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

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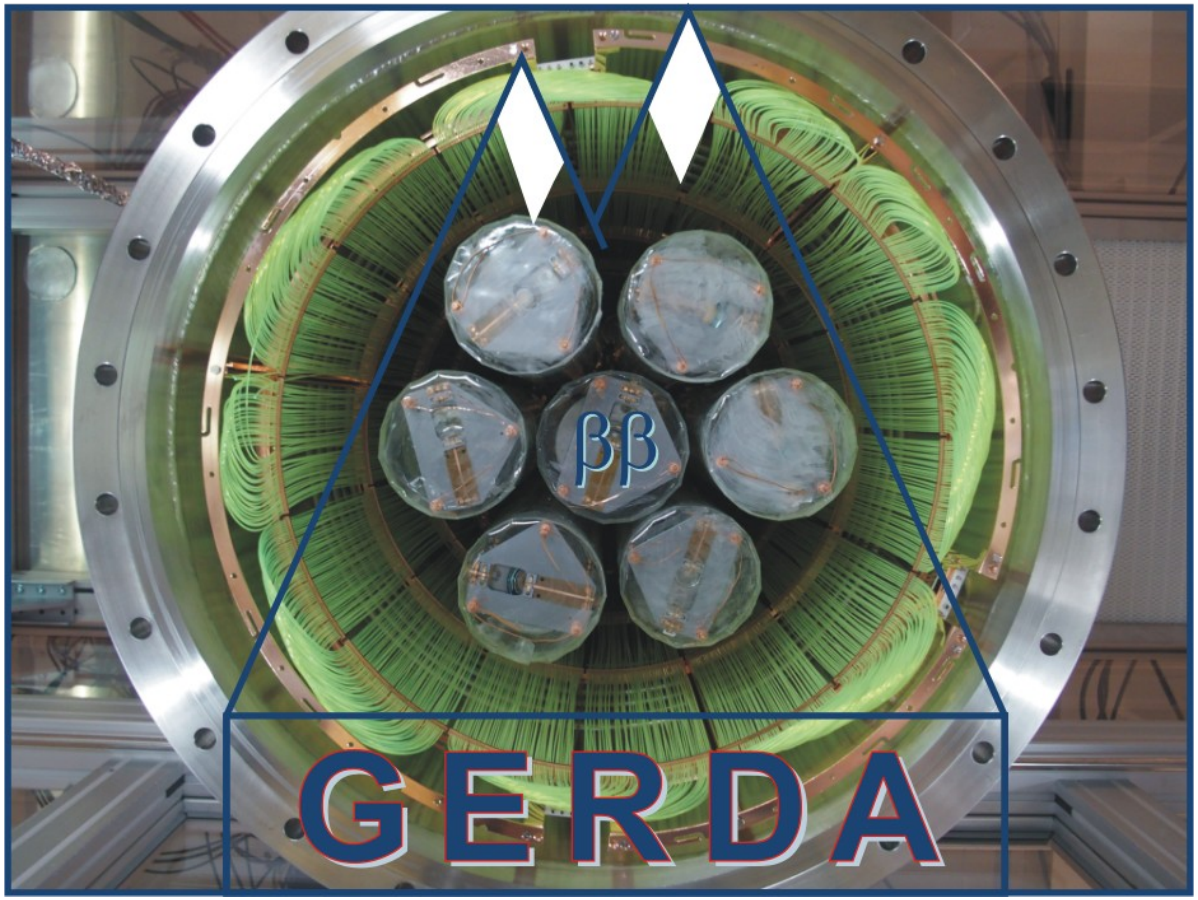
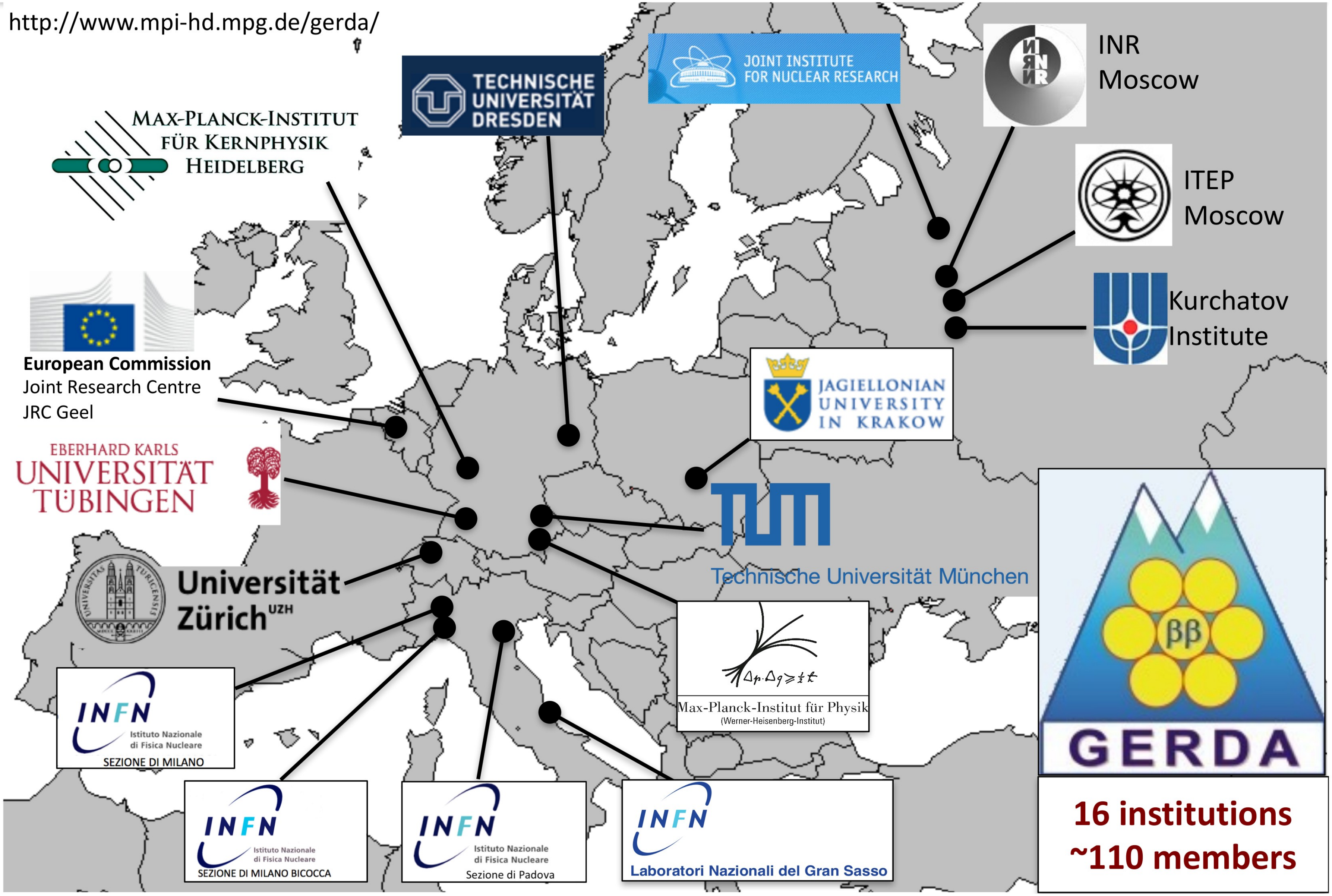
on behalf of the GERDA Collaboration

GERDA



The GERDA Collaboration

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



INR
Moscow

ITEP
Moscow

Kurchatov
Institute

European Commission
Joint Research Centre
JRC Geel

16 institutions
~110 members

motivation for $0\nu\beta\beta$ decay searches:

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

- would establish ***lepton number violation*** $\Delta L = 2$

$(Z, A) \rightarrow (Z+2, A) + 2e^-$; half-life > 10^{25} years

by far the most sensitive test of LNV

other possibilities to test *LNV*:

$\mu^- + (Z, A) \rightarrow e^+ + (Z-2, A)$; exp. $Br \leq 10^{-12}$

$K^+ \rightarrow \mu^+\mu^+\pi^-$; exp. $Br \leq 1.1\times10^{-9}$

$\bar{\nu}_e$ emission from the Sun; exp. $Br \leq 10^{-4}$

- more ***physics beyond standard model***
  - the process stands on equal footing with baryon number violation (i.e. *p* decay)
  - important to understand the origin of the neutrino mass

motivation for $0\nu\beta\beta$ decay searches:

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

- Possible interpretations of $0\nu\beta\beta$:
  - *Standard interpretation*: $0\nu\beta\beta$ decay is mediated by light and massive Majorana neutrinos (the ones which oscillate) and all other mechanisms potentially leading to $0\nu\beta\beta$ give negligible or no contribution
  - *Non-standard interpretations*: $0\nu\beta\beta$ decay is mediated by some other LNV physics (Higgs triplet, LR symmetric theories, SUSY theories, Majorons,...), and light and massive Majorana neutrinos (the ones which oscillate) potentially leading to $0\nu\beta\beta$ give negligible or no contribution

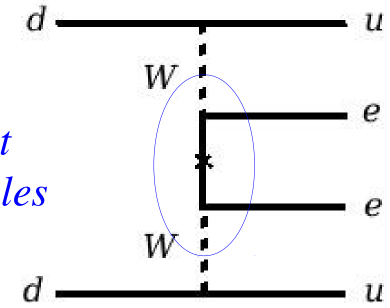
motivation for $0\nu\beta\beta$ decay searches:

(A, Z) → (A, Z+2)+2e$^-$

- Only way to determine if neutrino is its own antiparticle:

$\nu = \bar{\nu}$ ⇨ ***Majorana particle***

If YES:



exchange of light Majorana particles

- would provide access to ***absolute neutrino mass scale***

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{ee}\rangle}{m_e}\right)^2$$

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$$

nuclear matrix element

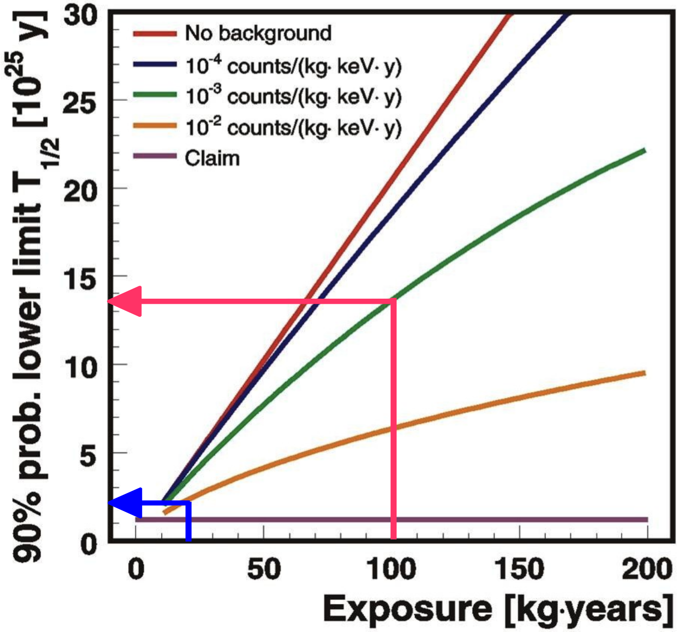
phase space factor

effective Majorana neutrino mass

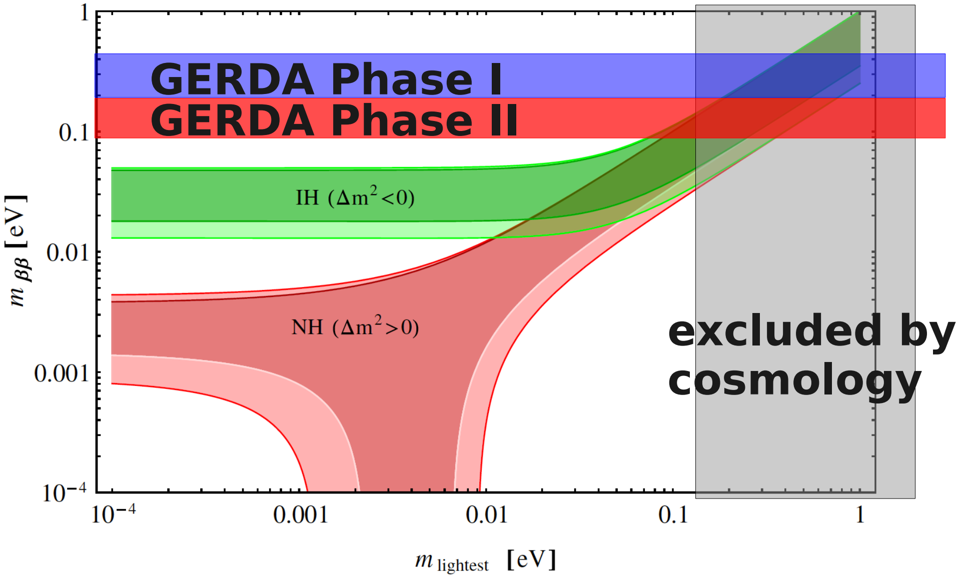
- would provide ***important input to cosmology***

GERDA physics goal

Phys. Rev. D 092003 (2006)



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



PRL 111, 122503 (2013)

Phase I:
(completed in 2013)

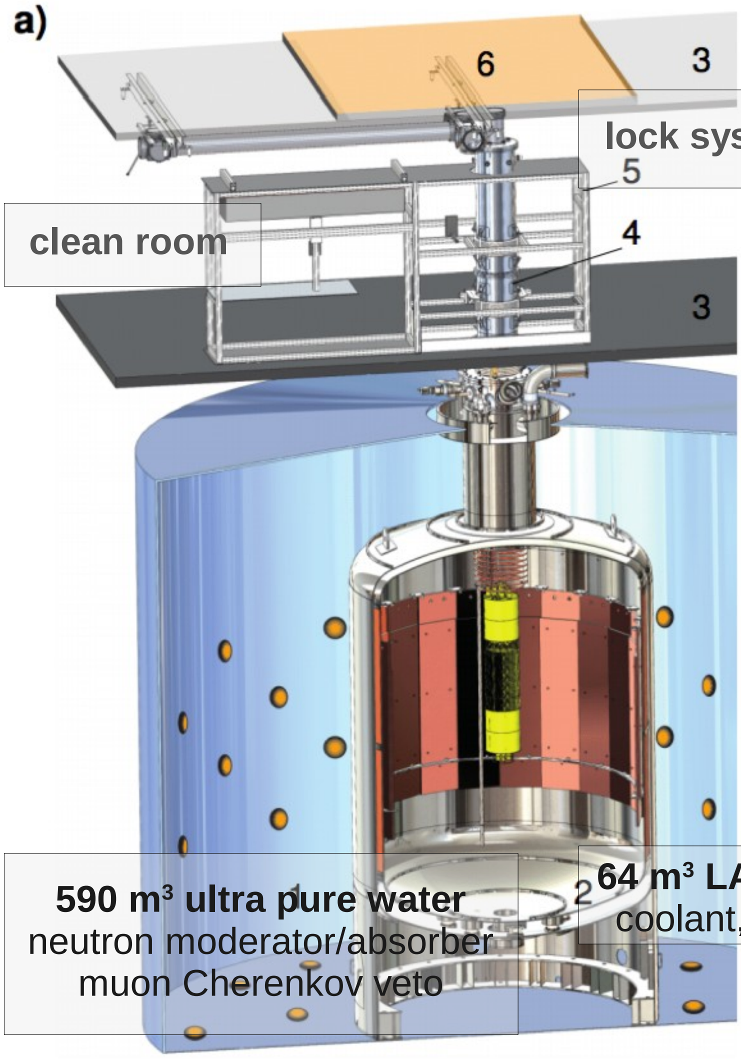
- reached BI of **10^{-2} cts/(keV·kg·yr)**
- exposure of **21.6 kg·yr** → **$T^{0\nu}_{1/2} > 2.1\cdot10^{25}$ yr (90% C.L.)**
- $<m_{ee}> \leq$ 0.2 - 0.4 eV

Nature 544, 47 (2017)

Phase II:
(started at the end of 2015)

- reach background of **10^{-3} cts/(keV·kg·yr)**
- reach an exposure of **100 kg·yr** → **$T^{0\nu}_{1/2} > 1.3\cdot10^{26}$ yr** (*sensitivity*)
- discovery potential up to **10^{26} yr** (*50% prob. chance for a 3σ* signal)
- $<m_{ee}> \leq$ 0.09-0.15 eV

Eur. Phys. C 73 (2013) 2330



plastic scintillator panels
muon veto

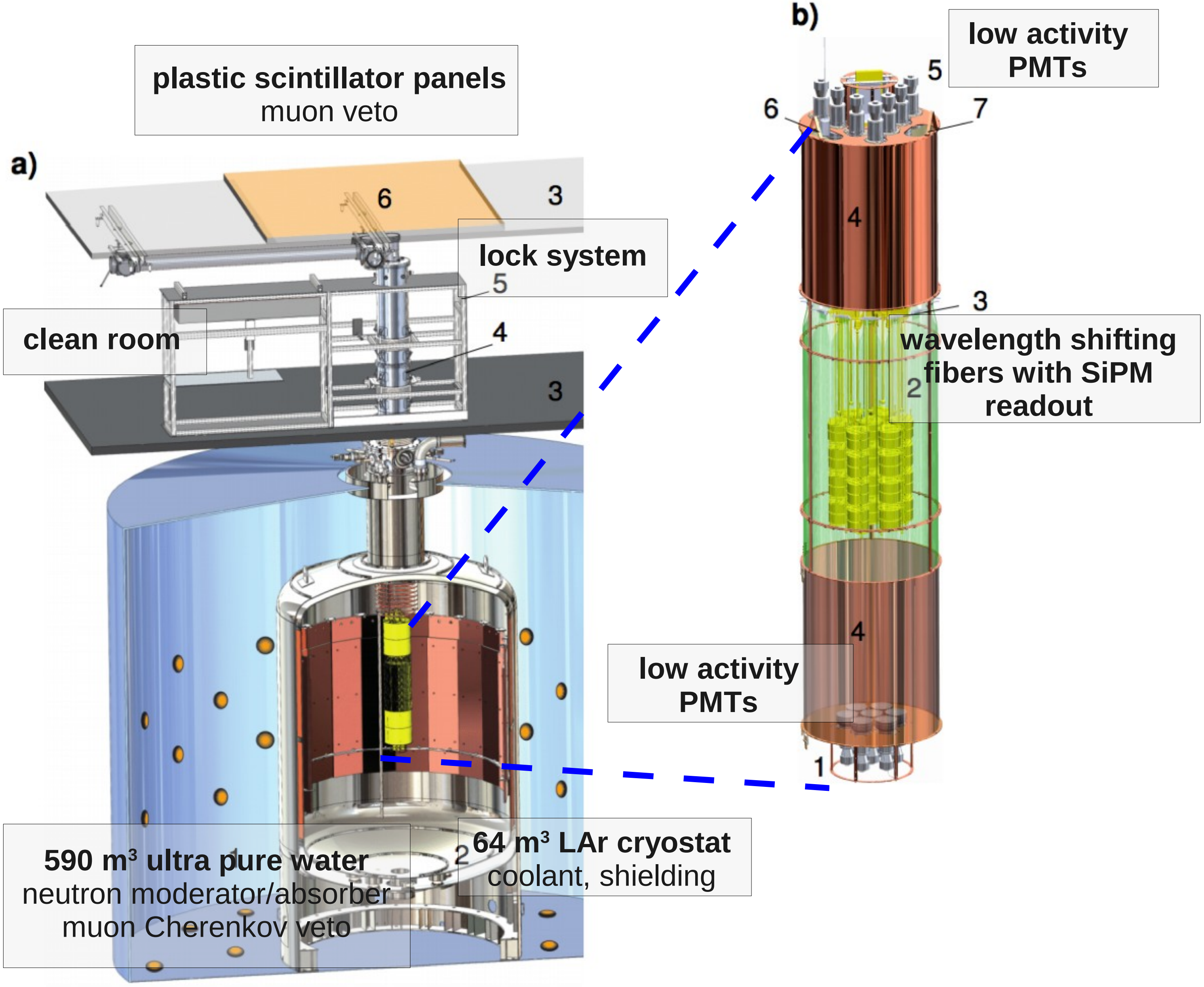
lock system

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

low activity PMTs

wavelength shifting fibers with SiPM readout

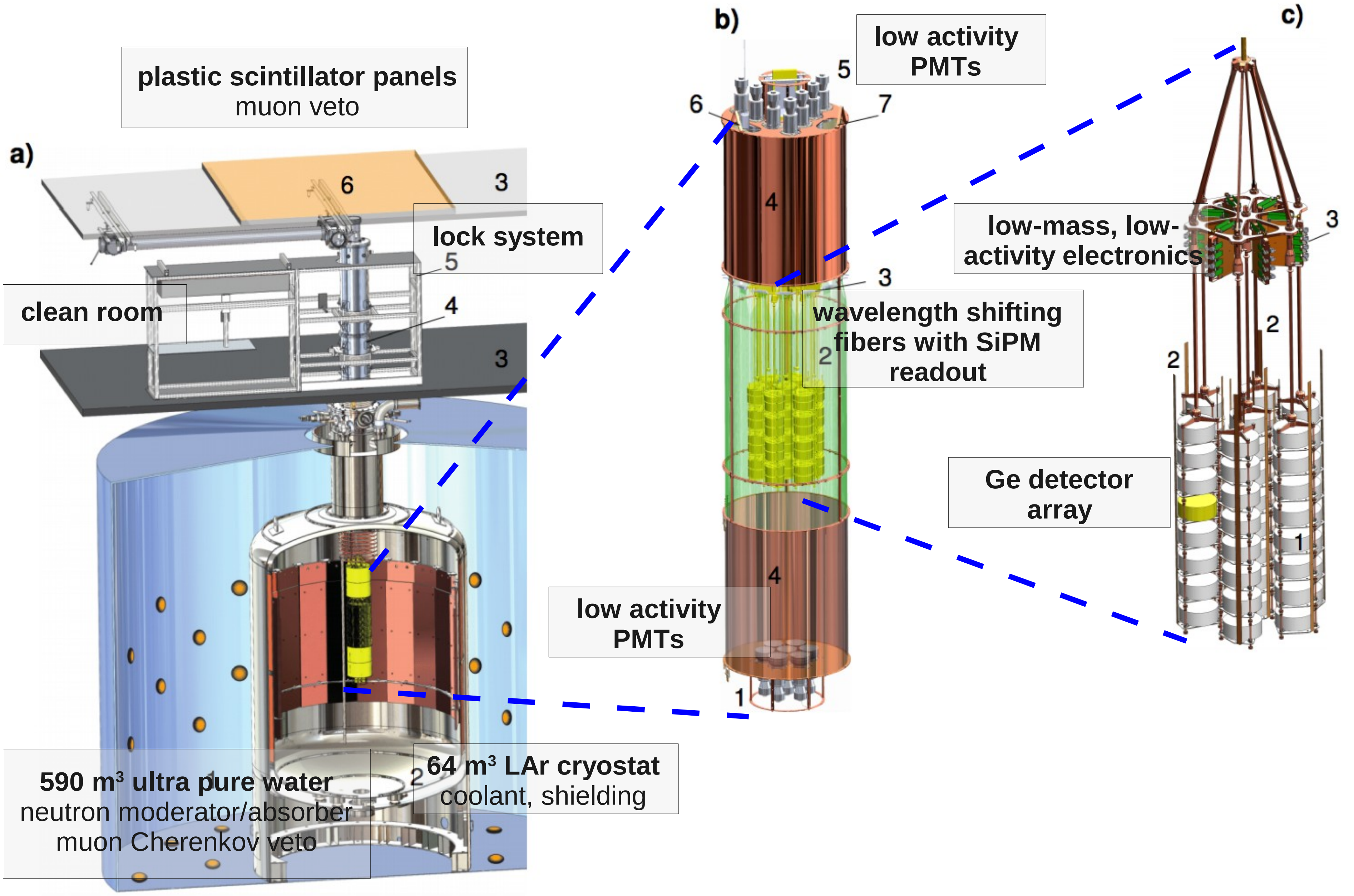
low activity PMTs

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

64 m³ LAr cryostat
coolant, shielding

a) overview

b) liquid argon (LAr) veto instrumentation



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

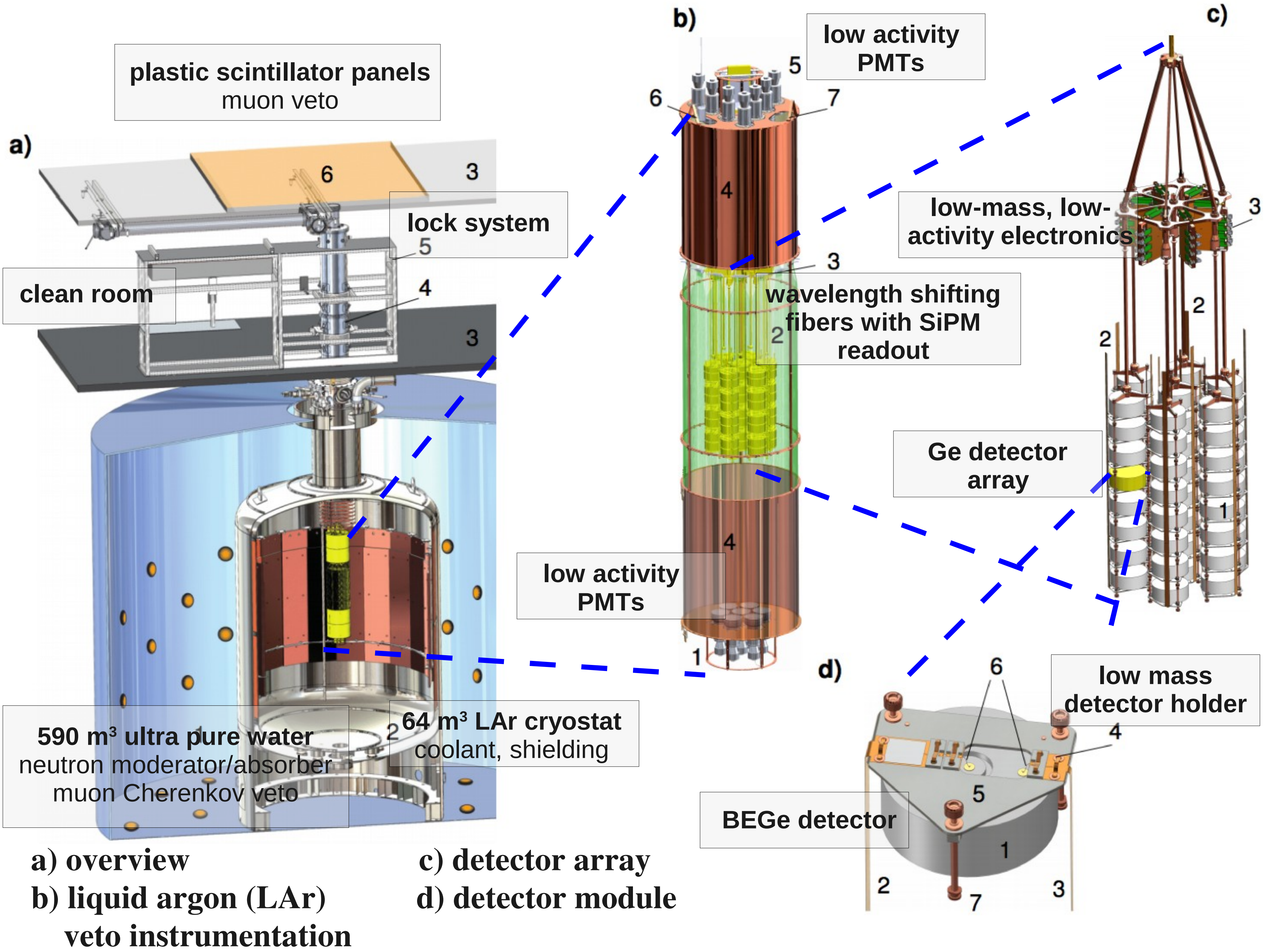
wavelength shifting fibers with SiPM readout

low activity PMTs

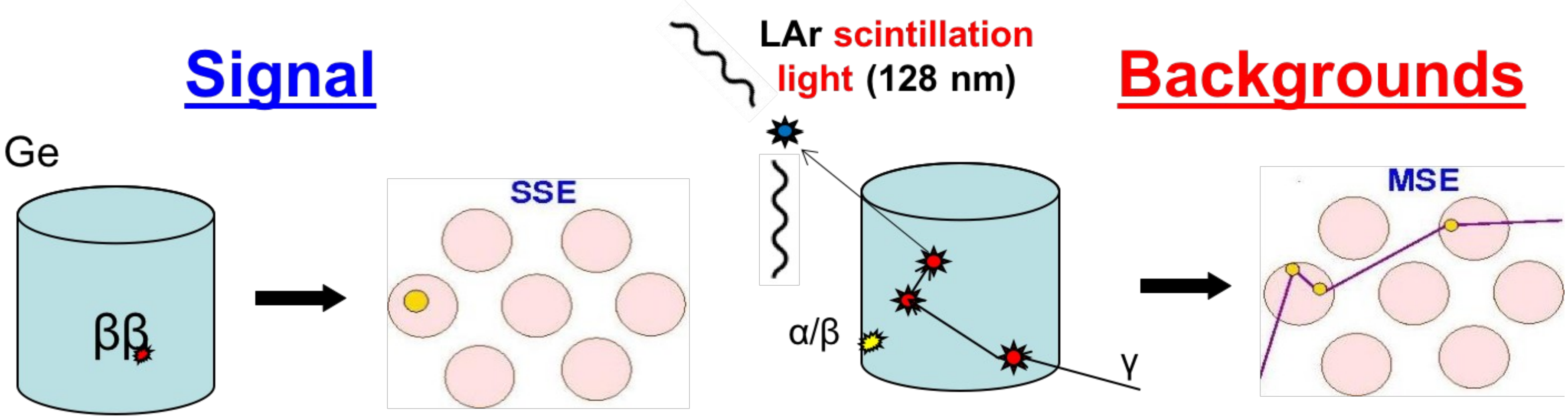
low-mass, low-activity electronics

Ge detector array

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


a)
plastic scintillator panels
muon veto
6
3
lock system
5
clean room
4
3
590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto
2
64 m³ LAr cryostat
coolant, shielding
b)
low activity
PMTs
5
6
7
4
3
wavelength shifting
fibers with SiPM
readout
2
4
low activity
PMTs
1
c)
low-mass, low-
activity electronics
3
2
2
Ge detector
array
1
d)
6
low mass
detector holder
4
5
BEGe detector
1
2
7
3
a) overview
b) liquid argon (LAr)
veto instrumentation
c) detector array
d) detector module

Background reduction tools



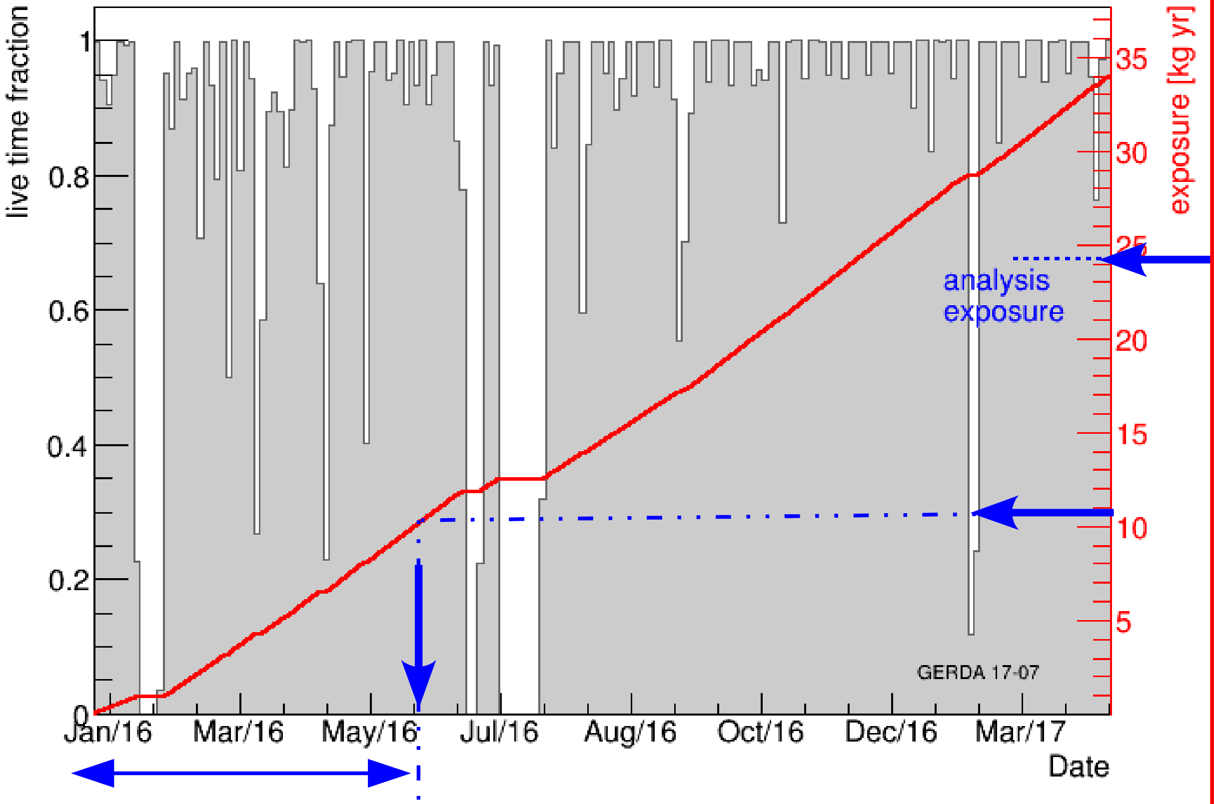
Point-like (single-site) energy deposition inside one HP-Ge diode

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

- ➢Data taking **in progress** !
- ➢Phase II exposure increased by **x3** with respect to the Nature paper
- ➢Valid exposure **34.4** kg·yr (**18.2** BEGe + **16.2** Coax) up to Apr 15th (analysis cutoff)
- ➢A few more kg·yr already in the bag (Apr-Jul) with blinded box of ± 25keV around $Q_{\beta\beta}$



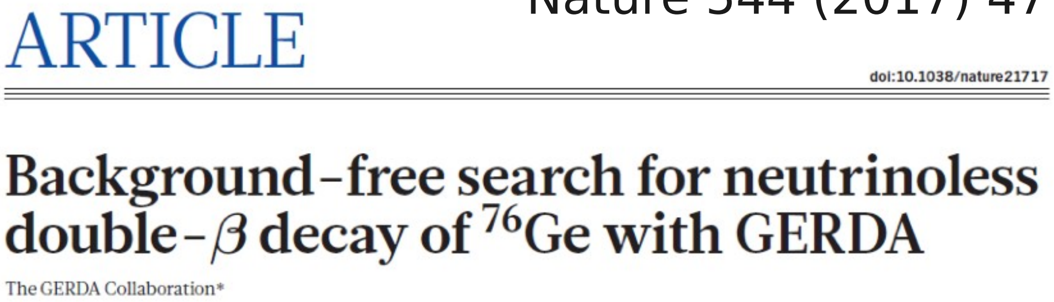
➢ **Phase II a:** 10.8 kg·yr already published in **Nature 544, 47–52**

➢ **New Data Release**

- ◆ Box opened for **BEGe dataset only** (**12.4 kg·yr**)
- ◆ New ^{enr}Coax data still in the box
  - • confident to improve background by better rejection of α events from the groove
  - • Rejection a posteriori would spoil the blinding concept
  - • Even worse in case of signal
- ◆ Total unblinded exposure: **23.2 kg·yr** from Phase II

Phase IIa results

Nature 544 (2017) 47

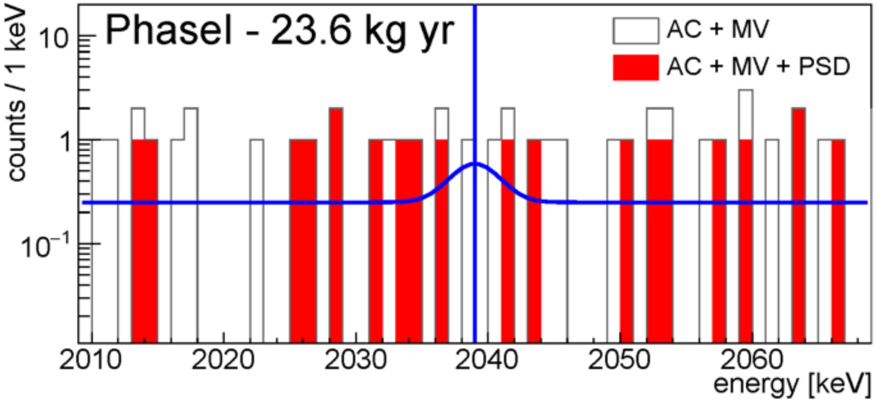

ARTICLE

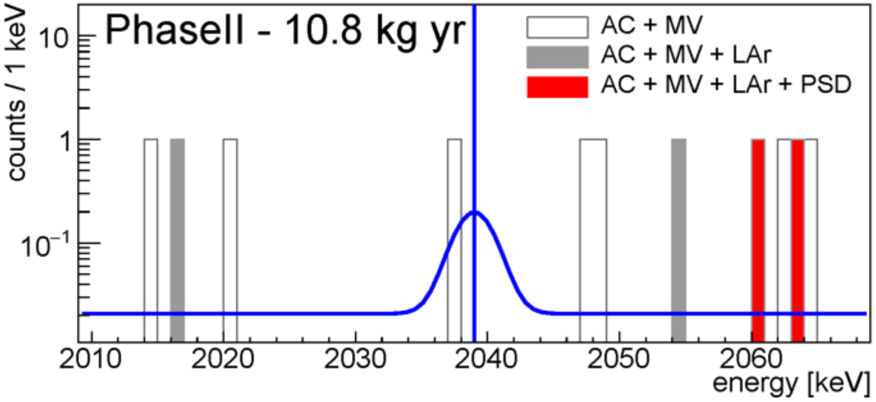
doi:10.1038/nature21717

Background-free search for neutrinoless double-β decay of ^{76}Ge with GERDA

The GERDA Collaboration*

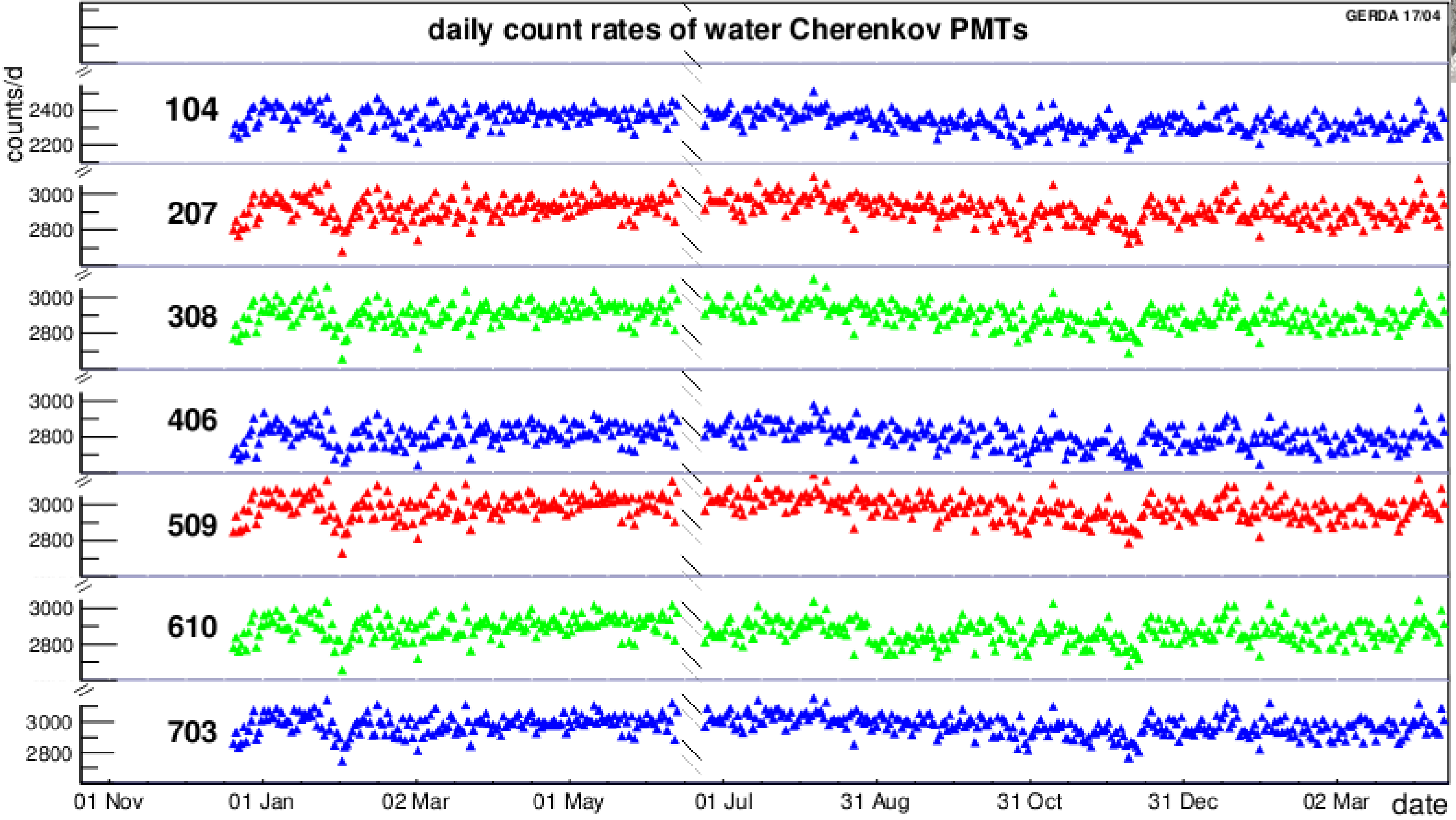
- new limit on $T^{0\nu}_{1/2}$ (Phase I + Phase IIa)
  $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% CL) (median sensitivity $4.0 \cdot 10^{25}$ yr)
- Background Index (BI):
  Coax: $3.5^{+2.1}_{-1.5} \cdot 10^{-3}$ cts/(keV·kg ·yr); FWHM: 4.0(2) keV
  BEGe: $0.7^{+1.1}_{-0.5} \cdot 10^{-3}$ cts/(keV· kg ·yr); FWHM: 3.0(2) keV
- BI/ε = 3.5 cts/(ROI·ton·yr) using BEGe
  ROI: ± 0.5 FWHM





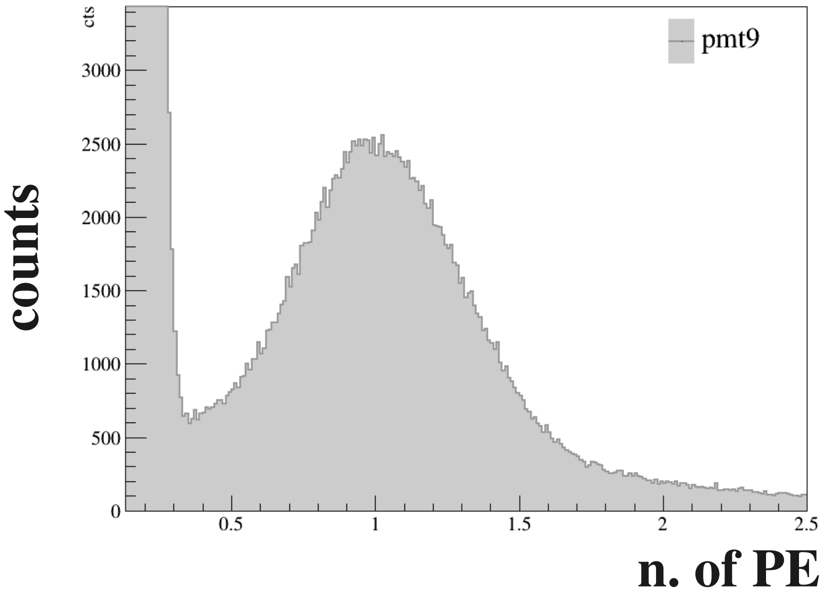
Muon Veto

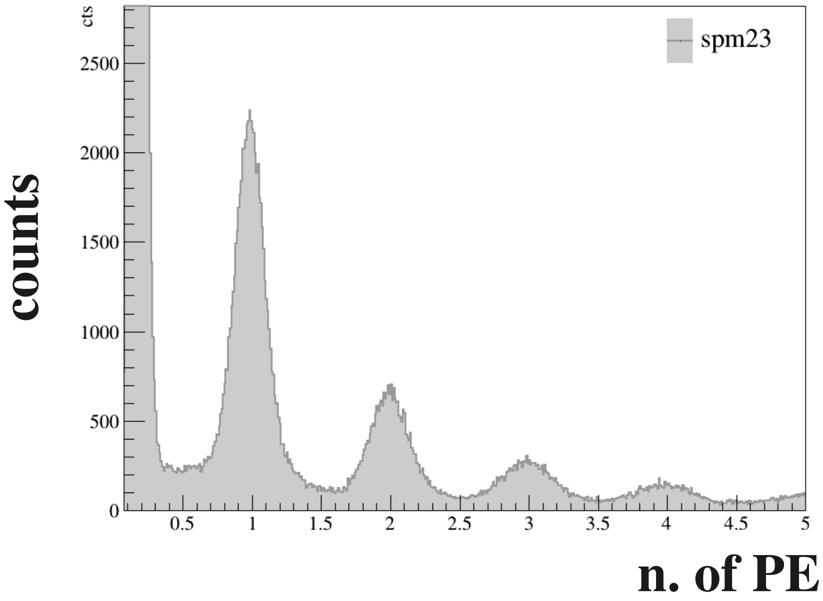
EPJC 76 (2016) 298



since 2010: 7 PMTs in water tank dead (no effect on eff.), >99% μ identification
~0.1% dead time; very reliable and stable

LAr Veto





read out all channel if Ge triggers
→ offline veto

- all channels working
- gain stable with time

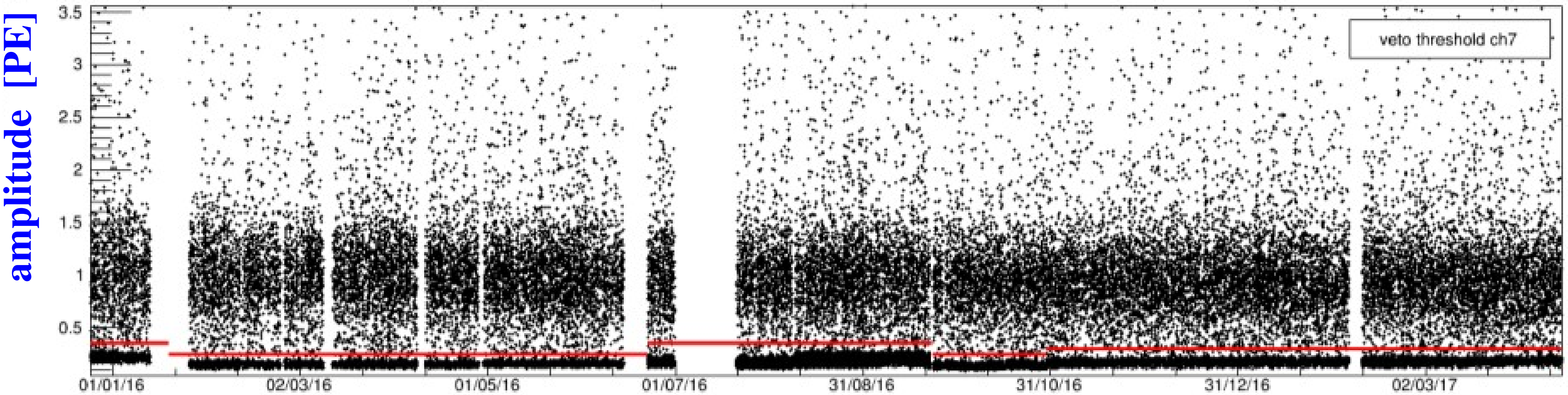
low noise →veto cut ~0.5 p.e.

reject ~ 2.3% of pulser events

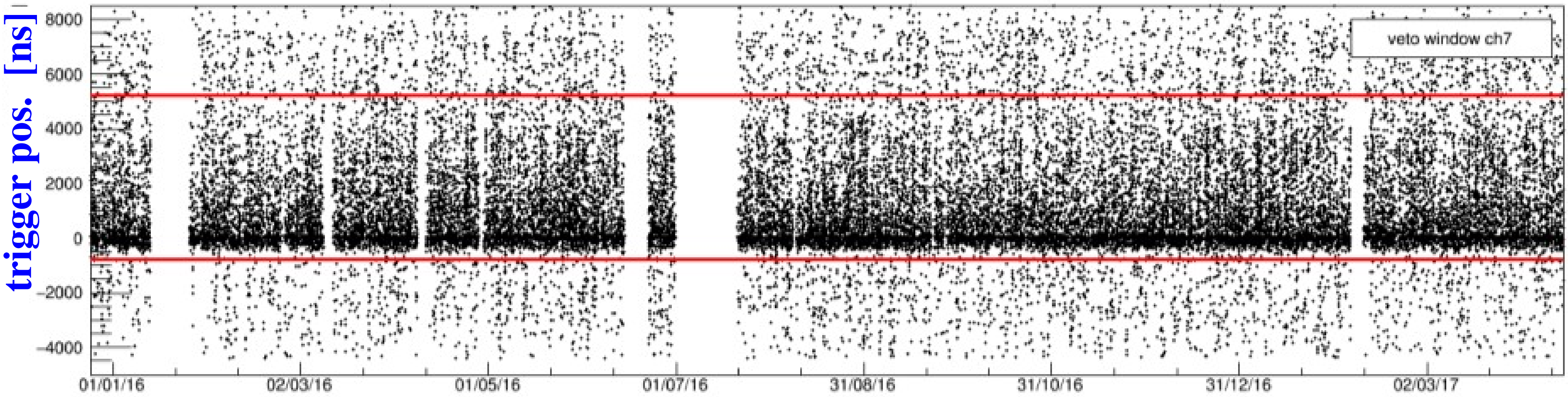
LAr Veto

PMTs

- stability of the amplitude vs. time
- stability of the trigger position vs. time



01/01/16 **02/03/17**

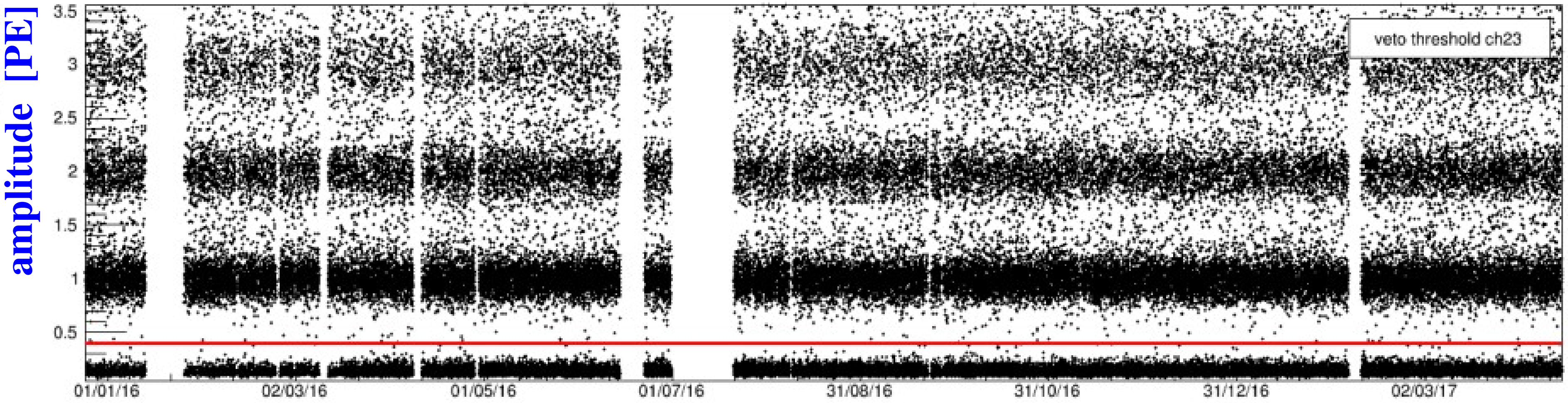


01/01/16 **02/03/17**

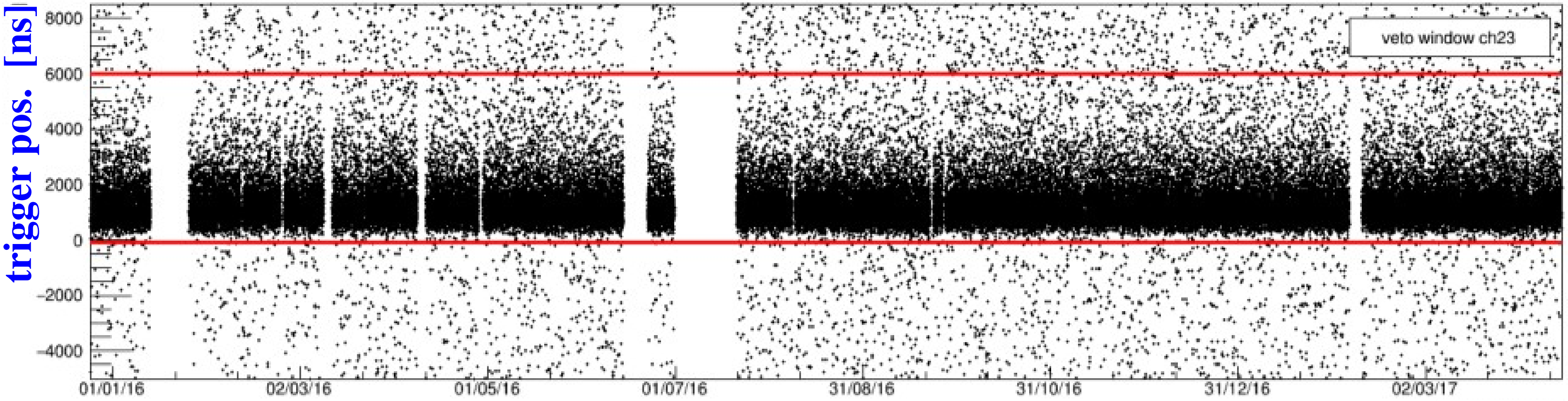
LAr Veto

SIPMs

- stability of the amplitude vs. time
- stability of the trigger position vs. time

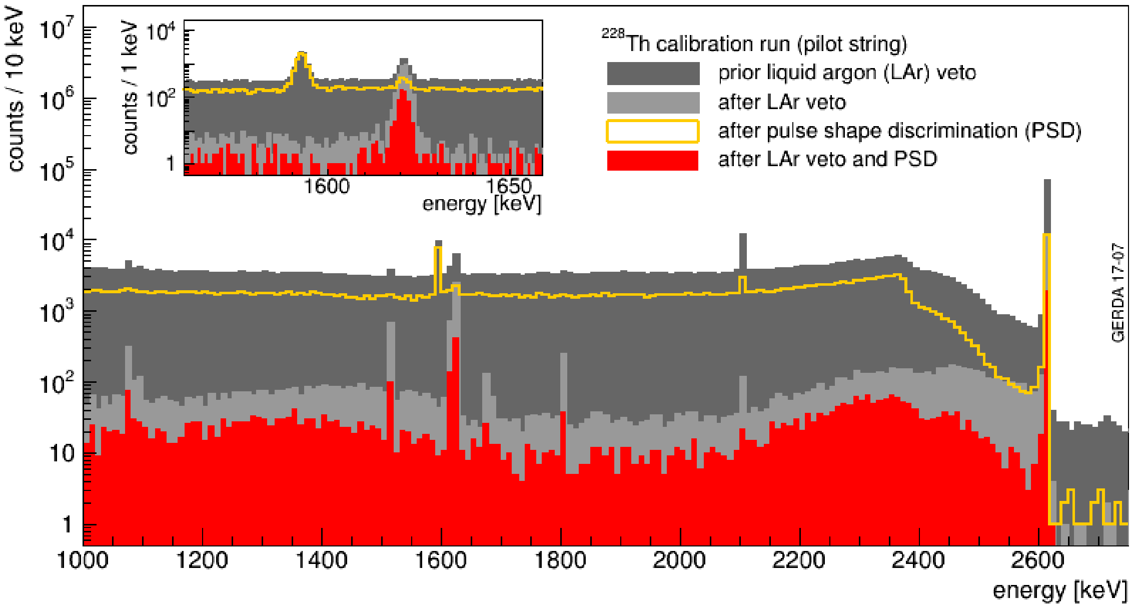


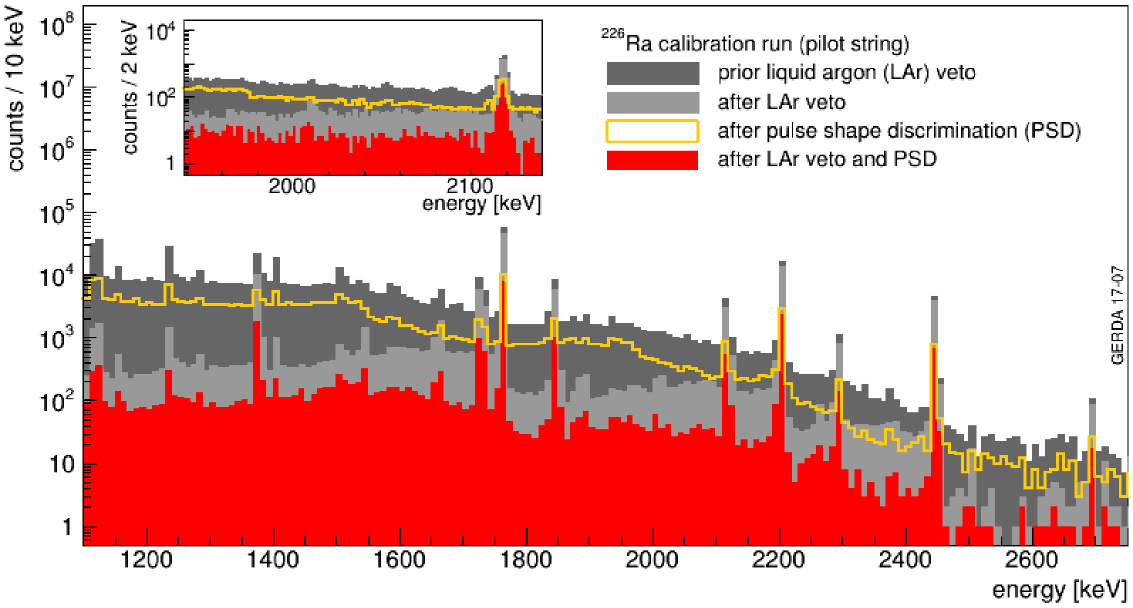
01/01/16 **02/03/17**



01/01/16 **02/03/17**

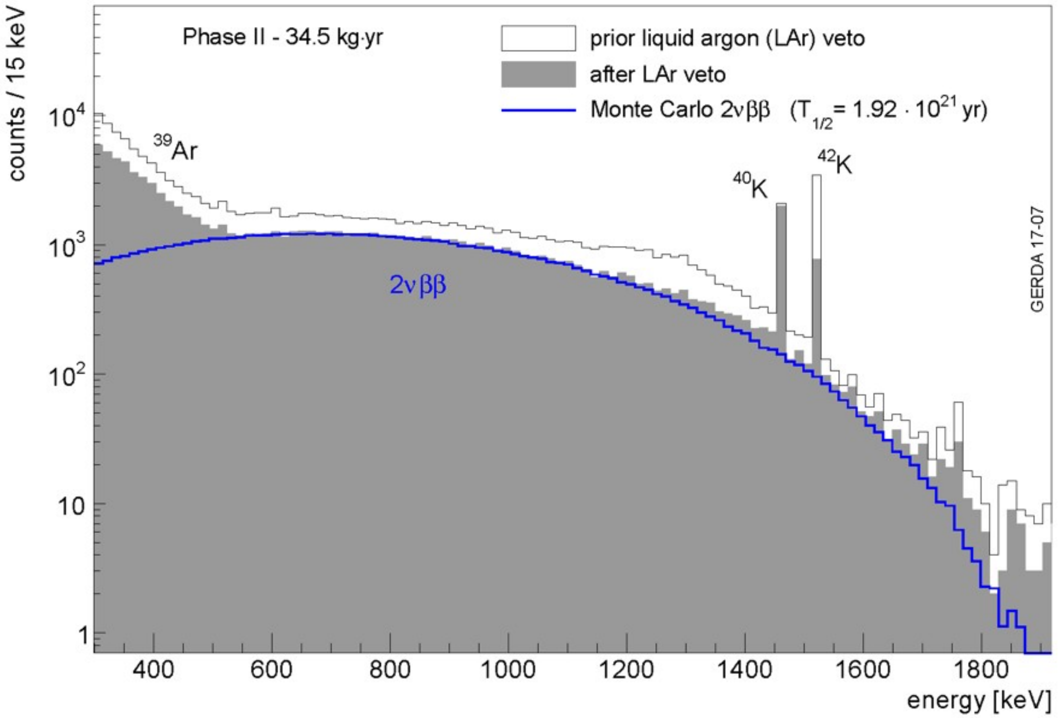
LAr veto bkg suppression





- 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 available for deposition in the LAr
- Combining with PSD & anticoincidence the overall supp. factors become:
  345 (25) for ^{228}Th
  29 (3) for ^{226}Ra

LAr veto background suppression

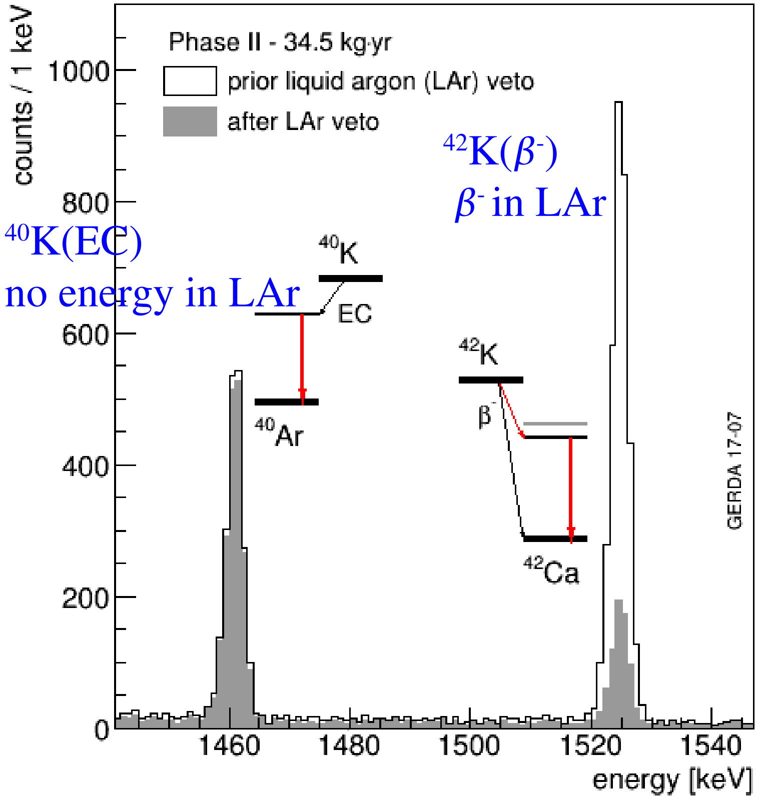


γ-lines from:

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

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

\+ e- (up to 2 MeV)



$^{42}K(\beta^-)$

β^- in LAr

^{40}K(EC)

no energy in LAr

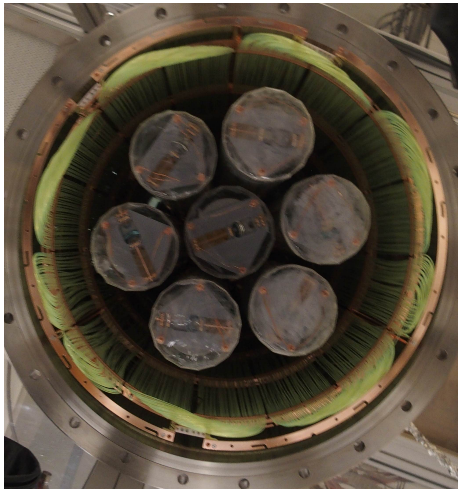
- $^{40}K/^{42}K$ Compton continuum fully suppressed
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I

[EPJC 75 (2015) 416]

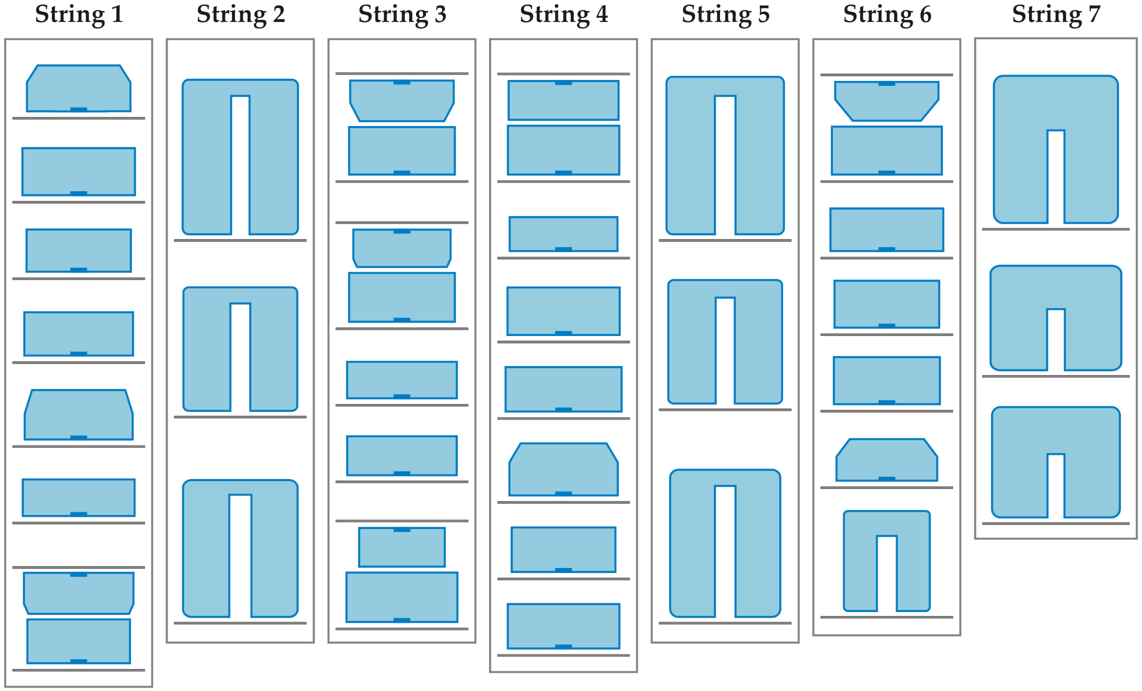
Ge detectors

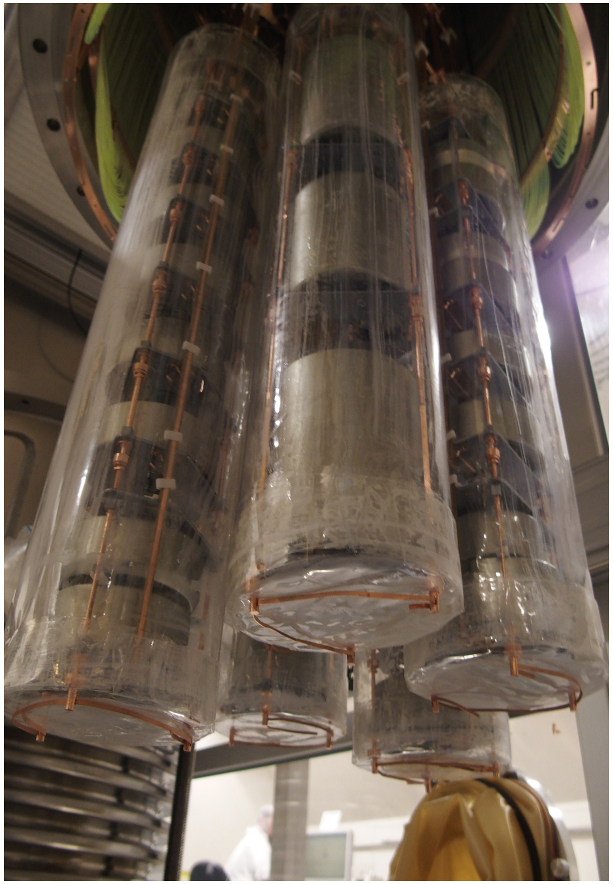
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

→ **35.8 kg of enr detectors**

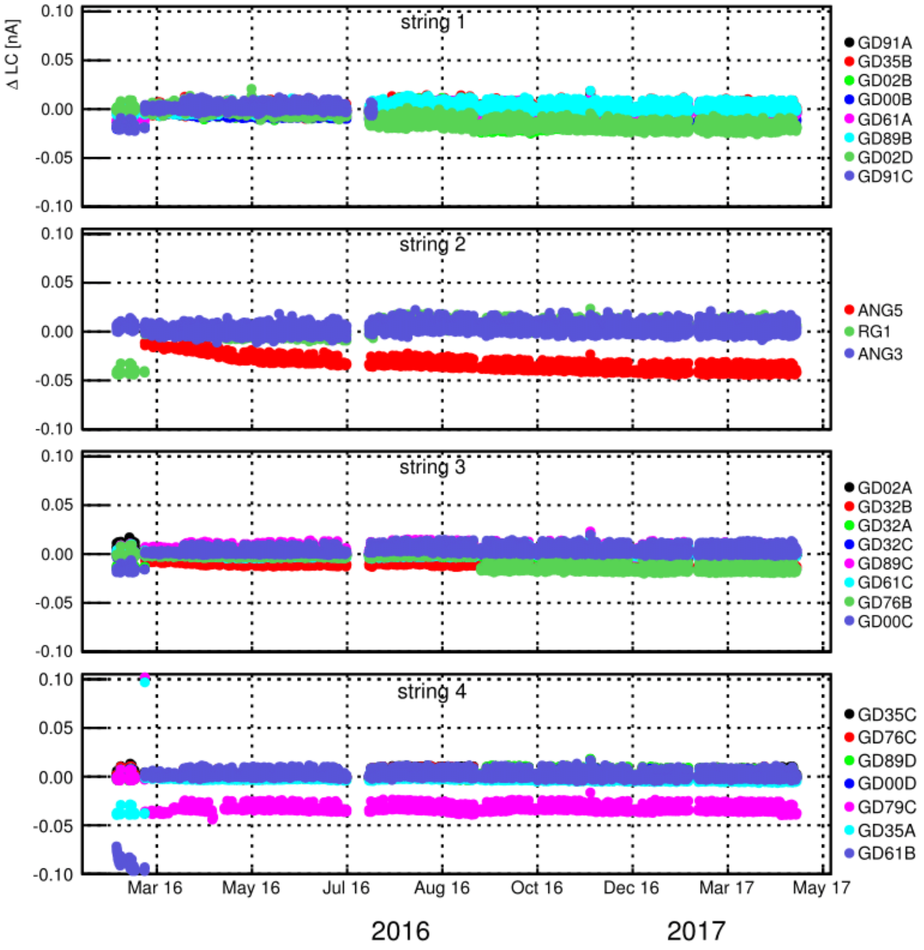


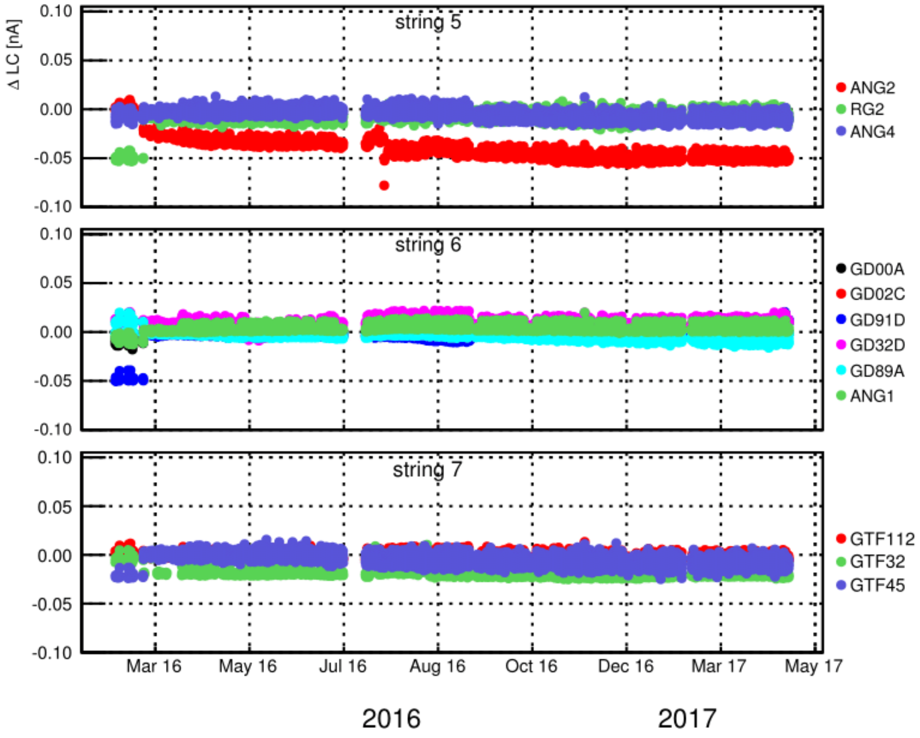
3 diodes lost (burn-out JFET)





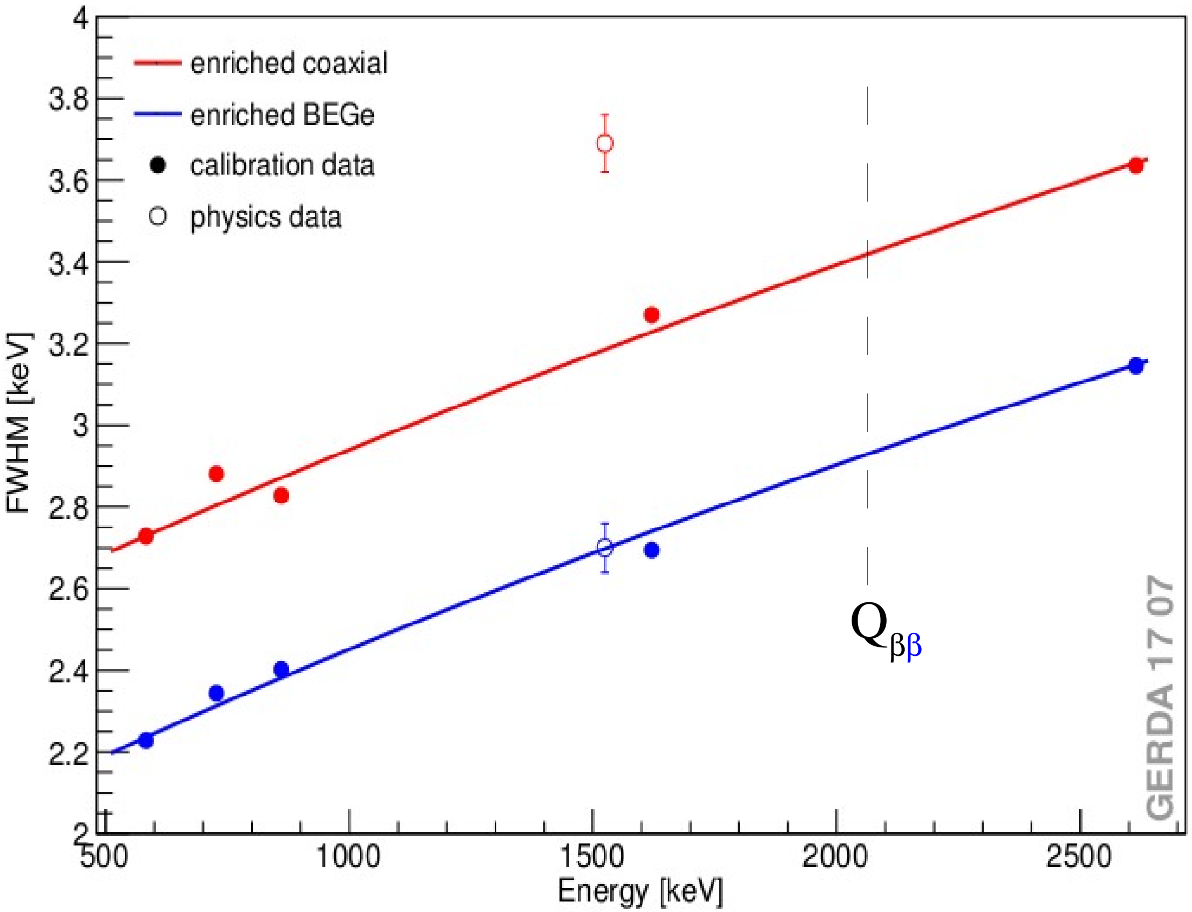
Ge detectors: leakage current





- ➢Leakage currents rather stable
- ➢In the first months temporary increase of LC during calibration for some detectors. Effect now almost disappeared.

Ge detectors: energy calibration



Procedure:

- ◆ weekly ^{228}Th calibrations
- ◆ comparison with ^{42}K, ^{40}K peaks in physics data
- ◆ stability btw. calib: every 20 s pulser injected into FE
- ◆ ZAC filter for E reconstruction

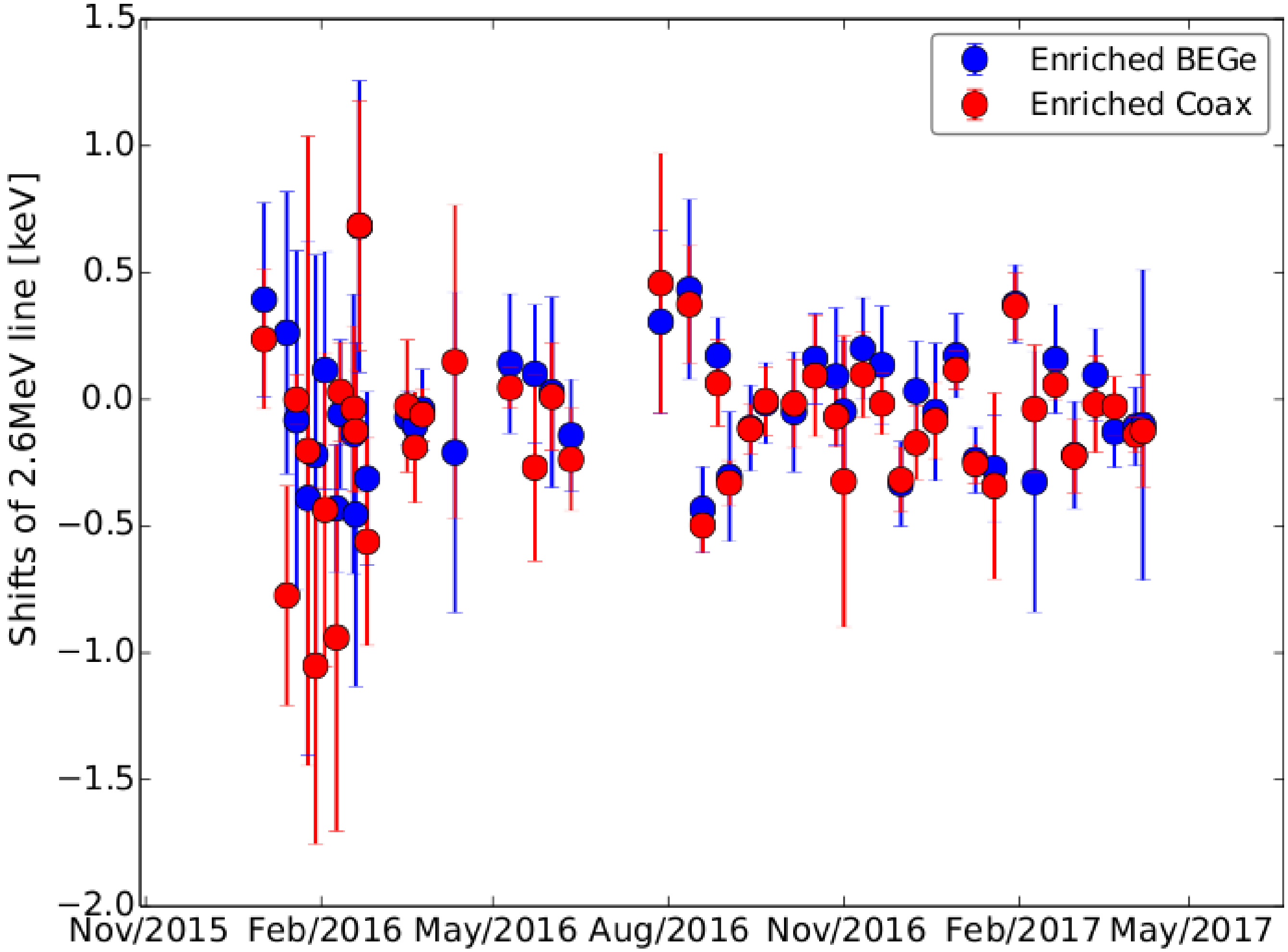
[EPJC 75 (2015) 255]

➢FWHM resolution curves from calibration and physics data

➢@$Q_{\beta\beta}$: FWHM(**BEGe**) = **2.9 ± 0.1** keV

FWHM(**Coax**) = **4.0 ± 0.2** keV (add correction due to diff. calib - physics)

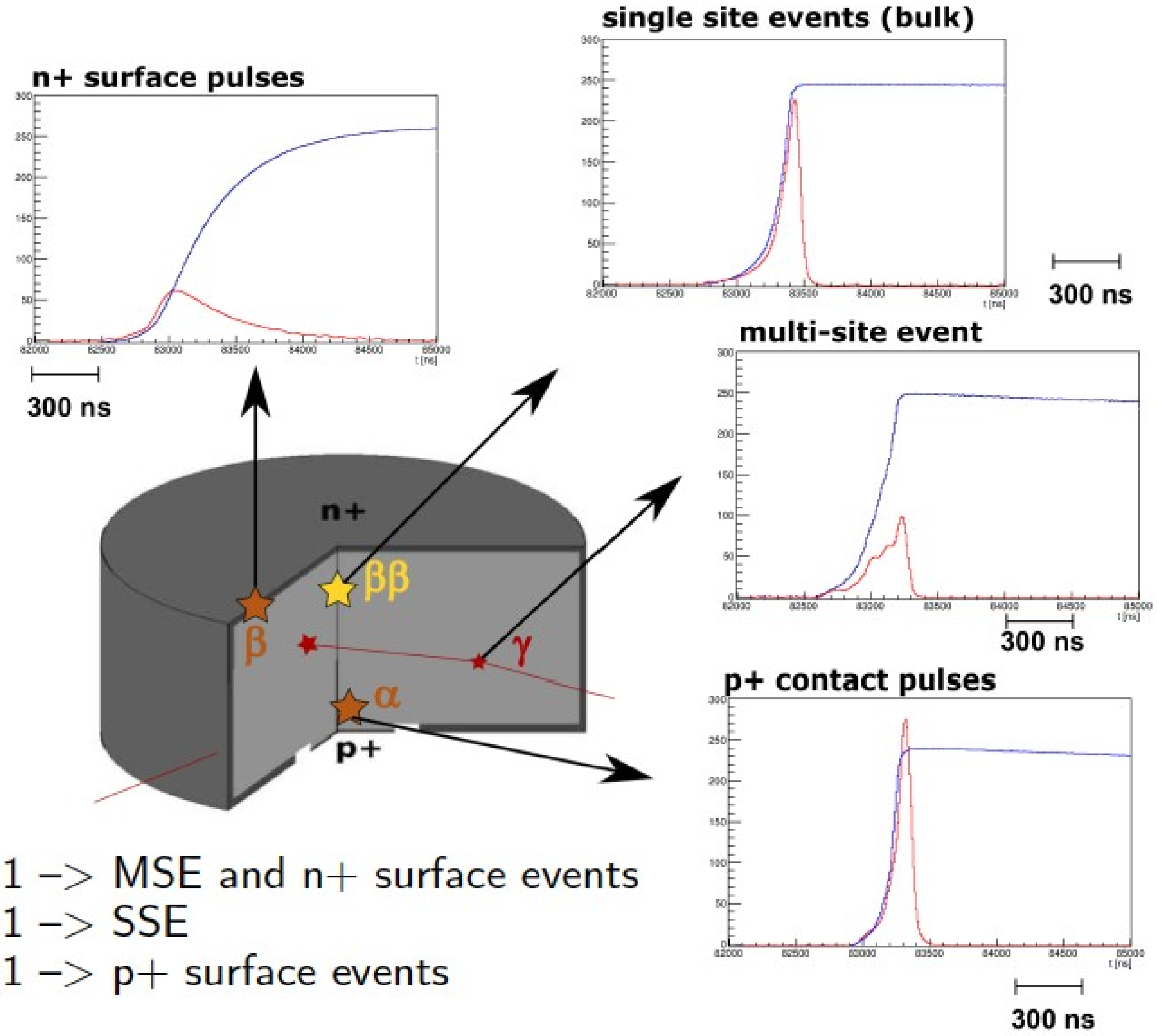
Ge detectors: energy shift



- shifts @ ^{208}Tl line very limited (within 1 keV); sufficient to allow the merger of the data from all periods
- data with energy shift greater than 1 keV are not used in the analysis

Pulse Shape Discrimination: BEGe

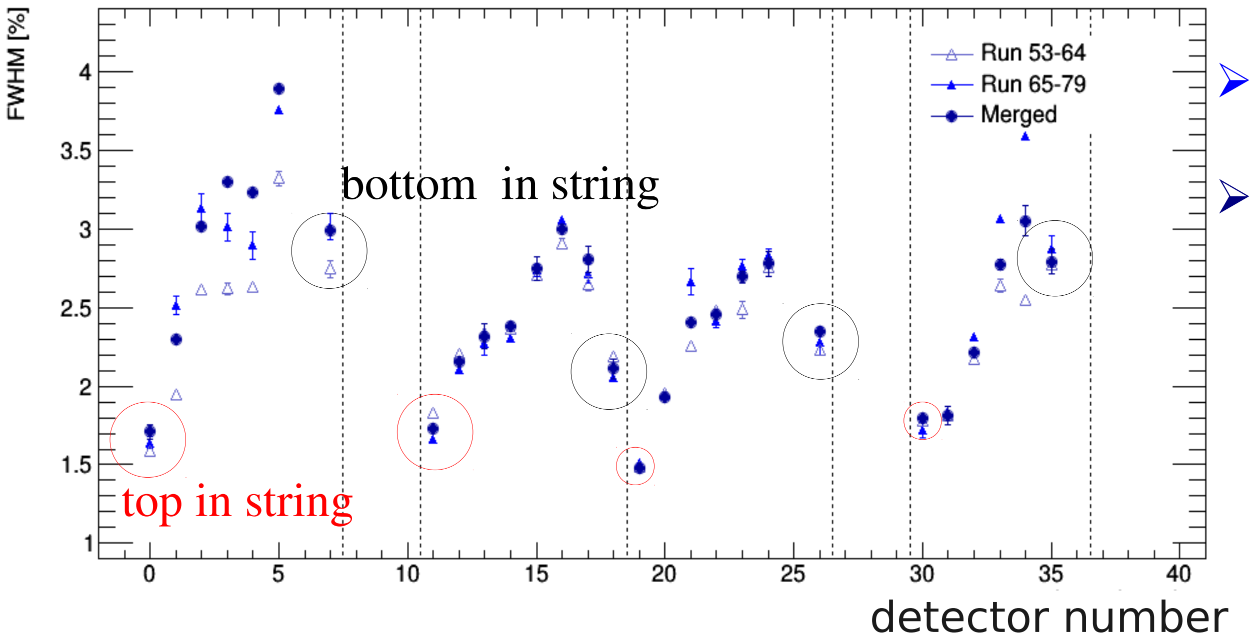
- ➢Event classification using the ratio: Current/Energy i.e. **A/E** variable



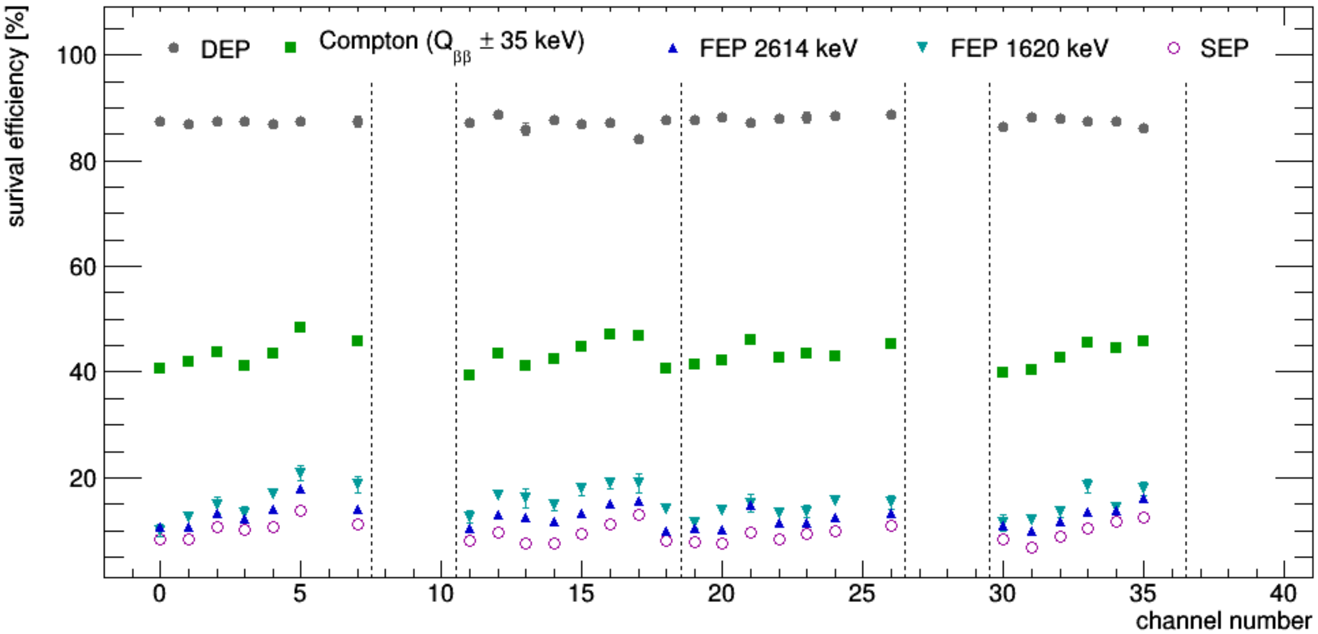
A/E<1 –> MSE and n+ surface events
A/E~1 –> SSE
A/E>1 –> p+ surface events

A/E resolution of DEP events versus detector

PSD: BEGe



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

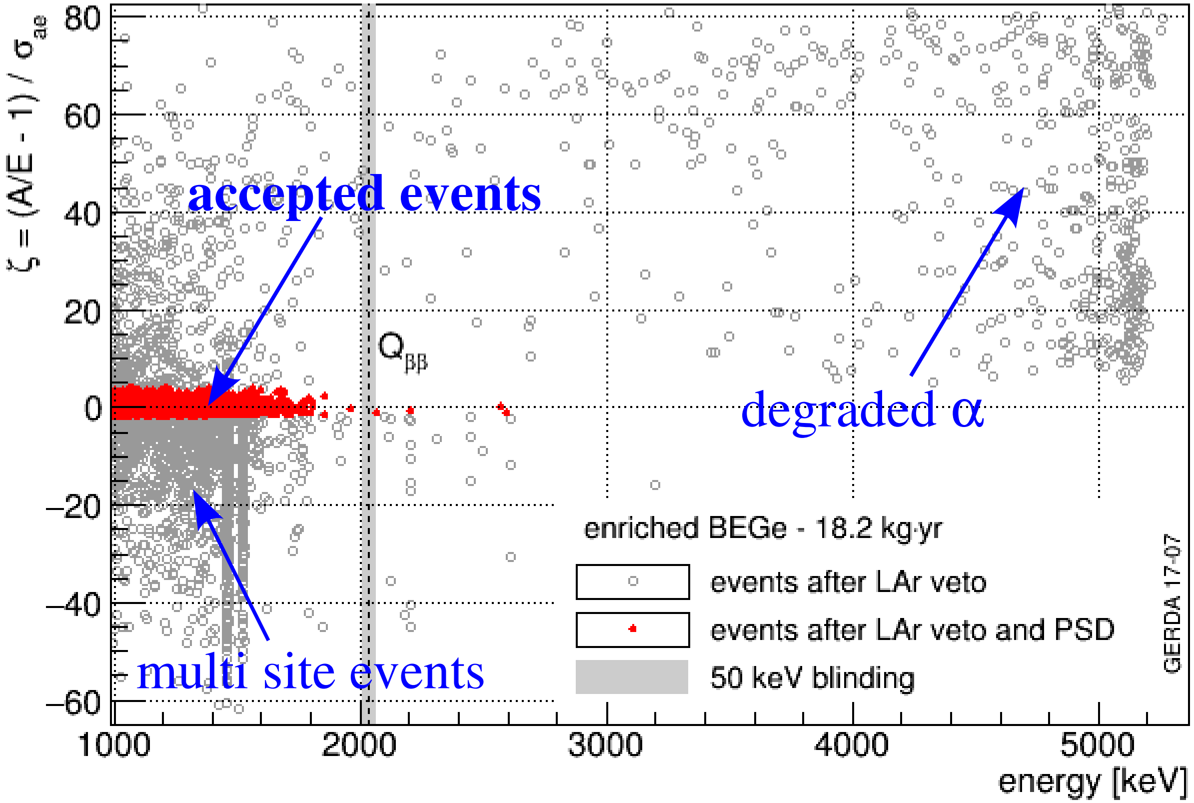


DEP events

Compton at $Q_{\beta\beta}$

FEP @ 2614 keV
FEP 1620 keV, SEP

Pulse Shape Discrimination: BEGe

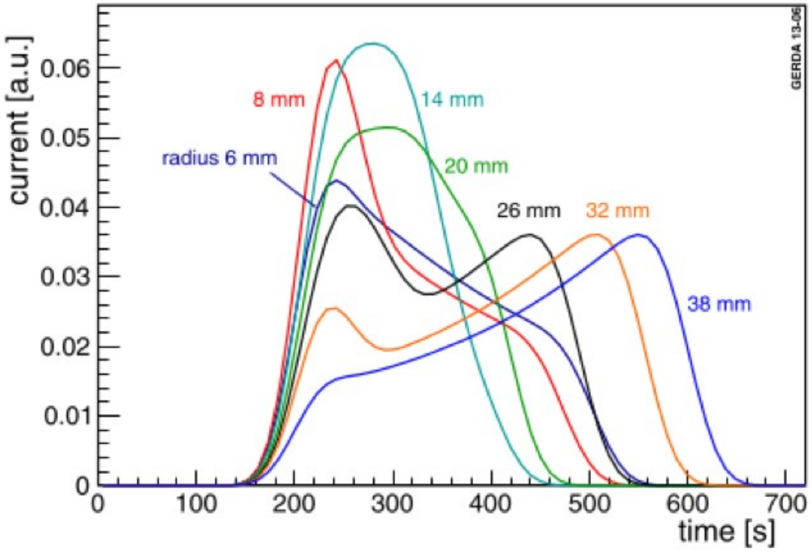


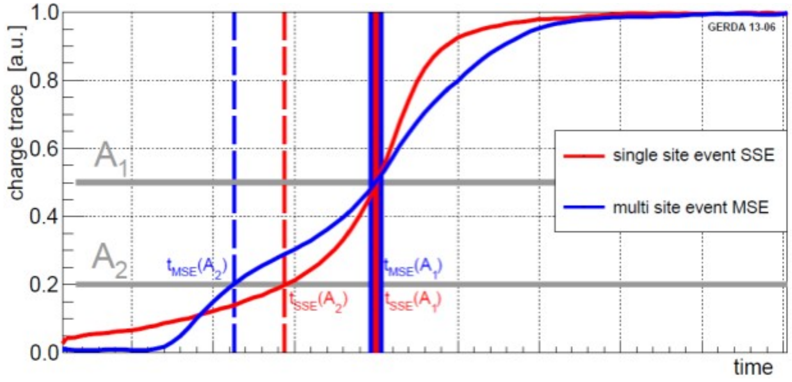
- ➢Event by event selection
- ➢Acceptance for 0νββ events: **(87.4±2.6)%**
  - ◆ estimated from ^{208}Tl DEP
  - ◆ double checked at low energy with 2νββ events (after LAr cut)

Pulse Shape Discrimination: Coax

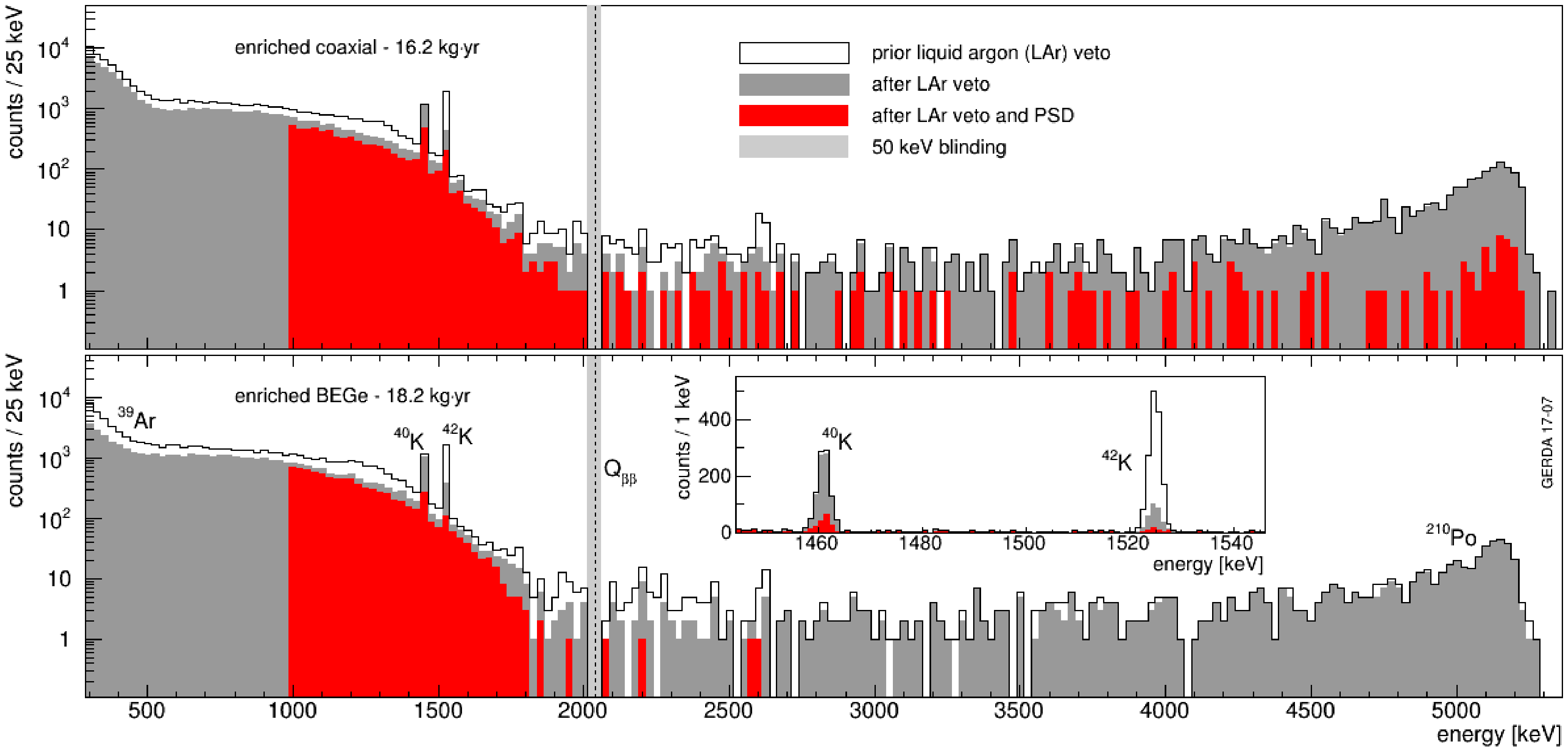
- PSD for Coax detectors less effective than for BEGes
- Artificial Neural Network (**ANN**) as in Phase I:
  - Trained on signal (SSE): ^{208}Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): ^{212}Bi @ 1620 keV γ-line
  - Acceptance for 0νββ events (**85±5**)%
    - Double check with Compton edge and 2νββ events
    - MC simulation of waveforms
- New ingredient in PhaseII: dedicated ANN for α
  - Test/train from data
  - Acceptance for 0νββ events (**93±1**)%
- Combined acceptance: (**79±5**)%

Current Pulses for SSE





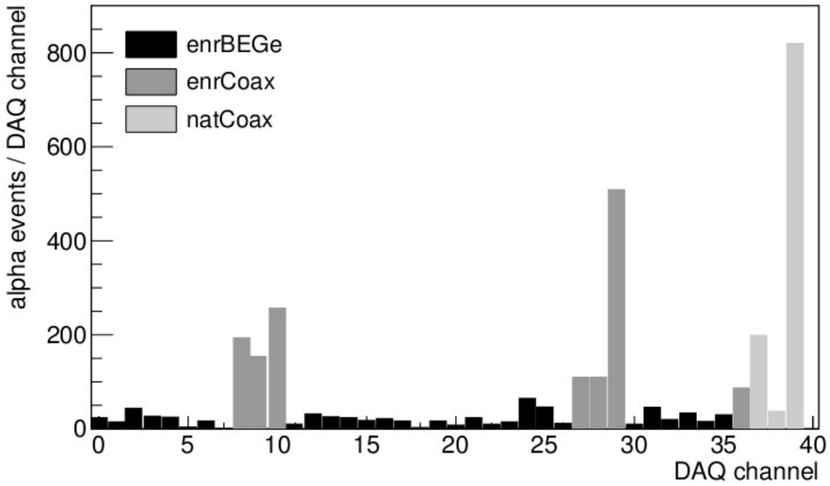
Phase II GERDA spectra



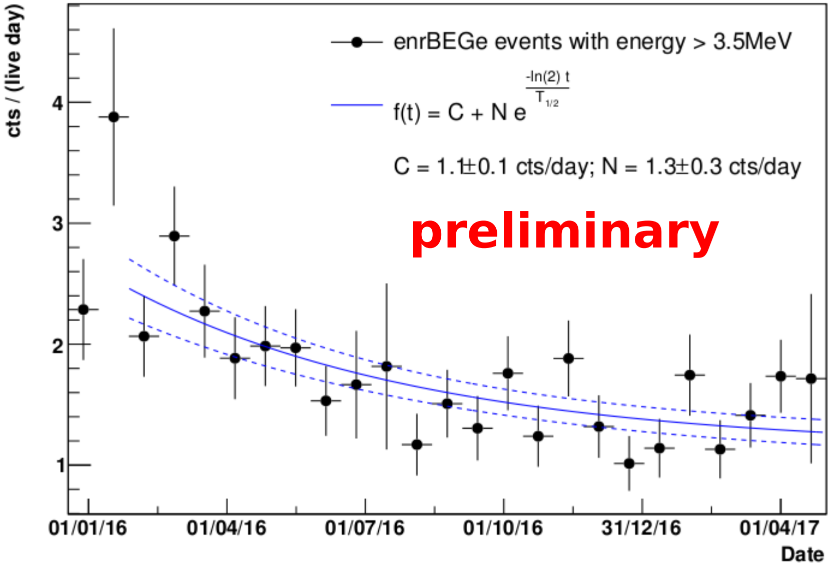
- Most prominent feature: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ lines, α
- PSD of BEGe clears completely the α region
- LAr and PSD highly effective cuts
- Final background at $Q_{\beta\beta}$ $\mathcal{O}(10^{-3}$ counts/keV· kg· yr)

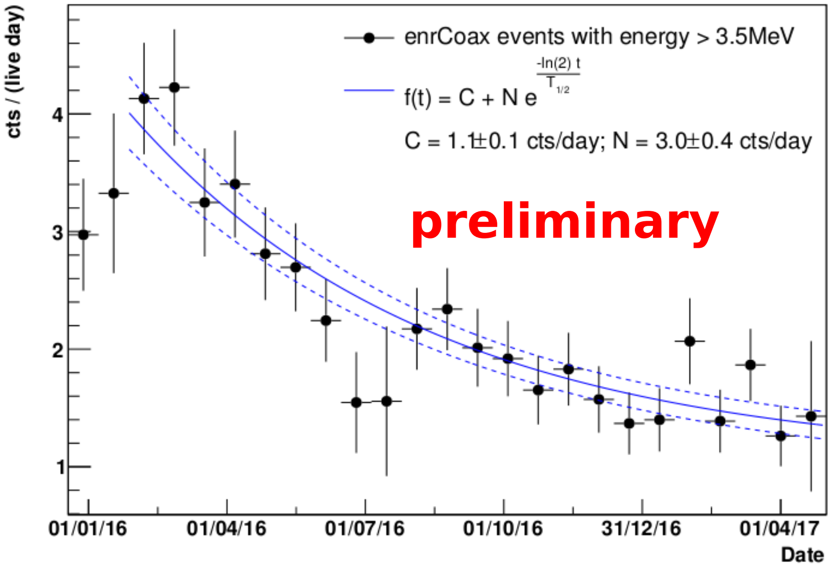
Alpha rate

- Alpha rate different among detectors
  - Higher for Coax detectors
  - BEGE/coax same order if normalized according to the detector surface



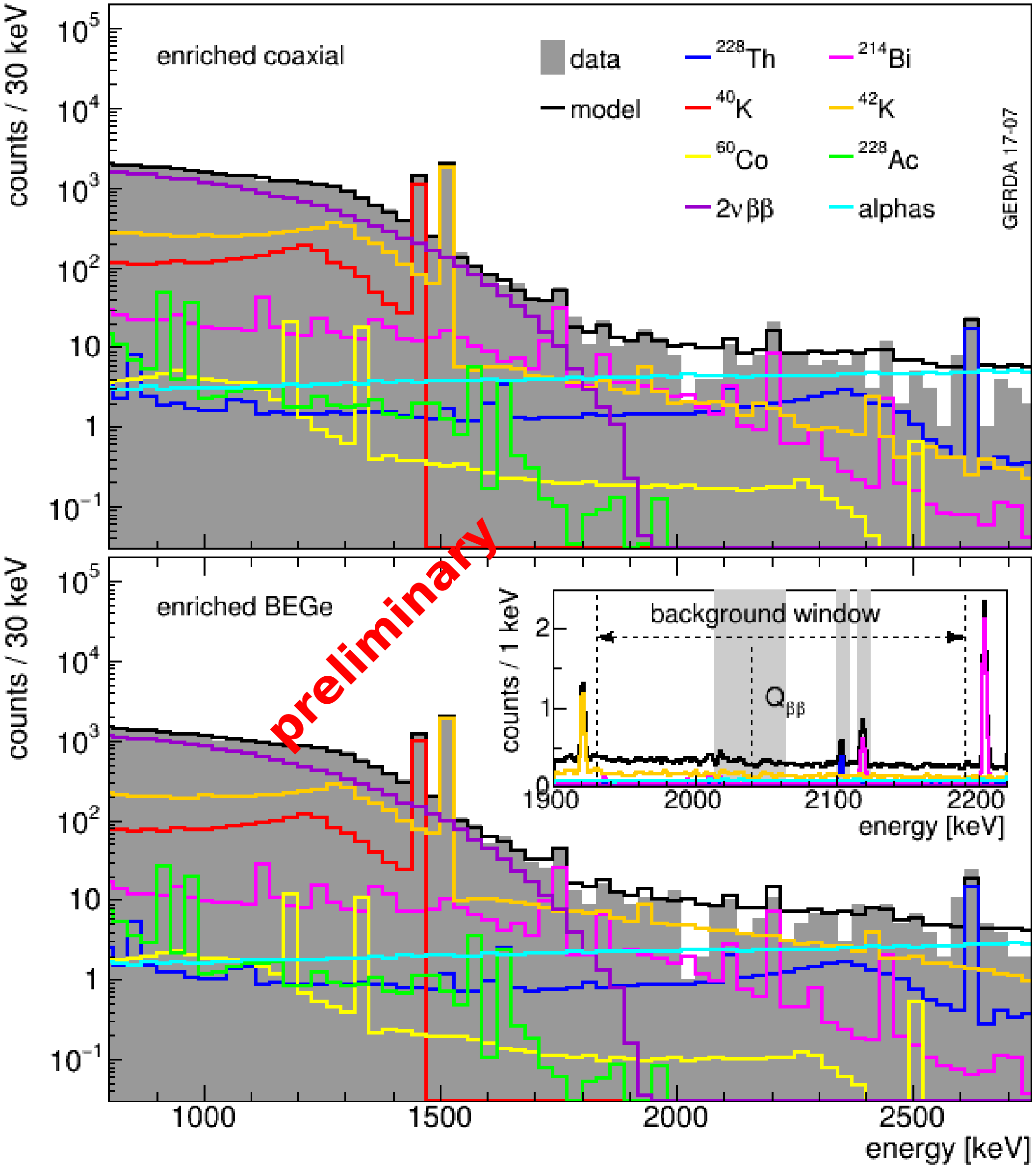
- Part of the α component is decaying away (^{210}Po, $T_{1/2}$ = 138 days)





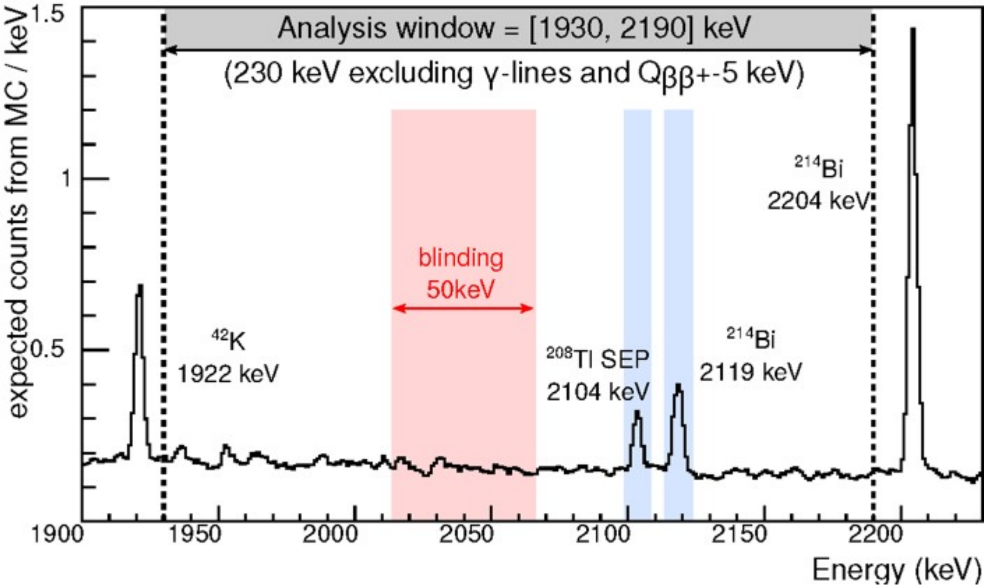
Background Model

- ➤Similar approach as in Phase I
  - EPJ C 74 (2014) 2764
  - Mostly same components considered
  - Fit range: 565 -5320 keV
- ➤Also same problem: difficult to disentangle components, also due to the low statistics
- ➤ The spectra are considered before LAr and PSD cuts
  - work in progress to have a full combined fit including LAr, PSD and multi-detectors events
    - PDF derived by MC
    - screening measurements included
- ➤Observed γ-lines from ^{42}K, ^{40}K, Th chain (^{228}Ac,^{208}Tl), U chain (^{214}Bi, ^{214}Pb)



Background Model

- The background model confirms the flatness of the background around the ROI and inside the blinding window as in Phase I
- The expected spectrum is roughly composed as follows: ~ 30% of events from α, 30% e^- from ^{42}K and 30% from 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



Unblinding at Krakow

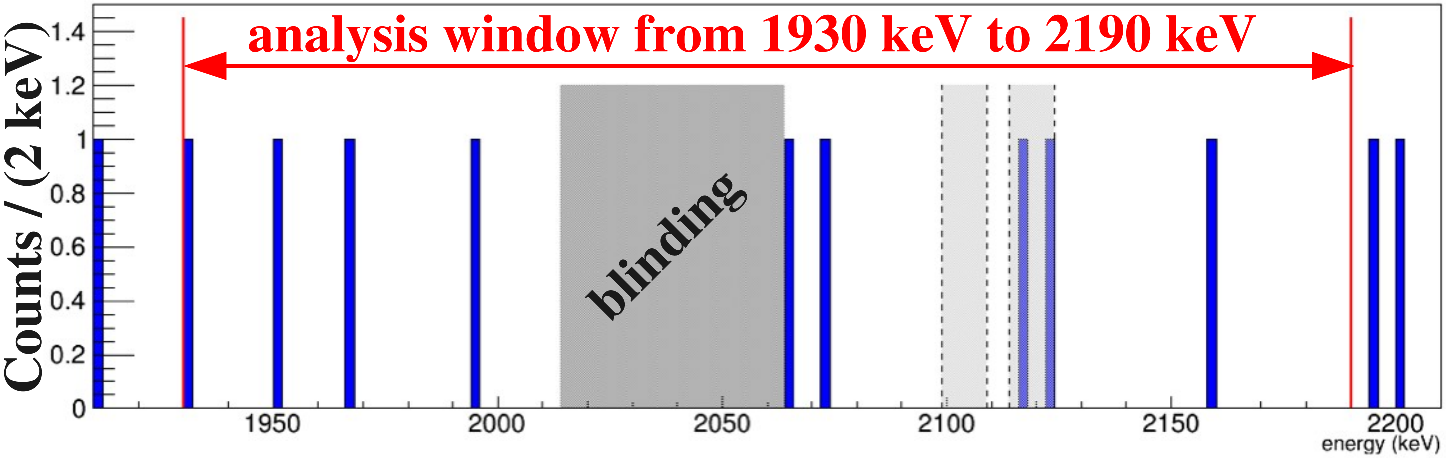
GERDA collaboration meeting at Krakow, 30 June:
unblinding of ± 25 keV around $Q_{\beta\beta}$

Spectra in the ROI

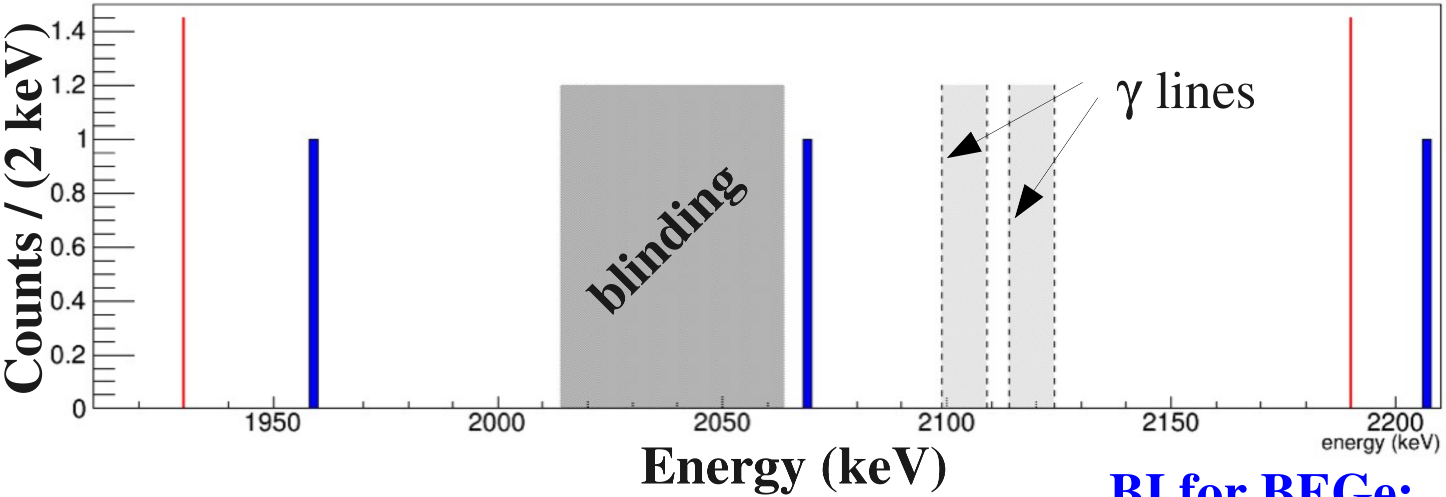
BI for Coax:

7 cts (+2 known in blinded box)

$2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV· kg · yr)



^{enr}Coax
16.2 kg·yr
(after all cuts)



^{enr}BEGe
18.2 kg·yr
(after all cuts)

BI for BEGe:

2 cts

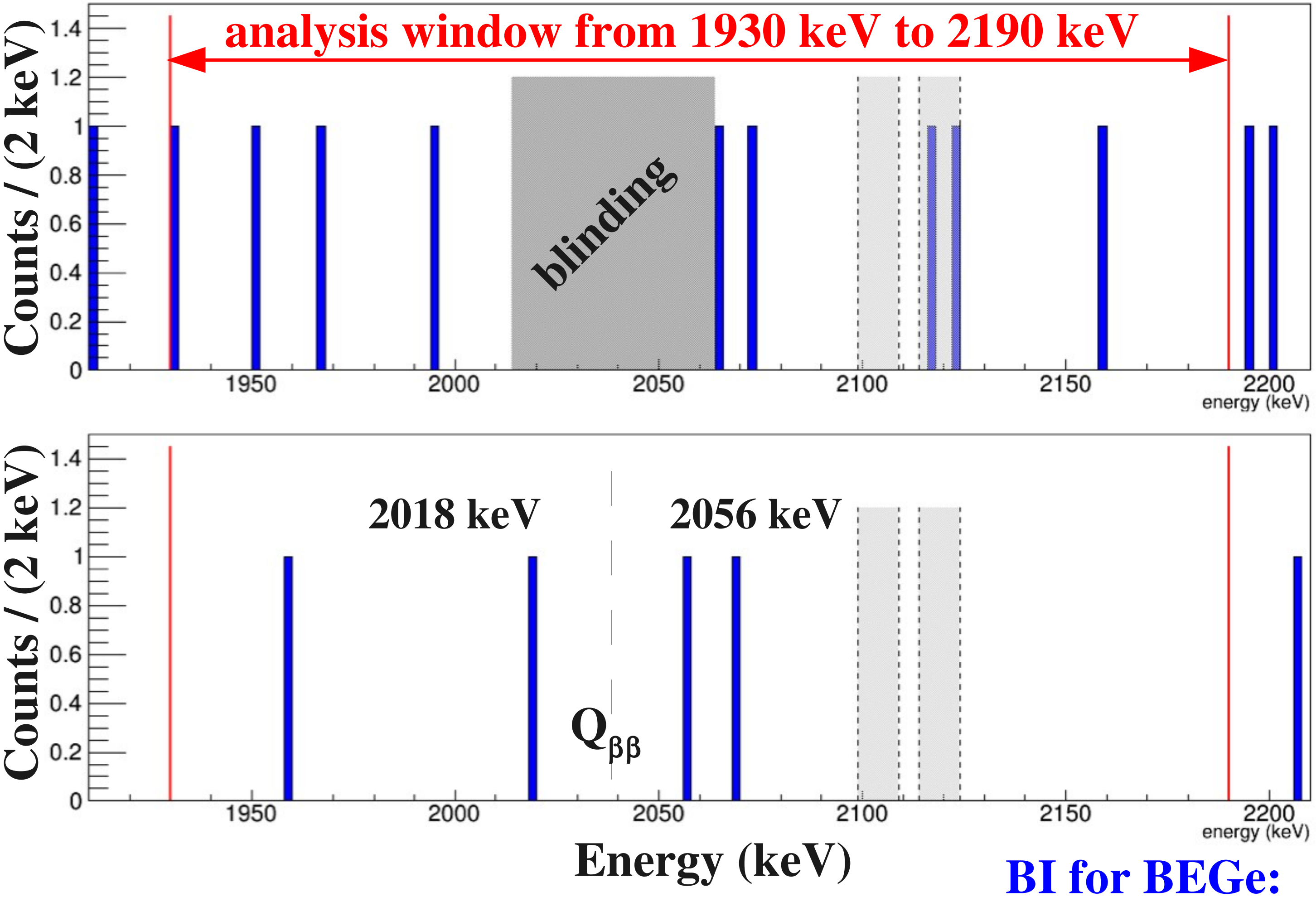
$0.5^{+0.5}_{-0.3} \cdot 10^{-3}$ cts/(keV ·kg · yr)

Spectra in the ROI

BI for Coax:

7 cts (+2 known in blinded box)

$2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV· kg · yr)



^{enr}Coax

16.2 kg·yr

(all cuts)

Previously unblinded: 5.0 kg·yr

^{enr}BEGe

18.2 kg·yr

(after all cuts)

BI for BEGe:

2 cts + 2 new (> 10σ from $Q_{\beta\beta}$)

$1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ cts/(keV ·kg · yr)

Statistical Analysis

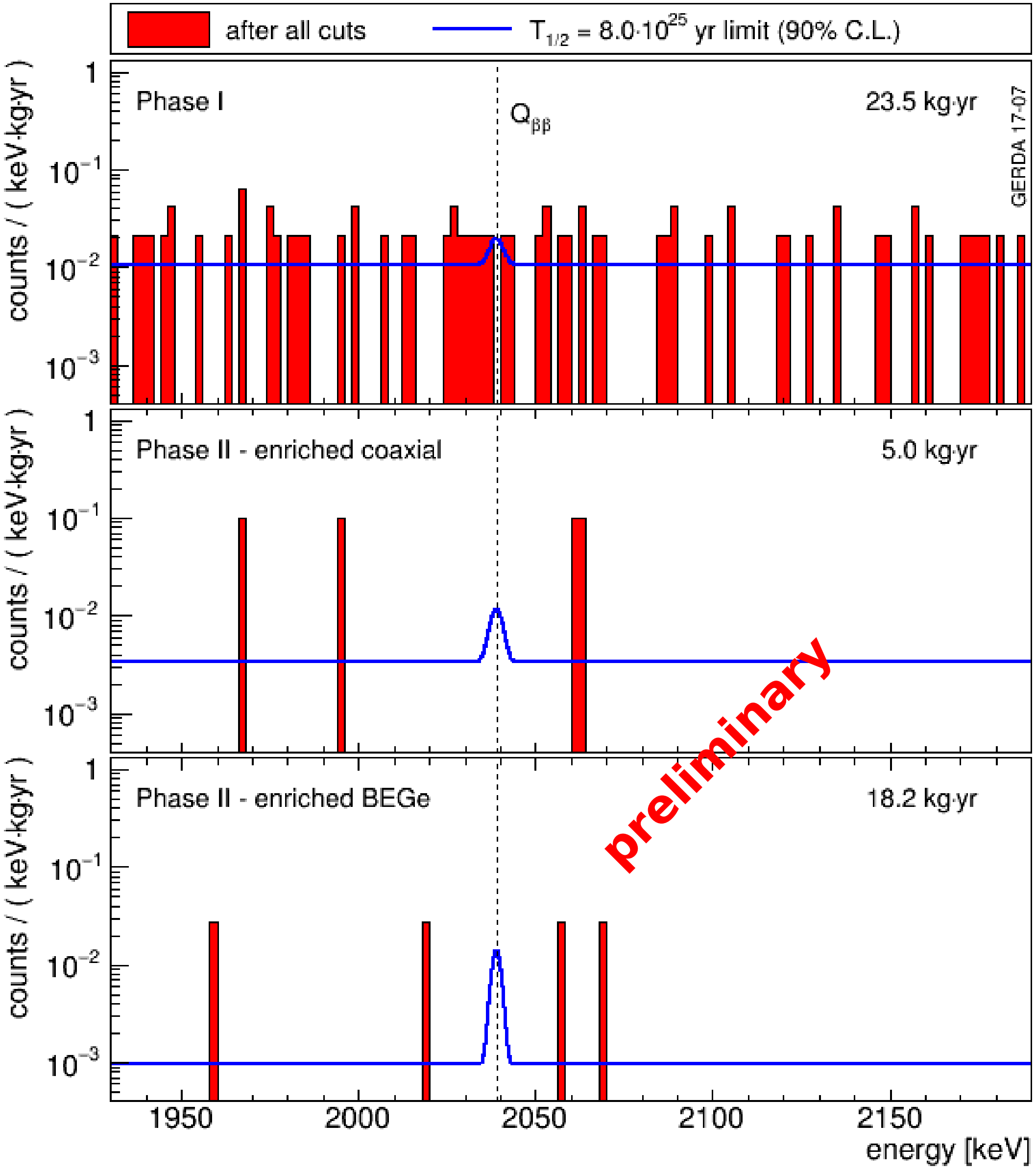
dataset	exposure [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(kevkgyr)]
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.57(3)	30±10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIb BEGe	**18.2**	**2.9(1)**	**0.60(2)**	$\mathbf{1.0^{+0.6}_{-0.4}}$

same as in Nature 544 (2017) 47

Total exp. 46.7 kg

- **Combined** unbinned **maximum likelihood** fit (flat background + gaussian signal) of the 6 spectra:
  - **Frequentist:** test statistics and method as in Cowan et al., EPJC 71 (2011)1554 (2 side-test statistics)
  - **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 $N^{0\nu} = 0$

  $T^{0\nu}_{1/2}$ **> 8.0·10^{25} yr @ 90% C.L.**

  It was 5.3·10^{25} yr in Phase IIa

  Median Sensitivity (NO Signal)

  $T^{0\nu}_{1/2}$ **> 5.8·10^{25} yr @ 90% C.L.**

  30% of MC realizations yield limit stronger than data

- upper limit on

  $m_{\beta\beta} < 0.12 - 0.27$ eV

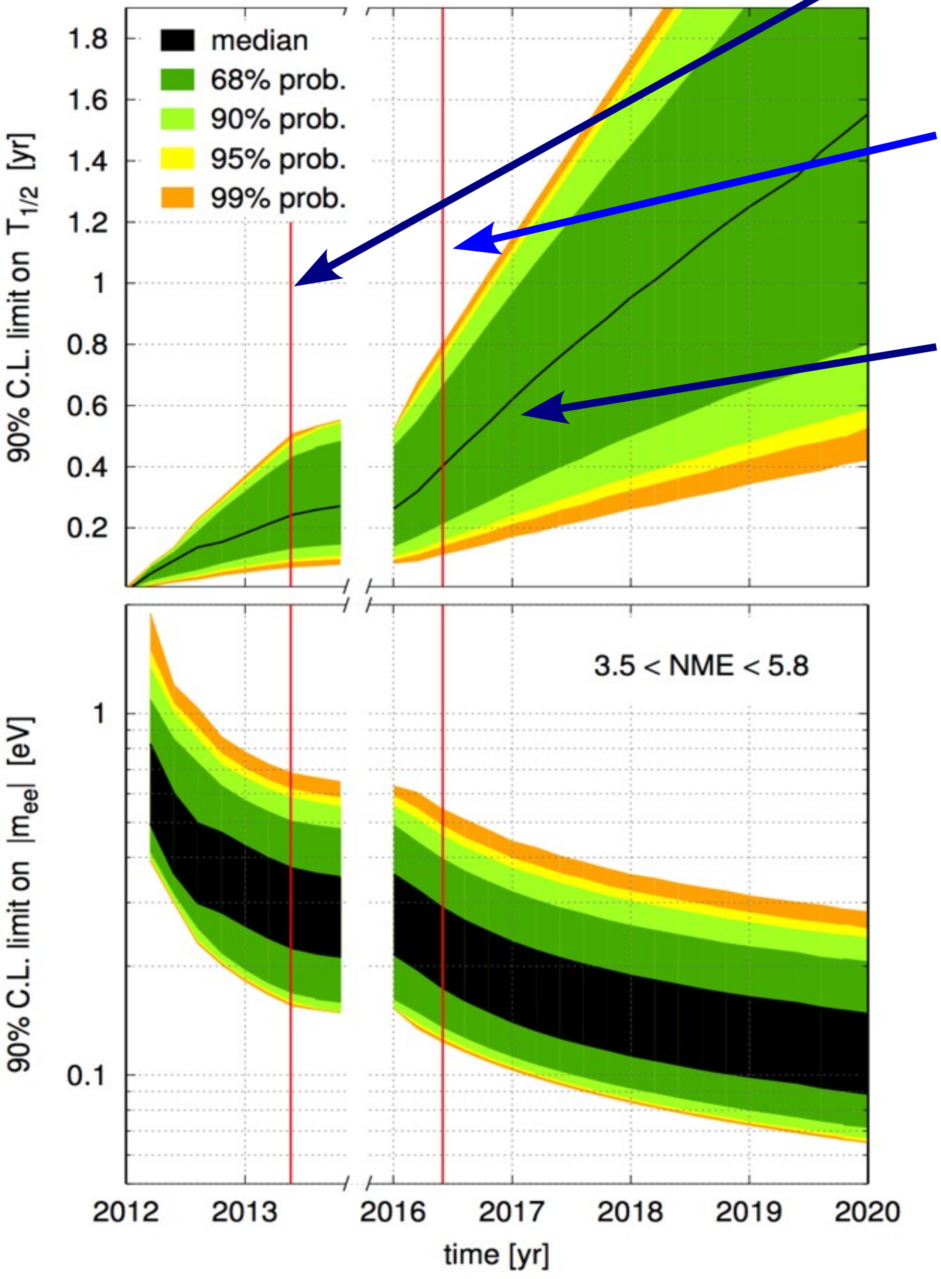
- **Bayesian (preliminary results):**

  $T^{0\nu}_{1/2}$ **> 5.1·10^{25} yr @ 90% C.I.**

  Median Sensitivity:

  $T^{0\nu}_{1/2}$ **> 4.5·10^{25} yr @ 90% C.I.**

Future ...



- **Phase I:** (23.5 kg·yr)
  - Sensitivity: **$2.4 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% CL)
- **Phase II a**: (Phase I + **10.8 kg·yr**)
  - Sensitivity: **$4.0 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% CL)
- **This release** (Phase IIa + **12.4 kg·yr**)
  - Sensitivity: **$5.8 \cdot 10^{25}$ yr**
  - Limit: $T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr (90% CL)
- Already available:
  - **11.2 kg·yr** of validated coax data
  - **~5 kg·yr** of data (Coax & BEGe) taken after Apr 15th
- The sensitivity of **10^{26} yr** will be reached in the middle of **2018**
- Final goals:
  - 100 kg·yr @ BI = 10^{-3} cts/(keV·kg·yr)
  - Sensitivity: **$1.3 \cdot 10^{26}$ yr**
  - Discovery potential up to **10^{26} yr** (*50% prob. chance for a 3*σ signal)

Conclusions

- GERDA is **running smoothly** and with **high efficiency**
- We have collected **more than 35 kg·yr** of really good data: i.e. more than 1/3 of Phase II exposure (100 kg·yr)
- With the present release we have obtained:
  - Limit on $T^{0\nu}_{1/2}$ **> 8.0·10^{25} yr (90% CL)**
  - Median Sensitivity: **5.8·10^{25} yr** (better than KamLand-Zen)
  - BI(^{enr}Coax): **$2.7^{+1.0}_{-0.8}$ ·10^{-3} cts/(keV· kg · yr)**

    BI(^{enr}BEGe): **$1.0^{+0.6}_{-0.4}$ ·10^{-3} cts/(keV ·kg · yr)**
  - $m_{\beta\beta}$ **< 0.12 – 0.27 eV**

preliminary

- With more data we confirm to have **reached** our **background index goal**
- **Lowest bkg** (~10x) in ROI respect to experiment using other isotopes
- Next year we are ready to break the wall of **10^{26} yr in median sensitivity**
- This result suggests future Ge experiments with 200 kg and beyond