First Results of GERDA Phase II

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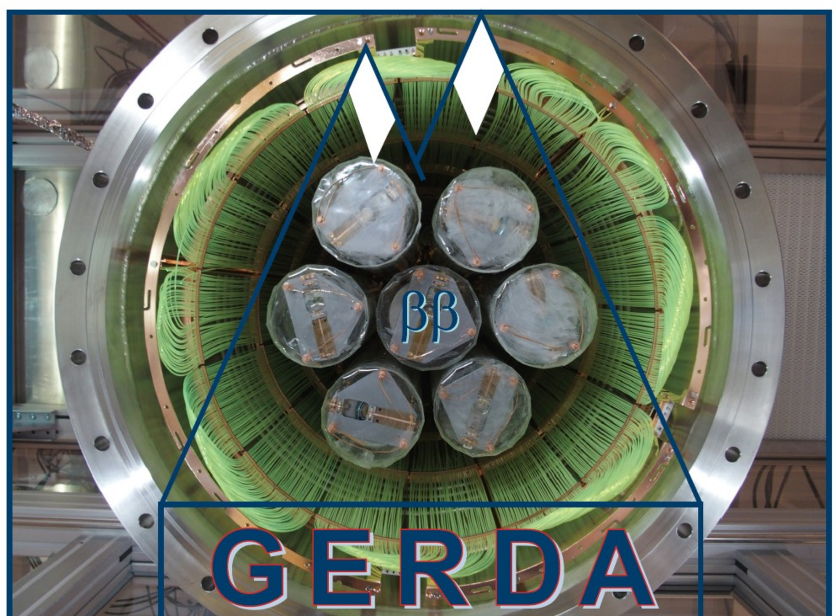
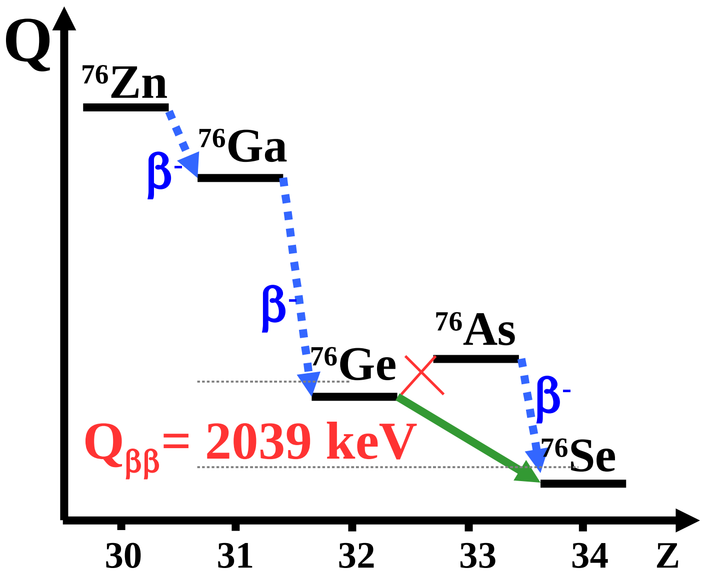
October 17, 2016



The GERDA Collaboration:
searching for neutrinoless double beta decay

Double Beta Decay



Double beta decay ($2\nu\beta\beta$)

- single β decay energetically forbidden
- (A,Z) → (A,Z+2) + $2e^-$ + $2\bar{\nu}$
- e.g. ^{76}Ge, ^{136}Xe, ^{130}Te, ^{116}Cd
- half-life of $2\nu\beta\beta$ decay of ^{76}Ge measured by GERDA (most recent and precise measurement):

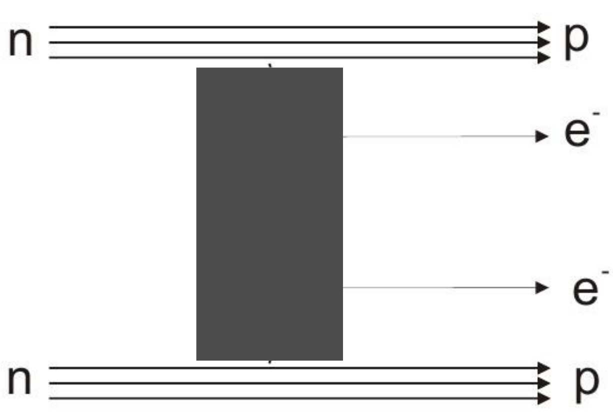
$$T_{1/2}^{2\nu} = (1.926 \pm 0.095) \times 10^{21}\ \mathrm{yr}$$

EPJC 75 (2015) 416

Neutrinoless double beta decay ($0\nu\beta\beta$)

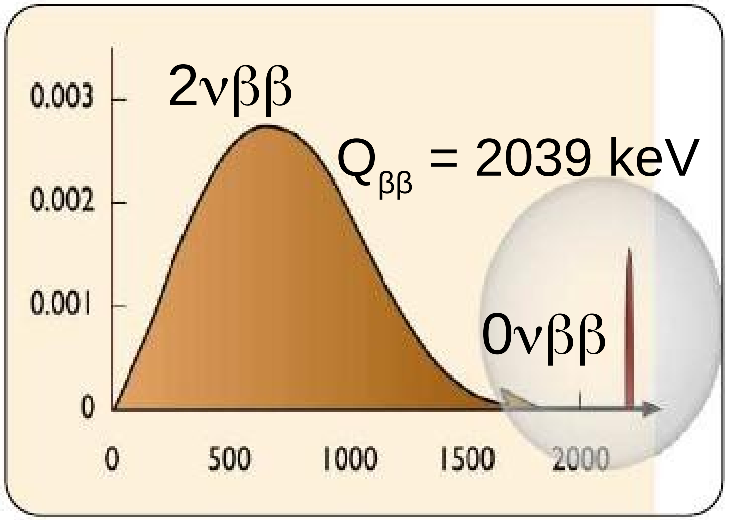
- (A,Z) → (A,Z+2) + $2e^-$
- lepton number violated by **ΔL = 2**

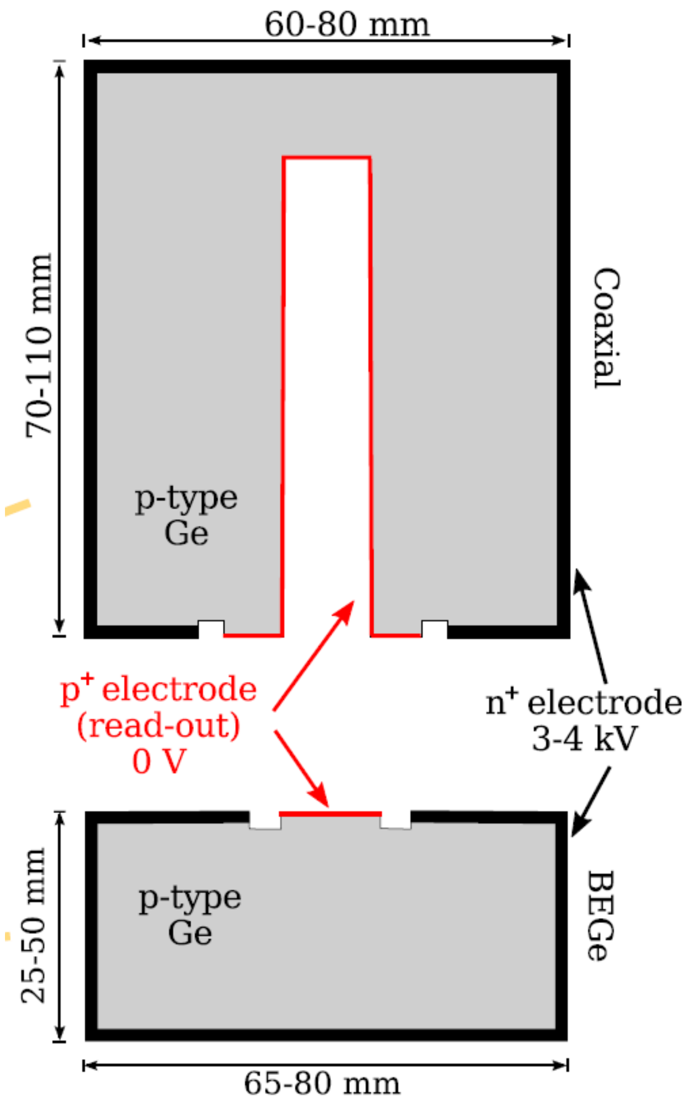
  → **physics beyond SM**
- proof of Majorana mass component of neutrinos



Signature & Experimental Challenges

- Measure sum energy of electrons





High Purity Germanium (HPGe) Detectors

- excellent energy resolution (0.1% FWHM)
- low intrinsic background
- high detection efficiency of ββ: source = detector
- HPGe detectors isotopically **enriched** in ^{76}Ge (~87%)
- discrimination of signal- from background like events using pulse shape analysis

The **Germanium Detector Array**

concept:
operate bare HPGe detectors in LAr which serves as coolant & shielding

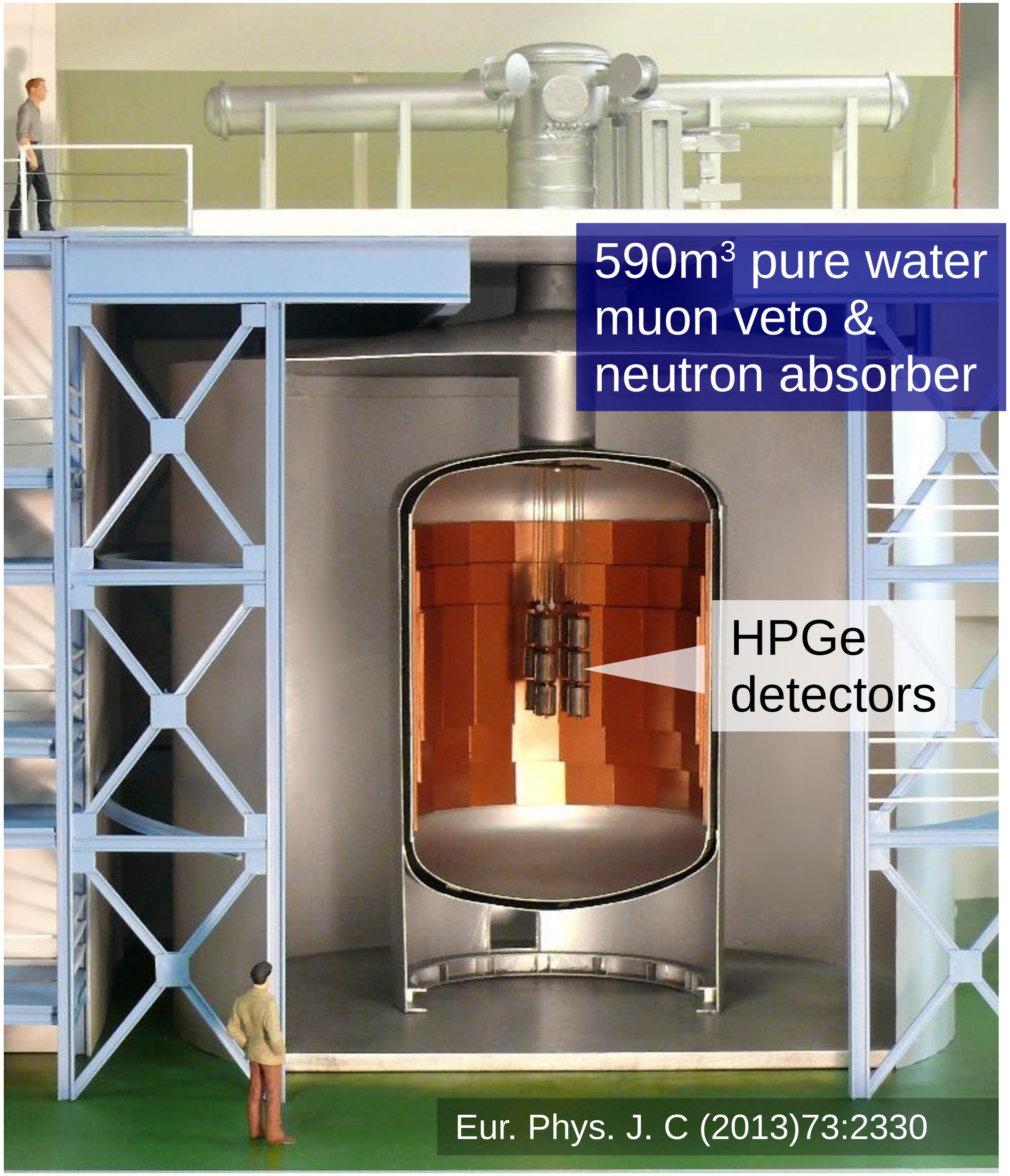
Phase I (Nov 2011- May 2013)

- **17.8 kg** enriched semi-coaxial + **3.6 kg** enriched BEGe
- exposure 21.6 kg y
- BI ~ 10^{-2} cts/(keV· kg· yr)
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

PRL 111, 122503 (2013)

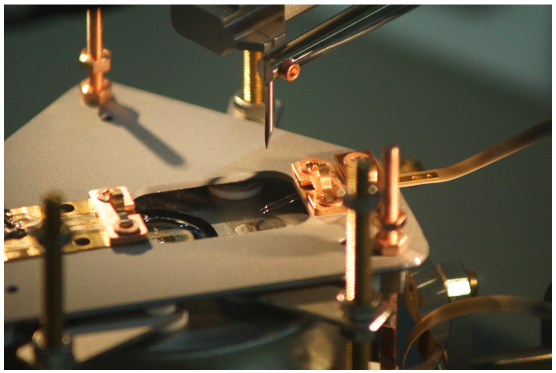
Phase II (Dec 2015 -)

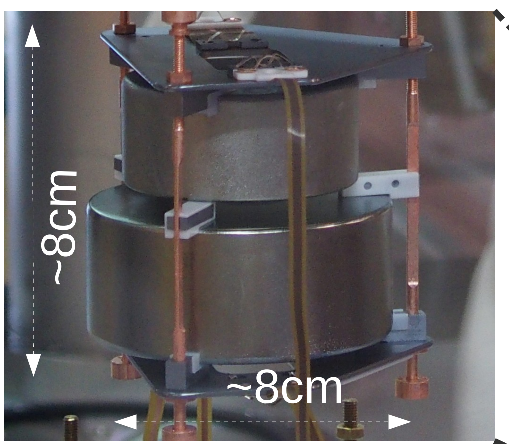
- **30** enriched **BEGe** (= **20.0 kg**) + 7 enriched semi-coaxial (= **15.8 kg**)
- **LAr instrumentation**
- goal: BI ~ 10^{-3} cts/(keV· kg· yr)

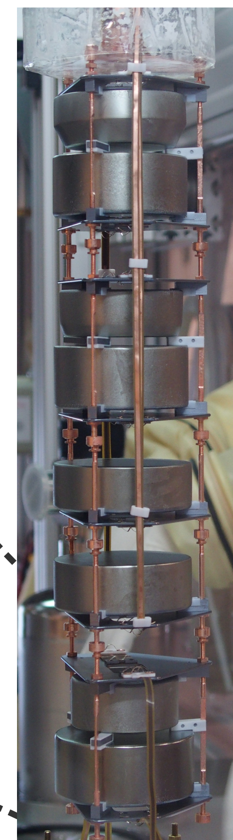


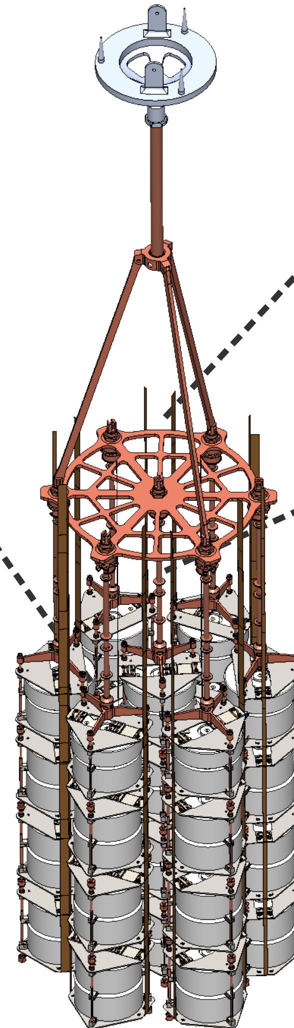
GERDA Phase II Array

wire bonding for contacting









low radioactivity electronics

new low mass holders with reduced mass and Cu → Si

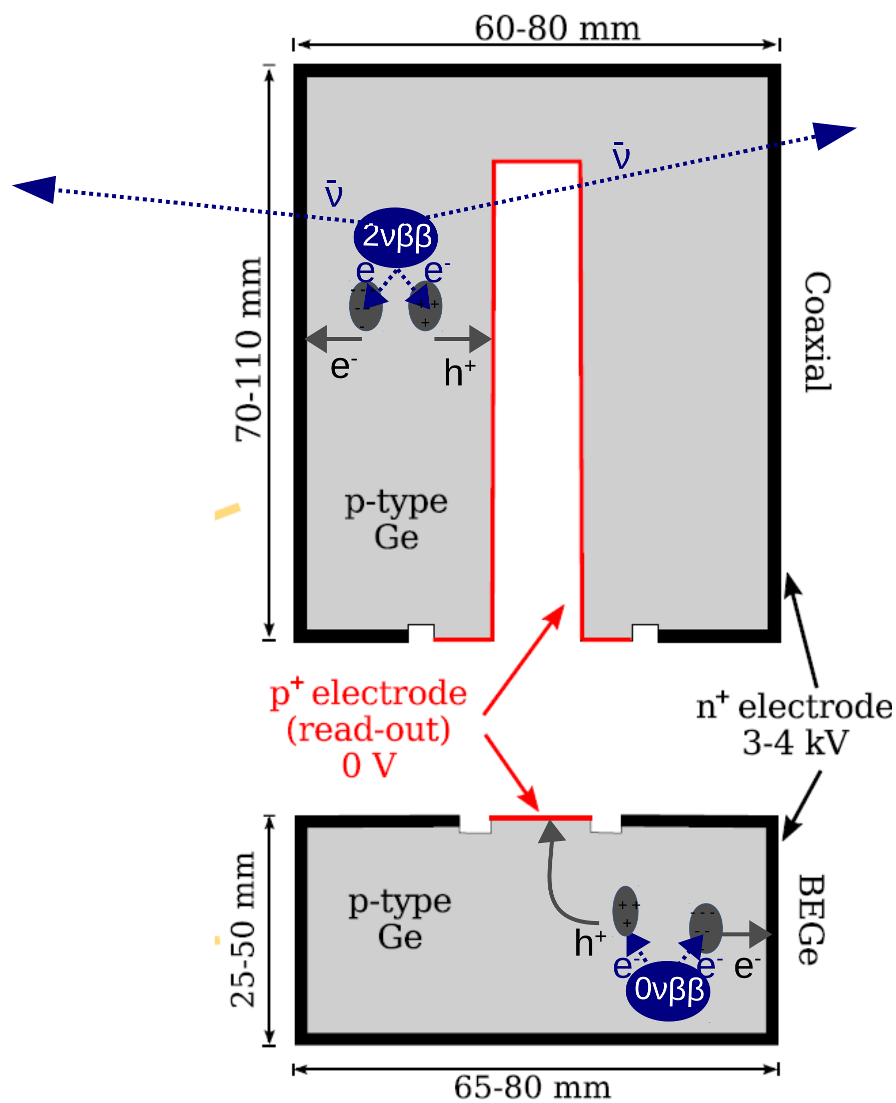
Discriminating Signal from Background Events

ββ event

- local energy deposition (SSE) in single detector

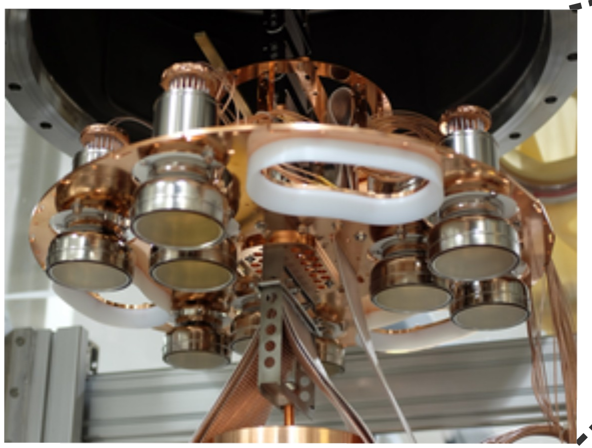
background event

- energy deposition in multiple locations (MSE) in single detector or on detector surface
  → **pulse shape analysis**
- coincident energy deposition in more than one detector
  → **detector anti-coincidence**
- additional energy deposition in LAr
  → **LAr veto**

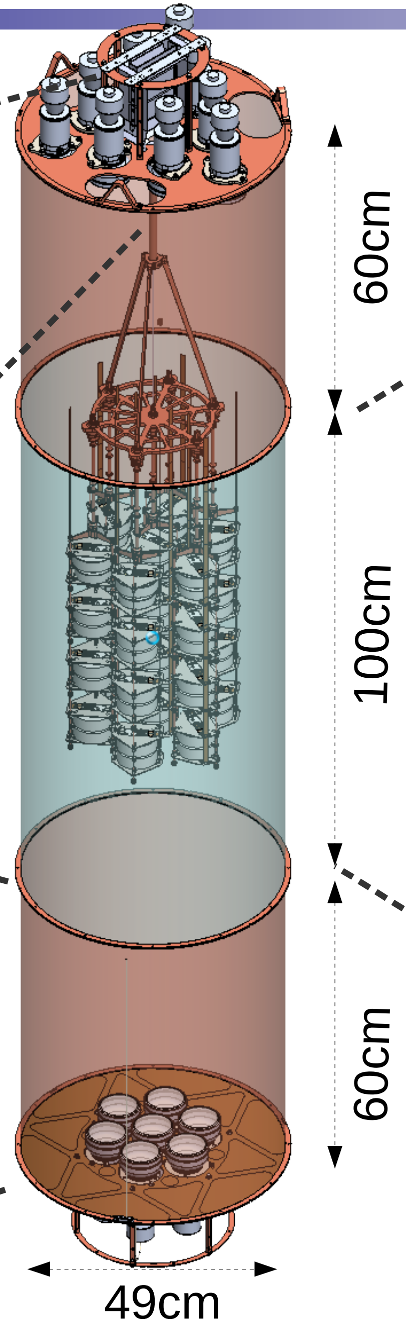


LAr Instrumentation – Hybrid Design

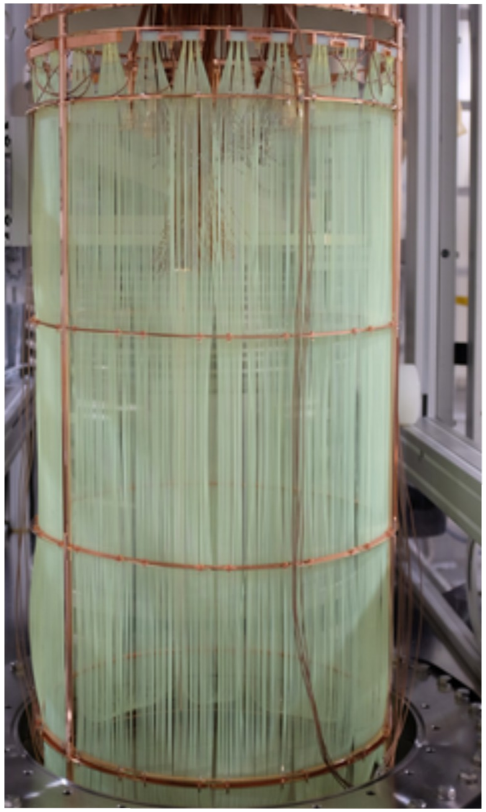
16 photomultiplier tubes (PMTs)



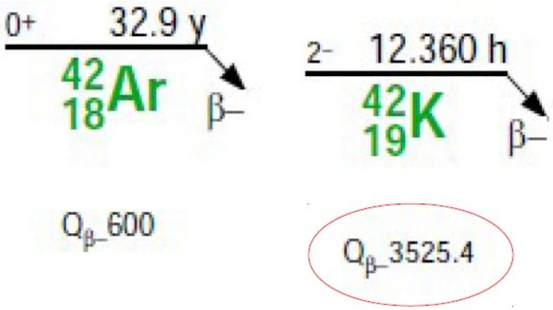
Cu cylinder with wavelength shifting reflector foil



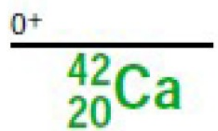
810 wavelength shifting fibers coupled to SiPMs



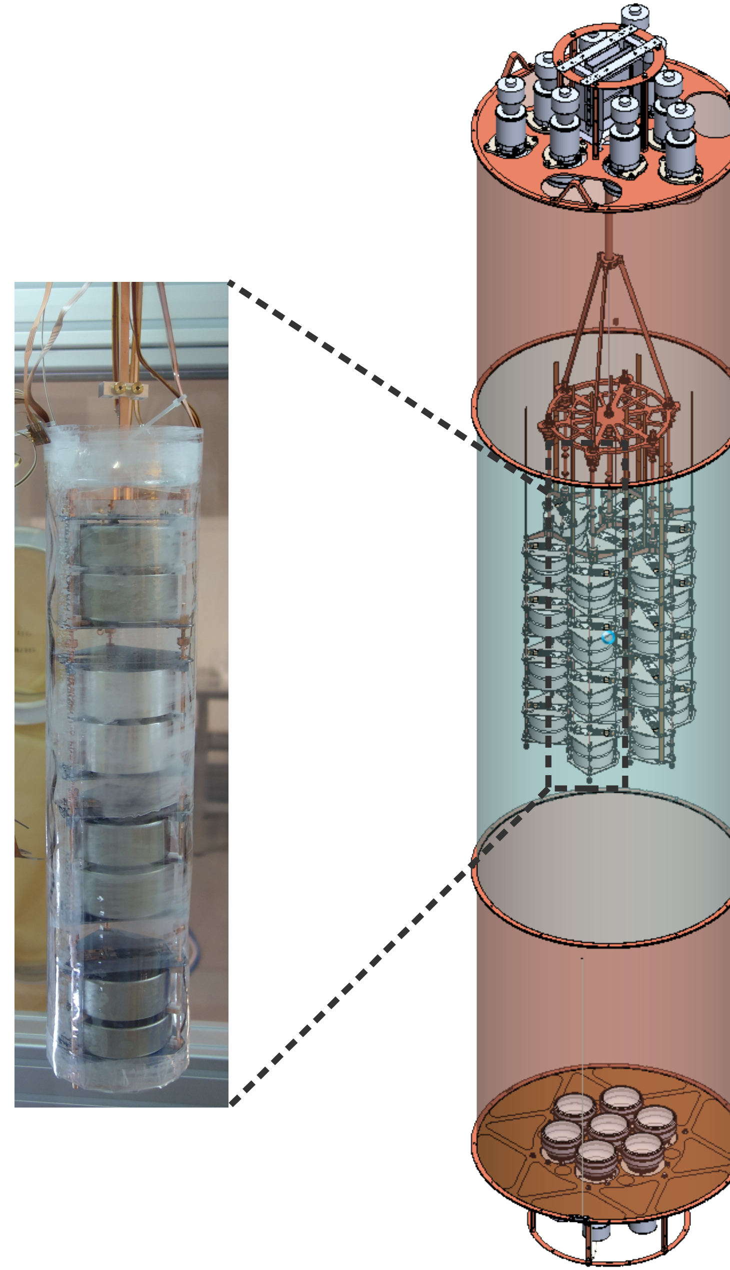
^{42}K Background



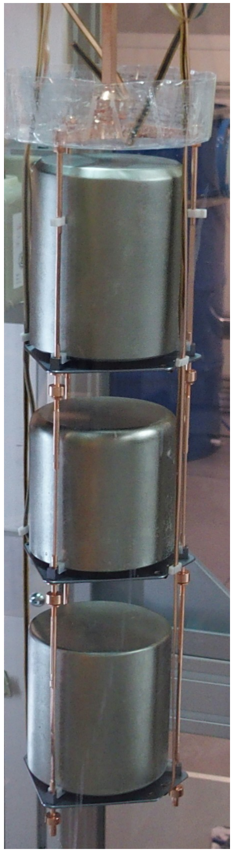
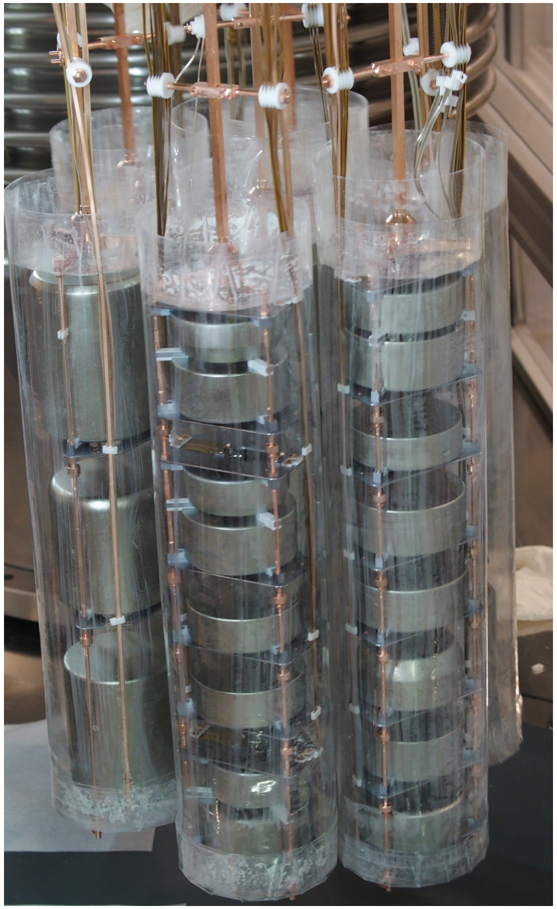
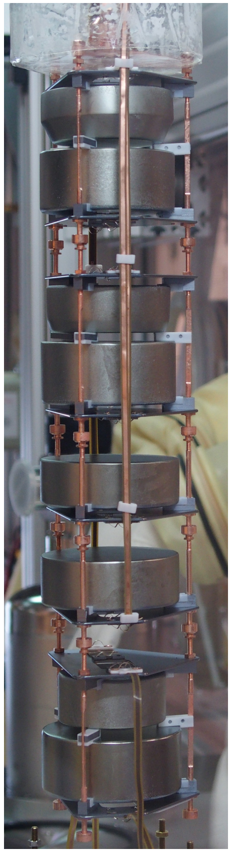
(charged) ^{42}K drift in field of Ge detectors



- solution:
  transparent nylon cylinder coated with wave length shifter
- tested in test cryostet LArGe
- nylon from BOREXINO

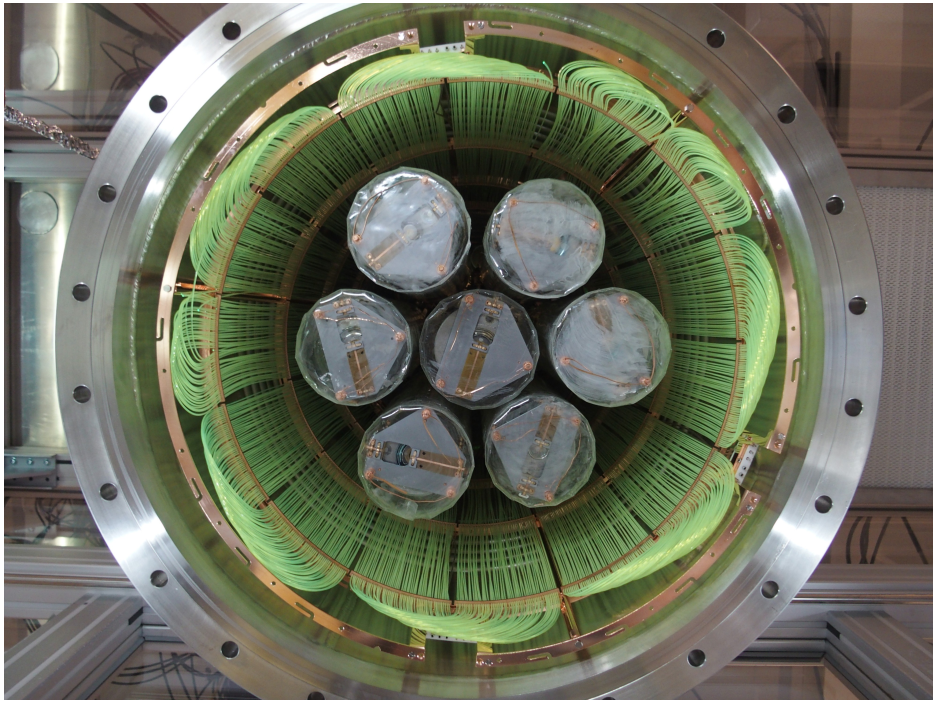


Start of GERDA Phase II

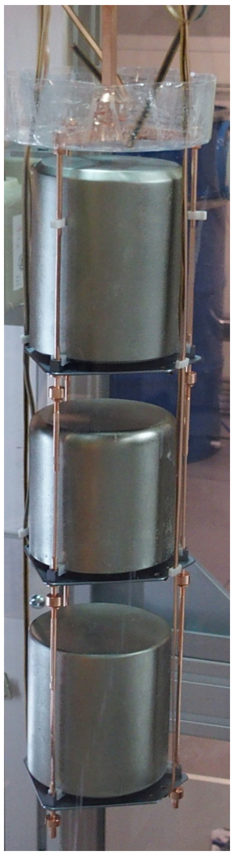
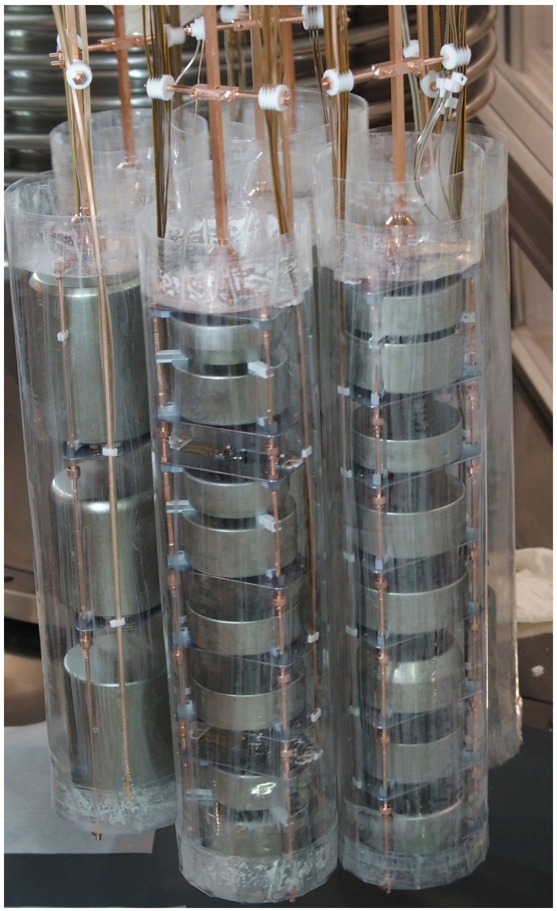
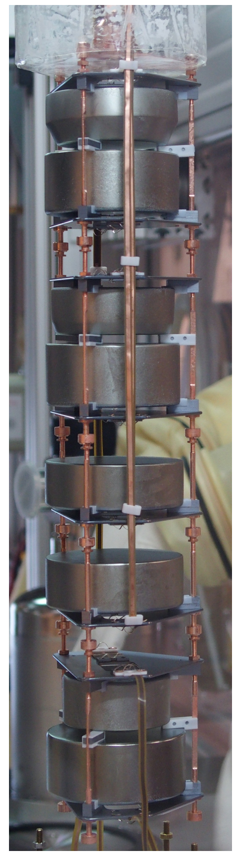




Full Integration of Phase II Array finished in December 2015

- all Ge and LAr detector channels working



Start of GERDA Phase II

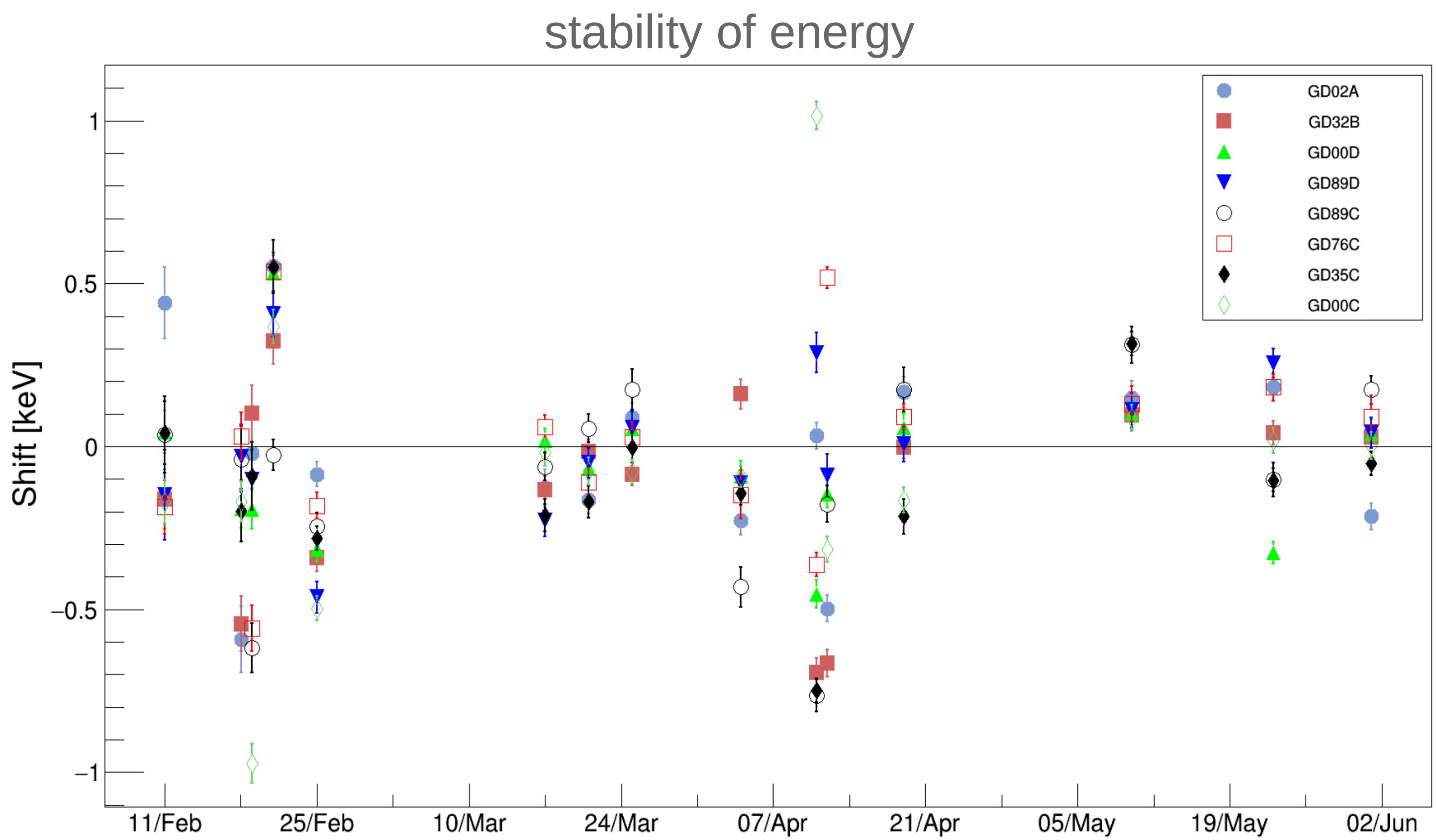
Full Integration of Phase II Array finished in December 2015

- all Ge and LAr detector channels working

First data release in June 2016

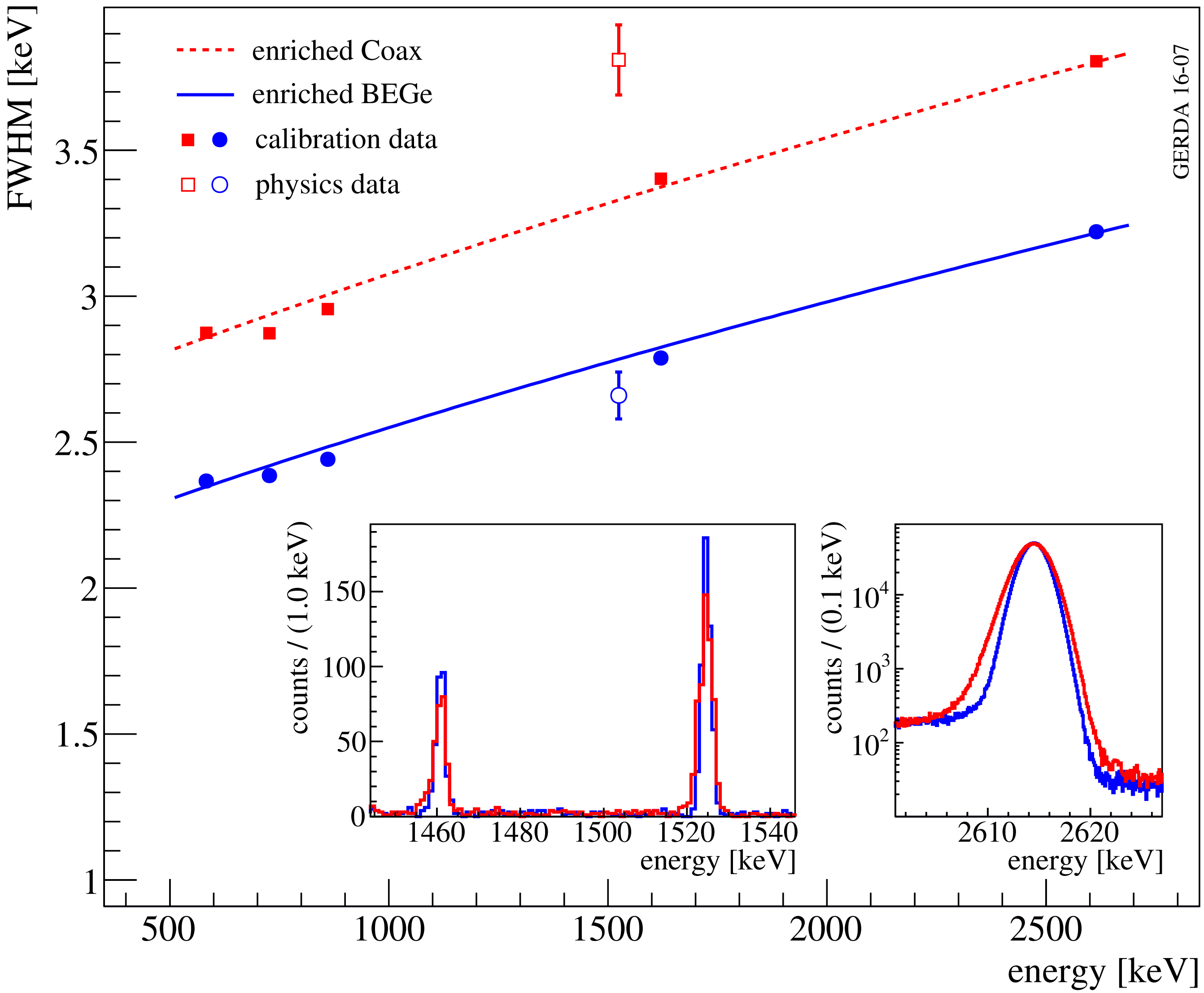
- 35 out of 37 detectors used for analysis
- blinded region: $Q_{\beta\beta}$ ± 25 keV
- quality cuts (phys. acc. > 99.9%)
- events in coincidence with muon veto (phys. acc.~ 99.9 %)

Detector Performance



- all but one diode at operational HV and LC stable
- rate of non-physical events higher than in Phase I: ~2/min, presumably discharges
- 82% average duty cycle
- few detectors (partially) excluded from $T_{1/2}$ analysis due to gain instabilities

Energy Resolution



FWHM @ 2.6 MeV:

- BEGe's:

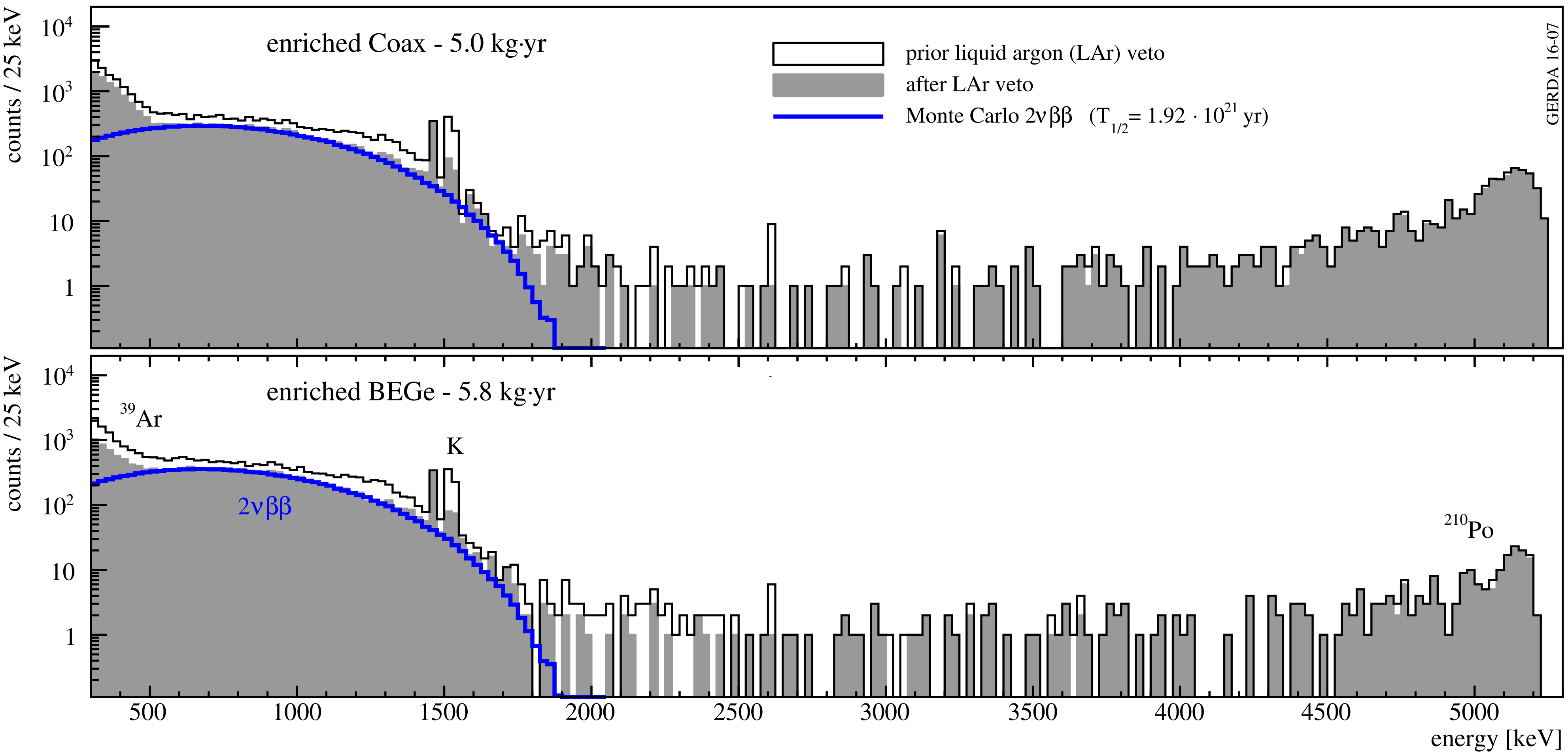
  2.6 – 4.0 keV

- Coax:

  3.4 – 4.4 keV

Performance of the LAr Veto

- $2\nu\beta\beta$:bck = 96:4 (1.0-1.3 MeV)



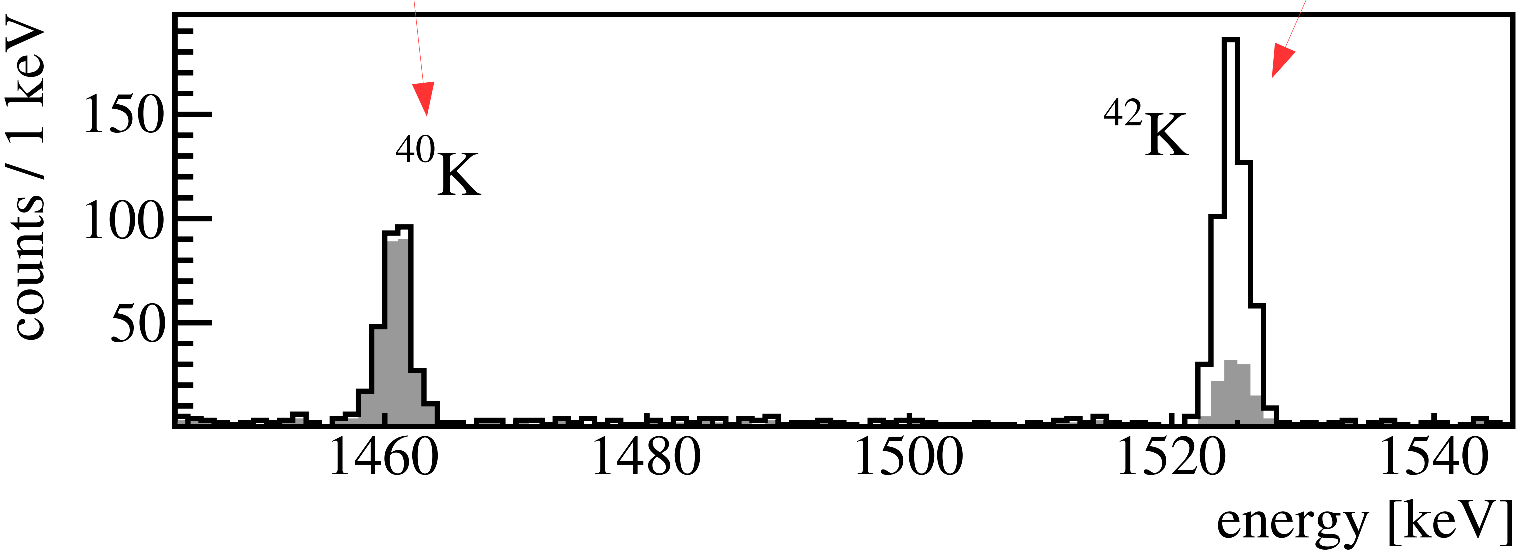
$2\nu\beta\beta$ MC with $T_{1/2} = 1.9 \cdot 10^{21}$ yr from Phase I EPJC 75 (2015) 416

Performance of the LAr Veto

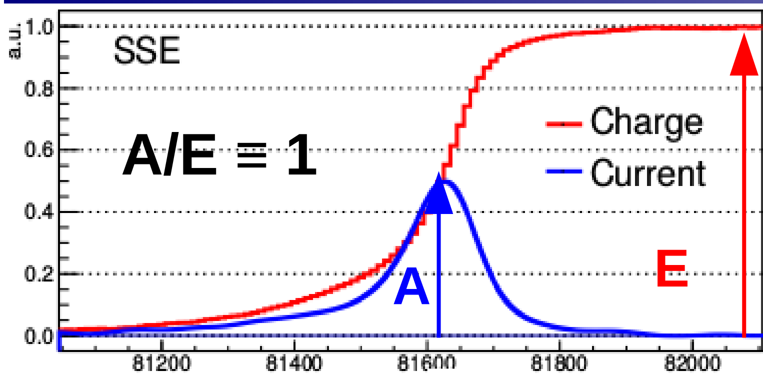
- random coincidences: 2.3%
- ^{42}K line suppressed by factor 5-6

$^{42}K \rightarrow {}^{42}Ca$
+ γ (1.5 MeV) in Ge
+ β^- ($\leq$ 2 MeV) in LAr

$^{40}K \rightarrow {}^{40}Ar$ (EC)
no energy in LAr

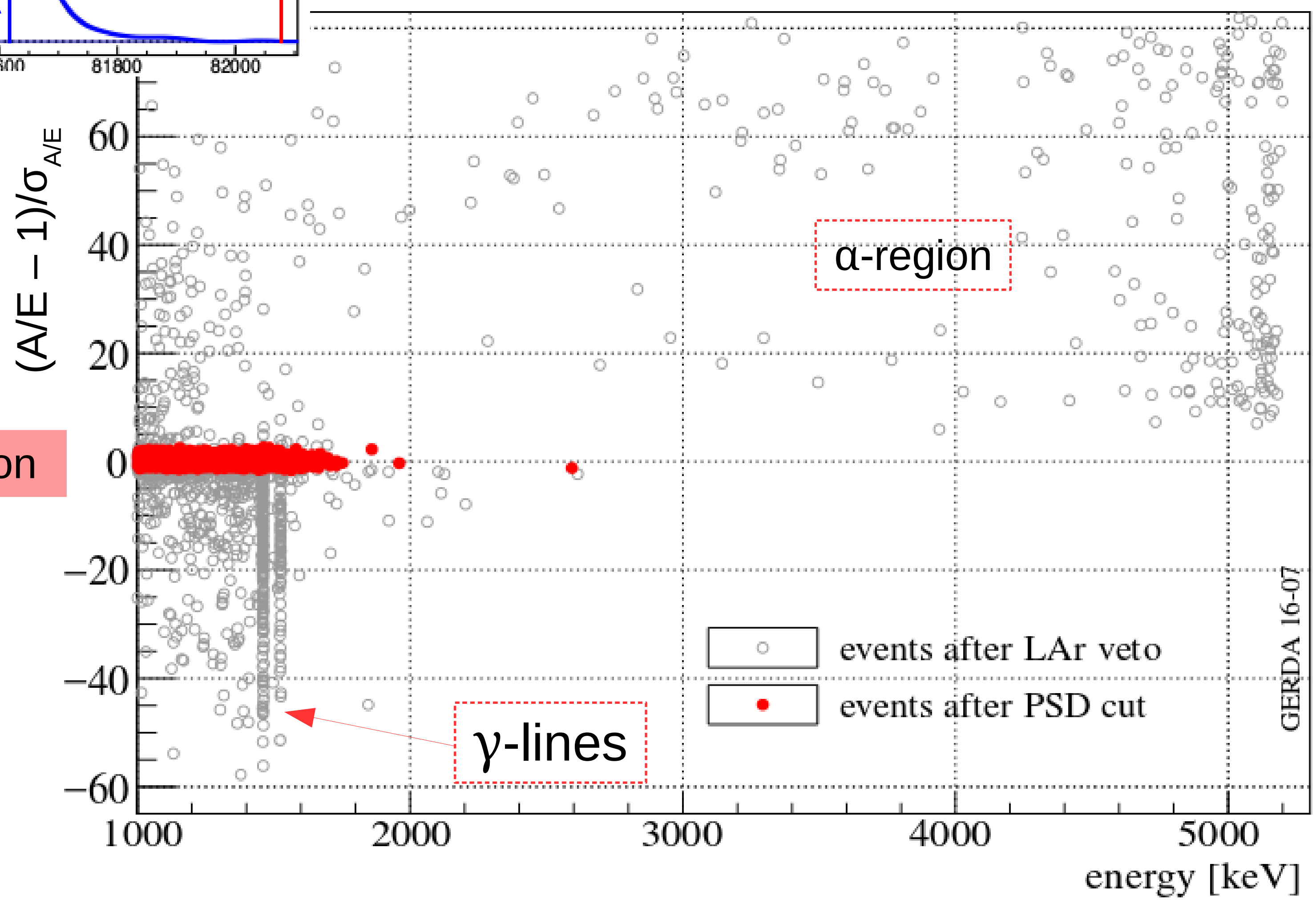


Pulse Shape Analysis: A/E for BEGe

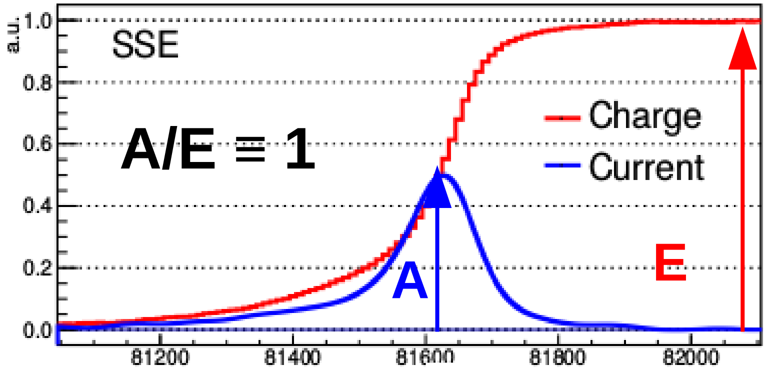


detector current time profile
used to discriminate signal from background events

Signal region

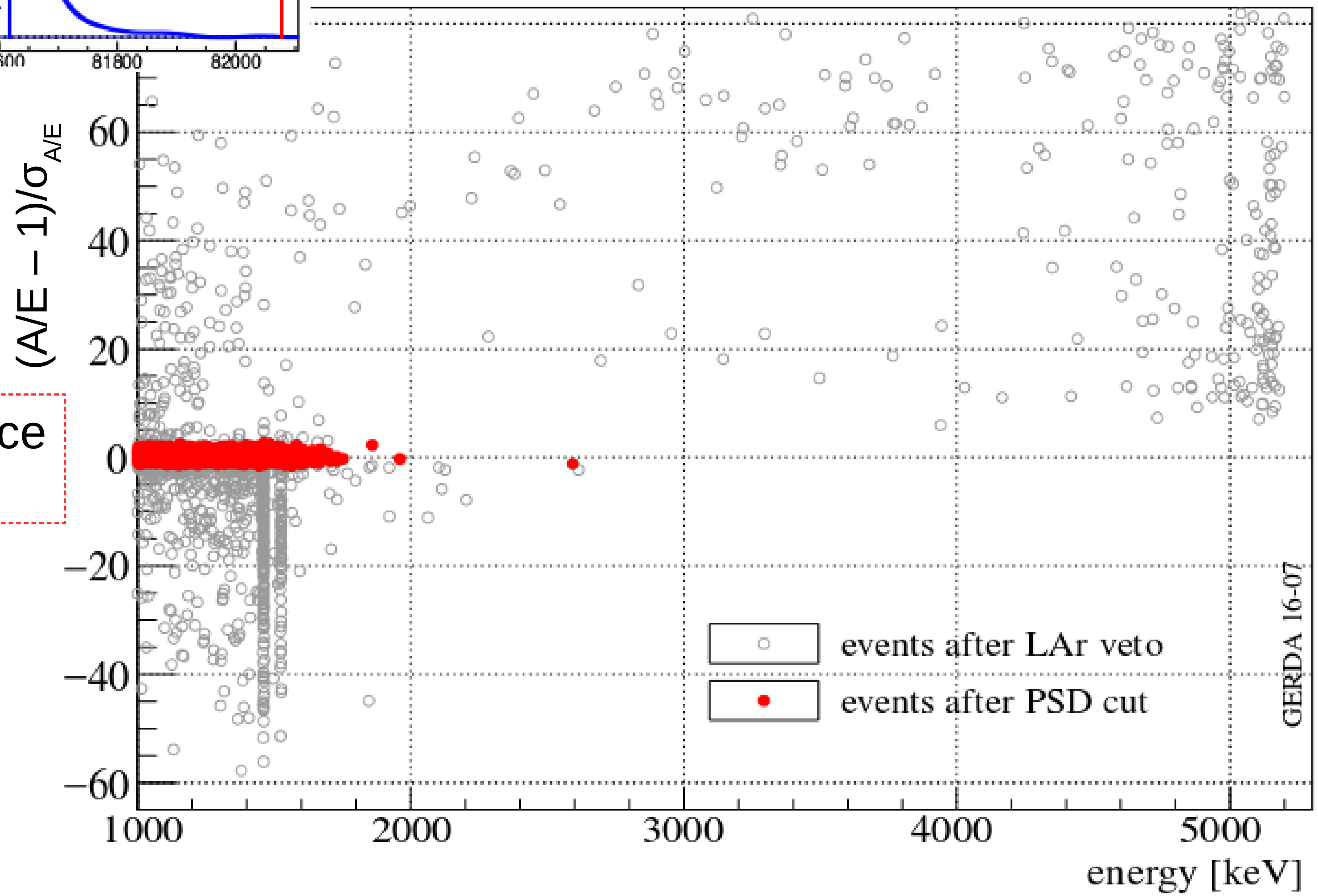


A/E Analysis for BEGe's



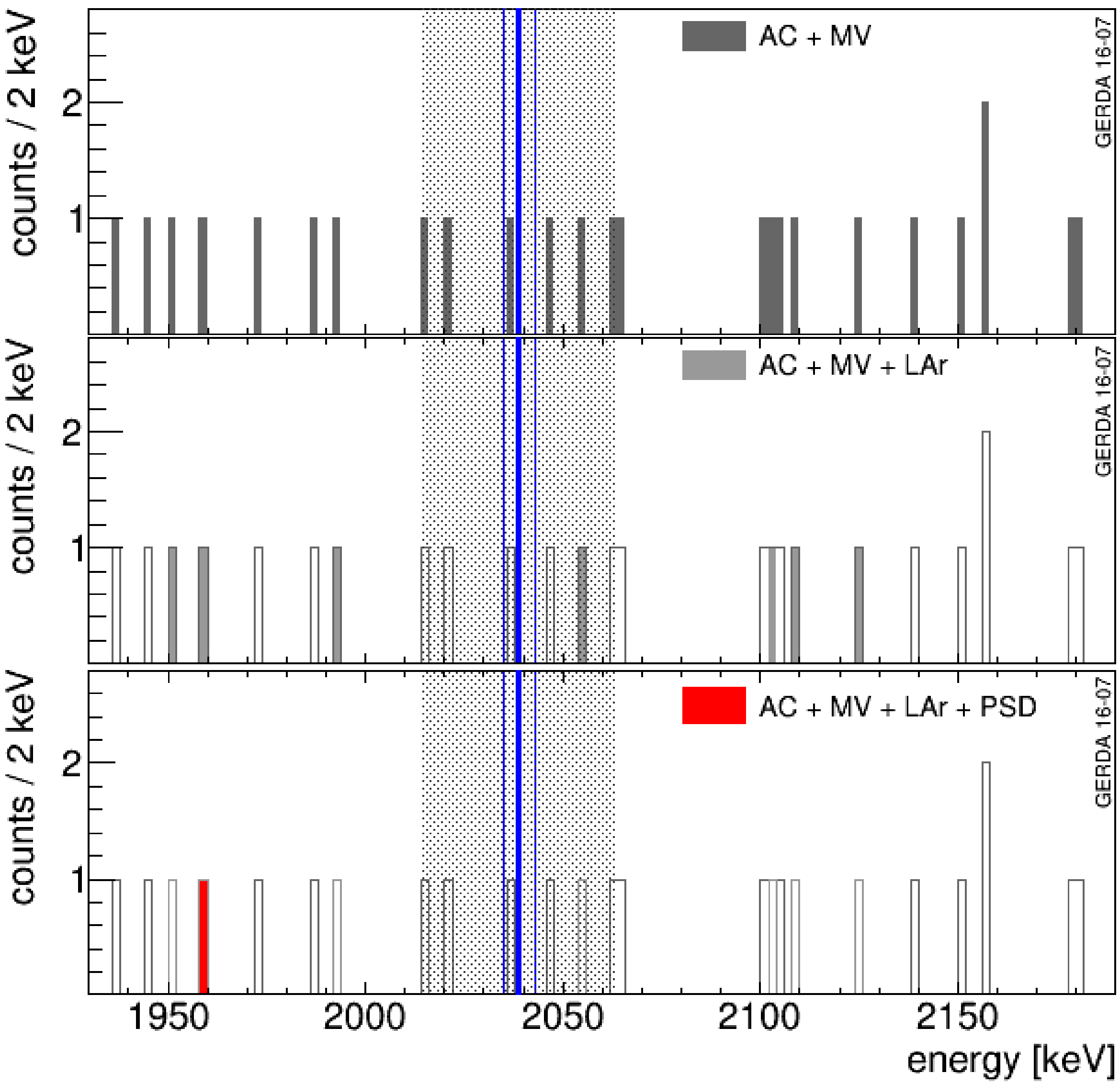
80% of background events rejected at $Q_{\beta\beta}$ and keep high signal efficiency = **87(1) %**

2νββ acceptance 85^{+2}_{-1} %



Background Suppression LAr + PSD

BEGe, 5.8 kg · yr



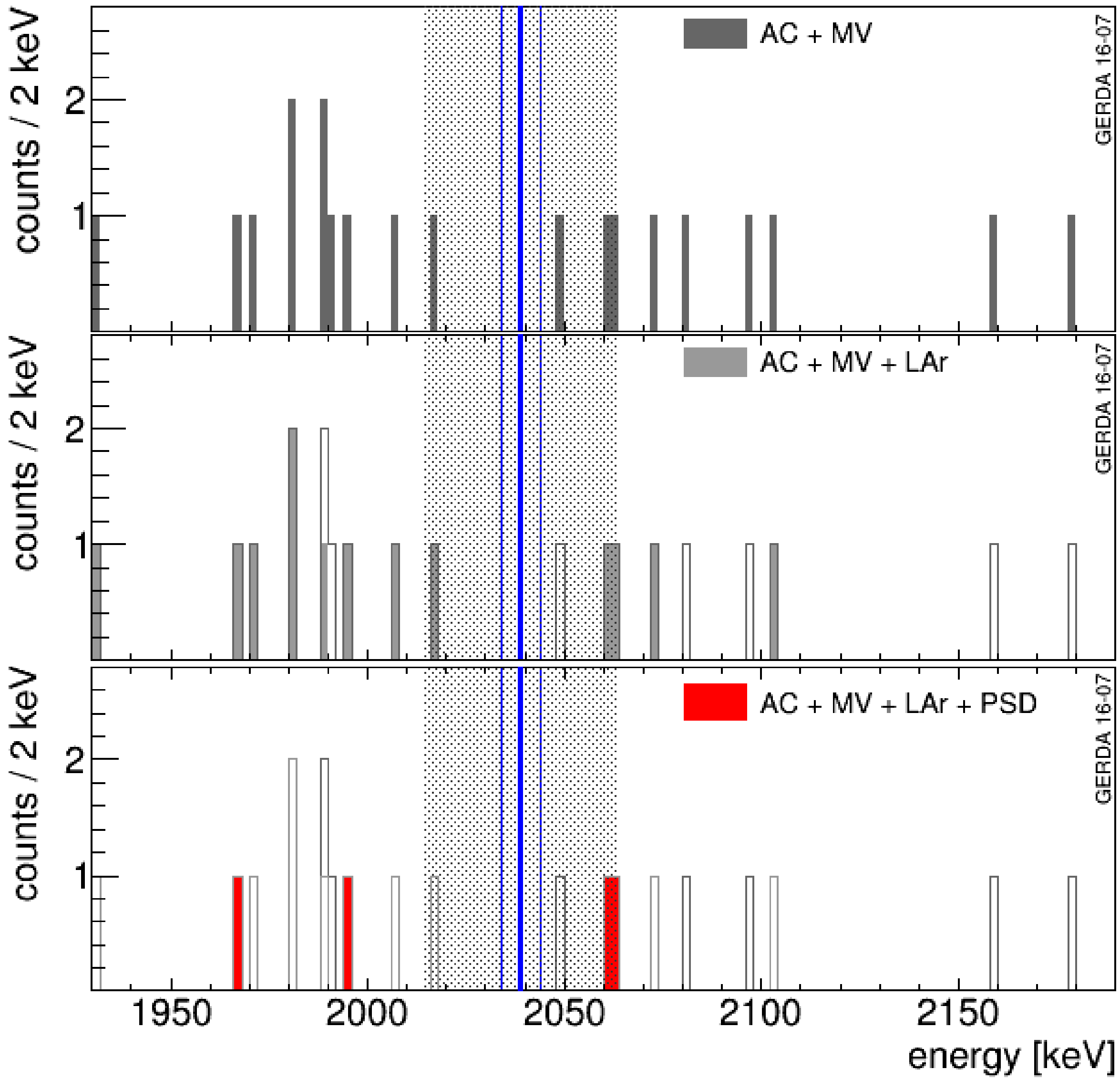
$$BI^{AC,MV} = 15.7^{+3.8}_{-3.1} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

$$BI^{AC,MV,LAr} = 4.5^{+2.2}_{-1.6} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

$$BI^{AC,MV,LAr,PSD} = 0.7^{+1.1}_{-0.5} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

Background Suppression LAr + PSD

Coax, 5.0 kg · yr



$$BI^{AC,MV} = 16.5^{+4.2}_{-3.5} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

$$BI^{AC,MV,LAr} = 10.4^{+3.5}_{-2.7} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

$$BI^{AC,MV,LAr,PSD} = 3.5^{+2.1}_{-1.5} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

Summary of Data Sets

data set	exposure [kg yr]	signal eff	Energy resolution (keV, FWHM)	Background index 10^{-3} cnts/(keV kg yr)
Phase II BEGe	**5.8**	**0.60 (2)**	**3.0 (2)**	$\mathbf{0.7^{+1.1}_{-0.5}}$
Phase II coax	**5.0**	**0.51 (7)**	**4.0 (2)**	$\mathbf{3.5^{+2.1}_{-1.5}}$

Phase II coax:

- PSD efficiency still preliminary

signal efficiency including active volume, enrichement fraction and FEP efficiency as well as detection eff LAr + PSD

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Phase I gold	17.9	0.57 (3)	4.3 (1)	11 ± 2
Phase I silver	1.3	0.57 (3)	4.3 (1)	30 ± 10
Phase I BEGe	2.4	0.66 (2)	2.7 (2)	5^{+4}_{-3}

Phase I:
- PSD efficiency reduced from 90% to 83%
- new energy reconstruction to improve energy resolution from 4.8 (3.2) keV to 4.3 (2.7) keV for coax (BEGe) EPJC 75 (2015) 255

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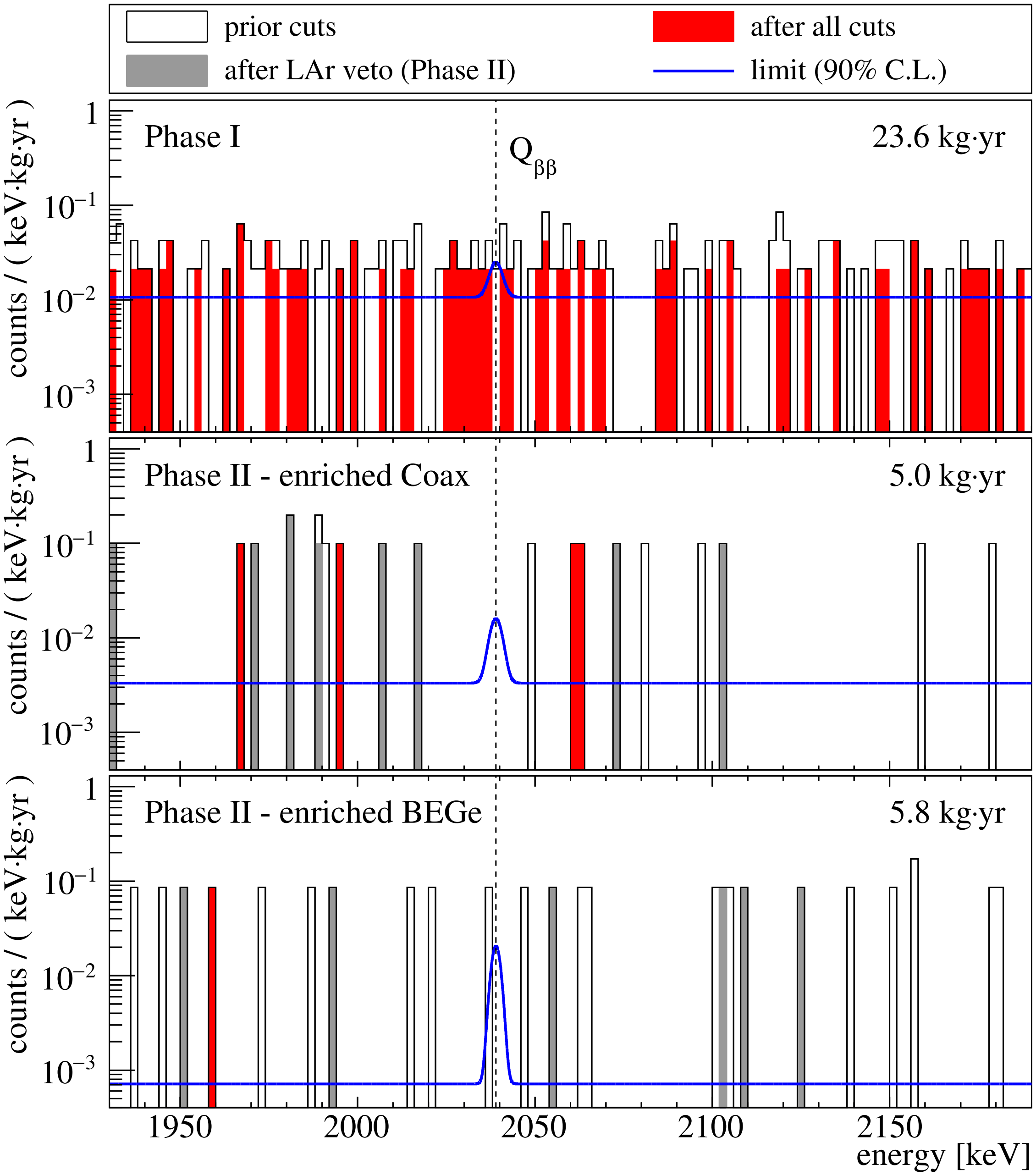
Phase I BEGe	2.4	0.66 (2)	2.7 (2)	5^{+4}_{-3}
Phase I extra	1.9	0.58 (4)	4.2 (2)	5^{+4}_{-3}

Runs 47 + 49 from Phase I:

- unpublished, blinded
- May 31st – Sept 30th 2013

Spectrum at $Q_{\beta\beta}$



Extended unbinned profile likehood:

- flat background in 1930-2190 keV
- signal = Gaussian with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- 7 parameters: 6 BI + common $T_{1/2}$

- best fit for $N_{0\nu} = 0$
- lower limit $T_{1/2}^{0\nu} > 5.2 \cdot 10^{25}$ yr *+

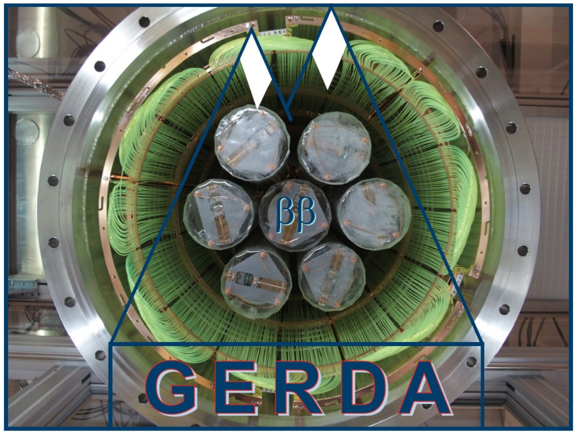
  with $T_{1/2}^{0\nu}$ sensitivity $4.0 \cdot 10^{25}$ yr

  (90 % C.L.)

* preliminary

+Frequentist approach after Cowan et al., EPJC 71 (2011) 1554

Summary



- GERDA Phase II started successfully in December 2015
- **reached goal of background level of**
- **10^{-3} counts/(keV · kg · yr)**

  → typically order of magnitude lower background count rate per ROI than competing experiments

- FWHM = 3.0 keV (4.0 keV) BEGe (Coax) at $Q_{\beta\beta}$

* preliminary

- no hint for $0\nu\beta\beta$ signal
- $m_{\beta\beta} < 0.15 – 0.33$ eV *

	median sensitivity (10^{25} yr)	lower limit $T_{1/2}$ (10^{25} yr)
Bayesian (90% CI)	3.0 *	3.5 *
Frequentist (90% C.L.)	4.0 *	5.2 *

Summary

- GERDA Phase II started successfully in December 2015
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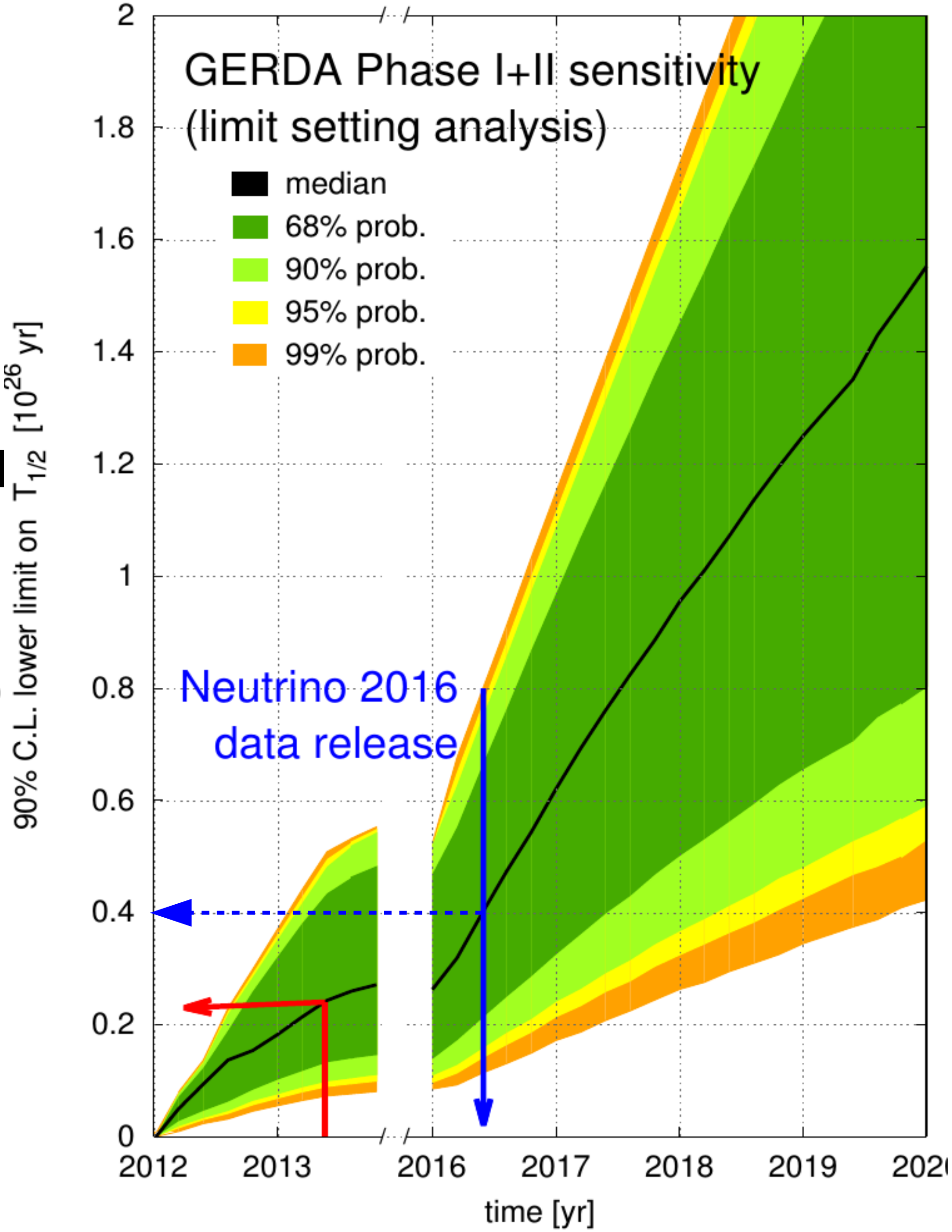


Bonus Slides

Comparison to other Experiments

		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/t yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	m_{ee} limit [meV]
Gerda II	Ge	35/27	3	5	15	80-190
MajoranaD	Ge	30/24	3	5	15	80-190
EXO-200	Xe	170/80	88	220	6	80-220
Kamland-Z	Xe	383/88 750/??	250	40 ?	20	44-120
Cuore	Te	600/206	5	300	9	50-200
NEXT-100	Xe	100/80	17	30	6	80-220
SNO+	Te	2340/260	190	60	17	36-150
nEXO	Xe	5000/4300	58	5	600	8-22

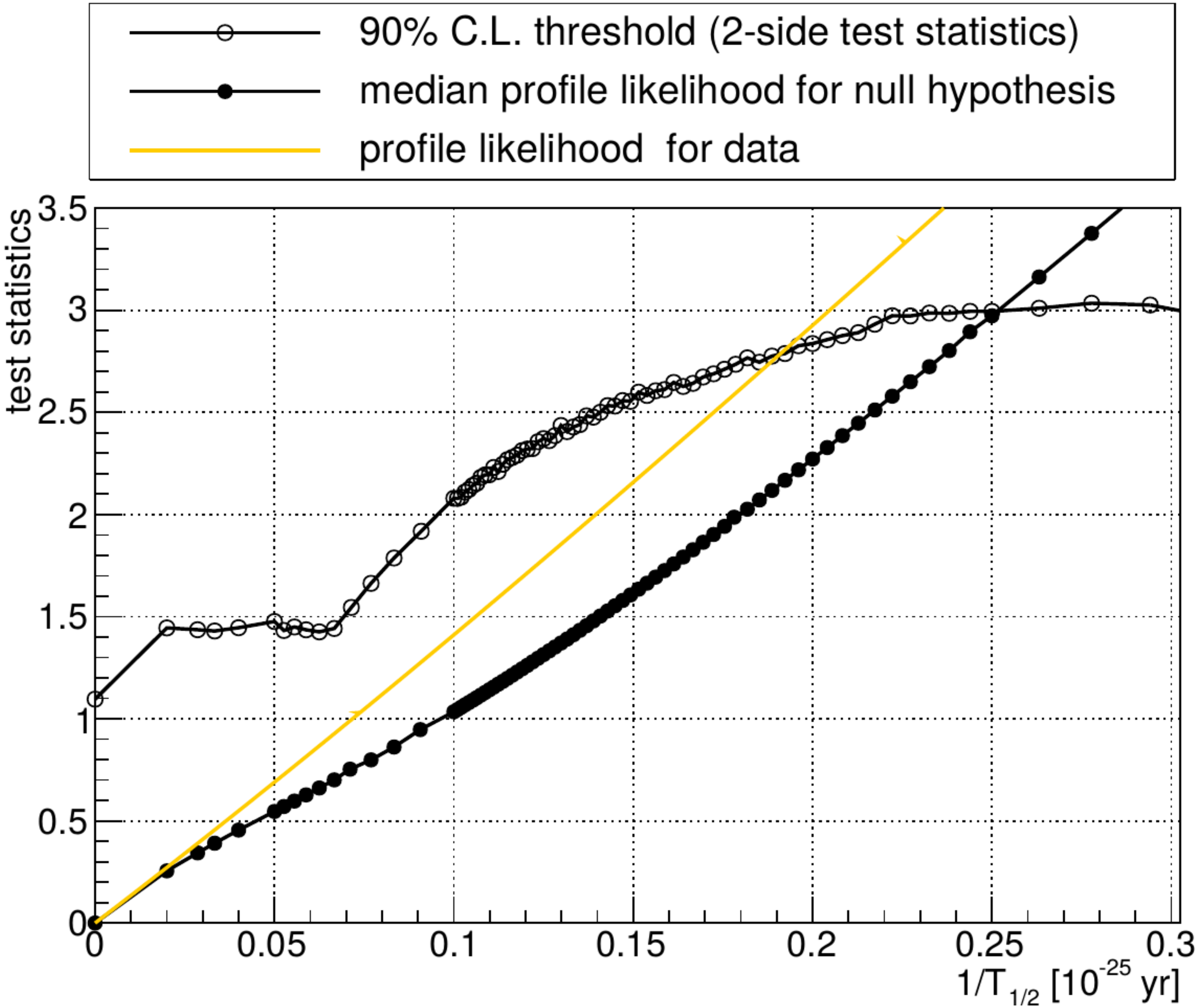
table from B. Schwingenheuer

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

[&] kg of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

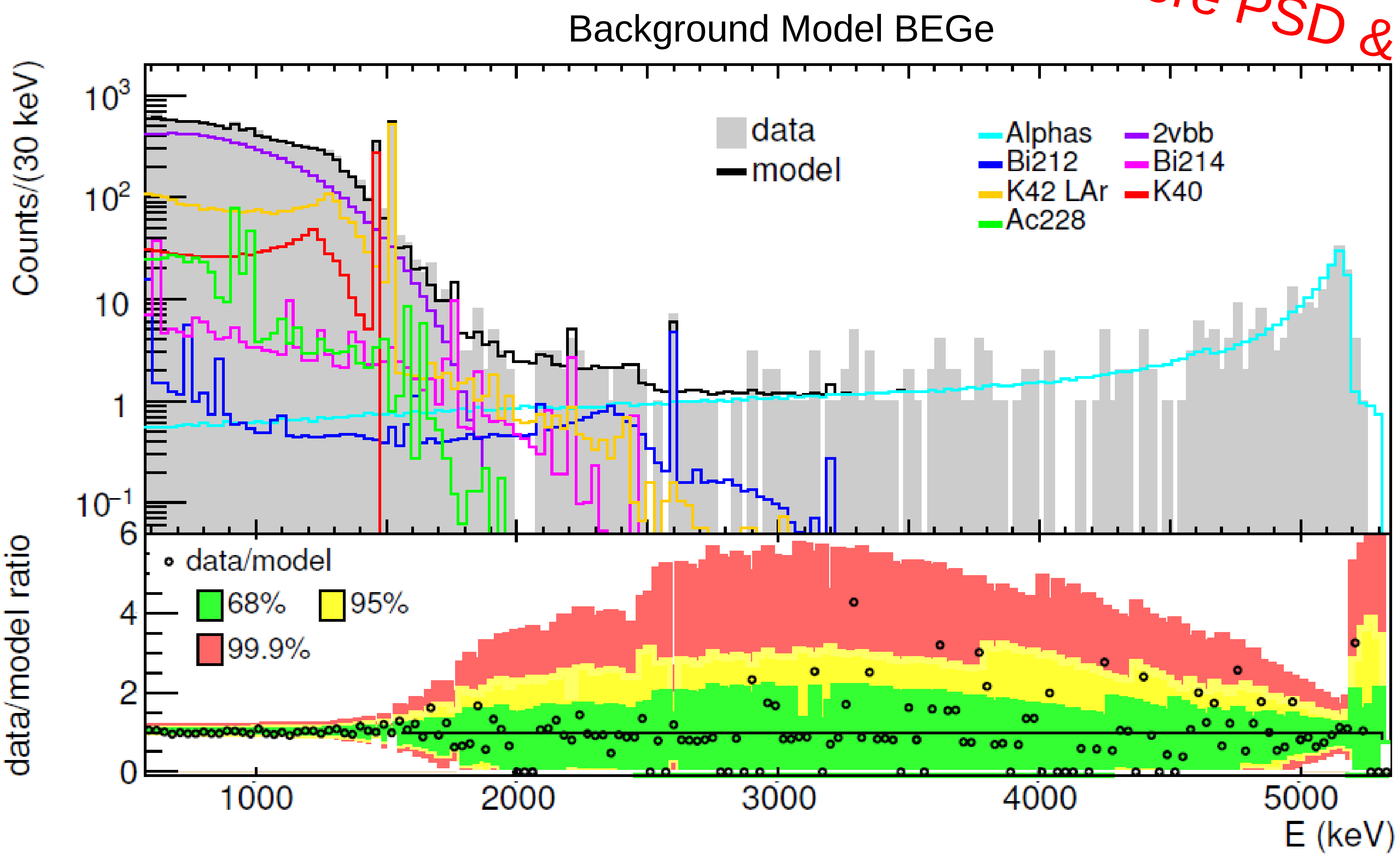
Note: values are design numbers except for EXO-200, Kamland-Zen and GERDA

Profile Likelihood



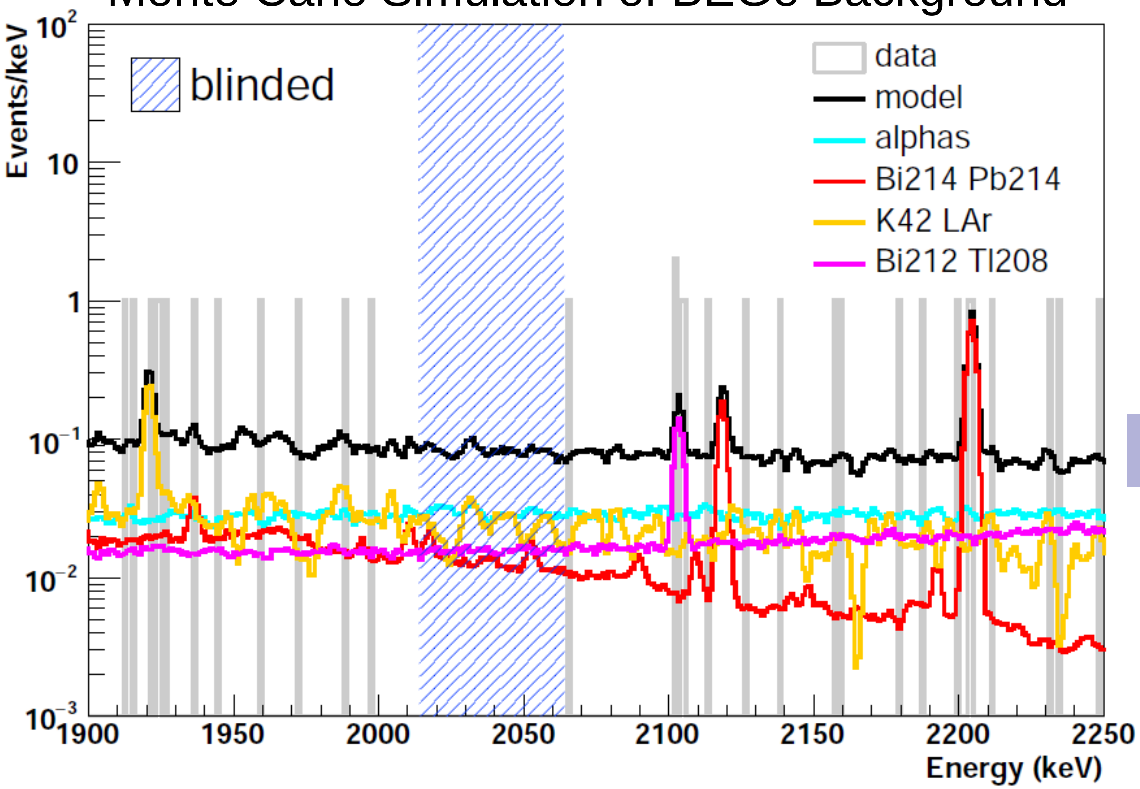
Background Model

Preliminary results
before PSD & LAr veto



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

Monte Carlo Simulation of BEGe Background



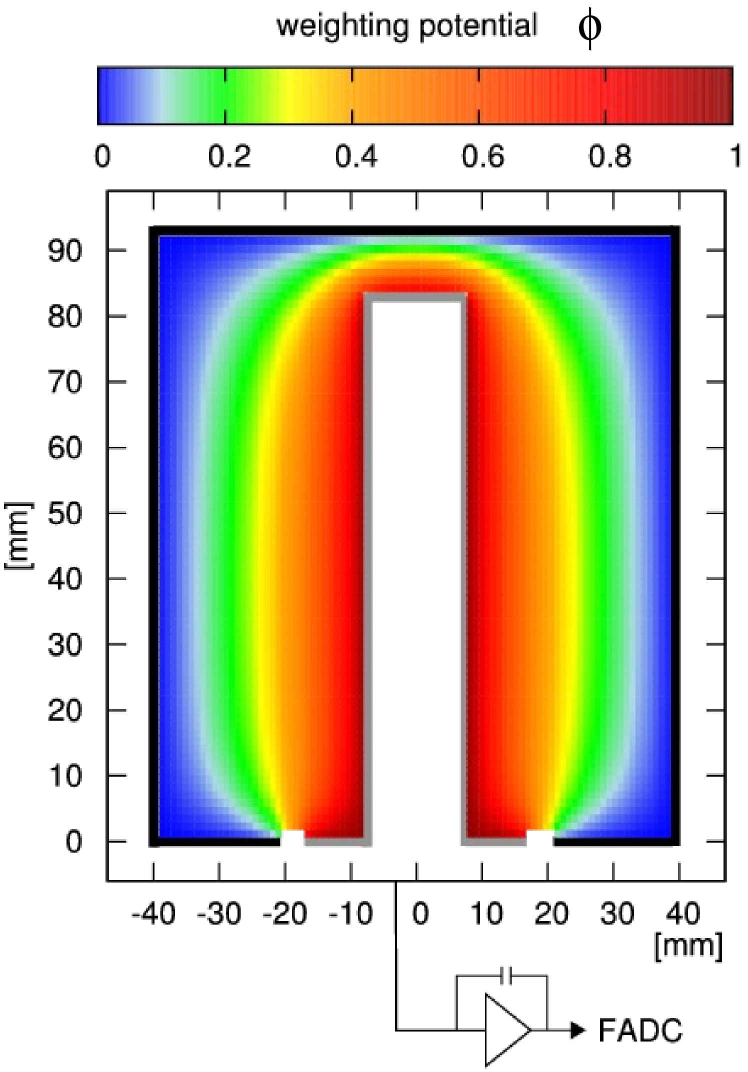
Preliminary results before PSD & LAr veto

expect flat background in ROI

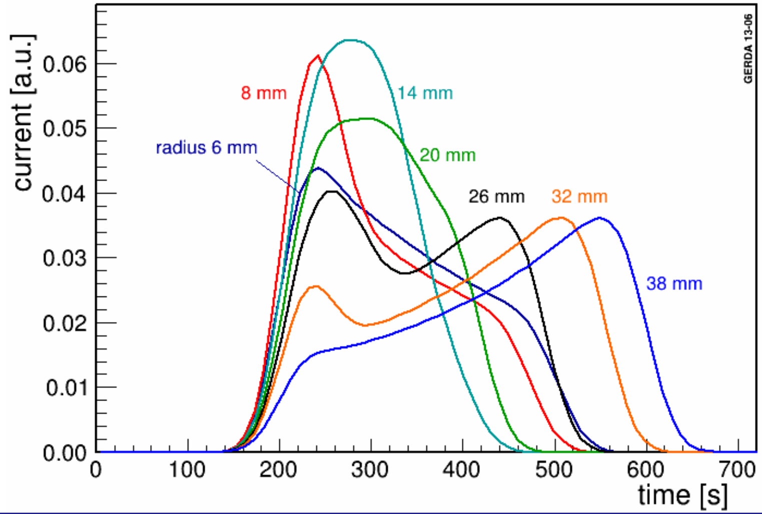
	^{enr}BEGe	^{enr}Coax
α	~ 1/3	~ 1/3
^{214}Bi and ^{208}Tl	~ 1/3	~ 1/3
^{42}K LAr	~ 1/3	~ 1/3
BI counts/(keV kg yr)	0.014	0.015

PSD with Coaxial HPGe

more detail in Eur.Phys.J C73 (2013) 2583



current signal = q · v · Δ ϕ
q: charge, v: velocity

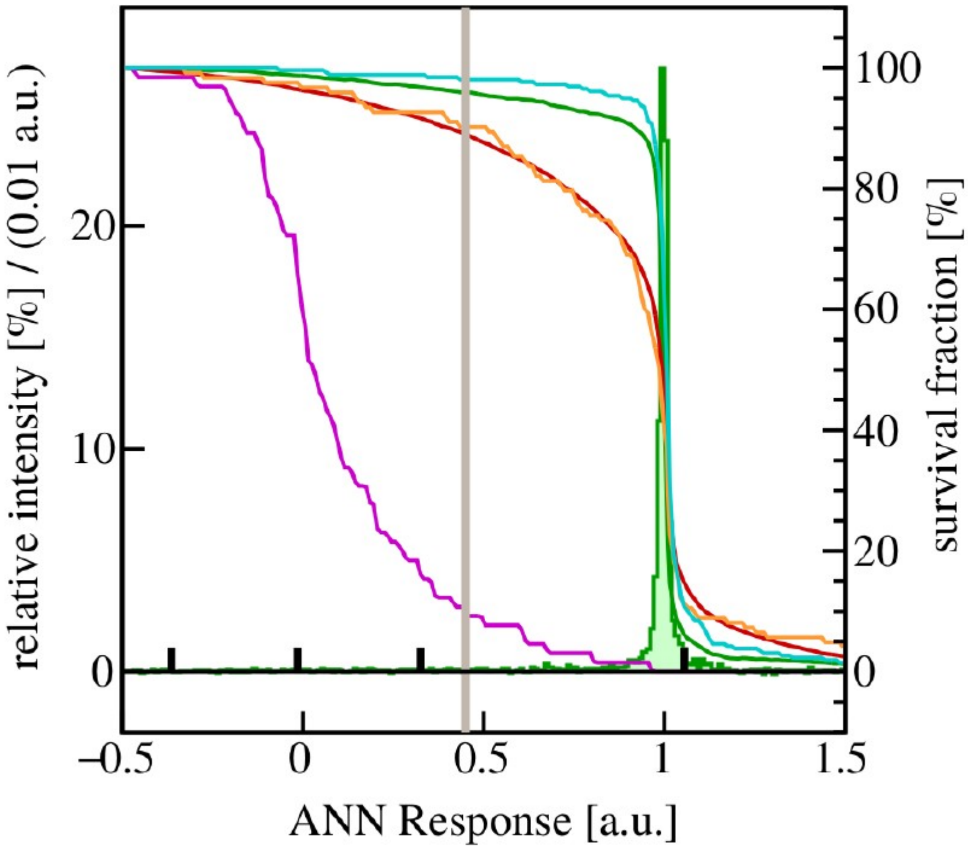


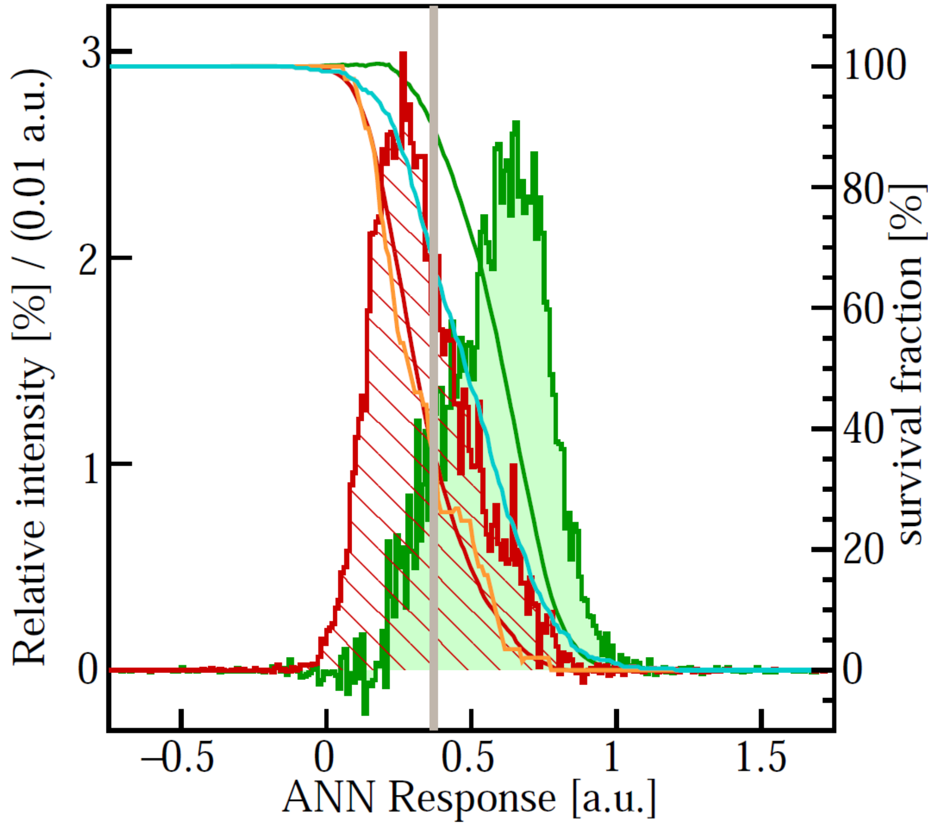
- To identify signal like events artificial neural network algorithm TMlpANN from TMVA is used
- Input variables: times when charge pulse reach 1%, 3%, … , 99% of maximum amplitude
- DEP events of at 1503 keV serve as signal sample
- FEP events at 1621 keV as multi site event sample

45% of background events rejected at Qbb with a $0\nu\beta\beta$ efficiency of 90^{+5}_{-9} %

- $2\nu\beta\beta$ efficiency 85 ± 2 %

Coax PSD





— $2\nu\beta\beta$ [1000 keV,1300 keV]

— α [3500 keV,4500 keV]

□ ^{208}Tl DEP
— ^{212}Bi FEP
— ^{42}K FEP

□ ^{208}Tl DEP

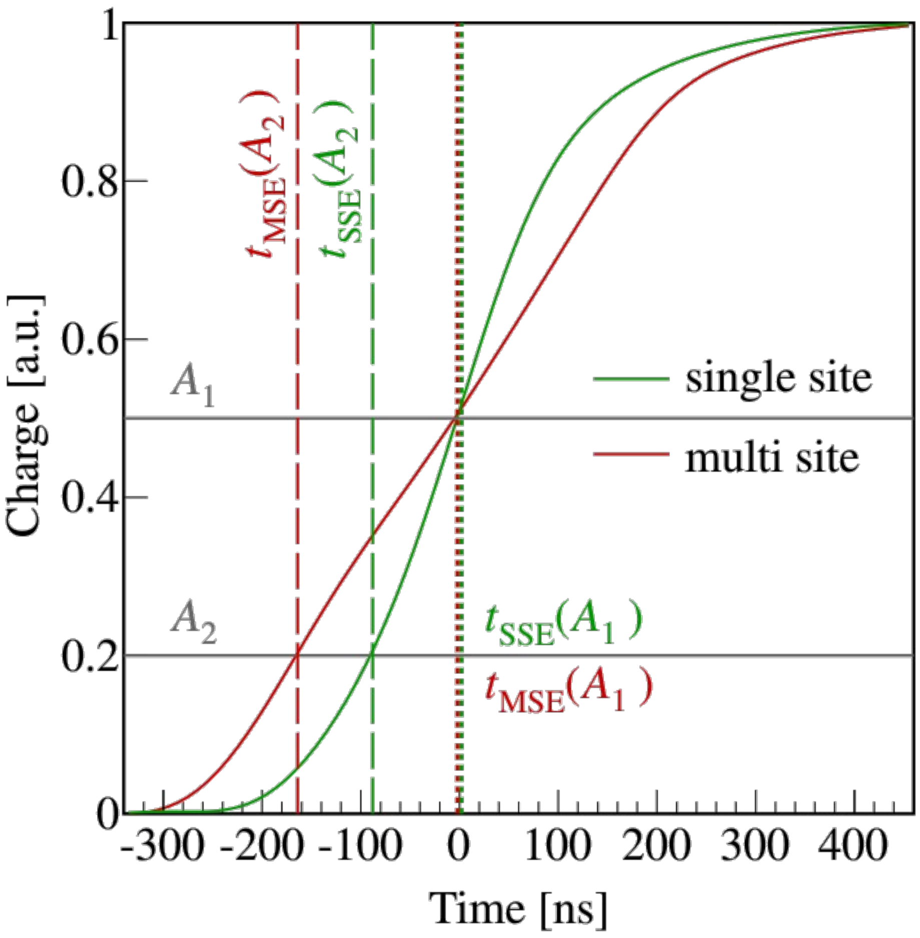
□ ^{208}Tl SEP

Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)



A/E analysis by A. Kirsch

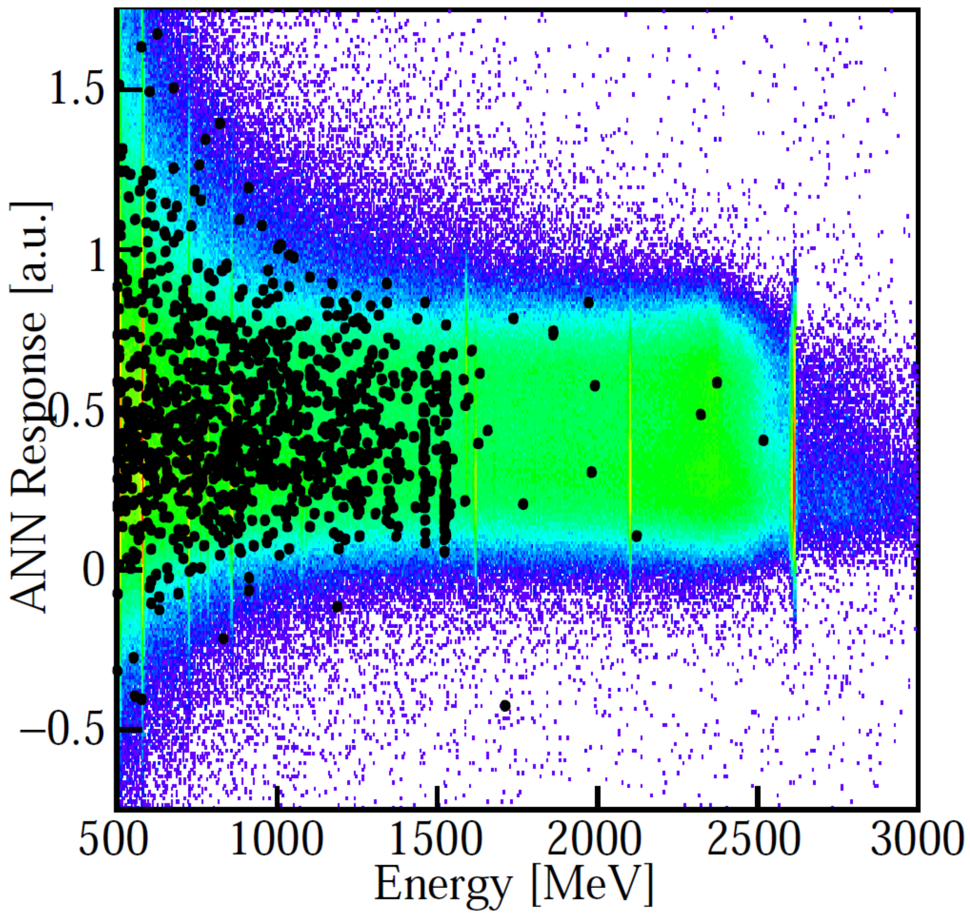
Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)

- MSE/ SSE discrimination:
  - SSE sample: DEP of ^{208}Tl peak at 1593 keV
  - MSE sample: FEP of ^{212}Bi at 1621 keV



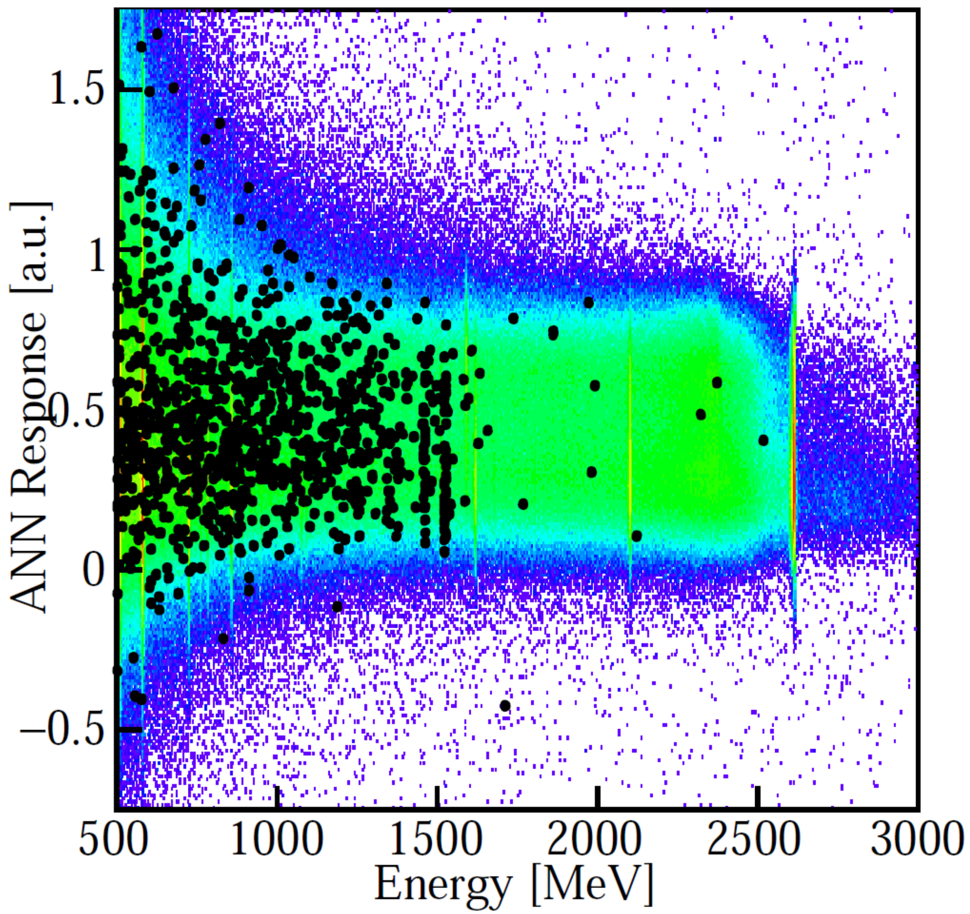
Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)

- MSE/ SSE discrimination:
  - cut set to 90 % acceptance of DEP events
  - preliminary signal efficiency 80 ± 9 %



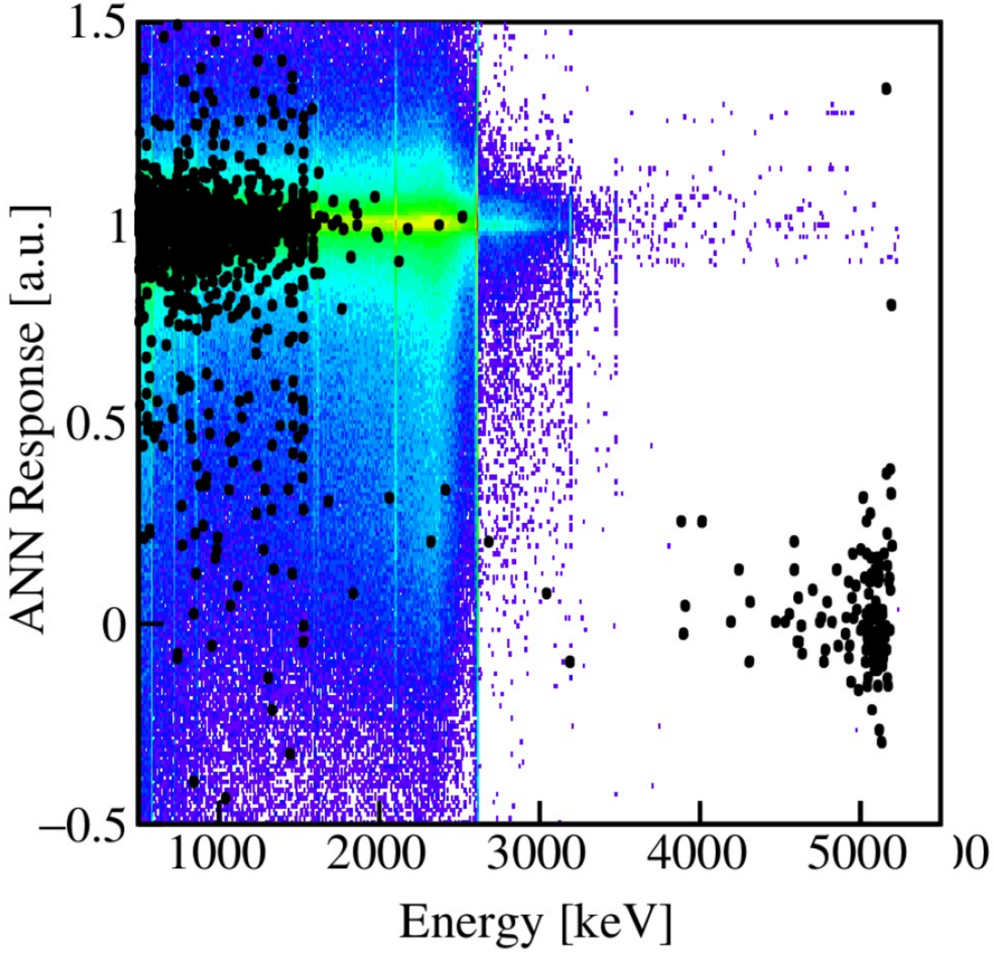
Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)

- MSE/ SSE discrimination:
  - cut set to 90 % acceptance of DEP events
  - preliminary signal efficiency 80 ± 9 %
- α/ SSE discrimination :
  - SSE sample: phy events in 1.-1.3 MeV
  - α sample: phy events 3.5 – 5.5 MeV



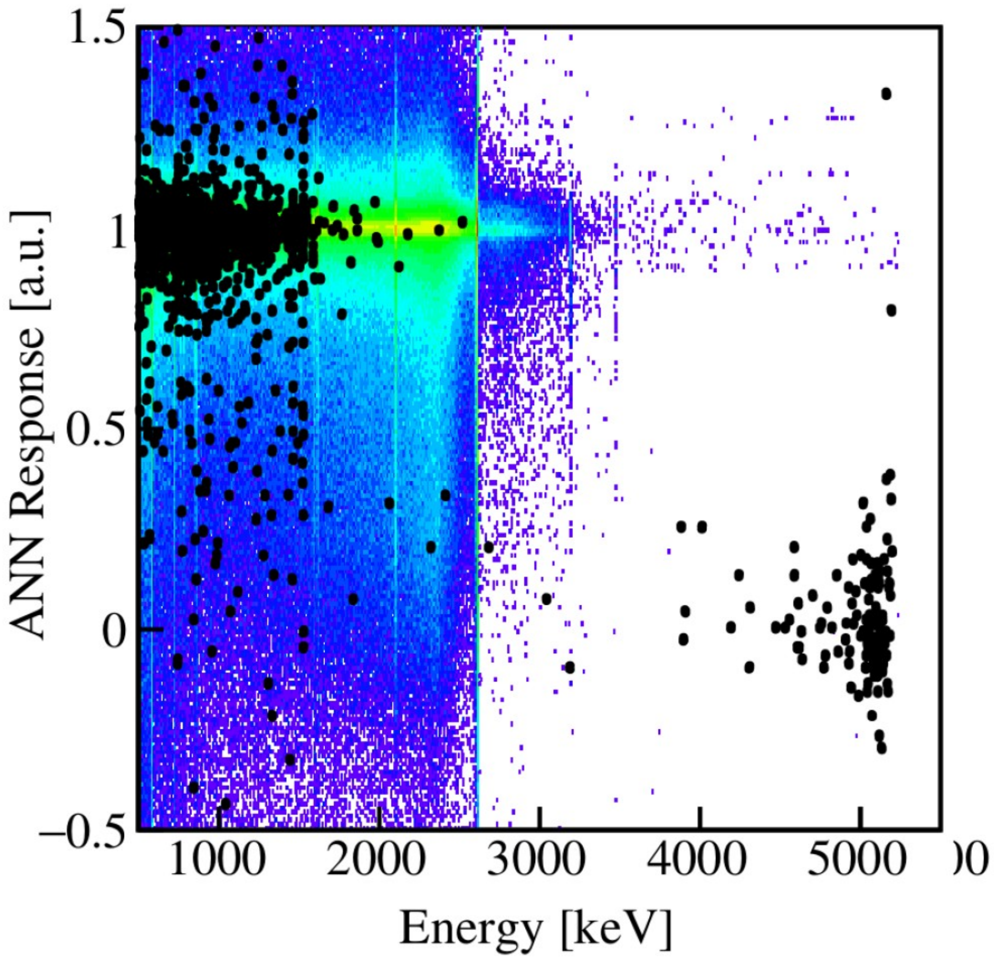
Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)

- MSE/ SSE discrimination:
  - cut set to 90 % acceptance of DEP events
  - preliminary signal efficiency 80 ± 9 %
- α/ SSE discrimination :
  - cut set to 10 % acceptance α events
  - signal efficiency 96 ± 1 %

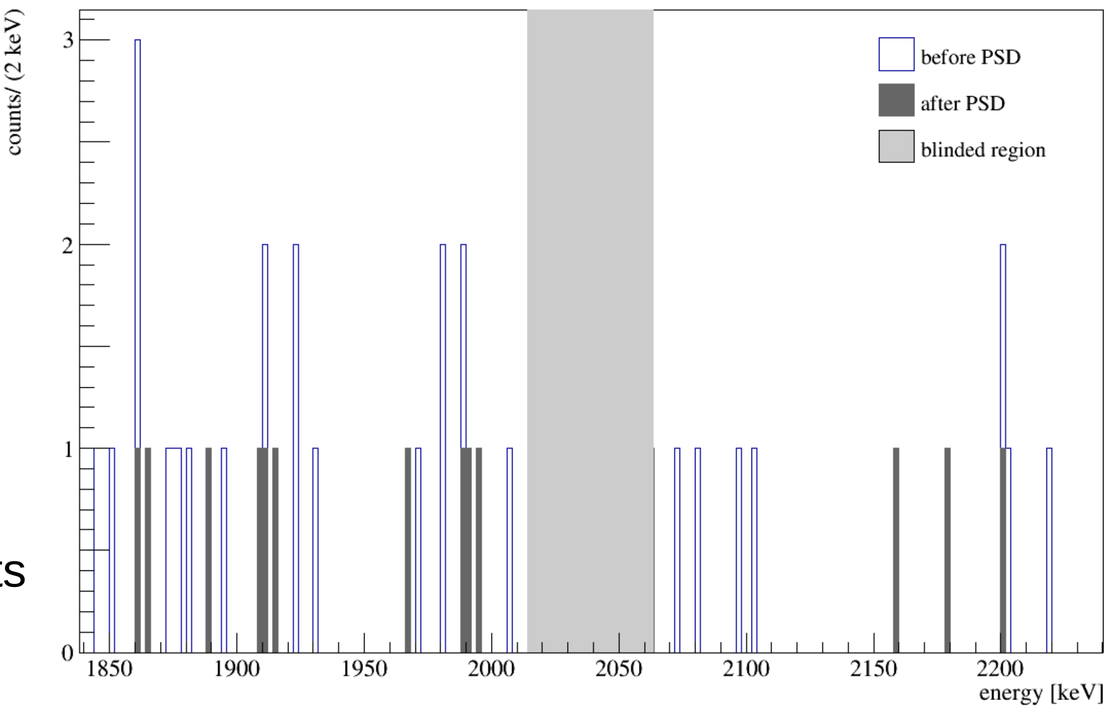


Coax PSD

- TMlpAnn Algorithm:

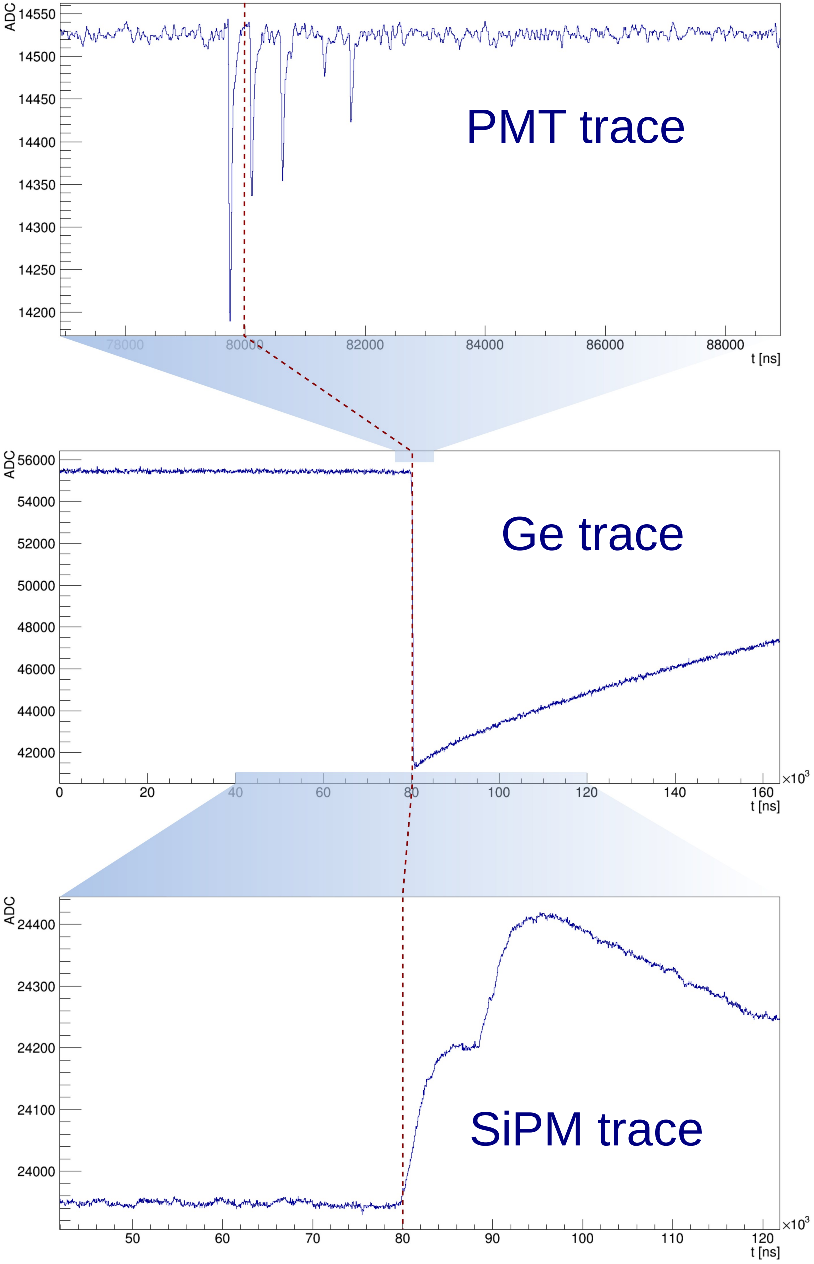
  50 input variables with

  t(A=0.01), t(A=0.02), …, t(A=0.99)
- MSE/ SSE discrimination:
  - cut set to 90 % acceptance of DEP events
  - preliminary signal efficiency 80 ± 9 %
- α/ SSE discrimination :
  - cut set to 10 % acceptance α events
  - signal efficiency 96 ± 1 %
- total signal efficiency 76 ± 10 %
- 65 % of background in ROI rejected

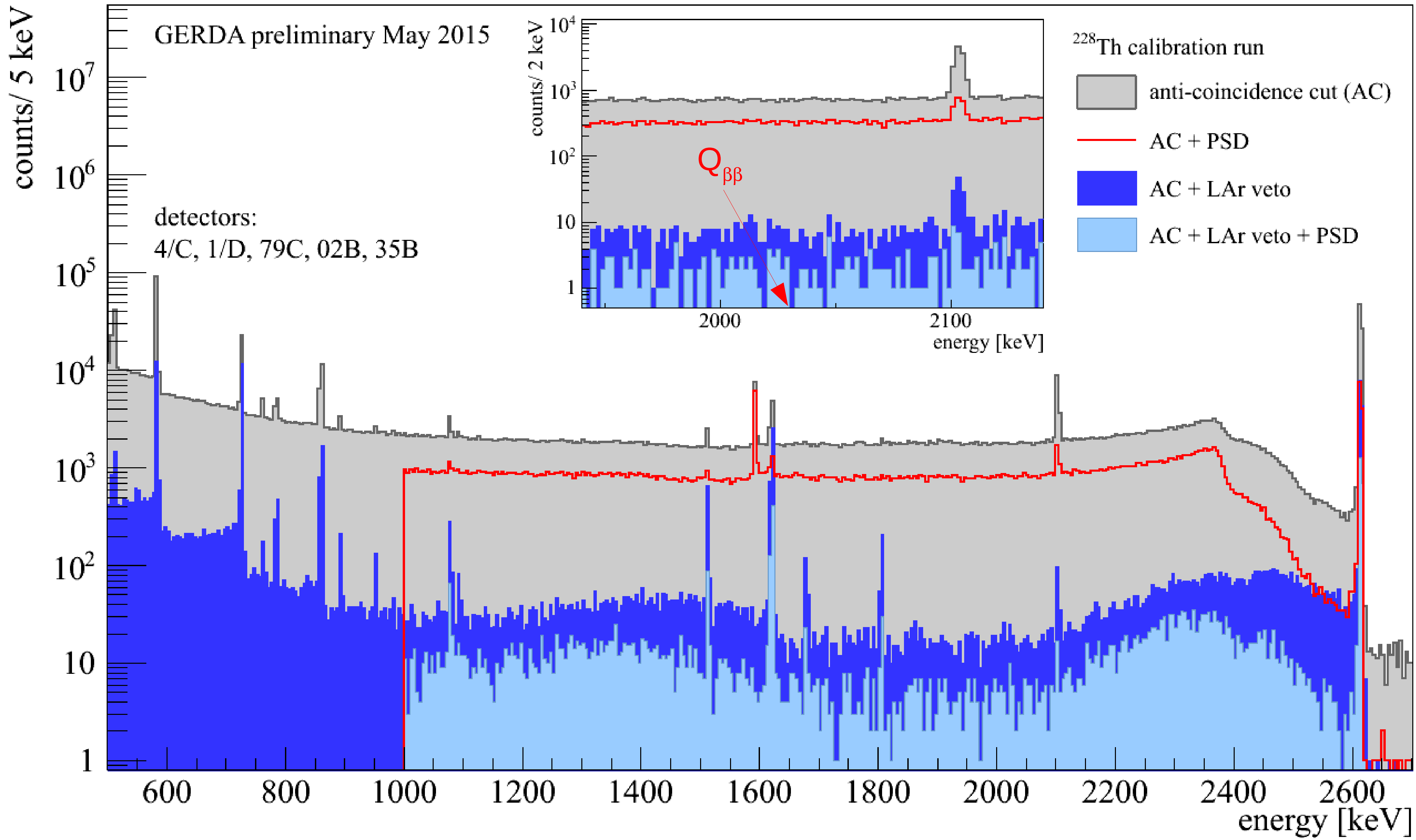


LAr Veto

- events in coincidence with LAr veto
- fraction of random coincidences 2.3%



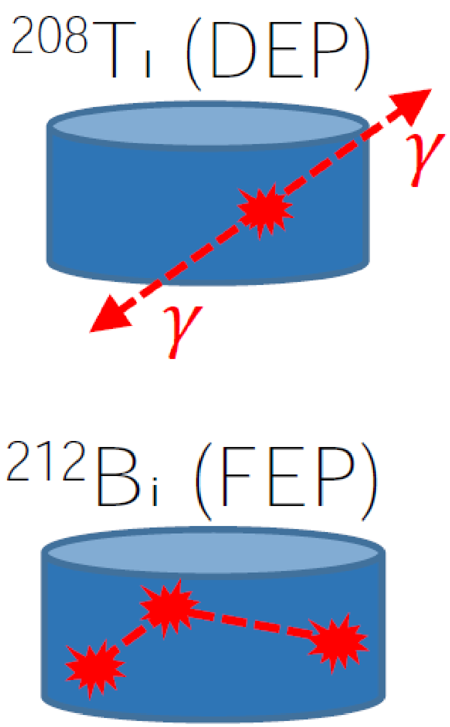
^{228}Th Suppression

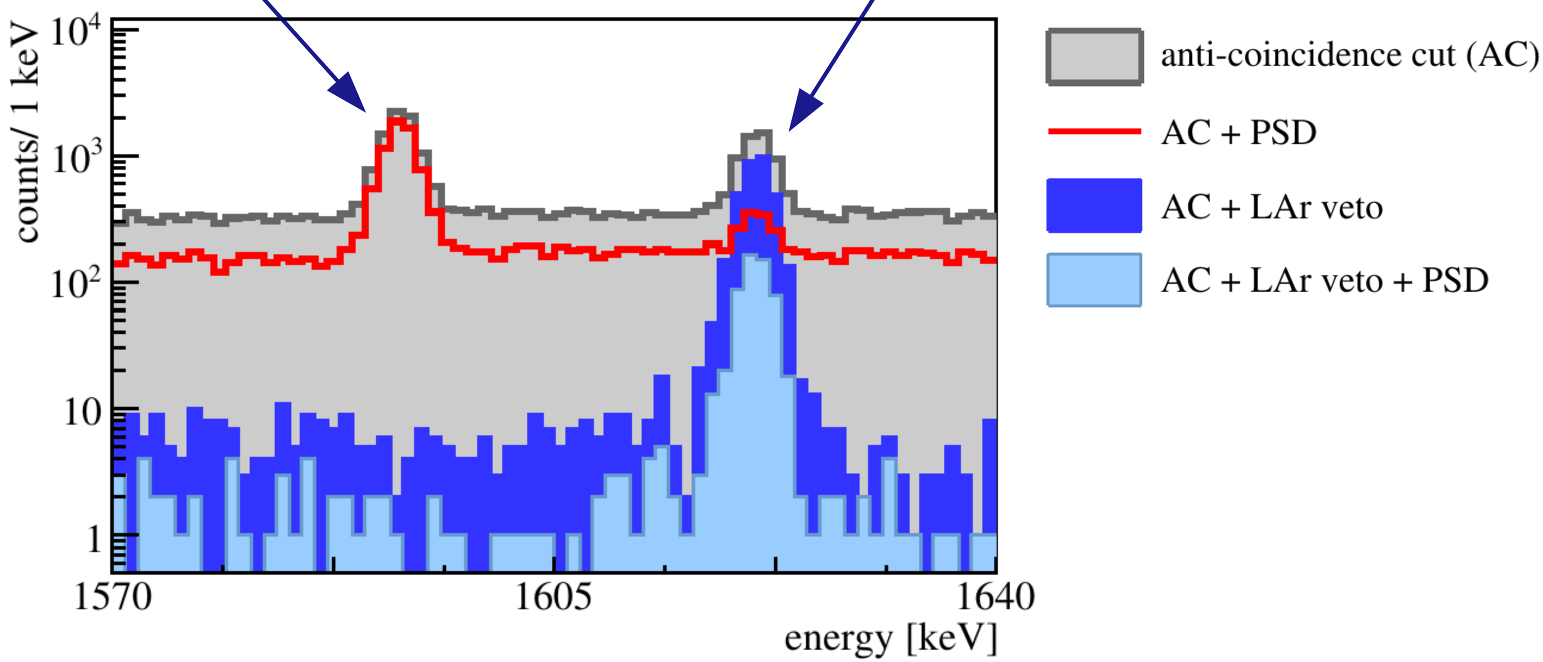


^{228}Th Suppression

DEP events of the ^{208}Tl 2.6 MeV line
= signal-like events

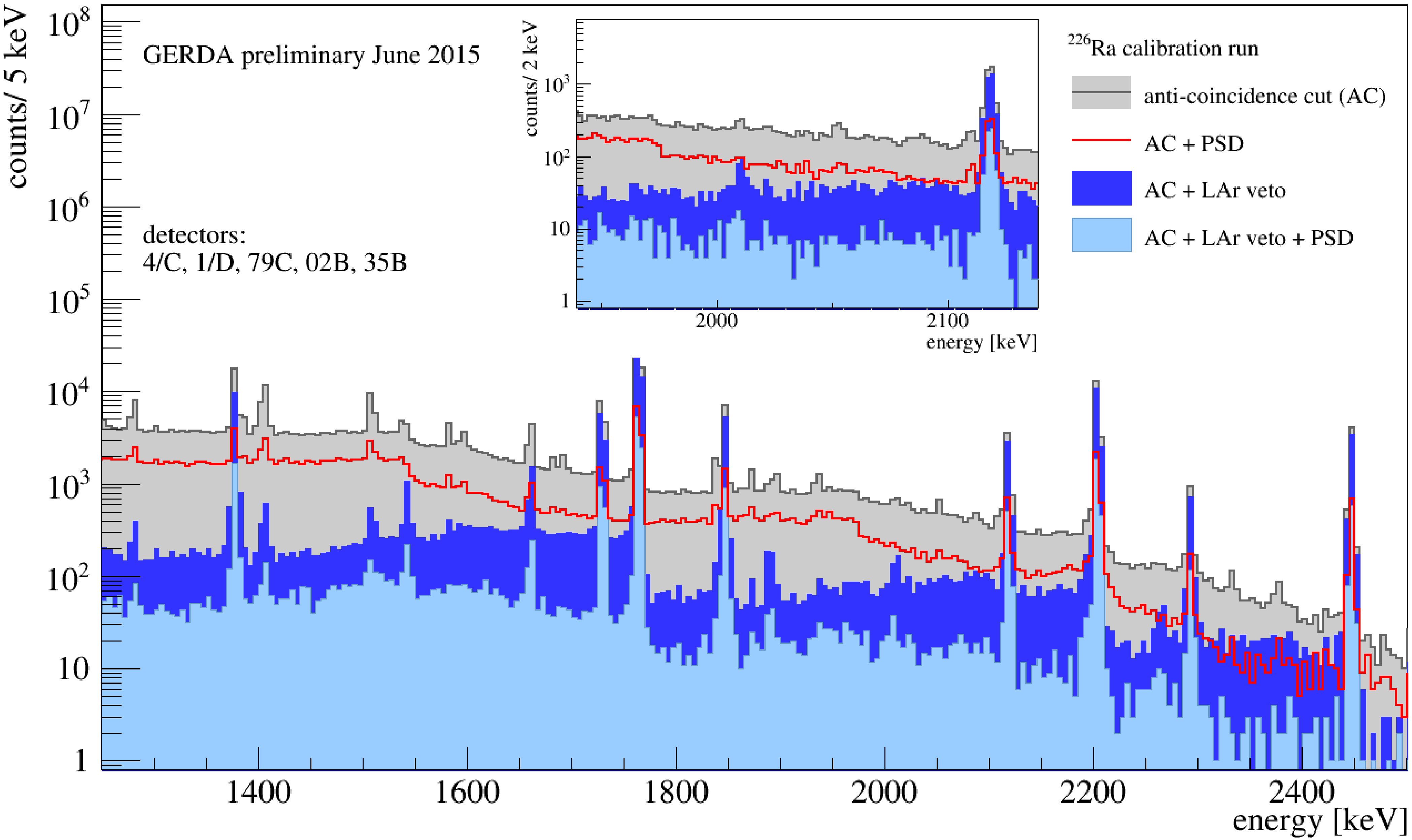
FEP events of the ^{212}Bi 1.6 MeV line
= background events





In case of discovery PSD will show if γ or 0νββ line

^{226}Ra Suppression



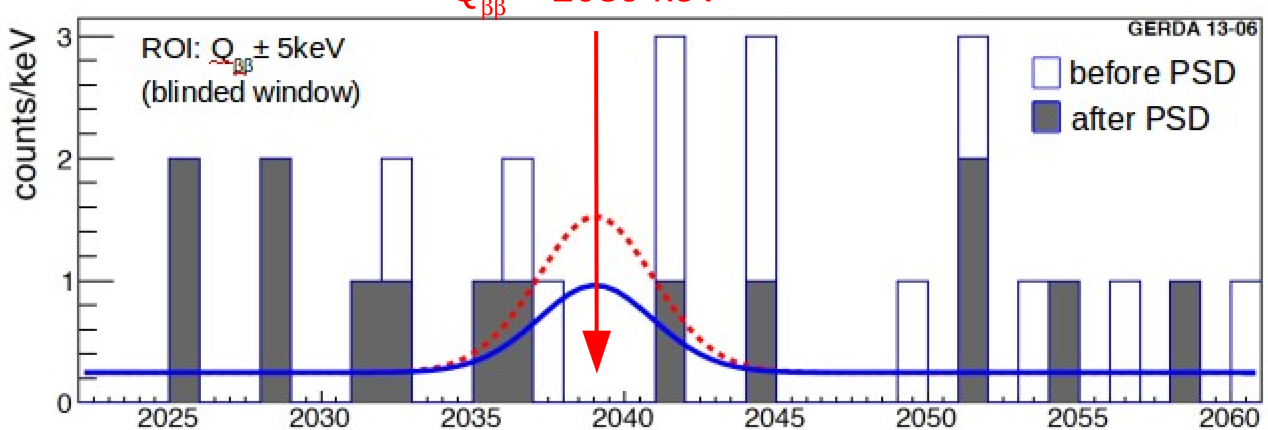
Results from GERDA Phase I

- 21.6 kg · y exposure
- blind analysis: events in ROI not available for analysis
- background index (BI) after pulse shape discrimination

$$BI = 1.0(1) \cdot 10^{-2} \frac{\text{counts}}{\text{keV kg yr}}$$

- 10 times better BI than previous experiments

$Q_{\beta\beta}$ = 2039 keV



number of events in $Q_{\beta\beta} \pm 2\sigma_E$ after cuts (gray):

- 2.0 ± 0.3 expected from background
- 3 observed

no signal observed at $Q_{\beta\beta}$

profile likelihood: best fit for $N_{0\nu\beta\beta}$ = 0

→ limit on the half-life

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\ \text{yr}$$

(90% C.L.)

→ **claim rejected with 99% probability**

GERDA: 90% lower limit ($T^{0\nu}_{1/2}$) [Phys. Rev. Lett. 111 (2013) 122503]

Claim: $T^{0\nu}_{1/2} = 1.19 \times 10^{25}$ yr [Phys. Lett. B 586 198(2004)]