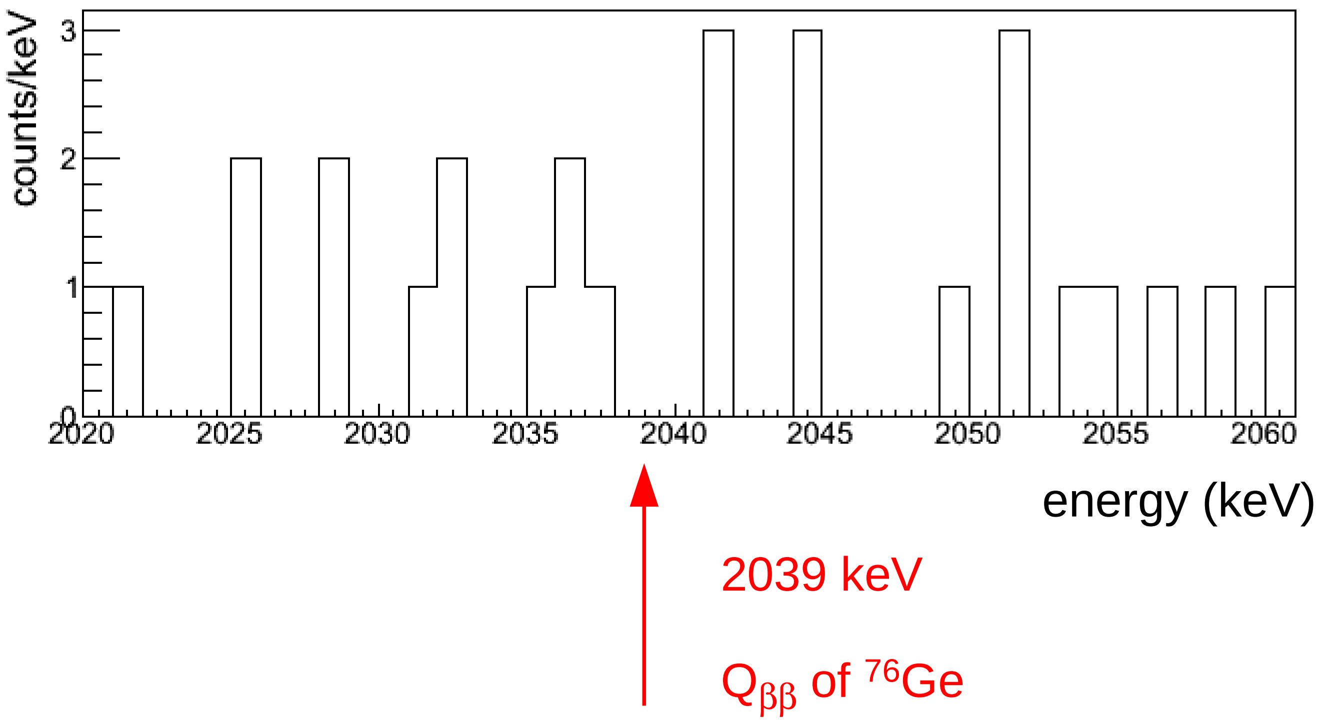
neutrinoless double beta decay in ^{76}Ge with GERDA

on behalf of the GERDA collaboration
Peter Grabmayr
Kepler Center für Astro- und Teilchenphysik
Eberhard Karls Universität Tübingen

Erice 18. September 2013

summed electron energy spectrum



without PSD

outline:

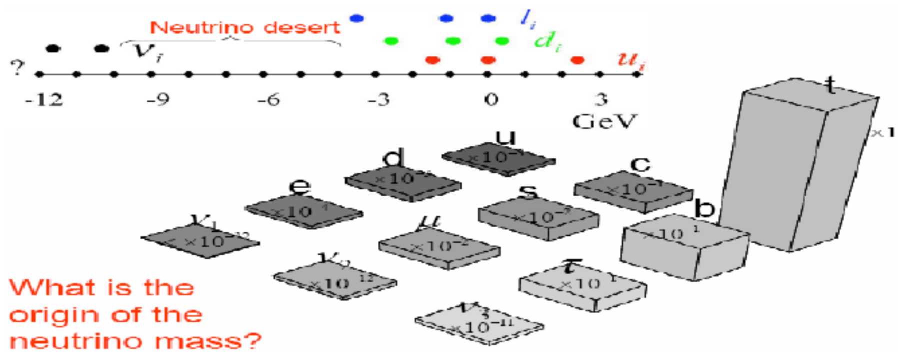
- introduction
- GERDA experiment
- GERDA results
- (future Phase II)

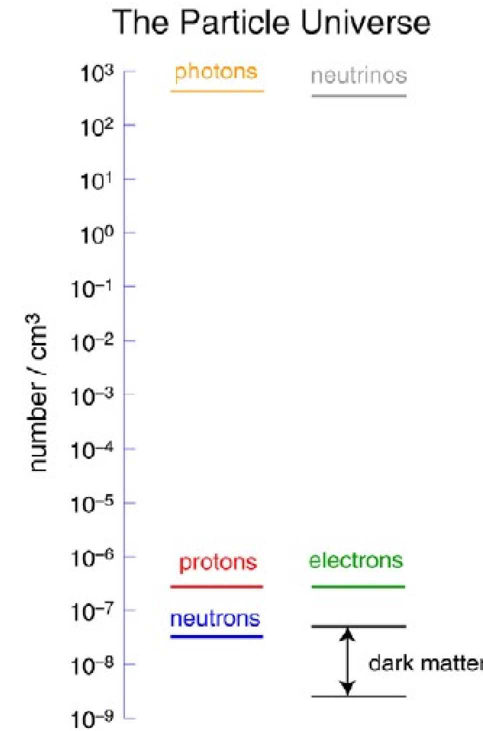
neutrinos

neutrinos and photons are the most abundant particles

Standard Model of Particle Physics: very successful

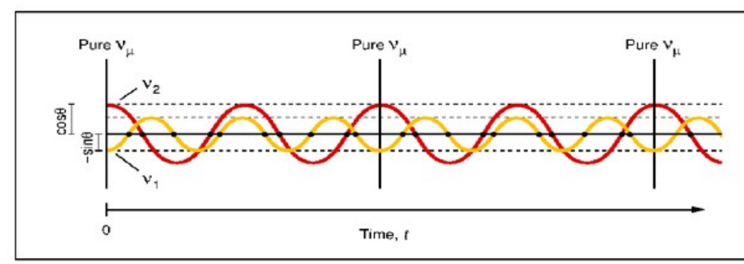
masses, Higgs, DM, SUSY





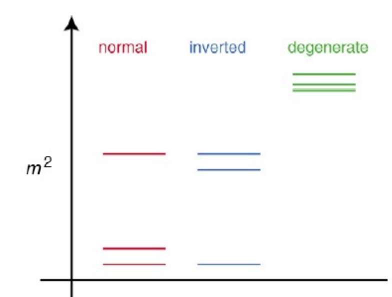
properties of ν are key

spin ½, no charge, left-handed



mass: yes (from oscillations),

but which value ?



cosmology: flat ΛCDM $\Sigma m_\nu < 0.28$ eV

β-decay: Tritium $m_{\nu e}^2 = \Sigma_i m_i^2 \cdot |U_{ie}|^2 < 2.3$ eV

0ν2β: eff. mass $m_{\beta\beta} = |\Sigma_i m_i \cdot U_{ie}^2| < 0.4$ eV

search for properties of ν !

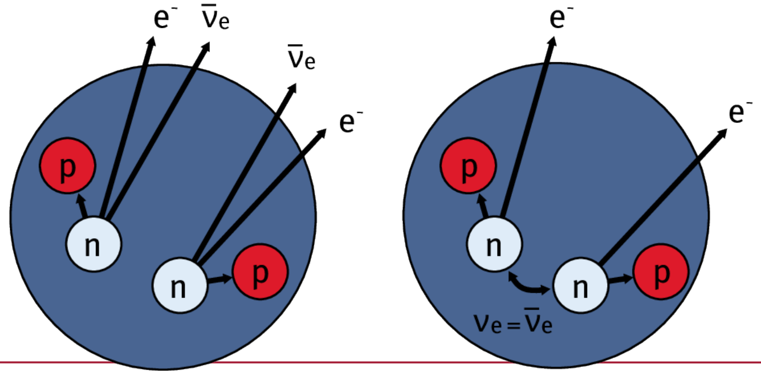
absolute mass scale, hierarchy

most interesting: is ν of Majorana type?

$$\nu \equiv \bar{\nu}$$

lepton number violation
extension to Standard Model

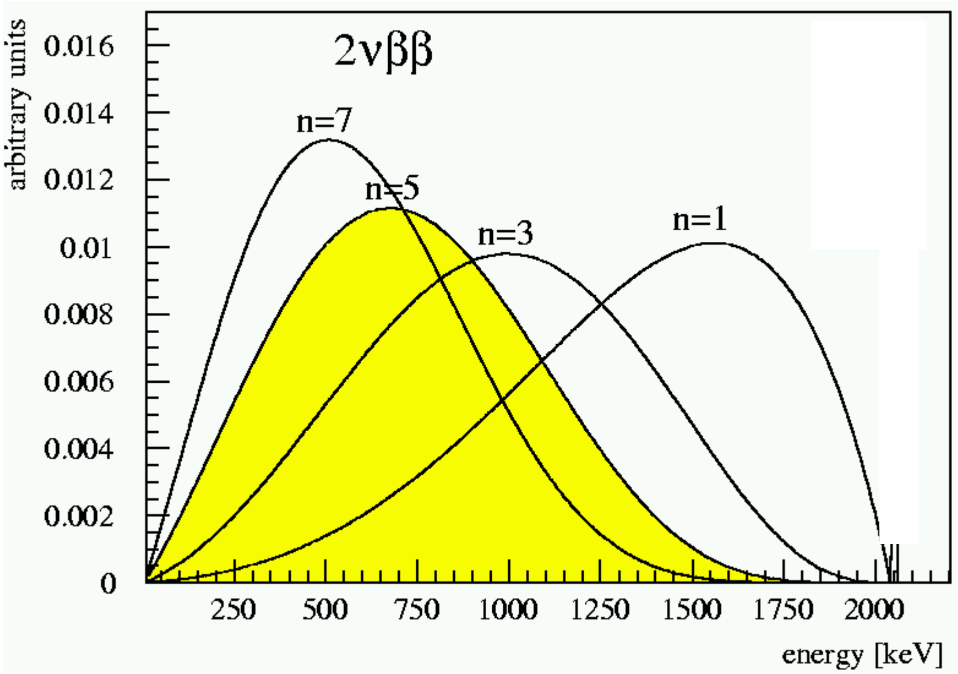
0νββ decay



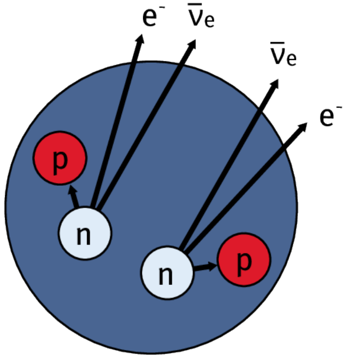
spectral shapes

sum energy spectrum of both electrons

2νββ: spectrum



New phase space calculations
J.Kotila, F.Iachello



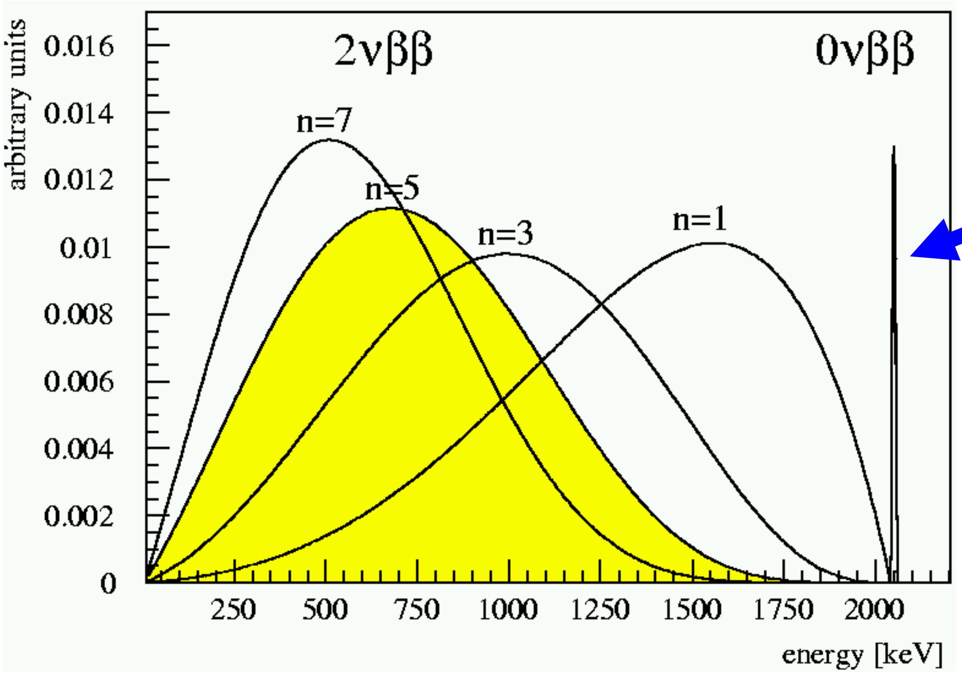
ν, Majoron,..

$2\nu2\beta$: $T_{1/2} \sim 10^{(18\text{-}21)}$ yr

spectral shapes

sum energy spectrum of both electrons

0νββ: peak at Q-value of nuclear transition



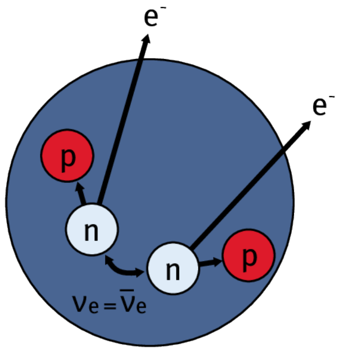
observation of peak ? ⟷ Majorana nature

measured quantity: cts ⇒ half-life

link to eff. neutrino mass

$$1/T_{1/2} = PS * ME^2 * (m_\nu / m_e)^2$$

nuclear physics input needed !



2ν2β: $T_{1/2} \sim 10^{(18\text{-}21)}$ yr

0ν2β: $T_{1/2} > 10^{25}$ yr

half life estimate for $0\nu\beta\beta$

$$T_{1/2} = \ln 2 \cdot (N_A/A) \cdot M \cdot (N_{\beta\beta} / t)^{-1}$$

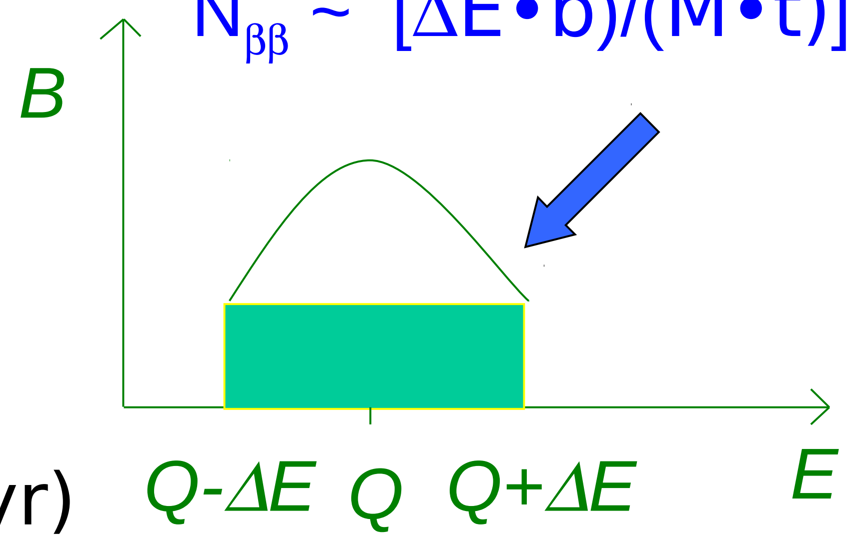
signal sensitivity ≈ stat. precision of background $N_{obs} = \sqrt{N_{BG}}$

background ~ detector mass

$$S_{1/2} \propto a \cdot \varepsilon \, [\, (M \cdot t) / (\Delta E \cdot b)\,]^{1/2}$$

$$N_{\beta\beta} \sim [\Delta E \cdot b)/(M \cdot t)]^{1/2}$$

- a : isotopical abundance
- ε : detection efficiency
- M : mass
- t : measuring time
- ΔE : energy resolution
- b : background cts/(keV kg yr)

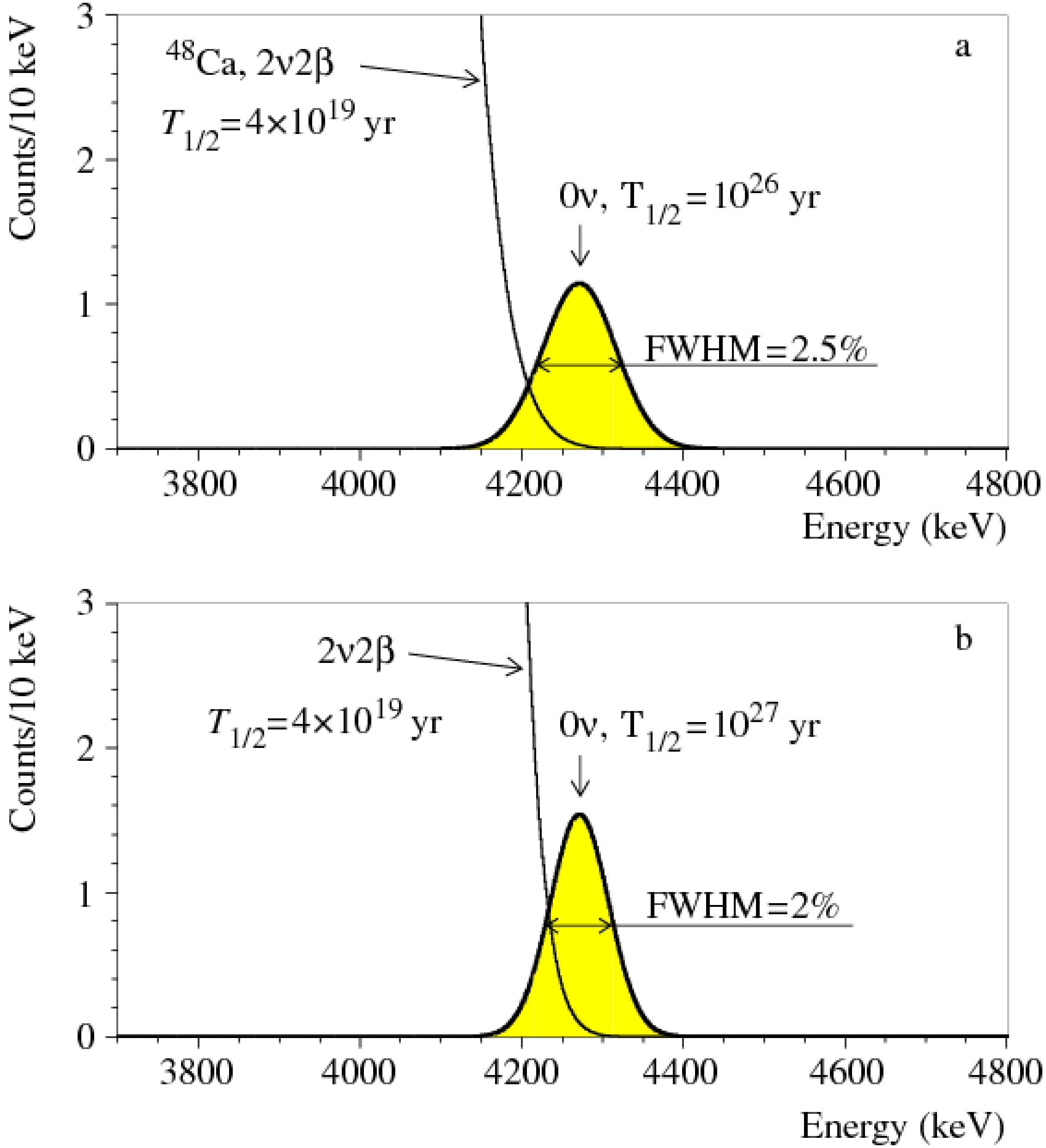


Region Of Interest

resolution

^{48}Ca

ratio 2ν/0ν !!!



FWHM = 2,**5** %

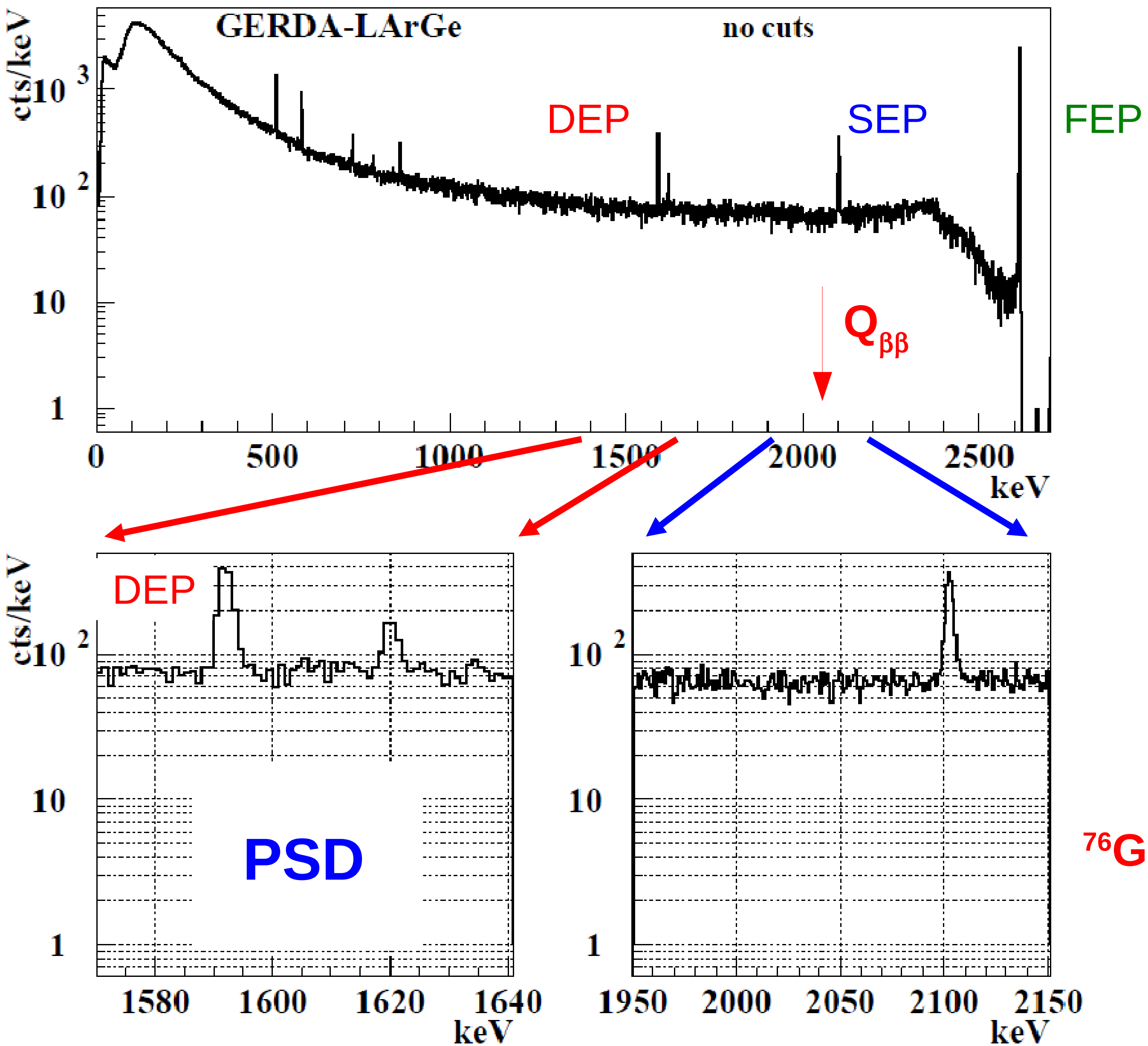
$T_{1/2} = 10^{26}$ yr

FWHM = 2,**0** %

$T_{1/2} = 10^{27}$ yr

⇒ Ge: 0,2%

^{228}Th spectrum



^{228}Th
2615 keV

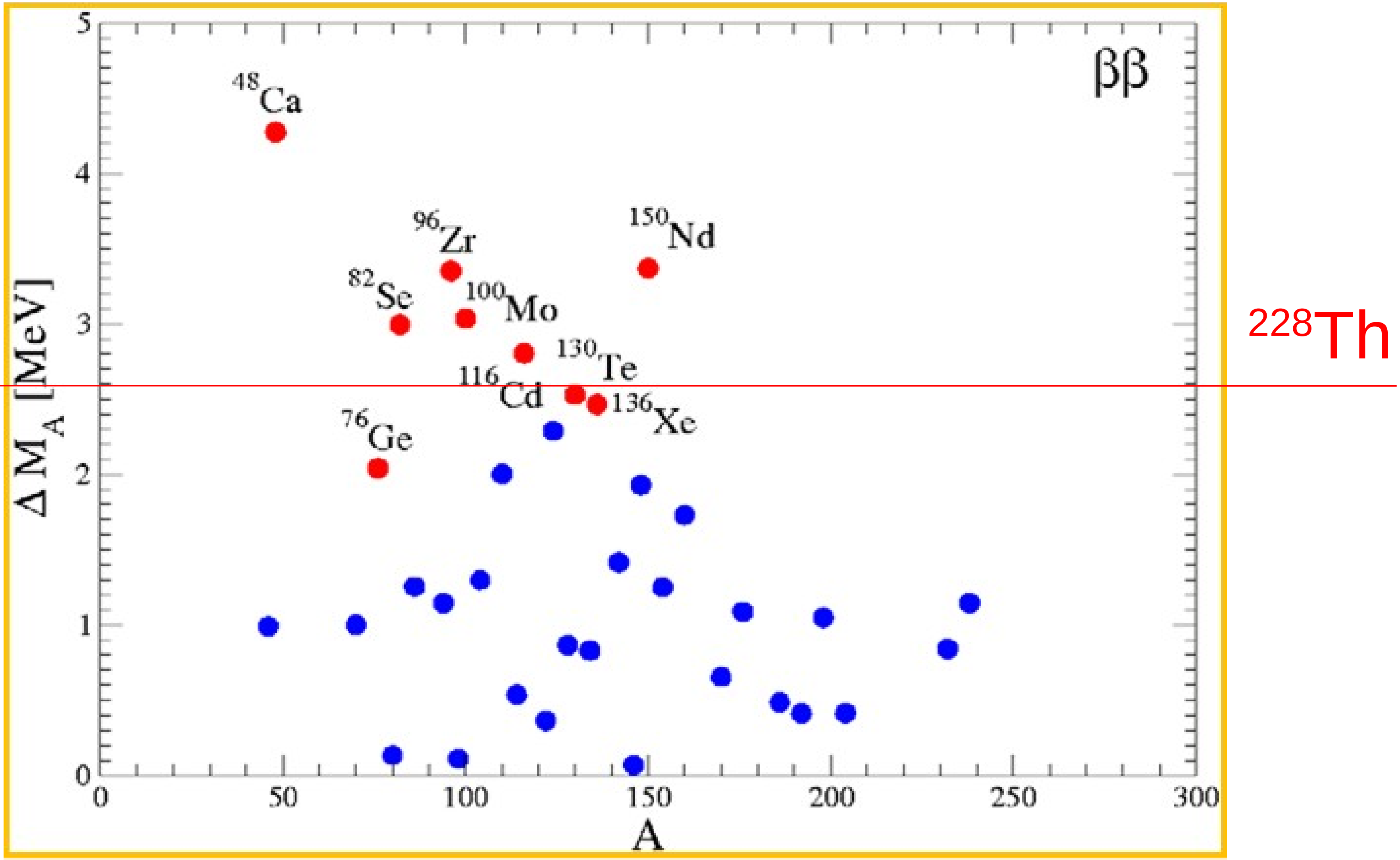
^{208}Tl (radon)

appears in natural decay chains

big source of background

^{76}Ge:
$Q_{\beta\beta}$ = 2039 keV

candidates


ββ
48Ca
96Zr
150Nd
82Se
100Mo
130Te
116Cd
136Xe
76Ge
Δ M_A [MeV]
A
0
1
2
3
4
5
0
50
100
150
200
250
300
228Th

experiments

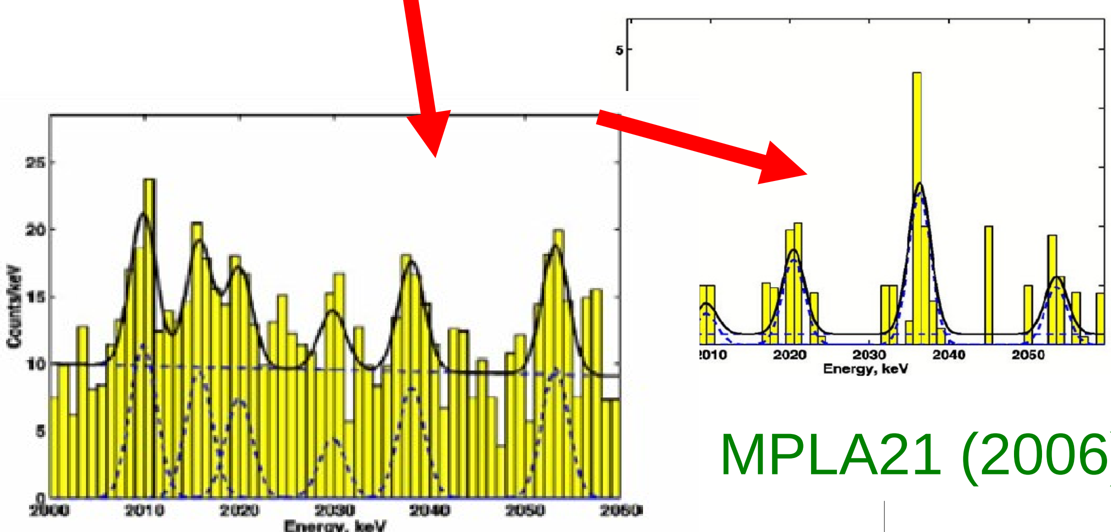
NEMO/SuperNEMO	^{100}Mo	DC tracking
cuoricino/cuore	^{130}Te	bolometer
Majorana/GERDA	^{76}Ge	ionisation
EXO/NEXT	^{136}Xe	TPC (szint.+ ion.)
Kamland-Zen	^{136}Xe	szintillation

Candles	^{48}Ca	szintillation
SNOW++	^{150}Nd	szintillation
MOON	^{100}Mo	MWPC+PLfibres
COBRA	CdZnTe	ionisation+track?
LUCIFER	$CdWO_4$	bolometer

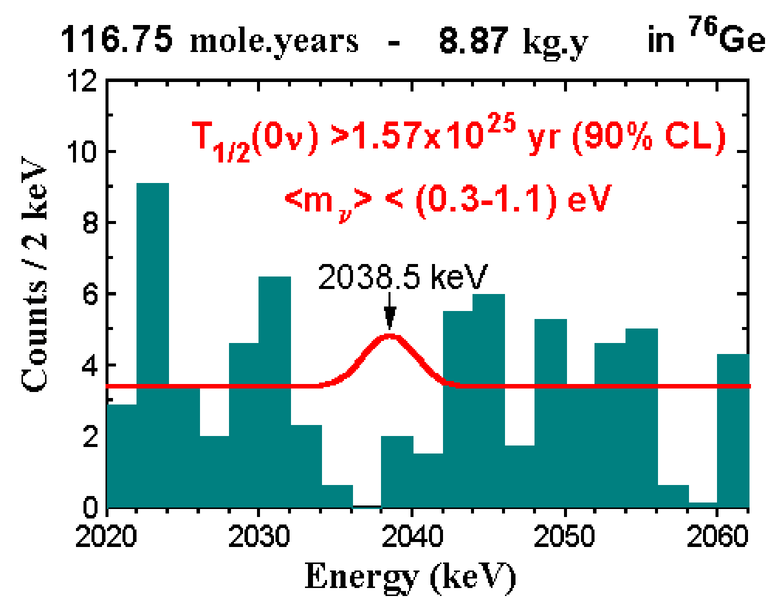
^{76}Ge experiments

previous experiments: HDM (5 det) and IGEX (3 det)

Klapdor-Kleingrothaus et al.	Aalseth et al.
Phys Lett B586 (2004) 198	Phys Rev D65 (2002) 092007
71.7 kg·yr	8.9 kg·yr
$T_{1/2}$> 1,9 ·10 ^{25} yr (90%CL)	$T_{1/2}$> 1,6 ·10 ^{25} yr (90%CL)



MPLA21 (2006)



doubts (see B.S. in Ann.Physik 525 (2013) 269)

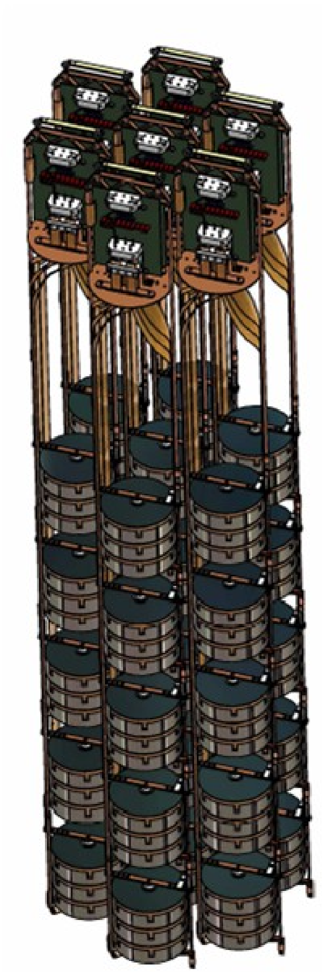
GERDA – the novel idea

G. Heusser, Ann. Rev. Nucl. Part Sci. 45 (1995) 543

"...low Z material around detector..."
"...mount the Ge diodes directly in cryo-liquid"

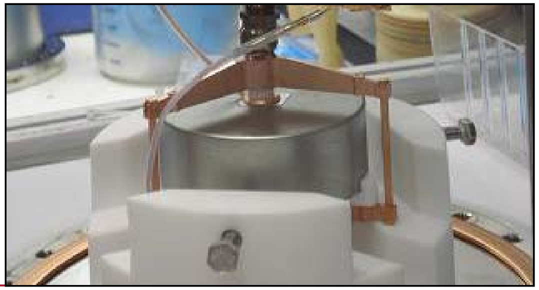
reduced radioactivity of environment
less muon-induced background

Ge diodes – enriched to 86%
selected material for holder and FE
liquid argon
stainless steel cryostat
water to moderate neutrons and
as muon veto (Cherenkov)
underground LNGS 3400 m w.e.



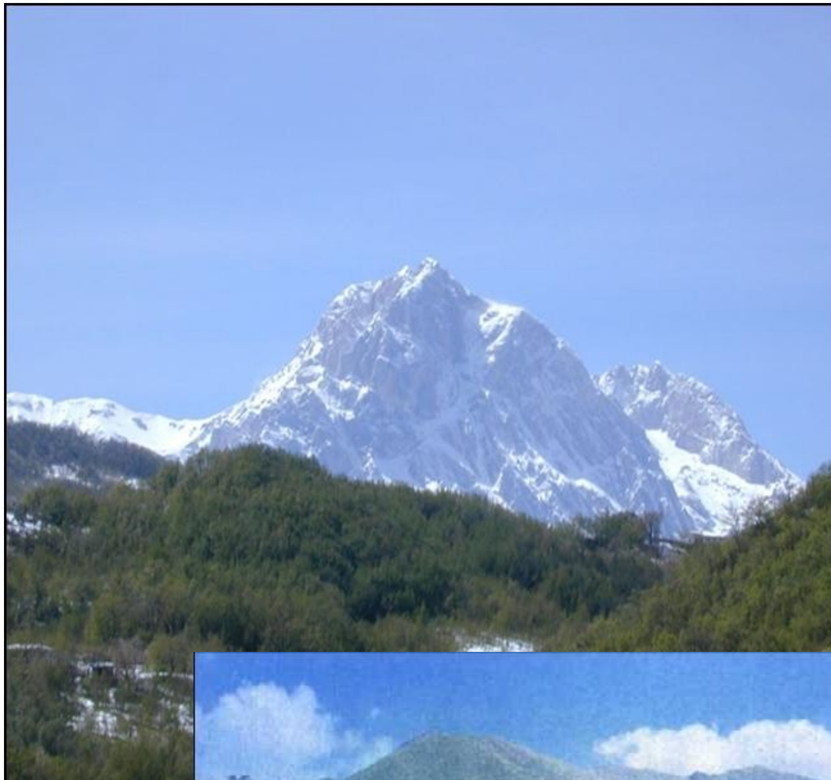
analysis: anti-coincidence, PSD

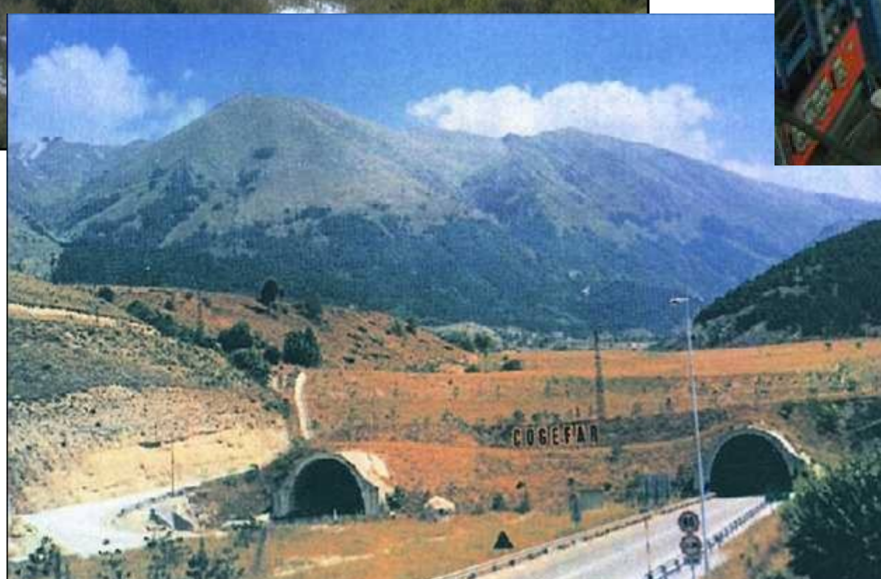
Phase I: aim at FWHM < 5 keV & BI ~ 10^{-2} cts/(keV·kg·yr)

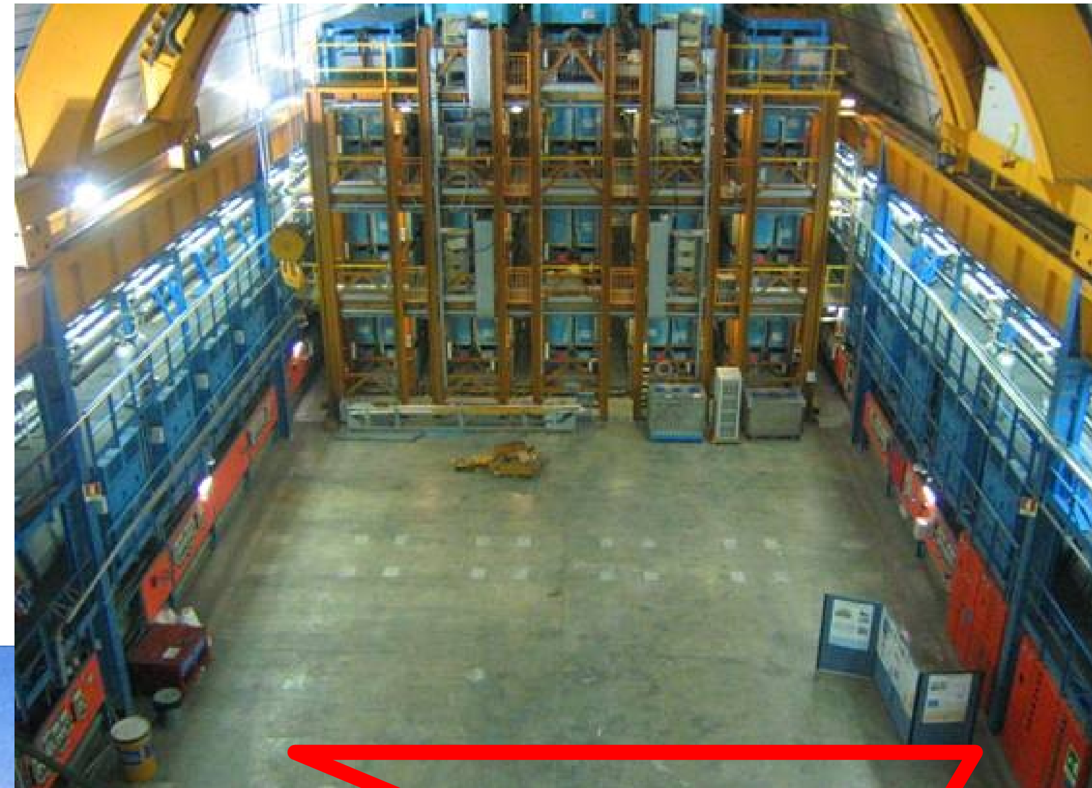


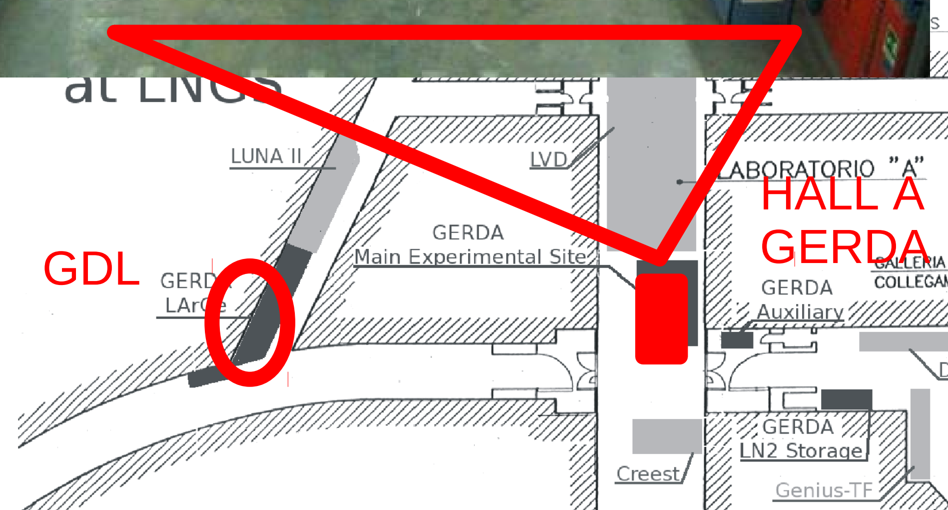
→ HdM, Majorana: closed compact shielding

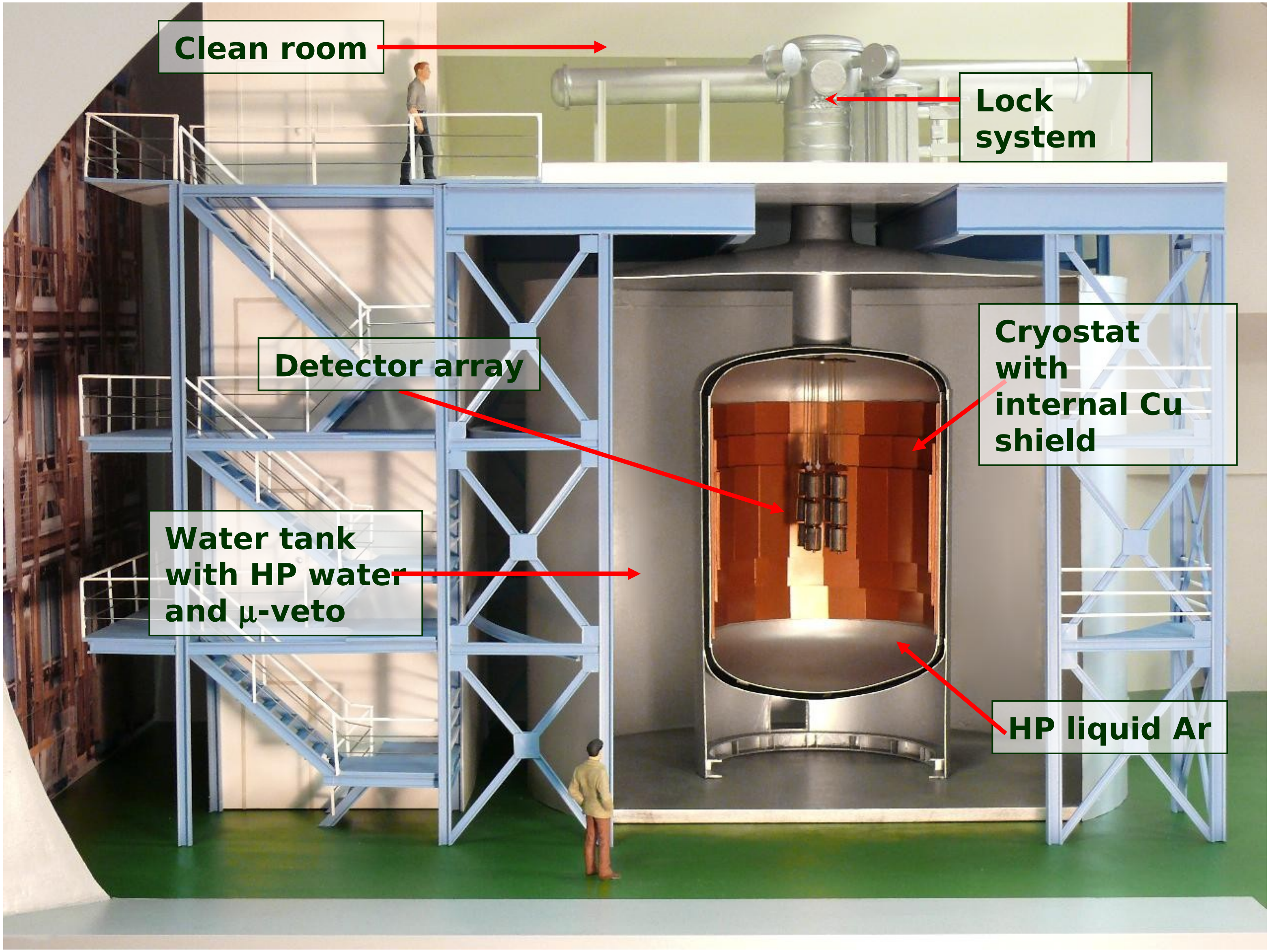
GERDA @ LNGS




COGEFAR



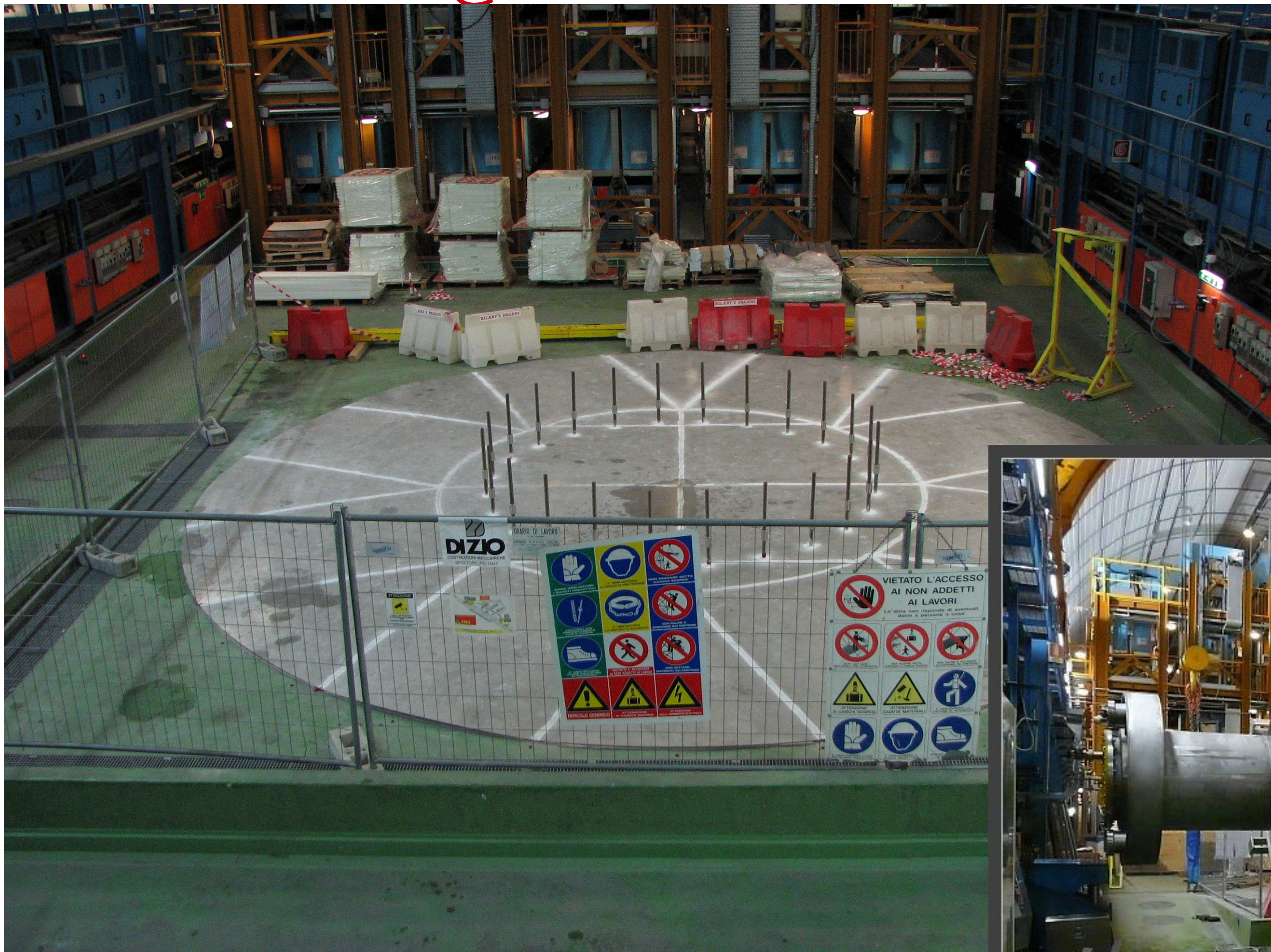

LUNA II
LVD
LABORATORIO "A"
HALL A
GERDA
GDL
GERDA
Main Experimental Site
GERDA
Auxiliary
GERDA
LN2 Storage
Creest
Genius-TF



GERDA : design and construction

proposal 2004

construction @ LNGS



February 2008

March 2008

construction @ LNGS

March 2008

construction @ LNGS

May 2008

construction @ LNGS

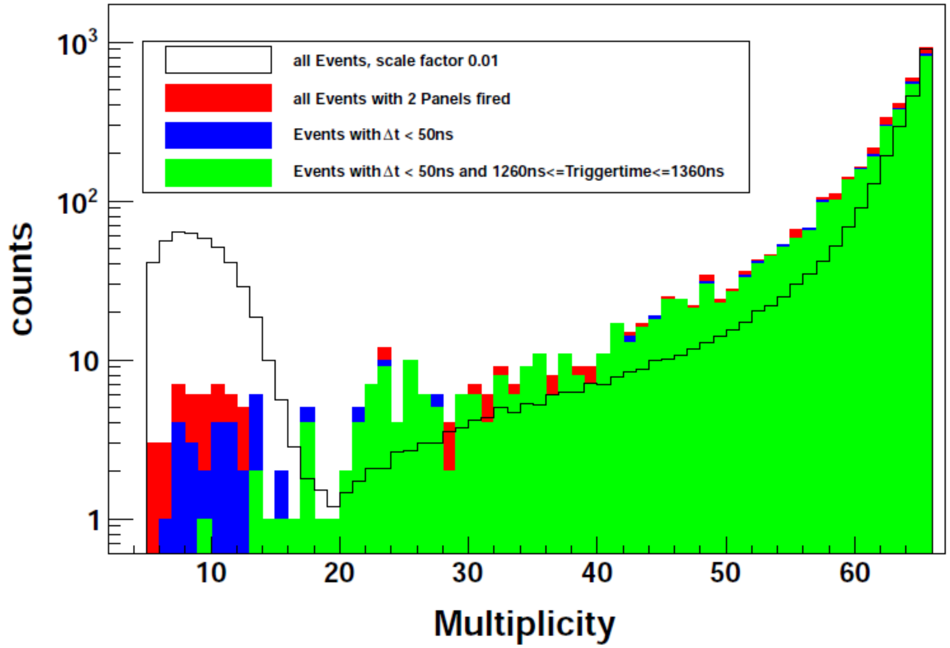
March 2009

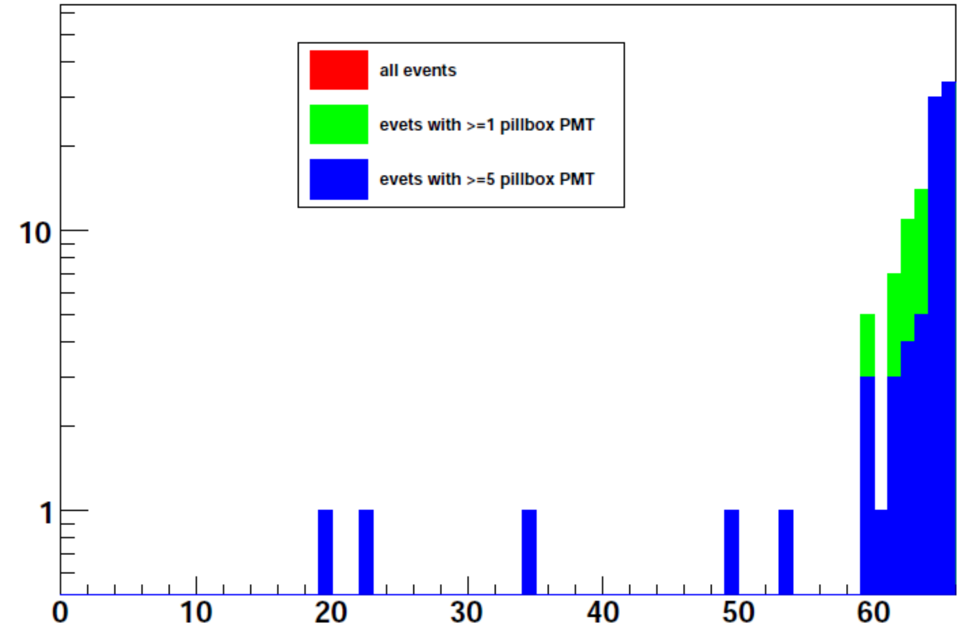
Clean room, lock

cryogenic
infra structure

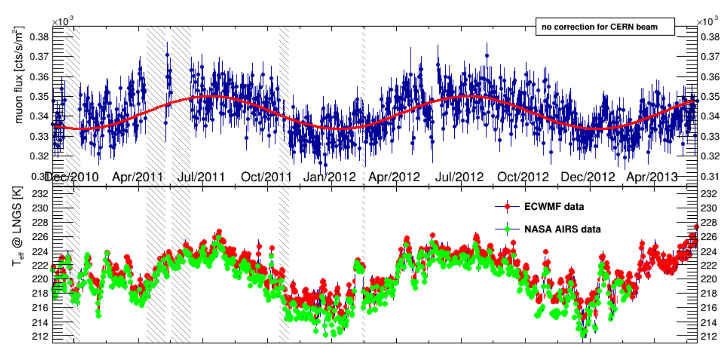
Multiplicity of 66 Cherenkov PMT

3 failed in 3 yr





muon rejection efficiency ε > 97 %



Path of new 37.5 kg of enrGe (86% enrichment in 76Ge):

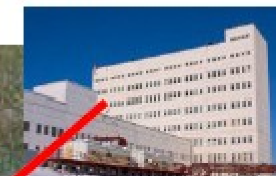
from isotope separation to final Phase II detectors

3) Crystal pulling at Oak Ridge (USA)

4) Detector production at Olen (Be)

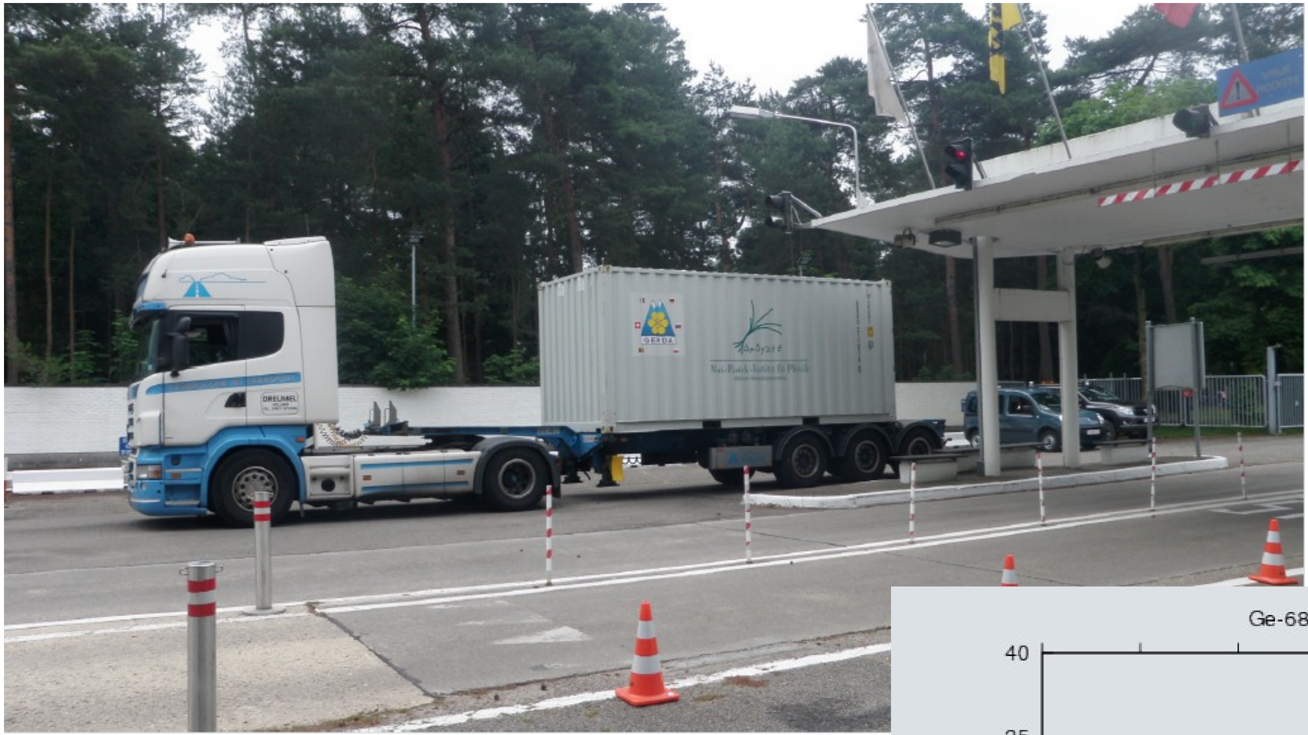
2) Reduction and zone refinment at Goettingen (Germany)

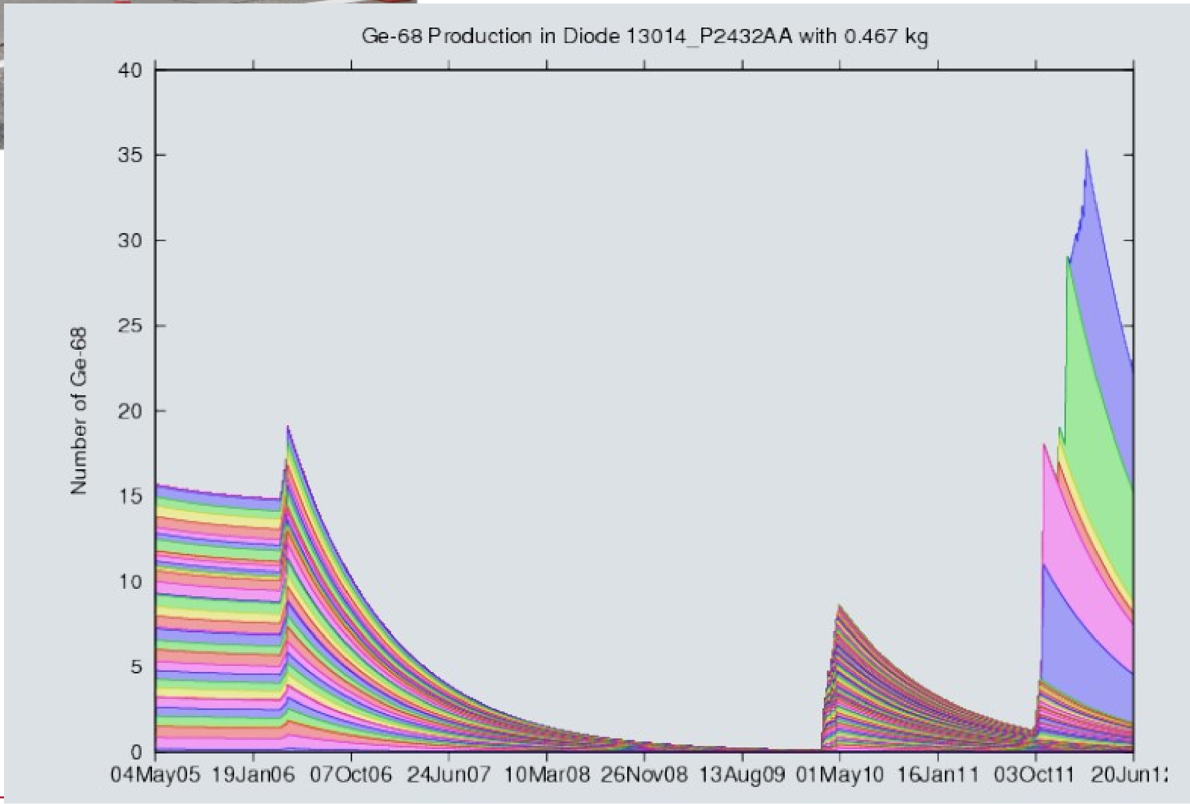
1) Isotope enrichement at ECP, Svetlana (Ru)



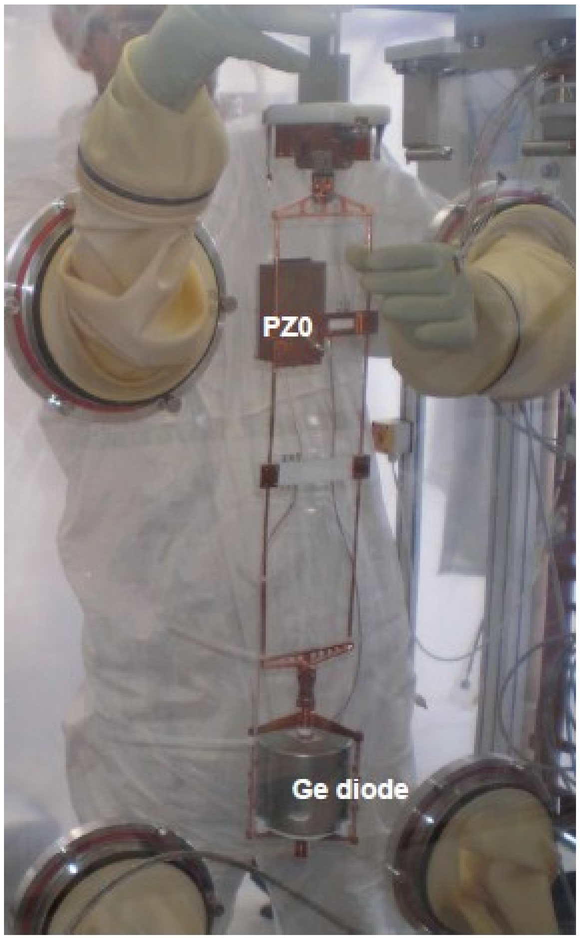
To minimize activation by cosmic ray:

- Transportation by truck or ship in shielded containers
- deep underground storage




Ge-68 Production in Diode 13014_P2432AA with 0.467 kg
Number of Ge-68
0
5
10
15
20
25
30
35
40
04May05
19Jan06
07Oct06
24Jun07
10Mar08
26Nov08
13Aug09
01May10
16Jan11
03Oct11

mounting diodes

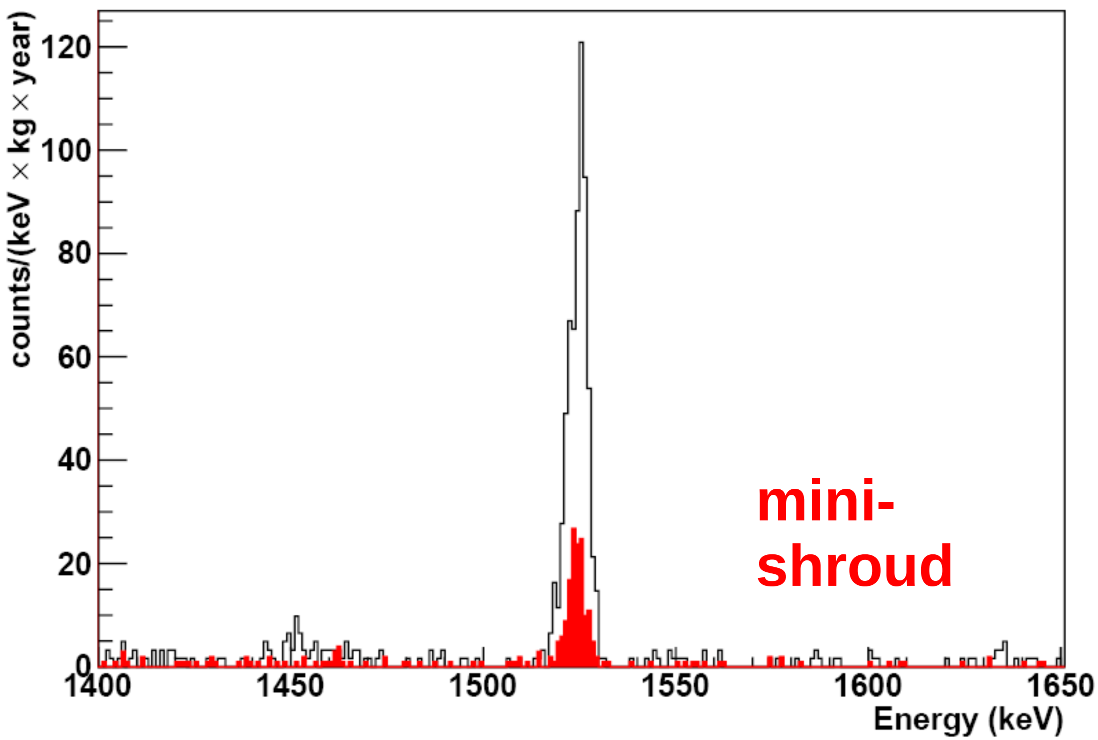


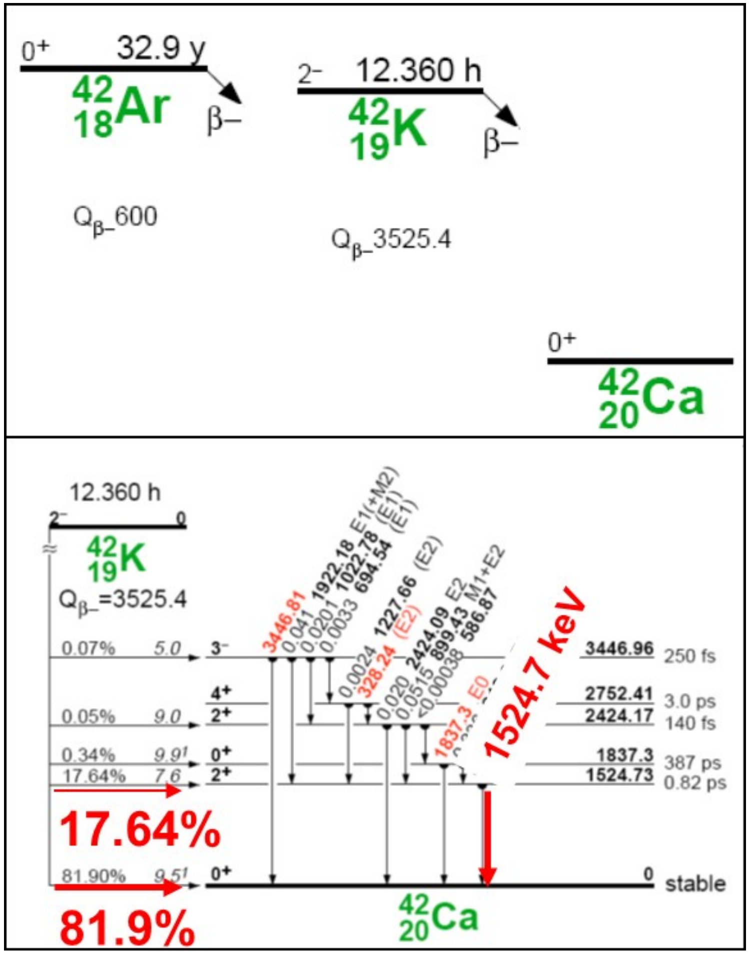
note distance between diode and preamplifier

^{42}Ar

GERDA proposal: $^{42}Ar/^{nat}Ar$ < 3 10^{-21}
Barabash et al (2002)

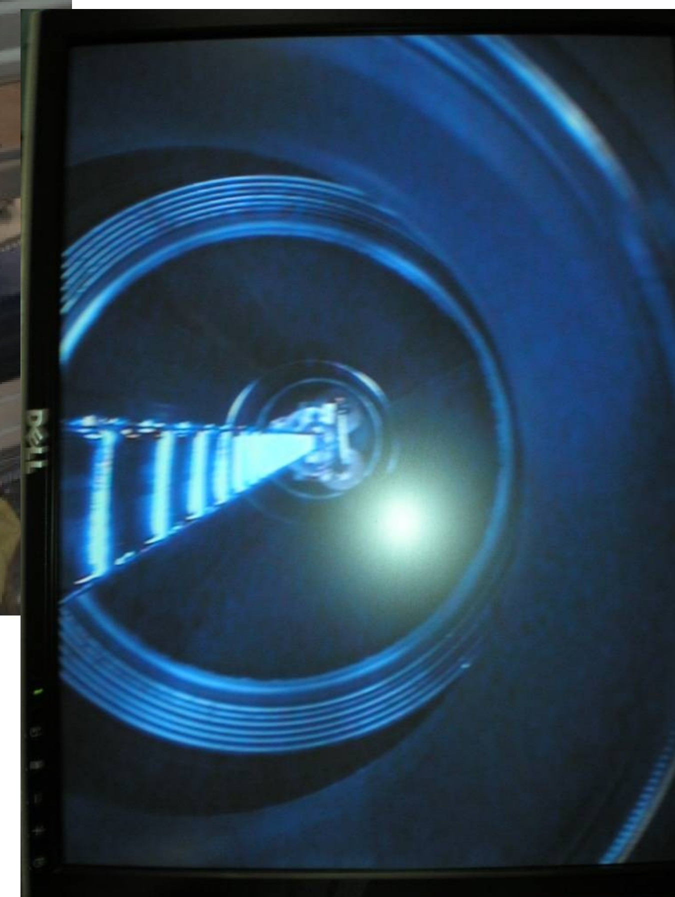
GERDA measurement





GERDA result:
true value ~2 times higher

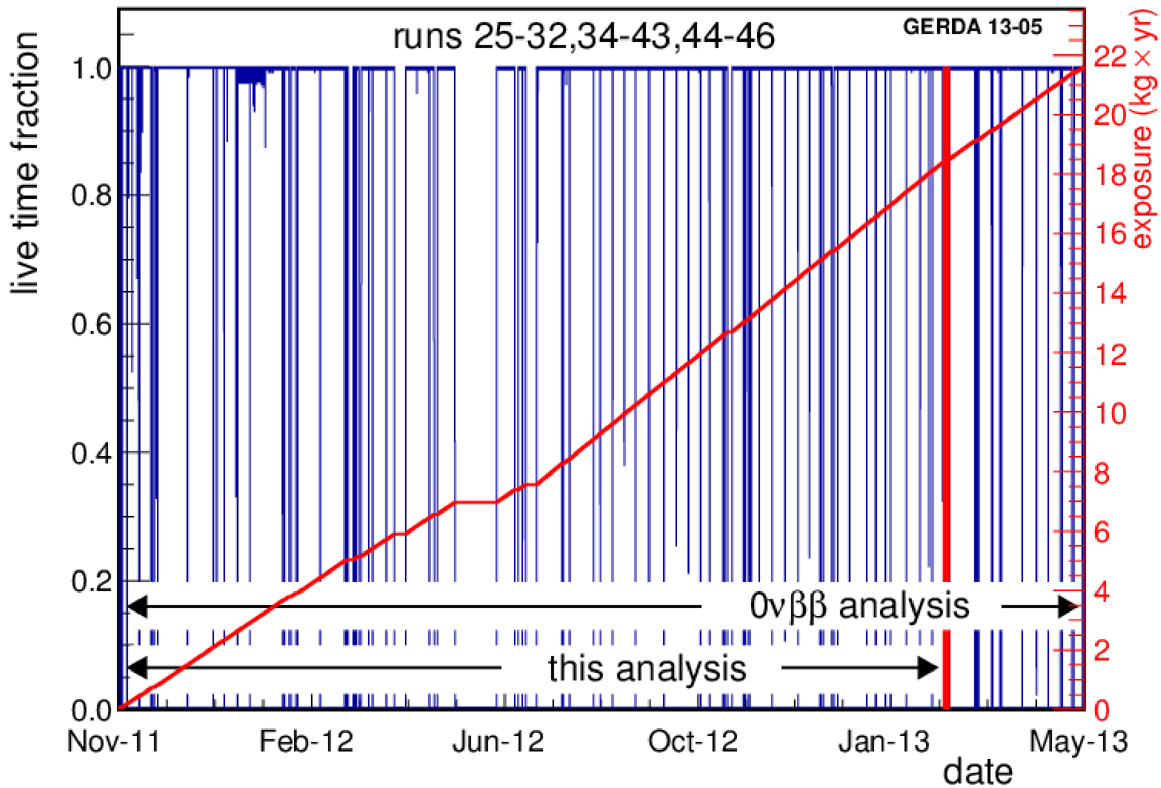
inserted of 1 & 3 string arm: total of 8 enriched + 3 natural diodes in October 2011

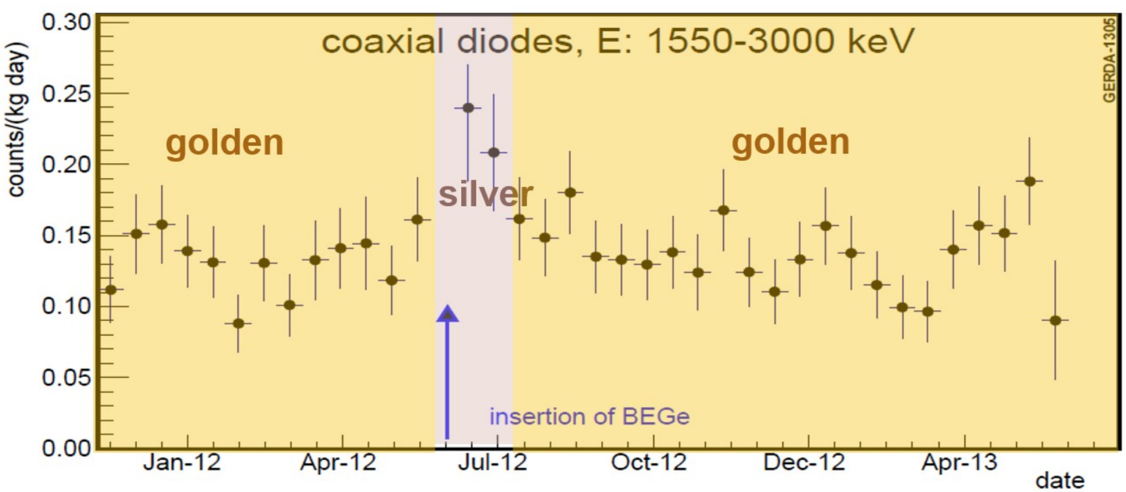


2 enriched detectors had problems from the very beginning, removed from physics analysis:

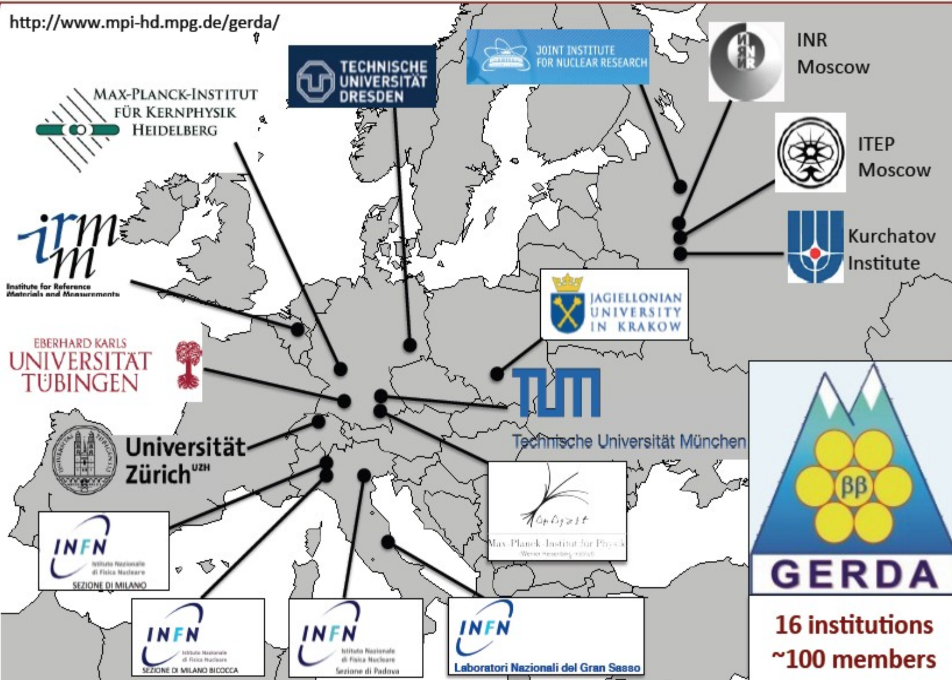
6 enriched detectors with 14.6 kg total mass
3 natural detectors with 7.6 kg total mass

add 5 BEGe detectors





3 data sets:
- golden
- silver
- BEGe

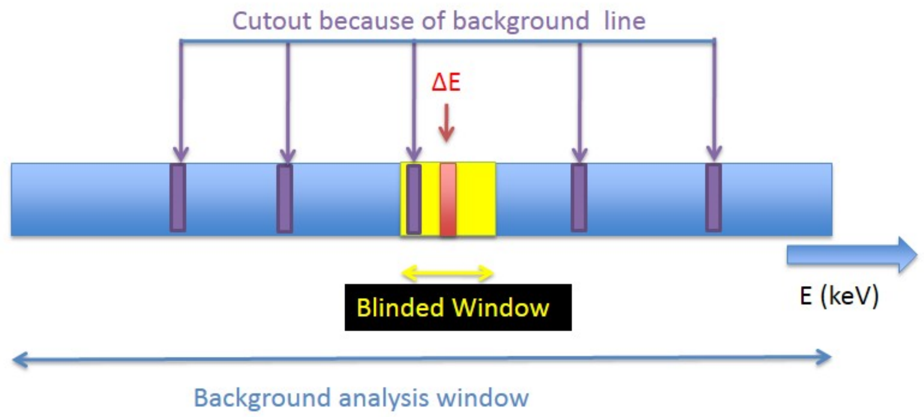


Dubna, June 2013

analysis: blinding & publications

blinding of data within $Q_{\beta\beta} \pm 20$ keV

[raw data copied to backup; but not converted to analysis standard MGDO]



EPJC 73 (2013) 2330 the GERDA experiment (setup)

JPG 40 (2013) 035110 $T_{1/2}^{2\nu} = 1.84\ (^{+14}/_{-10}) \times 10^{21}$ yr

EPJC accepted the background & models arXiv:1306.5084

EPJC accepted PSD: pulse shape for coax & BEGe arXiv:1307.2610

unblinding after fixing the parameters/procedures (@ Dubna meeting June 2013)

spectra with/without PSD uncovered @ Dubna

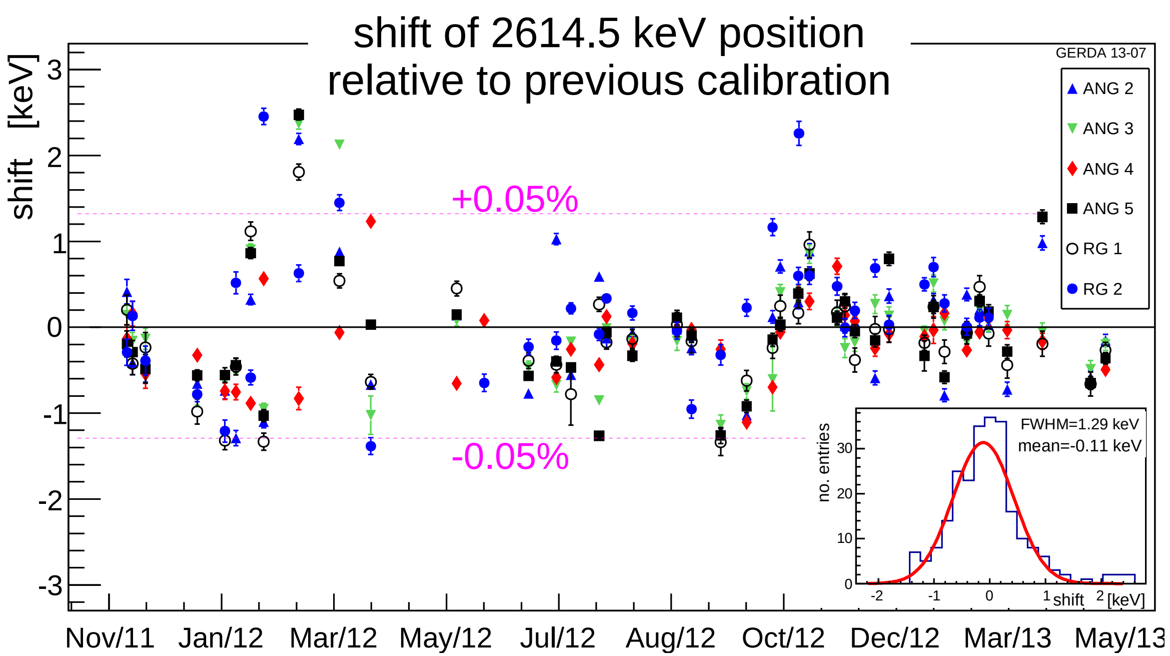
PRL 111 (2013) limit for $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

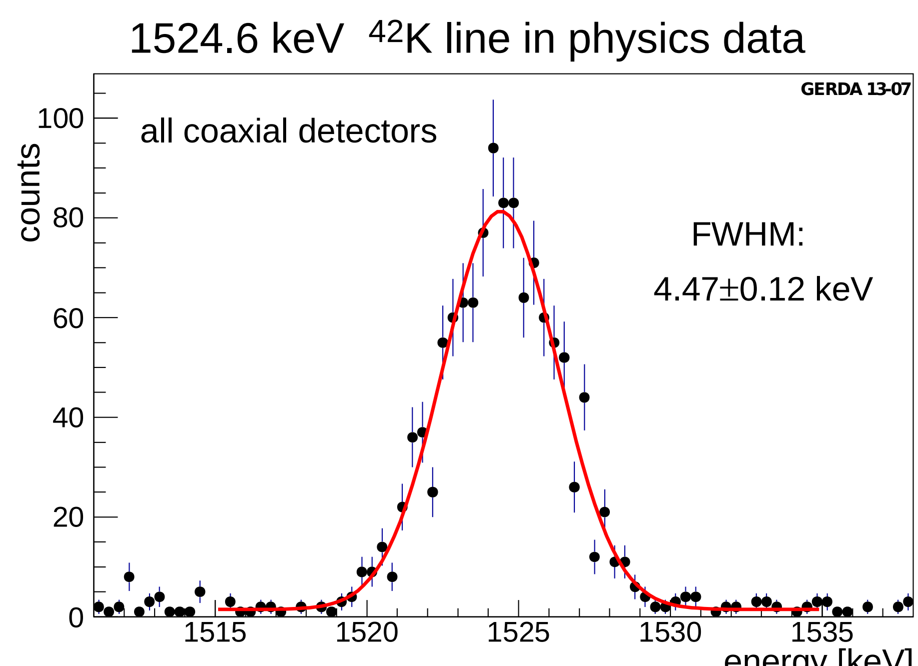
calibration & data processing

processing: diode → amplifier → FADC → filter → energy, rise time, PSD

selection: anti-coincidence muon / 2nd Ge (~20% rejected, @ $Q_{\beta\beta}$), quality cuts (~9% reject), pulse shape discrimination (~50% reject)

calibration: ^{228}Th (bi)weekly & pulser every 20 seconds for short term drifts

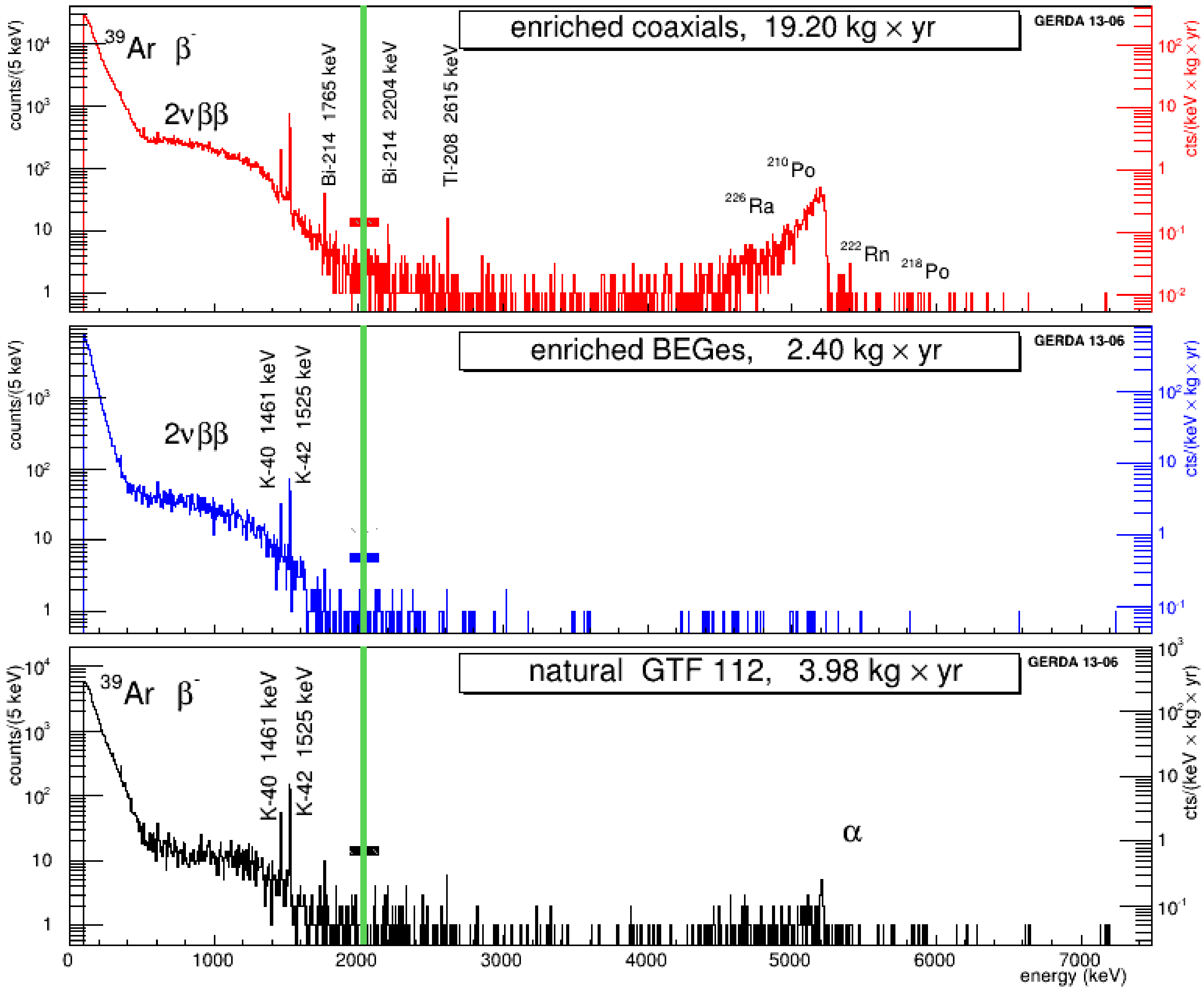




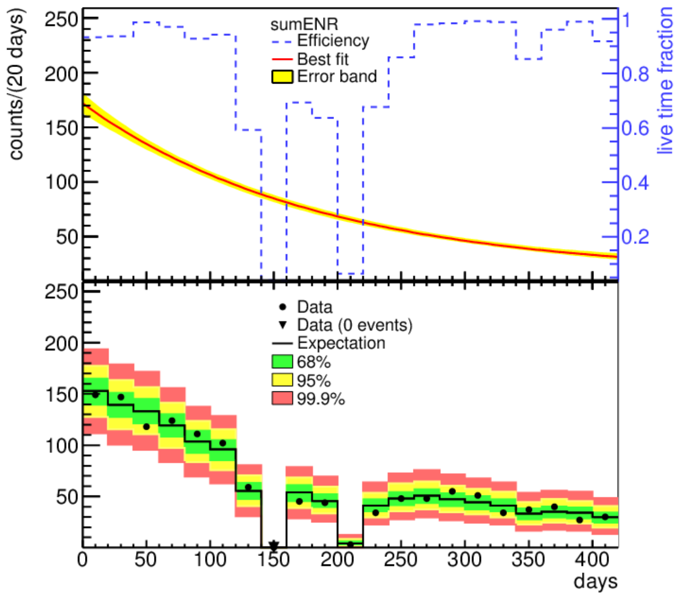
shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$

peak pos. within 0.3 keV at correct position
FWHM ~ 4% larger than expected from calibration data

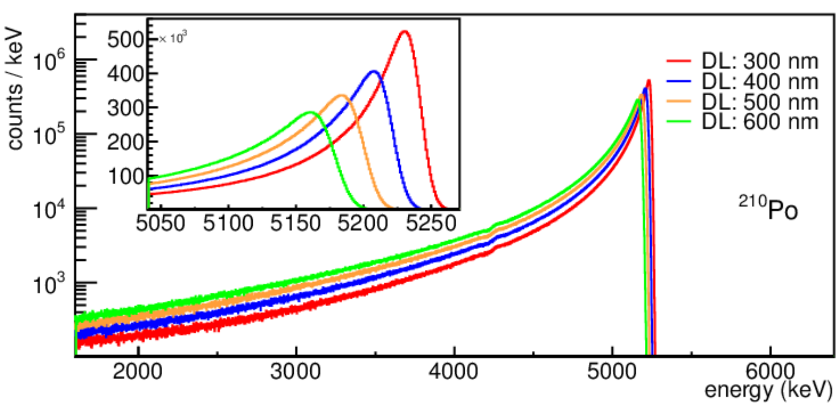
summed electron energy spectra



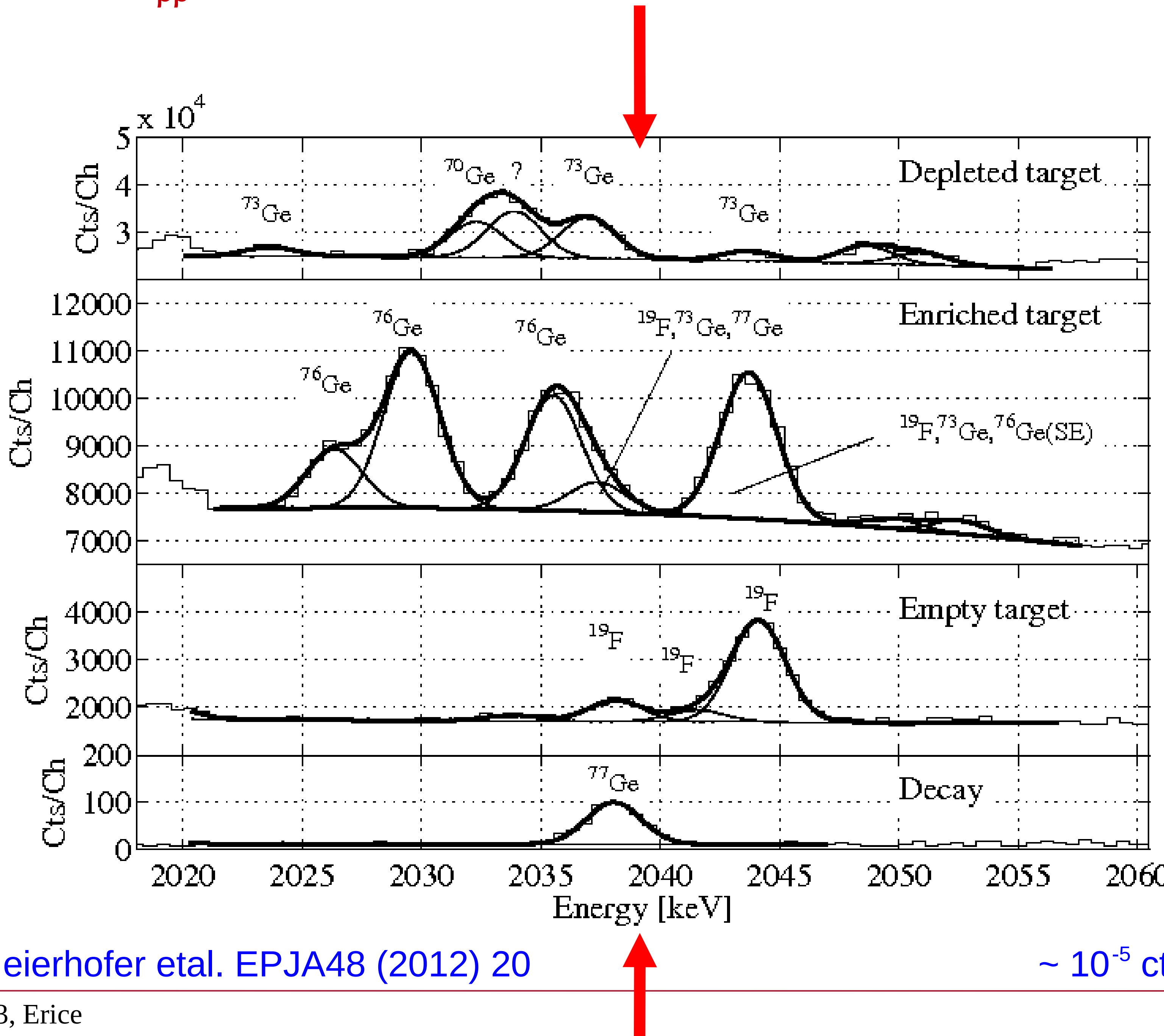
backgrounds α & γ



isotope	energy [keV]	^{enr}Ge (6.10 kg yr) tot/bck [cts]	rate [cts/(kg yr)]	HdM (71.7 kg yr) rate [cts/(kg yr)]
^{40}K	1460.8	125/42	$13.5^{+2.2}_{-2.1}$	181 ± 2
^{60}Co	1173.2	182/152	$4.8^{+2.8}_{-2.8}$	55 ± 1
	1332.3	93/101	<3.1	51 ± 1
^{137}Cs	661.6	335/348	<5.9	282 ± 2
^{228}Ac	910.8	294/303	<5.8	29.8 ± 1.6
	968.9	247/230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1
^{208}Tl	583.2	333/327	<7.6	36 ± 3
	2614.5	10/0	$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5
^{214}Pb	352	1770/1688	$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8
^{214}Bi	609.3	351/311	$6.8^{+3.7}_{-4.1}$	105 ± 1
	1120.3	194/186	<6.1	26.9 ± 1.2
	1764.5	24/1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7
	2204.2	6/3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5



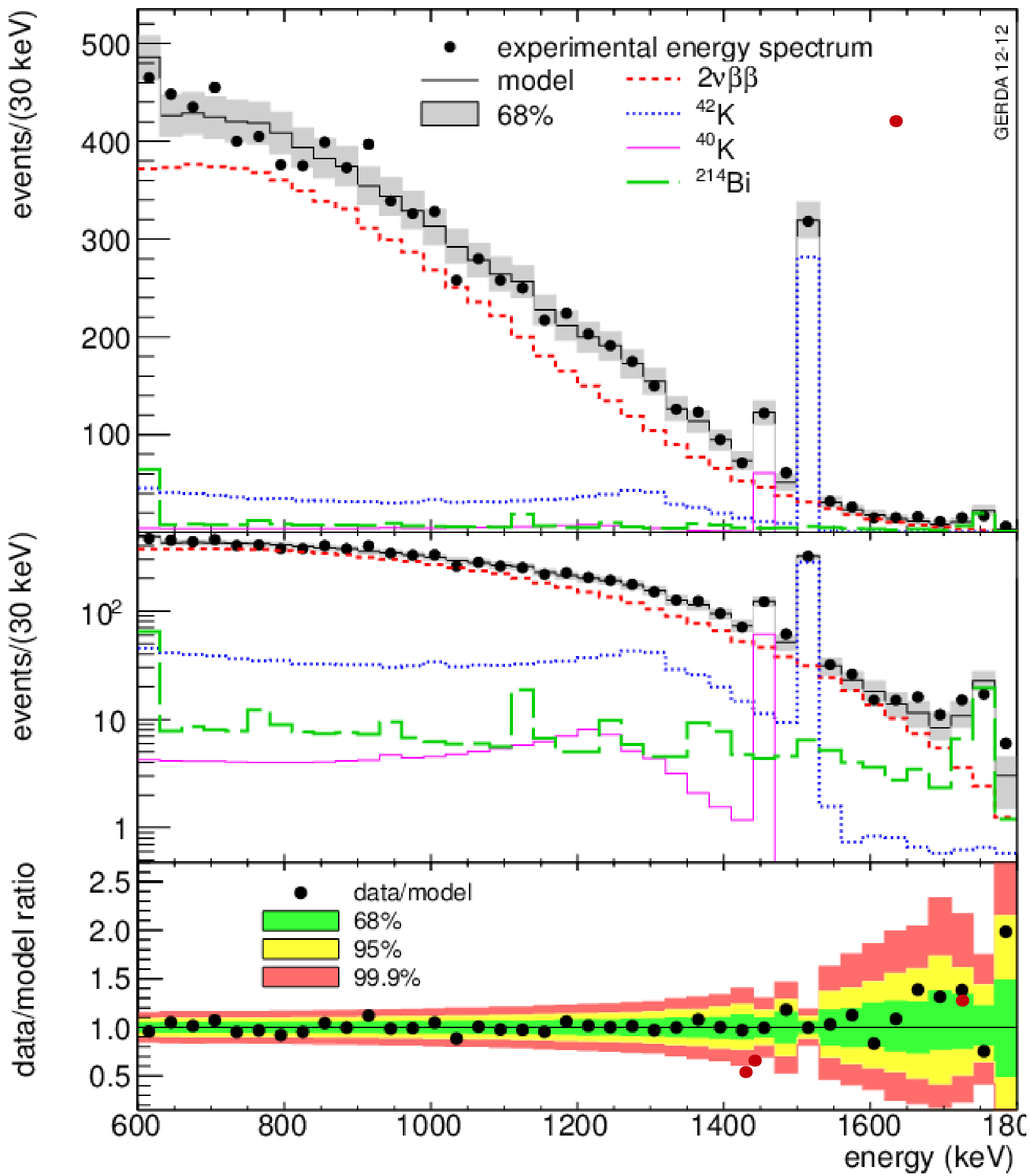
(n,γ) in the $Q_{\beta\beta}$ region

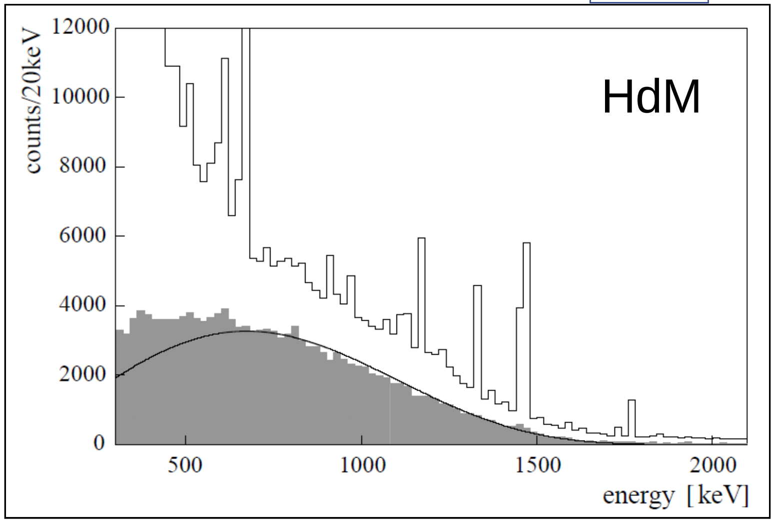


G. Meierhofer etal. EPJA48 (2012) 20

~ 10^{-5} cts/(keV kg yr)

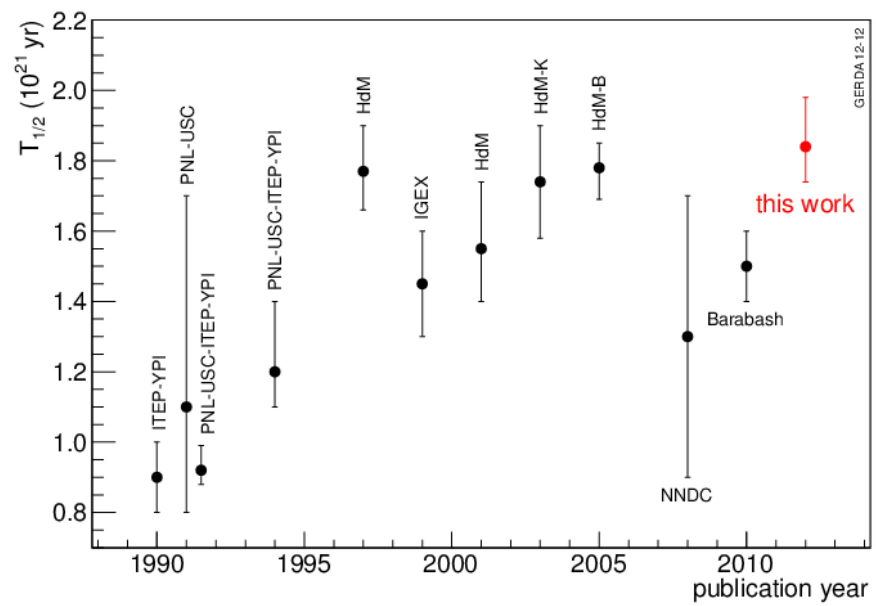
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

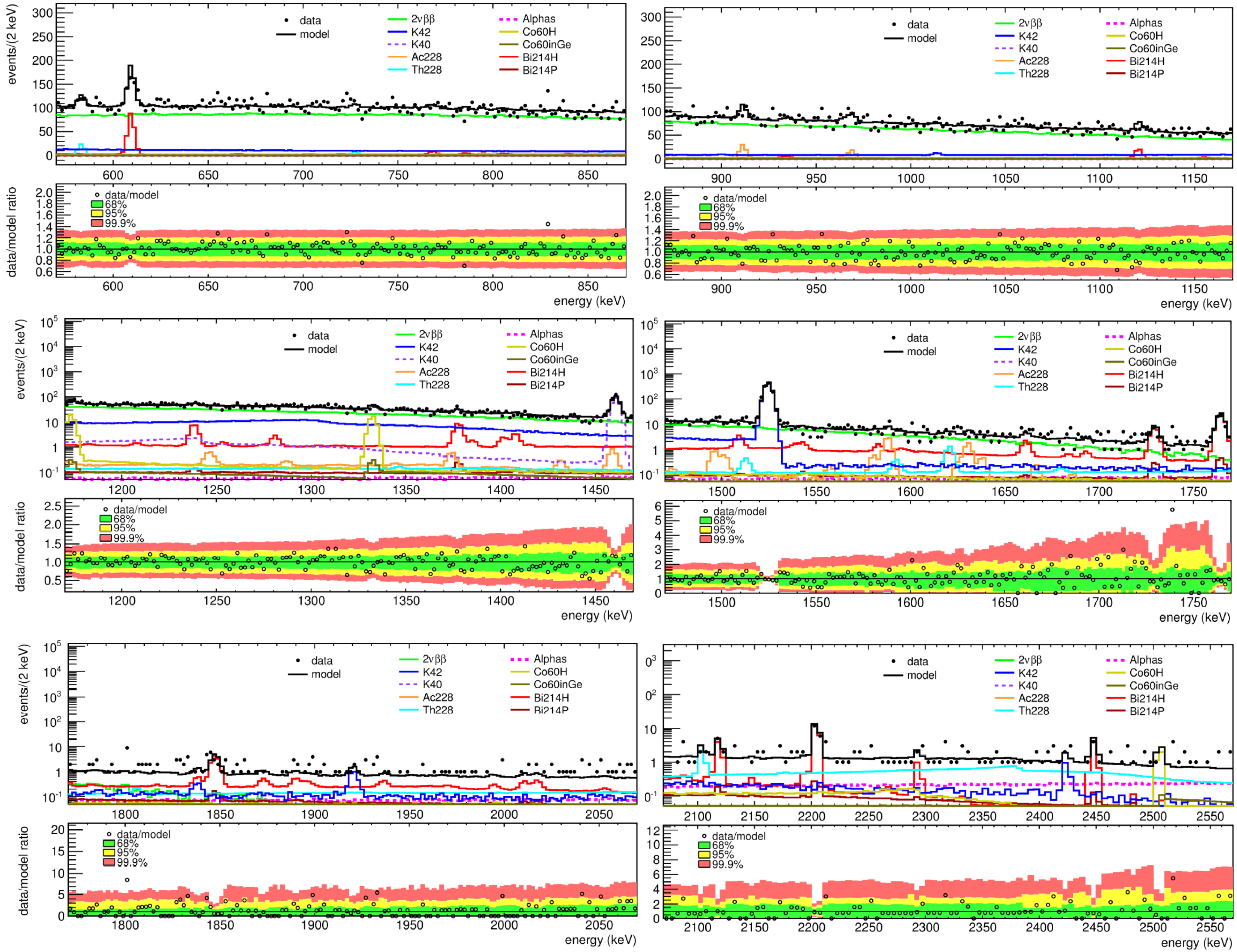




5.04 kg yr exposure

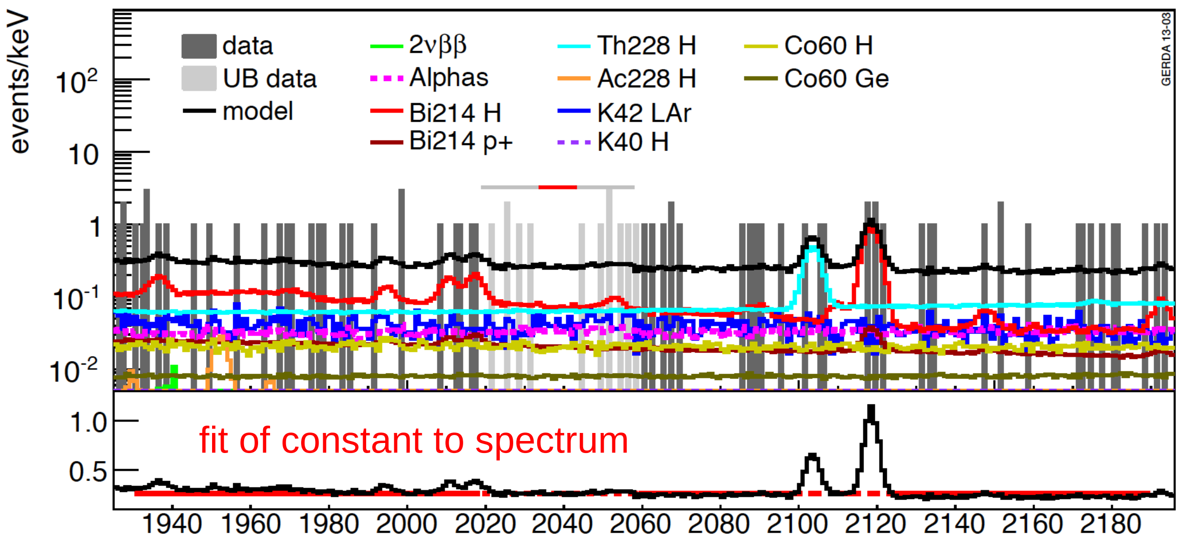
$T_{1/2}^{2\nu} = 1.84\ (^{+14}/_{-10}) \cdot 10^{21}$ yr



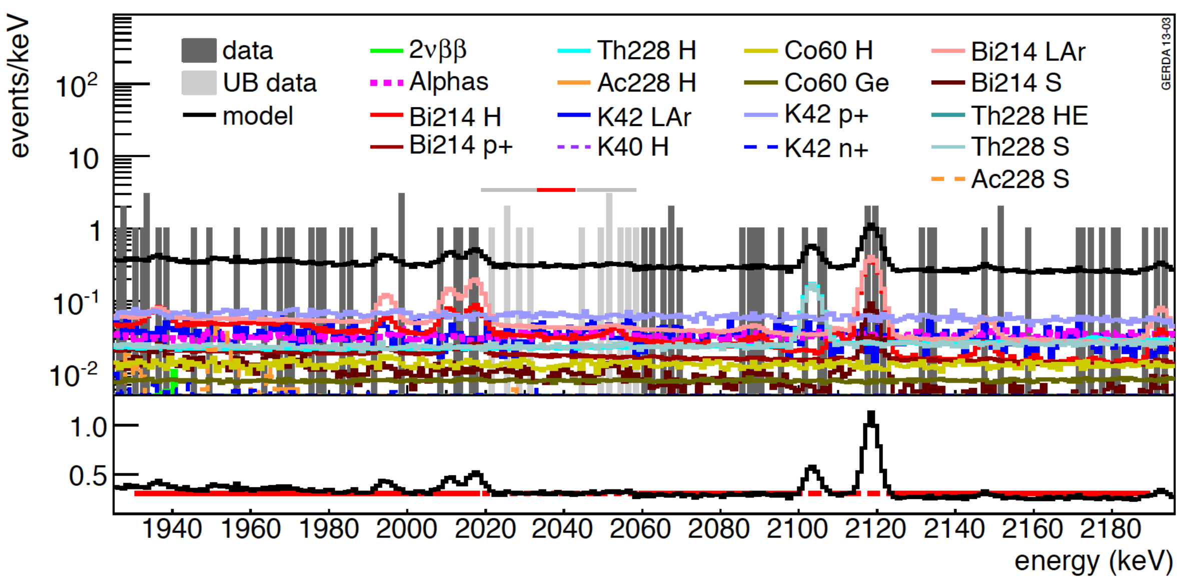

data
model
2νββ
K42
K40
Ac228
Th228
Alphas
Co60H
Co60inGe
Bi214H
Bi214P
events/(2 keV)
data/model ratio
data/model
68%
95%
99.9%
energy (keV)

background model @ $Q_{\beta\beta}$

"minimal fit" (all known contributions)



"maximum fit" (many possible contributions added)



blinded window (grey+red)

No line expected in blinding region

background flat between
1930-2190 keV
(without 2104±5 keV,
without 2119±5 keV),

expect << 1 event in other weak ^{214}Bi lines (e.g. 2017, 2053 keV)

partial unblinding (grey window)
after fixing of calibration & bkg model,
no line in grey interval,
expected 8.6-10.3 evts in grey part &
see 13 events

findings

total exposure of 21.6 kg yr between Nov. 2011 and May 2013

3 data sets: golden, silver, BEGe

weekly calibration runs with ^{228}Th source

mean resolution at 2 MeV: coax 4.8 keV, BEGe 3.2 keV FWHM (50 cm diode-CC2)

energy scale stable within ±1.3 keV

the strongest gamma line is 1525 keV from ^{42}K

dominated by ^{214}Bi and ^{228}Th

nearby sources (det. holders etc.) and surface contaminations

far sources do not matter

background flat between 1930-2190 keV

pulse shape discrimination (PSD)

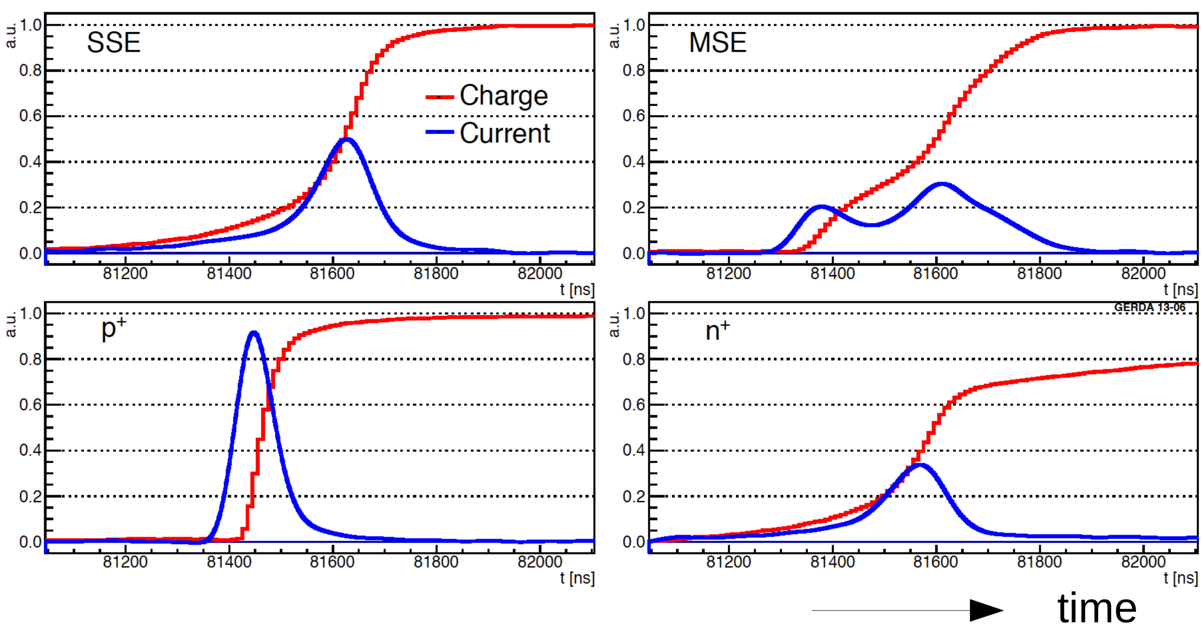
pulse shape discrimination to select $0\nu\beta\beta$ events

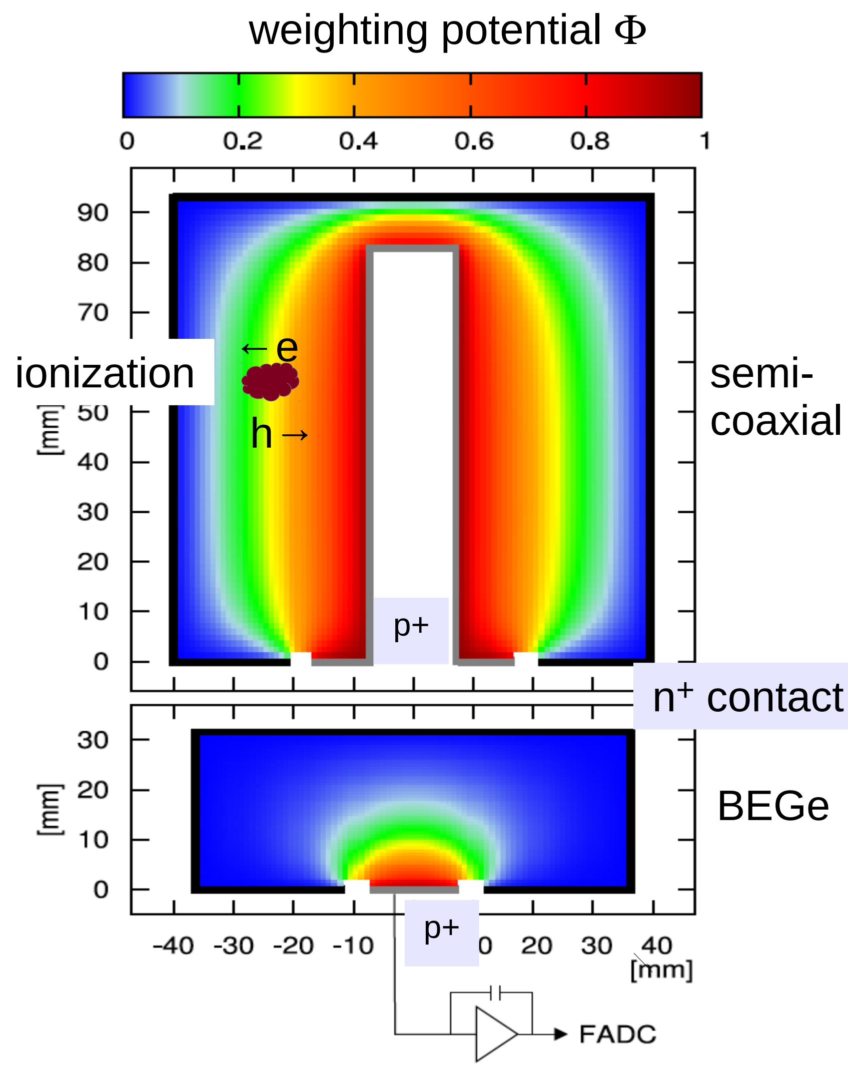
$0\nu\beta\beta$ events: range of 1 MeV electrons in Ge is ~1 mm
→ single drift of electrons & holes, single site event (SSE)

background from γ's: range of MeV γ in Ge >10x larger
→ often sum of several electron/hole drifts,
multi site events (MSE)

surface events: only electrons or holes drift

charge and current signal for BEGe detectors (data events)





$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

(Shockley-Ramo theorem)

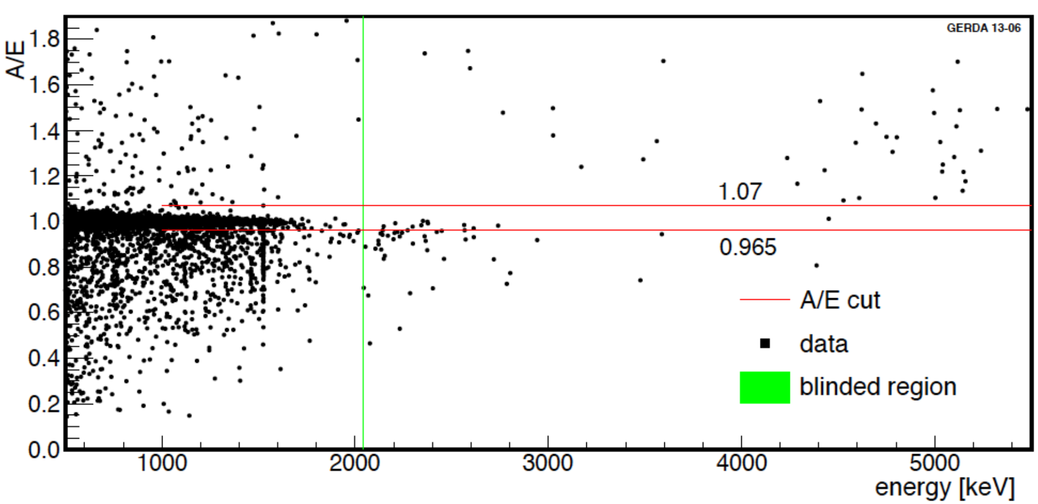
PSD for BEGe

use double escape peak (DEP) of ^{228}Th spectrum as proxy (two 511 γ escape detector!) for 0νββ

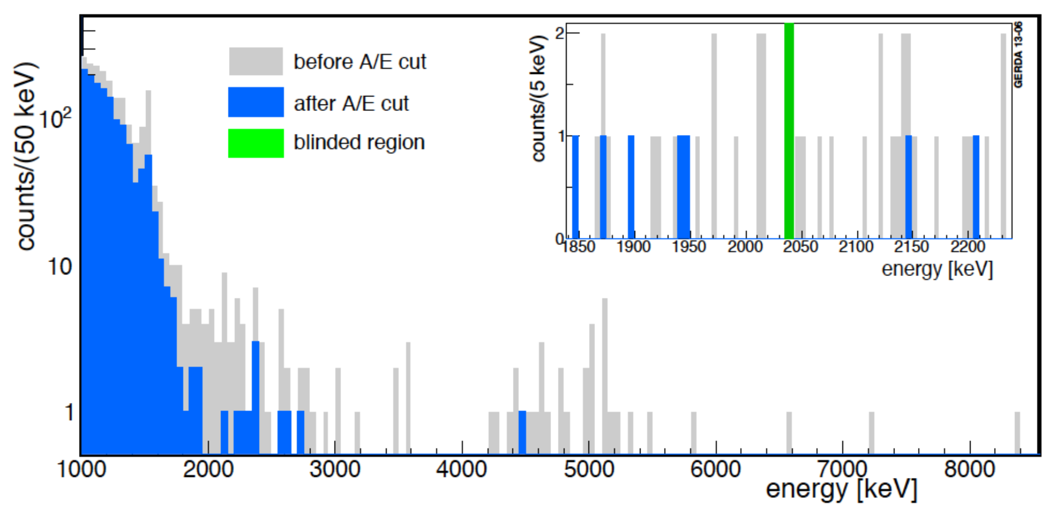
aim: develop the PSD method with ^{228}Th calibration data and then apply it to physics data

Method: A/E = max. of current pulse “A” / energy “E” is robust & simple & well understood
accept events 0.965 < A/E < 1.07 (normalization A/E for DEP events = 1)

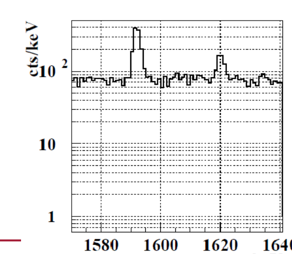
A/E versus E for physics data



spectrum before (grey) & after (blue) cut

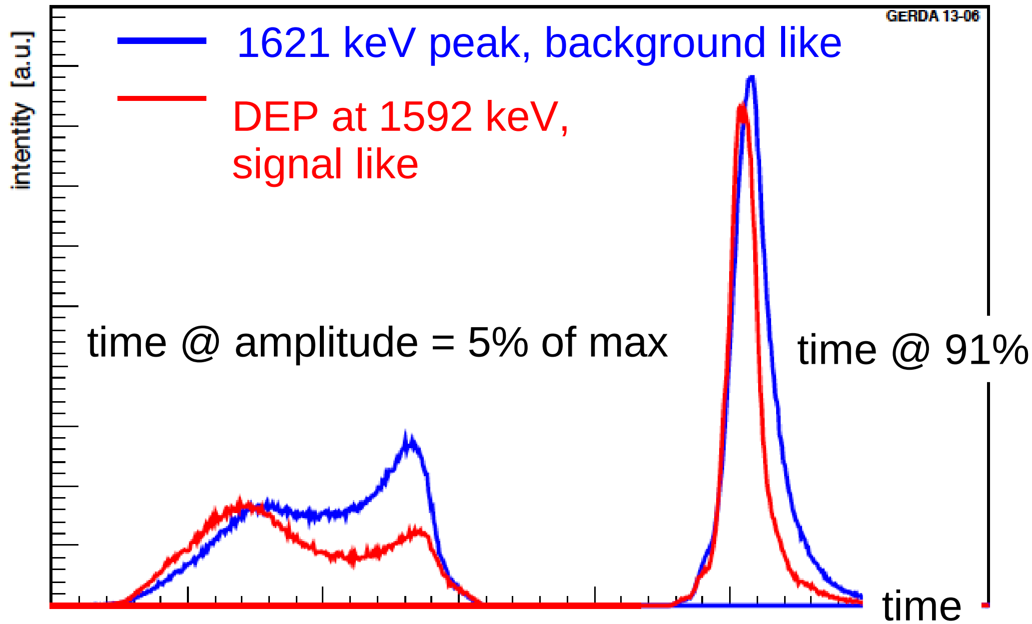


0νββ efficiency = 92±2 % determined from DEP efficiency & simulation
2νββ efficiency = 91±5 % in good agreement to DEP efficiency
reject >80% of background events



PSD for semi-coaxial: neural network (ANN)

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



tested many methods implemented in TMVA, selected artificial neural network TMlpANN

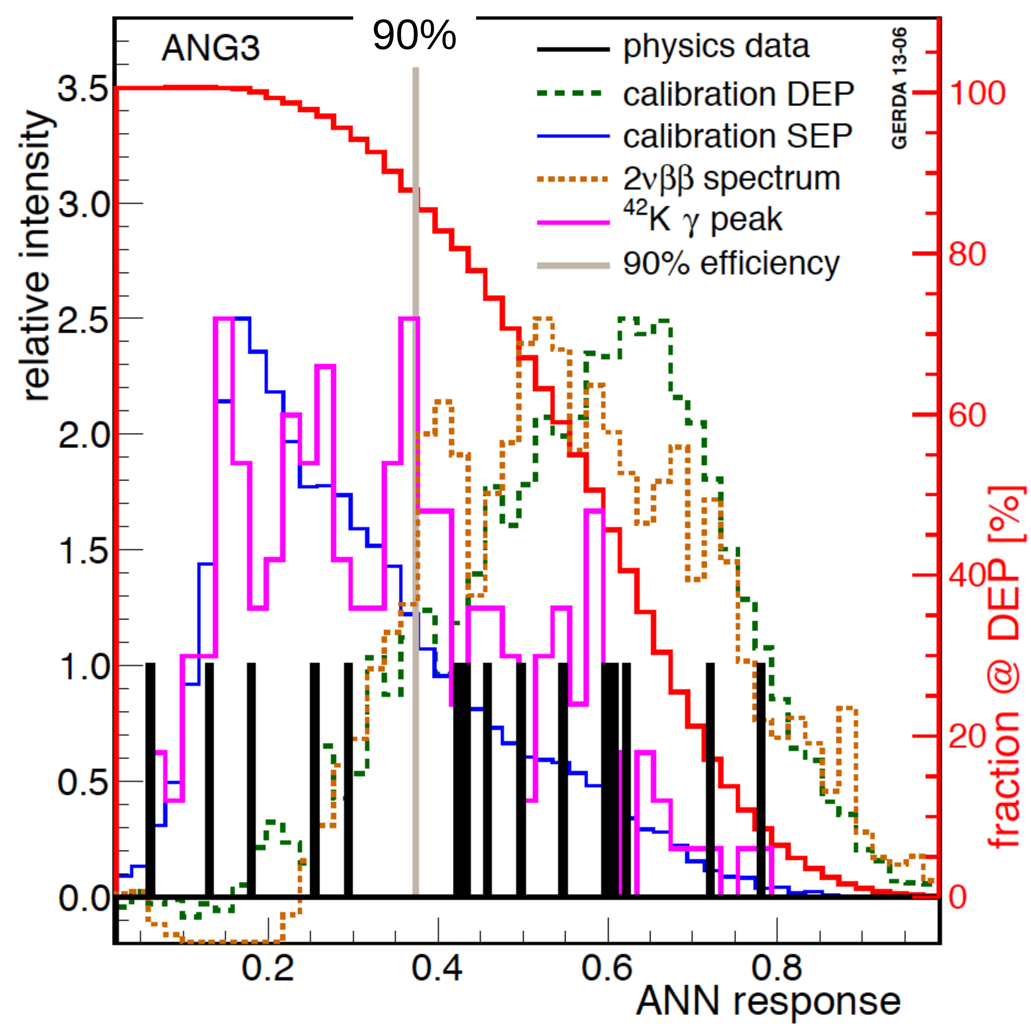
select **ANN** cut position @ DEP survival = 90%

cross checks:
$2\nu\beta\beta$ eff. = 85±2 %,
Compton edge eff. = 85-94%,
^{56}Co DEP (1576 keV) eff. = 83%-95%
^{56}Co DEP (2231 keV) eff. = 83%-93%

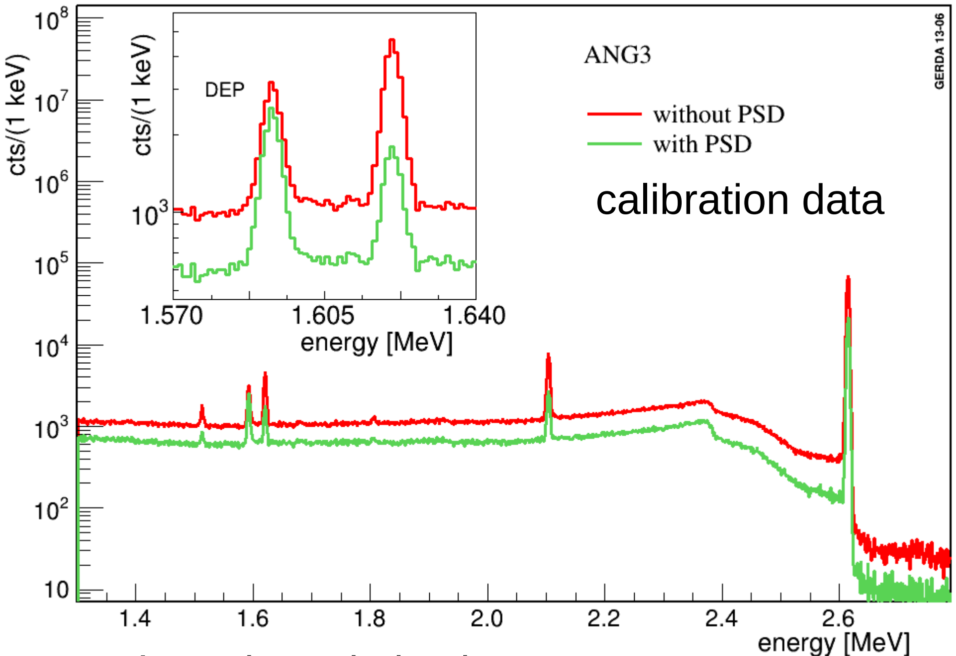
$$0\nu\beta\beta\,\text{efficiency} = 0.90^{+0.05}_{-0.09}$$

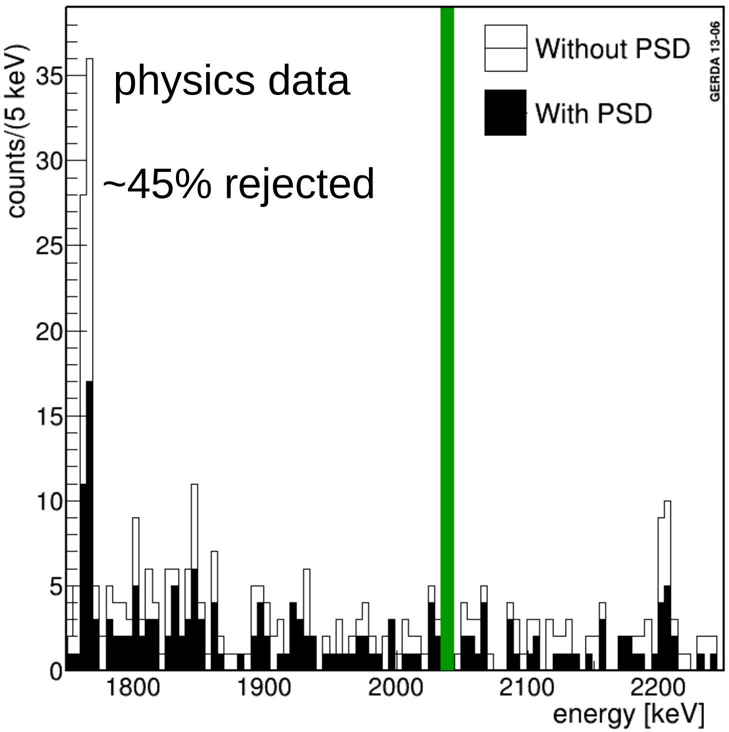
example: ANG3 ANN response, 1st period

DEP survival

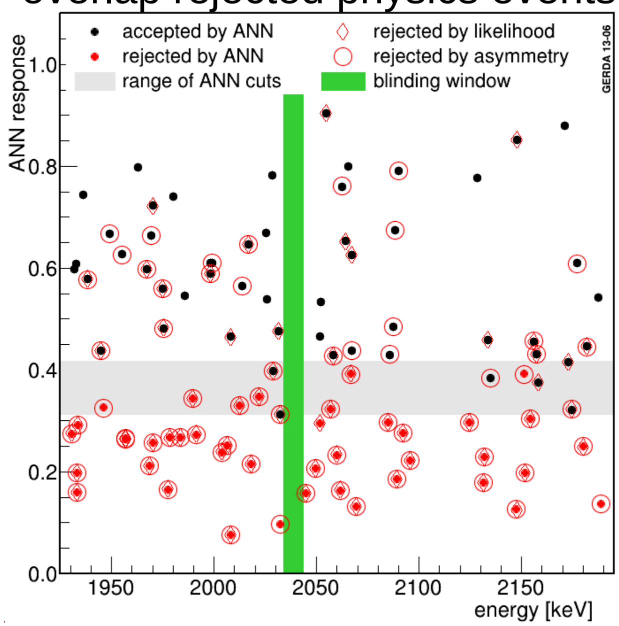


PSD for semi-coaxial





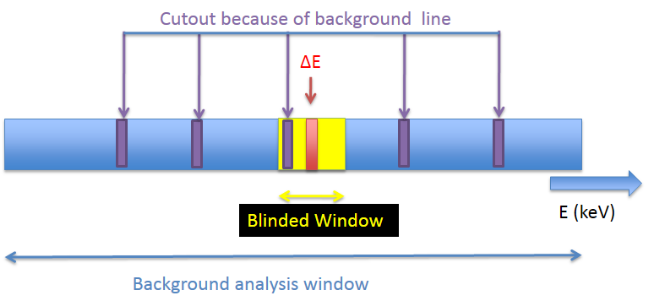
overlap rejected physics events

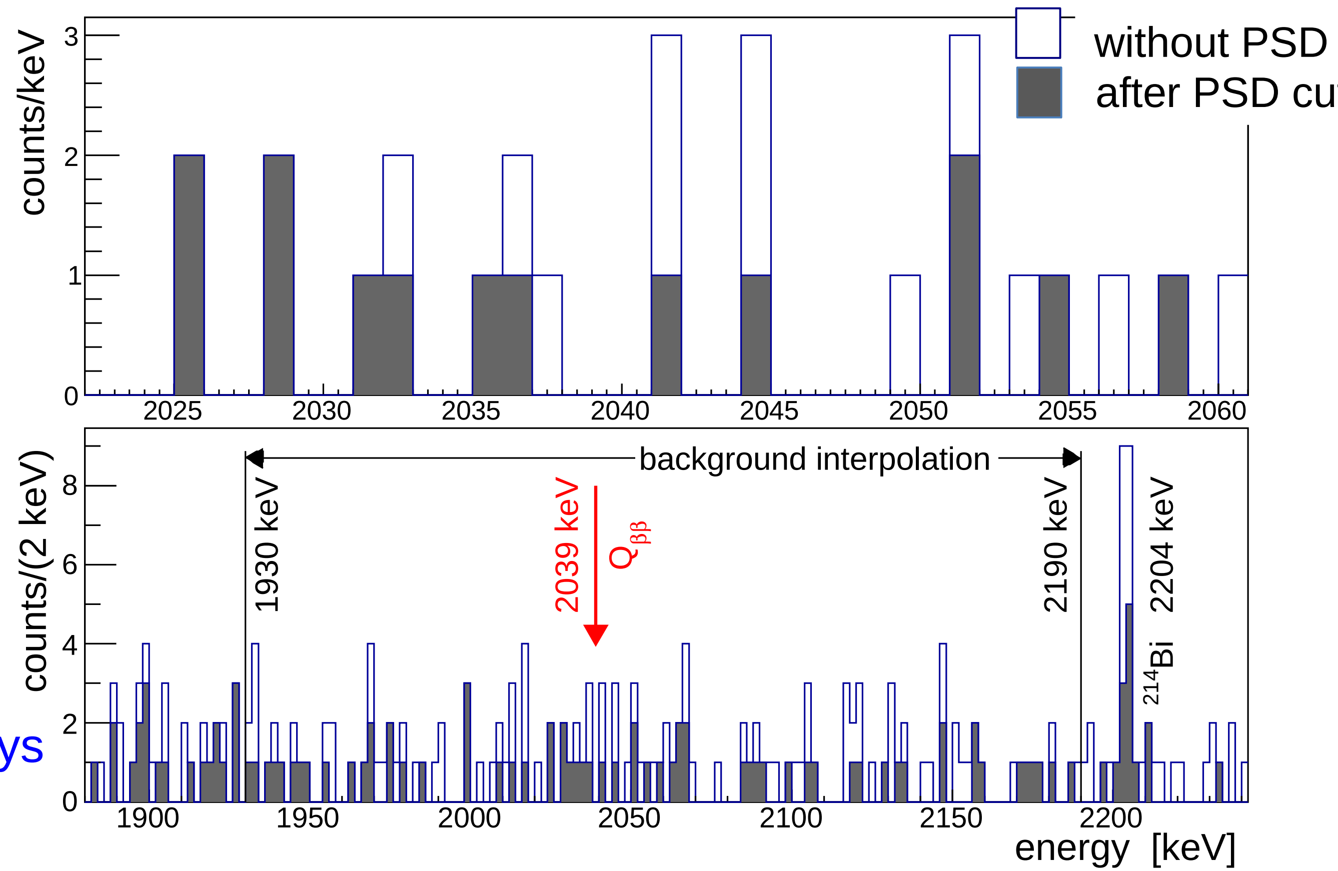


cross check ANN classification with 2 other methods:
1) projective likelihood trained with Compton edge evt
2) “current pulse asymmetry * A/E”

90% of ANN rejected events also rejected by both,
3% only rejected by ANN
→ classification of background like events meaningful

unblinding





calibration & stability
data sets defined
background model
PSD parameters fixed
analysis methods defined

whole collaboration during 4 days
unblinding of final ±5 keV

evt cnt in ±5 keV	golden	silver	BEGe	total
expt. w/o PSD	3.3	0.8	1.0	5.1
obs. w/o PSD	5	1	1	7
expt. w/ PSD	2.0	0.4	0.1	2.5
obs w/ PSD	2	1	0	3

no peak in spectrum at $Q_{\beta\beta}$,

event count consistent with bkg,
→ GERDA sets a limit

half life limit for ^{76}Ge $0\nu\beta\beta$

$$T^{0\nu}_{1/2} = \frac{\ln 2 \cdot N_A}{m_{enr} \cdot N^{0\nu}} M \cdot t \cdot f_{76} \cdot f_{av} \cdot \epsilon_{fep} \cdot \epsilon_{psd}$$

exposure averaged efficiencies

data set	$M*t$	f_{76}	f_{av}	ε_{fep}	ε_{psd}
golden	17.9 kg yr	0.86	0.87	0.92	0.90
silver	1.3 kg yr	0.86	0.87	0.92	0.90
BEGe	2.4 kg yr	0.88	0.92	0.90	0.92

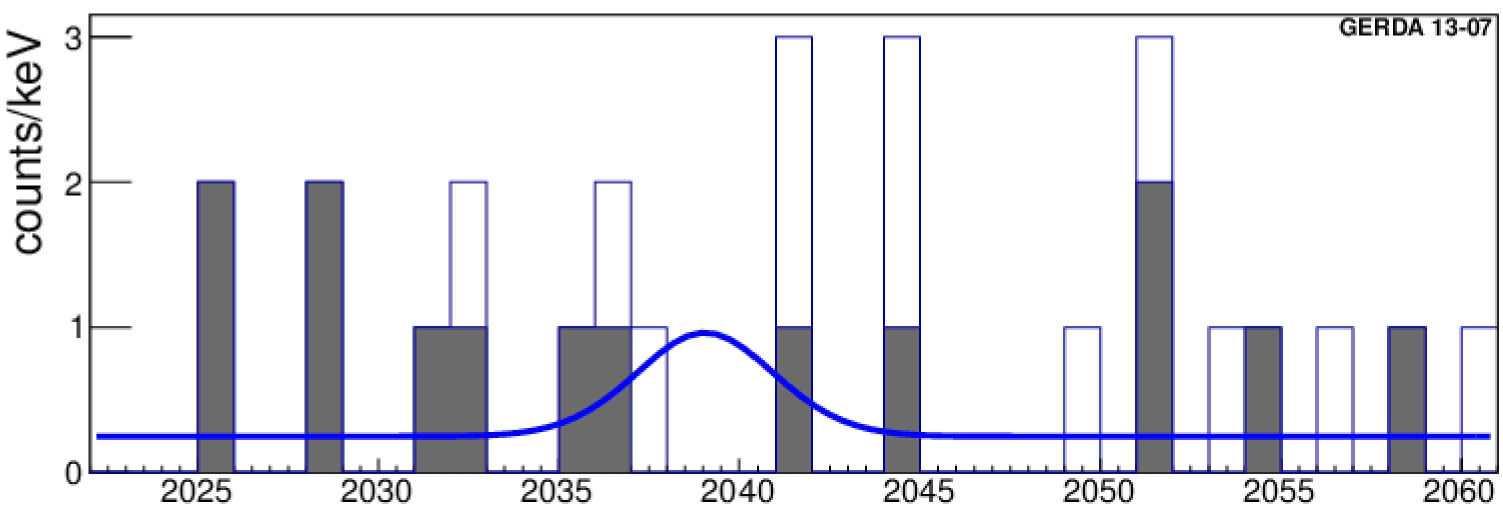
fit 3 data sets in 1930-2190 keV interval: constant (for bkg) + gauss (for signal),

4 parameters: 3x bkg level & $1/T^{0\nu}$
$1/T^{0\nu} > 0$ constrain

fix gaussian μ=(2039.06±0.2) keV, σ=(2.0±0.1)/(1.4±0.1) keV for coax/BEGe

systematic uncertainties on f, ε, μ, σ: Monte Carlo sampling & averaging

frequentist: profile likelihood fit → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) (sensitivity = 2.4 10^{25} yr)

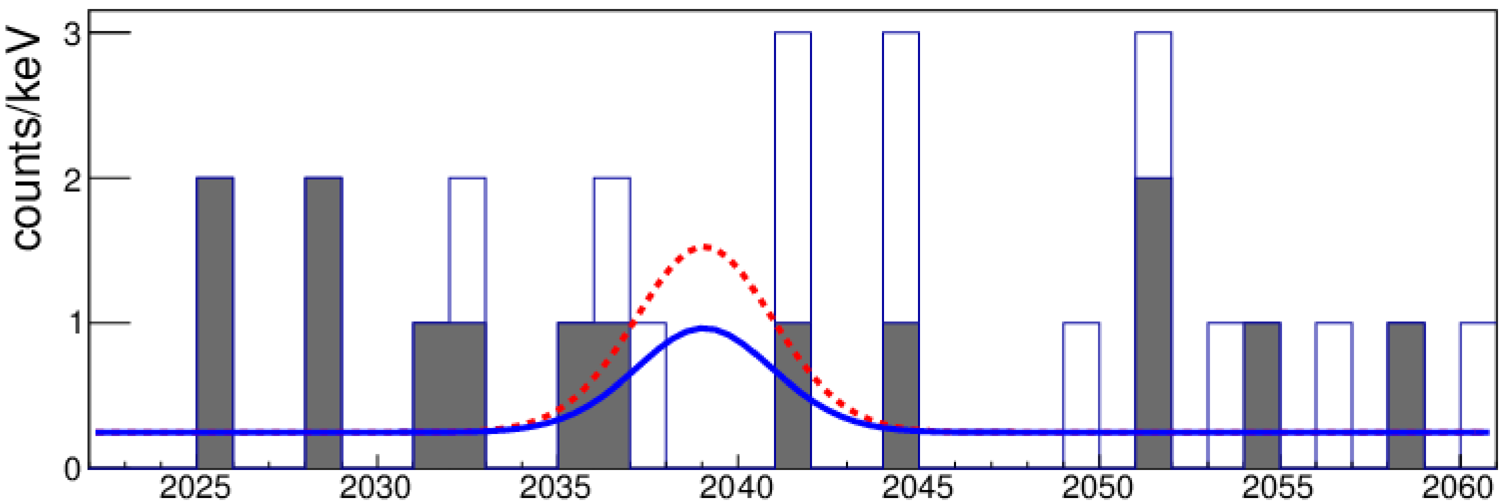


half life limit for ^{76}Ge $0\nu\beta\beta$

frequentist: profile likelihood fit → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) (sensitivity = 2.4 10^{25} yr)

Bayes: flat 1/T prior 0 - 10^{-24} yr → best fit $N^{0\nu}$=0, $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr (90% C.I.) (sensitivity = 2.0 10^{25} yr)

adding HdM [1] & IGEX[2] spectra to profile likelihood fit → $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge

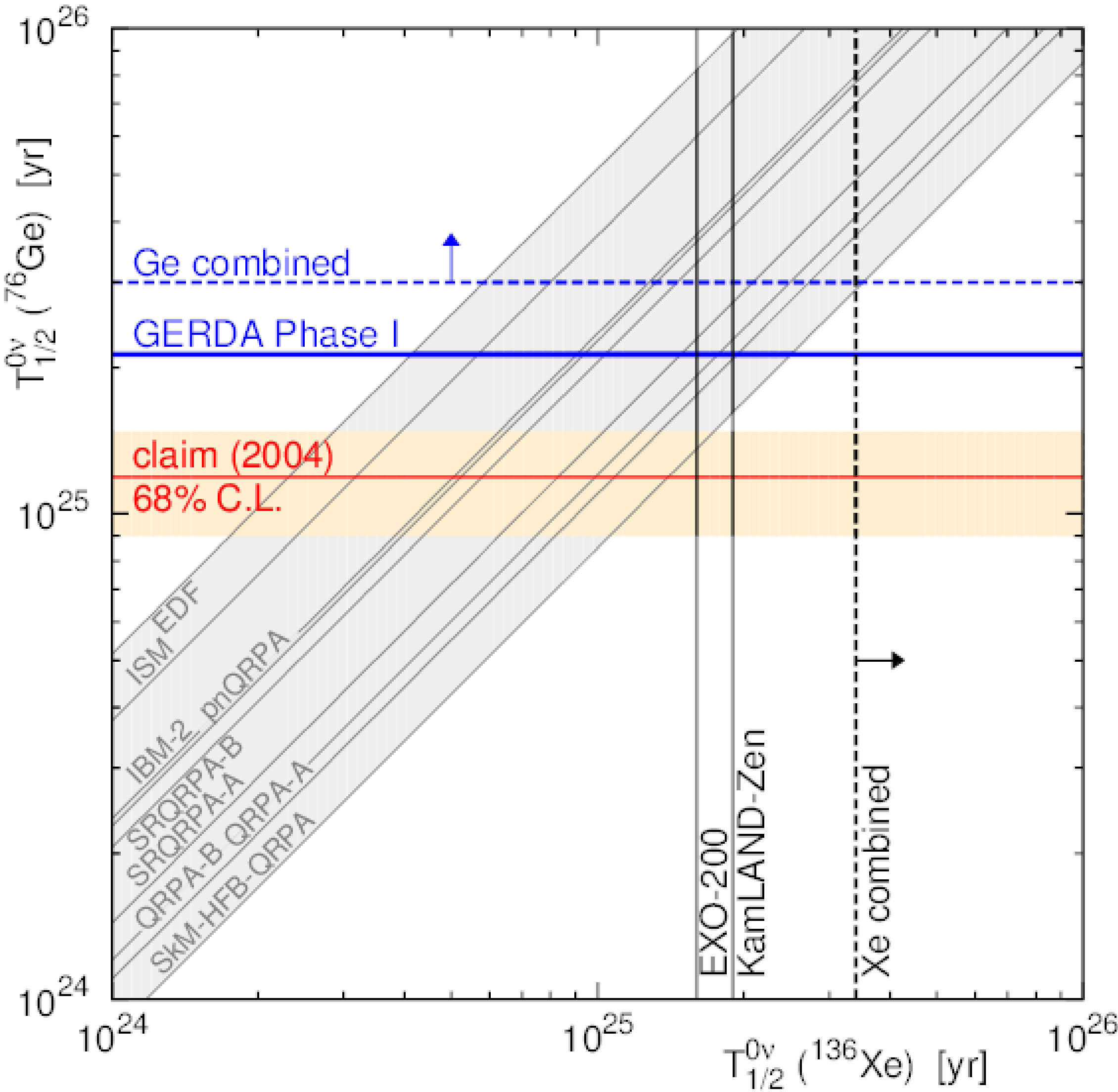


Assuming the claimed signal [3] then GERDA should see 5.9±1.4 $0\nu\beta\beta$ events in ±2σ interval above Bkg = 2.0±0.3,

→ probability p(N0n=0 | H1=signal+bkg) = 1%, claim ruled out @ 99%
→ Bayes factor H1(=signal+bkg) / H0(=bkg only) = 0.024

[1] Euro Phys J A12 (2001) 147. [2] Phys Rev D65 (2002) 092007. [3] $T_{1/2}(^{76}Ge)=1.19 \times 10^{25}$ yr, Phys Lett B586 (2004) 198.

comparison



include HdM & IGEX

model free: no NME needed

compare to Xe:

NME needed, which ?

smallest NME ratio ^{136}Xe/^{76}Ge ~ 0.4

⇒ weakest exclusion

gives total Bayes factor H1/H0 = 0.0022

→ claim of ^{76}Ge signal is strongly disfavored

summary

new experiments on $0\nu\beta\beta$

Kamland-Zen,EXO, GERDA, Majorana

^{136}Xe, ^{76}Ge

GERDA for ^{76}Ge

new $T_{1/2}^{2\nu} = 1.84\,(^{+14}/_{-10}) \cdot 10^{21}$ yr

new limit

$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

in 2013 we still do not know

.... if he is right

data taking Phase I stopped, new analysis with improved resolution
GERDA Phase II with add. 20 kg BEGe and LAr instrumentation
(A. Wegmann, 23.10.)