2018 data release GERDA Phase II: search for $0\nu\beta\beta$ of ^{76}Ge

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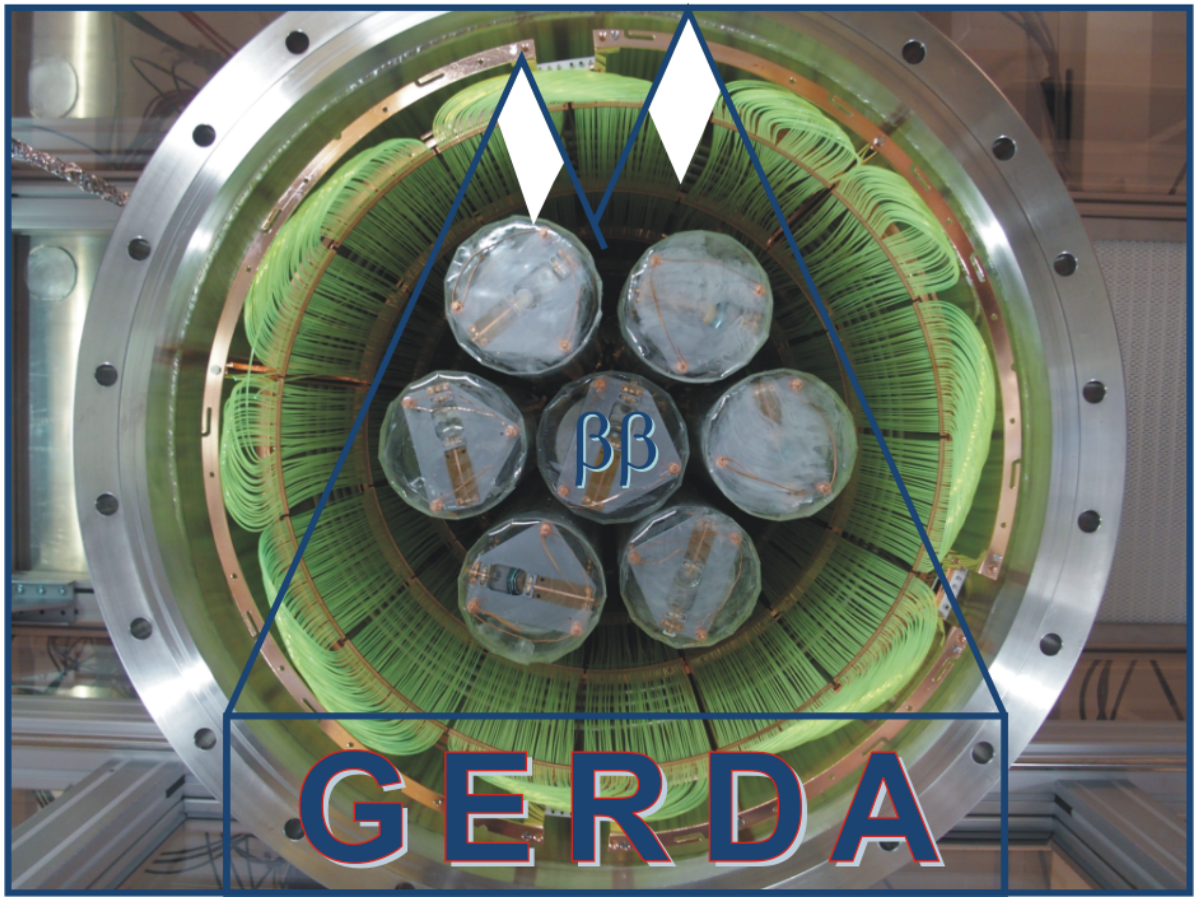
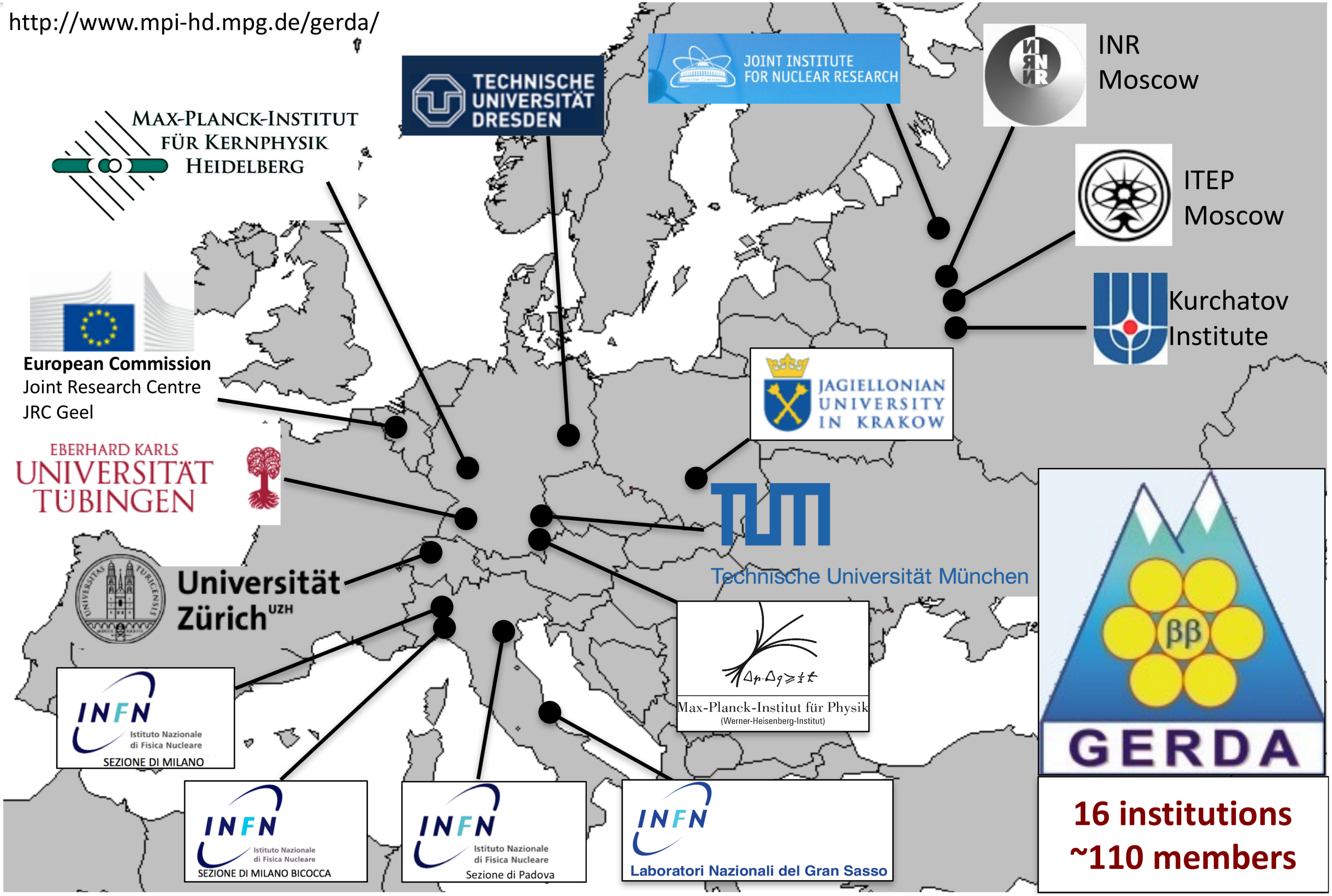
on behalf of the GERDA Collaboration



The GERDA Collaboration

http://www.mpi-hd.mpg.de/gerda/



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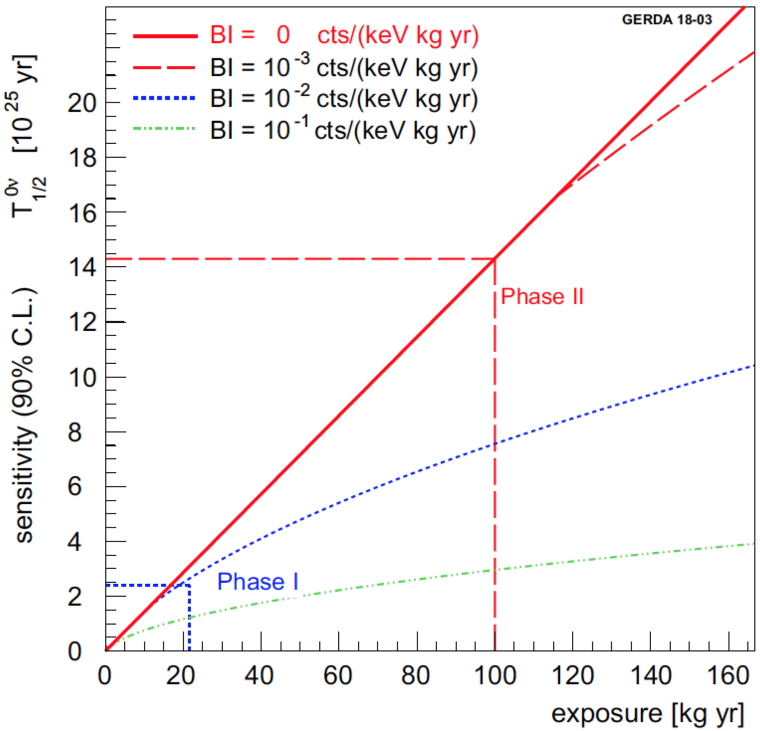
ββ
GERDA

16 institutions
~110 members

GERDA Phase II physics goals

- reach background of **10^{-3} cts/(keV·kg·yr)**
- collect an exposure of **100 kg·yr**
- sensitivity: $T^{0\nu}_{1/2}$ **> 1.3·10^{26} yr** (90% CL)
- discovery potential up to **10^{26} yr**
  (*50% prob. chance for a 3σ* signal)
- $\langle m_{ee} \rangle \leq$ 0.09-0.15 eV



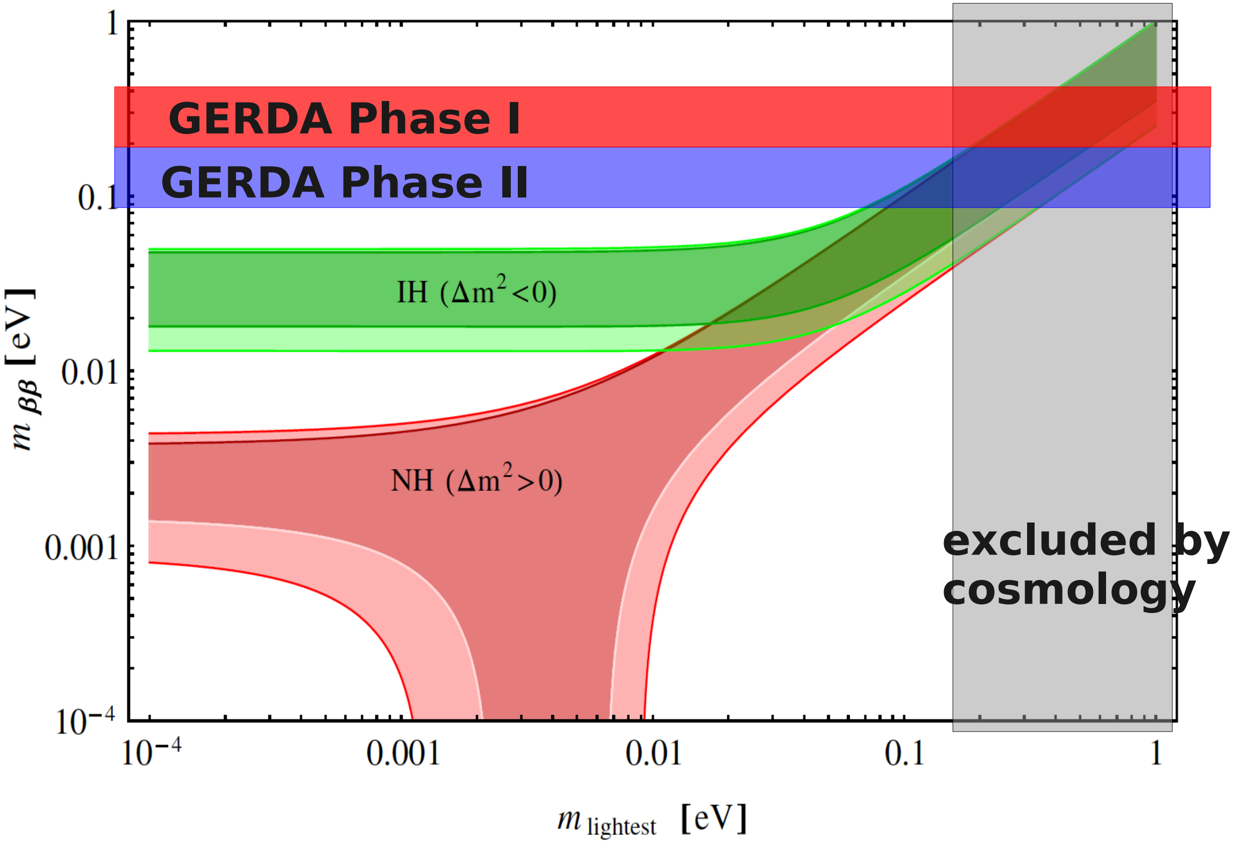
Phase II started at the end of 2015;
past achievements:

- reached background index of **10^{-3} cts/(keV·kg·yr)**
- fully analyzed an exposure of **23.2 kg·yr**
- sensitivity of $T^{0\nu}_{1/2}$ **= 5.8·10^{25} yr** (90% CL)
- no signal found: lower limit $T^{0\nu}_{1/2}$ **> 8.0·10^{25} yr** (90% CL)
- $\langle m_{ee} \rangle \leq$ 0.12-0.26 eV

Nature 544, 47 (2017)
PRL 120, 132503 (2018)

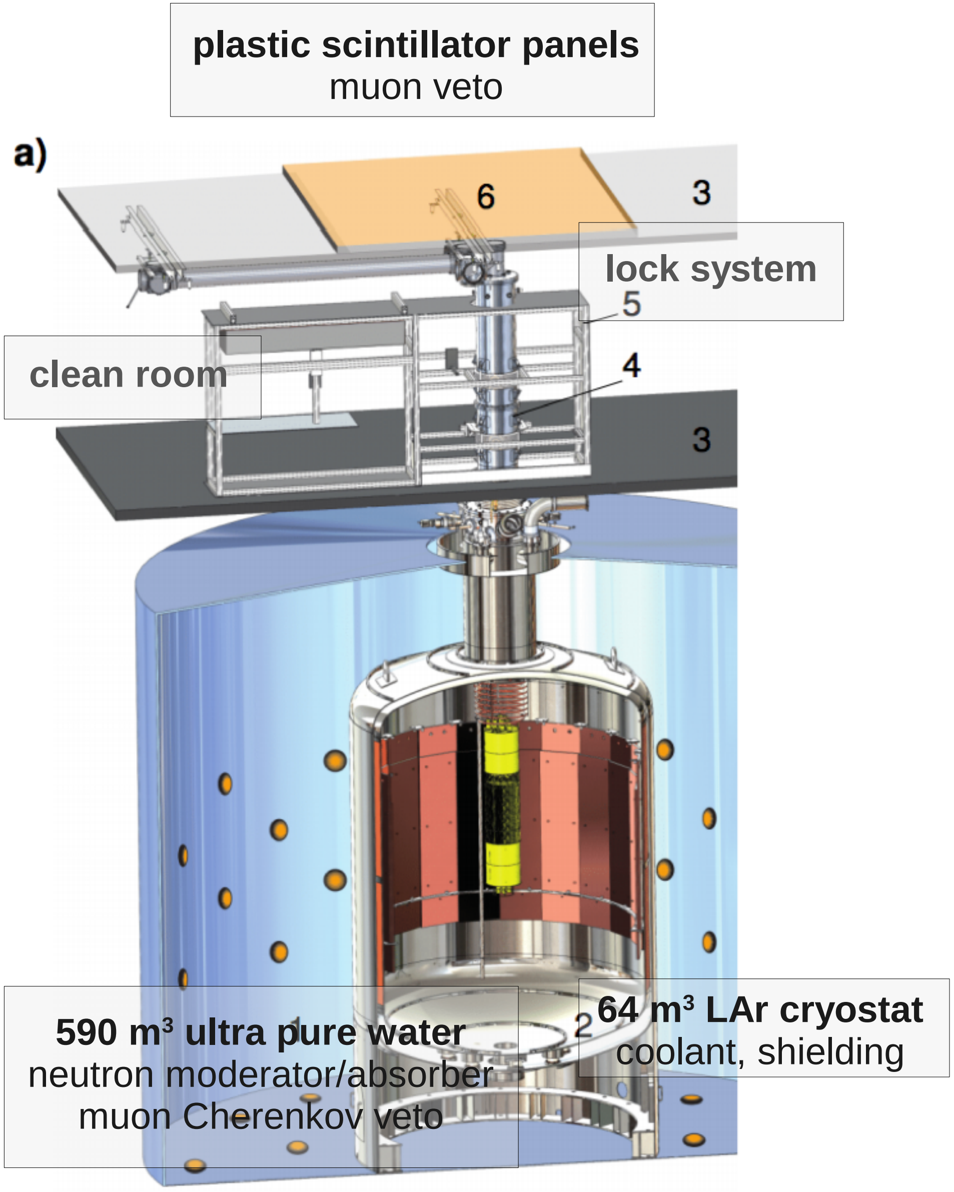
GERDA physics goal

S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)



$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2 \qquad \langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

Phase I: Eur. Phys. C 73 (2013) 2330
Phase II: Eur. Phys. C 78 (2018)



plastic scintillator panels
muon veto

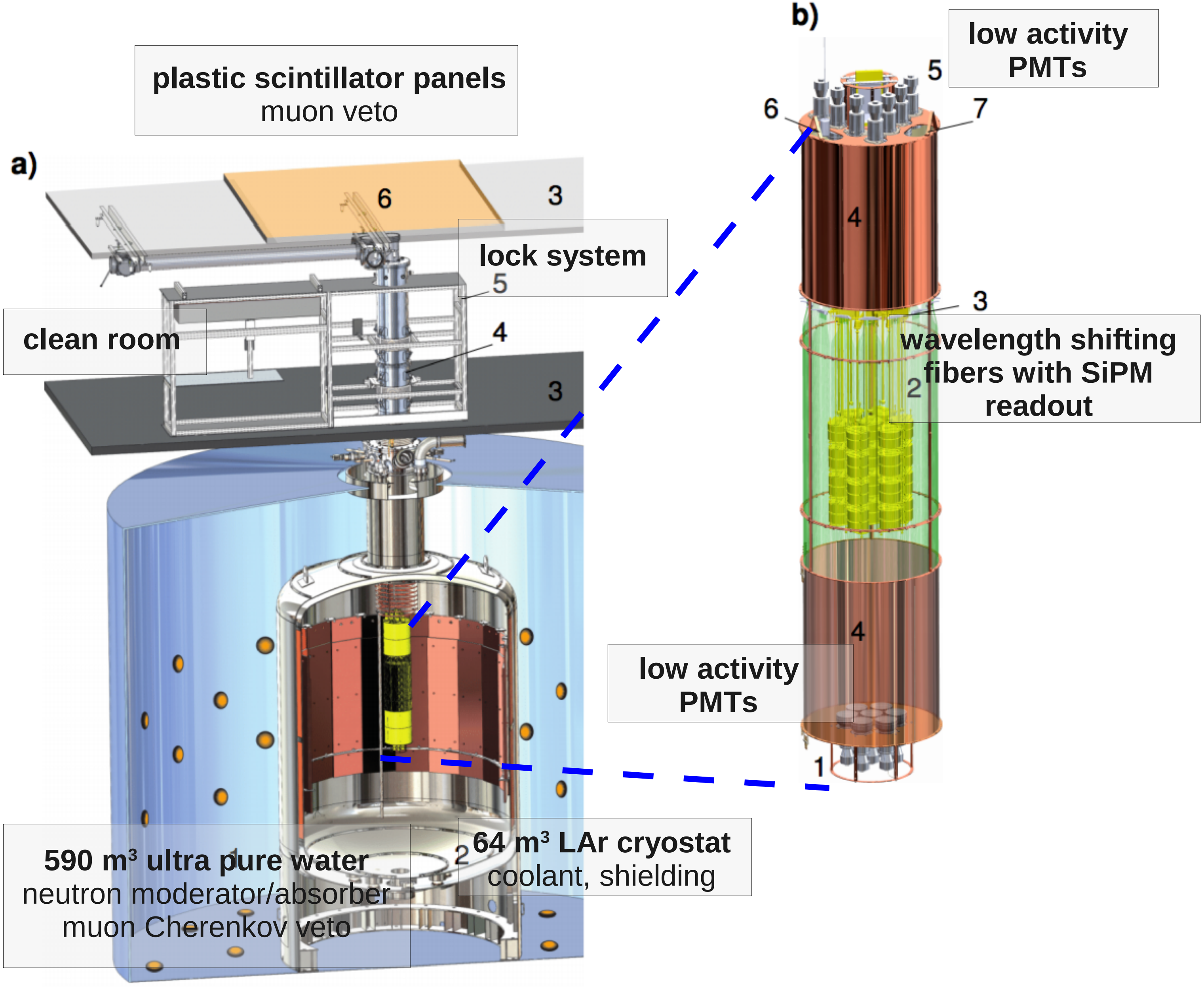
lock system

clean room

590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

64 m³ LAr cryostat
coolant, shielding

a) overview



plastic scintillator panels
muon veto

lock system

clean room

590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto

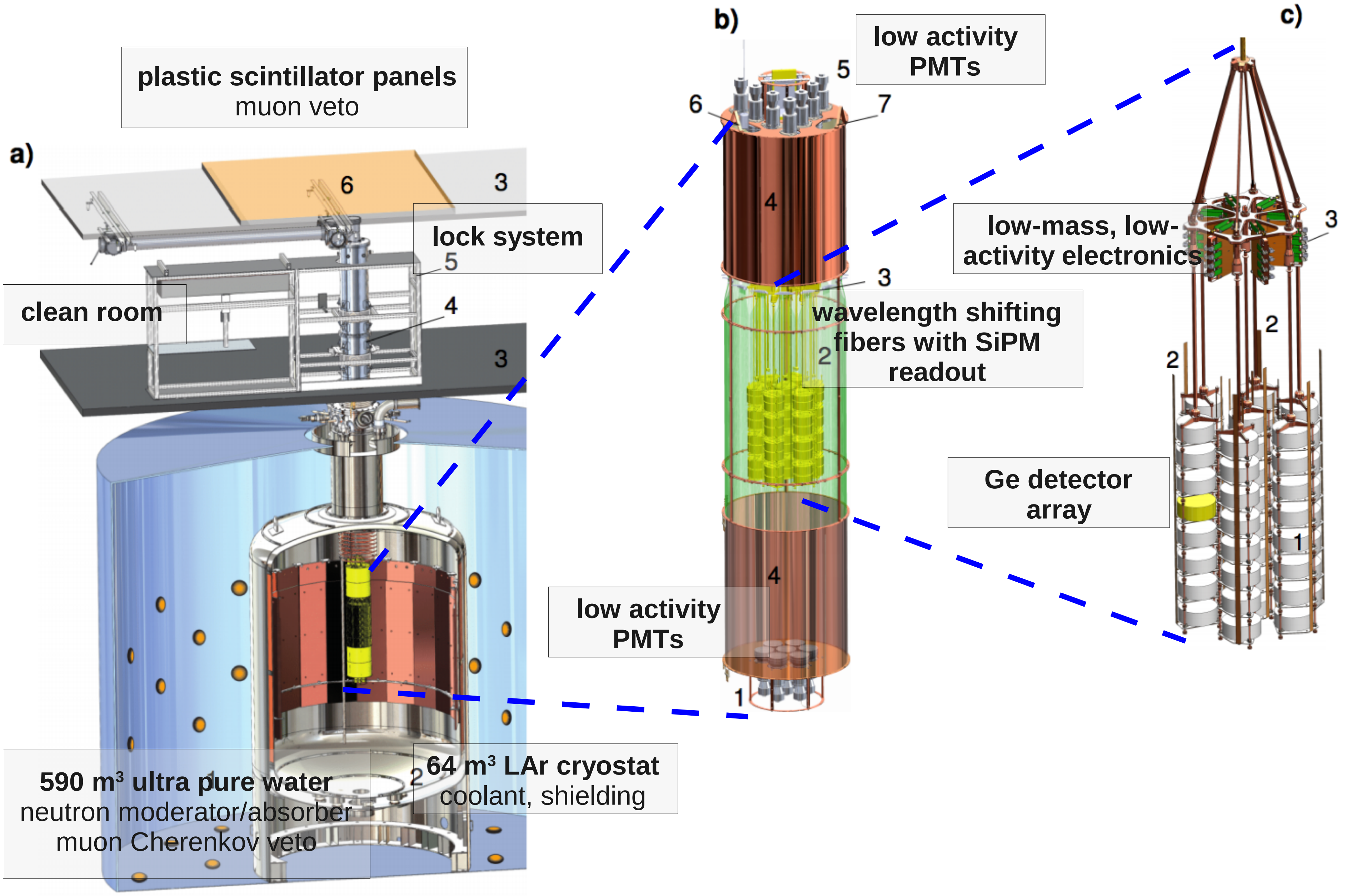
64 m³ LAr cryostat
coolant, shielding

low activity PMTs

wavelength shifting fibers with SiPM readout

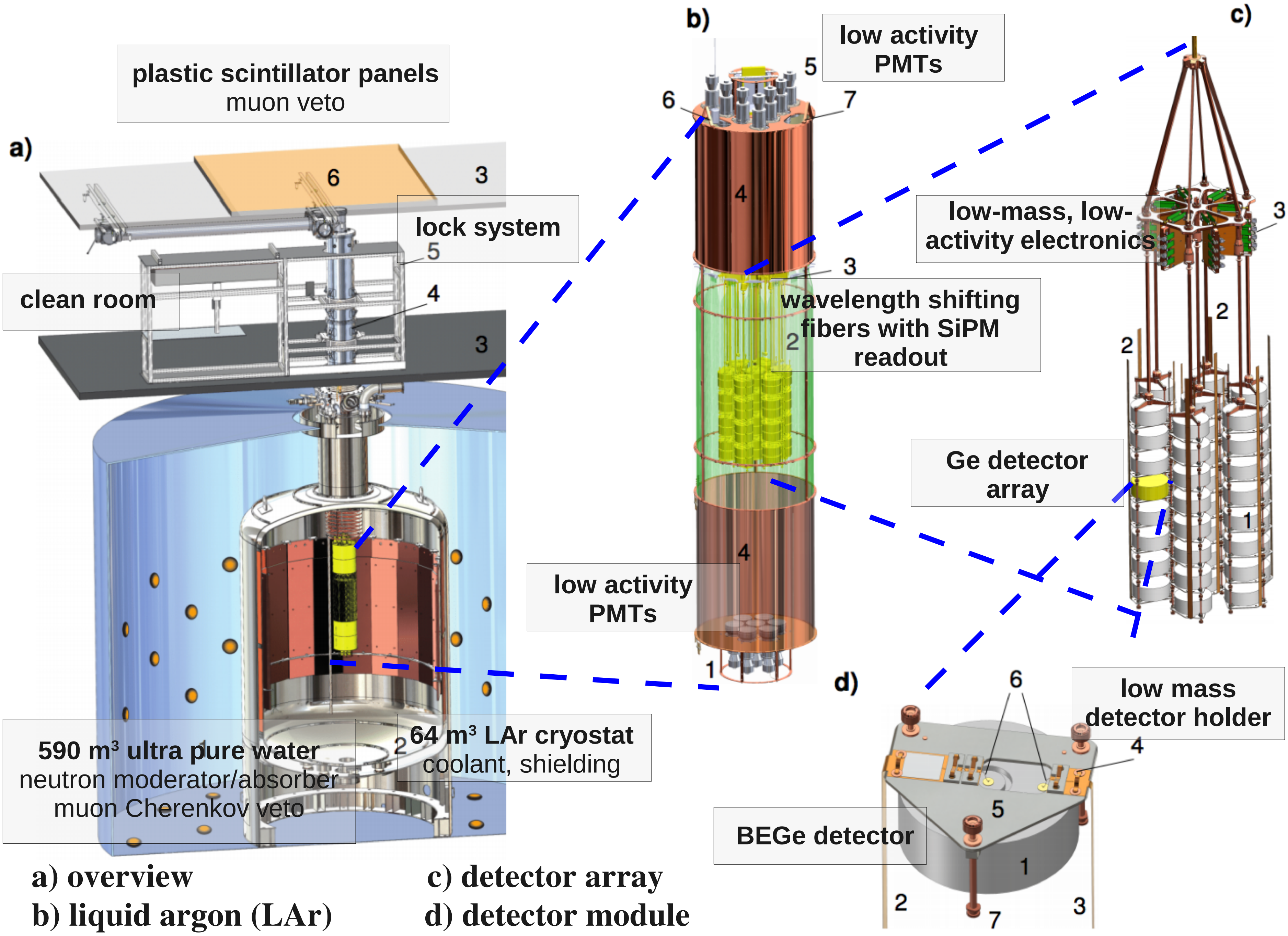
low activity PMTs

a) overview
b) liquid argon (LAr) veto instrumentation



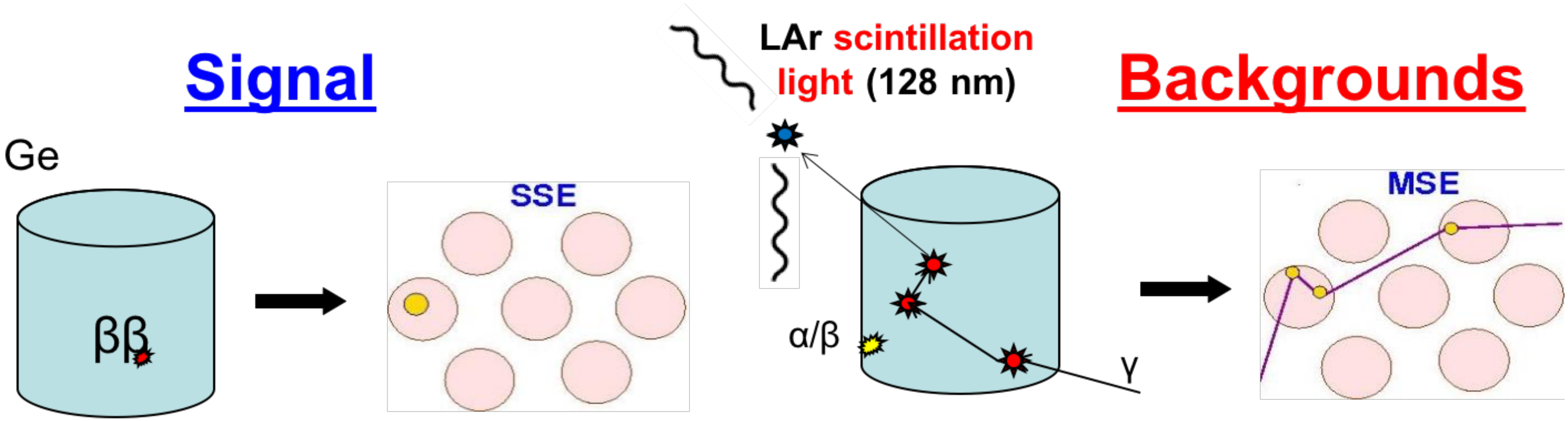
a) overview c) detector array

b) liquid argon (LAr) veto instrumentation



a) overview
b) liquid argon (LAr)
veto instrumentation
c) detector array
d) detector module

Background reduction tools



Signal

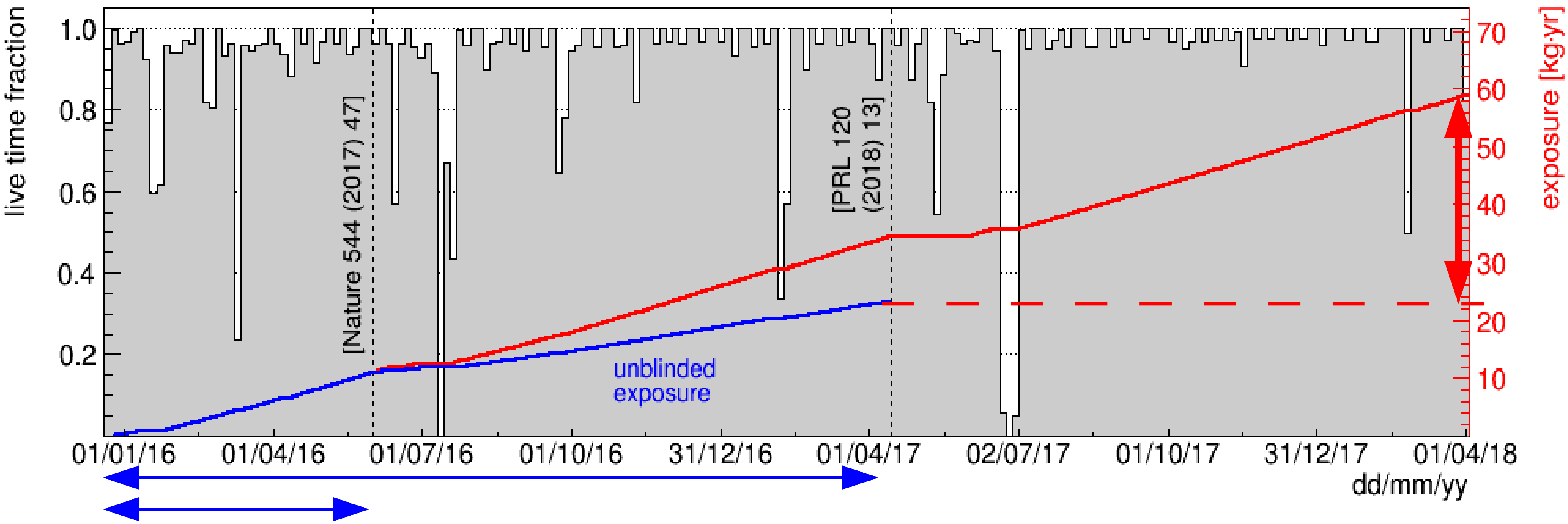
Point-like (single-site) energy deposition inside one HP-Ge diode

Backgrounds

Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

- ➢ **Anti-coincidence** with the **muon veto** (MV)
- ➢ Anti-coincidence **between detectors** (cuts multi-site) (AC)
- ➢ **Active veto** using LAr scintillation (LAr Veto)
- ➢ **Pulse shape** discrimination (PSD)

Status of Phase II data-taking



10.8 kg·yr published in **Nature 544, 47 (2017)**

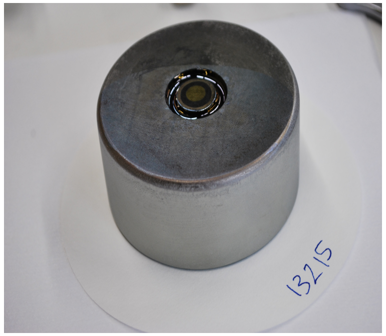
23.2 kg·yr published in **PRL 120, 132503 (2018)**

- **New Data Release**
  - **new** exposure analyzed: **23.07** kg·yr **(Coax)** + **12.64** kg·yr **(BEGe)**
  - **Total** Phase II data analyzed: **58.93** kg·yr

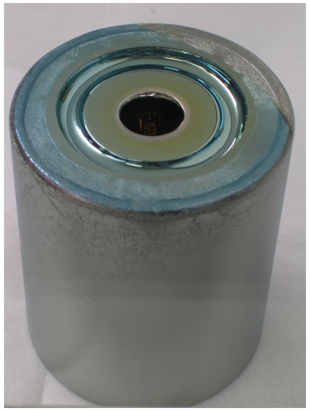
Ge detectors

- 30 enriched BEGe (20.0 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

→ **35.8 kg of enr detectors**

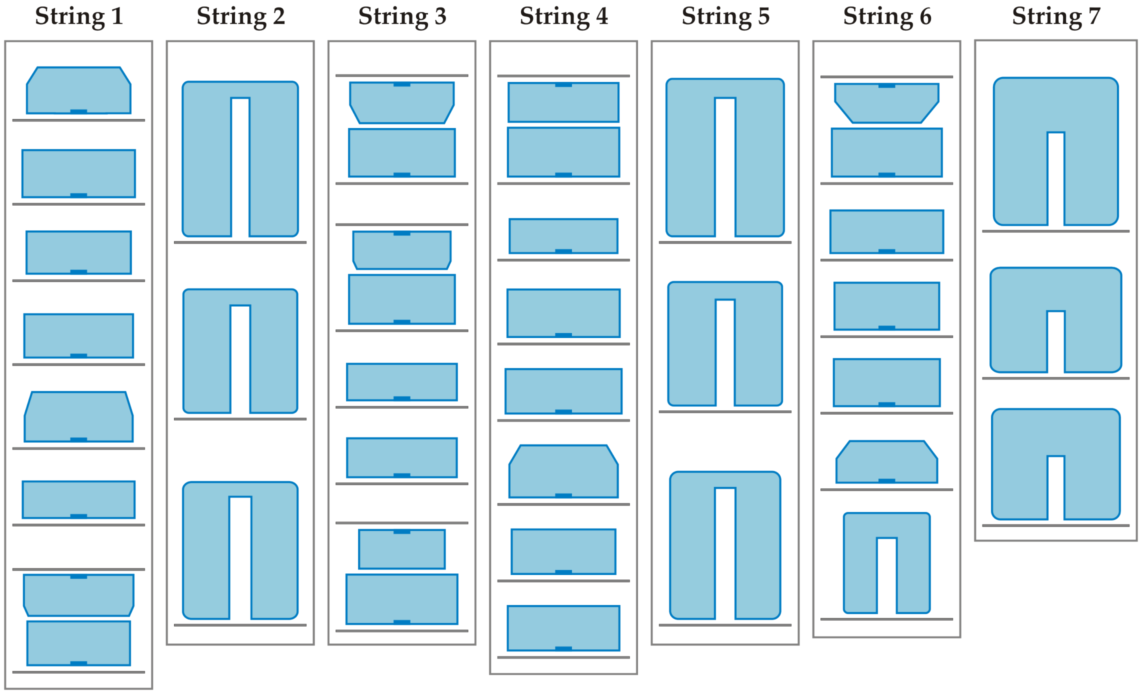


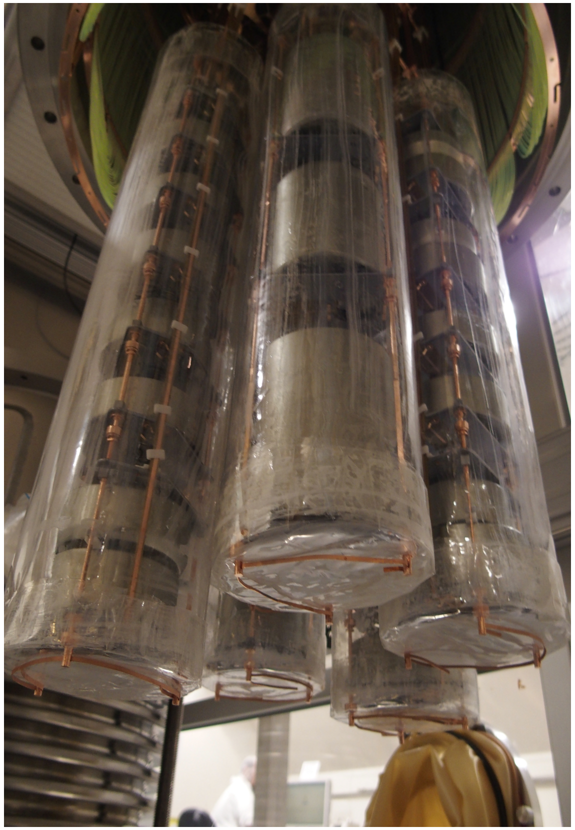
BEGe detector



coaxial detector

3 diodes lost (burn-out JFET)



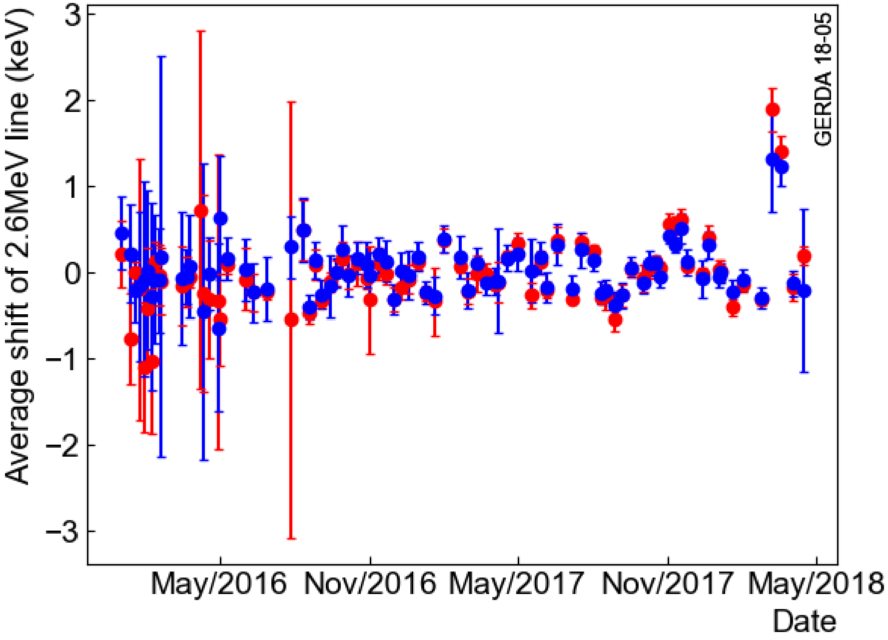


Ge detectors: energy calibration

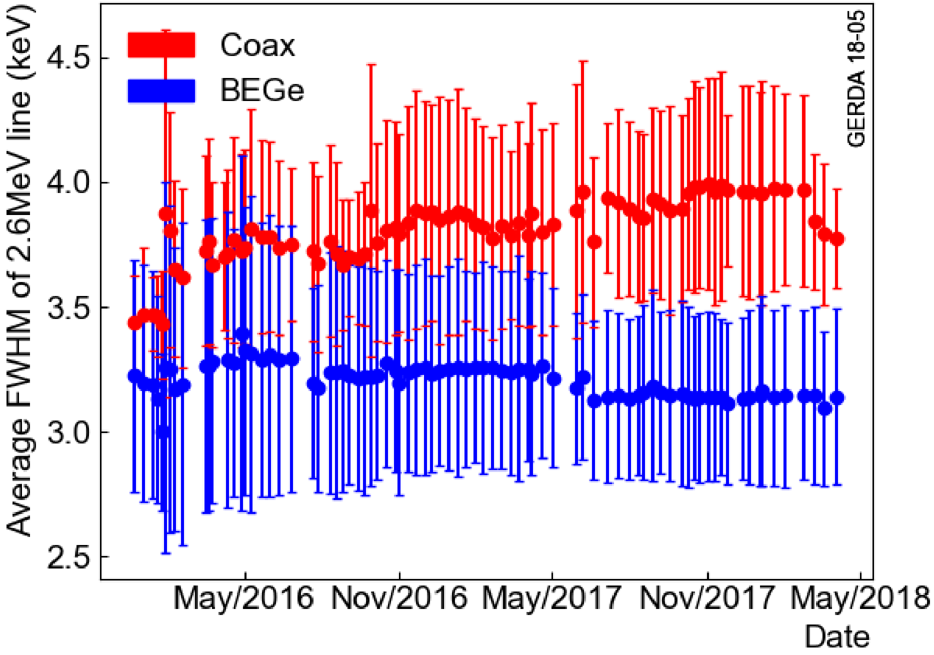
Procedure:

- weekly ^{228}Th calibrations
- comparison with γ lines in physics data
- stability between calibration: every 20 s pulser injected into FE
- ZAC filter for E reconstruction

[EPJC 75 (2015) 255]



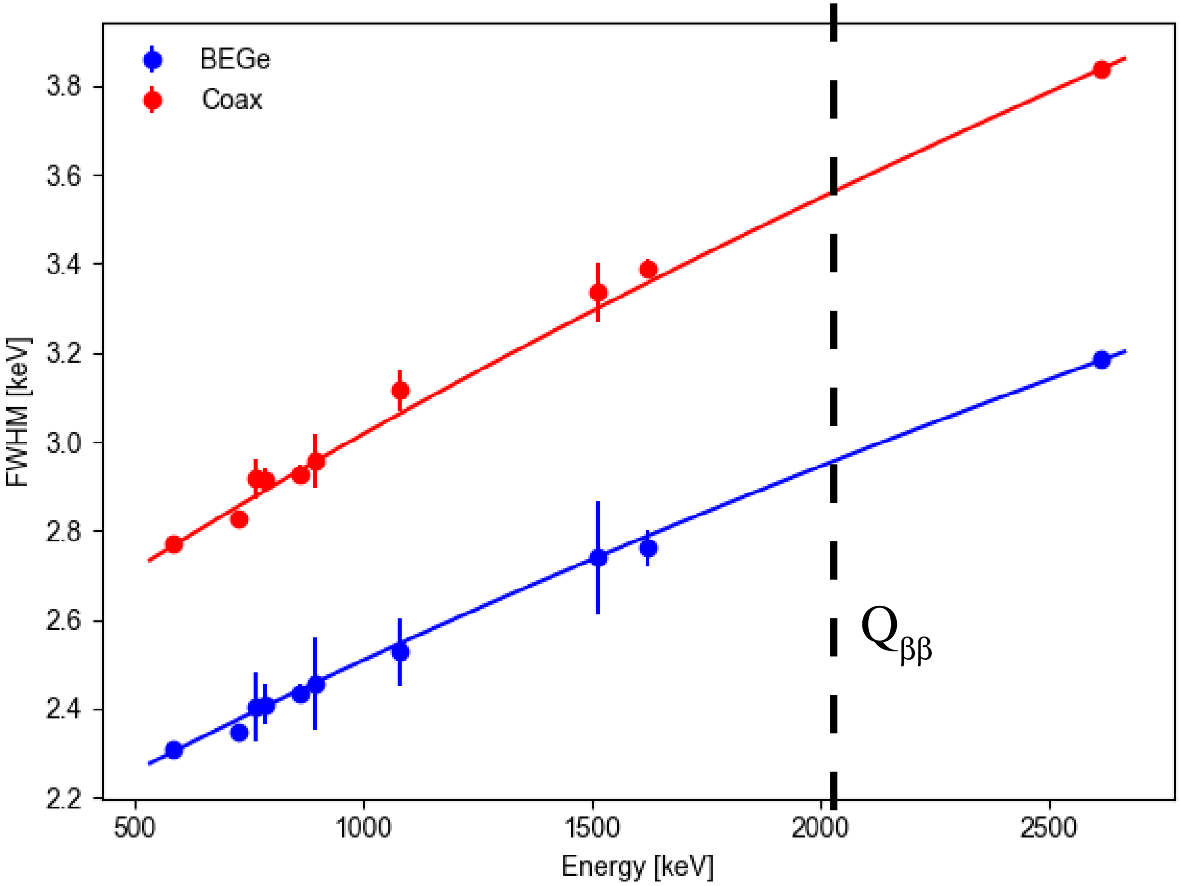
Average shifts in the *E* scale between calibrations over time. Used to monitor instabilities for data selection



Average resolution versus time

Used to monitor detector instabilities

Ge detectors: energy calibration

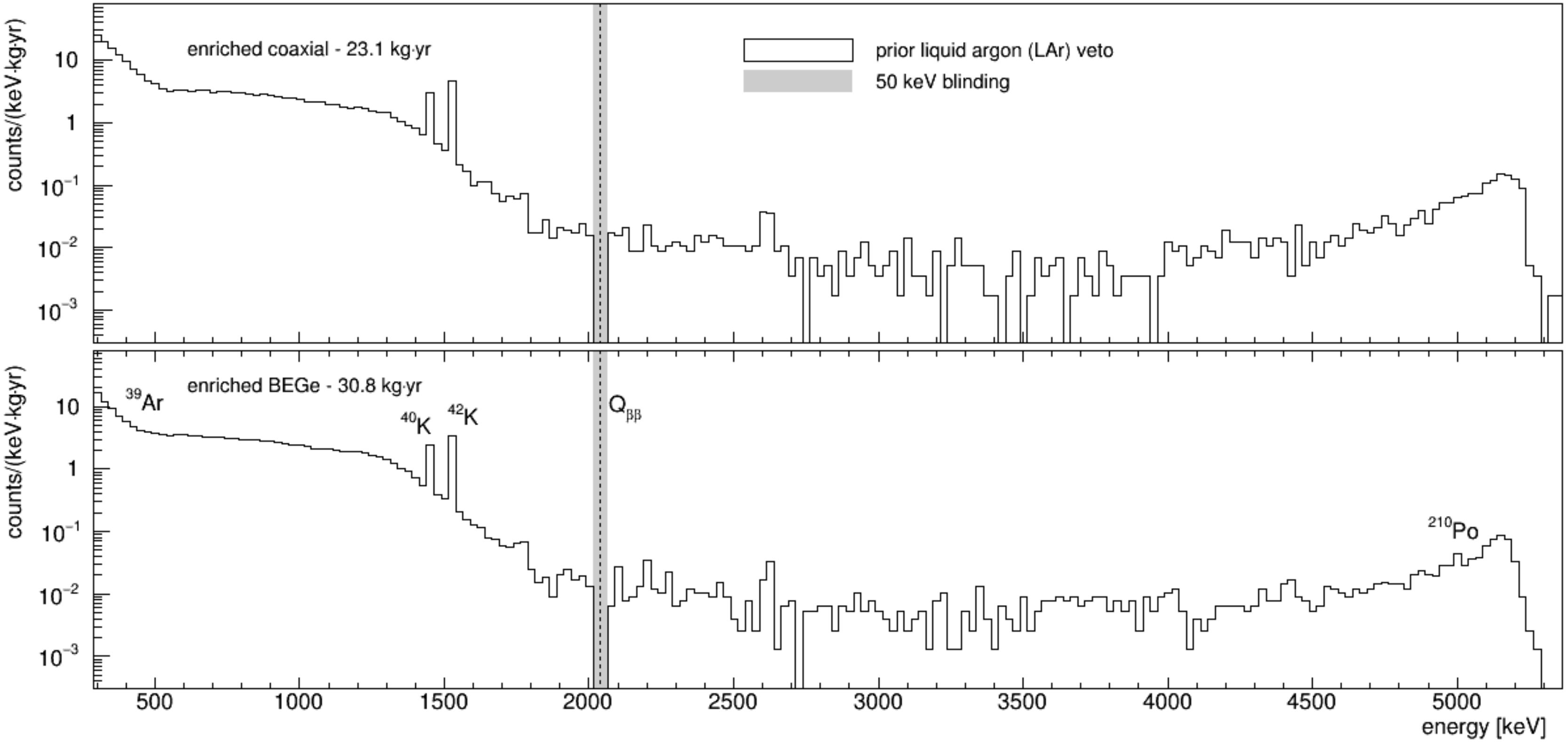


- ➢FWHM resolution curves from calibration:

  @$Q_{\beta\beta}$: FWHM(**BEGe**) = **3.0 ± 0.1** keV

  FWHM(**Coax**) = **3.6 ± 0.1** keV

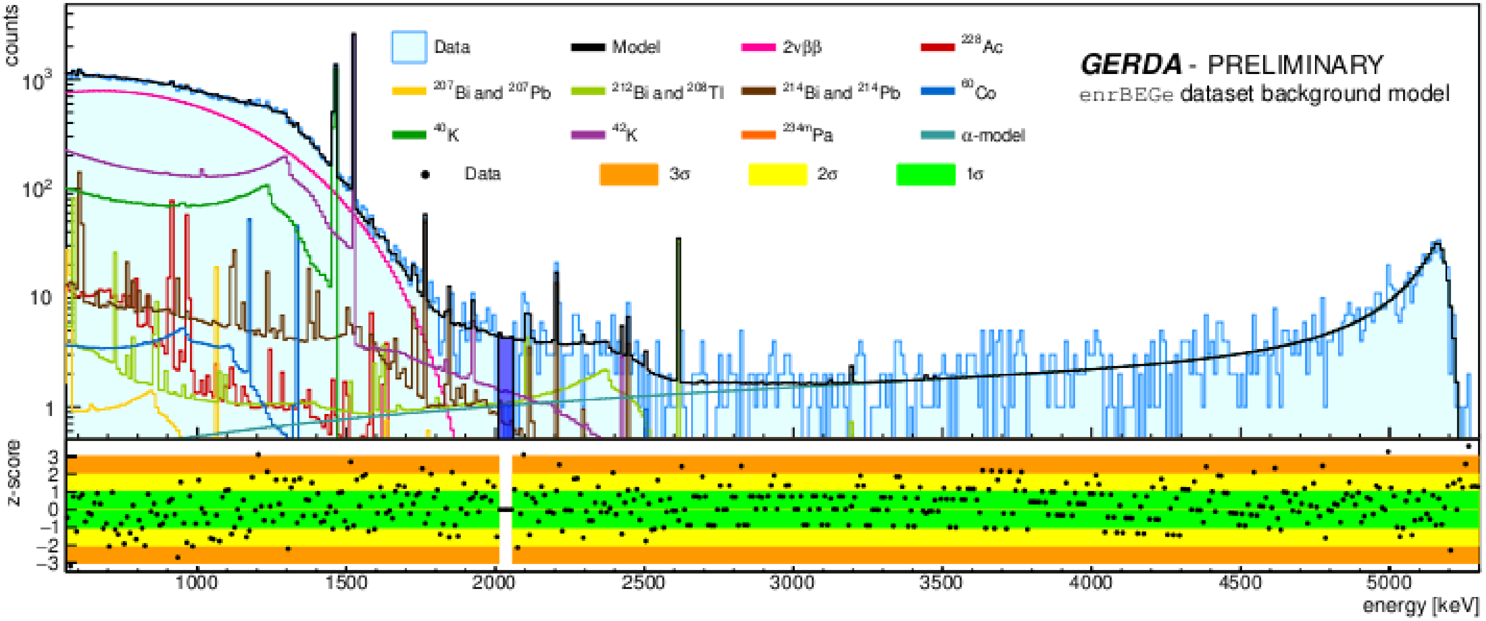
Phase II GERDA spectra



- Spectra after quality cuts, Muon Veto cut and AntiCoincidence cut
- Most prominent feature: ^{39}Ar β (< 500 keV), $2\nu\beta\beta$, ^{42}K and ^{40}K γ lines, α in the high energy part of the spectrum

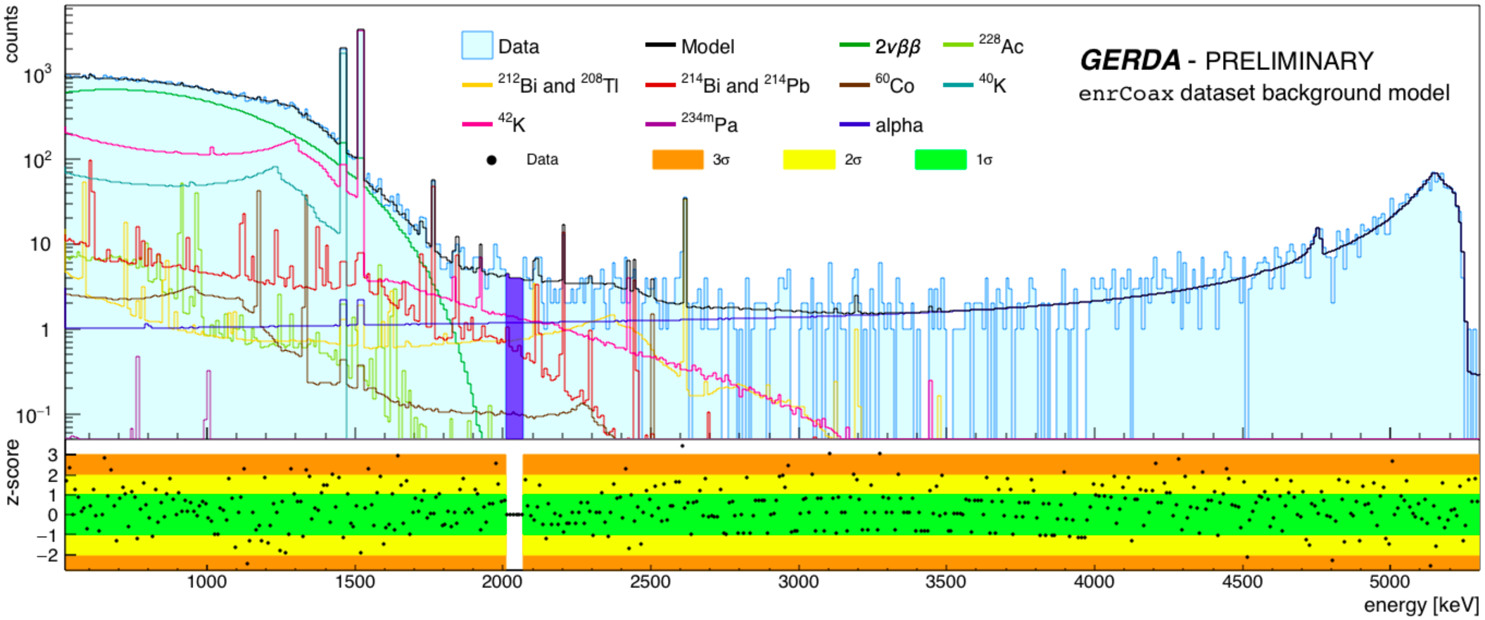
Background Model for Phase II data

- full GERDA experimental setup is reproduced in a GEANT4 framework
- bkg contaminations: 2νββ in the enriched detectors , ^{42}K in LAr, ^{40}K, ^{232}Th, ^{238}U decay chains, ^{60}Co in detector holders, cables, electronic components, LAr instrumentation …
- PDFs built from the MC output and used later in the fits
- Runtime ON/OFF detectors and run livetimes are taken into account
- Both anti-coincidence and coincidence spectra simultaneously taken into account
- Bayesian statistical analysis fits
- Known inventory screening used as priors

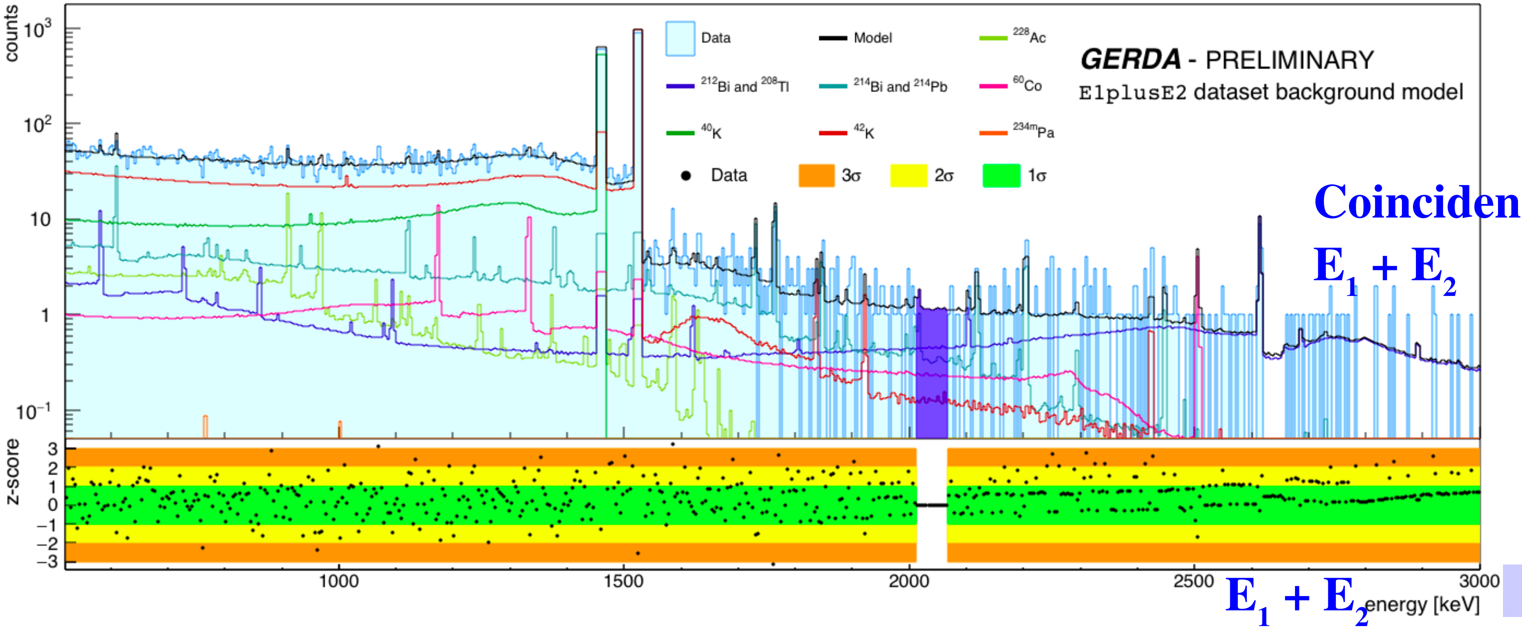


Enriched BEGe spectrum

Background Model



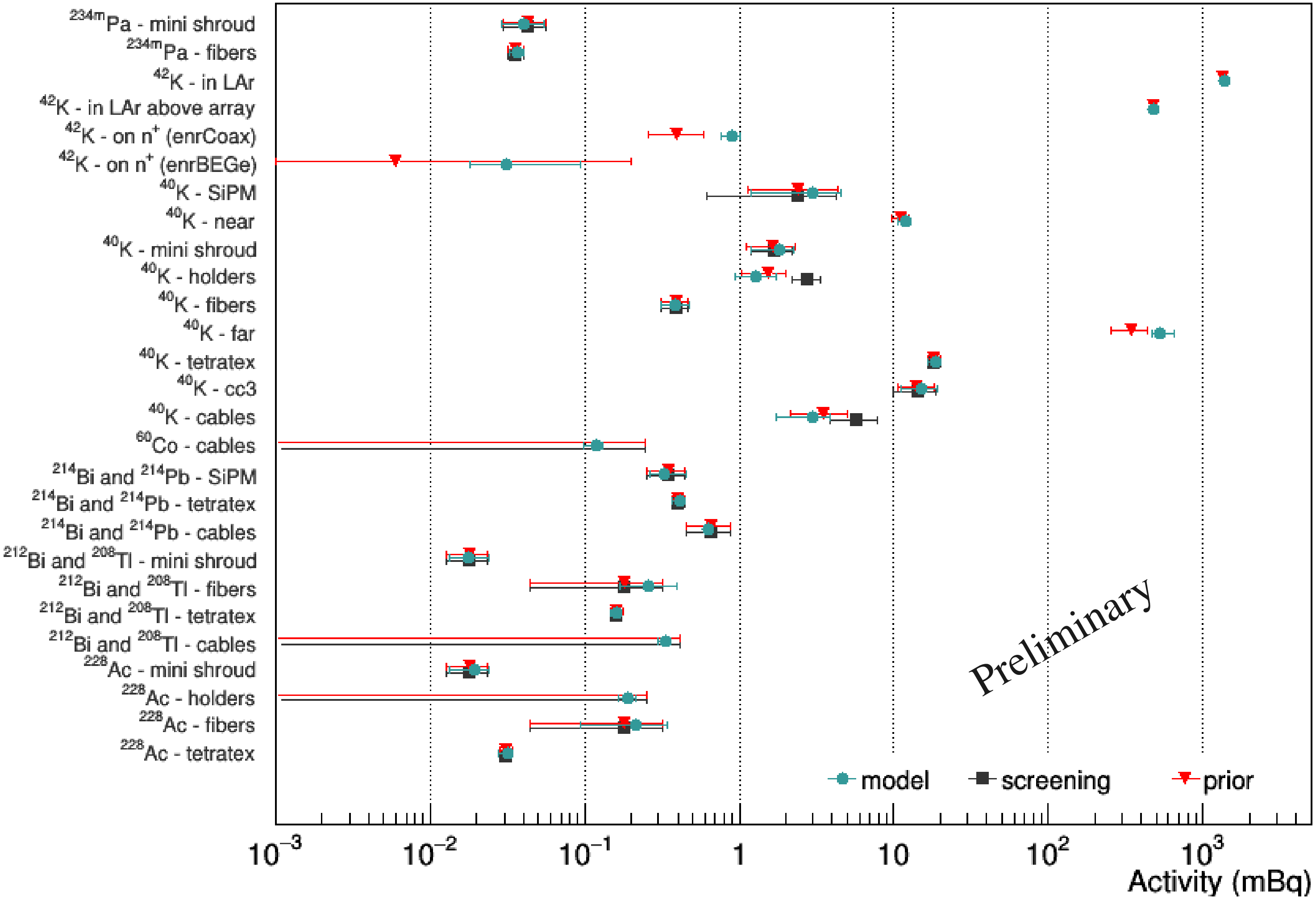
Enriched Coax spectrum



Coincidence spectrum: $E_1 + E_2$

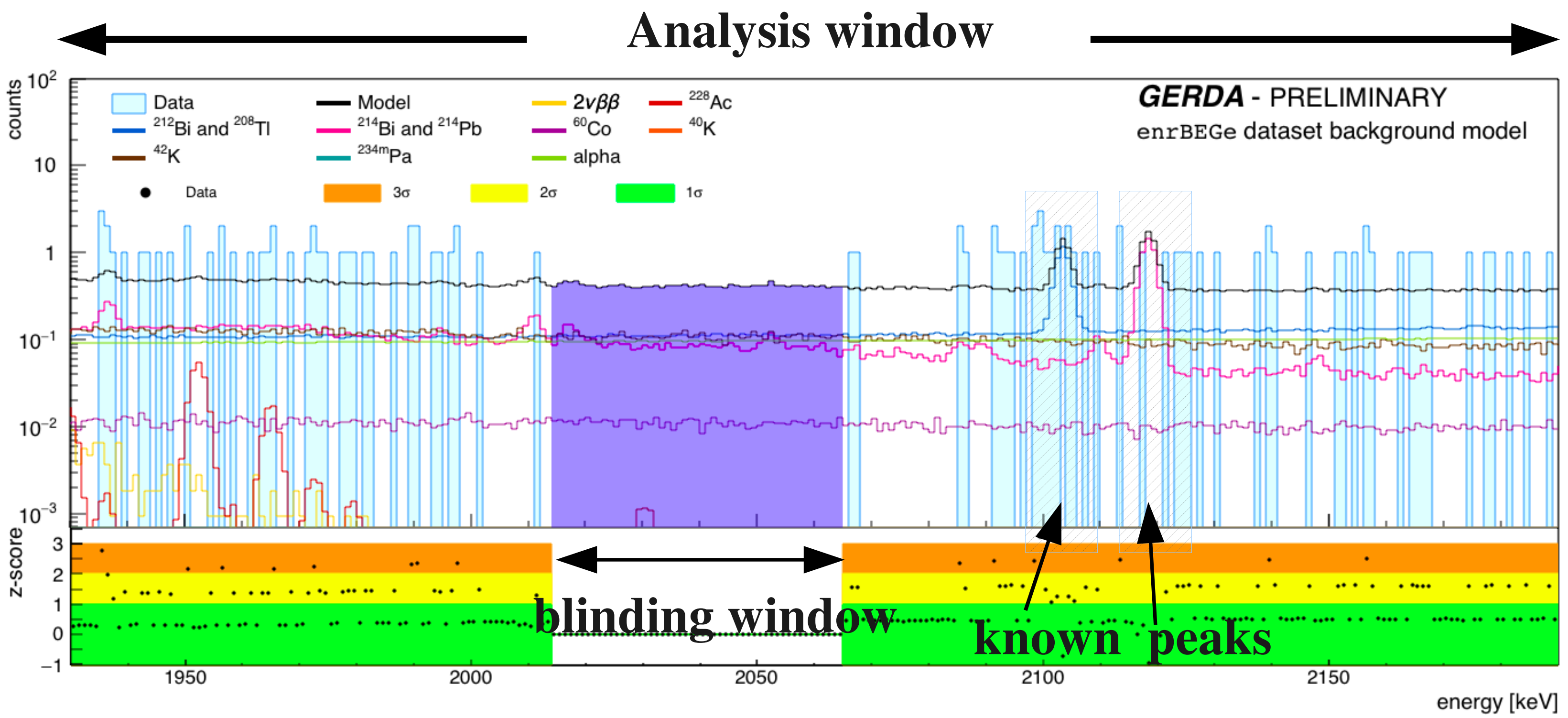
$E_1 + E_2$

Background Model: Results



- ◆ Very good agreement between model and screening measurements

Background Model: Predictions



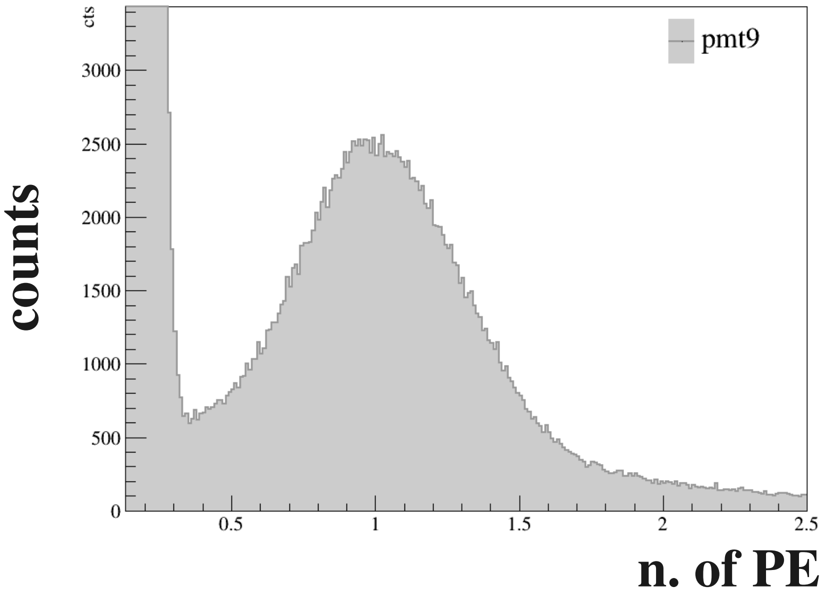
Analysis window

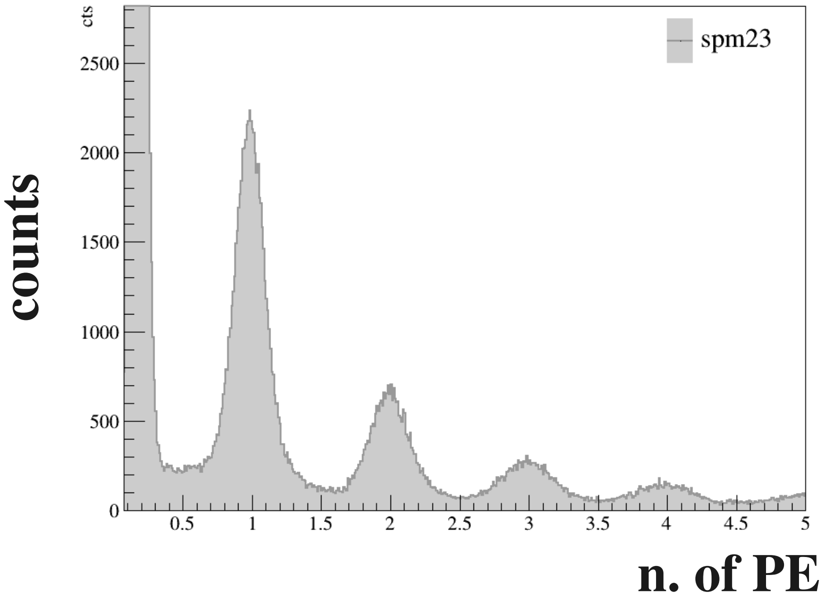
blinding window

known peaks

- ➢The background model confirms the **flatness of the background around the ROI** and in the analysis window as in Phase I
- ➢The expected spectrum is roughly composed in almost equal percentage of : events from α, e^- from ^{42}K and γ coming from ^{212}Bi + ^{208}Tl and ^{214}Bi + ^{214}Pb as in Phase I
- ➢Use the same **analysis window** as in Phase I
  - 1930 – 2190 keV excluding the interval 2104 ±5 keV and 2119 ±5 keV of known peaks

LAr Veto



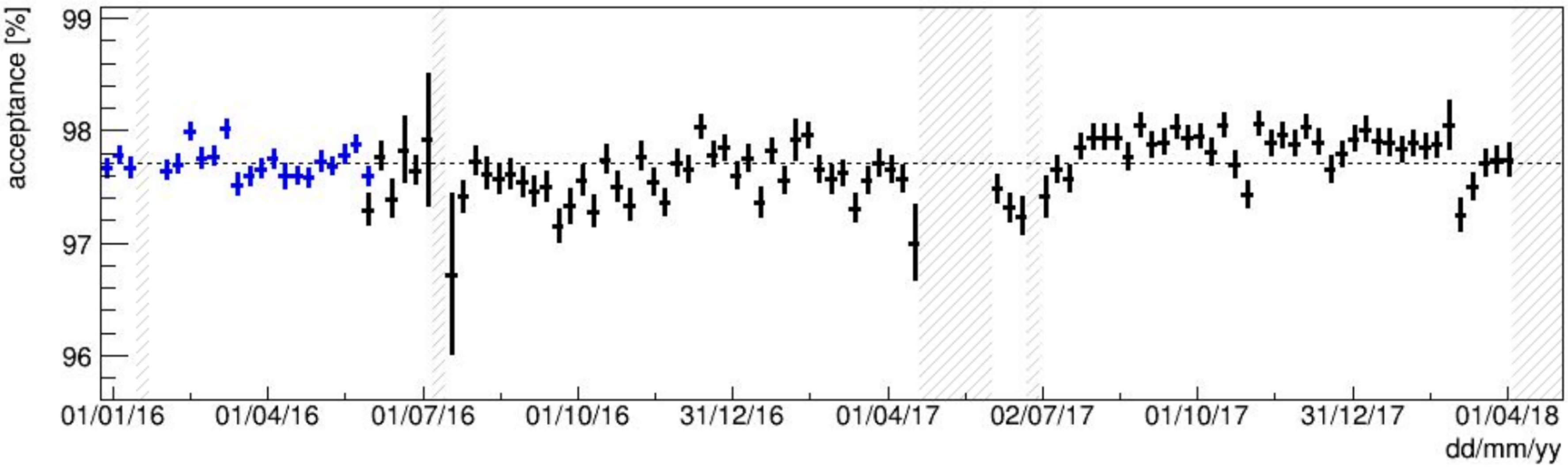


read out all channels if Ge triggers
→ offline veto

- all channels working
- gain stable with time

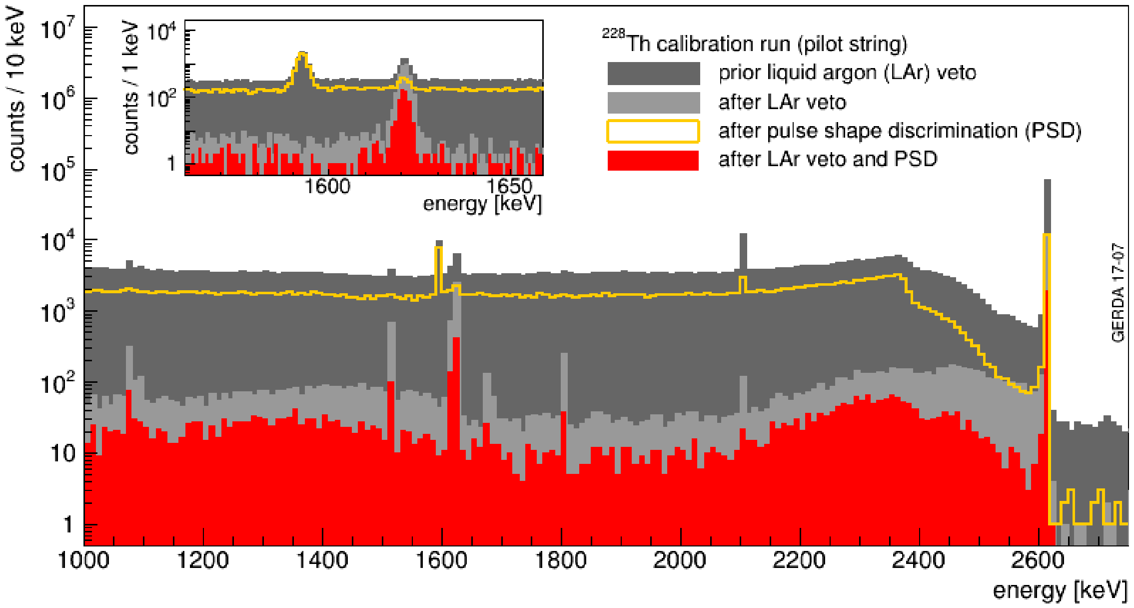
low noise → veto cut ~0.5 p.e.

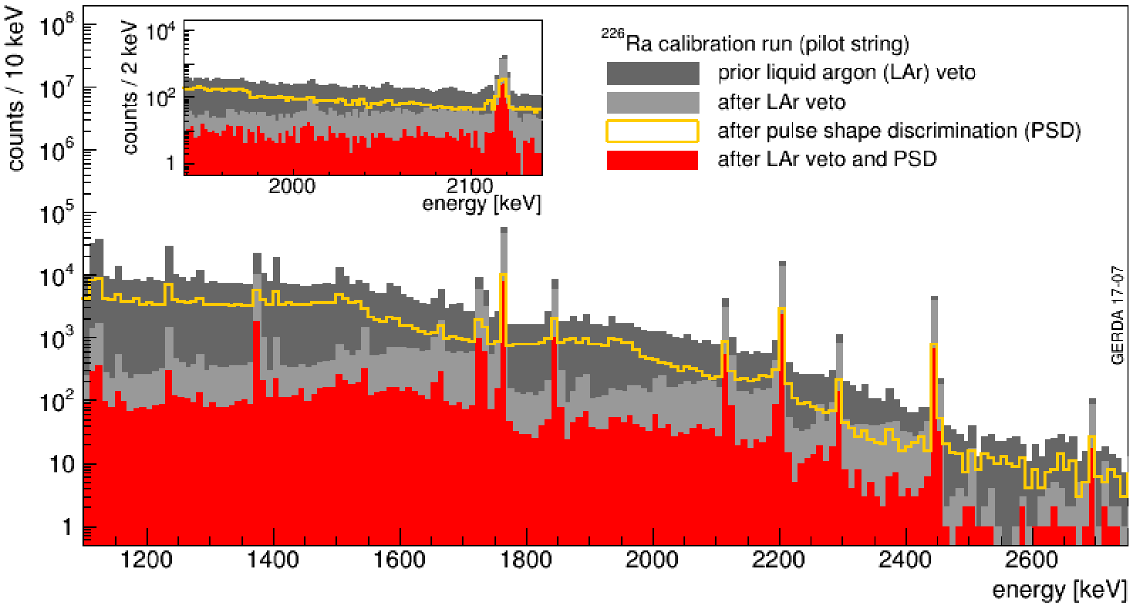
LAr Veto Acceptance



- acceptance stable in time
- first calculated through test pulses and then through random triggers
- acceptance value: **(97.7 ± 0.1)%**

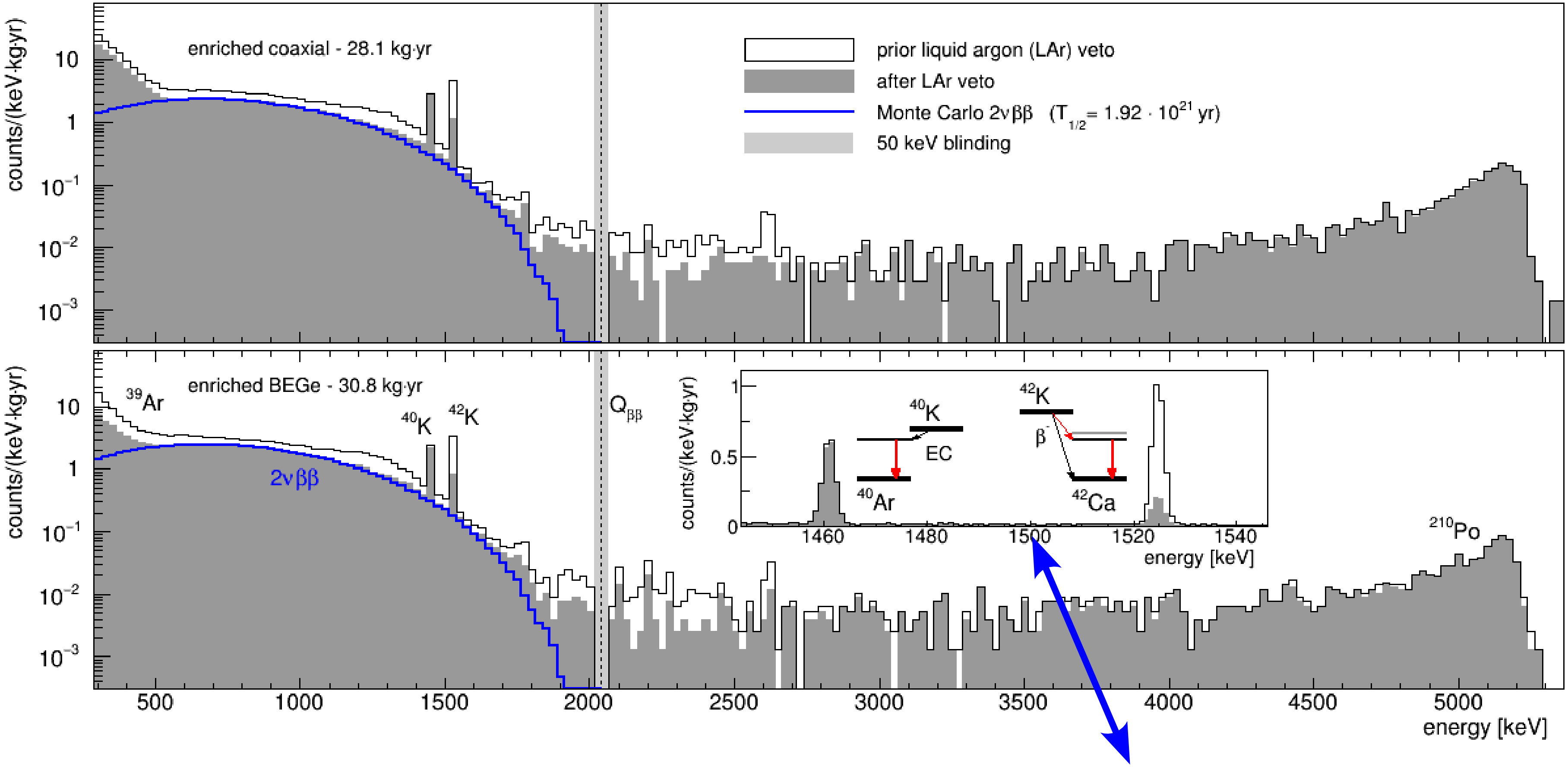
LAr veto bkg suppression





- Tested with ^{228}Th and ^{226}Ra sources
- Suppression factor higher with ^{228}Th (98(4)) than with ^{226}Ra (5.7(2)) source due to more energy in LAr
- Combining with PSD & anticoincidence the overall supp. factors become:
  345 (25) for ^{228}Th
  29 (3) for ^{226}Ra

LAr veto background suppression



- ^{40}K/^{42}K Compton continuum mostly suppressed
- $T^{2\nu}_{1/2} = 1.9\cdot10^{21}$ yr taken from Phase I

[EPJC 75 (2015) 416]

γ-lines from:

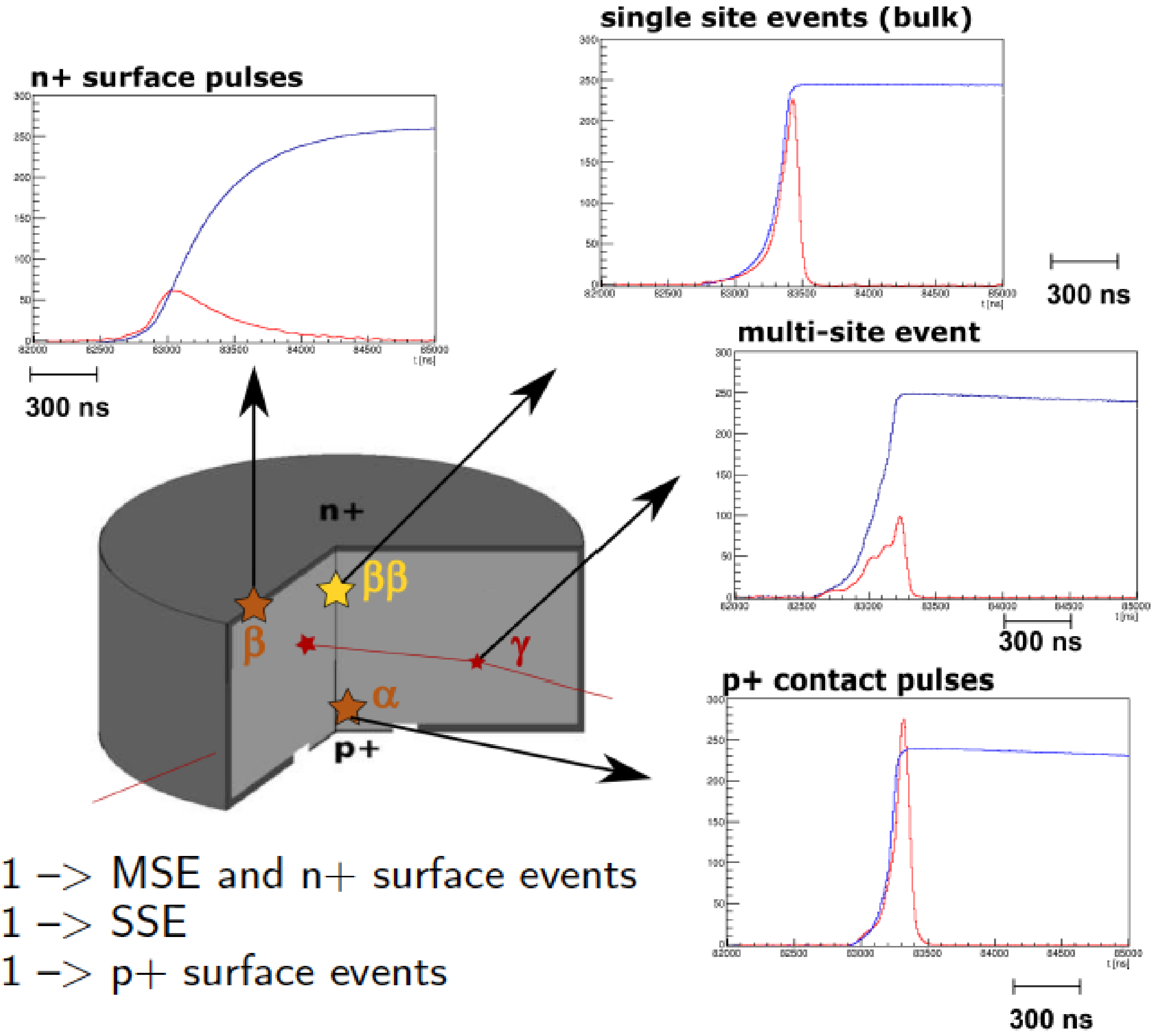
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + \gamma$ (1.4 MeV) [EC]

$^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca} + \gamma$ (1.5 MeV)

\+ e- (up to 2 MeV)

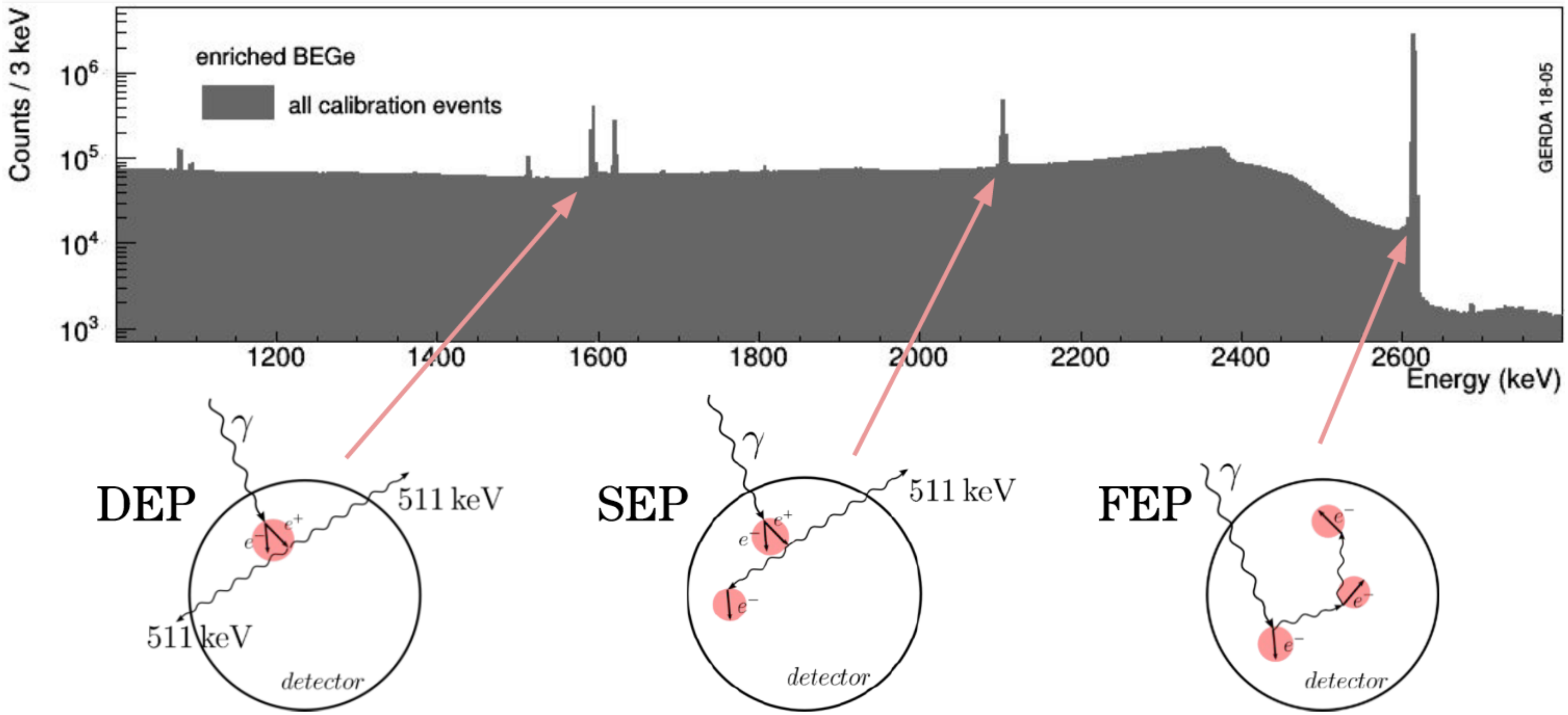
Pulse Shape Discrimination: BEGe

- Event classification using the ratio: Current/Energy i.e. **A/E** variable



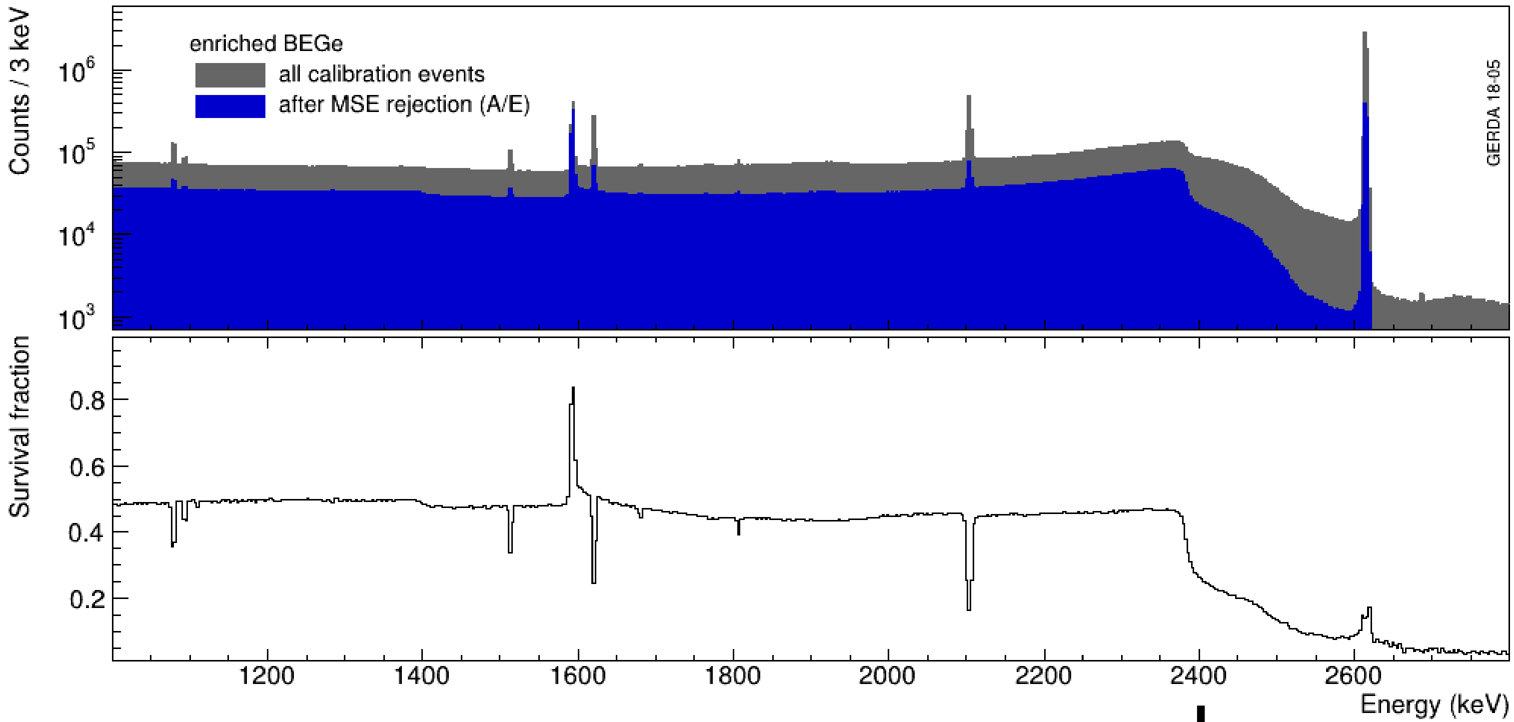
A/E<1 –> MSE and n+ surface events
A/E~1 –> SSE
A/E>1 –> p+ surface events

Pulse Shape Discrimination: BEGe

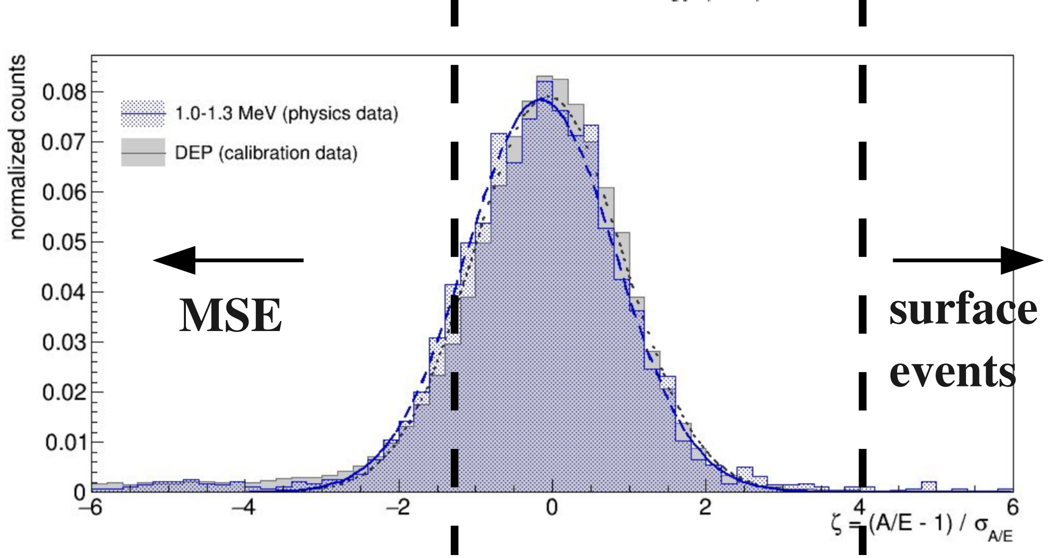


- ◆ Double escape peak (DEP) events from ^{208}Tl used as proxy for SSE
- ◆ Full Energy peak (FEP) events from ^{212}Bi used as proxy for MSE

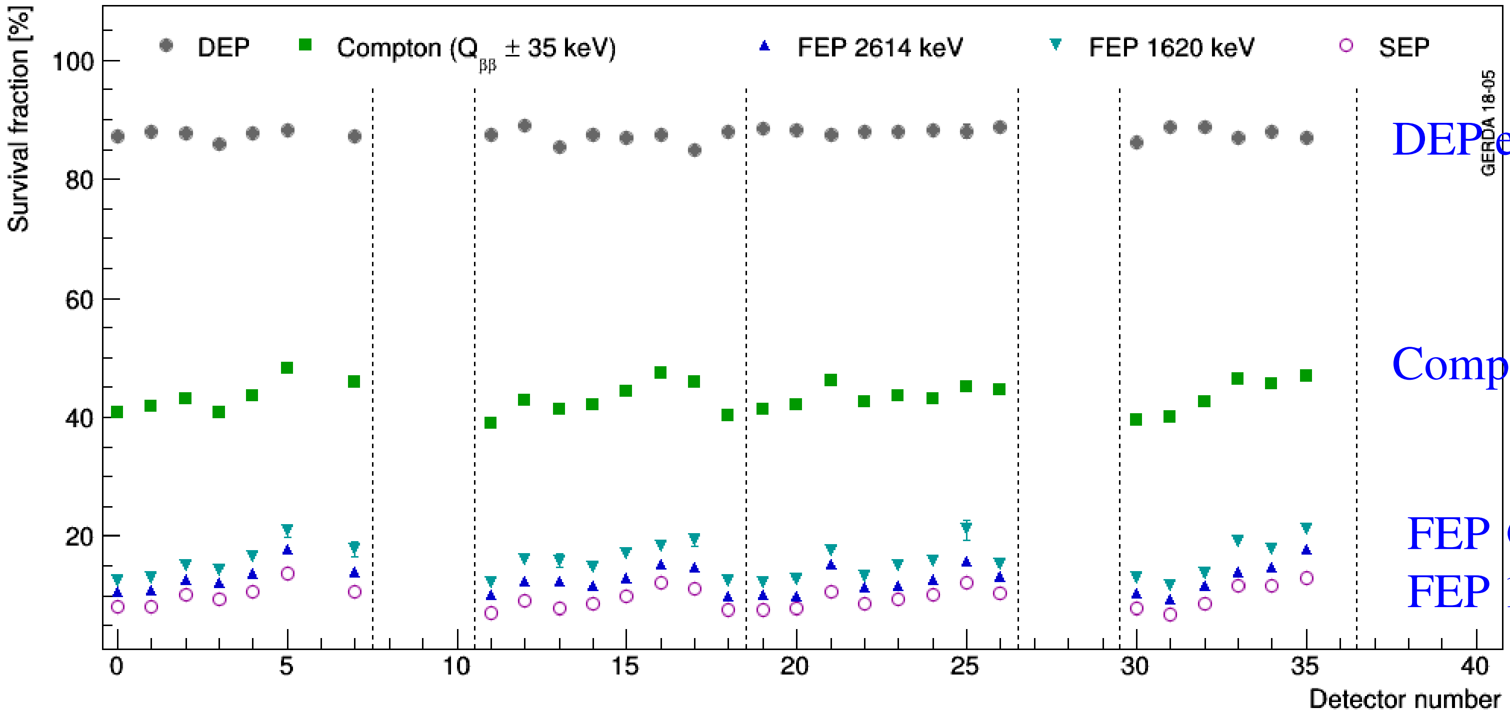
Pulse Shape Discrimination: BEGe



- low cut of the A/E distribution to have 90% DEP survival probability
- then a high cut (at 4σ) on A/E distribution is placed in order to cut surface events



Pulse Shape Discrimination: BEGe



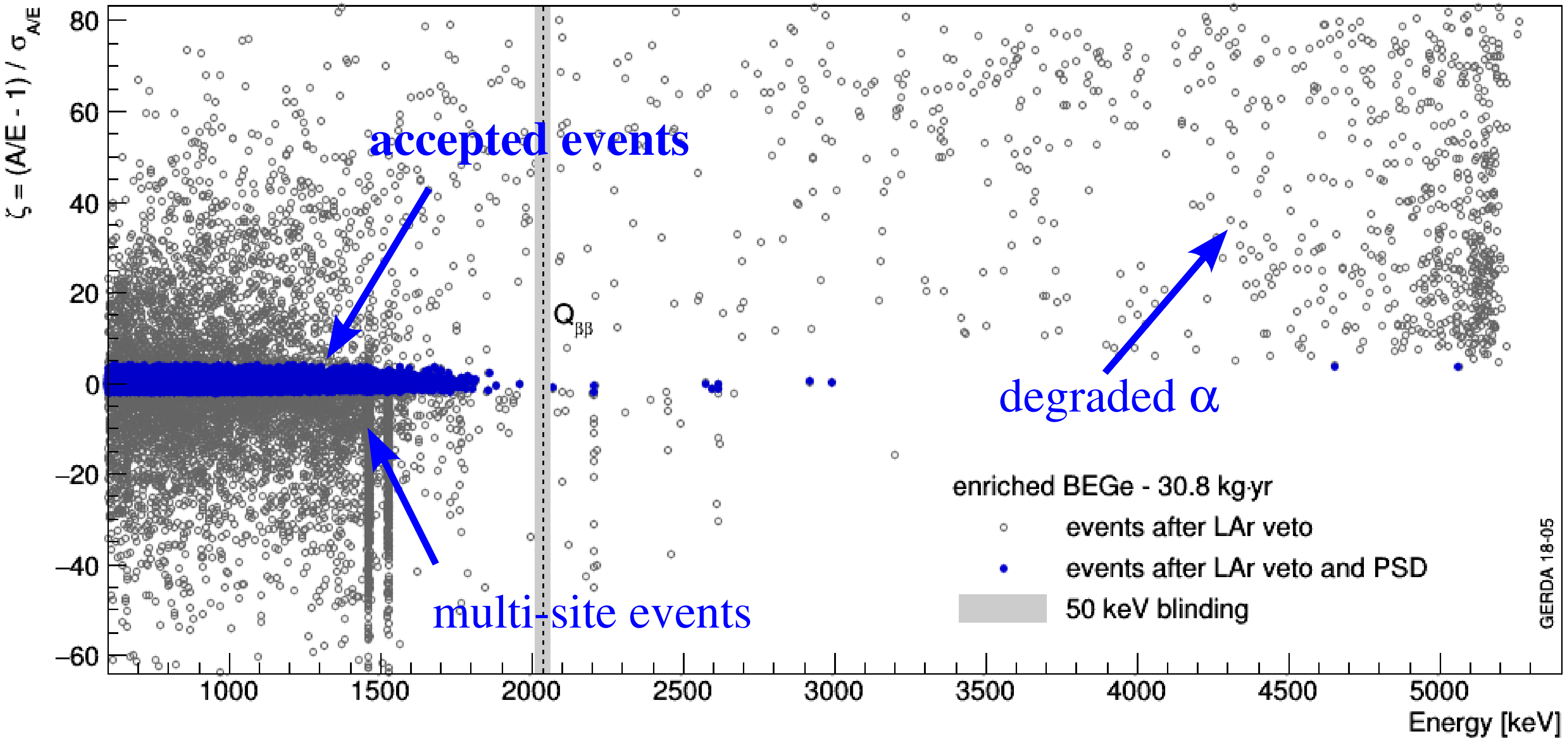
DEP events

Compton at $Q_{\beta\beta}$

FEP @ 2614 keV

FEP 1620 keV, SEP

Pulse Shape Discrimination: BEGe


accepted events

multi-site events

degraded α

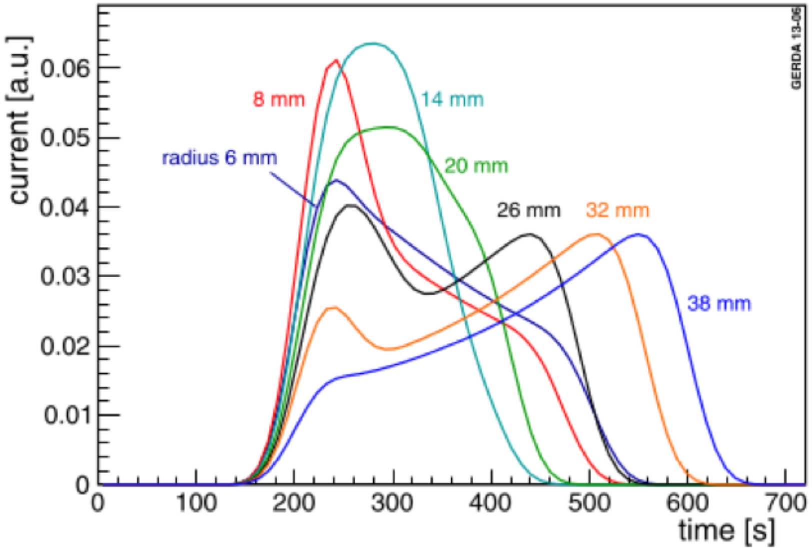
- Event-by-event selection
- Acceptance for 0νββ events: **(87.6 ± 2.5)%**
  - estimated from ^{208}Tl DEP
  - double checked at low energy with 2νββ events (after LAr cut): (85.4 ± 1.9)%

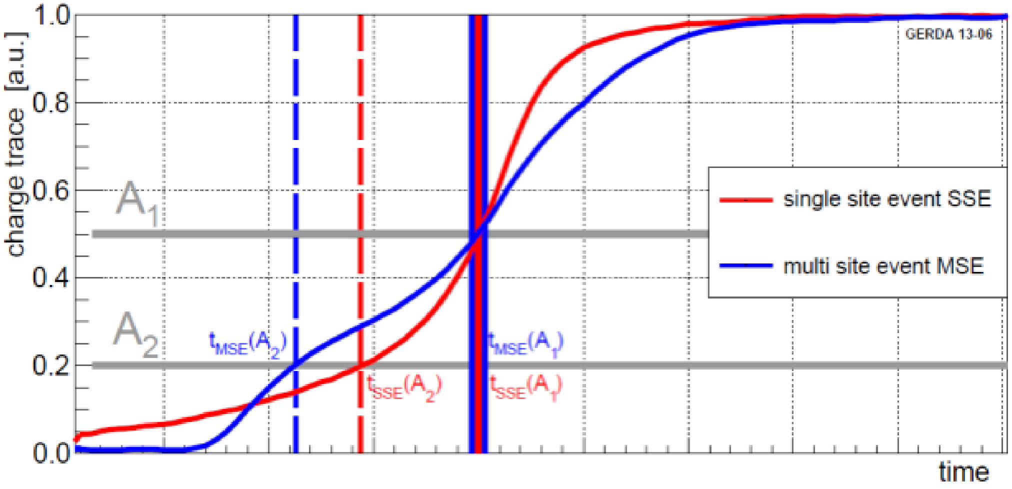
Pulse Shape Discrimination: Coax

- PSD for Coax detectors less effective than for BEGes

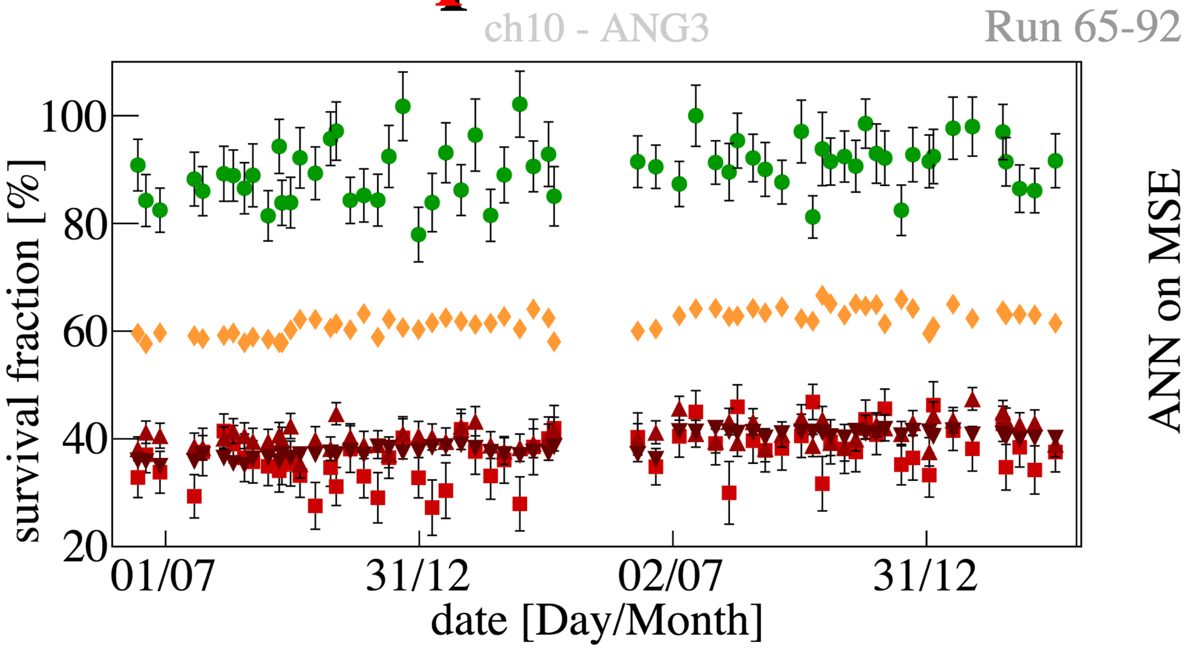
- Artificial Neural Network (**ANN**) as in Phase I:
  - Trained on signal (SSE): ^{208}Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): ^{212}Bi @ 1620 keV γ-line

Current Pulses for SSE





Pulse Shape Discrimination: Coax



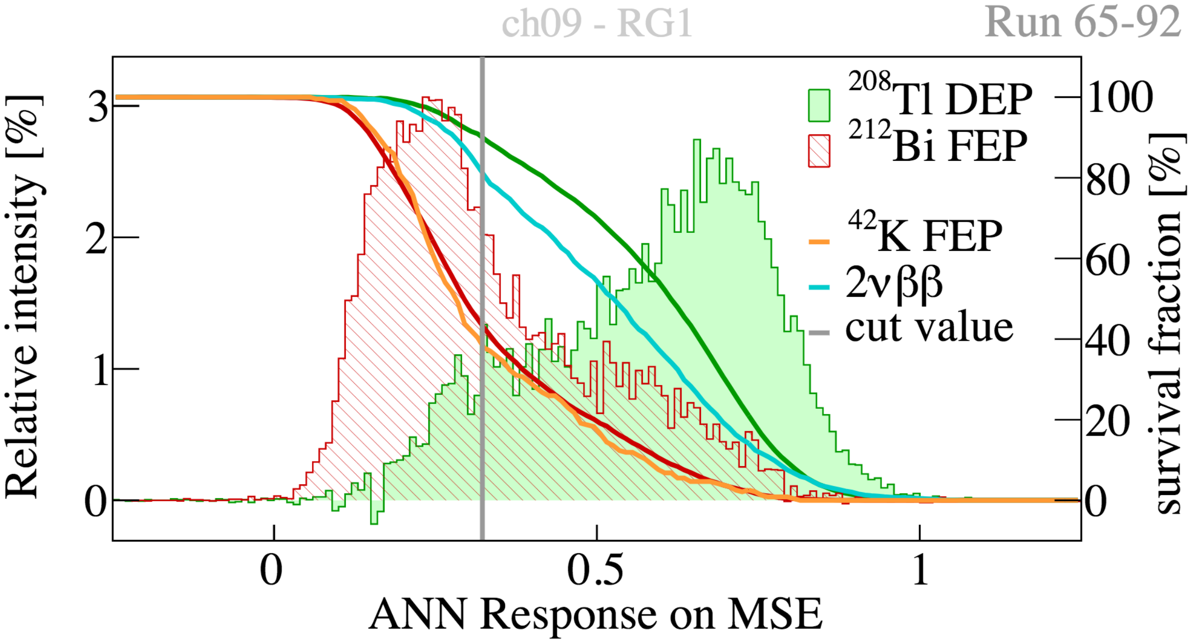
- Example of **time stability** of ANN for a coaxial detector

  ^{208}Tl DEP

  $Q_{\beta\beta}$ ± 25 keV

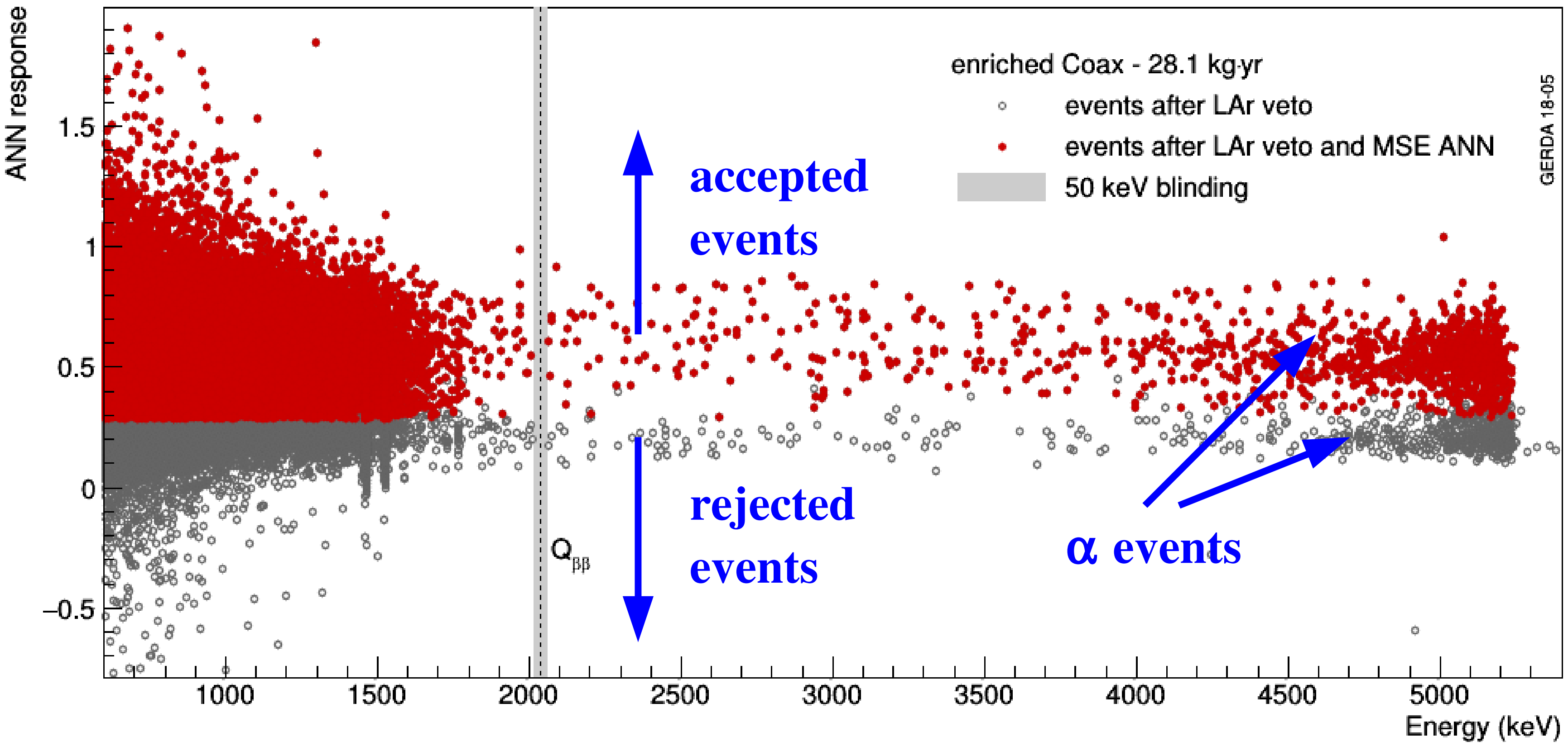
  ^{208}Tl SEP

  ^{212}Bi FEP



- Example of **ANN response** for a coaxial detector

Pulse Shape Discrimination: Coax



accepted events

rejected events

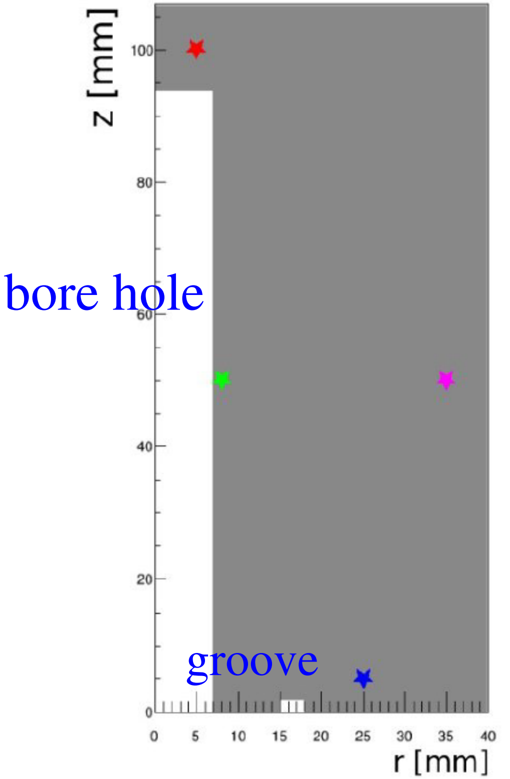
α events

- Acceptance for 0νββ events (**84 ± 5**)%
  - MC simulation of waveforms
  - Double check with 2νββ events

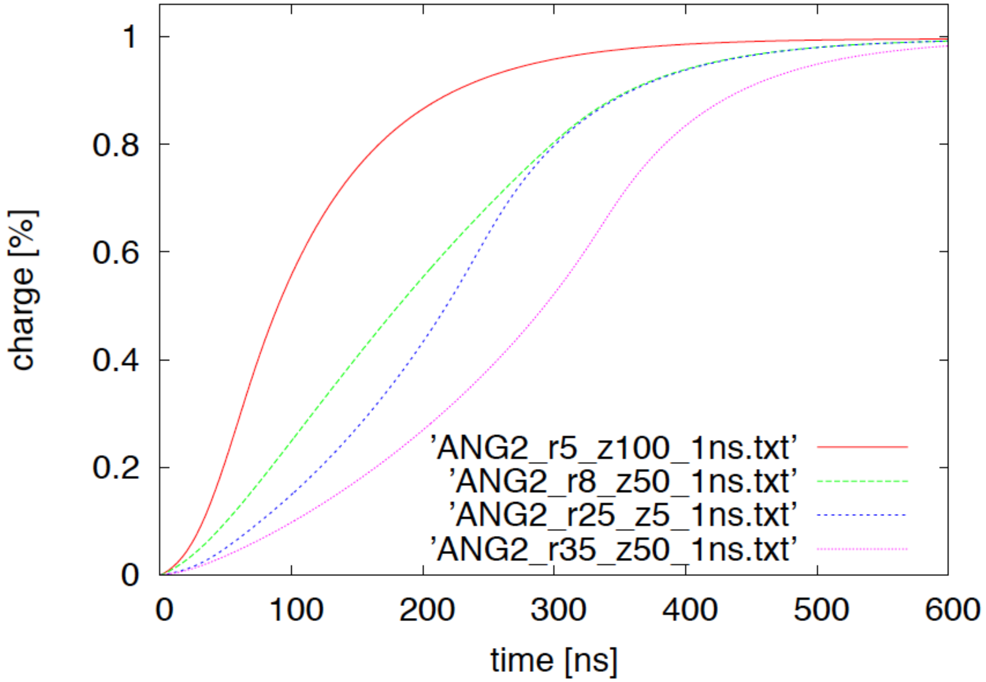
Pulse Shape Discrimination: Coax

- New rejection method for **α events** based on their (fast) **rise time**

coaxial detector

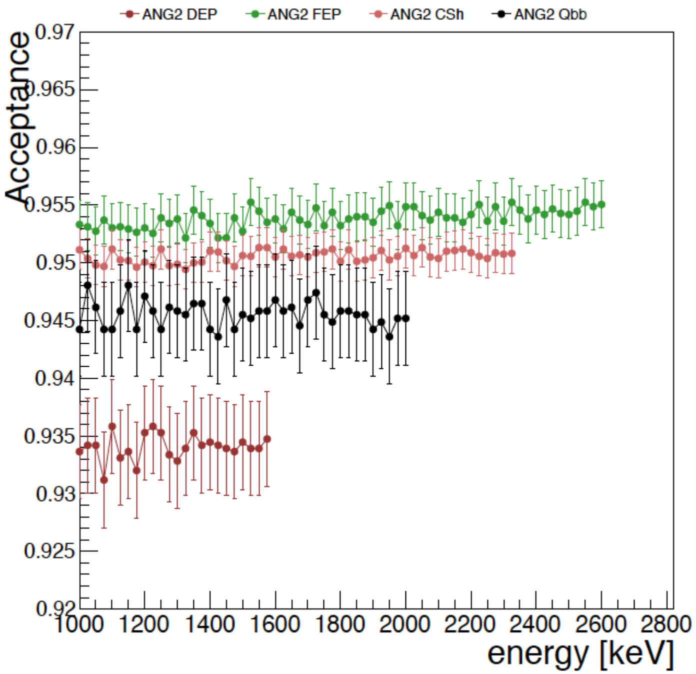


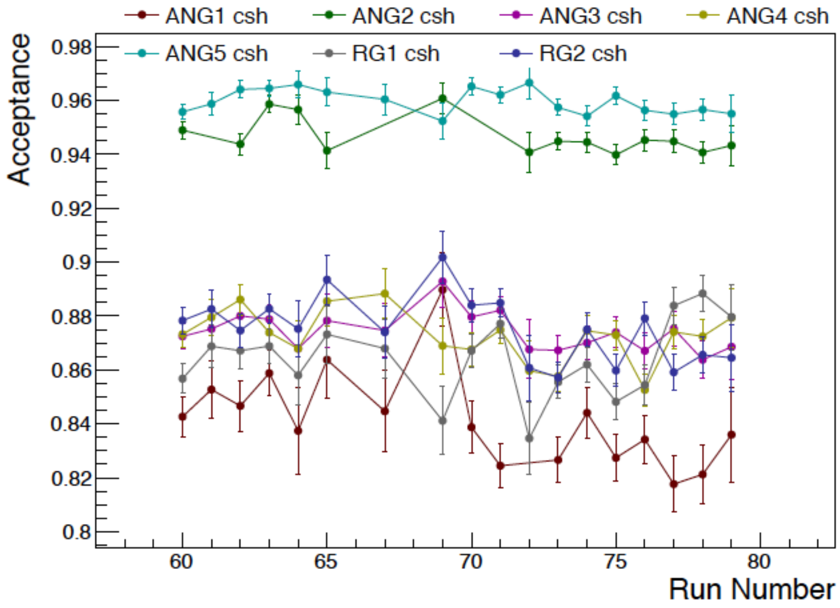
MC simulation



- Events with **rise time** (10%-90% of the rising part the pulse) faster than 180-220 ns (depending on specific detector) are rejected as **α events**

Pulse Shape Discrimination: Coax

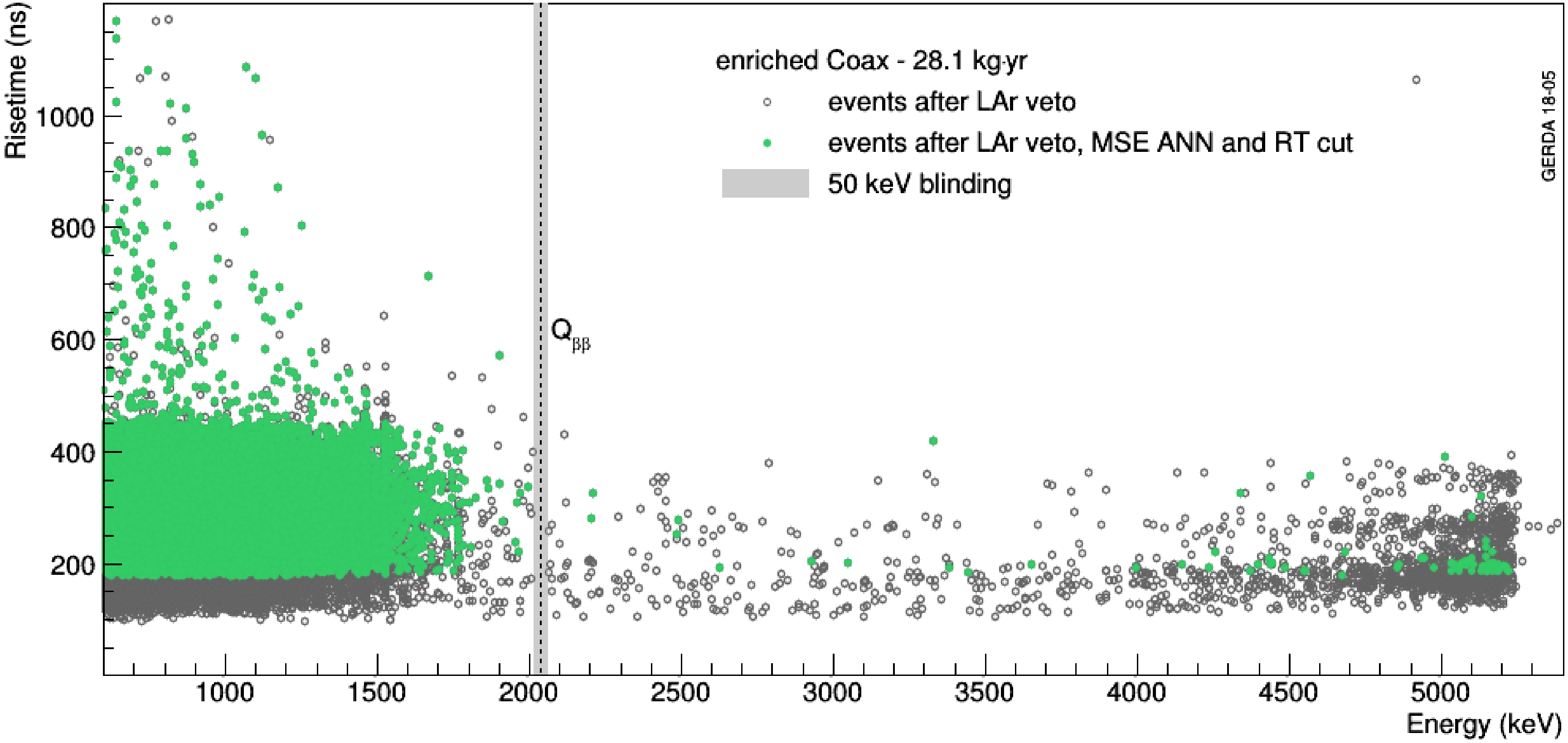




- Example of **Energy stability** of the RT method for a particular detector, using different event samples.

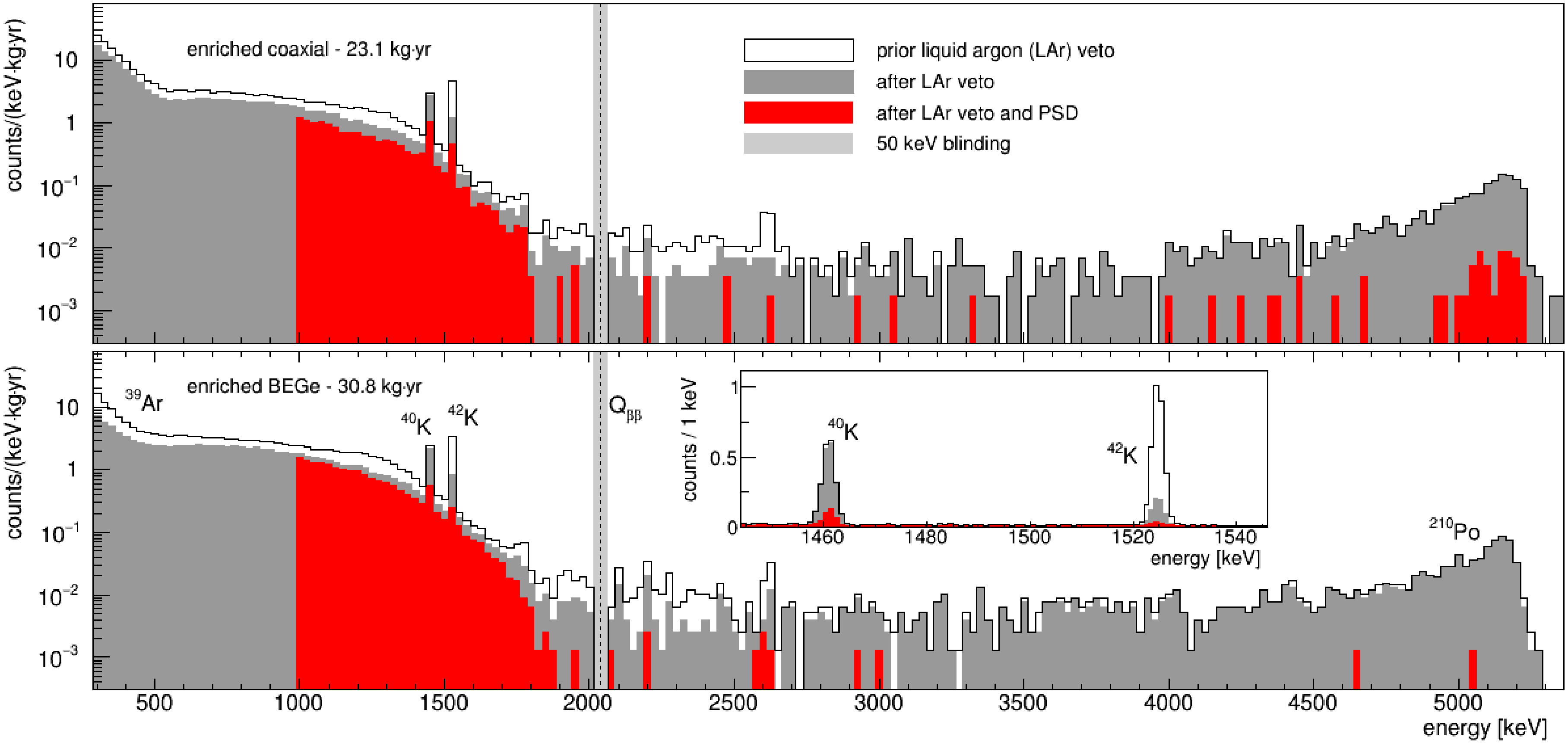
- **Time stability** of the RT method for all the detectors

Pulse Shape Discrimination: Coax



- **RT Acceptance** for 0νββ events (**85 ± 1**)%
    - estimated from 2νββ events
- **Total acceptance** (ANN and RT) for 0νββ events : (**71 ± 4**)%

Phase II GERDA spectra

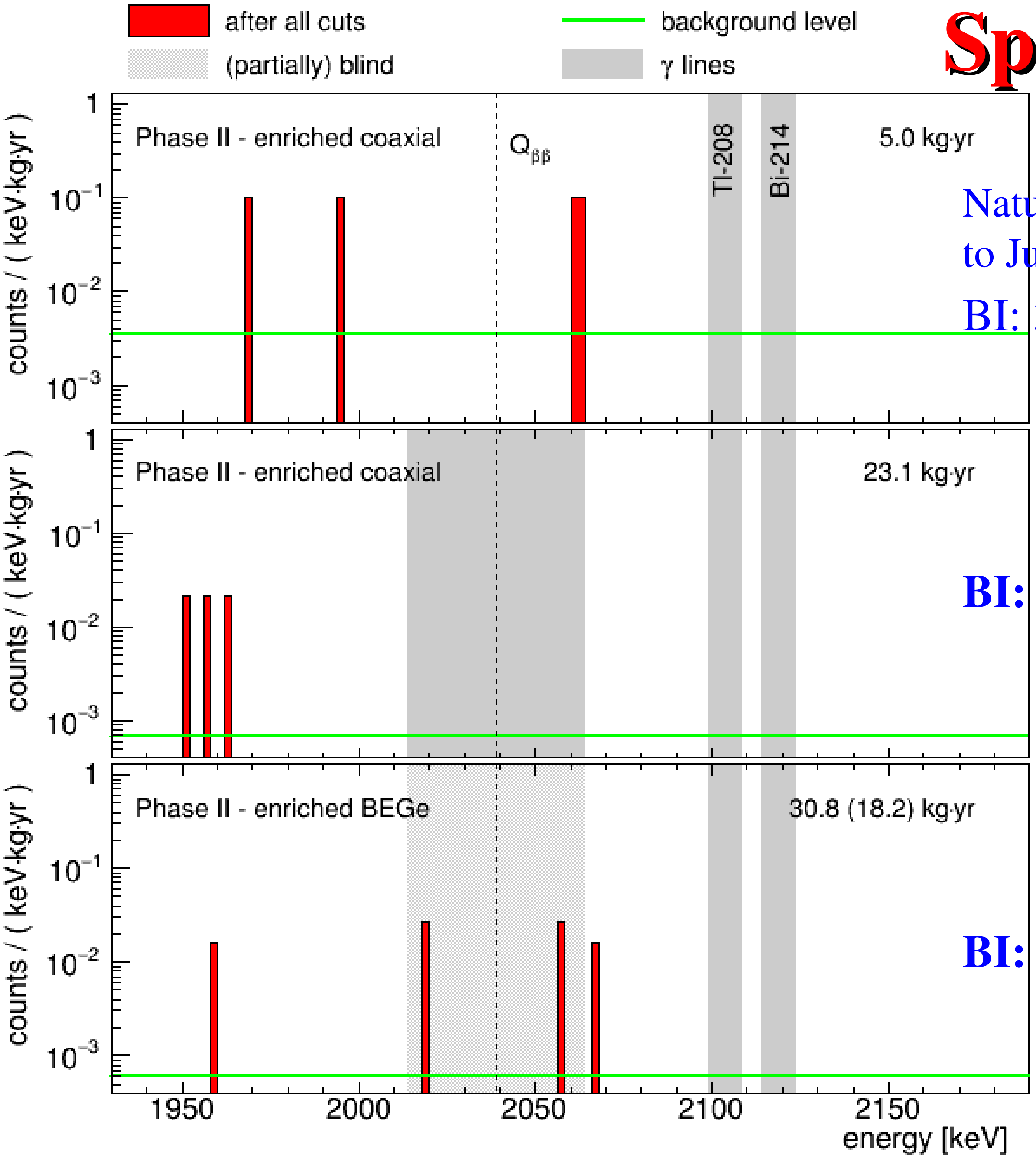


- LAr and PSD highly effective cuts
- background index at $Q_{\beta\beta}$ (*before unblinding*)

BEGe: $0.6^{+0.4}_{-0.3}\ 10^{-3}$ counts/(keV·kg·yr)

Coax: $0.7^{+0.5}_{-0.3}\ 10^{-3}$ counts/(keV·kg·yr) ⟵ Coax and BEGe have now the same low BI

Spectra in the ROI



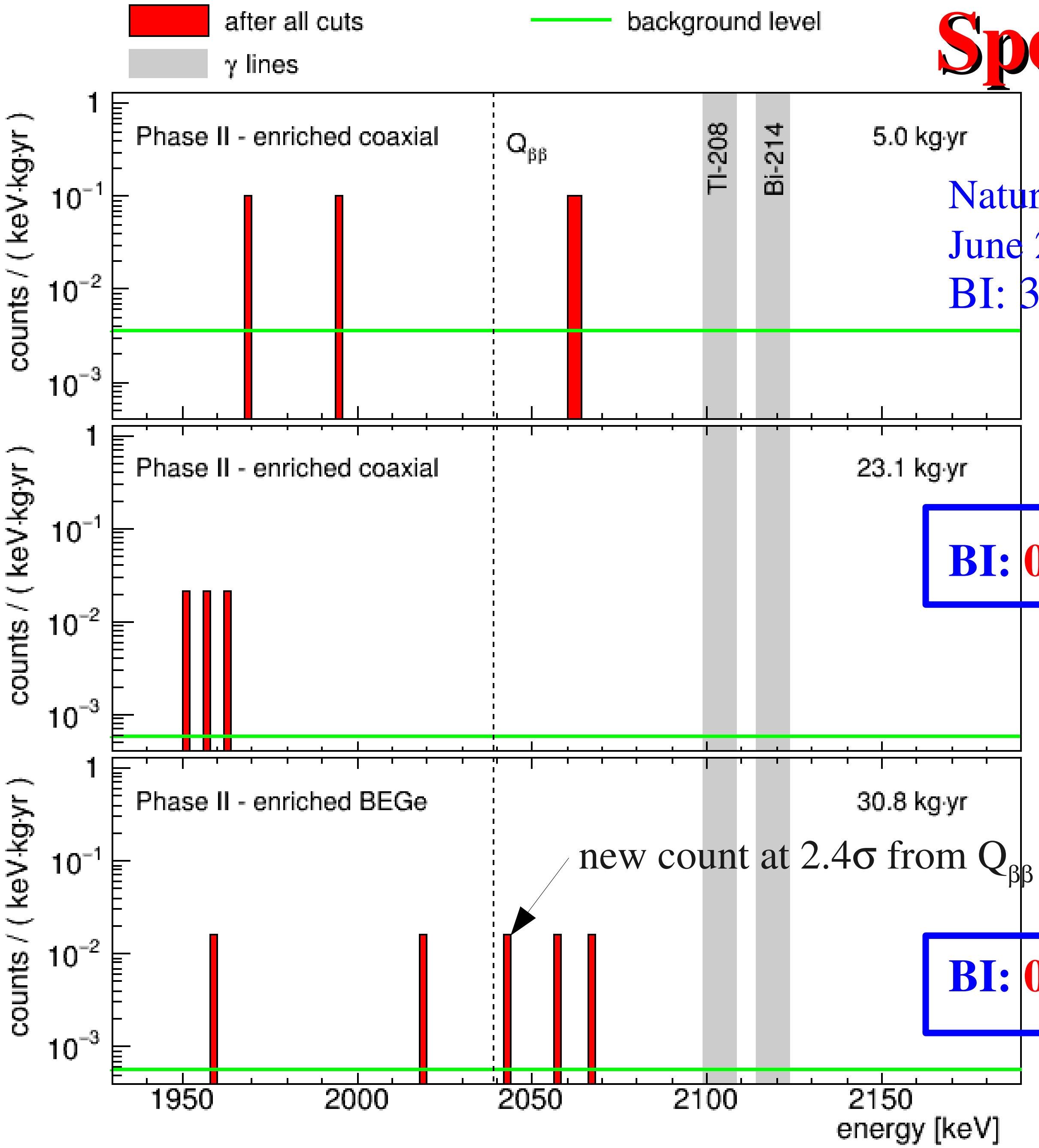
Nature release: data from Dec. 2015 to June 2016

BI: $3.5^{+2.1}_{-1.5} \cdot 10^{-3}$ cts/(keV·kg·yr)

BI: $\mathbf{0.7^{+0.5}_{-0.3} \cdot 10^{-3}}$ cts/(keV·kg·yr)

BI: $\mathbf{0.6^{+0.4}_{-0.3} \cdot 10^{-3}}$ cts/(keV·kg·yr)

Spectra in the ROI



new count at 2.4σ from $Q_{\beta\beta}$

Nature release: data from Dec. 2015 to June 2016
BI: $3.5^{+2.1}_{-1.5} \cdot 10^{-3}$ cts/(keV·kg·yr)

BI: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg·yr)

after the unblinding the amplitude of the energy window for the BI calculation changes from 190 keV to 230 keV

BI: $0.6^{+0.4}_{-0.3} \cdot 10^{-3}$ cts/(keV·kg·yr)

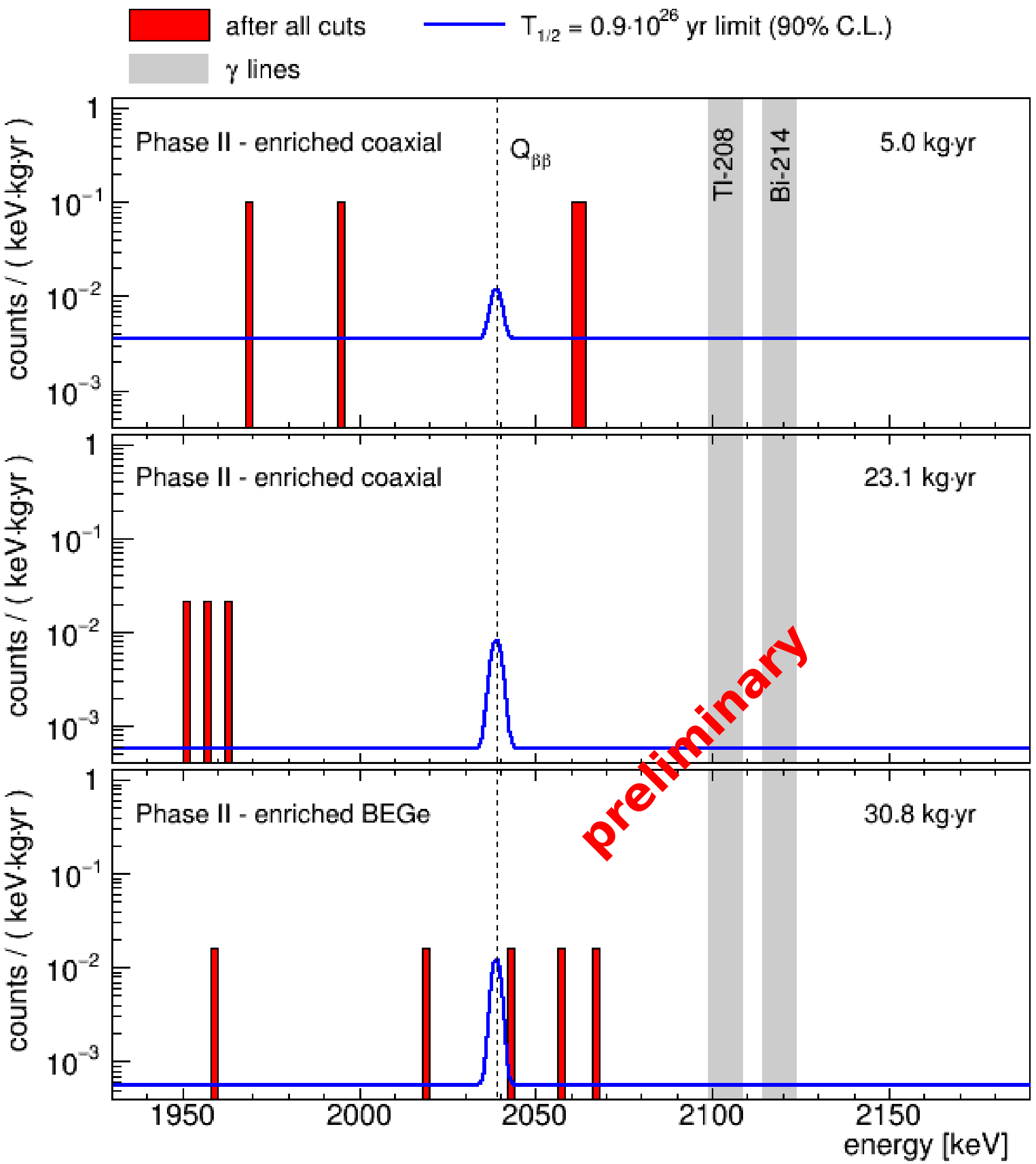
Statistical Analysis

dataset	exposure [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(kevkgyr)]
PI golden	17.9	4.3 ± 0.1	0.57 ± 0.03	11 ± 2
PI silver	1.3	4.3 ± 0.1	0.57± 0.03	30±10
PI BEGe	2.4	2.7 ± 0.2	0.66 ± 0.02	5^{+4}_{-3}
PI extra	1.9	4.2 ± 0.2	0.58 ± 0.04	5^{+4}_{-3}
PII coaxial-1	5.0	3.6 ± 0.1	0.52 ± 0.04	$3.5^{+2.1}_{-1.5}$
PII coaxial-2	**23.1**	**3.6 ± 0.1**	**0.48 ± 0.04**	$\mathbf{0.6^{+0.4}_{-0.3}}$
PII BEGe	**30.8**	**3.0 ± 0.1**	**0.60 ± 0.02**	$\mathbf{0.6^{+0.4}_{-0.3}}$

Total exp. 82.4 kg

- **Combined** unbinned **maximum likelihood** fit (flat background + gaussian signal) of the 7 spectra:
  - **Frequentist:** test statistics and method described in Nature 544, 47 (2017)
  - **Bayesian:** flat prior on $1/T^{0\nu}_{1/2}$ between 0 and 10^{-24} yr^{-1}
  - Systematic uncertainties folded as pull terms or by Monte Carlo

Statistical Analysis



- **Frequentist (preliminary results):**

  Best fit $N^{0\nu} = 0$

  $T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ **yr @ 90% C.L.**

  Median Sensitivity (NO Signal)

  $T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}$ **yr @ 90% C.L.**

  63% of MC realizations yield limit stronger than data

- upper limit on

  $m_{\beta\beta} < 0.11 - 0.26$ eV

- **Bayesian (preliminary results):**

  $T^{0\nu}_{1/2} > 0.7 \cdot 10^{26}$ **yr @ 90% C.I.**

  Median Sensitivity:

  $T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}$ **yr @ 90% C.I.**

  59% of MC realizations yield limit stronger than data

- Bayes factor: $P(H_1)/P(H_0) = 0.054$

  where:

  H_1:signal+background hypothesis

  H_0: background-only hypothesis

Status of the upgrade ...

◆ Start on 16th of April; End on 21st of May

Work done:

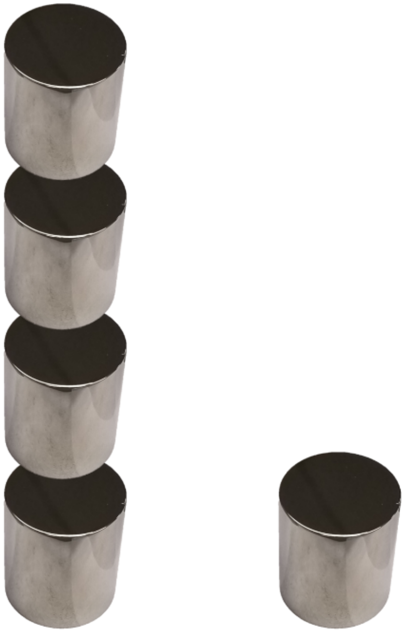
- **new enriched inverted coaxial detectors (9.5 kg)** in place of the natural coaxial detectors
- **repairs** of some broken JFET + some holders modification (from single to double configuration)
- installation of **protecting diodes** in the FE cards
- **new fiber curtain** with a factor 2 increase in light yield
- **exchange of the HV and signal cables** with cables having lower radioactivity budget

◆ In July a brief break to add two inverted coaxial detectors which have shown a too high LC

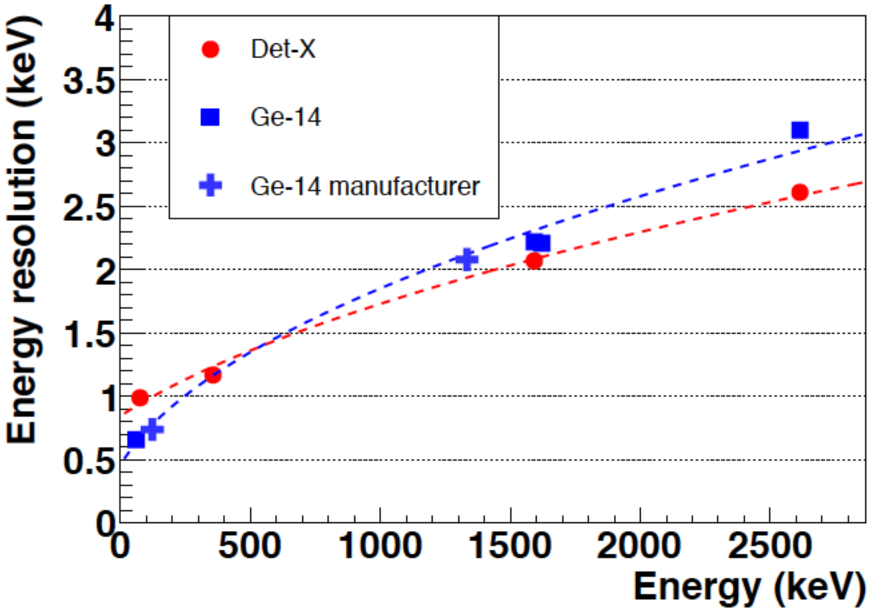
◆ plus other repairs

Status of the upgrade ...

- Results from **two prototypes of inverted coaxial detectors. The 5 in GERDA have similar performances**
- **Similar *E* resolution and PSD performances respect to BEGe detectors**
- But of **larger masses (~1.8 kg) than BEGe** detectors (~ 0.7 kg) ➔ **less** electronics channels and **less** cables ➔ **lower BI**



Energy resolution



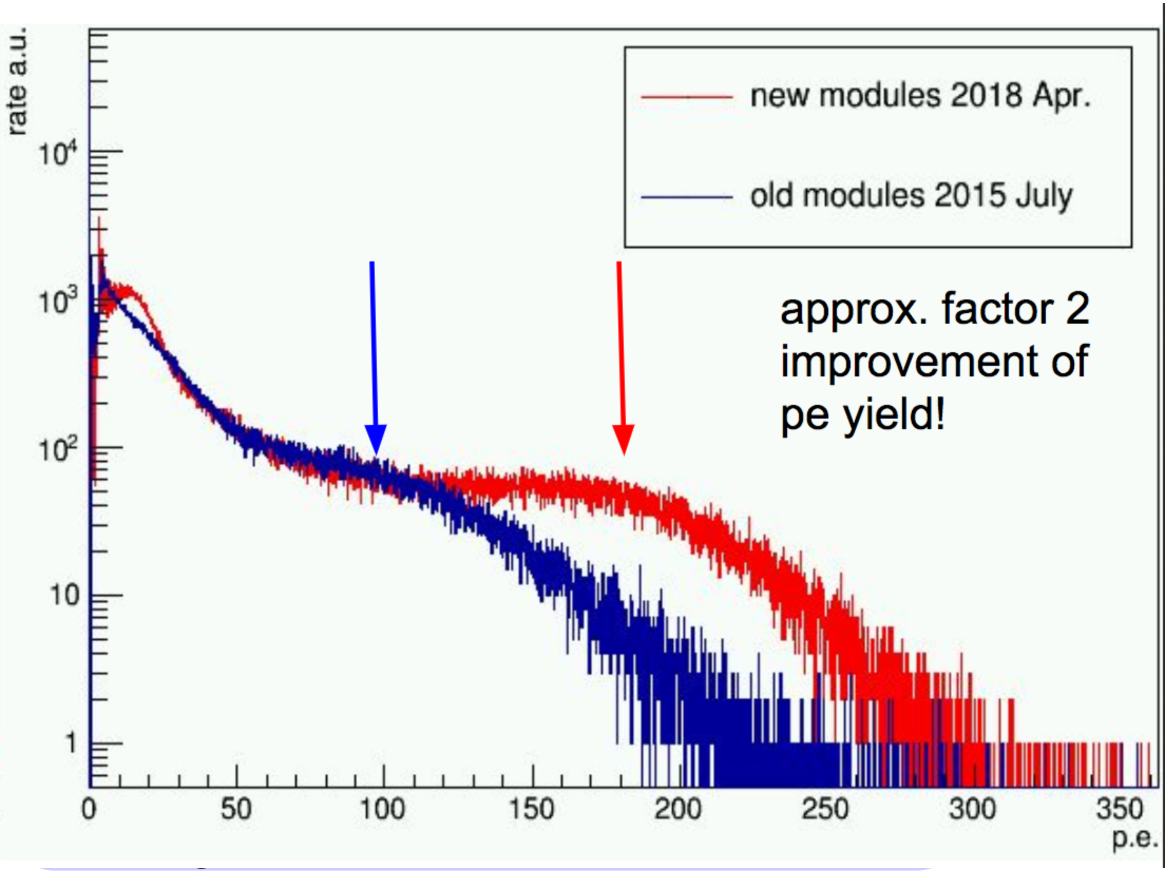
PSD (A/E) performances: survival fractions

(%)	Ge-14	Det-X	BEGe
^{208}Tl DEP	89.8	90.2	90.0
^{212}Bi FEP	9.6	8.4	11.5
$Q_{\beta\beta}$	32.7	35.6	37.8
^{208}Tl SEP	6.2	5.5	7.5
^{208}Tl FEP	8.6	8.0	7.7

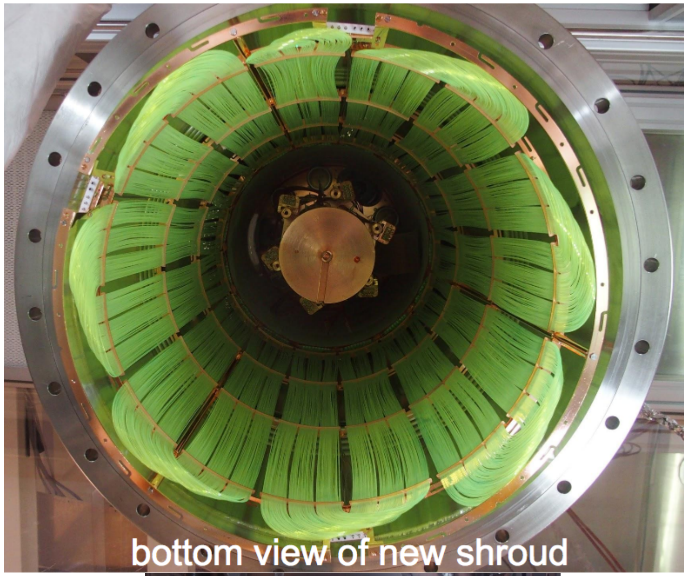
inverted coaxial prototypes

Status of the upgrade ...

- New fiber shroud with more fibers
- Better SiPMs modules
- higher light yield



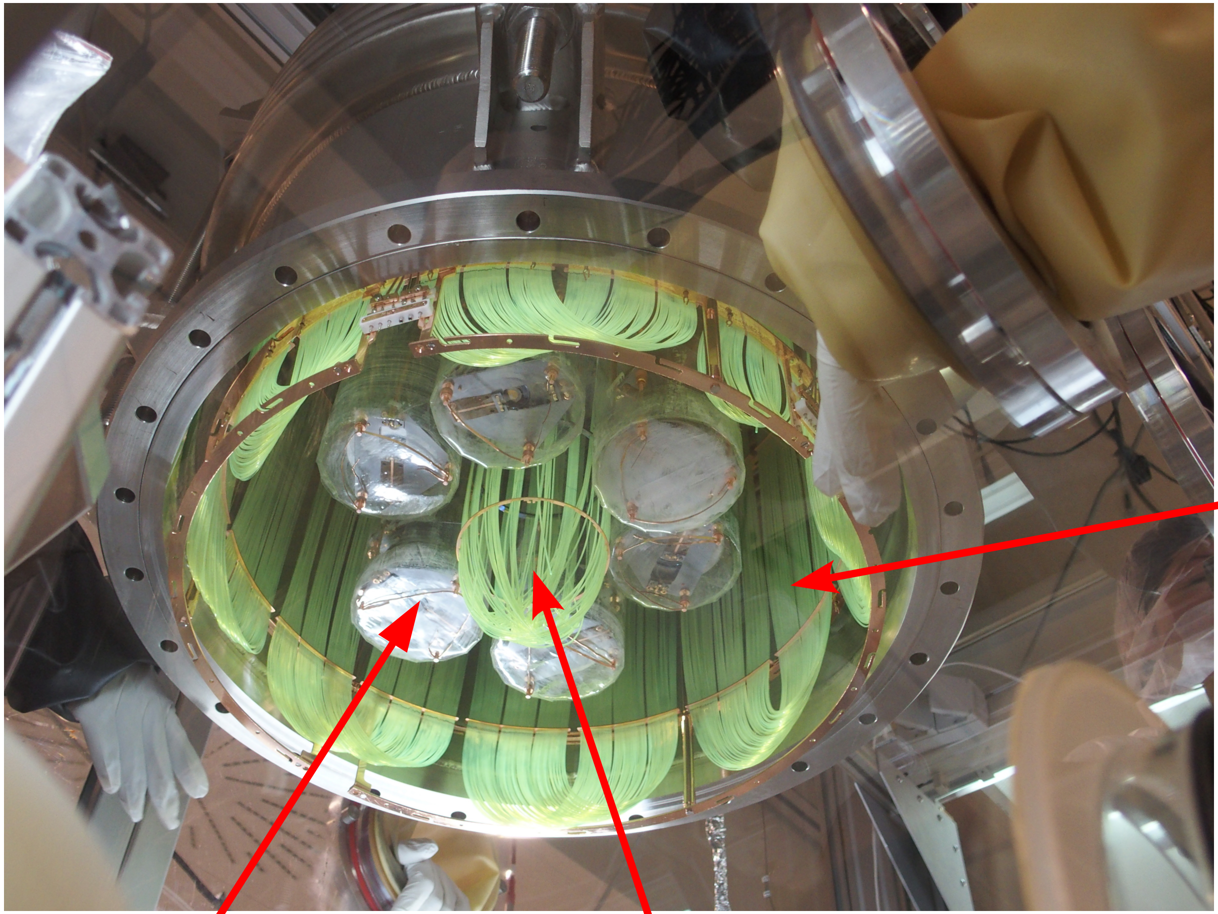
approx. factor 2 improvement of pe yield!



bottom view of new shroud

new shroud in the lock

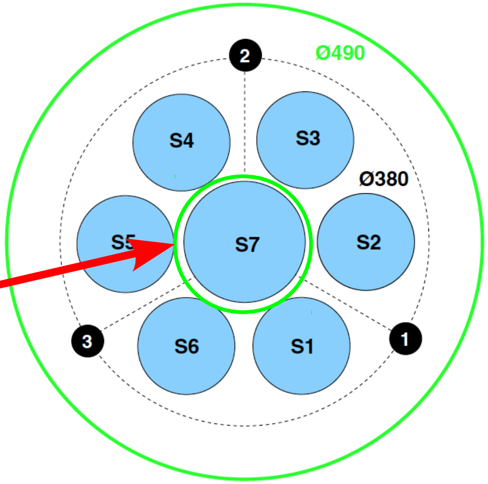
Status of the upgrade ...



fiber shroud

detectors string

central fiber shroud



Conclusions

- GERDA has worked **smoothly** and with **high efficiency since** december 2015
- We have collected ~ **59 kg·yr** of really good data: i.e. more than 50% of Phase II exposure (100 kg·yr)
- With the present data release we have obtained:
  - Limit on **$T^{0\nu}_{1/2} > 0.9\cdot10^{26}$ yr (90% CL)**
  - Median Sensitivity: **$1.1\cdot10^{26}$ yr** (*the best in the world!*)
  - BI(^{enr}Coax): **$0.6^{+0.4}_{-0.3}\cdot10^{-3}$ cts/(keV· kg · yr)**

    BI(^{enr}BEGe): **$0.6^{+0.4}_{-0.3}\cdot10^{-3}$ cts/(keV ·kg · yr)**
  - **$m_{ee} < 0.11 – 0.26$ eV**

preliminary

- **Lowest bkg** (~10x) in ROI respect to experiments using other isotopes, only roughly a factor 3 higher than the LEGEND-200 BI goal
- **Best median sensitivity** respect to all other experiments
- Upgrade of the apparatus to go **even lower** with the BI and test new type of Ge detectors
- promising future for a Ge experiment with 200 kg and beyond