Background Free Search for $0\nu\beta\beta$ Decay of ^{76}Ge with GERDA

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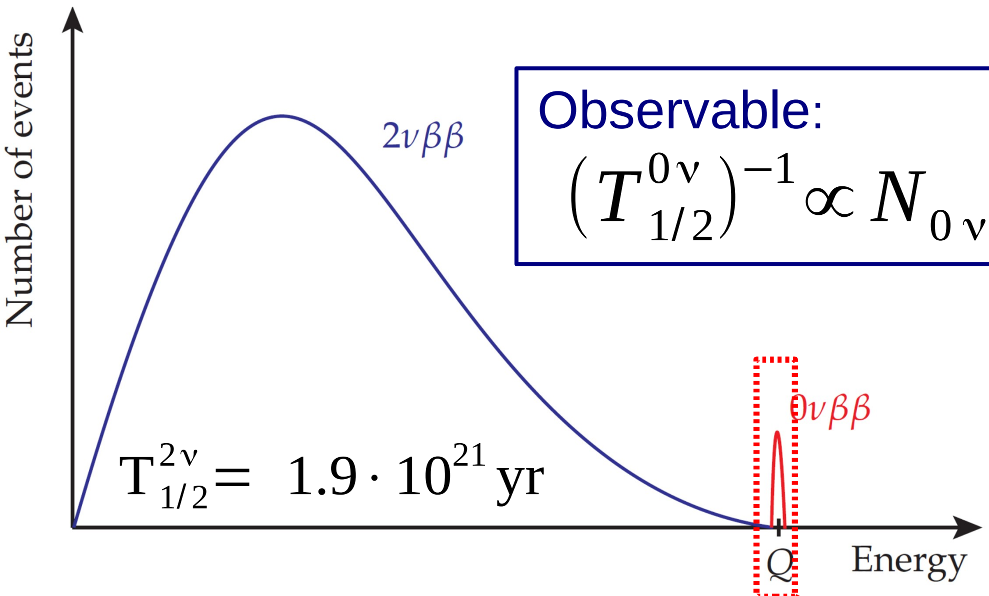
Rencontres de Moriond, Electro Weak
La Thuile, March 24 2017

The GERDA Collaboration: searching for neutrinoless double beta decay of ^{76}Ge

Signature & Experimental Challenges

- Measure sum energy of electrons



Observable:

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

- zero background regime

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

- background, i.e. statistical fluctuation limited scenario

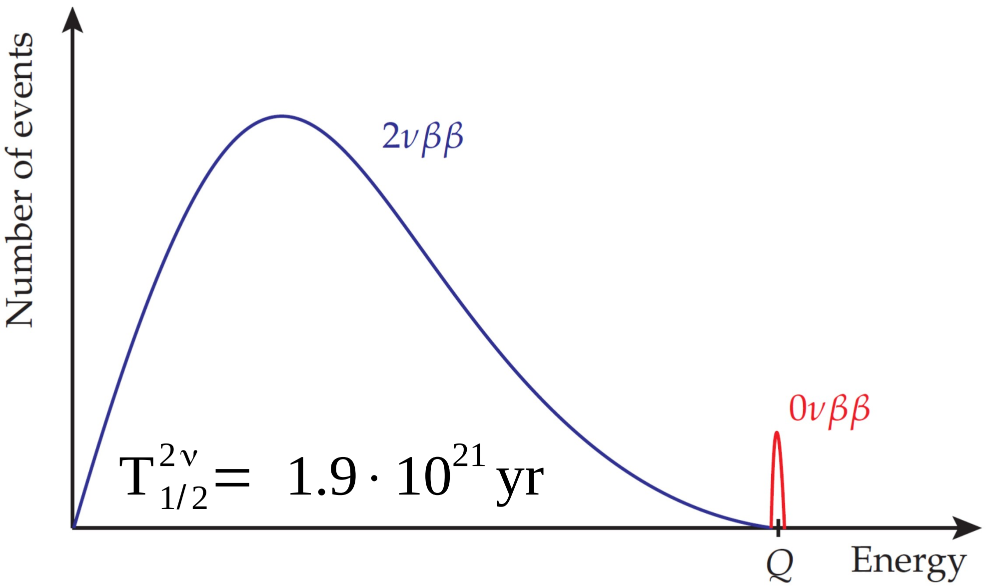
$$T^{0\nu}_{1/2} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

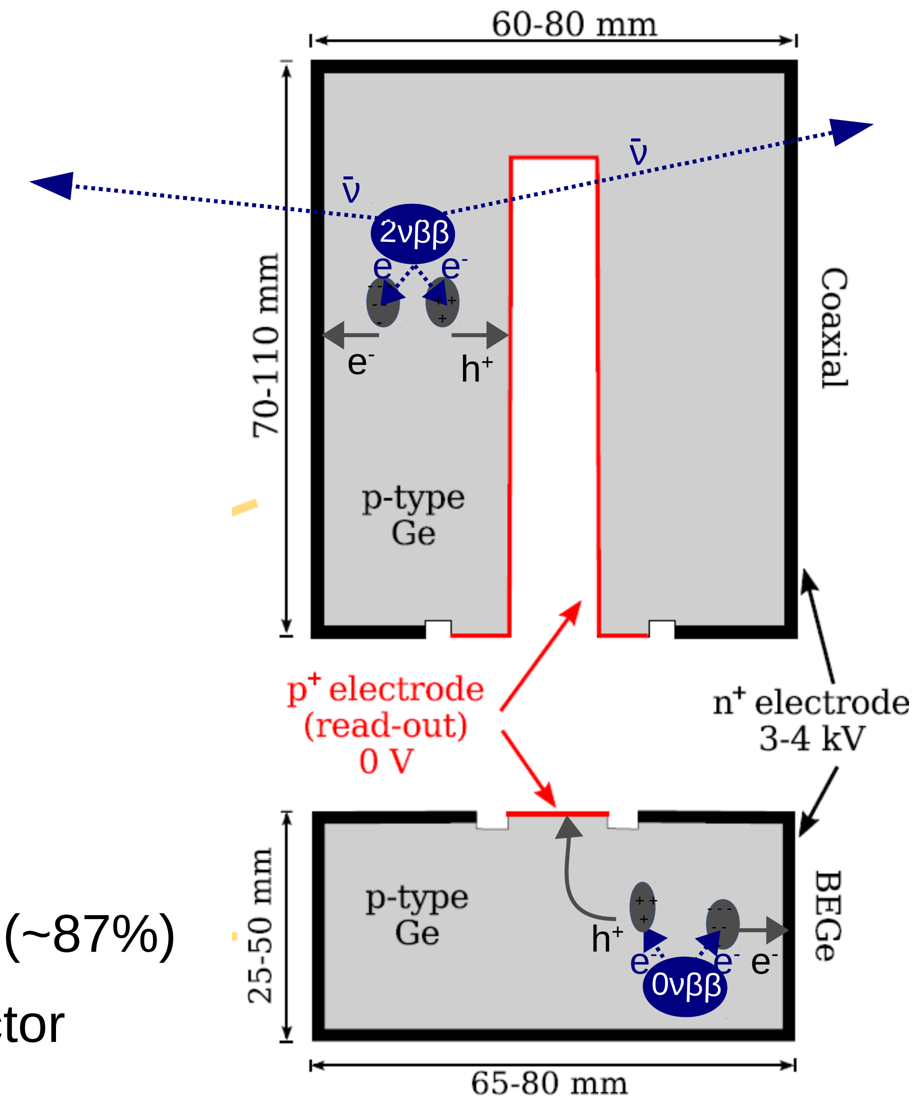
M·t: exposure [kg yr], ΔE: energy resolution,
BI: background index [counts/(keV kg yr)]

Need to achieve
- < 1 bck event in ROI
- excellent energy resolution

Germanium Detectors

- Measure sum energy of electrons

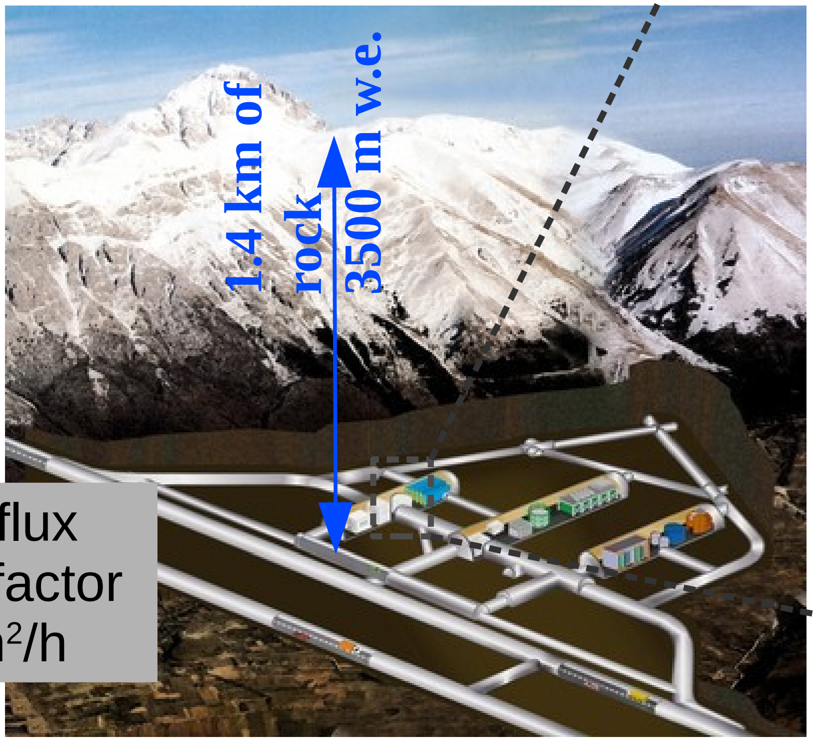




High Purity Germanium (HPGe) Detectors

- 3-4 keV FWHM at $Q_{\beta\beta}$ = 2039 keV (0.2%)
- HPGe detectors isotopically **enriched** in ^{76}Ge (~87%)
- high detection efficiency of ββ: source = detector
- “no” intrinsic background [Astropart.Phys. 91 (2017) 15-21]
- discrimination of signal- from background like events using pulse shape analysis

GERDA @ LNGS



cosmic muon flux reduced by a factor ~ 10^6 → 1 μ/m²/h

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

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

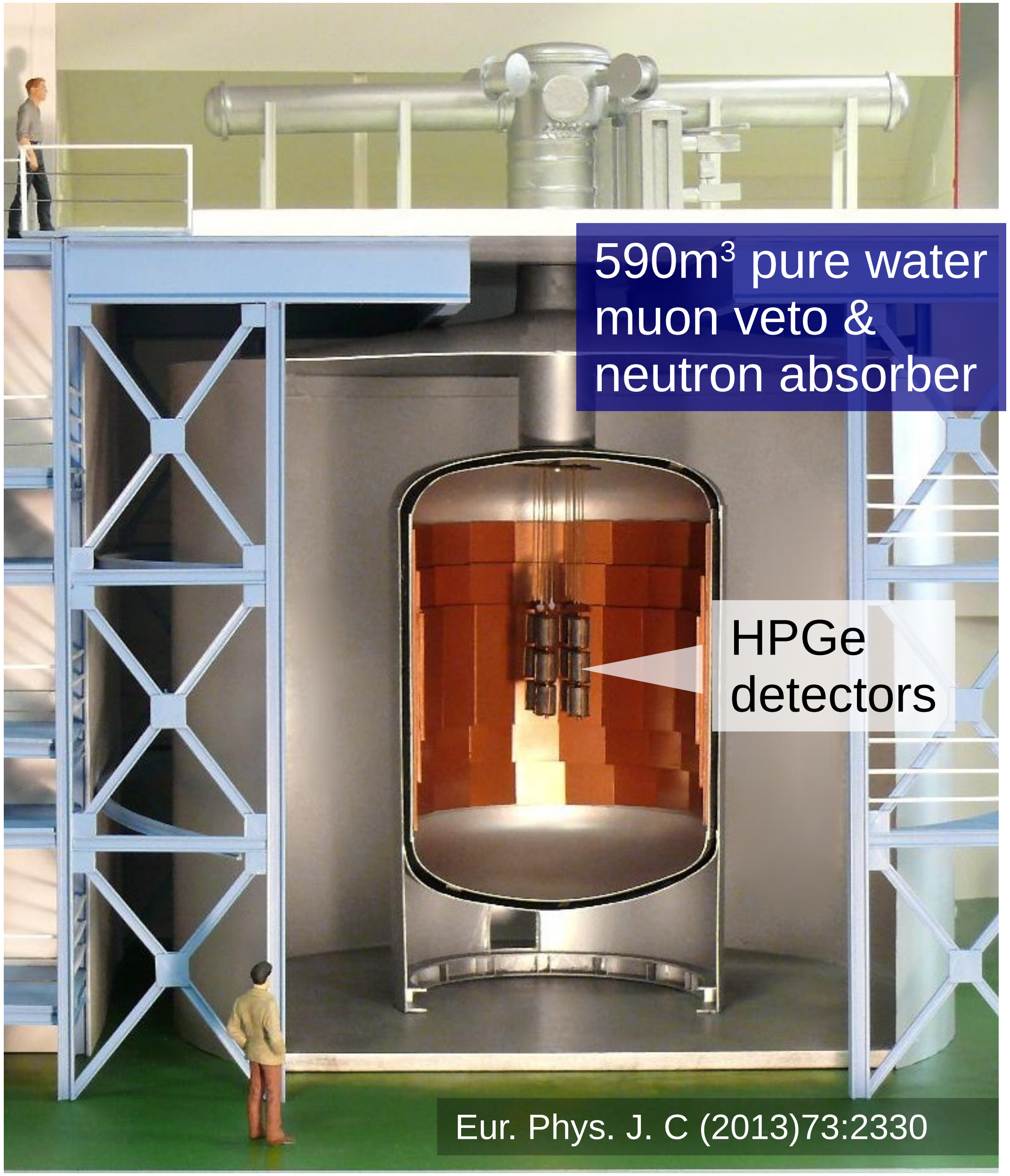
GERDA Phase I (Nov 2011- May 2013)

- **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)

GERDA Phase II (Dec 2015 -)

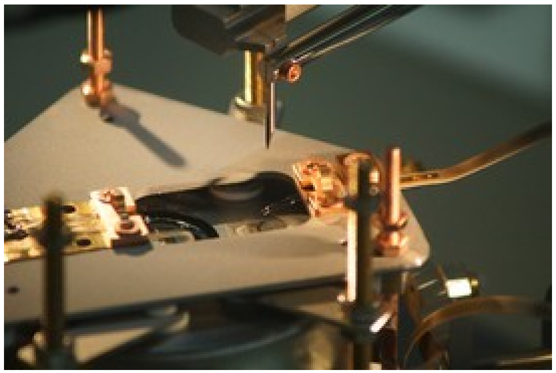
- **30** enriched **BEGe** (= **20.0 kg**) + 7 enriched semi-coaxial (= **15.6 kg**)
- **LAr instrumentation**
- goal: BI ~ 10^{-3} cts/(keV·kg·yr)

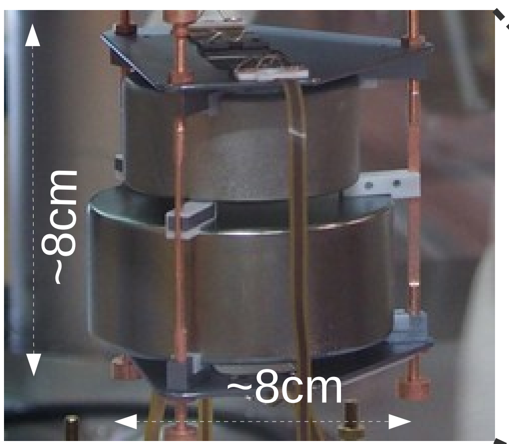


Eur. Phys. J. C (2013)73:2330

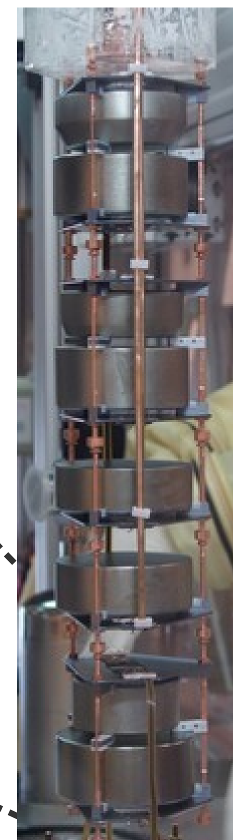
GERDA Phase II Array

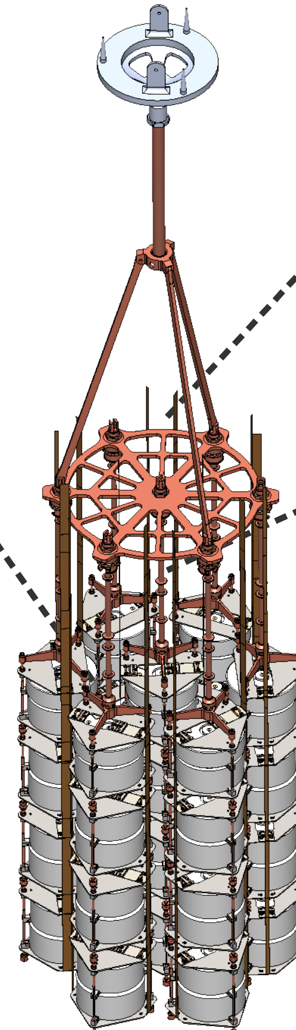
wire bonding for contacting

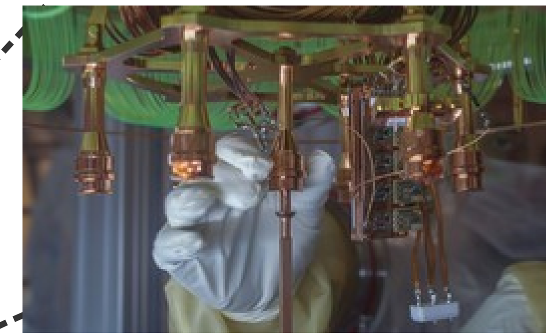




new low mass holders with reduced mass and Cu → Si







low radioactivity electronics

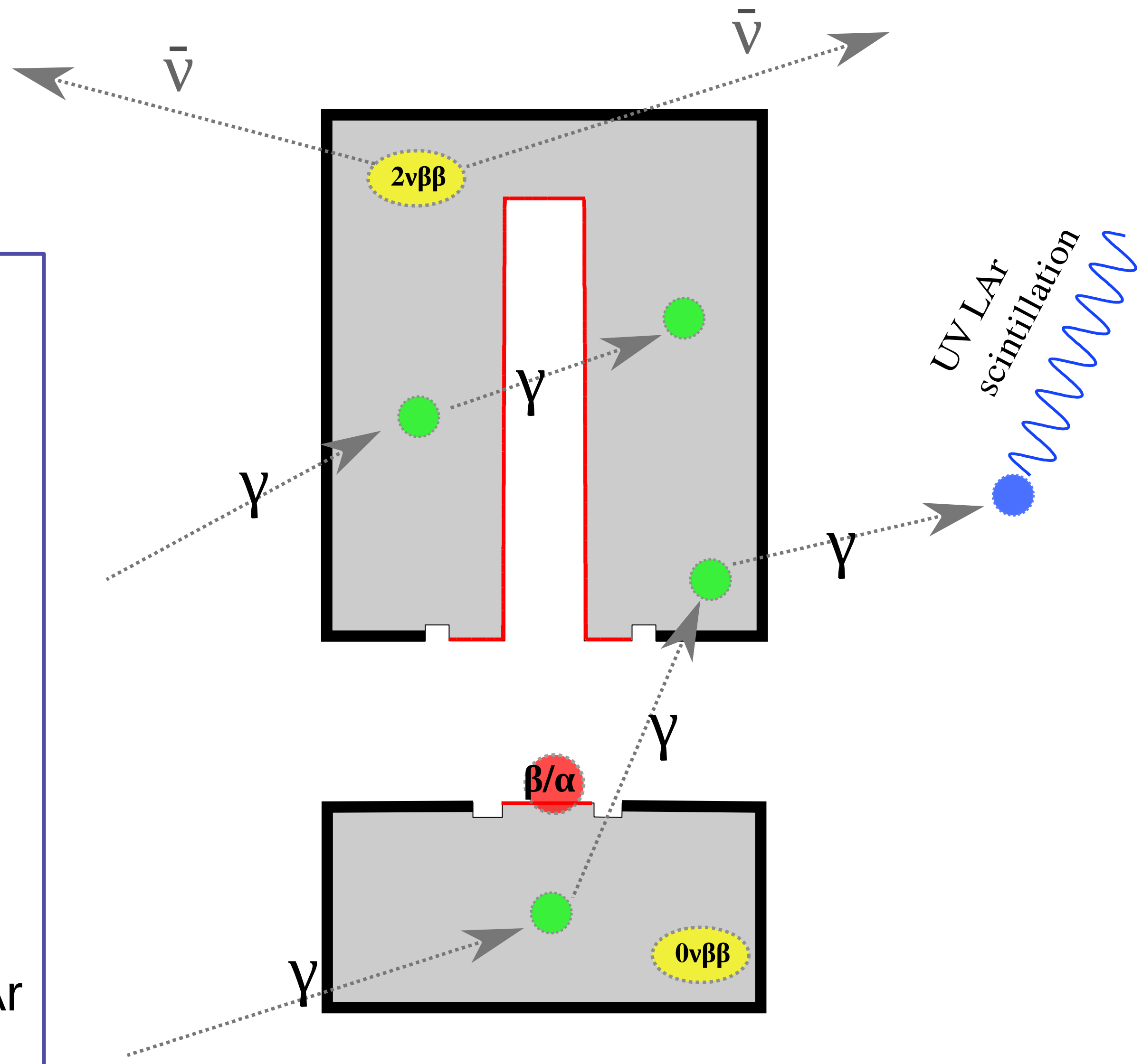
Discriminating Signal from Background Events

ββ event

- local energy deposition (SSE) in single detector

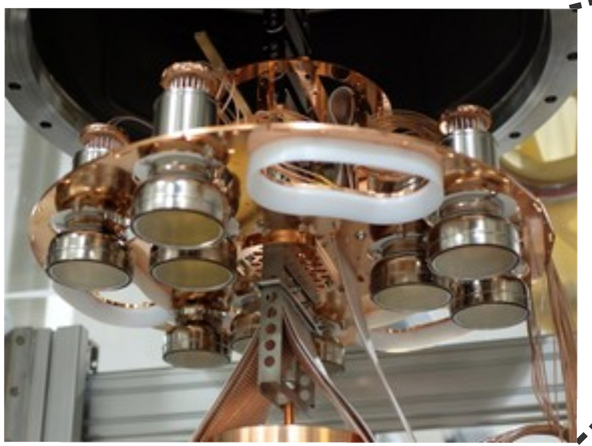
background event

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

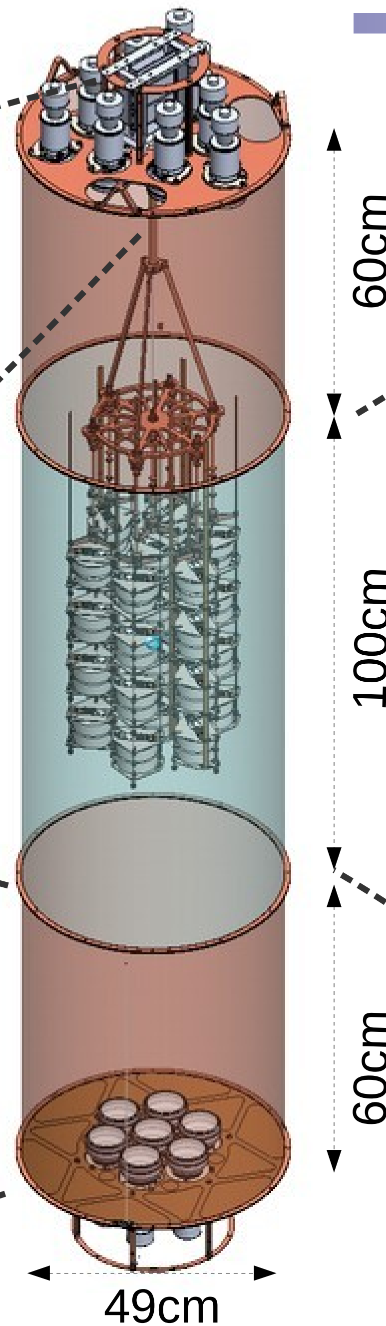


LAr Instrumentation – Hybrid Design

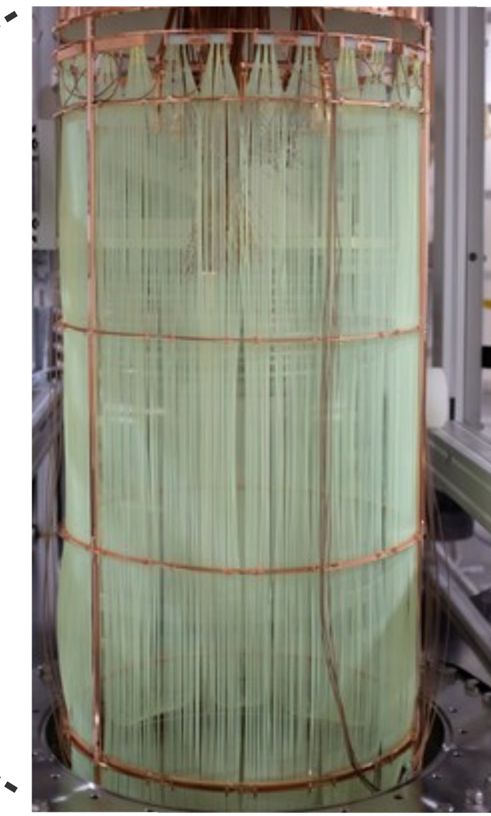
16 photomultiplier tubes (PMTs)



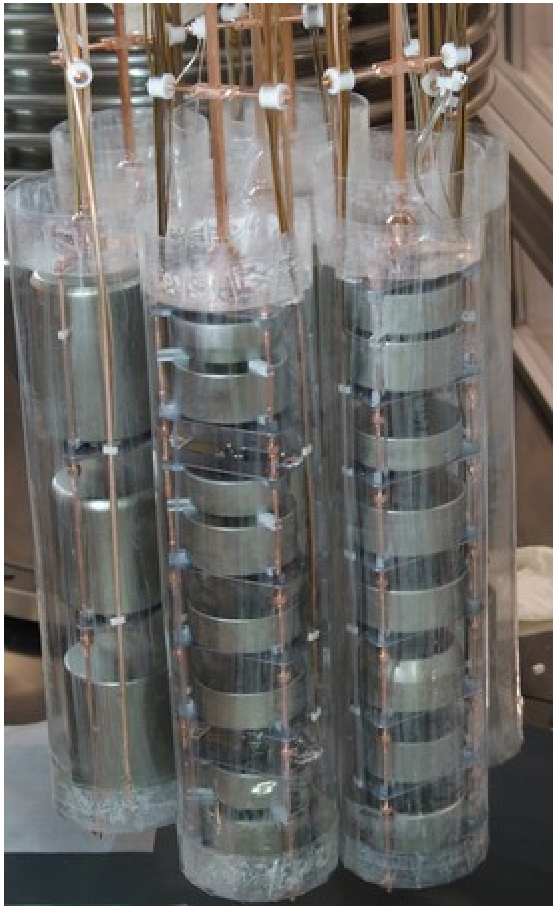
Cu cylinder with wavelength shifting reflector foil



810 wavelength shifting fibers coupled to SiPMs

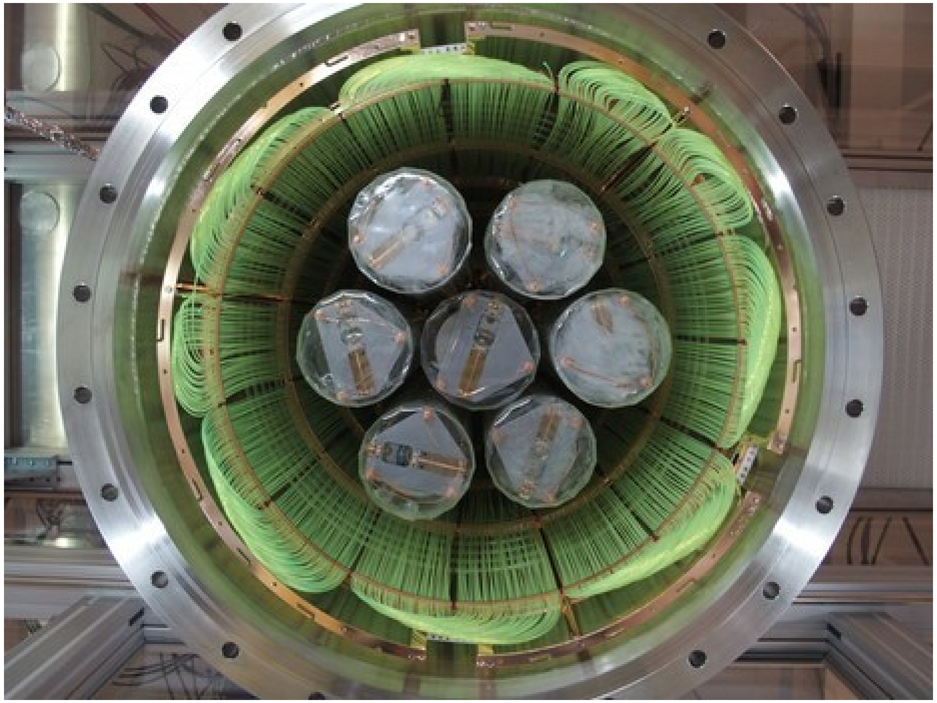


Start of GERDA Phase II

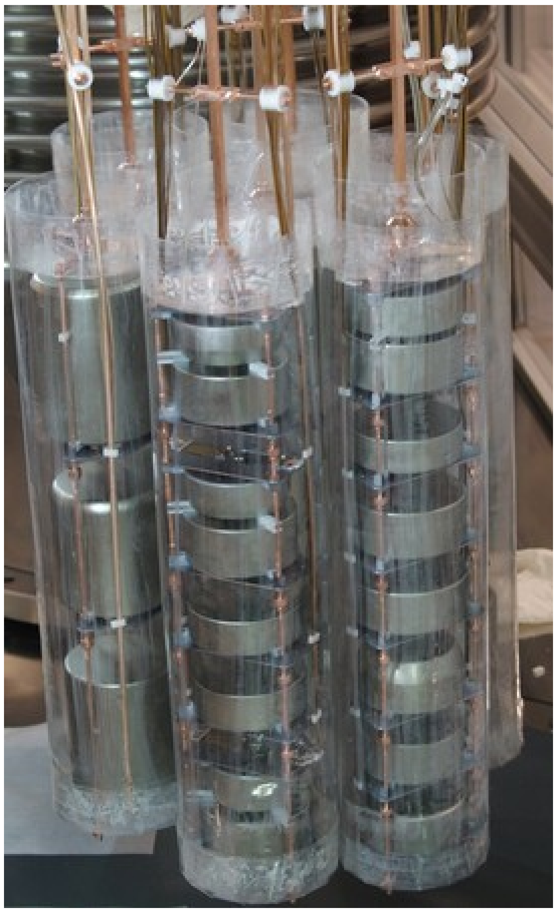
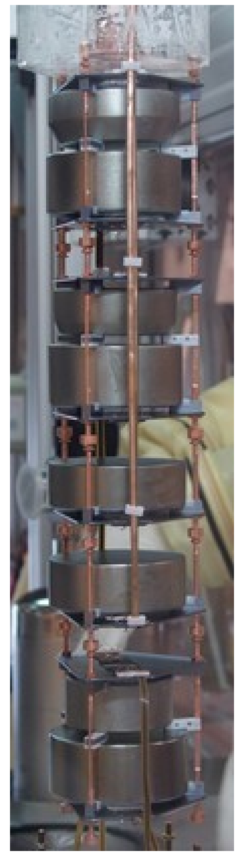


Full Integration of Phase II Array finished in December 2015

- all Ge and LAr detector channels working



Start of GERDA Phase II

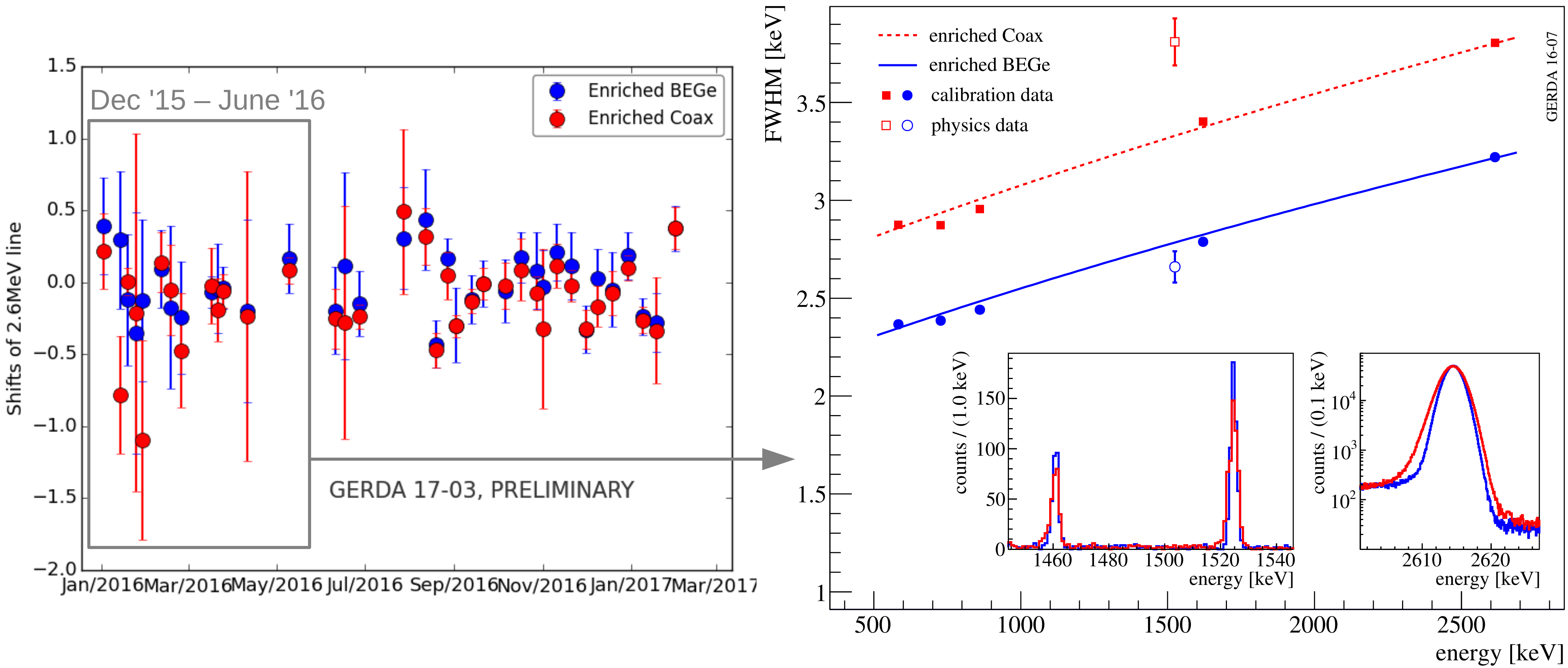
Full Integration of Phase II Array finished in December 2015

- 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 %)

Energy Scale and Resolution

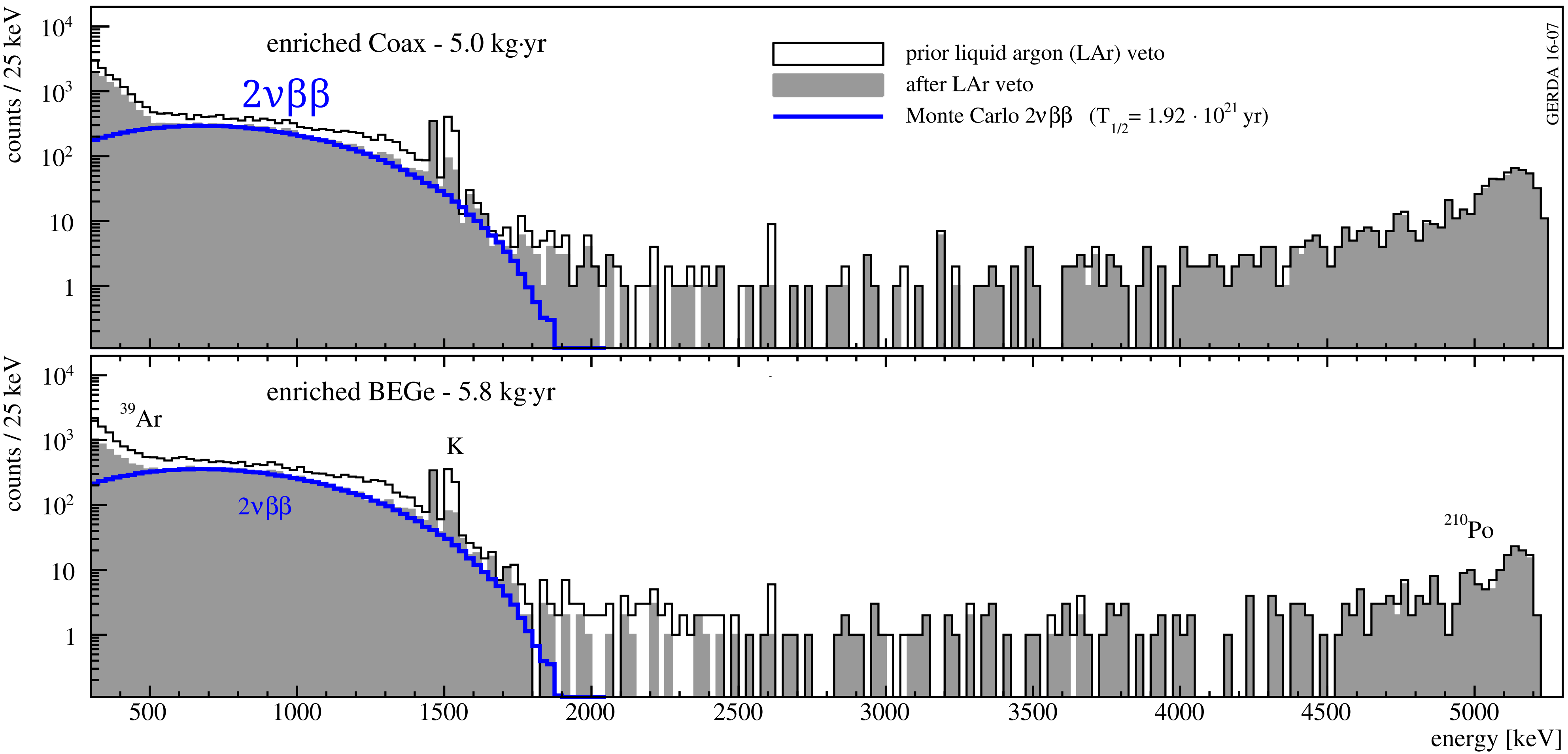


FWHM @ $Q_{\beta\beta}$:

- BEGe's: 3.0(2) keV
- Coax: 4.0(2) keV

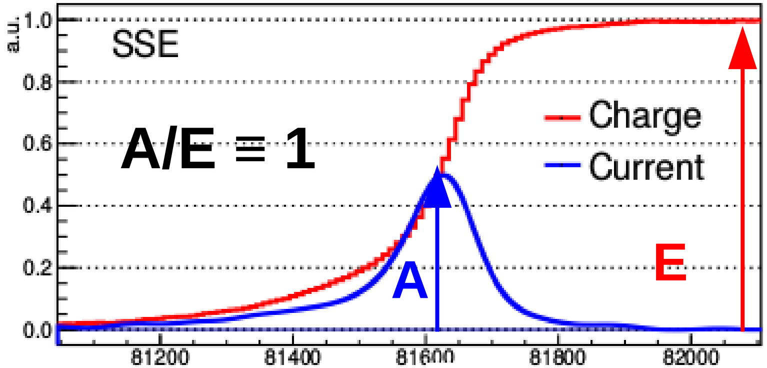
Performance of the LAr Veto

- 2νββ:bck = 96:4 (1.0-1.3 MeV)

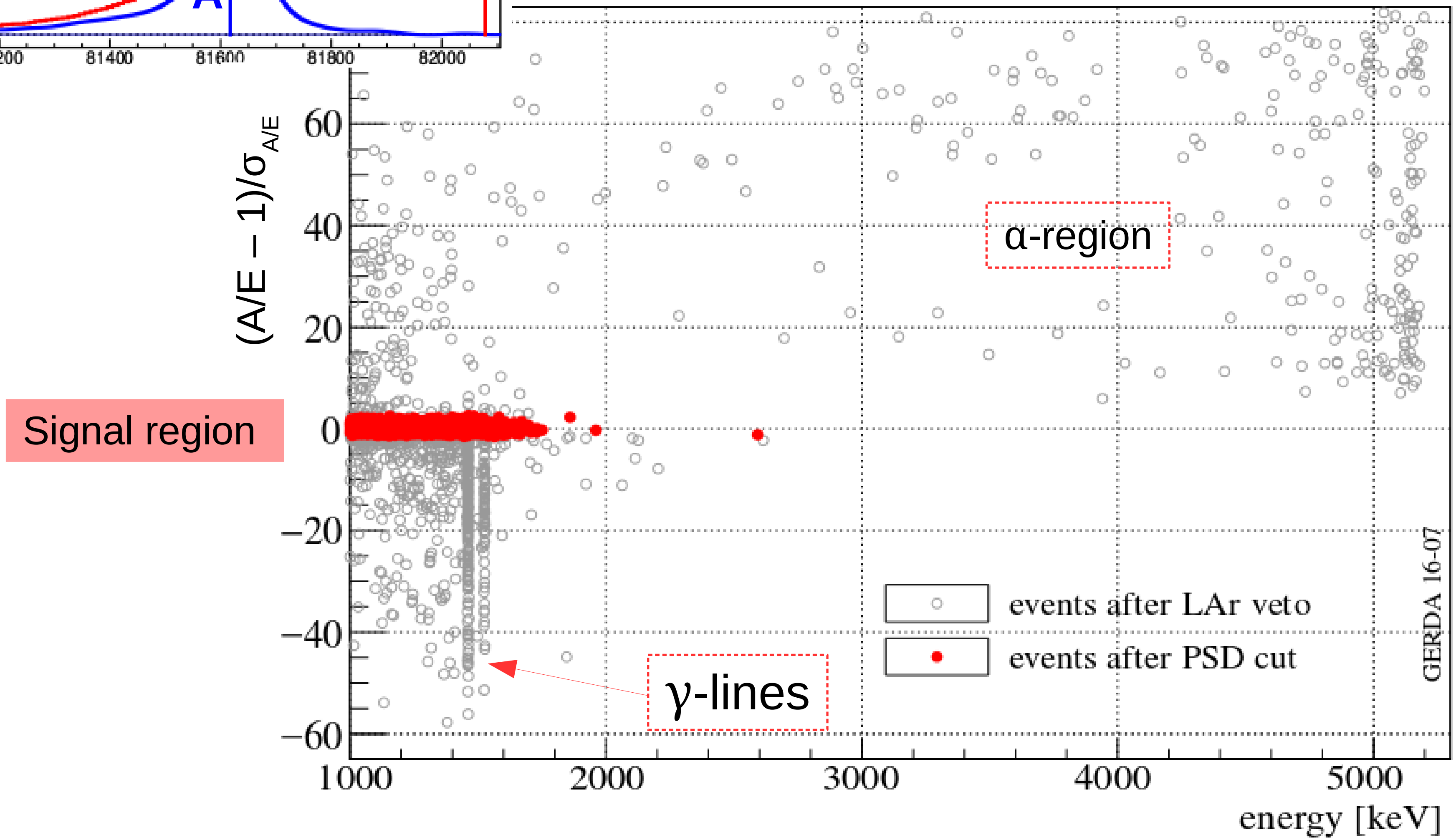


2νββ MC with $T_{1/2} = 1.9 \cdot 10^{21}$ yr from Phase I EPJC 75 (2015) 416

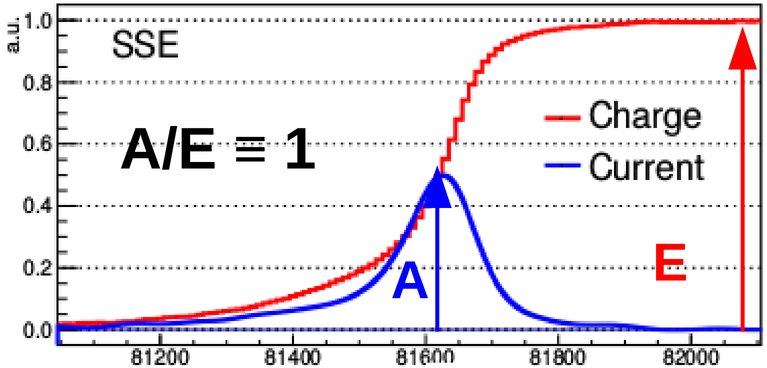
Pulse Shape Analysis: A/E for BEGe



detector current time profile
used to discriminate signal from background events

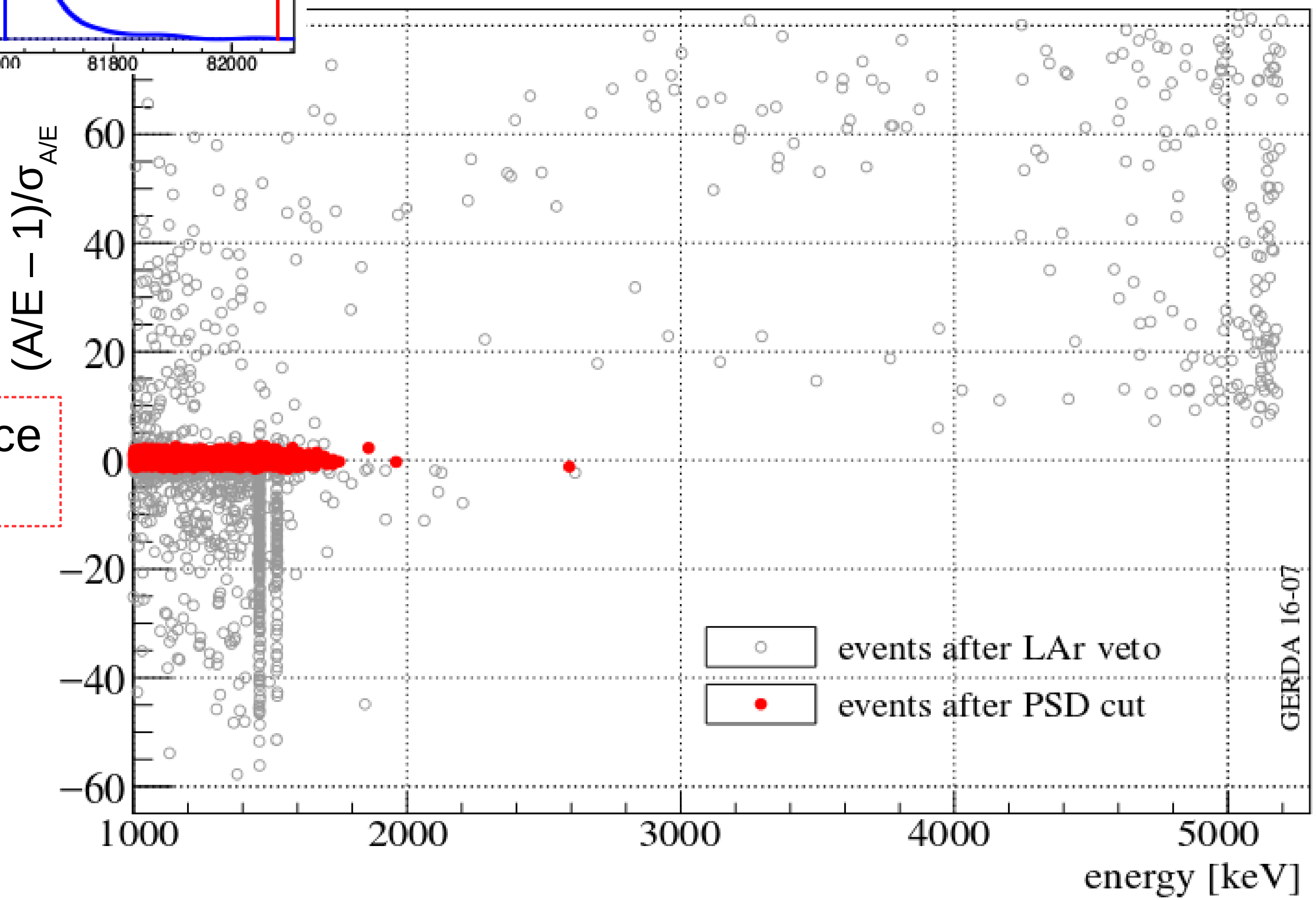


A/E Analysis for BEGe's



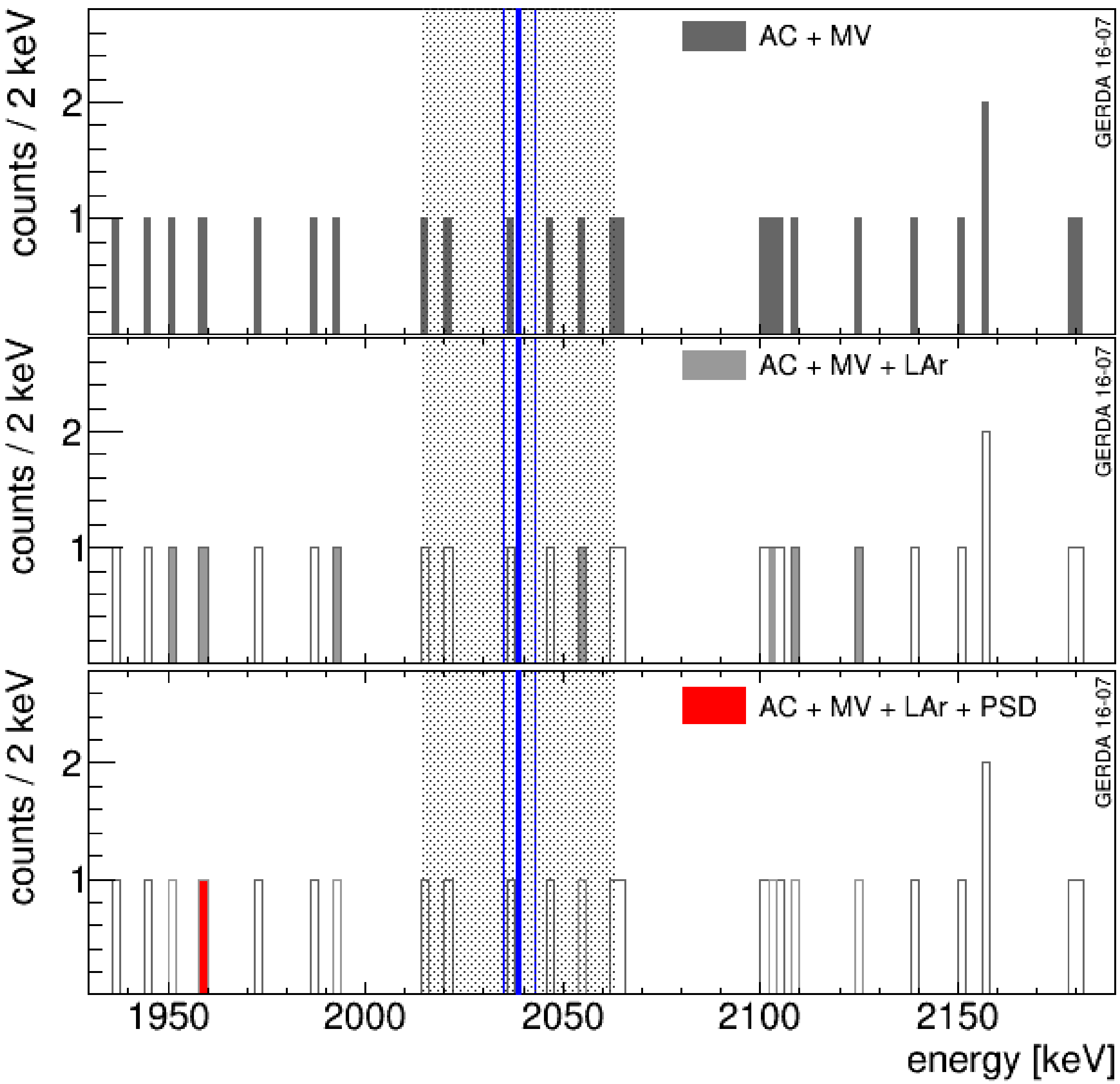
80% of background events rejected at $Q_{\beta\beta}$ and keep high signal efficiency = **87(2) %**

2νββ acceptance 85^{+2}_{-1} %



Background Suppression LAr + PSD

BEGe, 5.8 kg · yr

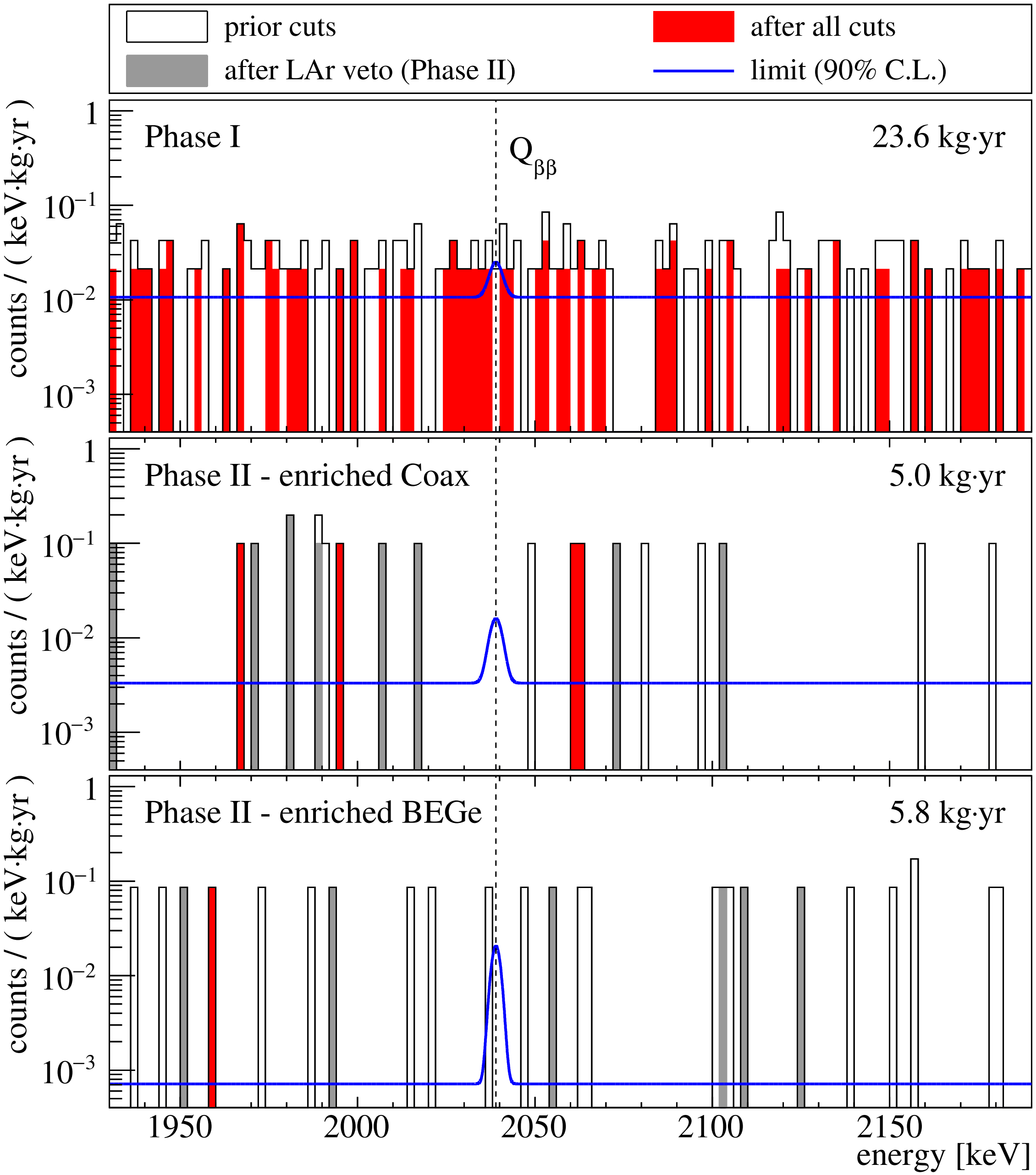


$$BI^{AC,MV} = 15.7^{+3.8}_{-3.1} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

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

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

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

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

Current Status of GERDA

Preliminary

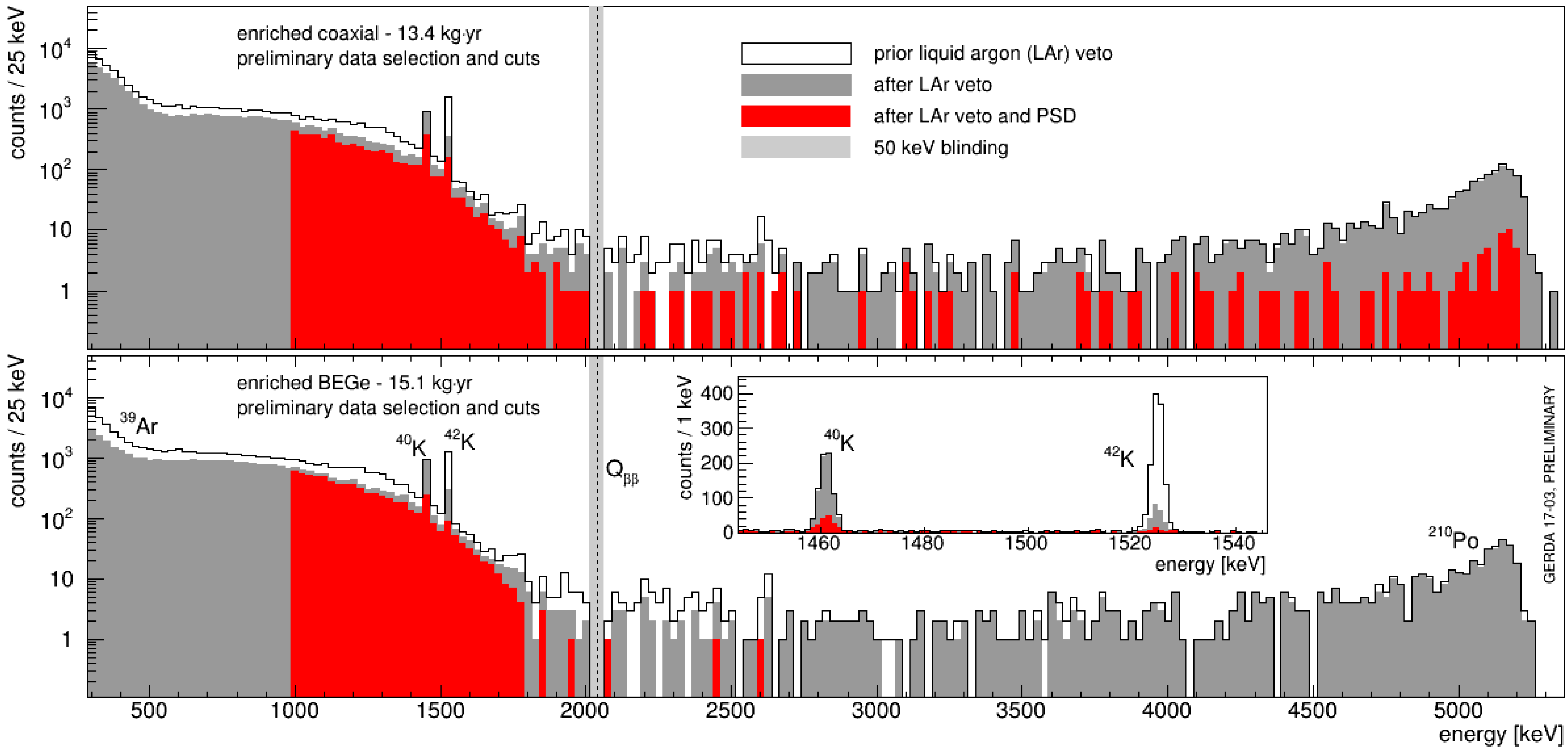
- since summer 2016 additional (blinded) data
- after LAr veto and PSD:

BEGe

$$BI = 0.6^{+0.6}_{-0.4} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

Coax

$$BI = 2.2^{+1.1}_{-0.8} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$



Conclusion

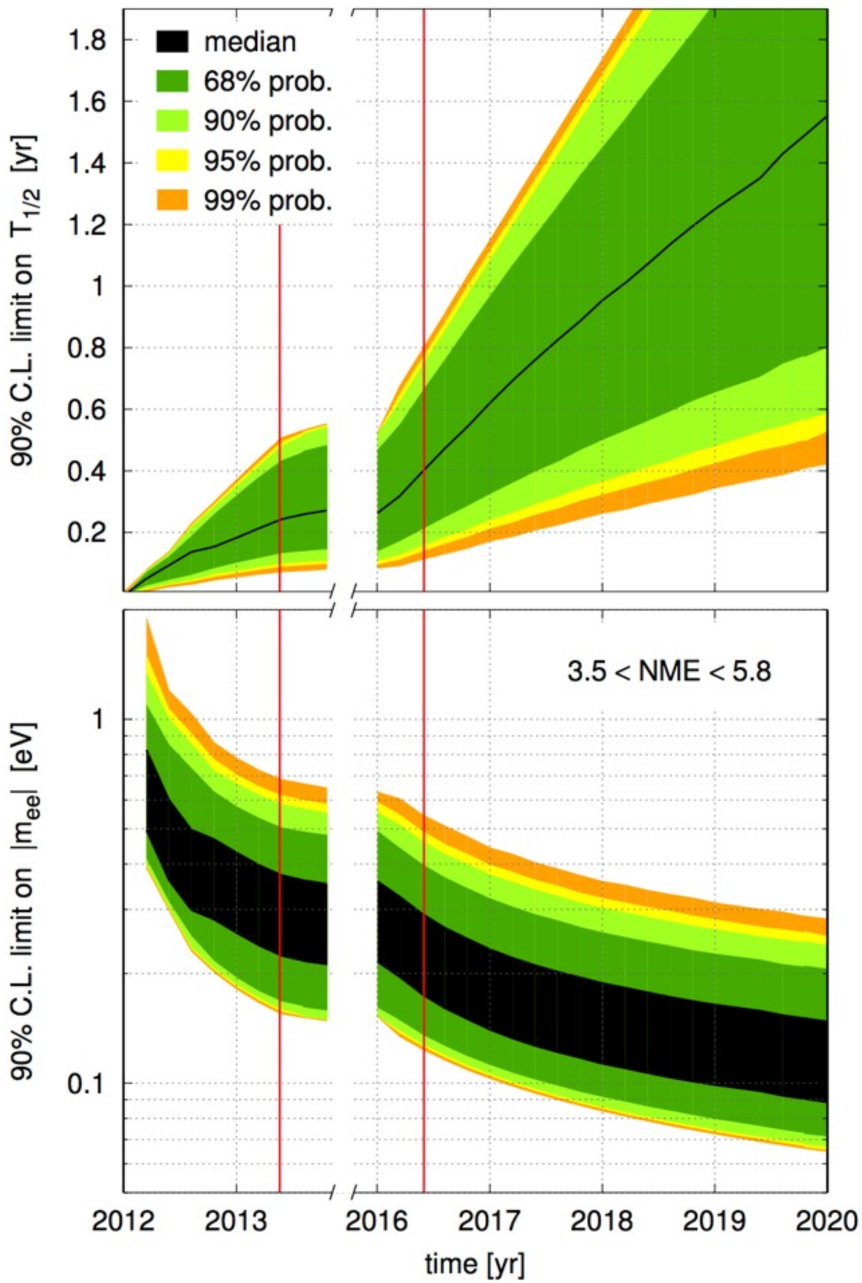
- GERDA sets new limit on the half-life of $0\nu\beta\beta$ decay of ^{76}Ge

$$T_{1/2}^{0\nu} > 5.3 \cdot 10^{25}\, yr\ @\ 90\ C.L.$$

$$m_{\beta\beta} < (150 - 330)\, meV$$

- best energy resolution: FWHM = 3.0 keV (4.0 keV) BEGe (Coax) at $Q_{\beta\beta}$
- flat background in ROI
- lowest background at $Q_{\beta\beta}$:
  10^{-3} counts/ (keV·kg·yr)
  will stay background-free

→ important ingredients for discovery



Beyond GERDA

- LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay)

- new collaboration formed in Oct 2016
  (=GERDA+Majorana+new groups)

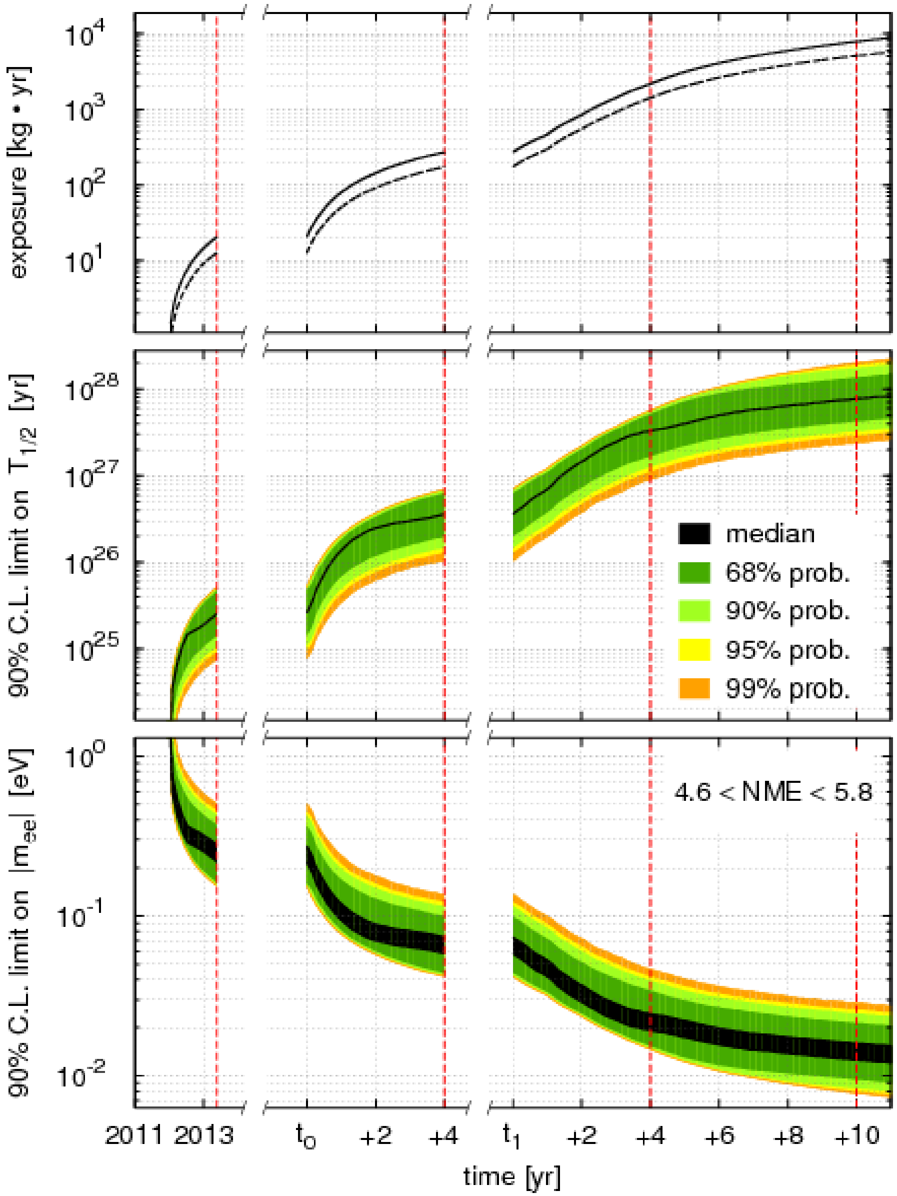
- Goals:

  - 1 t enriched Ge

  - first phase: 200 kg in existing infrastructure @ LNGS

  - reduce background with respect to GERDA → remain background-free

  → **best discovery potential**



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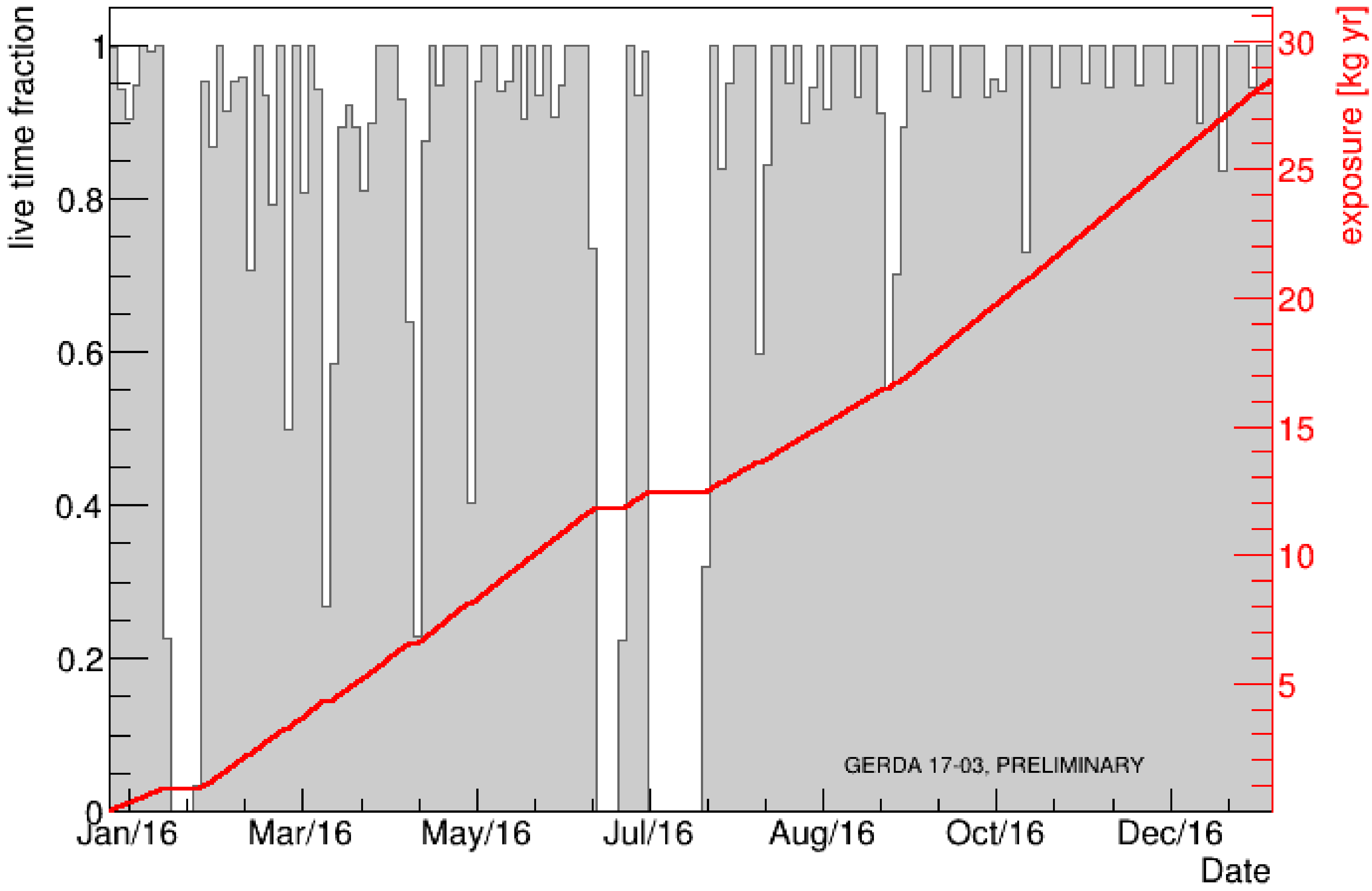
Bonus Slides

Duty Cycle



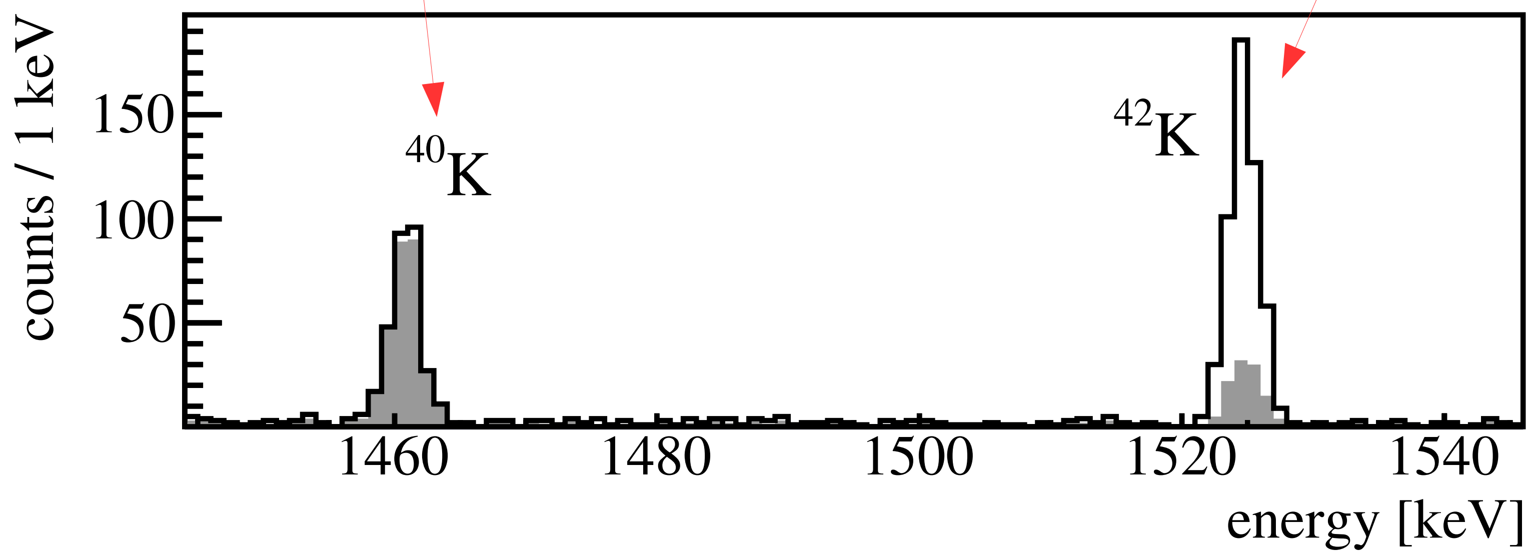
live time fraction
1
0.8
0.6
0.4
0.2
0
Jan/16
Mar/16
May/16
Jul/16
Aug/16
Oct/16
Dec/16
Date
exposure [kg yr]
30
25
20
15
10
5
GERDA 17-03, PRELIMINARY

Performance of the LAr Veto

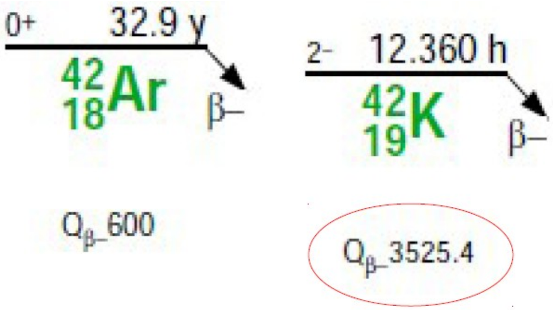
- random coincidences: 2.3%
- ^{42}K line suppressed by factor 5-6

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

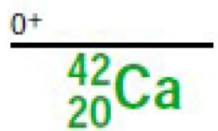
$^{40}K \rightarrow {}^{40}Ar$ (EC)
no energy in LAr



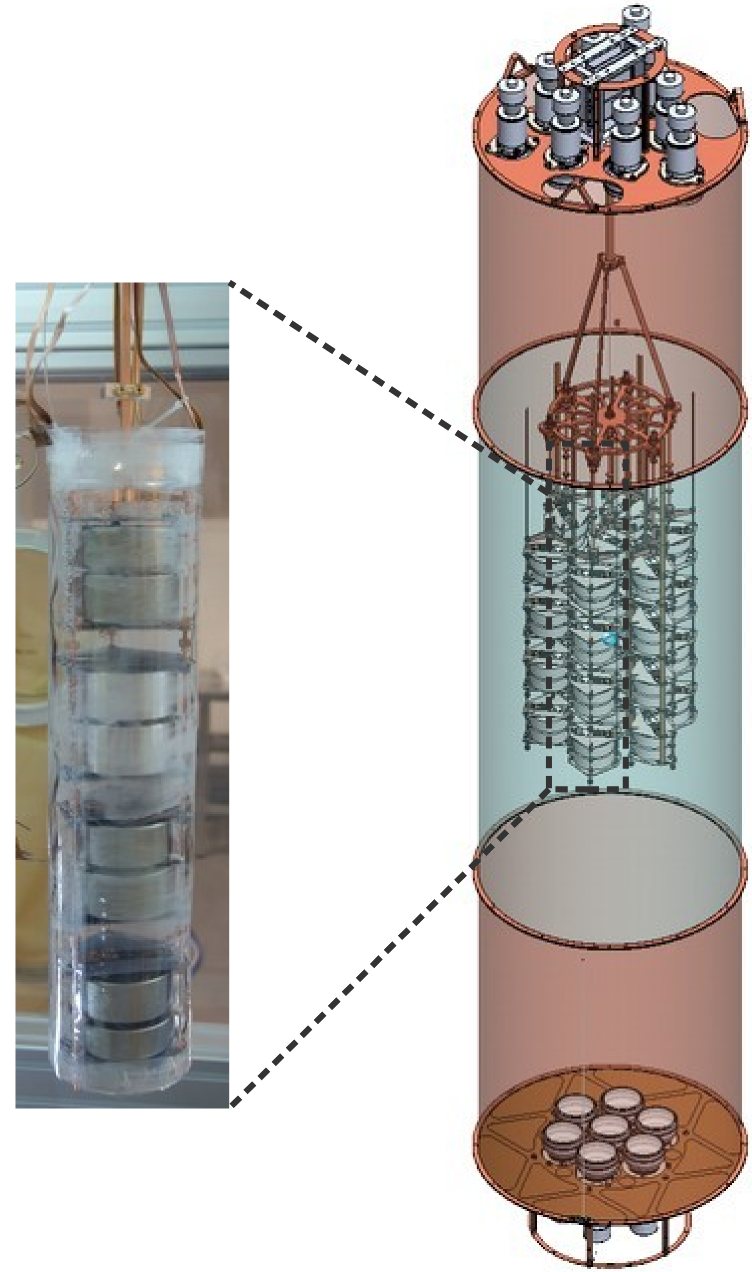
^{42}K Background



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



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



Signals of BEGe's

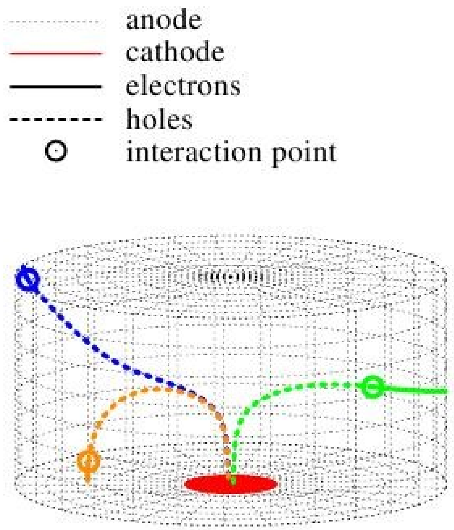
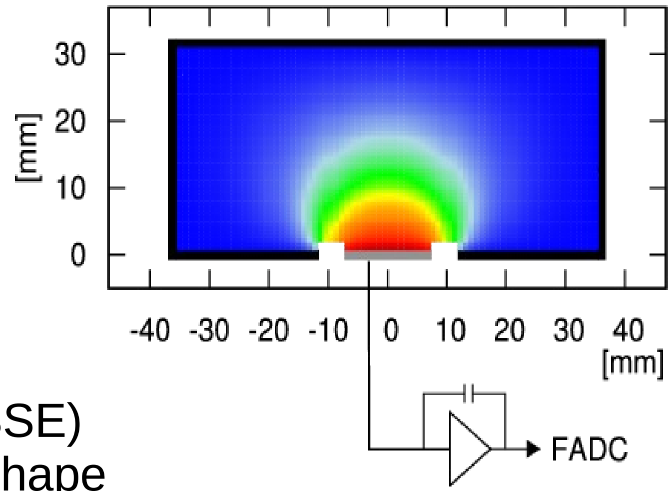


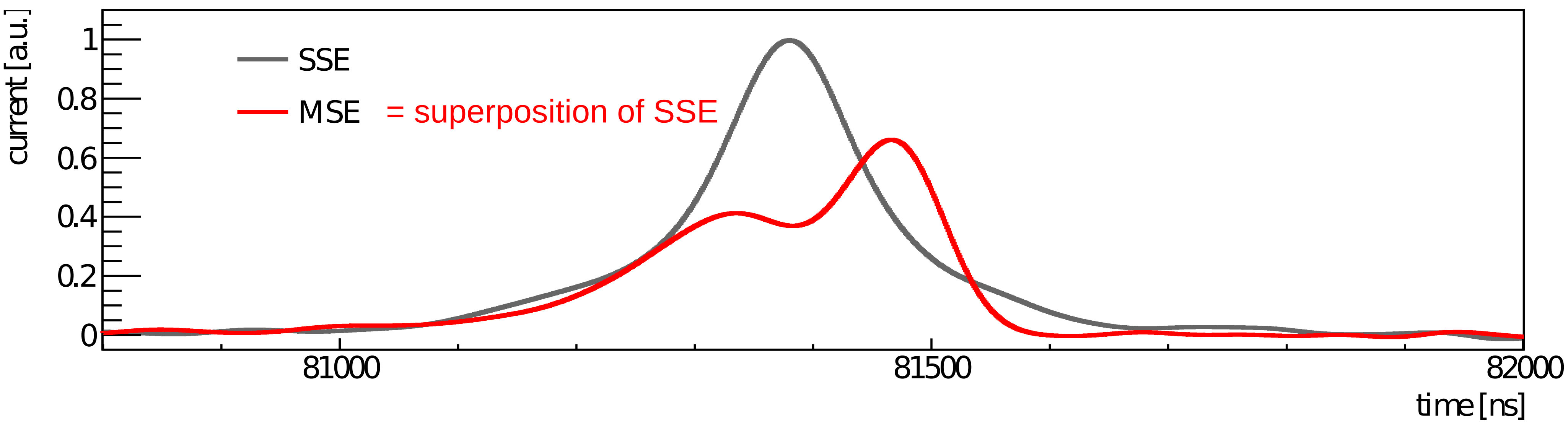
figure taken from JINST 6 P03005, 2011

- final drift paths of holes nearly independent of interaction point
- high gradient of weighting potential

→ single site events (SSE) have similar pulse shape

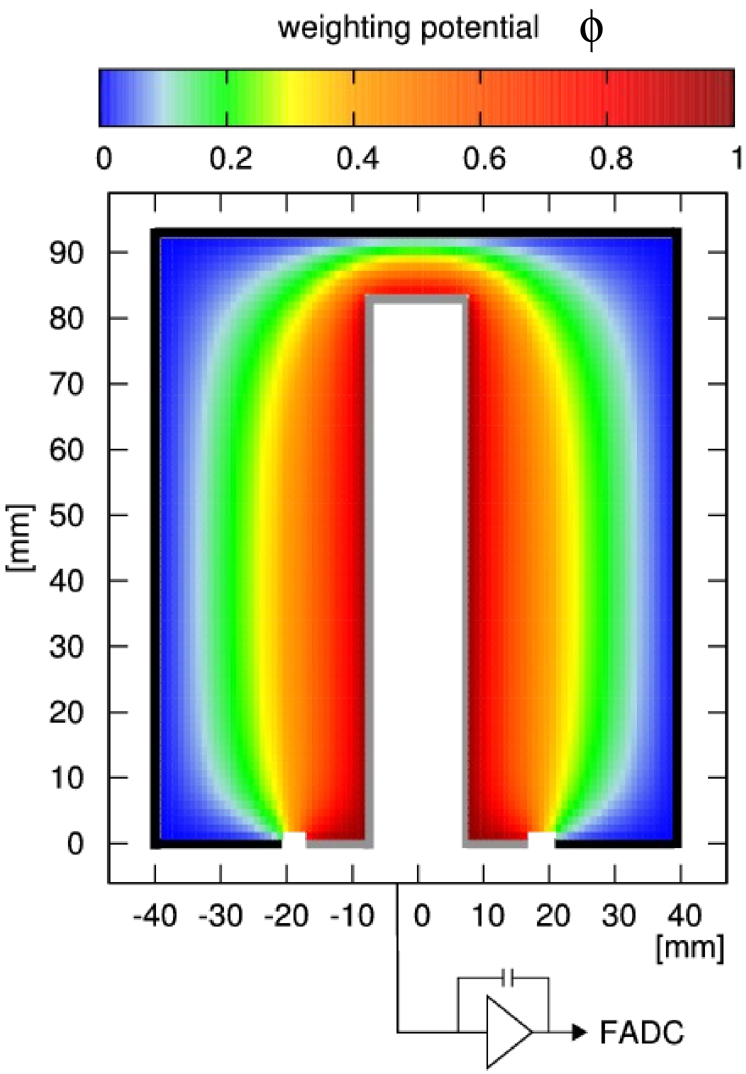


current signal = q · v · Δ ϕ
q: charge, v: velocity

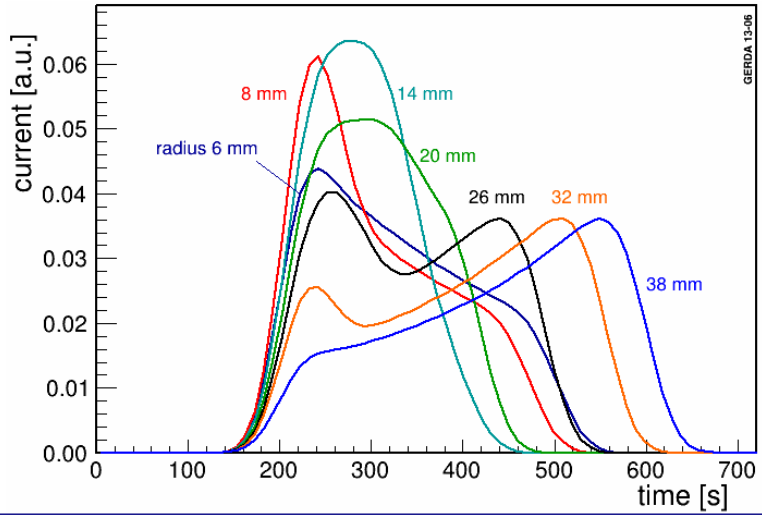


PSD with Coaxial HPGe

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



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

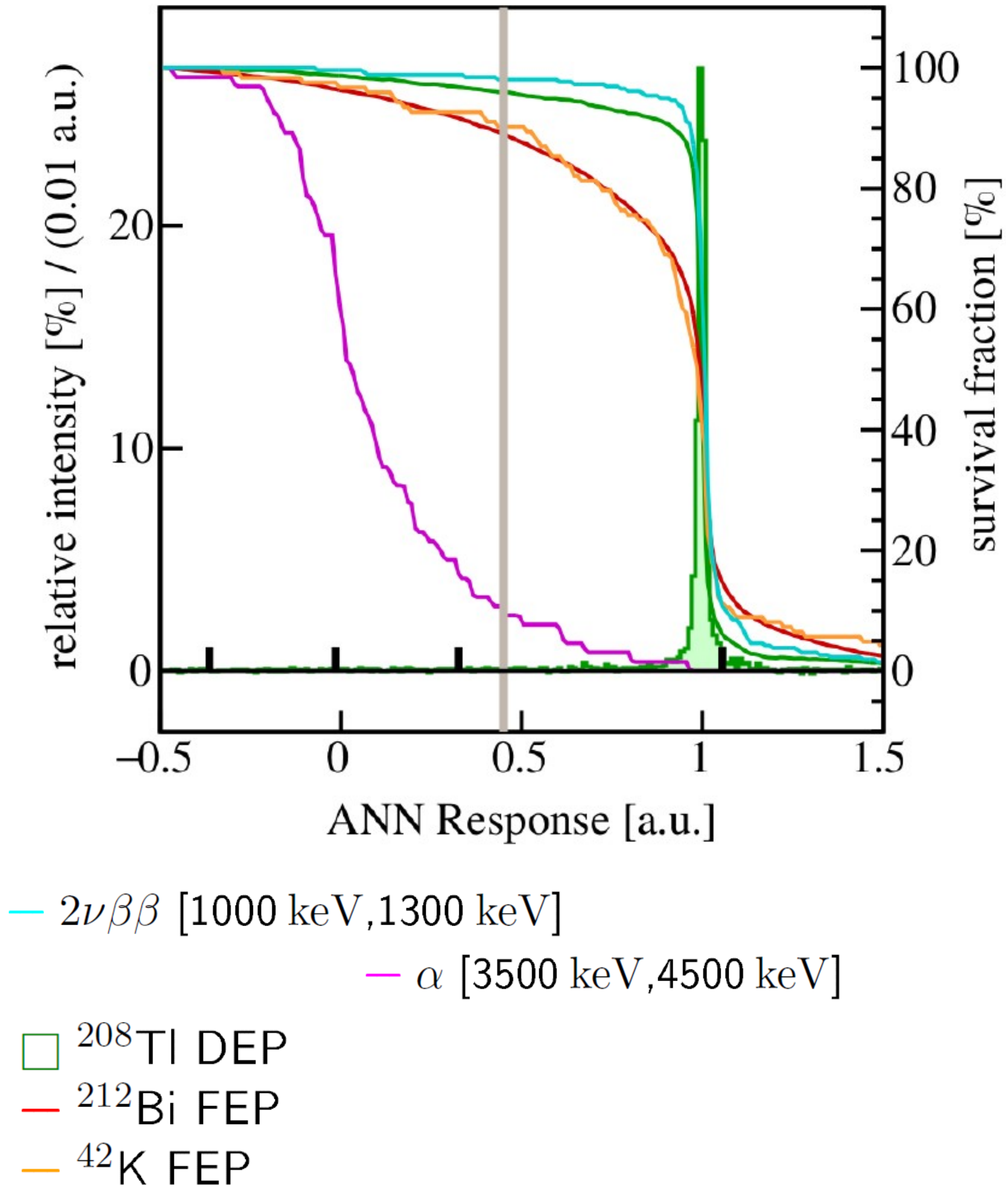


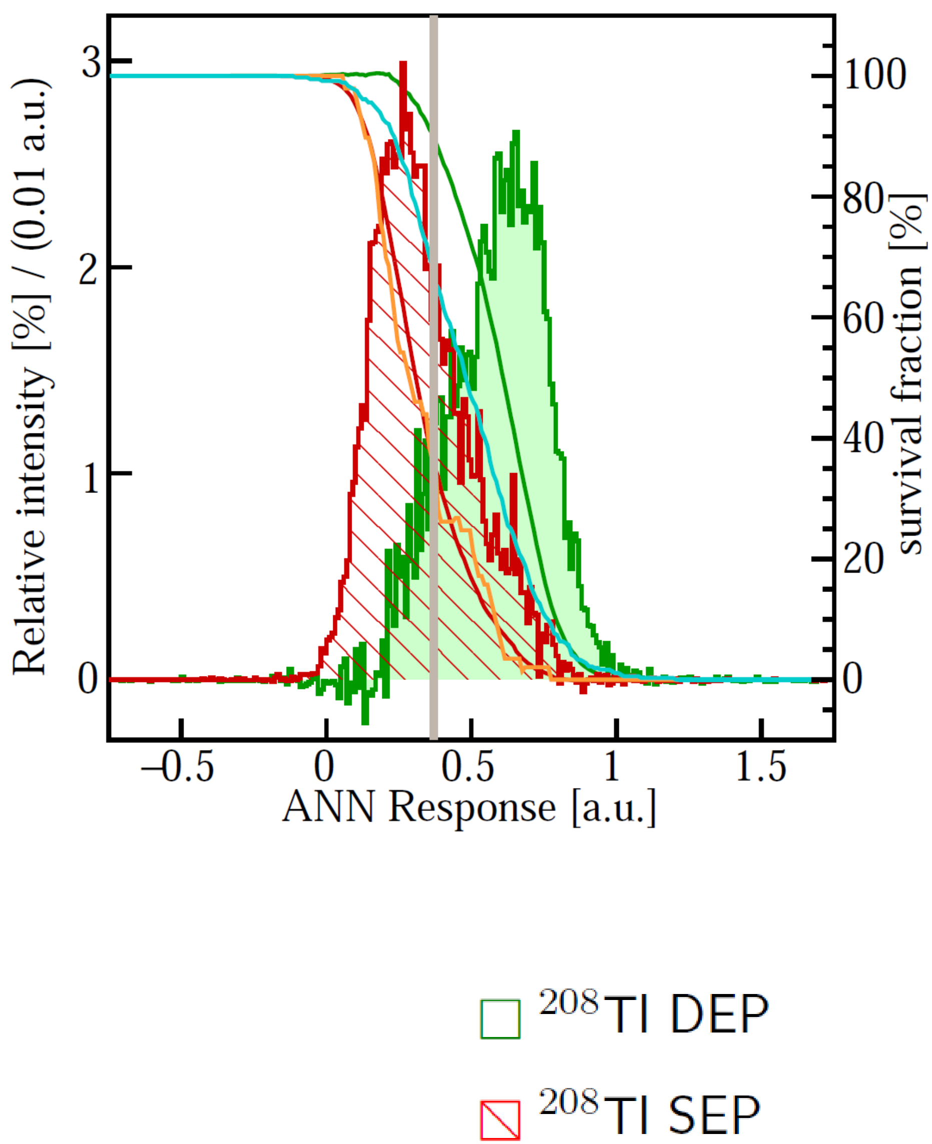
- To identify signal like events artificial neural network algorithm TMlpANN from TMVA is used
- Input variables: times when charge pulse reach 1%, 3%, … , 99% of maximum amplitude
- DEP events of at 1503 keV serve as signal sample
- FEP events at 1621 keV as multi site event sample

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 %

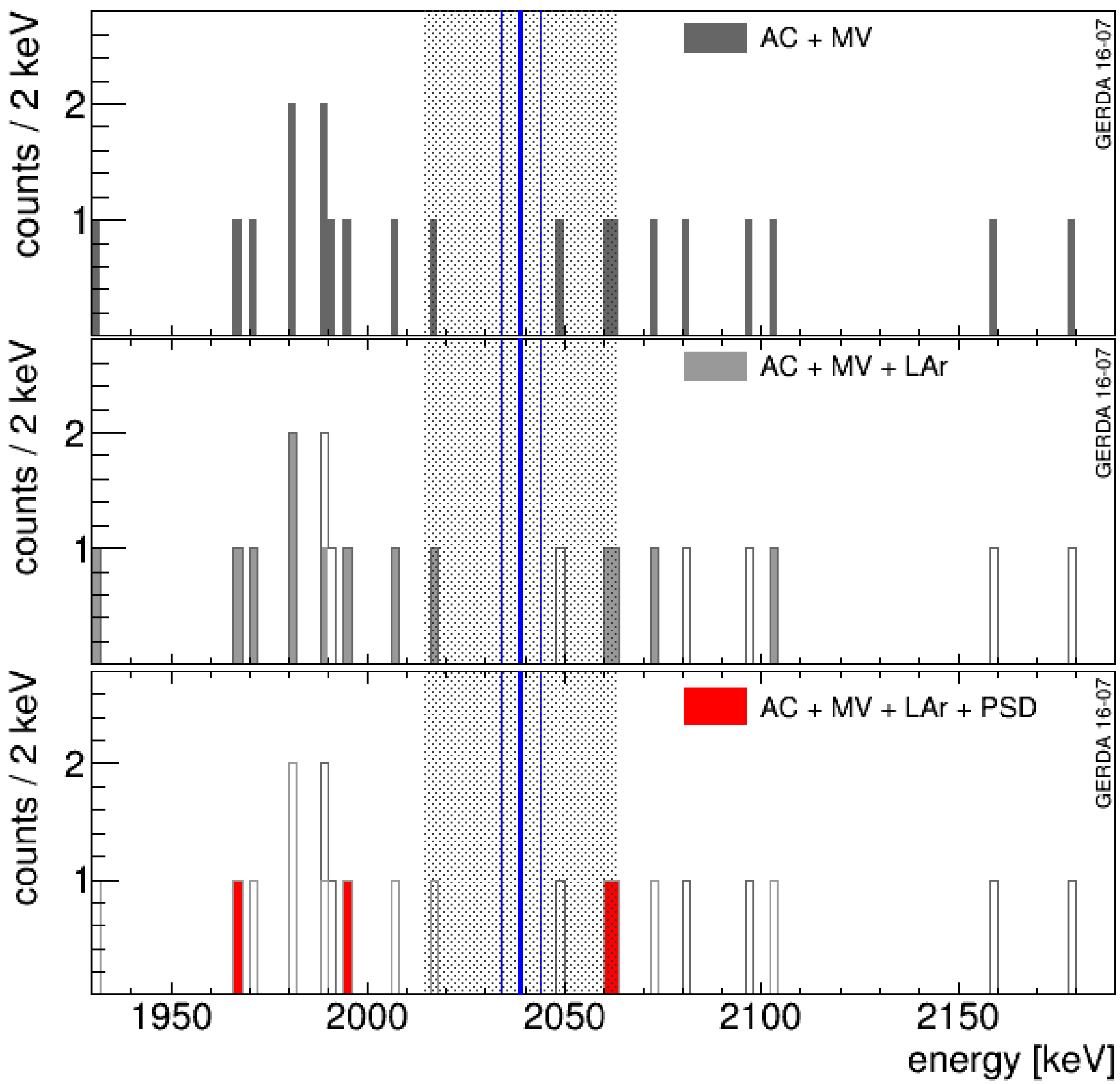
Coax PSD


relative intensity [%] / (0.01 a.u.)
survival fraction [%]
ANN Response [a.u.]
–0.5
0
0.5
1
1.5
0
10
20
0
20
40
60
80
100
— $2\nu\beta\beta$ [1000 keV,1300 keV]
— α [3500 keV,4500 keV]
^{208}Tl DEP
^{212}Bi FEP
^{42}K FEP


Relative intensity [%] / (0.01 a.u.)
survival fraction [%]
ANN Response [a.u.]
–0.5
0
0.5
1
1.5
0
1
2
3
0
20
40
60
80
100
^{208}Tl DEP
^{208}Tl SEP

Background Suppression LAr + PSD

Coax, 5.0 kg · yr



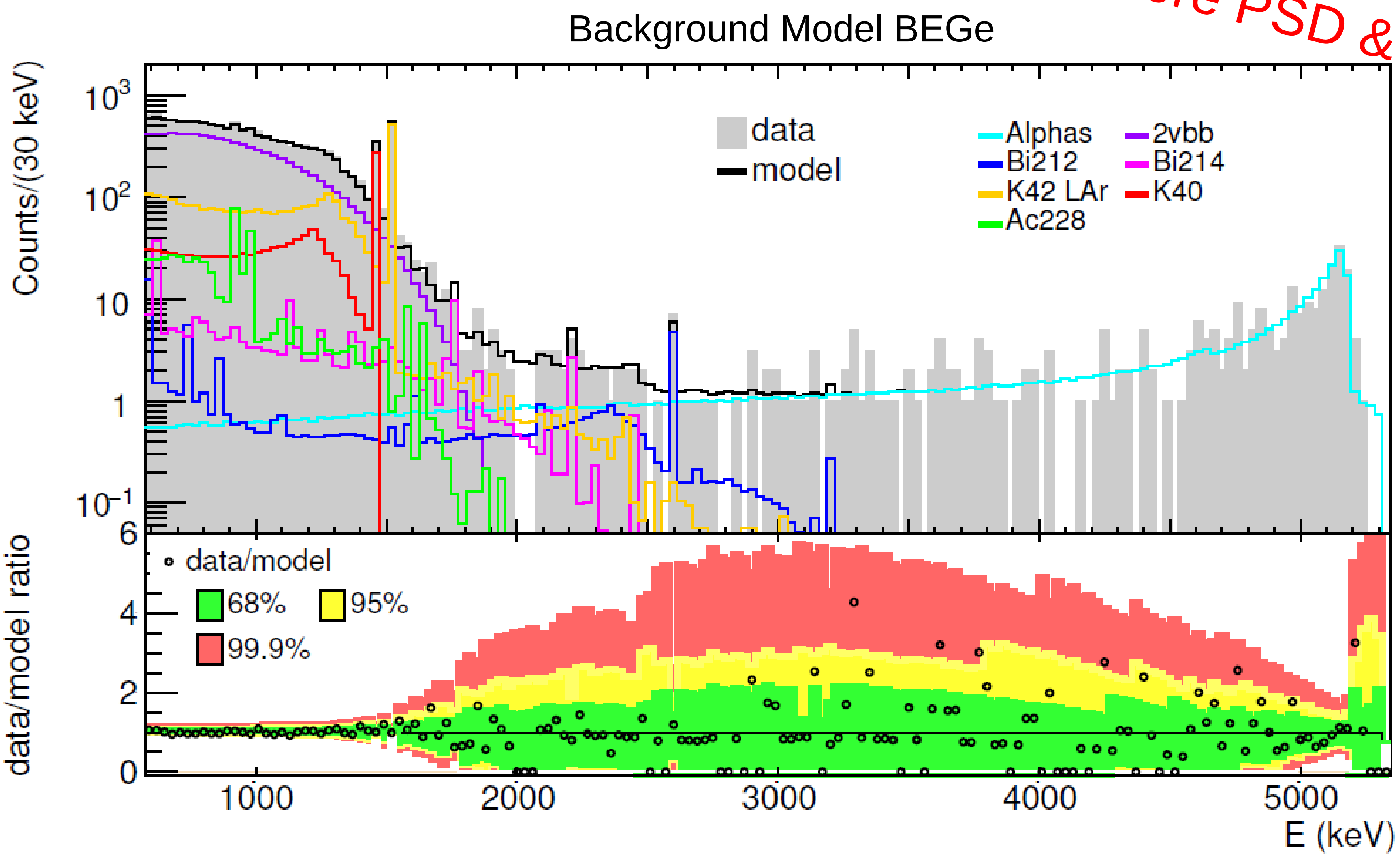
$$BI^{AC,MV} = 16.5^{+4.2}_{-3.5} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

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

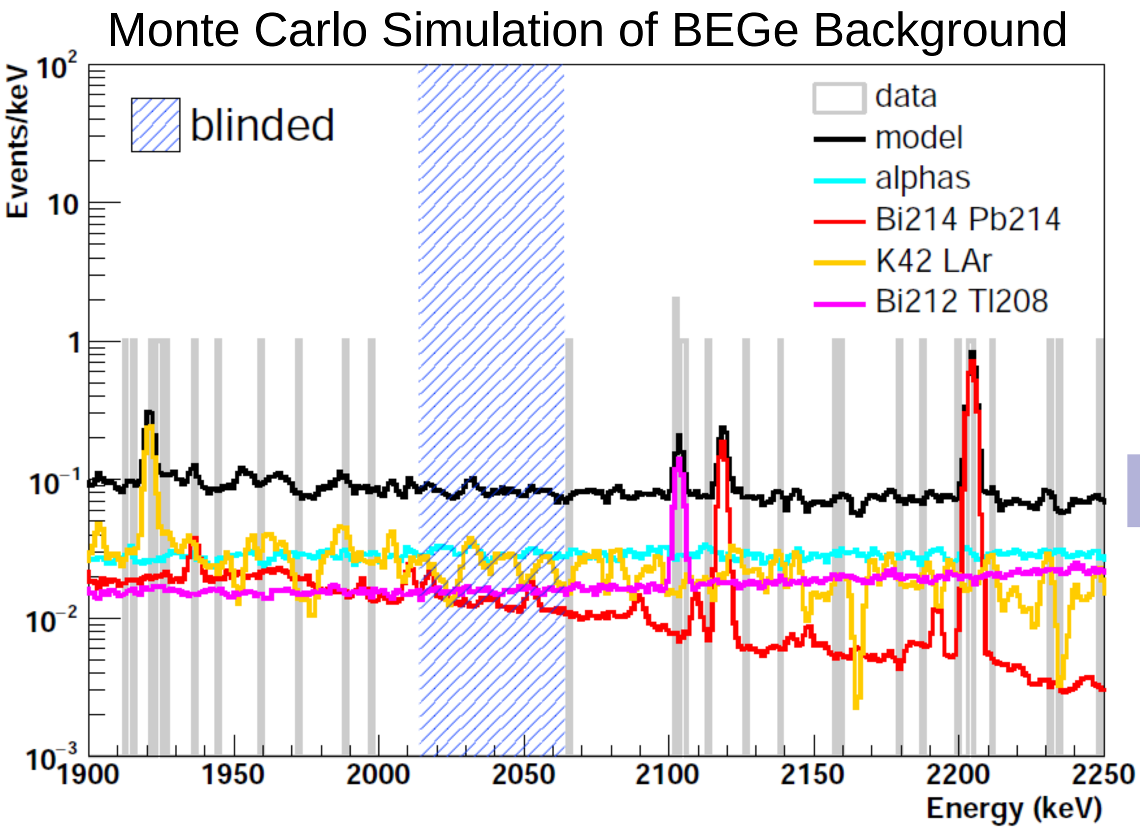
$$BI^{AC,MV,LAr,PSD} = 3.5^{+2.1}_{-1.5} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

Background Model

Preliminary results
before PSD & LAr veto



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



Preliminary results before PSD & LAr veto

expect flat background in ROI

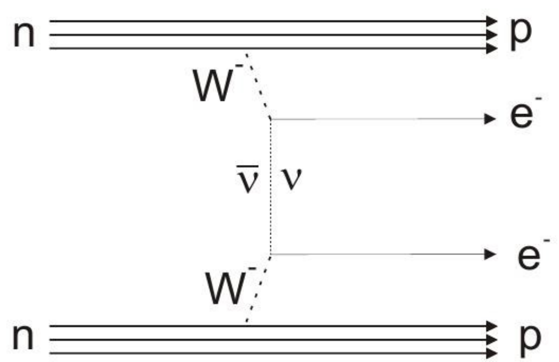
	^{enr}BEGe	^{enr}Coax
α	~ 1/3	~ 1/3
^{214}Bi and ^{208}Tl	~ 1/3	~ 1/3
^{42}K LAr	~ 1/3	~ 1/3
BI counts/(keV kg yr)	0.014	0.015

Effective Majorana Neutrino Mass

Assuming light Majorana neutrino exchange

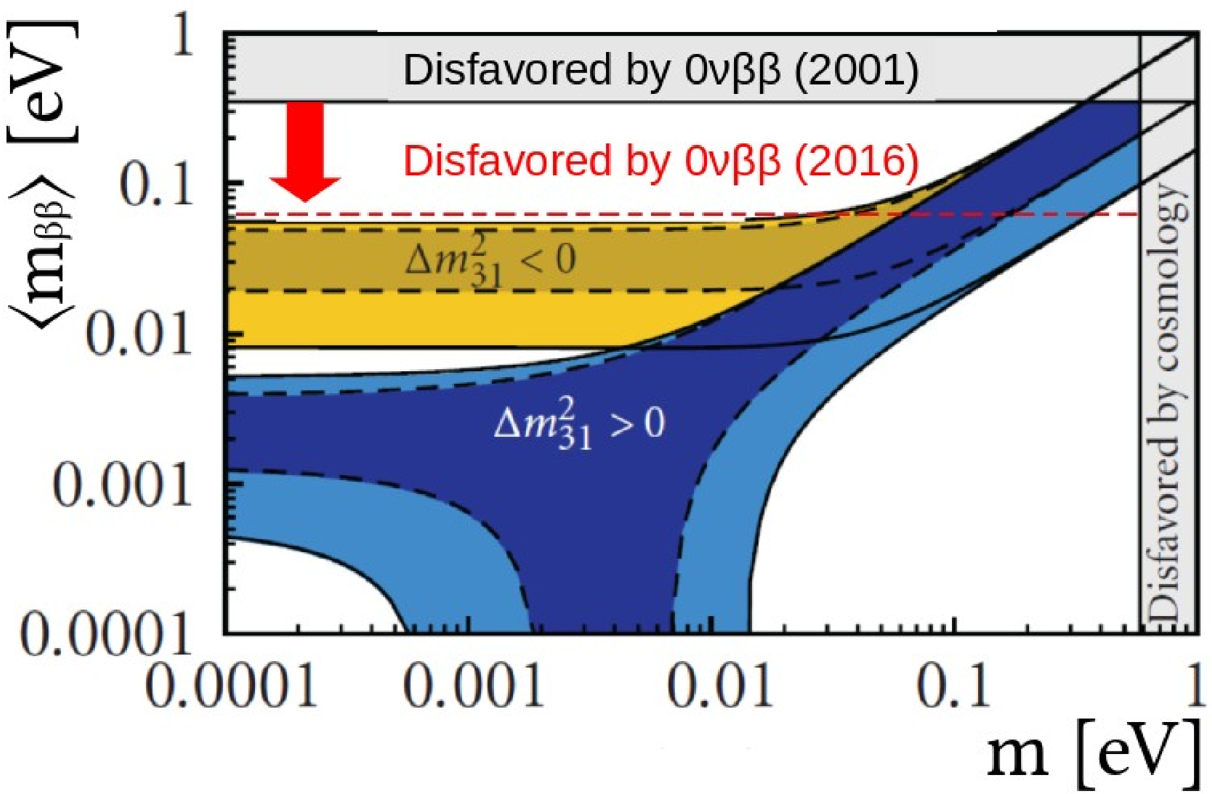
- $\left(T^{0\nu}_{1/2}\right)^{-1} \propto |m_{ee}|^2$

observable



- effective Majorana mass:

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



Modified figure from Nucl. Part. Phys. Proc., 260:188–193, 2015

Access to

- absolute neutrino mass scale
- mass hierarchy

Phase I + II Data Sets

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto N_{0\nu} = \frac{\ln 2 \cdot N_A}{m_{76}} \frac{M \cdot t}{T_{1/2}^{0\nu}} \cdot \epsilon \cdot \epsilon_{PSD} \cdot \epsilon_{LAr}$$

N_A: Avogadro's constant, m_{76}: molar mass of ^{76}Ge
M·t: exposure [kg yr], $T_{1/2}$: half-life of 0νββ decay,
ε_{LAr}: LAr efficiency, ε_{PSD}: PSD efficiency,
ε: exposure averaged efficiency incl. active volume, enrichement, FEP

data set	exposure [kg yr]	signal eff	Energy resolution (keV, FWHM)	Background index 0.001 cnts/(keV kg yr)
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 extra	1.9	0.58 (4)	4.2 (2)	5^{+4}_{-2}
Phase II coax	**5.0**	**0.53 (4)**	**4.0 (2)**	$\mathbf{3^{+3}_{-1}}$
Phase II BEGe	**5.8**	**0.60 (1)**	**3.0 (2)**	$\mathbf{0.7^{+1.3}_{-0.5}}$

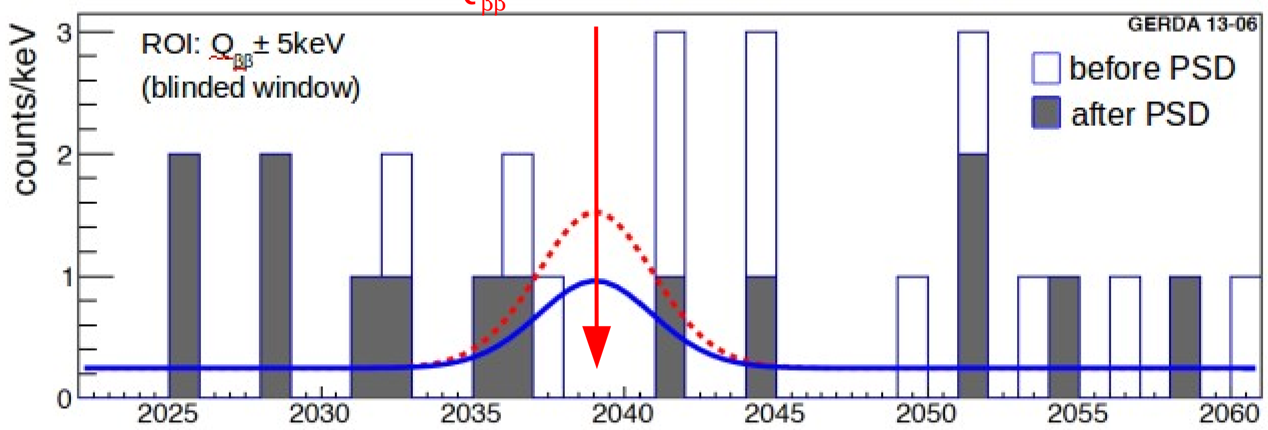
Results from GERDA Phase I

- 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)]