GERDA Phase II: First Results

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for the GERDA collaboration

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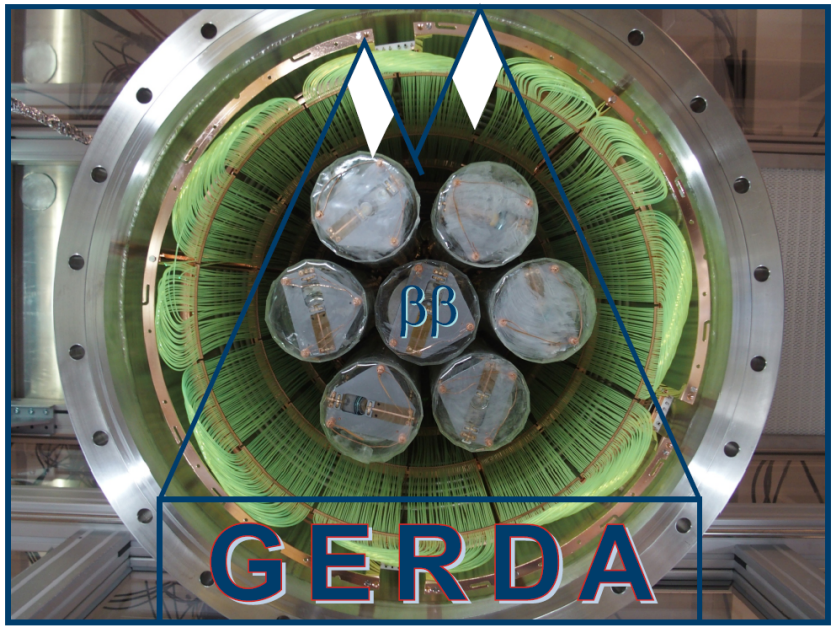
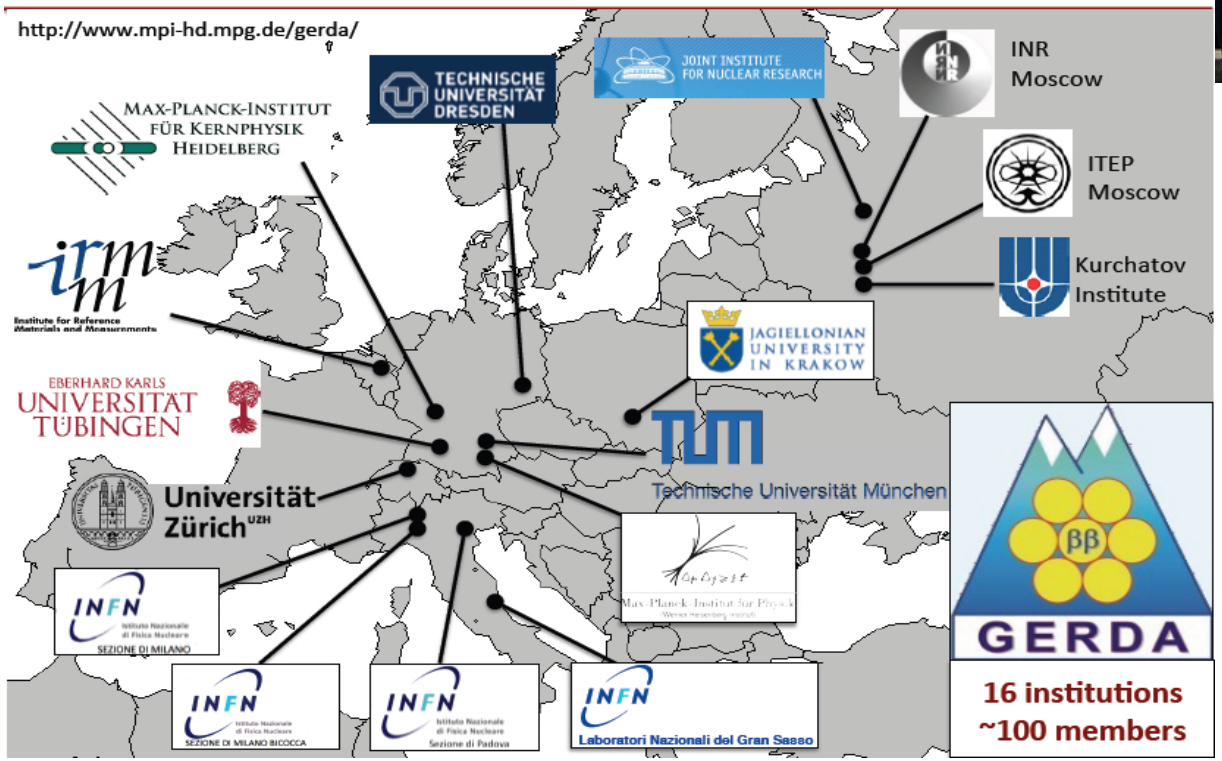
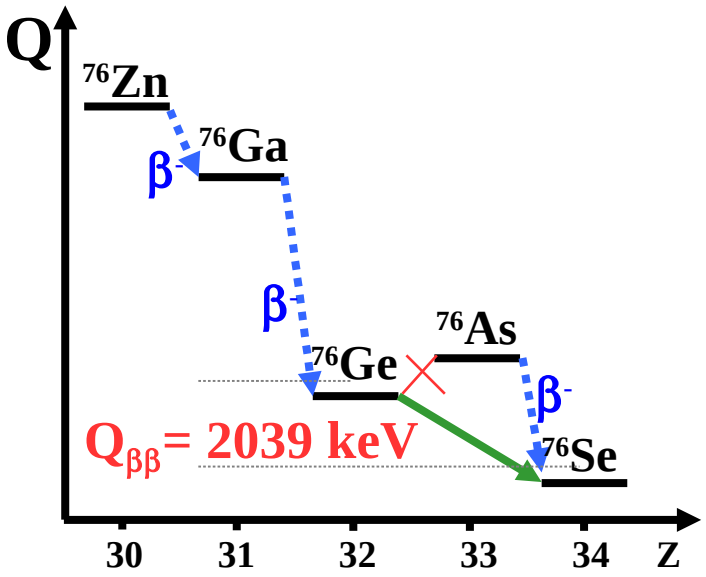
MPIK Heidelberg, 29.06.2016



The GERDA Collaboration: searching for neutrinoless double beta decay



Double Beta Decay



Double beta decay (2νββ)

- 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 2νββ decay of ^{76}Ge measured by GERDA (most recent and precise measurement):

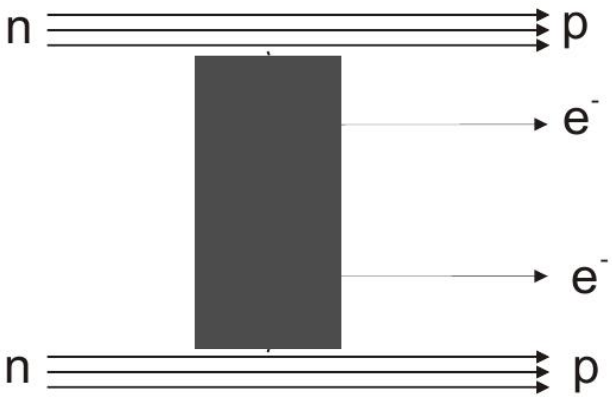
$$T^{2\nu}_{1/2} = (1.926 \pm 0.095) \times 10^{21}\,\mathrm{yr}$$

arXiv:1501.02345v1

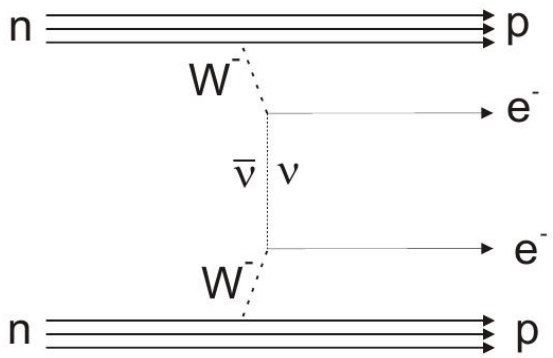
Neutrinoless double beta decay (0νββ)

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

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



Effective Majorana Neutrino Mass



Assuming light Majorana neutrino exchange

- $\left(T^{0\nu}_{1/2}\right)^{-1} \propto \left|m_{ee}\right|^2$

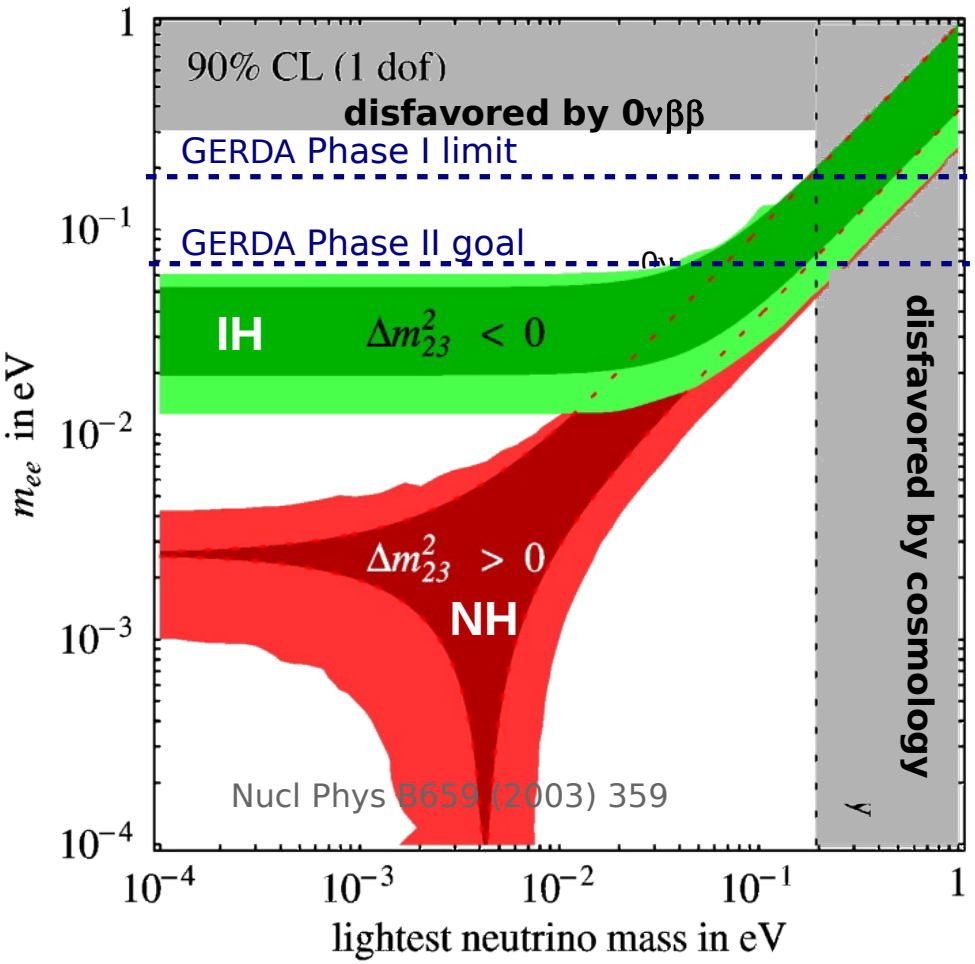
observable

- effective Majorana mass:

$$\left|m_{ee}\right| \equiv \left|\sum_i U_{ei}^2 m_i\right|$$

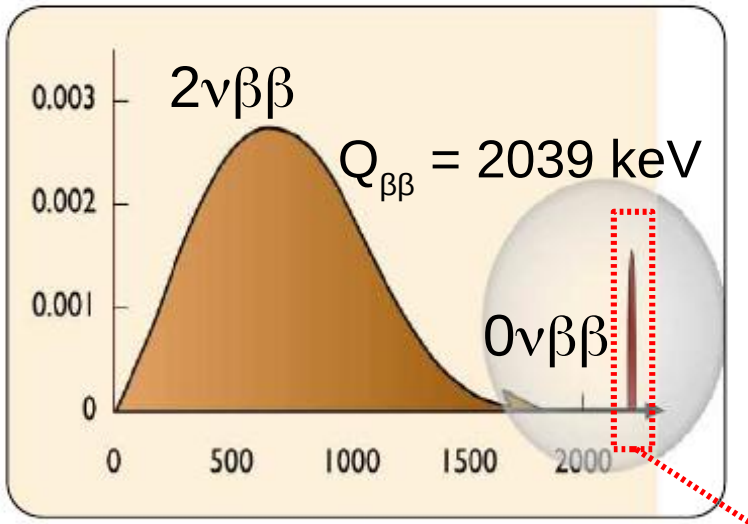
Access to

- absolute neutrino mass scale
- mass hierarchy



Signature & Experimental Challenges

- Measure sum energy of electrons



If 0νββ allowed, signal rate orders of magnitude smaller than rate of 2νββ decay

- half-life of 2νββ decay of ^{76}Ge measured by GERDA :

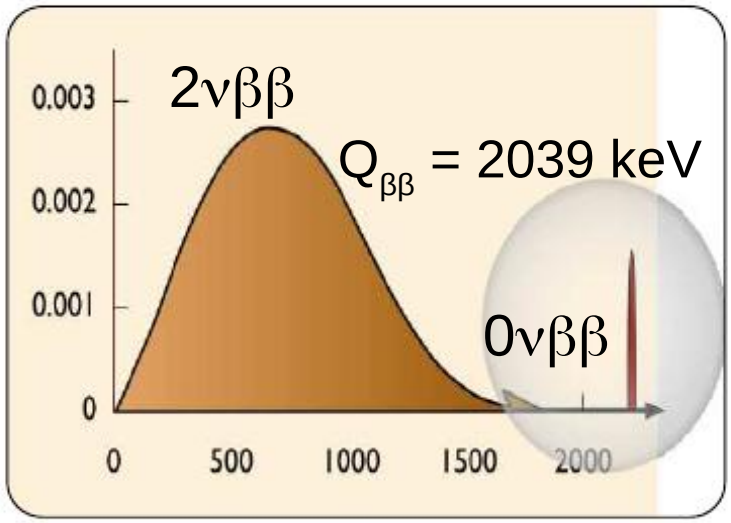
$$T^{2\nu}_{1/2} = (1.926 \pm 0.095) \times 10^{21}\ \text{yr}$$

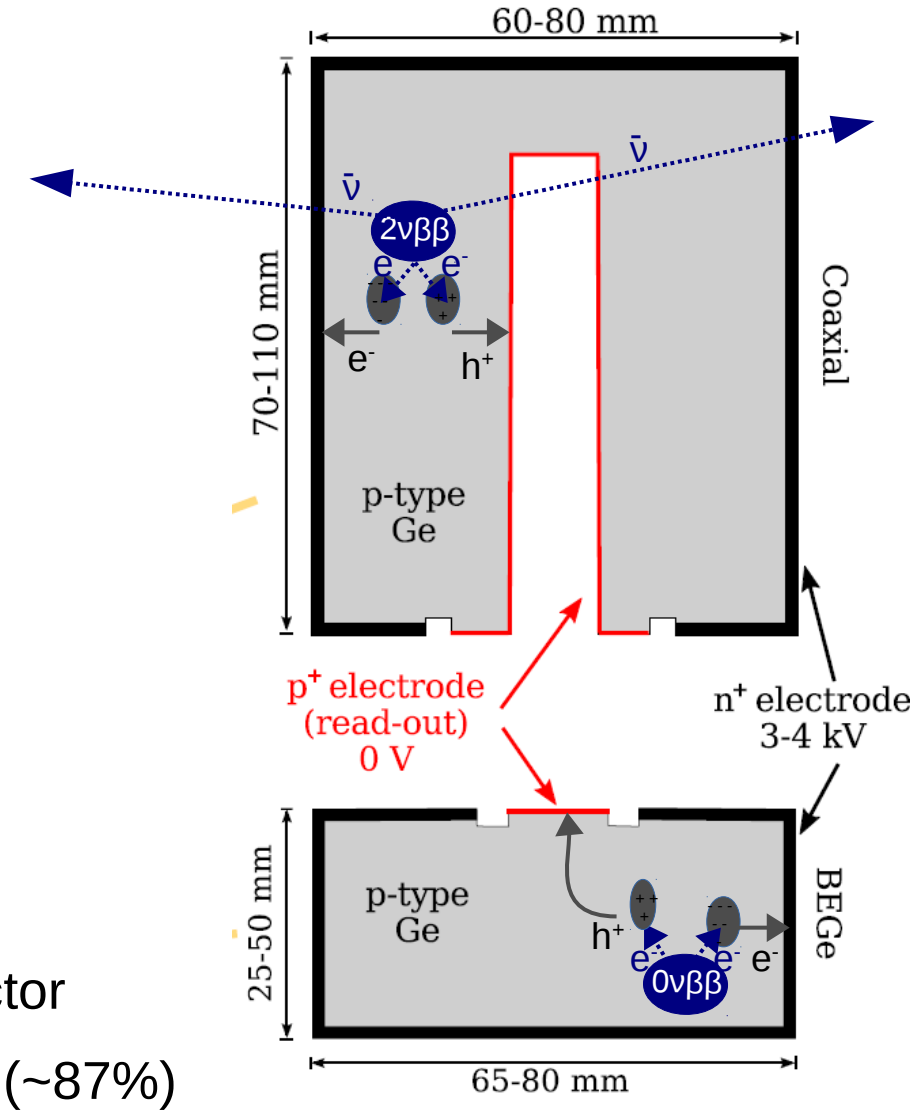
arXiv:1501.02345v1

Need to achieve
- high detection efficiency
- very low background in ROI

Germanium Detectors

- Measure sum energy of electrons

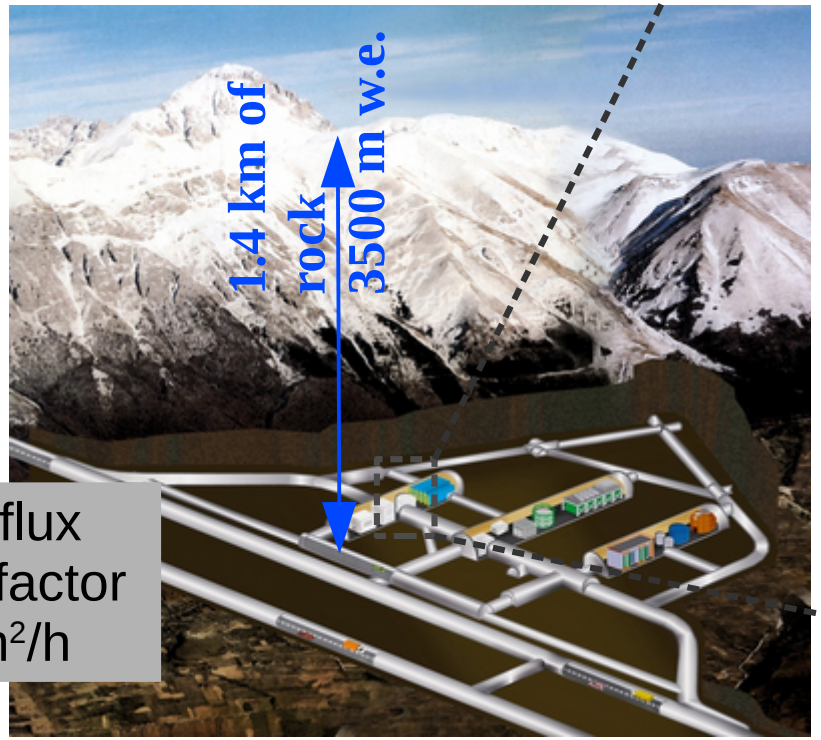




High Purity Germanium (HPGe) Detectors

- 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

GERDA @ LNGS



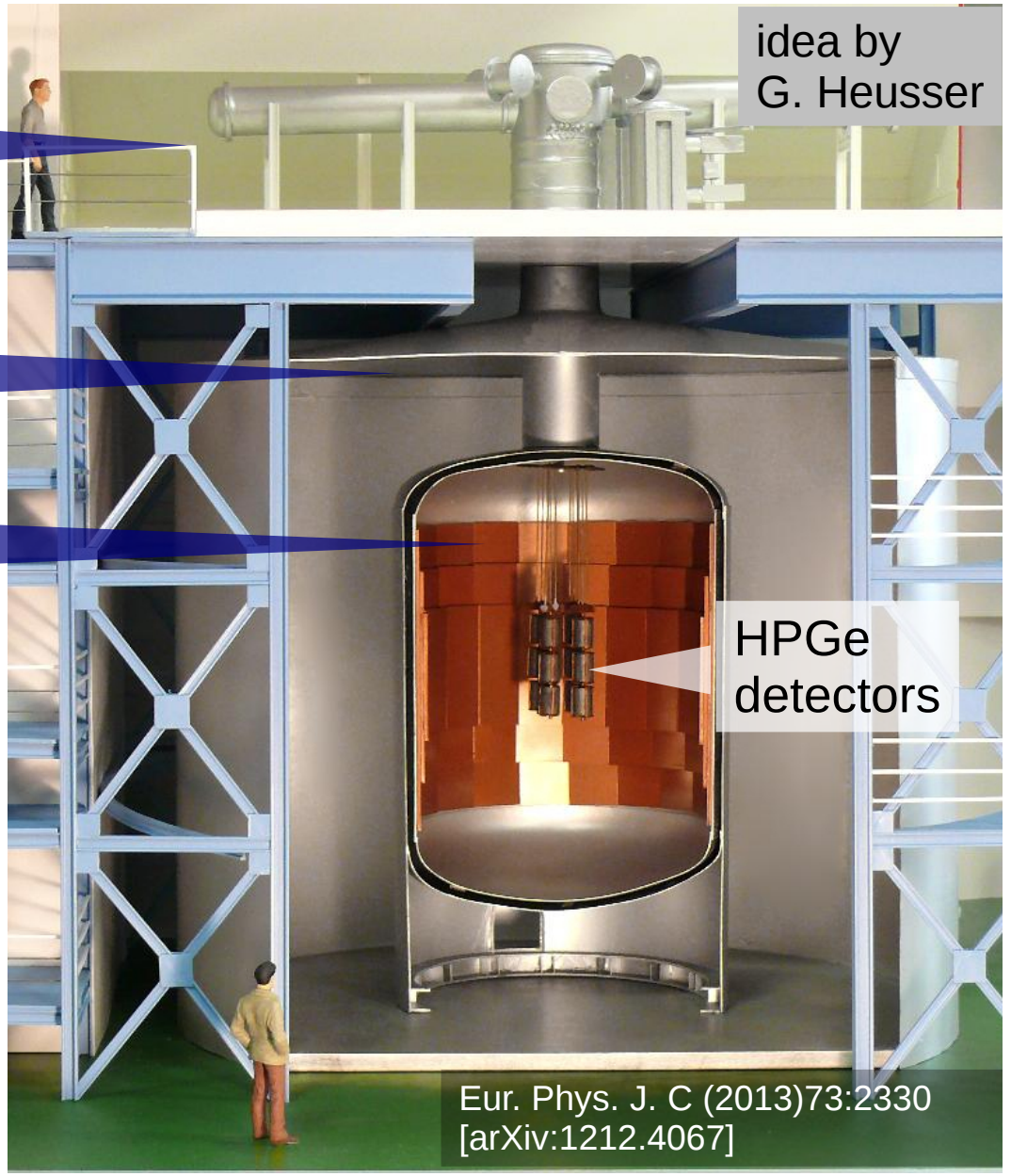
cosmic muon flux
reduced by a factor
~ 10^6 → 1 μ/m^2/h

The **Ger**manium **D**etector **A**rray

clean room with lock

590m³ pure water muon veto & neutron absorber

64m³ liquid argon (LAr) coolant & shielding



GERDA Phase I (Nov 2011- May 2013)

- 4 strings with HPGe detectors:
  - 5 HDM experiment
  - 3 IGEX experiment
  - 5 new BEGe detectors

GERDA Phase II (Dec 2015 -)

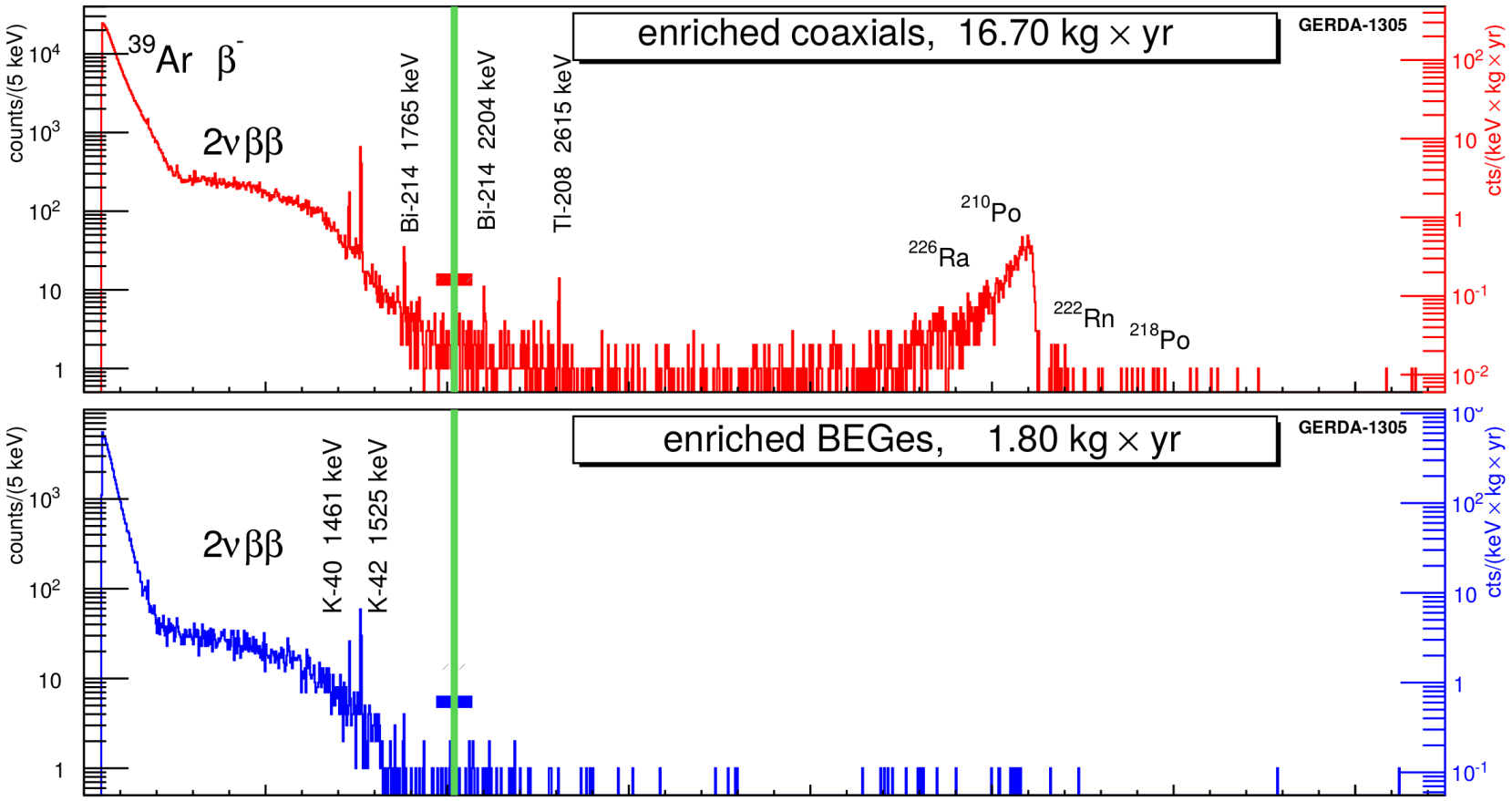
- 7 strings with HPGE detectors:
  - 30 enriched BEGe detectors
  - 7 + 3 semi-coaxial detectors
- LAr instrumentation

GERDA Phase I Background

more details in EPJ C74 (2014) 2764

GERDA Phase I reached an unprecedented signal-to-background ratio:

- 3:1 in 570-2039 keV
- 4:1 in 600-1800 keV

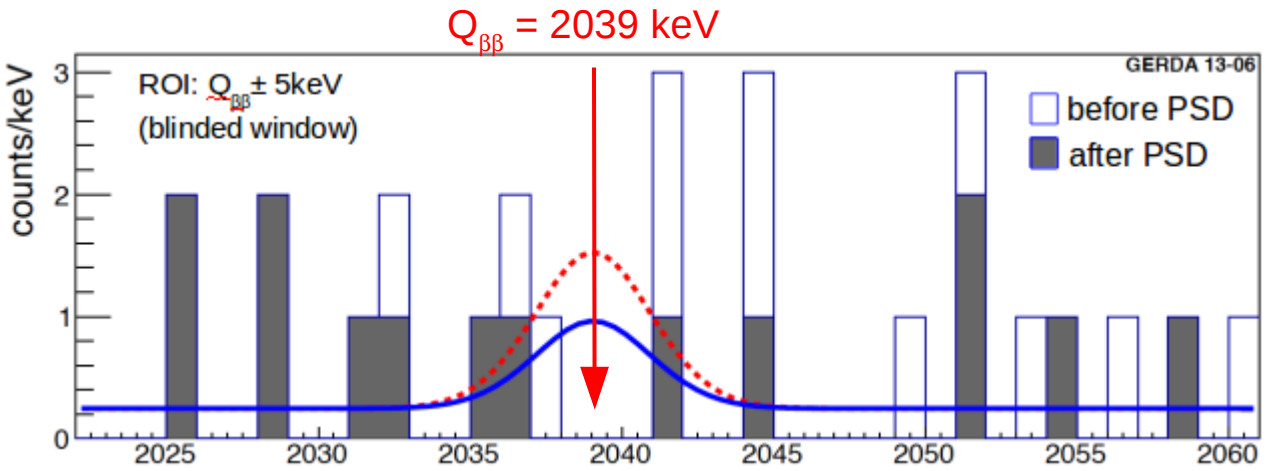


Results from GERDA Phase I

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

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

- 10 times better BI than previous experiments



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

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

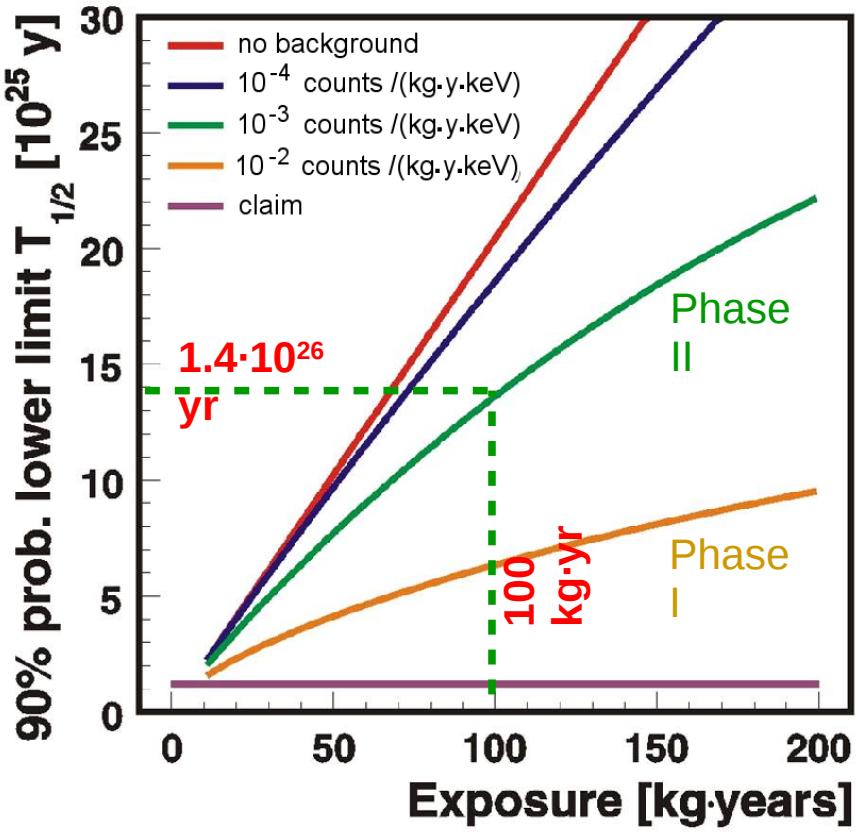
(90% C.L.)

→ 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)]

GERDA Phase II Goal



- zero background regime

$$T_{1/2}^{0\nu} \propto M \cdot t$$

- background, i.e. statistical fluctuation limited scenario

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

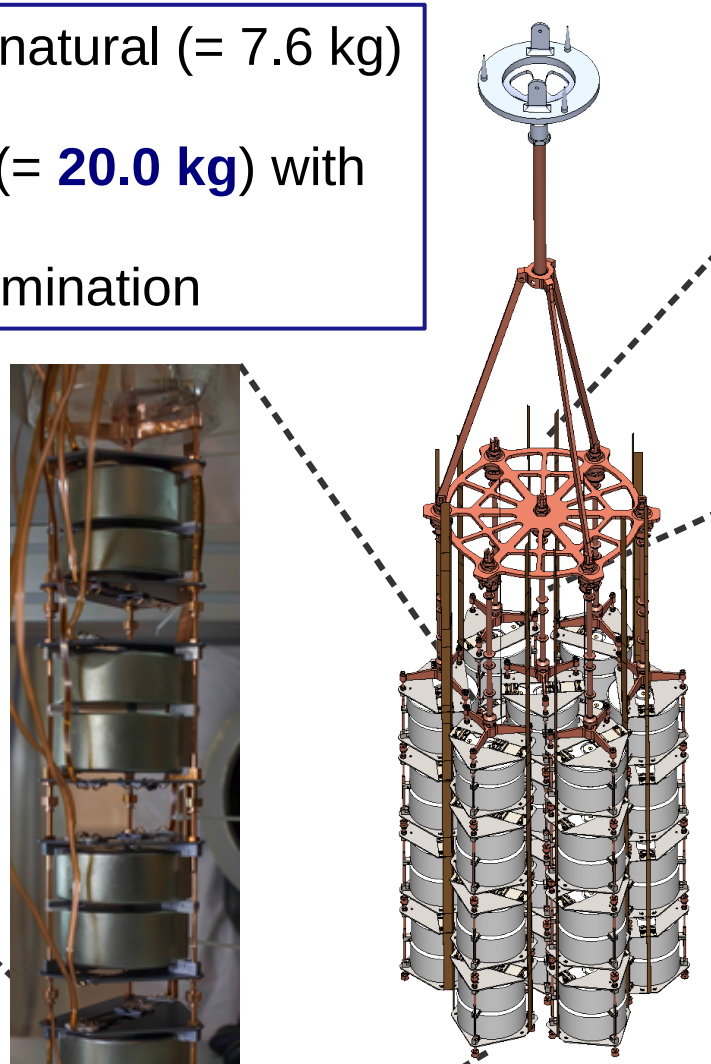
M·t: exposure [kg yr], ΔE: energy resolution,
BI: background index [counts/(keV kg yr)]

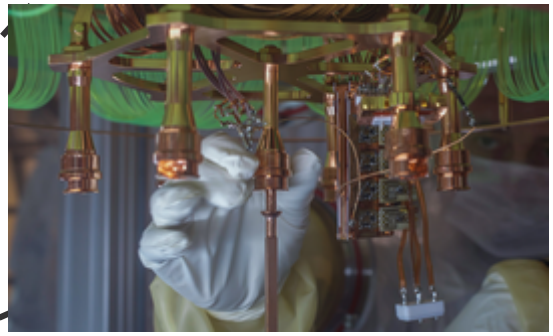
Phase II Goal: $T_{1/2}^{0\nu}$ in range of 10^{26} yr

- increase of exposure → increase detector mass
- improvements in energy resolution (but limited to given technology)
- significant **reduction of background** to re-enter background free regime
  → BI of 10^{-3} counts/(keV kg yr)

GERDA Phase II Array

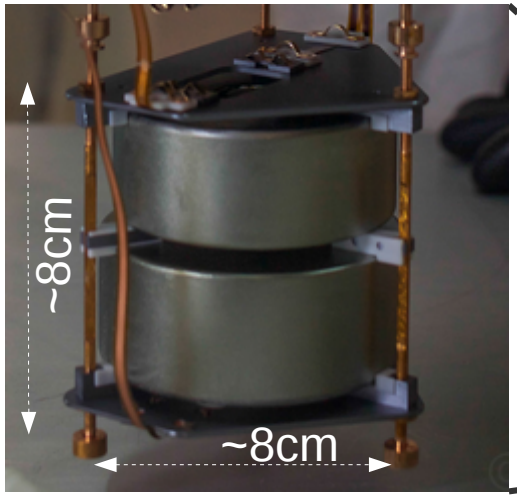
- 7 **enriched** (= **15.8 kg**) and 3 natural (= 7.6 kg) semi-coaxial HPGe detectors
- 30 **enriched** BEGe detectors (= **20.0 kg**) with
  - better energy resolution
  - enhanced pulse shape discrimination





low radioactivity electronics

new low mass holders with reduced mass and Cu → Si



material screening: J. Schreiner, et al.

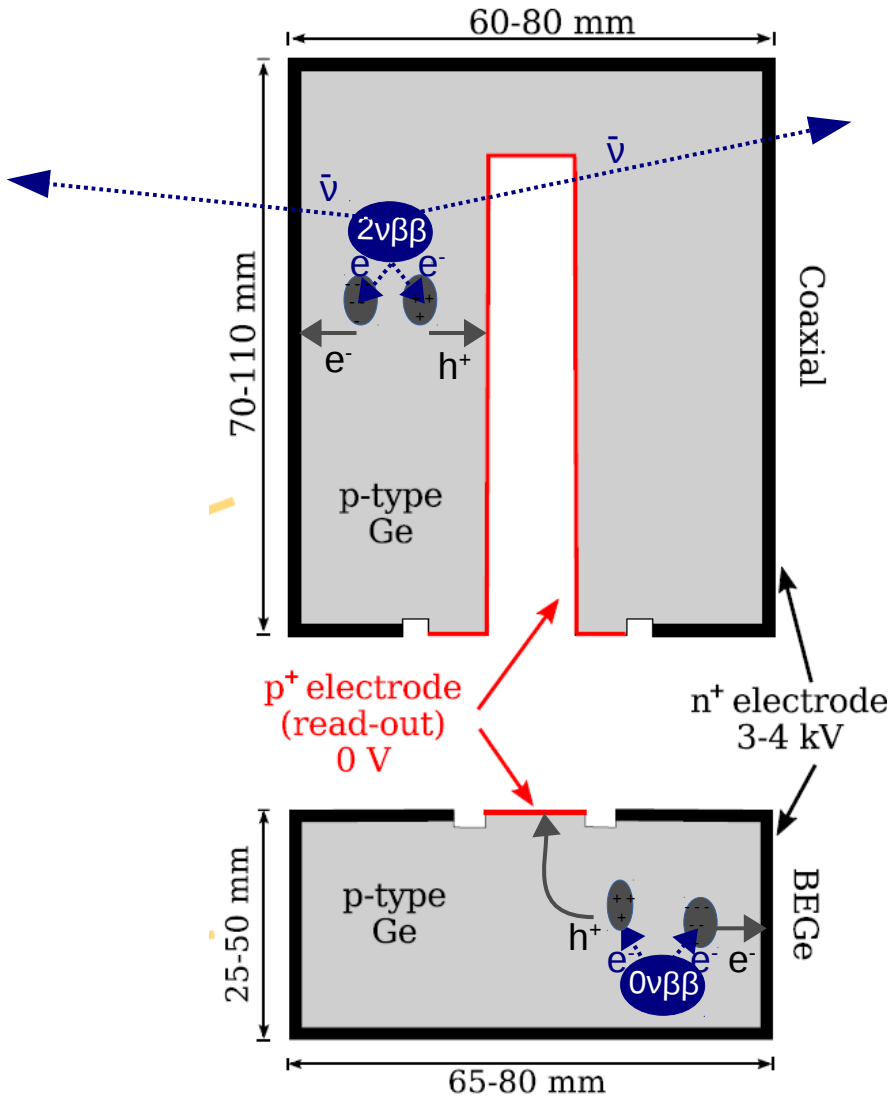
Discriminating Signal from Background Events

ββ event

- local energy deposition (SSE) in single detector

background event

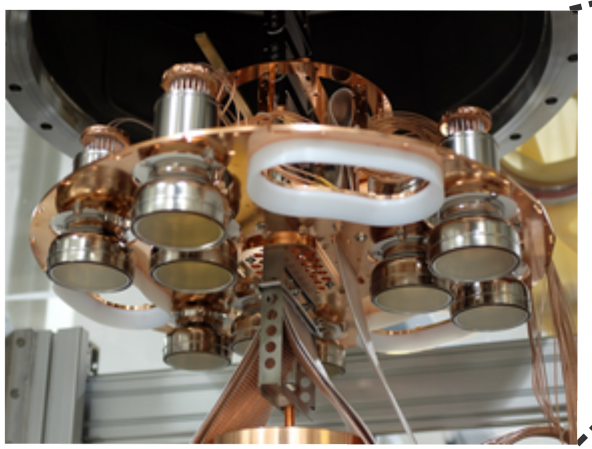
- energy deposition in multiple locations (MSE) in single detector
  → **pulse shape analysis**
- coincident energy deposition in more than one detector
  → **detector anti-coincindence**
- additional energy deposition in LAr
  → **LAr veto**



LAr Instrumentation – Hybrid Design

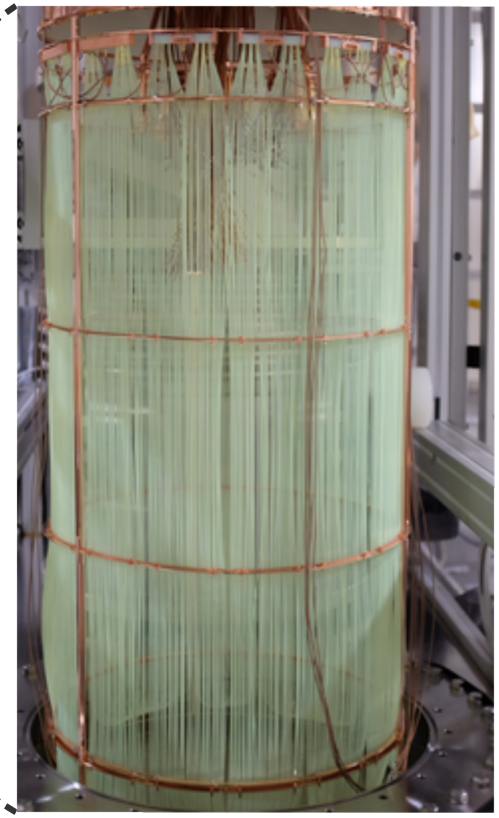
concept successfully tested in LArGe

16 photomultiplier tubes (PMTs)



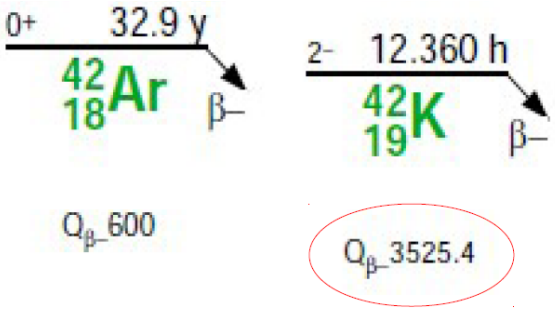
Cu cylinder with wavelength shifting reflector foil

810 scintillating fibers coupled to SiPMs

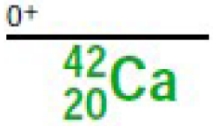


PMT part designed, built and tested by A. Wegmann, M. Heisel, K-T Knöpfle

^{42}K Background

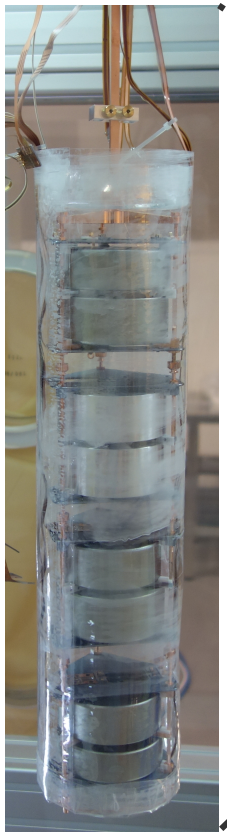


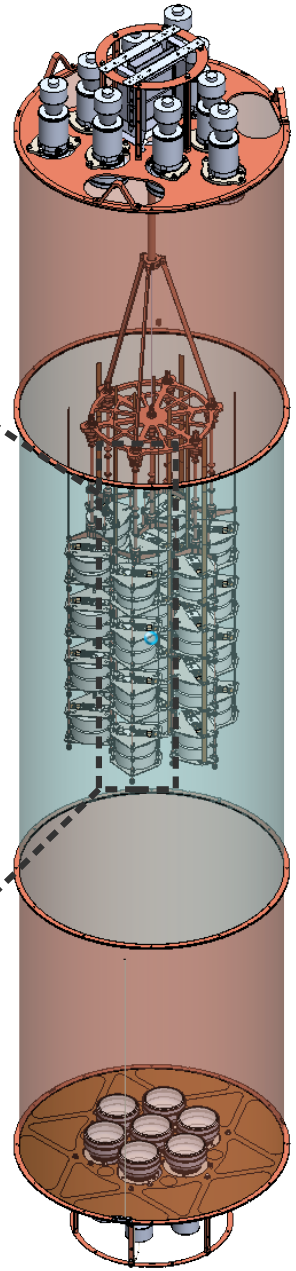
(charged) ^{42}K drift in field of Ge detectors



- tested in LArGe
- solution: transparent nylon cylinder coated with wave length shifter

designed,
built and tested by
A. Lubashevskiy,
A. Smolnikov, et. al

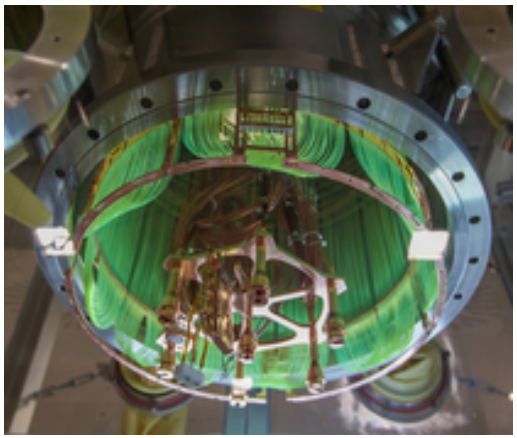


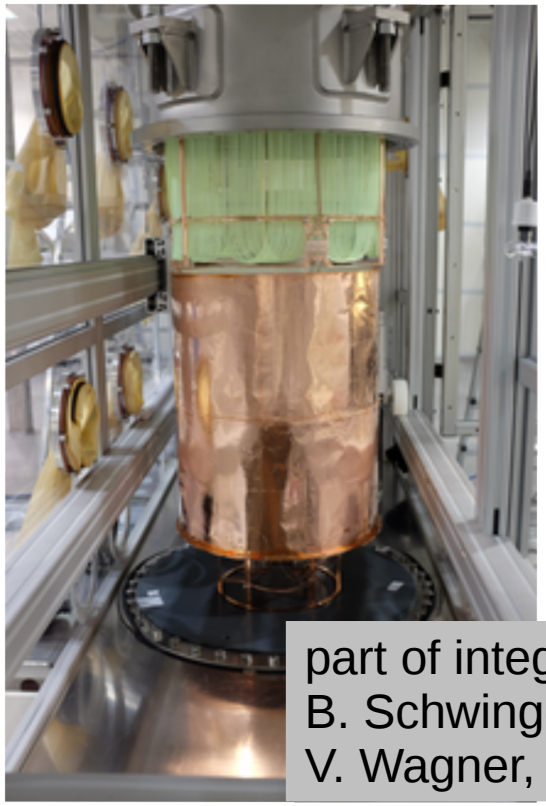


GERDA Phase II Commissioning

April '15: Pilot String

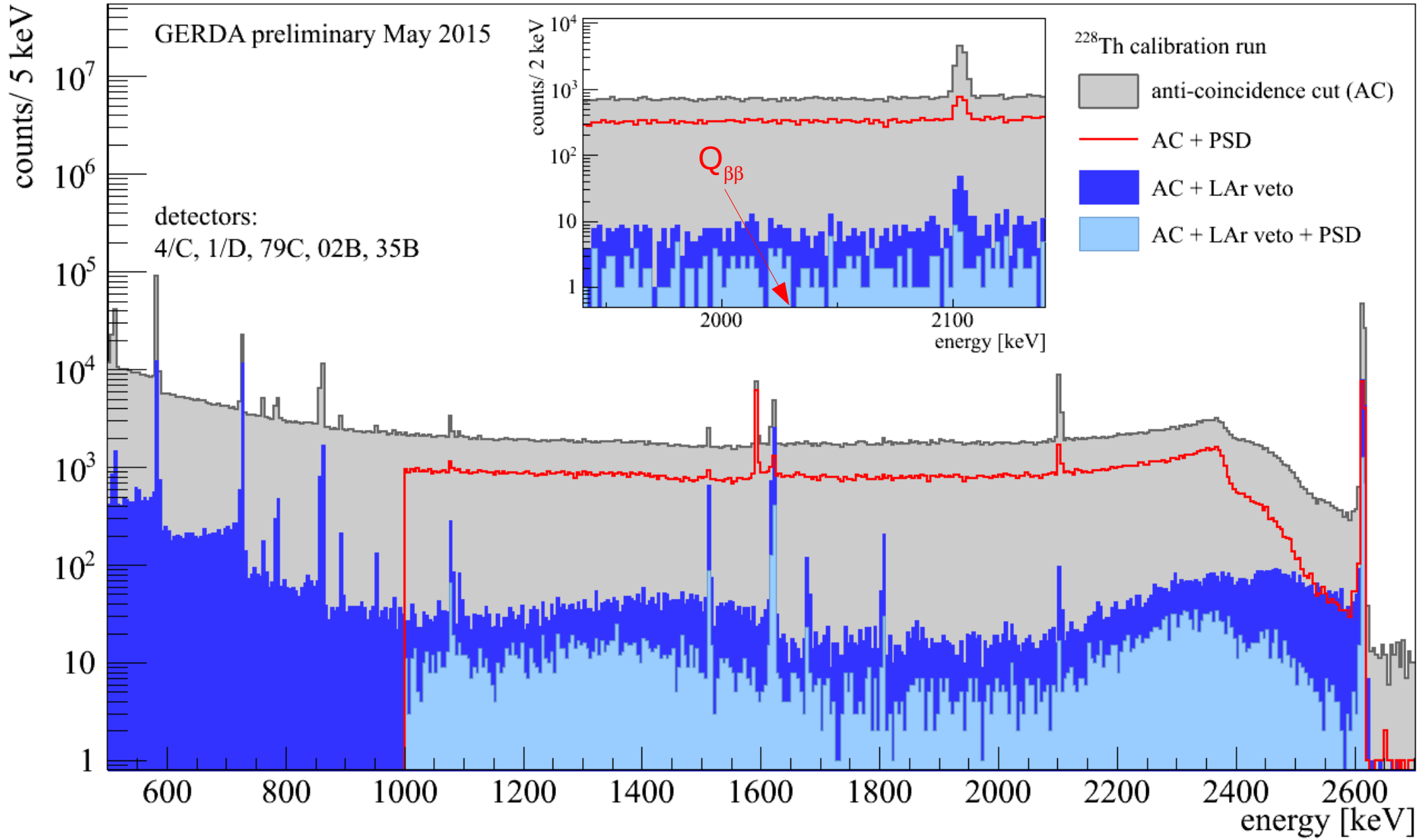
- integration of full string with 8 BEGe
- test new components, e.g. BEGe's, read-out electronics, contacting, etc
- commissioning of LAr veto





part of integration team
B. Schwingenheuer,
V. Wagner,

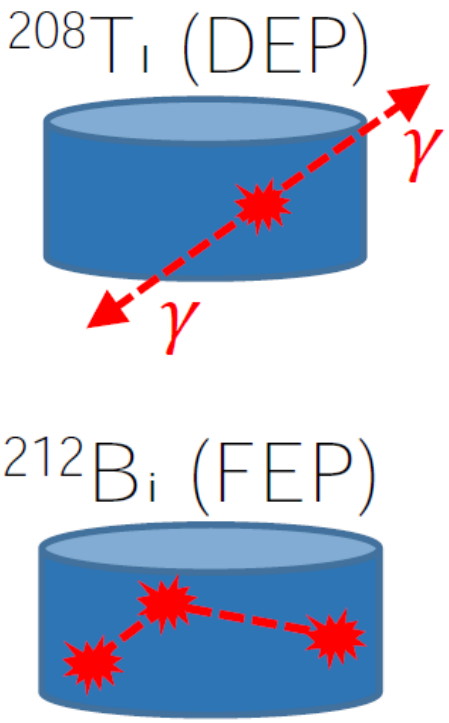
^{228}Th Suppression

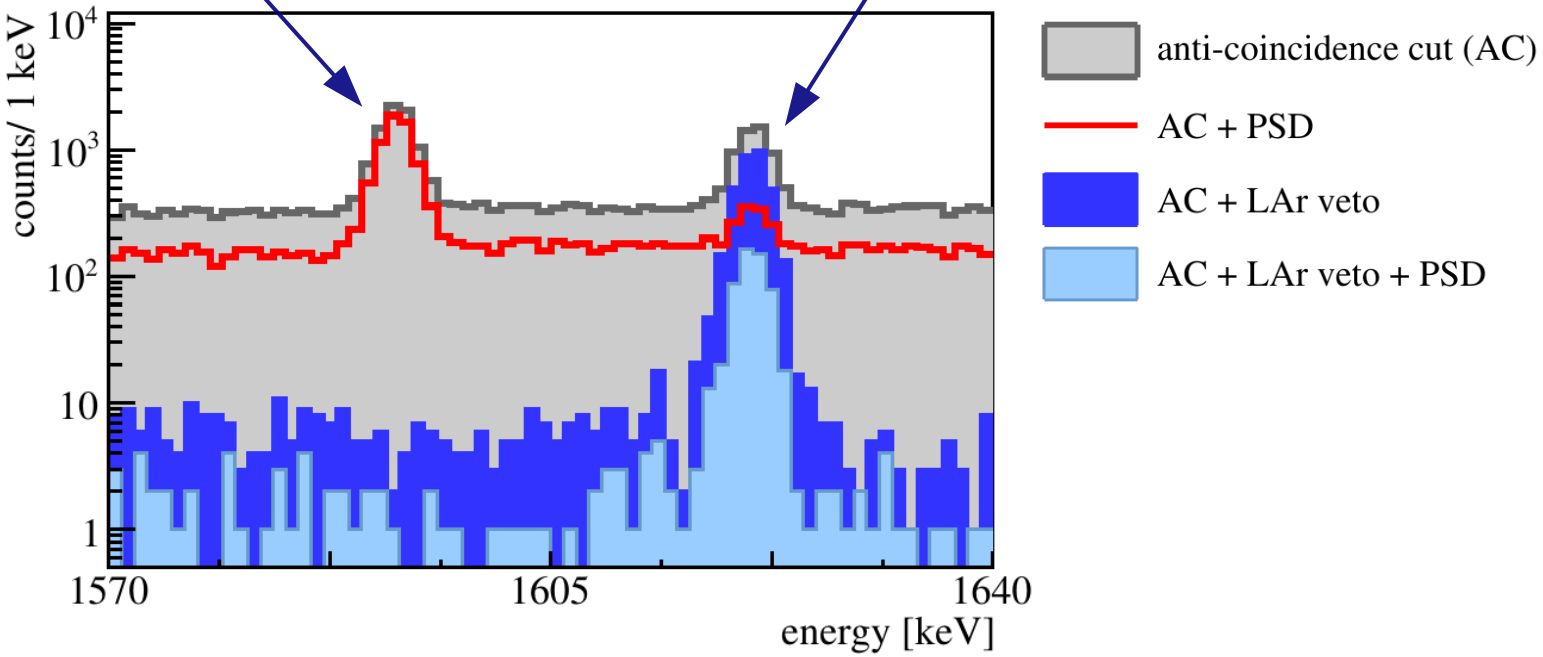


^{228}Th Suppression

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

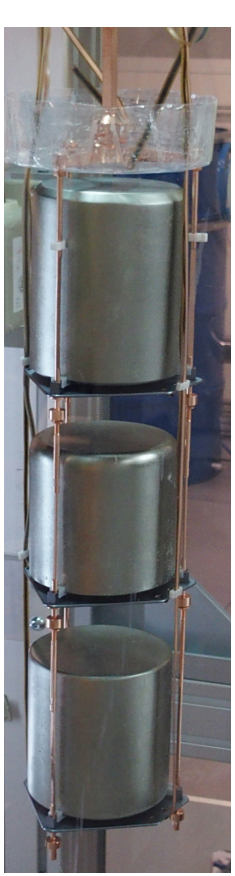
FEP events of the ^{212}Bi 1.6 MeV line
= background events

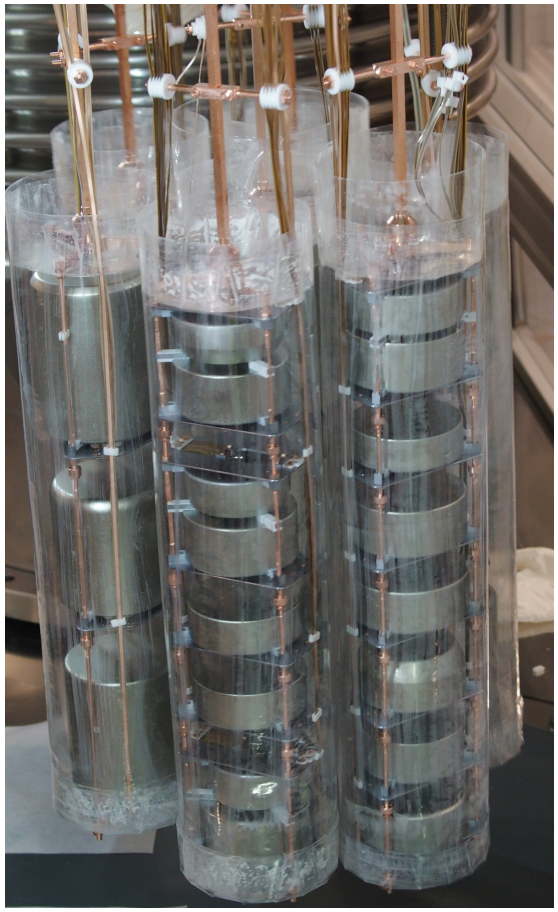


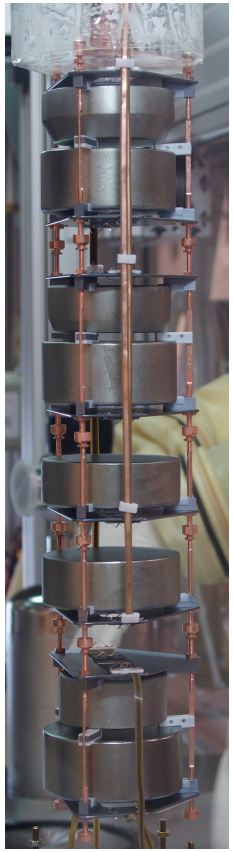


In case of discovery PSD will show if γ or 0νββ line

Start of GERDA Phase II



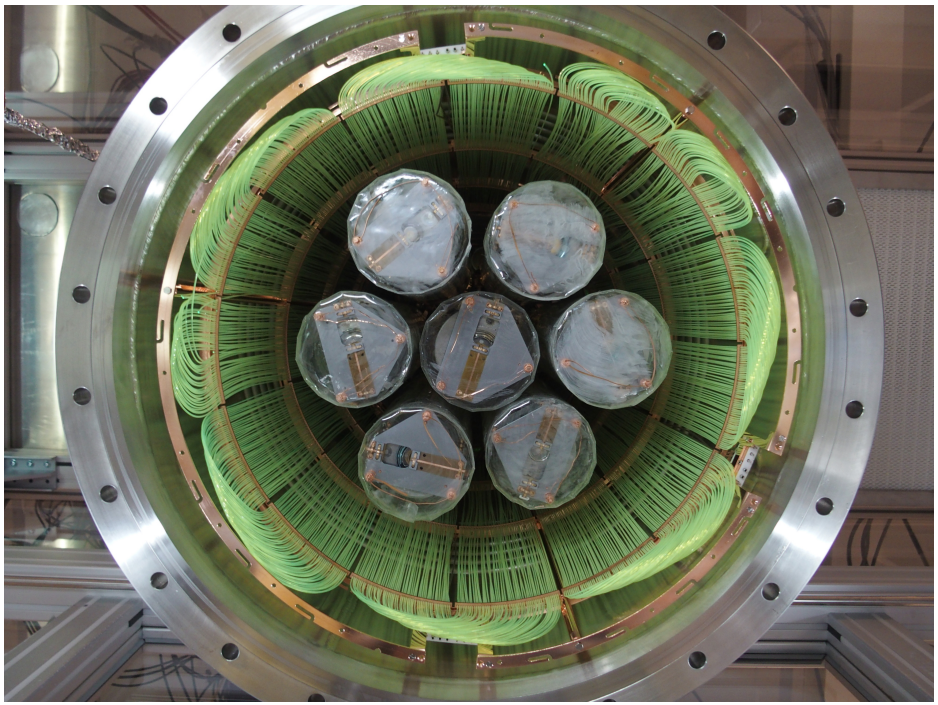




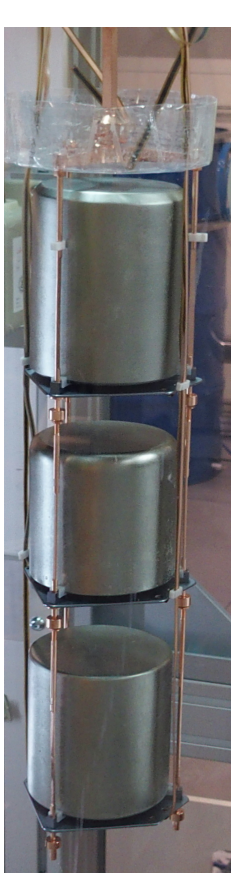
Integration of Phase II Array

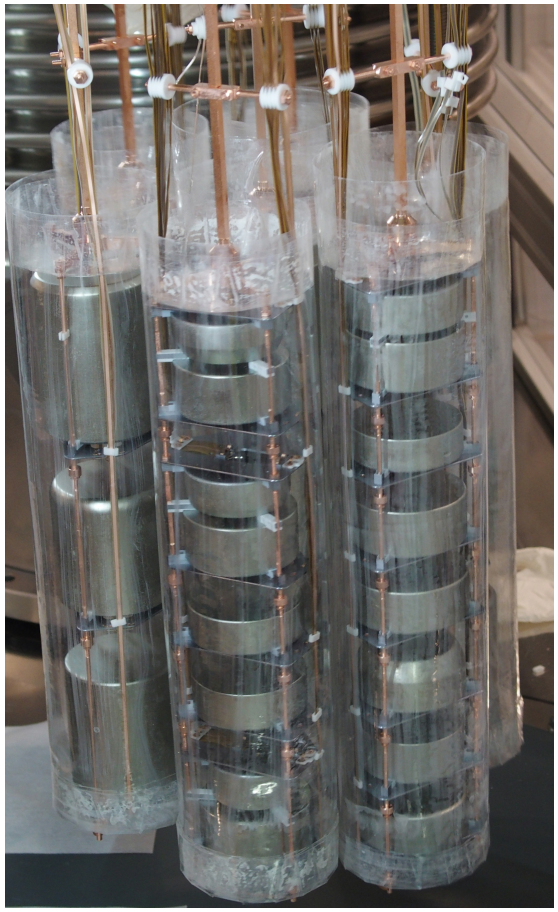
in December 2015

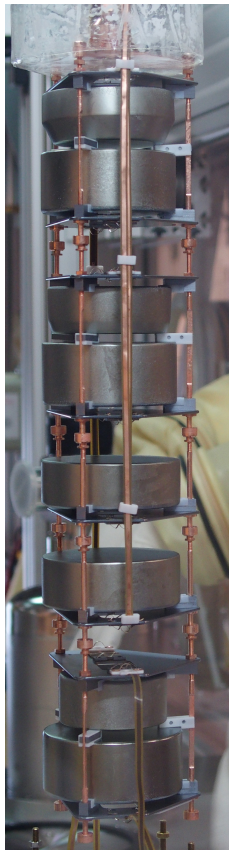
- 30 enr BEGe's
- 9 semi-coaxial HP^{enr}Ge
- 3 semi-coaxial HP^{nat}Ge



The Phase II Array







Integration of Phase II Array

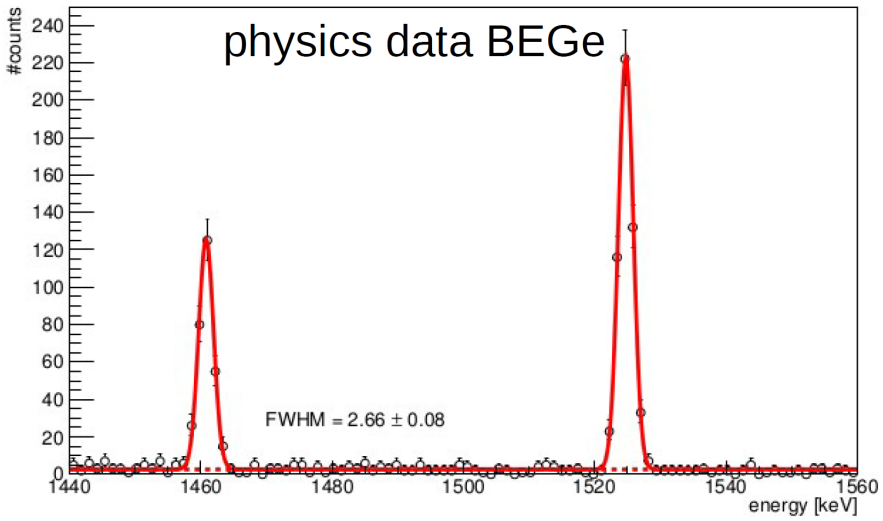
in December 2015

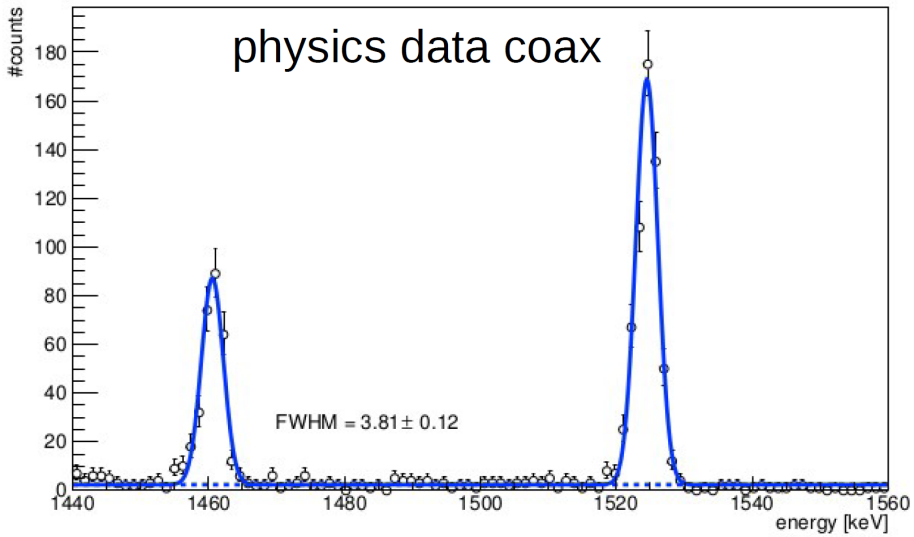
- 30 enr BEGe's
- 9 semi-coaxial $HP^{enr}Ge$
- 3 semi-coaxial $HP^{nat}Ge$

First data release in June 2016

- blinded region: 2014 – 2064 keV
- quality cuts ($\varepsilon > 99.9\%$)
- events in coincidence with muon veto ($\varepsilon \sim 99.9\ \%$)
- detector-detector coincidence

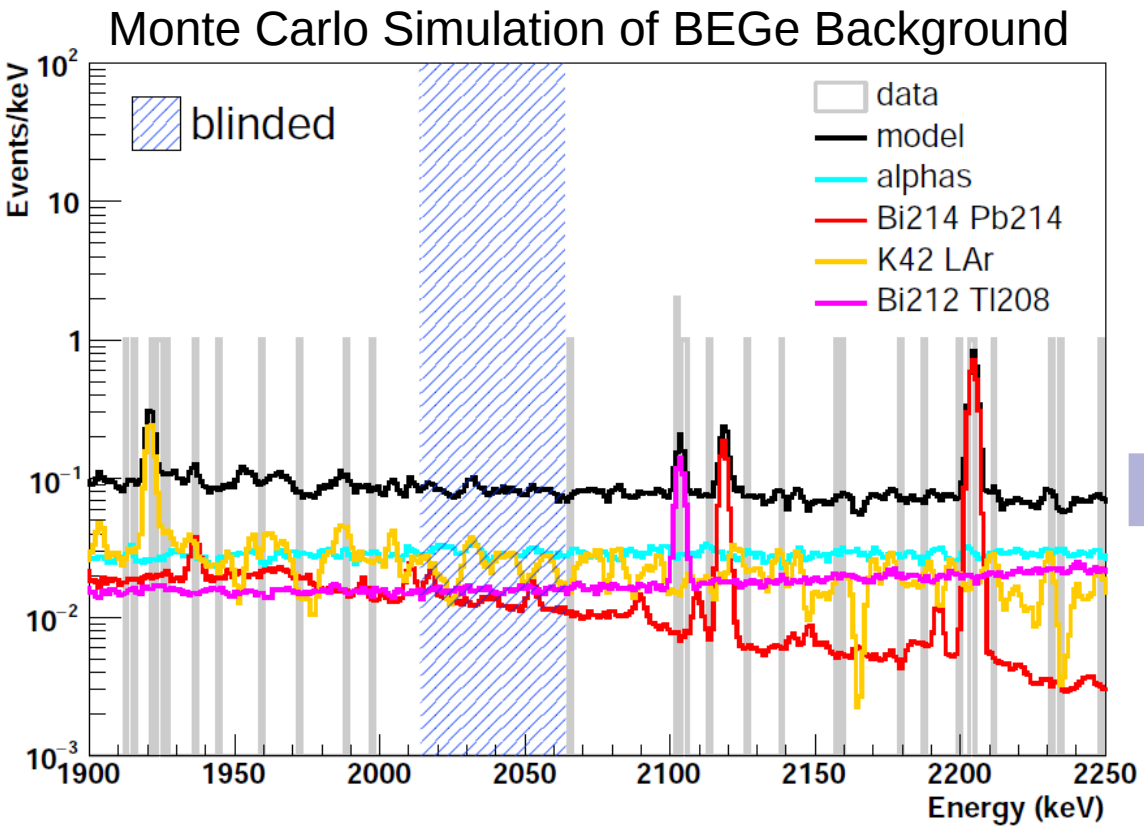
Energy Resolution





	BEGe		Coax	
FWHM at	keV		keV	
$Q_{\beta\beta} = 2039$ keV	3.0 ± 0.2	0.15 %	4.0 ± 0.2	0.20 %
^{40}K/ ^{42}K lines	2.7 ± 0.1	0.13 %	3.8 ± 0.1	0.19 %

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



Preliminary results before PSD & LAr veto

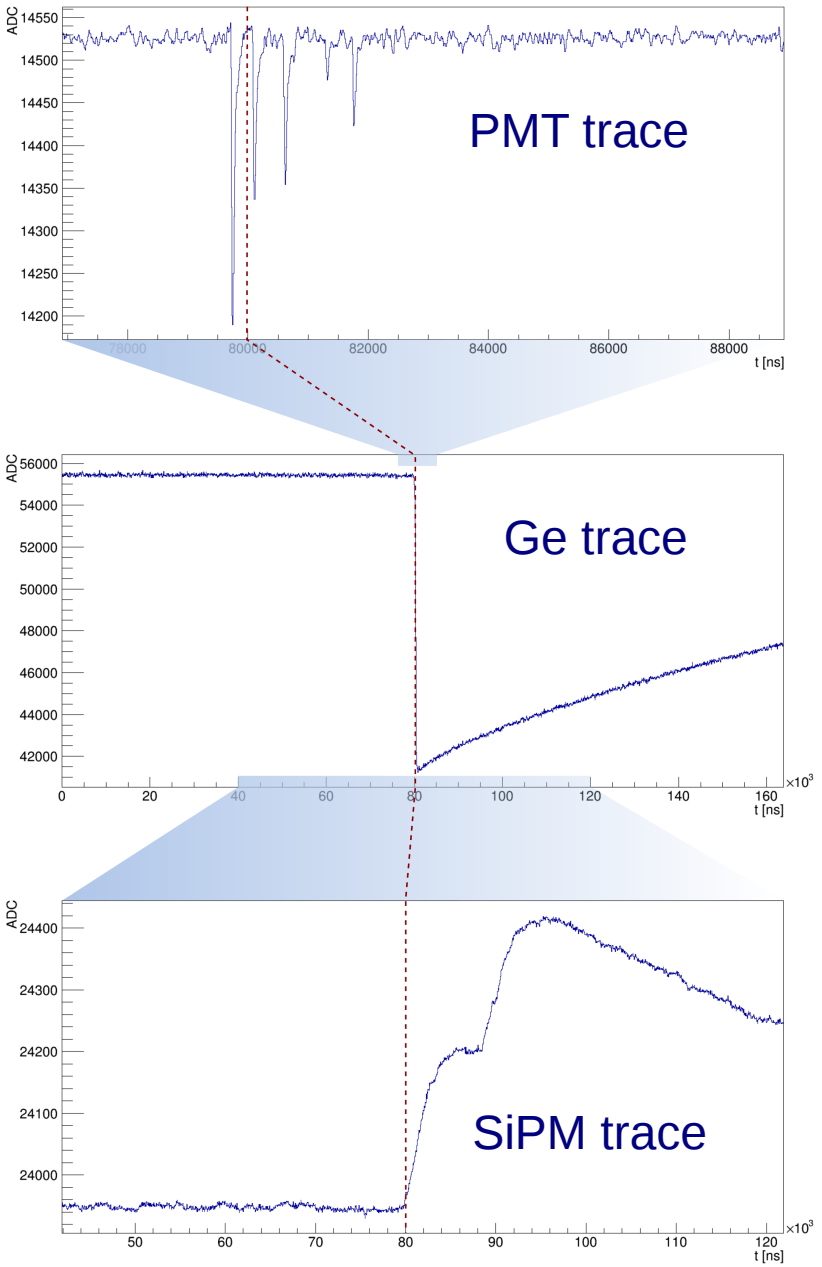
expect flat background in ROI

integration of Phase II geometry into MaGe by J. Hakenmueller

	^{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

LAr Veto

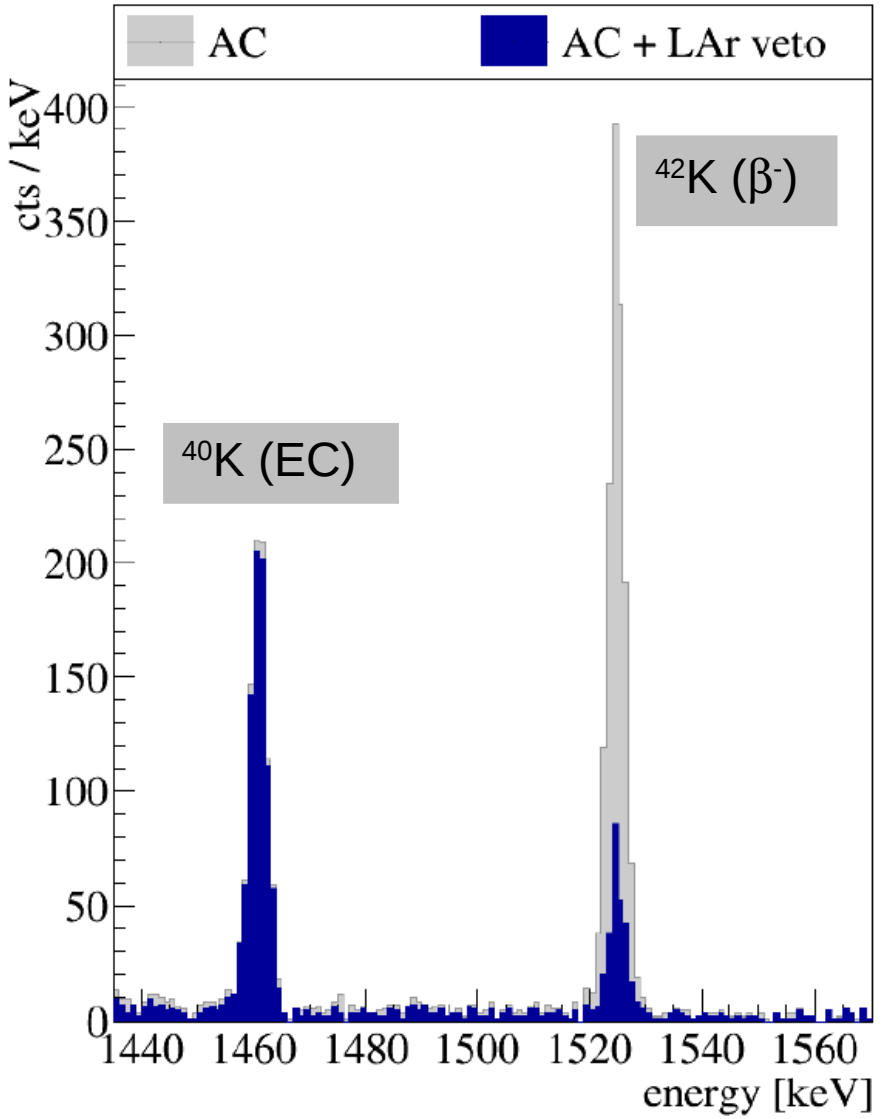
- events in coincidence with LAr veto
- fraction of random coincidences 2.3%



analysis of PMT traces
by A. Wegmann

LAr Veto

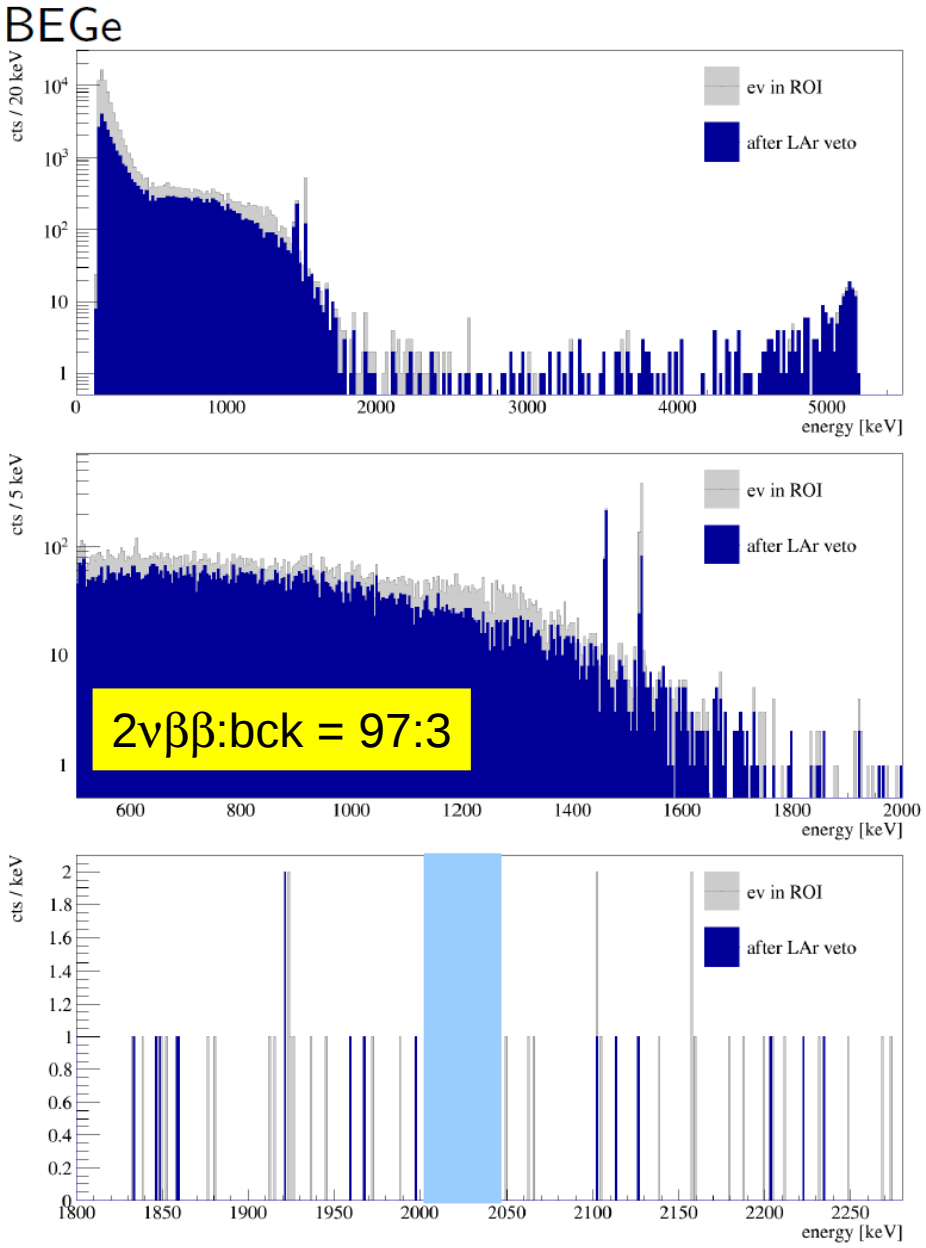
- events in coincidence with LAr veto
- fraction of random coincidences 2.3%
- ^{40}K FEP at 1460 keV fully accepted
- ^{42}K FEP at 1525 keV suppressed by factor ~5



analysis of PMT traces by A. Wegmann

LAr Veto

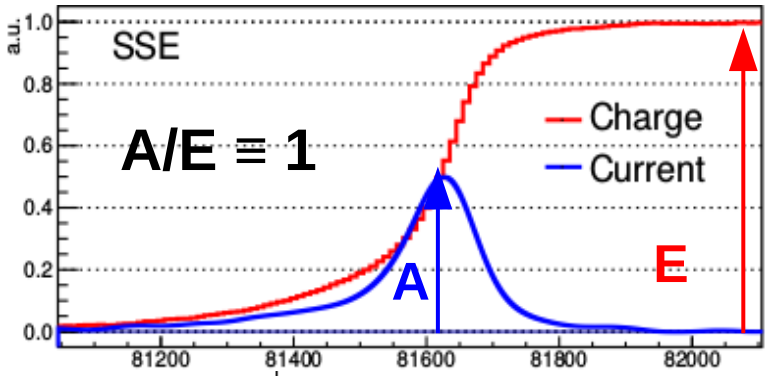
- events in coincidence with LAr veto
- fraction of random coincidences 2.3%
- ^{40}K FEP at 1460 keV fully accepted
- ^{42}K FEP at 1525 keV suppressed by factor ~5
- survival fraction in 1839-2239 keV:
  - 1/3 BEGe
  - 1/2 Coax



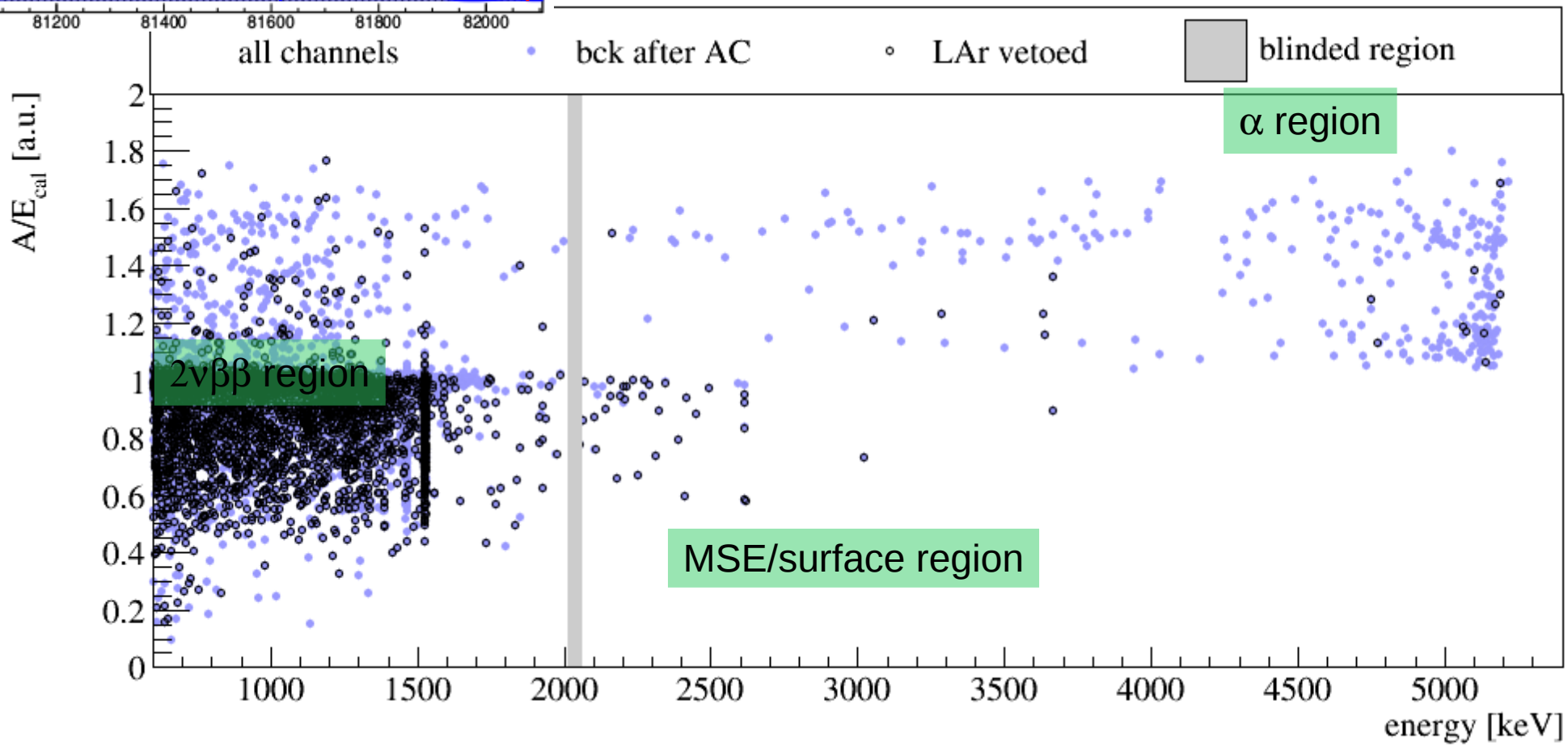
analysis of PMT traces by A. Wegmann

A/E Analysis for BEGe's

A/E analysis by V. Wagner

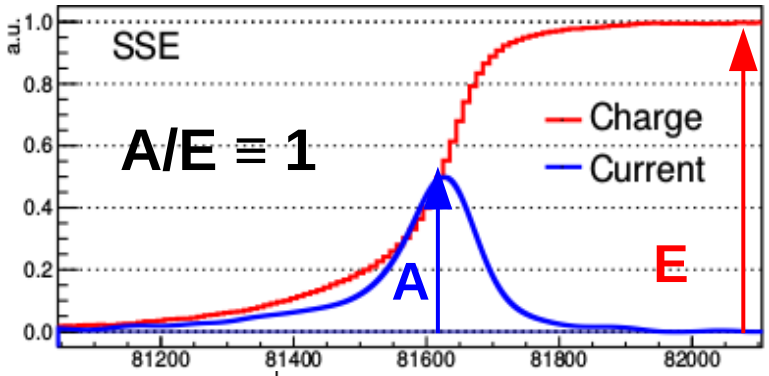


Already successfully used in GERDA Phase I:
> 80% of background events rejected at $Q_{\beta\beta}$
whereas signal efficiency = 92±2 %

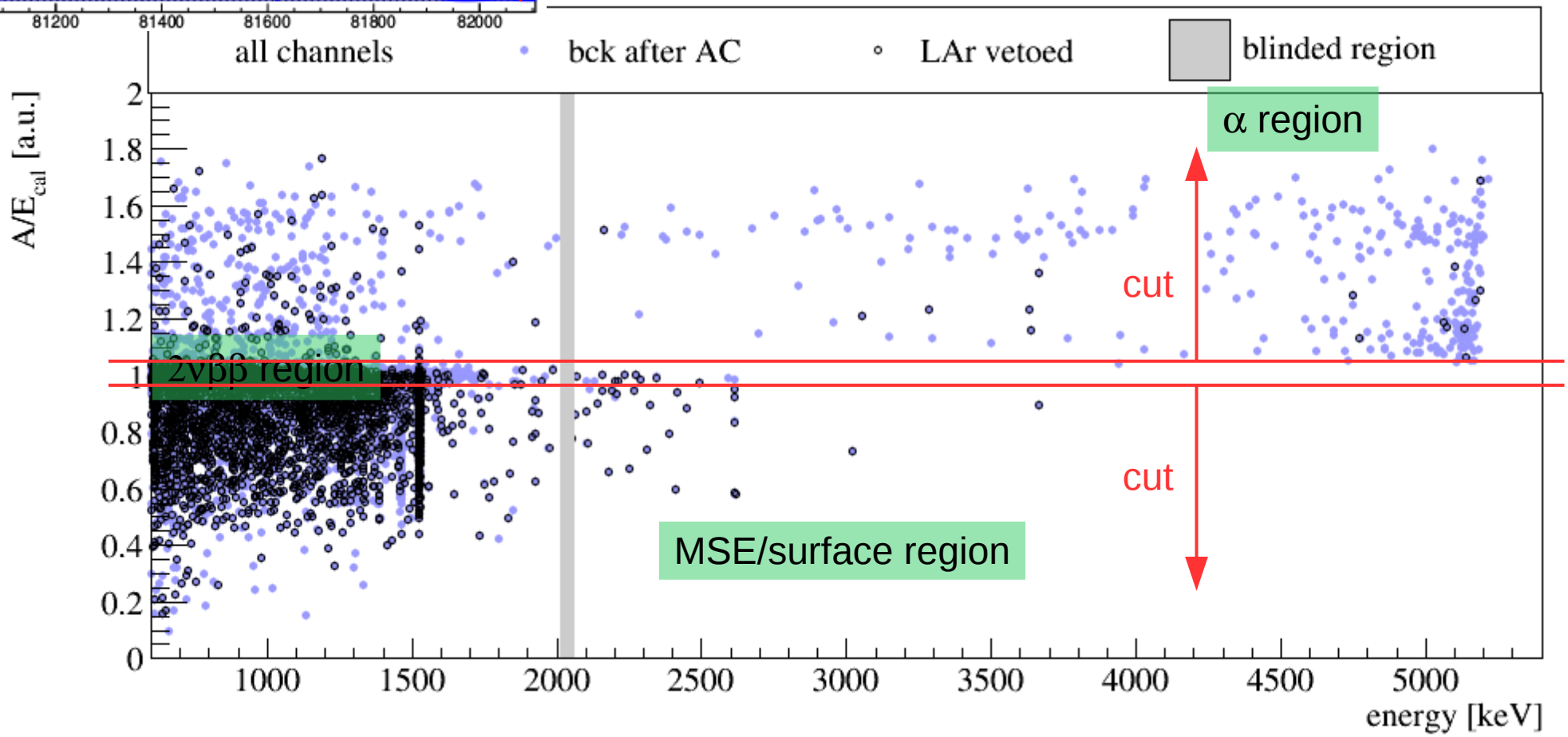


A/E Analysis for BEGe's

A/E analysis by V. Wagner

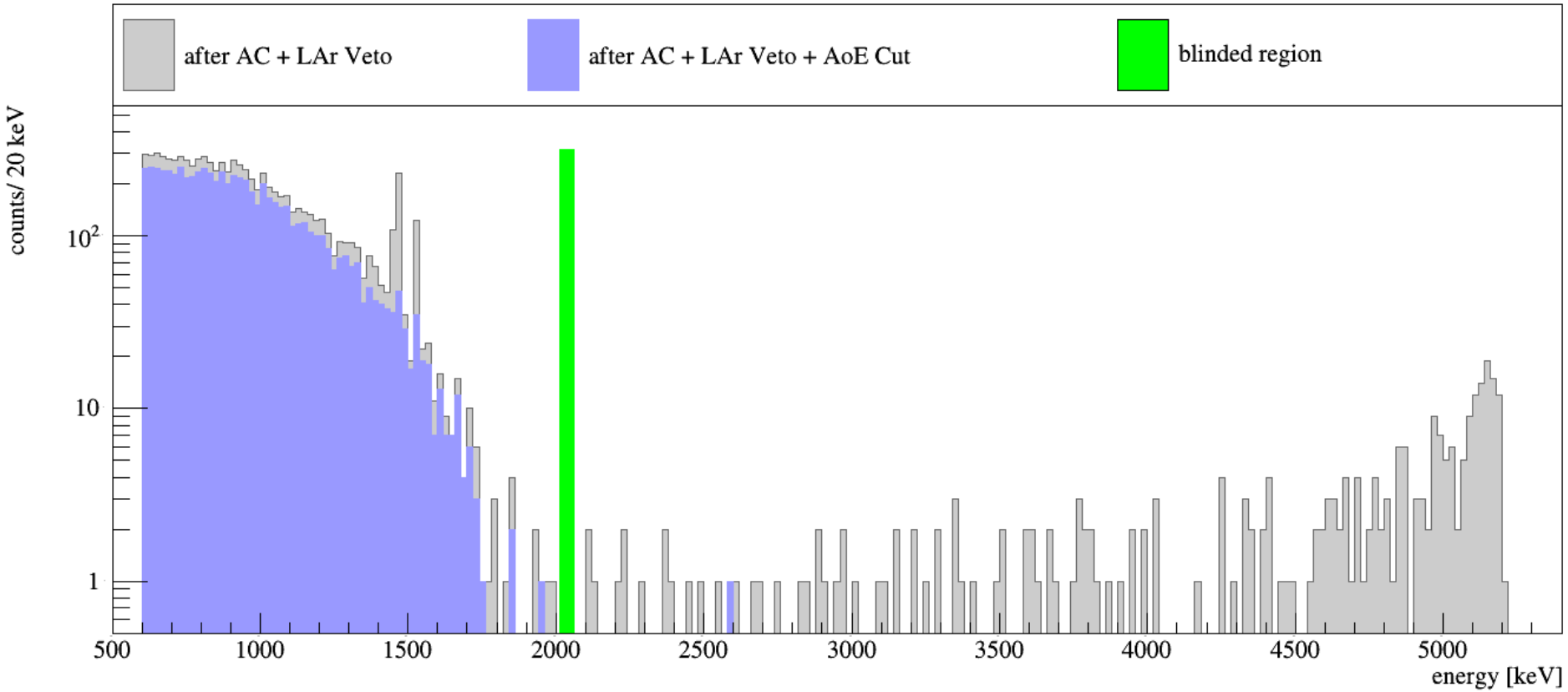


Already successfully used in GERDA Phase I:
> 80% of background events rejected at $Q_{\beta\beta}$
whereas signal efficiency = 92±2 %



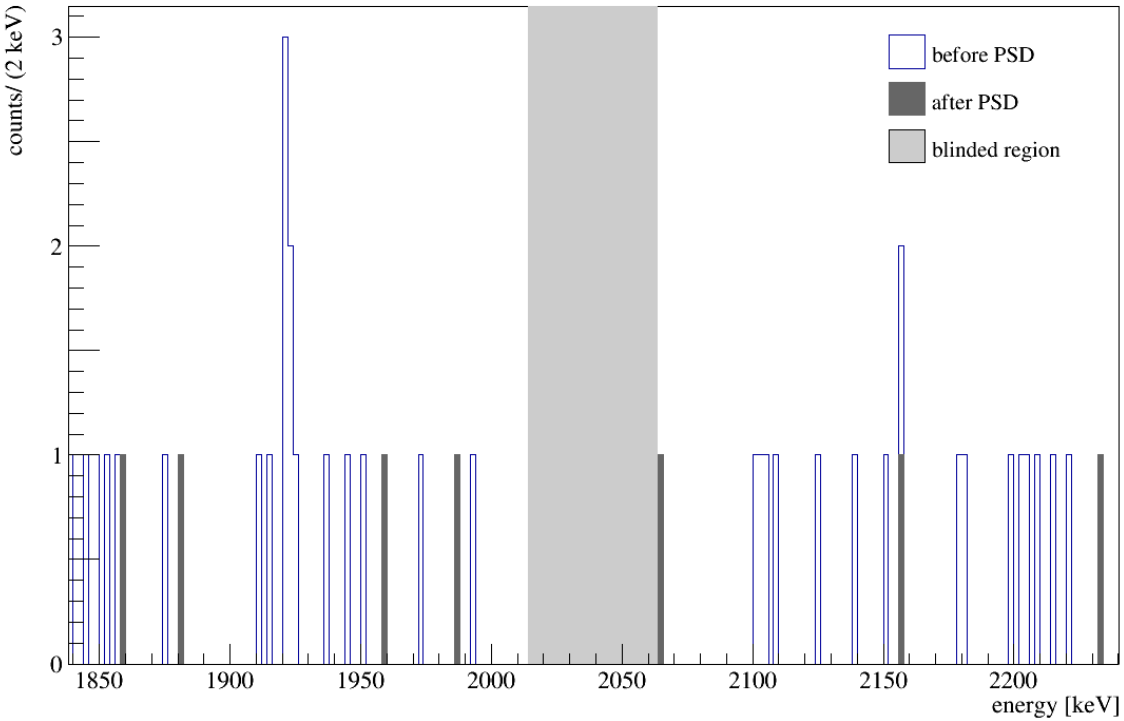
BEGe PSD

- DEP events used as proxy for $0\nu\beta\beta$
- signal efficiency: 87.3 ± 0.9 %
- $2\nu\beta\beta$ acceptance: 85.4 $^{+1.9}_{-0.8}$ %



BEGe PSD

- DEP events used as proxy for $0\nu\beta\beta$
- signal efficiency: 87.3 ± 0.9 %
- $2\nu\beta\beta$ acceptance: 85.4 $^{+1.9}_{-0.8}$ %
- 80 % of background in ROI rejected

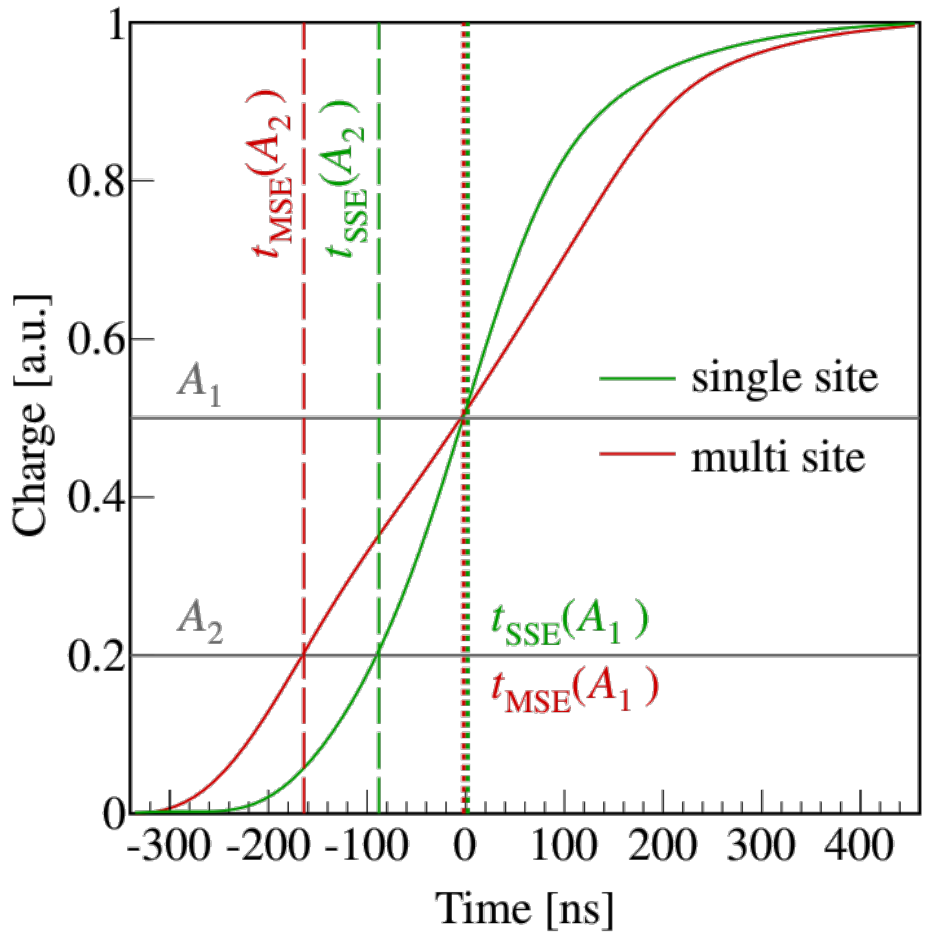


Coax PSD

- TMlpAnn Algorithm:

  50 input variables with

  t(A=0.01), t(A=0.03), …, t(A=0.99)



A/E analysis by A. Kirsch

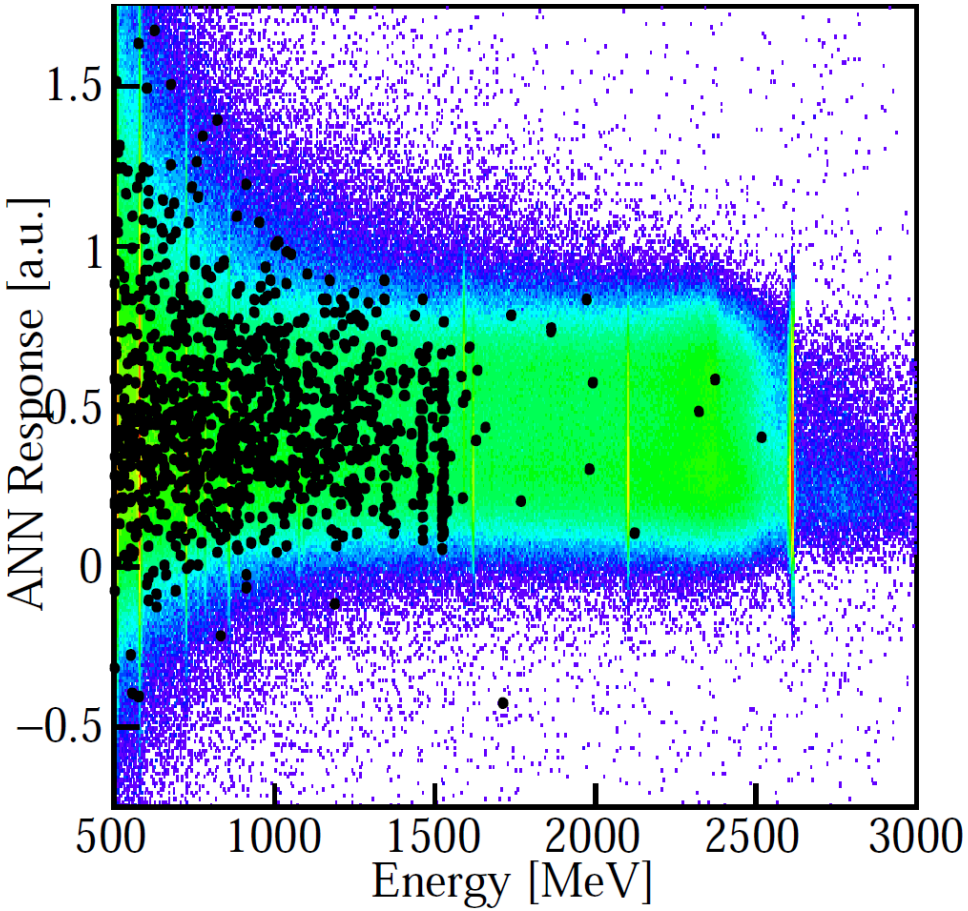
Coax PSD

- 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



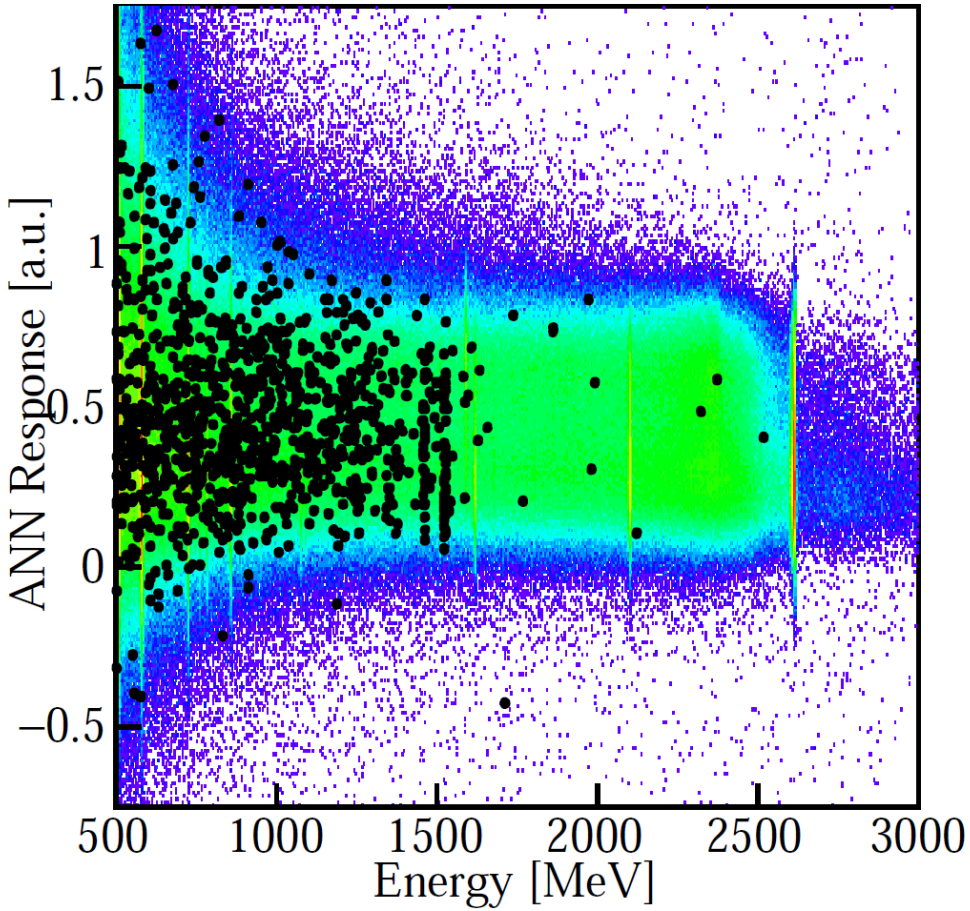
Coax PSD

- 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 %



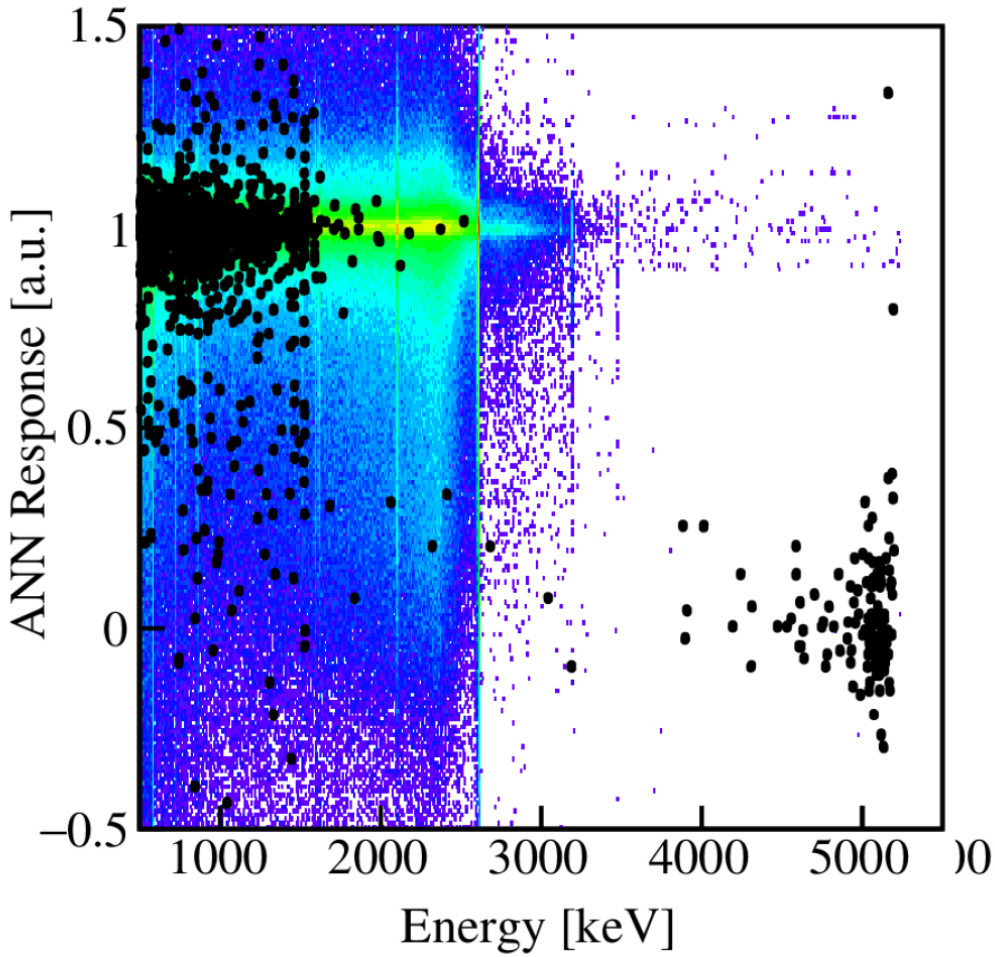
Coax PSD

- 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



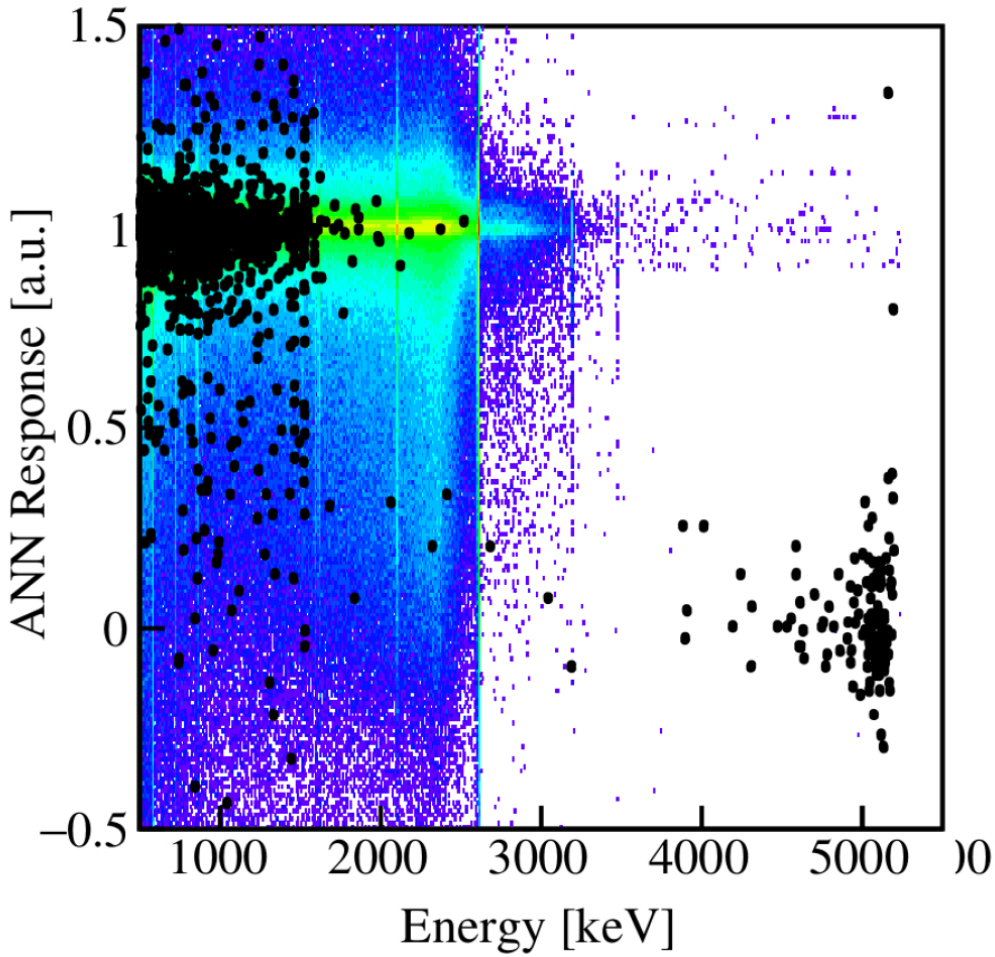
Coax PSD

- 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 %



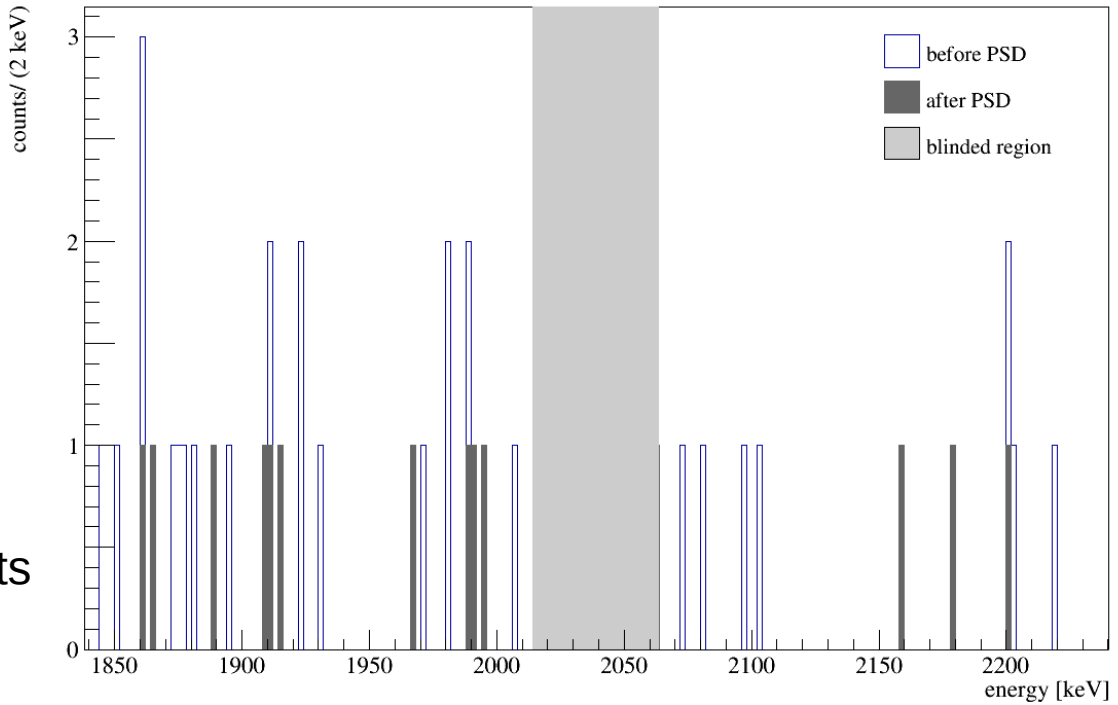
Coax PSD

- 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



Summary of Data Sets

data set	exposure [kg yr]	ε_{LAr}	ε_{PSD}	Energy resolution (keV, FWHM)	Background index 0.001 cnts/(keV kg yr)
Phase I gold	17.9	1	**0.83**	**4.3 ± 0.2**	11 ± 2
Phase I silver	1.3	1	**0.83**	**4.3 ± 0.2**	30 ± 10
Phase I BEGe	2.4	1	0.92	**2.7 ± 0.2**	5^{+4}_{-3}

Phase I:

- PSD efficiency reduced from 90% to 83% and found bug in ROOFIT
- new energy reconstruction to improve energy resolution from 4.8 (3.2) keV to 4.3 (2.7) keV for coax (BEGe)

Summary of Data Sets

data set	exposure [kg yr]	ε_{LAr}	ε_{PSD}	Energy resolution (keV, FWHM)	Background index 0.001 cnts/(keV kg yr)
Phase I gold	17.9	1	0.83	4.3 ± 0.2	11 ± 2
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Phase I BEGe	2.4	1	0.92	2.7 ± 0.2	5^{+4}_{-3}
Phase I extra	**1.9**	1	**0.83**	**4.2 ± 0.2**	$\mathbf{4.6^{+4.3}_{-2.5}}$

Runs 47 + 49 from Phase I:
- unpublished, blinded
- May 31st – Sept 30th 2013

Summary of Data Sets

data set	exposure [kg yr]	ε_{LAr}	ε_{PSD}	Energy resolution (keV, FWHM)	Background index 0.001 cnts/(keV kg yr)
Phase I gold	17.9	1	0.83	4.3 ± 0.2	11 ± 2
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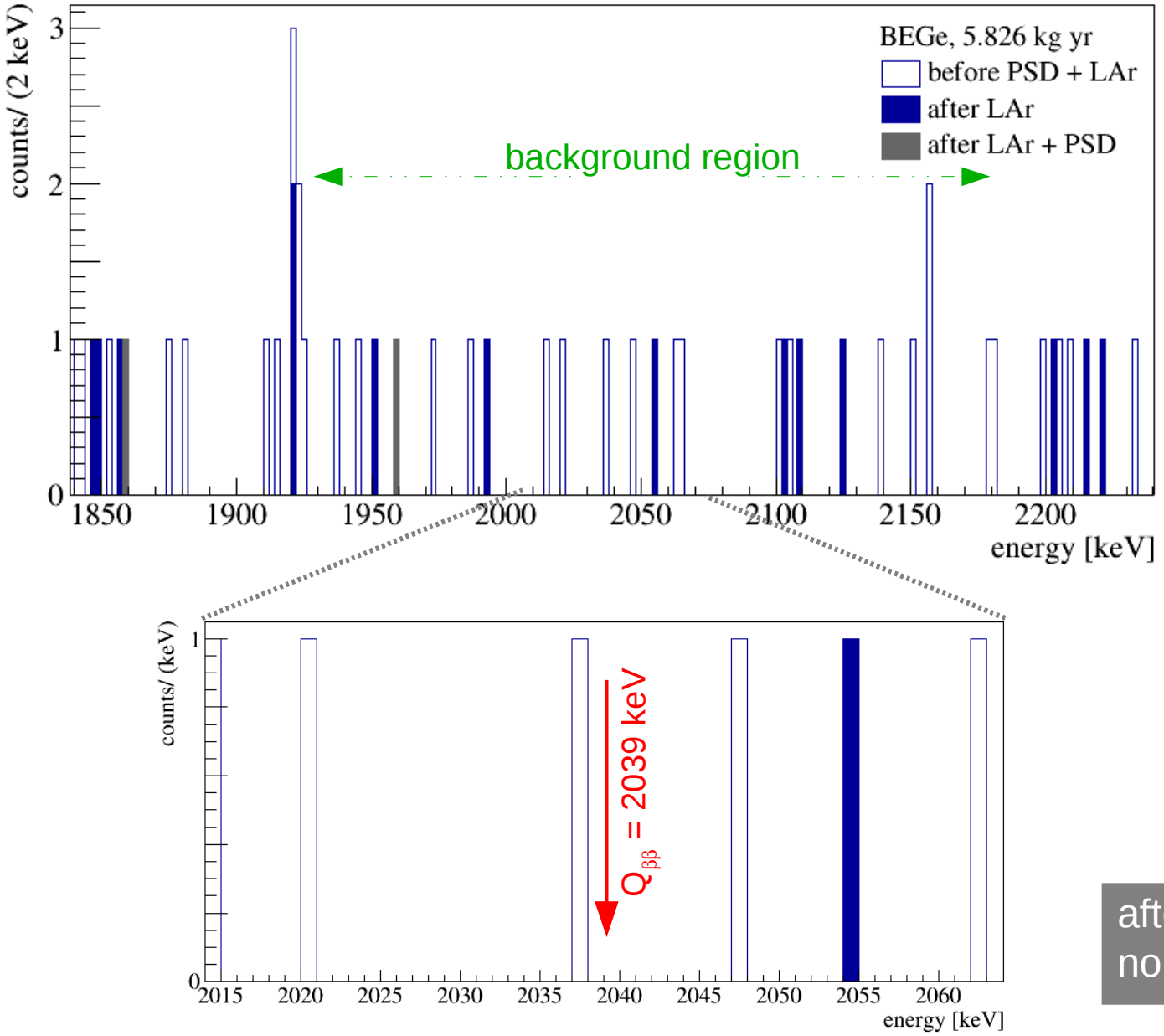
Phase I BEGe	2.4	1	0.92	2.7 ± 0.2	5^{+4}_{-3}
Phase I extra	1.9	1	0.83	4.2 ± 0.2	$4.6^{+4.3}_{-2.5}$
Phase II coax	**5.0**	**0.98**	**0.76**	**4.0 ± 0.2**	
Phase II BEGe	**5.8**	**0.98**	**0.87**	**3.0 ± 0.2**	

Phase II Coax:
- PSD efficiency still preliminary

Unblinding at Ringberg Castle

GERDA Collaboration Meeting
at Ringberg castle **17th June 2016**:
opening 50 keV blinded window around $Q_{\beta\beta}$

BEGe: Unblinded Spectrum



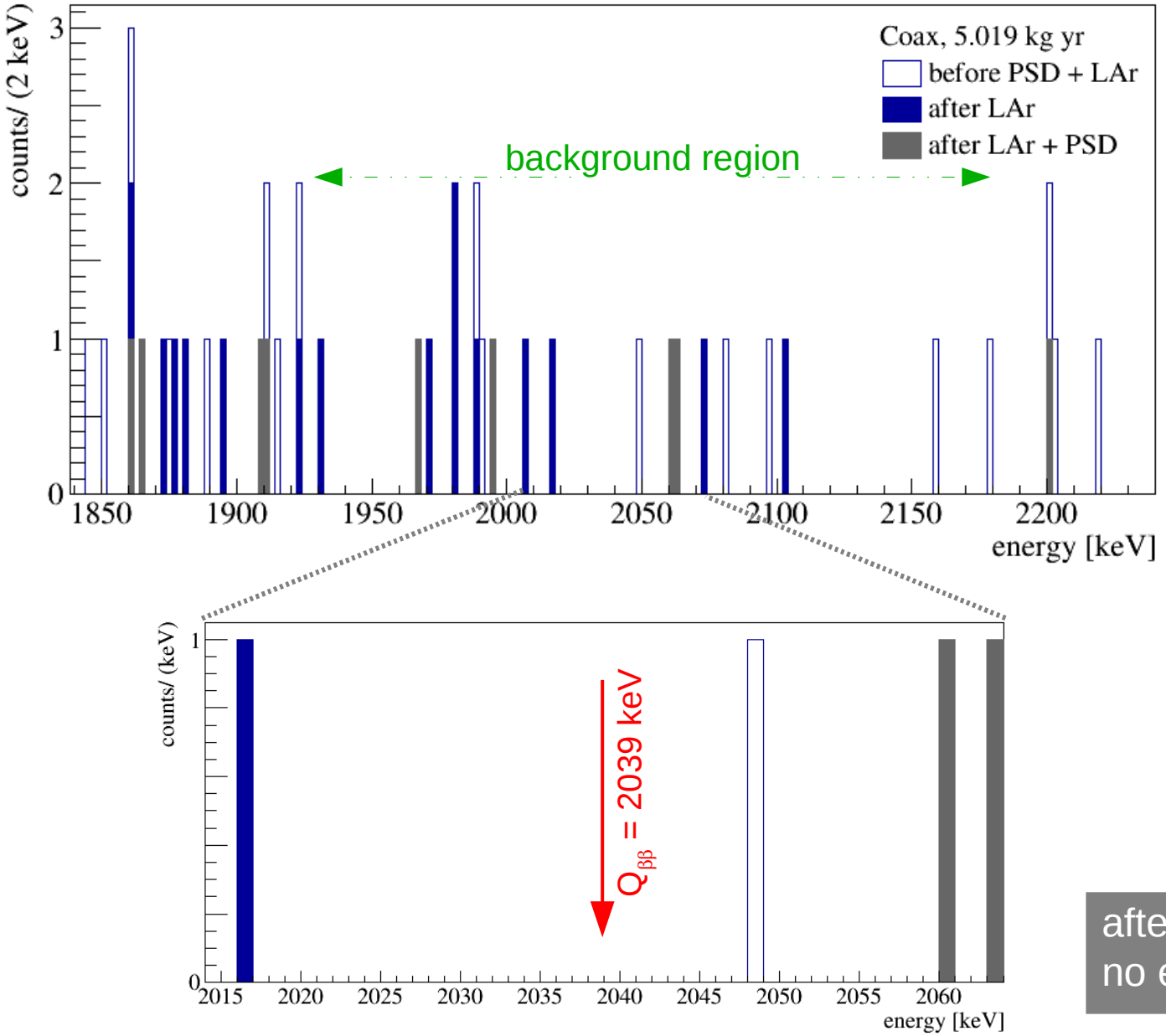
total # counts in background region	25
after LAr	7
after PSD	5
after LAr + PSD	1

after PSD + LAr veto

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

after PSD + LAr
no events left at $Q_{\beta\beta}$

Coax: Unblinded Spectrum



total # counts in background region	20
after LAr	13
after MSE cut	14
after α cut	14
after LAr + PSD	4

after PSD + LAr veto

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

after PSD + LAr
no events left at $Q_{\beta\beta}$

First Phase II Results

data set	sensitivity [10^{25} yr]	lower limit @ 90% C.L. [10^{25} yr]
Phase I (PRL)	2.2	2.18
Phase I (PRL) + new E	2.3	2.79
Phase I (PRL) + Run 47/49 + new E	2.5	

Phase I:

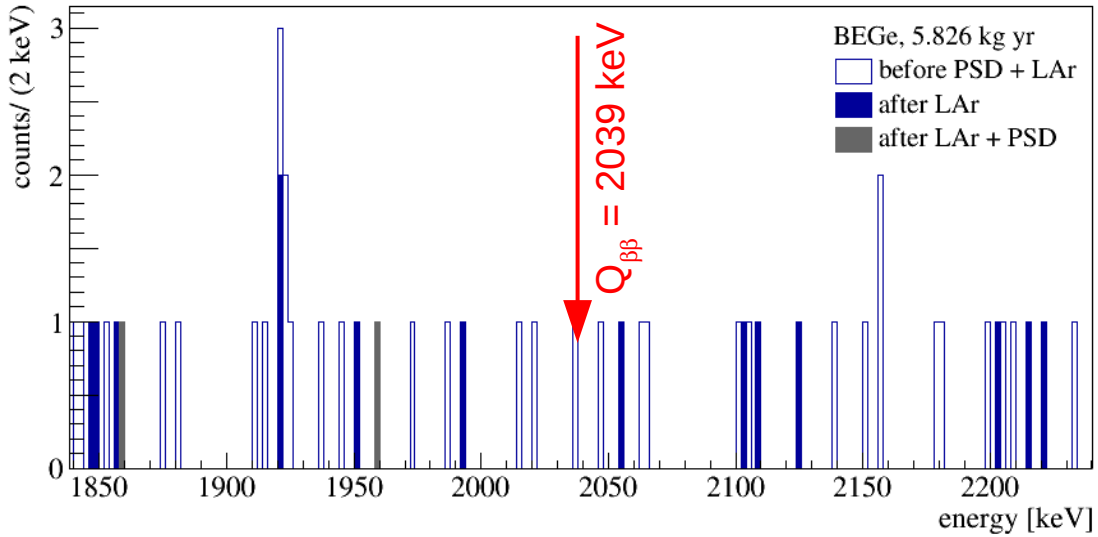
- PSD efficiency reduced from 90% to 83% and found bug in ROOFIT
- new energy reconstruction to improve energy resolution
  → events shift within σ
- Run 47/49 unpublished Phase I data set

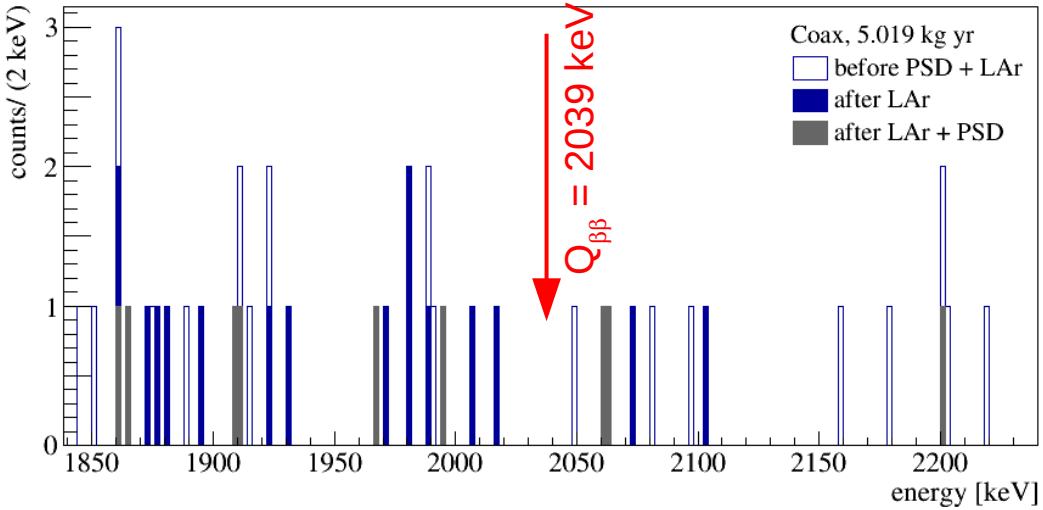
First Phase II Results

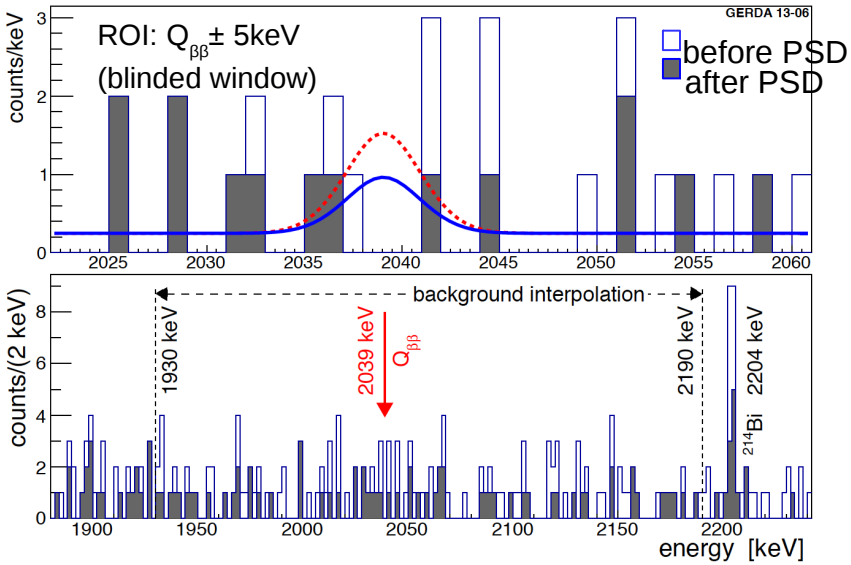
data set	sensitivity [10^{25} yr]	lower limit @ 90% C.L. [10^{25} yr]
Phase I (PRL)	2.2	2.18
Phase I (PRL) + new E	2.3	2.79
Phase I (PRL) + Run 47/49 + new E	2.5	
Phase II	**2.2**	

Phase II Coax:
- PSD efficiency still preliminary

Spectrum at $Q_{\beta\beta}$







Fit:

- 7 parameters: 6 BI + common $1/T_{1/2}$
- flat background + Gaussian in 1930-2190 keV range with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- best for for $N_{0\nu} = 0$

$$T_{1/2}^{0\nu} \propto \frac{M \cdot t \cdot \epsilon}{N^{0\nu}}$$

M·t: exposure,
$N^{0\nu}$: observed signal strength,
ε_{FEP}: detection efficiency

First Phase II Results

data set	sensitivity [10^{25} yr]	lower limit @ 90% C.L. [10^{25} yr]
Phase I (PRL)	2.2	2.18
Phase I (PRL) + new E	2.3	2.79
Phase I (PRL) + Run 47/49 + new E	2.5	
Phase II	**2.2**	
Phase II + Phase I (PRL) + Run 47/49 + new E	**3.1**	**3.5** (90 % credibility)

preliminary PSD efficiency

Phase II results: Bayesian fit with flat prior on 1/T between 0 and 10^{24} 1/yr

First Phase II Results

data set	sensitivity [10^{25} yr]	lower limit @ 90% C.L. [10^{25} yr]
Phase I (PRL)	2.2	2.18
Phase I (PRL) + new E	2.3	2.79
Phase I (PRL) + Run 47/49 + new E	2.5	
Phase II	**2.2**	
Phase II + Phase I (PRL) + Run 47/49 + new E	**4.0**	**5.3**

preliminary PSD efficiency

Phase II results:
profile likelihood fit for 2-sided test (optimized for signal search).
1-sided analysis is in preparation.

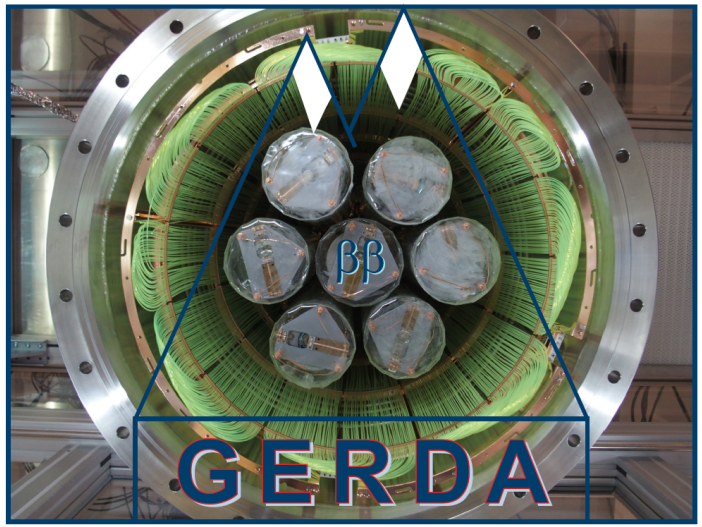
Summary

- GERDA Phase II started successfully in

  December 2015

- all Ge detectors and LAr channels working
- 38 out of 40 Ge detectors used for analysis
- reached goal of background level of

  0.001 counts/(keV kg yr)



- lowest background in ROI of all competing experiments

	median sensitivity (10^{25} yr)	lower limit $T_{1/2}$ (10^{25} yr)
Bayesian	3.1	3.5 (90% credibility)
Frequentist	4.0	5.3 (90% C.L.)