Decomposition of the GERDA Phase I background spectrum

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MAX-PLANCK-GESELLSCHAFT

Outline

- **Motivation of the GERDA experiment: Search for 0νββ decay.**

- **Experimental setup and data from the first phase of the experiment.**

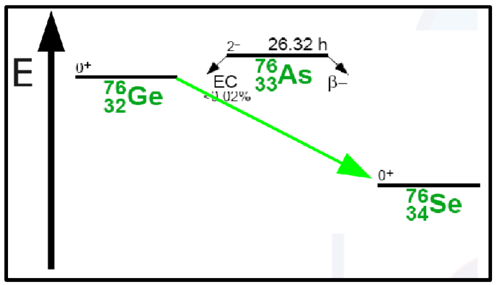
- **Analysis of the Phase I data:**
  - **modeling of the individual background components**
  - **decomposition of the background spectrum.**

Motivation

GERDA experiment is searching for the neutrinoless double beta ($0\nu\beta\beta$) decay of ^{76}Ge.

Neutrino accompanied double beta decay

$2\nu\beta\beta$: (A, Z) → (A, Z+2) + $2e^-$ + $2\bar{\nu}_e$



→ SM process

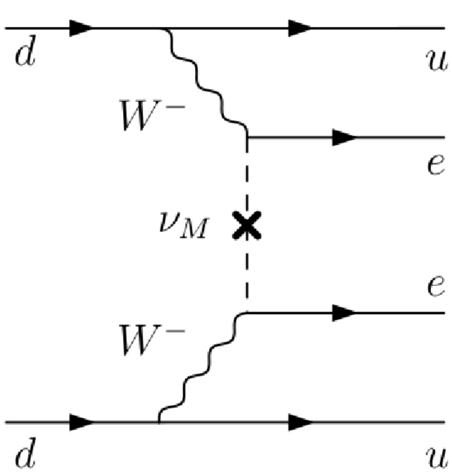
→ Observed for eleven isotopes
⇒ $T_{1/2} \sim (10^{19} – 10^{24})$ yr

GERDA result [arXiv:1212.3210v1] (2012)
$T_{1/2}$ (^{76}Ge) = $(1.8\ ^{+0.14}_{-0.10})\ 10^{21}$ yr

→ Rarest decay measured in lab

Neutrinoless double beta decay

$0\nu\beta\beta$: (A, Z) → (A, Z+2) + $2e^-$



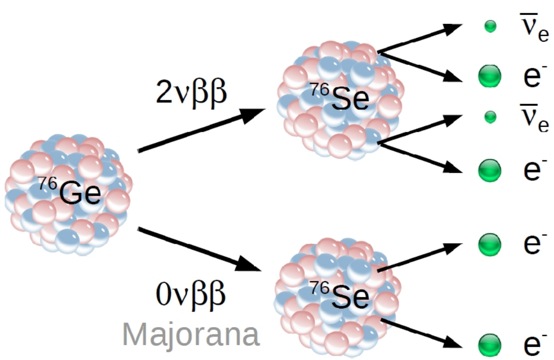
→ Non SM process
⇒ Lepton number violation: **ΔL = 2**

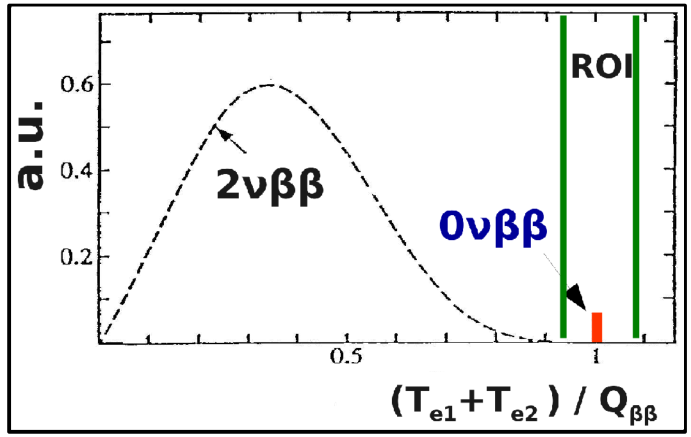
→ Nature of neutrino: $\nu = \bar{\nu}$ ⇔ Majorana?

→ Determination of effective Majorana **ν** mass
$(T_{1/2})^{-1} \propto \langle m_{\beta\beta}\rangle^2$

Motivation

GERDA experiment is searching for the neutrinoless double beta (0νββ) decay of ^{76}Ge.





Experimental signal of 0νββ:

excess at the Q value of ββ decay
→ $Q_{\beta\beta}$ (^{76}Ge) = 2039 keV

0νββ decay is a very rare process ($T_{1/2} > 10^{25}$ y)

limit: $T^{0\nu}_{1/2}(^{76}\text{Ge}) > 1.9 \times 10^{25}$ y (90% C.L.) Eur. Phys. J. A 12, 147154 (2001)

claim: $T^{0\nu}_{1/2}(^{76}\text{Ge}) = (2.23^{+0.44}_{-0.31}) \times 10^{25}$ y Mod. Phys. Lett. A21, 1547-1566 (2006)

$$\text{sensitivity on } T_{1/2} \propto \kappa \cdot \frac{N_A}{M_A} \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

- ⇒ Large exposure $(M \cdot t)$
- ⇒ High fraction of ^{76}Ge (κ)
  isotopic enrichment ∼ 86%
- ⇒ Low background in the ROI (b)
- ⇒ Good energy resolution (ΔE)
  HPGe: ∼0.2% @ $Q_{\beta\beta}$ = 2039 keV
- ⇒ High signal detection efficiency (ϵ)
  ∼ 85-95% (source = detector)

GERDA Phase I: $T_{1/2} > 2 \times 10^{25}$ y → test the claim

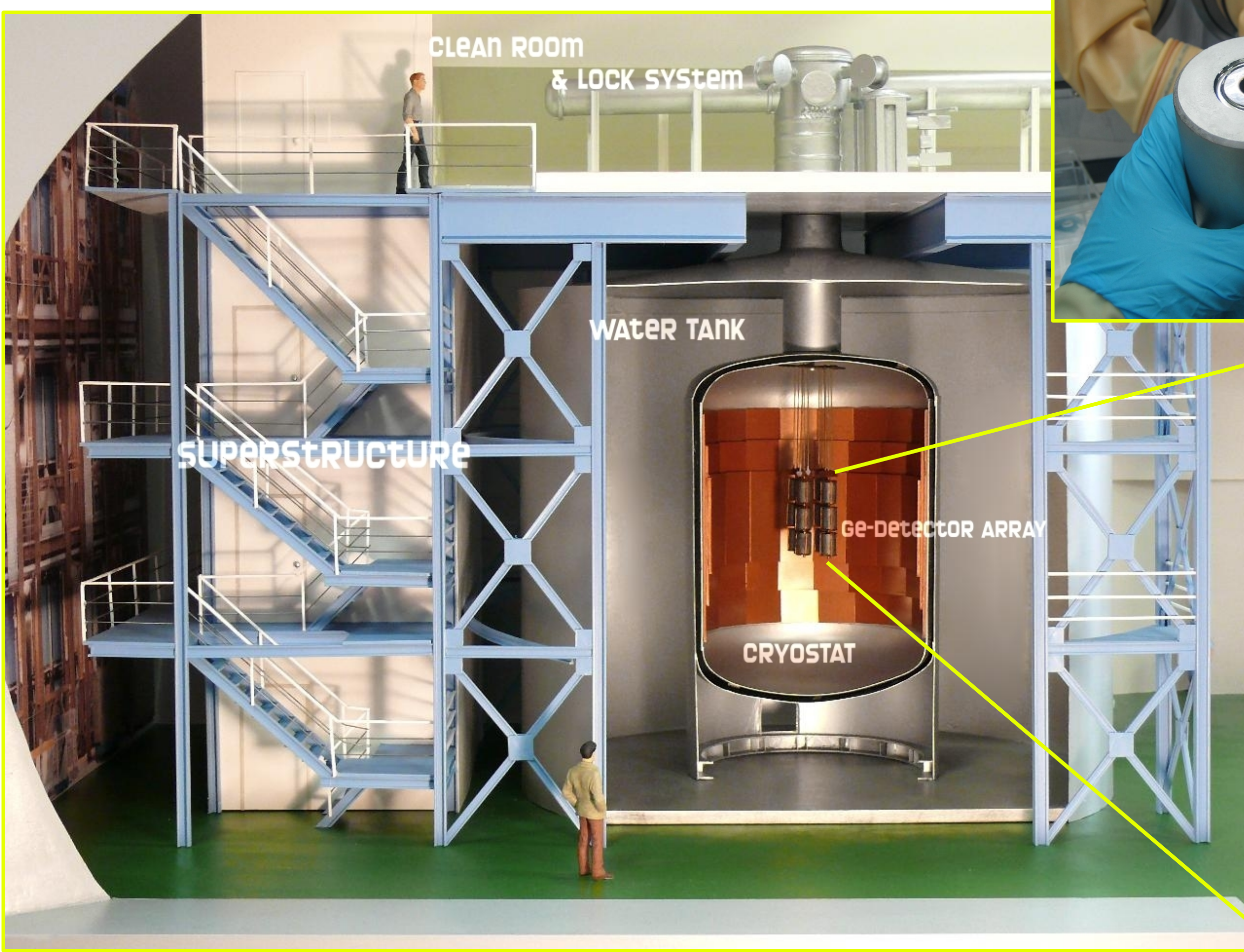
GERDA Phase II: $T_{1/2} > 10^{26}$ y → higher sensitivity
⇒ Lower BI ⇒ Background characterization & suppression

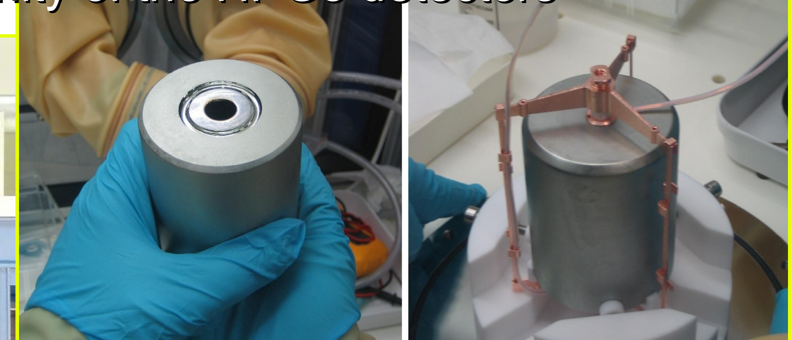
Experimental setup

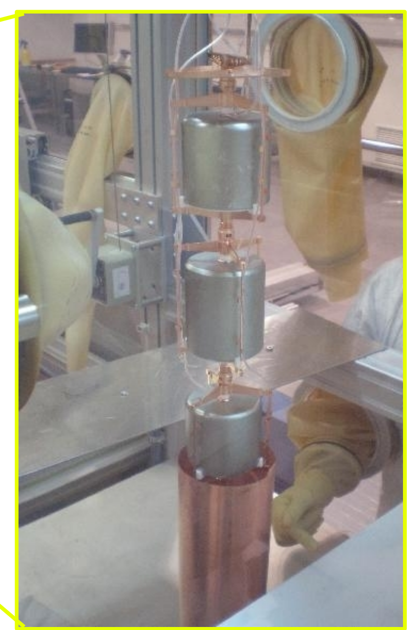
- **Underground location: @ LNGS of INFN, Italy**
cosmic ray induced muon flux reduced by a factor of 10^6
+ active muon veto

- **Novel idea: HPGe detectors directly submerged in LAr**
cooling & high purity shield

- **Minimal amount of screened material in the vicinity of the HPGe detectors**

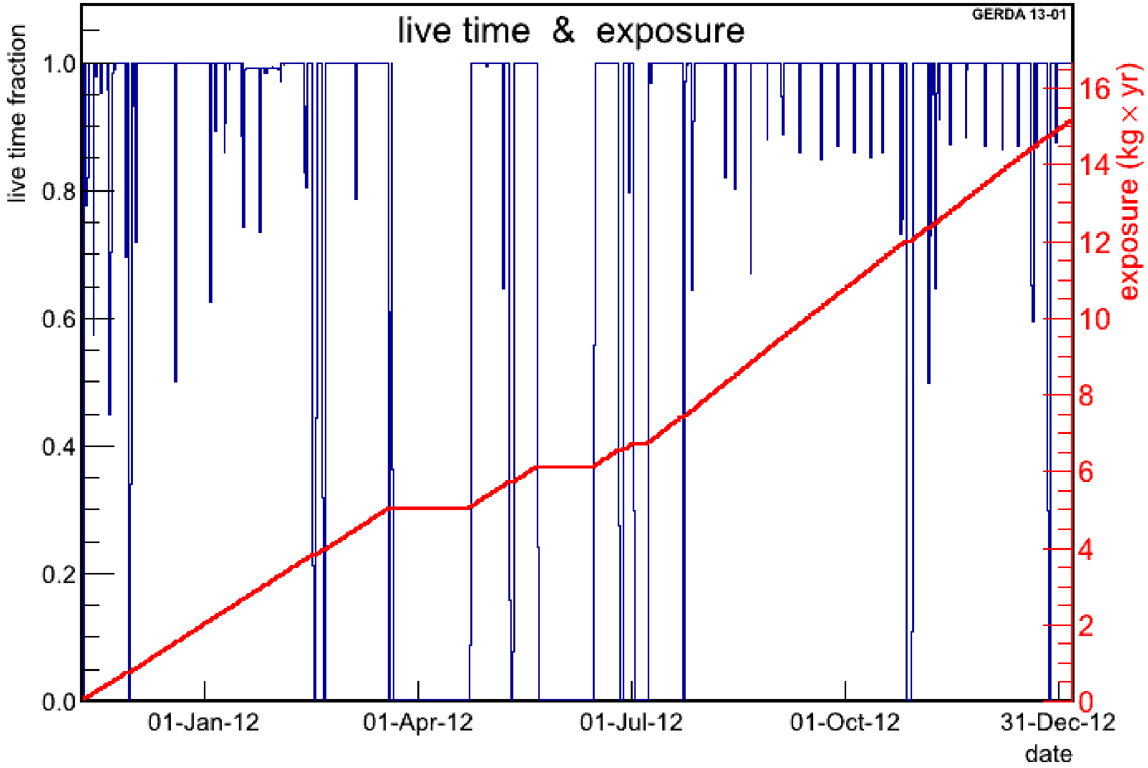


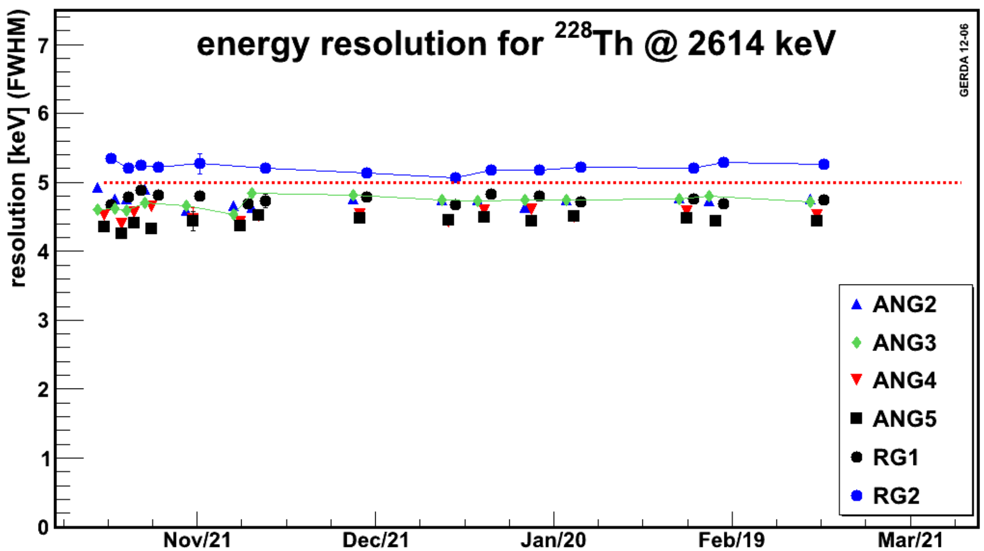




GERDA Phase-I data-taking

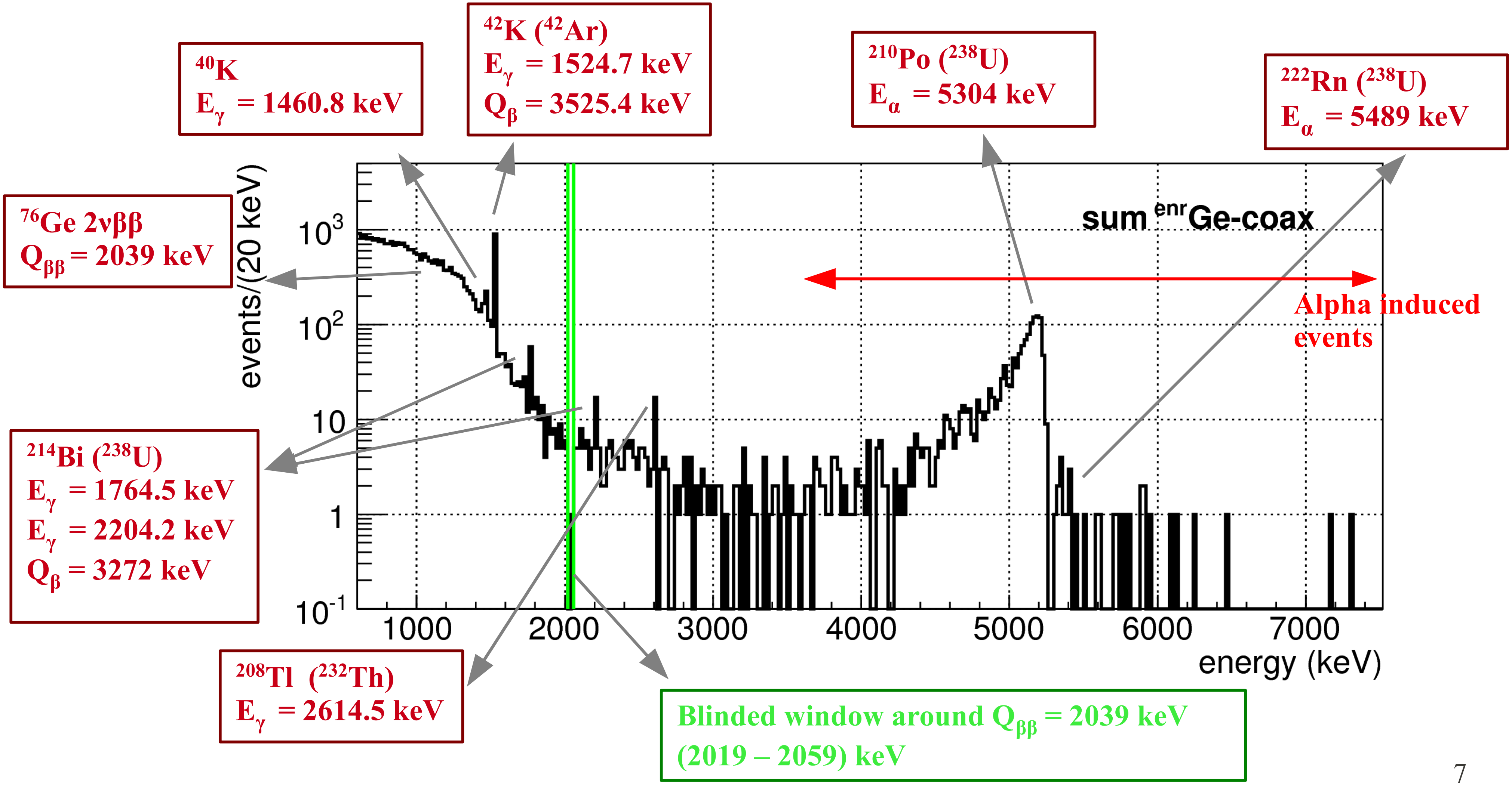
started on November 2011



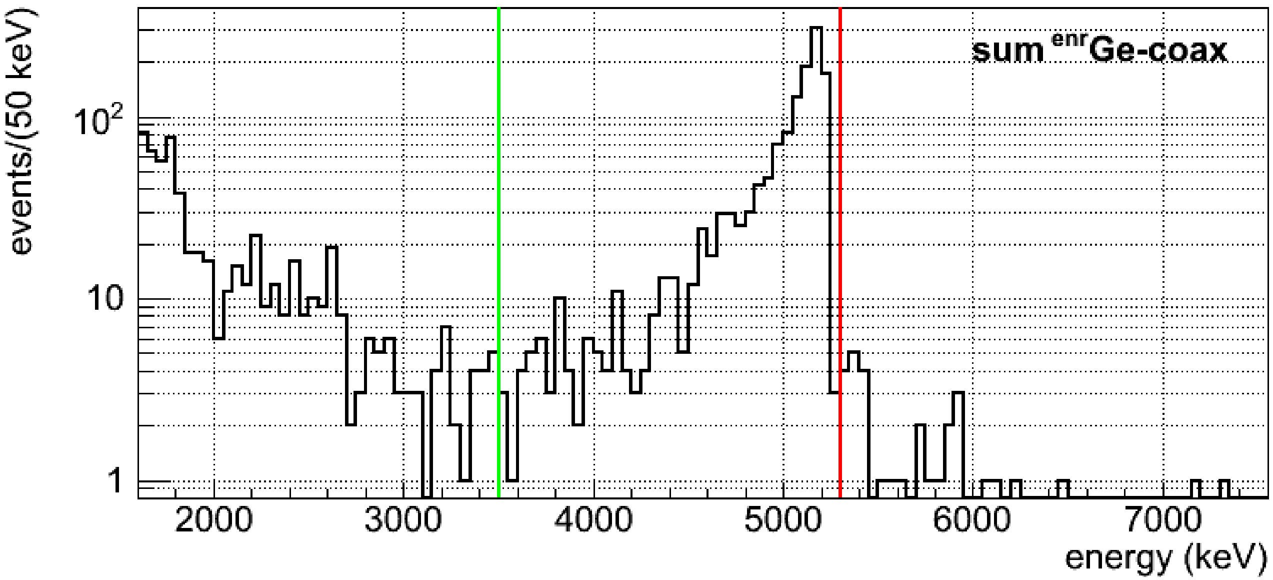


GERDA Phase-I data

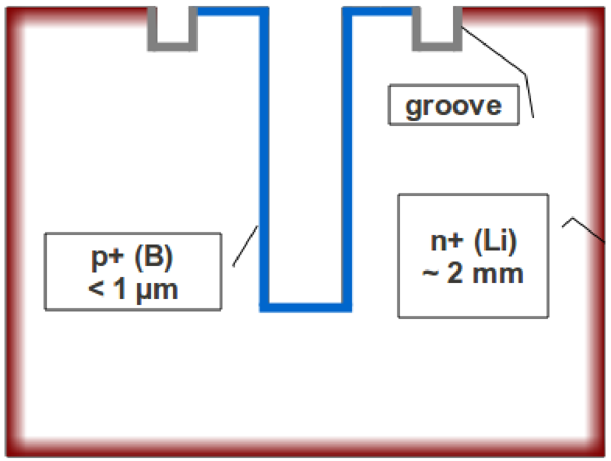
The data set used in this work is taken between 9 November 2011 and 5 January 2013
→ total live DAQ time: 340.96 days
→ total mass of the considered 6 ^{enr}Ge-coax detectors: 14.63 kg
→ total exposure: 13.66 kg·y



Alpha-induced events



enrGe-coax detector of Phase I



The range of alpha particles with energies 4 MeV to 9 MeV
→ 14 µm – 41 µm in Ge
→ 34 µm – 113 µm in LAr

Ra-226 (E_α = 4.8 MeV, $T_{1/2}$ = 1600 y)

Rn-222 (E_α = 5.5 MeV, $T_{1/2}$ = 3.8 d)

Po-218 (E_α = 6.0 MeV, $T_{1/2}$ = 183 s)

Pb-214 ($T_{1/2}$ = 0.45 h)

Bi-214 ($T_{1/2}$ = 0.33 h)

Po-214 (E_α = 7.7 MeV, $T_{1/2}$ = 164 µs)

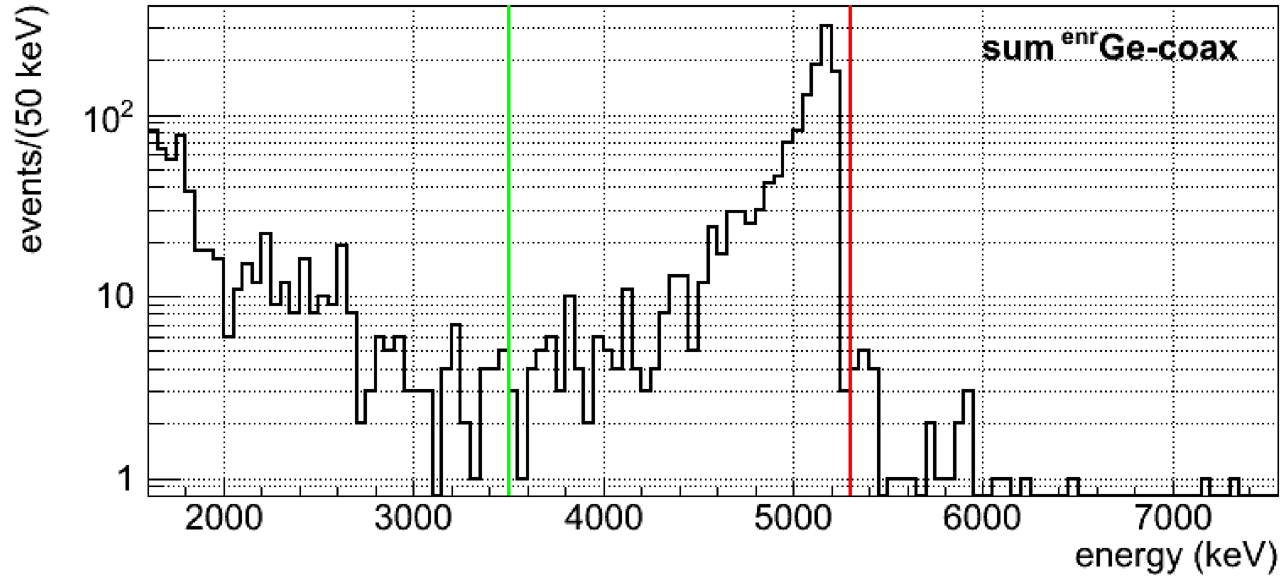
Pb-210 ($T_{1/2}$ = 22.3 y)

Bi-210 ($T_{1/2}$ = 5.01 d)

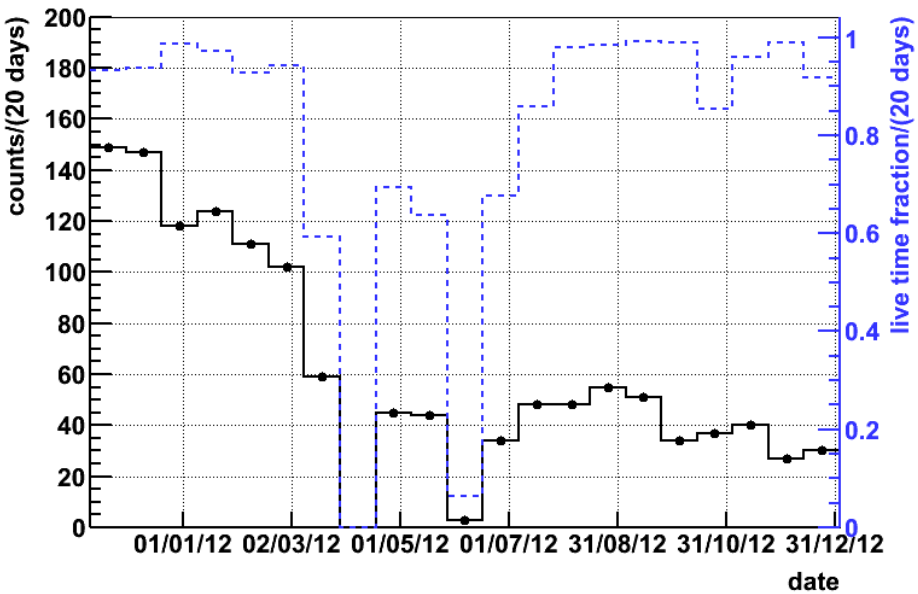
Po-210 (E_α = 5.3 MeV, $T_{1/2}$ = 138.4 d)

Pb-206 (stable)

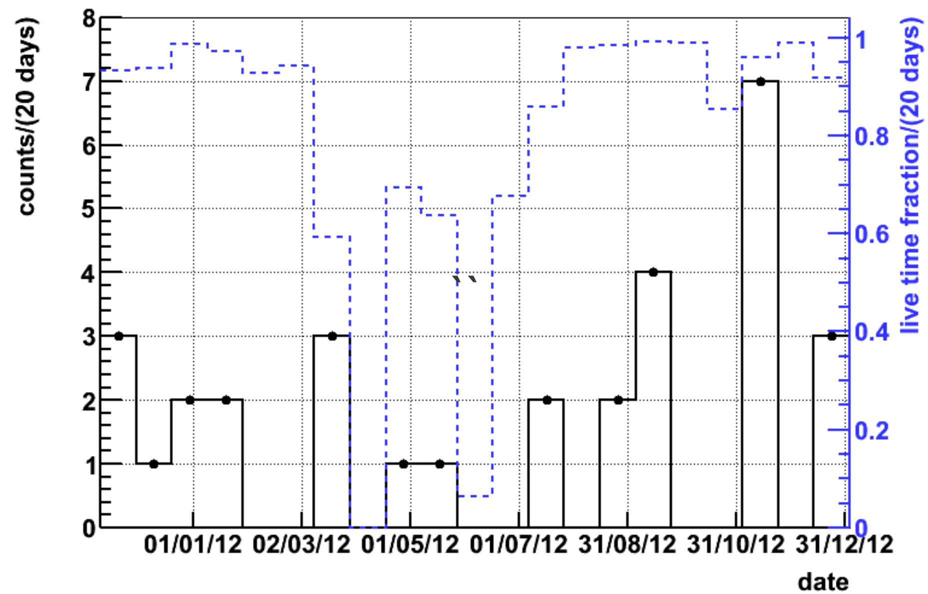
Alpha-induced events



Events with 3500 keV< E < 5300 keV in sum ^{enr}Ge-coax



Events with E > 5300 keV in sum ^{enr}Ge-coax



Alpha-induced events

Statistical analysis procedure:

Event rate distribution of events with 3500 keV< E < 5300 keV in sum ^{enr}Ge-coax
Model: exponentially decaying event rate

- Fit the distribution with an exponential function $N(t) = N_0 \cdot e^{-ln2\, t/T_{1/2}}$ half-life $\mathbf{T_{1/2}}$ initial rate $\mathbf{N_0}$

- Maximized quantity posterior probablitiy: $P(\vec{\lambda}|\vec{n}) \propto P(\vec{n}|\vec{\lambda}) P_0(\vec{\lambda})$

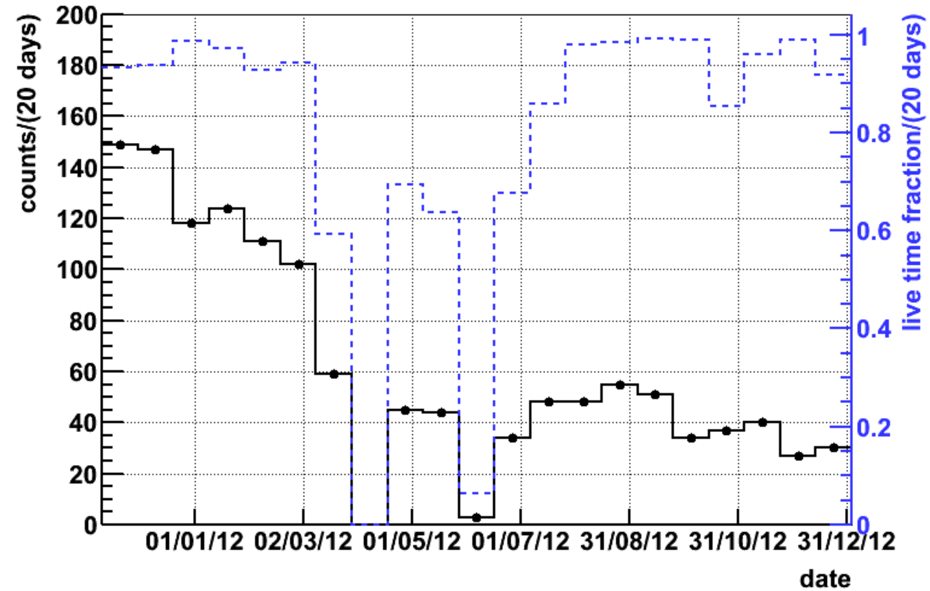
- Set a prior on the half life parameter: $P_0\,(T_{1/2})$ = Gaus(138.4, 0.2) half-life of ^{210}Po

- Likelihood:

$$P(\vec{n}|\vec{\lambda}) = \prod_i P(n_i|\lambda_i) = \prod_i \frac{e^{-\lambda_i} \lambda_i^{n_i}}{n_i!}$$

- n_i : raw number of counts in i-th bin
(not scaled, not corrected for livetime fraction)
- λ_i : expectation in the i-th bin
corrected with the live time fraction in that bin

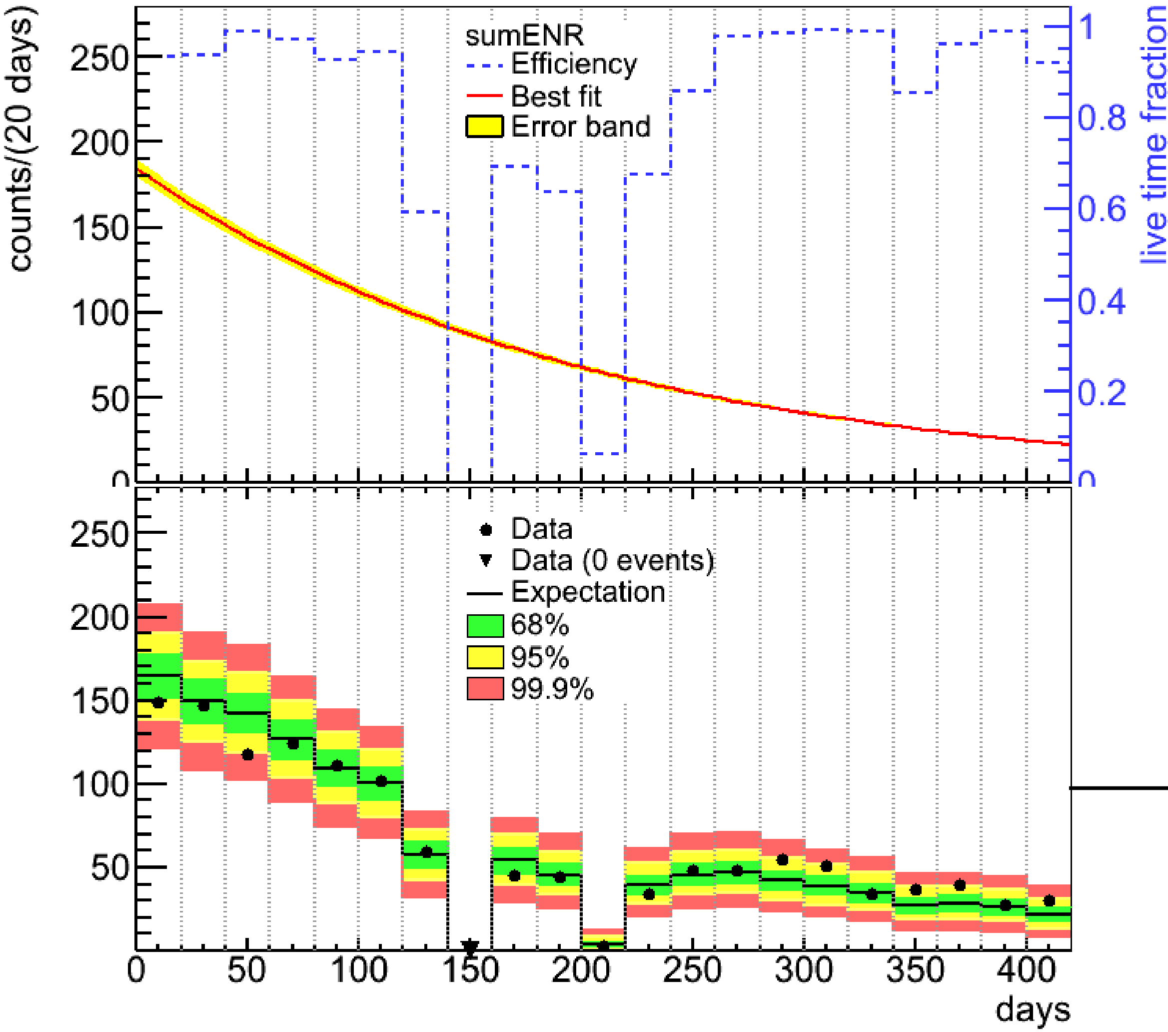
$$\lambda_i = \epsilon_i \int_{(i-1)\Delta t}^{i\Delta t} N_0 \cdot e^{-ln2\, t/T_{1/2}}\, dt$$



Alpha-induced events

Event rate distribution of events with 3500 keV< E < 5300 keV in sum ^{enr}Ge-coax

Model: exponentially decaying event rate



Parameters:

N_0 = (9.26 ± 0.26) cts/day

$T_{1/2}$ = (138.4 ± 0.2) days

p-value of the fit: 0.11

Expectation

$$\lambda_i = \epsilon_i \int_{(i-1)\Delta t}^{i\Delta t} N_0 \cdot e^{-ln2\, t/T_{1/2}}\, dt$$

$$P(\vec{n}|\vec{\lambda}) = \prod_i P(n_i|\lambda_i) = \prod_i \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!}$$

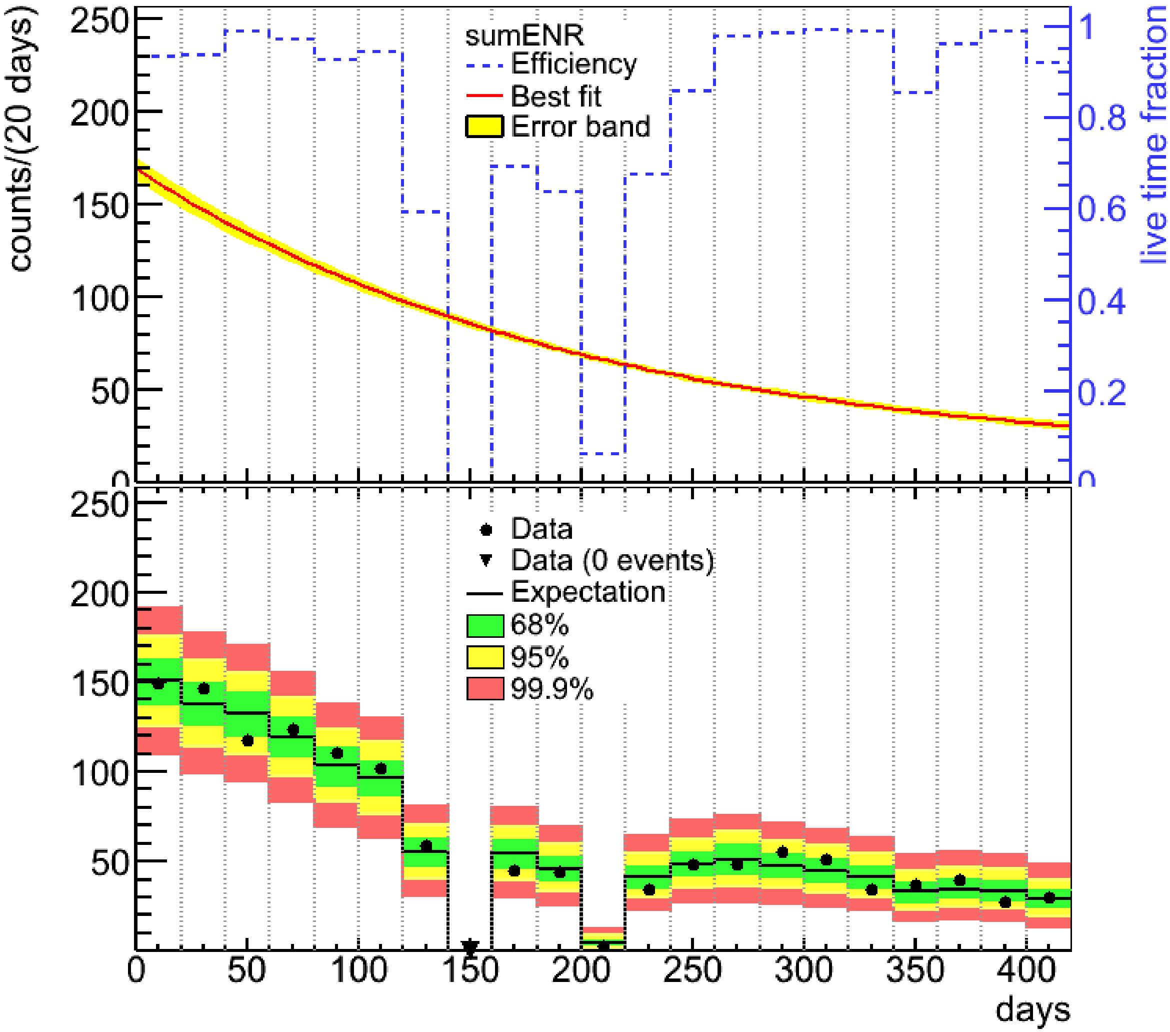
Colored probability intervals:

R. Aggarwal and A. Caldwell, Eur. Phys. J. Plus 127 24 (2012)

Alpha-induced events

Event rate distribution of events with 3500 keV< E < 5300 keV in sum ^{enr}Ge-coax

Model: exponential + constant rate



Parameters:

C = (0.57 ± 0.16) cts/day

N_0 = (7.91 ± 0.44) cts/day

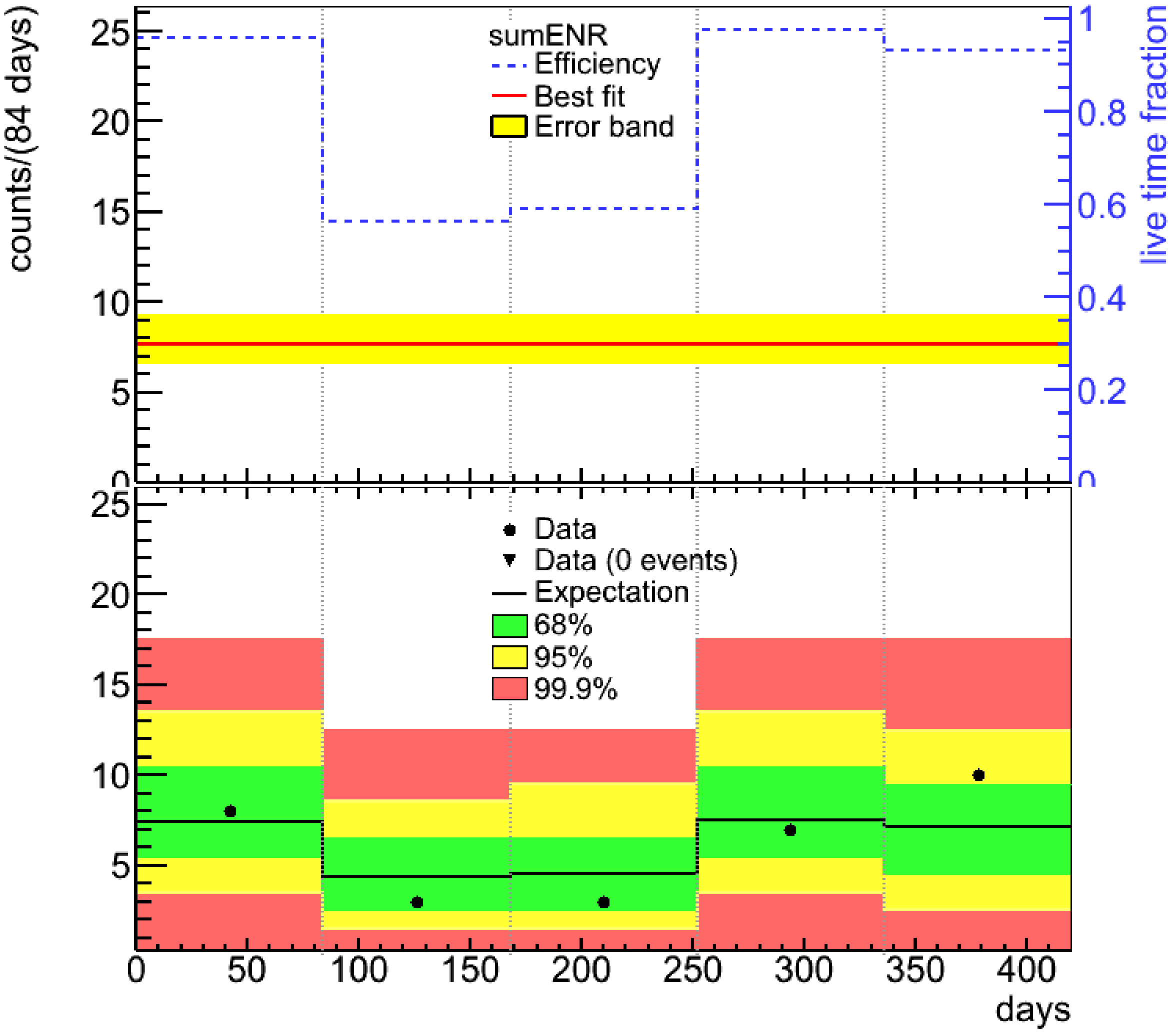
$T_{1/2}$ = (138.4 ± 0.2) days

p-value of the fit: 0.87

Alpha-induced events

Event rate distribution of events with E > 5300 keV in sum ^{enr}Ge-coax

Model: constant rate



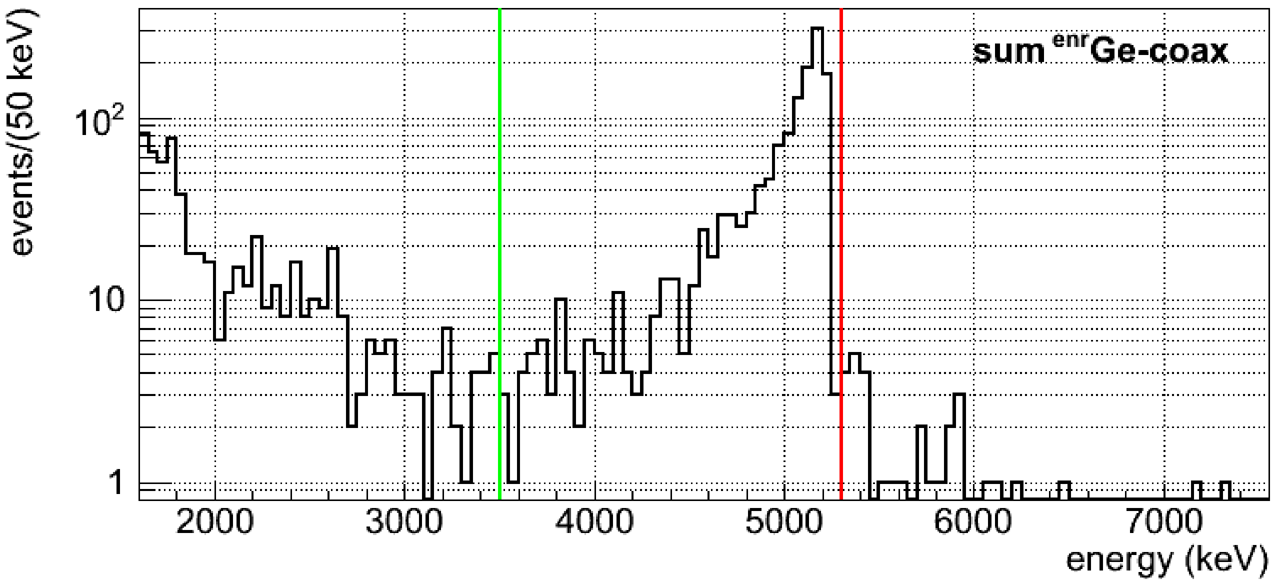
Parameters:

C = (0.09 ± 0.02) cts/day

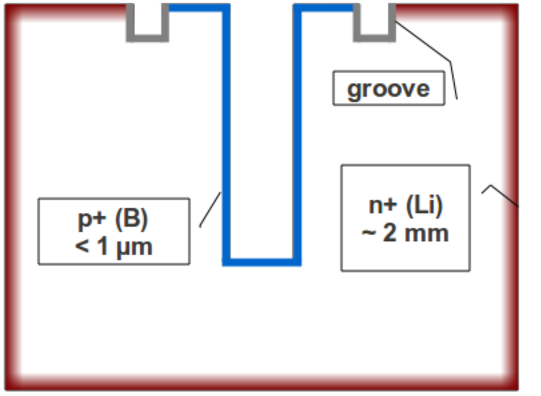
p-value of the fit: 0.86

Results stable wrt. choice of histogram binning.

Alpha-induced events



enrGe-coax detector of Phase I



Simulated sources to model the energy spectrum:

1) Po-210 (E_α = 5.3 MeV) decays on the p+ contact surface (thin dead layer)

2) Ra-226 & daughters on the p+ contact surface (thin dead layer)

{

Ra-226 (E_α = 4.8 MeV)

Rn-222 (E_α = 5.5 MeV)

Po-218 (E_α = 6.0 MeV)

Pb-214

Bi-214

Po-214 (E_α = 7.7 MeV)

}

3) Rn-222 & daugters decay very close to the p+ contact surface (inLAr)

{

Rn-222 (E_α = 5.5 MeV)

Po-218 (E_α = 6.0 MeV)

Pb-214

Bi-214

Po-214 (E_α = 7.7 MeV)

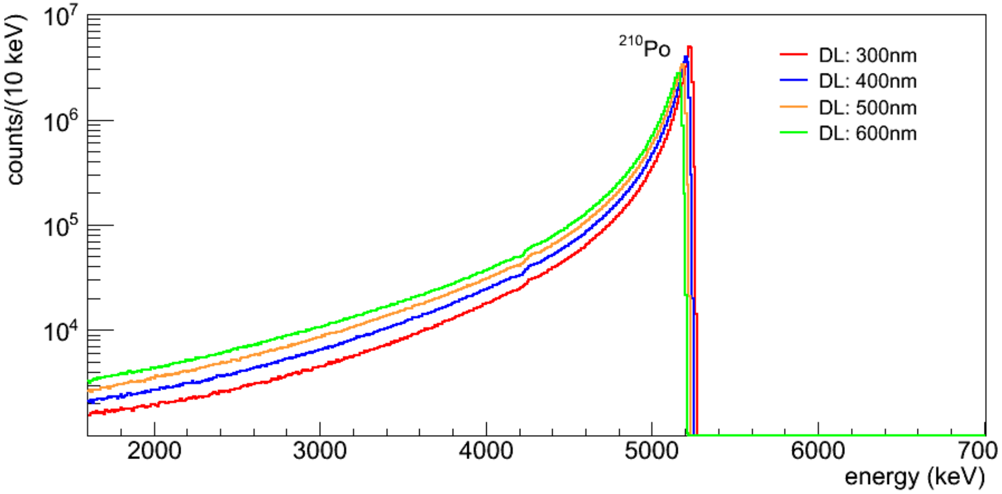
}

All simulations for different DL thicknesses (100nm...1µm)

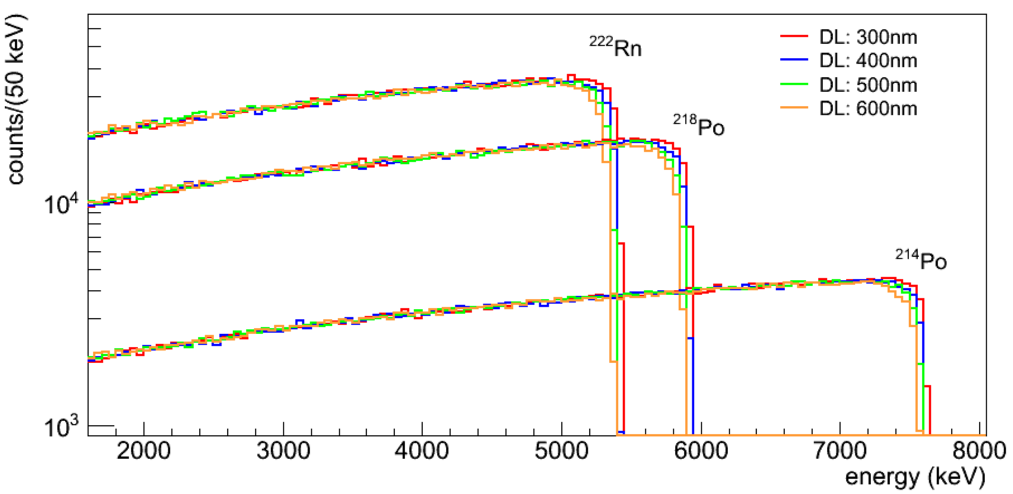
Alpha-induced events

MC simulation of possible scenarios in GEANT4 based MaGe framework.
→ important parameter: thickness of the dead layer

Po-210 (E_α = 5.3 MeV) on p+ surface



Rn-222 & daugters in LAr close to p+ surface



Maximum likelihood fit of the data from sum ^{enr}Ge-coax with the simulated spectra
- Fit window: **(3500 – 7500) keV → divided to 80 bins with each bin 50 keV**

$$P(\vec{n}|\vec{\lambda}) = \prod_i P(n_i|\lambda_i) = \prod_i \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!}$$

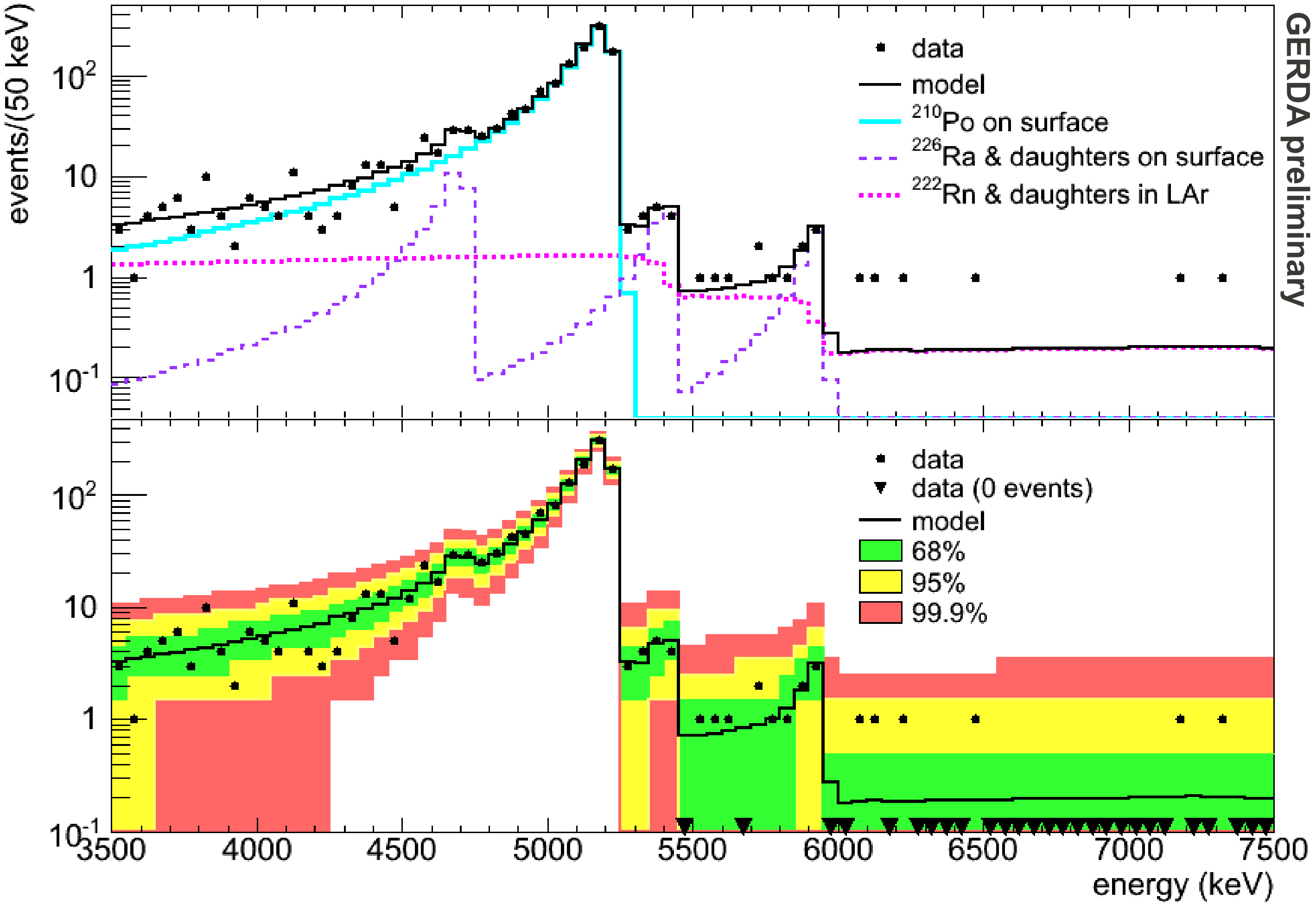
$$\lambda_i = \sum \lambda_{i,M} = \lambda_{i,Po210sur} + \lambda_{i,Ra226sur} + \lambda_{i,Rn222sur} + \lambda_{i,Po218sur} + \lambda_{i,Po214sur} + \lambda_{i,Rn222LAr} + \lambda_{i,Po218LAr} + \lambda_{i,Po214LAr}$$

$$\lambda_{i,M} = N_M \int_{\Delta E_i} f_M(E)dE$$

Alpha-induced events

Data from the sum ^{enr}Ge-coax detectors superimposed with the best fit model.

- **fit window: (3500 – 7500) keV**
- **p-value of the fit: 0.7**
- **80 bins with 50 keV width**
- **Out of 80 data points ~ 74% in the green and ~ 98% in the yellow band**



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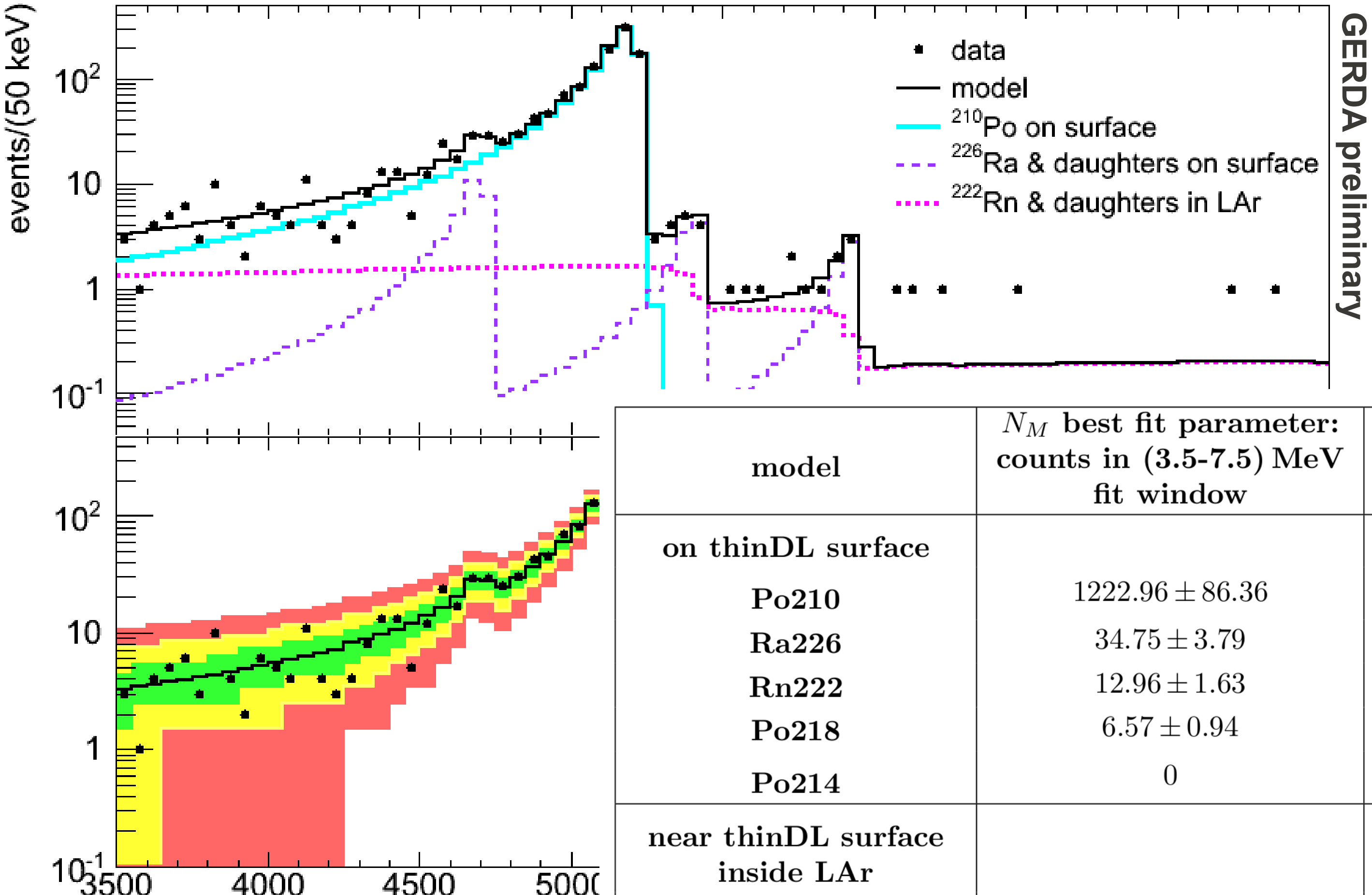
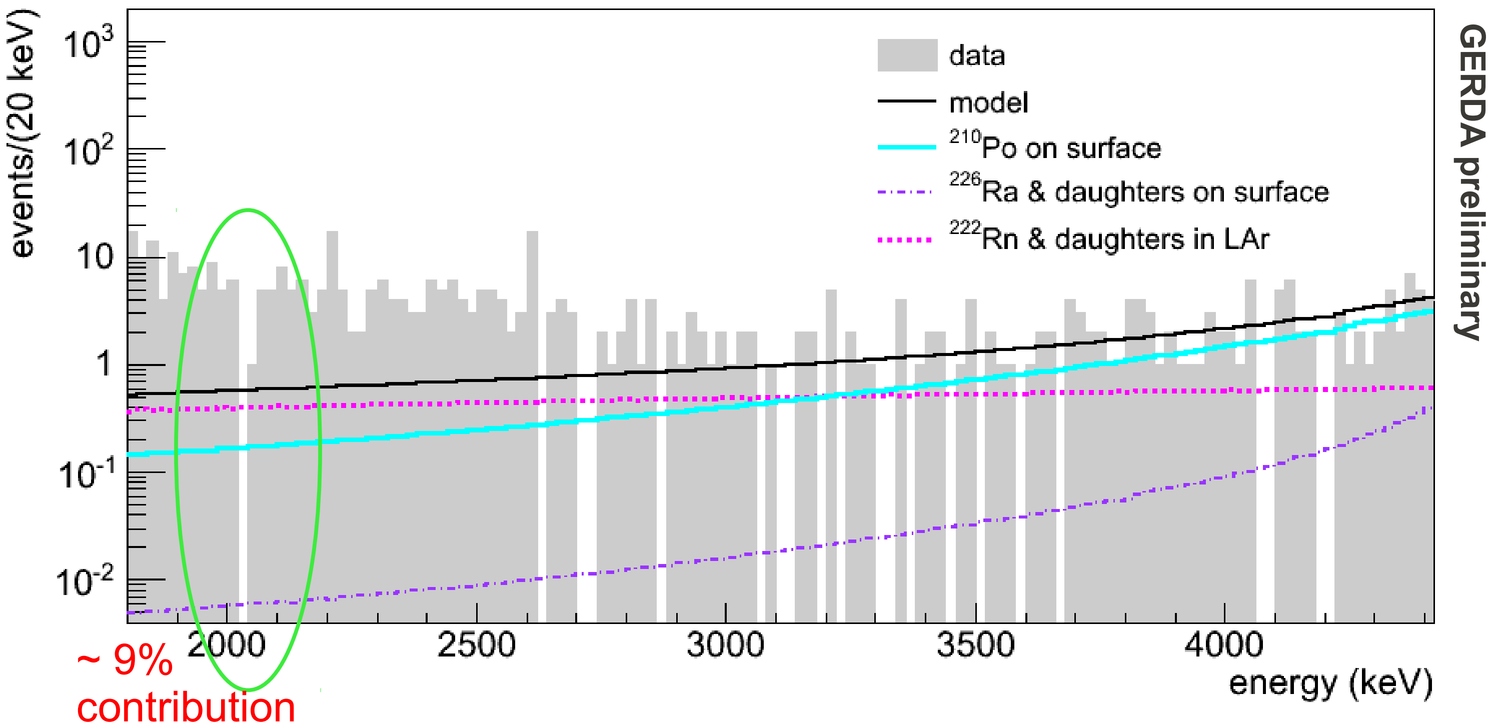


model	N_M best fit parameter: counts in (3.5-7.5) MeV fit window	extrapolation of best fit model: counts in (0-7.5) MeV window
on thinDL surface		
Po210	1222.96 ± 86.36	1244.52 ± 87.88
Ra226	34.75 ± 3.79	37.54 ± 4.09
Rn222	12.96 ± 1.63	13.16 ± 1.66
Po218	6.57 ± 0.94	6.65 ± 0.95
Po214	0	0
near thinDL surface inside LAr		
Rn222	35.97 ± 4.83	78.05 ± 10.48
Po218	20.45 ± 2.57	38.19 ± 4.80
Po214	13.71 ± 2.08	20.16 ± 3.06

Alpha-induced events

Extrapolation of the best fit model to the region of interest (ROI = 160 keV window around $Q_{\beta\beta}$)

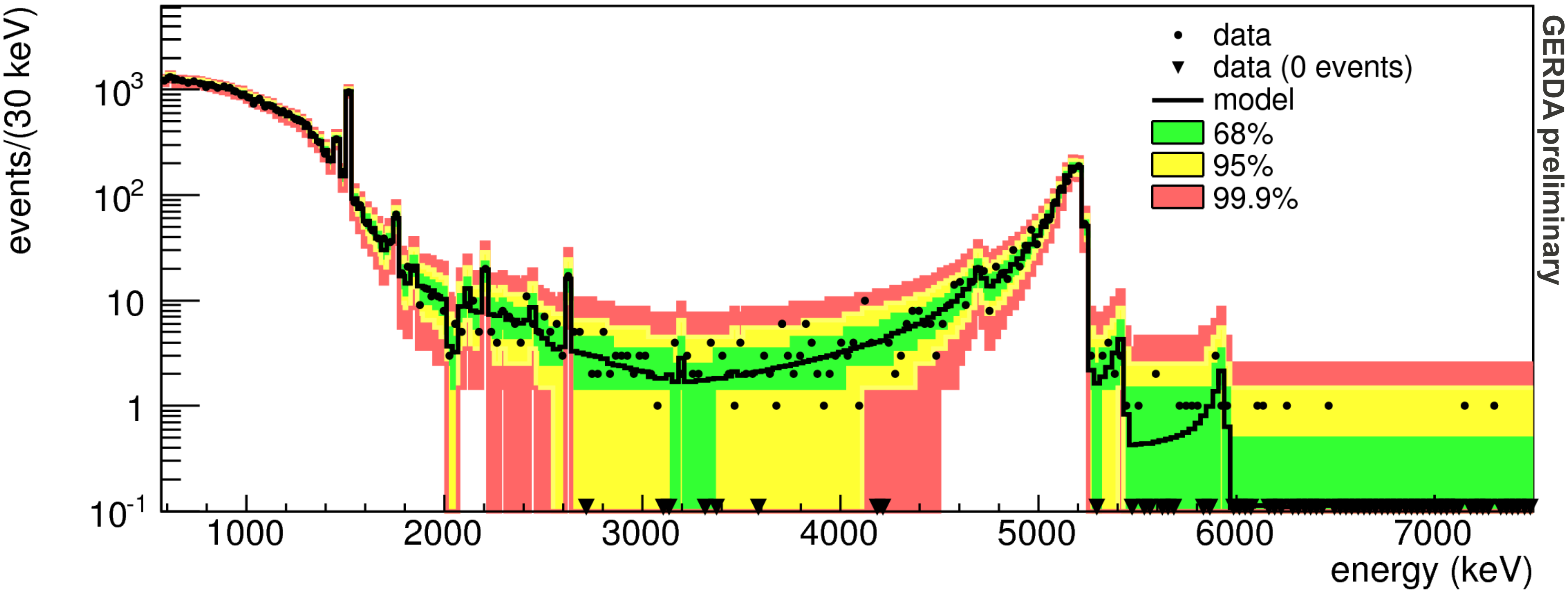


fit window [keV]	3500 – 7500			4000 – 7500		
bin width [keV]	25	50	100	25	50	100
p-value	0.54	0.71	0.85	0.51	0.77	0.87
counts in ROI						
^{210}Po on surface	1.391	1.385	1.400	1.396	1.387	1.412
^{226}Ra on surface	0.043	0.047	0.044	0.045	0.049	0.045
^{222}Rn in LAr	3.217	3.227	3.317	2.866	2.871	2.956
total	4.651	4.659	4.761	4.306	4.305	4.412

Decomposition of the background spectrum

Data from the sum ^{enr}Ge-coax detectors superimposed with the best fit model.
→ Model of the individual background components obtained through MC simulations.

- **fit window: (570 – 7500) keV**
- **p-value of the fit: 0.3**
- **231 bins with 30 keV width**
- **out of 231 data points ~ 73% in the green and ~ 97% in the yellow band**



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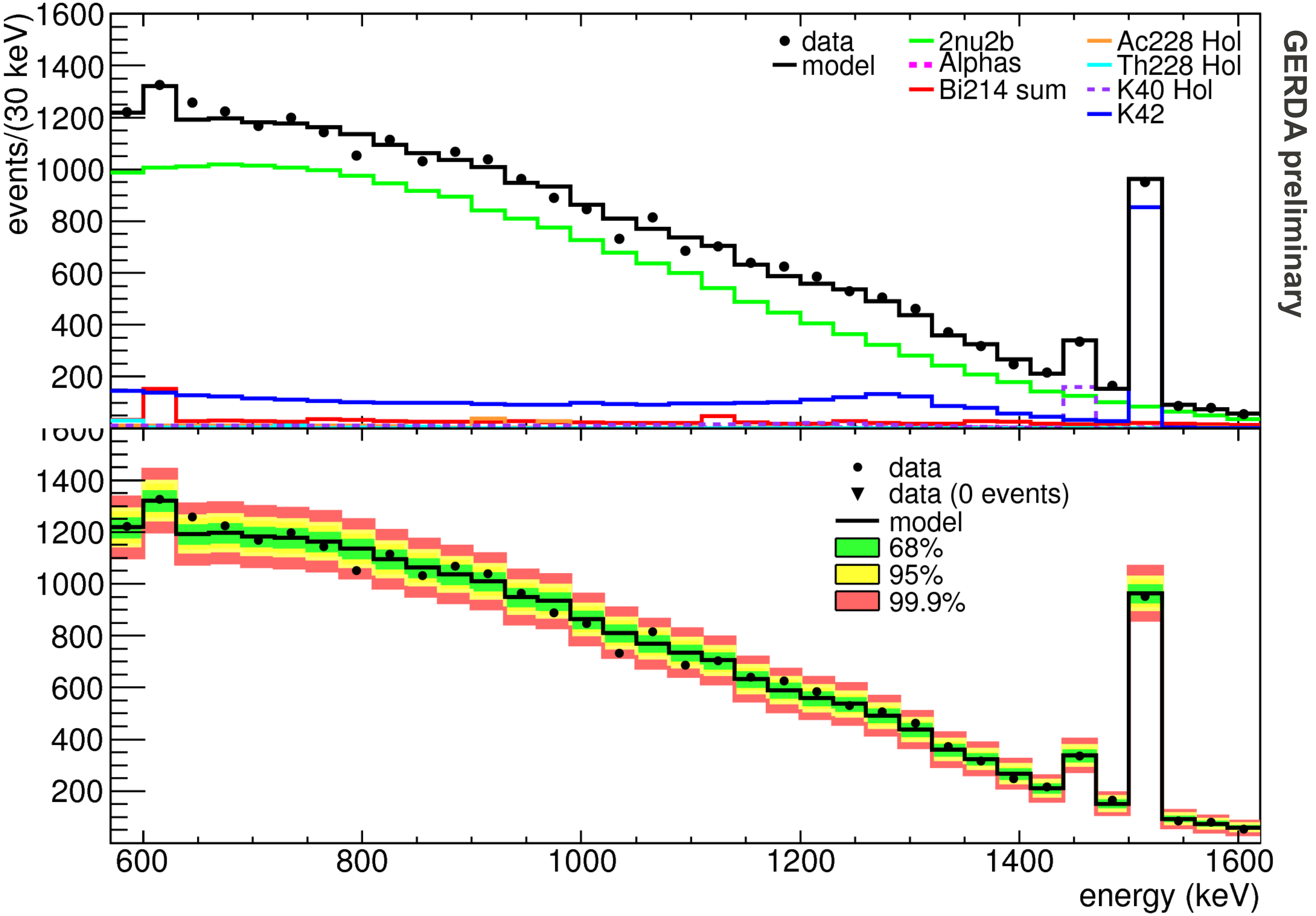

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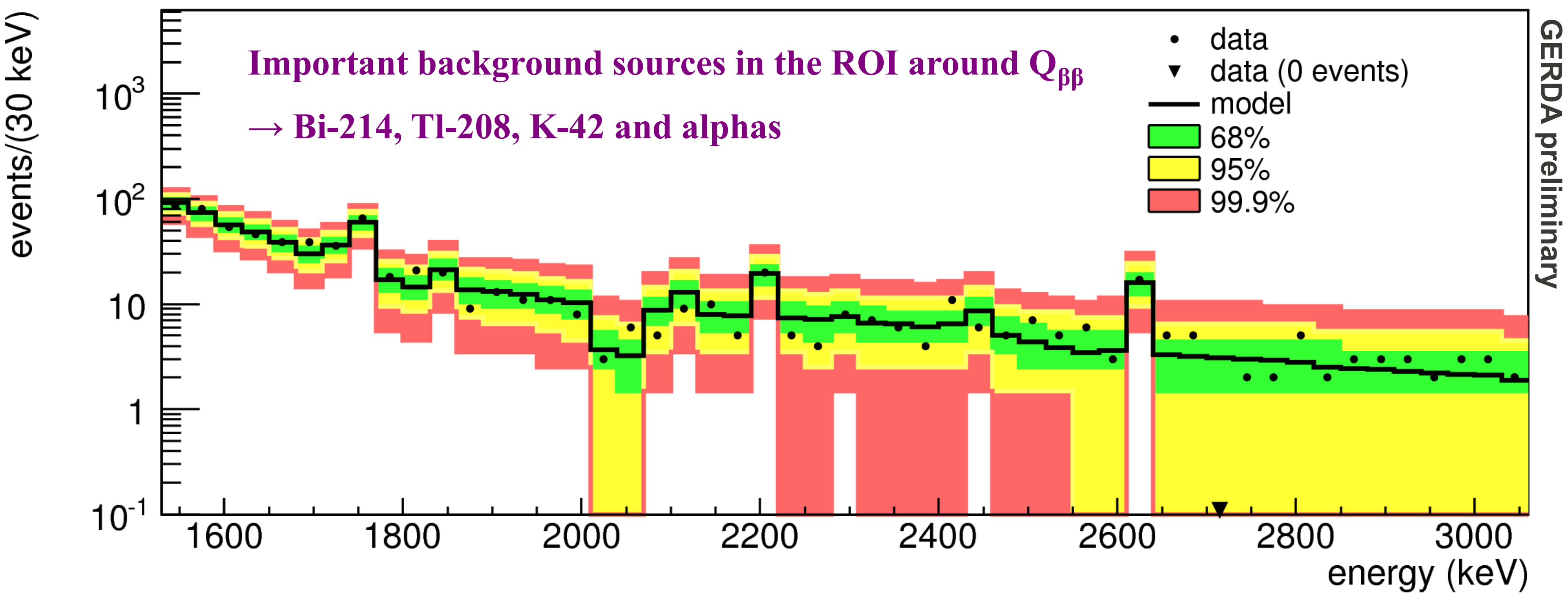
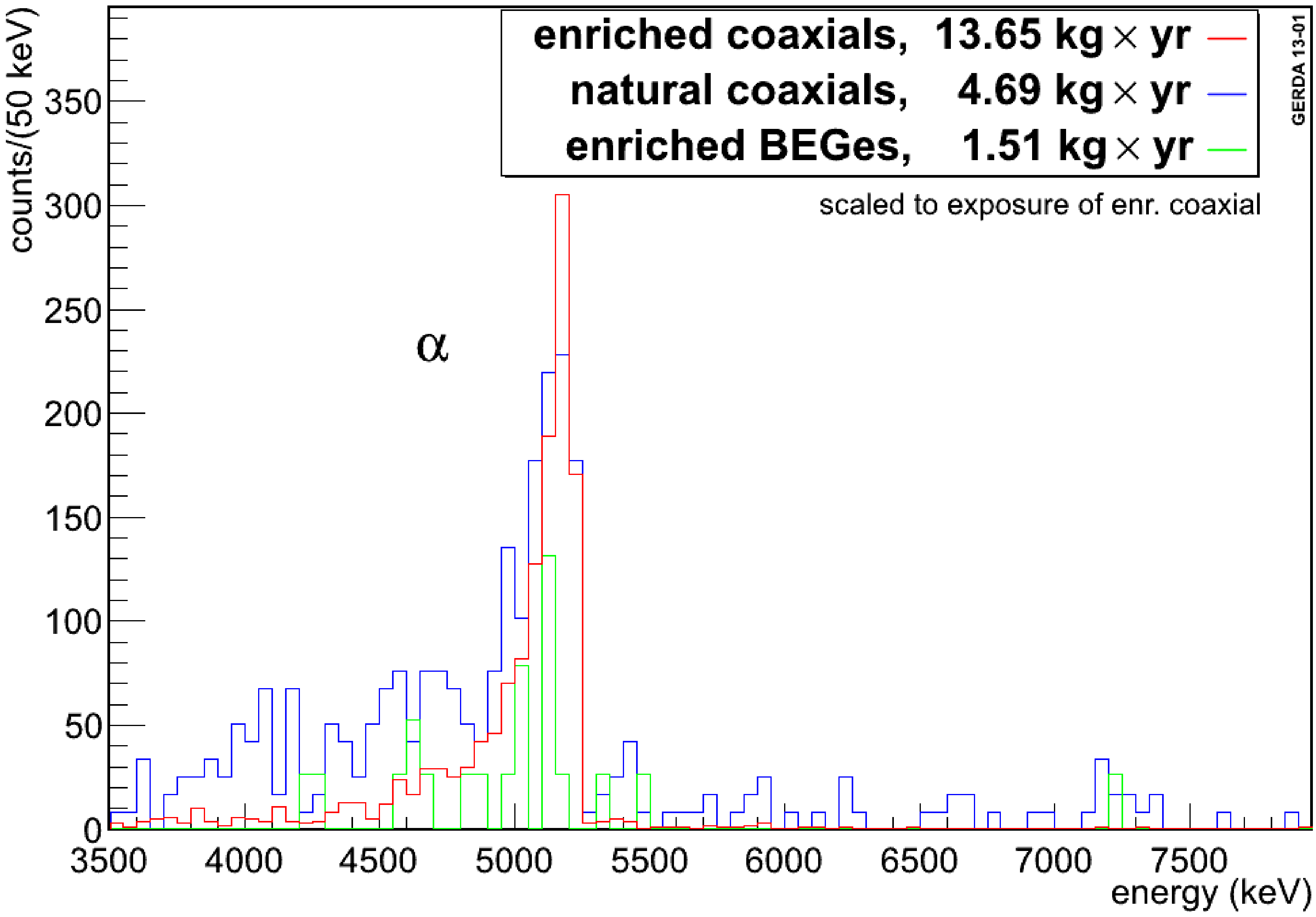


Conclusion

- **Physics data-taking of GERDA Phase I ongoing.**
- **Blind analysis: will be opened when a sufficient exposure is acquired.**
- **Background decomposition aroud $Q_{\beta\beta}$: promising results**
  → understanding the background and mitigating it further in Phase II
  → estimation of the expected number of background events in the signal region.

Backup


enriched coaxials, 13.65 kg × yr
natural coaxials, 4.69 kg × yr
enriched BEGes, 1.51 kg × yr
GERDA 13-01
scaled to exposure of enr. coaxial
α
counts/(50 keV)
0
50
100
150
200
250
300
350
3500
4000
4500
5000
5500
6000
6500
7000
7500
energy (keV)