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

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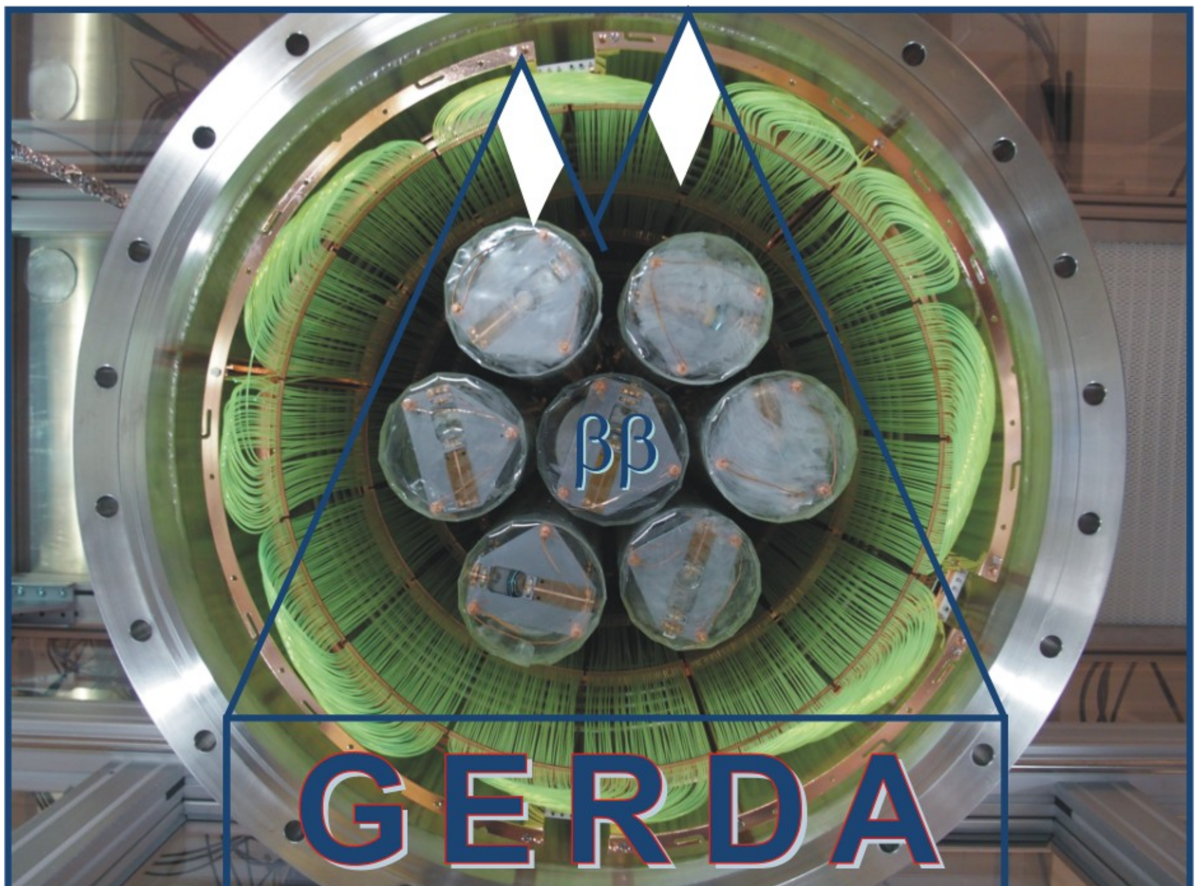
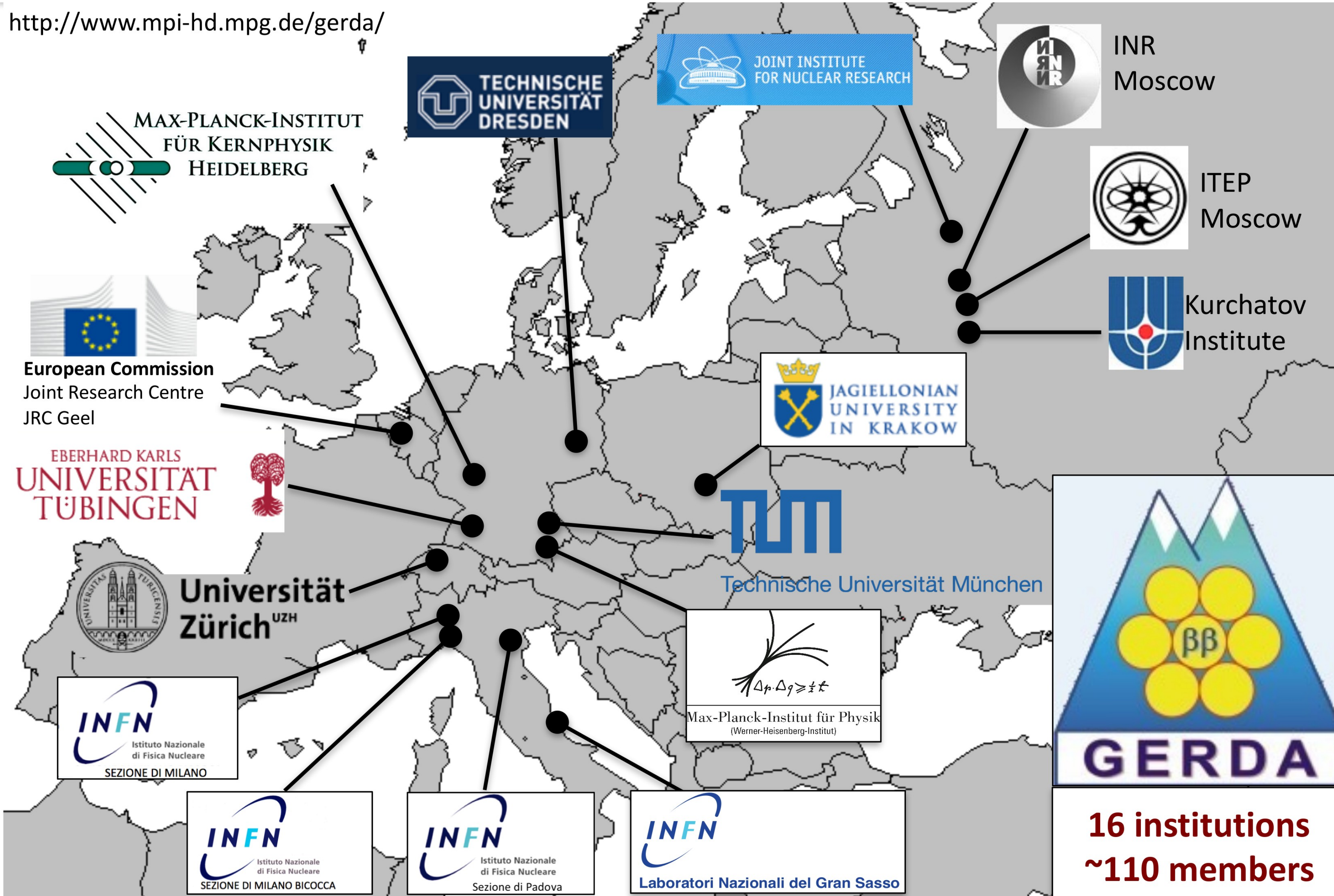


The GERDA Collaboration



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:

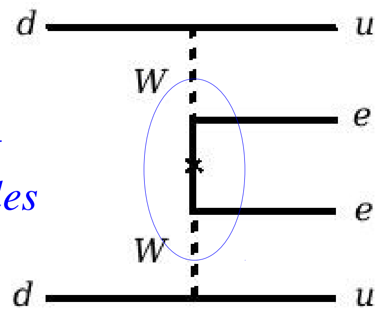
$(A, Z) \rightarrow (A, Z+2)+2e^-$

- 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

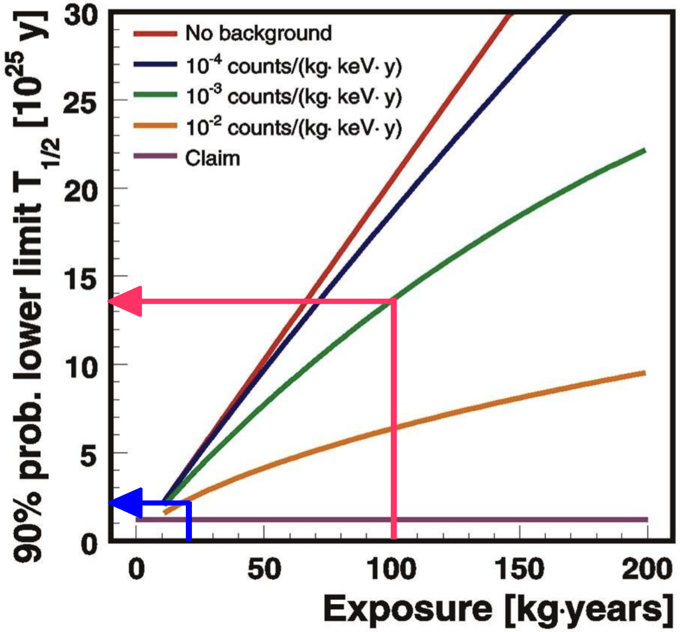
phase space factor

effective Majorana neutrino mass

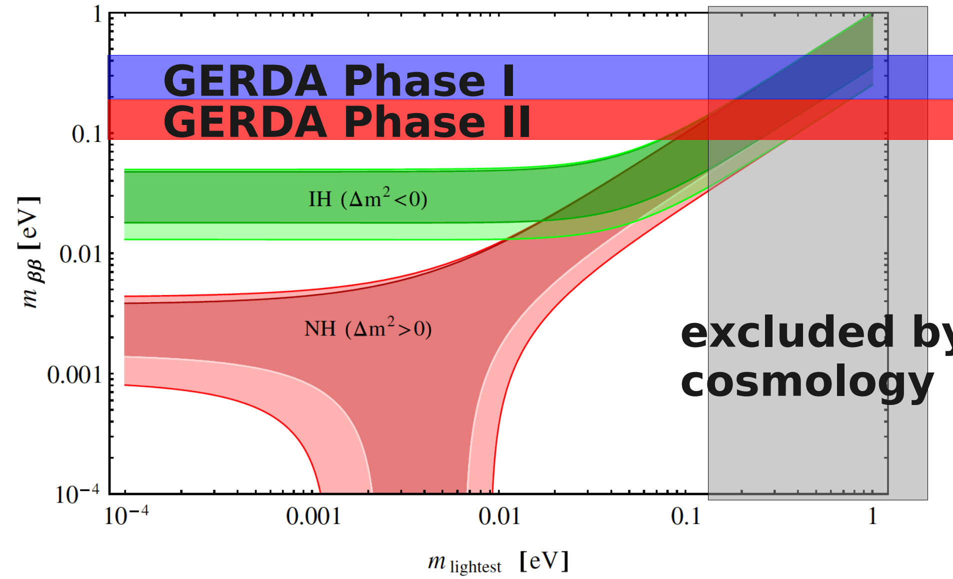
- would provide ***important input to cosmology***

GERDA physics goal

Phys. Rev. D 092003 (2006)



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



PRL 111, 122503 (2013)

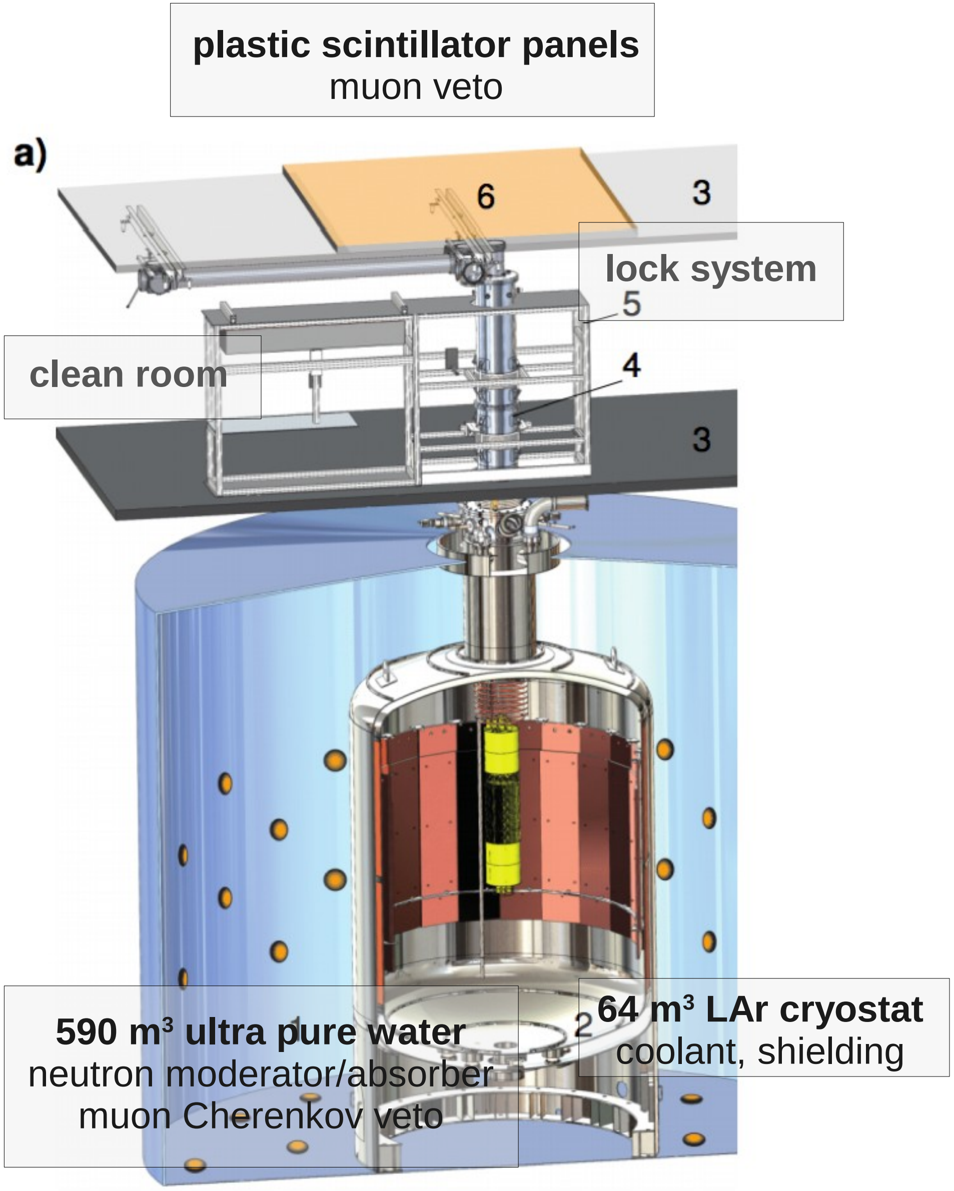
Phase I:
(completed in 2013)

- 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.)**
- $\langle m_{ee}\rangle \leq$ 0.2 - 0.4 eV

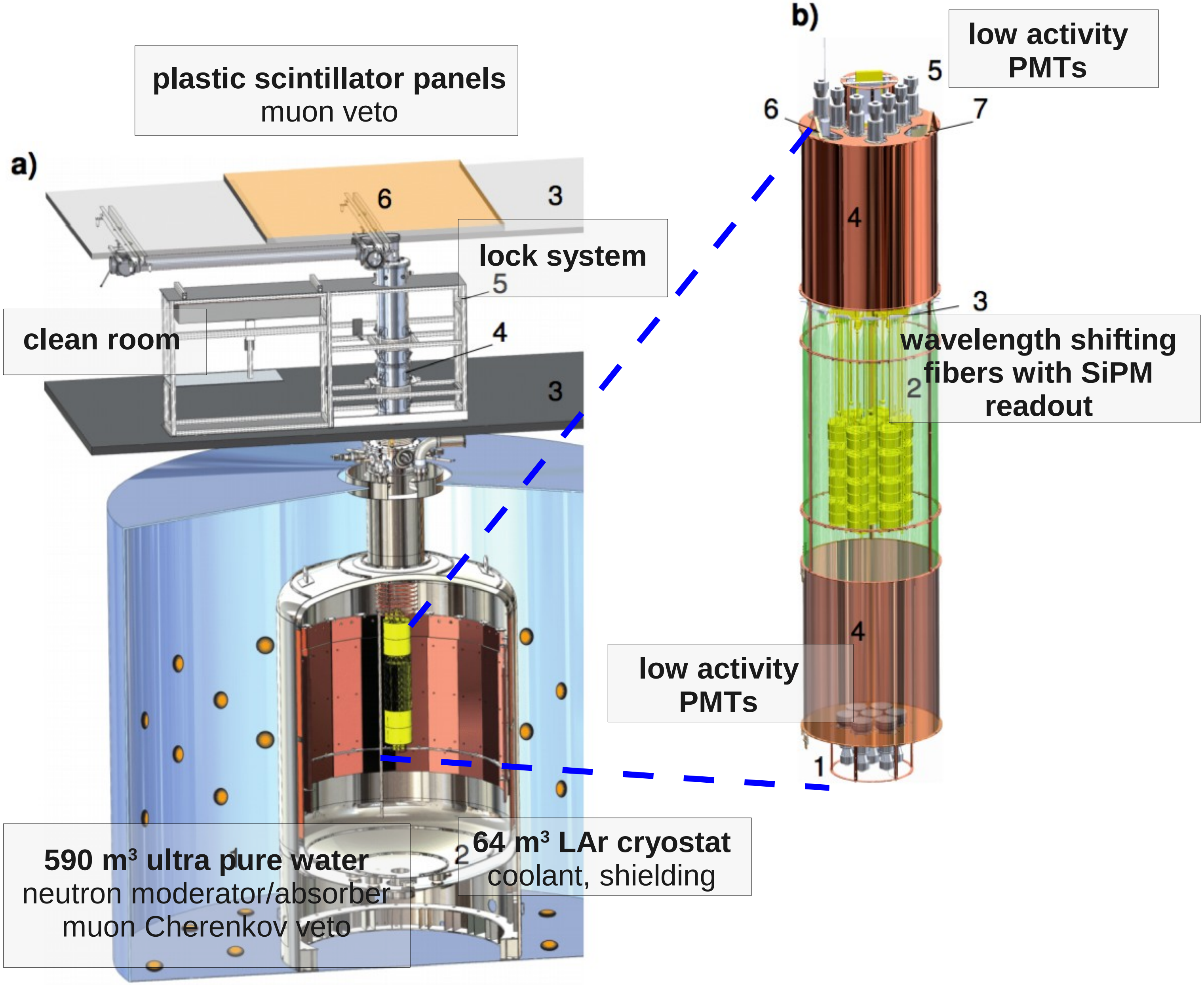
Nature 544, 47 (2017)

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)
- $\langle m_{ee}\rangle \leq$ 0.09-0.15 eV

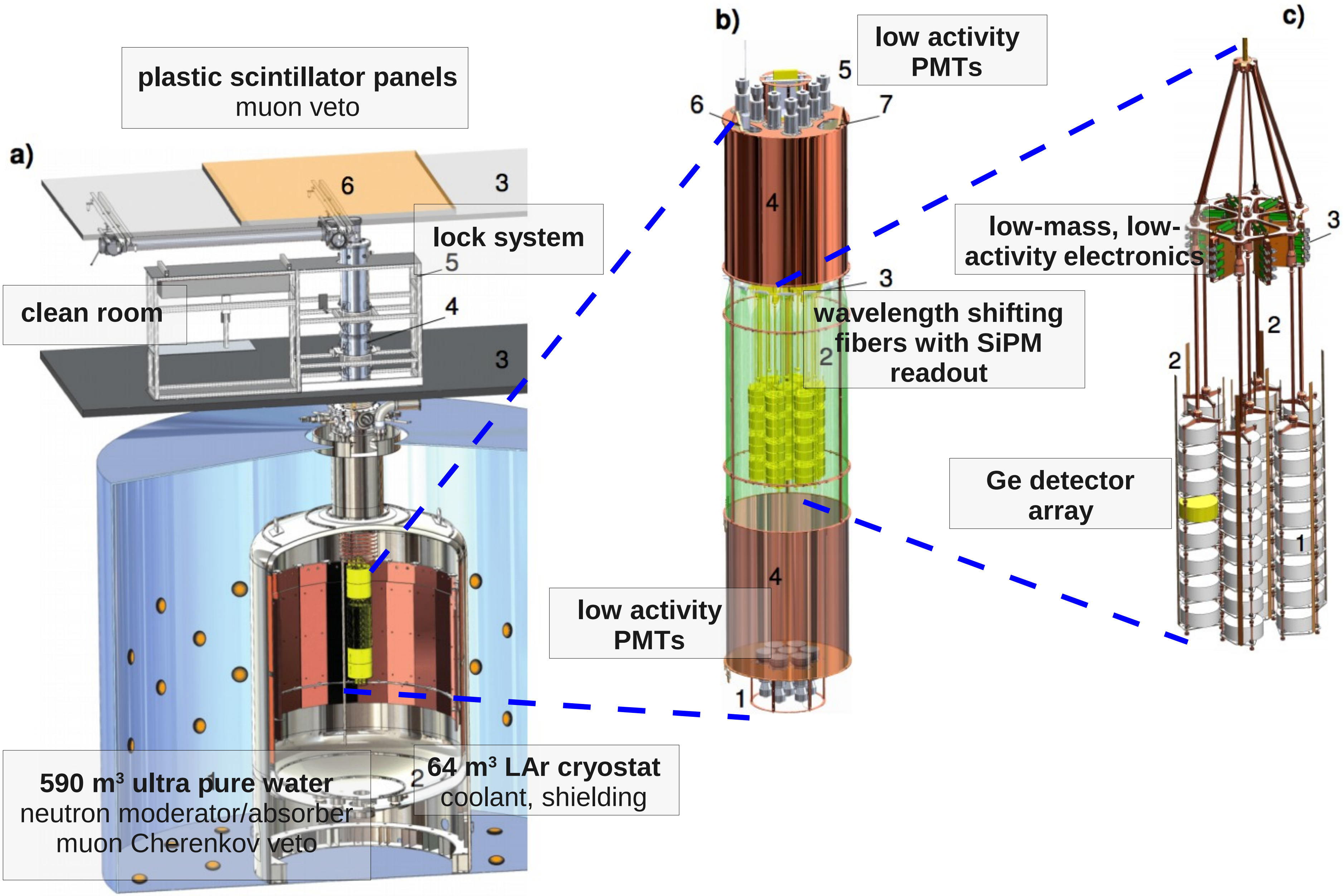

plastic scintillator panels
muon veto
a)
6
3
lock system
5
clean room
4
3
590 m³ ultra pure water
neutron moderator/absorber
muon Cherenkov veto
2
64 m³ LAr cryostat
coolant, shielding

a) overview



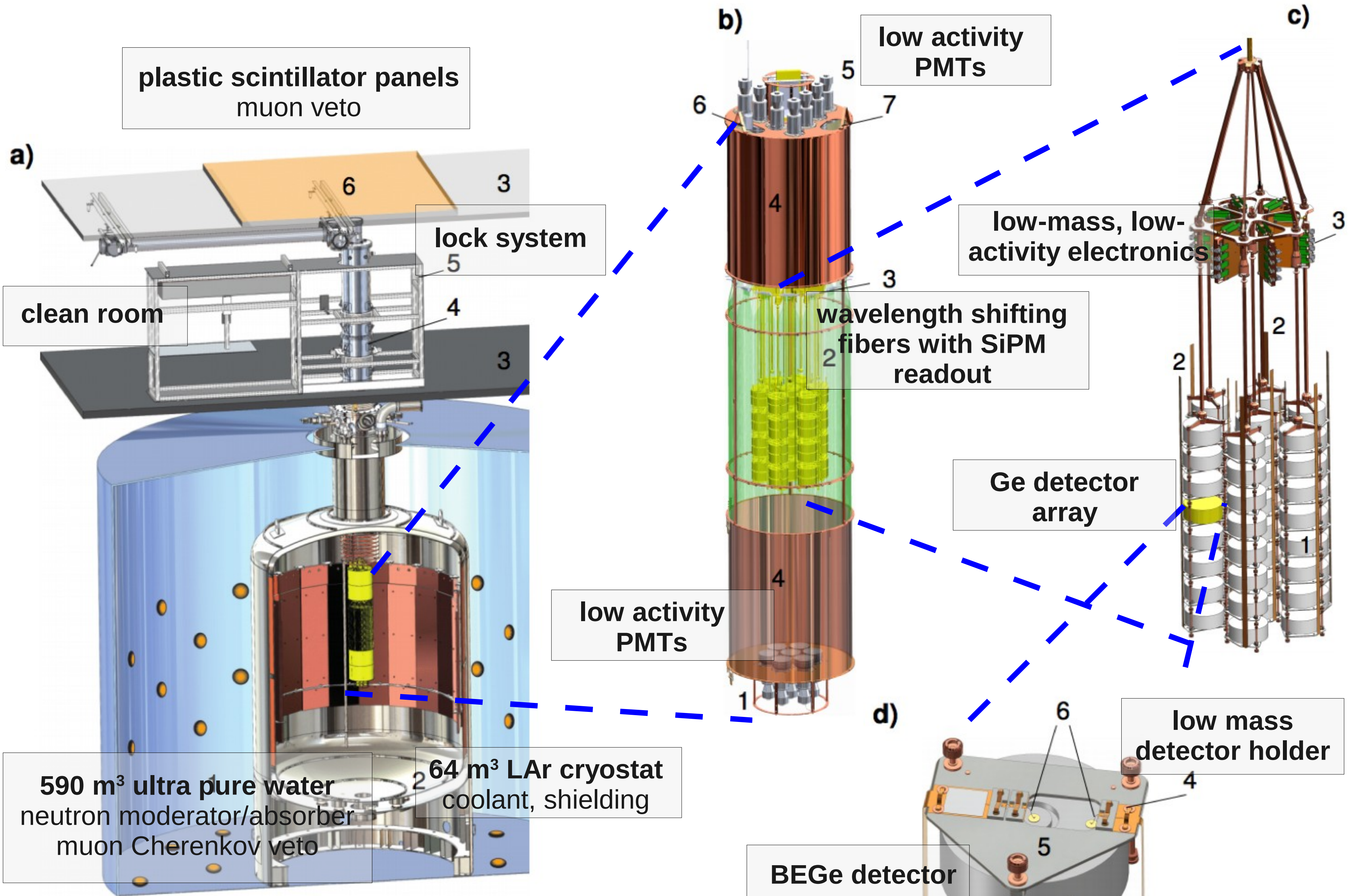
a) overview

b) liquid argon (LAr) veto instrumentation



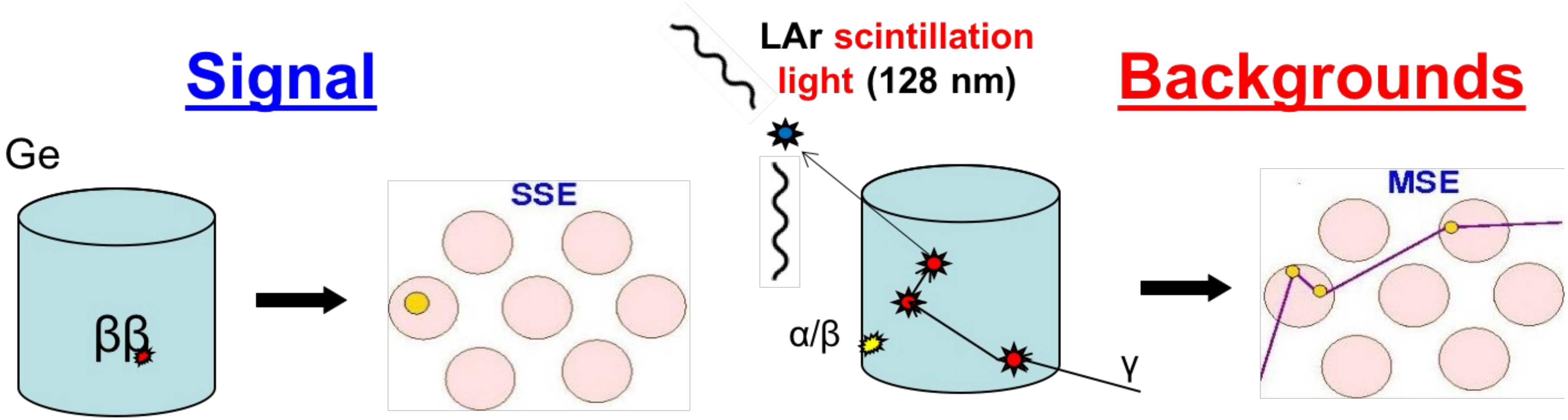
a) overview
b) liquid argon (LAr)
veto instrumentation

c) detector array



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

Background reduction tools



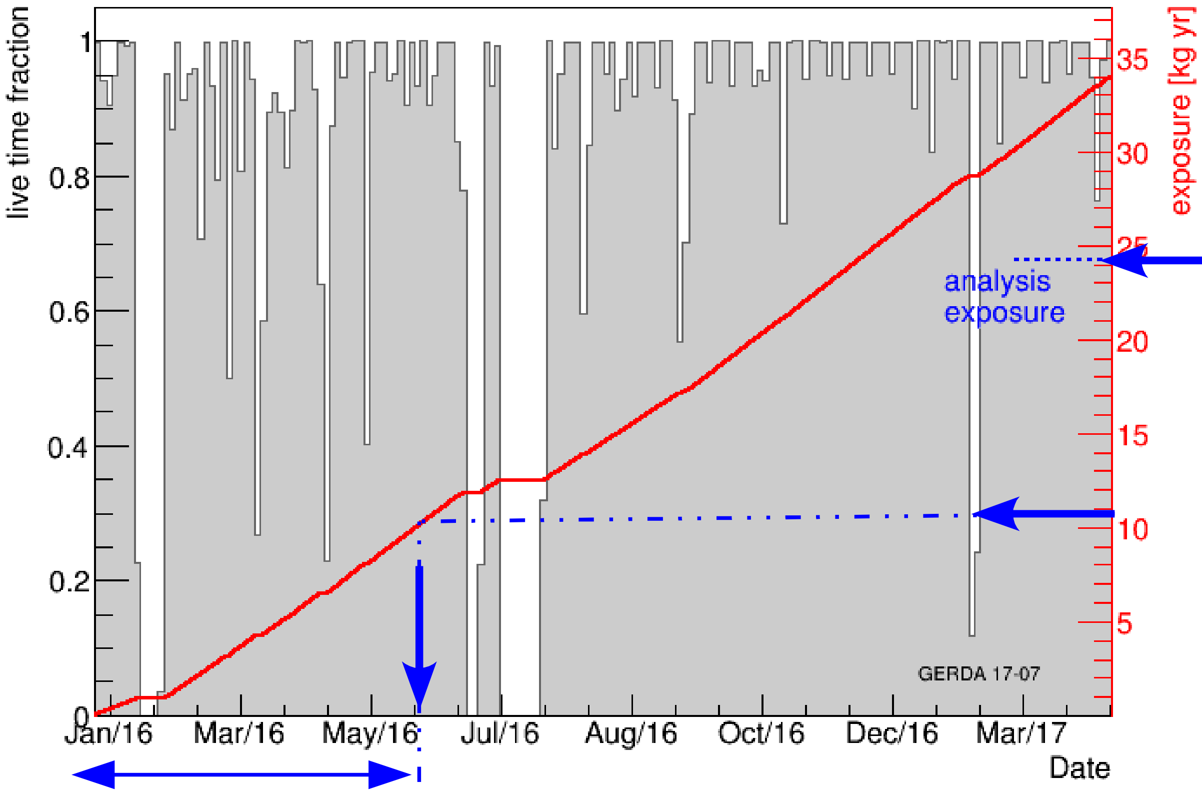
Point-like (single-site) energy deposition inside one HP-Ge diode

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 $Q_{\beta\beta}$

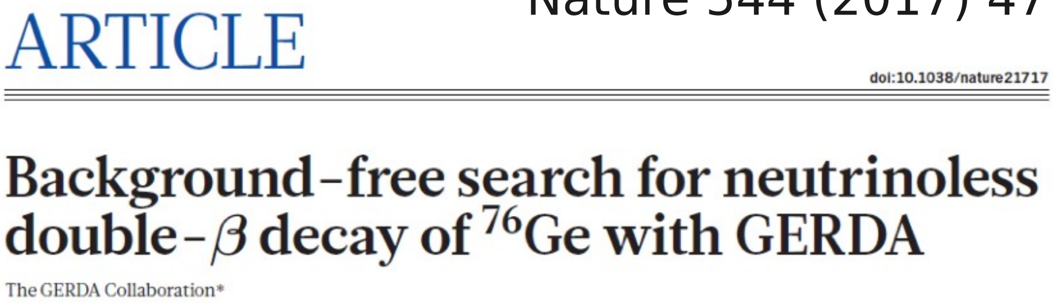


- **Phase II a:** 10.8 kg·yr already published in **Nature 544, 47–52**

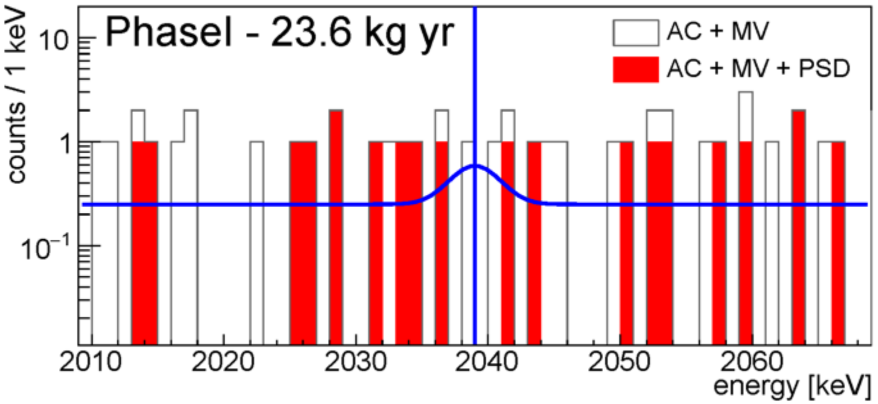
- **New Data Release**
  - Box opened for **BEGe dataset only** (**12.4 kg·yr**)
  - New ^{enr}Coax data still in the box
    - confident to improve background by better rejection of α events from the groove
    - Rejection a posteriori would spoil the blinding concept
    - Even worse in case of signal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

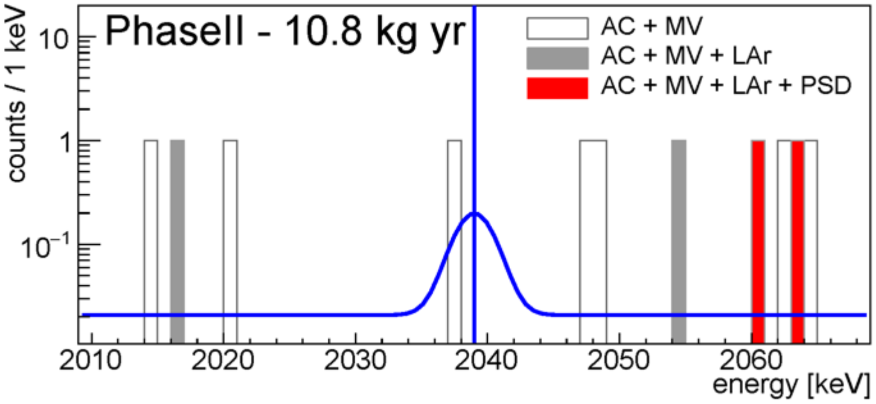
Phase IIa results

Nature 544 (2017) 47



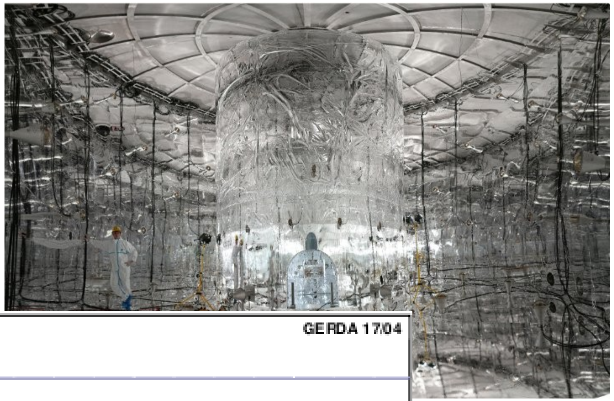
- new limit on $T^{0\nu}_{1/2}$ (Phase I + Phase IIa)
  $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr (90% CL) (median sensitivity $4.0 \cdot 10^{25}$ yr)
- Background Index (BI):
  Coax: $3.5^{+2.1}_{-1.5} \cdot 10^{-3}$ cts/(keV·kg ·yr); FWHM: 4.0(2) keV
  BEGe: $0.7^{+1.1}_{-0.5} \cdot 10^{-3}$ cts/(keV·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

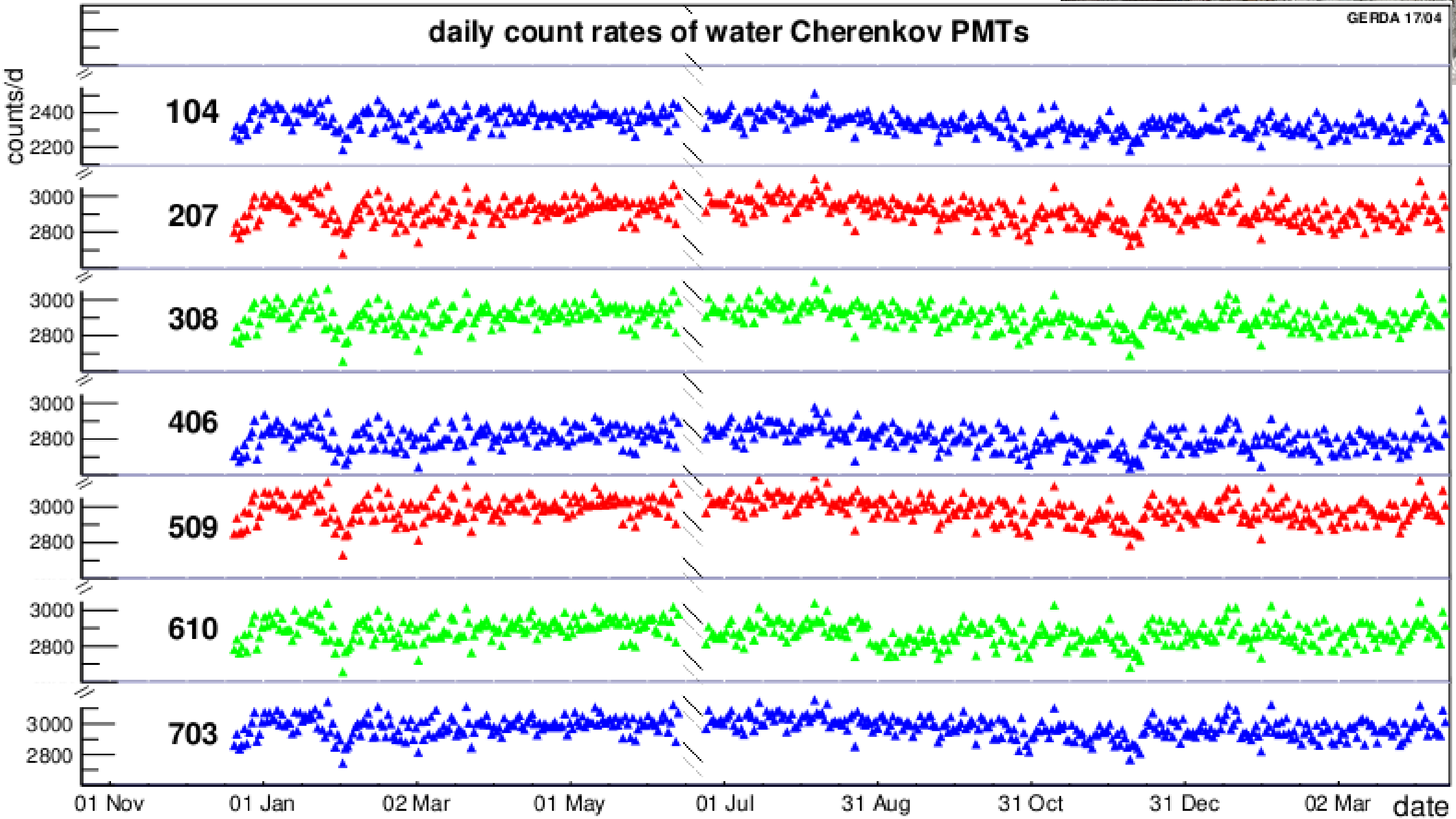




Muon Veto

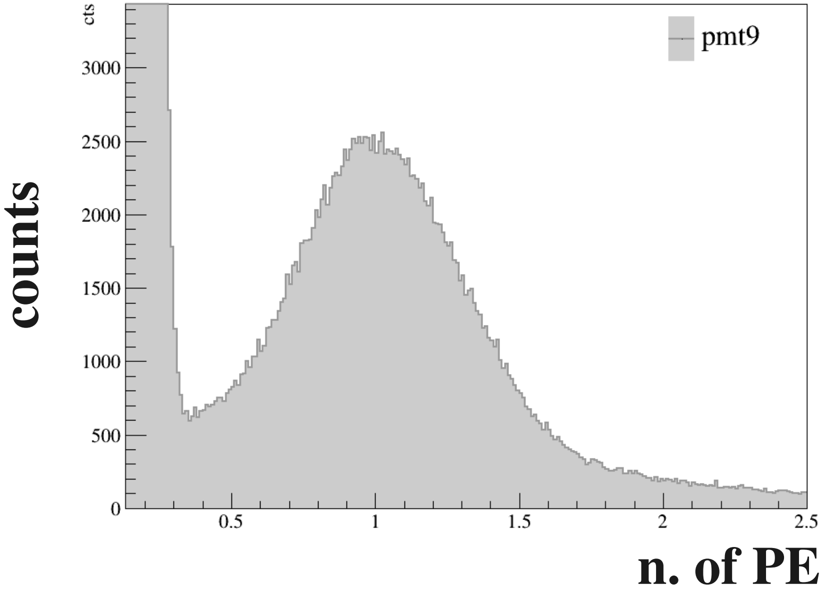
EPJC 76 (2016) 298

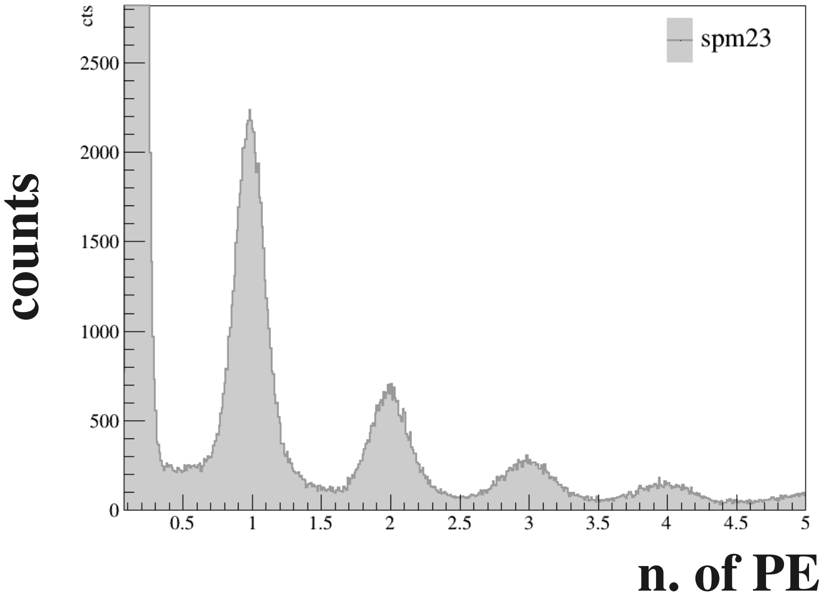




since 2010: 7 PMTs in water tank dead (no effect on eff.), >99% μ identification ~0.1% dead time; very reliable and stable

LAr Veto





read out all channel if Ge triggers
→ offline veto

- all channels working
- gain stable with time

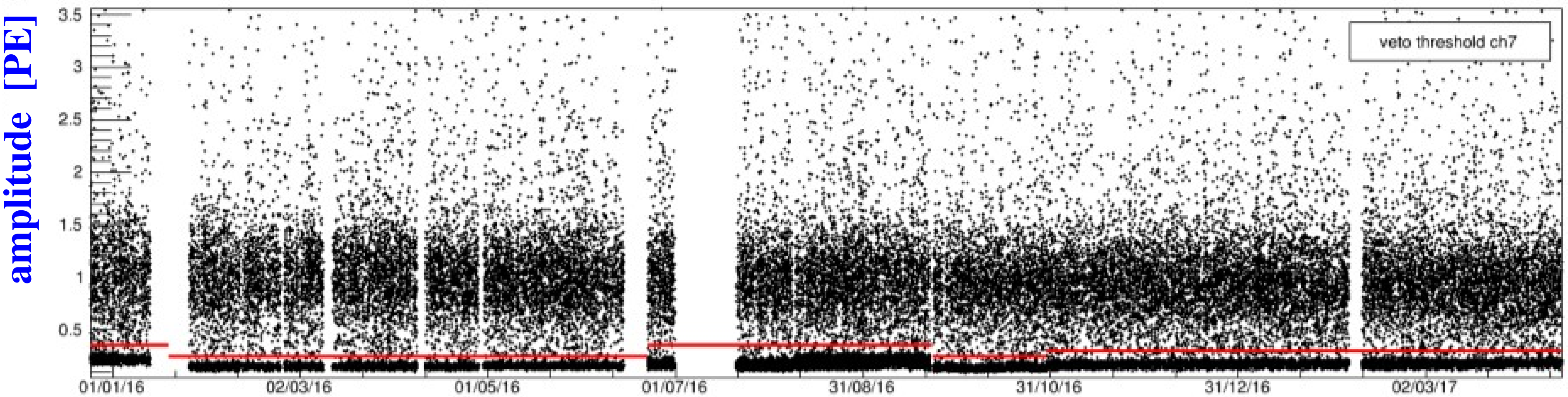
low noise → veto cut ~0.5 p.e.

reject ~ 2.3% of pulser events

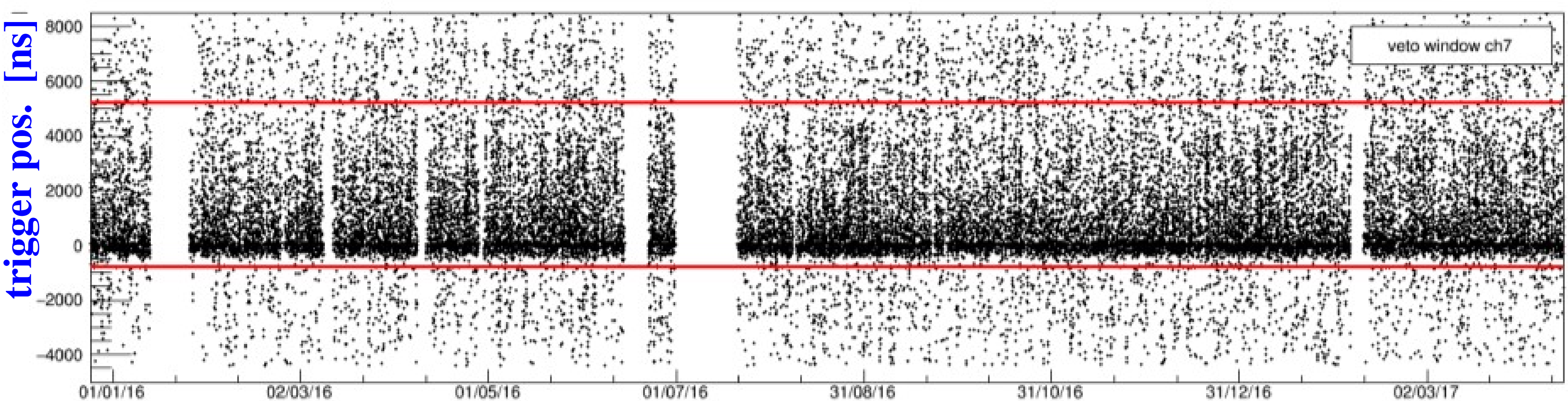
LAr Veto

PMTs

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



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

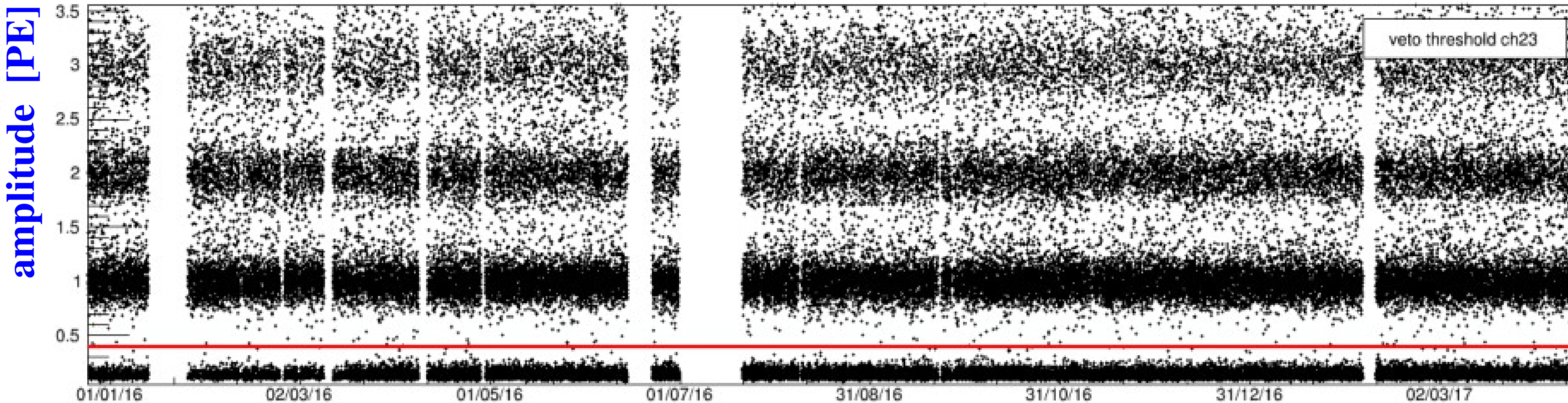


01/01/16 **02/03/17**

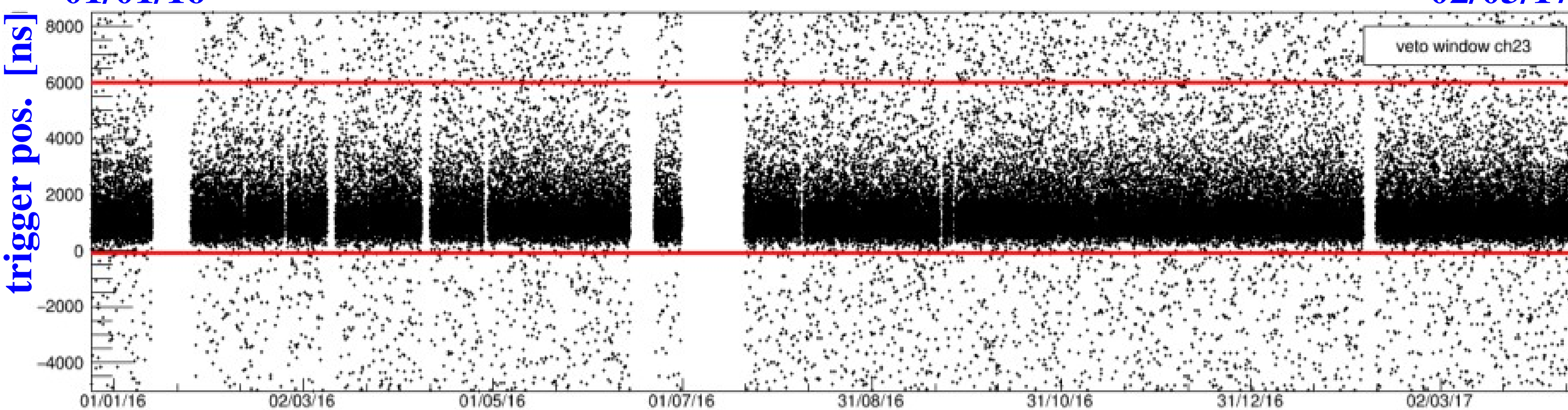
LAr Veto

SIPMs

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

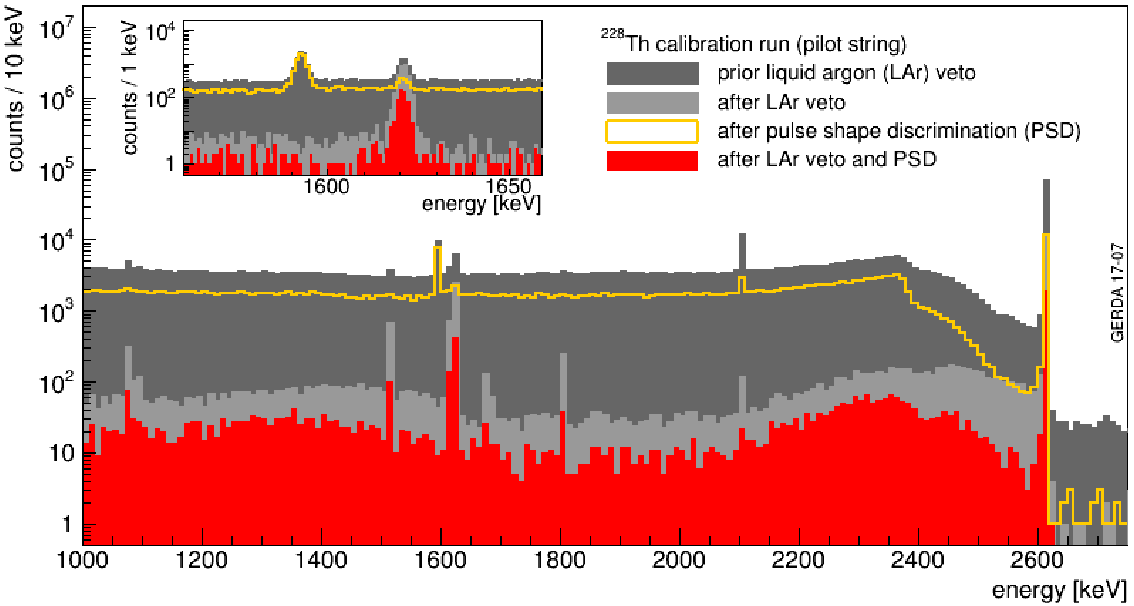


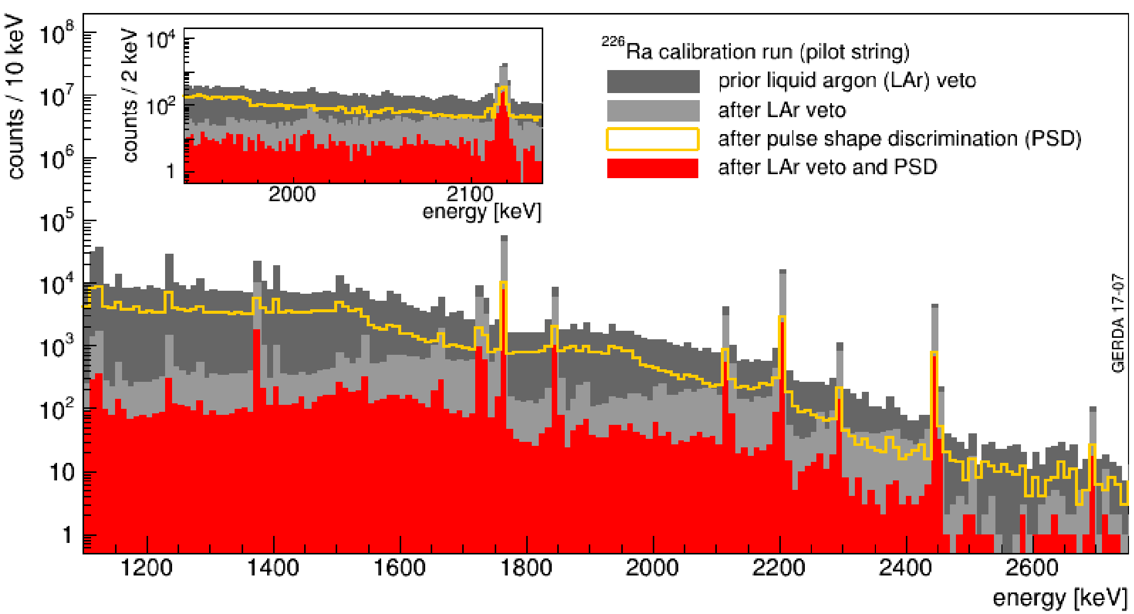
01/01/16 **02/03/17**



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

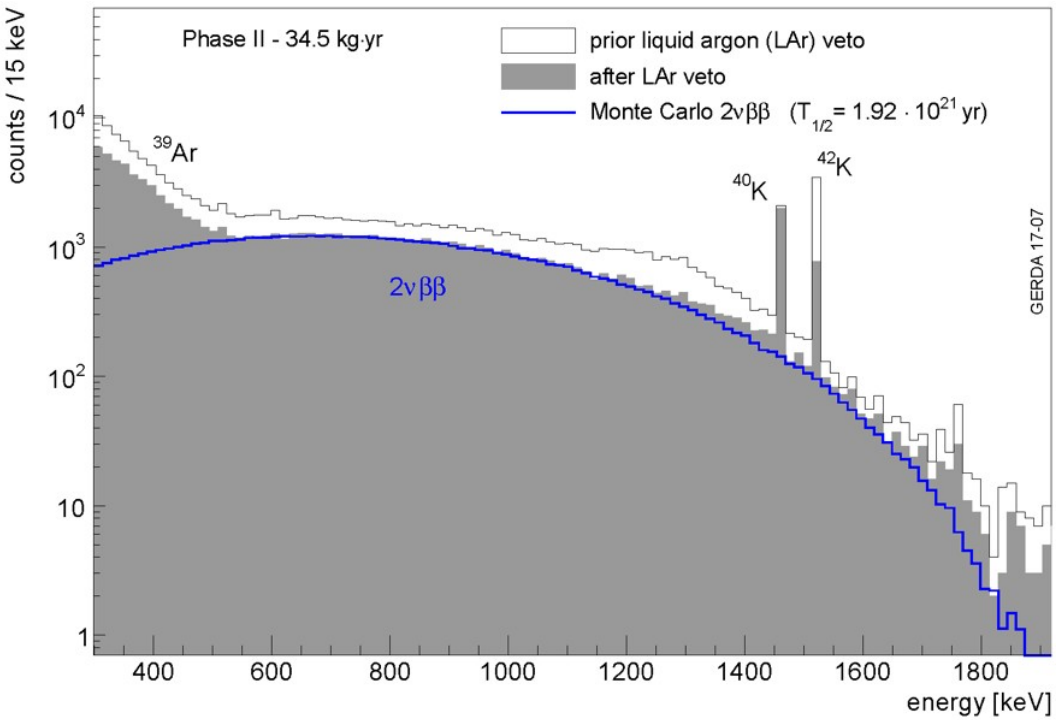
LAr veto bkg suppression





- 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

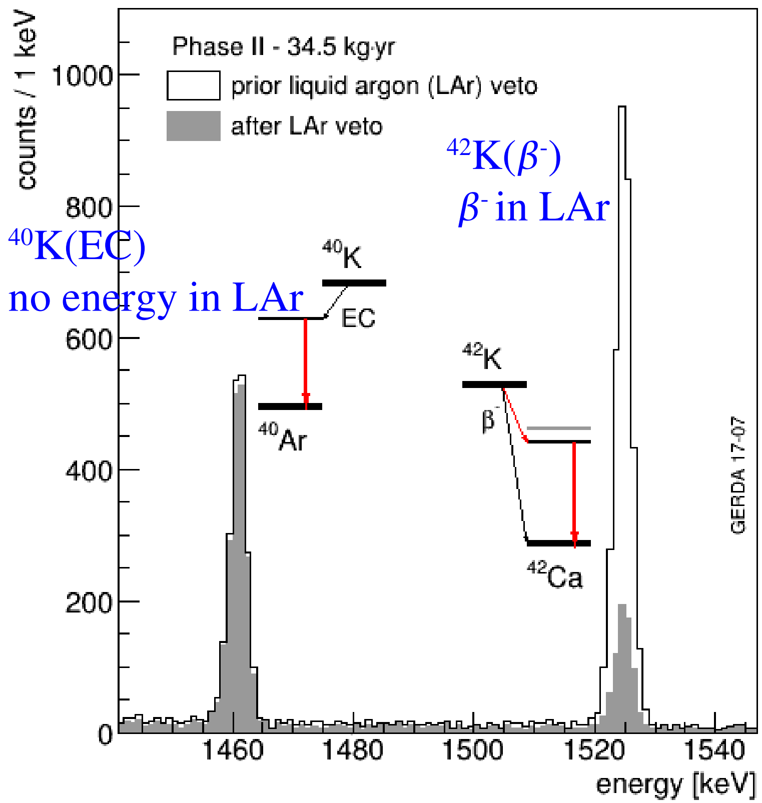


γ-lines from:

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

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

+ e- (up to 2 MeV)



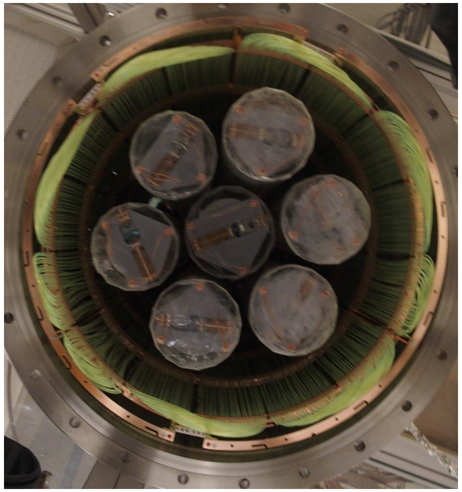
- $^{40}K/^{42}K$ Compton continuum fully suppressed
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I

[EPJC 75 (2015) 416]

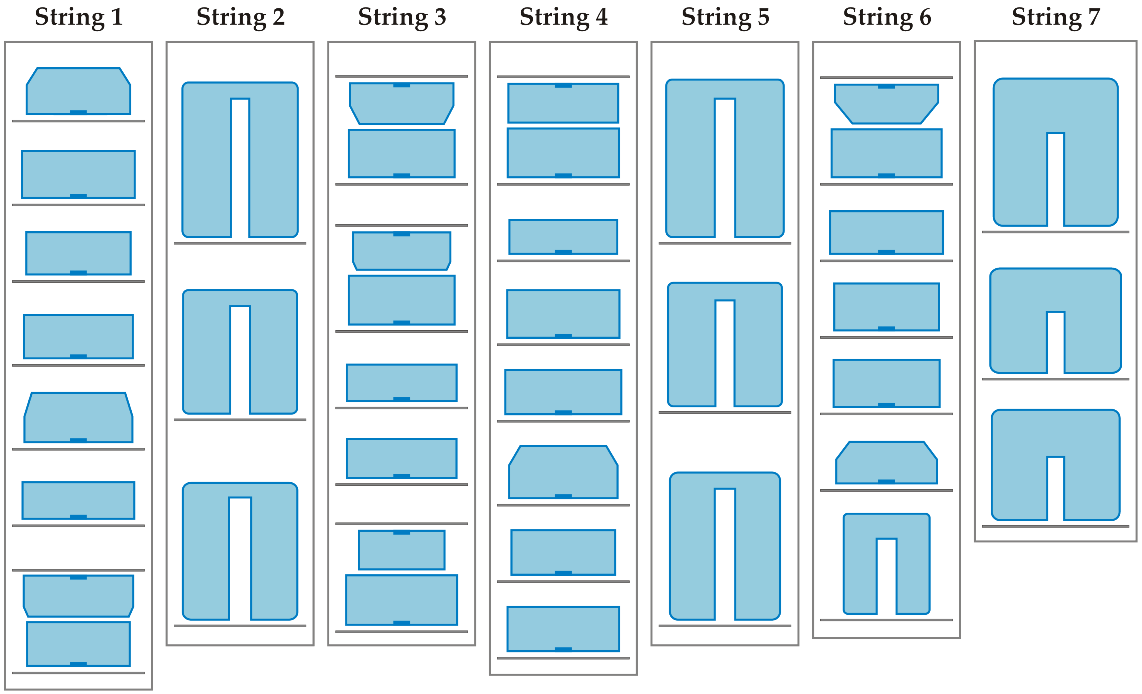
Ge detectors

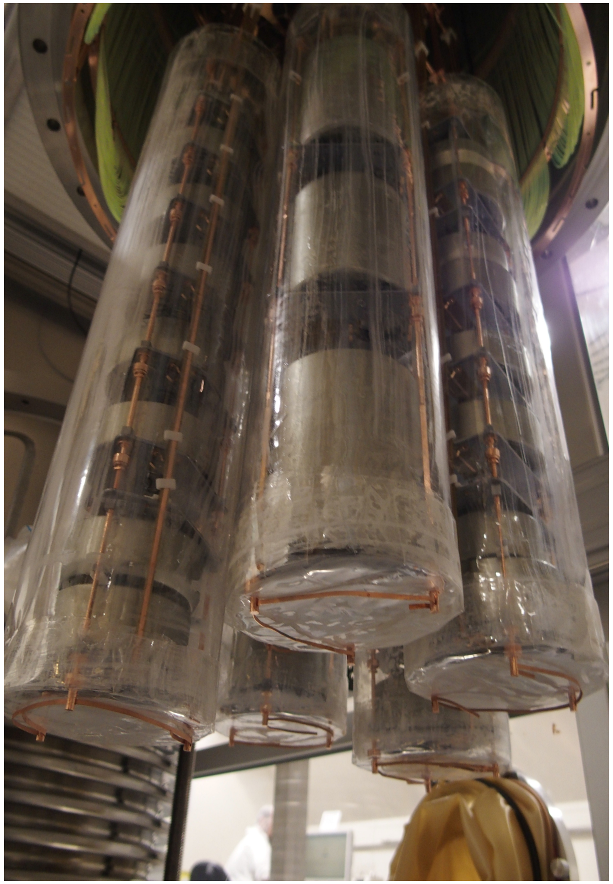
- 30 enriched BEGe (20 kg)
- 7 enriched Coax (15.8 kg)
- 3 natural Coax (7.6 kg)

→ **35.8 kg of enr detectors**

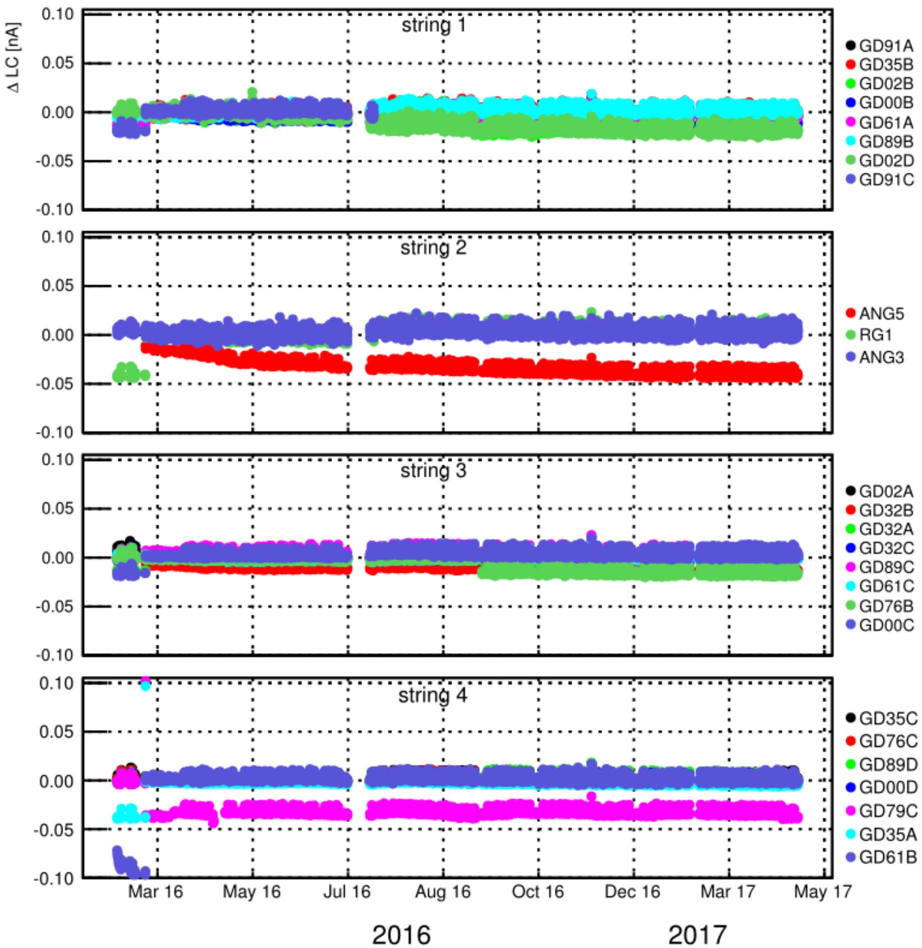


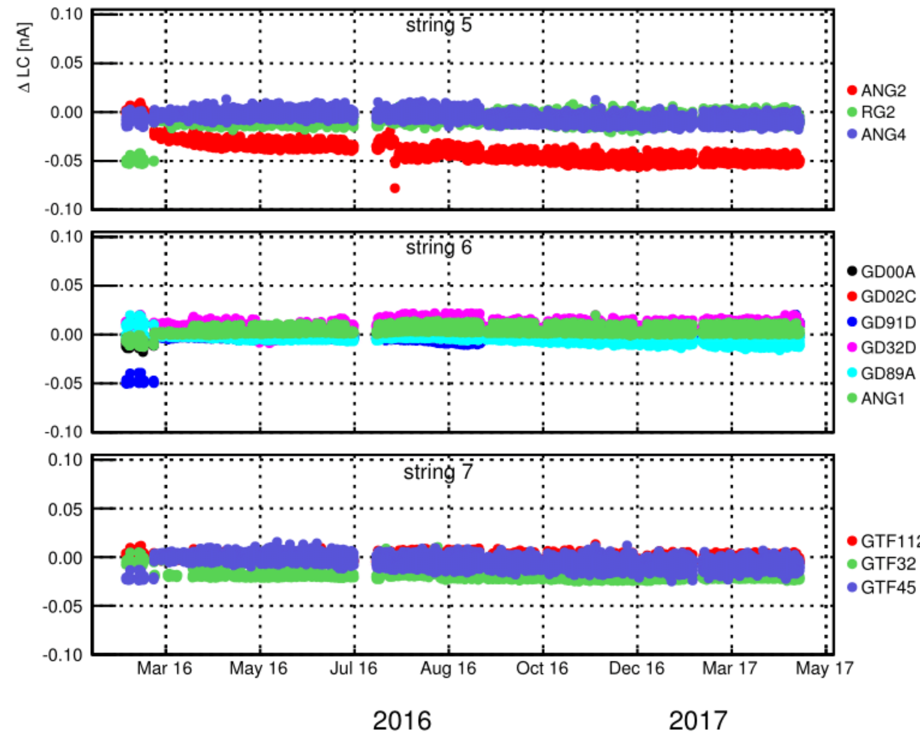
3 diodes lost (burn-out JFET)





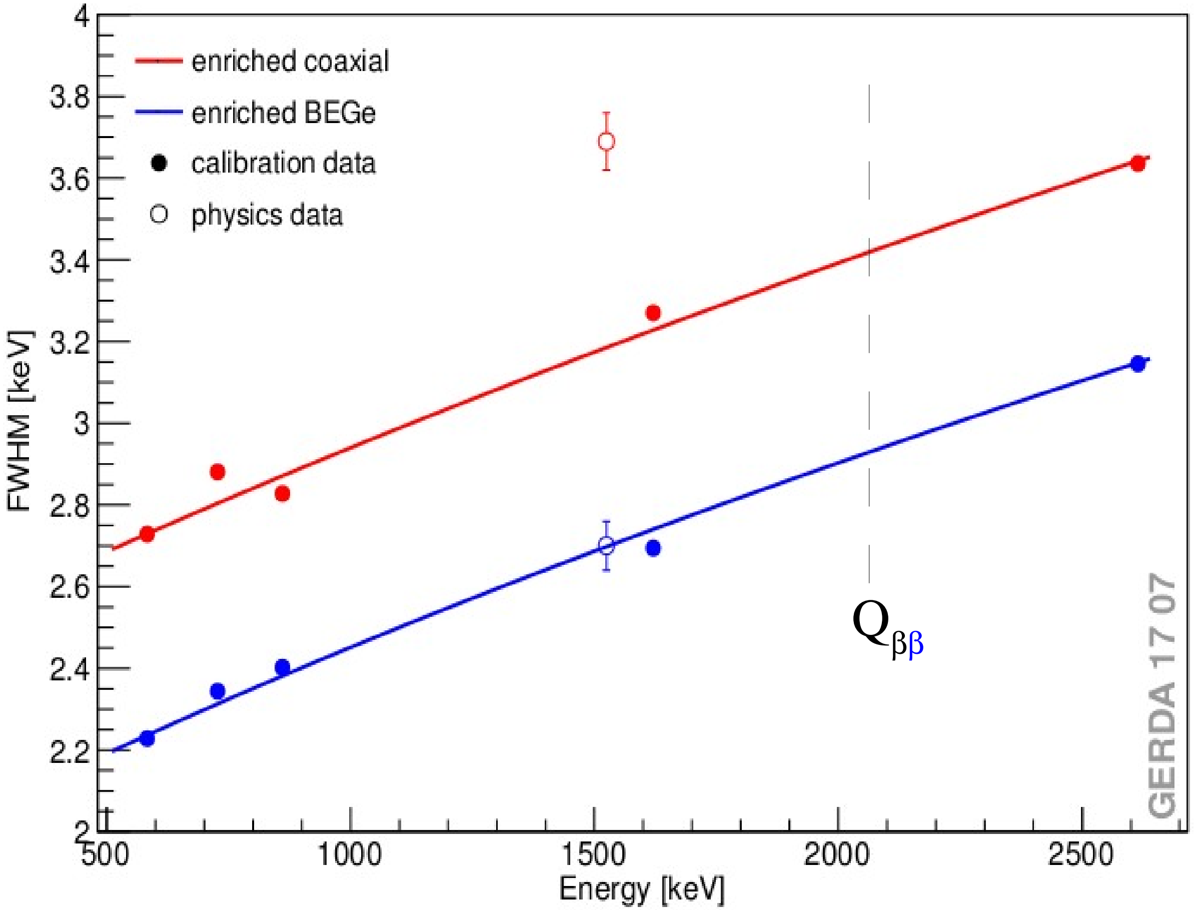
Ge detectors: leakage current





- 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:

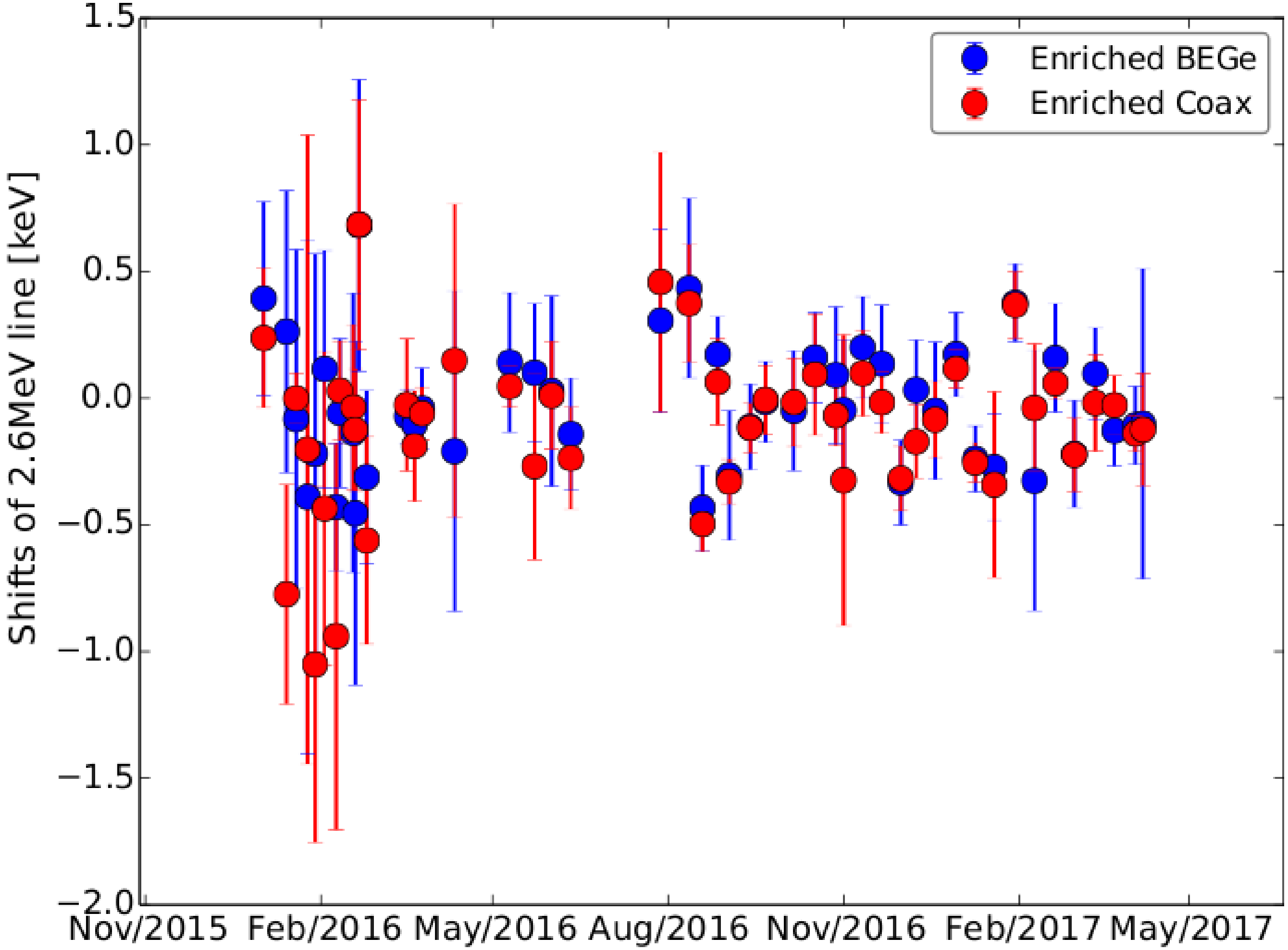
- weekly ^{228}Th calibrations
- comparison with ^{42}K, ^{40}K peaks in physics data
- stability btw. calib: every 20 s pulser injected into FE
- ZAC filter for E reconstruction

[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)

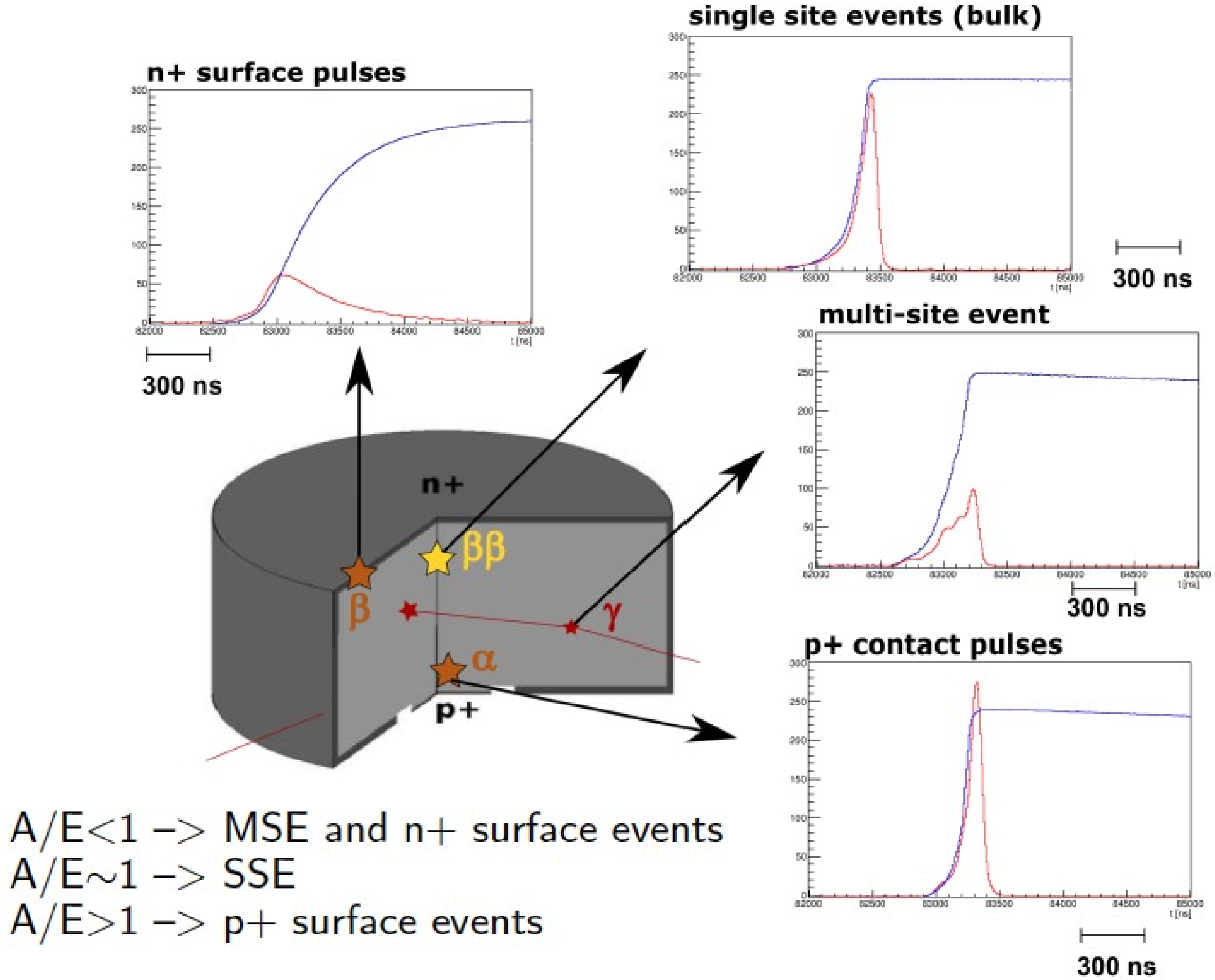
Ge detectors: energy shift



- 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

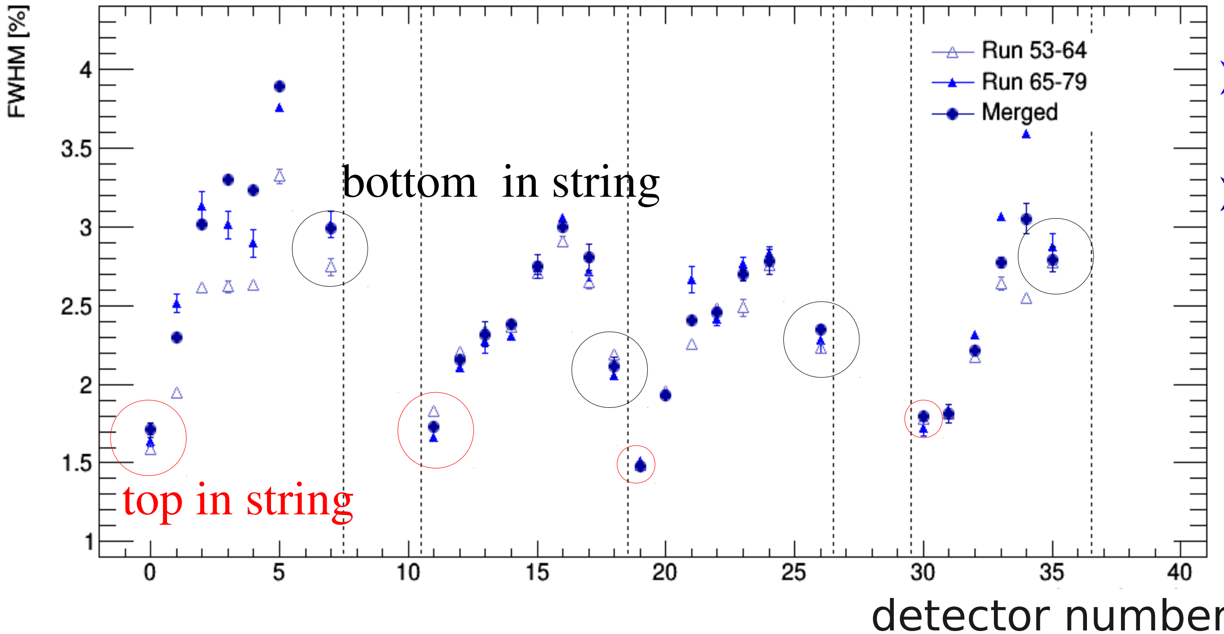
Pulse Shape Discrimination: BEGe

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

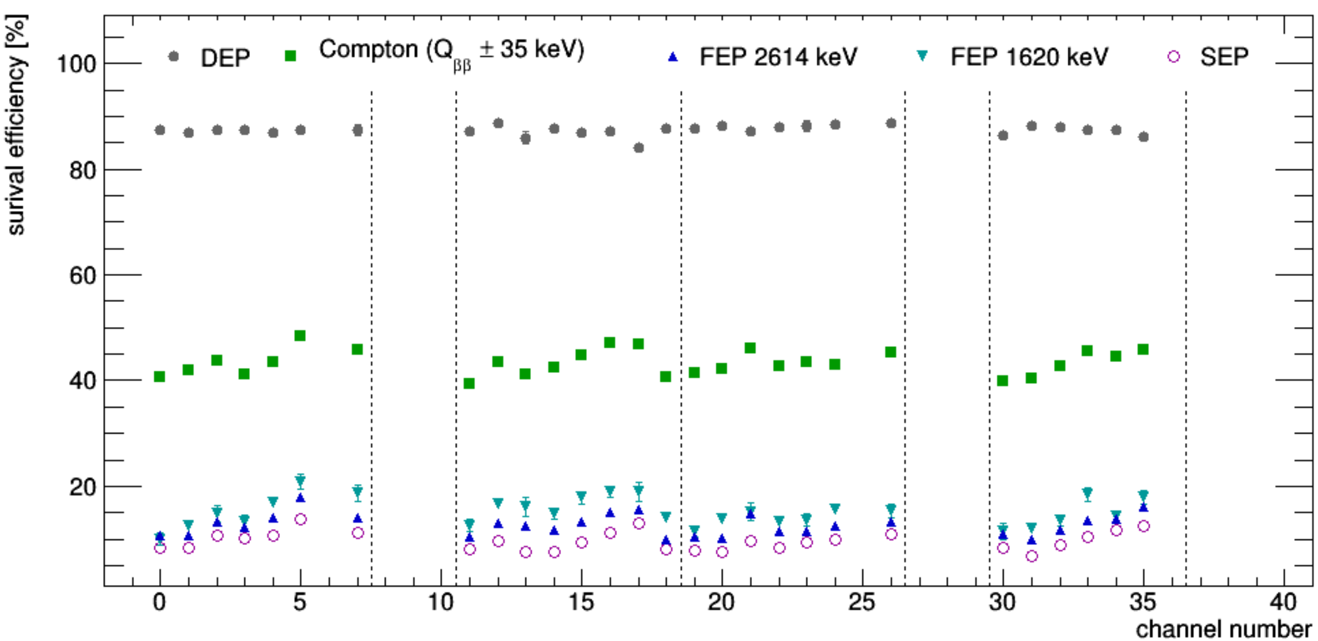


A/E resolution of DEP events versus detector

PSD: BEGe



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

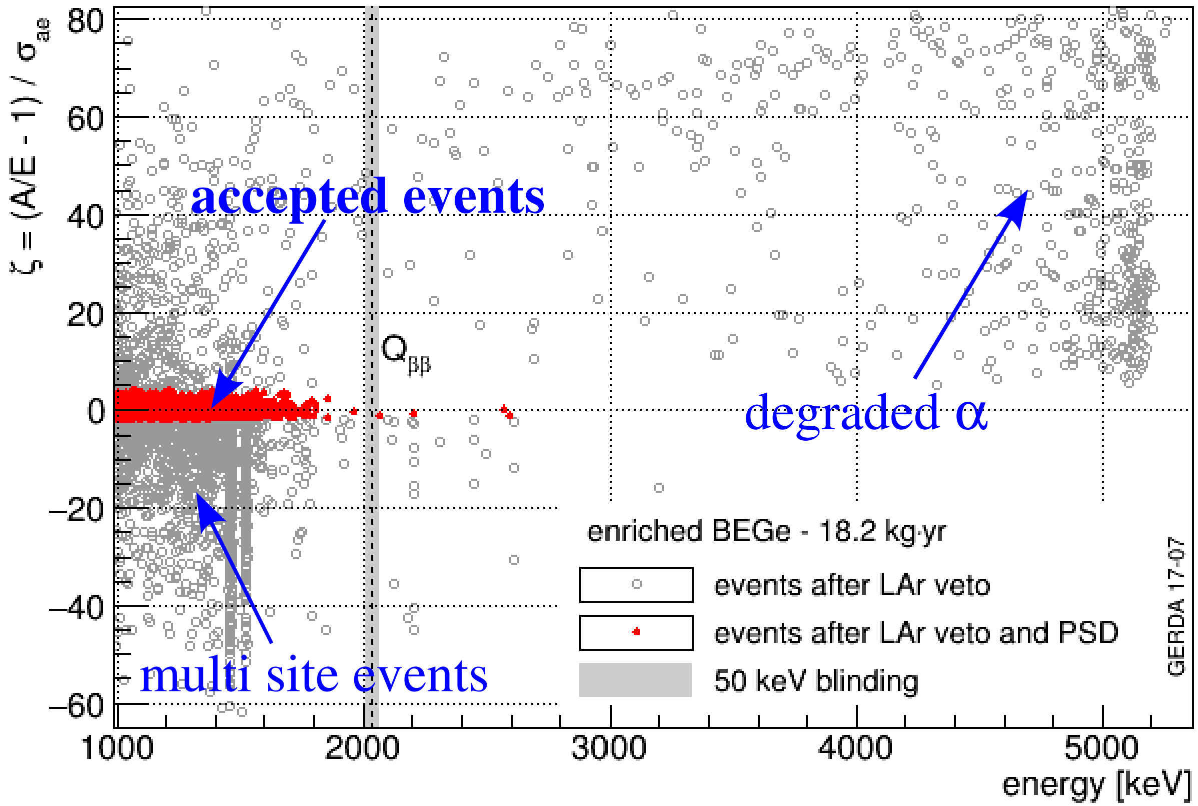


DEP events

Compton at $Q_{\beta\beta}$

FEP @ 2614 keV
FEP 1620 keV, SEP

Pulse Shape Discrimination: BEGe

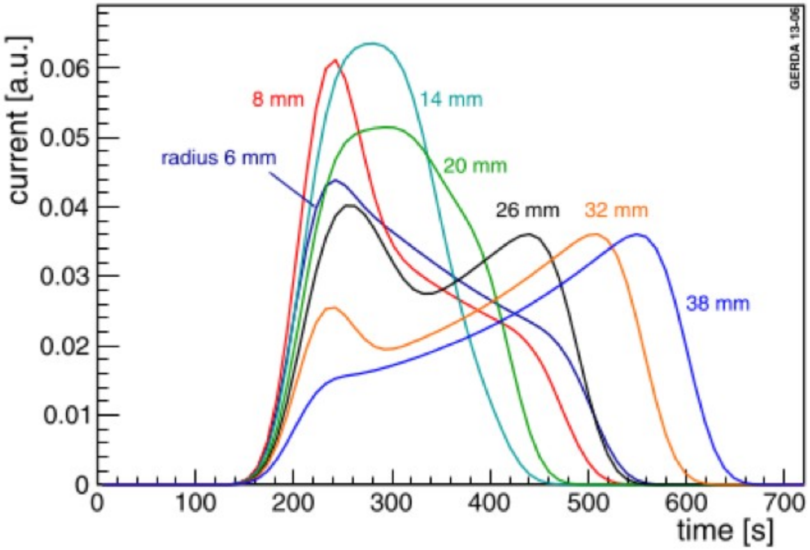


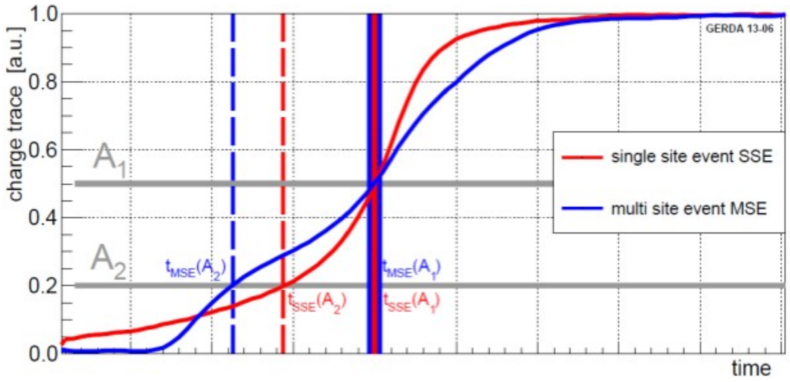
- Event by event selection
- Acceptance for $0\nu\beta\beta$ events: **(87.4±2.6)%**
  - estimated from ^{208}Tl DEP
  - double checked at low energy with $2\nu\beta\beta$ events (after LAr cut)

Pulse Shape Discrimination: Coax

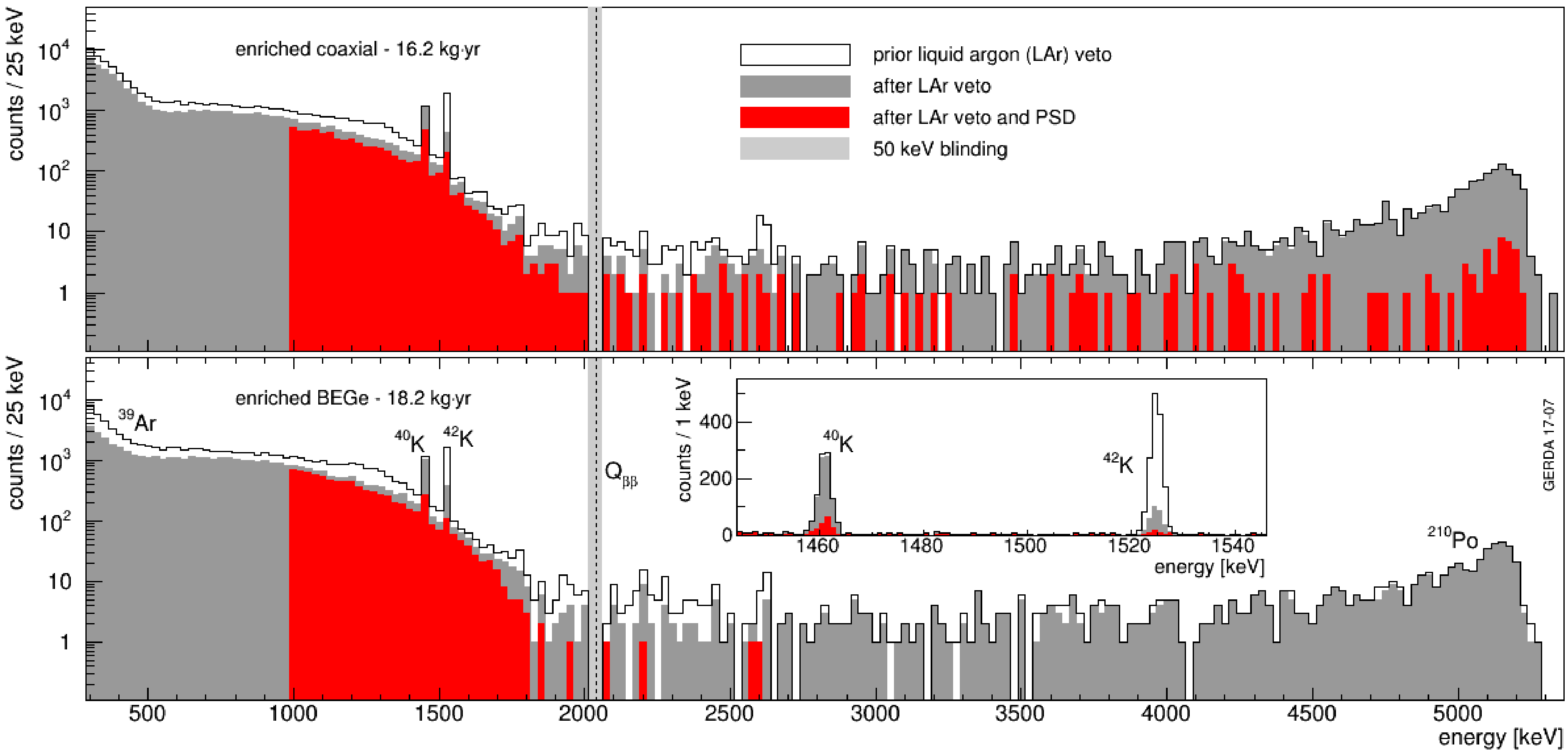
- PSD for Coax detectors less effective than for BEGes
- Artificial Neural Network (**ANN**) as in Phase I:
  - Trained on signal (SSE): ^{208}Tl (2614 keV) DEP at 1592 keV
  - Background (MSE): ^{212}Bi @ 1620 keV γ-line
  - Acceptance for 0νββ events (**85±5**)%
    - Double check with Compton edge 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





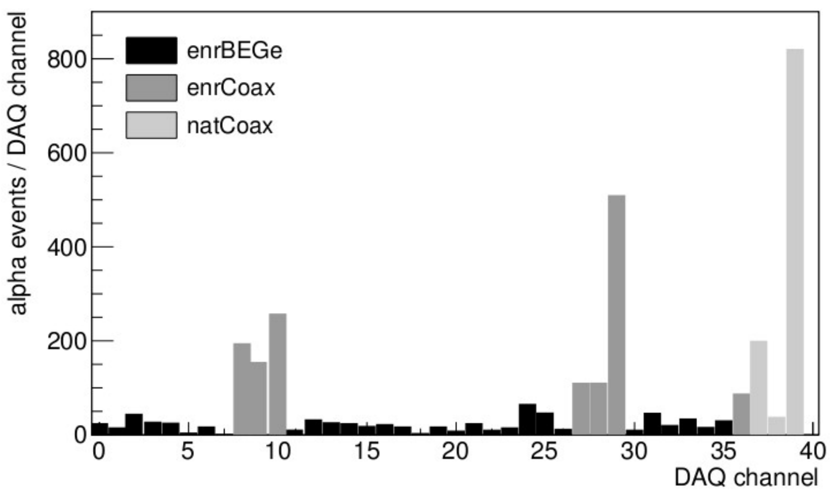
Phase II GERDA spectra

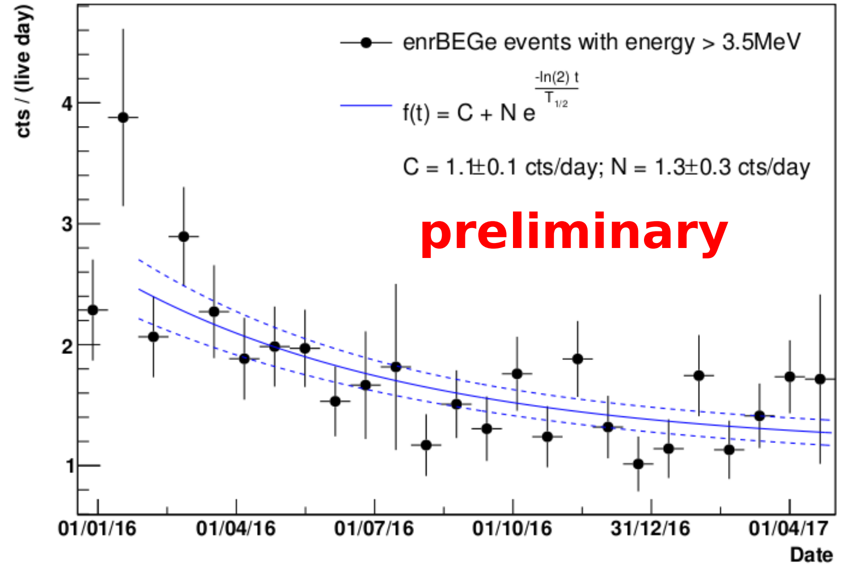


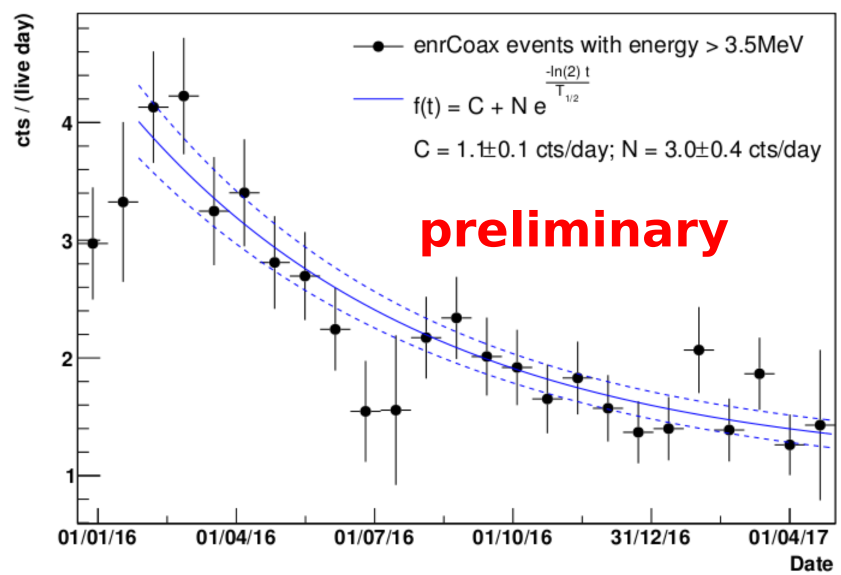
- Most prominent feature: ^{39}Ar β (< 500 keV), 2νββ, ^{42}K and ^{40}K γ lines, α
- PSD of BEGe clears completely the α region
- LAr and PSD highly effective cuts
- Final background at $Q_{\beta\beta}$ $\mathcal{O}(10^{-3}$ counts/keV· kg· yr)

Alpha rate

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



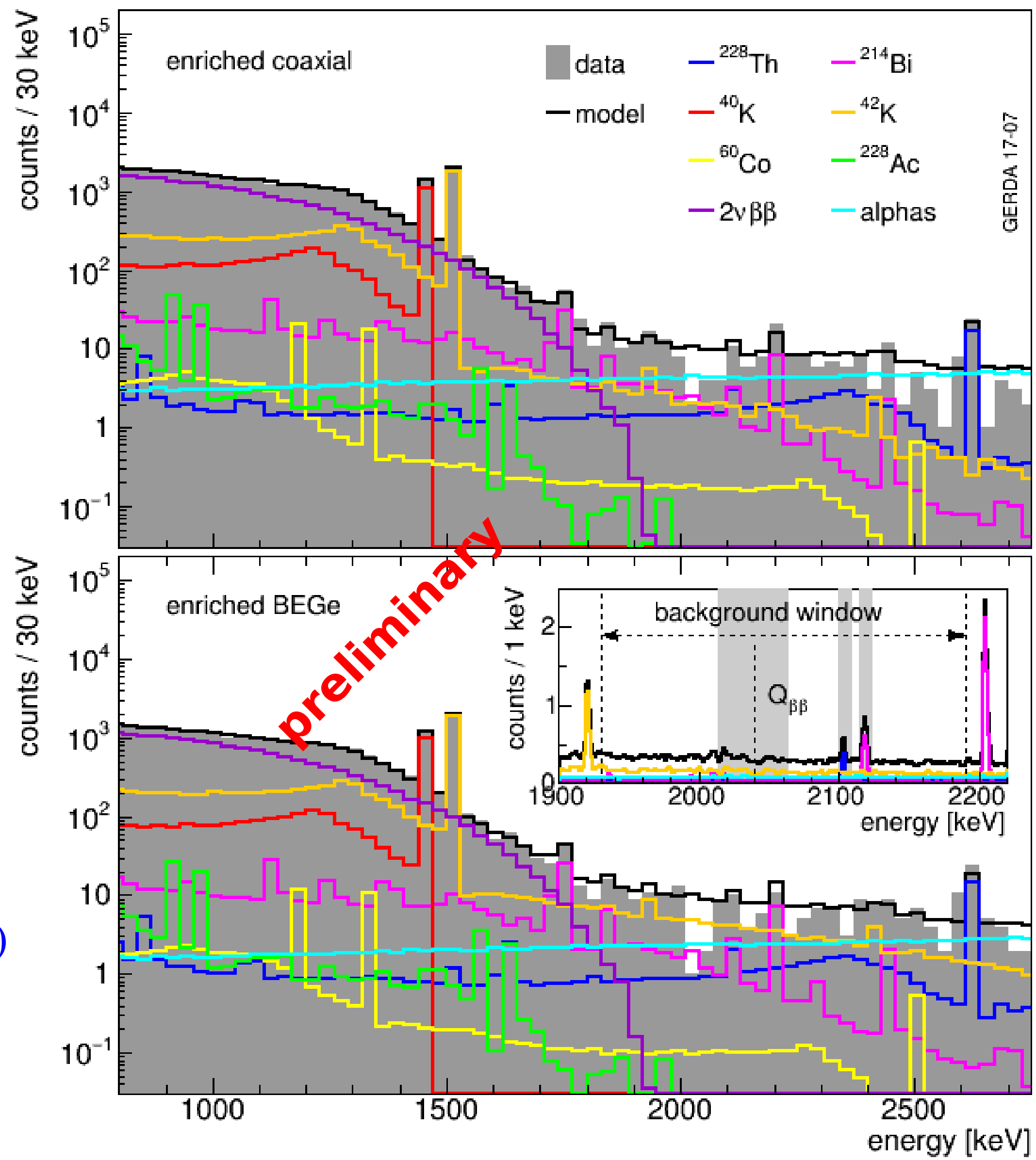




- Part of the α component is decaying away (^{210}Po, $T_{1/2}$ = 138 days)

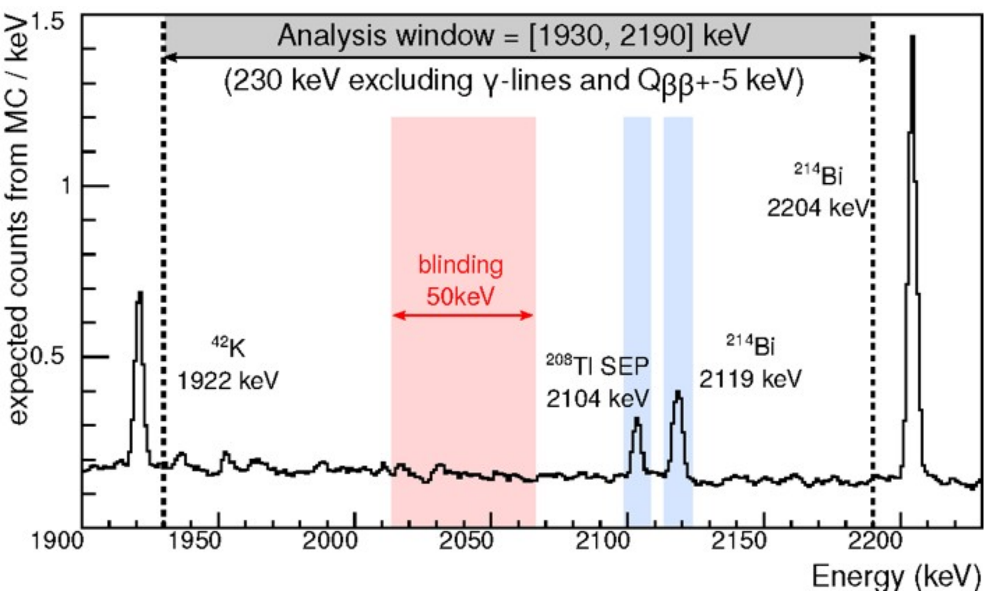
Background Model

- 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

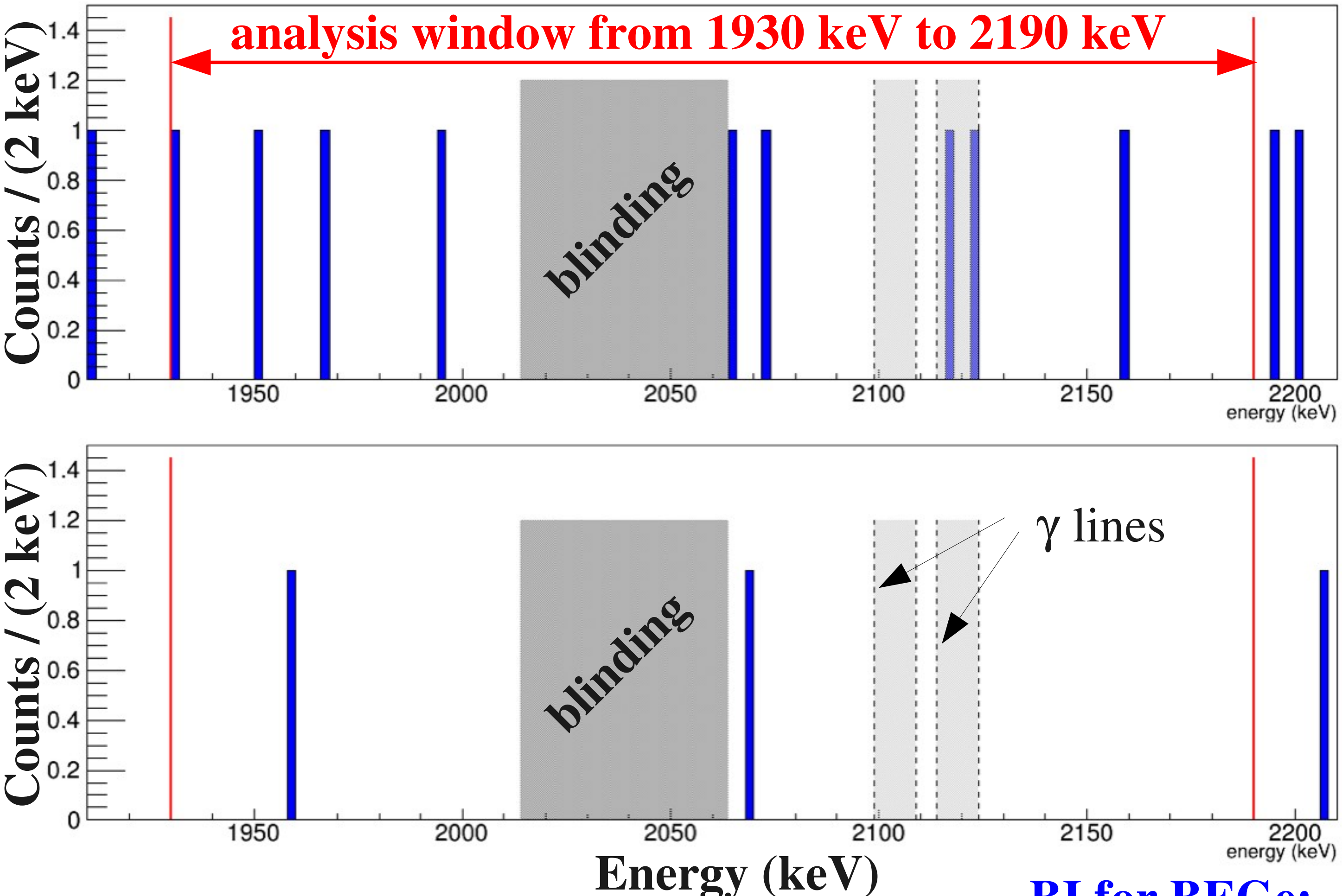
GERDA collaboration meeting at Krakow, 30 June:
unblinding of ± 25 keV around $Q_{\beta\beta}$

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

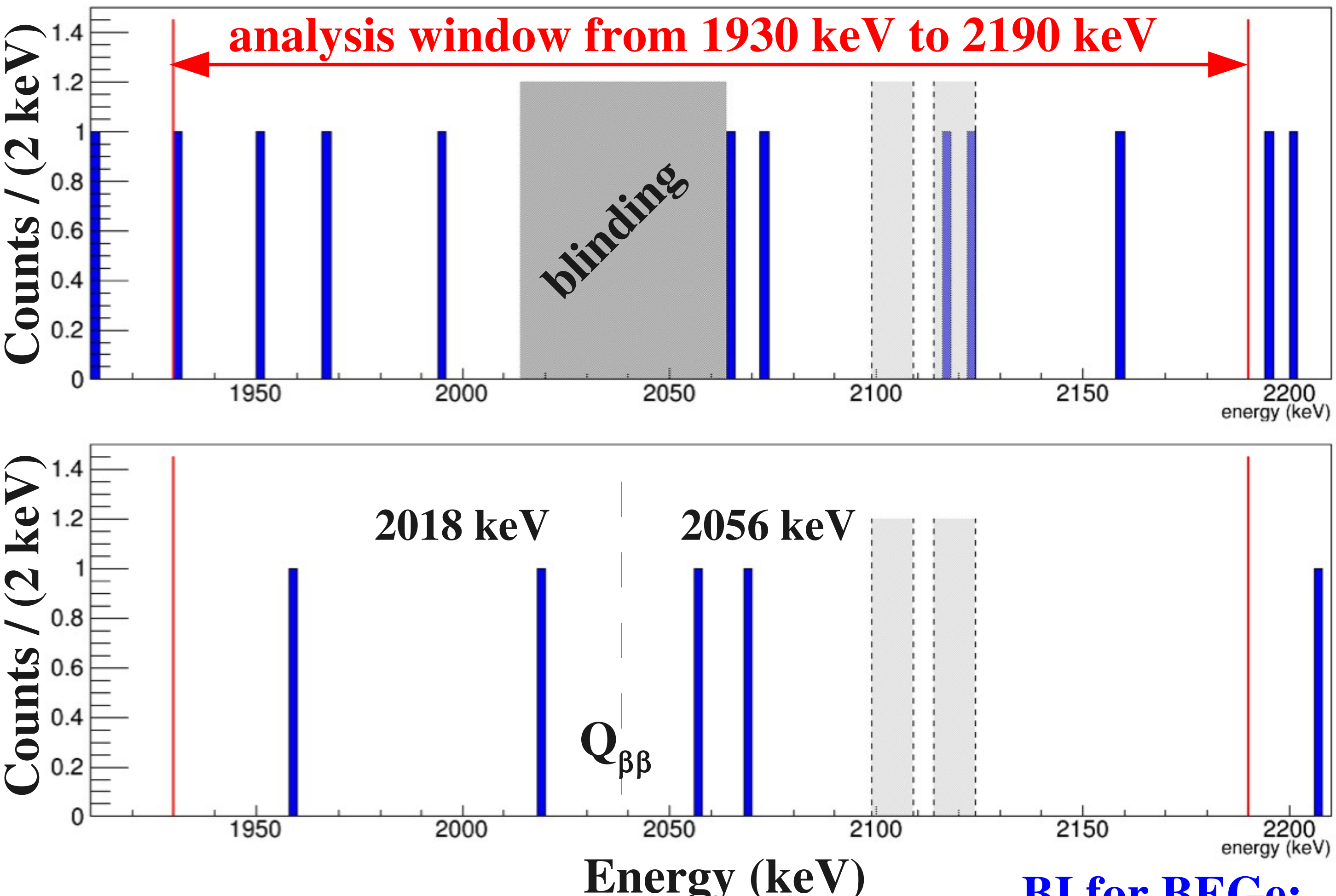
$0.5^{+0.5}_{-0.3} \cdot 10^{-3}$ cts/(keV ·kg · yr)

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)

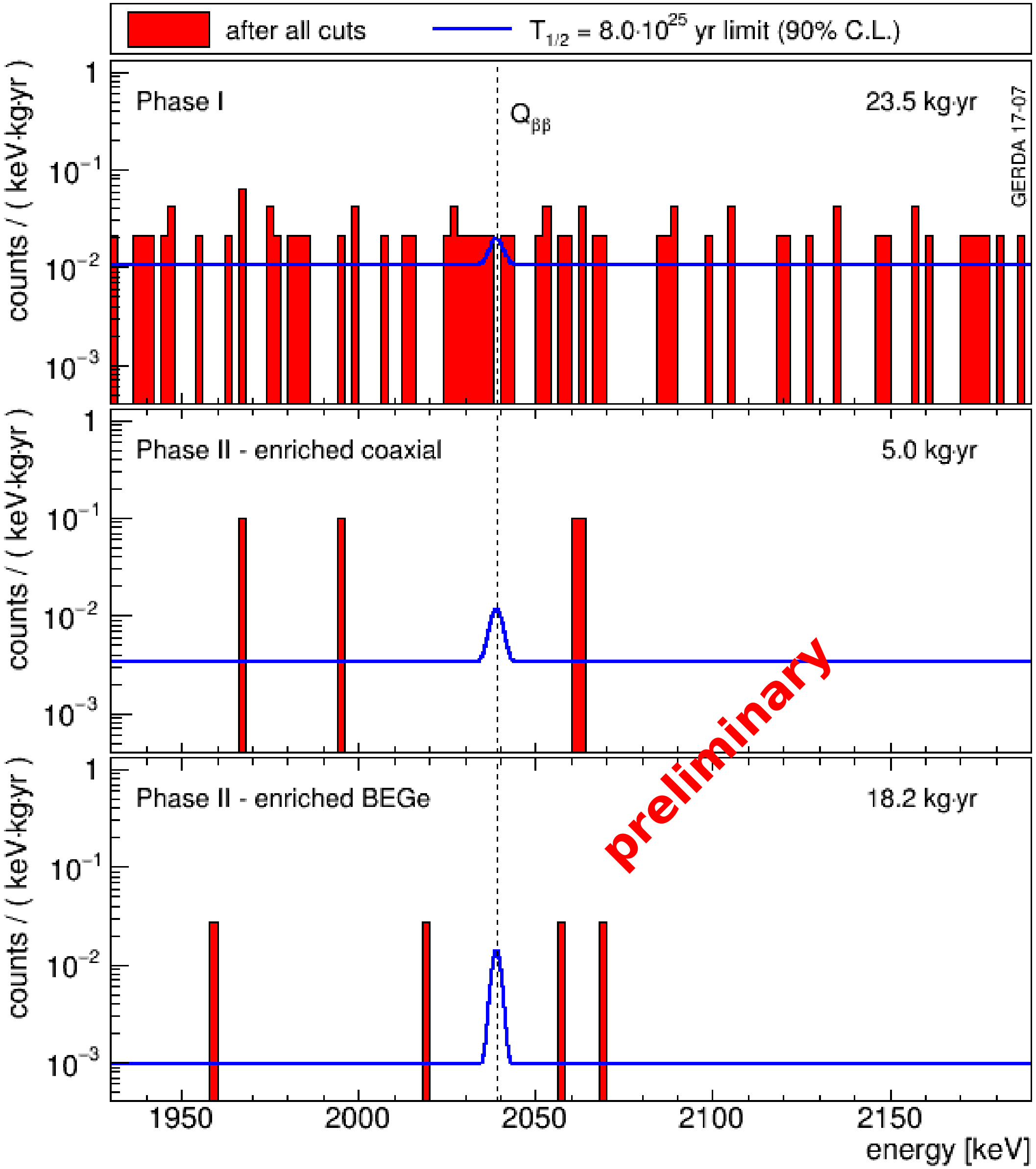
Statistical Analysis

dataset	exposure [kg·yr]	FWHM [keV]	ϵ	BI [10^{-3}cts/(kevkgyr)]	
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2	same as in Nature 544 (2017) 47
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)**	$\mathbf{1.0^{+0.6}_{-0.4}}$	

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 $N^{0\nu} = 0$

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

  It was $5.3 \cdot 10^{25}$ yr in Phase IIa

  Median Sensitivity (NO Signal)

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

  30% of MC realizations yield limit stronger than data

- upper limit on

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

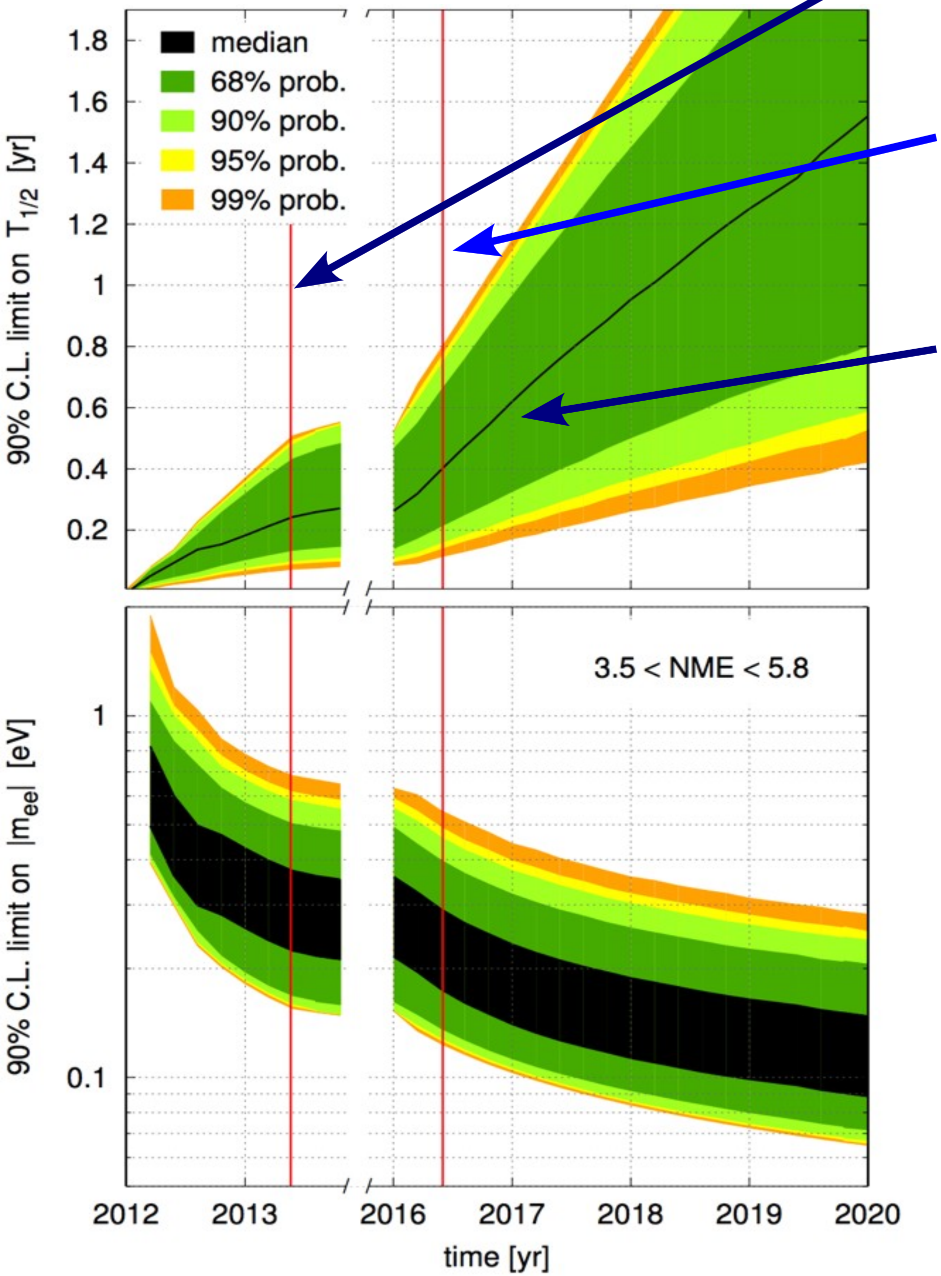
- **Bayesian (preliminary results):**

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

  Median Sensitivity:

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

Future ...



- **Phase I:** (23.5 kg·yr)
  - Sensitivity: **2.4·10^{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: **4.0·10^{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: **5.8·10^{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: **1.3·10^{26} yr**
  - Discovery potential up to **10^{26} yr** (*50% prob. chance for a 3σ* 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 **$T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}$ yr (90% CL)**
  - Median Sensitivity: **$5.8 \cdot 10^{25}$ yr** (better than KamLand-Zen)
  - BI(^{enr}Coax): **$2.7^{+1.0}_{-0.8} \cdot 10^{-3}$ cts/(keV· kg · yr)**

    BI(^{enr}BEGe): **$1.0^{+0.6}_{-0.4} \cdot 10^{-3}$ 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