Background characterization for the GERDA experiment

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on behalf of the GERDA Collaboration

Workshop in Low Radioactivity Techniques @ LNGS, 10-12 April 2013

Outline

- Physics motivation and goals of the GERDA experiment
- Experimental setup and status of Phase-I data taking
- Analysis of Phase-I data:
  - measurement of the $T_{1/2}$ of 2νββ decay of ^{76}Ge
  - background due to alpha-induced events
  - decomposition of the background spectrum
- Conclusions

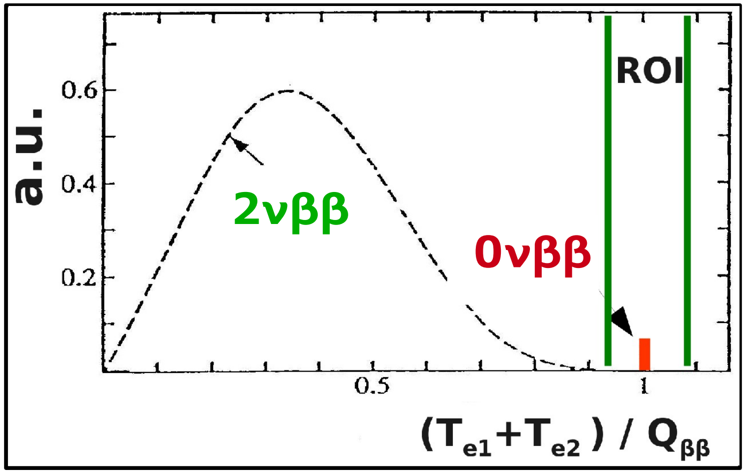
Motivation

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

Neutrino accompanied double beta decay (2νββ)

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

- → SM process, observed
- → $T_{1/2} \sim (10^{19} - 10^{24})$ yr
  Rarest decay measured in lab
- → Experimental signature:
  continuous spectrum of the sum of electrons kinetic energies



Neutrinoless double beta decay (0νββ)

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

- → Non SM process: $\Delta L = 2$
- → More rare than 2νββ
- → Experimental signature: peak at $Q_{\beta\beta}$

Goals

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

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

claim: $T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) = 1.2{\times}10^{25}$ y [Phys. Lett. B 586 (2004) 198-212]

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

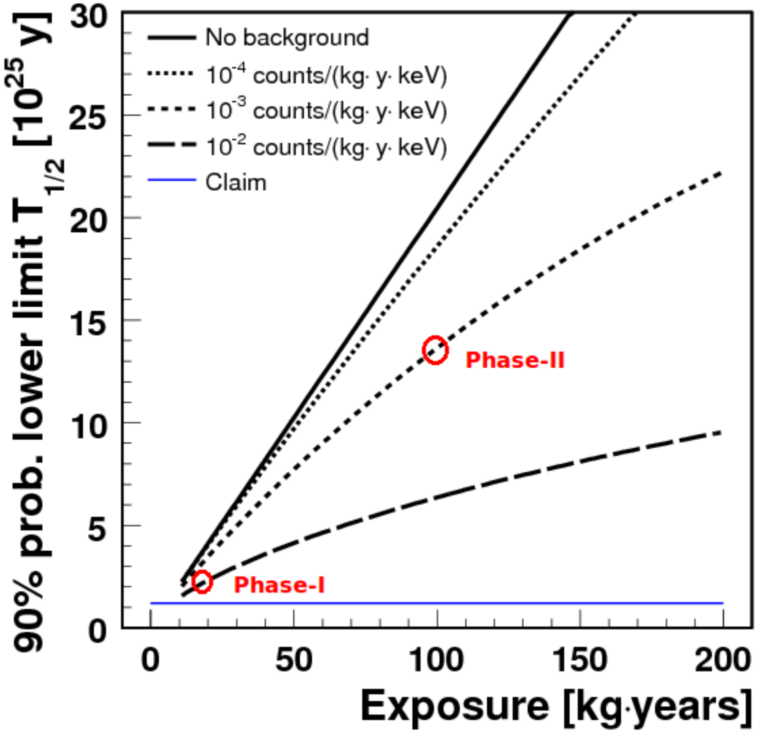
Phase-II: $T_{1/2} > 10^{26}$ y

For a higher sensitivity on the $T_{1/2}$

→ larger exposure

→ lower background rate around $Q_{\beta\beta}$

▷ Background characterization & suppression



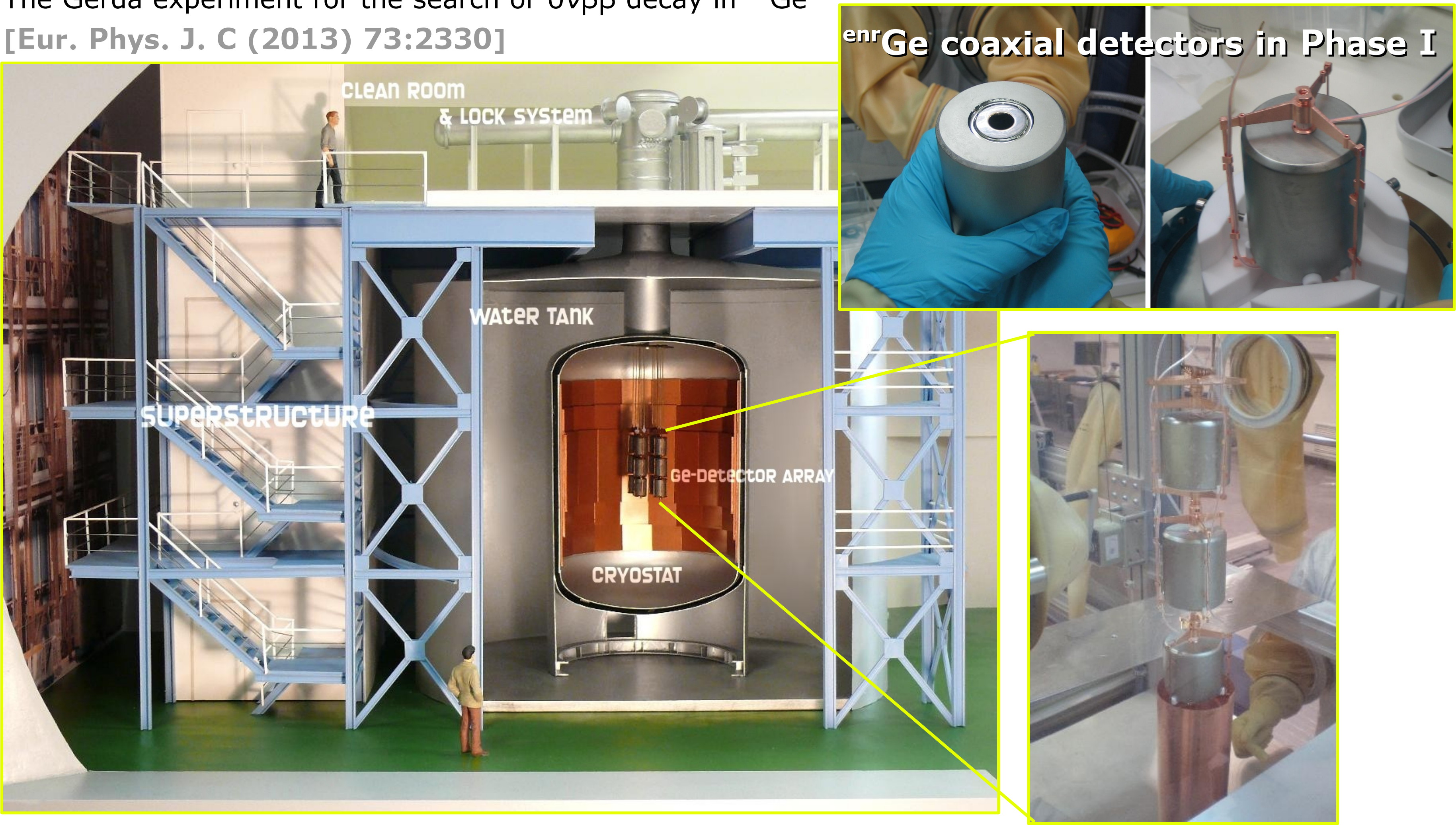
[Phys. Rev. D 74, 092003 (2006)]

Experimental setup

GERDA @ LNGS of INFN, Italy

- HPGe detectors directly submerged in LAr
- High-purity shields: LAr, H_2O
- Active muon veto: detection of Cherenkov radiation in water
- Minimal amount of screened material around the detectors

The Gerda experiment for the search of 0νββ decay in ^{76}Ge
[Eur. Phys. J. C (2013) 73:2330]



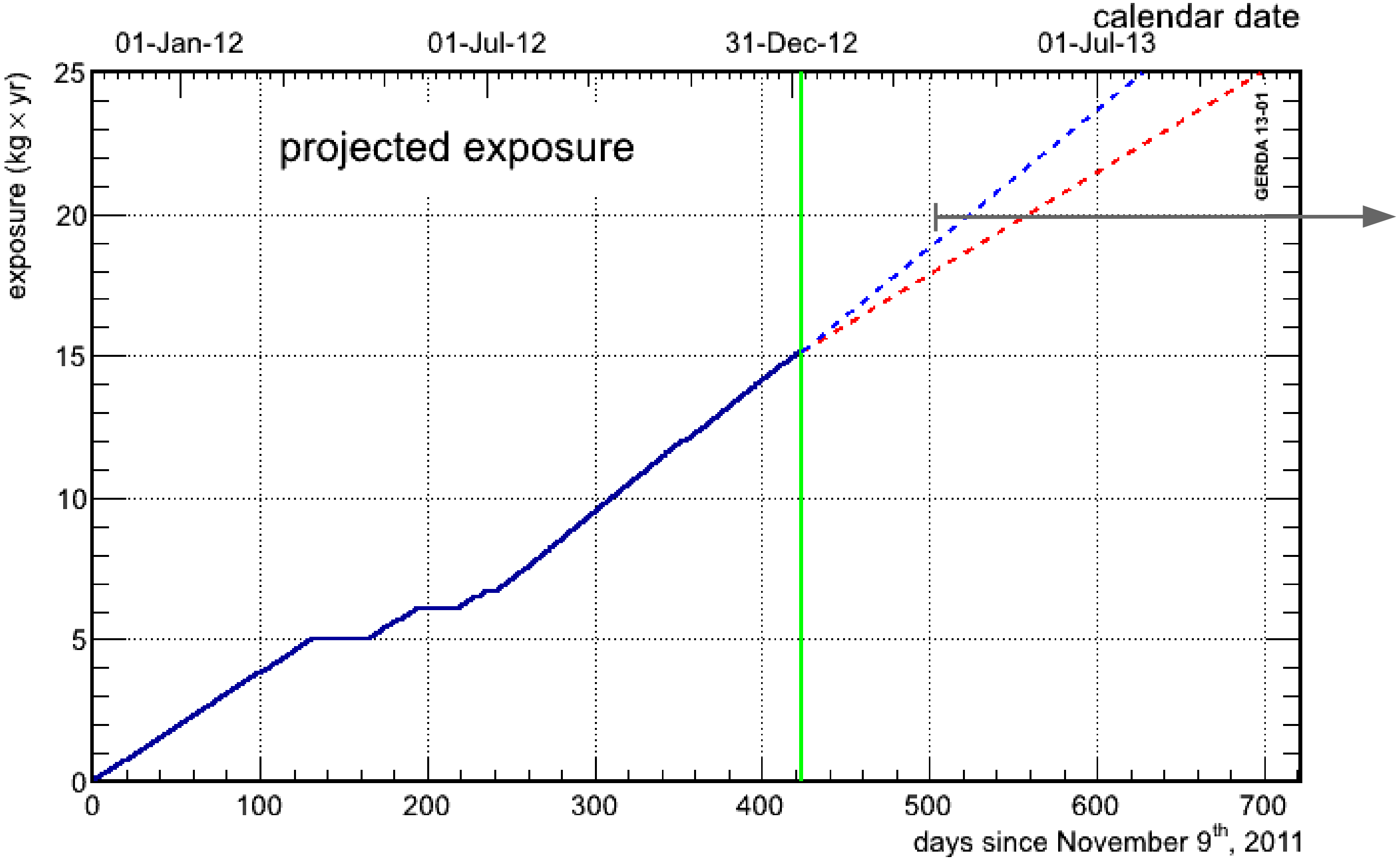
Phase-I data-taking

Phase-I started on 9 November 2011 with 3 ^{nat}Ge and 8 ^{enr}Ge (from HdM and IGEX) coax detectors

2 ^{nat}Ge detectors removed, 5 ^{enr}Ge BEGe detectors deployed on July 2012

^{enr}Ge mass for physics analysis: 14.6 kg (coaxial) and 3.6 kg (BEGe)

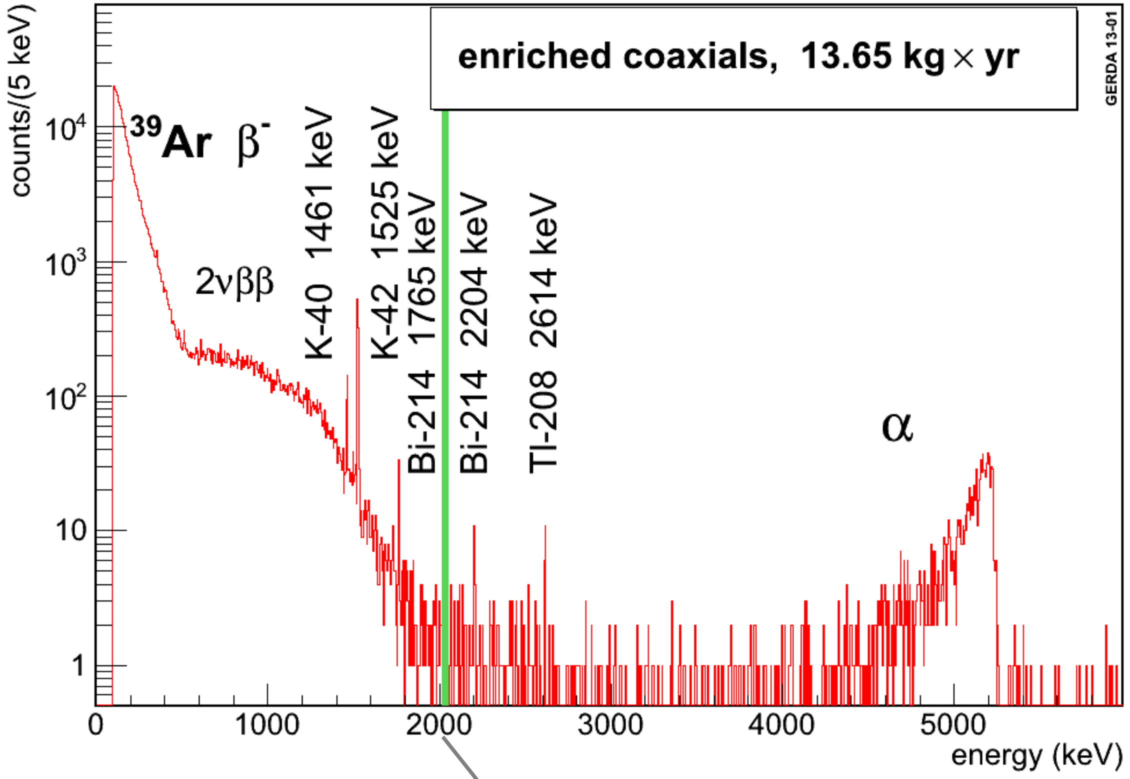
Energy resolution: FWHM at $Q_{\beta\beta}$ = 4.5 keV (mass weighted average for the ^{enr}Ge coax detectors)
Stability: energy resolution within ~0.5 keV, energy scale within ~1 keV.



Spring 2013:
20 kg·yr exposure
→ can check the claim

Summer 2013:
Transition from Phase I to Phase II starts

Phase-I background spectrum



Blinded window: 40 keV around $Q_{\beta\beta}$ = 2039 keV

9 November 20 11 – 5 January 2013
Live time: 340.94 days
Detectors: 6 ^{enr}Ge coax (14.63 kg)
Total exposure: 13.65 kg x yr

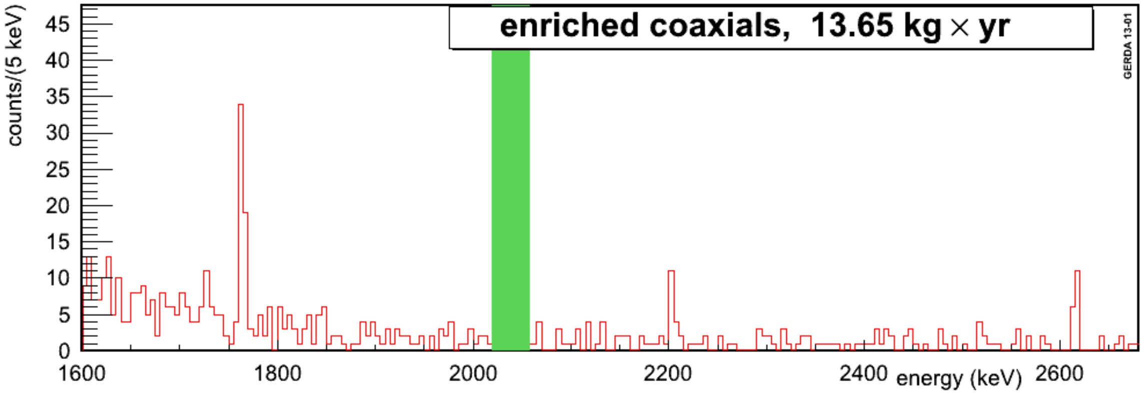
Background components:

No contribution at $Q_{\beta\beta}$

^{39}Ar (Q_β = 565 keV), **2νββ**, **^{40}K**, **^{228}Ac**

Contribution at $Q_{\beta\beta}$

- **^{42}K** (^{42}Ar) → Q_β = 3.5 MeV, E_γ = 2.4 MeV
- **^{214}Bi** (^{238}U) → Q_β = 3.3 MeV,
  E_γ = 2.1, 2.2, 2.4 MeV
- **^{208}Tl** (^{232}Th) → E_γ = 2.6 MeV
- **^{60}Co** → Q_β = 2.8 MeV
- **α-induced events** (from isotopes in ^{238}U chain)



Background index in $Q_{\beta\beta}$ ± 100 keV

0.022 cts/(keV kg yr) for 13.6 kg·yr data excluding 1.30 kg·yr (period following detector substitutions in July):

0.017 cts/(keV kg yr) for 12.3 kg·yr

10x lower than previous experiments (HdM, IGEX)

Phase I: Measurement of the $T_{1/2}$ of 2νββ of ^{76}Ge

^{enr}Ge coax detectors, total exposure: 5 kg·yr

2νββ spectrum clearly visible with the first 126 days data

Binned maximum likelihood fit

Fit window: 600 – 1800 keV

→ above ^{39}Ar end-point energy (Q_β = 565 keV)

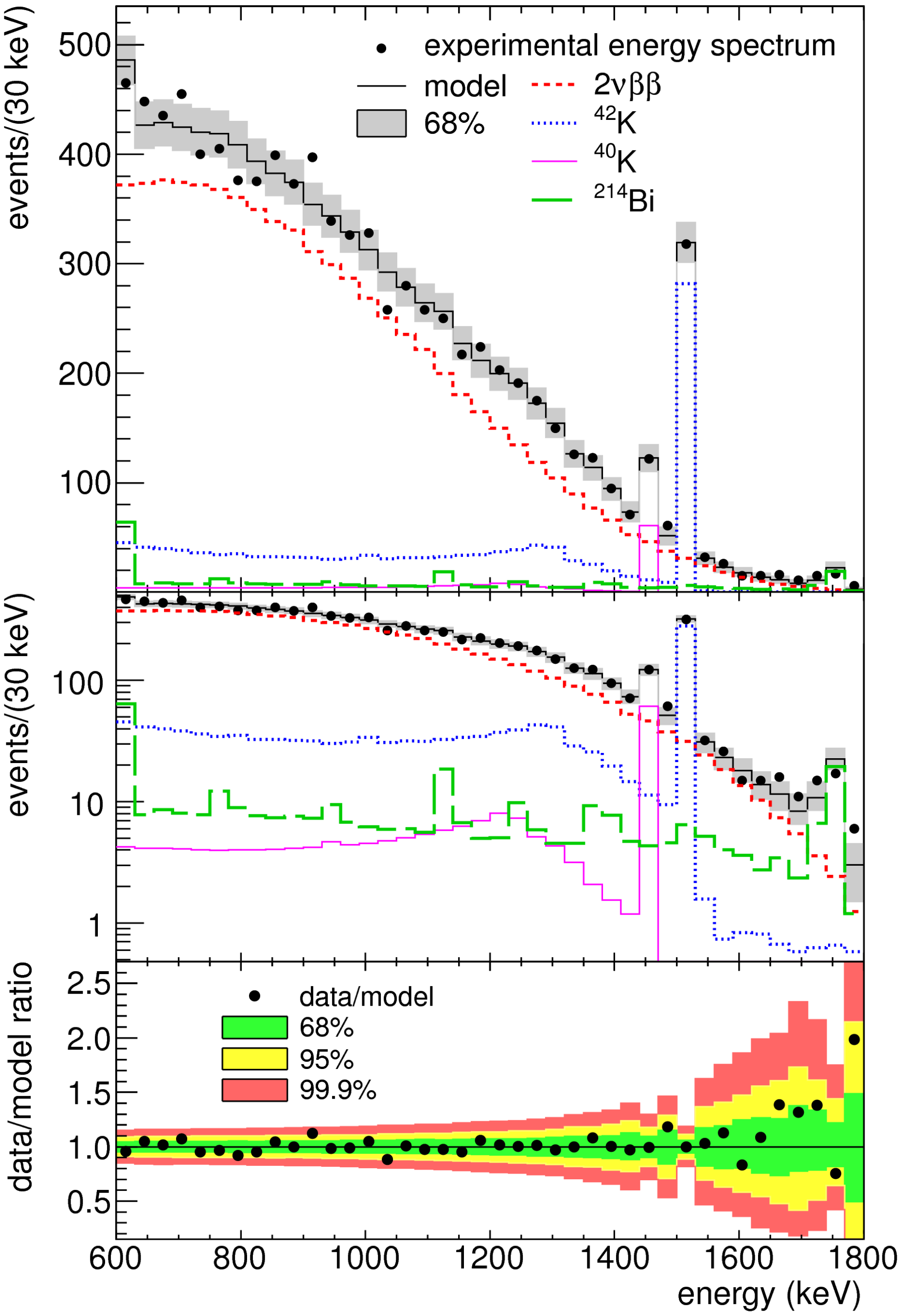
→ in E>1800 keV range 0.02% probability of 2νββ

Background components: ^{40}K and ^{214}Bi close source, ^{42}K in LAr

Fit Parameters: Active detector masses, enrichment fractions, background contributions, $T_{1/2}$ common parameter

$$\boxed{T_{1/2}^{2\nu} = \left(1.84^{+0.09}_{-0.08\,\mathrm{fit}}\ {}^{+0.11}_{-0.06\,\mathrm{syst}}\right) \times 10^{21}\,\mathrm{yr} = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\,\mathrm{yr}}$$

Item	Uncertainty on $T_{1/2}^{2\nu}$ (%)	
Non-identified background components	+5.3	
Energy spectra from ^{42}K, ^{40}K and ^{214}Bi	±2.1	
Shape of the $2\nu\beta\beta$ decay spectrum	±1	
Subtotal fit model		$^{+5.8}_{-2.3}$
Precision of the Monte Carlo geometry model	±1	
Accuracy of the Monte Carlo tracking	±2	
Subtotal Monte Carlo		±2.2
Data acquisition and selection		±0.5
Grand total		$^{+6.2}_{-3.3}$



Phase I: Measurement of the $T_{1/2}$ of $2\nu\beta\beta$ of ^{76}Ge

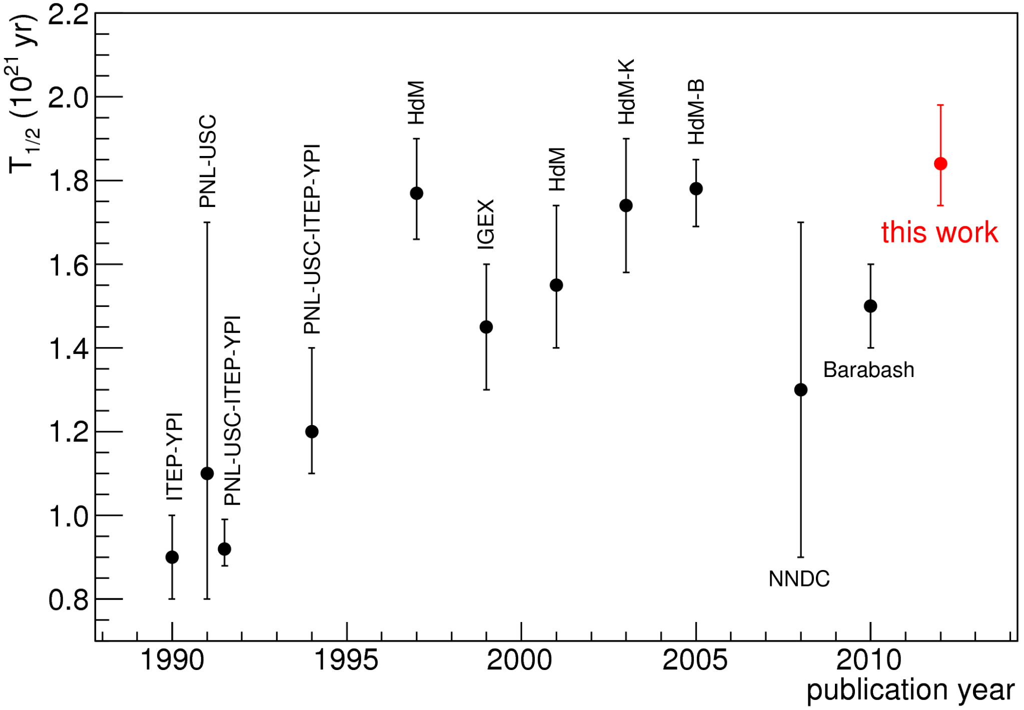
The GERDA collaboration [J. Phys. G 40 (2013) 035110]

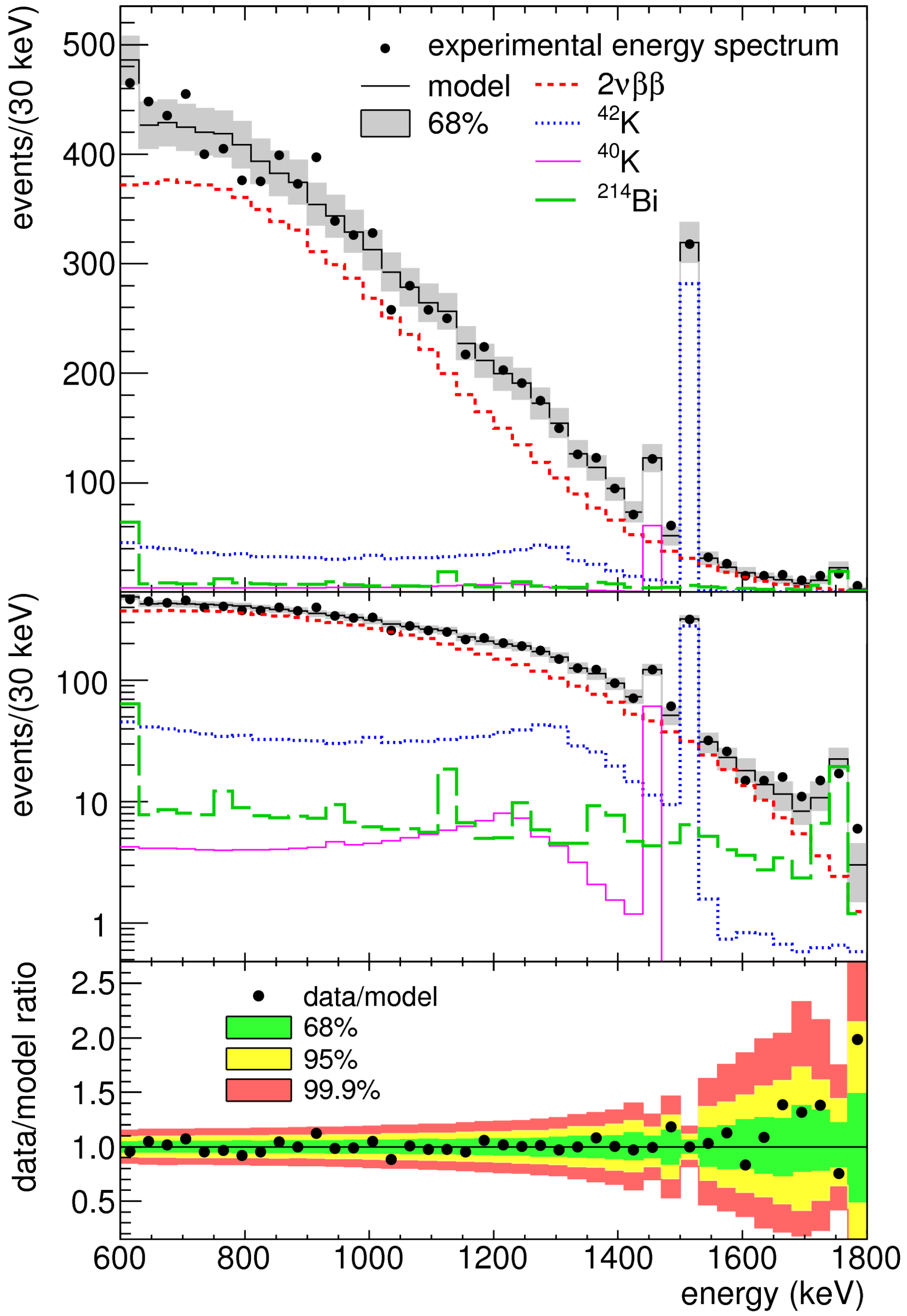
$$T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08\,\text{fit}}\ {}^{+0.11}_{-0.06\,\text{syst}}\right)\times 10^{21}\,\text{yr} = \left(1.84^{+0.14}_{-0.10}\right)\times 10^{21}\,\text{yr}$$

Signal-to-background ratio in the fit range 4:1

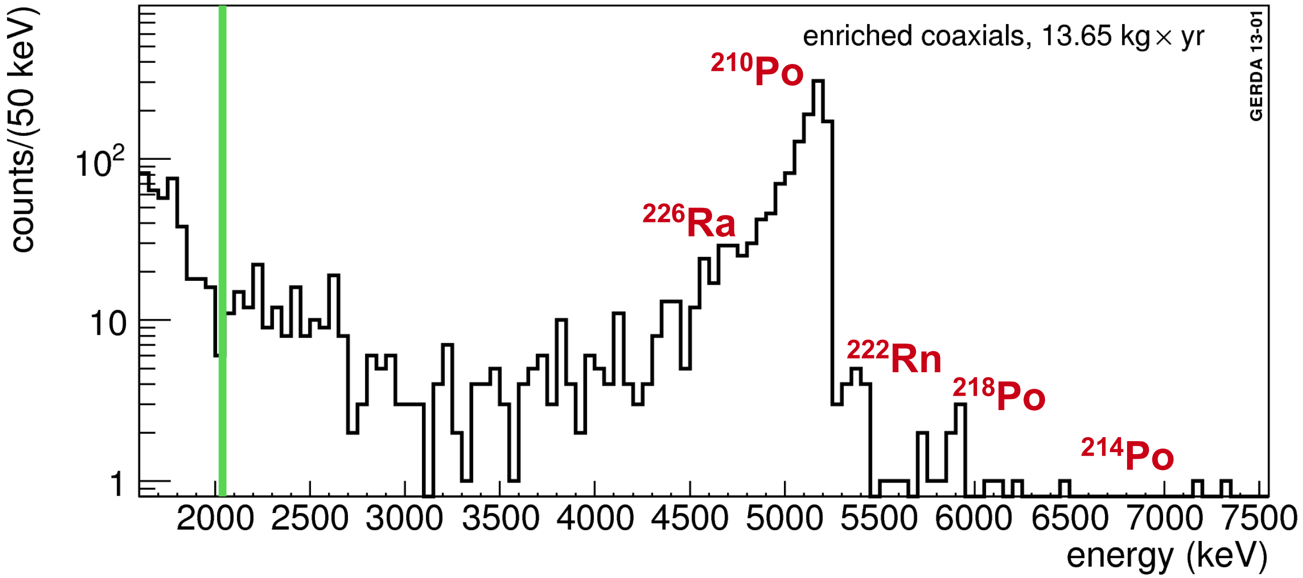
→ uncertainty comparable to previous measurements despite much smaller exposure

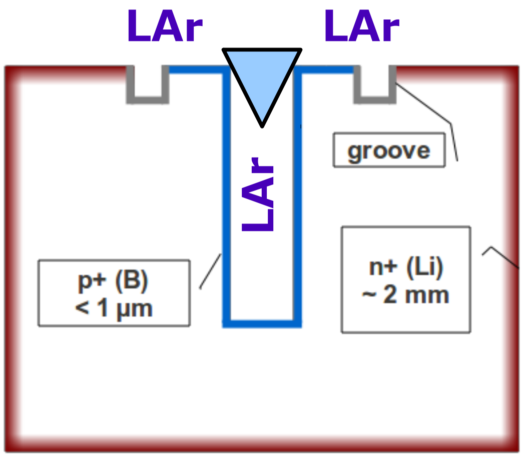
Good agreement with reanalysis of HdM data (HdM-K, HdM-B)





Phase I: Analysis of alpha-induced background





- Range of alphas with E ~ 4 MeV – 9 MeV
  → 14 µm – 41 µm in Ge
  → 34 µm – 113 µm in LAr

- Possible origin of alpha-induced events:
  → Separate ^{226}Ra and ^{210}Po contaminations on thin dead layer (thinDL) surfaces.

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

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

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

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

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

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

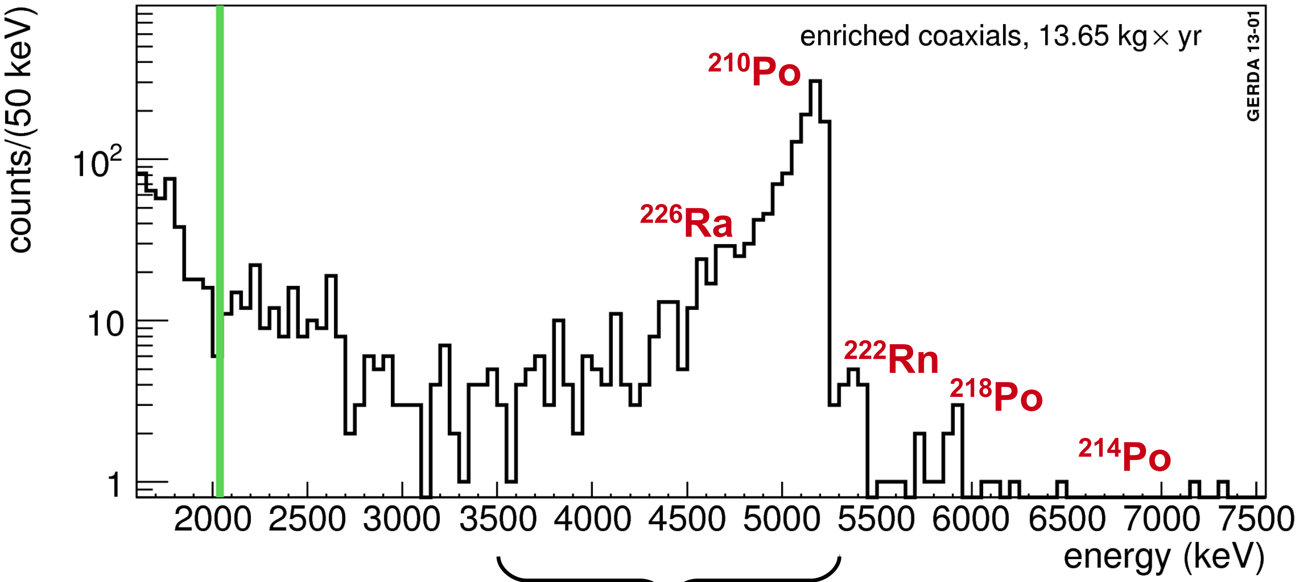
^{210}Pb ($T_{1/2}$ = 22.3 y)

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

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

^{206}Pb (stable)

Phase I: Analysis of alpha-induced background



^{226}Ra (E_α = 4.8 MeV,
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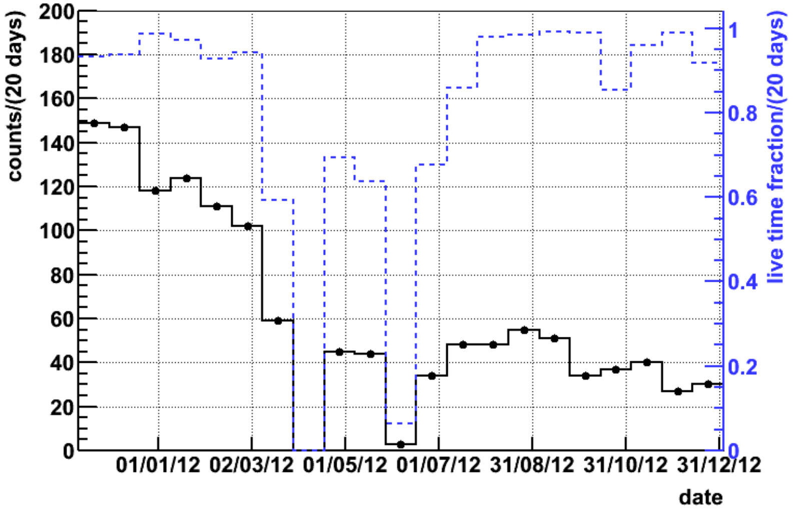
$_\alpha$ = 5.3 MeV,
$T_{1/2}$ = 138.4 d)

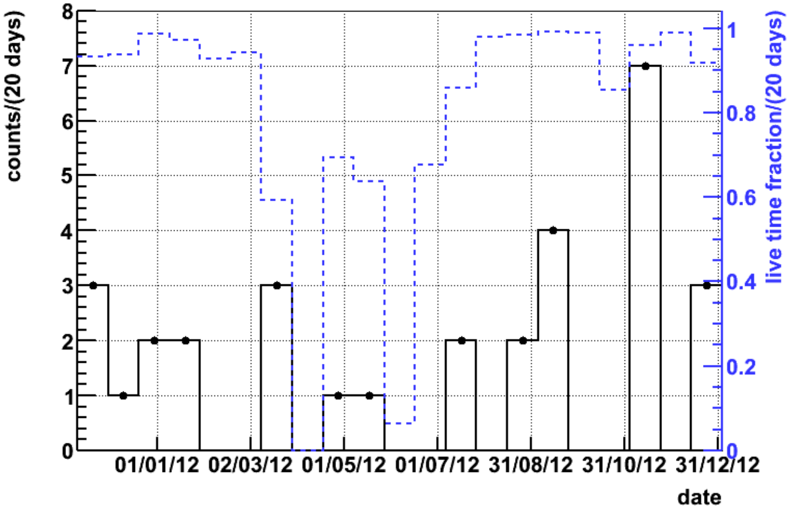
stable)

Expectation →

Exponential ($T_{1/2}$ = 138.4 d)
+ constant event rate

Constant event rate





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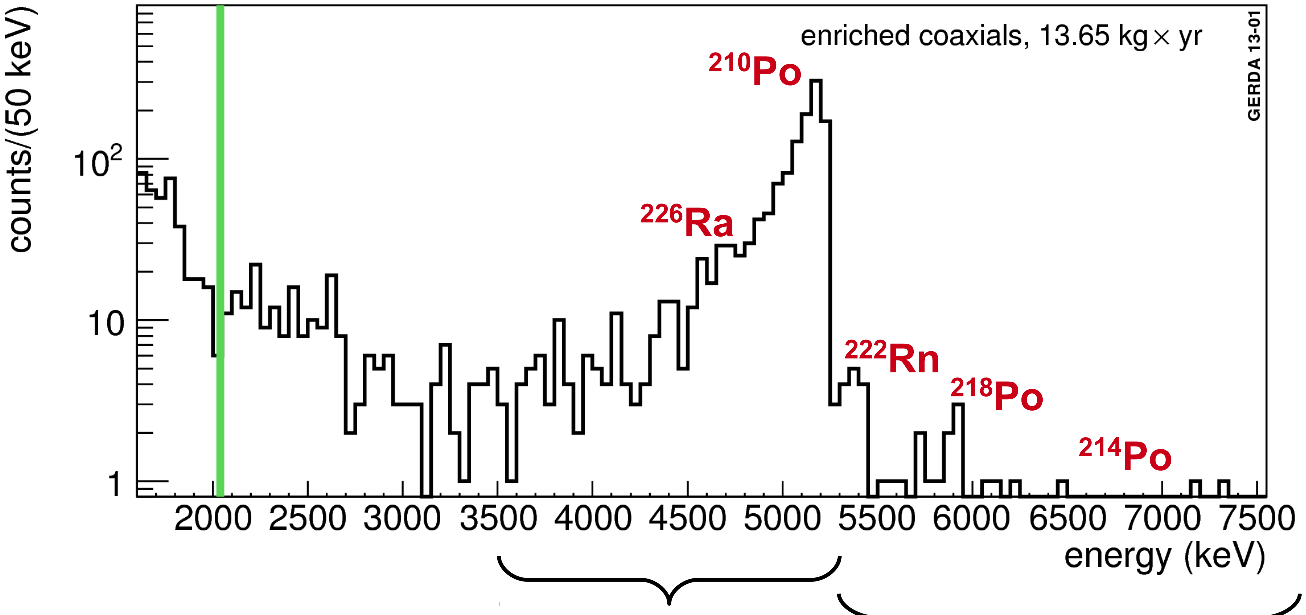

Expectation → **Exponential ($T_{1/2}$ = 138.4 d) + constant event rate** **Constant event rate**

Results from fitting the event rate distributions (details in the backup) :

	C [cts/day]	N_0 [cts/day]	$T_{1/2}$ [days]	p-value
(3.5 MeV < E < 5.3 MeV)				
expo		9.26 ± 0.26	138.4 ± 0.2	0.11
expo + const	0.57 ± 0.16	7.91 ± 0.44	138.4 ± 0.2	0.87
(5.3 MeV < E < 7.5 MeV)				
const	0.09 ± 0.02			0.86

Given a strong prior probability on the half life parameter

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

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

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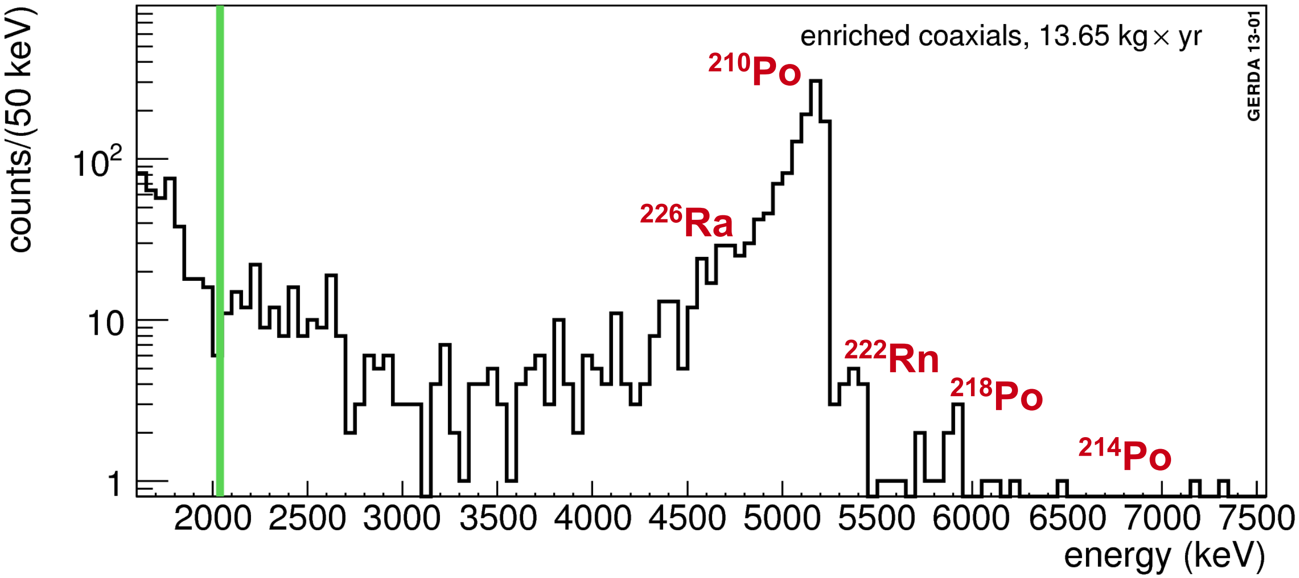

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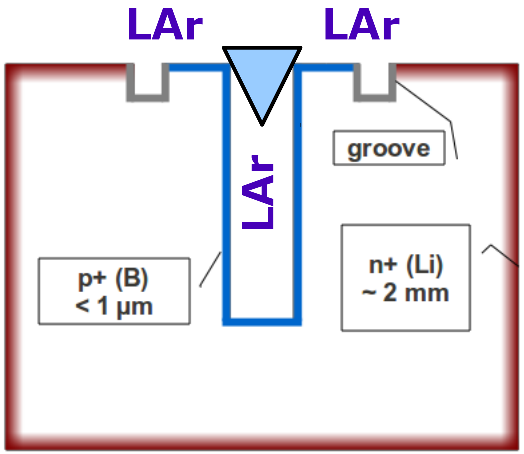
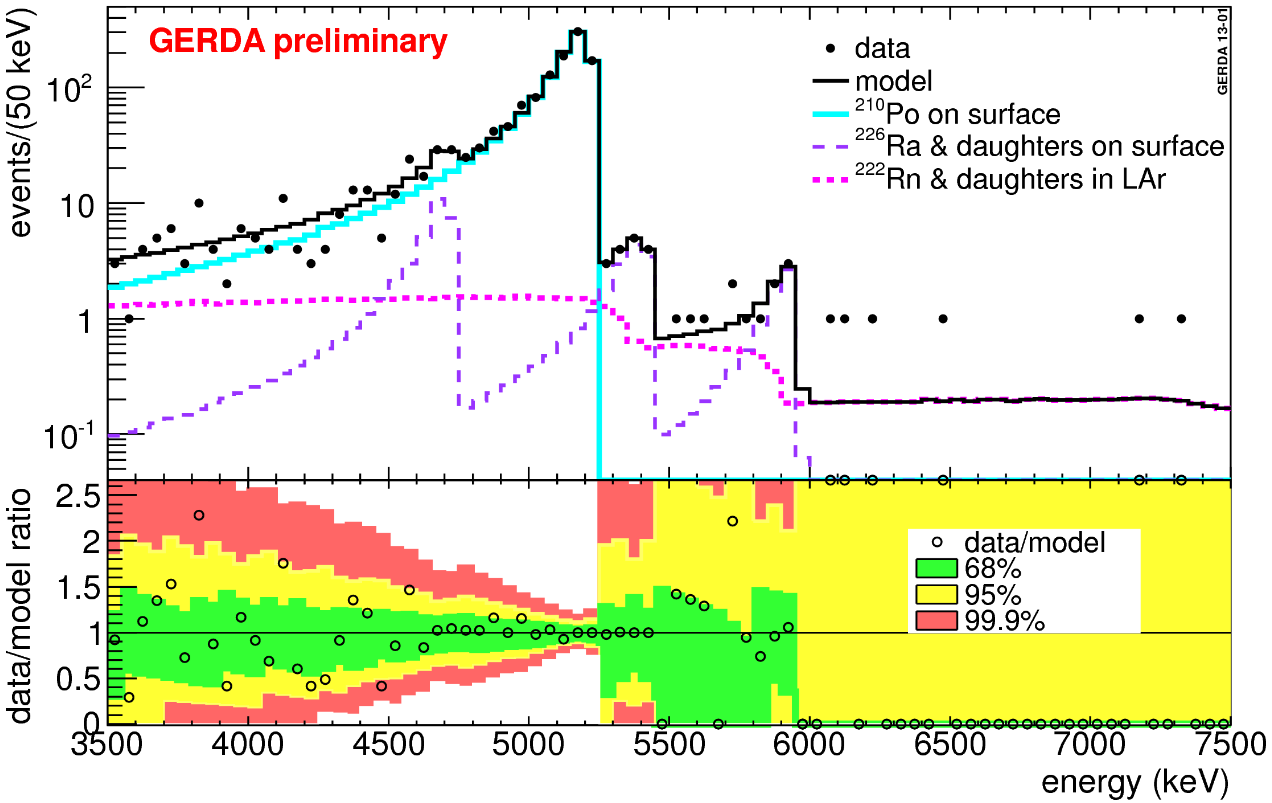


MC simulations to model the energy spectrum:

1) ^{210}Po on thinDL surface
2) ^{226}Ra & daughters on thinDL surface
3) ^{222}Rn & daughters in LAr close to thinDL surfaces

thinDL thickness: 300 ... 600 nm

Phase I: Analysis of alpha-induced background



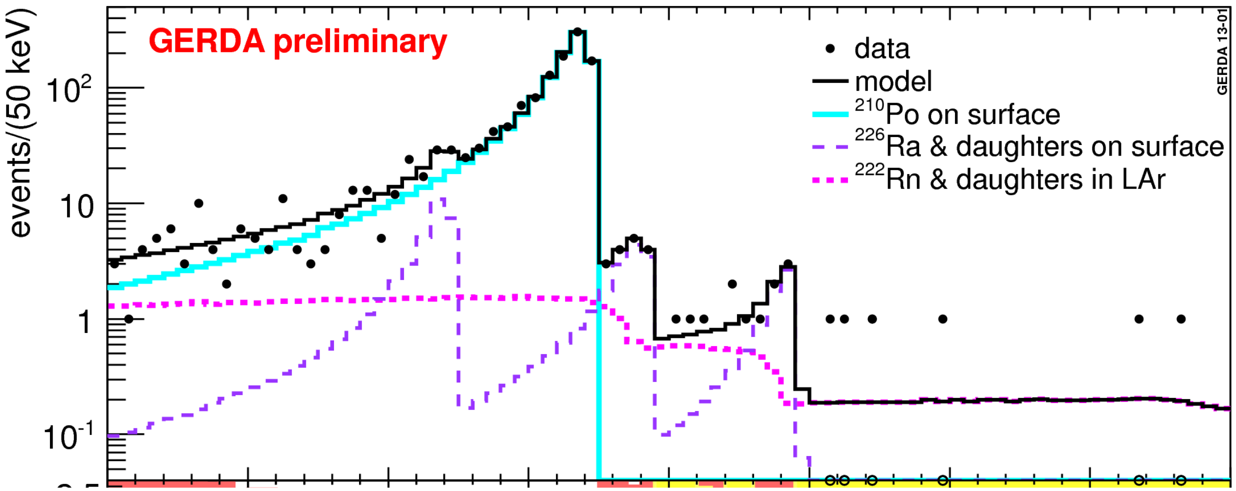
Colored probability intervals:
[R. Aggarwal and A. Caldwell, Eur. Phys. J. Plus 127 24 (2012)]

^{enr}Ge coaxials, exposure: 13.65 kg·yr

Binned maximum likelihood fit
Fit window: 3500 – 7500 keV
p-value: 0.7

Note: the model explains the α-induced events in **^{nat}Ge** detectors as well (backup)

Phase I: Analysis of alpha-induced background



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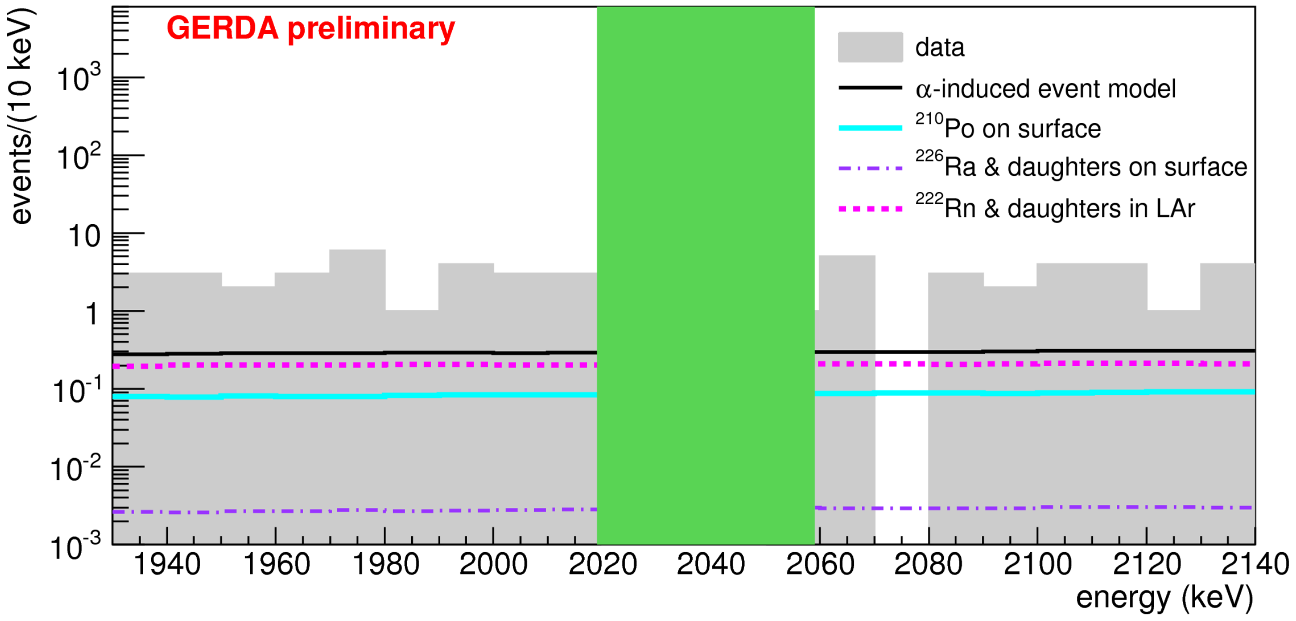
Extrapolation of the alpha-induced event model to ROI (160 keV): (1939 – 2019) plus (2059 – 2139) keV



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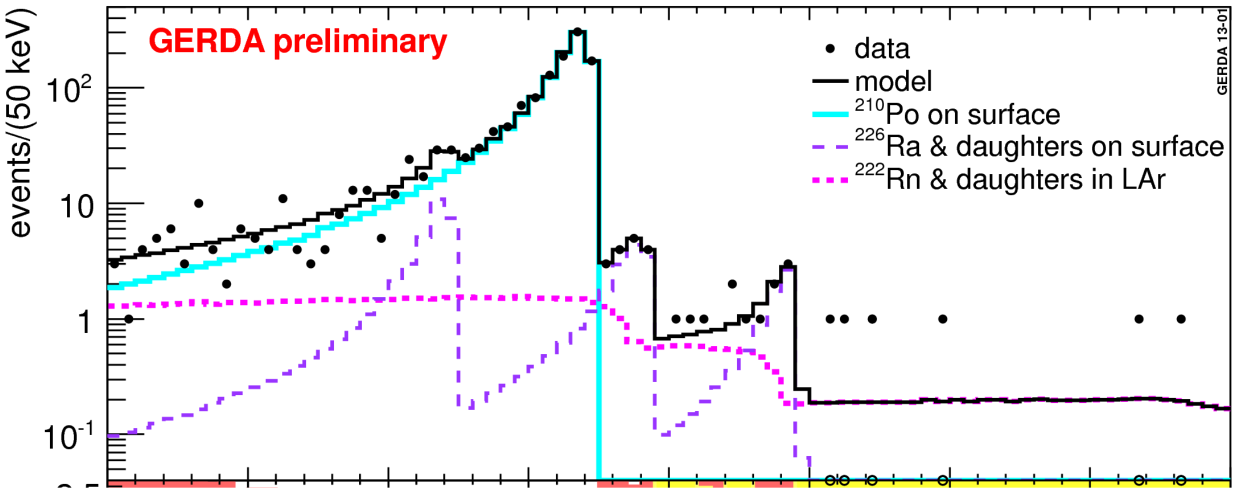

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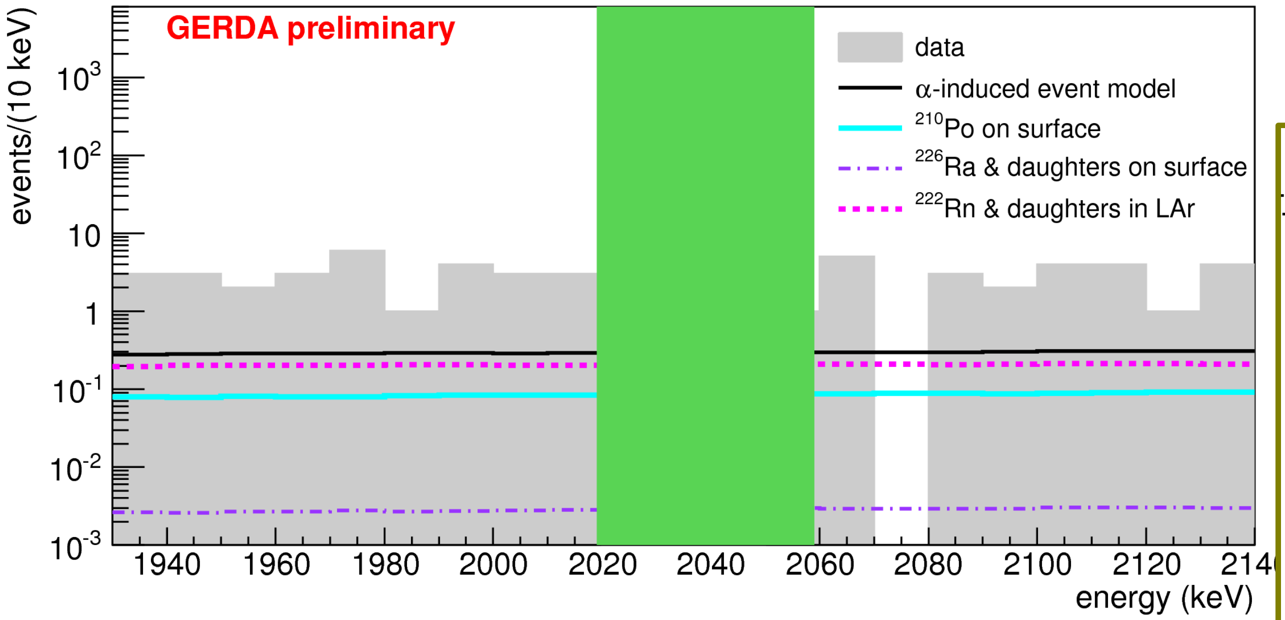
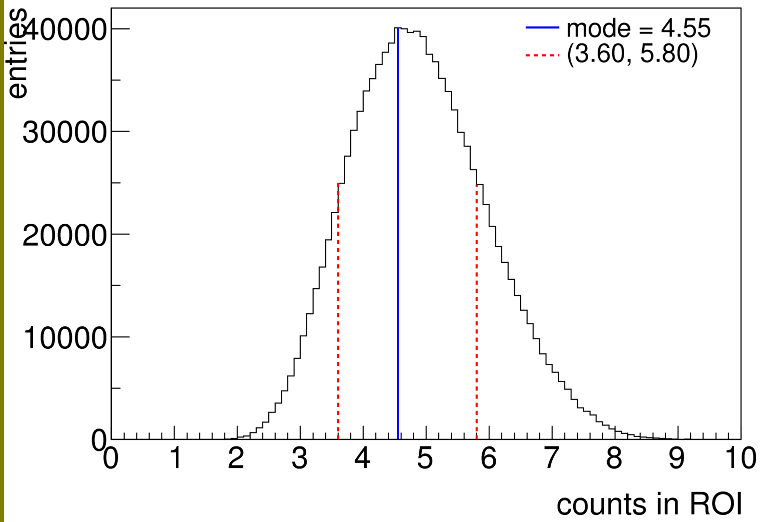


→ data: 49 events

→ alpha model: $4.55^{+1.25}_{-0.95}$ events

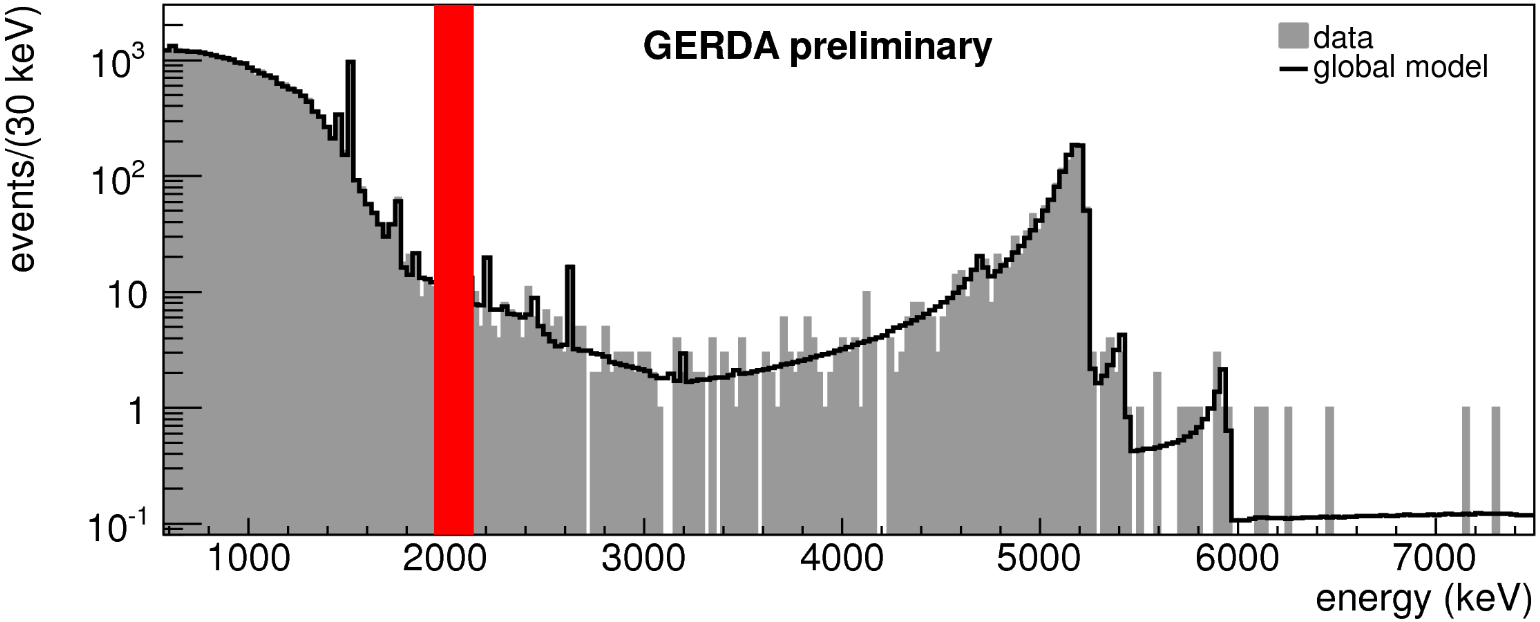
~ 9% contribution from alphas



Phase-I: decomposition of the background spectrum

Binned maximum posterior fit to the sum ^{enr}Ge coax spectrum in (570 – 7500) keV window

- fit window enlarged to include $Q_{\beta\beta}$
- background components considered in the global fit:
  → K-42, K-40, Bi-214, Ac-228 & Th228 (beta- / gamma-induced events)
  and alpha-induced event model
- p-value of the fit: 0.3



Work in progress: analysis with more background components, various source positions, different data sets is ongoing. systematics under investigation

Preliminary: Dominant background contributions around $Q_{\beta\beta}$
→ K-42, Bi-214, Tl-208 and alphas

Conclusions

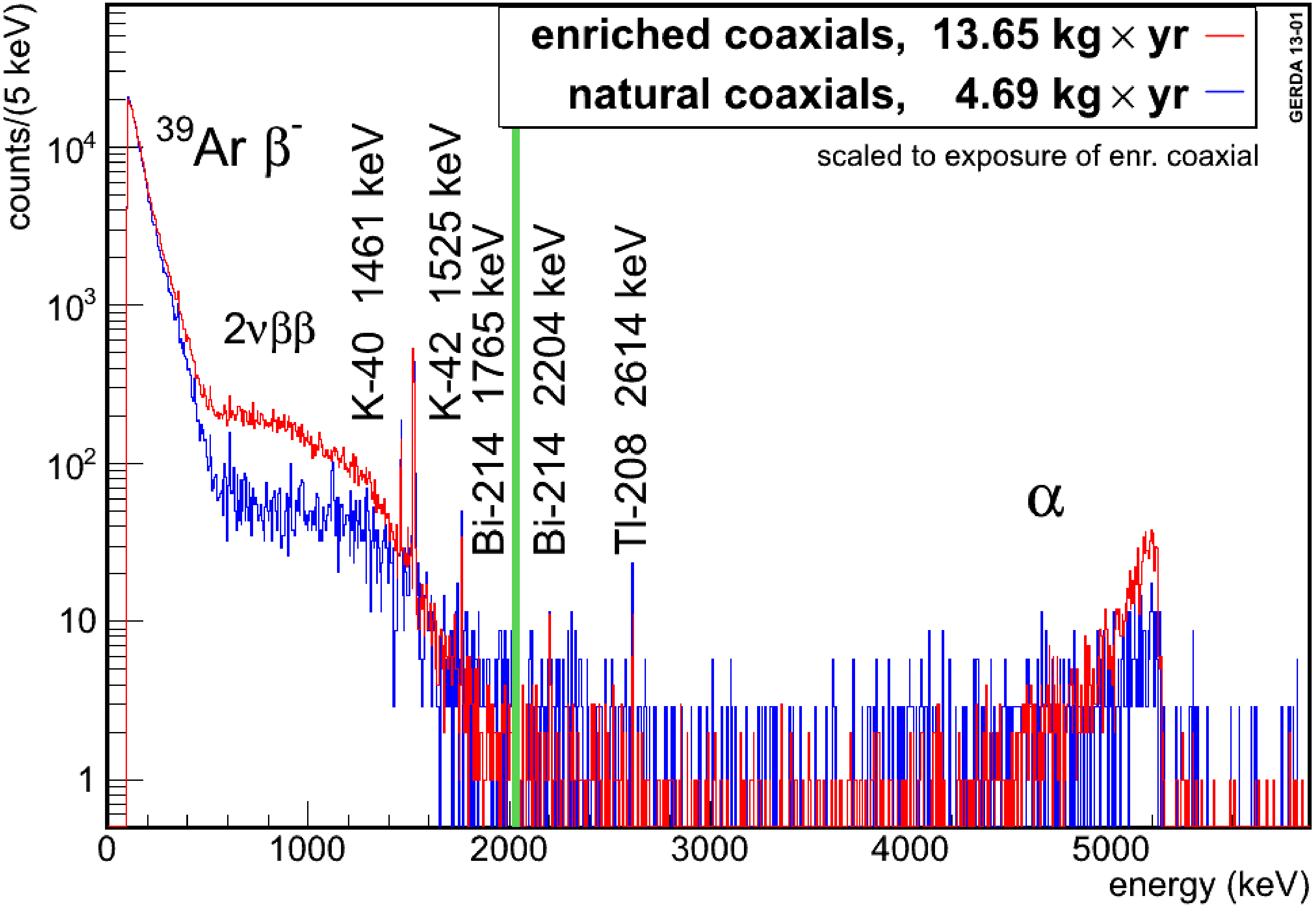
- GERDA Phase I started in Nov 2011 – ongoing.
- Phase I background an order of magnitude lower than HdM, IGEX.
- Measurement of $T_{1/2}$ of $2\nu\beta\beta$ with the first 5 kg·yr (s:b = 4:1)

$$\boxed{T^{2\nu}_{1/2} = \left(1.84^{+0.09}_{-0.08\ \mathrm{fit}}\ {}^{+0.11}_{-0.06\ \mathrm{syst}}\right) \times 10^{21}\,\mathrm{yr} = \left(1.84^{+0.14}_{-0.10}\right) \times 10^{21}\,\mathrm{yr}}$$

- Blind analysis: 40 keV window around $Q_{\beta\beta}$ = 2039 keV is blinded.
  - unblinding: after 20 kg·yr exposure collected (Spring 2013)
- Model the background energy spectrum before unblinding: Promising “preliminary” results !
  - for the upcoming $0\nu\beta\beta$ analysis: expected number of background events, shape of the background spectrum around $Q_{\beta\beta}$
  - for Phase II: understand the background sources in Phase I & mitigate it further

Backup

Phase-I data-taking



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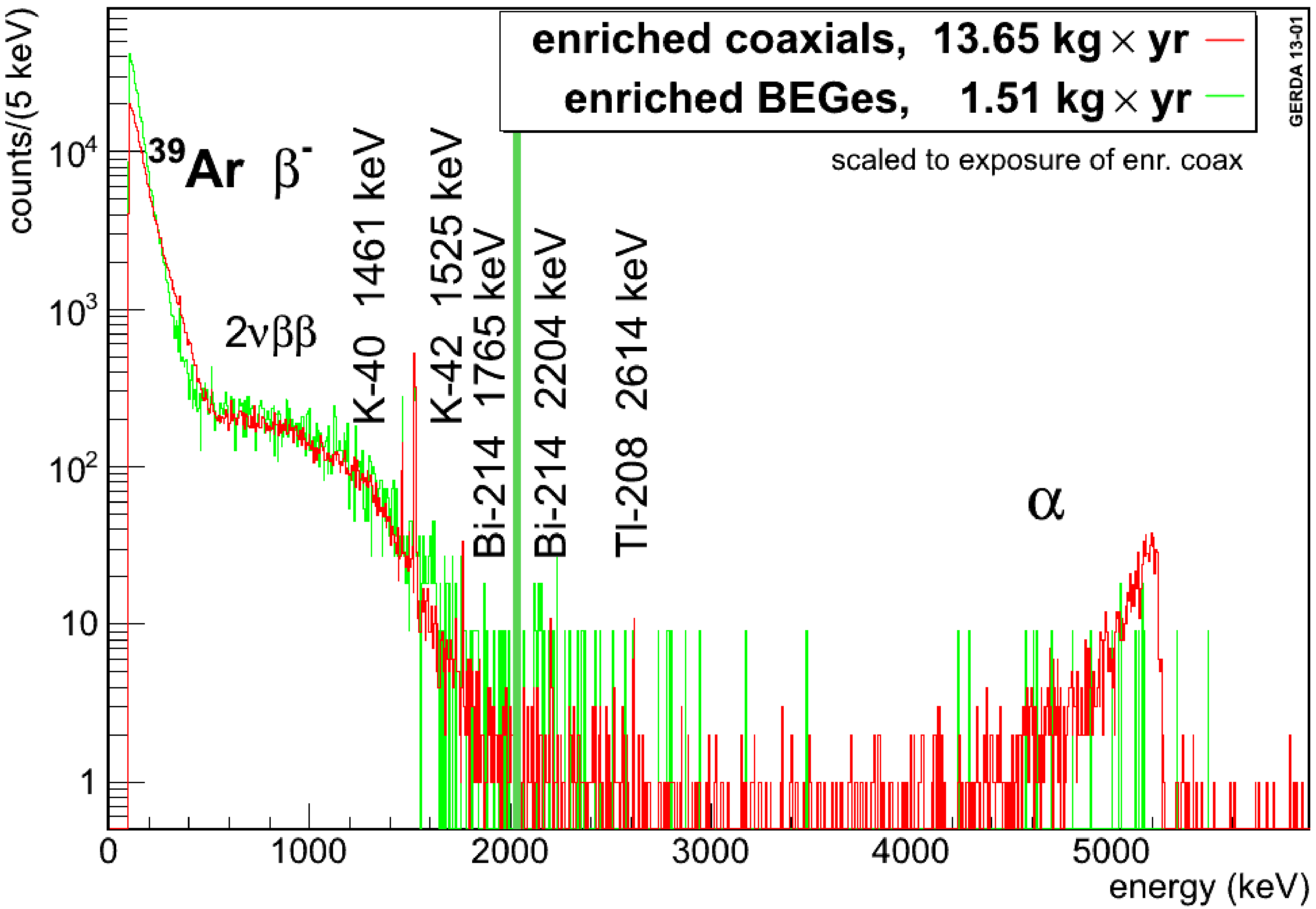

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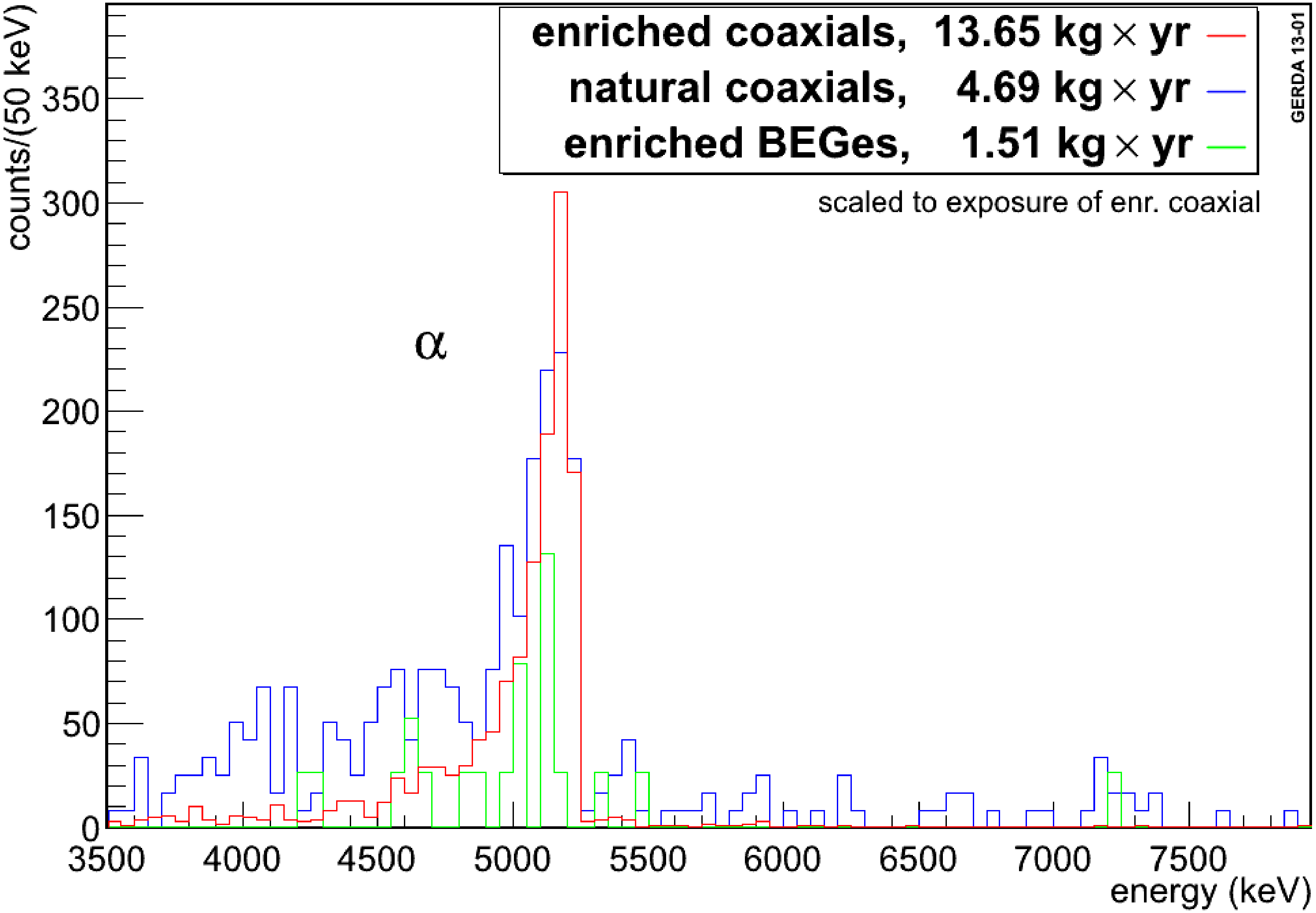

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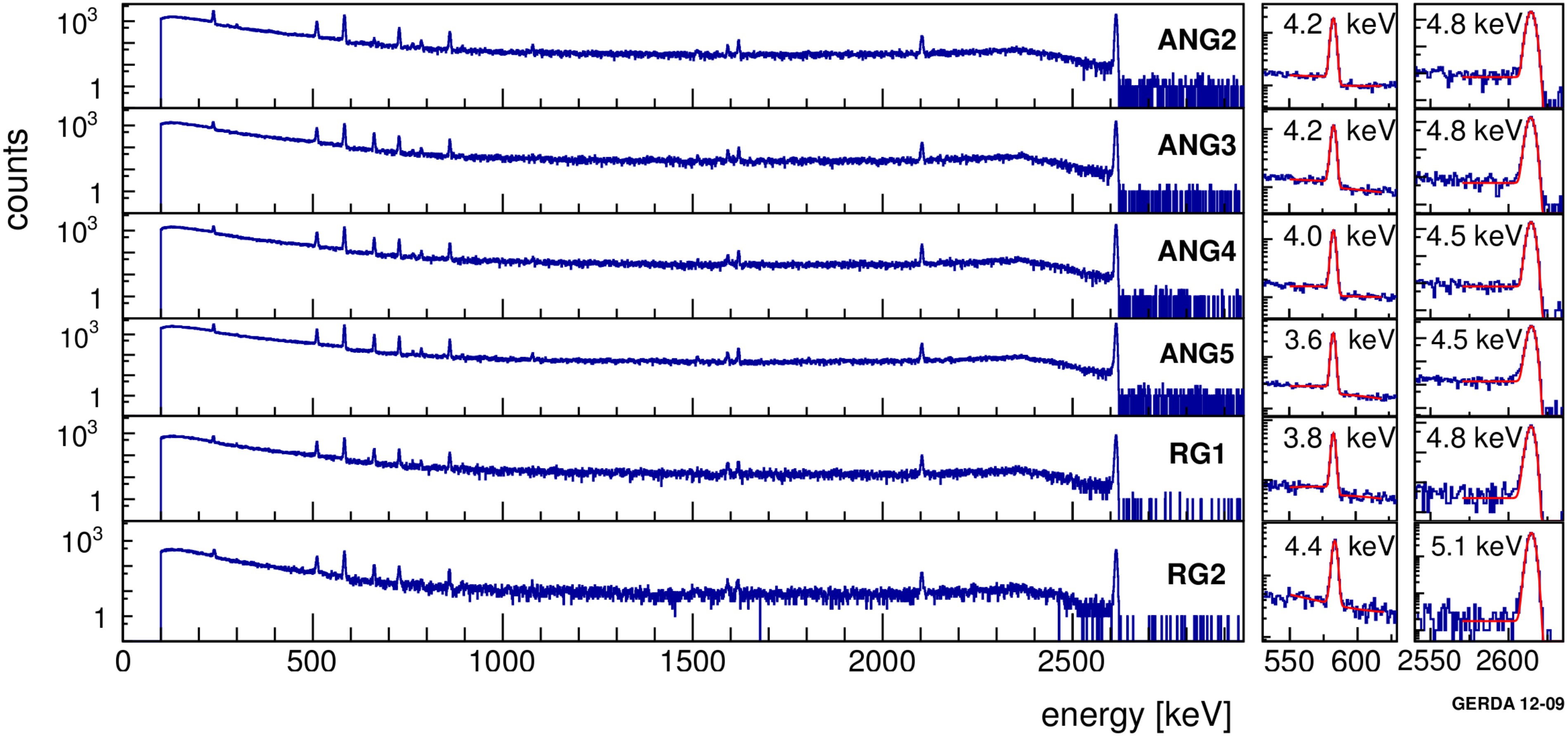

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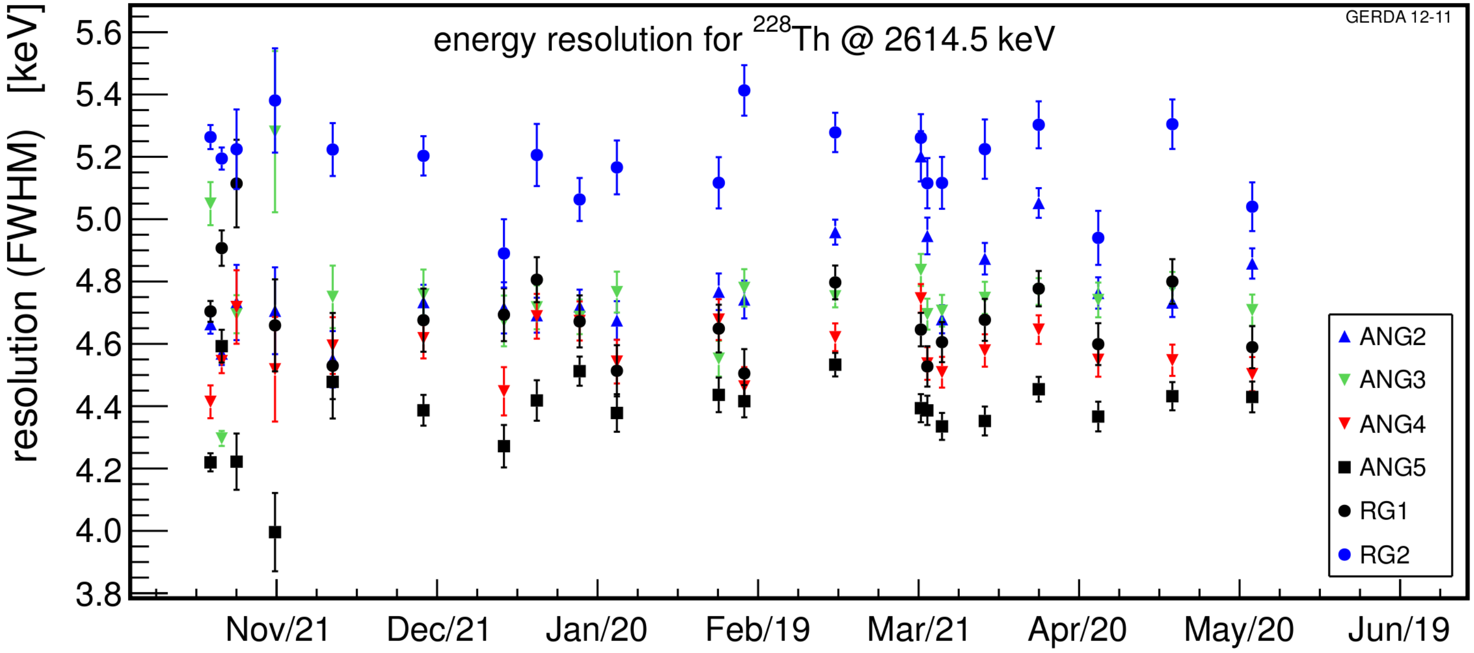

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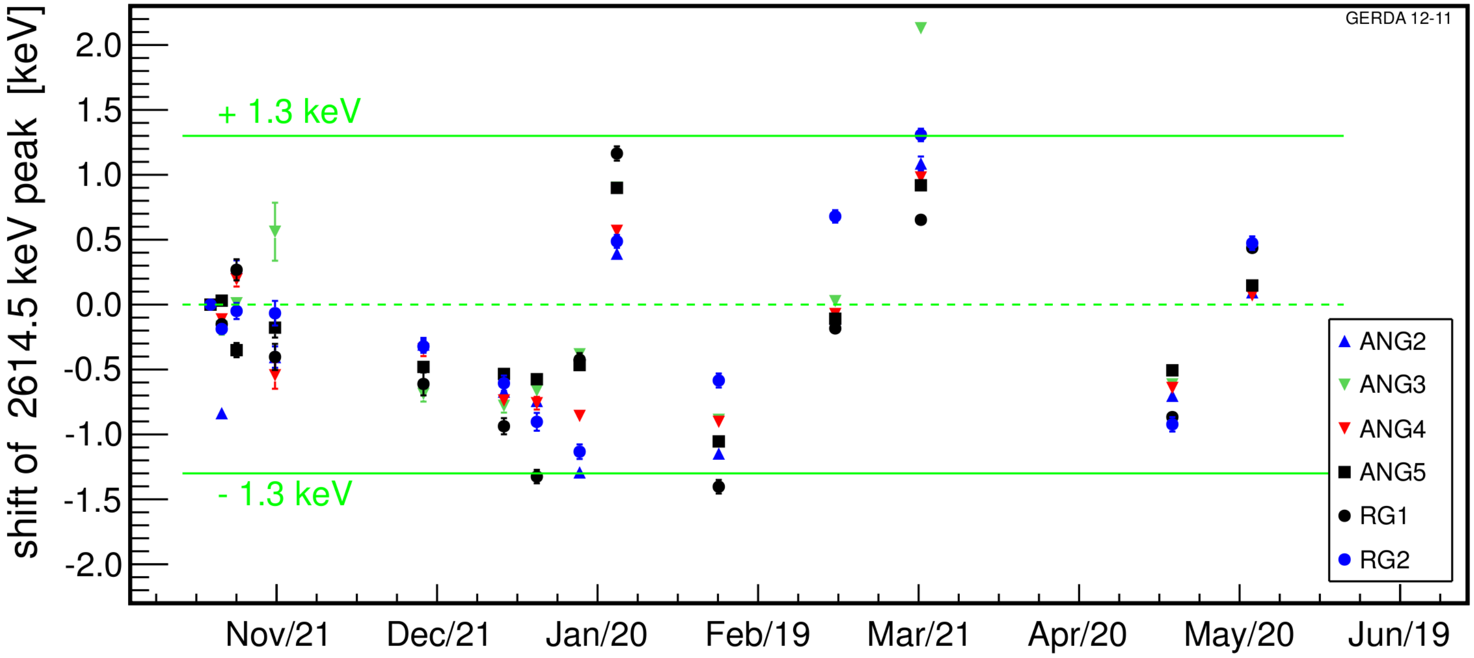


Phase I: Analysis of alpha-induced background

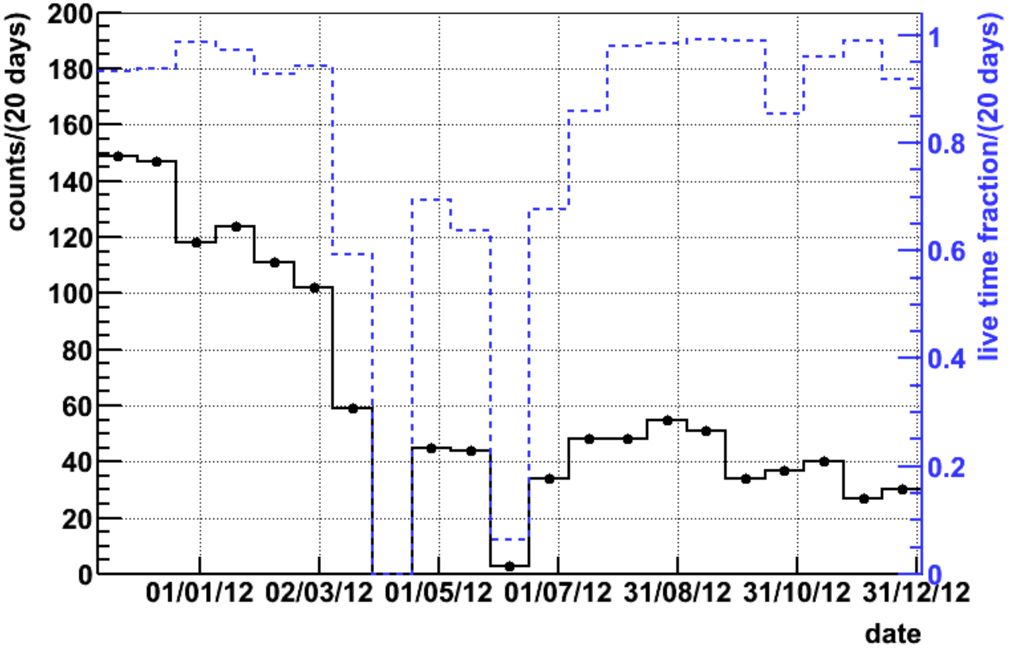
Analysis of event rate distributions:

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

- Maximized quantity posterior probability:

$$P(\vec{\lambda}|\vec{n}) \propto P(\vec{n}|\vec{\lambda}) P_0(\vec{\lambda})$$

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



- Likelihood:

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

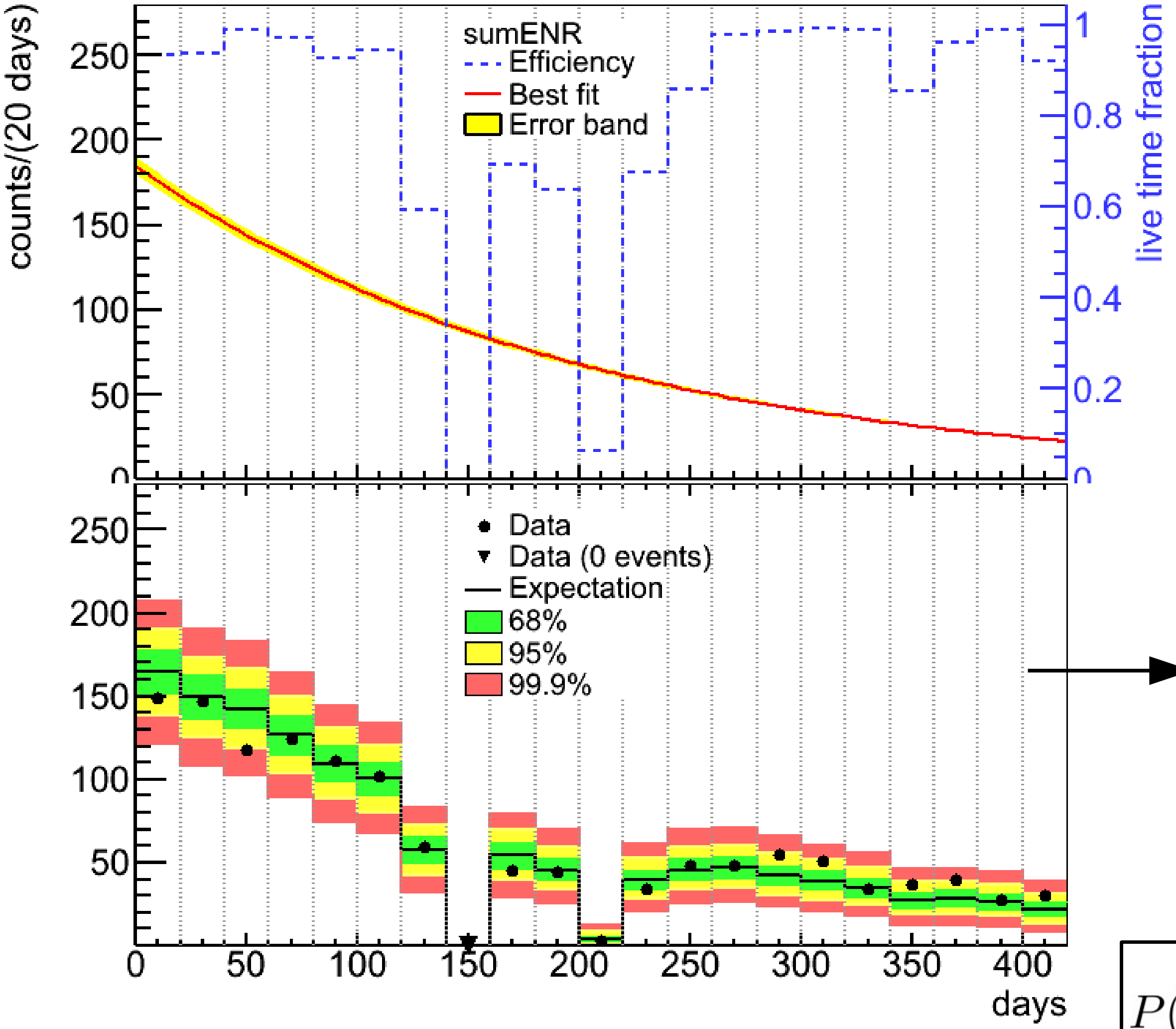
n_i : raw number of counts in i-th bin
(not scaled, not corrected for live time fraction,
λ_i : expectation in the i-th bin
corrected with the live time fraction in that bin

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

Phase I: Analysis of alpha-induced background

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

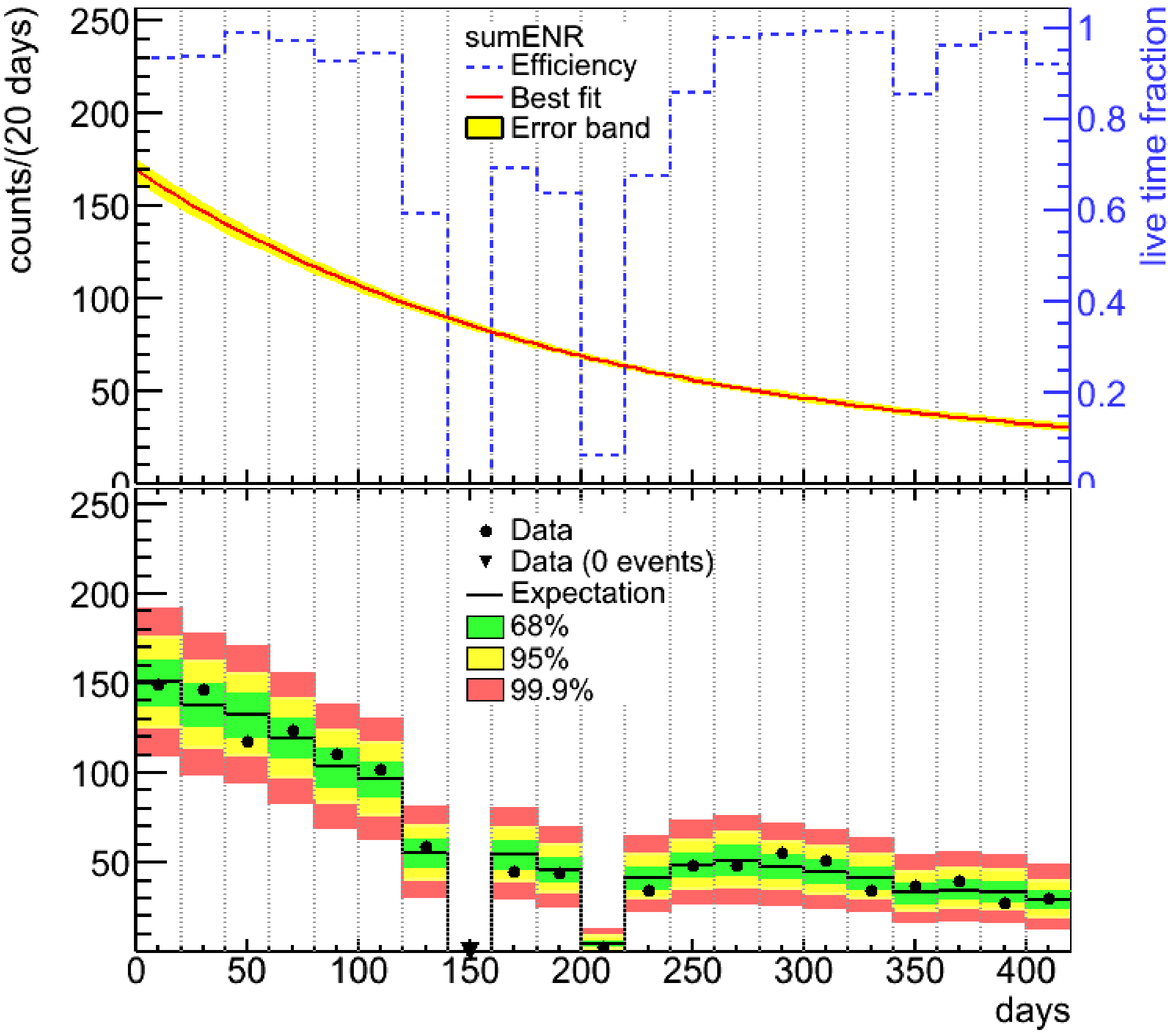
$$\lambda_i = \epsilon_i \int_{(i-1)\Delta t}^{i\Delta t} N_0 \cdot e^{-ln2\,t/T_{1/2}}\, dt$$

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

Phase I: Analysis of alpha-induced background

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

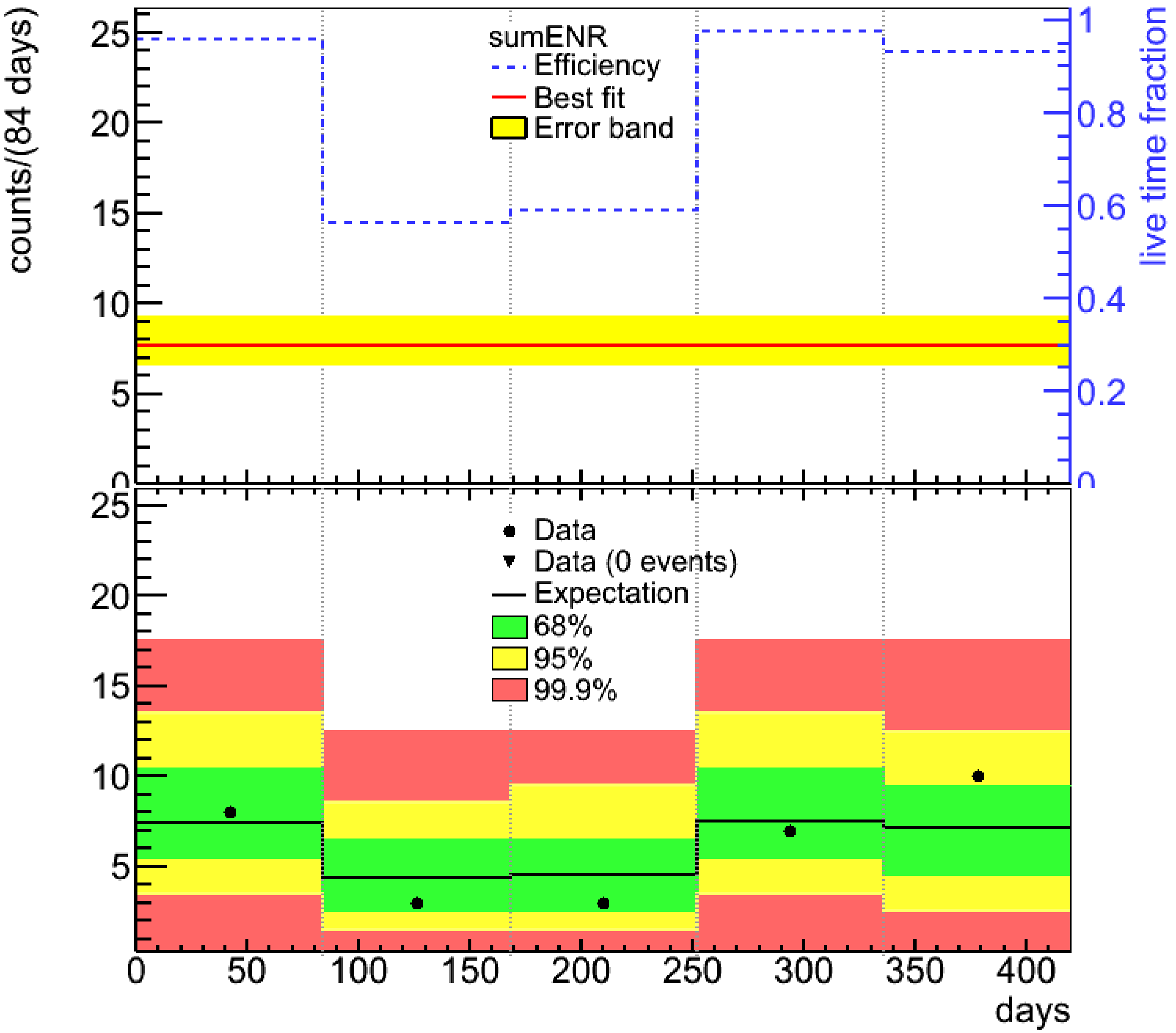
$T_{1/2}$ = (138.4 ± 0.2) days

p-value of the fit: 0.87

Phase I: Analysis of alpha-induced background

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

Model: constant rate



Parameters:

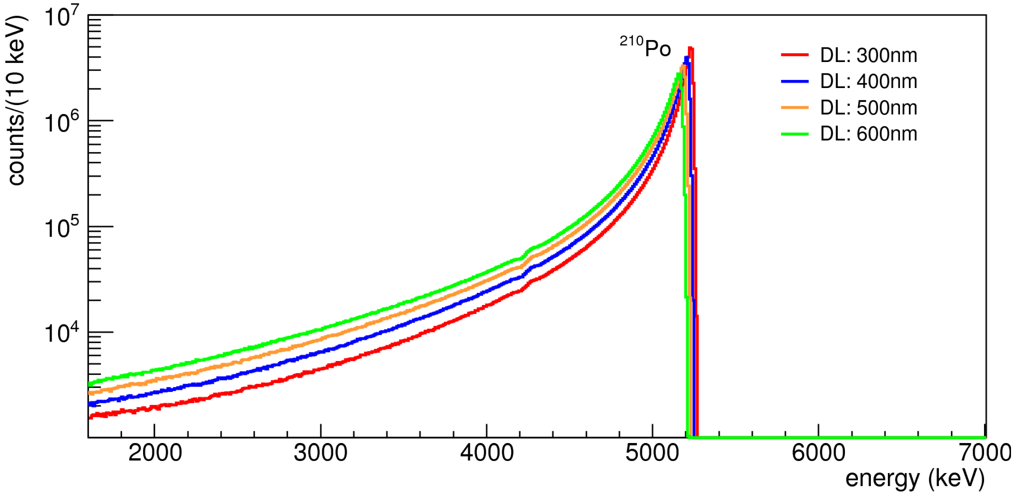
C = (0.09 ± 0.02) cts/day

p-value of the fit: 0.86

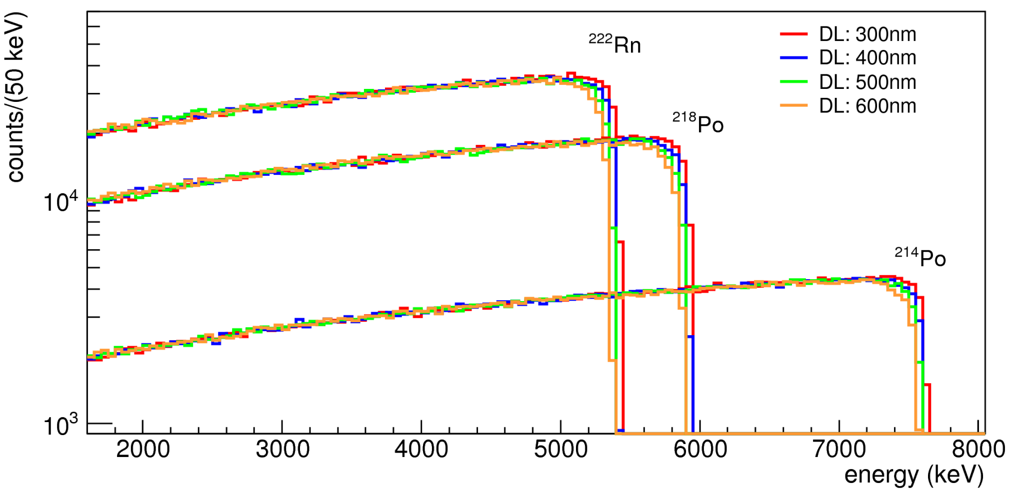
Phase I: Analysis of alpha-induced background

Simulated energy spectrum of different model components

^{210}Po on thinDL surface



^{222}Rn & daughters in LAr close to thinDL surface



Binned maximum posterior fit to the sum ^{enr}Ge-coax spectrum in (3500 – 7500) keV window

Maximized the posterior probability using Markov Chain Monte Carlo in Bayesian Analysis Toolkit BAT:

[A. Caldwell et. al., Comput. Phys. Commun. 180, 2197 (2009)]

Posterior probability: $P(\vec{\lambda}|\vec{n}) \propto P(\vec{n}|\vec{\lambda})P_0(\vec{\lambda})$

Likelihood:

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

n_i number of observed, λ_i number of expected events in i-th bin

$$\lambda_i = \sum \lambda_{i,M}$$

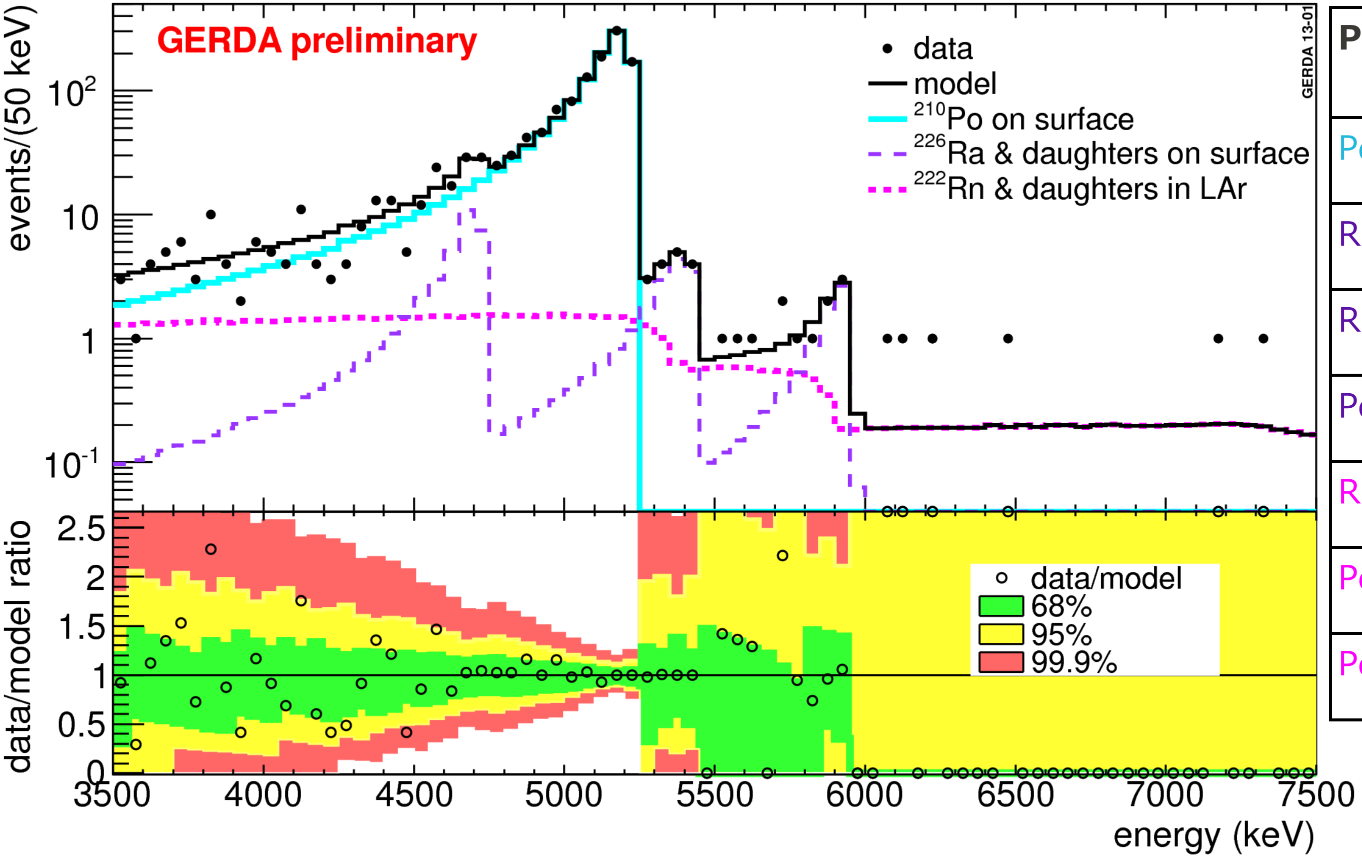
→ sum contribution of each model component M

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

scaling parameter for the component M

Phase I: Analysis of alpha-induced background

sumEnrCoax, all runs **fit window: (3500 – 7500) keV** **p-value: 0.72**



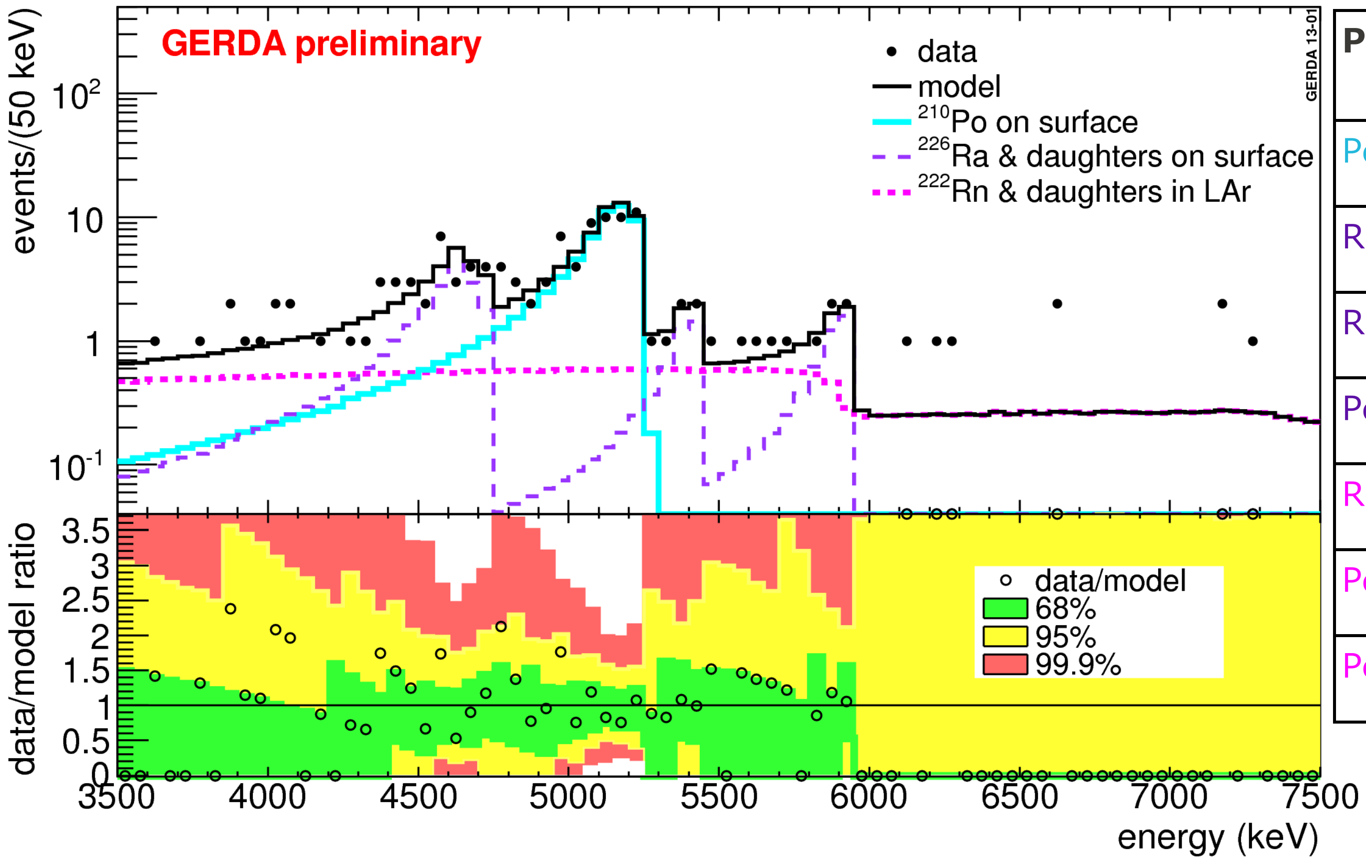
Parameters	**Mode (smallest int.)**
Po-210 sur	1205 (1160, 1240)
Ra-226 sur	39.5 (30.0, 55.0)
Rn-222 sur	20.5 (14.0, 28.0)
Po-218 sur	11.5 (7.0, 16.0)
Rn-222 in LAr	40.5 (26.0, 61.0)
Po-218 in LAr	22.5 (14.0, 38.0)
Po-214 in LAr	14.5 (9.0, 21.0)

Ra-226 on p+ surface:
A = 81.3/340.96/24/3600
A = 3 μBq

	BI [10^{-3} cts/(keV kg yr)]
alpha model	2.85 (2.3, 3.4)
Po-210 on surface	0.67 (0.64, 0.70)
Ra-226 & daughters on surface	0.045 (0.03, 0.06)
Rn-222 & daughters in LAr	2.15 (1.6, 2.7)

Phase I: Analysis of alpha-induced background

GTF112, golden data set **fit window: (3500 – 7500) keV** **p-value: 0.89**



Parameters	**Mode (smallest int.)**
Po-210 sur	55.0 (40, 70)
Ra-226 sur	18.5 (13, 26)
Rn-222 sur	10.5 (6, 15)
Po-218 sur	9.5 (6, 14)
Rn-222 in LAr	17.5 (9, 25)
Po-218 in LAr	15.5 (9, 24)
Po-214 in LAr	15.5 (10, 22)

Ra-226 on p+ surface:
A = 38/308.37/24/3600
A = 1.4 μBq

	BI [10^{-3} cts/(keV kg yr)]
alpha model	6.4 (5.1, 7.9)
Po-210 on surface	0.17 (0.13, 0.20)
Ra-226 & daughters on surface	0.16 (0.12, 0.20)
Rn-222 & daughters in LAr	6.1 (4.7, 7.5)