28th Rencontres de Blois on
Particle Physics and Cosmology
Château Royal de Blois, May 29 - June 03, 2016

CUORE-0 BACKGROUND ANALYSIS AND EVALUATION OF ^{130}Te 2νββ DECAY HALF-LIFE

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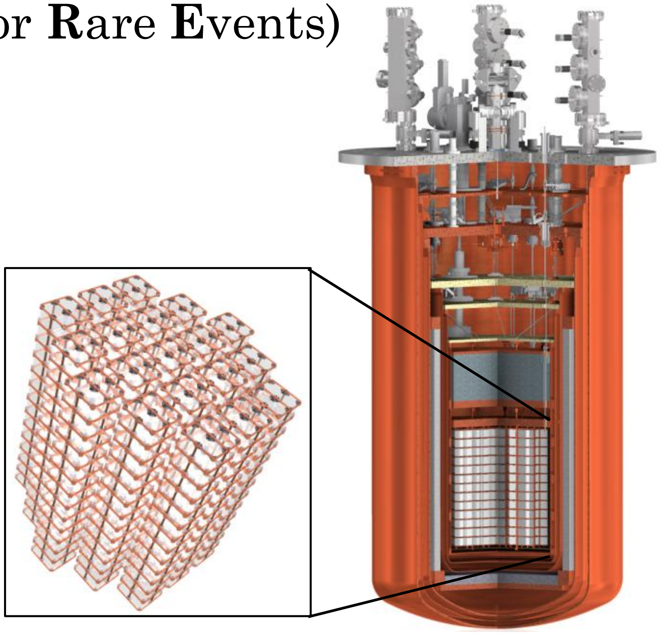
On behalf of the CUORE collaboration

THE CUORE EXPERIMENT

CUORE (**C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents)
→ search for **$0\nu\beta\beta$ decay of ^{130}Te**:

$$^{130}\mathrm{Te} \rightarrow {}^{130}\,\mathrm{Xe} + 2e^{-}$$



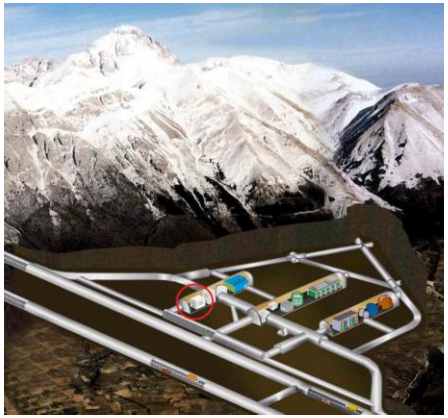
WHY?

$0\nu\beta\beta$ observation would demonstrate:

- ✓ lepton number is not conserved;
- ✓ neutrinos are massive Majorana particles.

HOW?

Detector composed by 988 TeO_2 bolometers (206 kg ^{130}Te).



WHERE?

Laboratori Nazionali del Gran Sasso (LNGS) – Italy.

WHEN?

Data taking by the end of 2016.

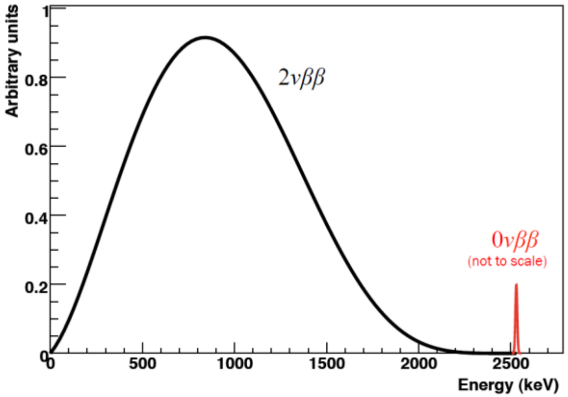
DETECTING DOUBLE-BETA DECAY

SIGNAL

- To detect the double-beta decay of ^{130}Te, we measure the energy of the two final-state electrons:

0νββ $^{130}\mathrm{Te} \rightarrow ^{130}\mathrm{Xe} + 2e^-$ (Q-value peak)

2νββ $^{130}\mathrm{Te} \rightarrow ^{130}\mathrm{Xe} + 2e^- + 2\overline{\nu}_e$ (continuum)



- To achieve high sensitivity, we need **low background** and **high resolution**.

BACKGROUND

- Contaminations of the experimental setup (crystals and cryostat shields):
  - ^{232}Th, ^{238}U and ^{40}K natural contaminations + cosmogenic activation (^{60}Co, …);
  - Environmental ^{222}Rn (resulting in ^{210}Pb surface implantation).
- Environmental muons and neutrons.

CUORE-0

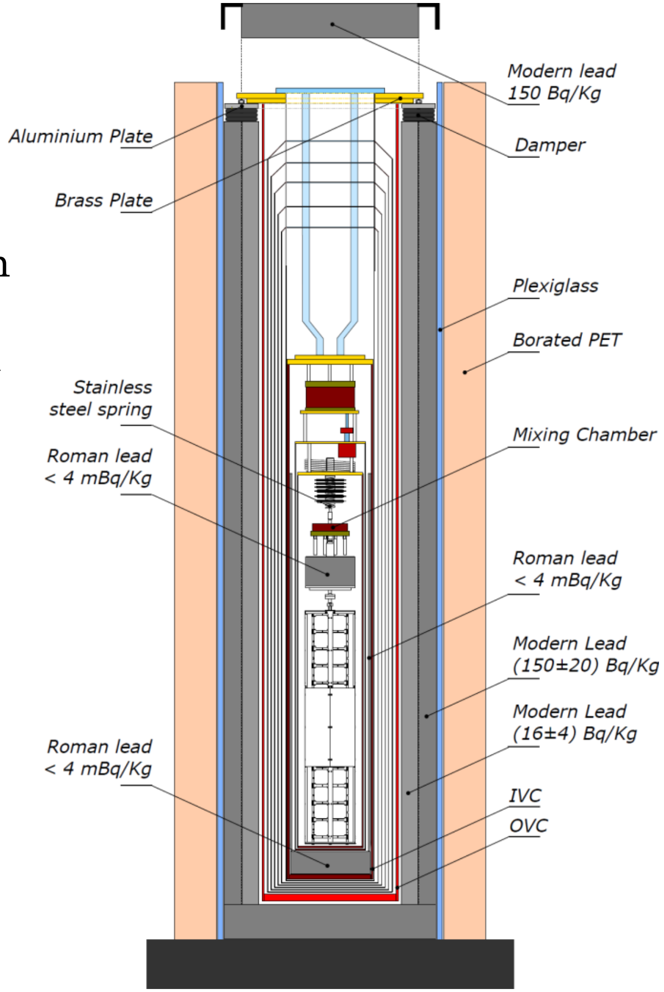
- First tower from the CUORE detector assembly line, operated from March 2013 to March 2015.

  → 35.2 kg·y TeO_2 exposure

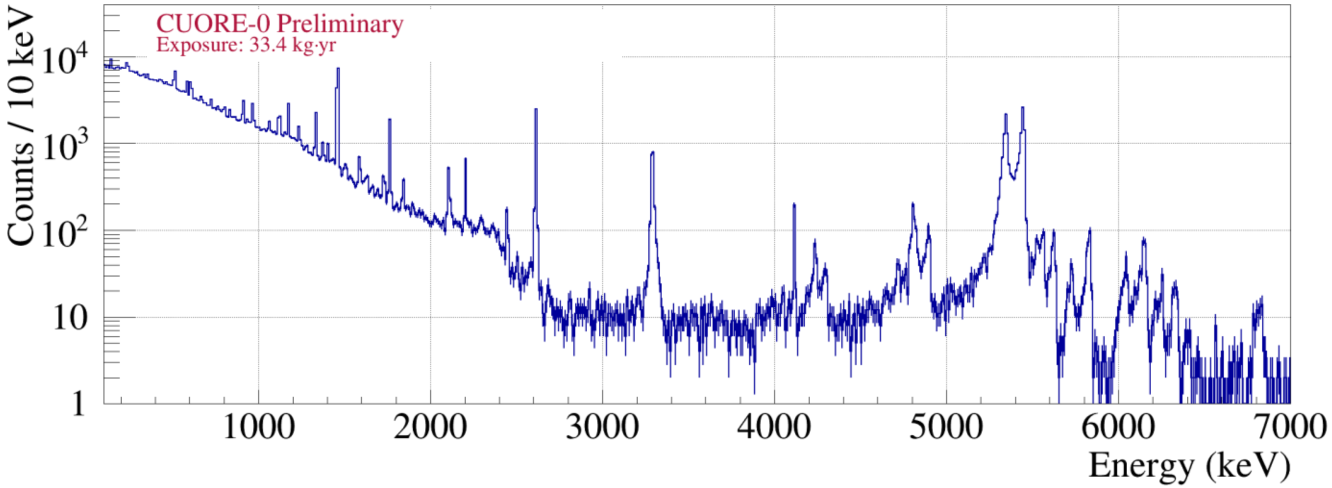
Proof of concept of CUORE detector in all stages:

- Test and debug of the CUORE tower assembly line.
- Test of the CUORE DAQ and analysis framework.
- Extend the physics reach while CUORE is being assembled.

- 52 TeO_2 crystals
- Total mass = 39 kg TeO_2 (10.9 kg ^{130}Te)
- Energy resolution: ~5 keV



CUORE-0 BACKGROUND ANALYSIS



In this analysis the first dataset (~5% of total statistics) was excluded, due to significant higher ^{222}Rn level.

ANALYSIS GOALS

- Disentangle and describe quantitatively the main **background** sources, evaluating their impact in the **$0\nu\beta\beta$ ROI.**
- Evaluate the **half-life of $2\nu\beta\beta$ decay of ^{130}Te**.

ANALYSIS SCHEME

Identify the background sources → Model each source through MC → Fit the MC spectra to the measured one

IDENTIFY THE BACKGROUND SOURCES

- Exploit ***a priori* information** from previous experiments, radioassay measurements of materials and cosmogenic activation calculations.

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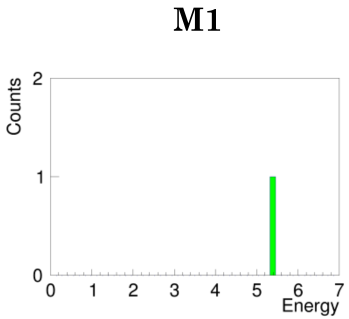
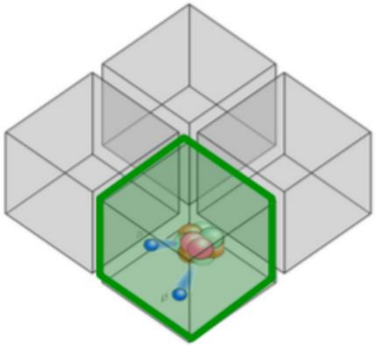
- Extract the maximum information **directly from CUORE-0 data**:
  - **coincidence** analysis (thanks to detector modularity);

Multiplicity 1

Event depositing energy
in a single crystal.





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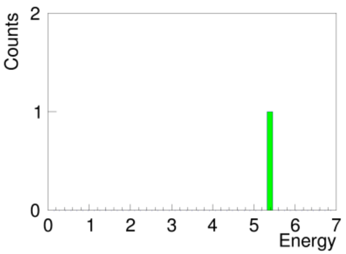
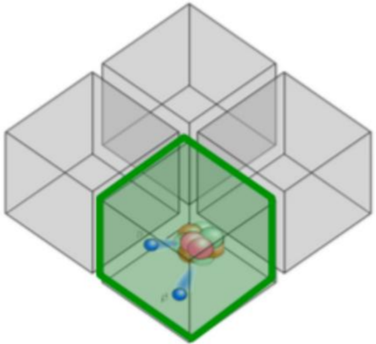
M1

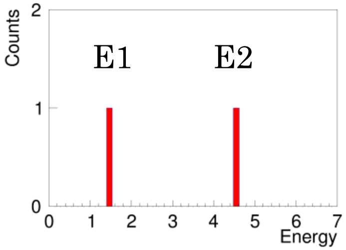




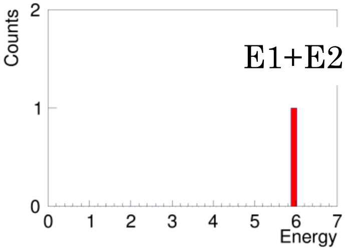
Multiplicity 2

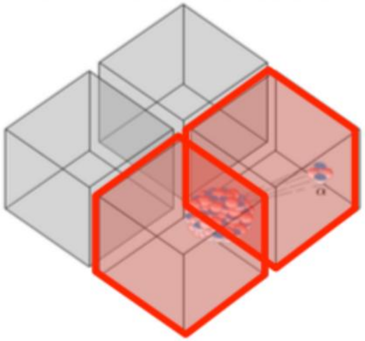
Simultaneous energy deposition in two crystals

M2



M2SUM





IDENTIFY THE BACKGROUND SOURCES

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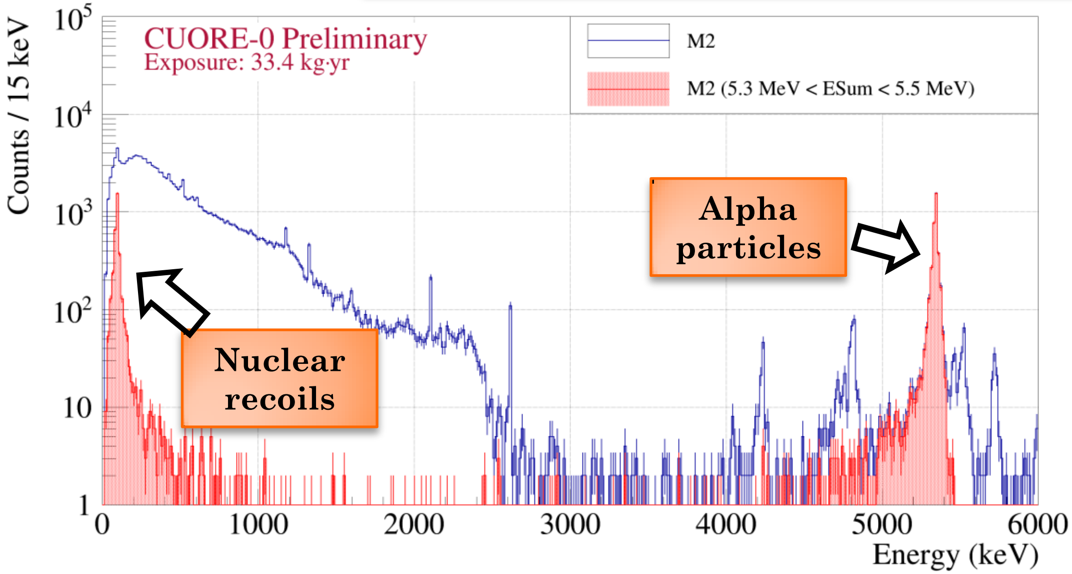
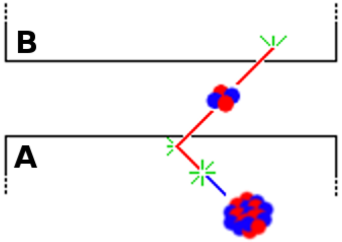
Particularly useful to identify contaminations on **crystal surfaces**



Alpha particles

Nuclear recoils



- α particle exiting from crystal A surface and interacting in crystal B;
- Recoil nucleus depositing energy in crystal A.

Red histogram: *M2 events with sum energy in the range 5.3 - 5.5 MeV (corresponding to* ^{210}*Po decay Q-value)*

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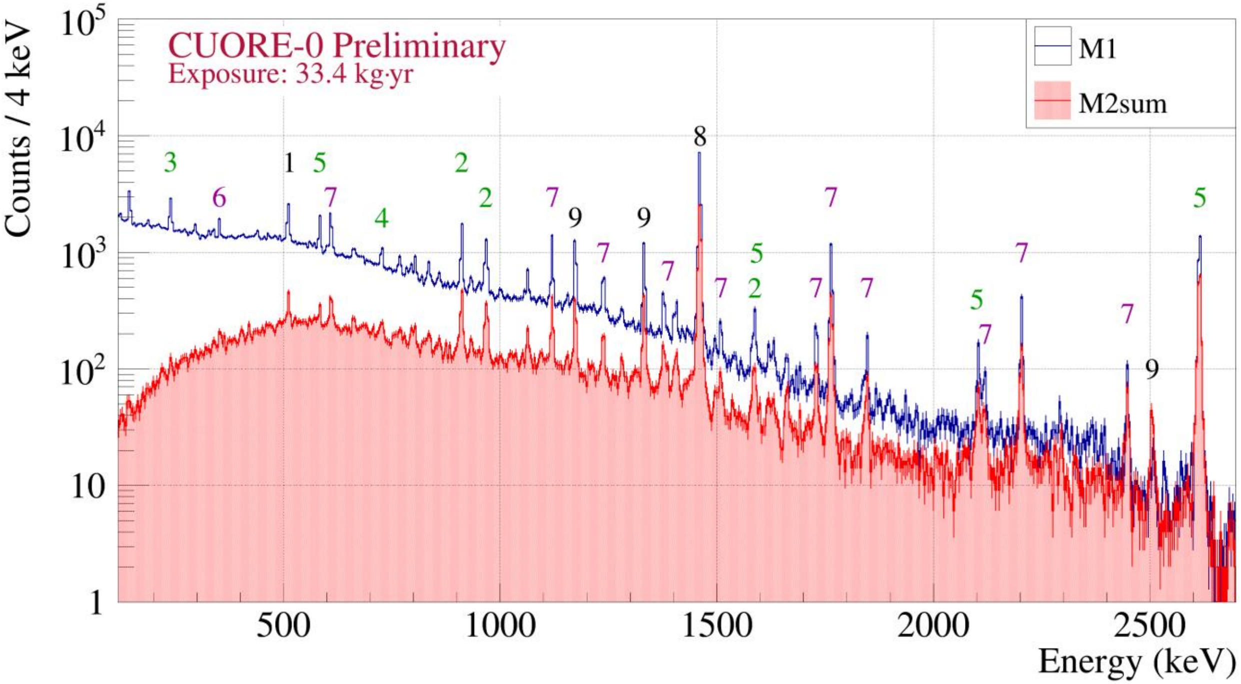
  - analysis of **gamma peaks**;



1) e^+e^- annihilation
2) ^{228}Ac
3) ^{212}Pb
4) ^{212}Bi
5) ^{208}Tl

^{232}Th decay chain

6) ^{214}Pb
7) ^{214}Bi

^{238}U decay chain

8) ^{40}K
9) ^{60}Co

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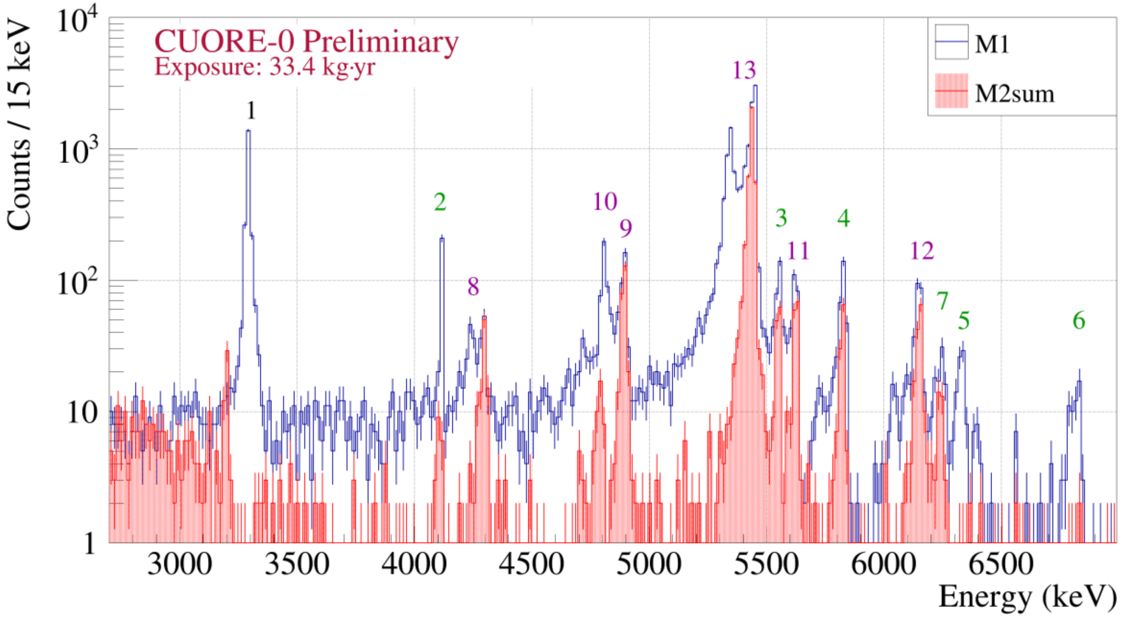
  - analysis of **alpha peaks**.



1) ^{190}Pt
2) ^{232}Th
3) ^{228}Th
4) ^{224}Ra
5) ^{220}Rn
6) ^{216}Po
7) ^{212}Bi
8) ^{238}U
9) ^{234}U+^{226}Ra
10) ^{230}Th
11) ^{222}Rn
12) ^{218}Po
13) ^{210}Po

^{232}Th decay chain (2–7)

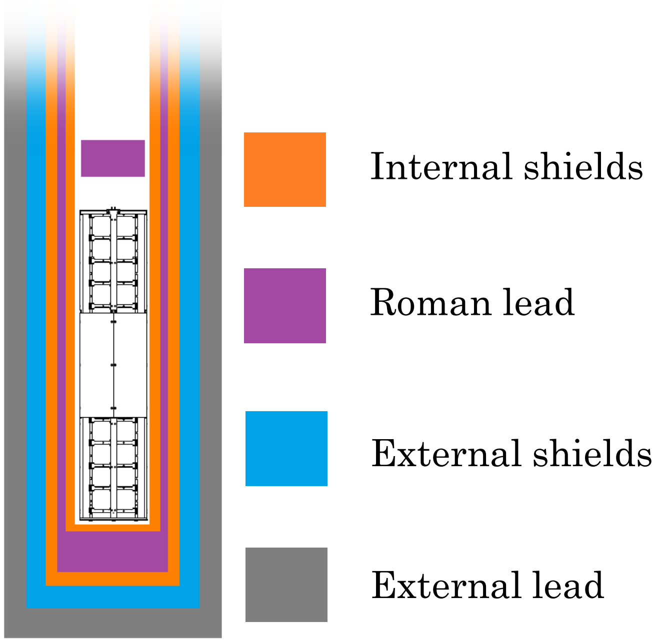
^{238}U decay chain (8–13)

MONTE CARLO SIMULATIONS

- Background sources simulated by means of a GEANT4 based MC code.
- CUORE-0 geometry modeled with high detail
- Careful reproduction of detector features (coincidences, resolution, thresholds…)
- Where possible we applied some simplifications, grouping the elements:
  - made with the same material;
  - producing similar spectral shape in the detector.

FAR sources

Only γ radiation

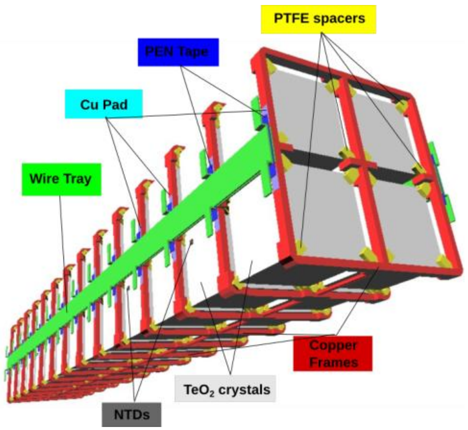


Schematic drawing (not to scale) of the different cryostat components used as "source positions" in MC simulations

NEAR sources

Crystals + Holder

α, β, γ radiation



FIT MODEL

- The CUORE-0 background spectrum was reconstructed as a linear combination of 57 sources.

$$\langle C^{exp}_{i,\alpha} \rangle = \sum_{j=1}^{57} N_j \langle C^{MC}_{ij,\alpha} \rangle \qquad \forall \text{ bin } i \qquad \alpha = M1, M2, M2Sum$$

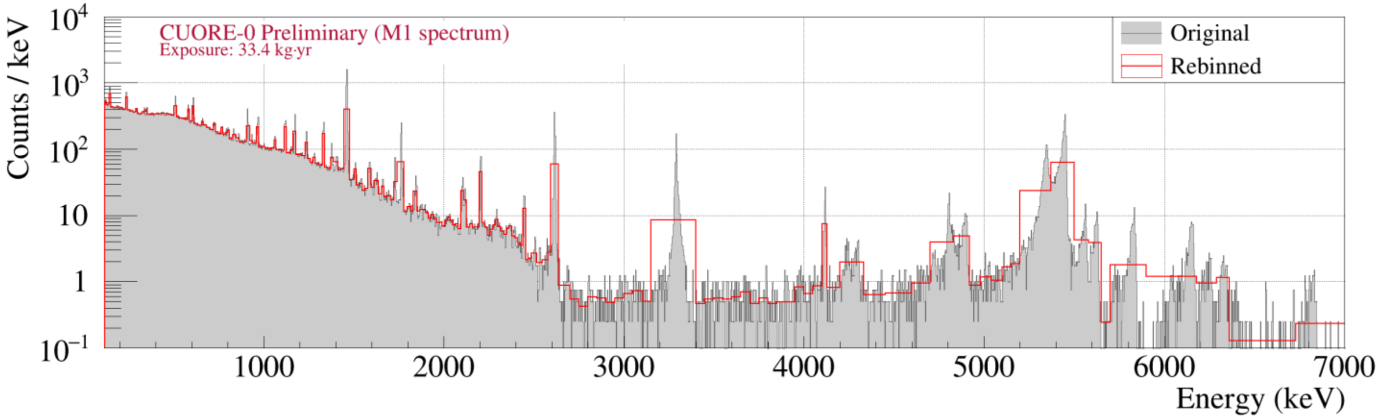
Activity of j-th source
≡ unknown fit parameter

The JAGS tool was used to define a **Bayesian** statistical model of the fit and solve it.

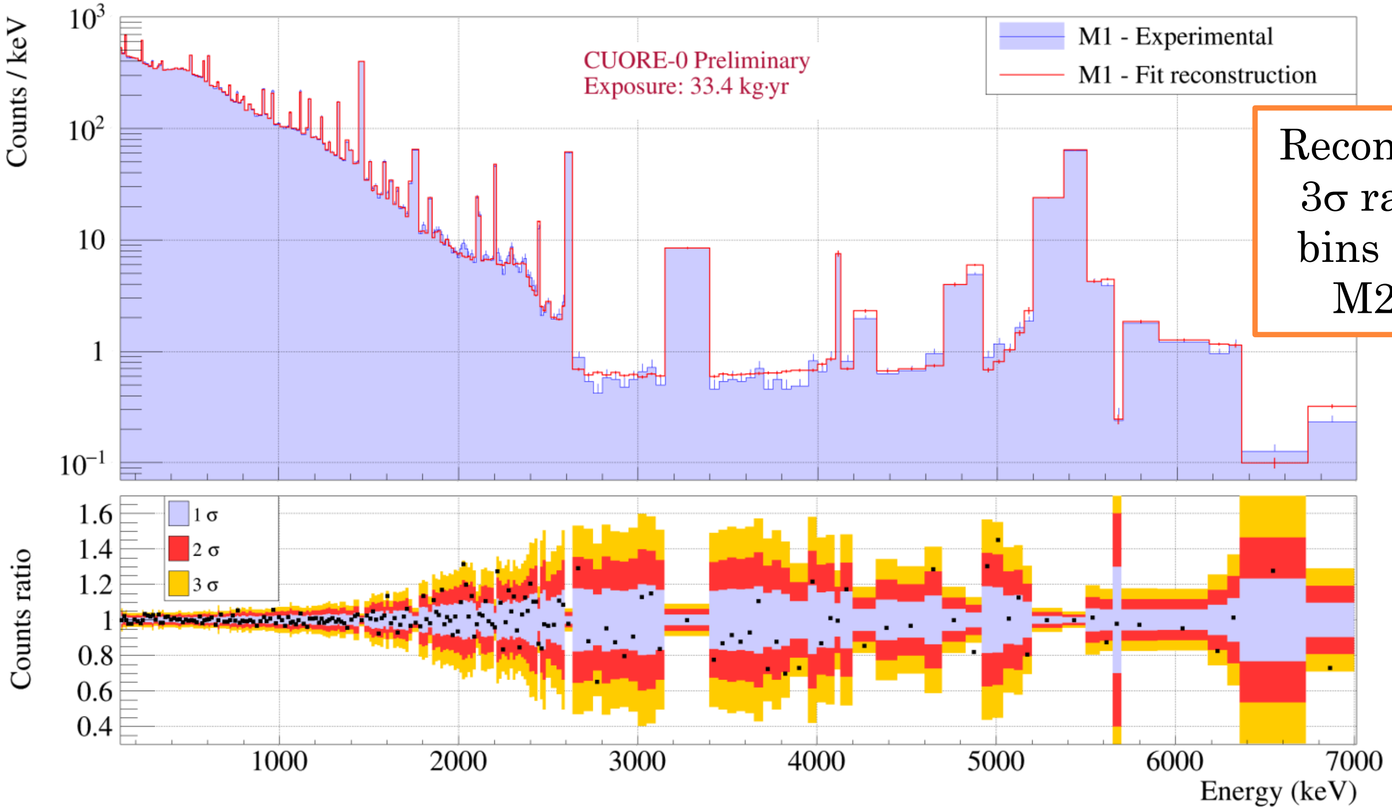
Priors from independent measurements were used.

- **Energy range**: 118 keV – 7 MeV
- **Binning**: optimized to maximize the informative content and minimize the effects of peculiar detector features (line shape…)

All the counts belonging to the same peak are included in a single bin.



FIT RESULTS



Reconstruction within 3σ range for most of bins (also in M2 and M2sum spectra).

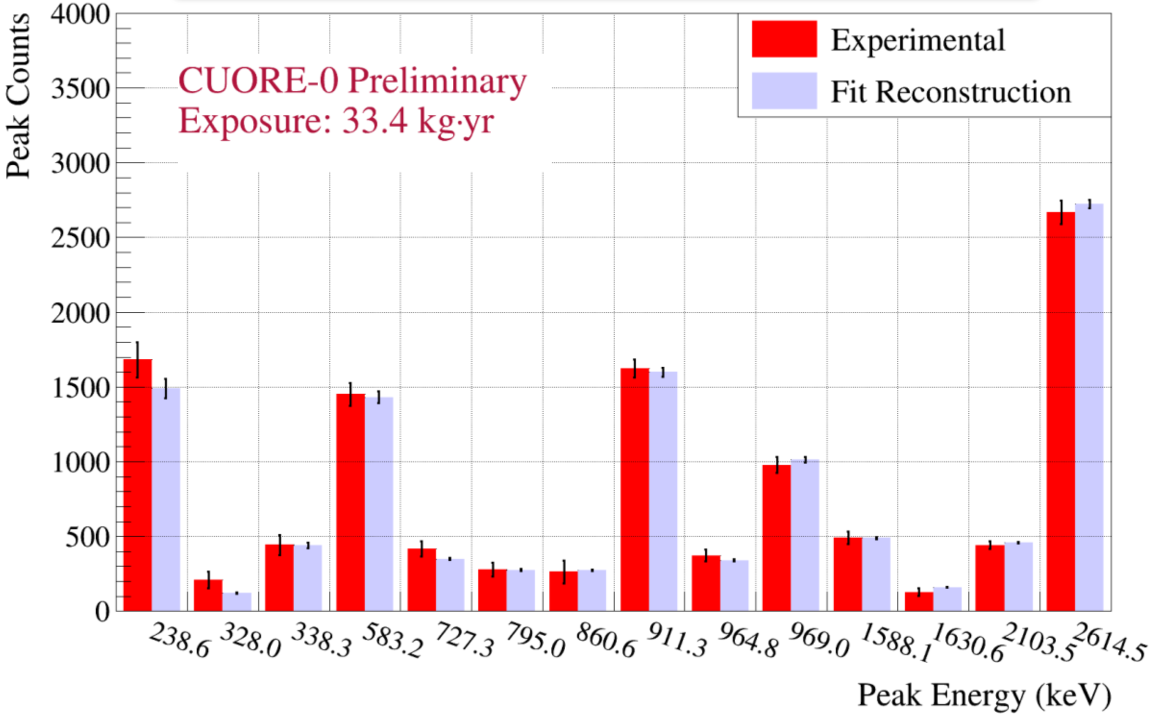
$$\tilde{\chi}^2 = 1.36$$ (with 57 parameters and 478 degrees of freedom)

We do not expect perfect statistical agreement between data and fit reconstruction because the systematic uncertainties related to MC simulations are not included in chi-squared calculation.

GAMMA LINES RECONSTRUCTION

- The good quality of the fit is also confirmed by the analysis of the reconstruction of the counts in the gamma lines.

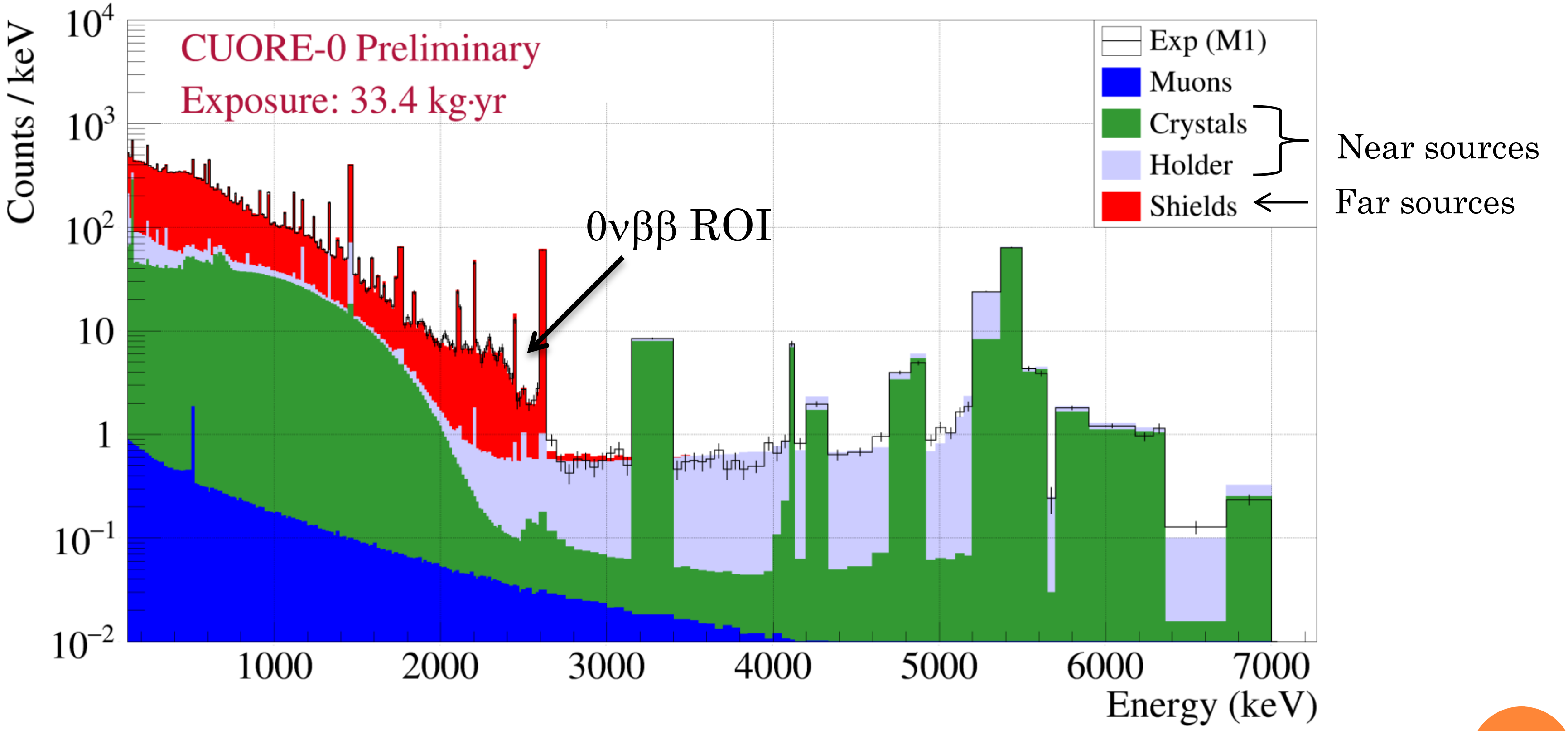
GAMMA LINES FROM ^{232}TH DECAY CHAIN



- Similar good agreement was also obtained for the gamma lines of the other isotopes.

BACKGROUND RECONSTRUCTION

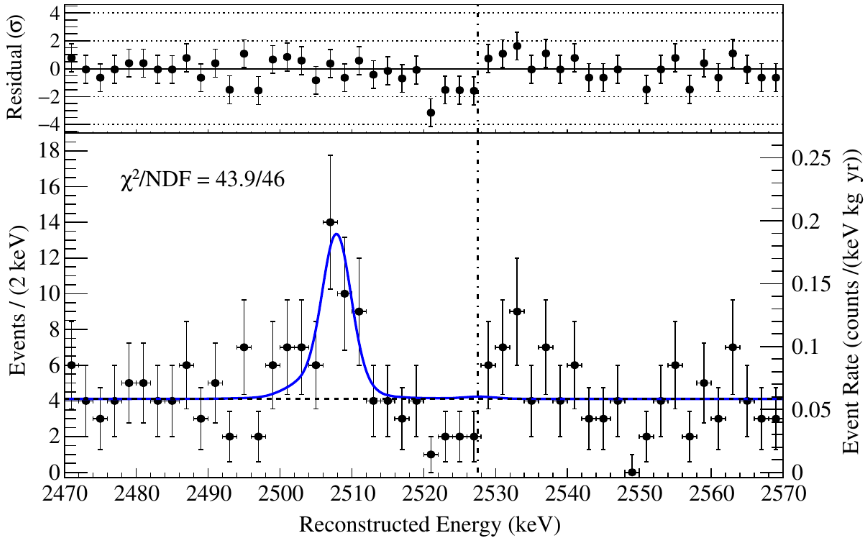
Stacked histogram showing the contributions to background ascribed to the sources in different positions of the experimental setup and to muons.



0νββ ROI RECONSTRUCTION

- The resulting background index in the ROI is:

0.058 ± 0.004 (stat.) ± 0.002 (syst.) counts/keV/kg/yr



PRELIMINARY

0νββ ROI background:

- Shields: ~72% ← Far sources
- Holder: ~21%
- Crystals: ~5%
- Muons: ~2%

Near sources

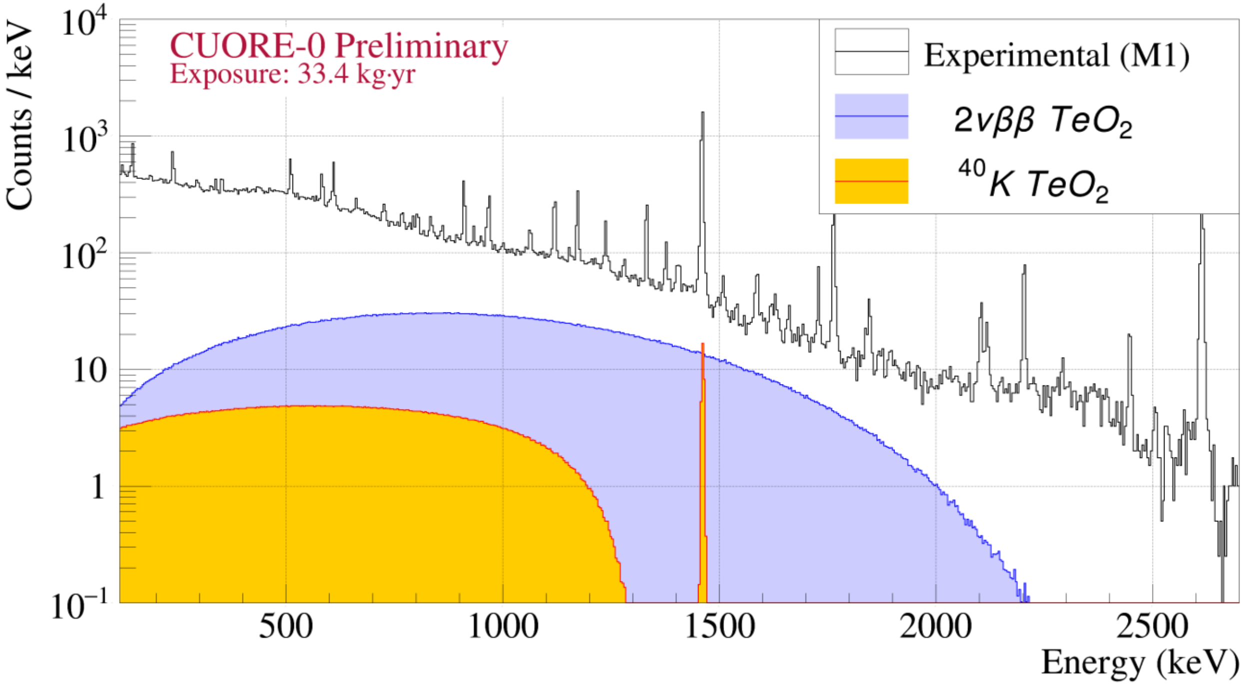
- We set a 90% C.L. Bayesian lower limit for ^{130}Te 0νββ: $T^{0\nu}_{1/2} > 2.7 \times 10^{24}$y
- Best limit for ^{130}Te 0νββ (combined with CUORICINO): $\boxed{T^{0\nu}_{1/2} > 4.0 \times 10^{24}\mathrm{y}\ [1]}$

[1]: K. Alfonso et al. (CUORE Collaboration), Phys. Rev. Lett. 115, 102502 (2015).

^{130}Te 2νββ HALF-LIFE EVALUATION

$$T^{2\nu}_{1/2} = [8.2 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{20}\,\mathrm{y}$$

PRELIMINARY



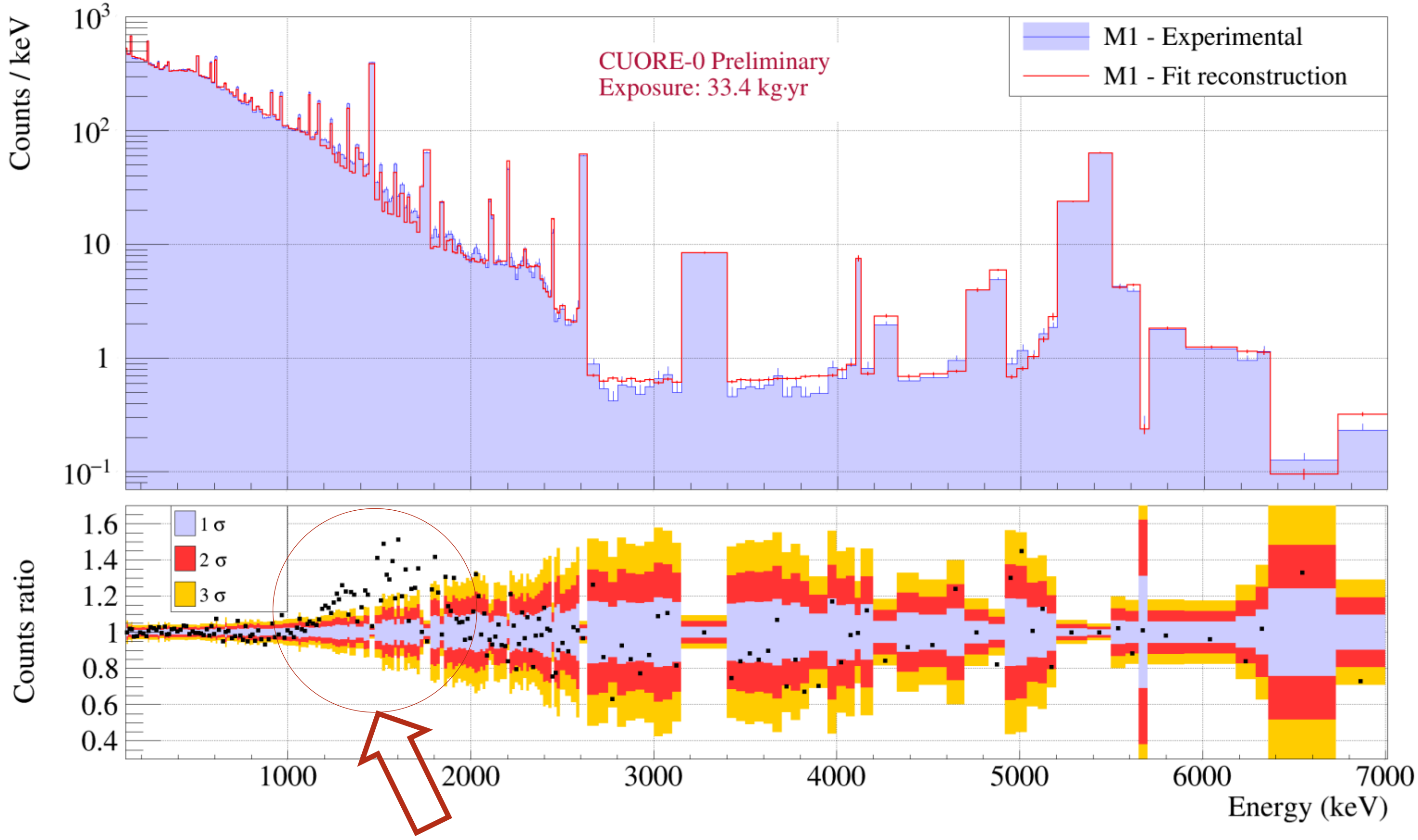
One of the main sources of systematic uncertainty is due to ^{40}K contamination in TeO$_2$ crystals.

2νββ decay produces **~10% of the events** in the M1 spectrum gamma region from 118 keV to 2700 keV.

FIT WITHOUT 2νββ COMPONENT

If the fit is performed without 2νββ source, the fit quality significantly deteriorates:

$$\Delta\chi^2 = 1.3 \times 10^3$$



SUMMARY

- The main **background** sources of CUORE-0 were identified and disentangled.
- Their impact in the **0νββ ROI** was evaluated.
  - → these results will be used for the background budget of CUORE

- The **half-life of 2νββ decay of ^{130}Te** was measured:

$$\boxed{T^{2\nu}_{1/2} = [8.2 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst})] \times 10^{20}\mathrm{y}}$$

PRELIMINARY

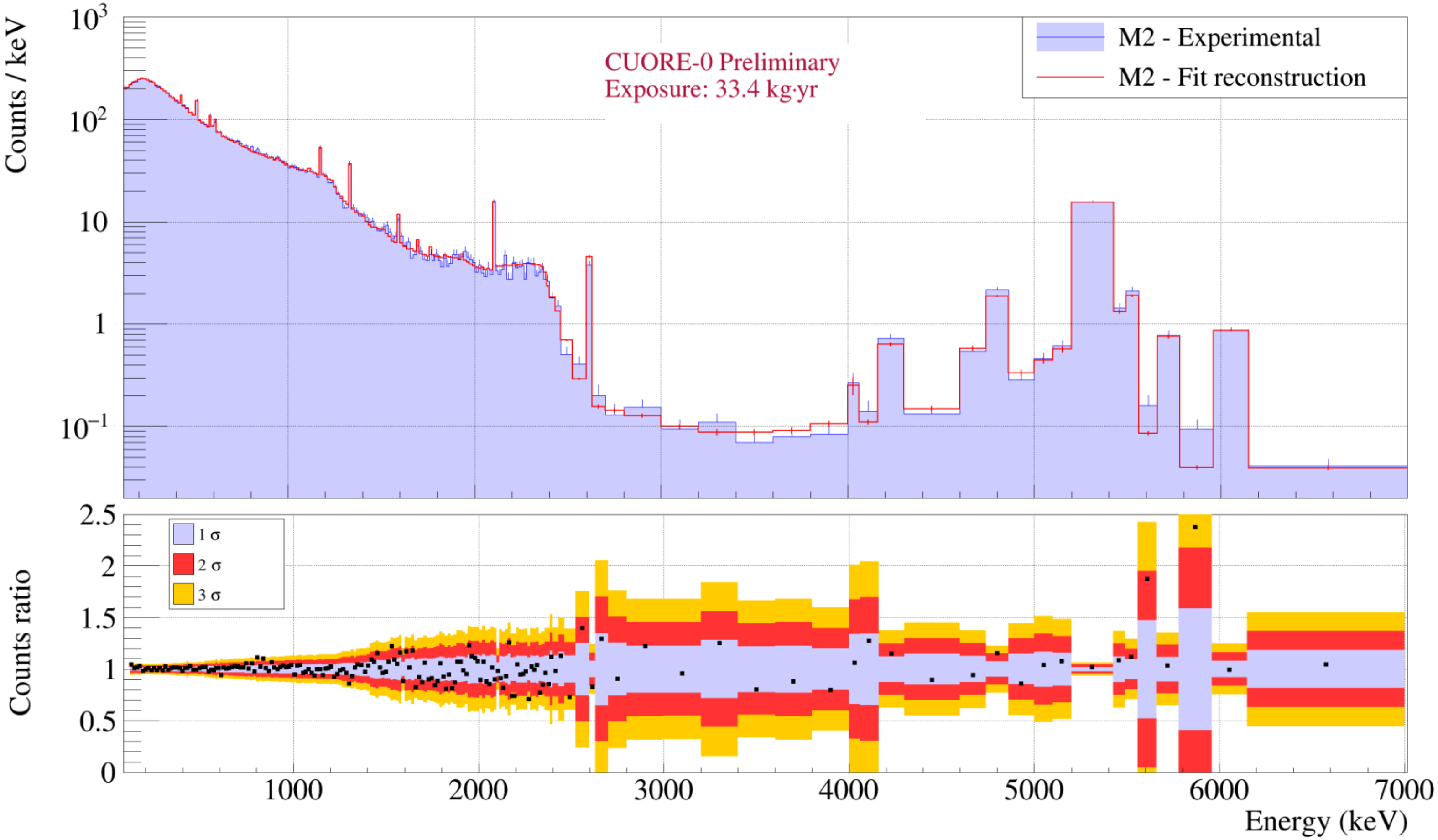
and resulted compatible with previous measurements from:

- NEMO [2]: $[7.0 \pm 0.9(\mathrm{stat}) \pm 1.1(\mathrm{syst})]10^{20}\mathrm{y}$
- MiDBD [3]: $[6.1 \pm 1.4(\mathrm{stat})^{+2.9}_{-3.5}(\mathrm{syst})]10^{20}\mathrm{y}$

[2]: R. Arnold et al. (NEMO-3 Collaboration), Phys. Rev.Lett., 107, 062504 (2011).
[3]: C. Arnaboldi et al., Phys. Lett. B, 557, 167 (2003).

BACKUP SLIDES

FIT RESULTS (M2 SPECTRUM)



FIT RESULTS (M2SUM SPECTRUM)