Study of the CUORE background sources: identification and prospects

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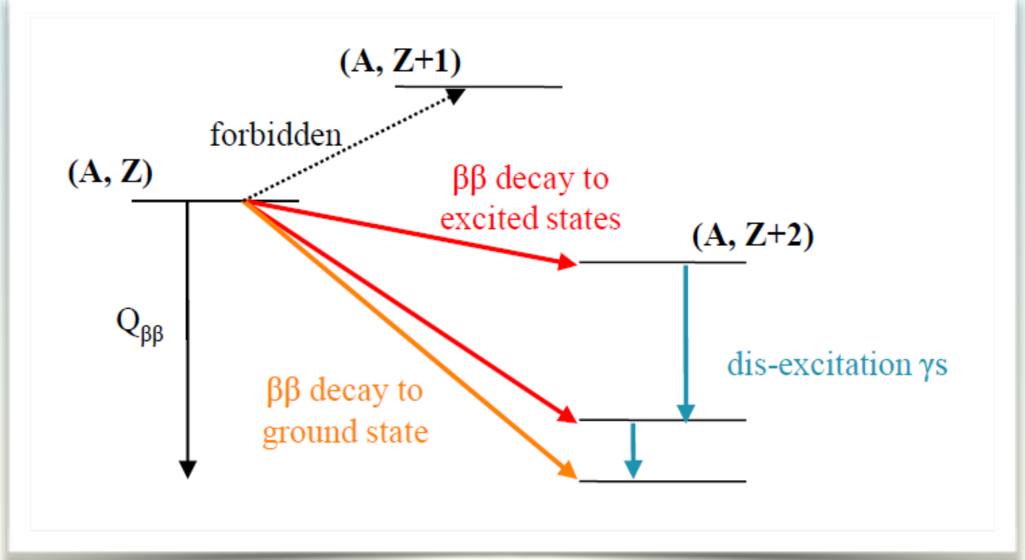
Neutrinoless double beta decay ($0\nu\beta\beta$)

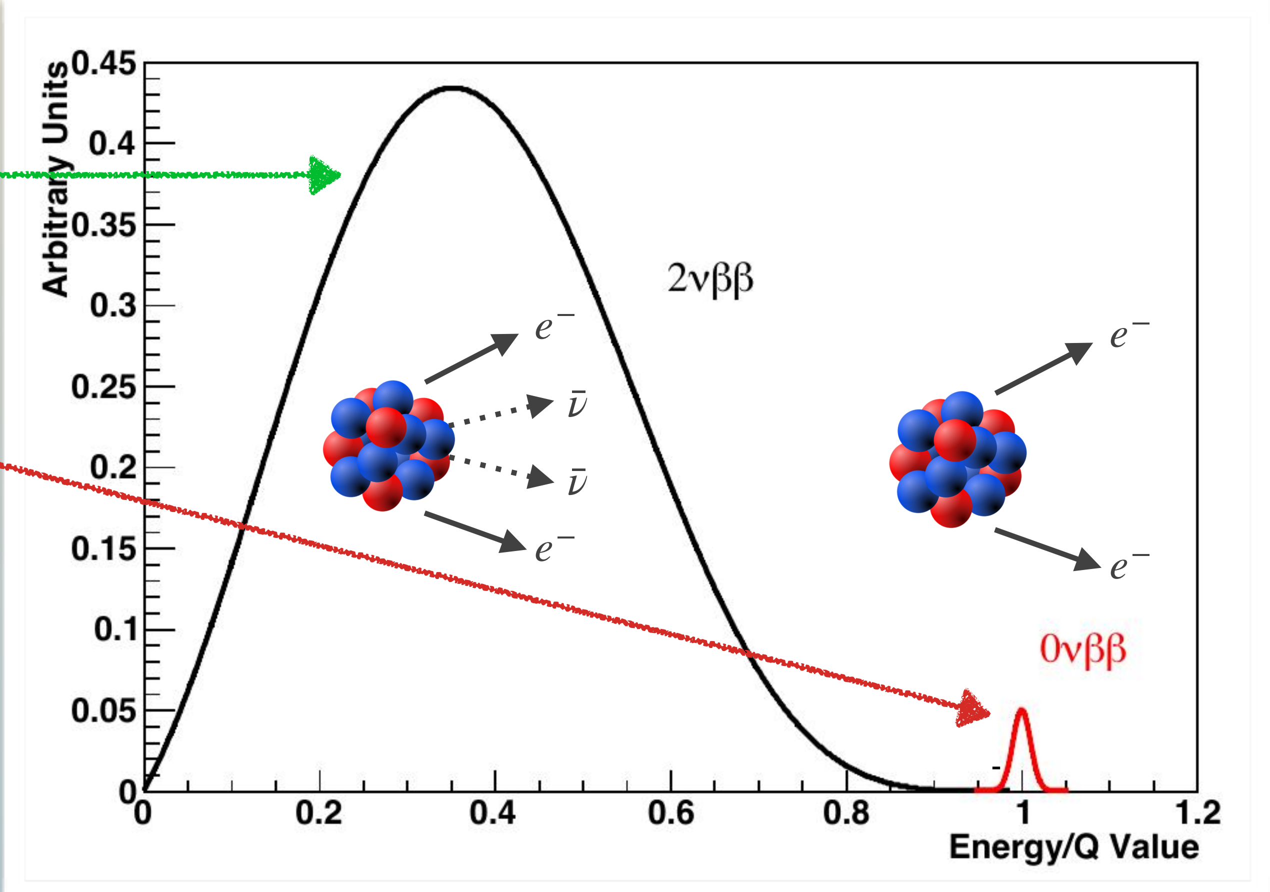
- Double beta decay: rare second order β decay
  $Z \rightarrow Z \pm 2$

- Allowed for certain even-even nuclei where the standard single β decay is energetically forbidden

- Two decay modes:
  - OBSERVED ✓ two-neutrino double beta decay — $|\Delta L| = 0$
  - **neutrinoless double beta decay ?** — $|\Delta L| = 2$

Standard Model forbidden





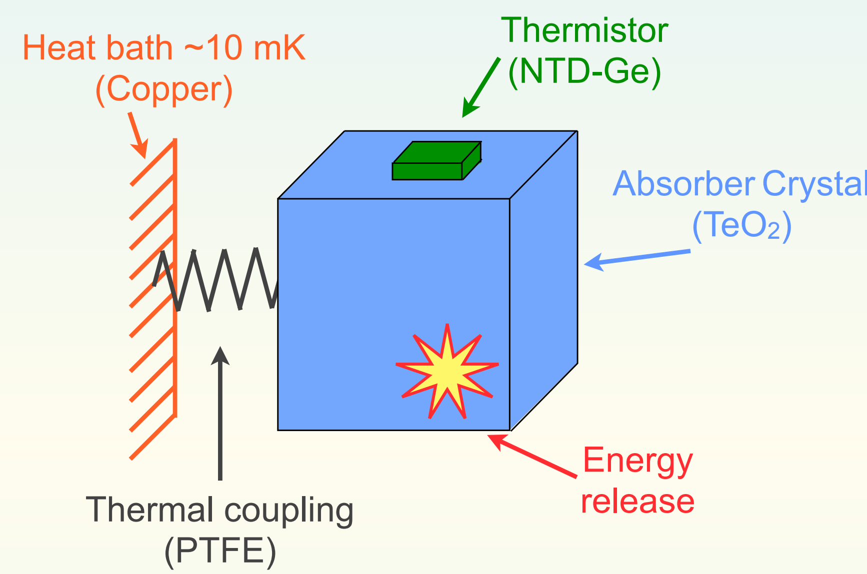
WHAT IF OBSERVED?

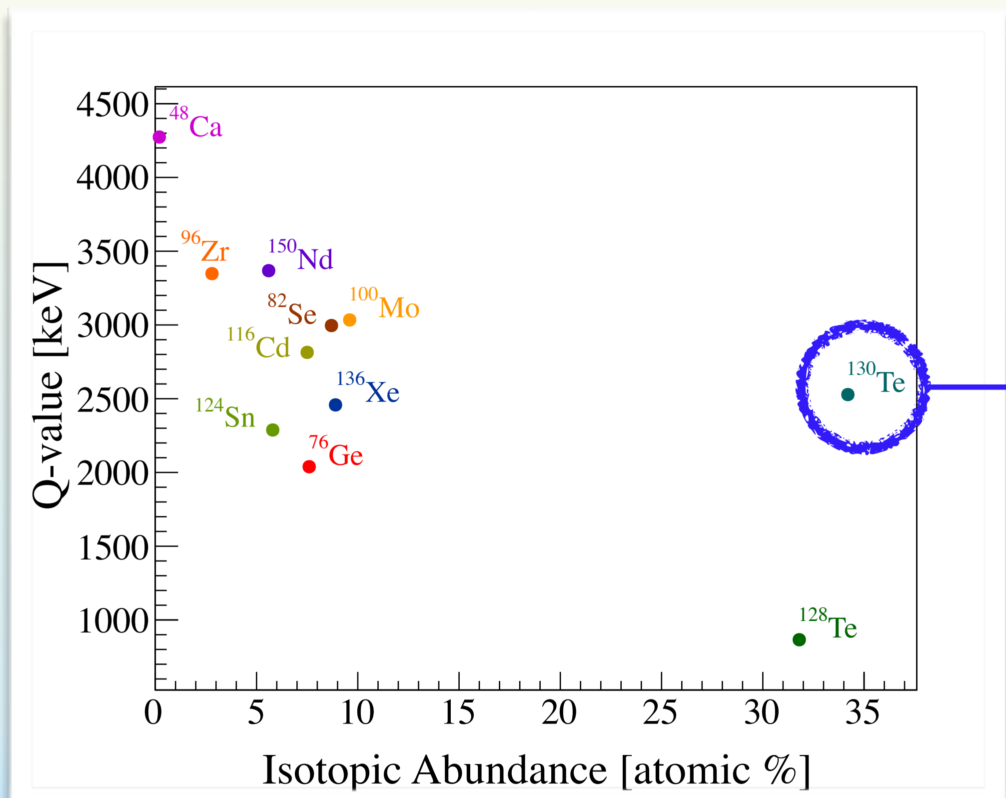
- Lepton number violation
- Majorana nature of the neutrino
- Constrains on absolute ν mass scale and hierarchy

CUORE: Cryogenic Underground Observatory for Rare Events

Search for $0\nu\beta\beta$ decay of ^{130}Te with cryogenic bolometers:

- Excellent energy resolution (few ‰)
- TeO_2 bolometer: ^{130}Te is a constituent of the detector itself $\longrightarrow$ $\epsilon \sim 90\,\%$
- Signal amplitude: $\propto \Delta T = \dfrac{\Delta E}{C(T)}$, $C(T) \propto T^3$
- **Cryogenic temperature needed (~10 mK)**



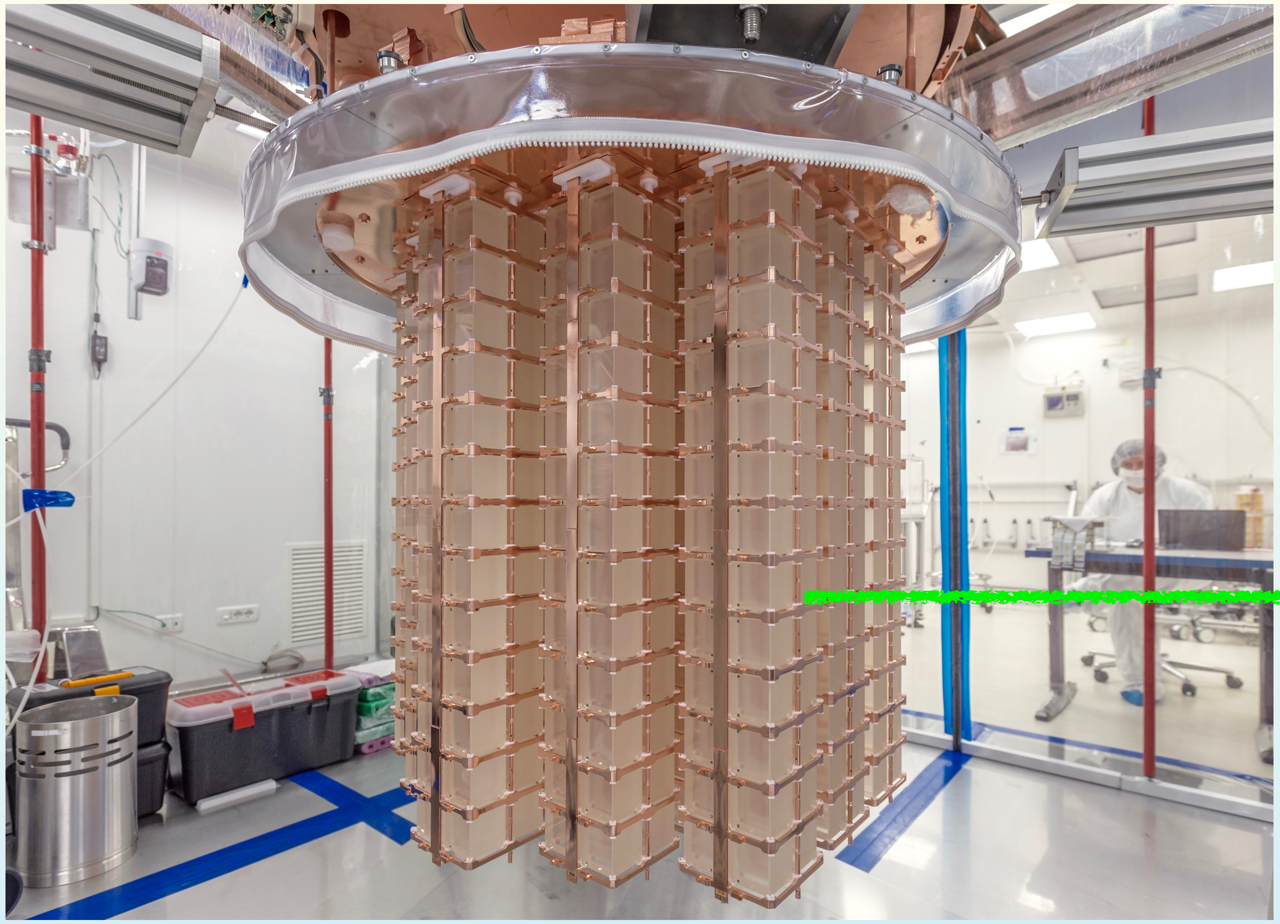


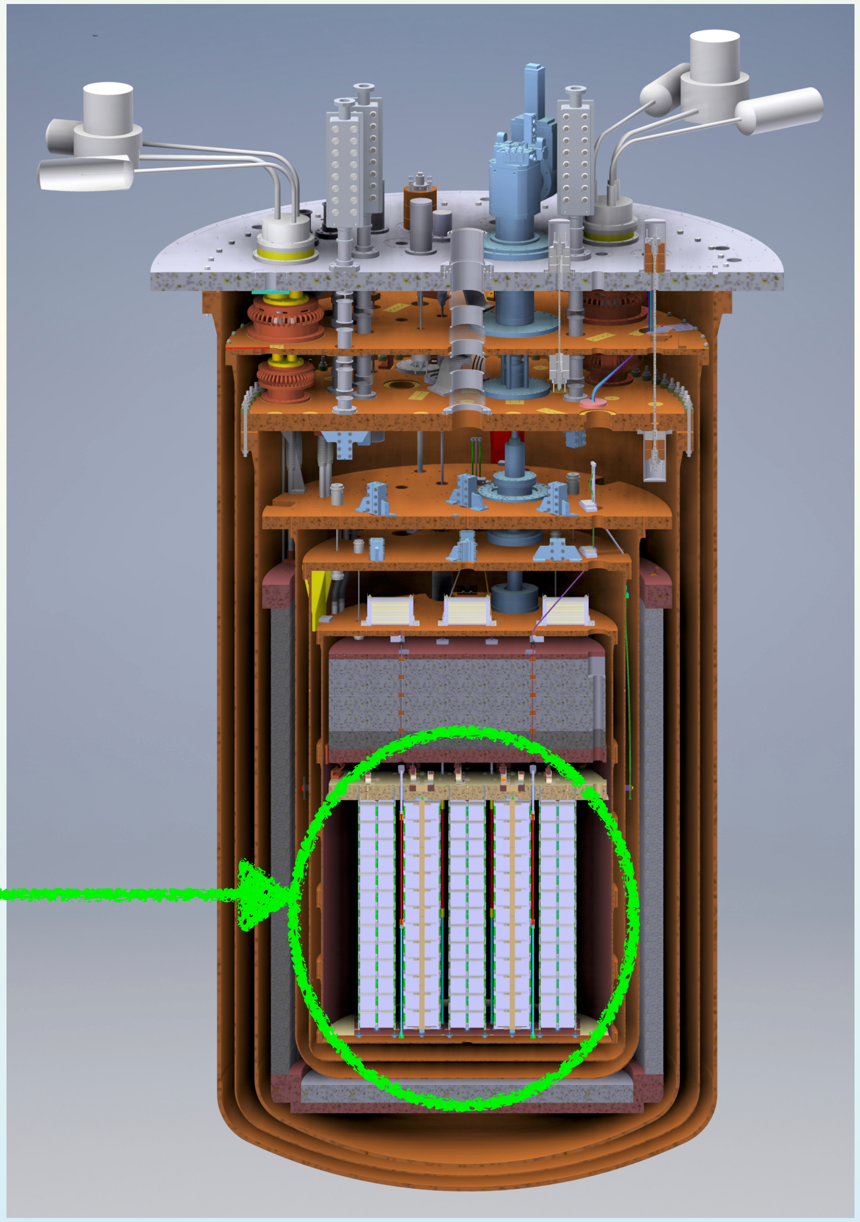
CUORE: $0\nu\beta\beta$ in ^{130}Te

- $\eta(^{130}\mathrm{Te}) = 34.167\%$
- $Q_{value} = 2528$ keV : between the highest ^{208}Tl peak and its Compton edge

CUORE: Cryogenic Underground Observatory for Rare Events

- 988 cryogenic TeO_2 bolometers
- 742 kg of total TeO_2 mass, with ~ 206 kg of ^{130}Te emitter isotope
- Bolometers working temperature: ~ 10 mK (custom built multi-stage cryostat)





CUORE background model

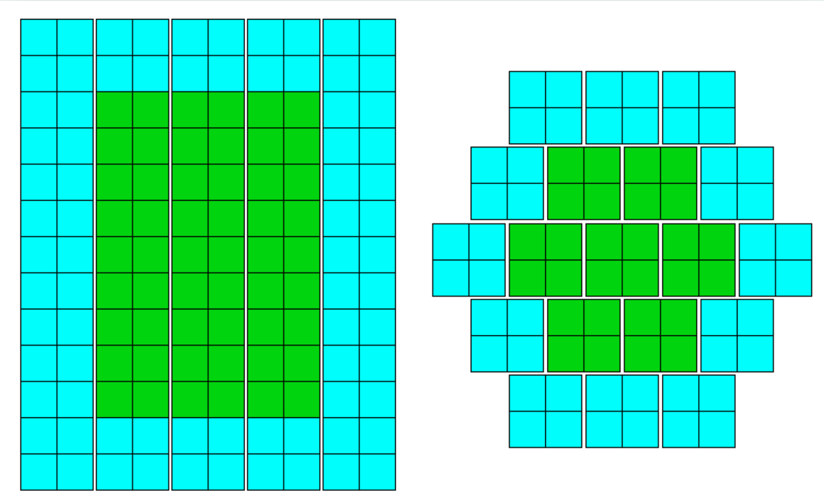
BACKGROUND MODEL: identify, locate and evaluate the intensity of all the sources contributing to the observed background spectra

Detailed Monte Carlo simulation →

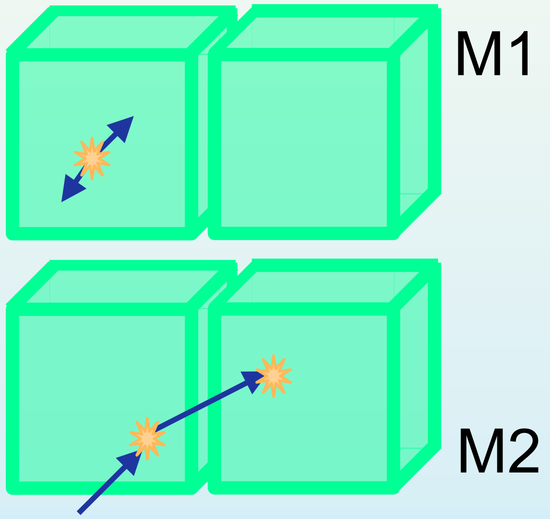
- Geometry of the experimental setup
- Radioactive sources and their locations
- Radiation interactions with the different parts of the detector
- Detector response, instrumental effects (thresholds, resolution,…)

Granularity of the detector exploited:

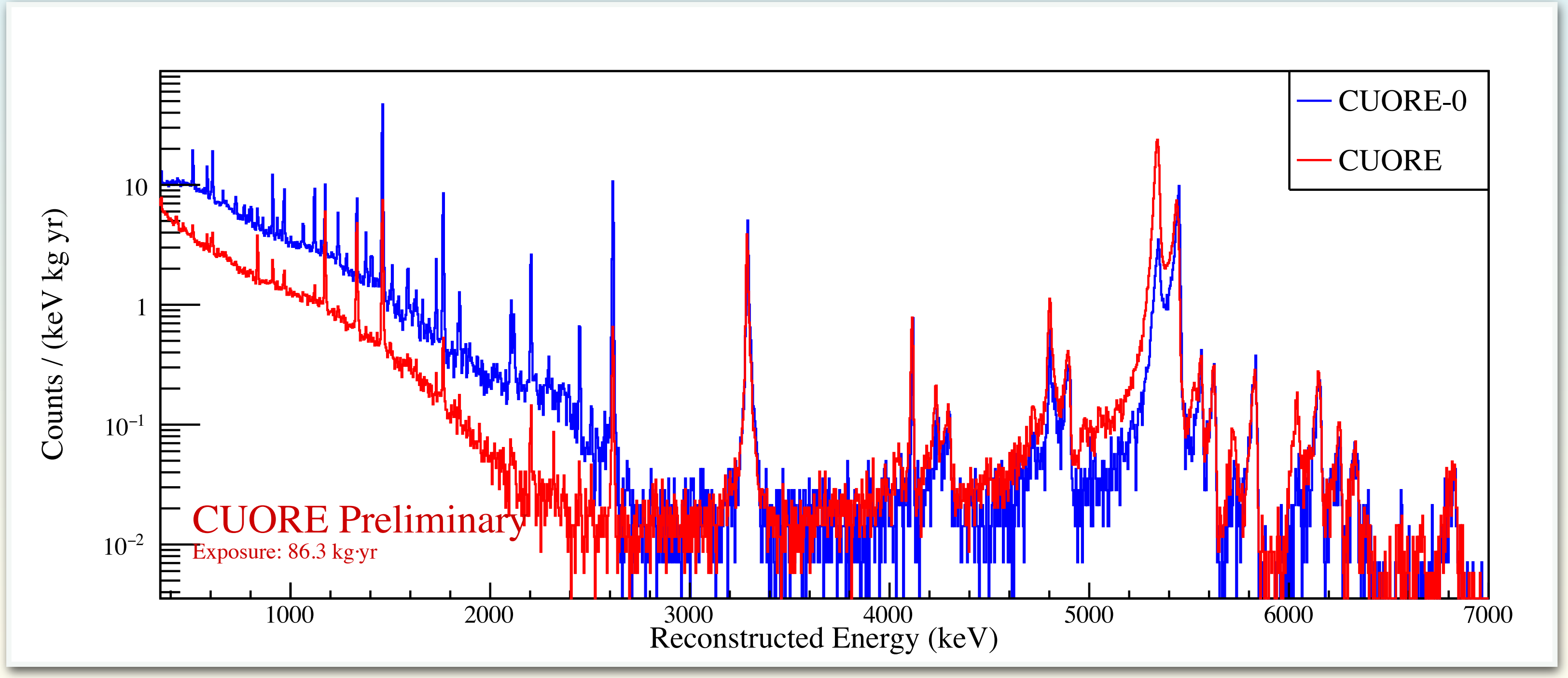
INNER AND OUTER LAYER



EVENT MULTIPLICITY (M1, M2, …)

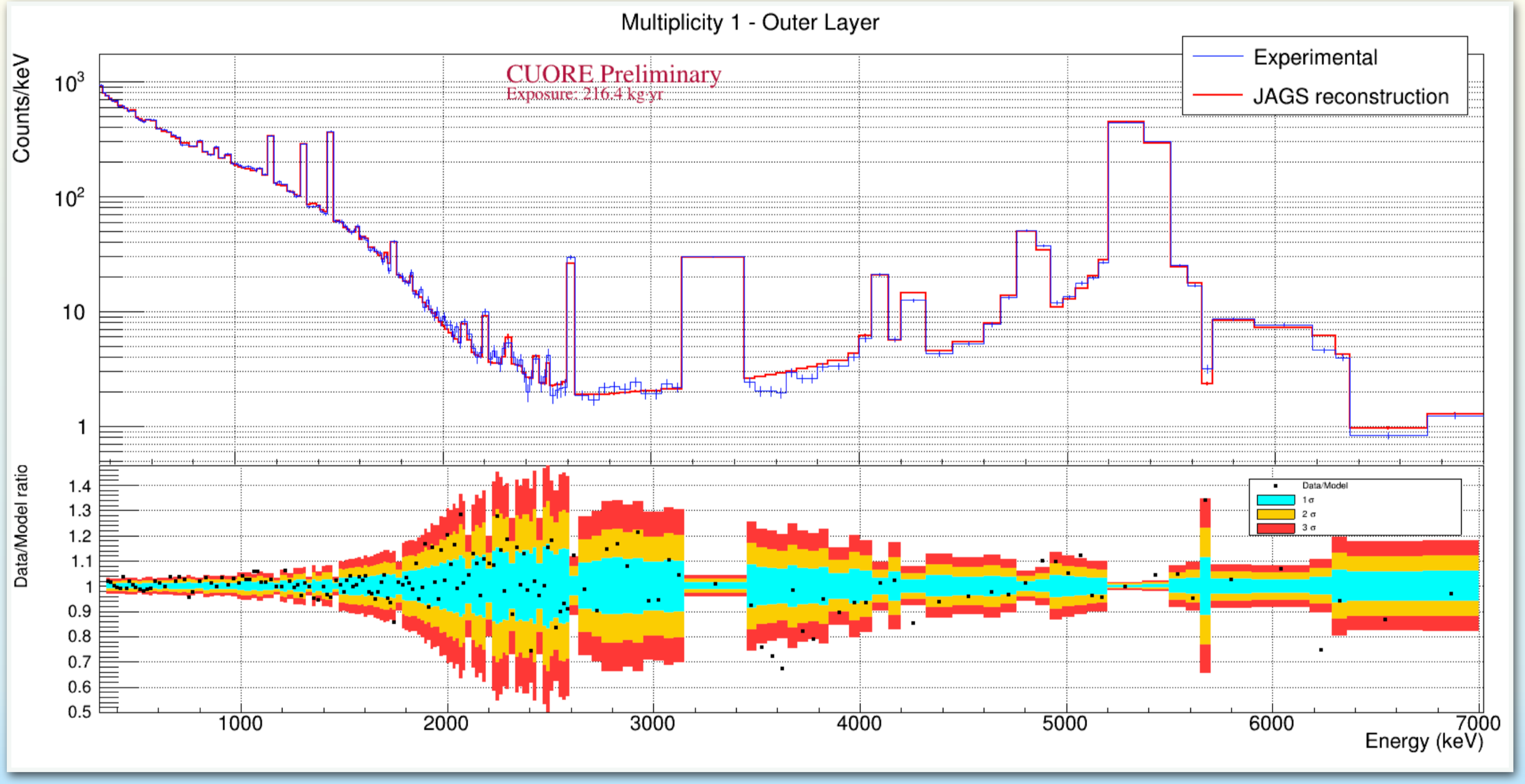


CUORE background model



Primary contribution to the background in CUORE: contamination of the crystal and the copper shields

- 60 background sources simulated
- Bayesian MCMC fit with flat priors (except muons):



Radioactive sources

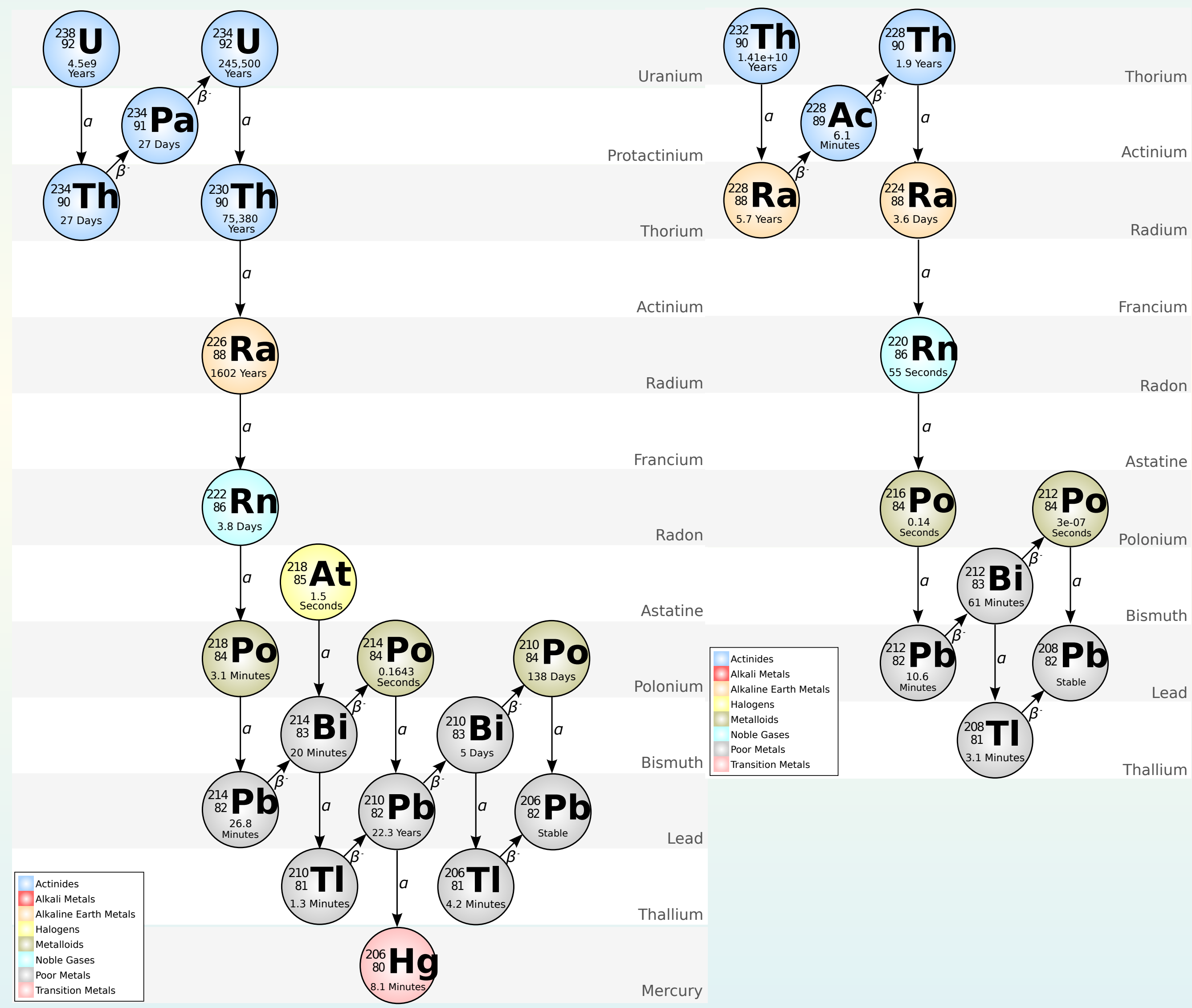
TeO_2 crystals and copper contamination:

α Region (above 2615 keV):

- All main α from ^{238}U chain
- All main α from ^{232}Th chain
- ^{190}Pt (crystal bulk)

$\beta - \gamma$ Region (below 2615 keV):

- tails of the degarded α emitted by material surfaces
- ^{232}Th chain γ lines
- ^{238}U chain γ lines
- ^{40}K (environment)
- ^{60}Co (Cu cosmogenic activation)
- ^{210}Po, ^{108m}Ag, ^{202}Pb, ^{207}Bi



A better understanding of the amount and the position of these contaminants will improve the present background model.

Understanding the radioactive sources

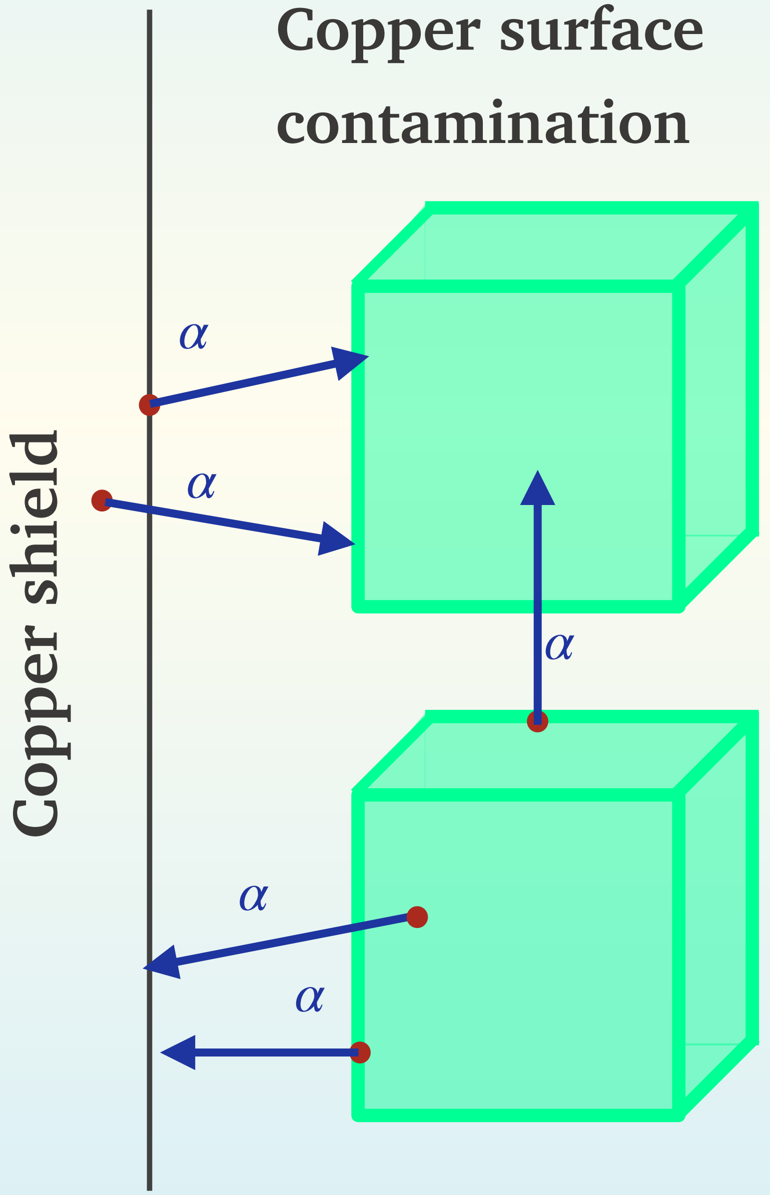
- Contaminations topology
- Time dependence of the contaminations rate
- Event correlations (coincidence)

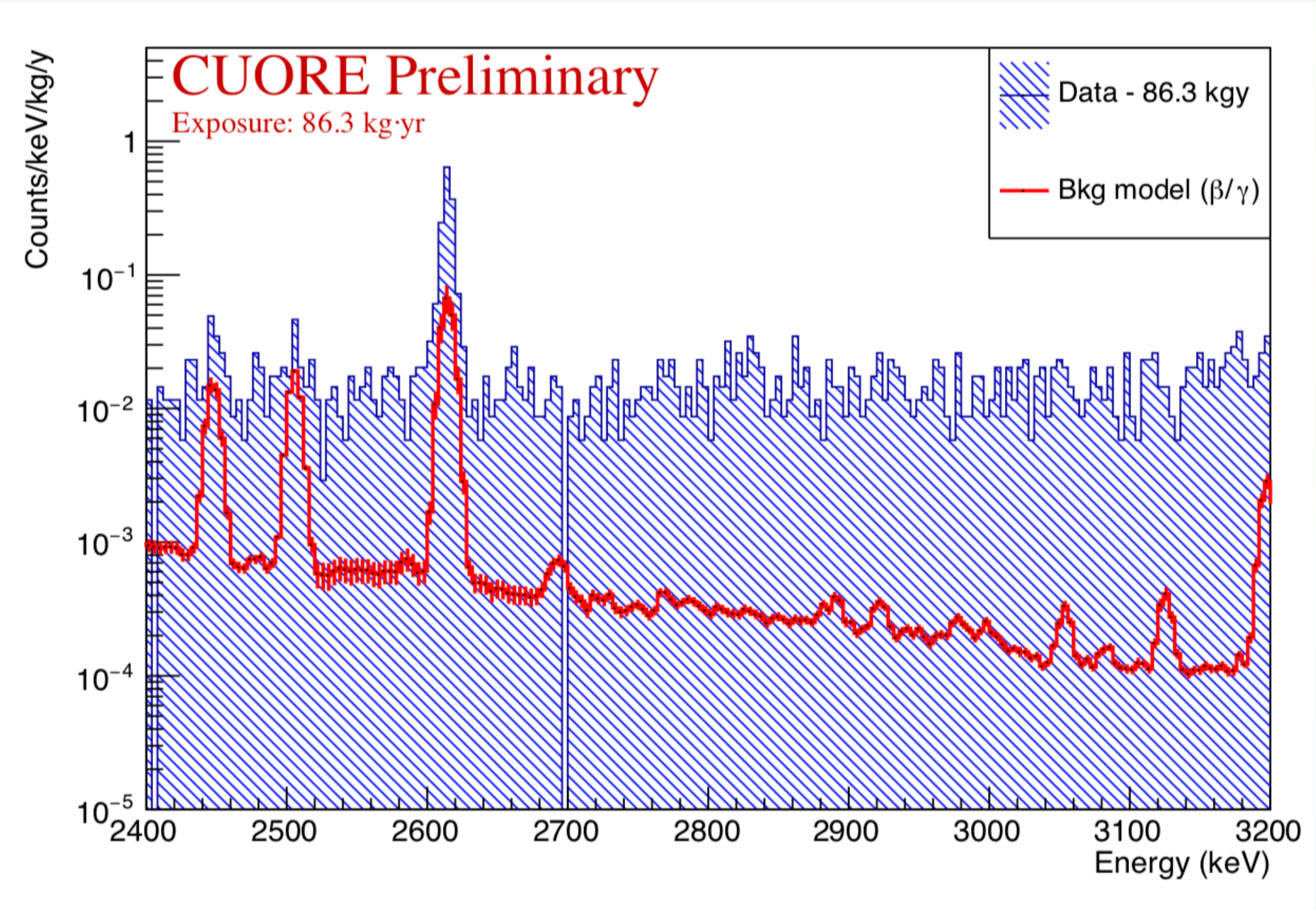
- The following preliminary analysis includes data from spring 2017 to mid-summer 2019 (~400 kg yr exposure)
- I was in charge of the online monitoring of the quality of about one third of these data

GOAL: include new input to the present background model for a precise and correct interpretation of the data and results

Degraded alpha

Part of the background in the CUORE ROI (2490 - 2575 keV) is due to degraded alphas.

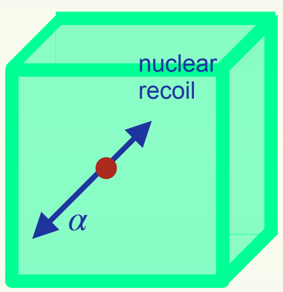




Alpha contributions

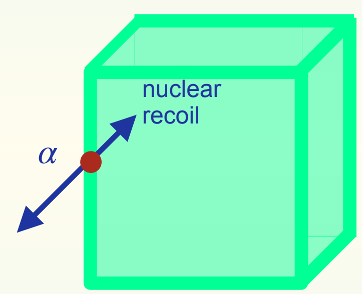
α decay: $E_{tot} = E(\alpha) + E(\text{nuclear recoil})$

Different positions of the contaminant correspond to different signatures:



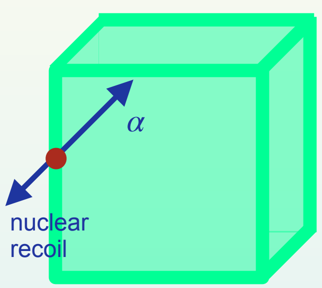
Bulk contaminant

M1, $E_{meas} = E_{tot}$



Surface contaminant

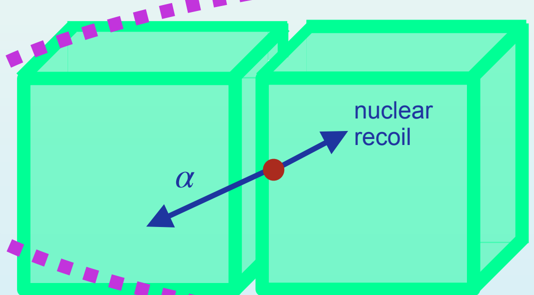
M1, $E_{meas} = E(\text{recoil})$



Surface contaminant

M1, $E_{meas} = E(\alpha)$

I started investigating this case of surface contamination



Surface contaminant

M2 single energy: $E^{(1)}_{meas} = E(\alpha)$, $E^{(2)}_{meas} = E(\text{recoil})$

M2 total energy: $E_{meas} = E_{tot}$

Alpha contributions

- Study of the alpha and recoil peaks positions in energy
- Fit function: Crystalball = Gaussian function ($\bar{x}$ = mean, σ = standard dev.) with a n power law tail smoothly joined to the Gaussian at $\bar{x} - \alpha\sigma$ (α and n are tail parameters)

$$f(x;\alpha,n,\bar{x},\sigma) = N \cdot \begin{cases} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} & \text{for } \frac{x-\bar{x}}{\sigma} > -\alpha \\ A \cdot \left(B - \frac{x-\bar{x}}{\sigma}\right)^{-n} & \text{for } \frac{x-\bar{x}}{\sigma} \leq \alpha \end{cases}$$

Where: $A = \left(\frac{n}{|\alpha|}\right)^n \cdot e^{-\frac{|\alpha|^2}{2}}$ $\quad B = \frac{n}{|\alpha|} - |\alpha|$ $\quad N$ = normalization factor depending on α, n

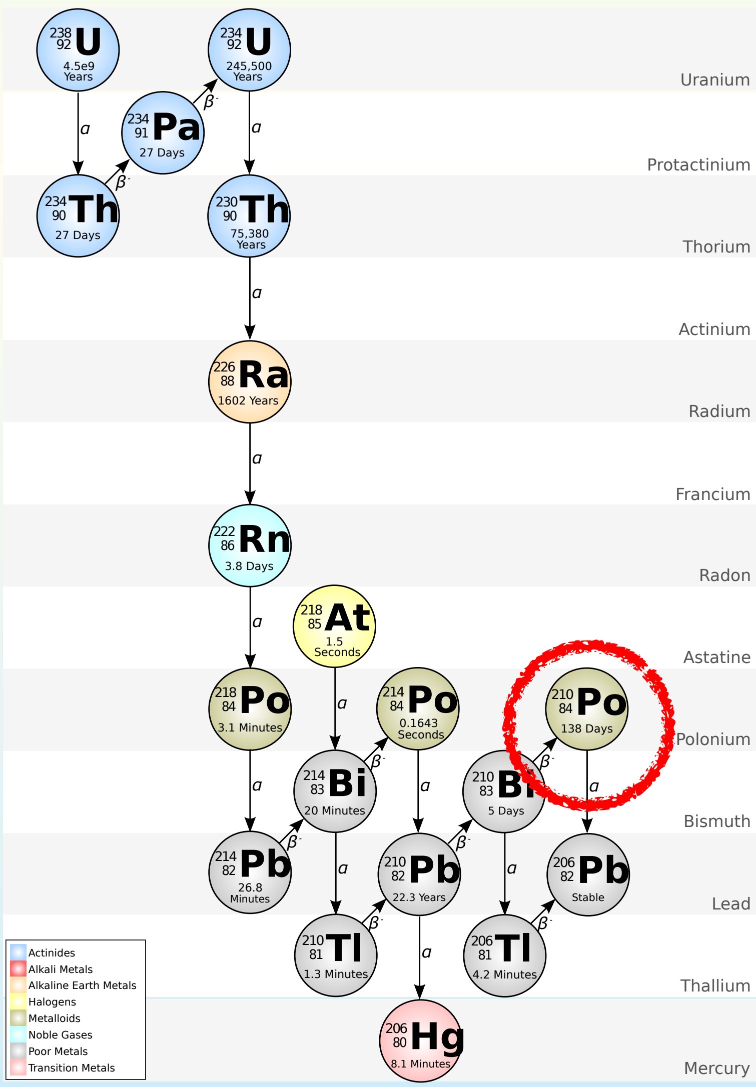
Fit parameters: N, α, n, $\bar{x}$, σ

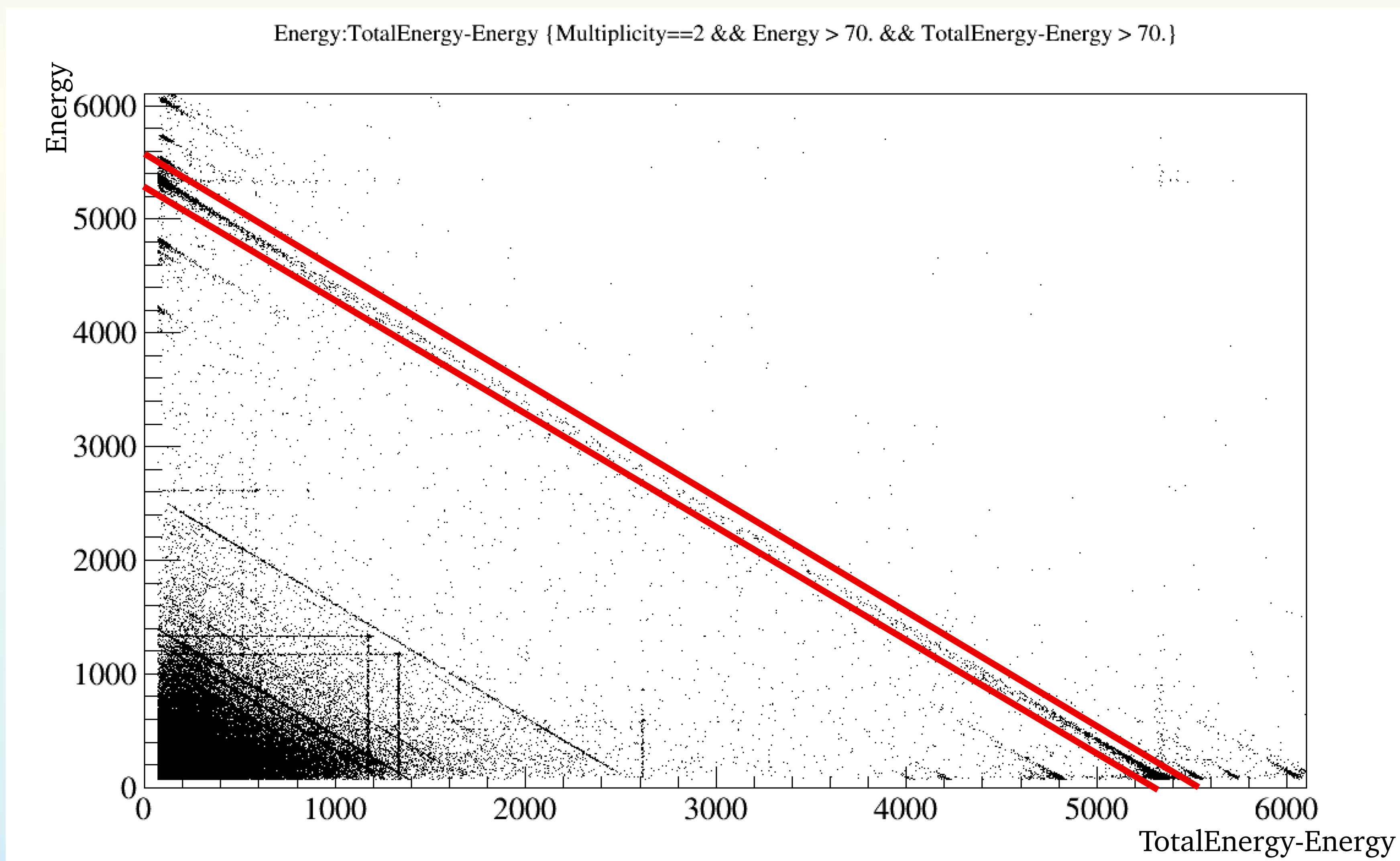
Alpha contributions: ^{210}Po

- $^{210}\mathrm{Po} \longrightarrow {}^{206}\mathrm{Pb} + \alpha$
- Events selection:
  - ➡ Multiplicity 2, single event energy spectrum
  - ➡ Cut on total energy to select the ^{210}Po α decay

^{210}Po alpha decay (nominal values)

- $E(\alpha) = 5304.38$ keV
- $E(\mathrm{recoil}) = 103.08$ keV
- $E_{tot} = 5407.46$ keV





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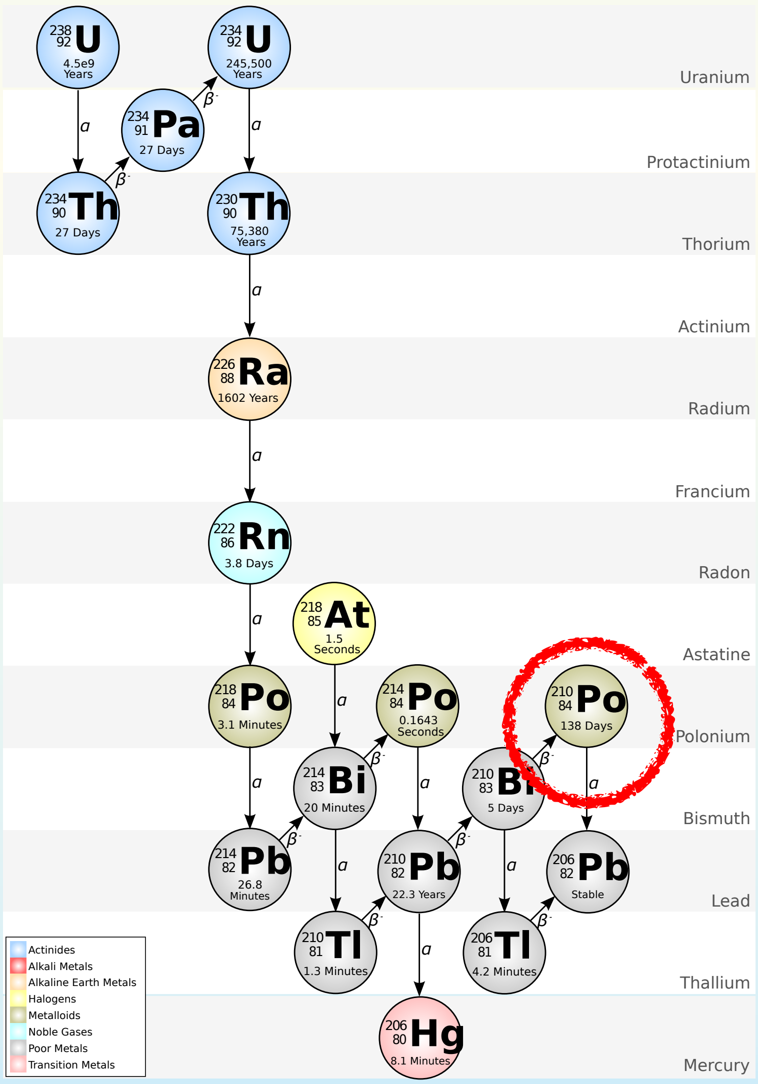

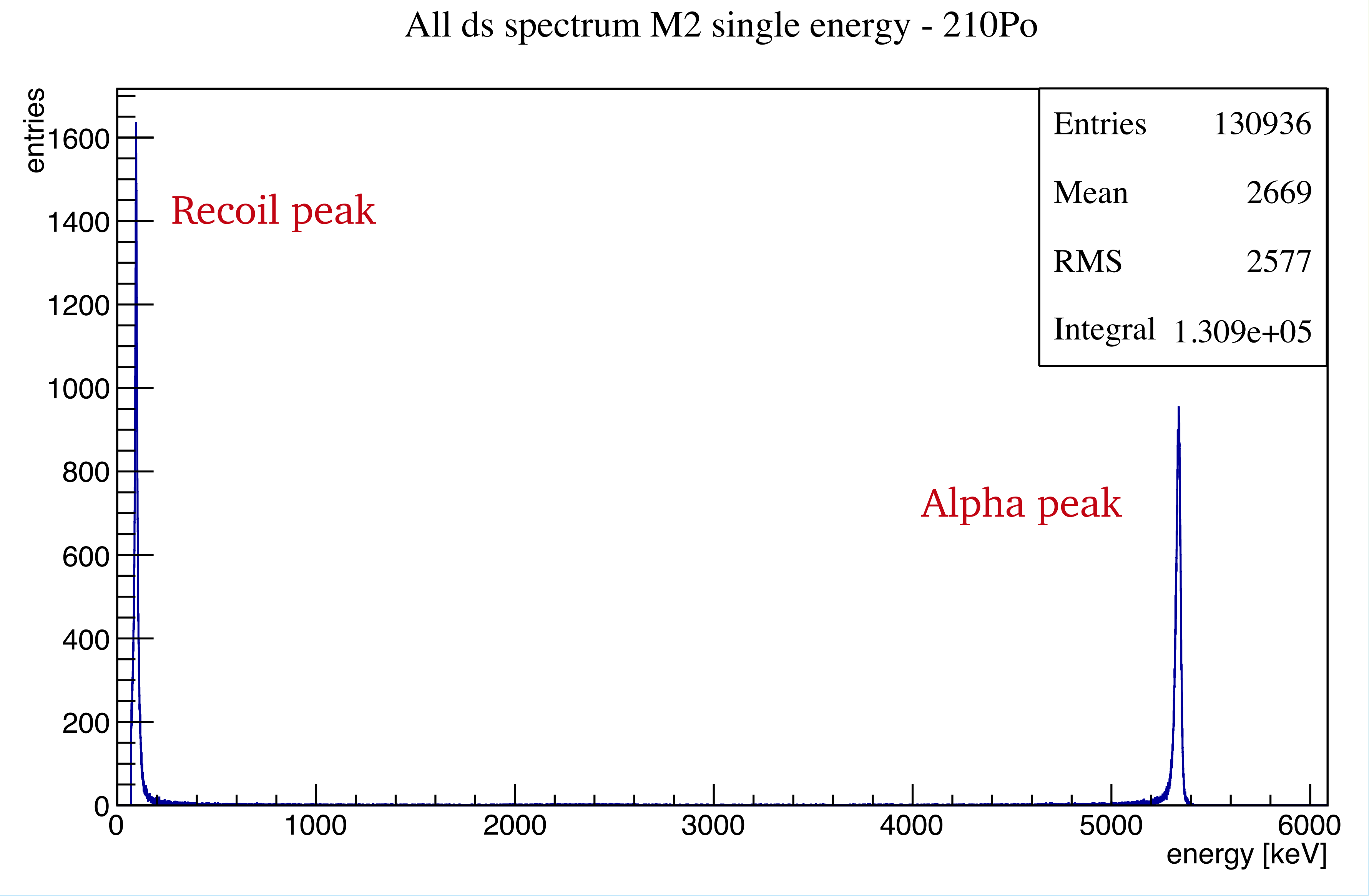

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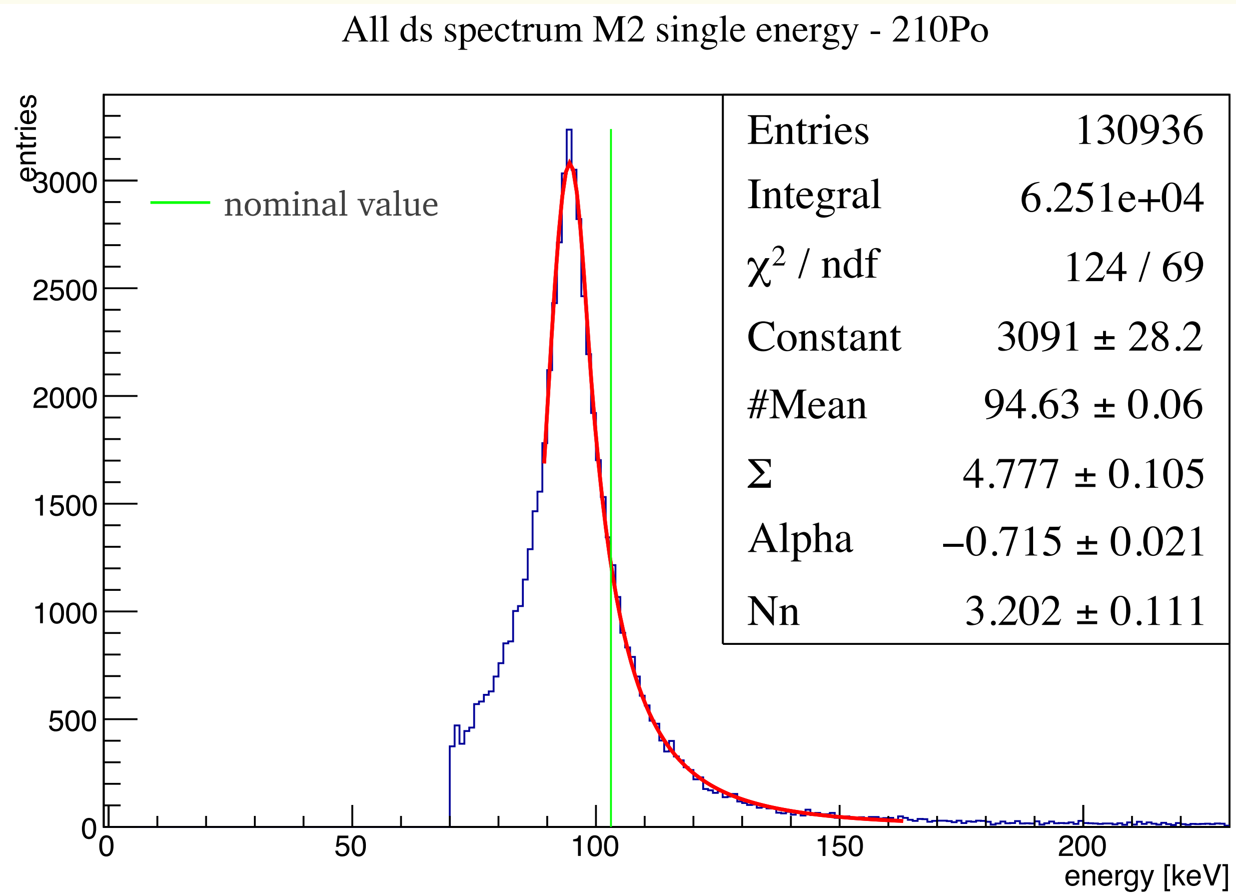
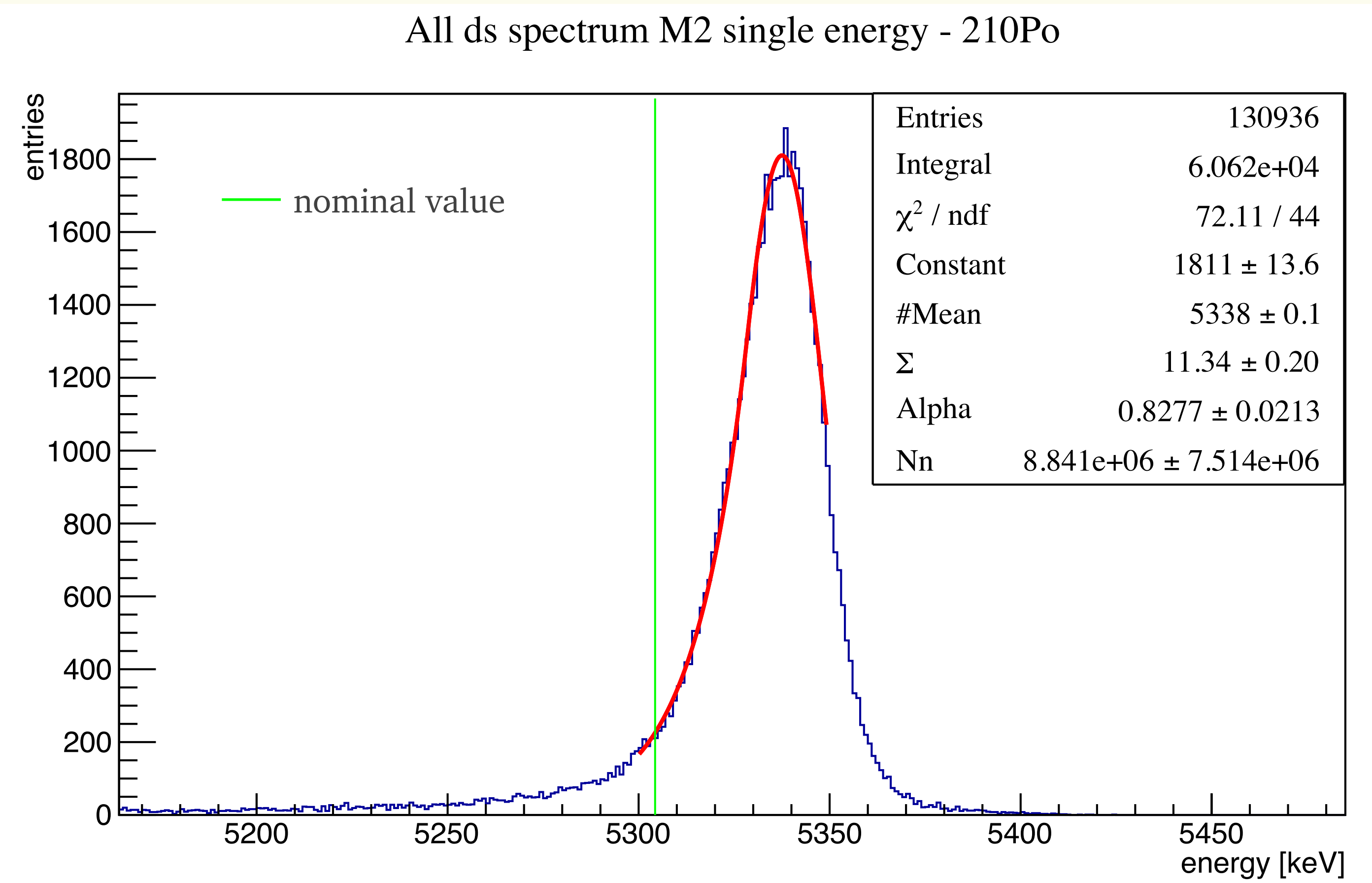


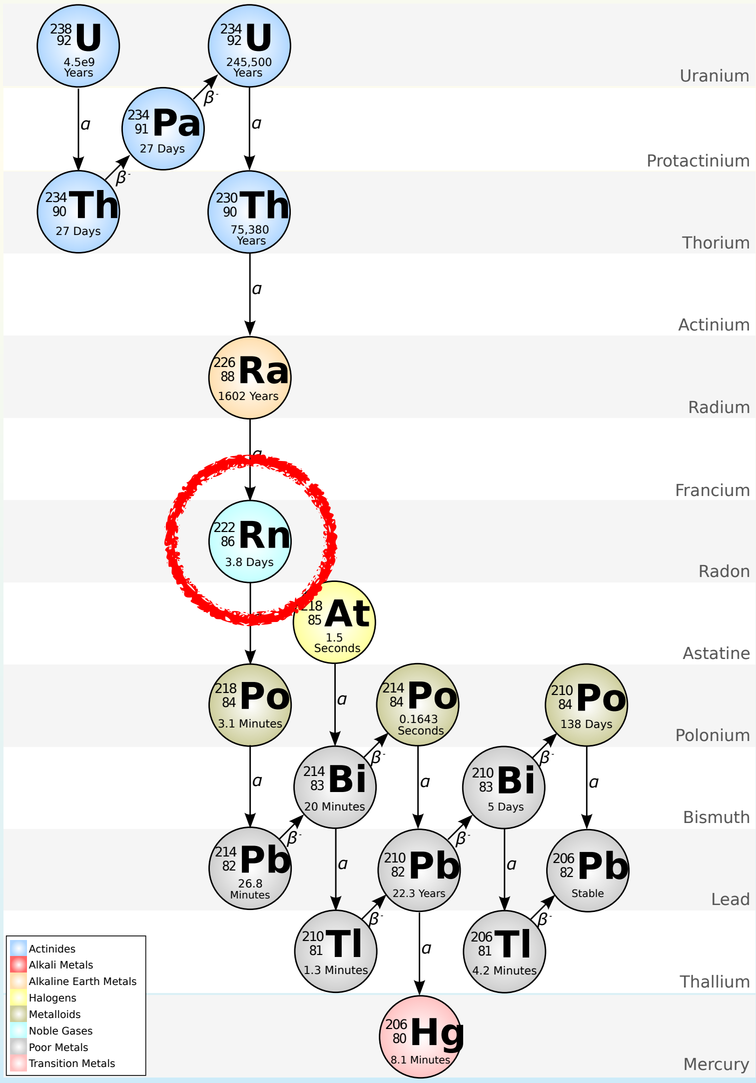


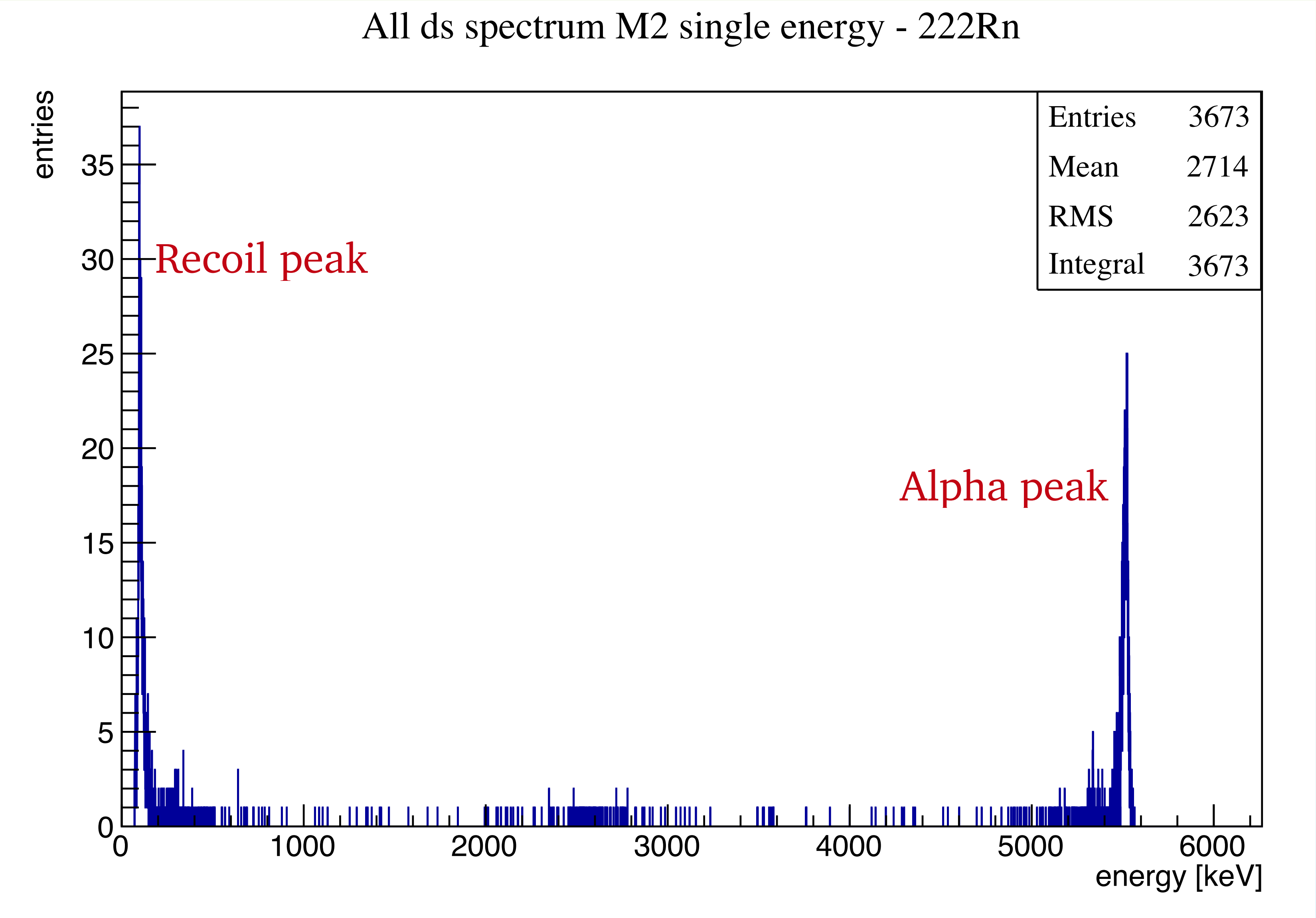
Alpha contributions: ^{222}Rn

- $^{222}\mathrm{Rn} \longrightarrow {}^{218}\mathrm{Po} + \alpha$
- Events selection:
  - ➡ Multiplicity 2, single event energy spectrum
  - ➡ Cut on total energy to select the ^{222}Rn α decay

^{222}Rn alpha decay (nominal values)

- $E(\alpha) = 5489.52$ keV
- $E(\mathrm{recoil}) = 100.78$ keV
- $E_{tot} = 5590.30$ keV





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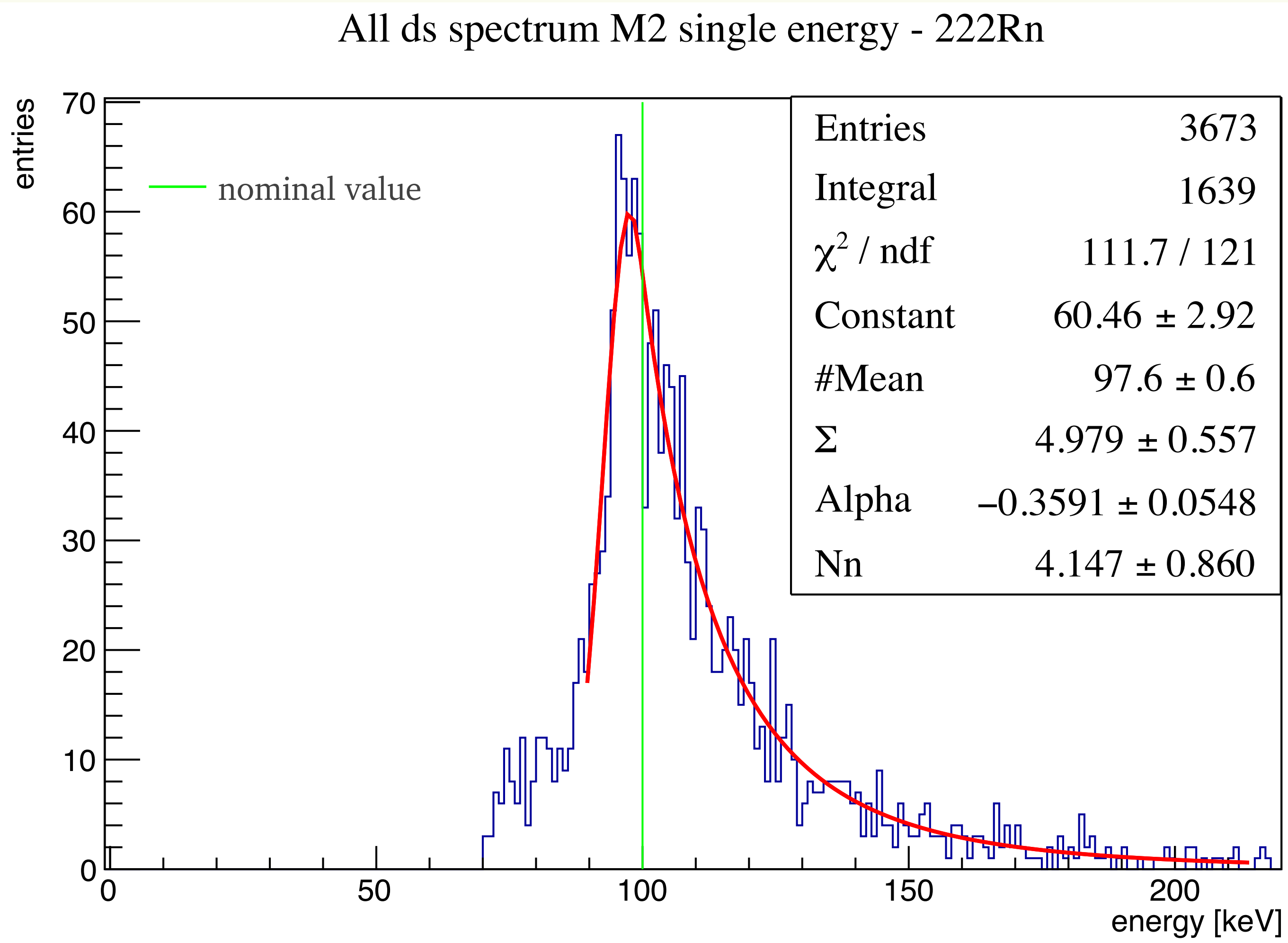
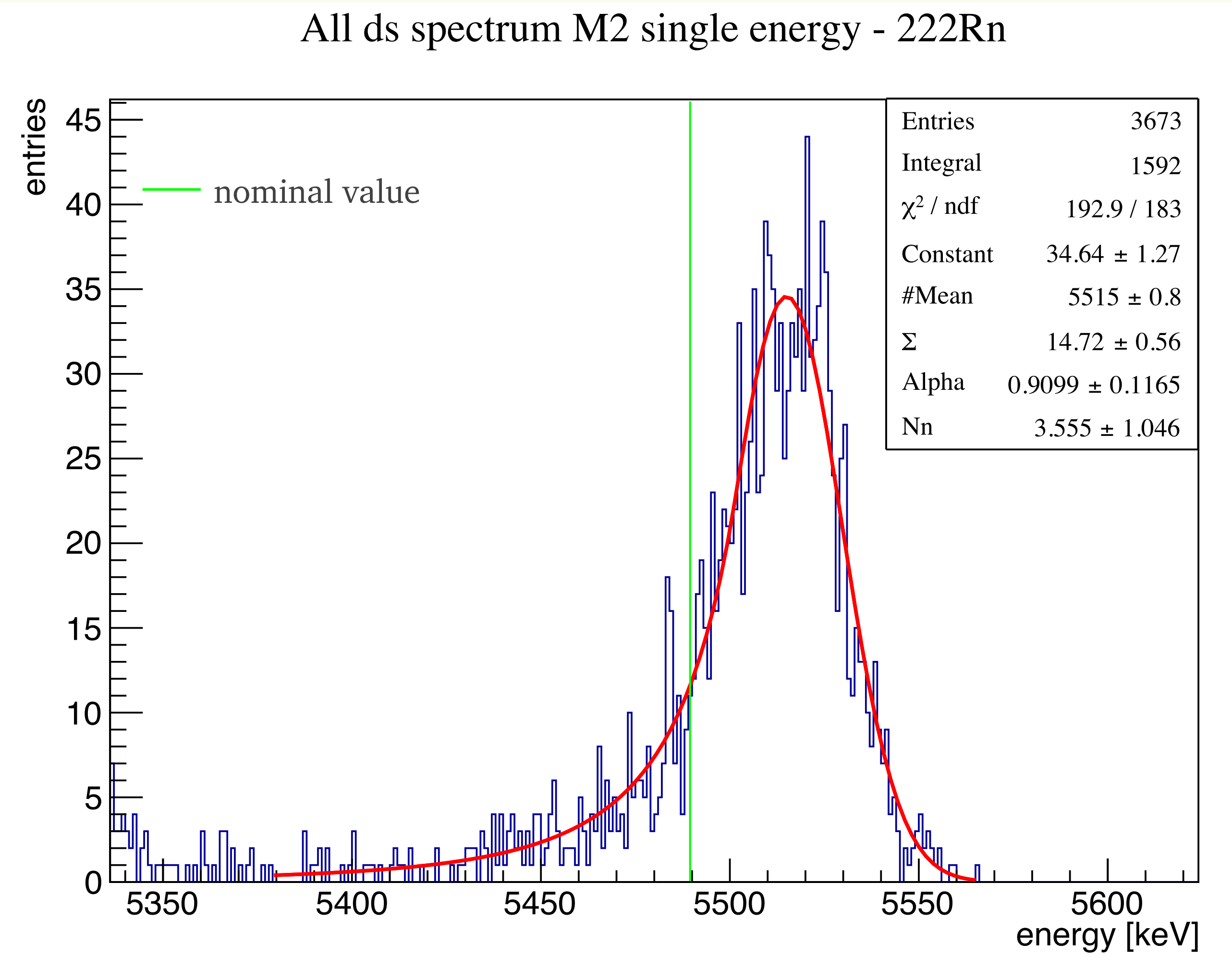
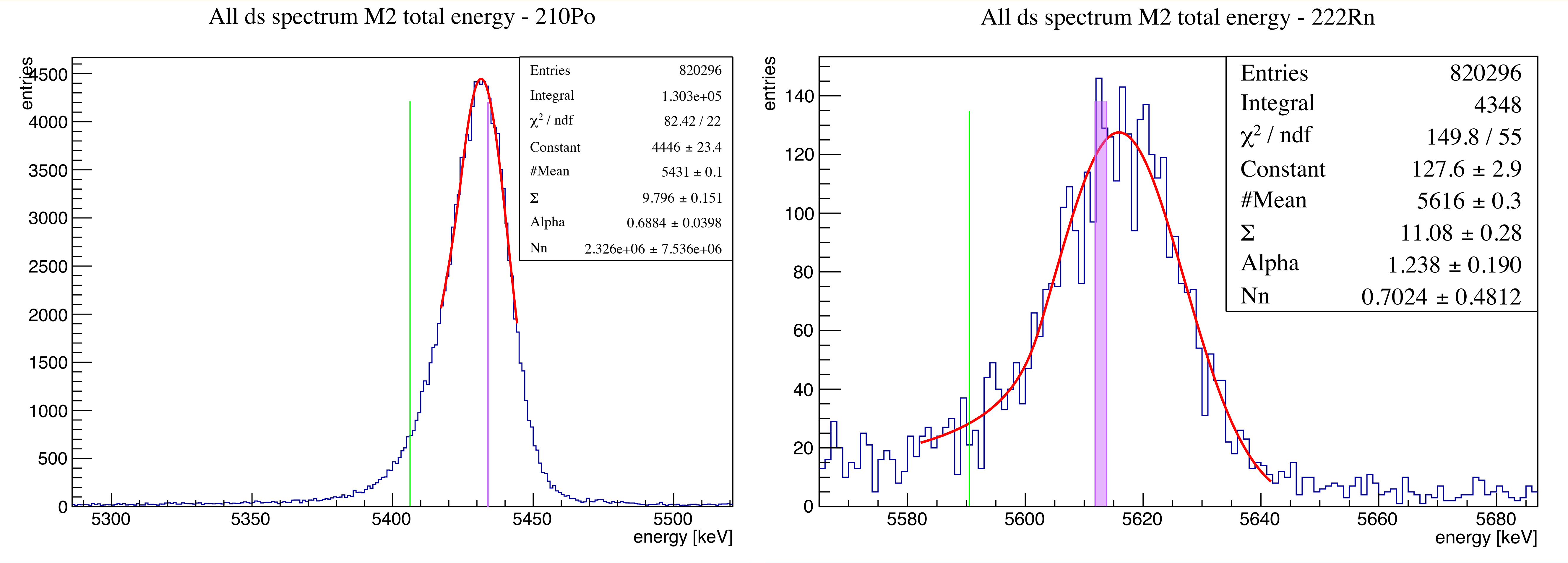




Alpha contributions

- Multiplicity 2, total energy spectrum (alpha+recoil)
- Zoom on Q_{value} peaks of ^{210}Po and ^{222}Rn alpha decay
- Green is nominal value, violet is the sum of reconstructed alpha and recoil peaks



Fit results

	Fit results	Nominal values
^{210}Po - alpha:	(5338.0±0.1) keV	5304.38 keV
^{222}Rn - alpha:	(5515.0±0.8) keV	5489.52 keV
^{210}Po - recoil:	(94.63±0.06) keV	103.08 keV
^{222}Rn - recoil:	(97.6±0.6) keV	100.78 keV

QUENCHING FACTOR (q)
An α particle interacting with TeO_2 crystals generates a signal that is higher than expected $\frac{E_{ee}}{E_{nominal}} \equiv q$

	Fit results	Reconstructed alpha+recoil	Nominal values
^{210}Po:	(5431.0±0.1) keV	(5432.6±0.1) keV	5407.46 keV
^{222}Rn:	(5616.0±0.3) keV	(5613±1) keV	5490.30 keV

- **Alpha peaks**: $(E_{meas}/E_{nom})_{Po} = 1.006$
  $(E_{meas}/E_{nom})_{Rn} = 1.005$ →

In CUORE-0 we had q=1.007; we don't expect a great difference in CUORE, this will be better quantified by studying all the possible alpha peaks

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- **Total energy peaks**: *fit results and sum of reconstructed alpha and recoil should be the same (Better fit model needed!)*

Outlook

NEXT STEPS:

- More precise modeling of the peaks
- Include fit systematics
- Study of other alpha peaks and calculation of quenching factor in CUORE
- Study of other recoil peaks and investigation of shifts origin
- Study of contaminations rate vs time, positions, …