First data release GERDA Phase II: Search for $0\nu\beta\beta$ of ^{76}Ge

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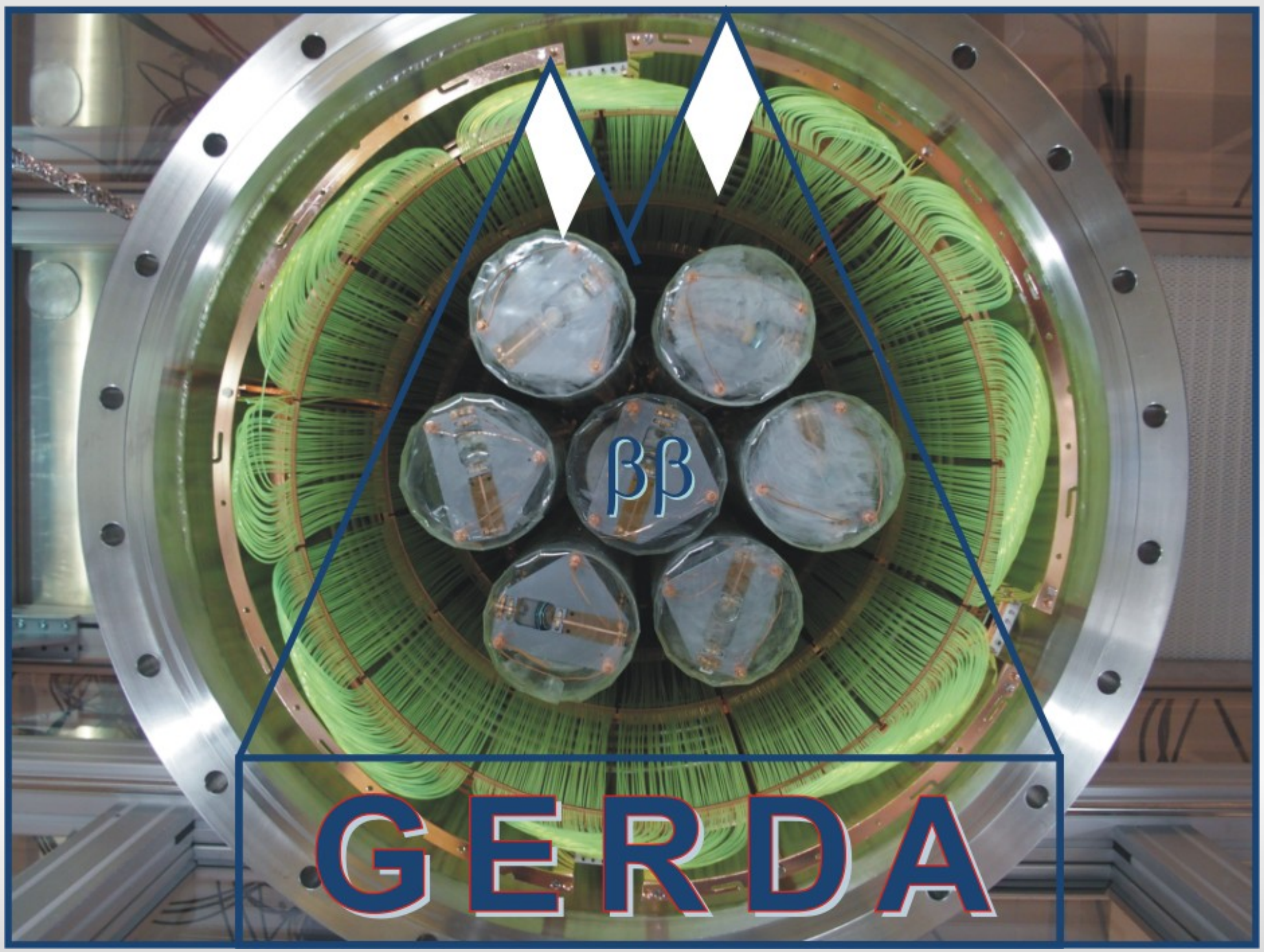
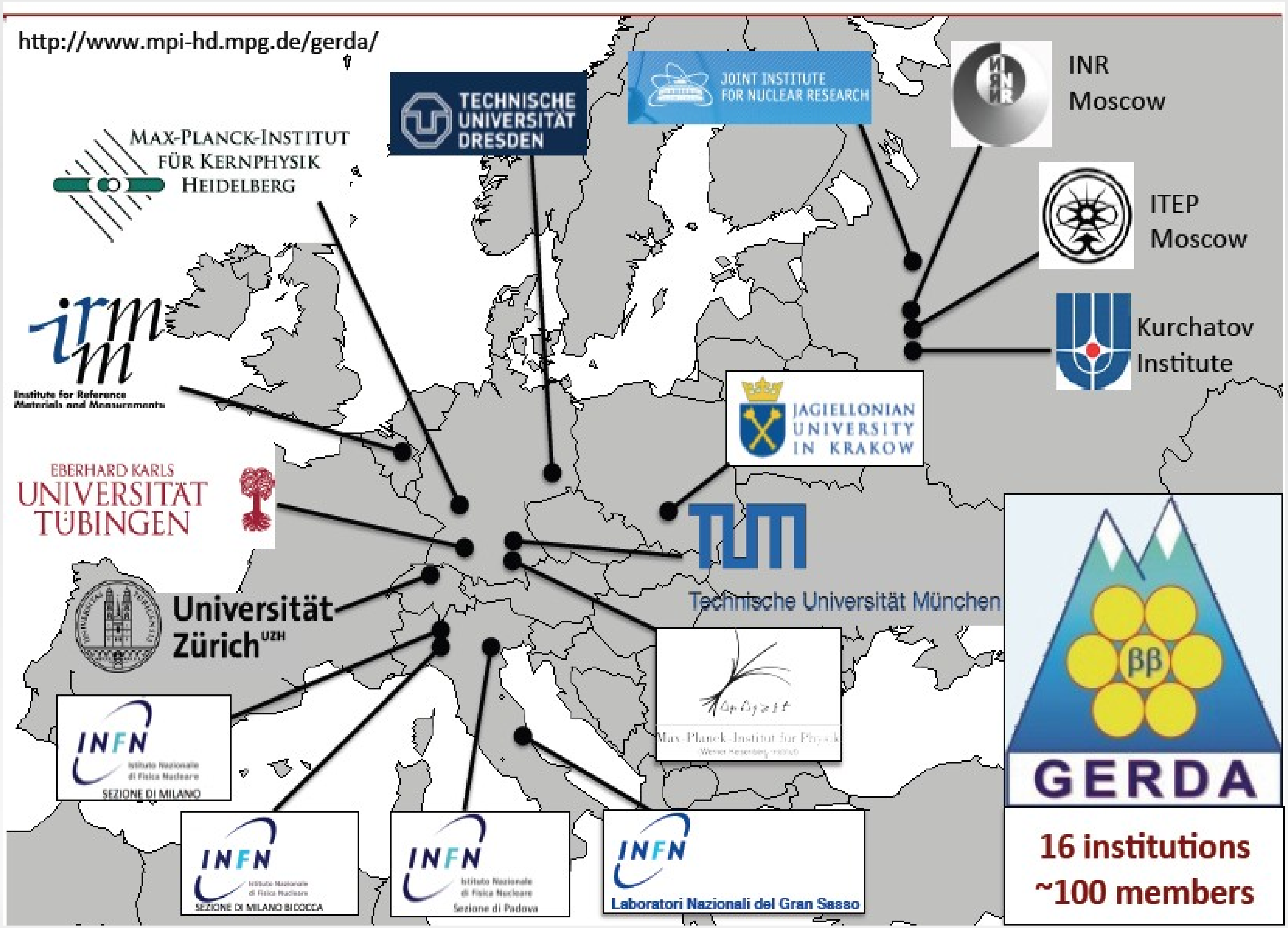
for the collaboration



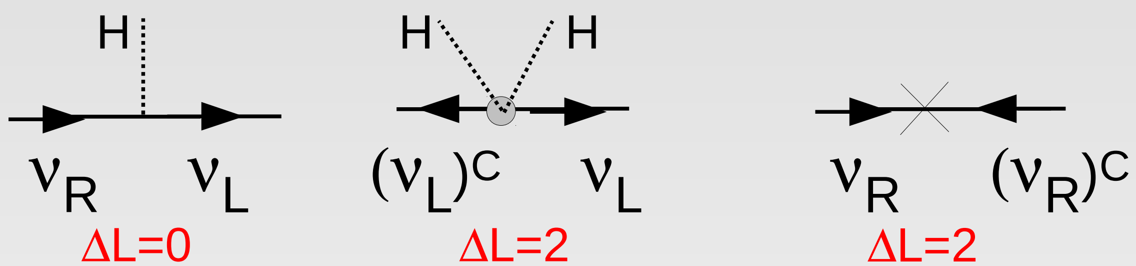
The collaboration



Neutrino mass: non-SM effect?

possible neutrino mass terms (ν has no electric charge): not only Dirac

$$L_{Yuk} = m_D \bar{\nu}_L \nu_R + m_L \bar{\nu}_L (\nu_L)^C + m_R (\bar{\nu}_R)^C \nu_R + h.c.$$



ν_L couples to Standard Model W,Z bosons, ν_R does not (SM singlet)

m_D ~ normal Dirac mass term

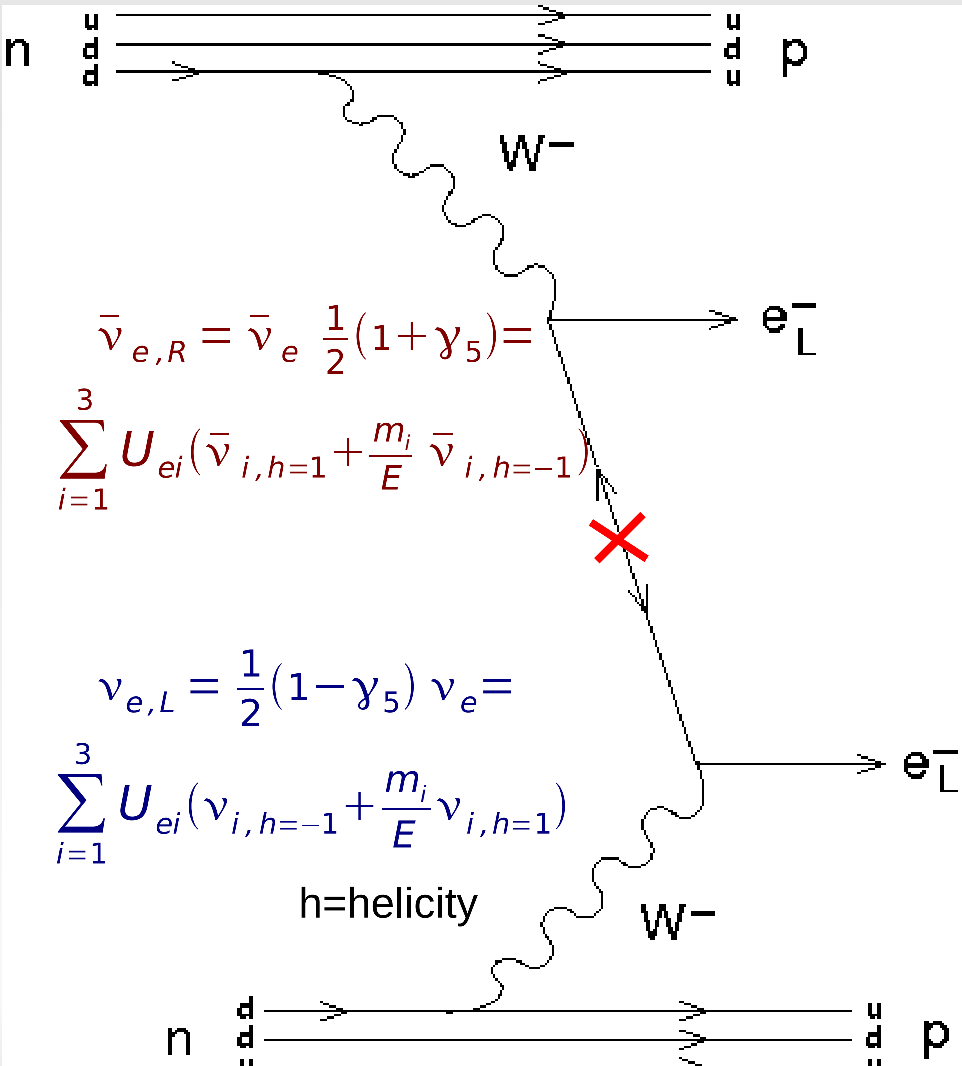
m_L, m_R new physics

eigen vector	$N \sim \nu_R + (\nu_R)^C$	$\nu \sim \nu_L + (\nu_L)^C$	Majorana particles
mass ($m_L \sim 0$)	m_R	m_D^2 / m_R	

in general: expect Lepton number violation & neutrino = Majorana

How to observe ΔL=2: 0νββ

Look for a process which can (only) occur if neutrino is Majorana particle



coupling strength ~ $m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_i$

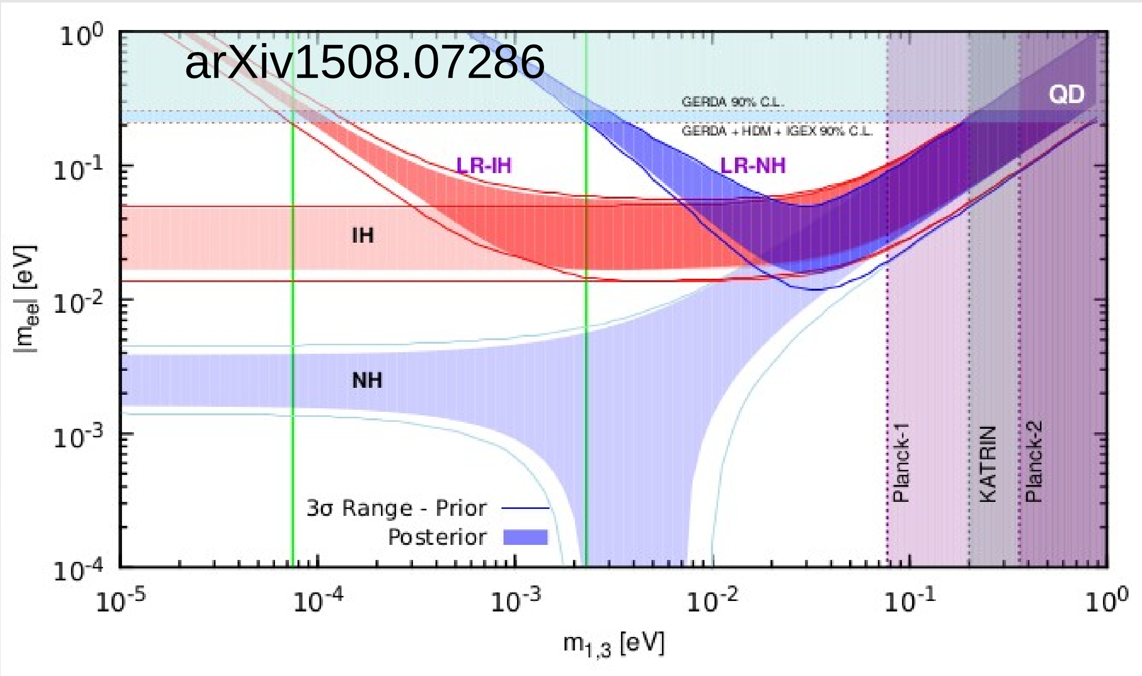
function of
- neutrino mixing parameters
- lightest neutrino mass
- 2 Majorana phases

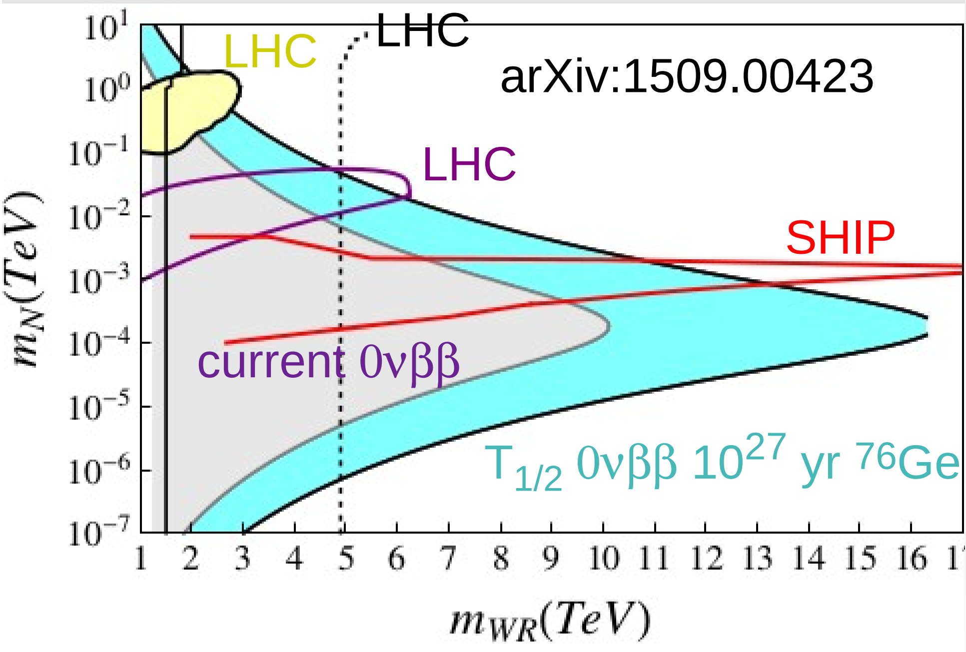
also possible: heavy N exchange

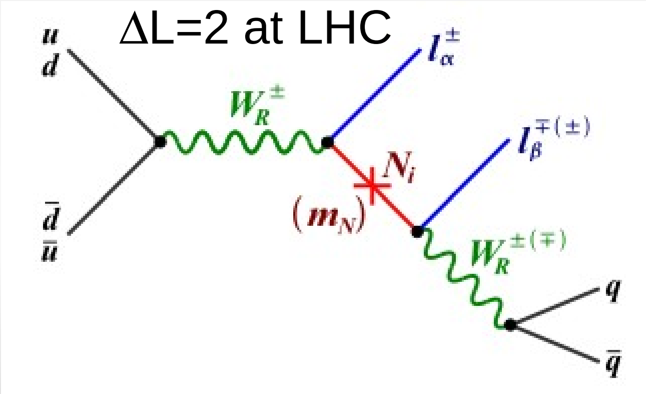
→ coupling strength ~ $\sum_{i=1}^{3} V_{ei}^2 / M_i$

LHC vs $0\nu\beta\beta$: other mechanisms

extensions of SM → other contributions to $0\nu\beta\beta$ possible, example LRSM
LHC might find W_R and/or $\Delta L=2$ process



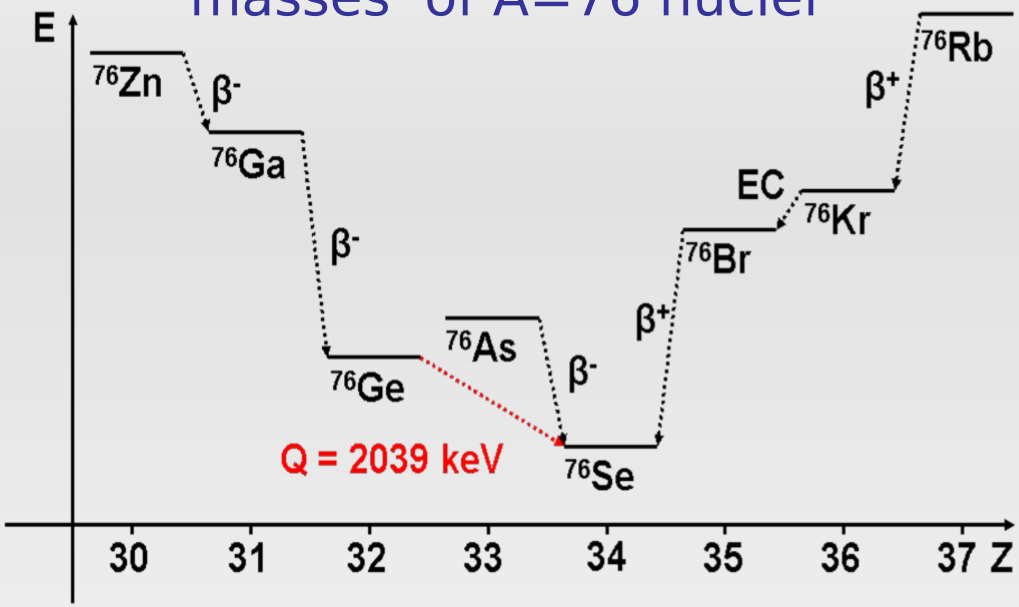




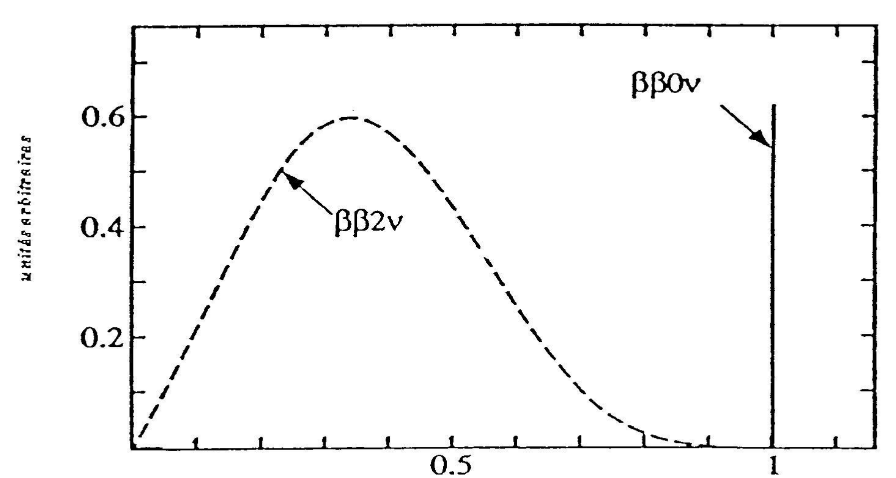
best case: find s.th. at LHC and $0\nu\beta\beta$ and lepton flavor violation $\mu \rightarrow e\,\gamma$

Neutrinoless double beta decay

masses of A=76 nuclei



experimental signature for ββ



sum electron energies / $Q_{\beta\beta}$

"single" beta decay not allowed

→ only "double beta decay"

$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\Delta L=0$

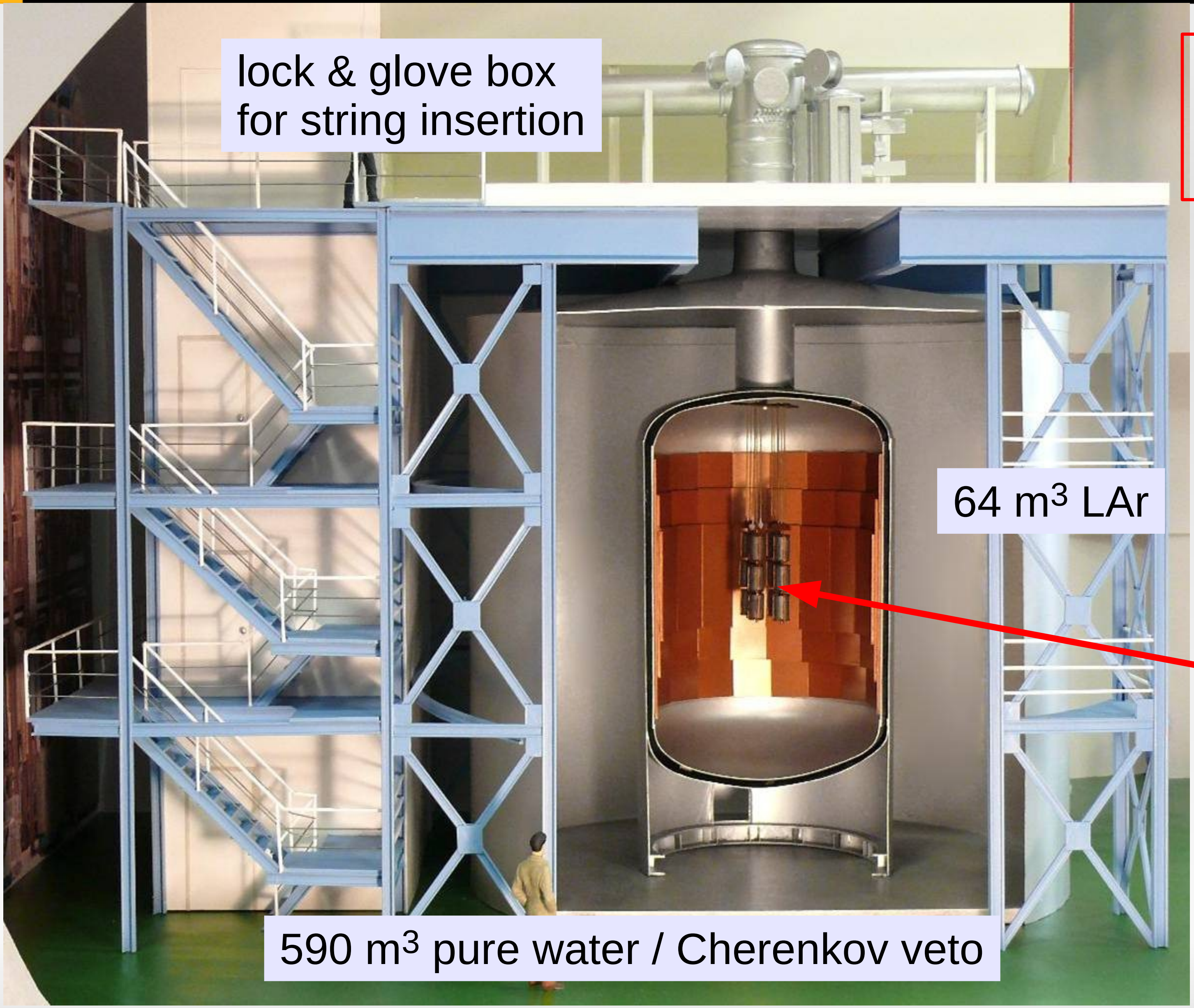
$(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $\Delta L=2$

0νββ: search for a line at Q value of decay

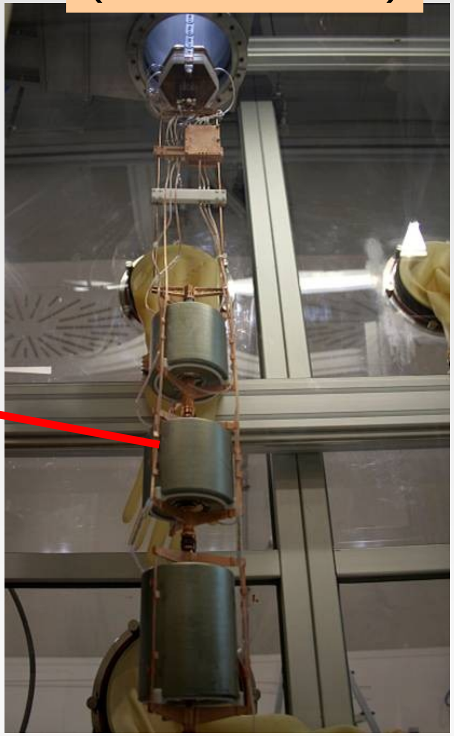
Note: similar process in principle also observable at accelerator or reactor or ...
For light Majorana neutrino:
- background too high
- flux too low compared to Avogadro N_A

GERDA: Ge in LAr @ Gran Sasso

basic idea: use clean & low Z liquids for shielding, active veto (no dead mat.)

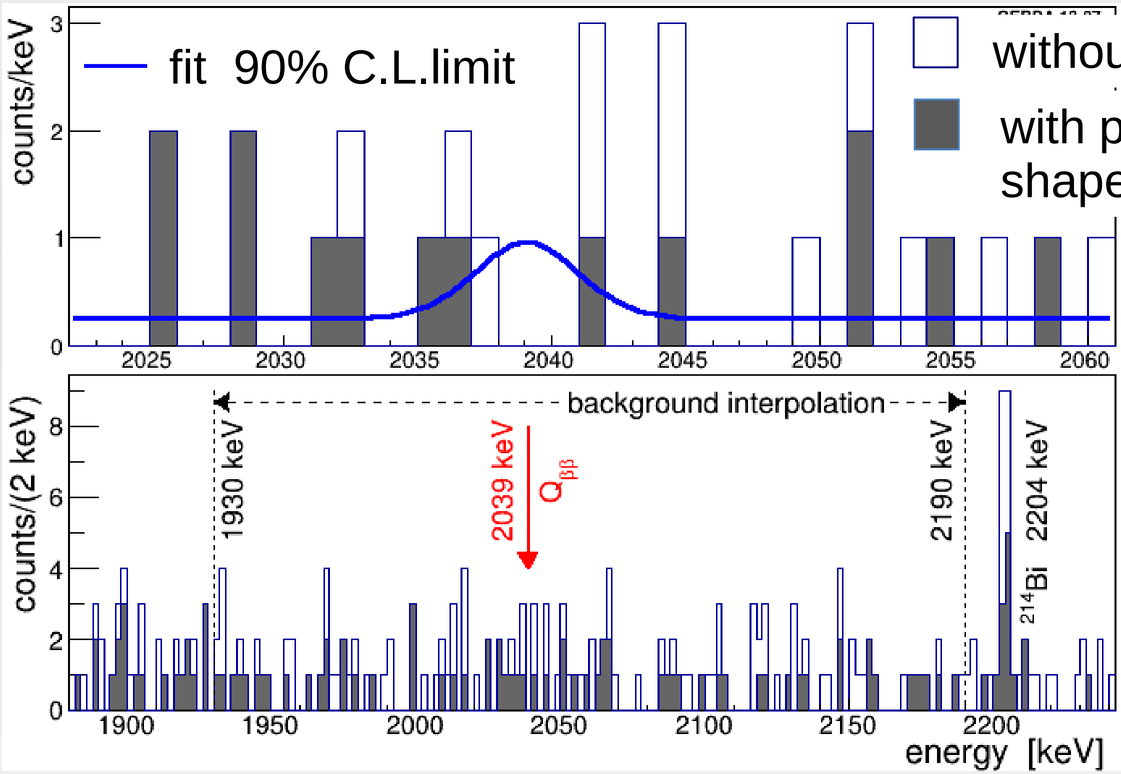


Ge detectors (^{76}Ge ~ 86%)



EPJ C73 (2013) 2330 based on idea of G. Heusser (1995)

GERDA Phase I result for 0νββ



events ±20 keV blinded

after calibration+selection finished
→ unblinding at meeting
in Dubna in June 2013

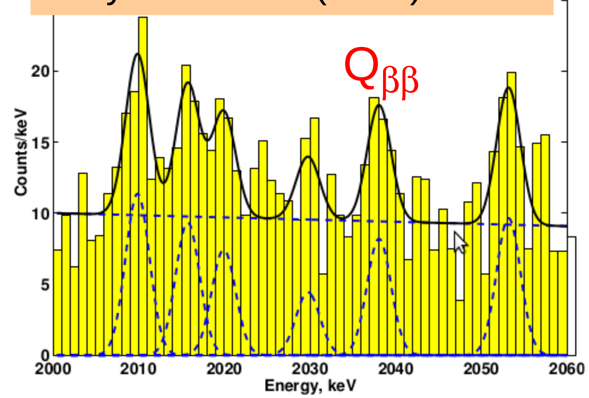
exposure 21.6 kg yr
backgr. 0.01 cnt/(keV kg yr)
after pulse shape cut

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

(sensitivity = 2.4 10^{25} yr)

PRL 111 (2013) 122503.

Klapdor-Kleingrothaus et al
PhysLett B586 (2004) 198



claimed signal: GERDA should see 5.9±1.4 0νββ events in ±2σ interval above background of 2.0±0.3

probability $p(N^{0\nu}=0 \mid H_1=\text{signal+bkg})$ = 1%, claim ruled out @ 99%

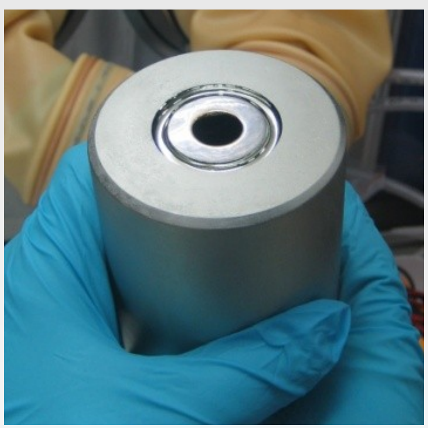
(GERDA best fit signal count $N^{0\nu}$ = 0)

Transition to Phase II

goals: 2x detector mass & factor 10 lower background
→ factor ~7 higher sensitivity of ~1.5 10^{26} yr (90% C.L.) limit

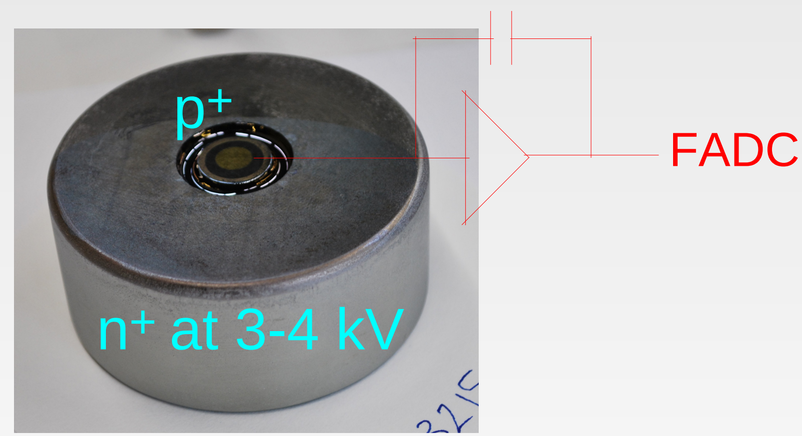
all hardware modified except for cryostat, water tank and clean room

8 (semi-)coaxial detectors
Heidelberg-Moscow + IGEX
17 kg total mass



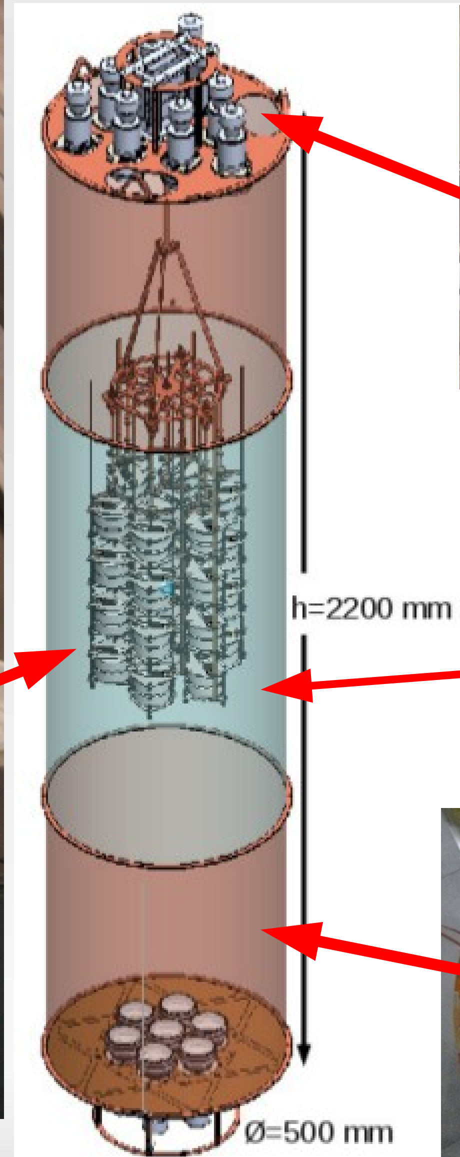
+

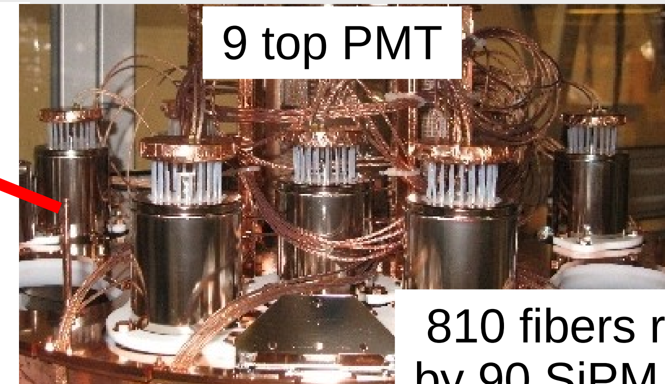
30 Broad Energy Ge det. (BEGe)
new detectors made by Canberra
20 kg total mass

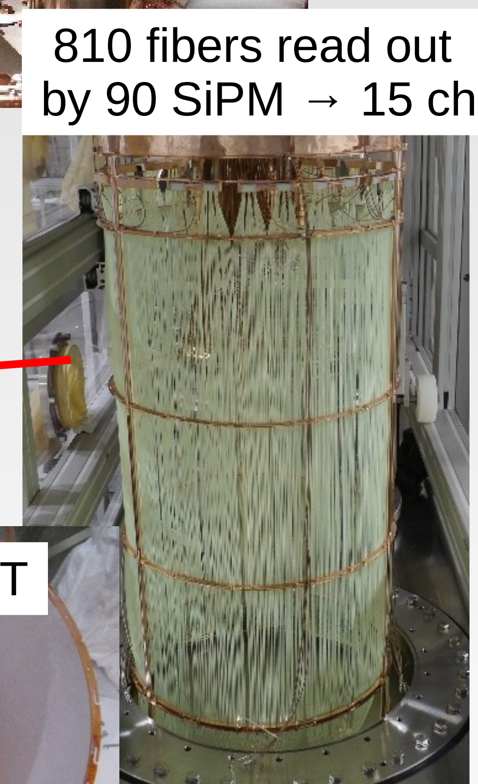


Phase I background: ^{208}Tl, ^{214}Bi, ^{42}K, surface alpha
→ measure all energy depositions (LAr veto) &
better detector pulse shape discrimination (BEGe)

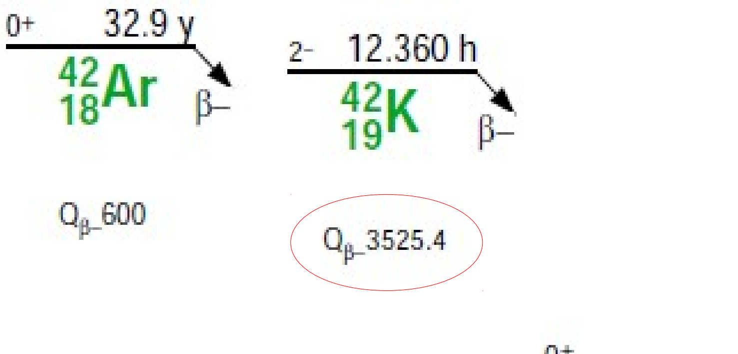
LAr veto of Phase II







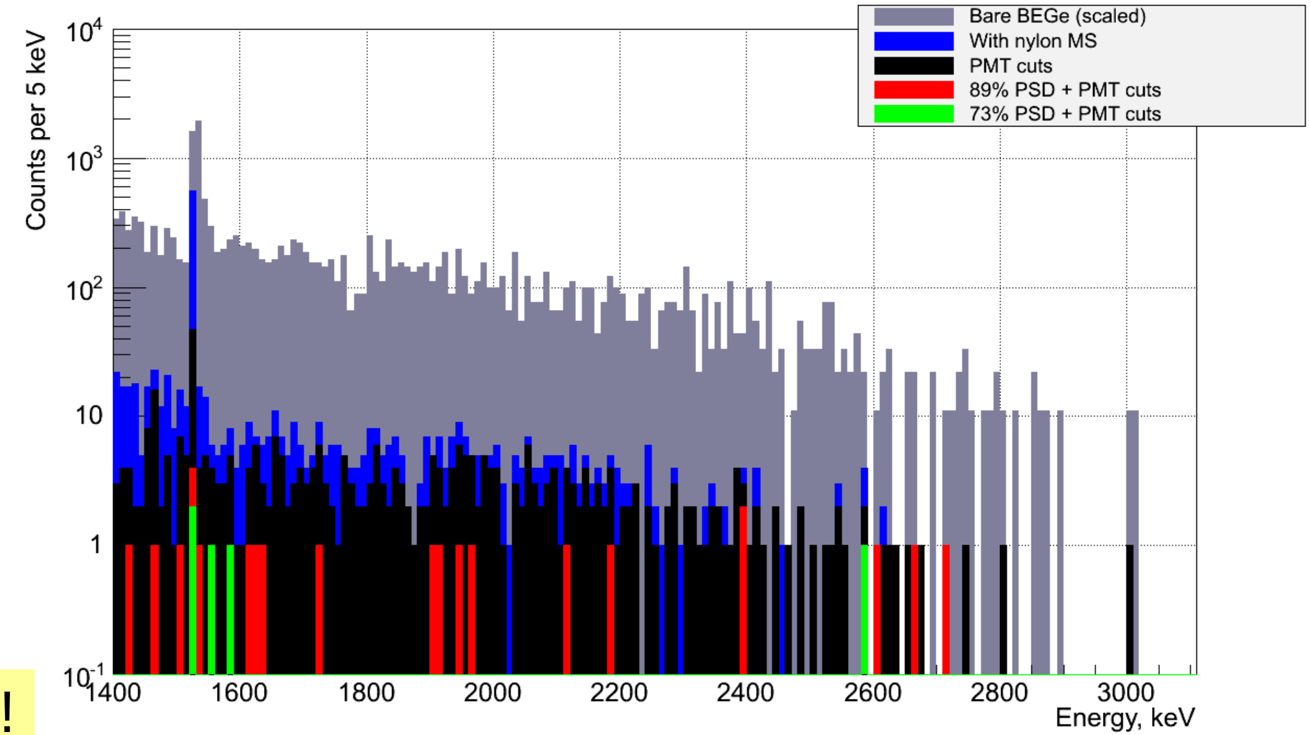
Nylon mini shroud: ^{42}Ar background



(charged) ^{42}K drift in field of Ge detectors

LArGe test stand result

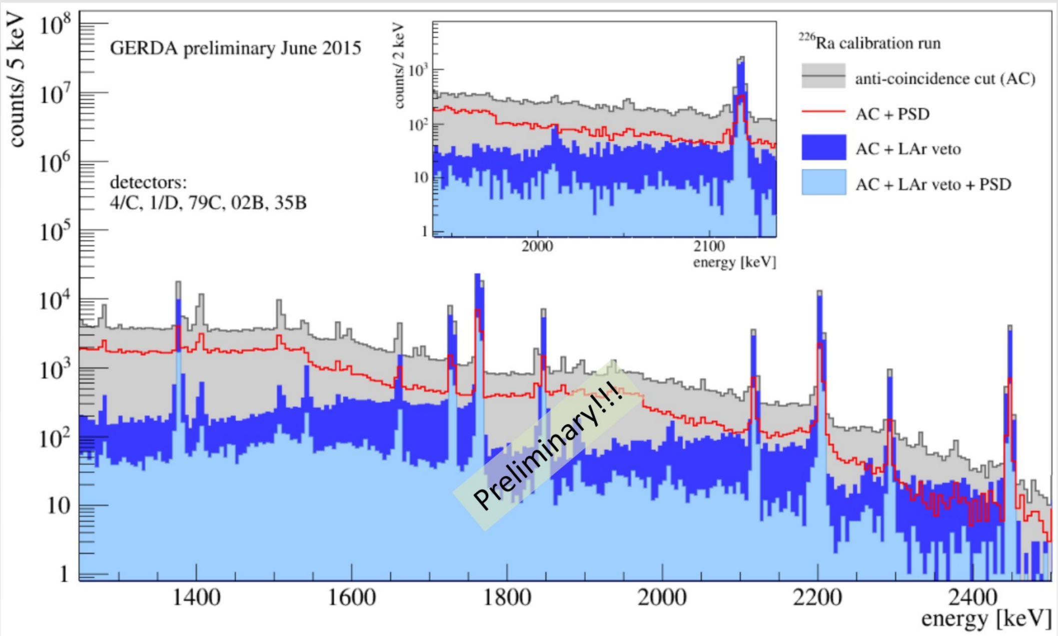
1 ton LAr doped with ^{42}Ar, ~200x abundance of nat. Ar
BEGe det. in nylon cylinder covered with TPB,
LAr veto with PMTs
→ background suppression factor SF = 15 from nylon,
limit volume from which ^{42}K can be collected
→ LAr veto + Ge det. pulse shape SF ~ 70



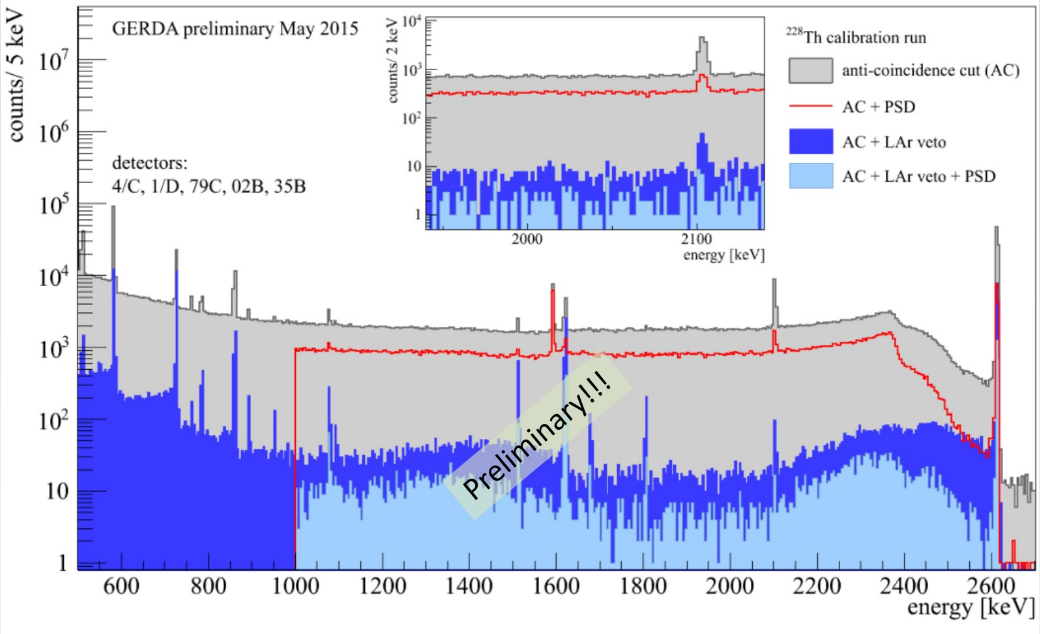
nylon from Borexino: thanks!!!

Argon veto commissioning performance

^{226}Ra calibration source



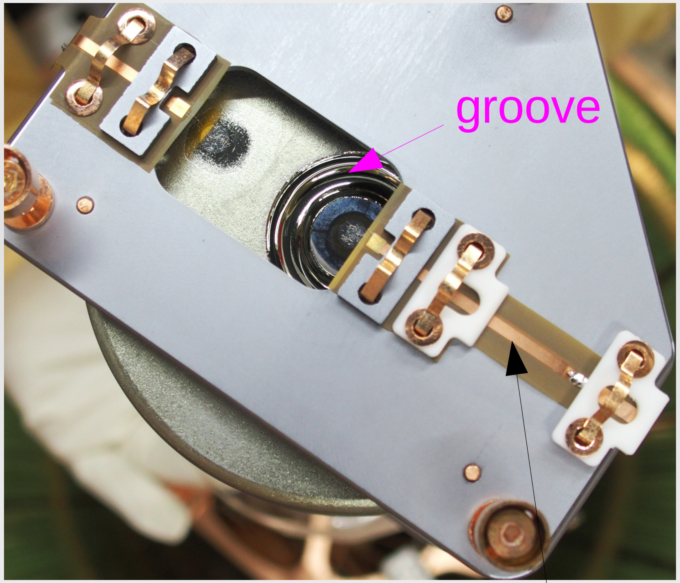
^{228}Th calibration source



	^{226}Ra	^{228}Th
veto suppression factor	5.1±0.2	85±3
combined with pulse shape & anti-coincidence	25±2.2	390±28

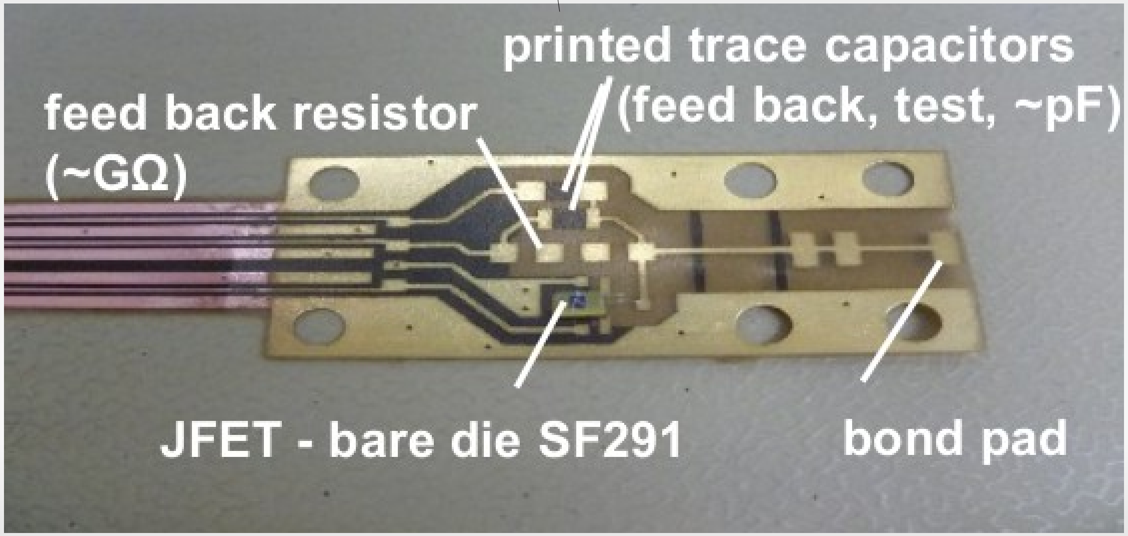
factors depend on isotope, location & detector configuration

Detector holder & electronics



goal: pure materials like mono-crystalline Si

80 g Cu/detector → ~15 g Cu/detector
11 g PTFE/detector → ~3 g PTFE/det
1 g Si/detector → 40 g Si/detector
reliable electrical contact → bonding

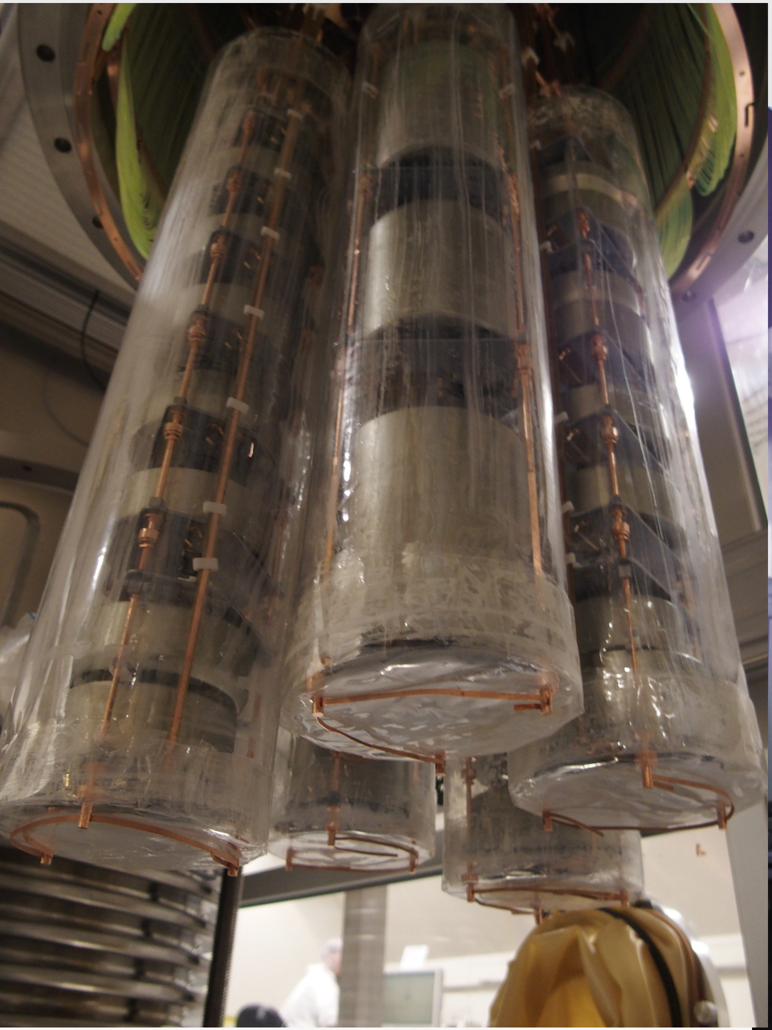


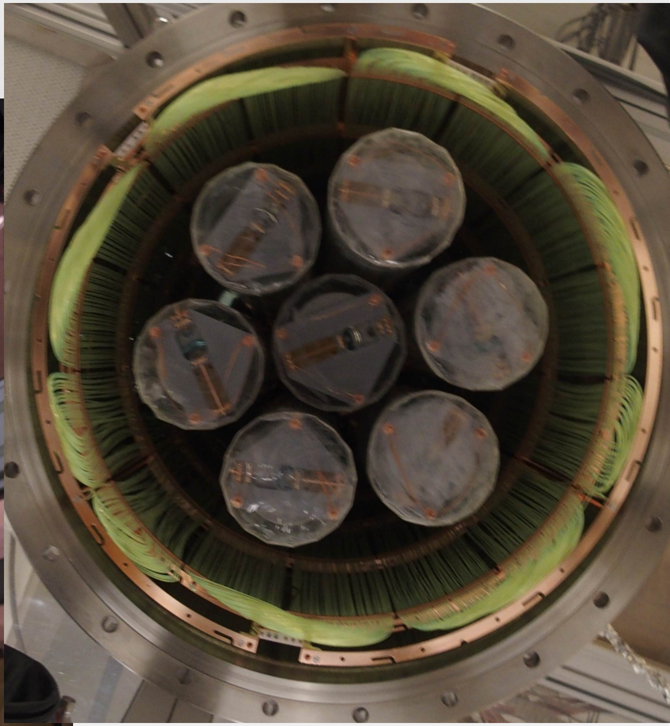
original goal: JFET at detector
problems with feedback R and JFET, ...

→ went back to 'Phase I' like readout:
entire charge sensitive amplifier
~ 35 cm above string

amplifier radioactivity reduced by x3 to P I
38 µBq/ch ^{226}Ra, 13 µBq/ch ^{228}Th

Phase II start December 2015

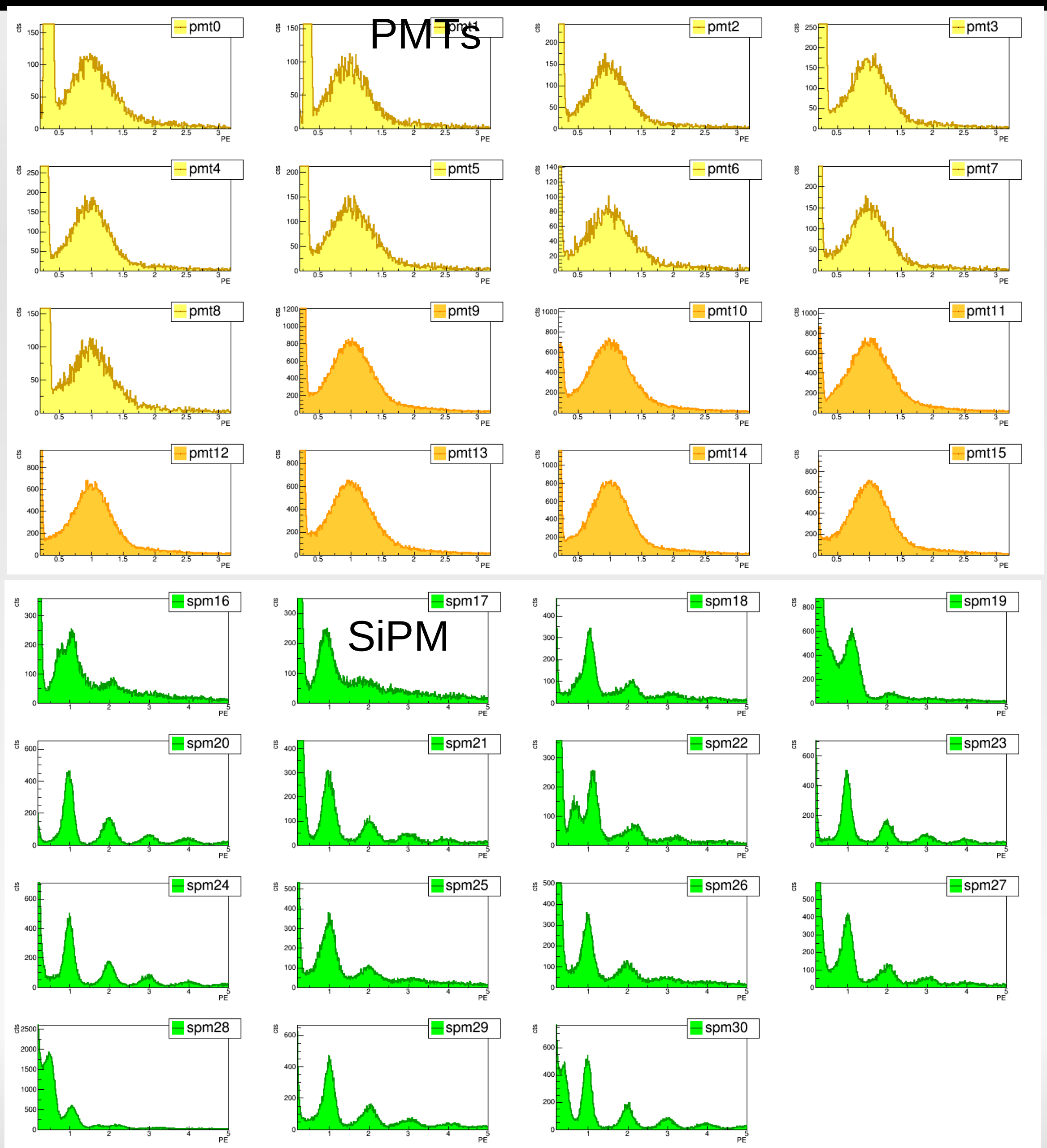




7 enriched coax (15.7 kg)
30 BEGe (20.0 kg)
3 natural coax (7.6 kg)

all channels working!!!
(2 BEGe not used for $T_{1/2}$)

LAr veto pulse height spectrum



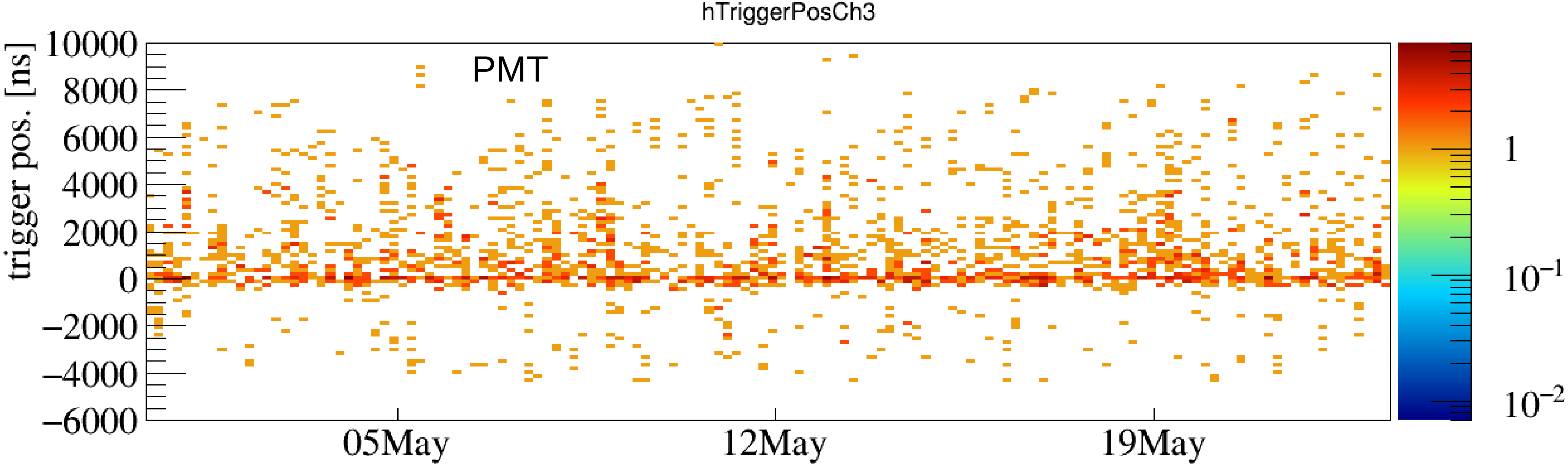
read out all channel if Ge triggers
→ offline veto

- all channels working
- gain stable with time

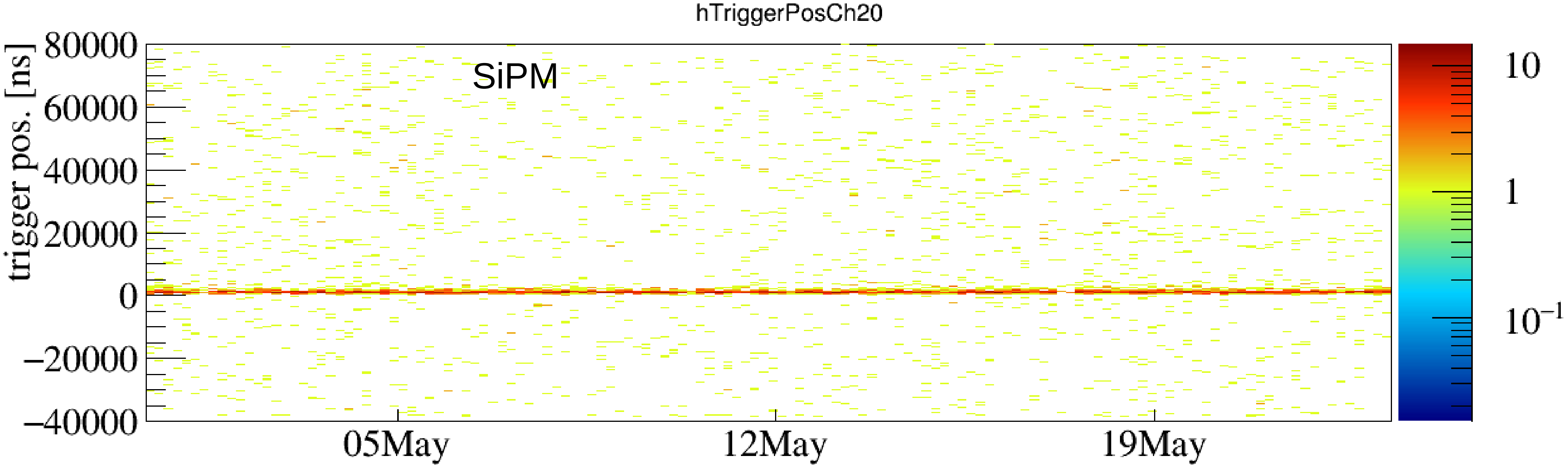
low noise → veto cut ~0.5 p.e.

reject ~ 2.3% of pulser events

LAr veto



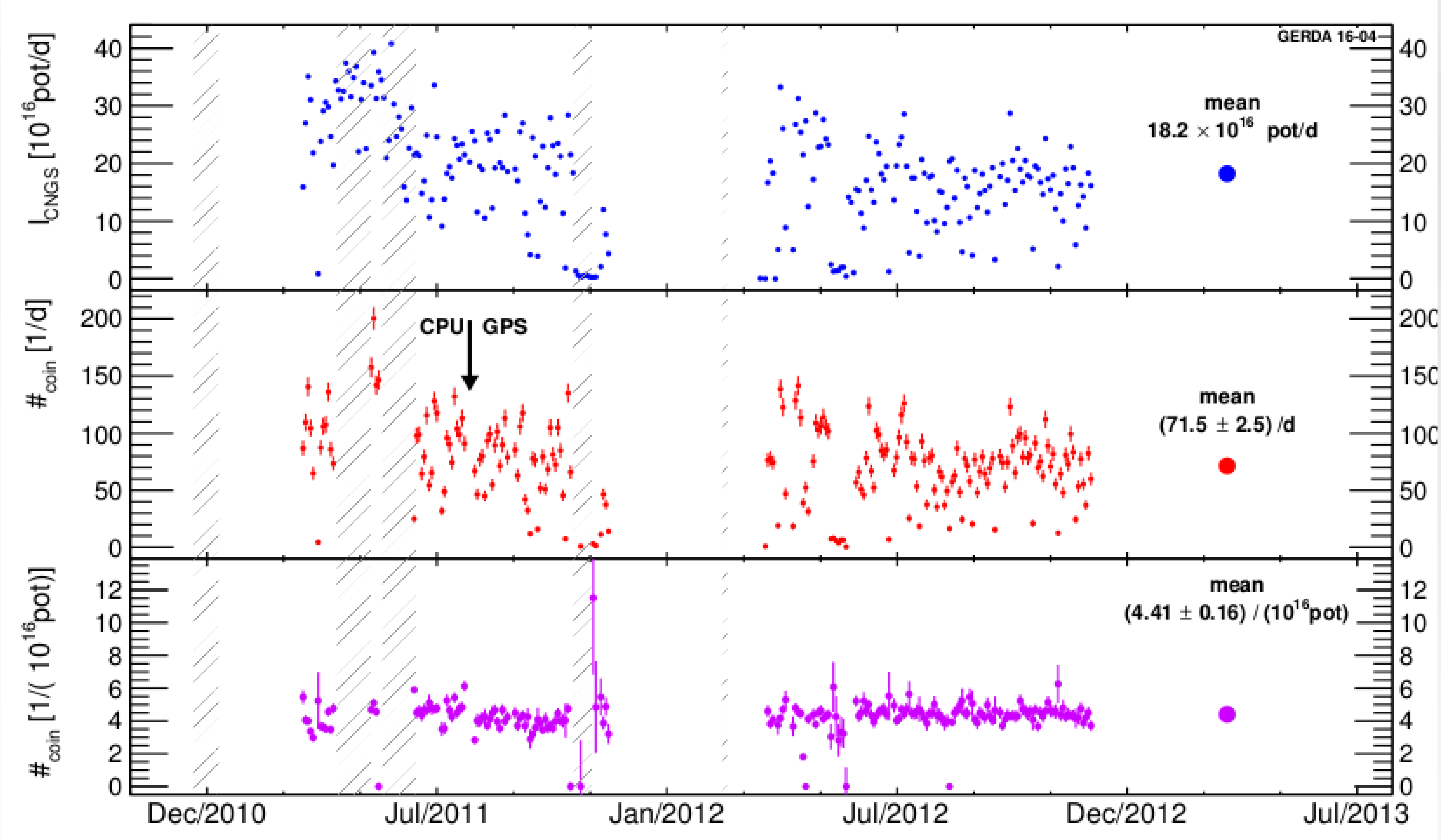
hTriggerPosCh3
PMT
trigger pos. [ns]
10000
8000
6000
4000
2000
0
−2000
−4000
−6000
05May
12May
19May
1
10^{-1}
10^{-2}



hTriggerPosCh20
SiPM
trigger pos. [ns]
80000
60000
40000
20000
0
−20000
−40000
05May
12May
19May
10
1
10^{-1}

Muon veto (EPJC 76 (2016) 298)

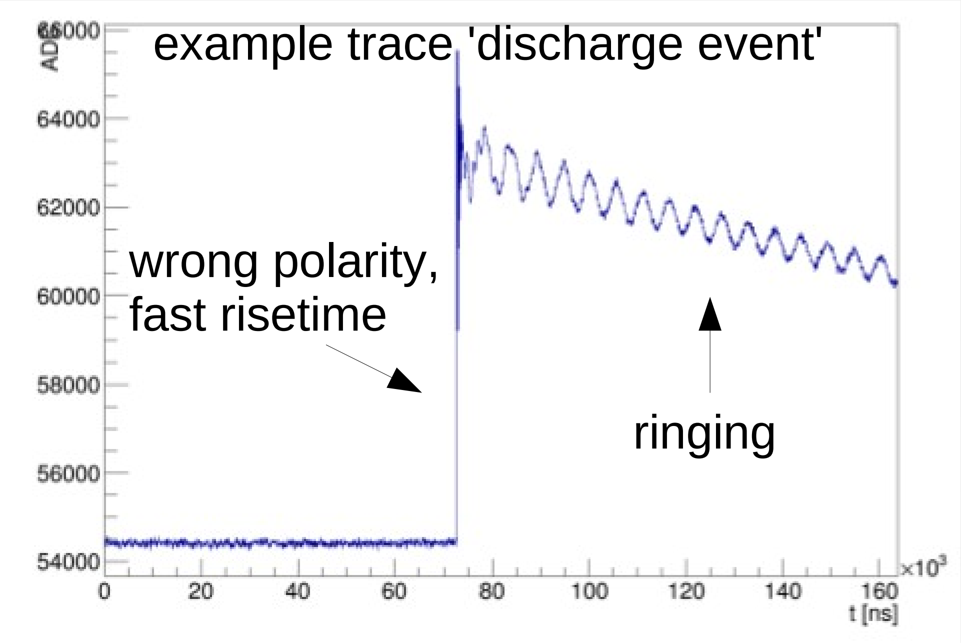
correlation CNGS beam & muon veto rate (arXiv:1601.06007)

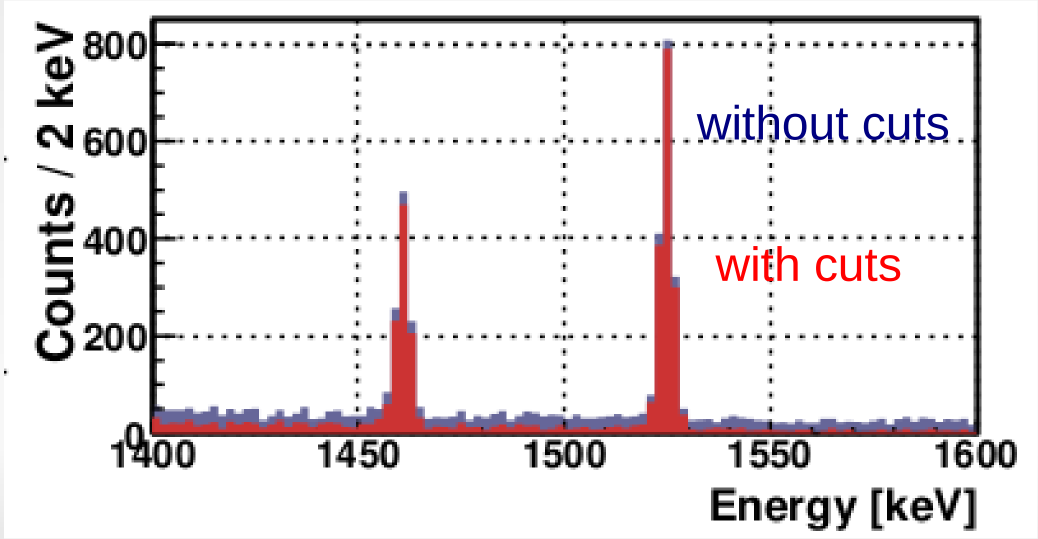


since 2010: 5 PMTs in water tank dead (no effect on eff.), >99% μ identification, ~0.1% dead time

very reliable and stable

Data quality





~50% of triggered events 'unphysical'

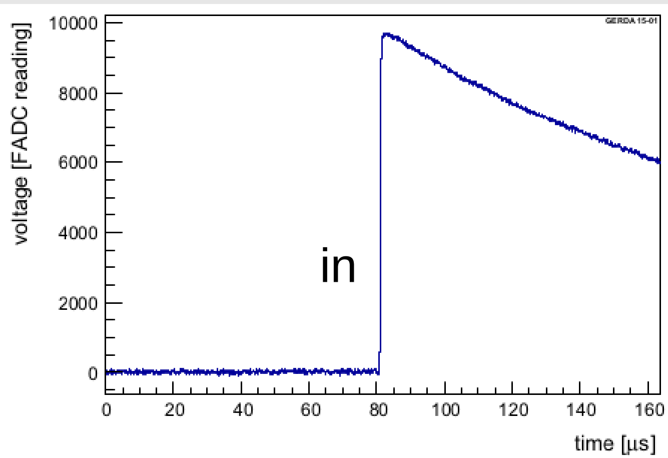
Easily identified by
- wrong polarity
- position of the rising edge
- rise time of edge

Applying to pulser events & γ lines
→ no loss of physical events

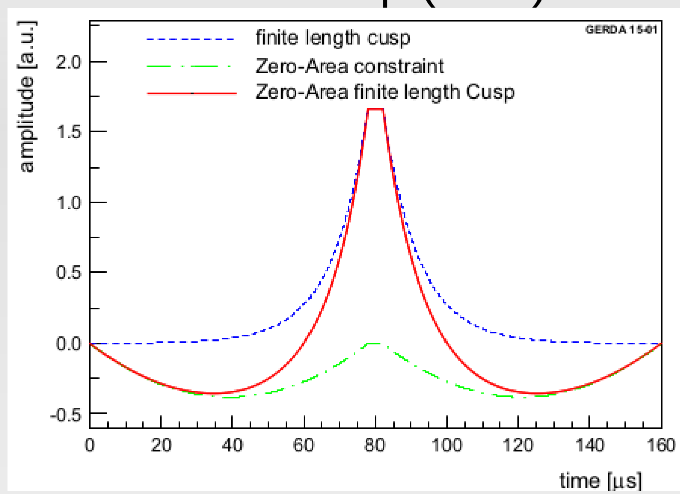
~100 % events remain in ^{40}K, ^{42}K peaks of physics data

Ge energy calibration: ZAC filter

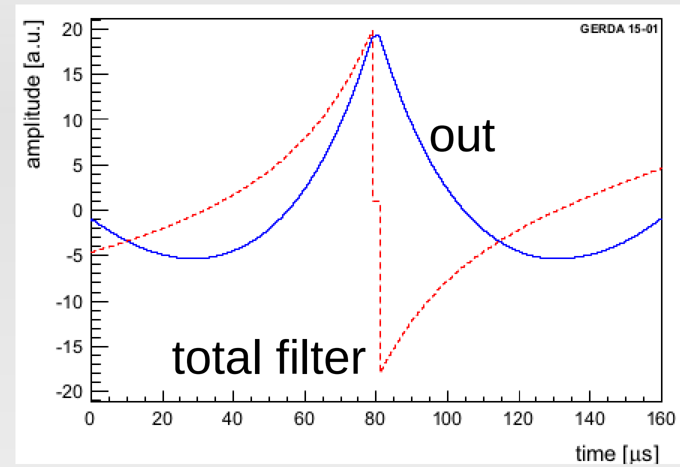
digitized input trace



digital filter constants
zero area cusp (ZAC)



convoluted trace
max = uncalibrated energy

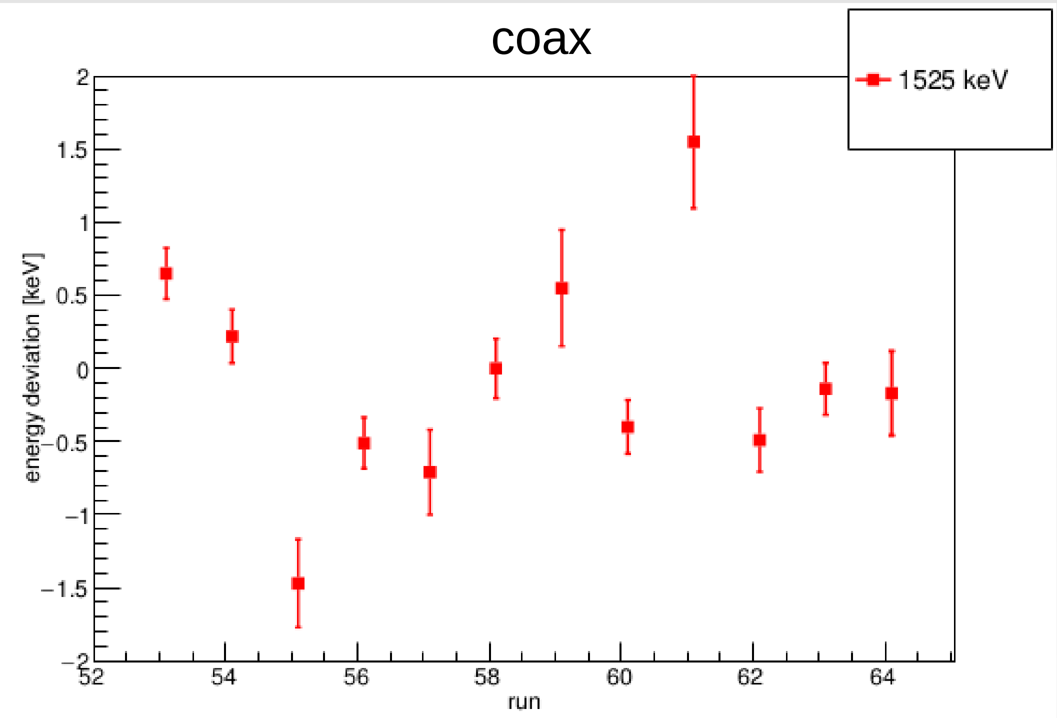


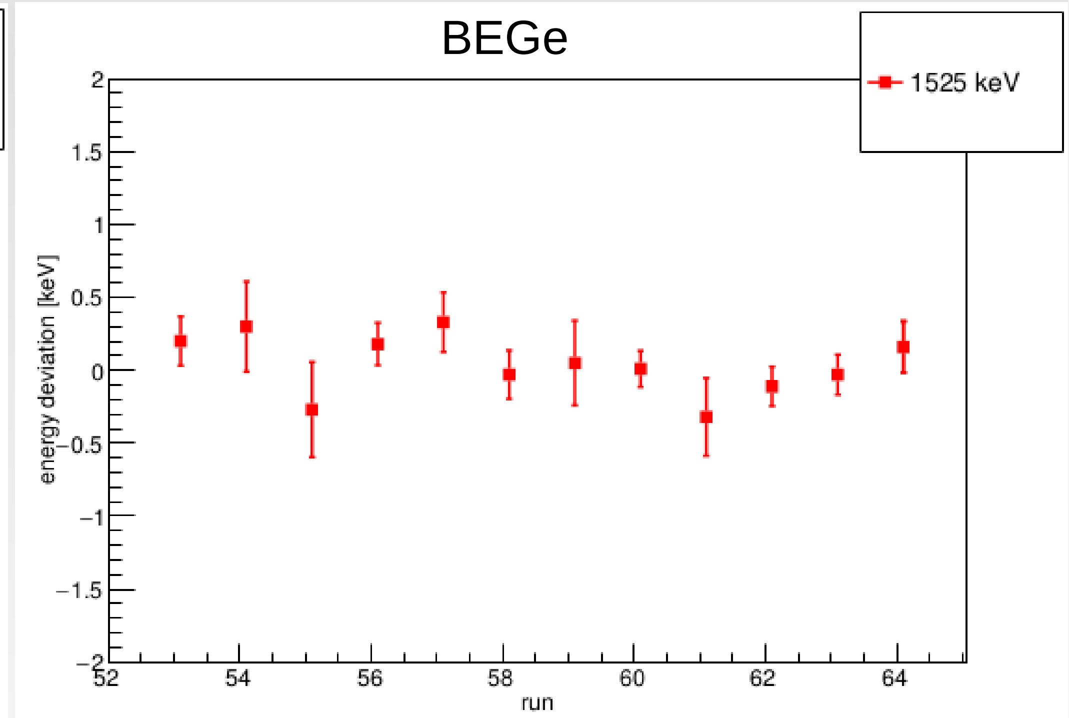
EPJC 75 (2015) 255: ZAC improves E resolution in case of low frequency noise (microphonics),
Phase I: average FWHM coax detectors 4.8 keV (gaussian) → 4.25 keV (ZAC) at $Q_{\beta\beta}$

procedure: weekly ^{228}Th calibrations → calibration curves
combined calibrations → expected peak position and FWHM
compare to ^{42}K and ^{40}K peaks in physics data → systematic
between calibrations: every 20 sec pulser injected into front-end

Ge energy calibration: stability

shifts of reconstructed ^{42}K peak position during Phase II
all detectors combined

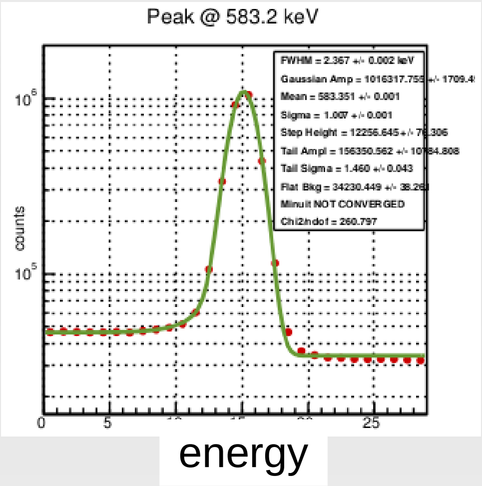


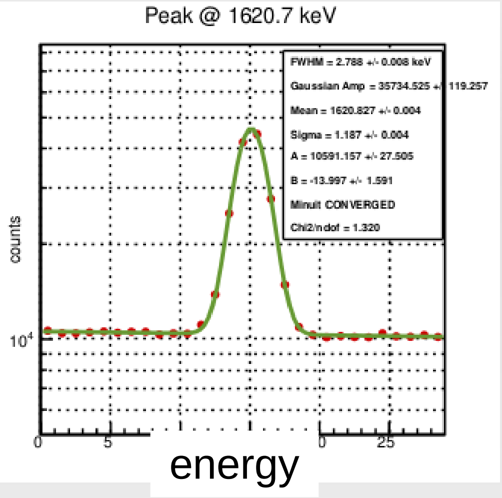


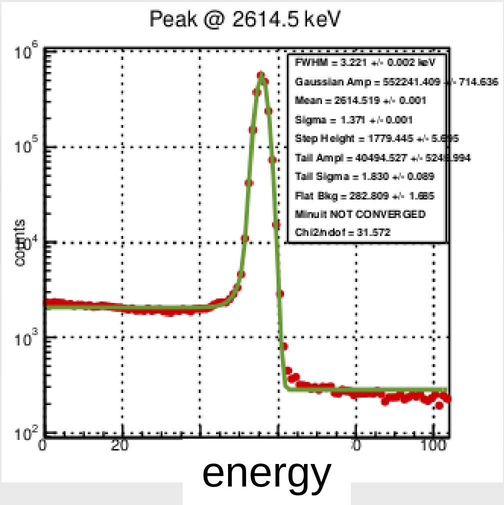
shifts within ±1 keV → 'small' compared to energy resolution of 3-4 keV FWHM

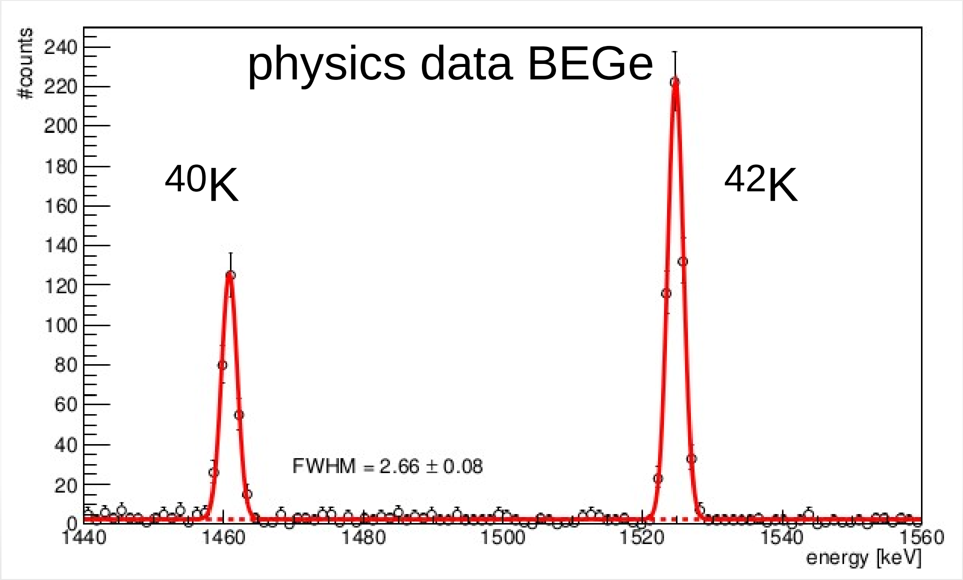
Ge energy: combined data

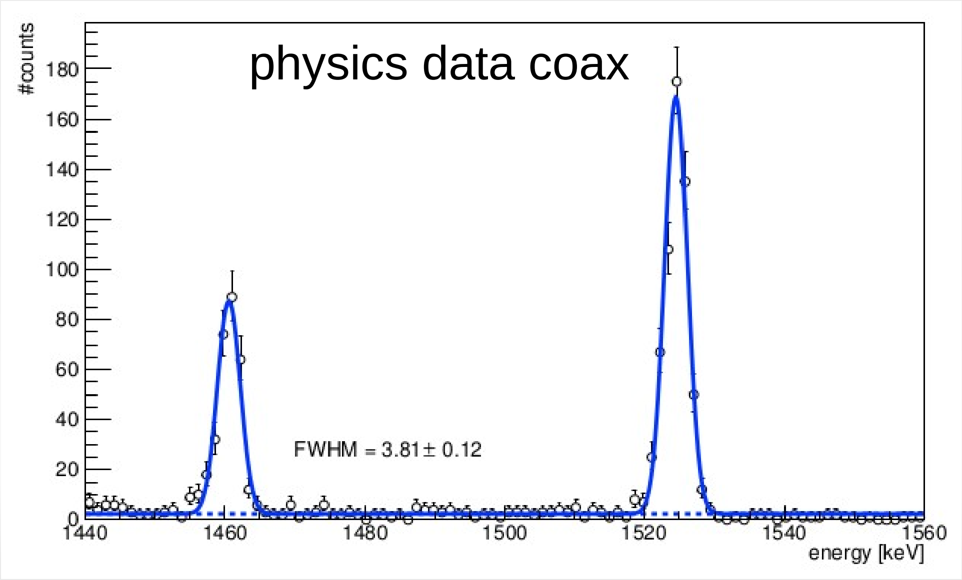
combined calibration data





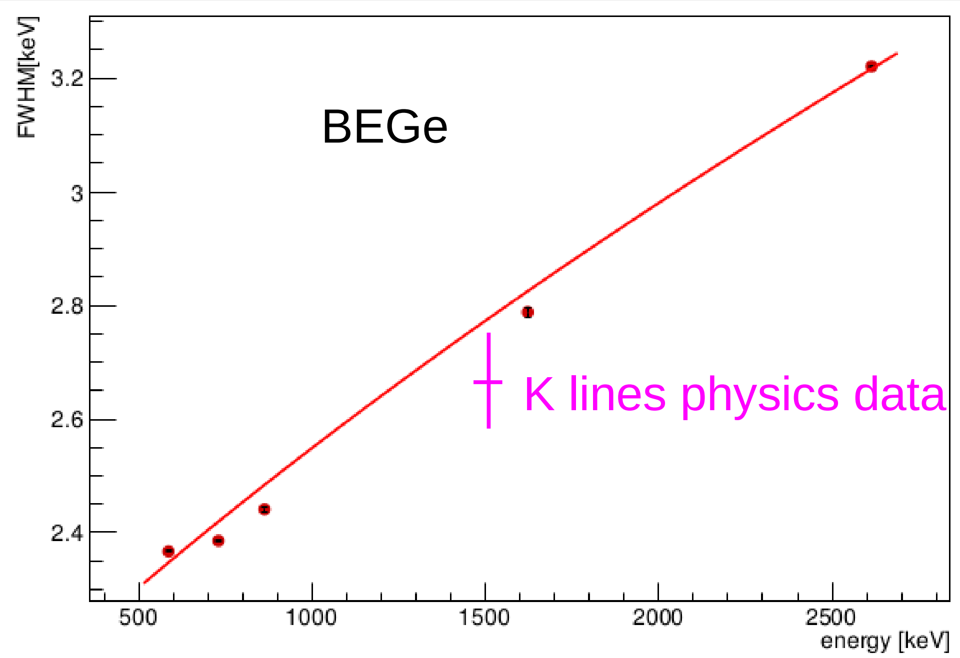


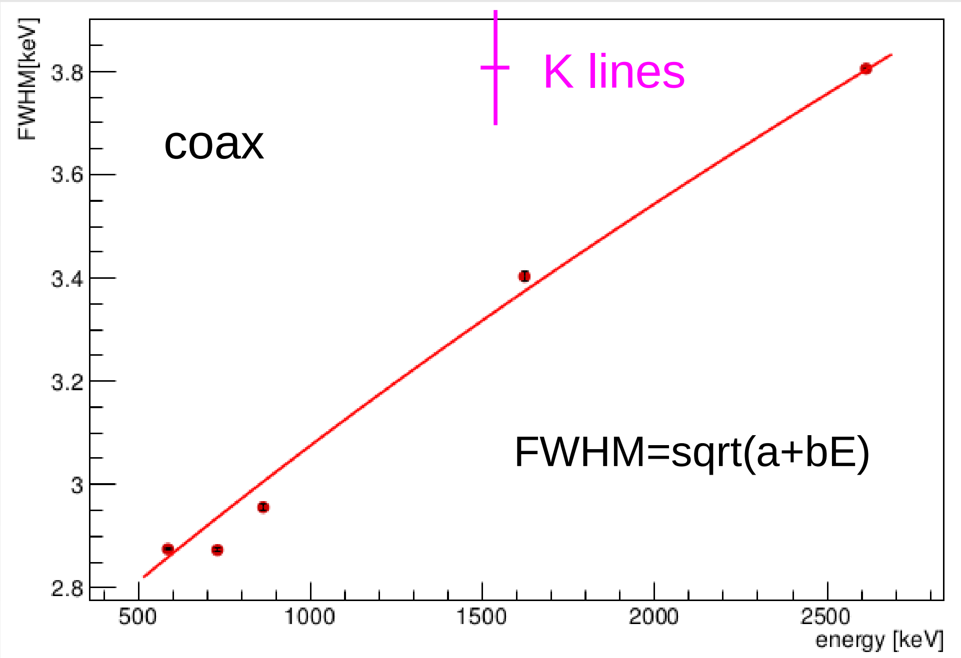




Ge energy calibration

FWHM resolution curves from calibration & physics data





FWHM @ $Q_{\beta\beta}$ 3.0±0.2 keV

FWHM @ $Q_{\beta\beta}$ 4.0±0.2 keV

(add correction due to difference calib-physics)

comparison peak positions from literature value
→ peak position uncertainty at $Q_{\beta\beta}$ ~ 0.2 keV

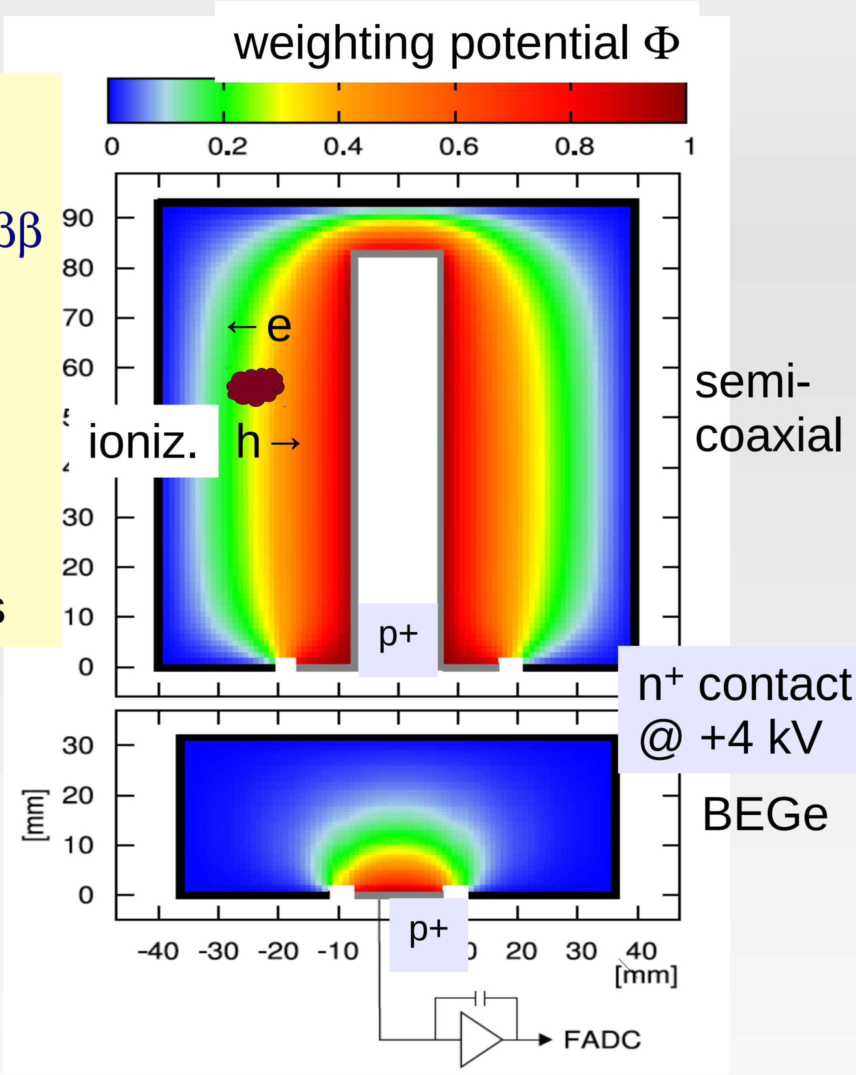
Pulse shape discr. (EPJC 73 (2013) 2583)

$0\nu\beta\beta$ events: range 1 MeV electrons in Ge ~1 mm
→ one drift of electrons & holes, single site event (SSE)
proxy: double escape peak (DEP) of 2.6 MeV γ and $2\nu\beta\beta$

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

→ pulse shape discrimination (PSD) to select $0\nu\beta\beta$ events



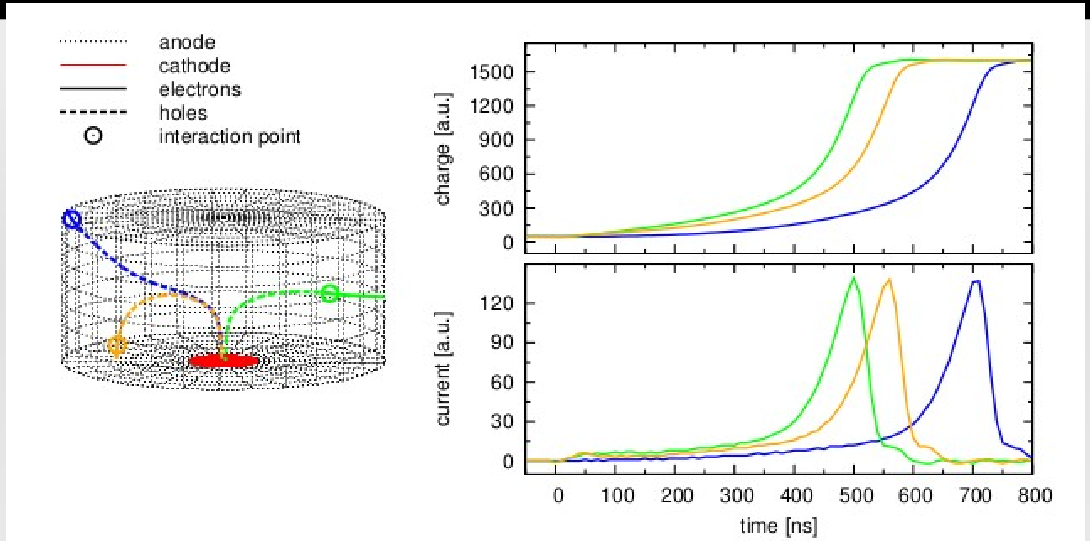
$$\text{current signal} = q \cdot v \cdot \nabla \Phi$$

q= charge, v = velocity
(Shockley-Ramo theorem)

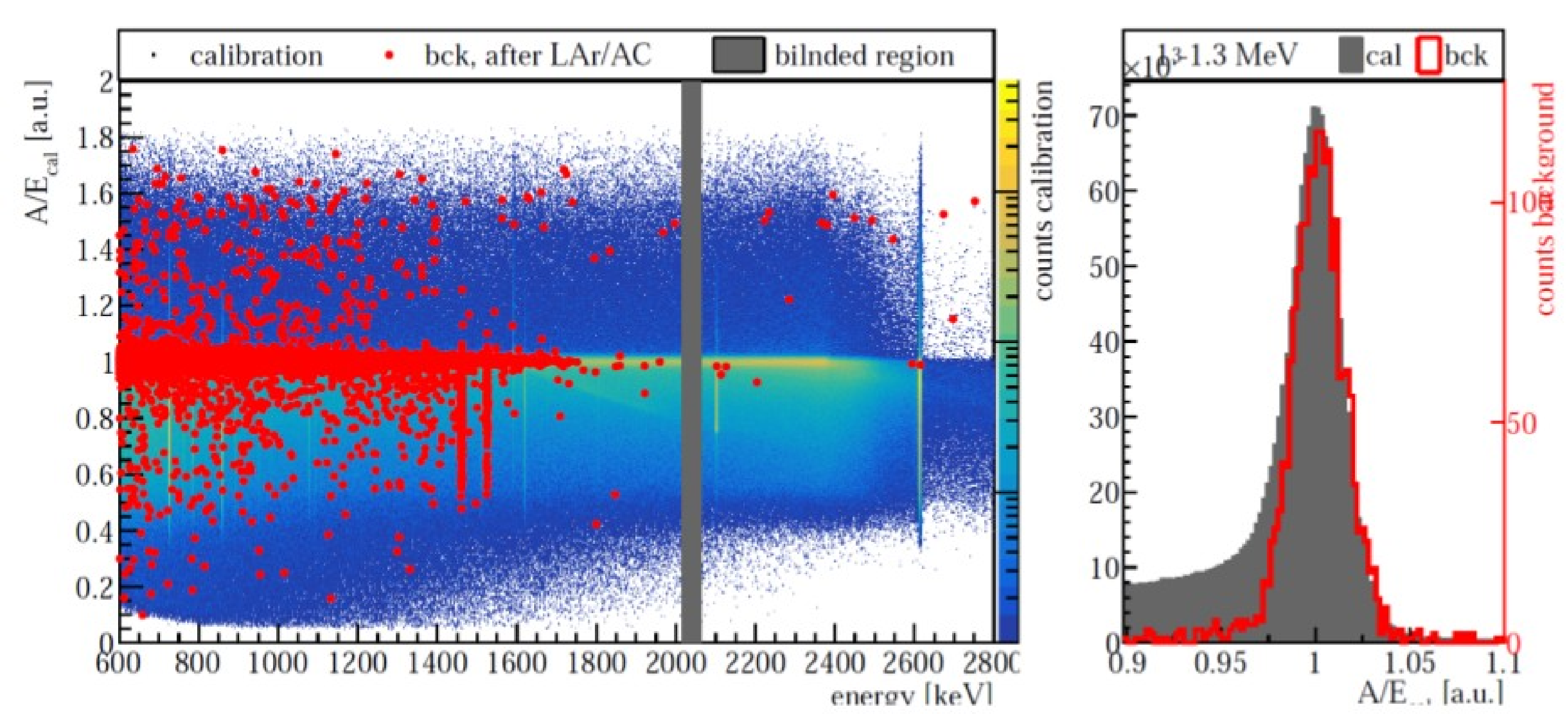
PSD for BEGe

single parameter:
max of current A / energy E

normalize to A/E of DEP evt
comparison to physics $2\nu\beta\beta$

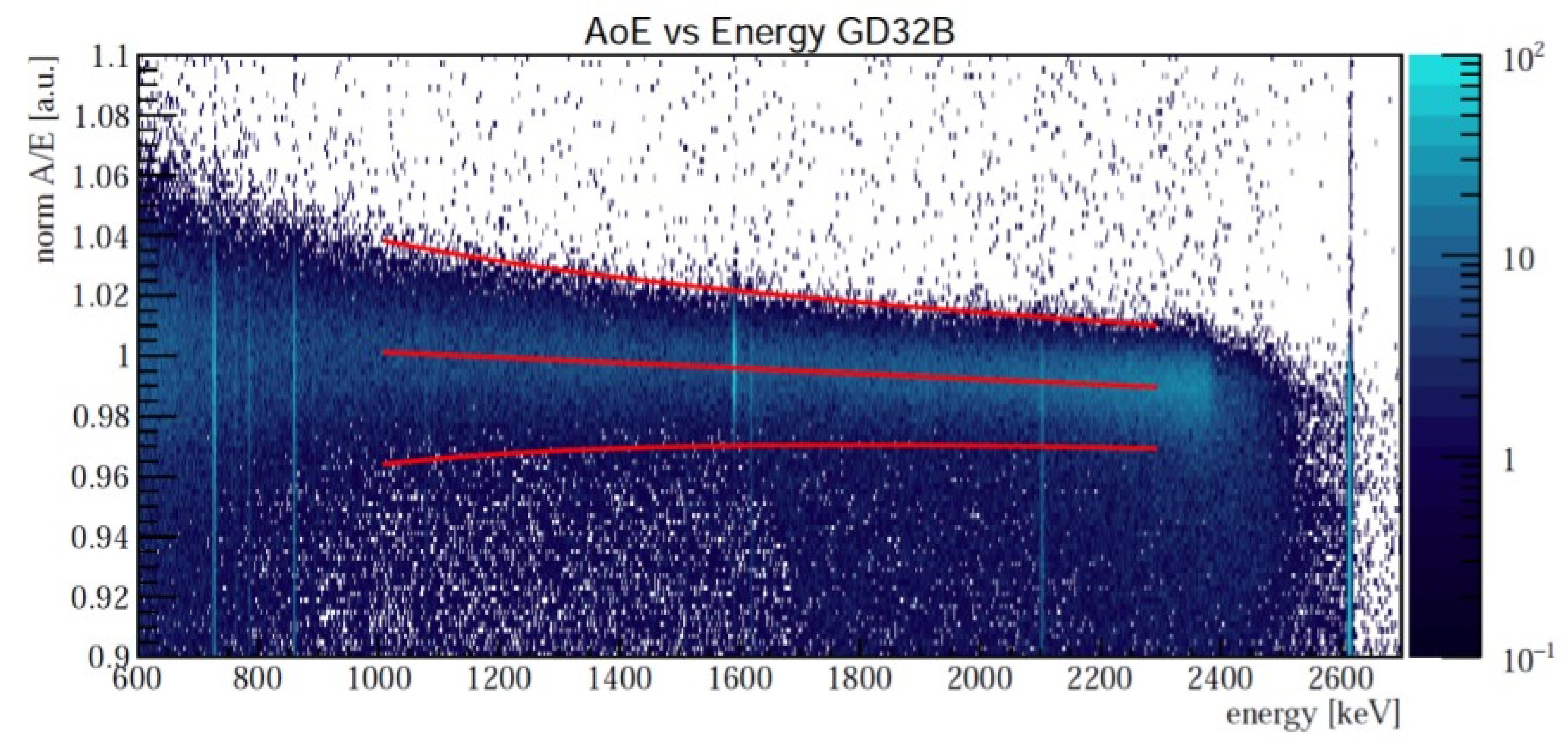


(a) Trajectories (b) Charge and current pulses



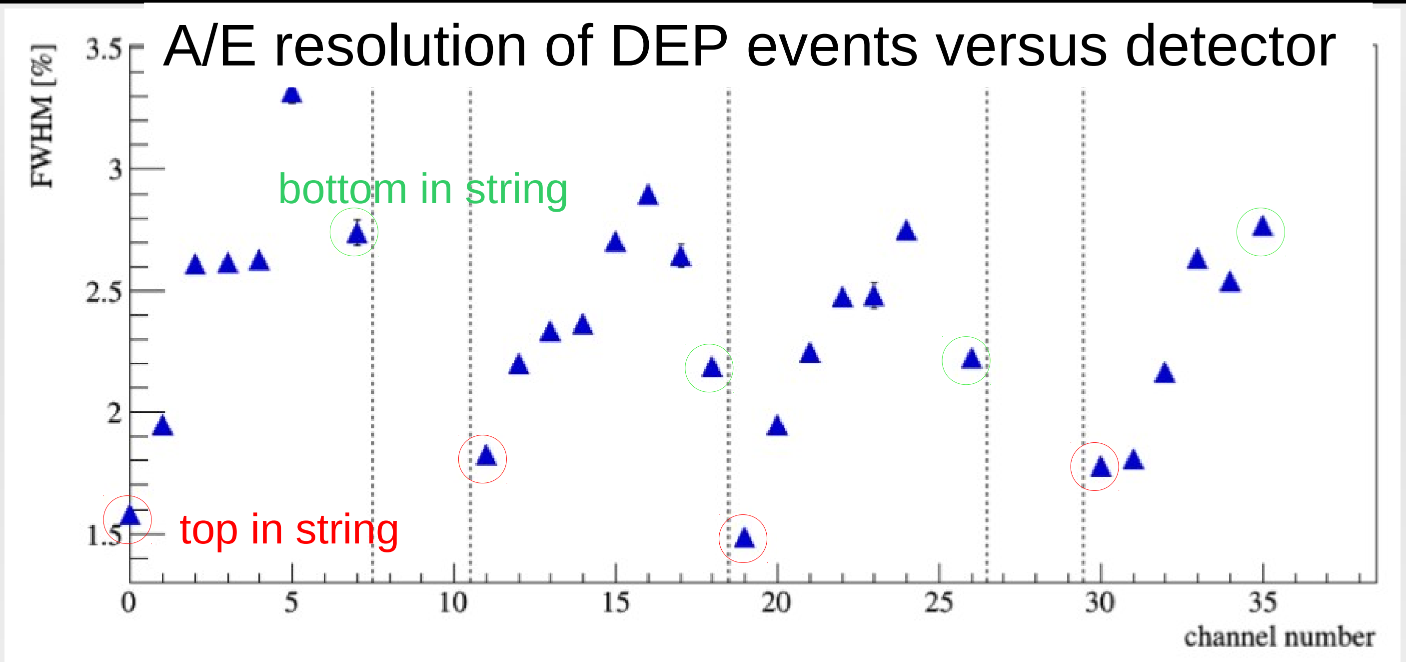
PSD for BEGe

^{228}Th calibration: A/E versus energy for one detector



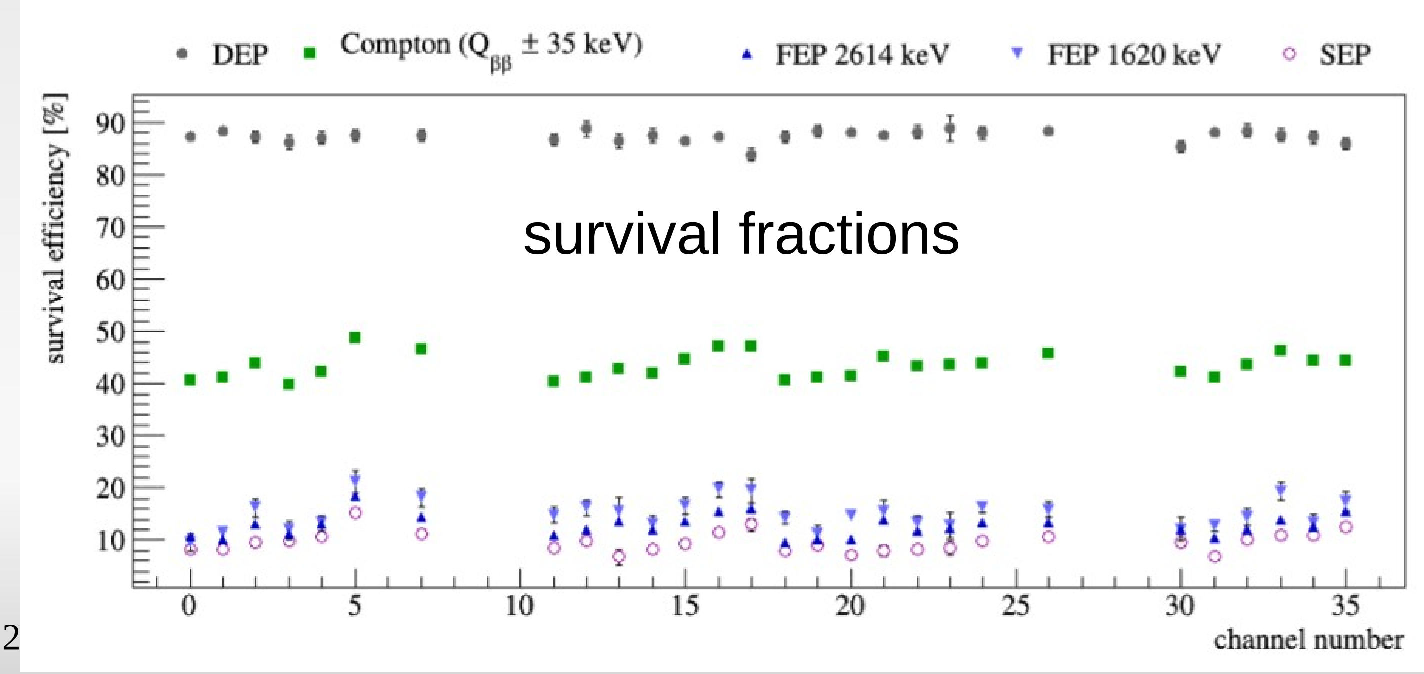
A/E lower cut (1-a) at 90% DEP efficiency, A/E high cut at 1+2a
single Compton scattered γ → energy dependence of cut

PSD for BEGe



strong dependence on position in string

Phase I:
FWHM 1.5-2%
little dependence on position in string



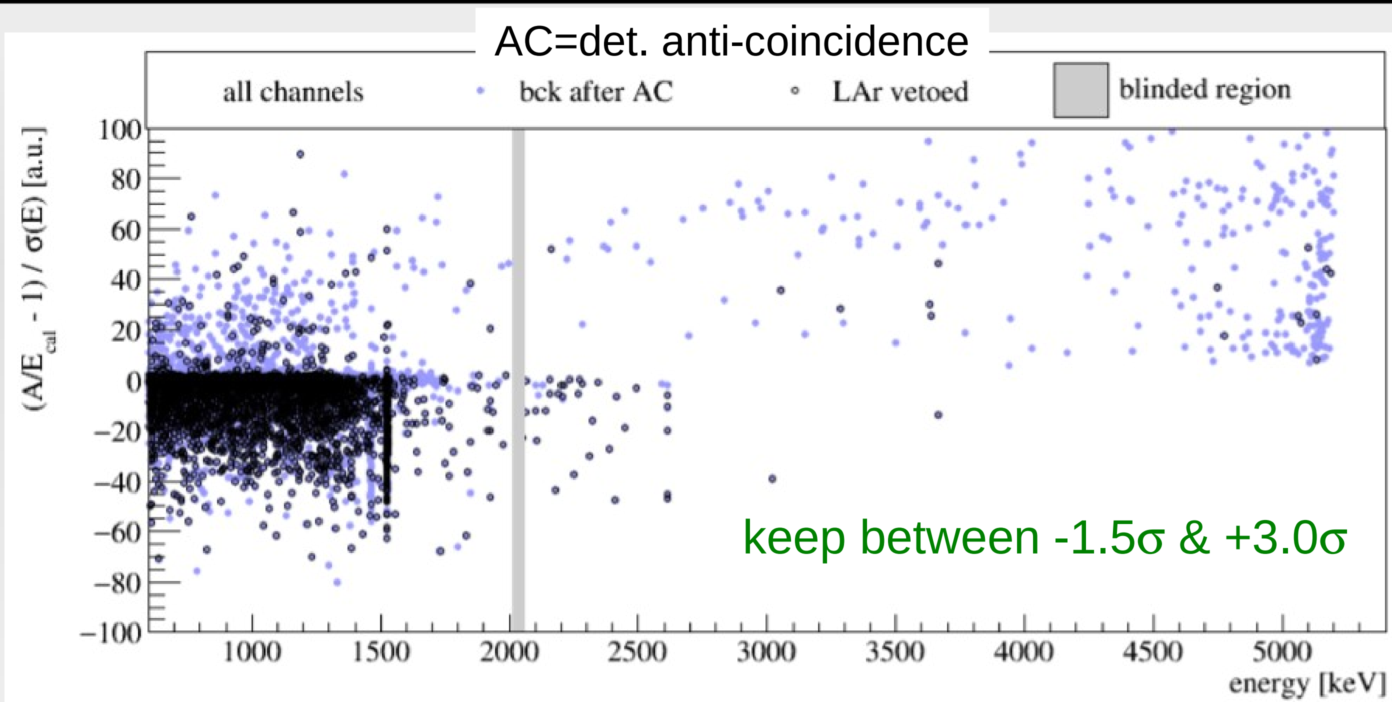
DEP events

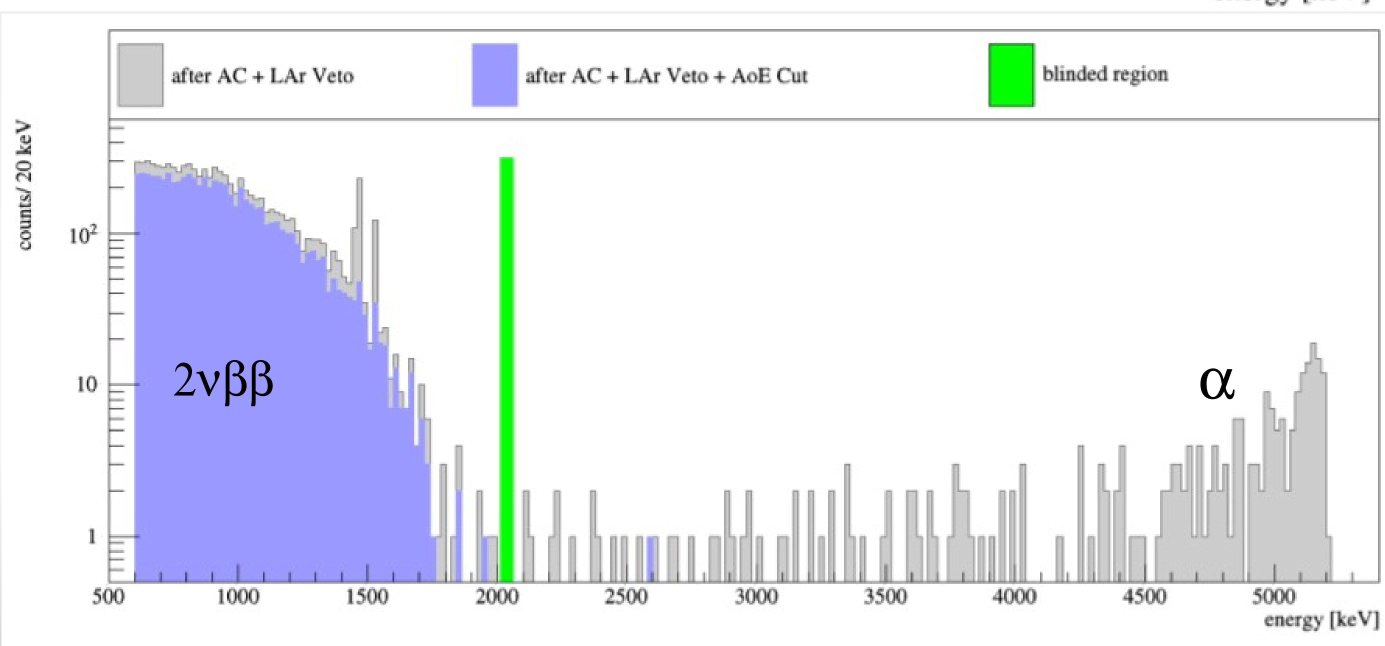
Compton at $Q_{\beta\beta}$

1621 keV γ

SEP

PSD for BEGe: physics events



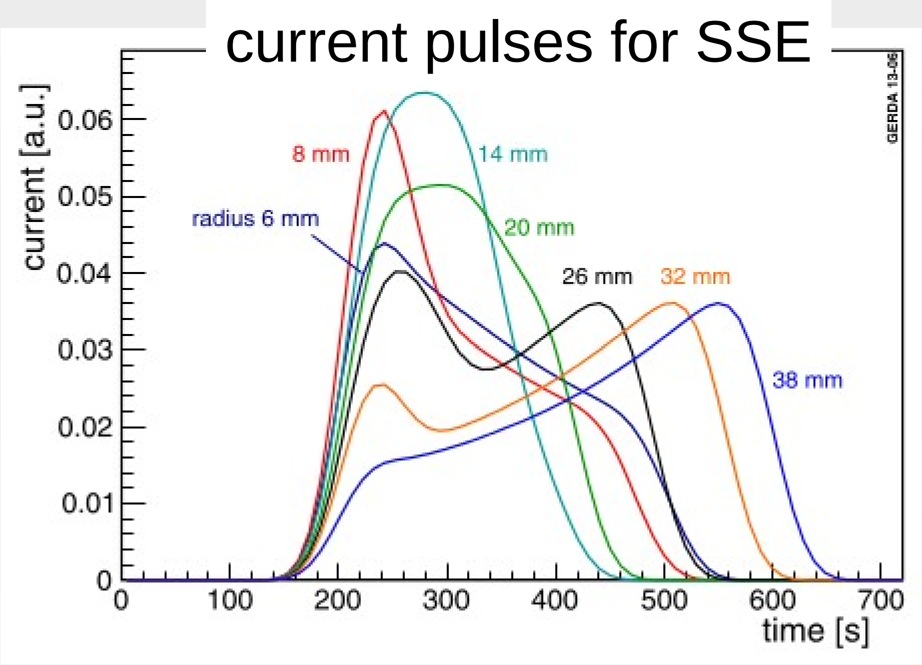


efficiency
DEP (87.3±0.2±0.8) %
2νββ (85.4±0.8±1.7) %

in $Q_{\beta\beta}$ ± 200 keV (blinded)
after PSD: 8/45 events
after LAr & PSD
3/45 events

in fit energy window: 1 evt

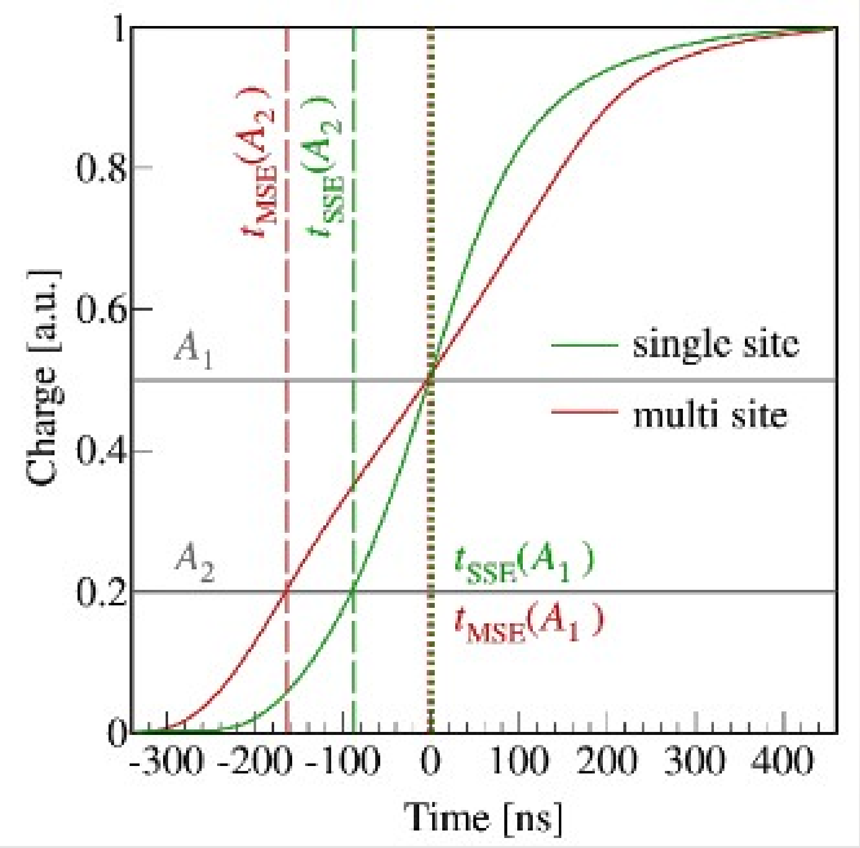
PSD for coax detectors



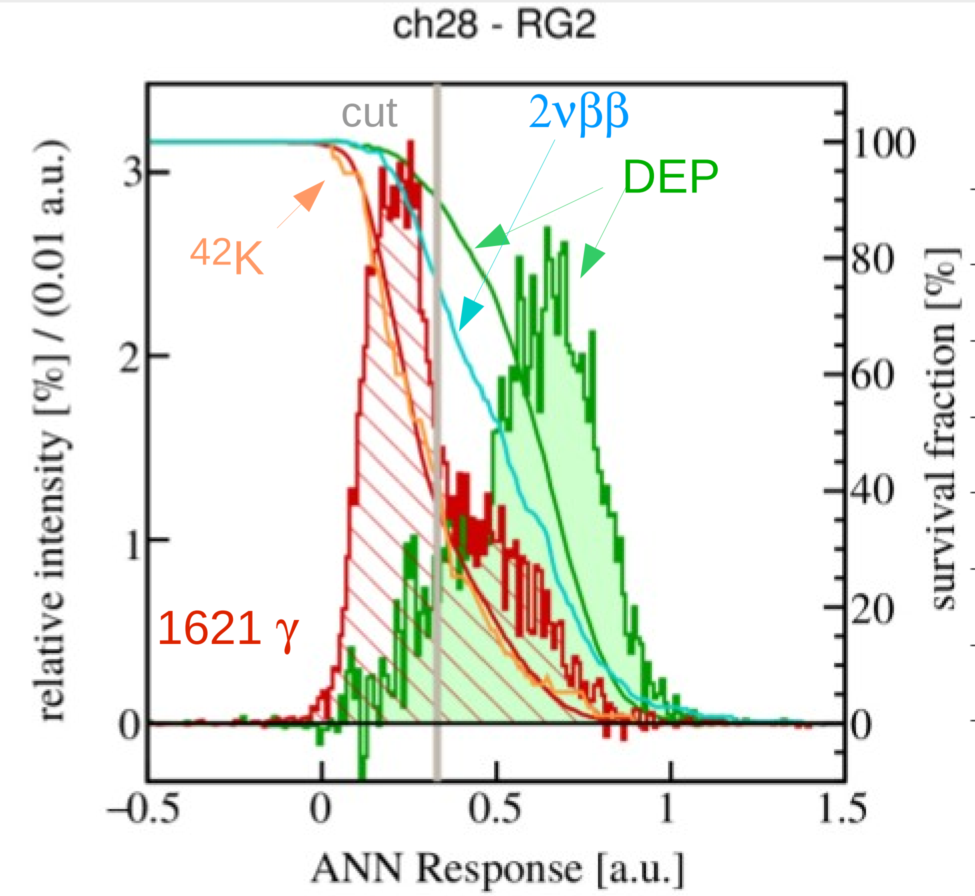
different shapes → no simple parameter
→ neural network:
2 methods using different inputs
& training samples

50 time stamps when charge reaches
1%, 3%, … 99% of maximum

training with
DEP (1593 keV) = signal
and 1621 keV line from ^{212}Bi = bkg
(all calibrations combined)
cut at 90% survival of DEP peak



PSD for coax detectors



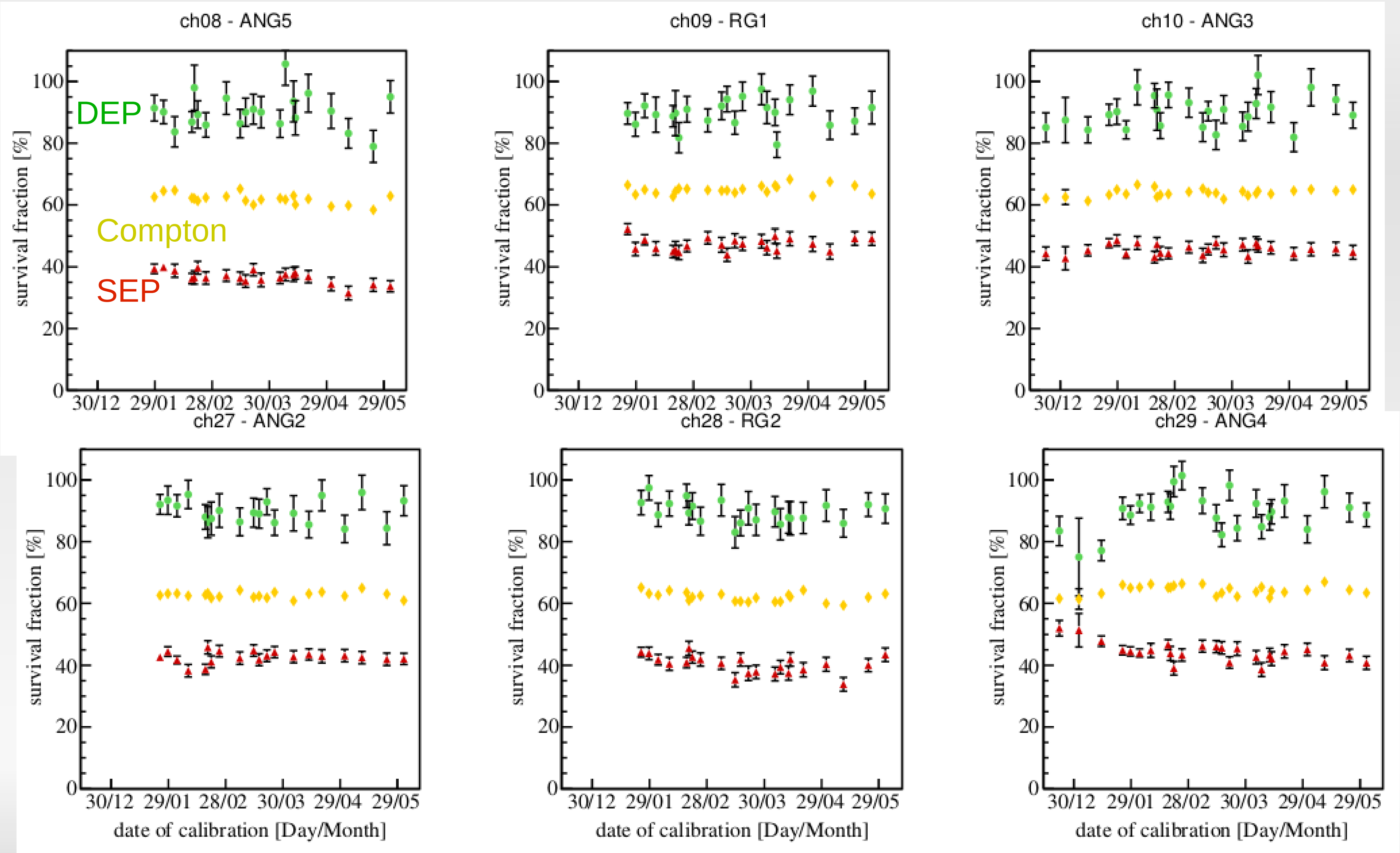
	calibration data				physics	
		DEP fixed @ 90 %				
	CC @ $Q_{\beta\beta}$	^{212}Bi FEP	^{208}Tl SEP	^{208}Tl FEP	$2\nu\beta\beta$	^{42}K FEP
ANG5	62.1 ± 0.3	35.3 ± 0.7	37.0 ± 0.4	38.0 ± 0.1	78.2 ± 2.6	38.9 ± 4.5
RG1	65.0 ± 0.3	43.2 ± 0.8	47.5 ± 0.5	44.5 ± 0.1	77.7 ± 2.7	47.5 ± 8.5
ANG3	63.9 ± 0.3	40.0 ± 0.7	45.7 ± 0.4	45.1 ± 0.1	77.8 ± 2.4	40.8 ± 6.1
ANG2	62.7 ± 0.3	38.4 ± 0.6	42.6 ± 0.4	40.1 ± 0.1	75.6 ± 2.4	38.1 ± 4.8
RG2	62.2 ± 0.3	36.4 ± 0.8	40.5 ± 0.4	41.1 ± 0.1	74.8 ± 2.6	42.7 ± 5.9
ANG4	64.6 ± 0.2	40.8 ± 0.7	44.2 ± 0.4	43.4 ± 0.1	73.0 ± 2.5	40.9 ± 5.3
ANG1	69.7 ± 0.3	49.0 ± 1.2	50.8 ± 0.6	51.0 ± 0.1	87.9 ± 2.8	58.6 ± 9.6

avg 77±1 %

in Phase I: exact same method 2νββ efficiency of (85±2)% for data, (83±3)% for MC
→ for now take preliminary 0νββ efficiency of 80±9 % (enlarged uncertainty)

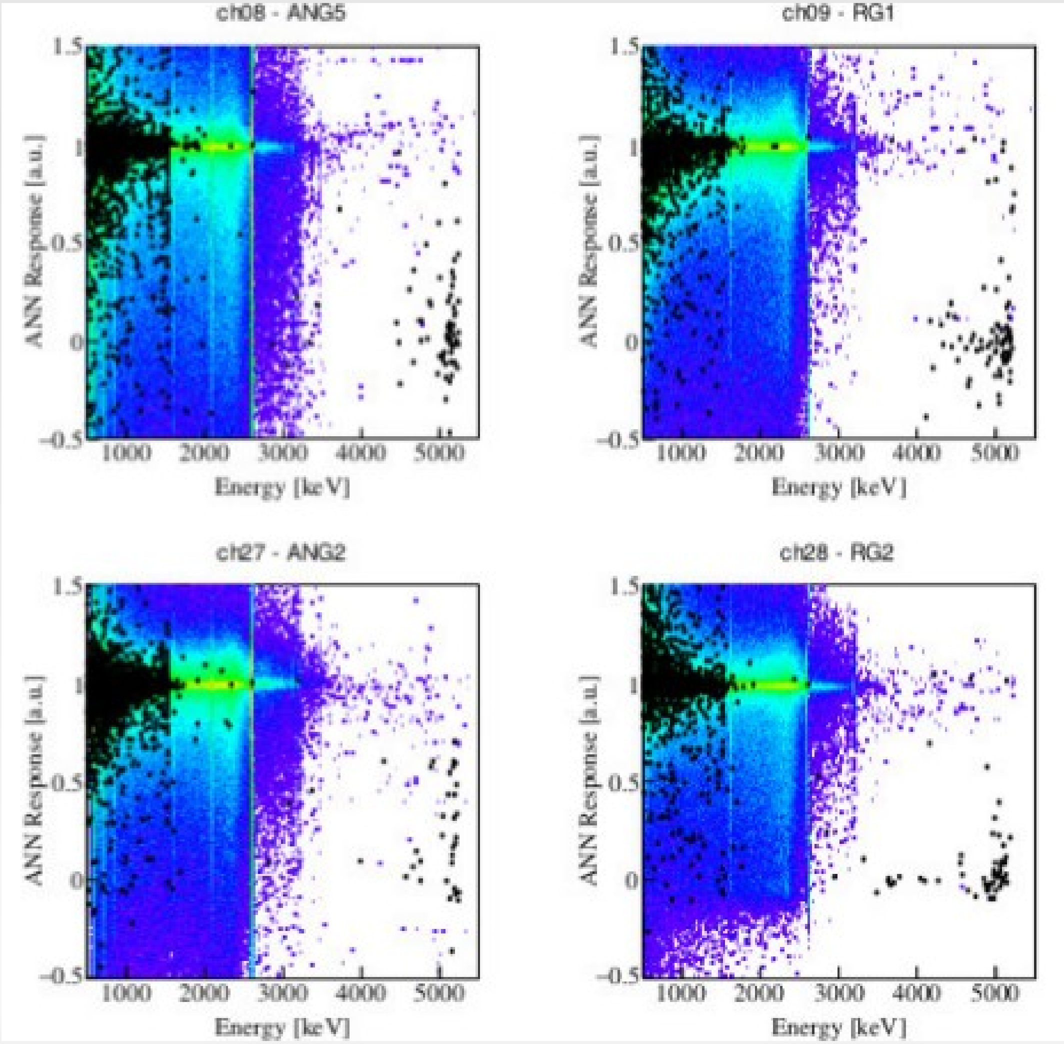
performing more cross checks and simulations → $T_{1/2}$ limit might change a little

PSD for coax detectors: stability



PSD for coax detectors: alpha

expect sizable α background not rejected by MSE/SSE PSD → 2nd method



color = calibration, black dots = physics

training: signal = 1-1.3 MeV physics (~75% $2\nu\beta\beta$ events)
background = 3.5-4.5 MeV physics (100% α)
cut at 10% survival for α

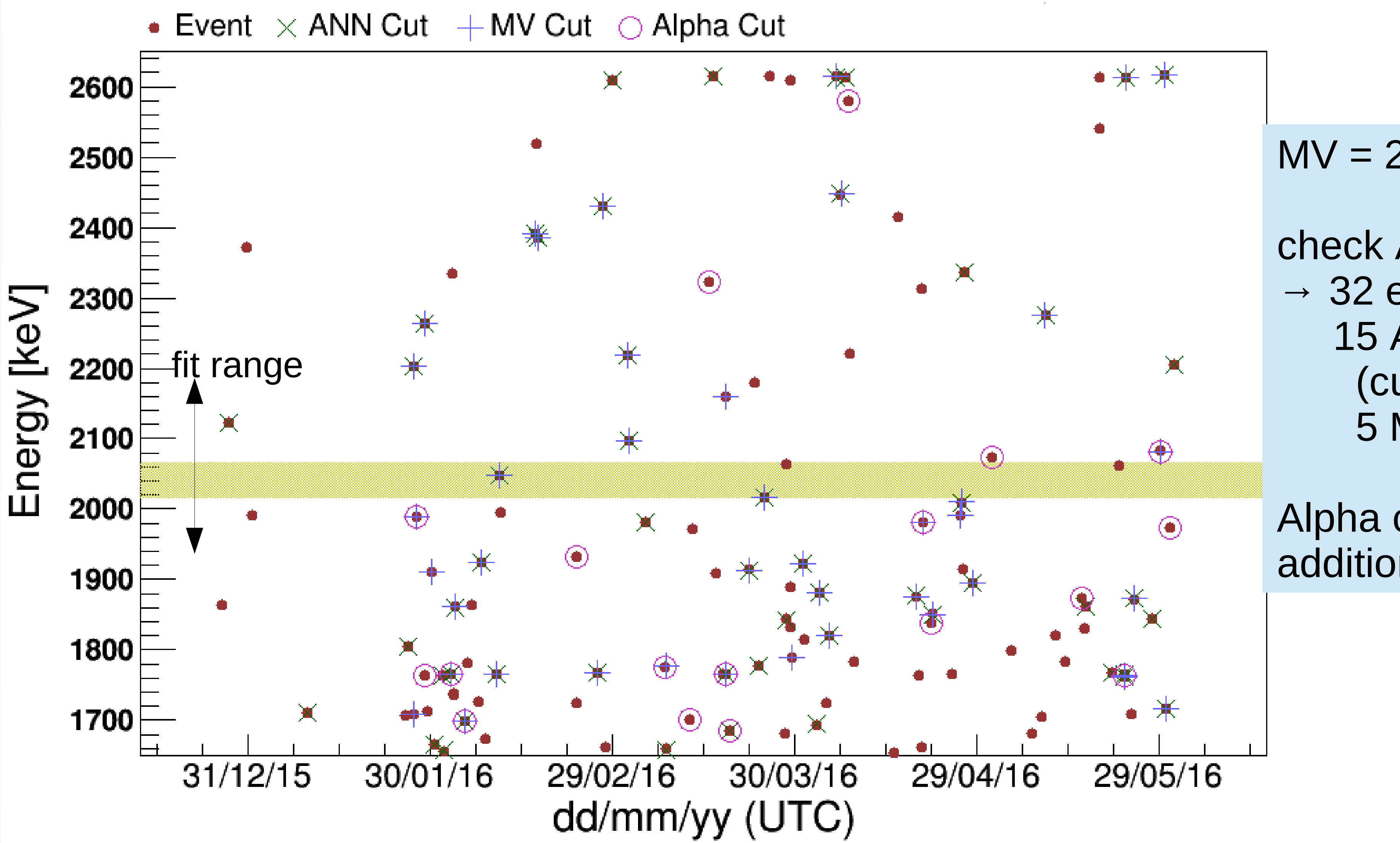
→ keep 90-98 % DEP in calibration
91-98 % $2\nu\beta\beta$ (ANG1 87%)

clear separation α versus signal
avg $2\nu\beta\beta$ efficiency (95.8±0.5)%

event count 1930-2190 keV physics data (blinded)

w/o	LAr	MSE	α	LAr + MSE	+ α
16	10	13	10	8	3

PSD for coax: comparison methods

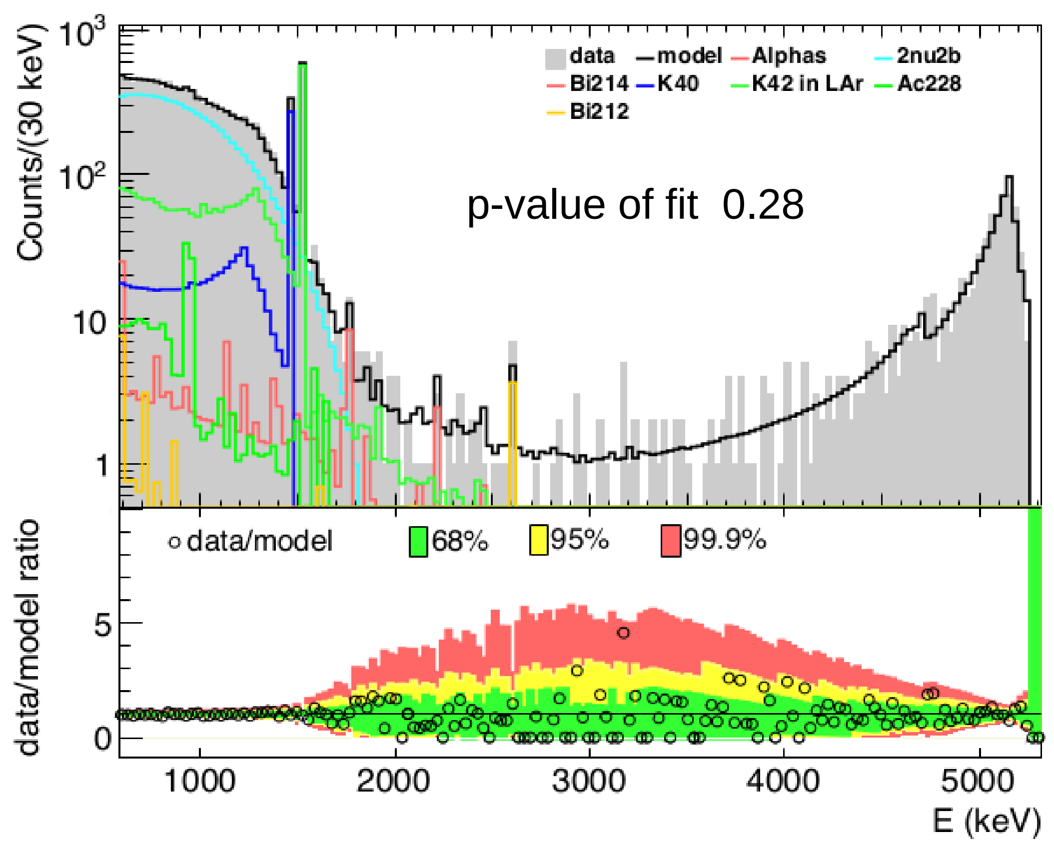


MV = 2nd method

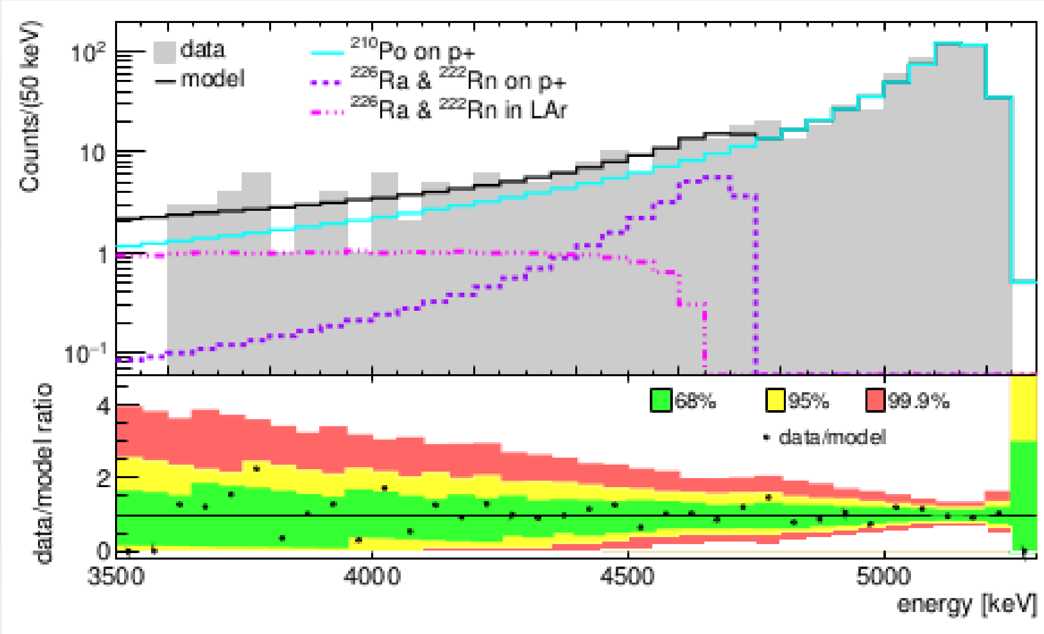
check ANN & MV
→ 32 evt both
15 ANN only
(cutting more)
5 MV only

Alpha cut removes additional events

Background spectrum: coax



fit [570:5300] keV with 30 keV binning
before LAr veto and PSD



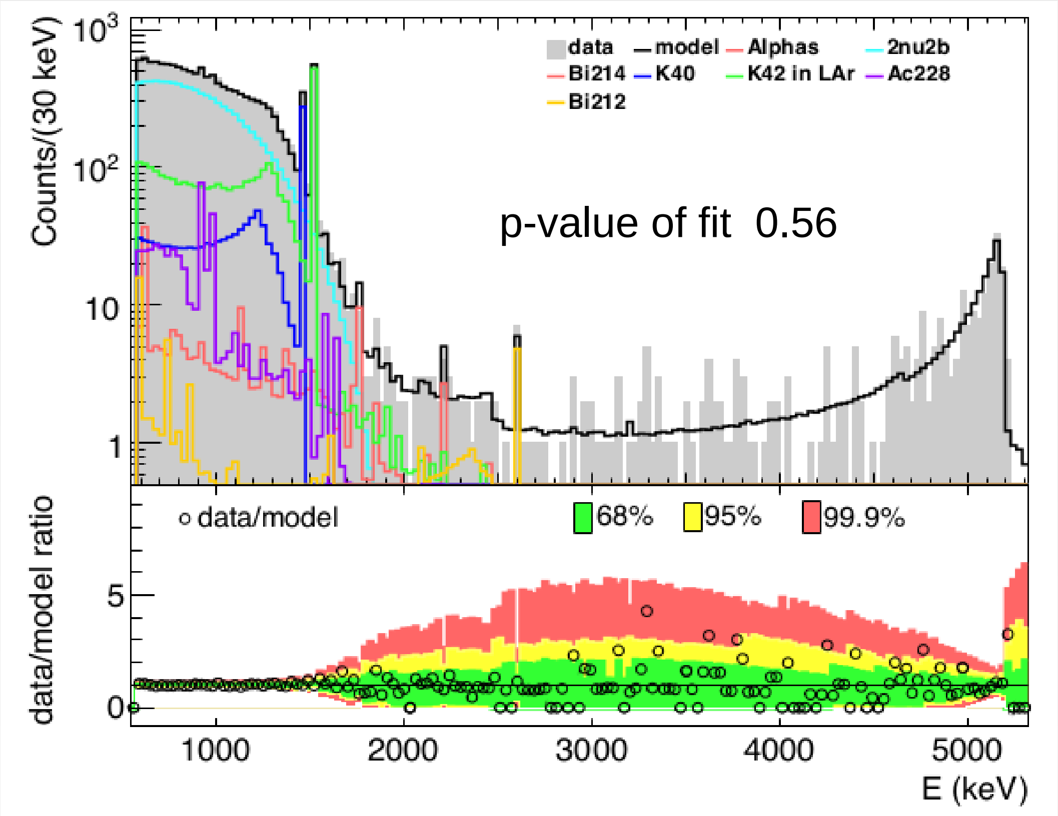
preliminary results:

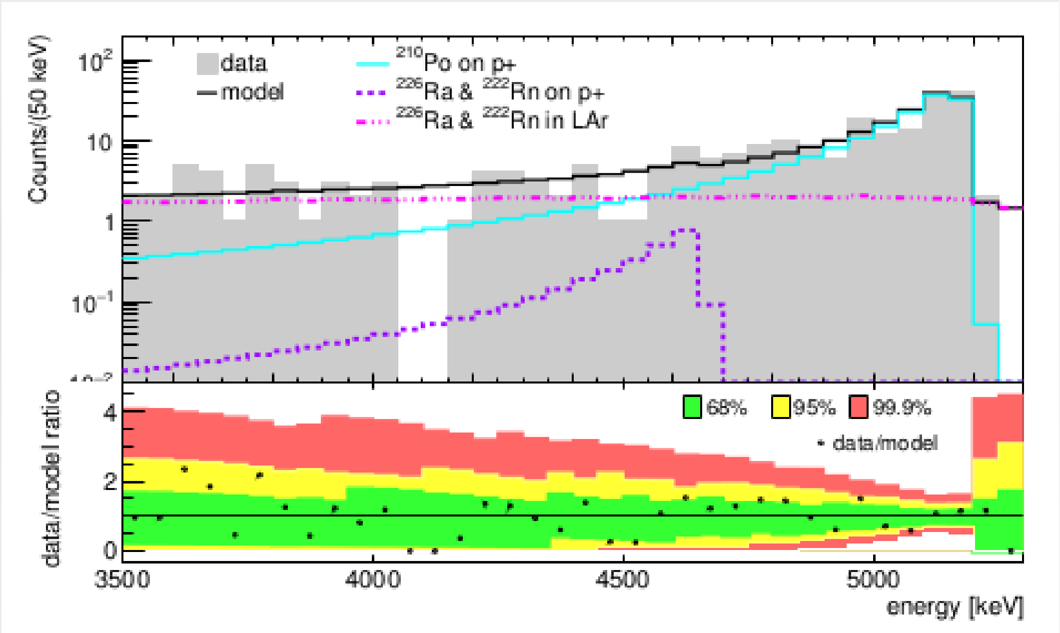
$2\nu\beta\beta$ $T_{1/2}$ = (1.84±0.05) 10^{21} yr
only statistical error

$2\nu\beta\beta$ half-life consistent with our published value of (1.93±0.09) 10^{21} yr
EPJC 75 (2015) 416.

same components like Phase I

Background spectrum: BEGe





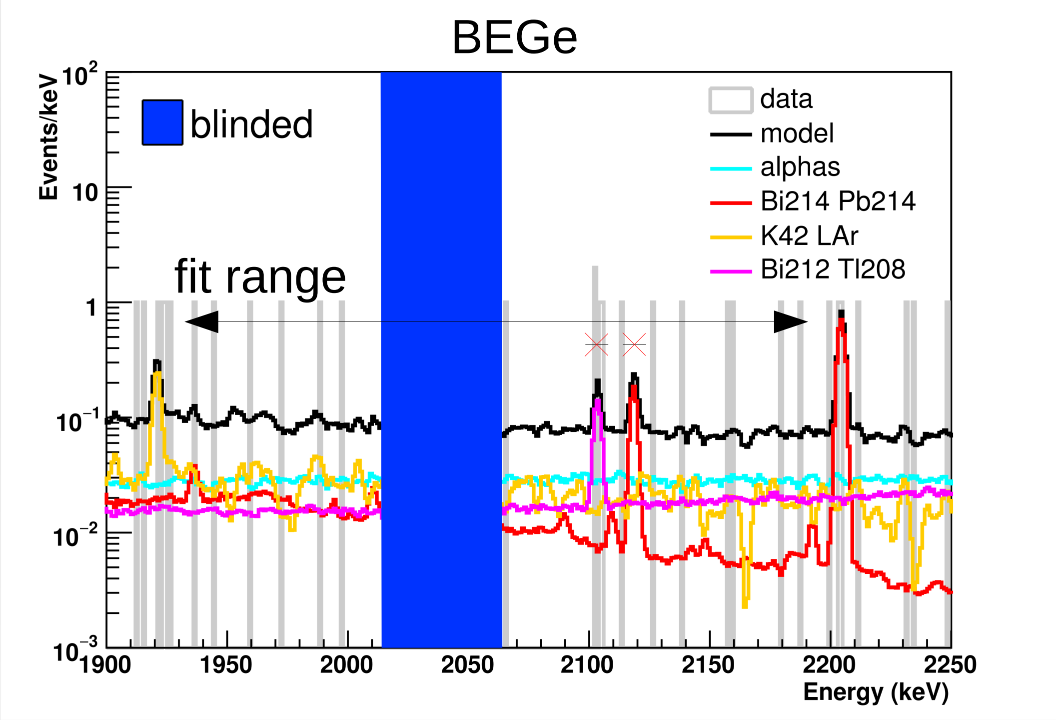
preliminary result:

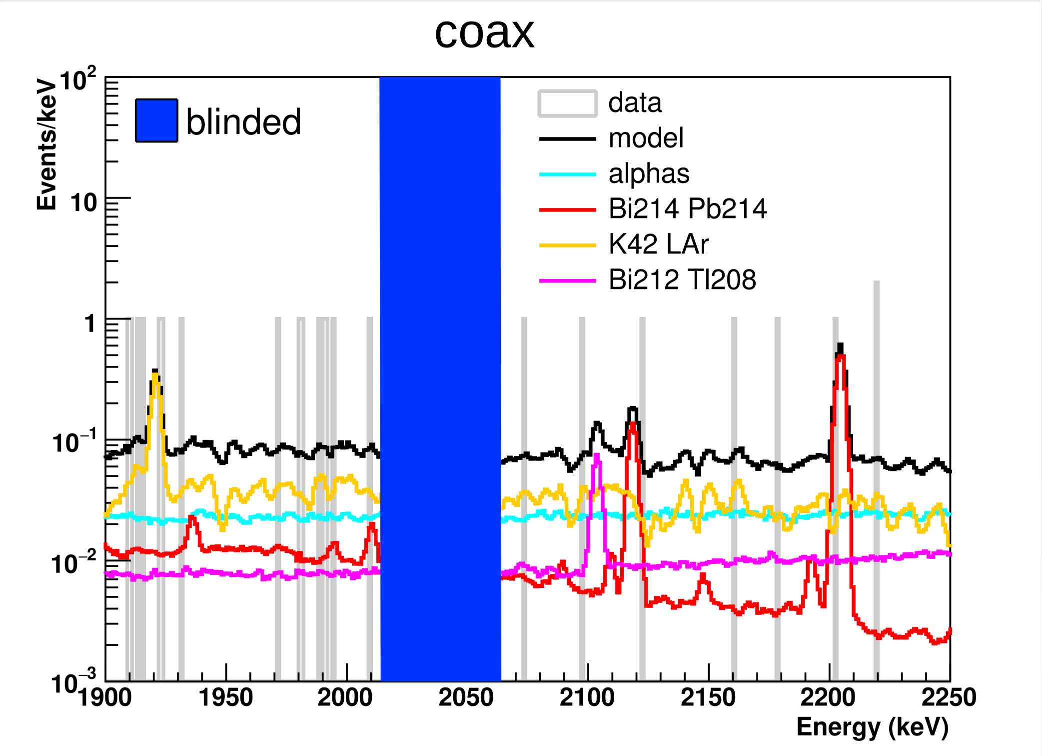
$2\nu\beta\beta$ $T_{1/2}$ = (2.00±0.05) 10^{21} yr

statistical error only

fewer ^{210}Po events than on coax detectors, flat energy component extends to $Q_{\beta\beta}$ effectively removed by A/E high side cut

Background spectrum at $Q_{\beta\beta}$





flat background spectrum before LAr veto and PSD selection
suppression for ^{228}Th and ^{226}Ra calibration data flat → final background flat
fit range 1930 – 2160 keV minus 2x10 keV intervals around 2004 keV and 2119 keV

^{226}Ra and ^{228}Th contamination levels consistent with screening results

~0.015 cnt/(keV kg yr) for BEGe and coax, Phase I coax/BEGe ~0.018/0.04 cnt/(keV kg yr)

Unblinding at Ringberg castle

GERDA collaboration meeting at Ringberg
17 June: unblinding of ± 25 keV around $Q_{\beta\beta}$

Data sets

	exposure [kg*yr]	FWHM [keV]	efficiency	final background 0.001cnt/(keV kg yr)
PI golden	17.9	4.27±0.13	0.57±0.03	11±2
PI silver	1.3	4.27±0.13	0.57±0.03	30±10
PI BEGe	2.4	2.74±0.20	0.66±0.02	5^{+4}_{-3}
PI extra	1.9	4.17±0.19	0.58±0.04	4^{+5}_{-2}
PII BEGe	5.8	3.0±0.2	0.60±0.02	$0.7^{+1.2}_{-0.5}$
PII coax	5.0	4.0±0.2	0.51±0.07	3^{+3}_{-1}

Notes:

PI golden/silver: Phase I PSD efficiency reduced from (90±9) % (for PRL in 2013) to (83±3) %
at same time bug in ROOFIT caused reduction limit → 90% CL of 2013 still valid,
use ZAC energy reconstruction now → energy shift with σ~1 keV

PI extra: 2 runs taken after the PRL data set in 2013

P2 coax: PSD efficiency is preliminary

exposure: calculated using total mass

efficiency: includes active volume fraction, enrichment, reconstruction of $0\nu\beta\beta$, PSD efficiency, LAr veto loss

background: evaluated in energy range used for the fit (240 keV), normalized to total mass

Event list Phase II

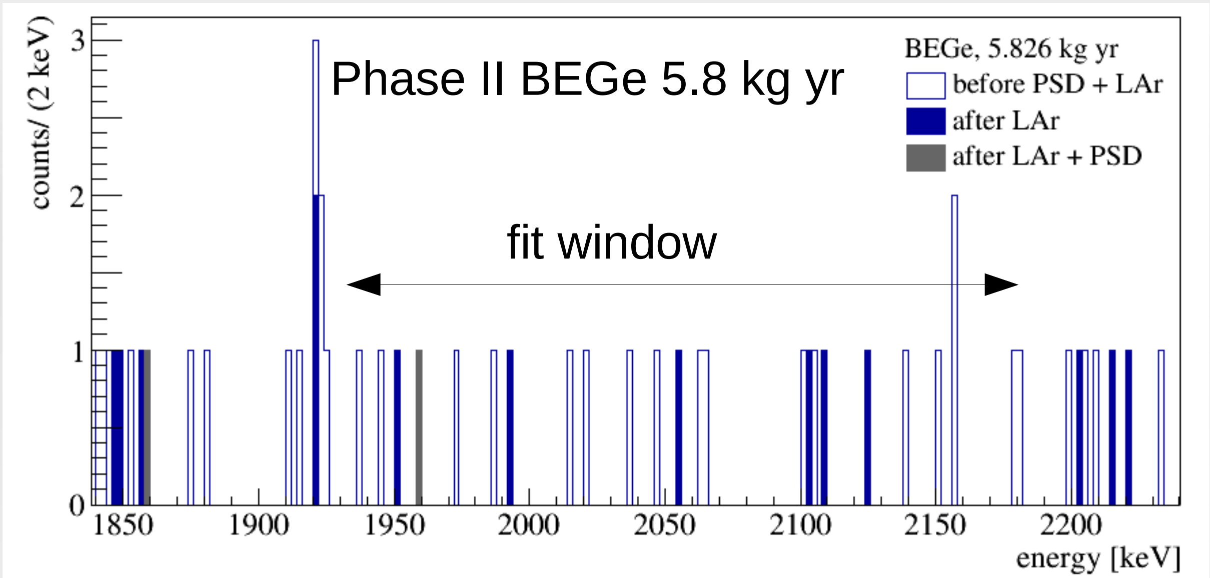
event list (time stamp & energy) from Phase II

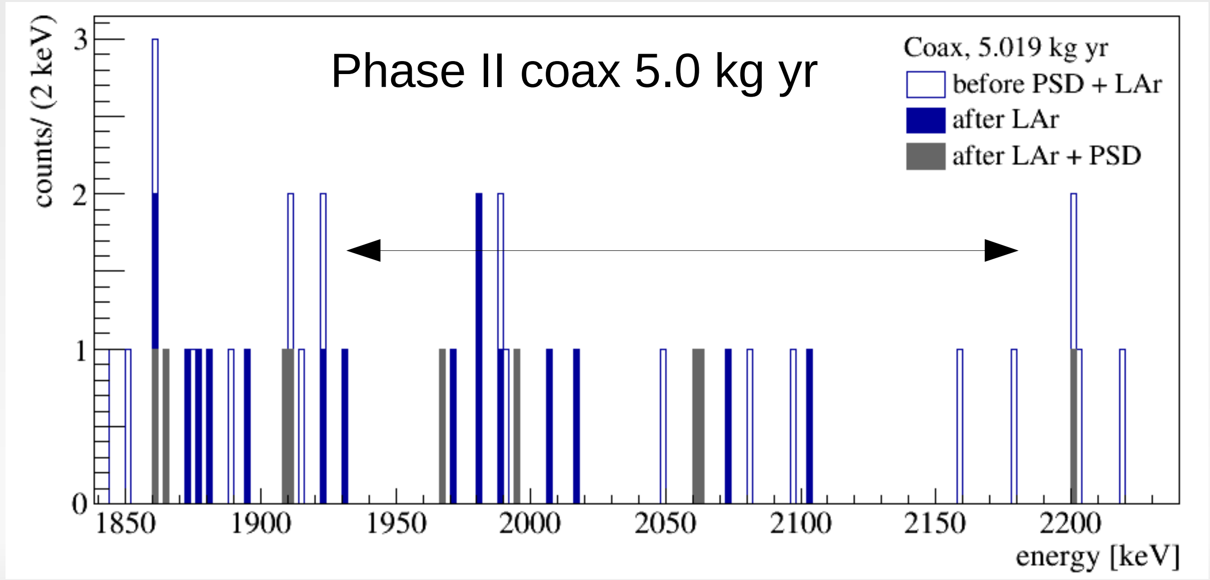
1455109448	1995.1585	ph2_coax
1457844153	1967.97775	ph2_coax
1457847659	1958.61056	ph2_bege
1459180818	2063.55544	ph2_coax
1463917480	2060.51564	ph2_coax

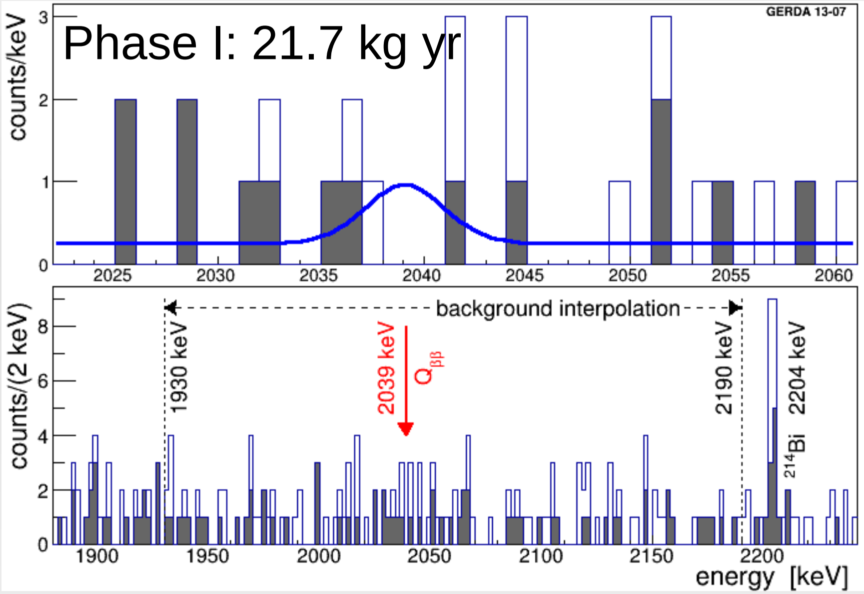
1 event in blinded energy window ±25 keV, closest event 21 keV from $Q_{\beta\beta}$

expect about 0.2 events within ±5 keV of $Q_{\beta\beta}$, see 0 events

Spectrum at $Q_{\beta\beta}$





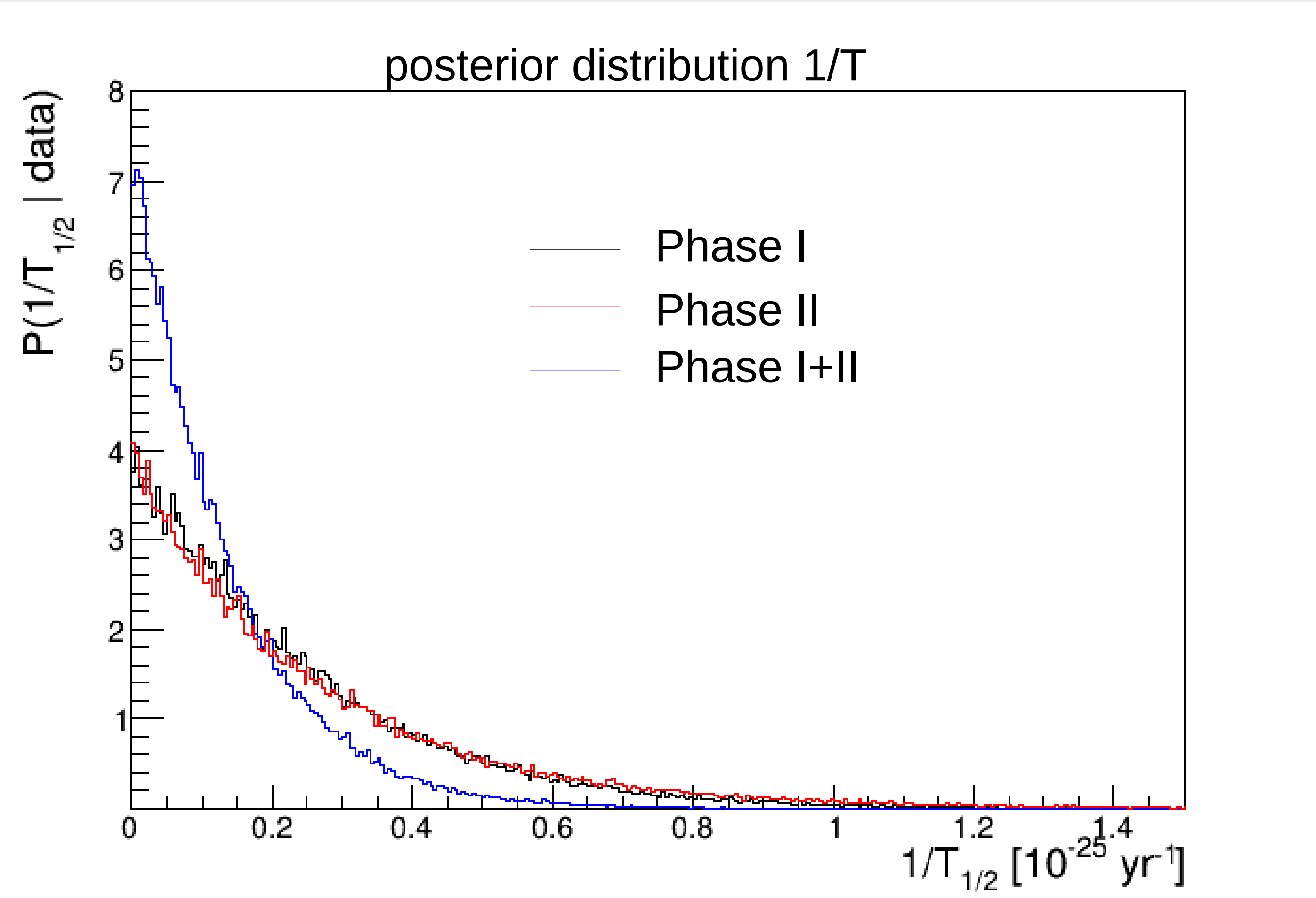


Fit:
- 7 parameters: 1/T, 6 backgrounds
- some systematic (peak pos, …) additional nuisance parameter in fit
- some systematics (active volume, …) handled by randoms sampling & averaging the fit limits

systematics → limit worsens by ~1%

1 BEGe & 4 coax events in 240 keV

Result Bayesian fit

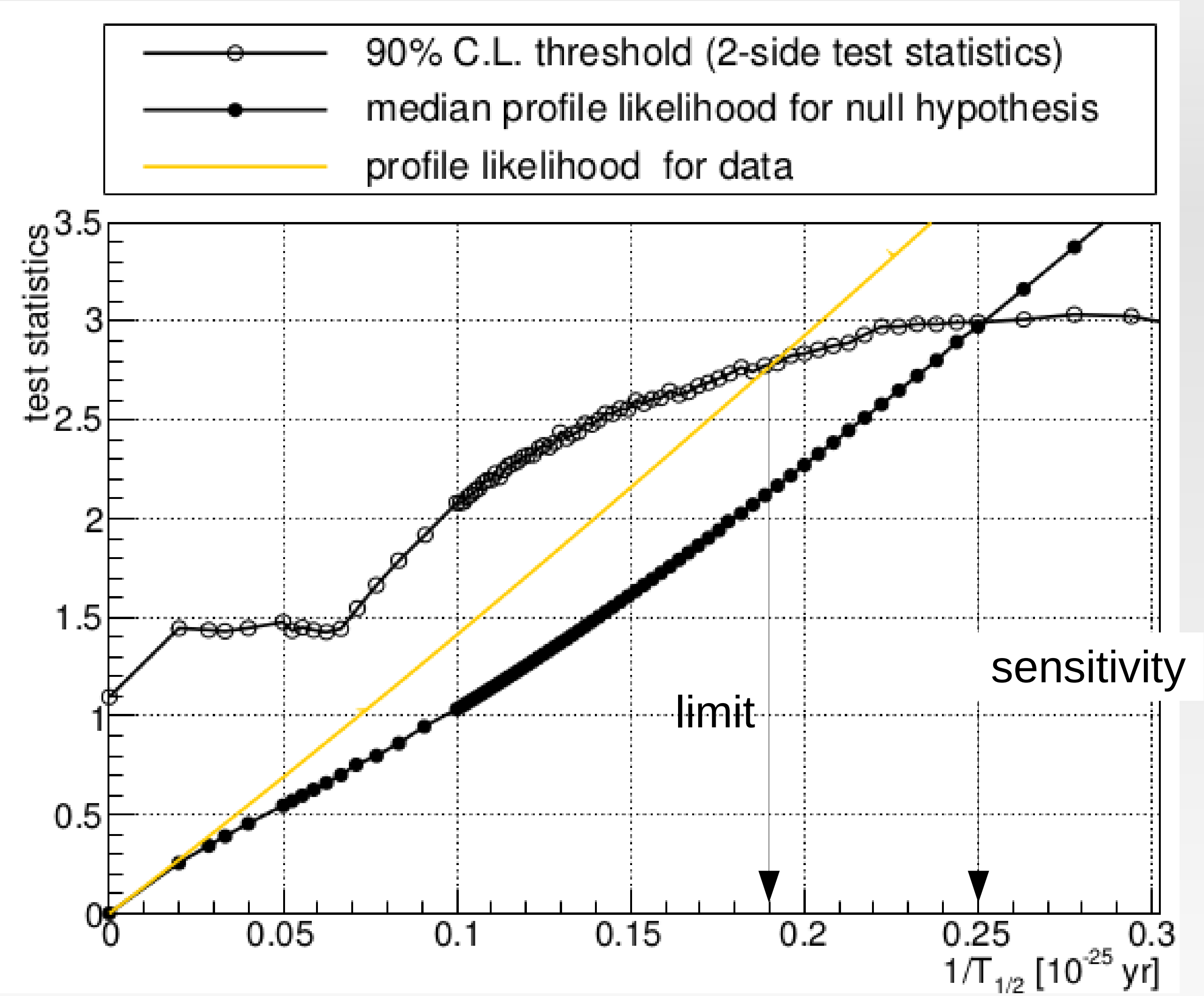


flat prior in 1/T from 0 to 10^{-24} 1/yr:

$N_{signal} < 3.1$ → $T_{1/2} > 3.5\ 10^{25}$ yr (90% credible interval)

median sensitivity 3.1 10^{25} yr, systematic error included

Frequentist: profile likelihood fit



$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% C.L.)   sensitivity 4.0 10^{25} yr

Summary

strong prejudice: $0\nu\beta\beta$ exists, $\Delta L=2$ process, possibly only observable ΔL,
(reminder: from cosmology we know B is violated – at least in early univ.)

GERDA Phase II started in December 2015

- all Ge detectors and LAr channels are working (2 BEGe not used for $T_{1/2}$)
- reached goal of background level $0.7^{+1.2}_{-0.5}\cdot 10^{-3}$ cnt/(keV kg yr) for BEGe (0.003 cnt/(keV kg yr for coax, factor 3 lower than in Phase I)
- lowest bkg (~10x) in ROI compared to exp. using other isotopes

$T_{1/2}$ limits 5.3 10^{25} yr (90% CL, frequentist) and
3.5 10^{25} yr (90% credible, Bayesian), will improve with time

This result suggests future Ge experiments with 200 kg and beyond