PRECISE DETECTION OF THE ^{148}SM ALPHA DECAY

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ALPHA DECAYS

- Energetically allowed for naturally occurring isotopes with mass greater than 142, starting from Cerium element
- For the elements lighter than bismuth, the available decay energy is smaller than 3 MeV, with reduced probability of tunneling through the nuclear potential barrier (life-times longer than 10^{11} y)
- Last year, ^{151}Eu alpha decay has been observed and the half-life was measured to be $T_{1/2} = 4.6\times10^{18}$ y

Scintillating bolometer technique offers new opportunities for the investigation of rare nuclear processes through a combination of good energy resolution, high detection efficiency, possibility of particle discrimination, and high flexibility at utilizing main absorber material.

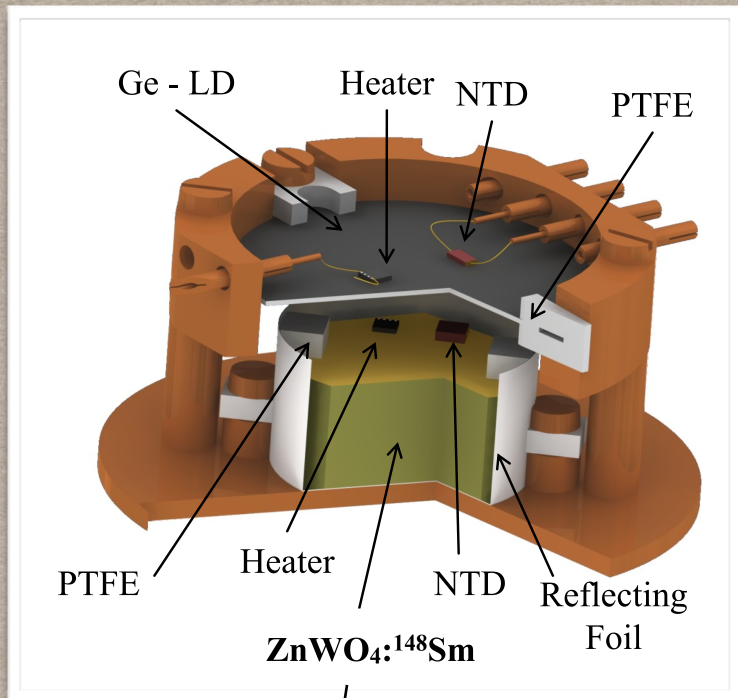
THE IDEA: DOPED $ZnWO_4$

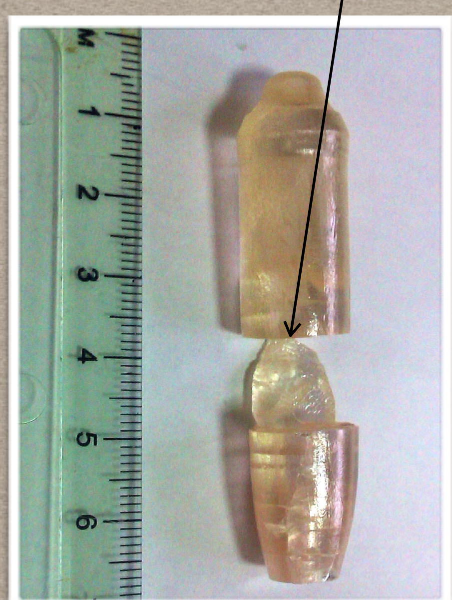
- Well-developed technology of production
- Non-hygroscopic material
- Good mechanical properties and easy handling
- High radiopurity
- High light yield at low temperature
- Successfully tested several times as a scintillating bolometer
- Can be doped by different elements up to level of about 1 wt%

Sm isotope	144	147	148	149	150	152	154
Enrichment, %	0.063(2)	0.909(8)	95.54(1)	2.569(9)	0.343(9)	0.384(6)	0.193(6)
Natural i.a.	3.07(7)	14.99(18)	11.24(10)	13.82(7)	7.38(1)	26.75(16)	22.75(29)

Our measurement turns to be a demonstrator for a new experimental approach!

THE DETECTOR

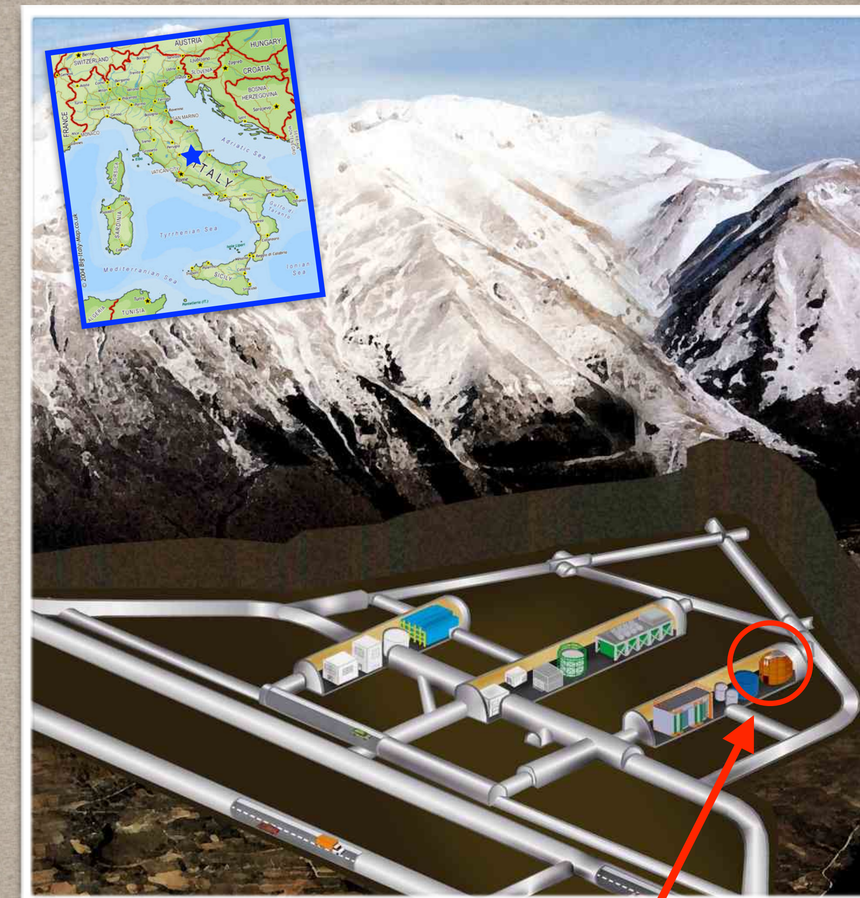




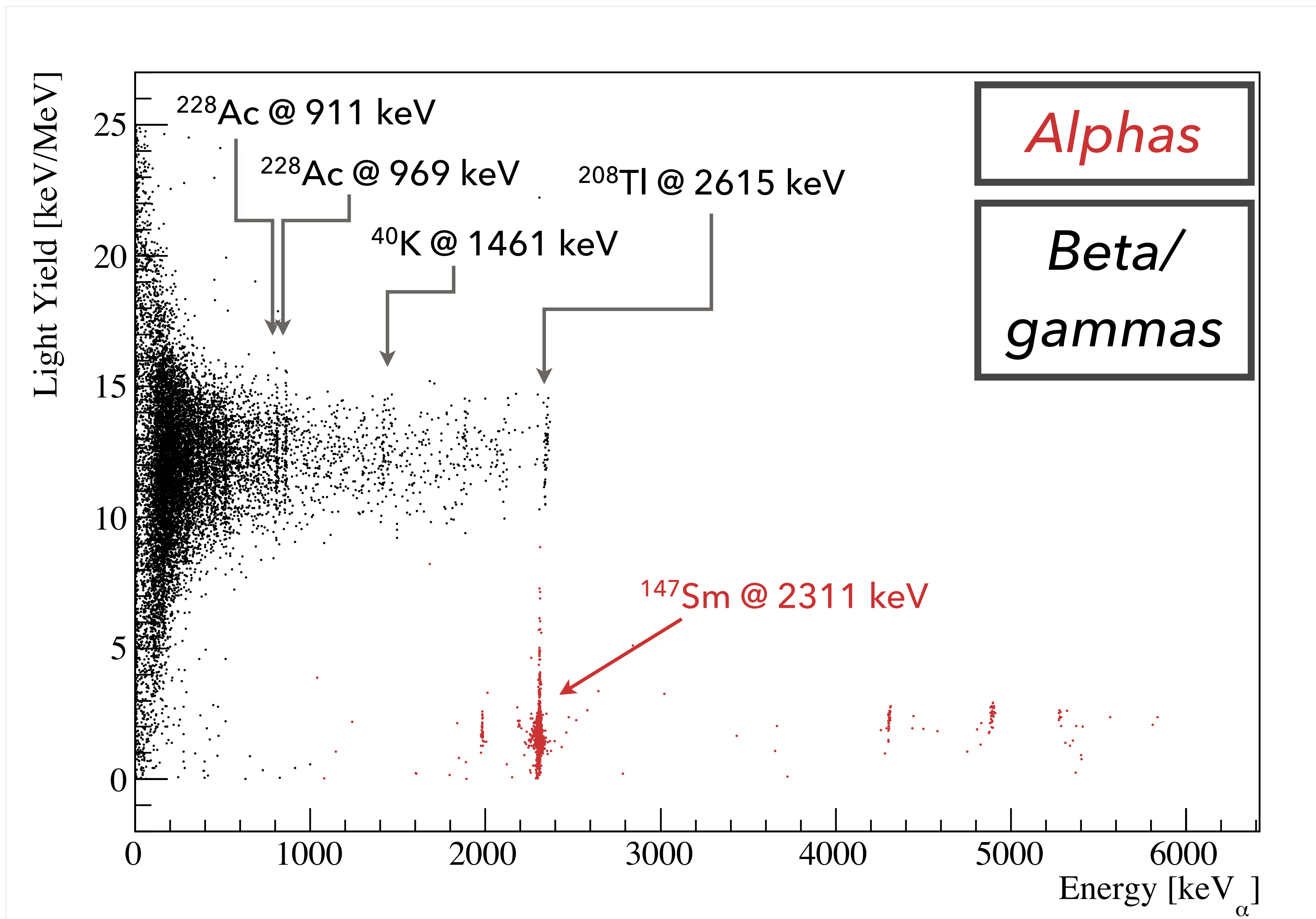
- 22.014 g $ZnWO_4$:^{148}Sm crystal
  - Growth: Czochralski method in air atmosphere
  - Materials: high purity (99.995%) ZnO, WO_3 plus $^{148}Sm_2O_3$ powder
  - Shape: irregular ($\varnothing$12 mm×20.7 mm)
- The crystal was surrounded by a reflecting foil (3M VM2002)
- The crystal was faced to a Ge disk ($\varnothing$50 mm×300 μm) used as light detector
- Both were equipped with NTD thermistors, glued via resin epoxy glue

THE DATA TAKING @LNGS

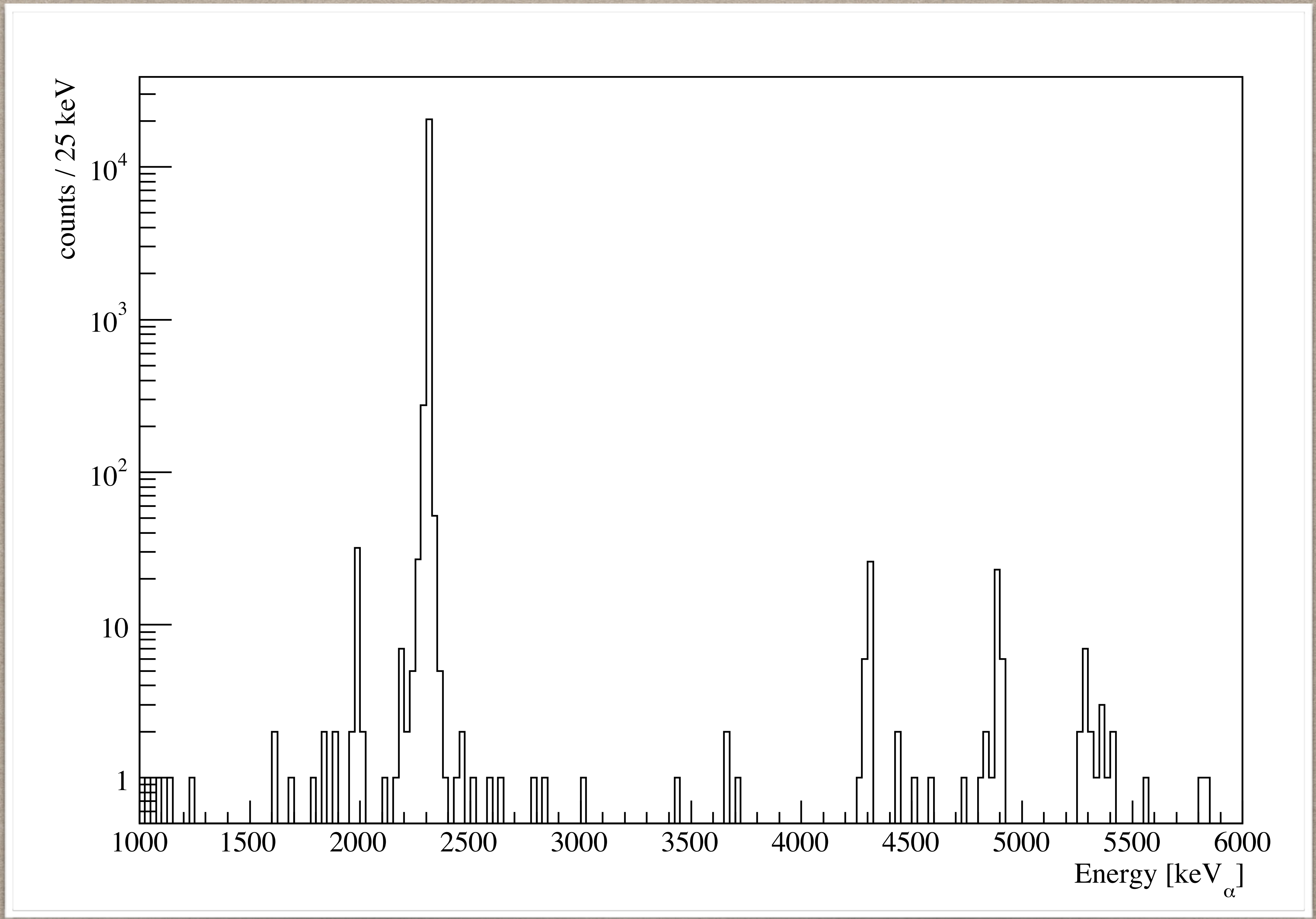
- Operated in Oxford 200 $^{3}He/^{4}He$ dilution refrigerator
- Data collected for a total live time of 364 h
- Detector calibrated using
  - γ lines from external ^{232}Th source
  - internal α line from ^{147}Sm
- Light detector was calibrated using ^{55}Fe source



LIGHT YIELD VS HEAT



ALPHA SPECTRUM



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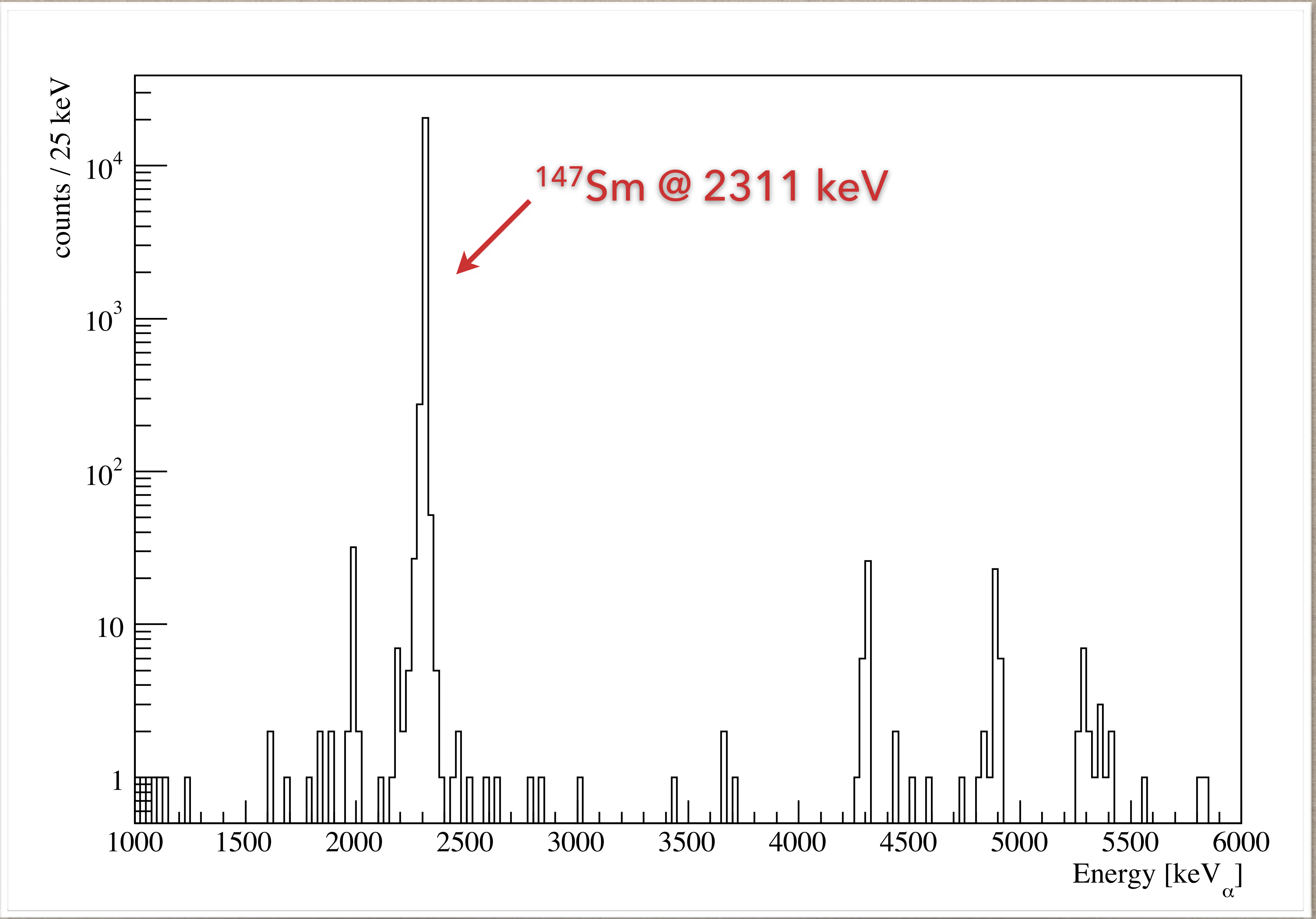
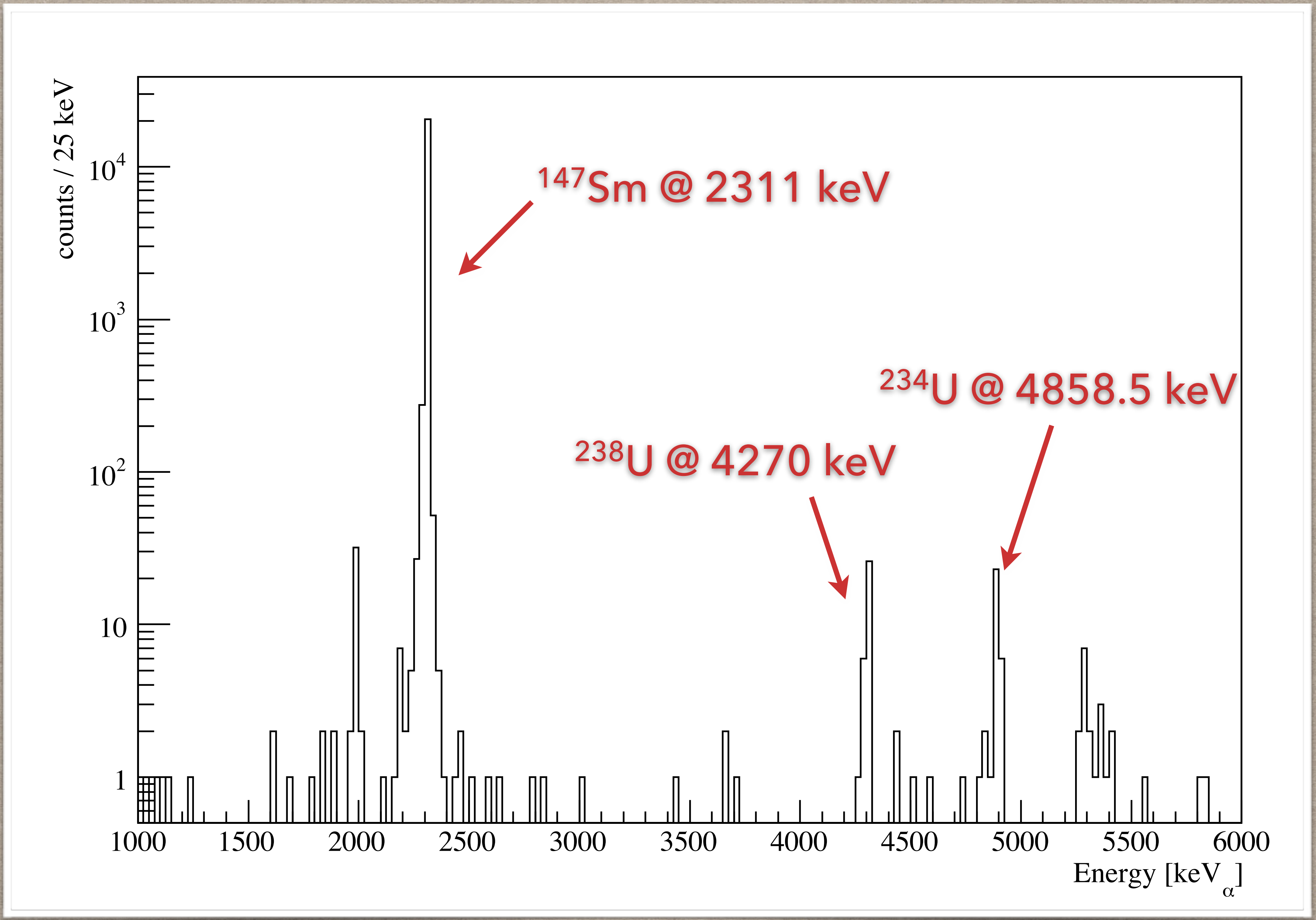
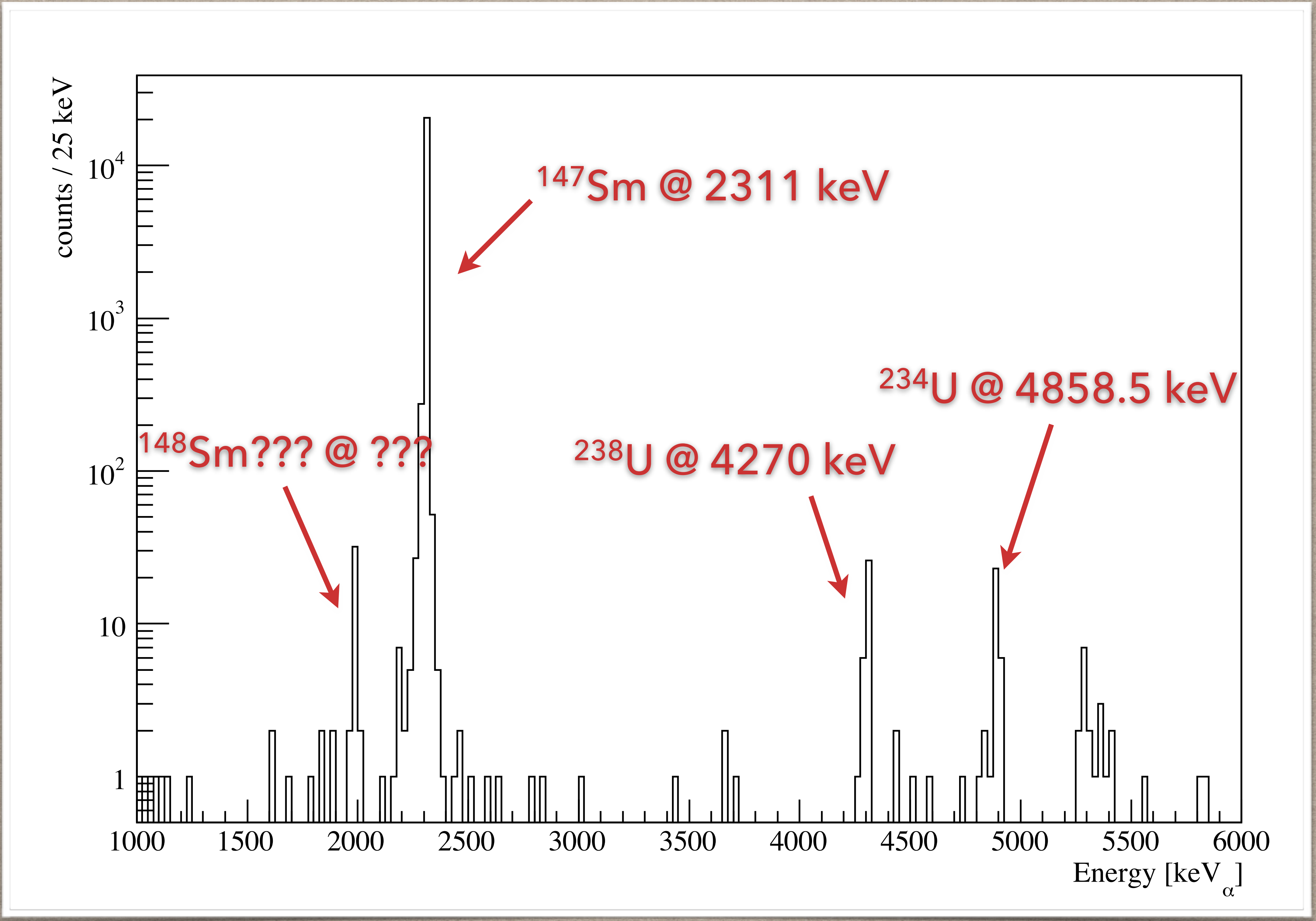


ALPHA SPECTRUM



ALPHA SPECTRUM



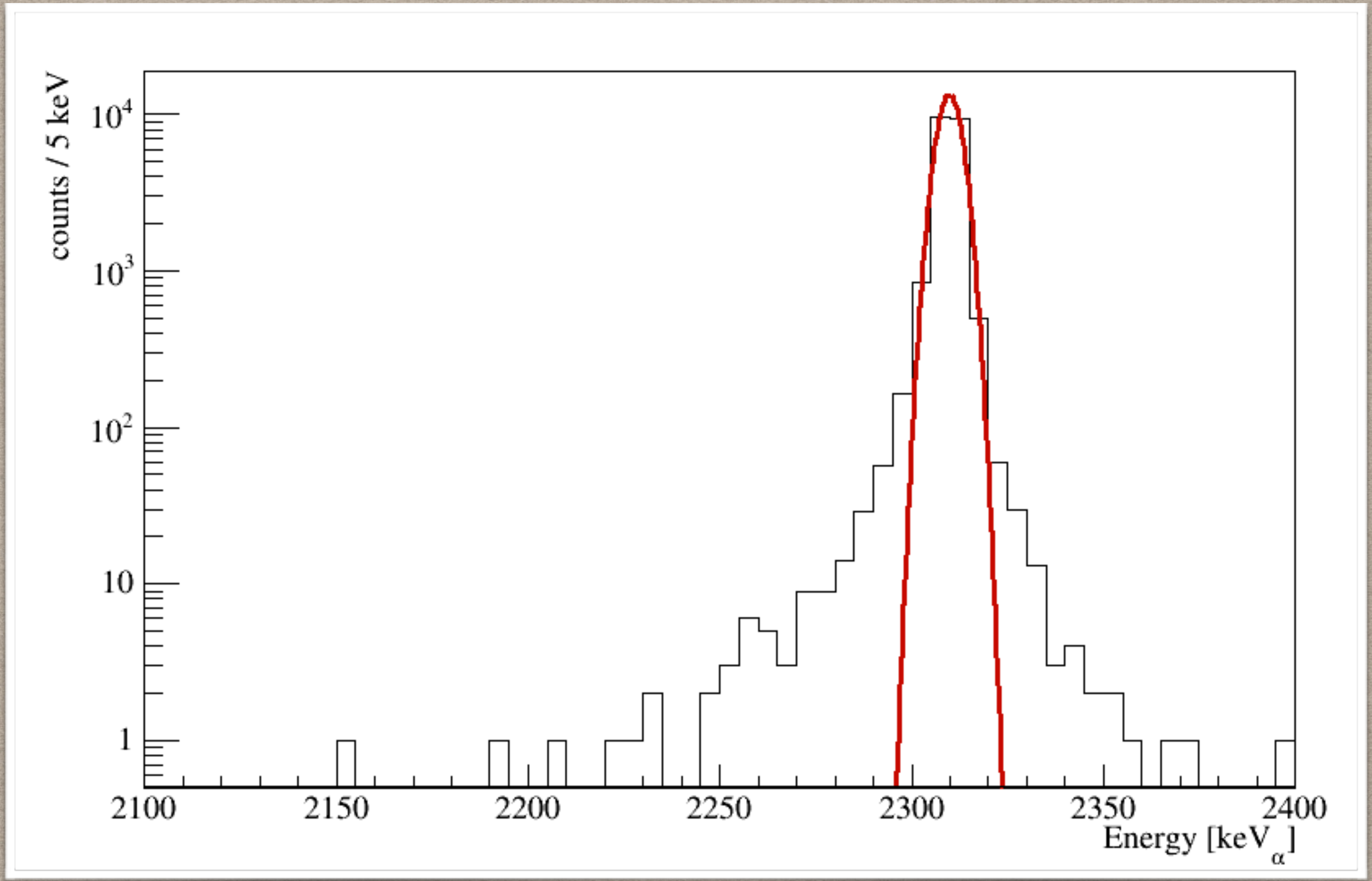
COULD IT BE ANYTHING ELSE?

HR-ICP-MS measurement

Isotope	Abundance [%]	Q_α [keV]	$T_{1/2}$ [y]	Concentration [10^{-6} g/g]	Expected events
^{144}Nd	23.798(19)	1905(1)	22.9×10^{14}	72	19.8
^{151}Eu	47.81(6)	1949(7)	4.62×10^{18}	< 10	< 0.002
^{152}Gd	0.20(1)	2203.0(1.4)	1.08×10^{14}	< 25	< 1.1

assuming Nd natural isotopic composition

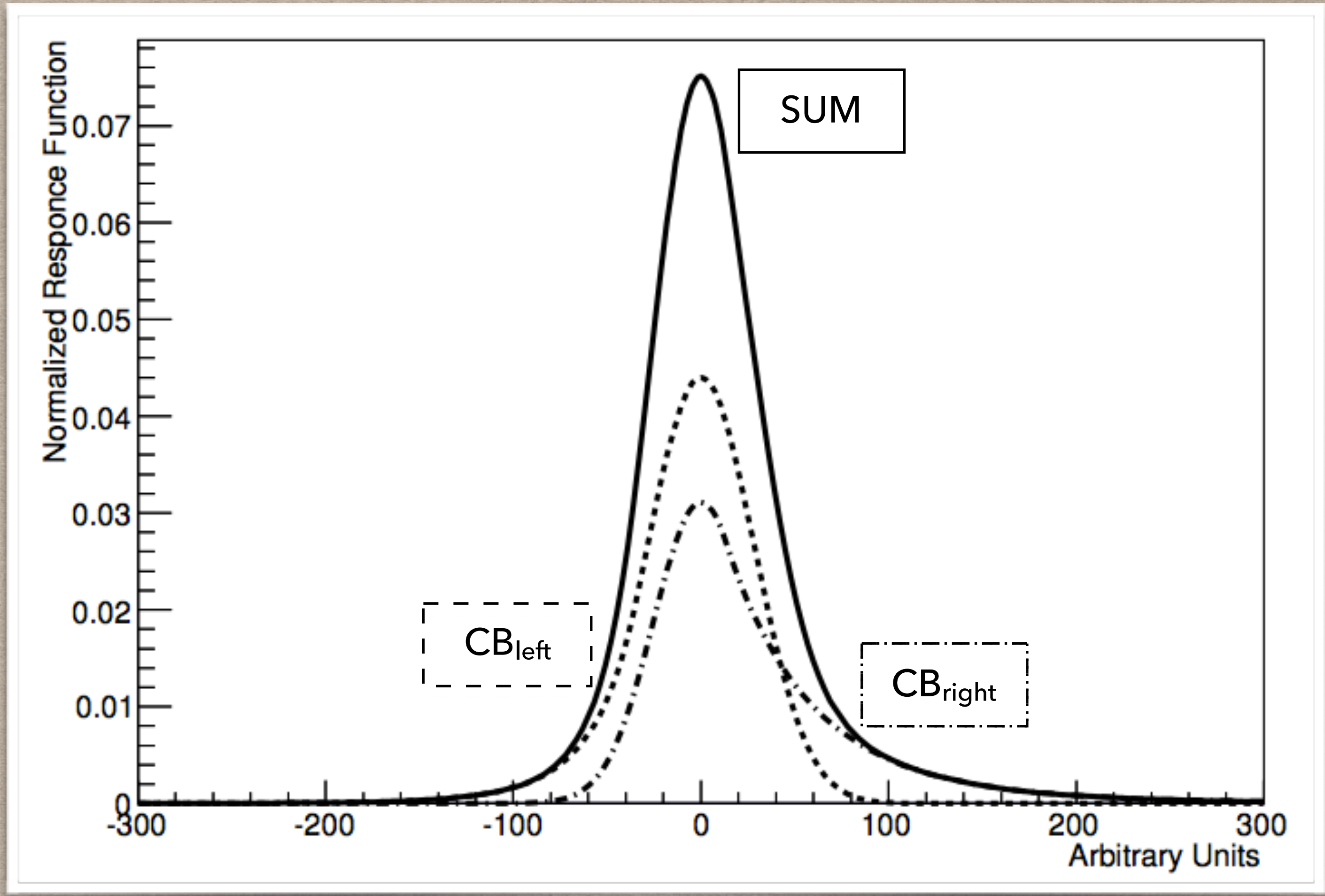
A CLOSER LOOK TO ^{147}SM PEAK



Gaussian shape does not fit the spectrum

NON-GAUSSIANITY

- There is no clear physics motivation but the detector response function is not a gaussian.
  - Possible explanations? Position effects, crystal inhomogeneity, surface events...????



- We use as detector response function a sum of two crystal balls, evaluating their parameters on the Sm peak

$$\mathrm{RF}(Q,E) = N \cdot [CB_{left}(Q,E) + \delta \cdot CB_{right}(Q,E)]$$

THE FIT PROCEDURE

Using RooFit toolkit we performed a fit:

- maximum likelihood
- unbinned
- extended
- simultaneous
    - Sm region (cut accepted)
    - Sm region (cut rejected)
    - ^{228}Ac peaks
    - ^{40}K peak
    - ^{208}Tl peak

To estimate the selection efficiency

To include the systematic errors due to the calibration (the calibration parameters are left free)

THE FIT PROCEDURE

$$
\begin{aligned}
FF(A) = {} & N_{147}\, RF(Q_{147}, E_{\alpha}(A)) \\
& + N_{148}\, RF(Q_{148}, E_{\alpha}(A)) \\
& + N_{Ac1}\, \mathrm{Gauss}(Q_{Ac1}, E_{\beta\gamma}(A)) \\
& + N_{Ac2}\, \mathrm{Gauss}(Q_{Ac2}, E_{\beta\gamma}(A)) \\
& + N_{K}\, \mathrm{Gauss}(Q_{K}, E_{\beta\gamma}(A)) \\
& + N_{Tl}\, \mathrm{Gauss}(Q_{Tl}, E_{\beta\gamma}(A))
\end{aligned}
$$

$$
\boxed{\begin{gathered}
E_{\beta\gamma}(A) = p_0 + p_1 A + p_2 A^2 \\
E_{\alpha}(A) = (p_0 + p_1 A + p_2 A^2) / QF
\end{gathered}}
$$

$$
\boxed{\frac{N_{148}}{N_{147}} = \frac{T_{147}}{T_{148}} R_{148/147}}
$$

THE FIT PROCEDURE

$$
\begin{aligned}
FF(A) = {} & N_{147}\, RF(Q_{147}, E_{\alpha}(A)) \\
& + N_{148}\, RF(Q_{148}, E_{\alpha}(A)) \\
& + N_{Ac1}\, Gauss(Q_{Ac1}, E_{\beta\gamma}(A)) \\
& + N_{Ac2}\, Gauss(Q_{Ac2}, E_{\beta\gamma}(A)) \\
& + N_{K}\, Gauss(Q_{K}, E_{\beta\gamma}(A)) \\
& + N_{Tl}\, Gauss(Q_{Tl}, E_{\beta\gamma}(A))
\end{aligned}
$$

$$
\boxed{\begin{aligned} E_{\beta\gamma}(A) &= p_0 + p_1 A + p_2 A^2 \\ E_{\alpha}(A) &= (p_0 + p_1 A + p_2 A^2) / QF \end{aligned}}
$$

$$
\boxed{\frac{N_{148}}{N_{147}} = \frac{T_{147}}{T_{148}} R_{148/147}}
$$

Gaussian constrains on known values

THE FIT PROCEDURE

$$
\begin{aligned}
FF(A) = {} & N_{147}\, RF(Q_{147}, E_{\alpha}(A)) \\
& + N_{148}\, RF(Q_{148}, E_{\alpha}(A)) \\
& + N_{Ac1}\, Gauss(Q_{Ac1}, E_{\beta\gamma}(A)) \\
& + N_{Ac2}\, Gauss(Q_{Ac2}, E_{\beta\gamma}(A)) \\
& + N_{K}\, Gauss(Q_{K}, E_{\beta\gamma}(A)) \\
& + N_{Tl}\, Gauss(Q_{Tl}, E_{\beta\gamma}(A))
\end{aligned}
$$

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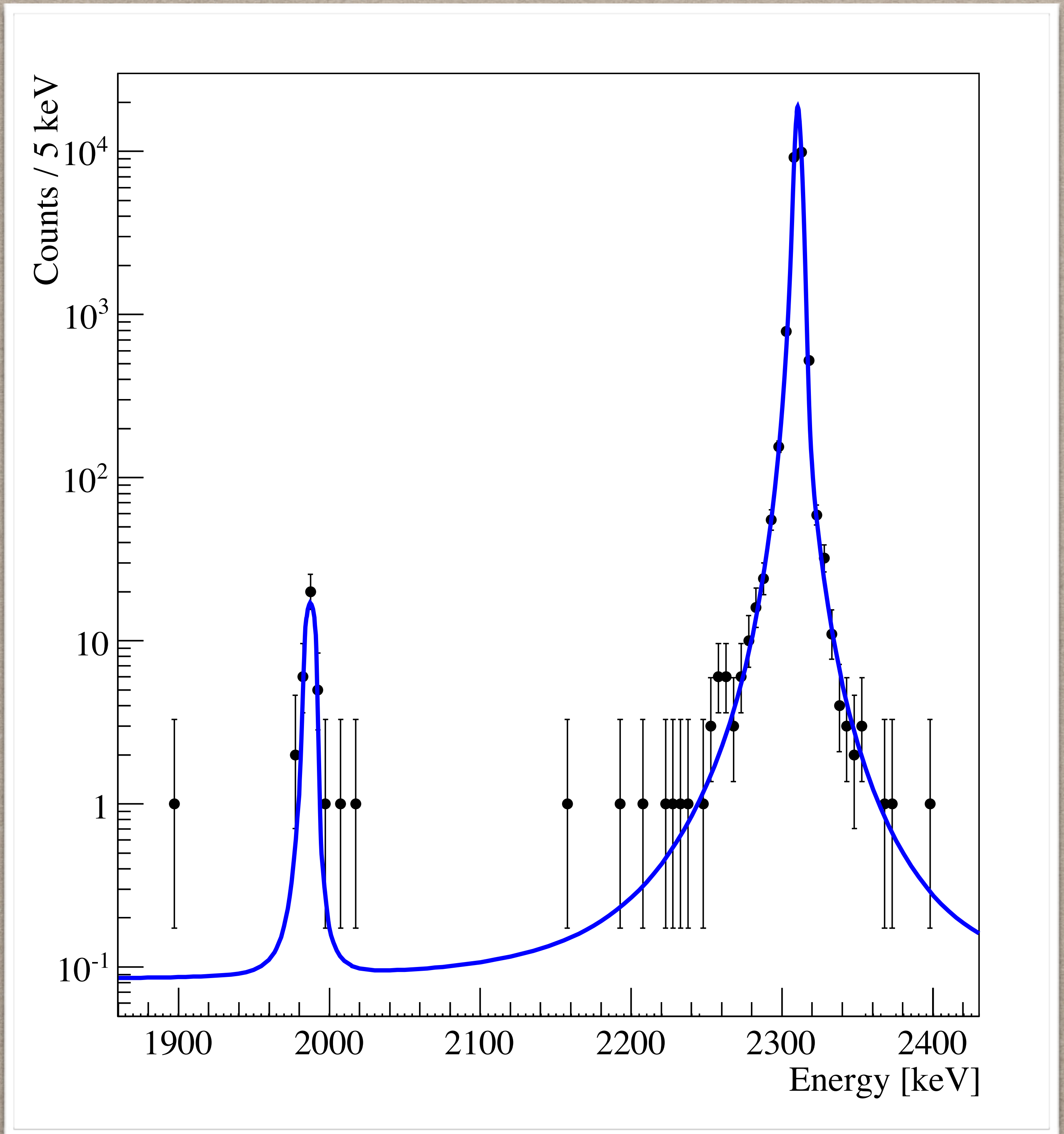
\boxed{\begin{gathered} E_{\beta\gamma}(A) = p_0 + p_1 A + p_2 A^2 \\ E_{\alpha}(A) = (p_0 + p_1 A + p_2 A^2) / QF \end{gathered}}
$$

$$
\boxed{\frac{N_{148}}{N_{147}} = \frac{T_{147}}{T_{148}} R_{148/147}}
$$

Gaussian constrains on known values

Many free parameters

THE RESULTING FIT



Half-life

$(6.4^{+1.2}_{-1.3}) \times 10^{15}$ y

Q-value

1987.3 ± 0.5 keV

FWHM resolution

4.7 ± 0.5 keV

Quenching Factor

1.1141 ± 0.0001

CONCLUSIONS

- We operated a 22.014 g $ZnWO_4$:^{148}Sm crystal as a bolometer, facing it to a bolometric Ge light detector inside a cryogenic facility at LNGS for a total live time of 364 hours.
- We report the precise measurement of ^{148}Sm α decay to ground state of ^{144}Nd with $T_{1/2} = (6.4^{+1.2}_{-1.3}) \times 10^{15}$ y.
- We evaluated its Q-value as 1987.3 ± 0.5 keV.

Paper in preparation

BACKUP

CRYSTAL BALL FUNCTION

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

$$A = \left(\frac{n}{|\alpha|}\right)^n \cdot \exp\left(-\frac{|\alpha|^2}{2}\right),$$

$$B = \frac{n}{|\alpha|} - |\alpha|,$$

$$N = \frac{1}{\sigma(C + D)}$$

$$C = \frac{n}{|\alpha|} \cdot \frac{1}{n-1} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right)$$

$$D = \sqrt{\frac{\pi}{2}}\left(1 + \operatorname{erf}\left(\frac{|\alpha|}{\sqrt{2}}\right)\right)$$