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

on behalf of the GERDA collaboration
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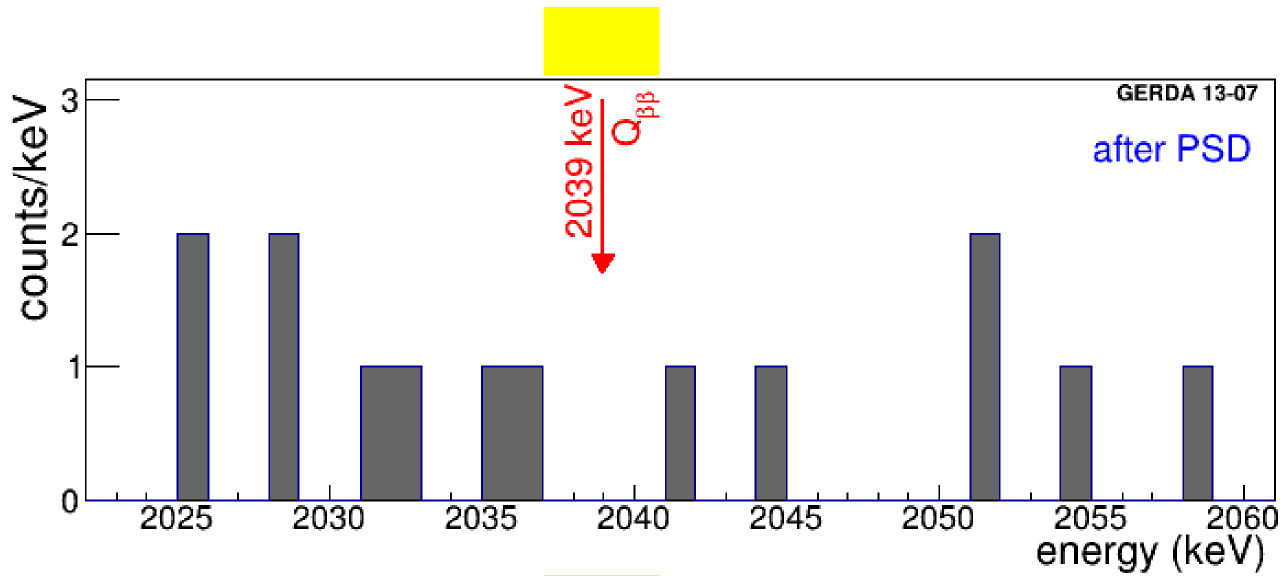
Eberhard Karls Universität Tübingen

Bad Honnef 22. April 2014

summed electron energy spectrum of GERDA Phase I



with PSD

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

no count !

resolution: ± 1σ (~4 keV)

outline:

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

search for properties of ν !

absolute mass scale, hierarchy

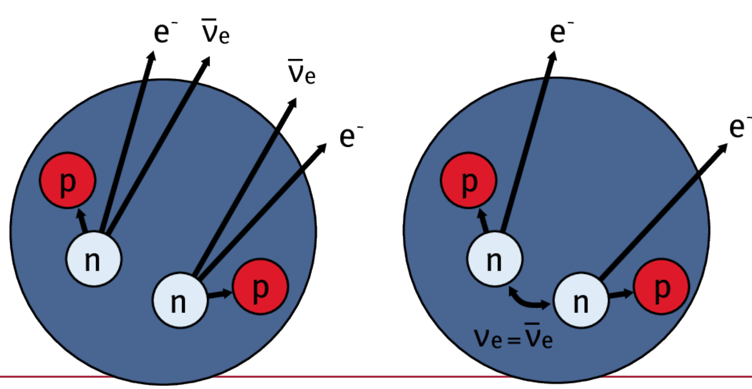
most interesting: is ν of Majorana type?

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

lepton number violation
extension to Standard Model
baryon asymmetry

0νββ decay

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



0ν2β:
$T_{1/2} > 10^{25}$ yr

Notes from the Editors: Highlights of the Year 2013 (by APS)

Physics looks back at the standout stories of 2013. (http://physics.aps.org/articles/v6/139)

Dark Matter is Still Obscure
Strangers from Beyond our Solar System
Light Stopped for One Minute
Four-Quark Matter
What's Inside a Black hole?

Majorana Fermions Annihilate in Nanowires

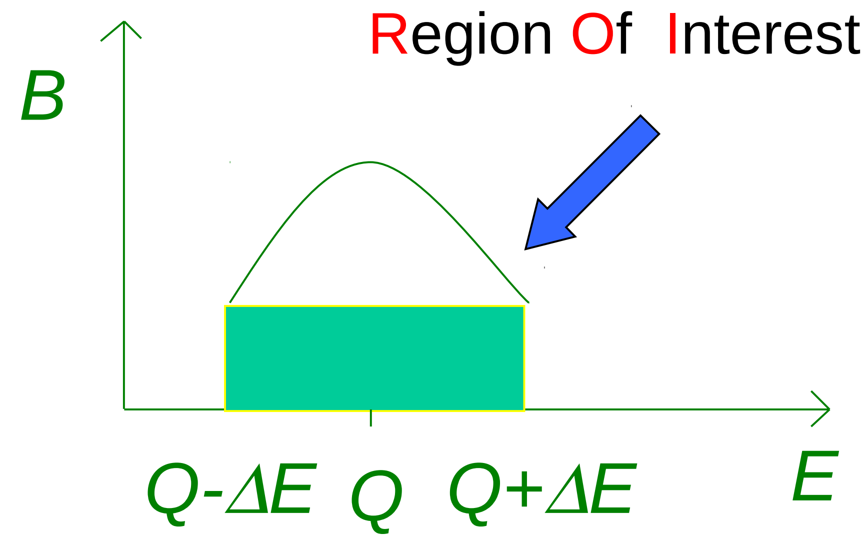
nanowires are Quasi-Particles

ν are

elementary particles

sensitivity $S_{1/2}$ for $0\nu\beta\beta$

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



$N_{obs} \sim M * t$ für $b = 0$

$N_{BG} \sim M * t * \delta E * b$

sensitivity $\sim N_{obs} / \sqrt{N_{BG}}$

background ~ detector mass

$$S_{1/2} \propto a * \varepsilon * \sqrt{\frac{M * t}{\delta E * b}}$$

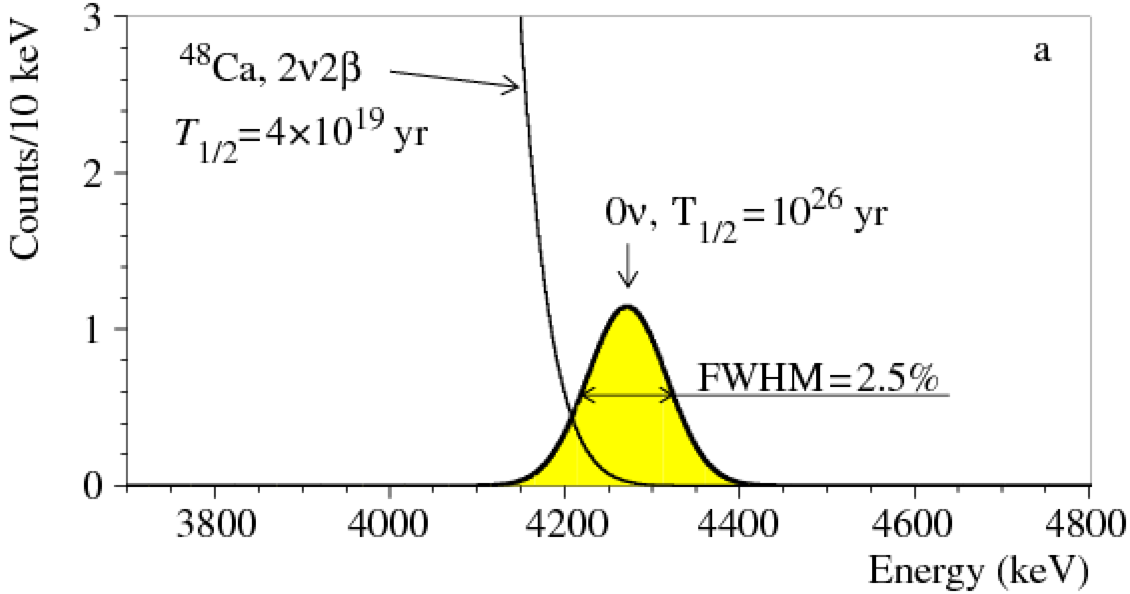
- a : isotop. enrichment
- ε : efficiency
- M : mass
- t : time of measurement
- δE : energ resolution
- b : background rate

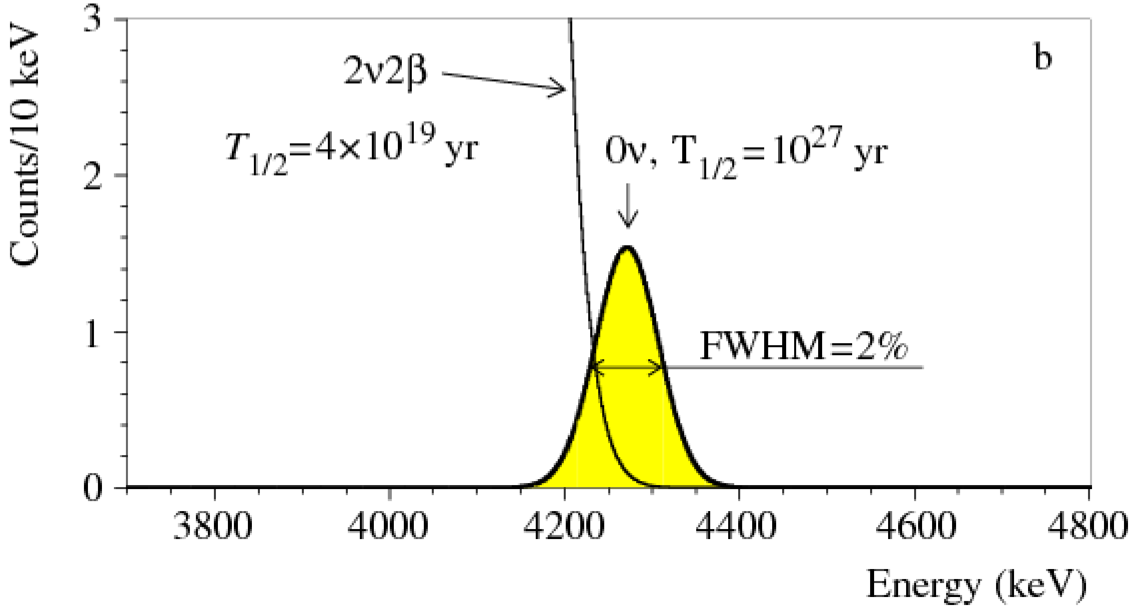
relevant units for background index:
cts/(mol yr δE)

cts/(kg yr keV)

resolution

^{48}Ca





ratio 2ν/0ν !!!

FWHM = 2,**5** %

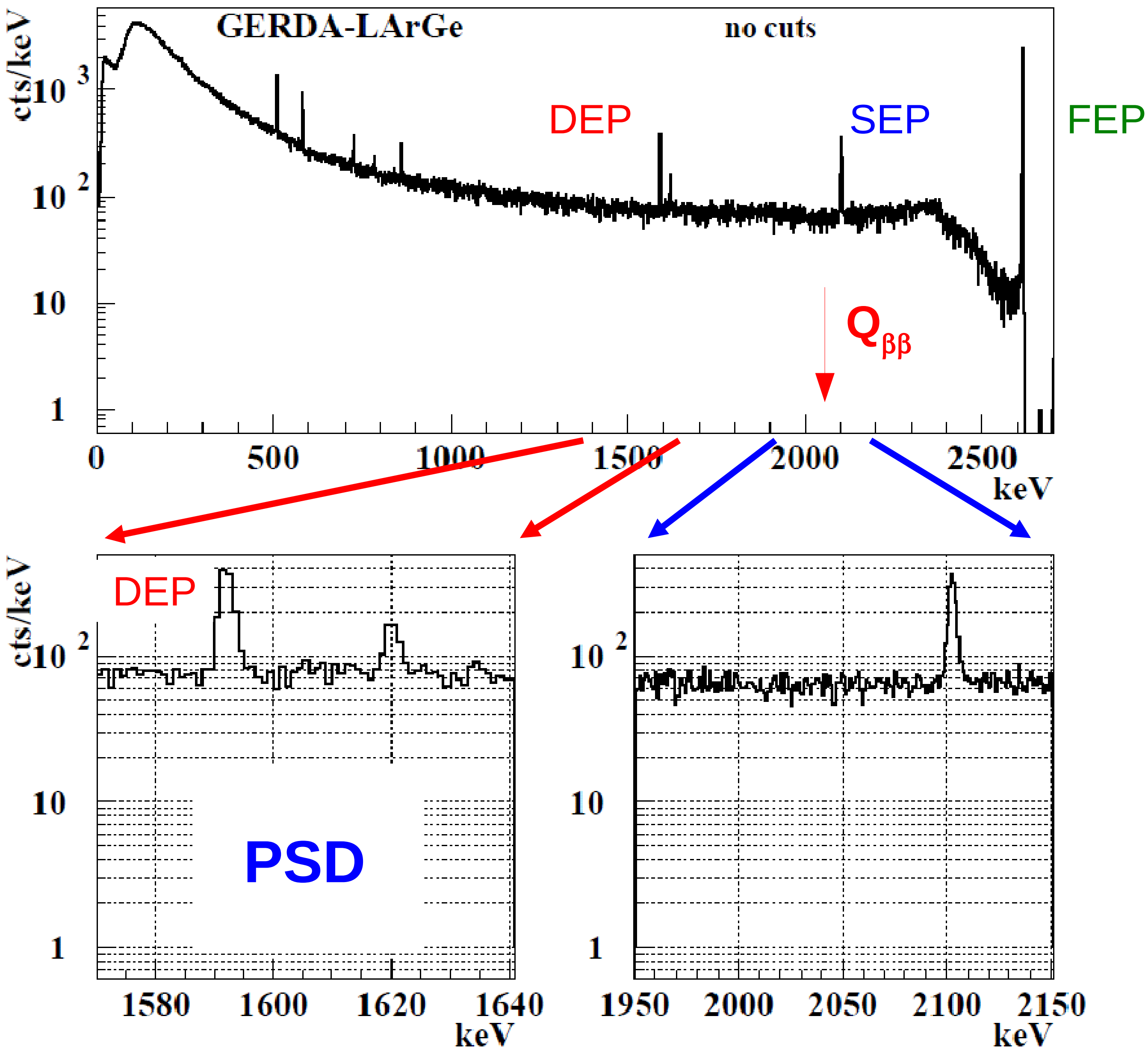
$T_{1/2} = 10^{26}$ yr

FWHM = 2,**0** %

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

⇒ Ge: 0,2%

^{228}Th spectrum



^{228}Th

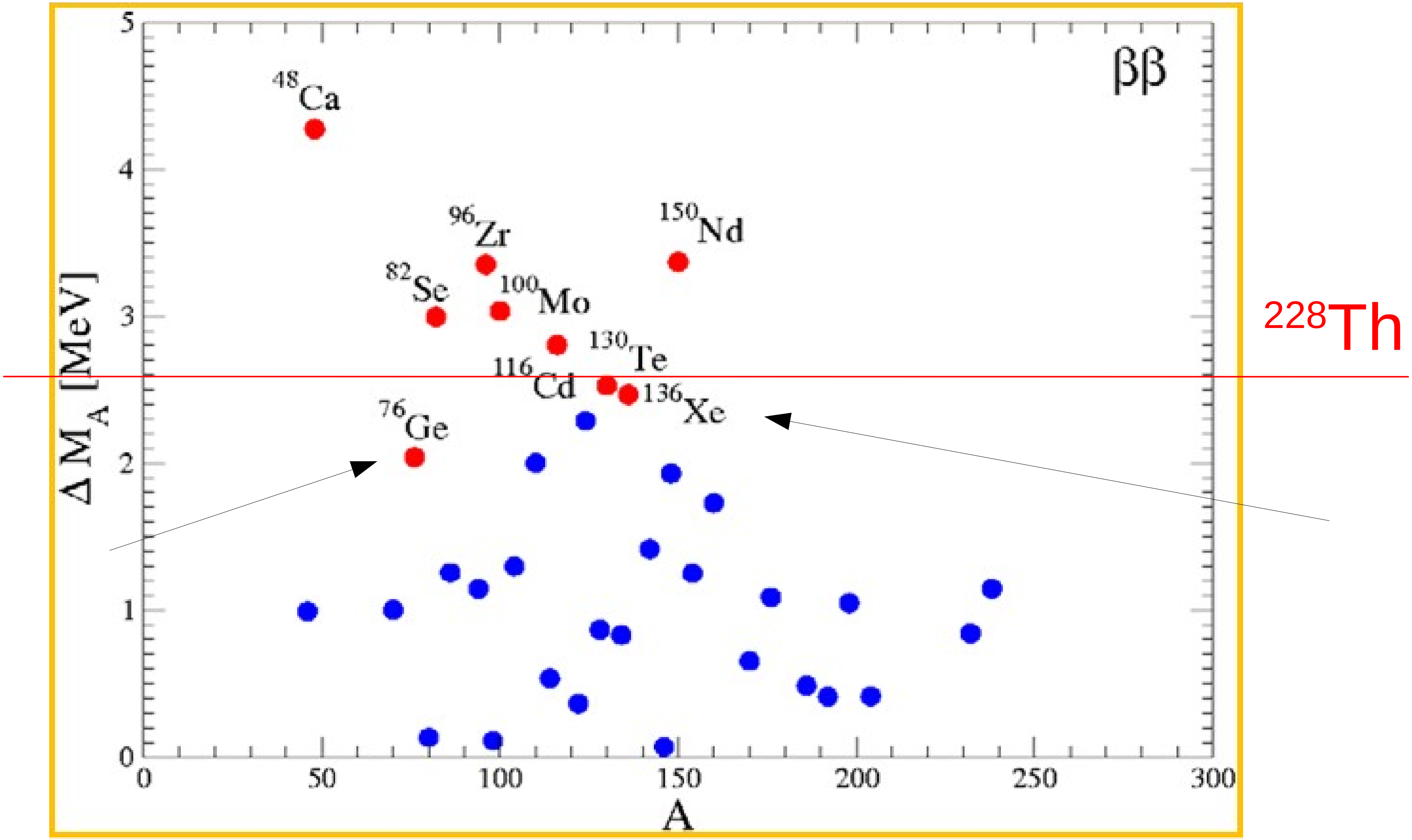
^{208}Tl : 2615 keV

appears in natural decay chains

big source of background

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

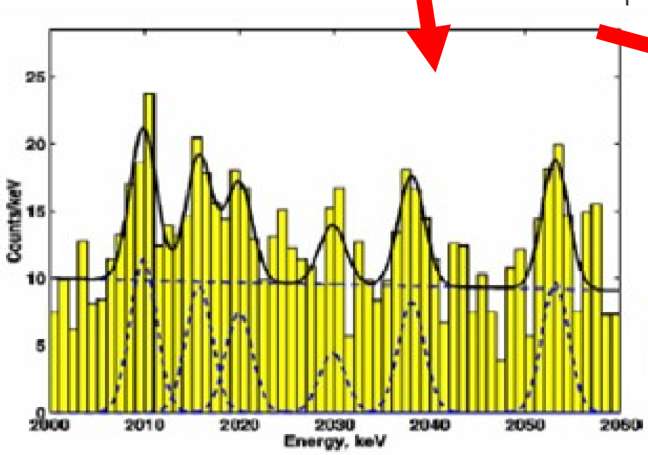
candidates

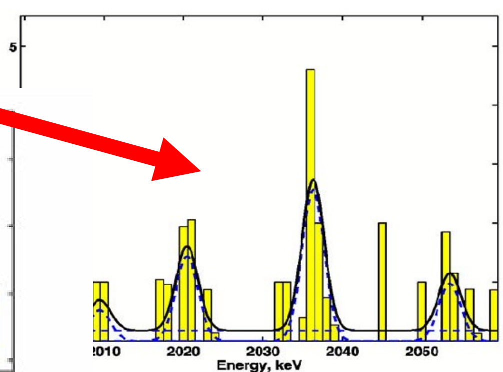

ββ
^{48}Ca
^{96}Zr
^{150}Nd
^{82}Se
^{100}Mo
^{130}Te
^{116}Cd
^{136}Xe
^{76}Ge
^{228}Th
ΔM$_A$ [MeV]
A
0
1
2
3
4
5
0
50
100
150
200
250
300

^{76}Ge experiments

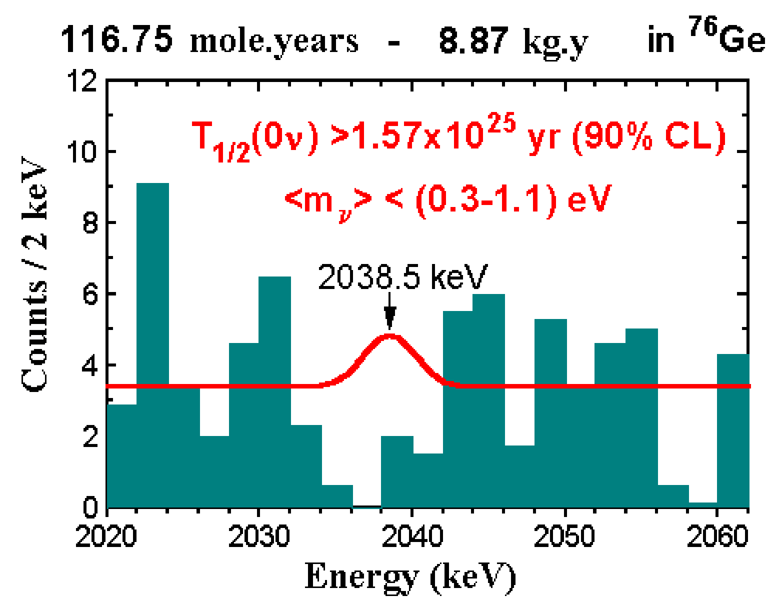
previous experiments: HDM (5 det) and IGEX (3 det)

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)





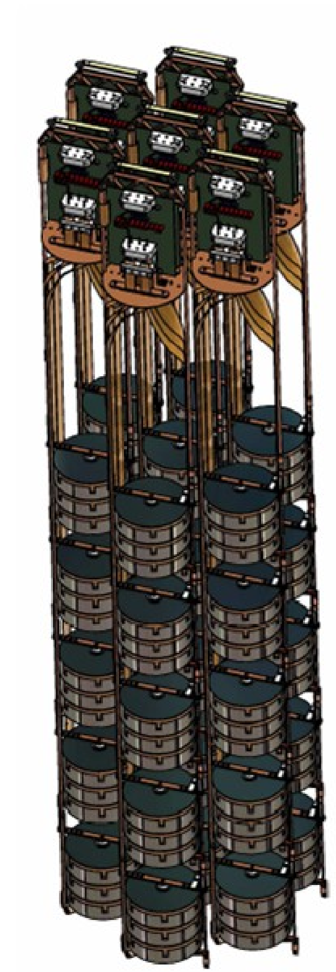
MPLA21 (2006)



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

GERDA – the novel idea

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



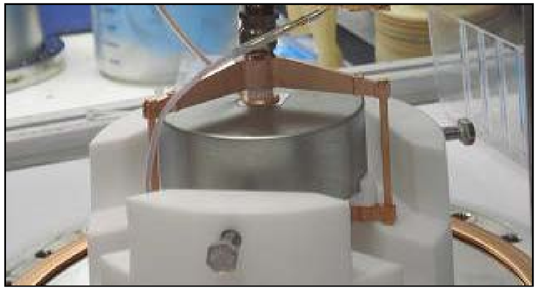
"...low Z material around detector..."
"...mount the Ge diodes directly in cryo-liquid"

reduced radioactivity of environment
less muon-induced background

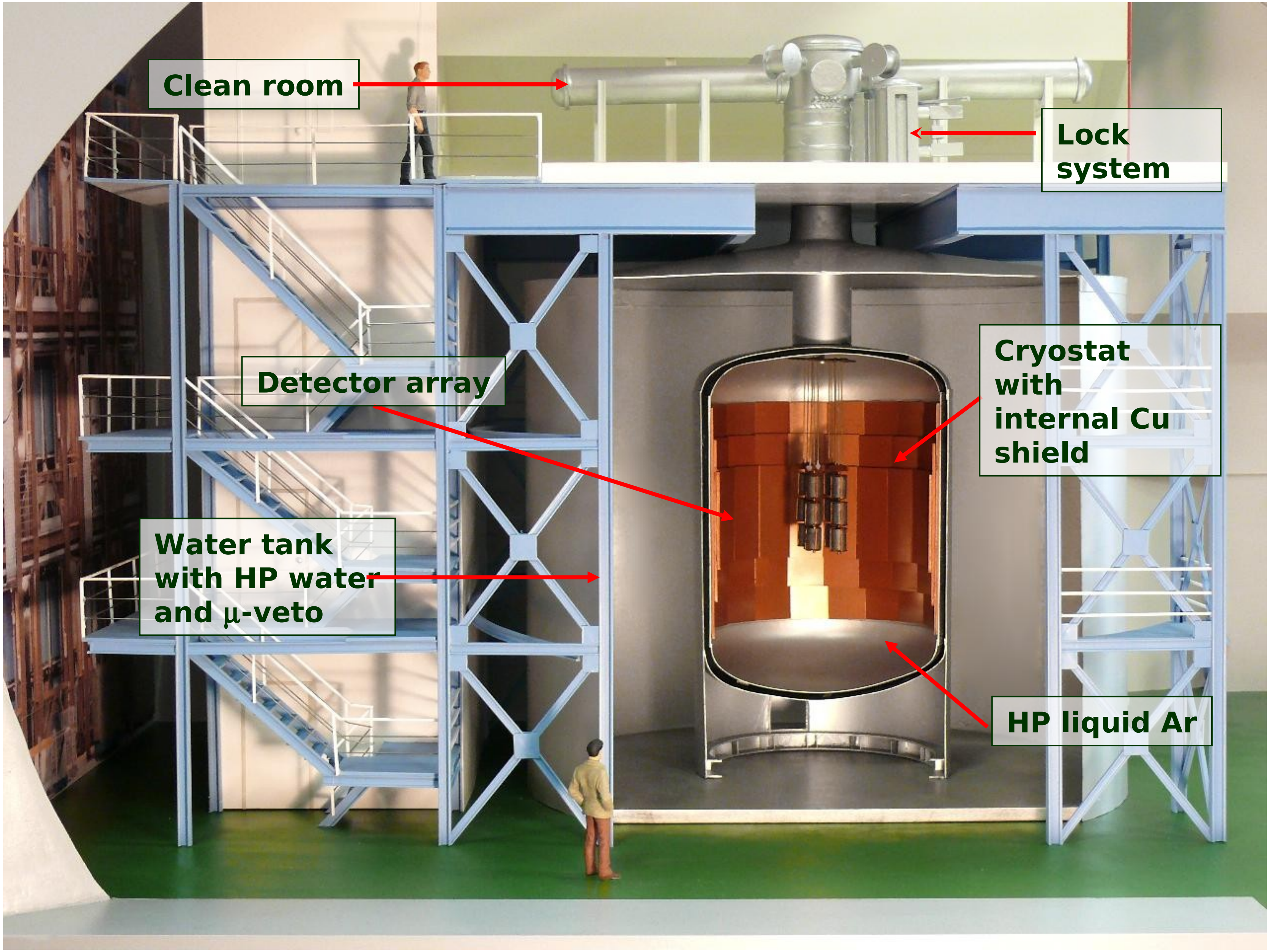
Ge diodes – enriched to 86%
selected material for holder and FE
liquid argon
stainless steel cryostat
water to moderate neutrons and
as muon veto (Cherenkov)
underground LNGS 3400 m w.e.

analysis: anti-coincidence, PSD

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



→ HdM, Majorana: closed compact shielding

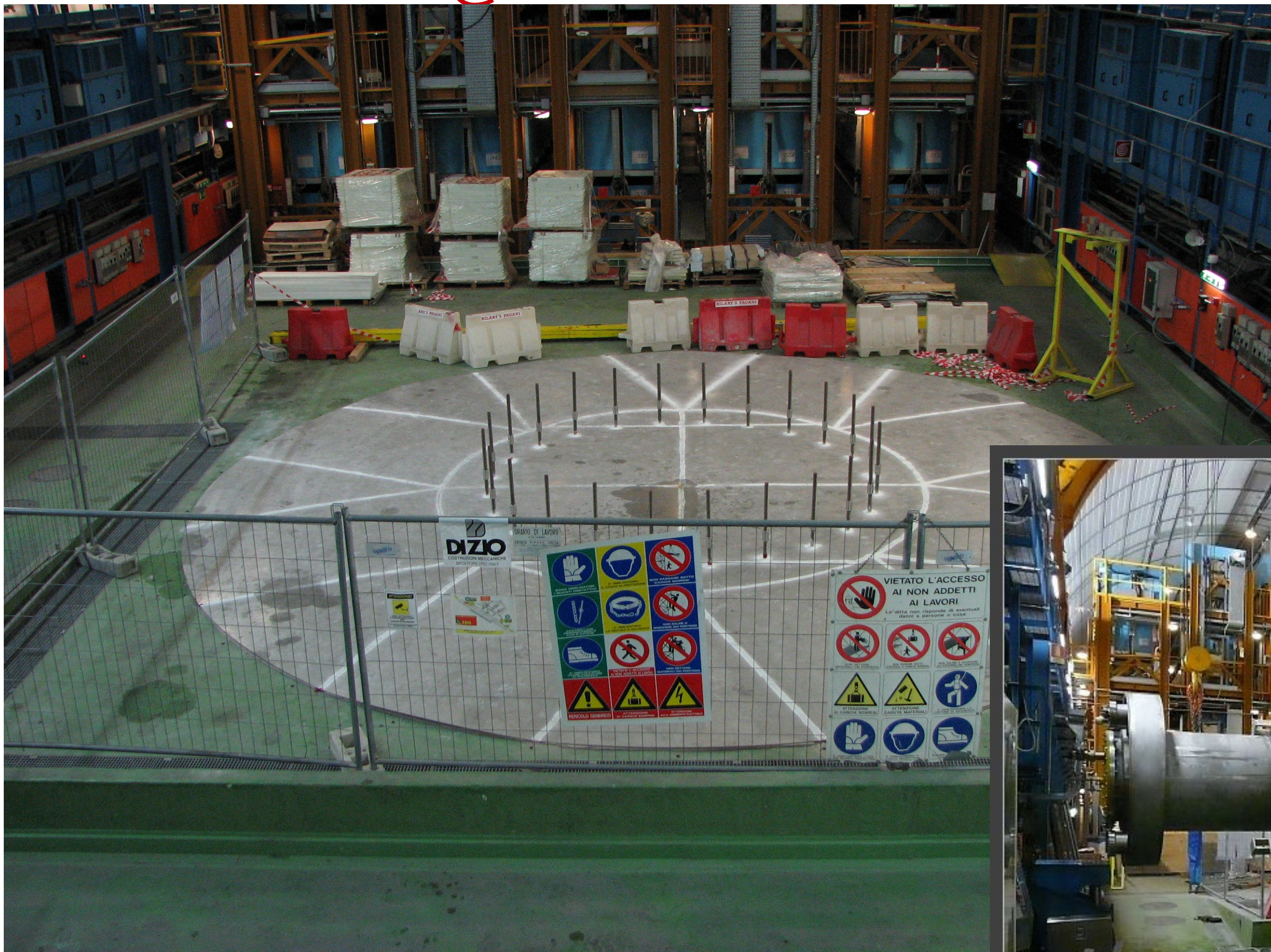


GERDA : design and construction

proposal 2004

LNGS, Hall A

construction @ LNGS



February 2008

March 2008

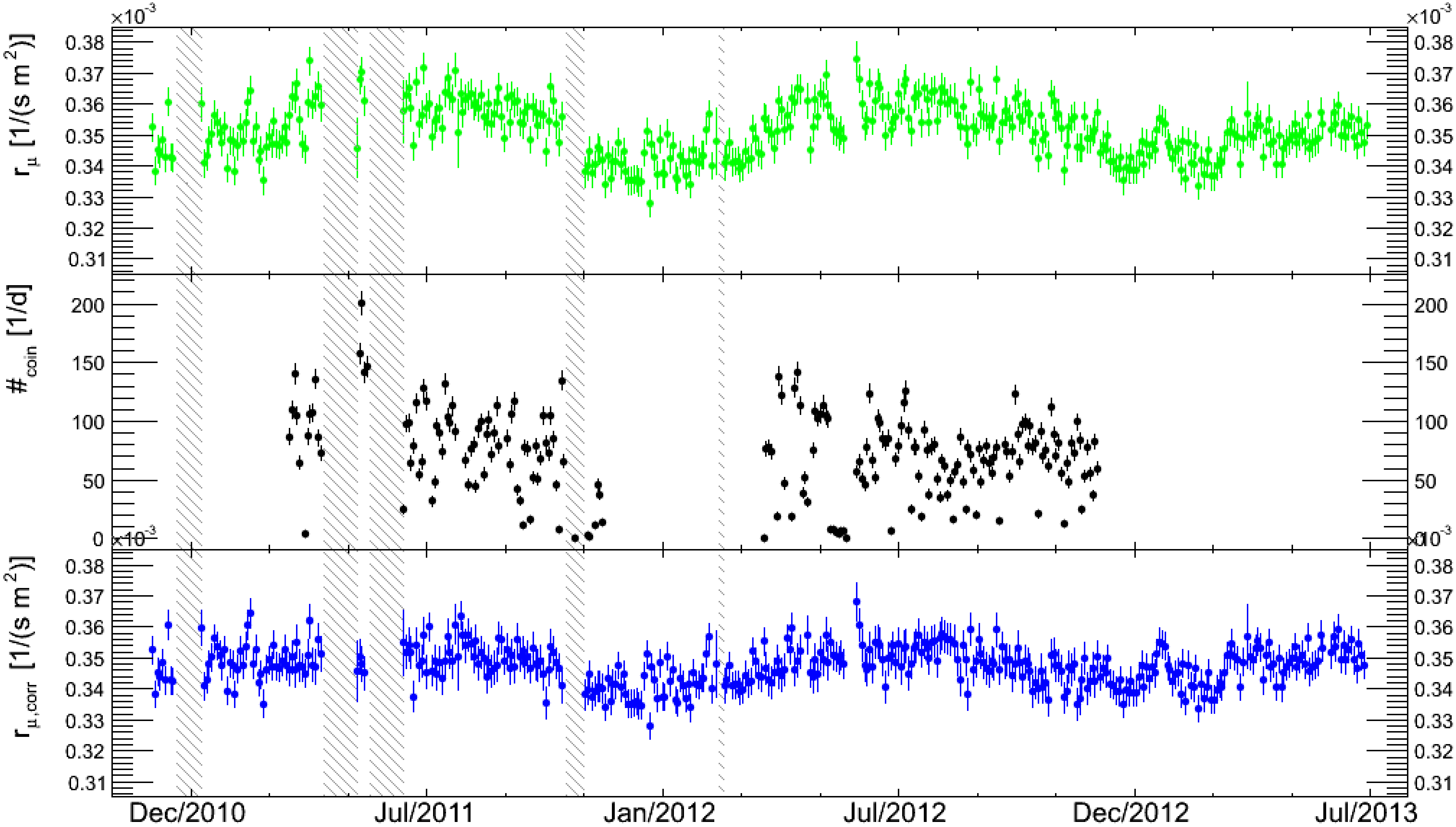
construction @ LNGS

March 2008

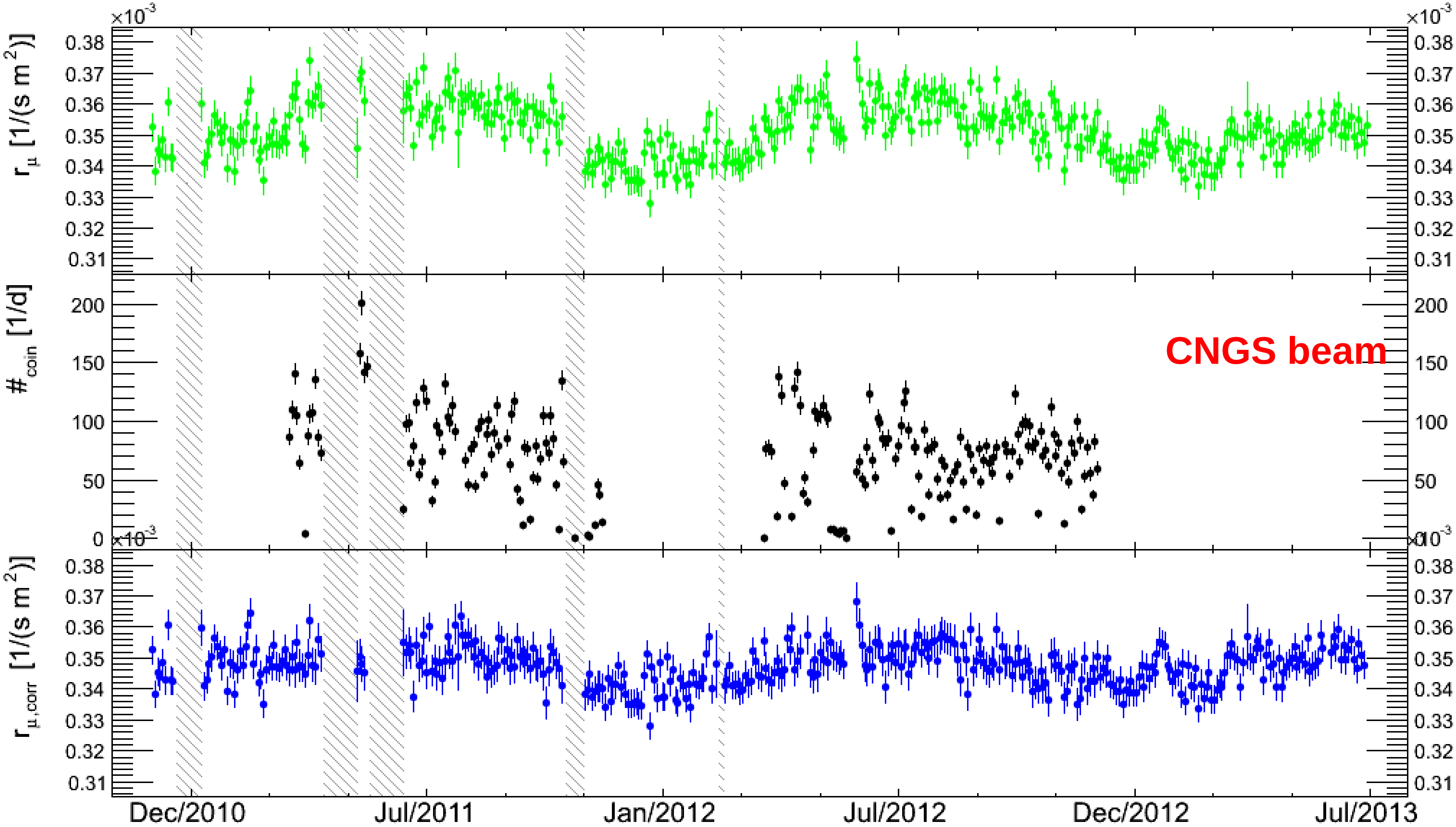
construction @ LNGS

May 2008

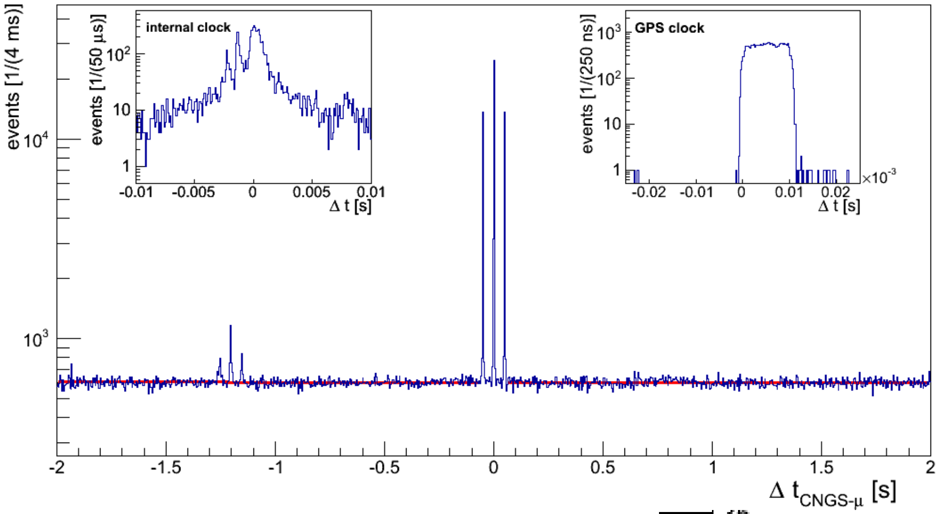
rate of 66 Cherenkov PMT

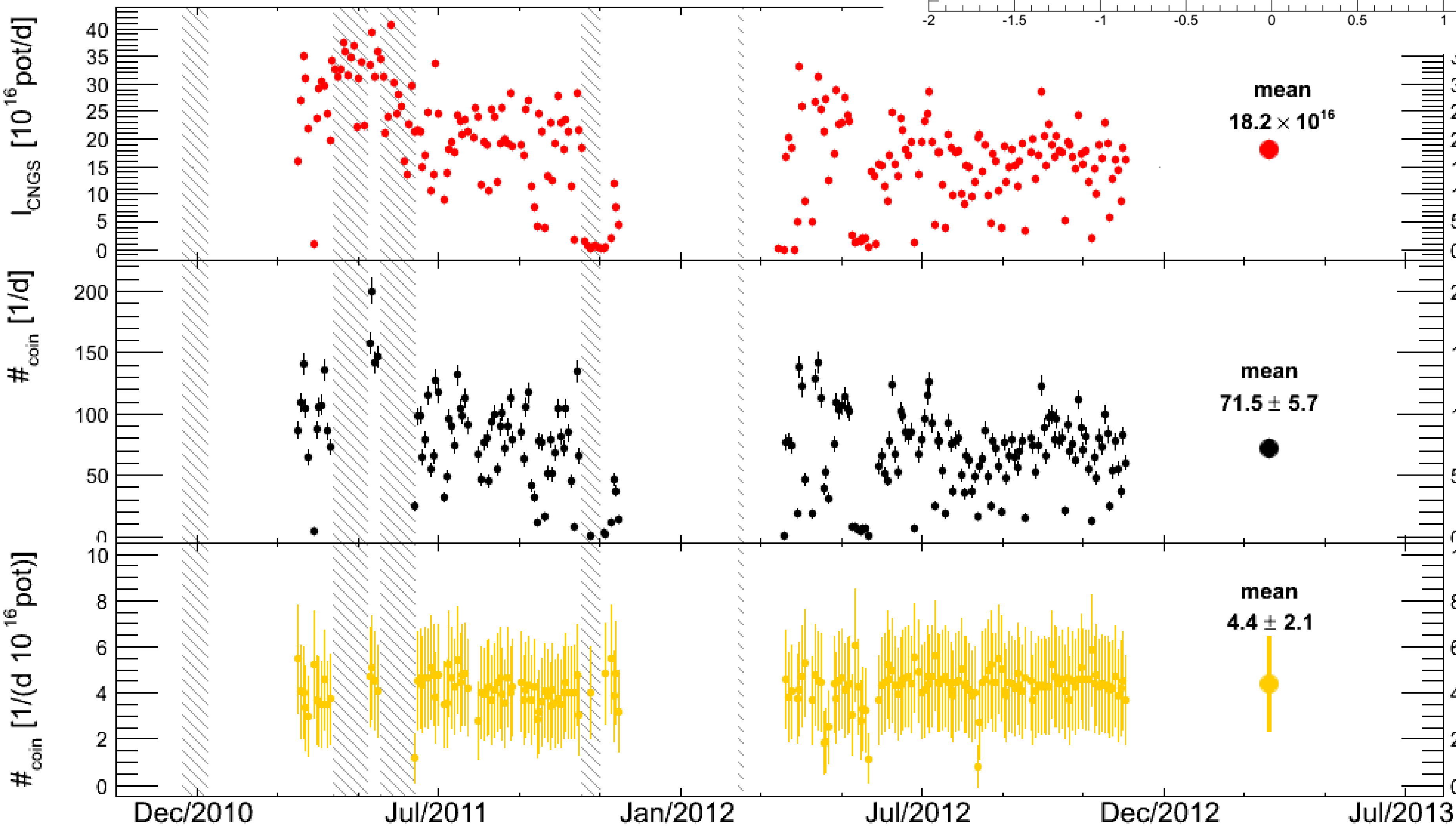


rate of 66 Cherenkov PMT

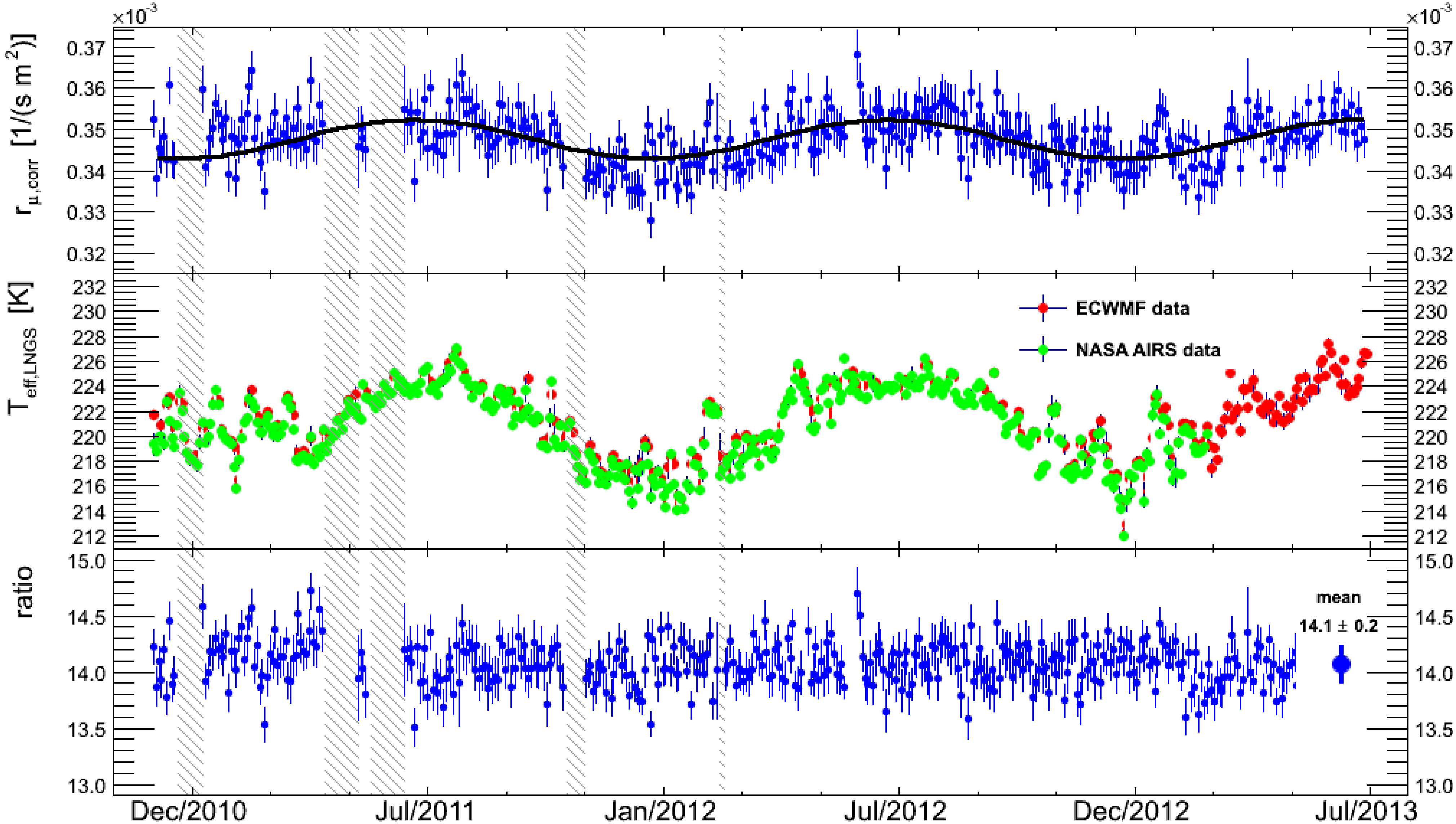


CNGS neutrino beam

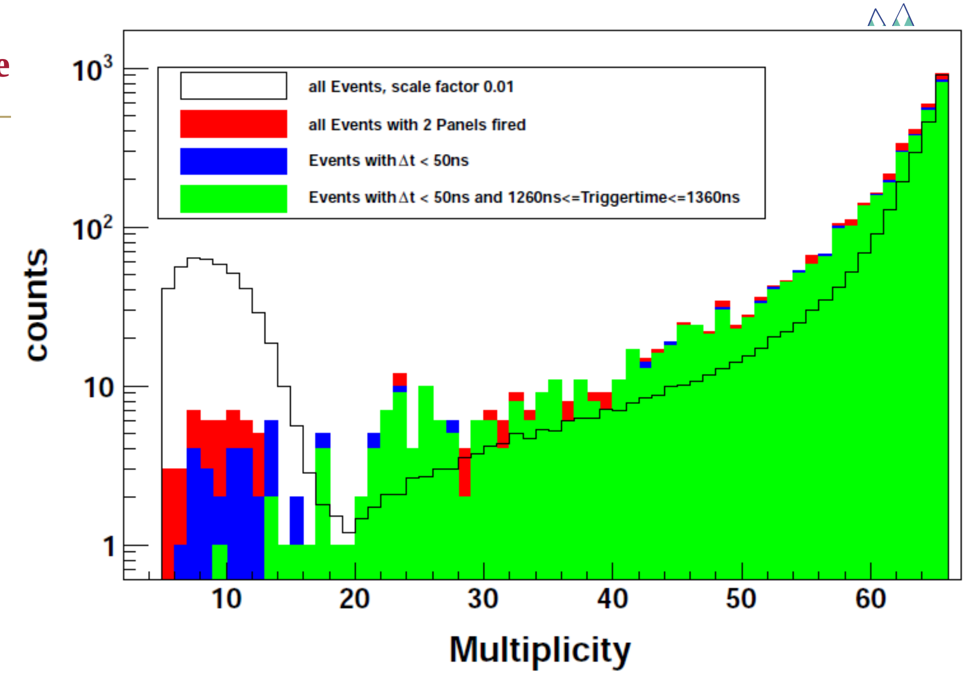




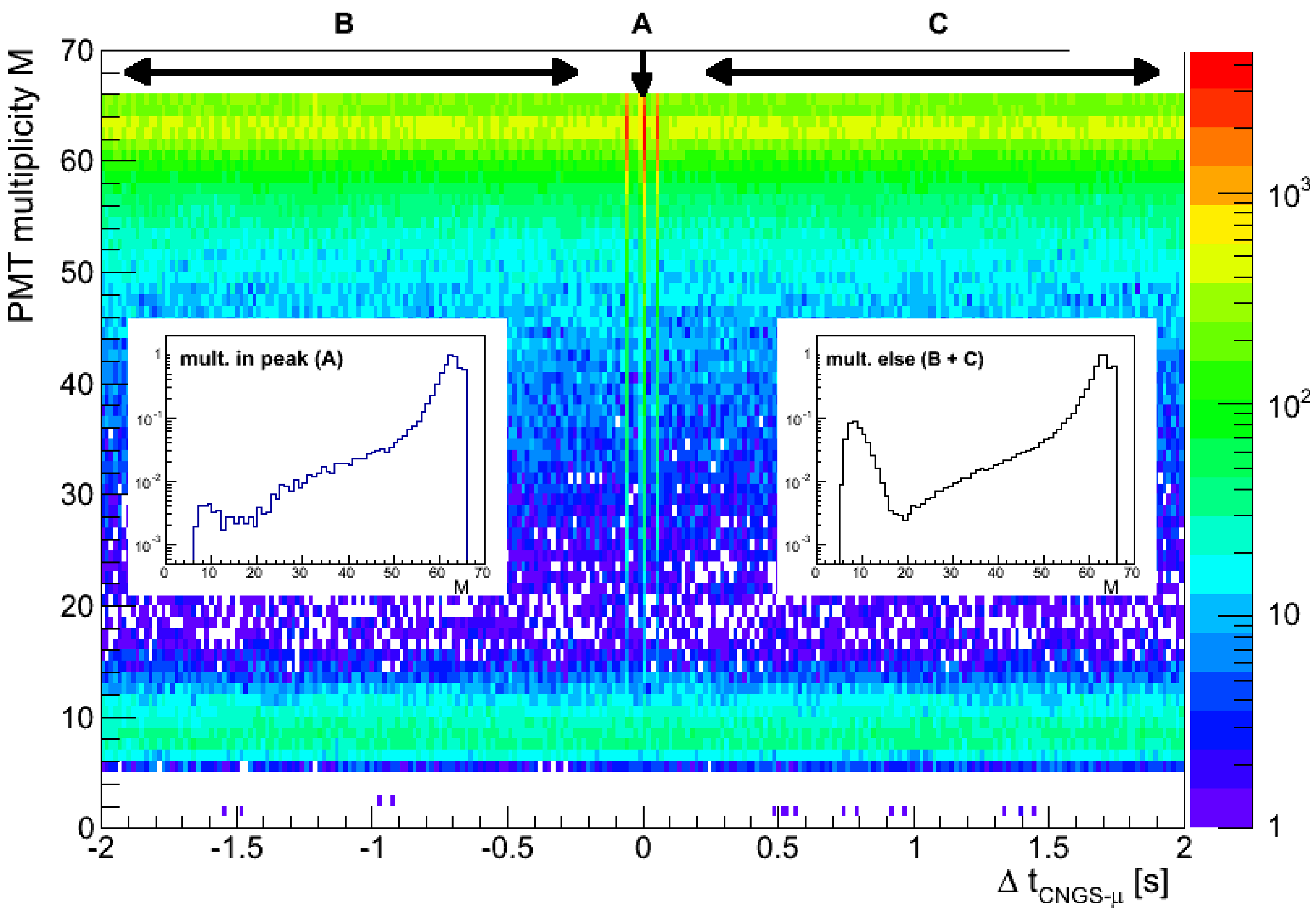
comparison to effective temperature



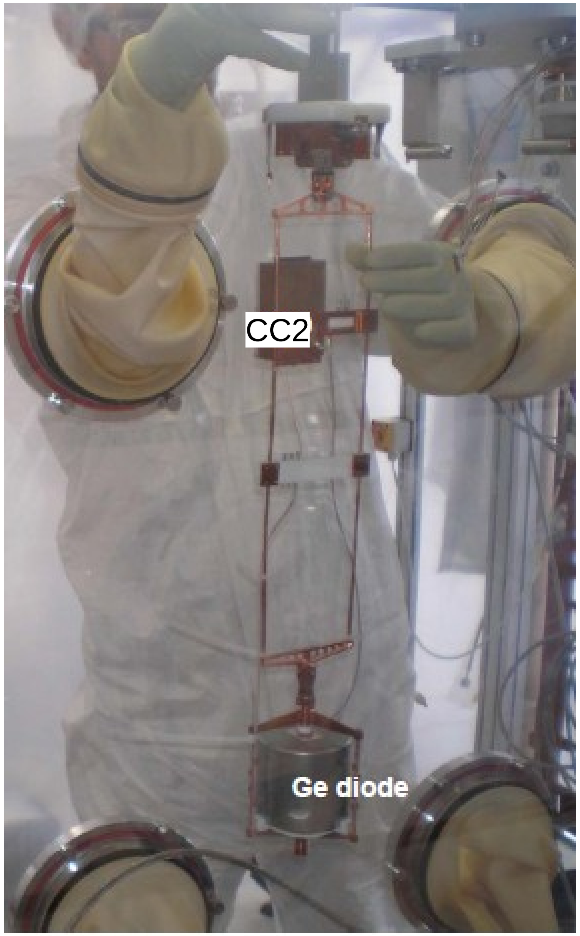
Multiplicity of 66 Cherenkov PMT



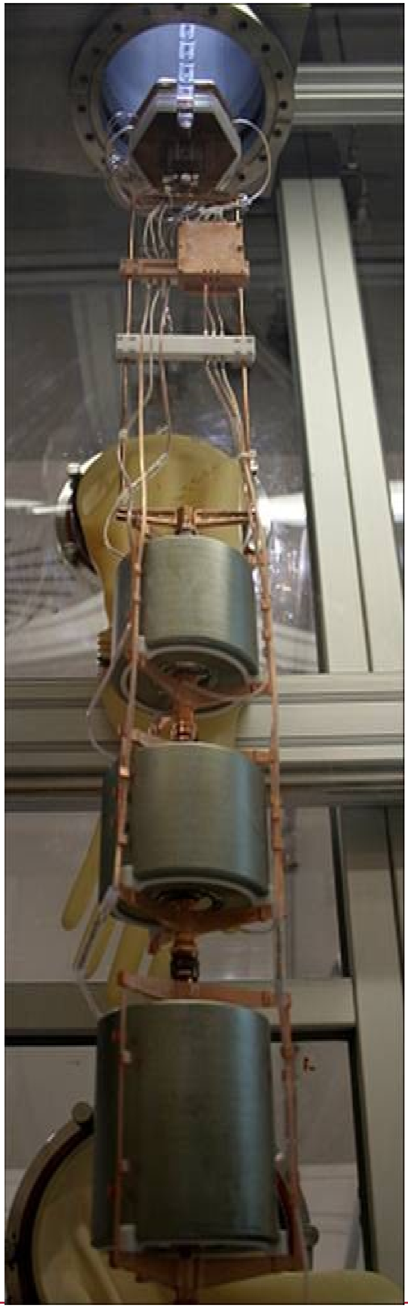
muon rejection efficiency ε > 97 %



mounting the diodes



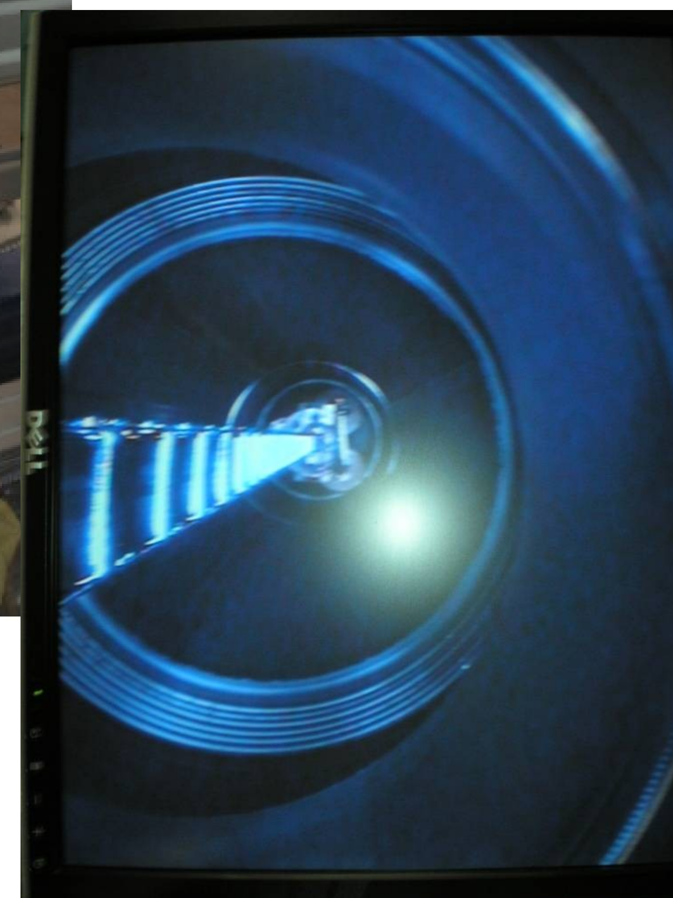
test in LARGE



note distance between diode and preamplifier

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

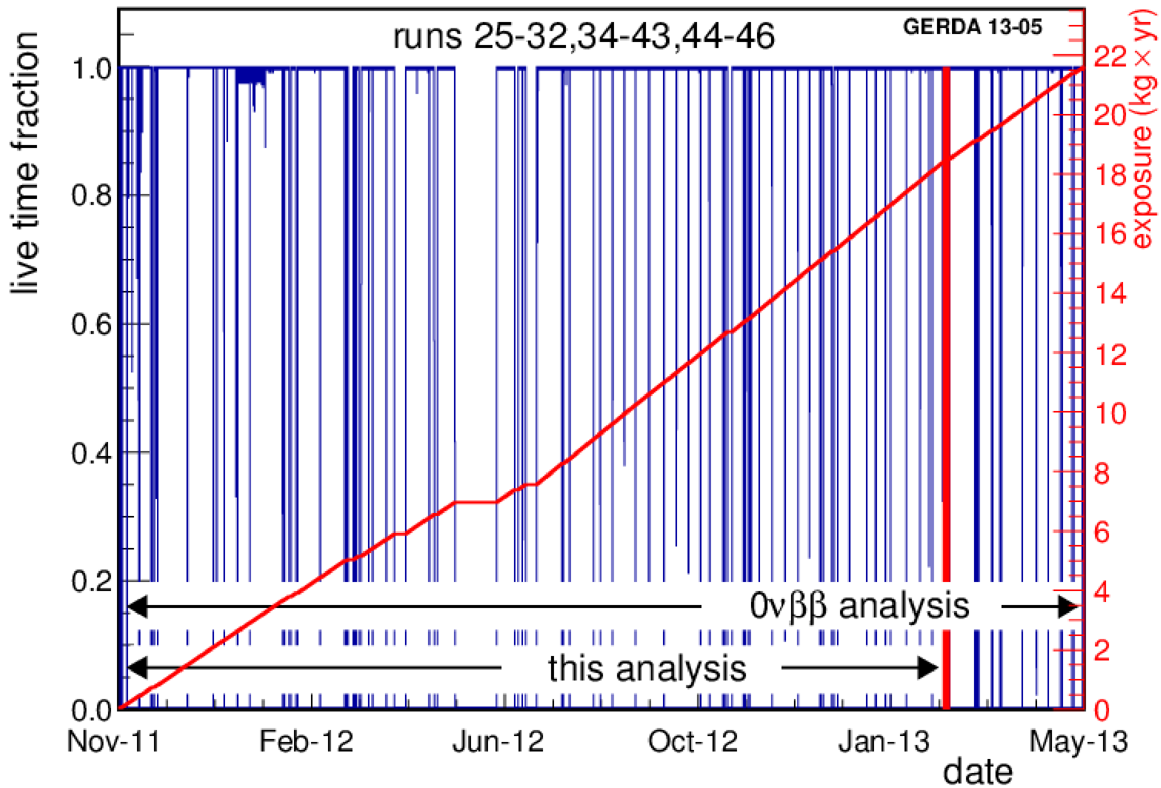


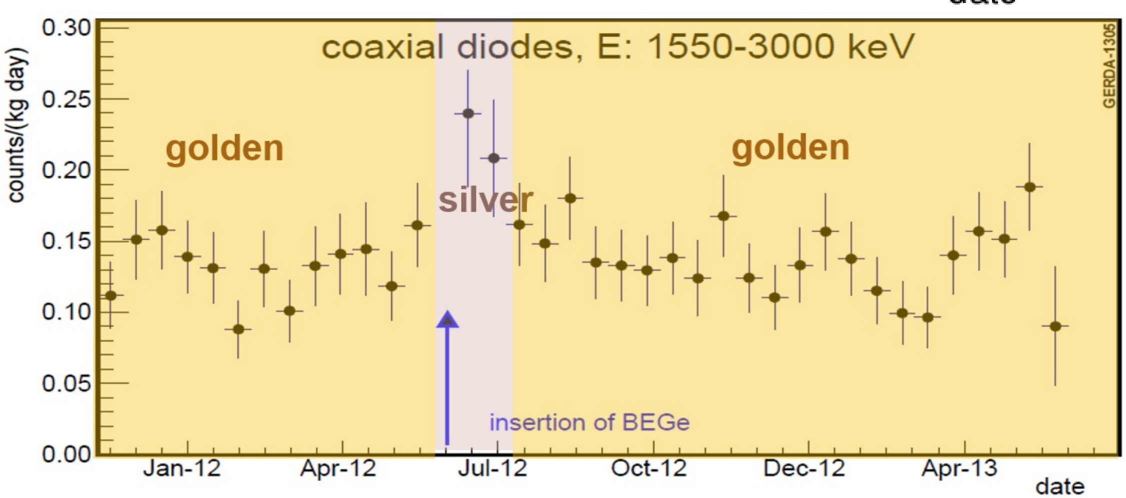



2 enriched detectors had problems from the very beginning, removed from physics analysis

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

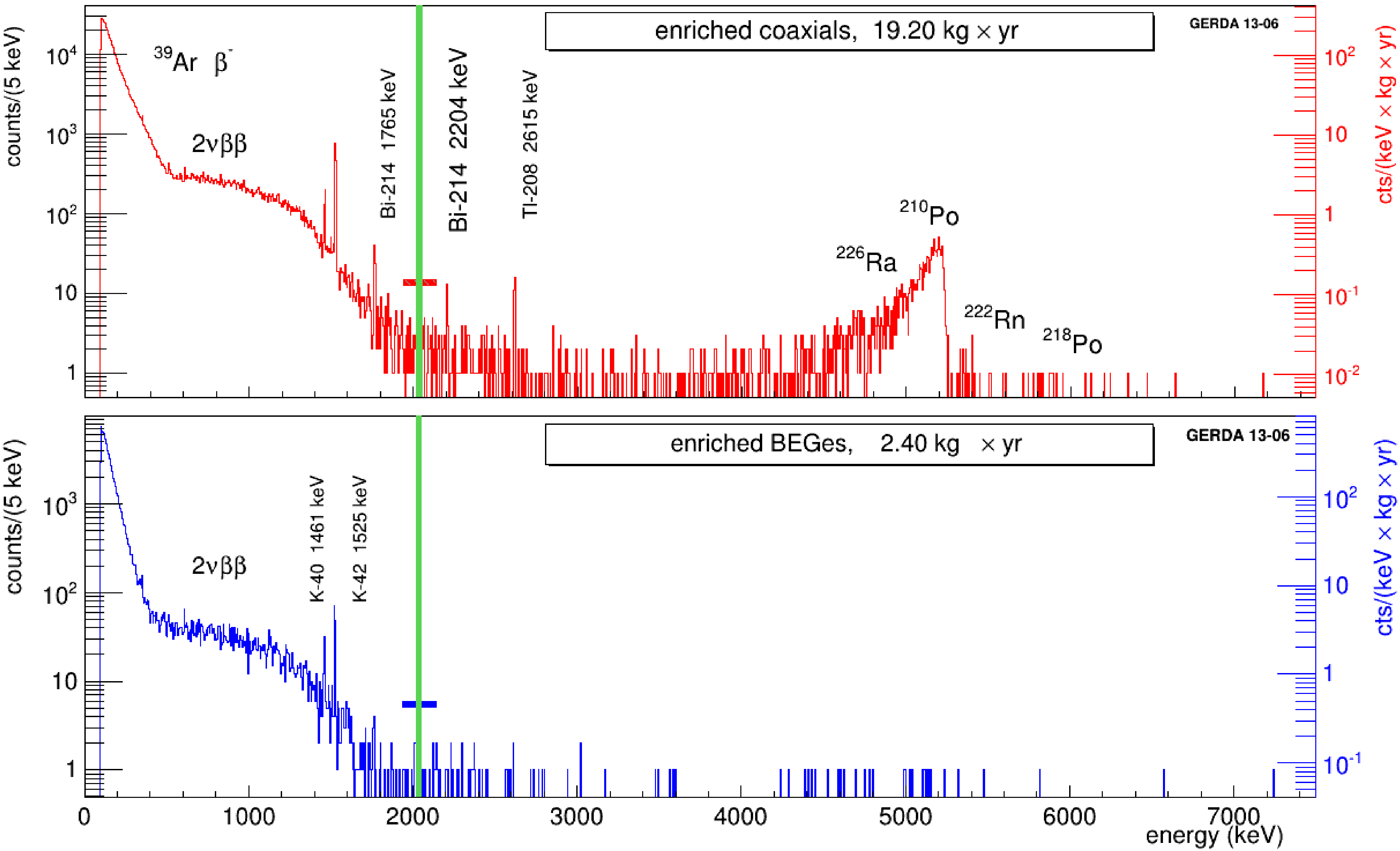
add 5 BEGe detectors





3 data sets:
- golden
- silver
- BEGe

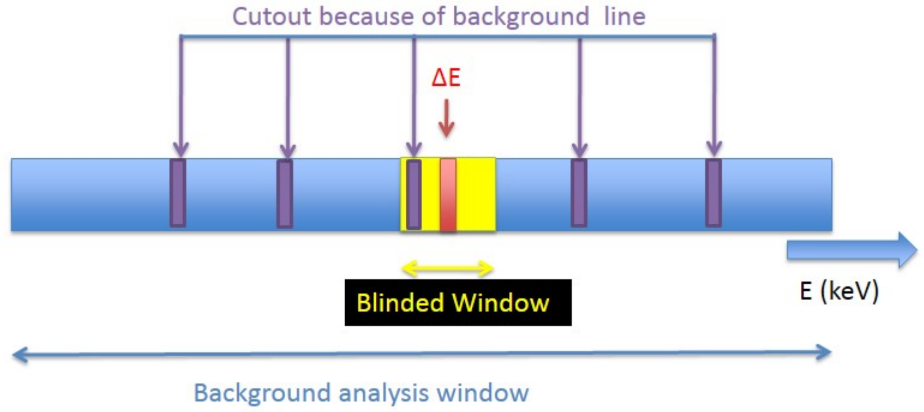
summed electron energy spectra



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]



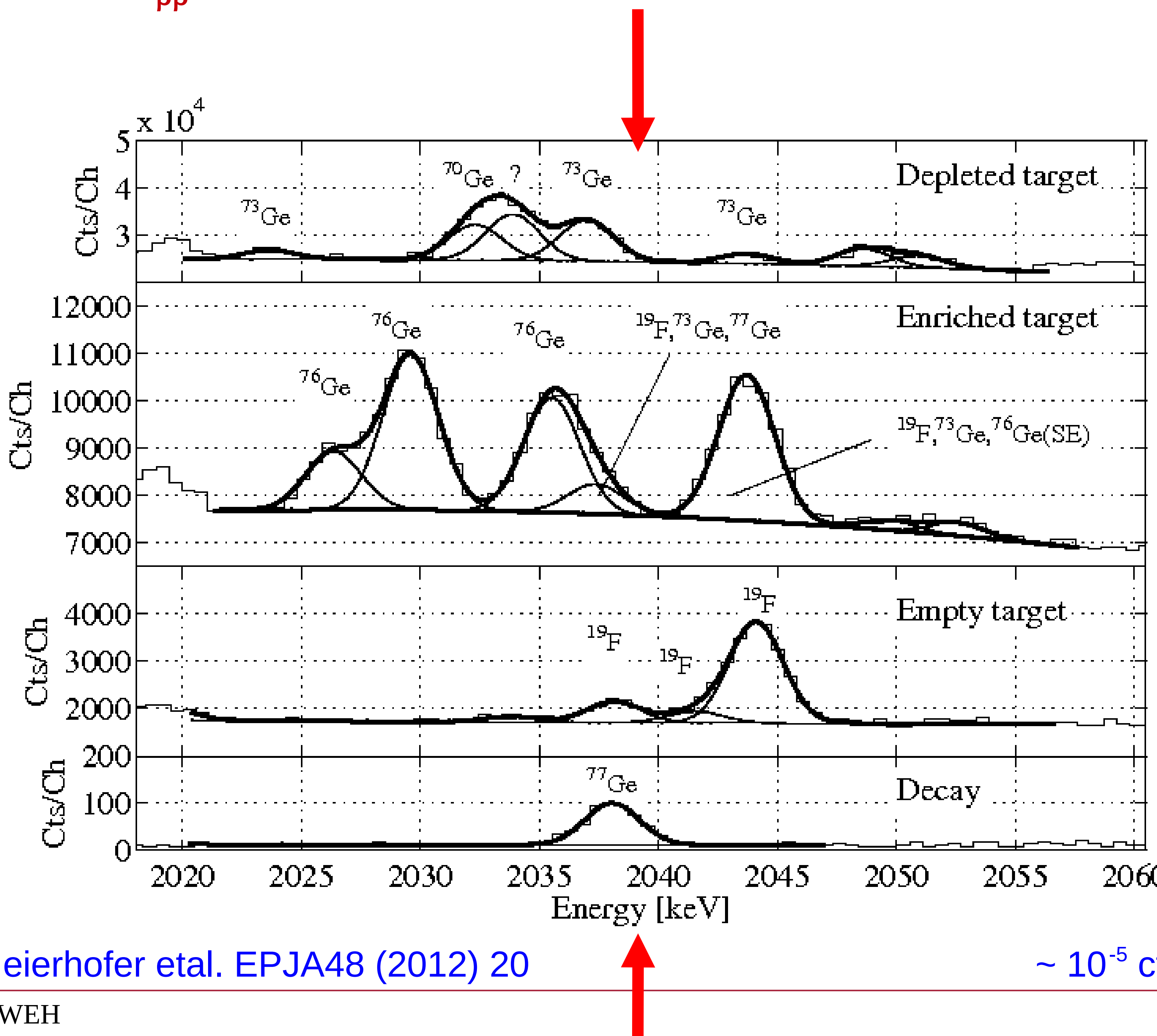
EPJC 73 (2013) 2330	the GERDA experiment (setup)
JPG 40 (2013) 035110	$T_{1/2}^{2\nu} = 1.84\ (^{+14}/_{-10})\ x\ 10^{21}$ yr
EPJC 74 (2014) 2764	the background & models
EPJC 73 (2013) 2583	PSD: pulse shape for coax & BEGe

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

spectra with/without PSD uncovered @ Dubna

PRL 111 (2013) 122503 limit for $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L. frequentist)

(n,γ) in the $Q_{\beta\beta}$ region



FRM II

G. Meierhofer etal. EPJA48 (2012) 20

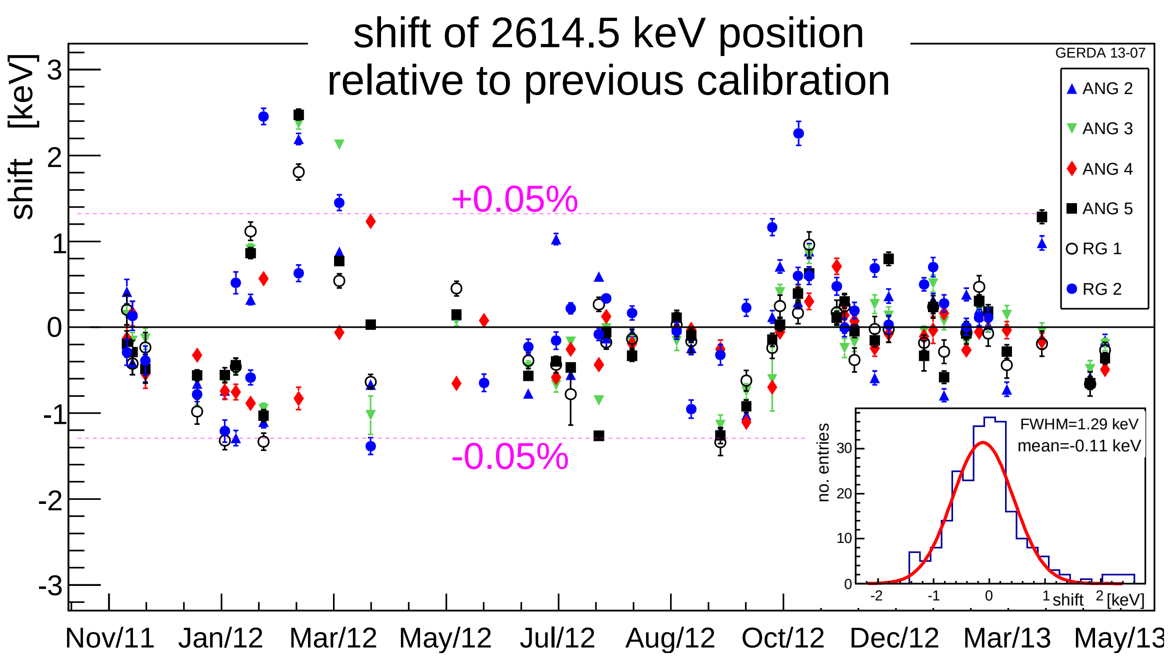
~ 10^{-5} cts/(keV kg yr)

calibration & data processing

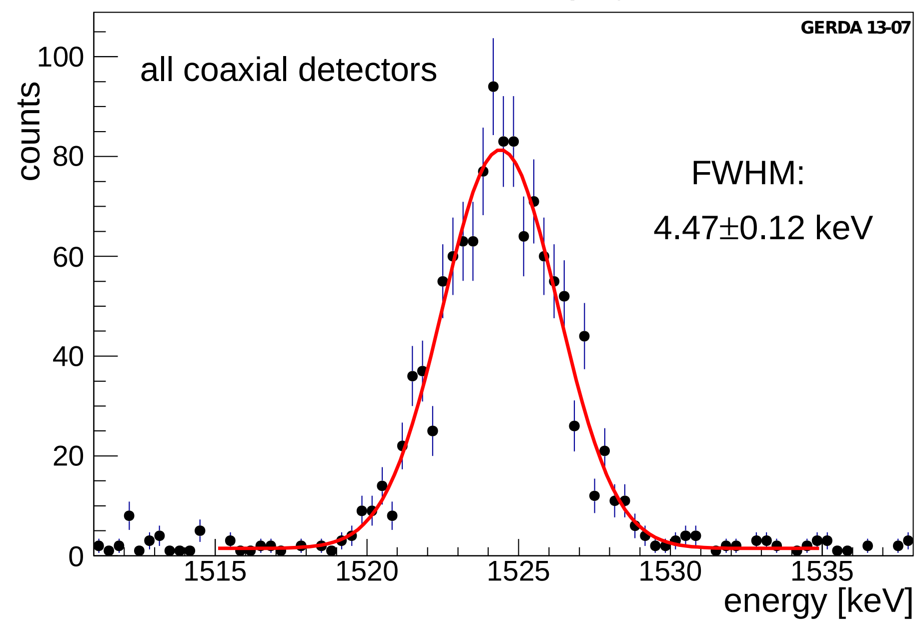
processing: diode → amplifier → FADC → filter → energy, rise time, PSD

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



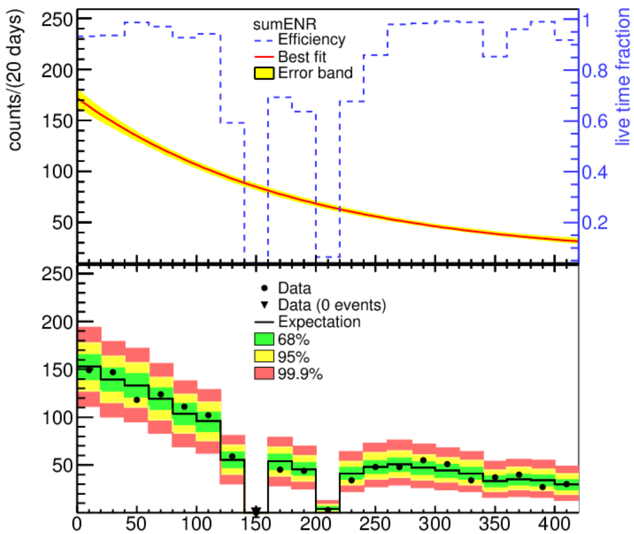
1524.6 keV ^{42}K line in physics data



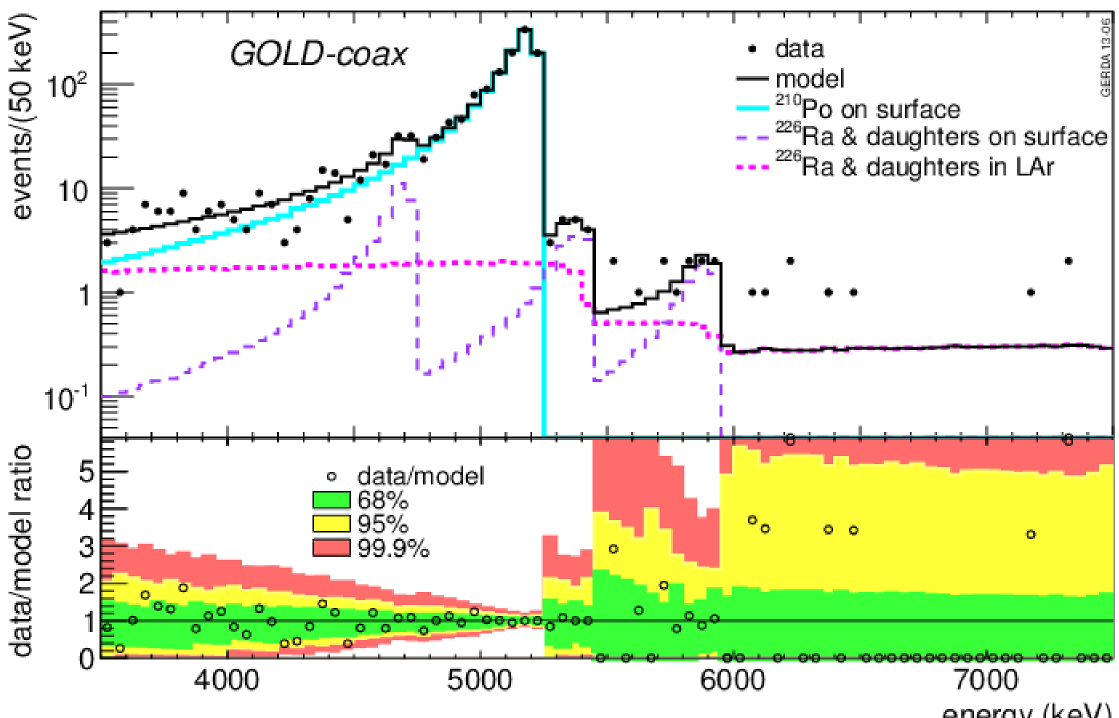
shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$

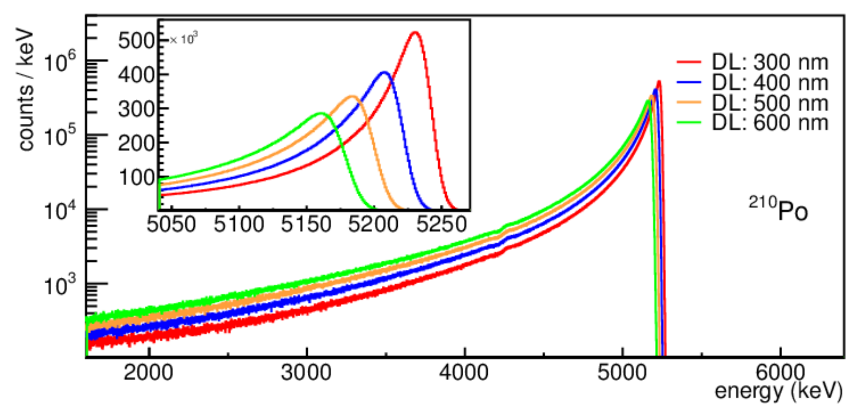
peak pos. within 0.3 keV at correct position
FWHM ~ 4% larger than expected from calibration data

backgrounds α & γ

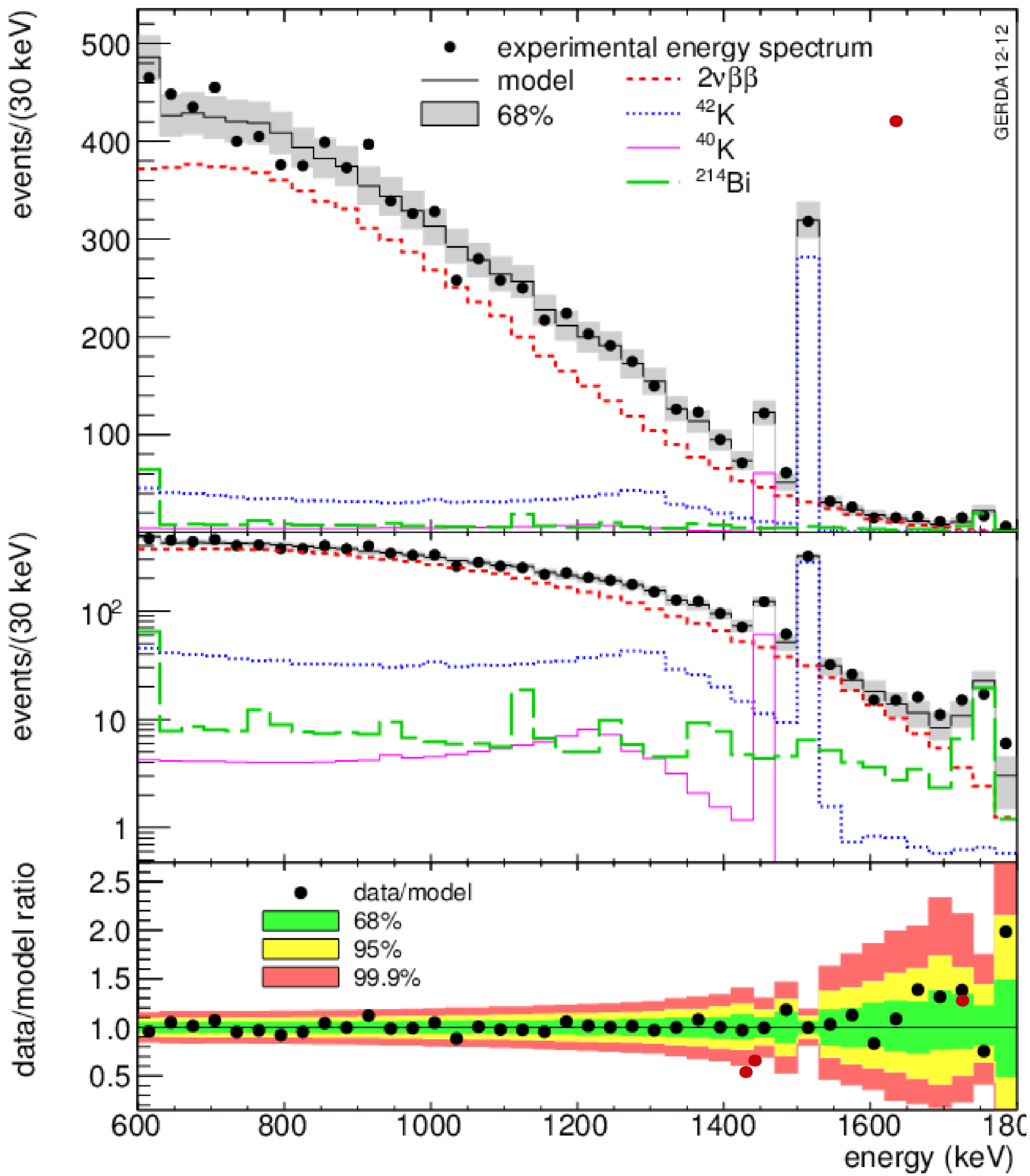


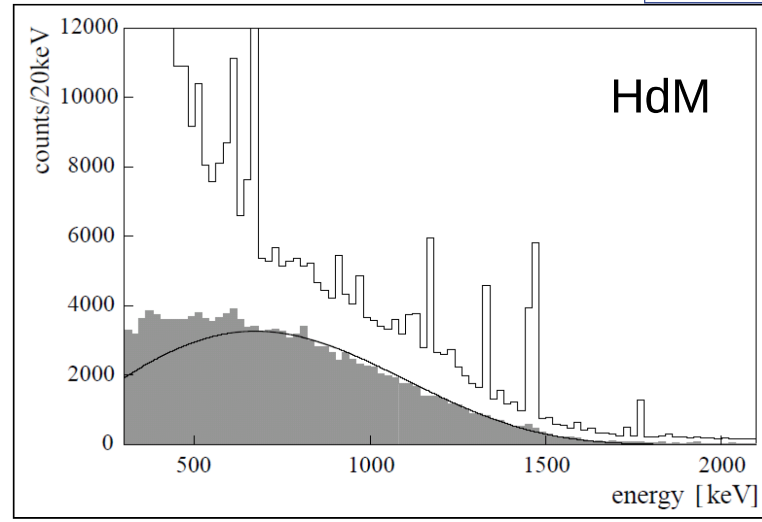
isotope	energy [keV]	^{enr}Ge (6.10 kg yr) tot/bck [cts]	^{enr}Ge (6.10 kg yr) rate [cts/(kg yr)]	HdM (71.7 kg yr) rate [cts/(kg yr)]
^{40}K	1460.8	125/42	$13.5^{+2.2}_{-2.1}$	181 ± 2
^{60}Co	1173.2	182/152	$4.8^{+2.8}_{-2.8}$	55 ± 1
	1332.3	93/101	<3.1	51 ± 1
^{137}Cs	661.6	335/348	<5.9	282 ± 2
^{228}Ac	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
	3	194/186	<6.1	26.9 ± 1.2
	5	24/1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7
	2	6/3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5





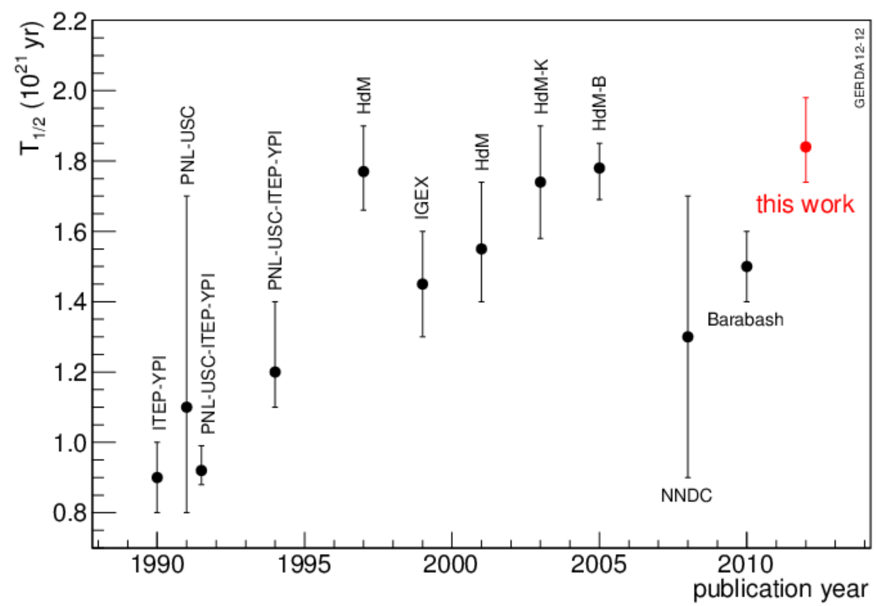
J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110





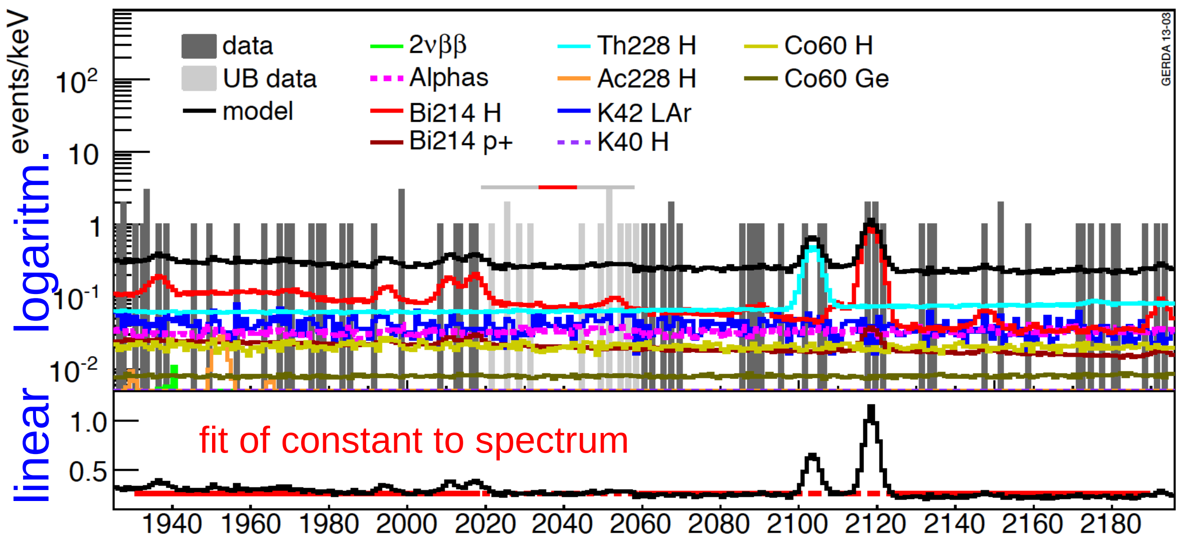
5.04 kg yr exposure

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

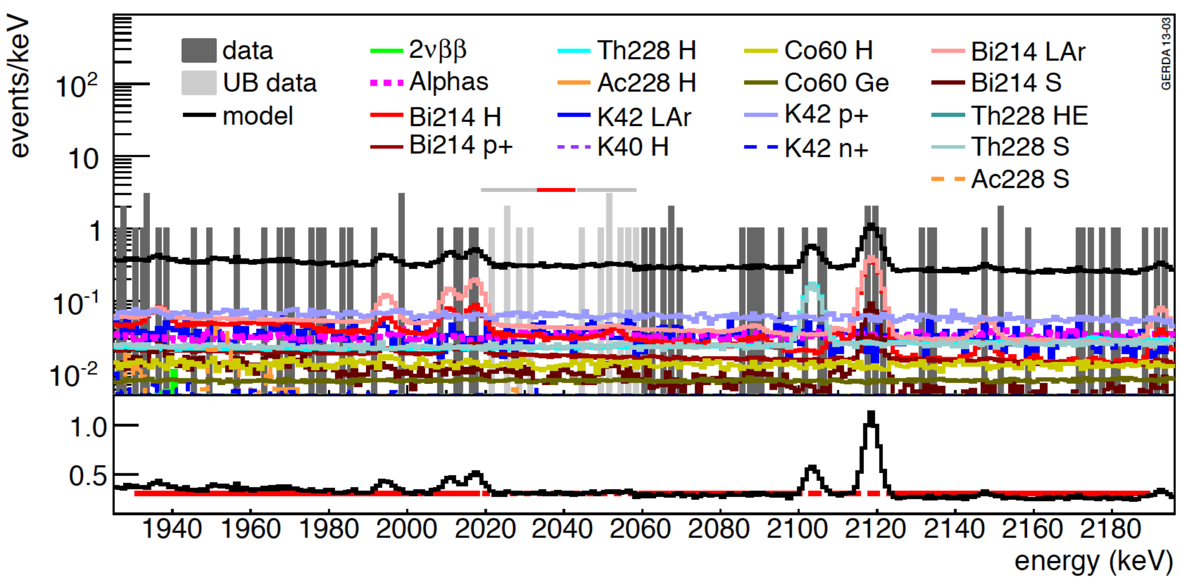


background model @ $Q_{\beta\beta}$

"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

pulse shape discrimination (PSD)

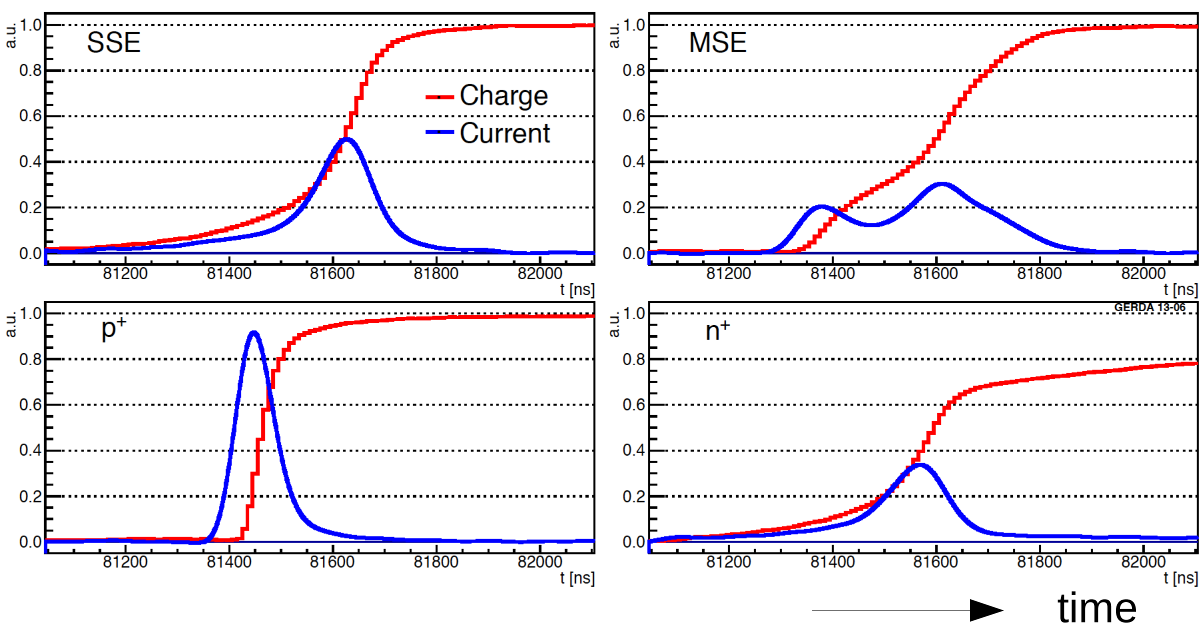
pulse shape discrimination to select 0νββ events

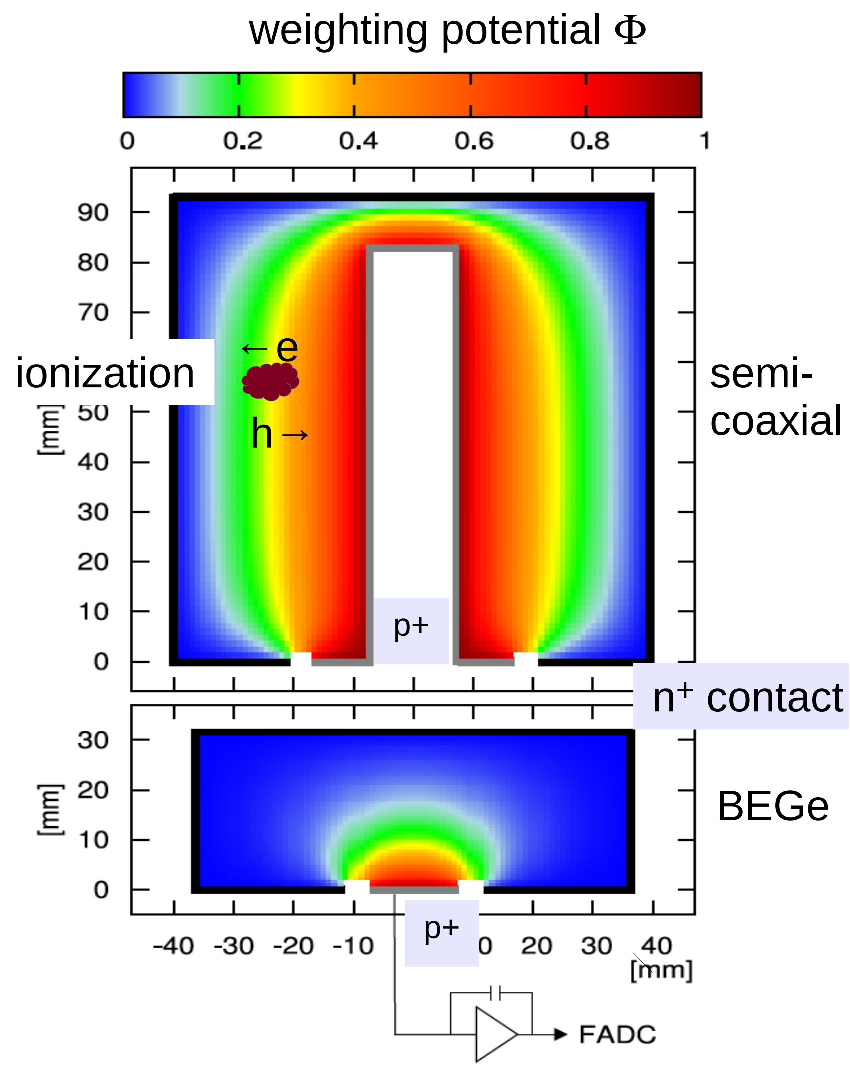
0νββ events: range of 1 MeV electrons in Ge is ~1 mm
→ single drift of electrons & holes, single site event (SSE)

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)

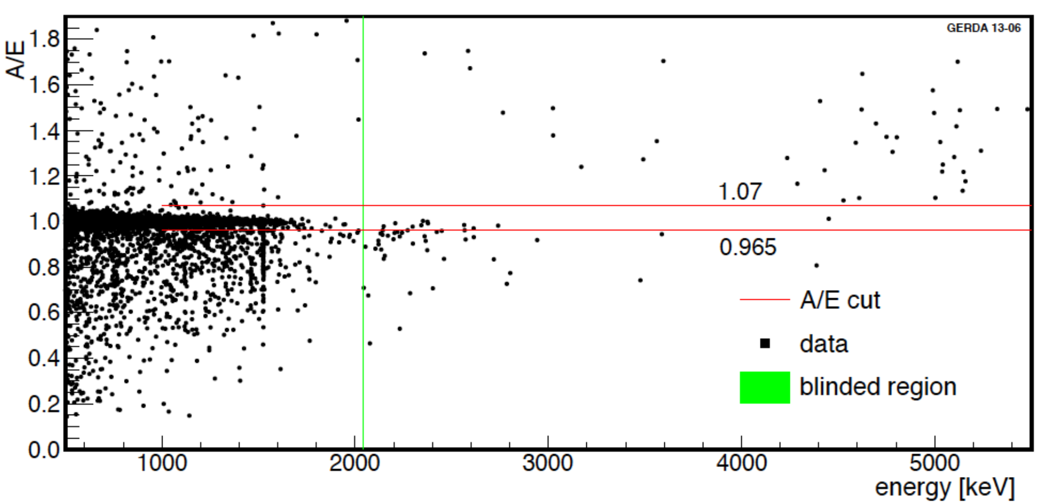
PSD for BEGe

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

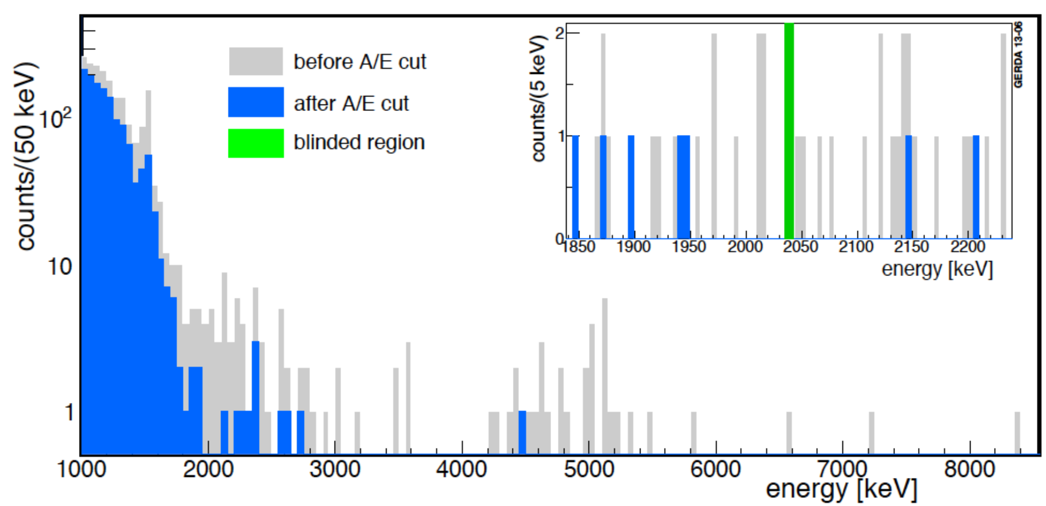
aim: develop the PSD method with ^{228}Th calibration data and then apply it to physics data

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)

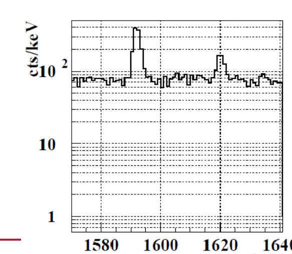
A/E versus E for physics data



spectrum before (grey) & after (blue) cut

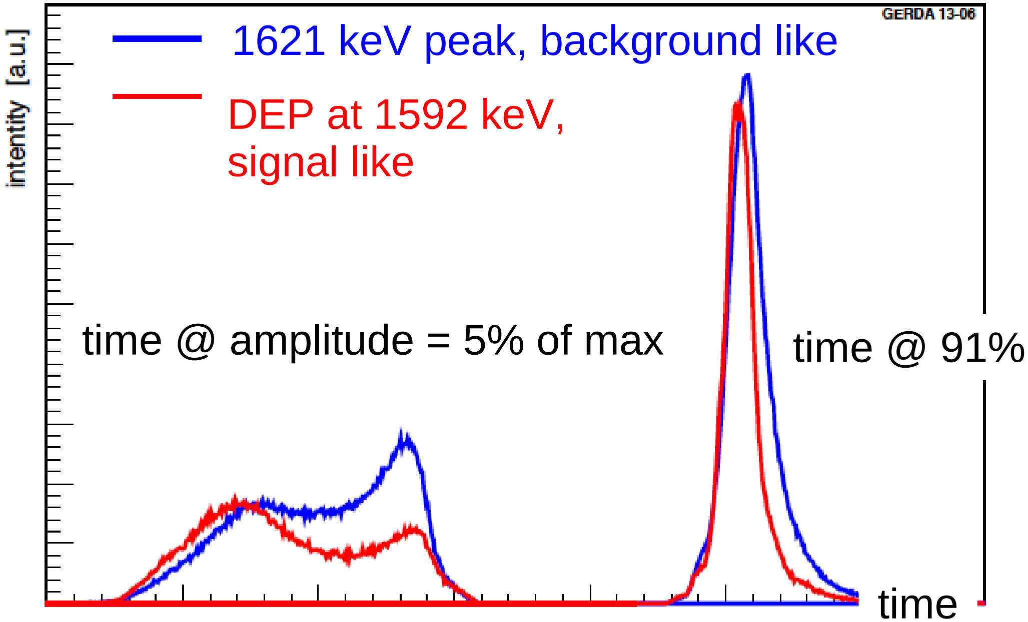


$0\nu\beta\beta$ efficiency = 92±2 % determined from DEP efficiency & simulation
$2\nu\beta\beta$ efficiency = 91±5 % in good agreement to DEP efficiency
reject >80% of background events



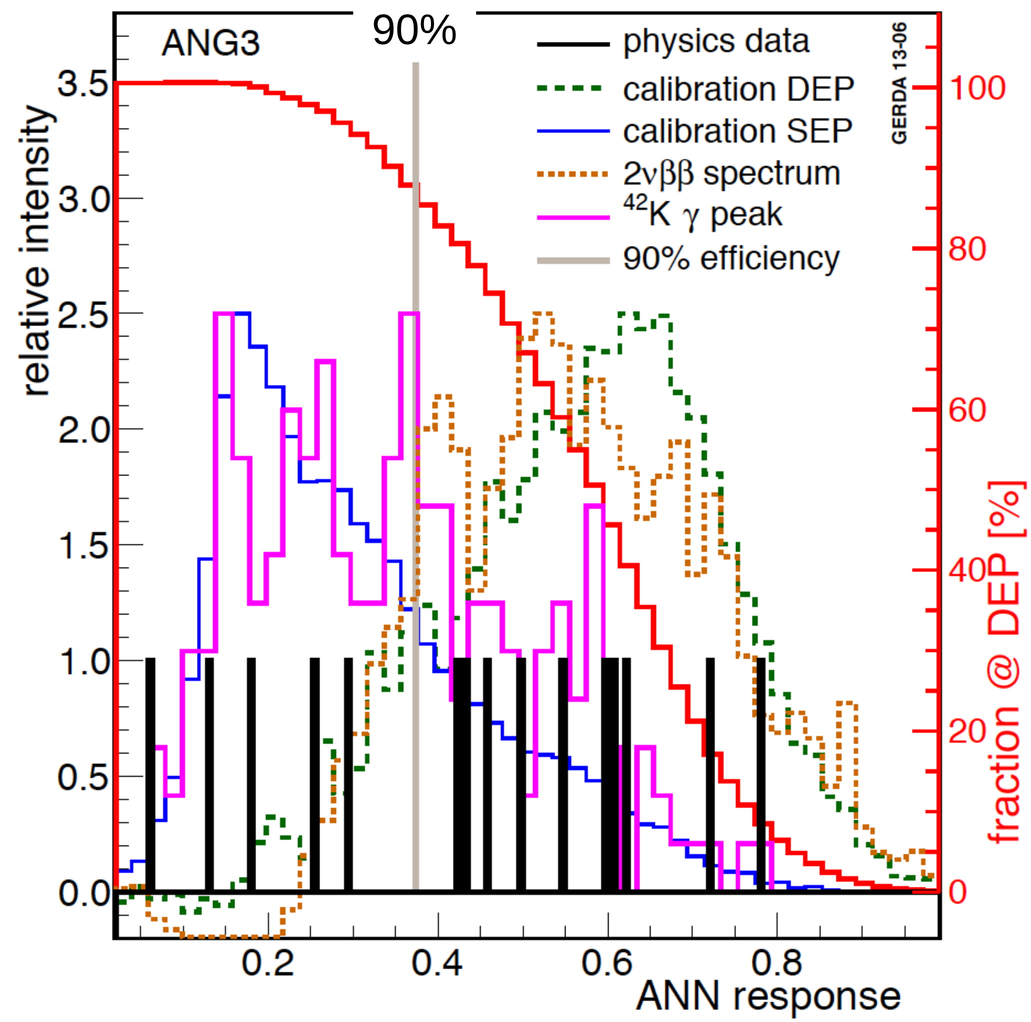
PSD for semi-coaxial: neural network (ANN)

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



example: ANG3 ANN response, 1st period

DEP survival



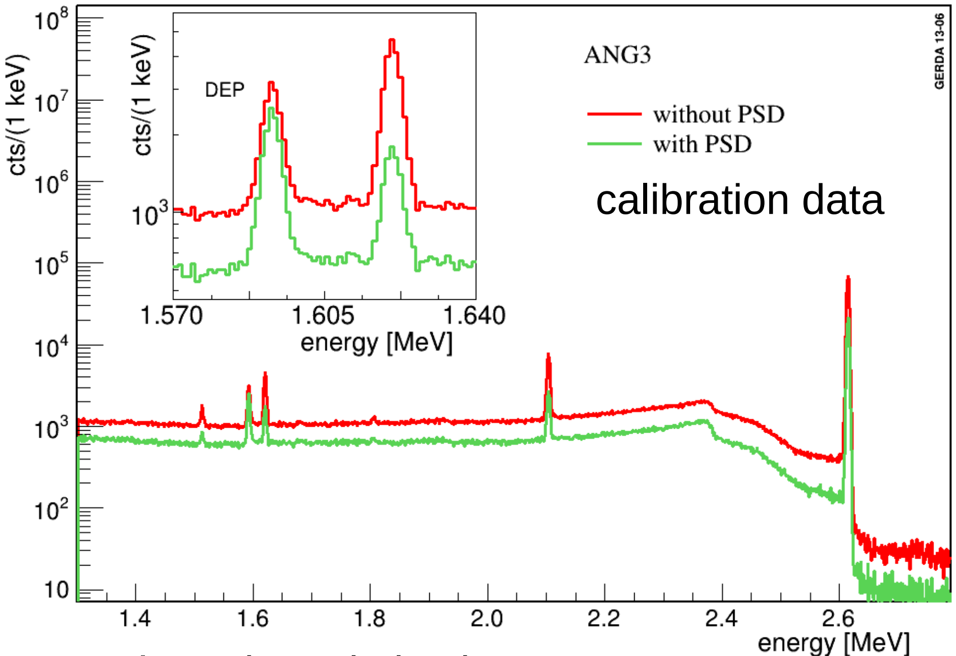
tested many methods implemented in TMVA, selected artificial neural network TMlpANN

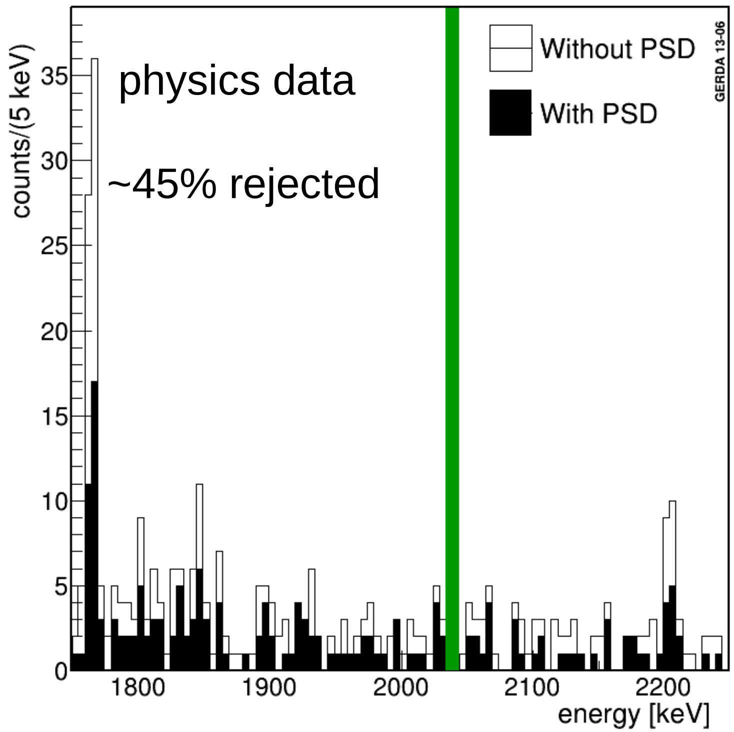
select **ANN** cut position @ DEP survival = 90%

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%

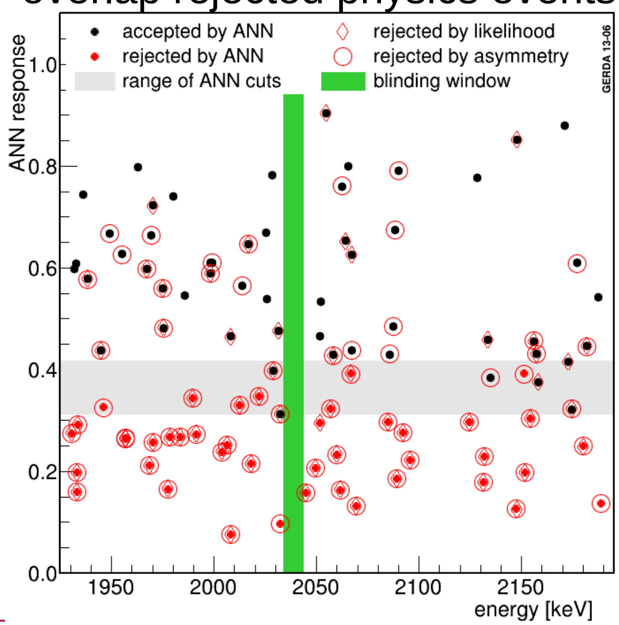
$$0\nu\beta\beta\,\text{efficiency} = 0.90^{+0.05}_{-0.09}$$

PSD for semi-coaxial





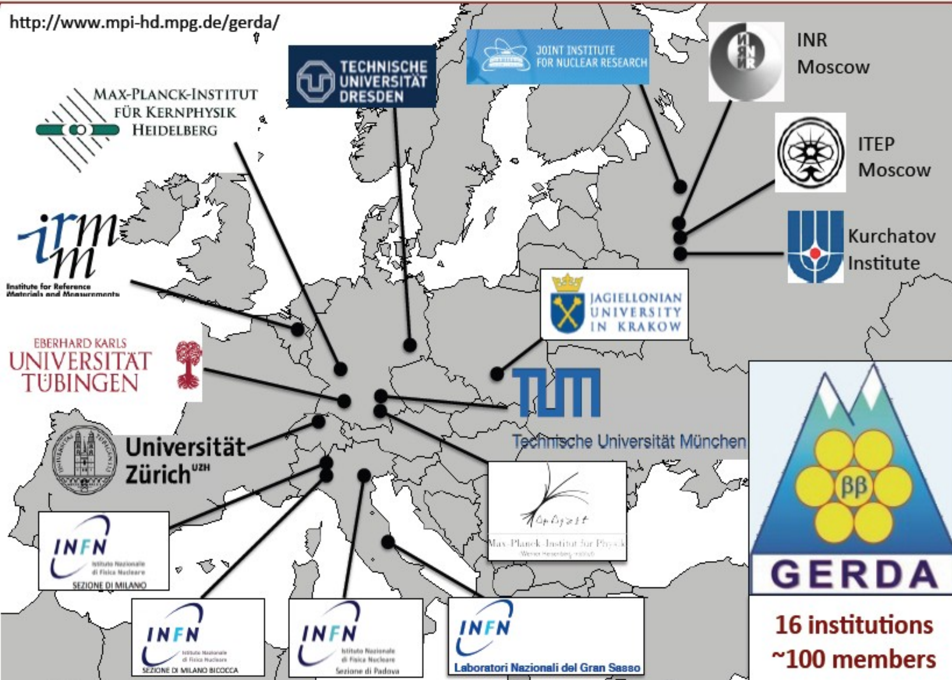
overlap rejected physics events



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

poster Vici Wagner



Dubna, June 2013

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

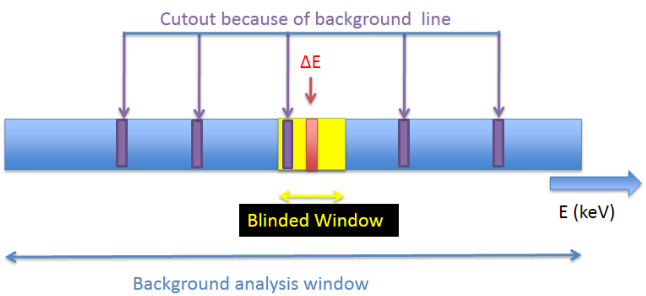
the strongest gamma line is 1525 keV from ^{42}K
dominated by ^{214}Bi and ^{228}Th
- nearby sources (det. holders etc.) and surface contaminations
- far sources do not matter

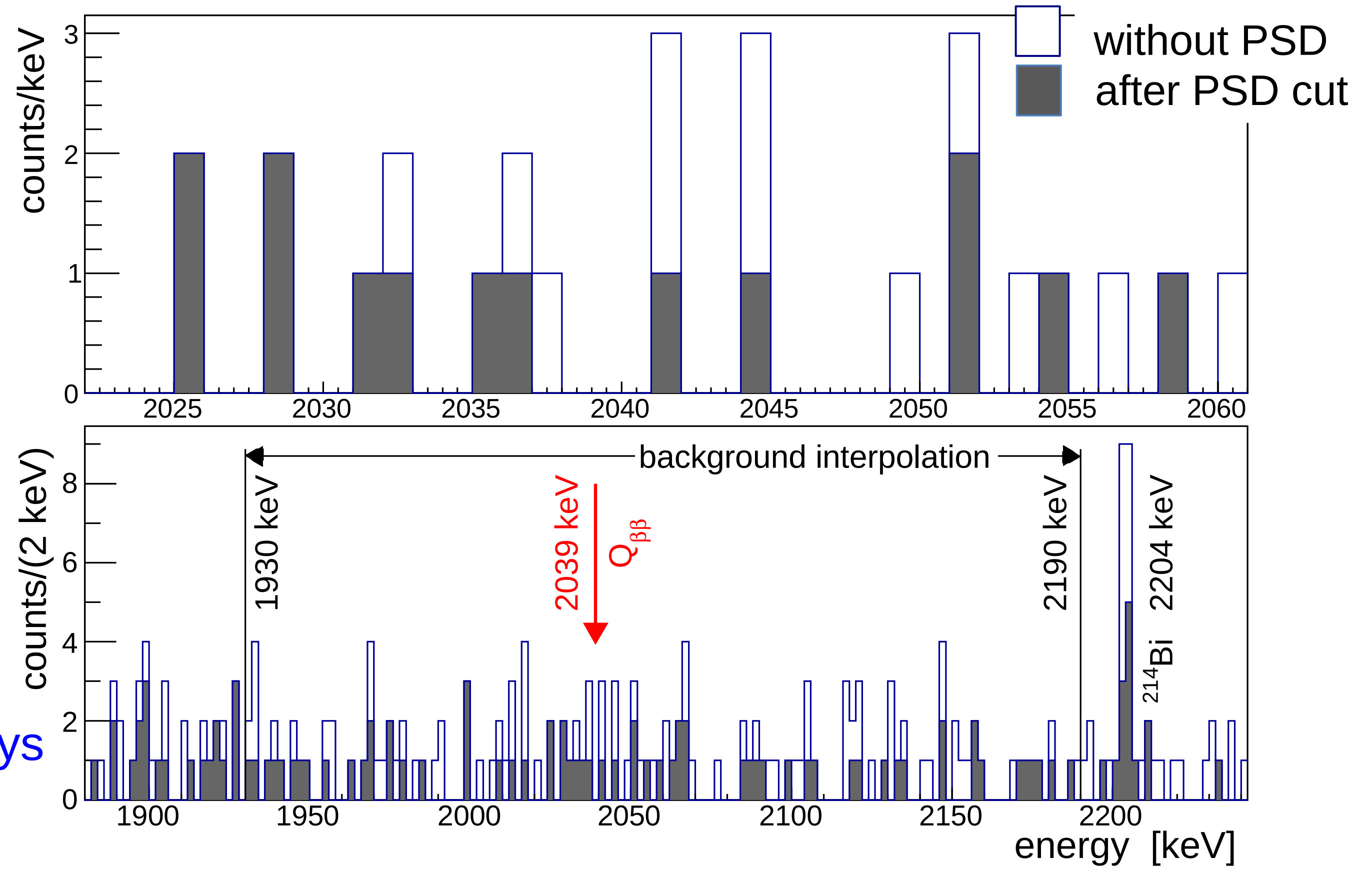
background flat between 1930-2190 keV

PSD gains another factor 2 in BI (11 ± 2) 10^{-3} cts/(kg yr keV)

(6 ± 1) 10^{-3} cts/(mol yr dE)

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 0νββ

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

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

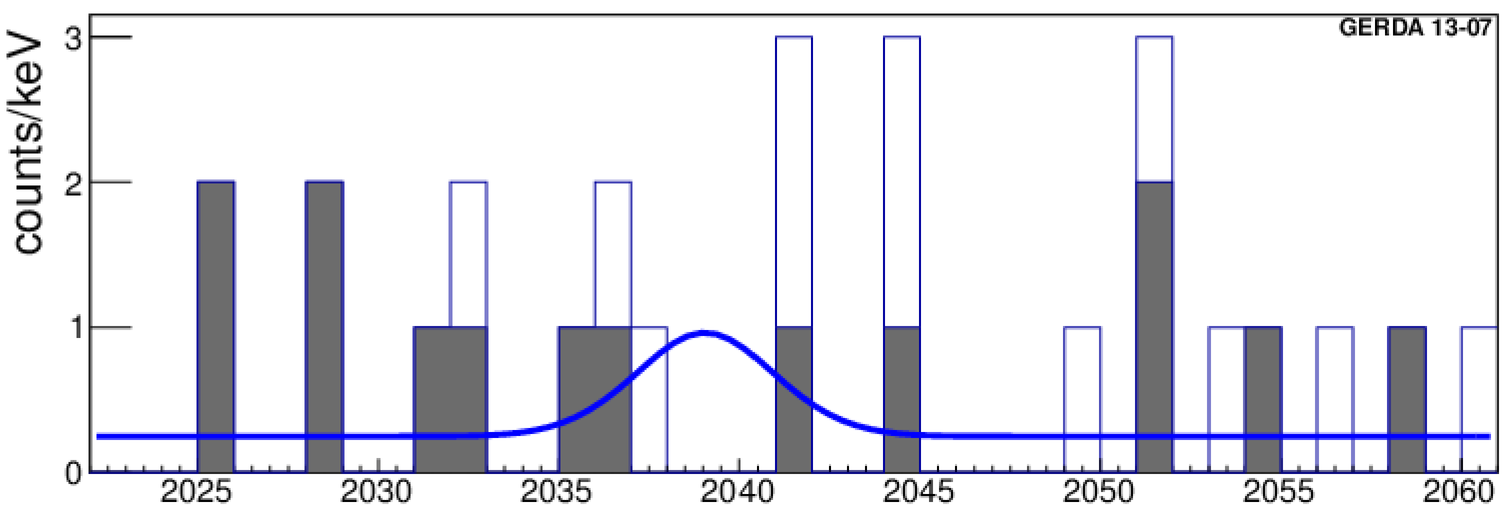
fit 3 data sets in 1930-2190 keV interval: constant (for bkg) + gauss (for signal),

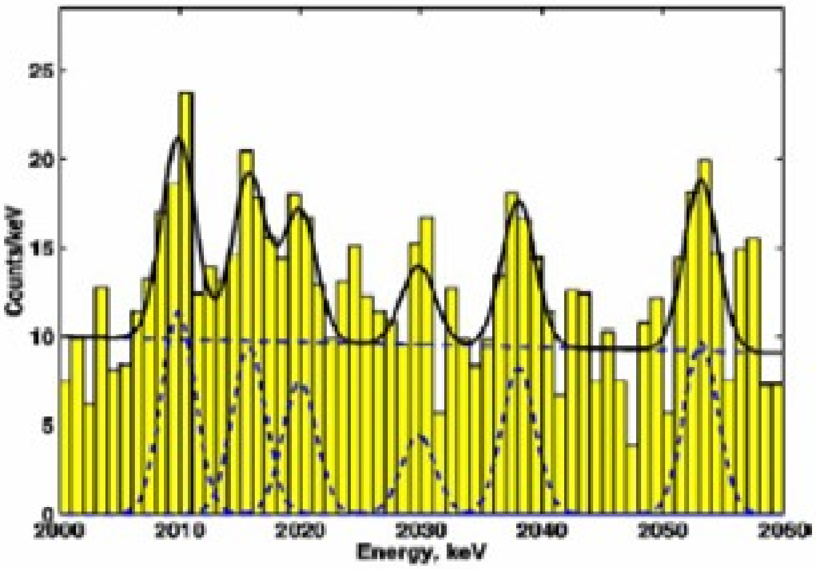
4 parameters: 3x bkg level & $1/T^{0\nu}$
$1/T^{0\nu} \geq 0$ constrain (best fit 1/T=0)

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, $T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}$ yr (90% C.L.) (sensitivity = 2.4 10^{25} yr)



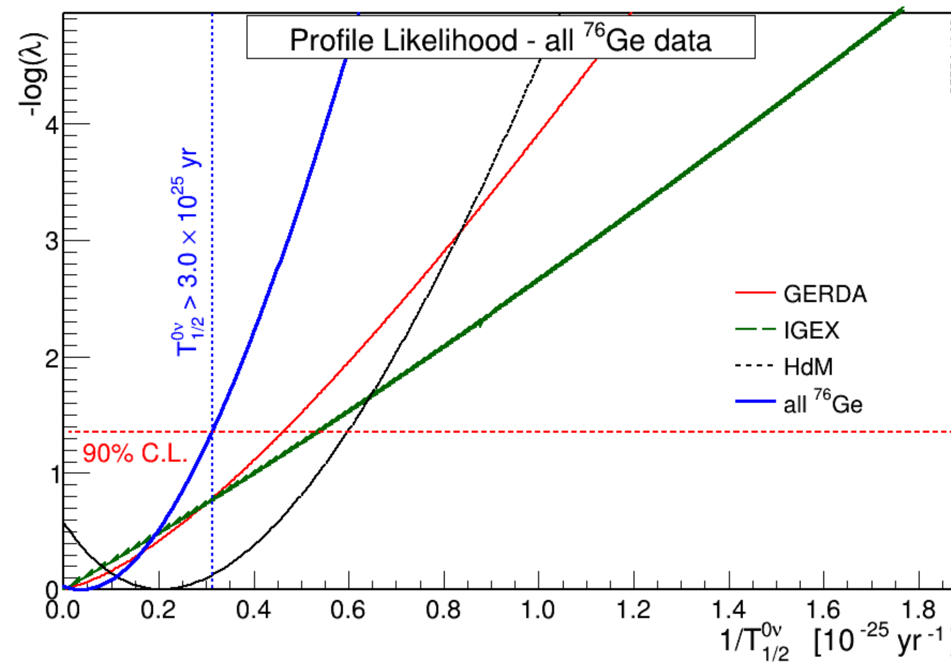


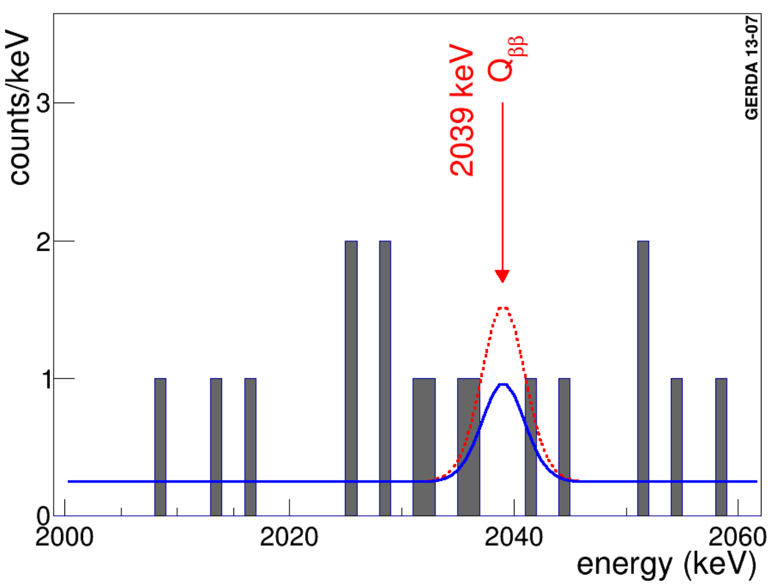
claim 2004

$\mathcal{E}$ = 71.7 kg yr

claim 2004:
excluded with 99%
Test of hypothesis
p = 0.01

$p(N^{0\nu}=0 \mid H1=\text{signal+bkg}) = 0.01$

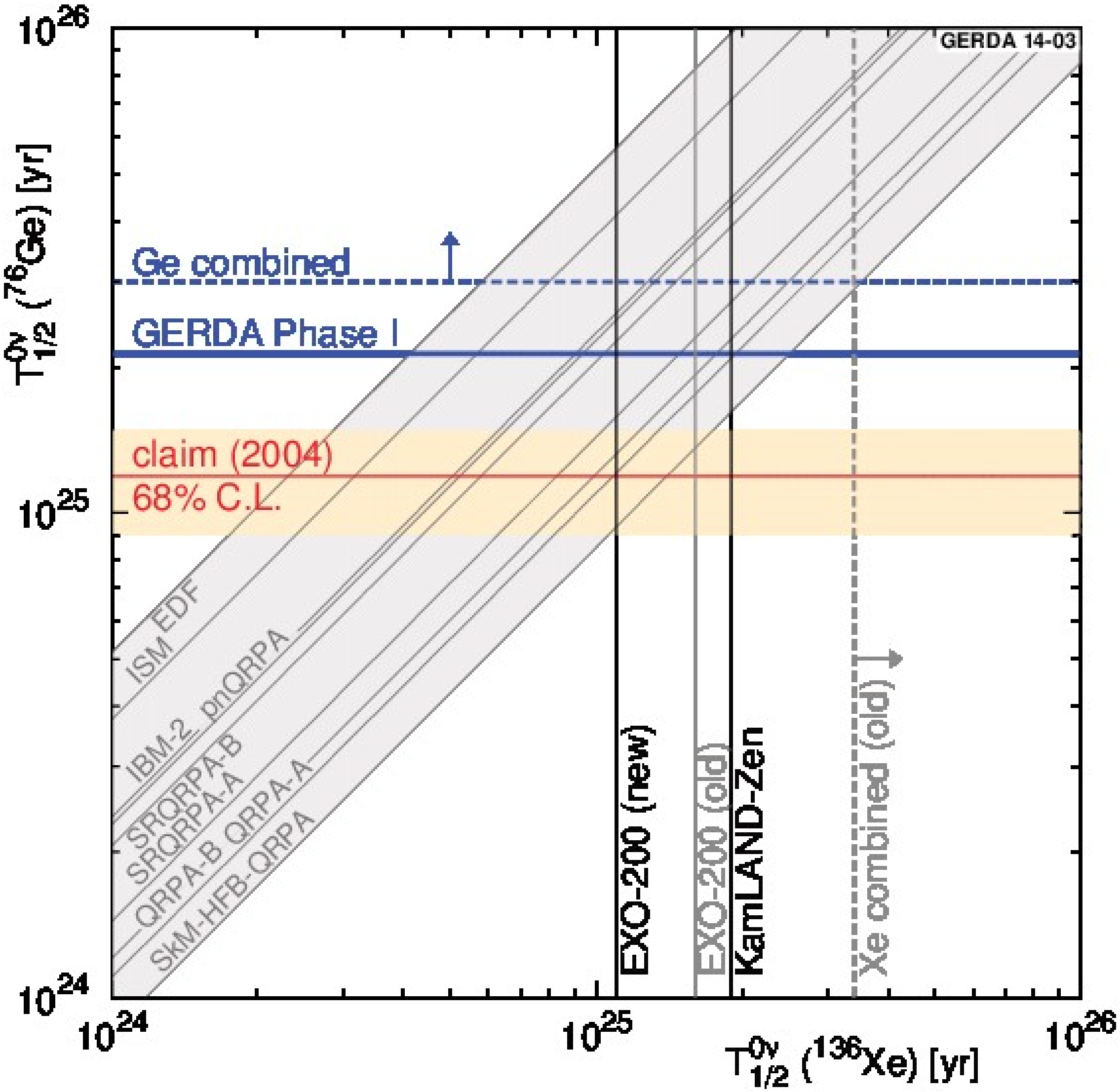




GERDA Phase I

BI = 1.1 10^{-2} cts/(kg yr keV)
$\mathcal{E}$ = 21.6 kg yr
S ~ 0.006 cts/(mol yr δE)

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

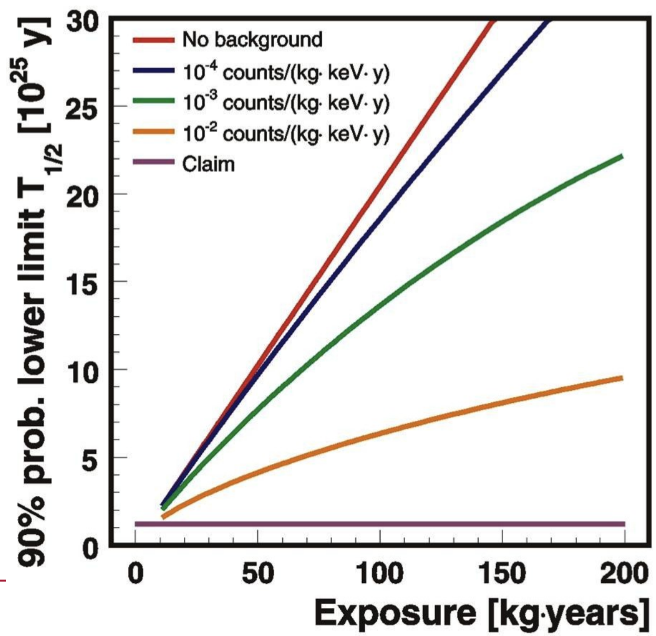
→ claim of ^{76}Ge signal is strongly disfavored

$0.2 < m_{\beta\beta} < 0.4$ eV

sensitivity for 0νββ decay

$$S_{1/2} \propto a * \varepsilon * \sqrt{\frac{M * t}{\delta E * b}}$$

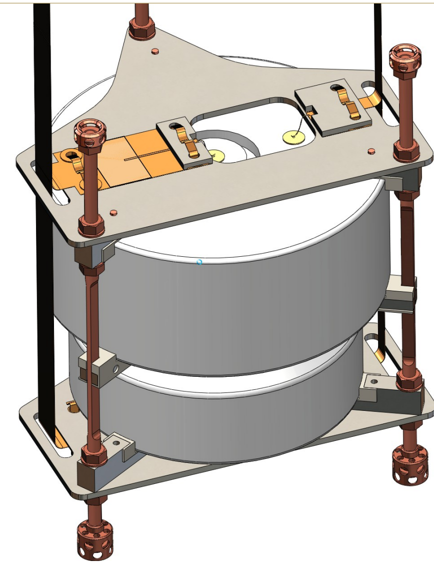
Experiment	$\mathcal{E}$ kg yr	δE %	BI 10^{-3} cts/(kg yr keV)	BI cts/(mol yr dE)	T1/2 > x •10^{25} yr (90%CL)
KamLAND-Zen I	27.5	4.2%			> 0.5
KamLAND-Zen II	89.5	4.2%	41	0.19	> 1.9
EXO-200 1	32.5	1.67%	1.5 ± 0.1	0.044	> 1.6
EXO-200 2	99.8	1.53%	1.7 ± 0.2	0.053	> 1.1
GERDA Phase I	21.6	0.2%,	11 ± 2	0.006	> 2.1

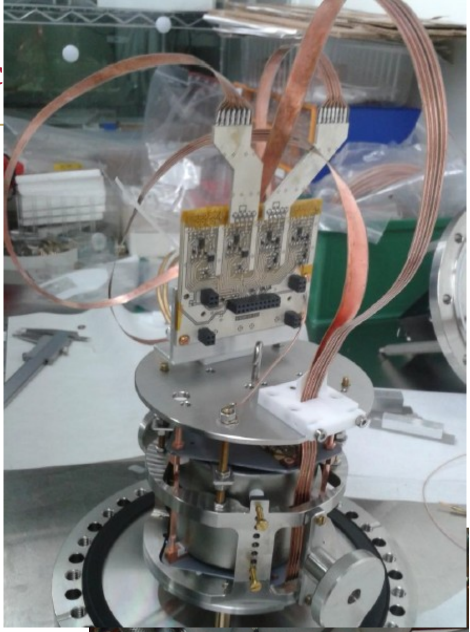


Phase II

1) additional 30 BEGe Detectors:
   + 20 kg, better PSD

2) new FE- electronics





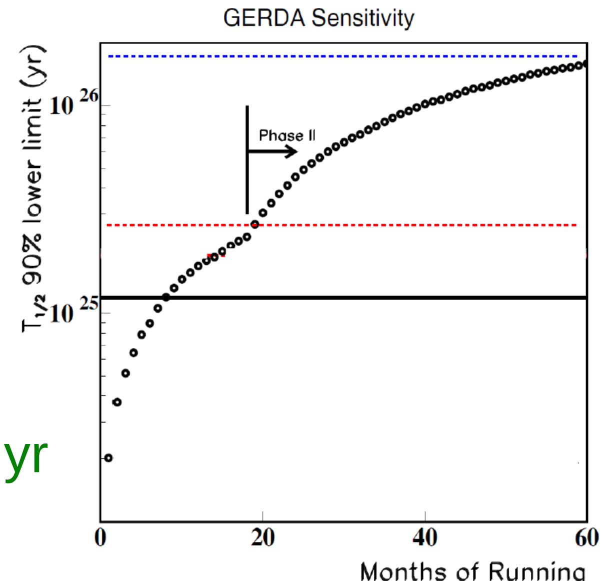
3) liquid-Argon-Instrumentation

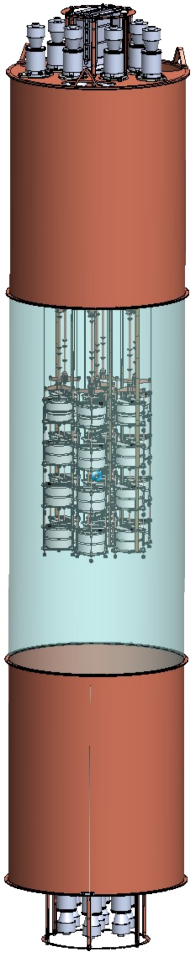
surface contaminations & Compton scattering produce scinillationslight (128nm) in LAr

readout with

a) WLS-fiber and SiPM

b) 3" PMT





goal: BI~10^{-3} cts/(keV·kg·yr)

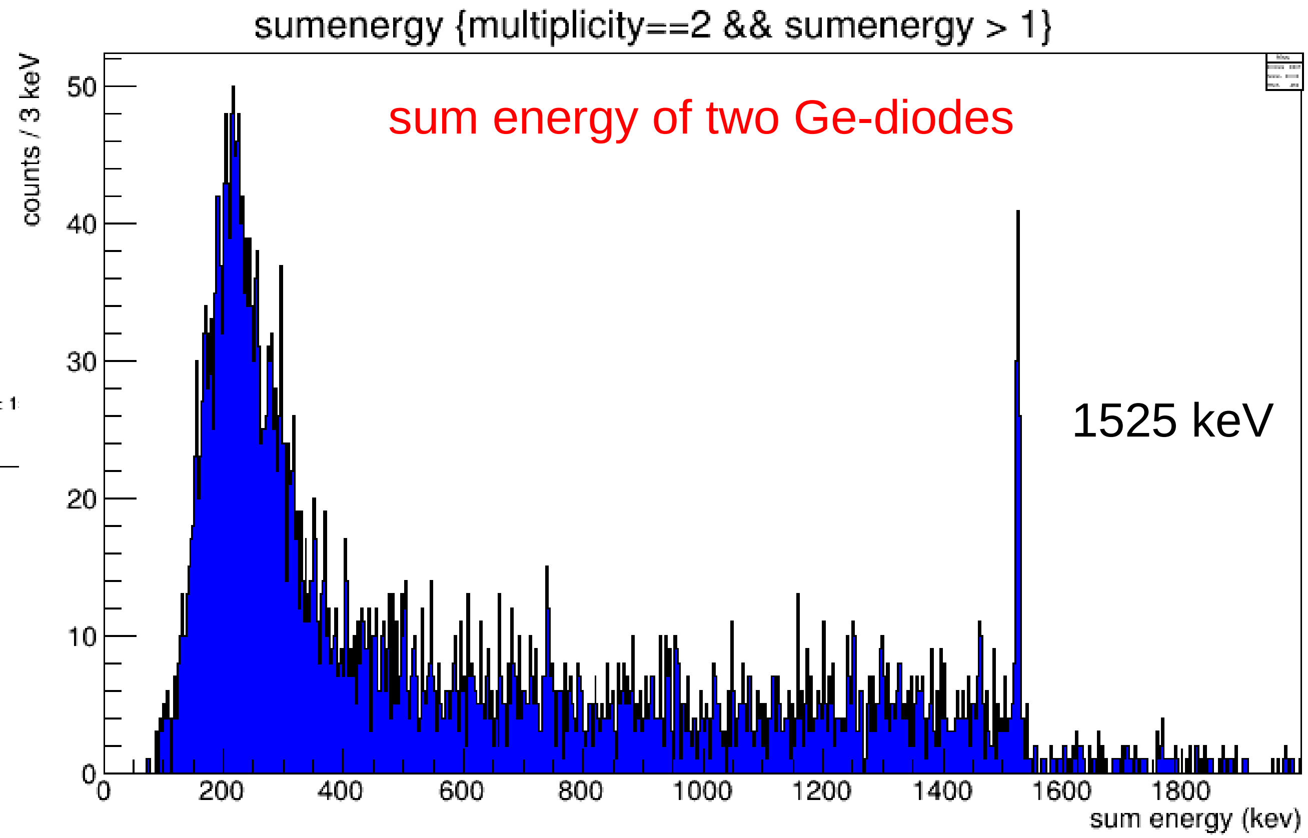
$\mathcal{E}$ ~ 100 kg yr ↷ $T_{1/2}$ ~ 10^{26} yr

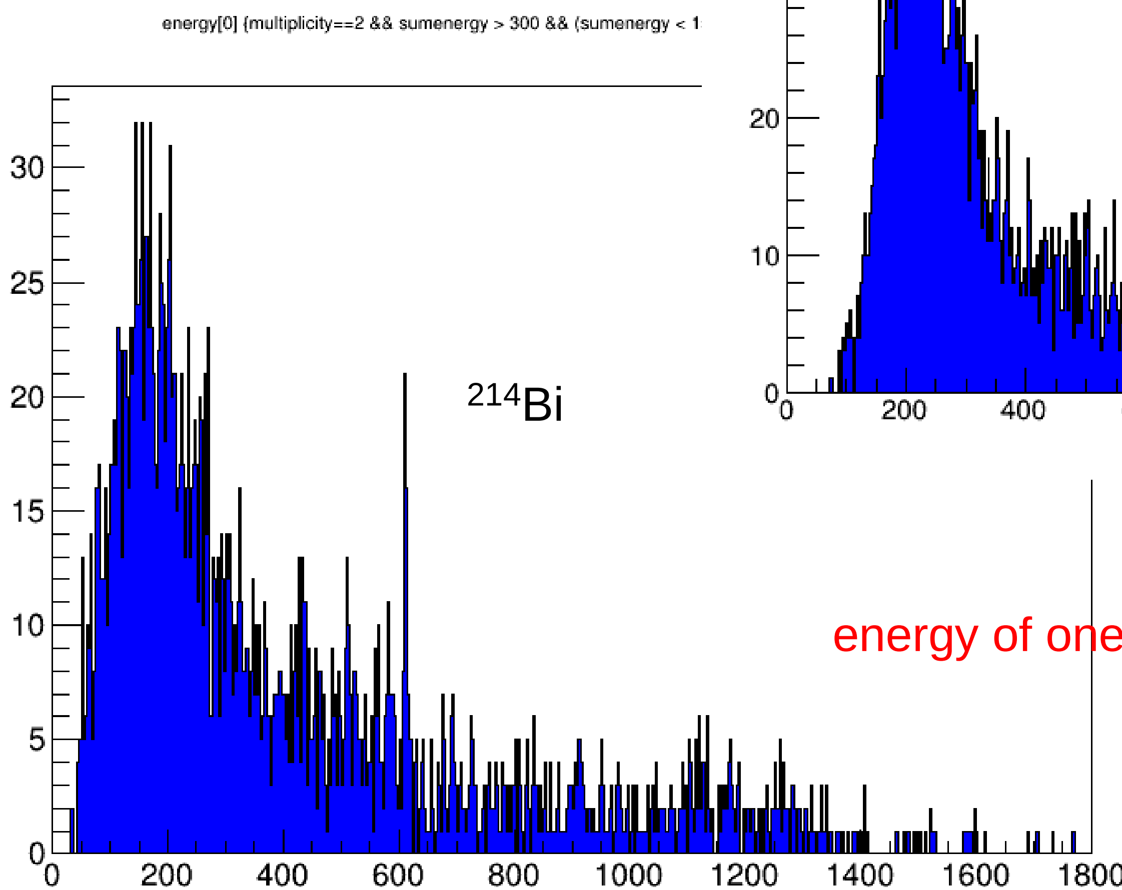
poster Anne Wegmann/Tobias Bode

further studies: γ–γ coincidences

a) background identification

b) 2νββ & 0νββ to excited states





energy of one diode (without 1525)

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)

data taking Phase I stopped, data analyzed & published

GERDA Phase II with add. 20 kg BEGe and LAr instrumentation

in 2014 we still do not know

.... if he is right