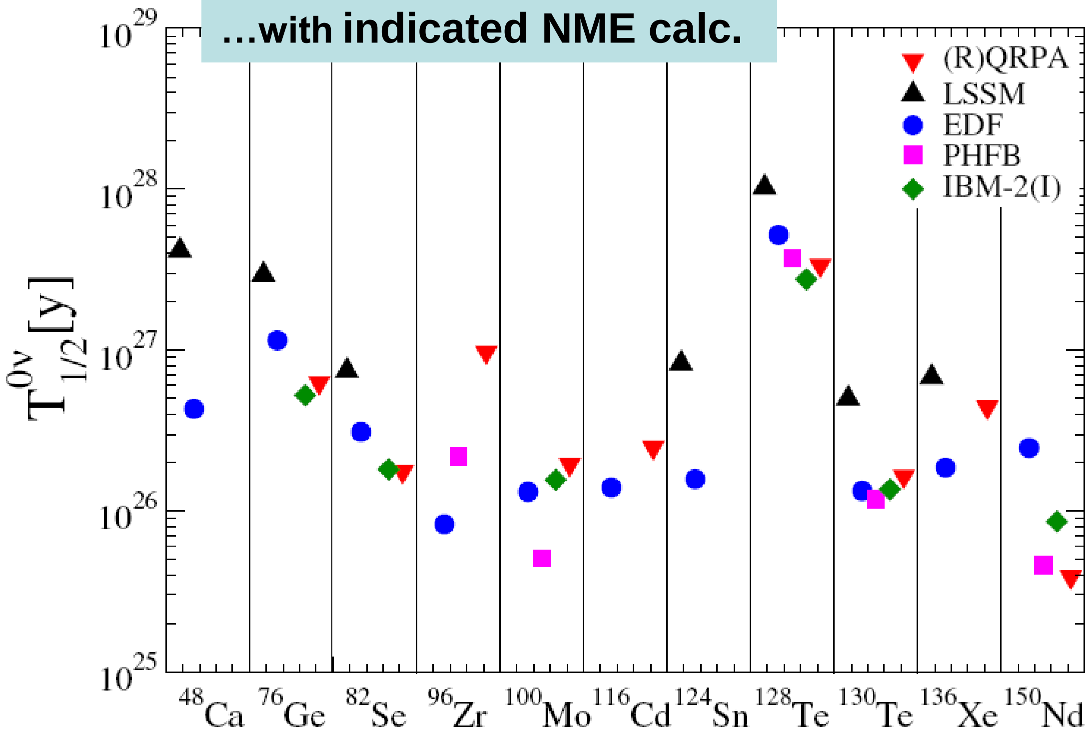
half life for light neutrino exchange

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

measured — phase space — nuclear matrix element — deduced

$T_{1/2}^{0\nu}$ theoretical predictions for $|m_{ee}|$ = 50 meV

…with indicated NME calc.



Vergados, Ejiri, Simkovic, Rep.Progr.Phys. 75 (2012) 106301

intro experimental sensitivity – to be increased!

detection efficiency (~1 if source=detector)

86%

72 kg yr
exposure [kg yr]

sensitivity*

$$T^{0\nu}_{1/2}(n_\sigma) = \frac{4.16 \times 10^{26} y}{n_\sigma} \left(\frac{\varepsilon a}{W}\right) \sqrt{\frac{Mt}{b\Delta(E)}}$$

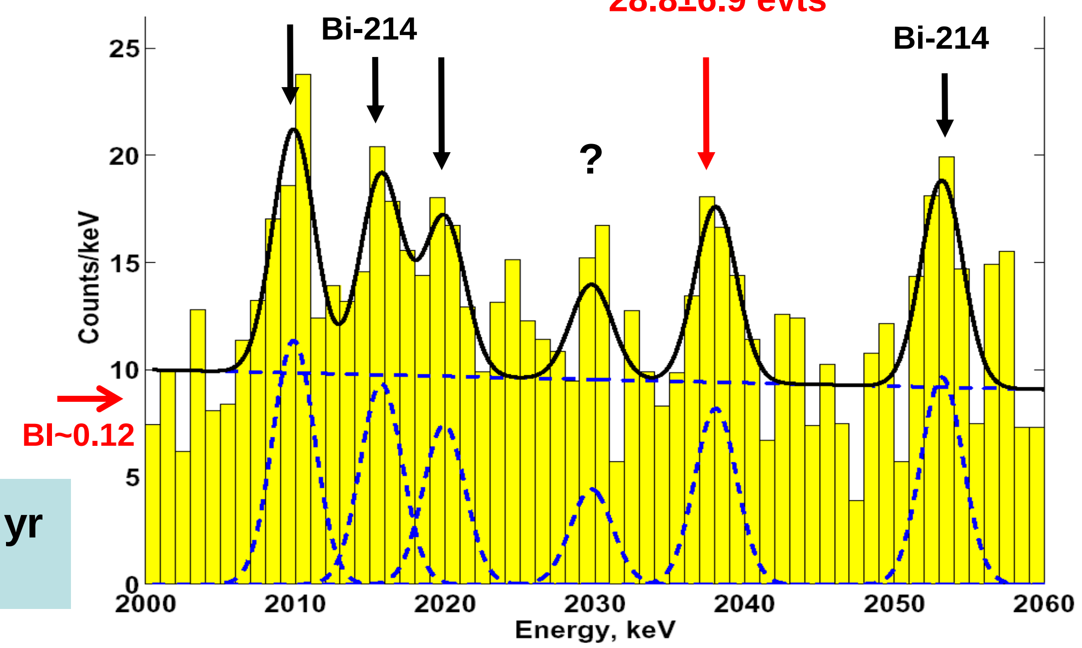
achieved with ^{76}Ge

~3.6 keV
instrumental spectral width

molecular weight
of source

► background index (BI) [cts/(keV·kg·yr)]
~0.1

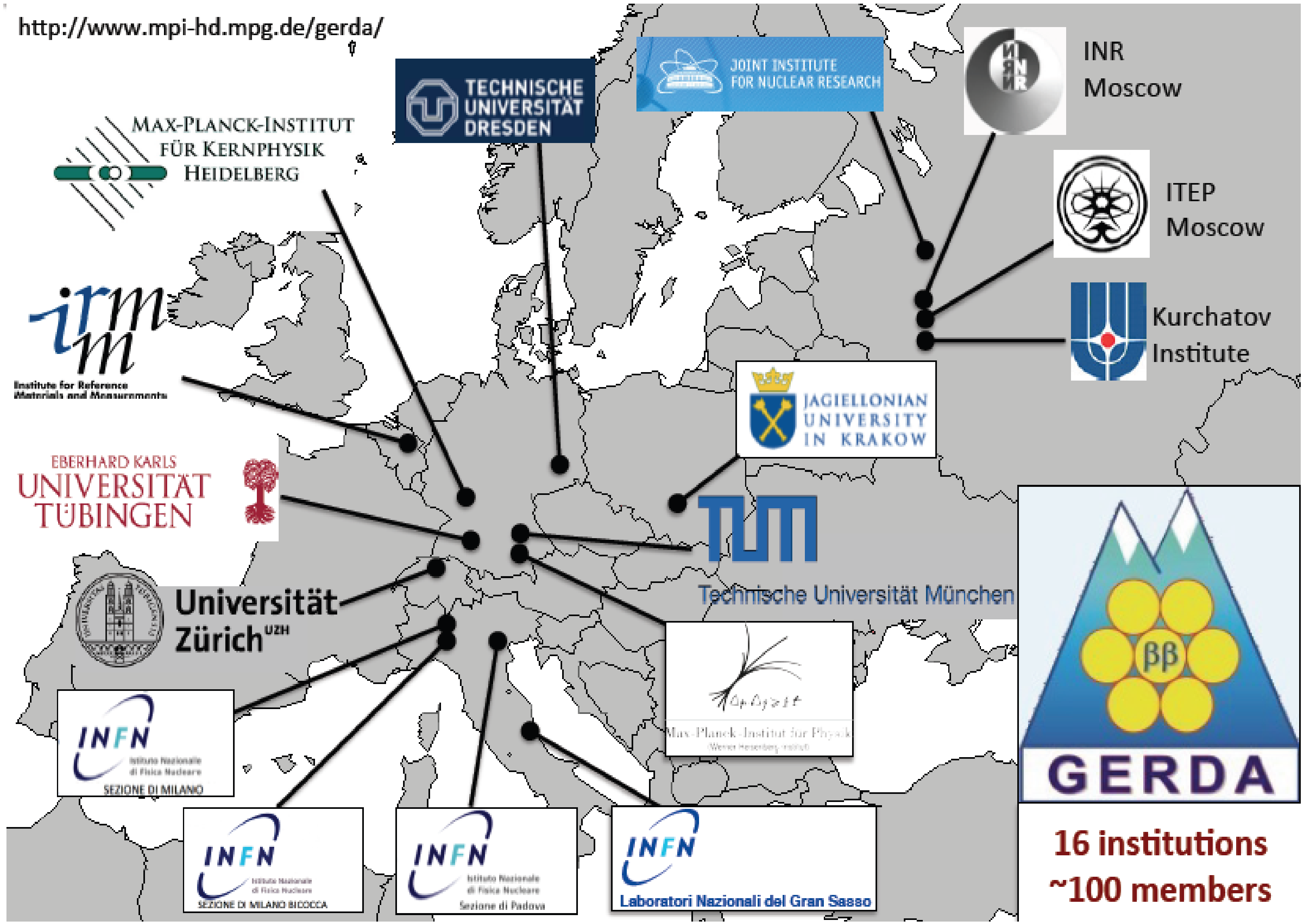
*RevModPhys 80(08)481



KKDC: 71.7 kg·yr: $T_{1/2}$ = 1.2(0.7-4.2)·10^{25} yr
$\langle m_{\beta\beta}\rangle$ = 0.44 (0.24 – 0.58) eV (3σ)

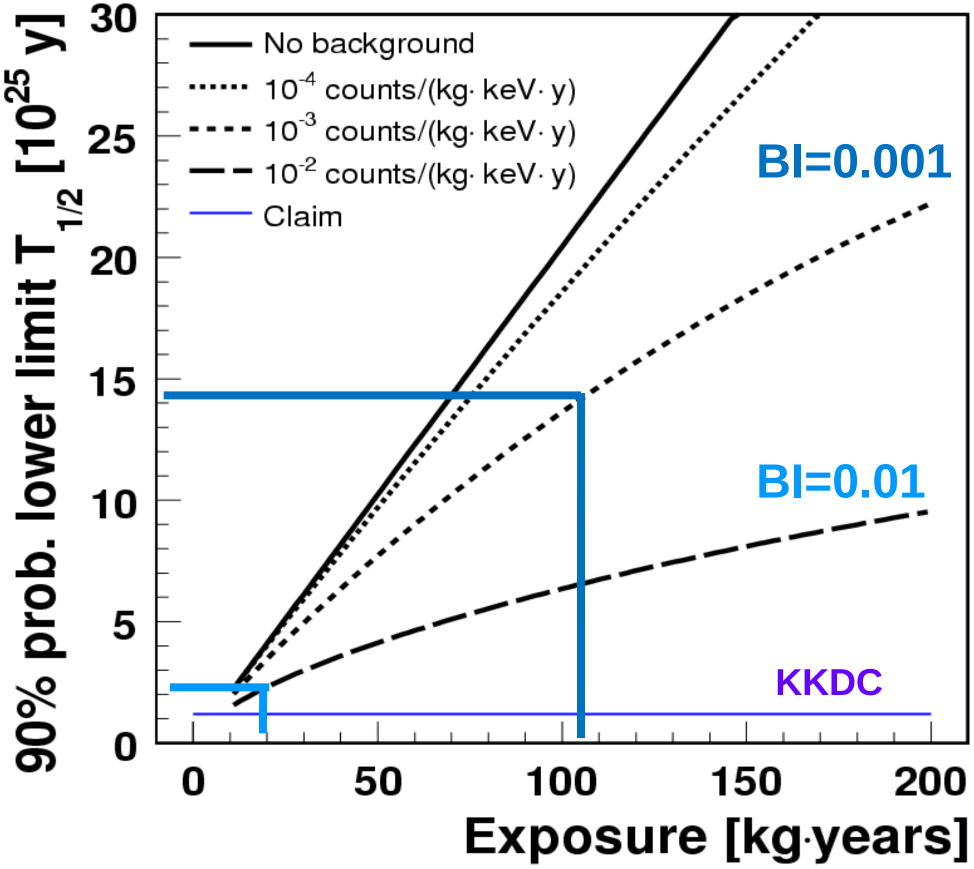
Phys Lett B586 (2004) 198

GERDA collaboration



GERDA goals

Reach background index (BI) at $Q_{\beta\beta}$ = 2039 keV of 0.01 / 0.001 cts / (keV·kg·yr) !



Phase II :

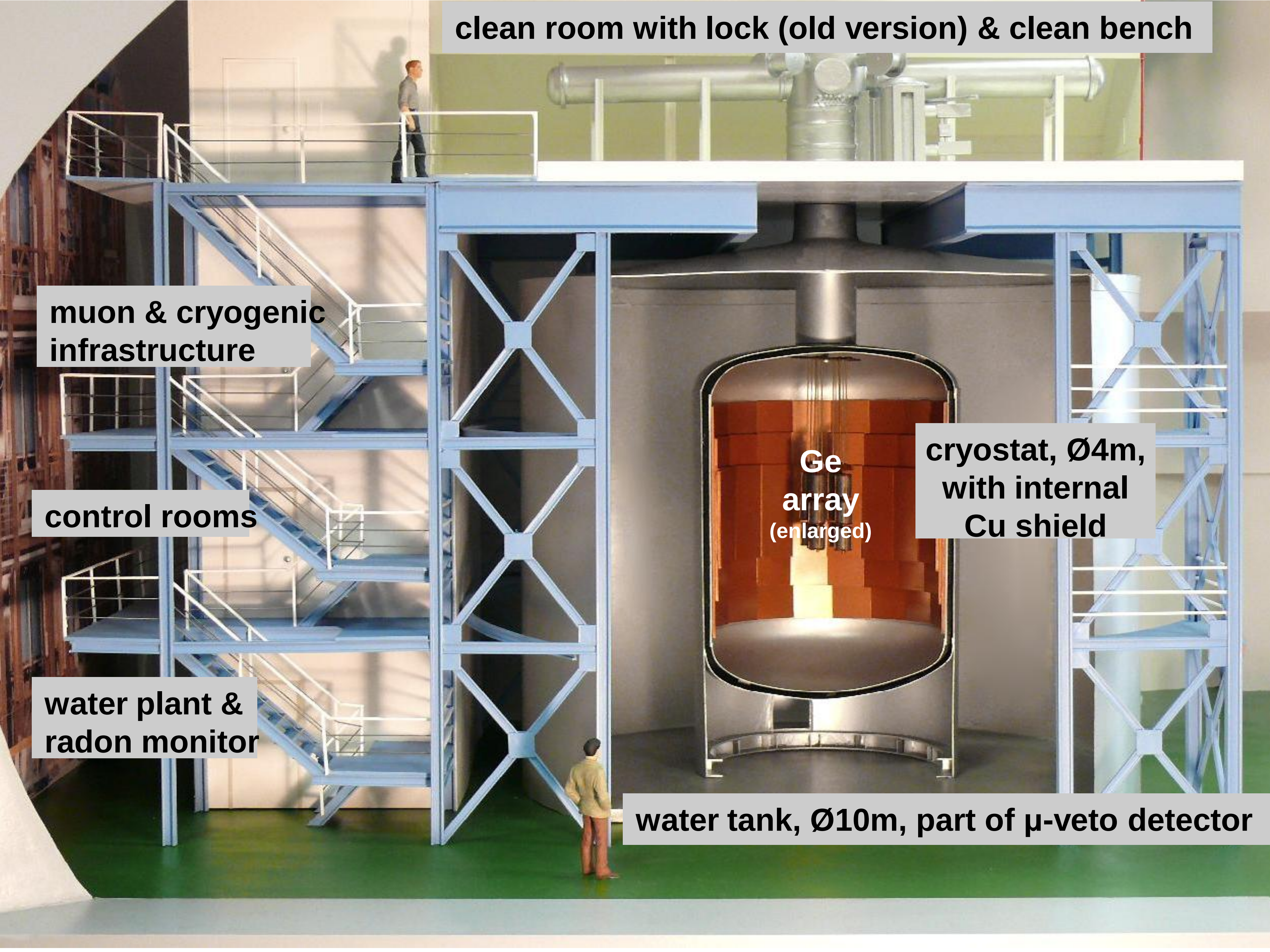
Phase I :

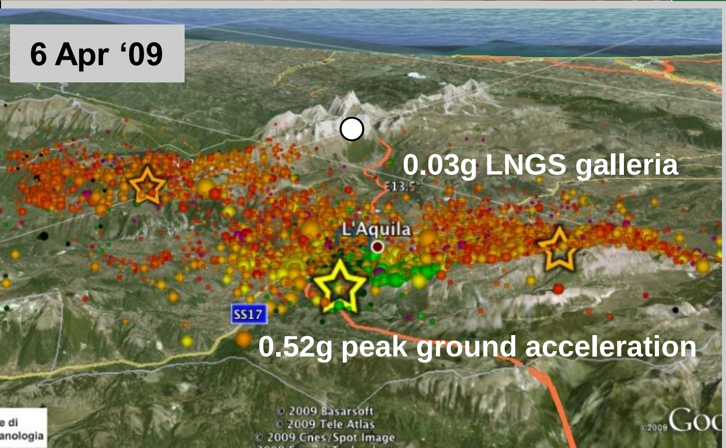
Phase III: depending on results worldwide collaboration for real big experiment
close contacts & MoU with MAJORANA collaboration

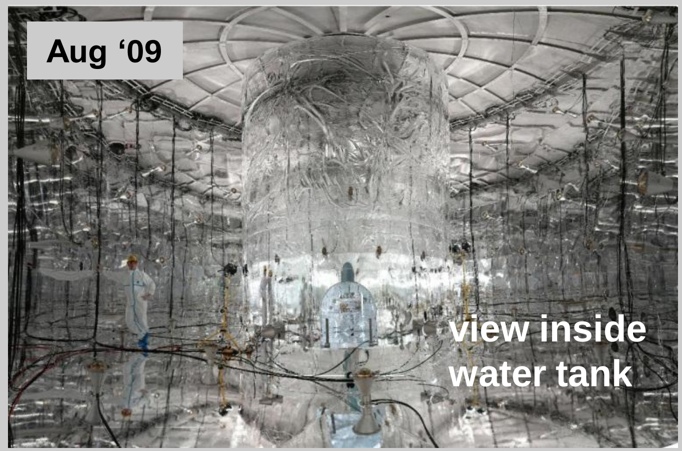
GERDA strategy:

underground site to suppress cosmics
improved shield, passive & active, against background radiation
discrimination between single- (0νββ) & multi-site events

LNGS: Laboratori Nazionali del Gran Sasso


clean room with lock (old version) & clean bench
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
Ge array (enlarged)
cryostat, Ø4m, with internal Cu shield
water tank, Ø10m, part of μ-veto detector





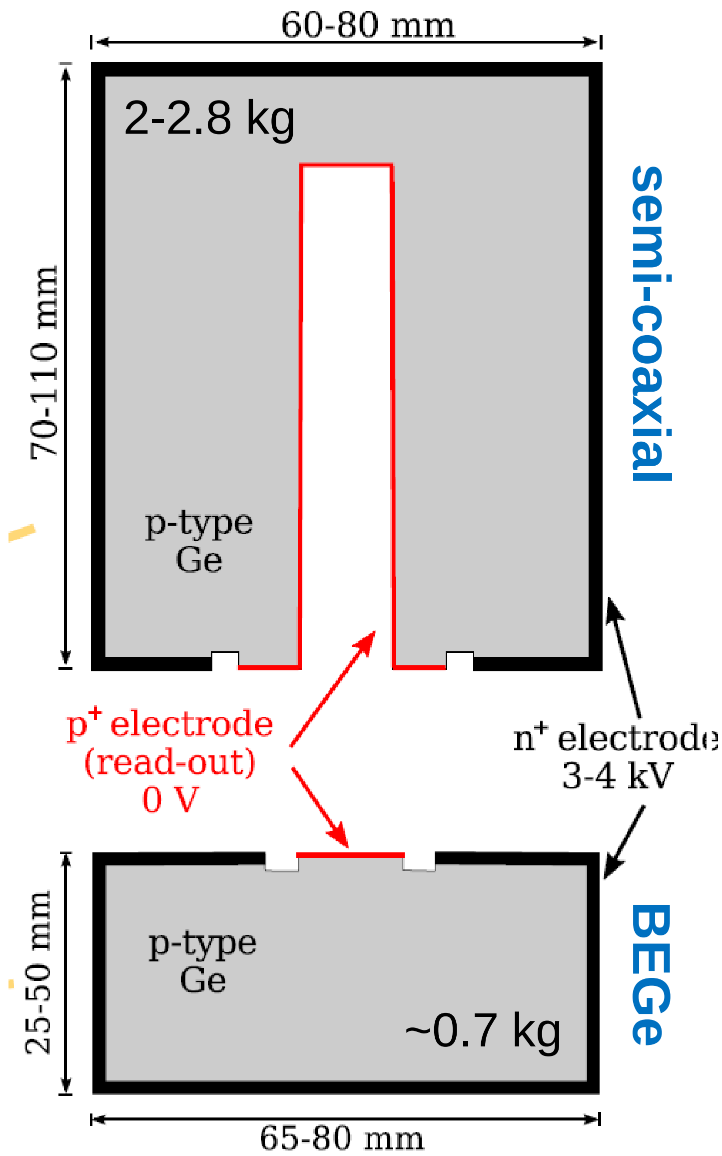
Cryostat filled since December 2009

Phase I detectors

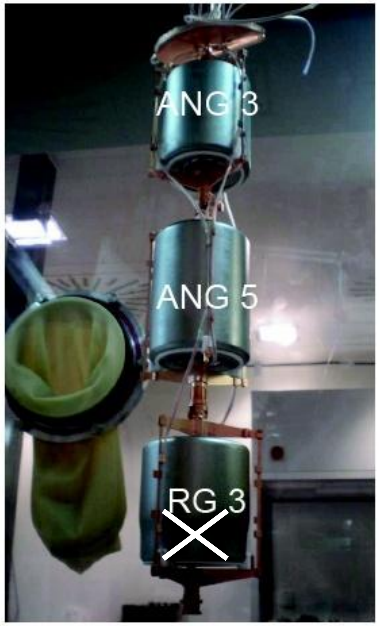
Refurbished semi-coaxial detectors from HdM & IGEX experiments

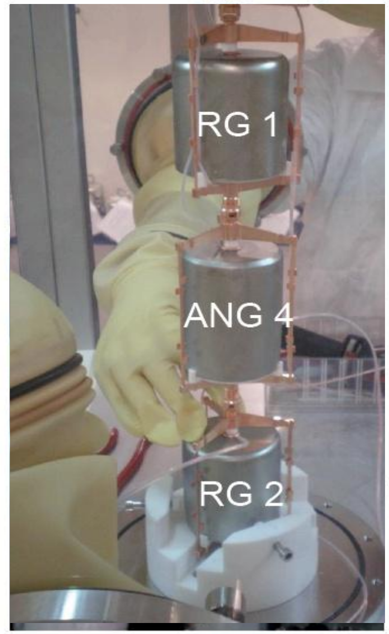
n+ conductive Li layer, separated by a groove from the boron implanted p+ contact

Phase II detector type, already used: BEGe – broad energy Ge detector ‚point-contact' detector with improved pulse shape discrimination power



Phase I the 4 detectors strings





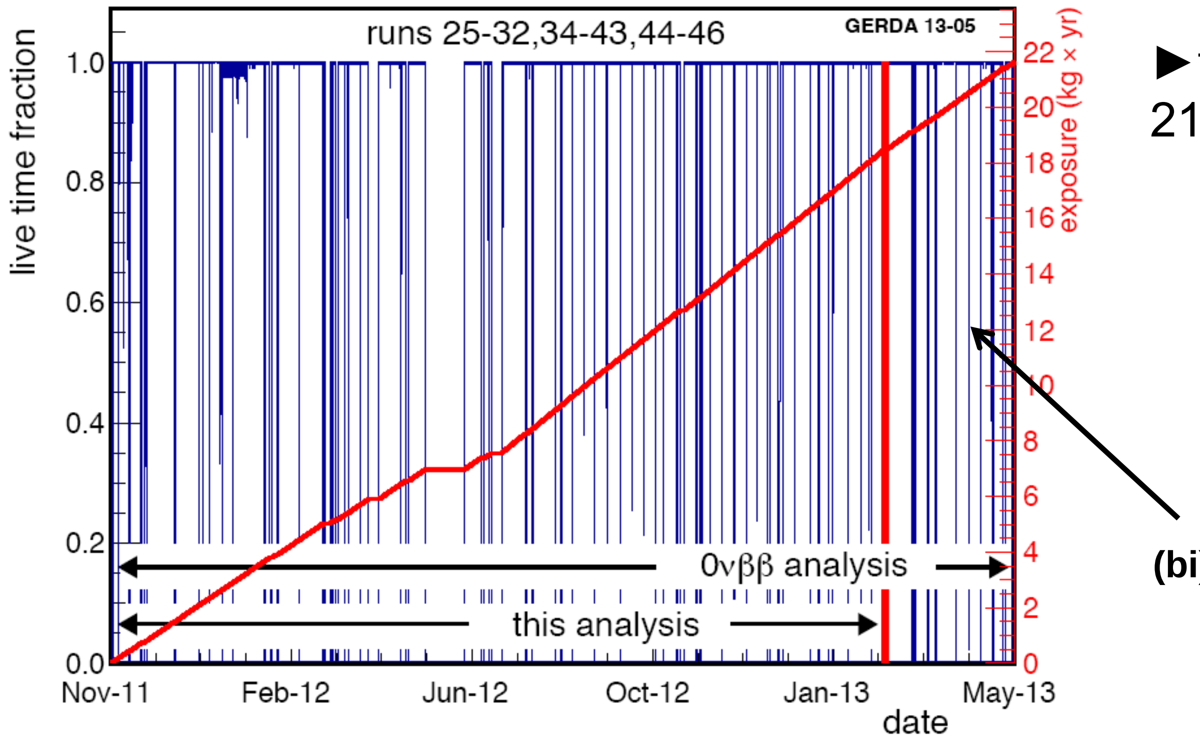
used in analysis:

since Nov 11: 6 enriched semi-coaxial : ANG2,3,4,5, RG1,2 14.63 kg
1 natural semi-coaxial: GTF112 2.96 kg

since Jul 12: 4 enriched BEGe : GD32B,C,D, GD35B 3.00 kg

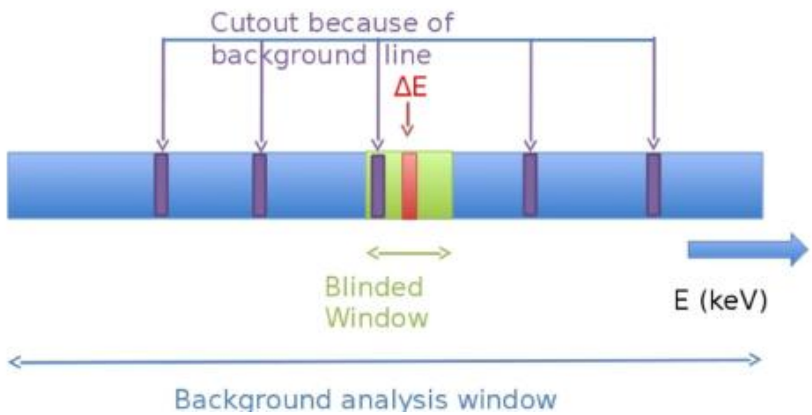
enrichment of Ge-76: 86%-87%

Phase I physics runs



► total exposure: 21.6 kg·yr

spikes indicating (bi)weekly calibration



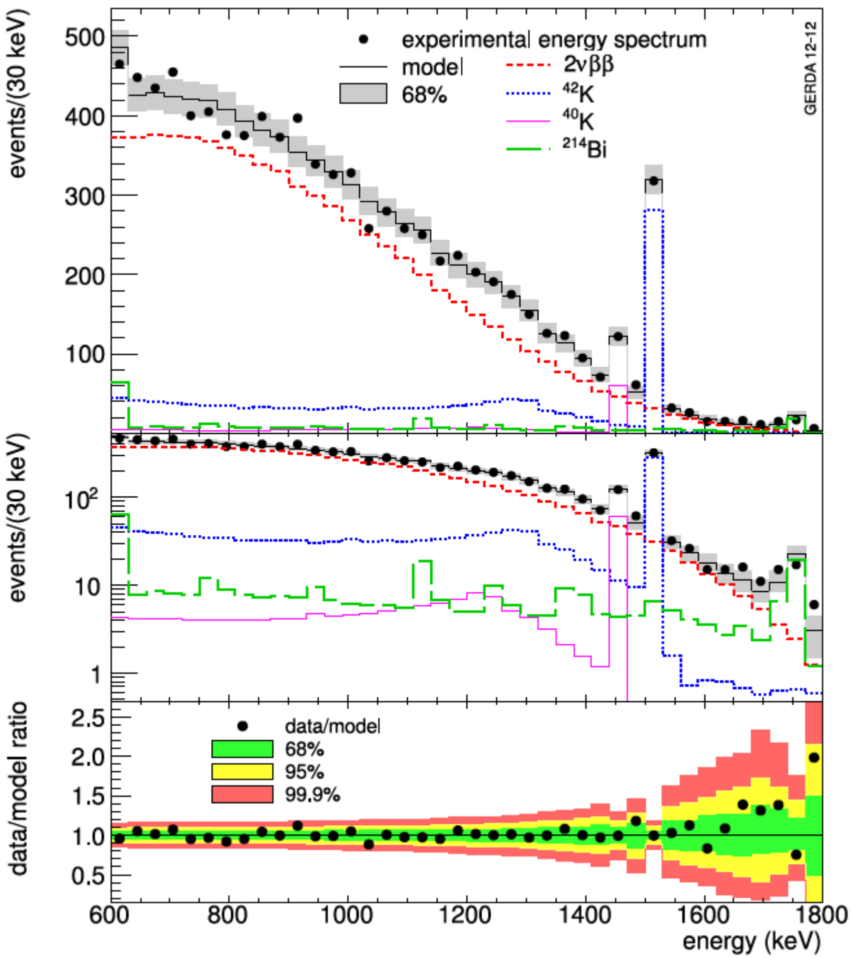
► blind analysis

Phase I

the 2νßß result

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

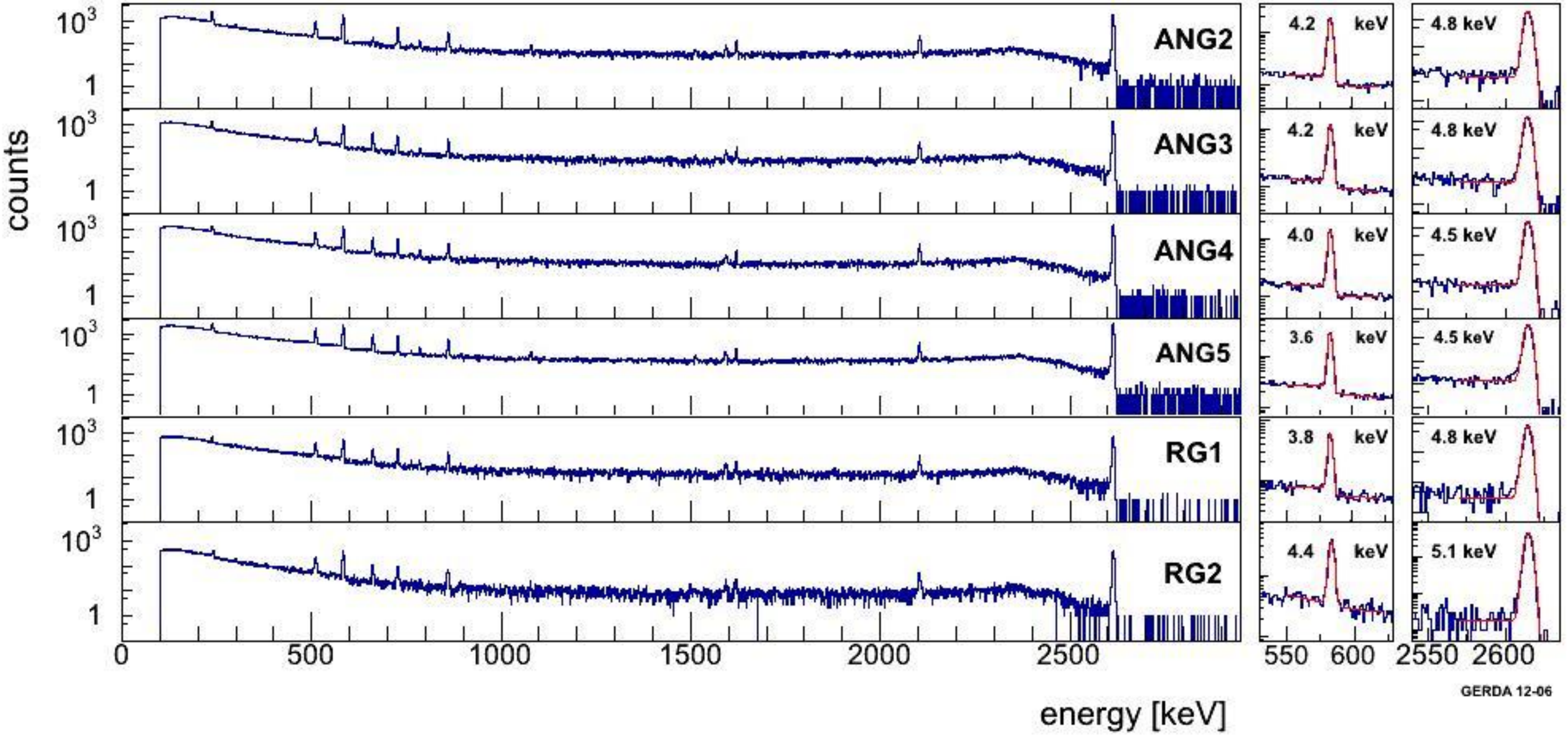


$$T^{2\nu}_{1/2} = (1.84\,^{+0.14}_{-0.10})\cdot 10^{21}\ \text{yr}$$

YET: 2νββ decays dominant yield between 600 keV and 1400 MeV!

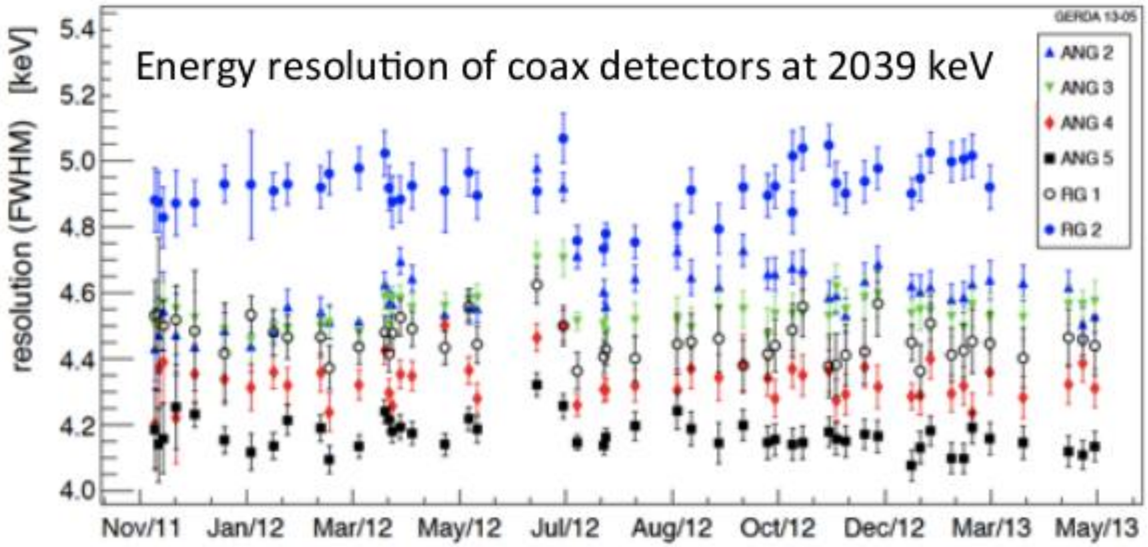
Item	Uncertainty on $T^{2\nu}_{1/2}$ (%)	
Non-identified background components	+5.3	
Energy spectra from ^{42}K, ^{40}K and ^{214}Bi	±2.1	
Shape of the $2\nu\beta\beta$ decay spectrum	±1	
Subtotal fit model		$^{+5.8}_{-2.3}$
Precision of the Monte Carlo geometry model	±1	
Accuracy of the Monte Carlo tracking	±2	
Subtotal Monte Carlo		±2.2
Data acquisition and selection		±0.5
Grand total		$^{+6.2}_{-3.3}$

Phase I   Th-228 calibration spectra

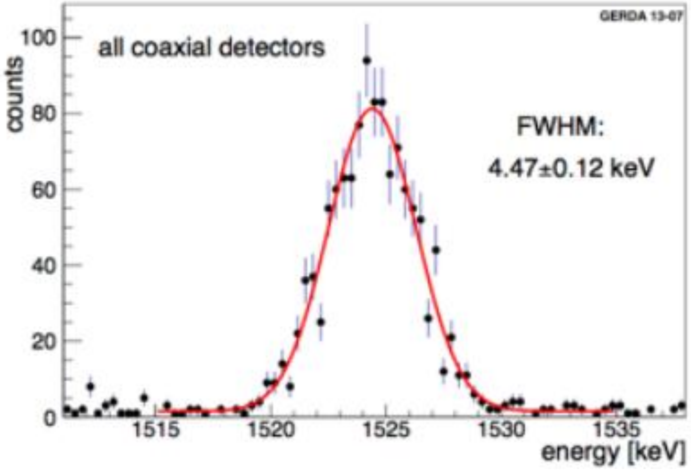


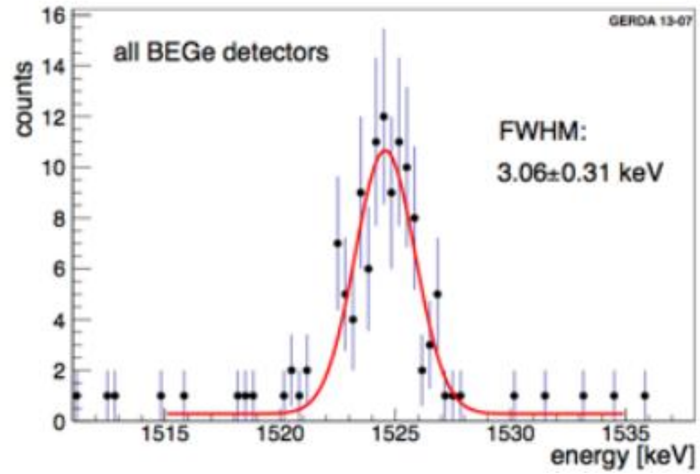
Phase I

stability

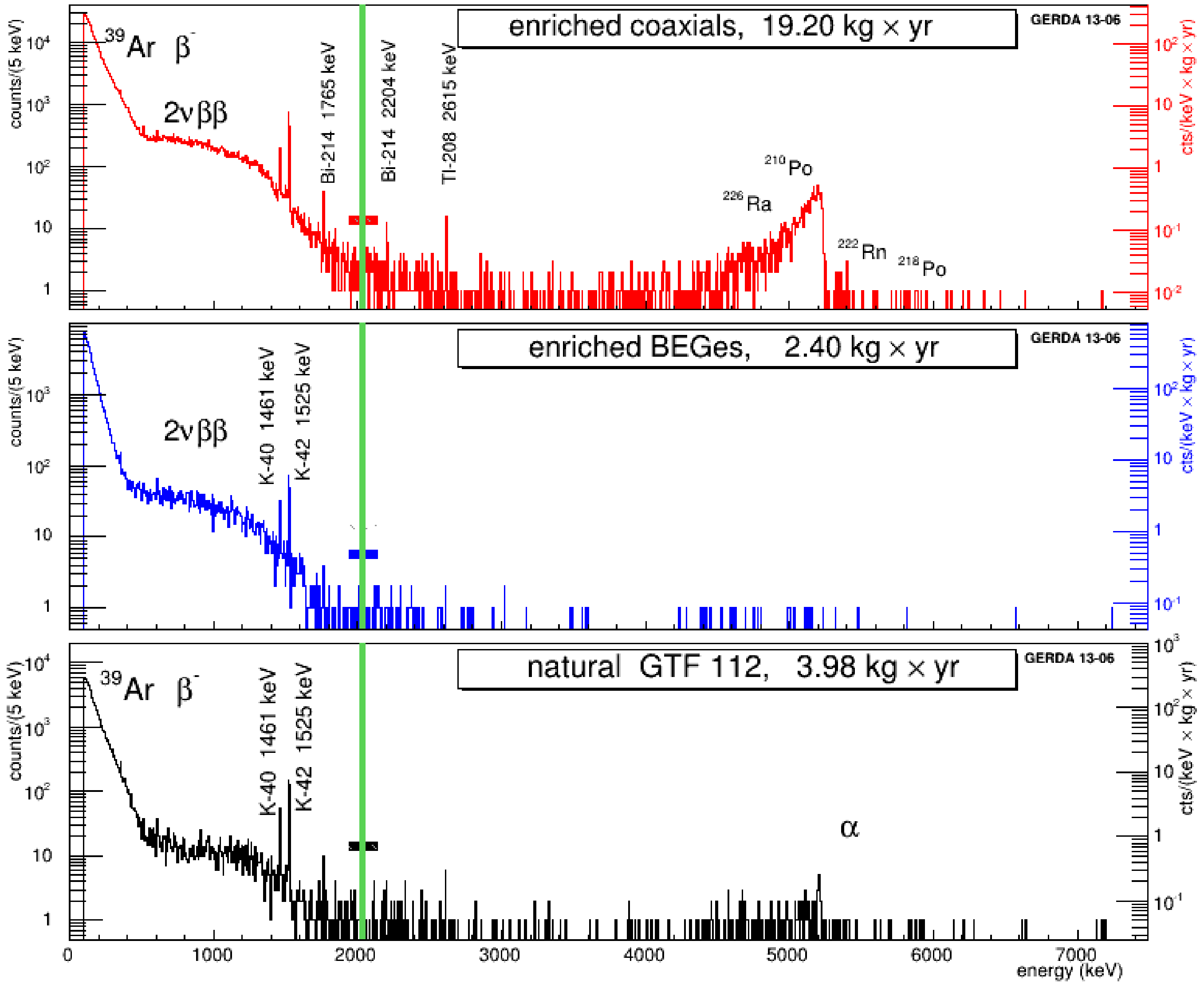


K-42 background line





Phase I measured spectra



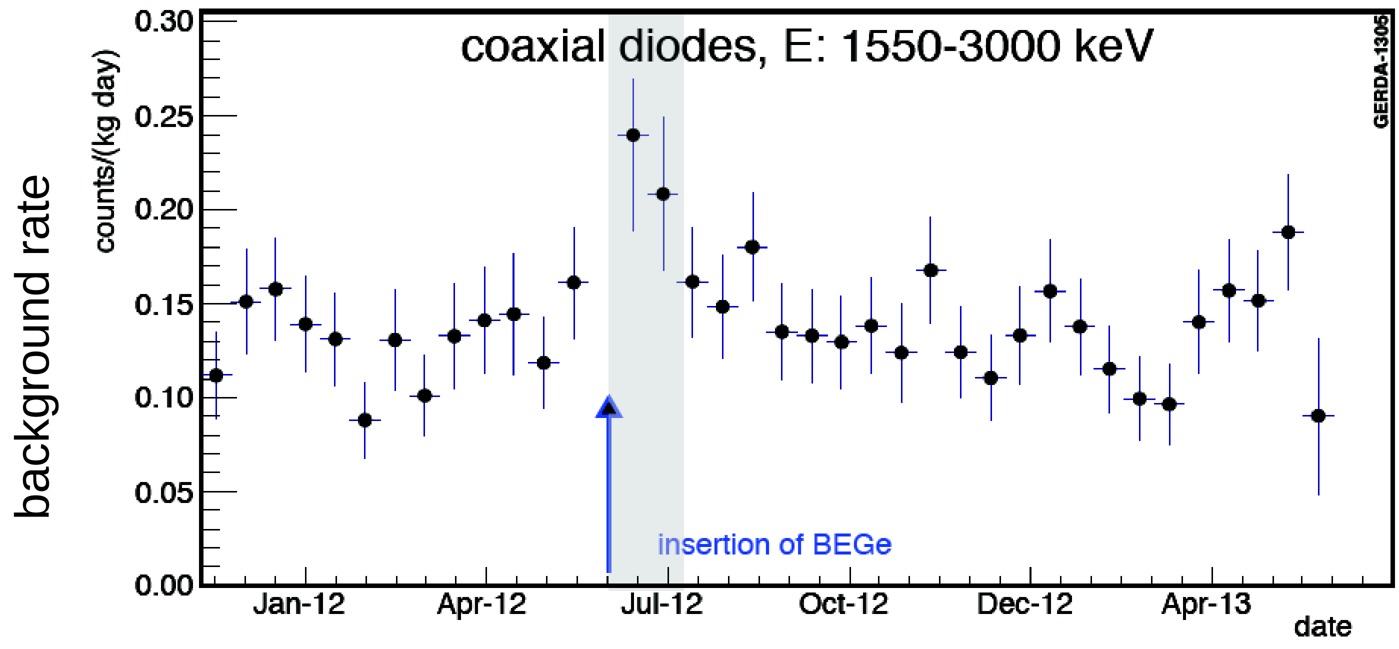
muon veto & Ge-Ge anti-coincidences applied

Blinded region of ($Q_{\beta\beta}$ ± 20) keV

Visible backgrounds:
- **Ar-39**
- **Alphas**
- **Indicated isotopes**
  - ► **K-42 at 1525 keV**
- **2v2β decay of Ge-76**

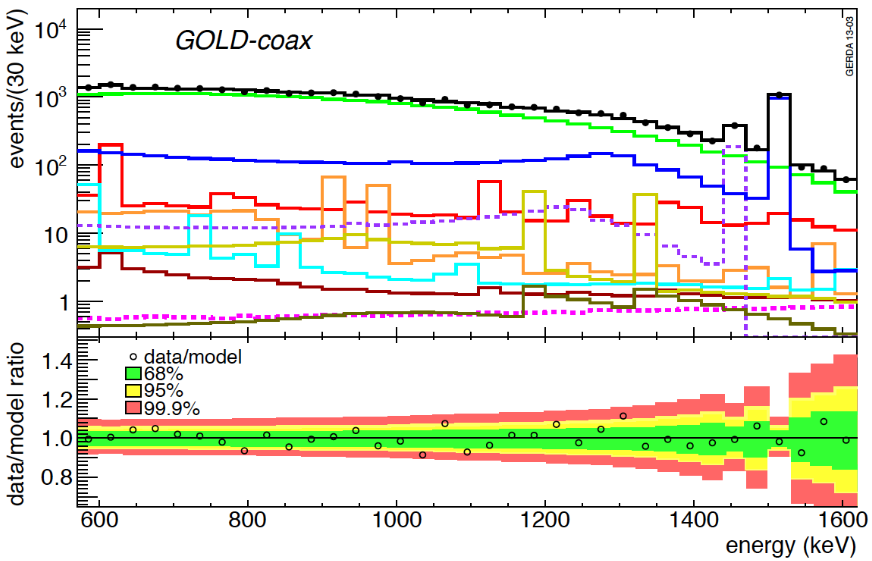
Phase I

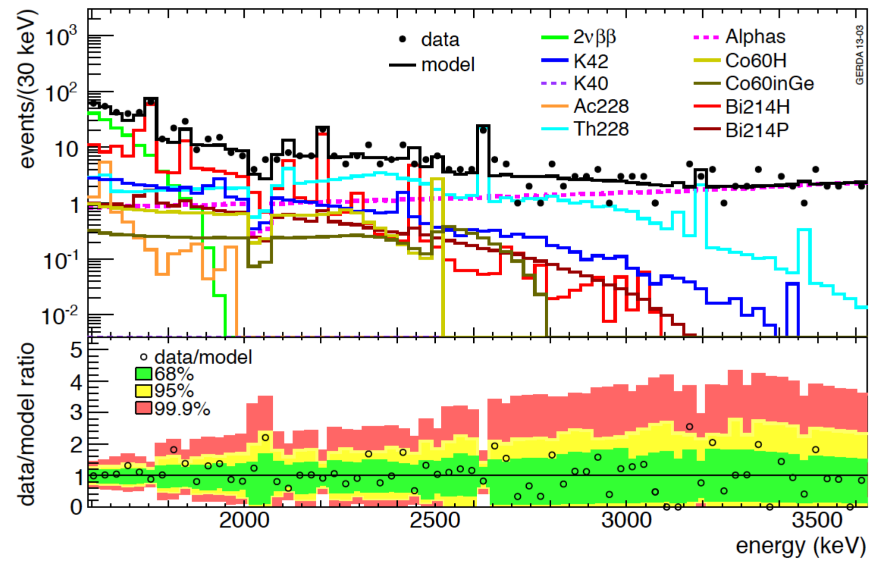
the 3 data sets



data set	detectors	exposure $\mathcal{E}$ this analysis	exposure $\mathcal{E}$ $0\nu\beta\beta$ analysis
		kg·yr	
SUM-coax	all enriched coaxial	16.70	19.20
GOLD-coax	all enriched coaxial	15.40	17.90
SILVER-coax	all enriched coaxial	1.30	1.30
GOLD-nat	GTF 112	3.13	3.98
GOLD-hdm	ANG 2, ANG 3, ANG 4, ANG 5	10.90	12.98
GOLD-igex	RG 1, RG 2	4.50	4.93
SUM-bege	GD32B, GD32C, GD32D, GD35B	1.80	2.40

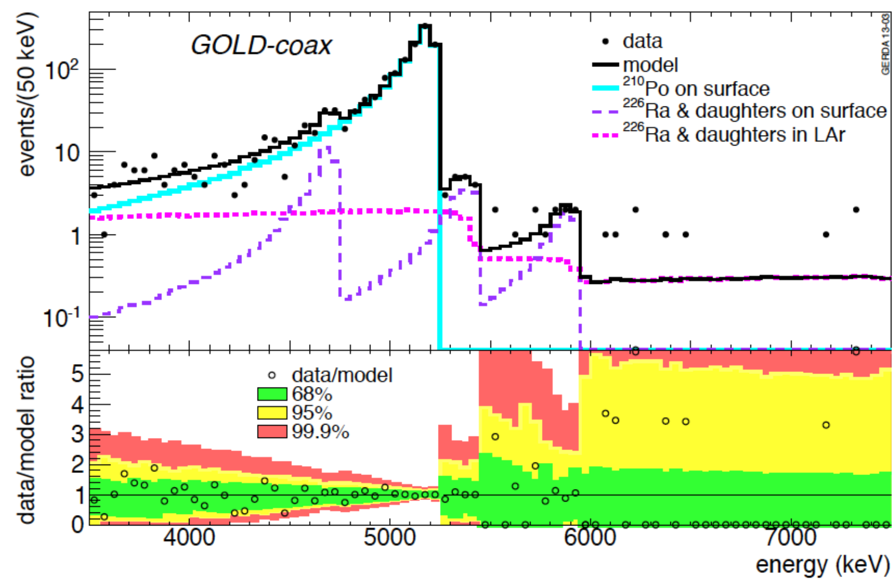
Phase I background model





fit of combination of MC spectra
to data between 570 keV & 7500 keV

► good fits, however not unique;
► close background sources dominate:
Ar-42, Th228, Ra-226 in holders,
α particles on detector surfaces.



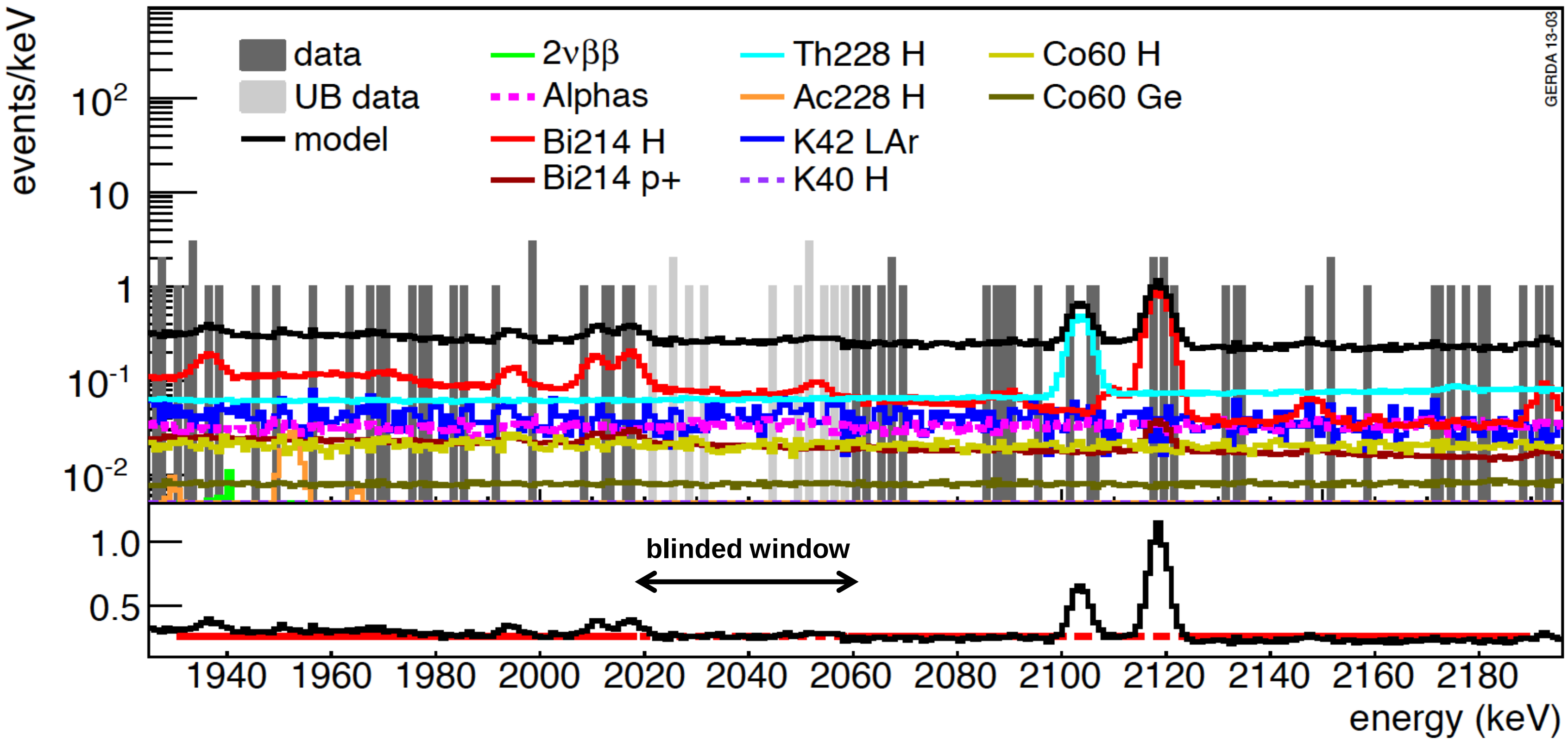
arXiv:81306.5084v1 (21 Jun 2013)
EPJC, in print

background model

source	location	units	*GOLD-coax* minimum	*GOLD-coax* maximum	*GOLD-nat* minimum
^{40}K [c])	det. assembly	μBq/det.	152[136,174]	151[136,174]	218[188,259]
^{42}K [c])	LAr	μBq/kg	106[103,111]	91[72,99]	98.3[92,108]
^{42}K [c])	p^+ surface	μBq		11.6[3.1,18,3]	
^{42}K [c])	n^+ surface	μBq		4.1[1,2,8.5]	
^{60}Co [c])	det. assembly	μBq/det.	4.9[3.1,7.3]	3.2[1.6,5.6]	2.6[0,6.0]
^{60}Co [c])	germanium	μBq	>0.4 [†])	>0.2 [†])	6[3.0,8.4]
^{214}Bi [c])	det. assembly	μBq/det.	35[31,39]	15[3.7,21.1]	34.1[27.3,42.1]
^{214}Bi [c])	LAr close to p^+	μBq/kg		<299.5	
^{214}Bi [m])	radon shroud	mBq		<49.9	
^{214}Bi [c])	p^+ surface	μBq	2.9[2.3,3.9] [†])	3.0[2.1,4.0] [†])	1.6[1.2,2.1] [†])
^{228}Th [c])	det. assembly	μBq/det.	15.1[12.7,18.3]	5.5[1.8,8.8]	15.7[10.0,25.0]
^{228}Ac [c])	det. assembly	μBq/det.	17.8[10.0,26.8]	<15.7	25.9[16.7,36.7]
^{228}Th [m])	radon shroud	mBq		<10.1	
^{228}Ac [m])	radon shroud	mBq		91.5[27,97]	
^{228}Th [f])	heat exchanger	Bq		<4.1	

arXiv:81306.5084v1 (21 Jun 2013)
EPJC, in print

Phase I background model



- background flat between 1930 keV – 2190 keV w/o 2104 keV & 2119 keV peaks, expect <<1 event in other weak Bi-214 lines
- no line expected in the blinded window

► linear fit with flat background excluding 2104±5 keV and 2119±5 keV peak regions

arXiv:81306.5084v1 (21 Jun 2013)
EPJC, in print

Phase I pulse shape discrimination

Exploits different pulse structure of

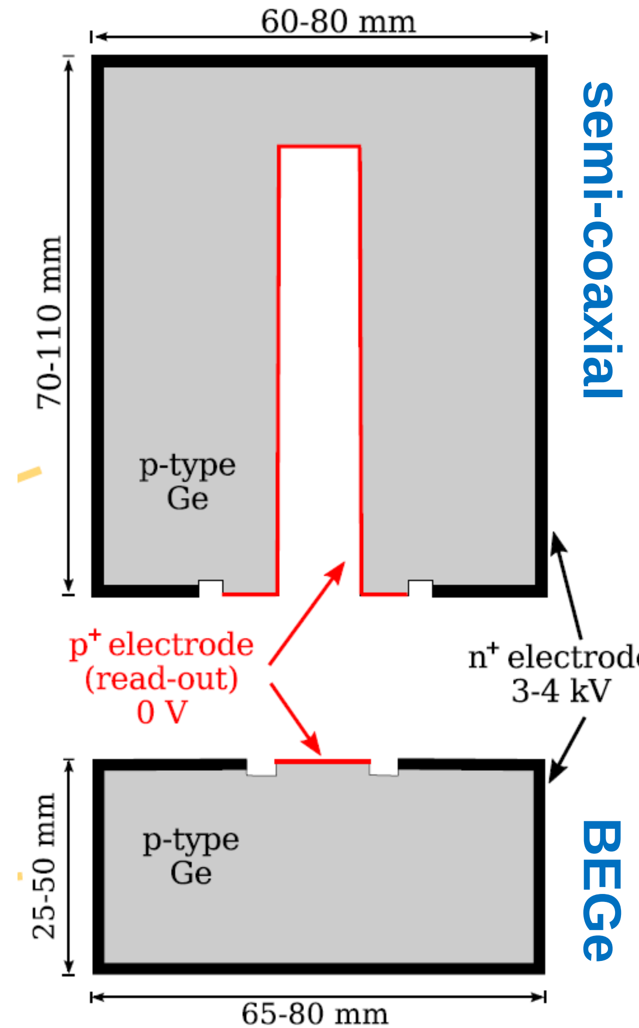
- single-site events (SSE)
- multi-site events (MSE).

0νββ events are SSE
(1 MeV electron has range of ~1mm)

Compton scatted MeV γ's more than 10x larger range ► MSE

Surface events: only electrons or holes drift ► characteristic pulse shape

weighting potential Φ



Eur.Phys.J. C73 (2013) 2583

Phase I pulse shape discrimination

Exploits different pulse structure of
- single-site events (SSE)
- multi-site events (MSE).

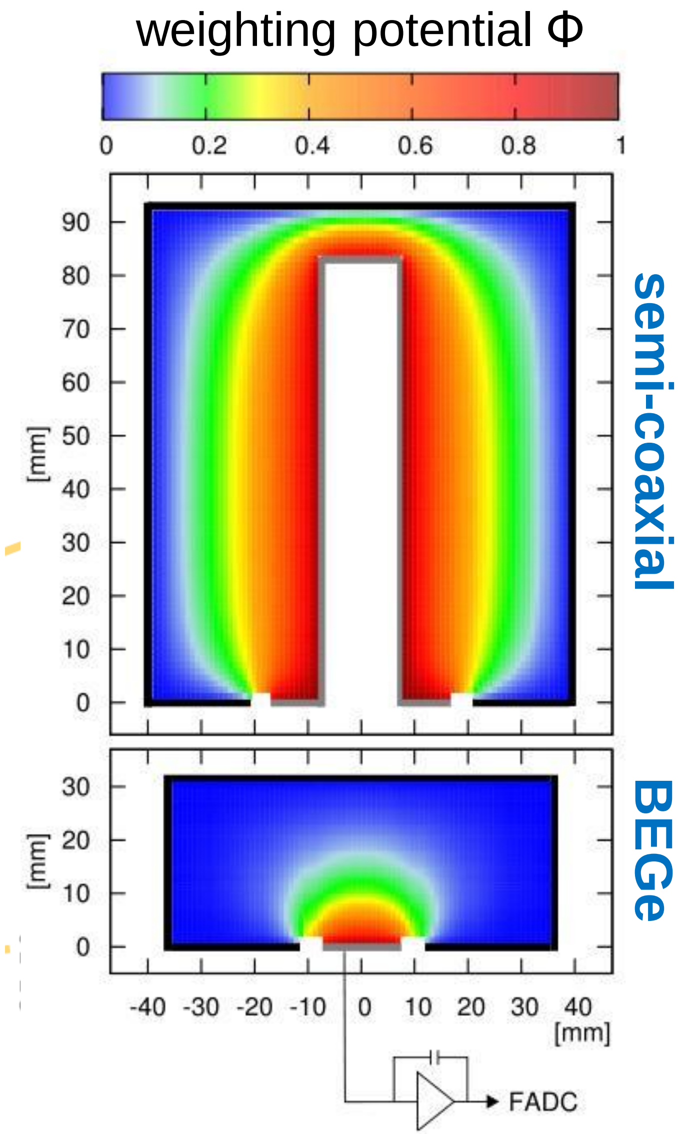
0νββ events are SSE
(1 MeV electron has range of ~1mm)

Compton scatted MeV γ's more than
10x larger range ► MSE

Surface events: only electrons or holes
drift ► characteristic pulse shape

Coaxial and BEGe diodes have very different
E-fields ► different PSD properties & algorithms,

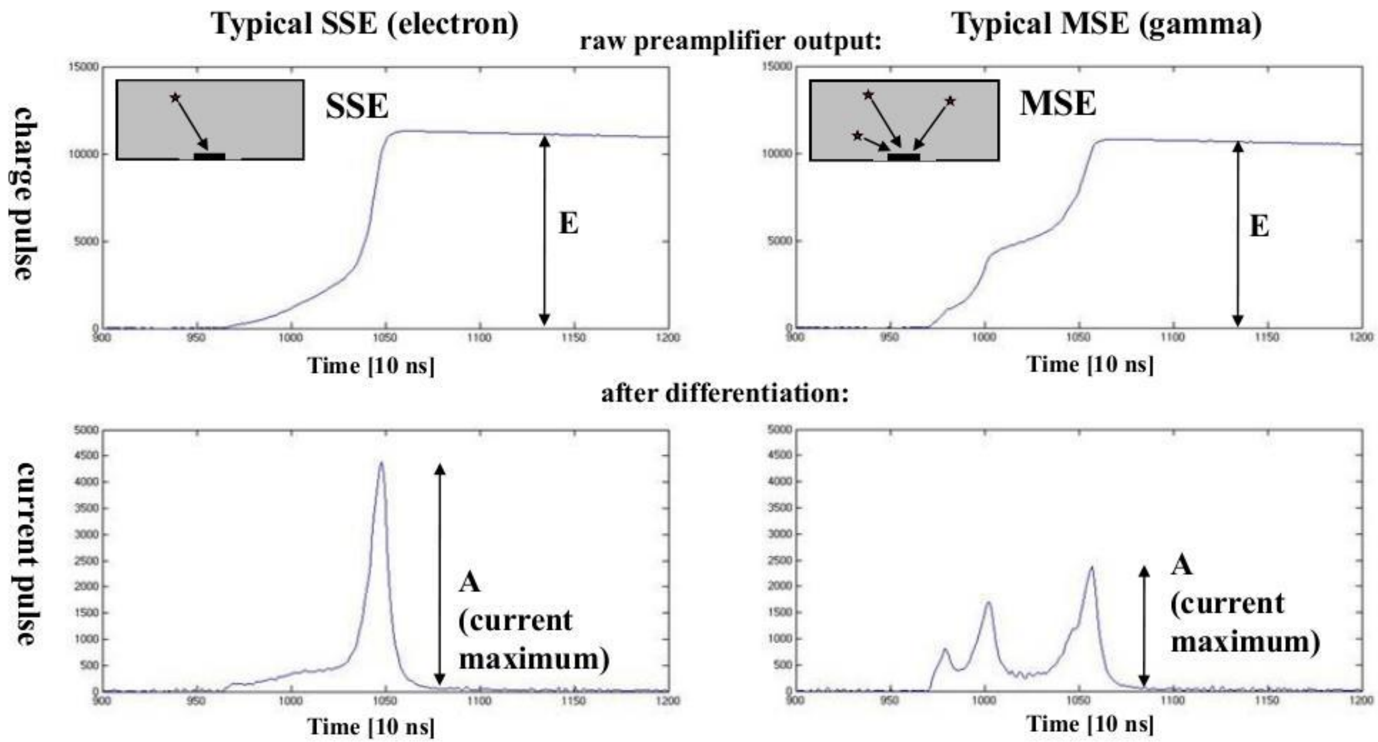
PSD developed with calibration & physics data:
double escape peak proxy for 0νββ, Compton edge,
2νββ spectrum (signal-like), FEP (bgnd-like).



Eur.Phys.J. C73 (2013) 2583

Phase I pulse shape discrimination

BEGe



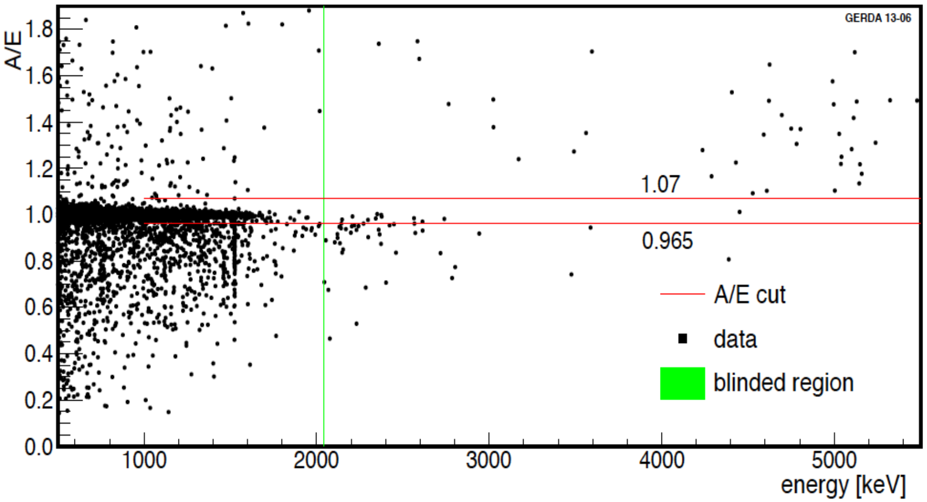
A/E ≡ 1 A/E < 1

A / E cut is robust, simple and well understood.

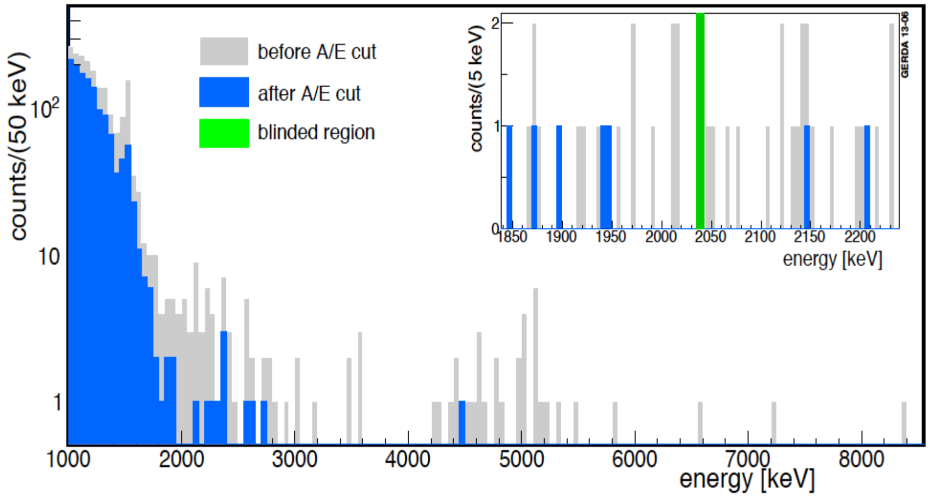
Phase I pulse shape discrimination

BEGe

A/E vs E for physics data



spectrum before & after cut



SSE accepted for 0.965 < A/E < 1.07

0νββ efficiency = 92 ± 2 % (from DEP efficiency & simulation)

2νββ efficiency = 91 ± 5 % (good agreement with DEP eff.

80% of background events rejected

Eur.Phys.J. C73 (2013) 2583

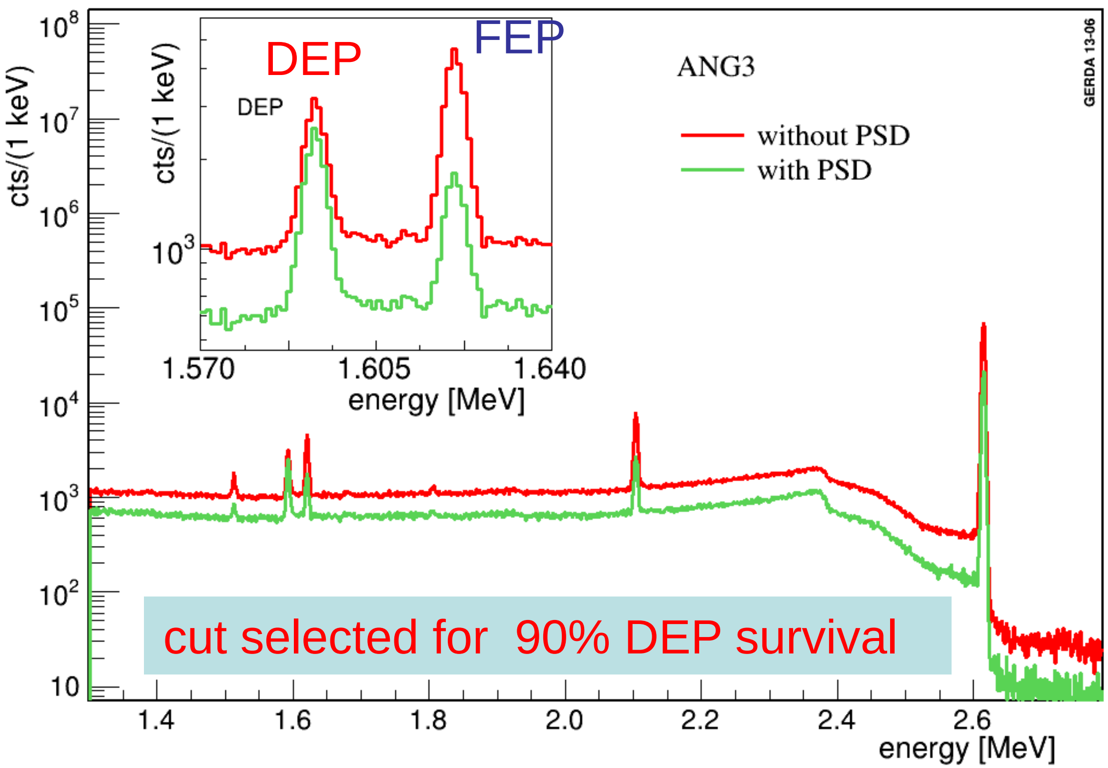
Phase I pulse shape discrimination

semi-coaxial:

artificial neural network (ANN) : TMIpANN implemented in TMVA

Input: time when charge signal reaches 1%, 3%, …, 99% of maximum amplitude

Th-228 calibration data



Cross checks:

2νββ eff = 85 ± 2 %

2.6 MeV γ Compton edge eff. = 85 – 94 %

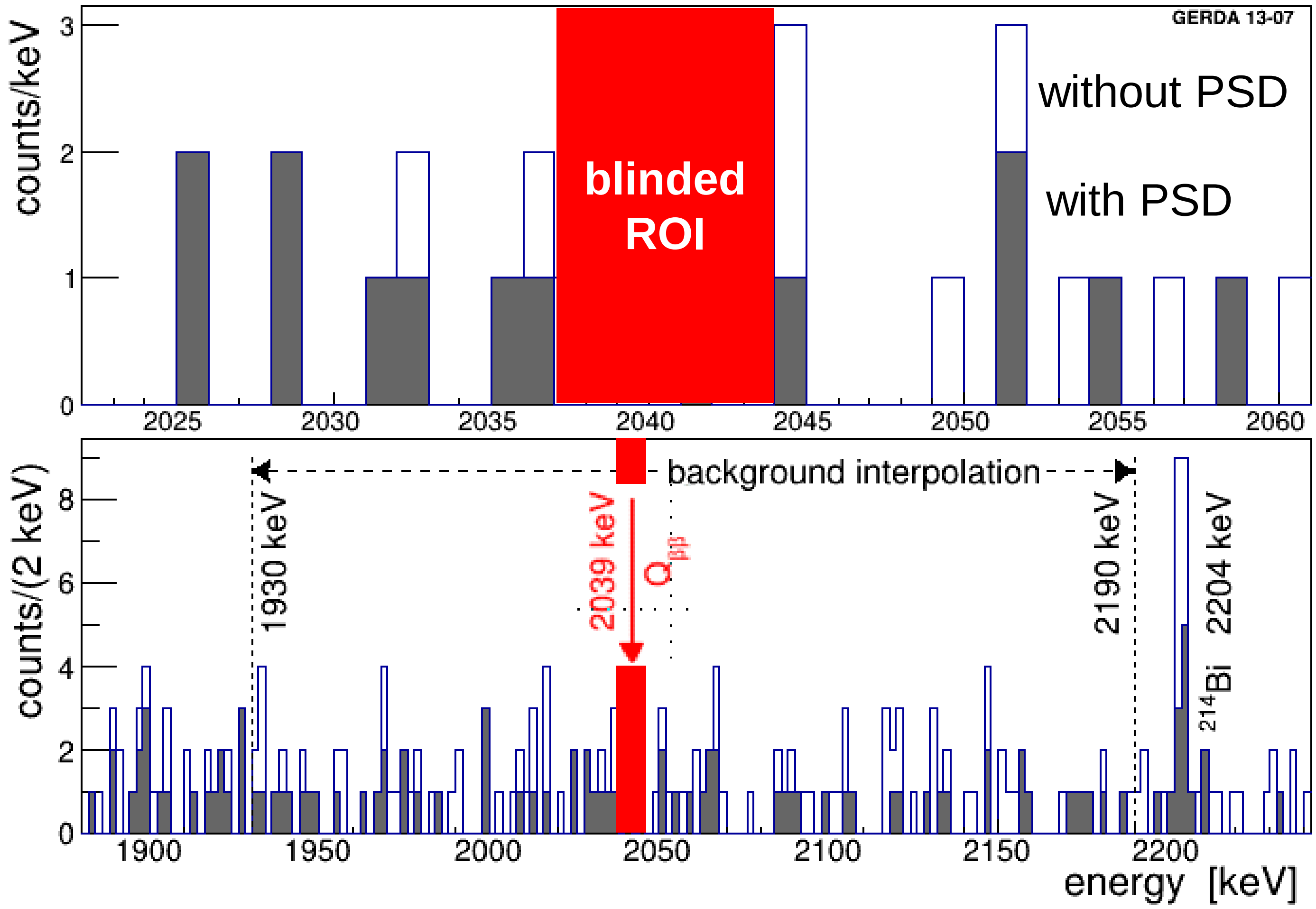
Co-56 DEP (1576 & 2231 keV) eff. = 83% - 93%

0νββ efficiency = $0.9^{+0.05}_{-0.09}$

ANN checked with 2 other methods: OK!

Eur.Phys.J. C73 (2013) 2583

the 0νββ result

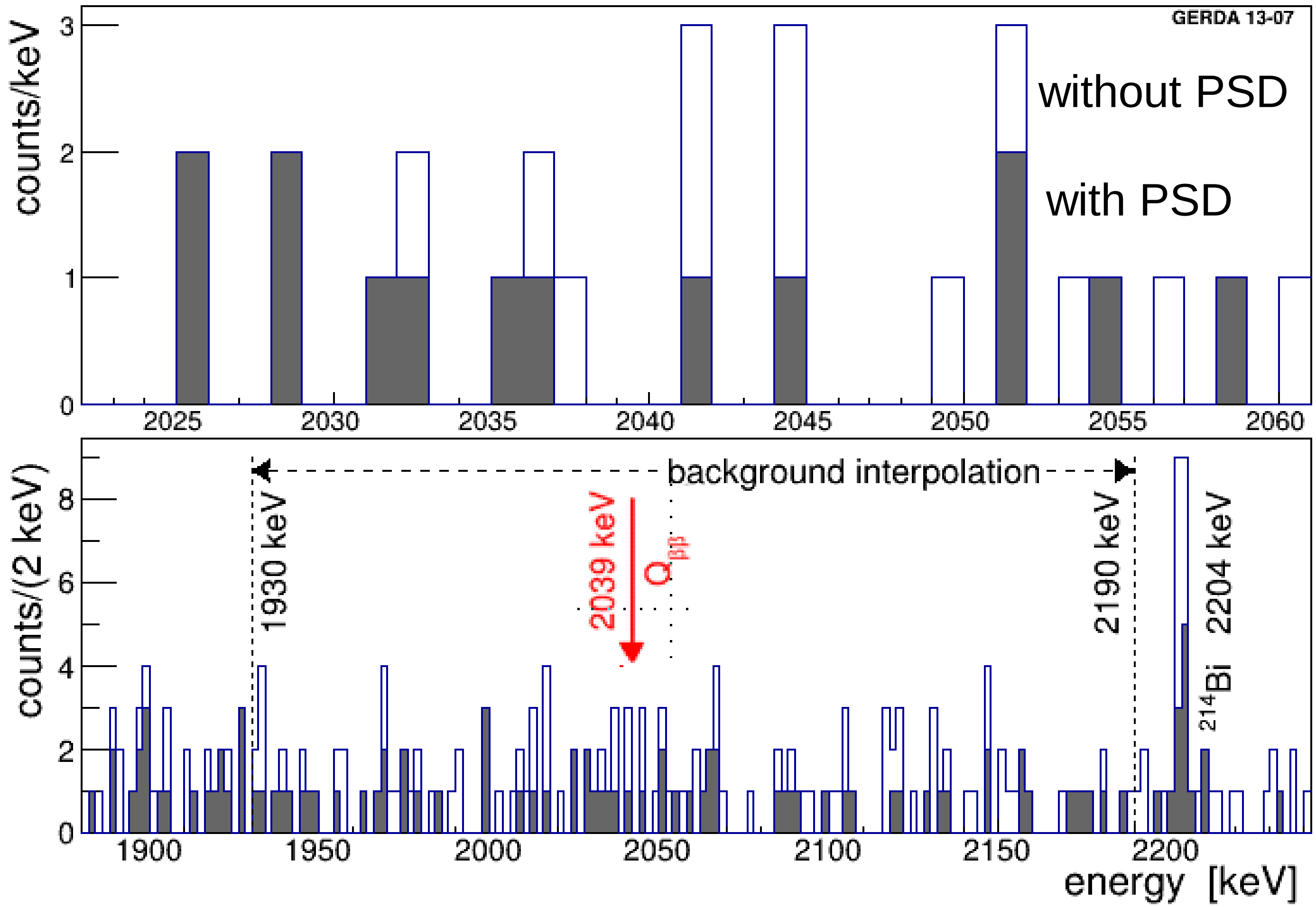


Expected background from interpolation: 5.1 events w/o PSD; 2.5 events with PSD

PRL 111 (2013) 122503

Phase I

the 0νββ result

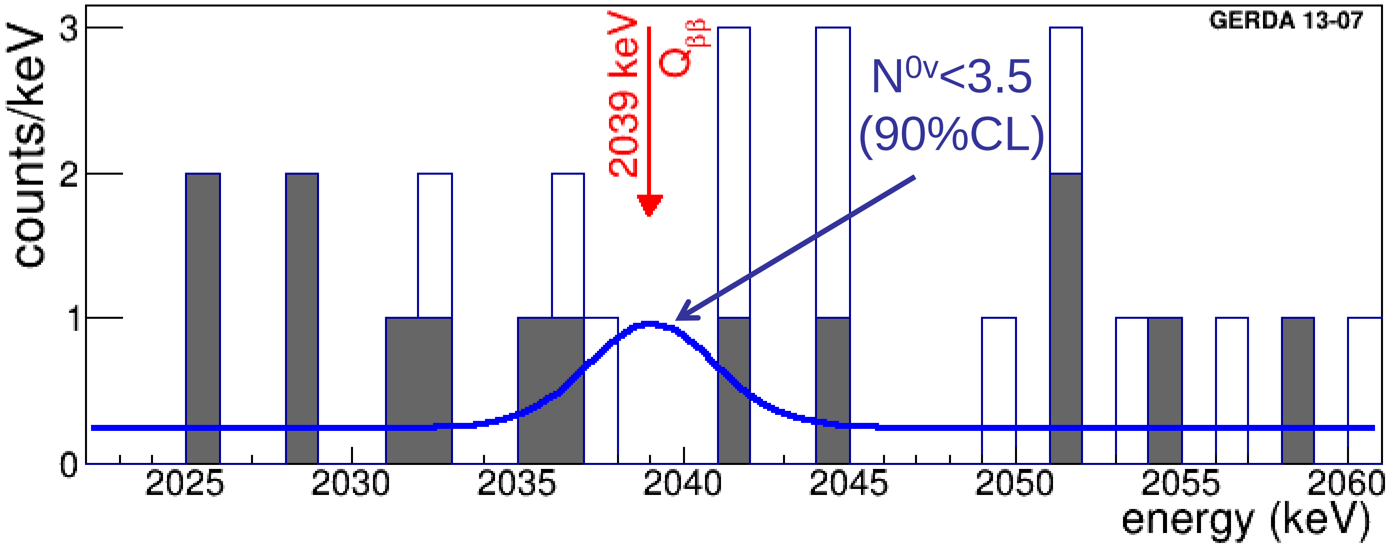


No peak!

Expected background from interpolation: 5.1 events w/o PSD, 2.5 events with PSD

observed: 7 events w/o PSD, 3 events with PSD

the 0νββ result



Profile likelihood fit: constant (bgnd) + gaussian (signal) μ= (2039.06±0.2) keV
to the 3 data sets σ =(2.0±0.1) / (1.4±0.1) keV coax/BEGe

Frequentist: best fit $N^{0\nu} = 0$; $T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.) - sensitivity. : $2.4\cdot10^{25}$ yr

Bayes: best fit $N^{0\nu} = 0$; $T^{0\nu}_{1/2} > 1.9\cdot10^{25}$ yr (90% C.I.) - sensitivity.: $2.0\cdot10^{25}$ yr
(flat 1/T prior)

PRL 111 (2013) 122503

Phase I

the 0νββ result

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

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

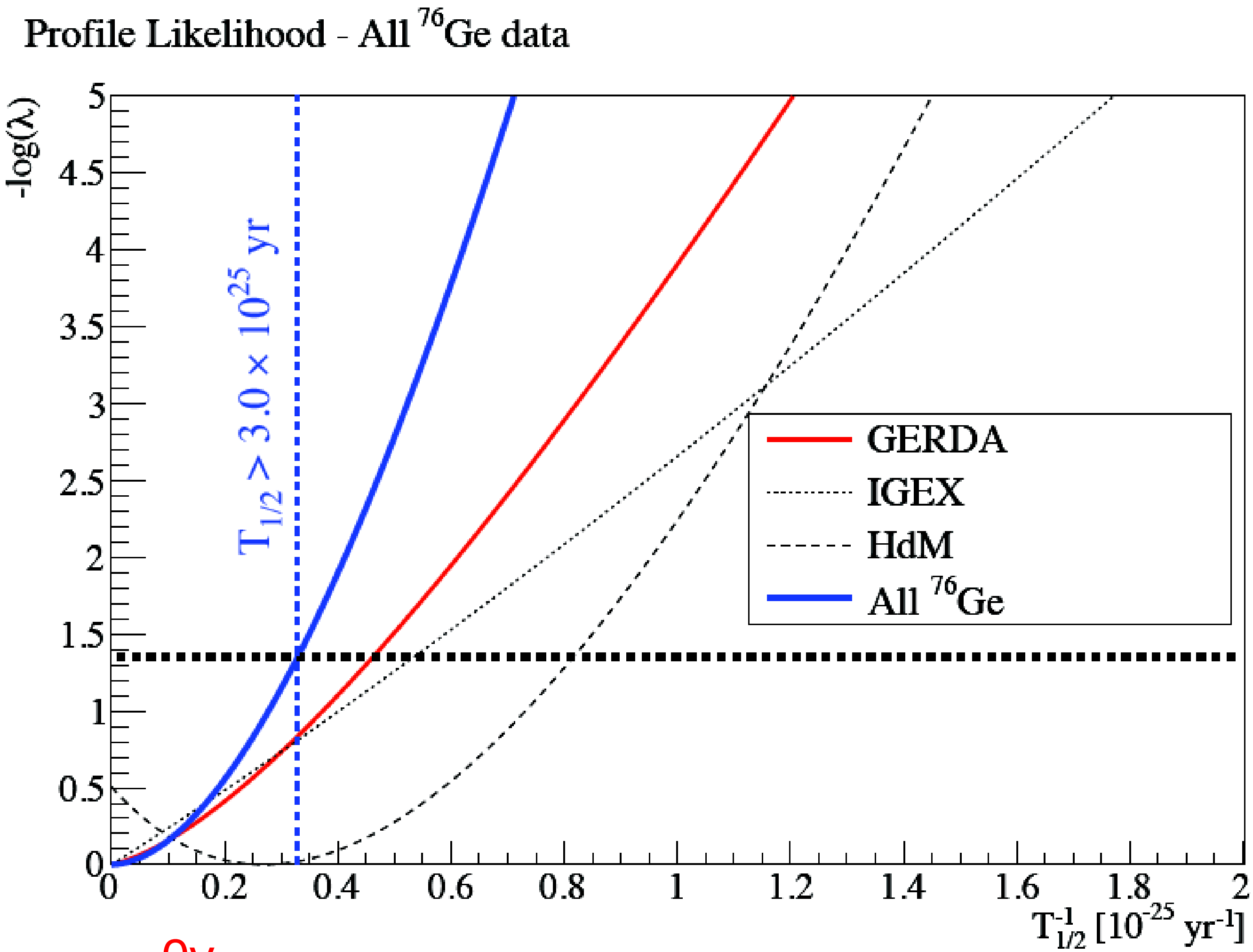
N_A: Avogadro number
E: exposure
ε: exposure averaged efficiency
m_{enr}: molar mass of enriched Ge
$N^{0\nu}$: signal counts / limit

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

	$<f_{76}>$	$<f_{av}>$	$<\varepsilon_{fep}>$	$<\varepsilon_{psd}>$	$<\varepsilon>$
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

Phase I GERDA + HdM + IGEX combined



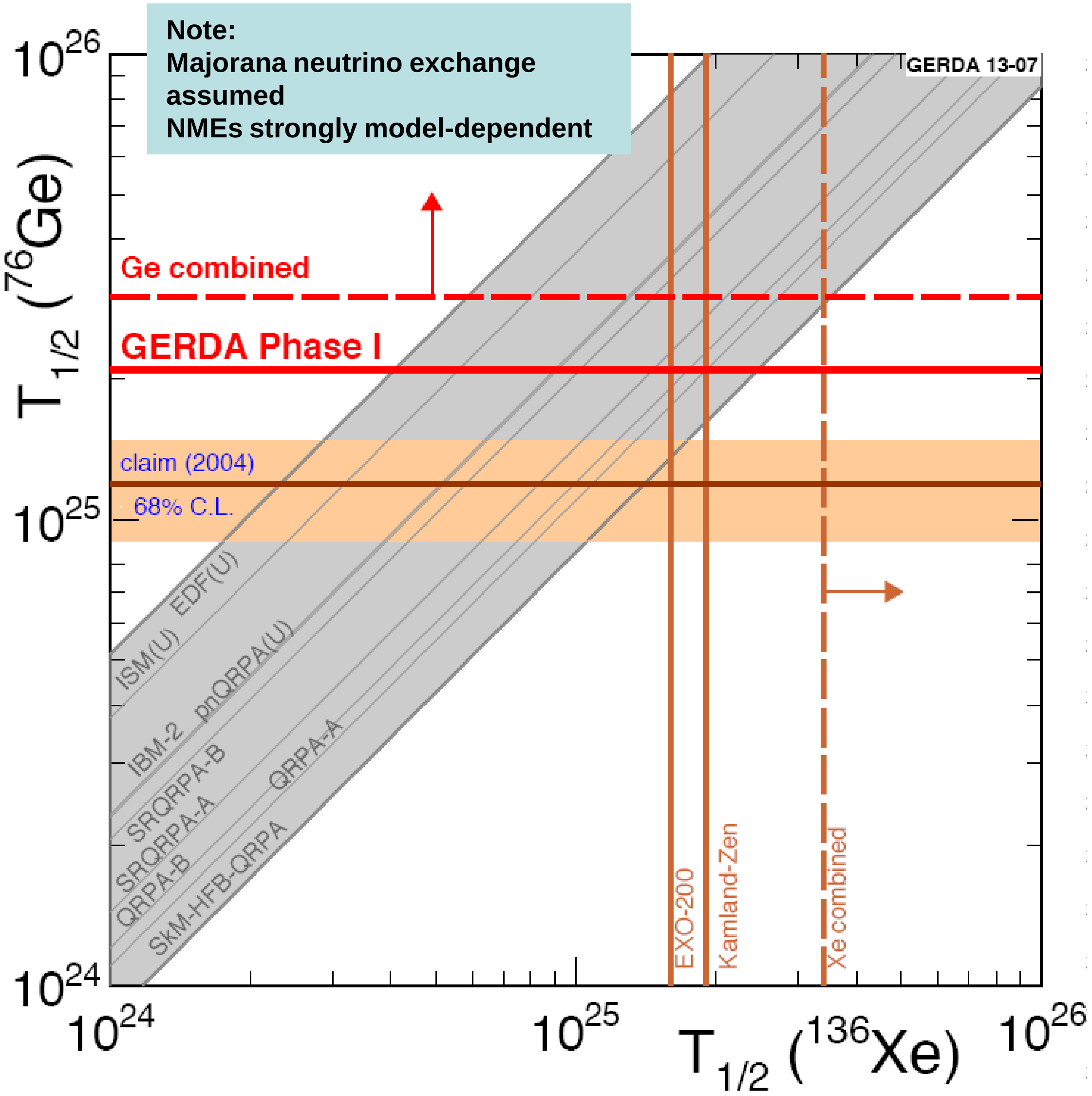
HdM: Eur.Phys.J. A12 (2001) 147
IGEX:Phys.Rev. D70 (2004) 078302
Phys.Rev. D65 (2002) 2002

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

almost identical limits with frequentist & Bayes approach

KK claim ($1.2 \cdot 10^{25}$ yr) strongly disfavored

combined EXO-200, KamLAND-Zen, GERDA results



PRL 111 (2013) 122503

Bayes factors:

EXO	0.23
KamLAND-Zen	0.40
GERDA	0.024
All combined	0.002

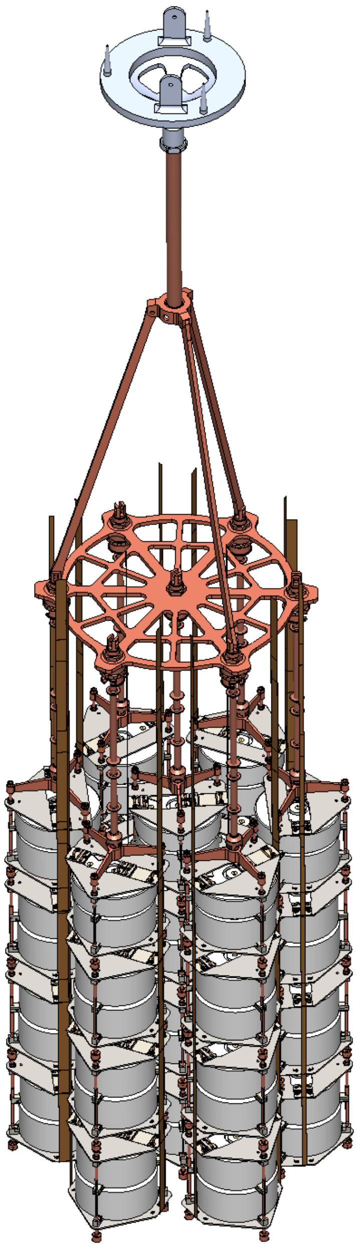
► the quest for 0νββ decay is open again!

GERDA phase II goal

sensitivity $T^{0\nu}_{1/2}$(Ge-76) ~ 1.4 $\cdot 10^{26}$ yr at 100 kg·yr

- reduce BI by another order of magnitude to 0.001
  - more BEGe detectors with better PSD (& resolution)
  - instrumentation of LAr to veto specific backgrounds
  - less & cleaner material in detector holders, cables, ..
- get exposure of ~100 kg·yr within 3 years
  - double detector mass (15 kg coaxial + 20 kg BEGe)

GERDA Phase II the detector array



New lock for Phase II will support 7 strings, e.g.:

- 4 strings, each with 4 pairs of BEGe's
- 3 strings, each with 3 semi coaxial Phase I diodes

Further reduction of material close to diodes:

- contacts by wire bonding
- new detector holders replacing Cu in part by Si
- Cuflon cables

Phase II hybrid LAr instrumentation

The LAr scintillation light can be used as a most efficient veto signal against specific types of background; suppression factors $>10^3$ demonstrated for Th-228 at $Q_{\beta\beta}$.

Cu shroud 1

Ø50 cm central window Cu, h~100 cm, covered by dense curtain of 1x1 mm^2 fibers on radius of 25 cm; readout by KETEK SIPMs arrays

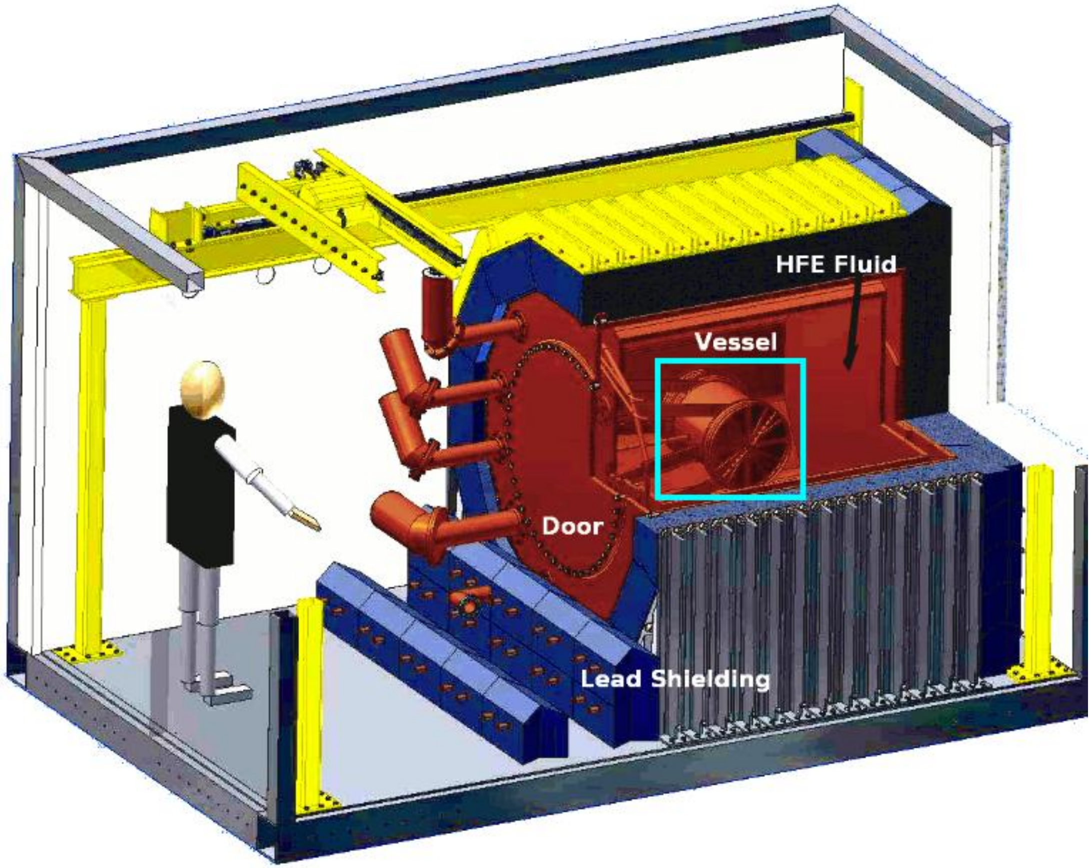
PMTs and SIPMs are deployed together with detector array through Phase II lock w/o LAr drainage

Cu shroud 2
Ø50 cm, h~60cm, t=0.1mm
w reflector & WLS (TPB)

7 (+9 on top) low background 3” PMTs
(Hamamatsu R11065-xx)

GERDA Phase II competitors

	type	isotope	enr. mass [mole]	FWHM [keV]	BI a)
EXO-200	liquid TPC	Xe-136	~580*	96	1.1



Running,
new data expected soon

*after fiducial volume cut

NB:
Ba-tagging would improve BI.

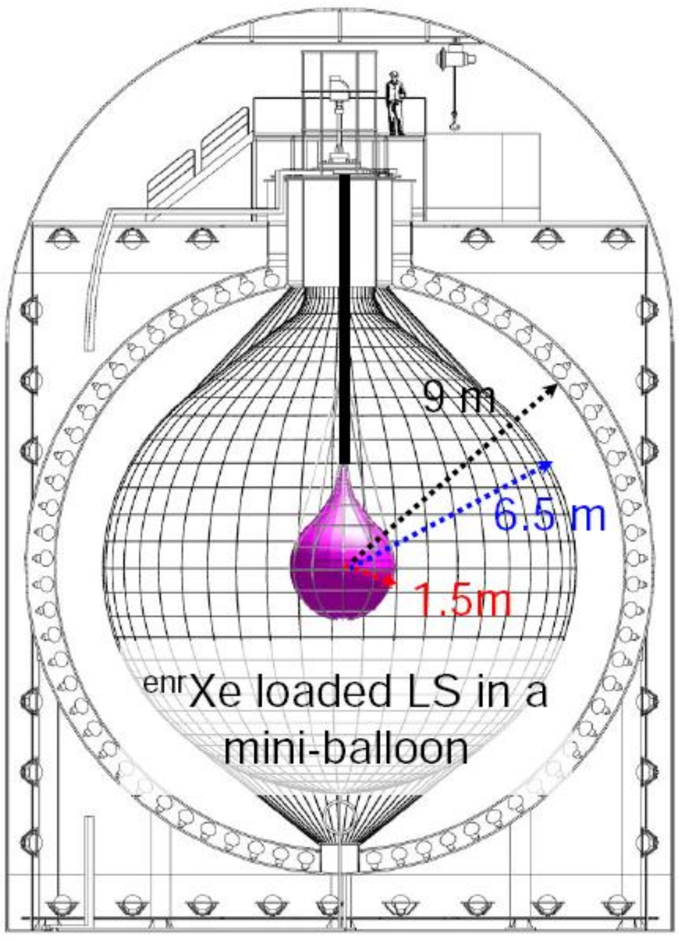
Gas TPC (NEXT) would improve Resolution and allow tracking.

see talk by C. Licciardi, Tuesday 16:40

a) 10^{-3} [cts/(keV kg yr)]

GERDA Phase II competitors

	type	isotope	enr. mass [mole]	FWHM [keV]	BI a)
EXO-200	liquid TPC	Xe-136	~580*	96	1.1
KamLAND-Zen	loaded scintillator	Xe-136	920-1320*	~ 240	0.15**



Running,
new data expected soon

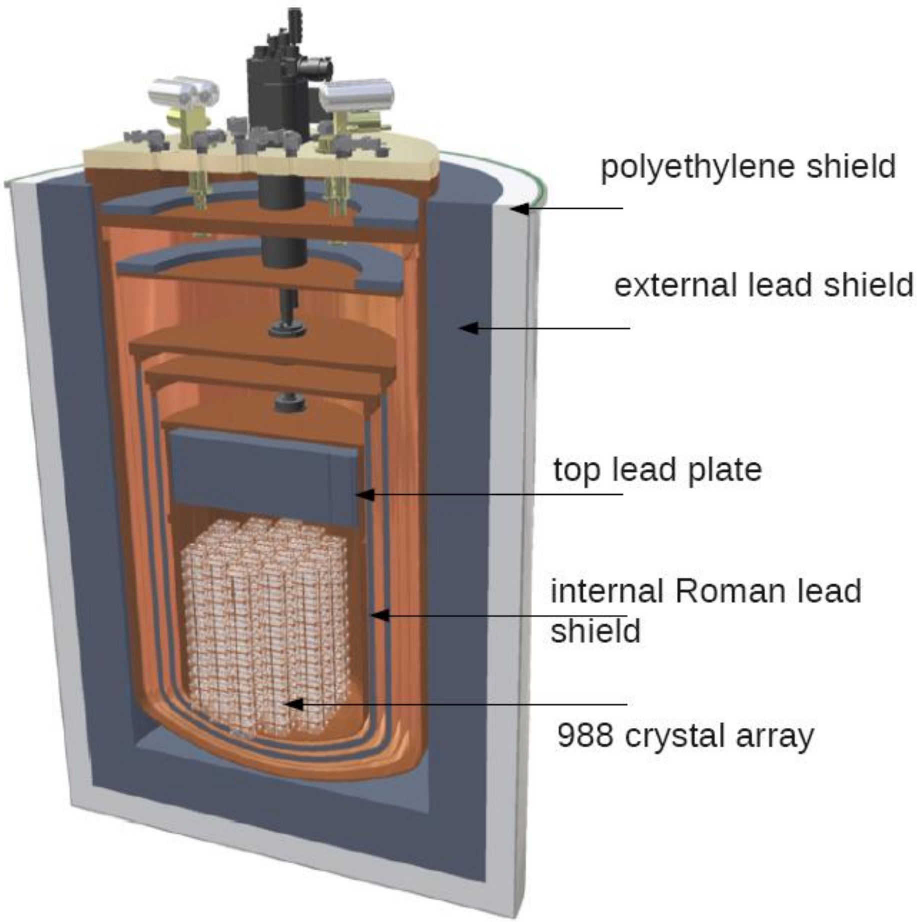
* after fiducial volume cut
** actually much larger - affected by Fukushima fall-out – will improve

NB:
Similar approach: SNO+ loaded with Te-130

a) 10^{-3} [cts/(keV kg yr)]

GERDA Phase II   competitors

	type	isotope	enr. mass [mole]	FWHM [keV]	BI a)
EXO-200	liquid TPC	Xe-136	~580*	96	1.1
KamLAND-Zen	loaded scintillator	Xe-136	920-1320*	~ 240	0.15**
CUORE	bolometer	Te-130	~1600	~5	10



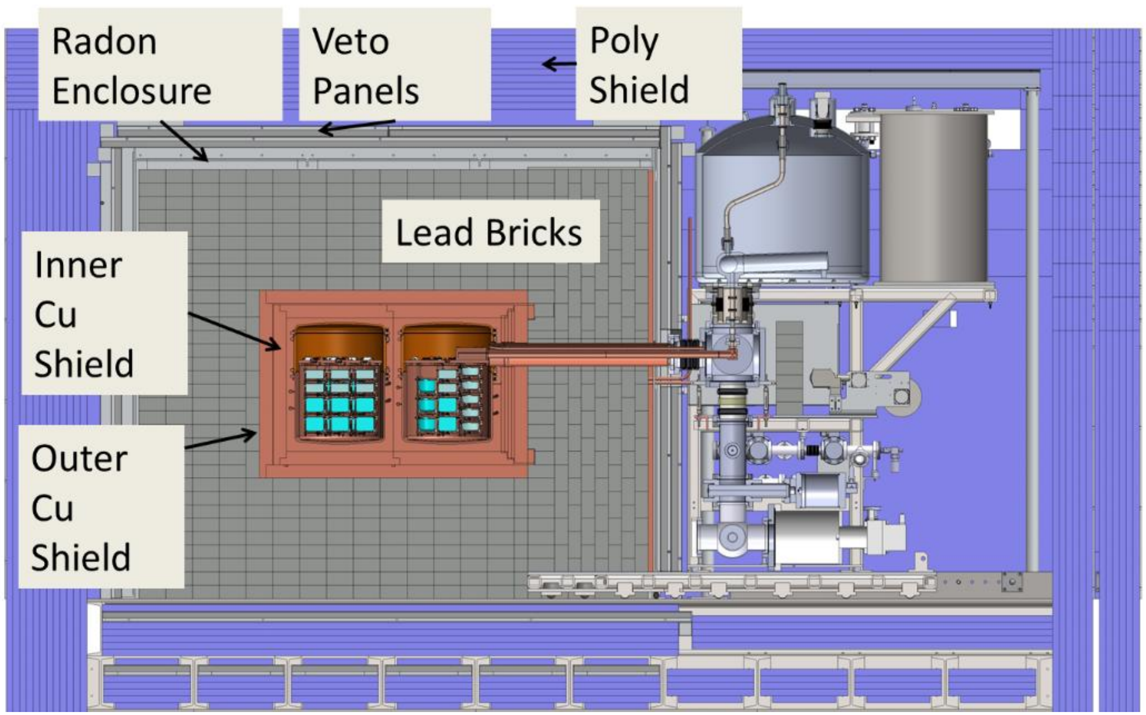
Under construction, one tower (CUORE0) running

NB:
Detection of heat & light would improve BI (LUCIFER).

a) 10^{-3} [cts/(keV kg yr)]

GERDA Phase II competitors

	type	isotope	enr. mass [mole]	FWHM [keV]	BI a)
EXO-200	liquid TPC	Xe-136	~580*	96	1.1
KamLAND-Zen	loaded scintillator	Xe-136	920-1320*	~ 240	0.15**
CUORE	bolometer	Te-130	~1600	~5	10
MAJORANA-D	ionization	Ge-76	~340	~4	0.75



Under construction, demonstrator for 1 ton scale experiment

a) 10^{-3} [cts/(keV kg yr)]

GERDA Phase II competitors

	type	isotope	enr. mass [mole]	FWHM [keV]	BI a)
EXO-200	liquid TPC	Xe-136	~580*	96	1.1
KamLAND-Zen	loaded scintillator	Xe-136	920-1320*	~ 240	0.15**
CUORE	bolometer	Te-130	~1600	~5	10
MAJORANA-D	ionization	Ge-76	~340	~4	0.75
GERDA II	ionization	Ge-76	~400	3-4	~1

All sensitivities beyond 10^{26} yr !

Optimum combination of mass <u>and</u> resolution <u>and</u> BI not (yet) realized.

a) 10^{-3} [cts/(keV kg yr)]

conclusion

GERDA Phase I results:

- unprecedented BI of
  0.018 ± 0.002 cts/(keV·kg·yr) w/o PSD
- no indication of peak at 2039 keV
- half life limit for 0νββ decay of Ge-76:
  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
  $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90% C.L.) with HdM + IGEX
  limit for effective Majorana neutrino mass
  $m_{\beta\beta} < 0.2 – 0.4$ eV

The HdM claim is even stronger disfavored when combining the limits from Ge-76 and Xe-136 (EXO-200 & KamLAND-Zen) .

The quest for 0νββ decay is open again!

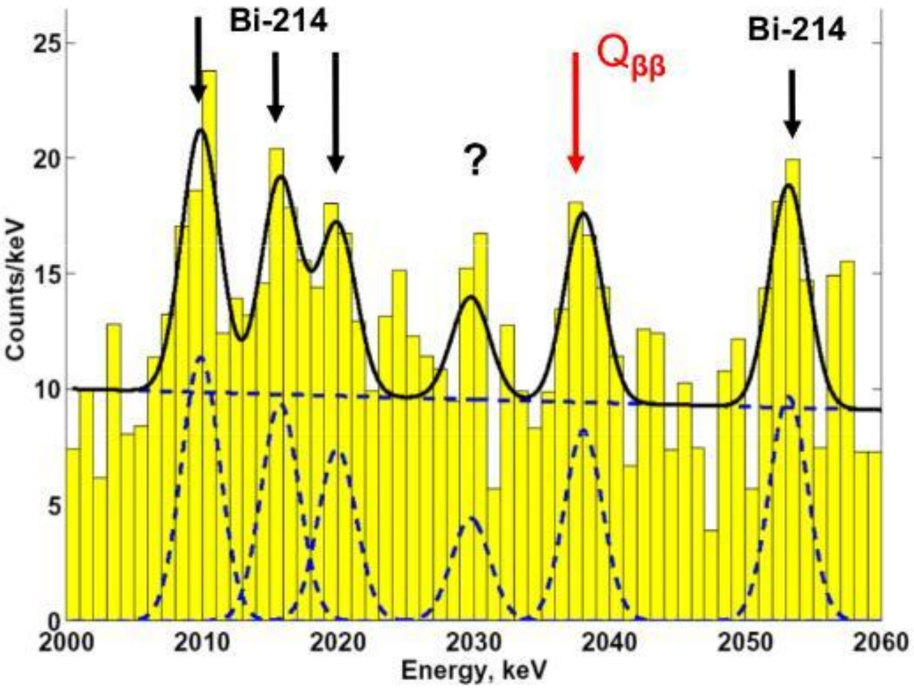
The next years will see a variety of experiments searching for 0νββ decay of Ge-76, Te-130 & Xe-136 with largely improved sensitivities.

End / Backup

The HdM claim

Exposure: 71.7 kg yr

Background: 0.11 counts/(keV kg yr) (without pulse shape)

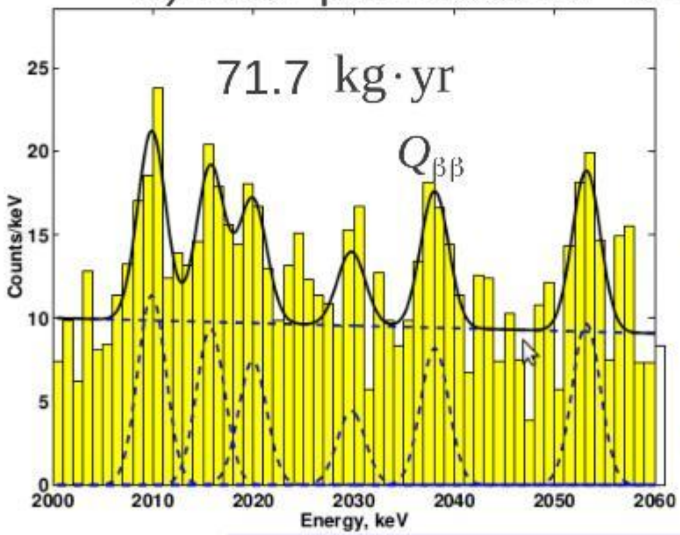


- $T^{0\nu}_{1/2} = 1.2(0.69 - 4.18) \times 10^{25}$ yr
  Phys. Lett. B 586, 198 (2004)
  3σ range
  4.2σ C.L. evidence for $0\nu\beta\beta$
- $T^{0\nu}_{1/2} = 2.23(1.92 - 2.67) \times 10^{25}$ yr
  Mod. Phys. Lett. A 21, 1547 (2006)
  Critized in arXiv:1210.7432
- $m_{\beta\beta}$=(0.24-0.58) eV / (0.29-0.35) eV

IGEX: $T^{0\nu}_{1/2} = 1.57 \times 10^{25}$ yr (90% C.L.)

Why does GERDA not use the KK 2006 result ?

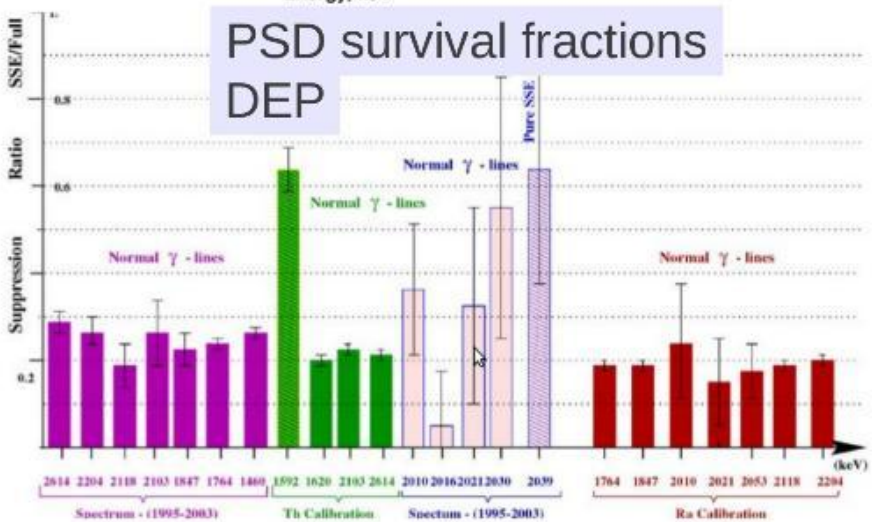
a) 2004 publications: NIM A522 371 & PL B586 198



entire data set: 71.7 kg·yr (active mass)
28.75 ± 6.86 signal events
$T^{0\nu}_{1/2} = \left(1.19^{+0.37}_{-0.23}\right) \cdot 10^{25}$ yr

data for PSD analysis: 51.4 kg·yr
19.58 ± 5.41 signal events
$T^{0\nu}_{1/2} = \left(1.25^{+0.49}_{-0.27}\right) \cdot 10^{25}$ yr

PSD survival fractions
DEP



with PSD applied:
12.36 ± 3.72 events
DEP survival fraction ~ 62%
→ $T^{0\nu}_{1/2} = 1.23 \cdot 10^{25}$ yr

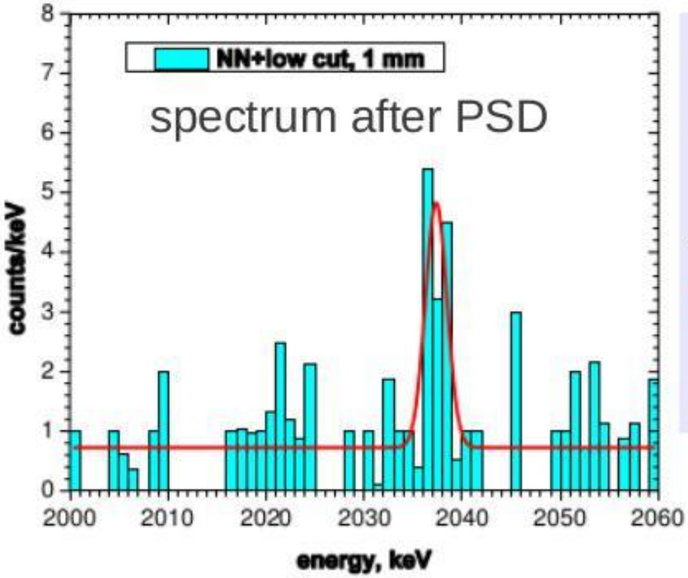
Without efficiency correction:
$T^{0\nu}_{1/2} = 1.98 \cdot 10^{25}$ yr

No efficiency correction is applied in any publication!

see B. Schwingenheuer, Ann. Phys. 525, 269 (2013) arXiv:1210.7432

Why does GERDA not use the KK 2006 result ?

b) 2006 publication: Mod Phys Lett A21 p. 1547-1566



fit gives 11.32±1.75 signal events

$\rightarrow T_{1/2}^{0\nu} = (2.23^{+0.44}_{-0.31}) \cdot 10^{25}$ yr

error on signal count not correct
since smaller than Poisson error

PSD based on 3 previous methods
(2 neural networks + pulse boardness)
& library of SSE pulses:
Event accepted IF pulse in library OR
found by neural network of Ref. 16 but
not by the other two neural networks

NO event overlap between the 2 sets!?

statement of publication:
- "multi site events are suppressed by 100%",
– $0\nu\beta\beta$ efficiency = 1 used for $T_{1/2}^{0\nu}$

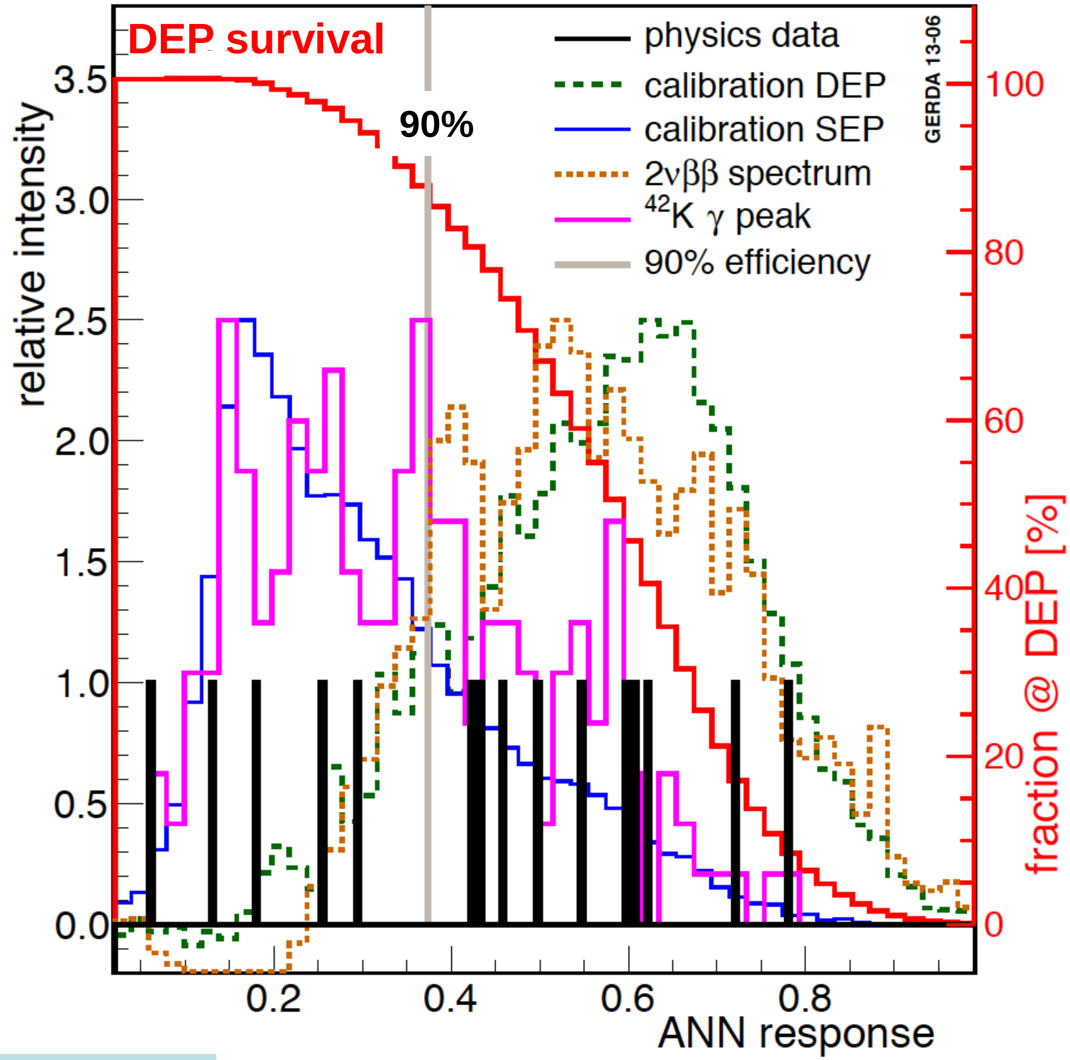
efficiency factor not considered
→ calculation of $T_{1/2}^{0\nu}$ not correct
→ GERDA does not use this result

see B. Schwingenheuer, Ann. Phys. 525, 269 (2013) arXiv:1210.7432

Phase I pulse shape discrimination

semi-coaxial

ANG3 ANN reponse



Selected ANN cut position at 90% DEP survival

Cross checks:

$2\nu\beta\beta$ eff = 85 ± 2 %

2.6 MeV γ Compton edge
eff. = 85 – 94 %

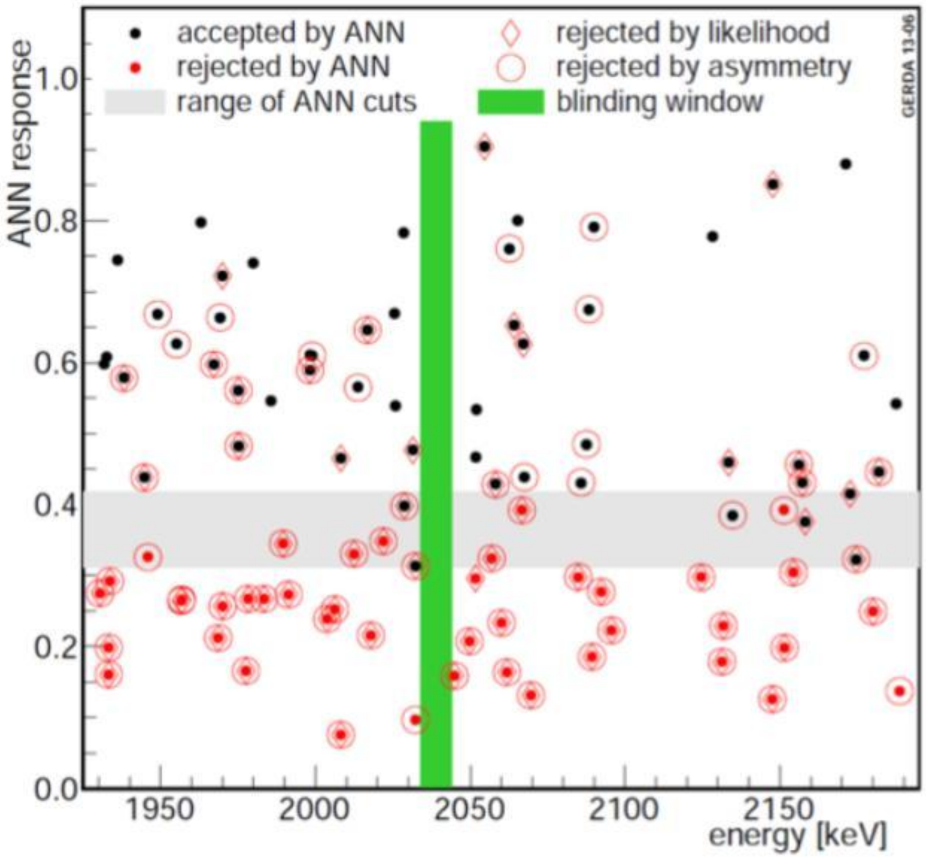
Co-56 DEP (1576 & 2231 keV)
eff. = 83% - 93%

$0\nu\beta\beta$ efficiency = $0.9^{+0.05}_{-0.09}$

ANN checked with 2 other methods: OK!

Eur.Phys.J. C73 (2013) 2583

Phase I pulse shape discrimination



Check of ANN with 2 other methods:
a) projective likelihood
b) current pulse asymmetry *A/E

► All events removed by ANN also removed by either a) or b)

► 90% of ANN rejected events also rejected by method a) & b)

► 3% exclusively rejected by ANN

Eur.Phys.J. C73 (2013) 2583