Background modeling for the COSINE-100 dark matter experiment

Eunju Jeon
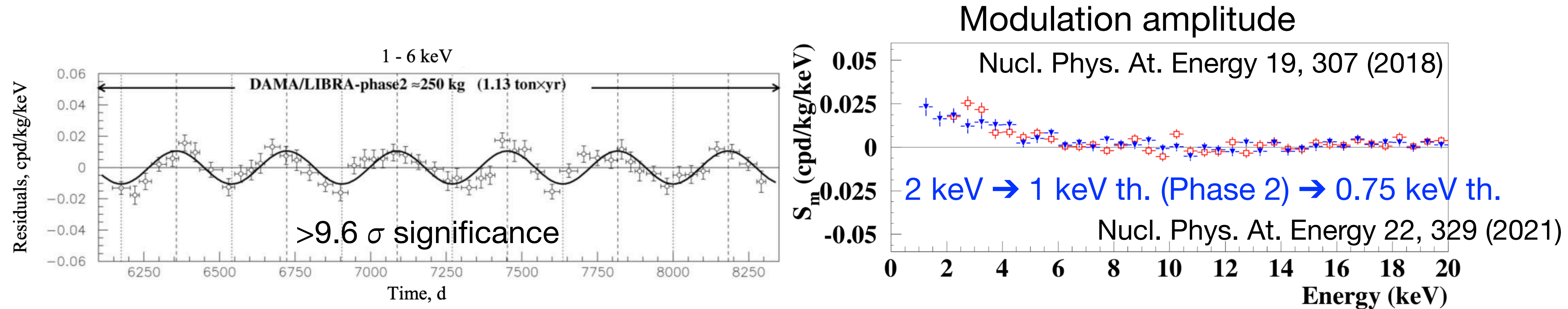**IBS CUP**
April 25, 2024

VIEnna Workshop on Simulations 2024 @Vienna
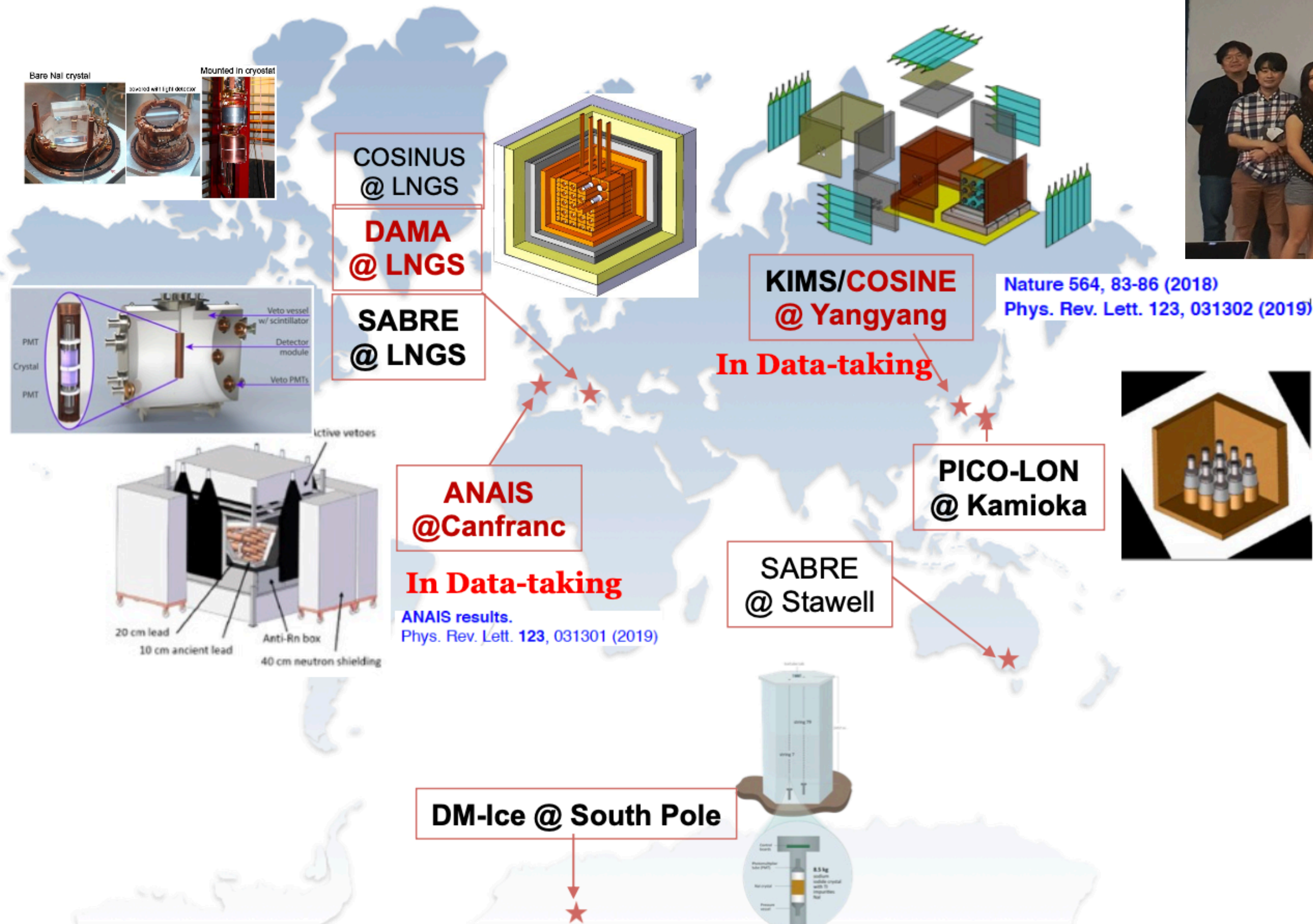
COSINE project (since 2015)

- DAMA/LIBRA experiment is to search for the DM annual modulation signature with an array of NaI(Tl) crystals → ***They claimed an observation of the dark matter***

Modulation amplitude

1 - 6 keV

DAMA/LIBRA-phase2 ≈250 kg (1.13 ton×yr)

>9.6 σ significance

Nucl. Phys. At. Energy 19, 307 (2018)

2 keV → 1 keV th. (Phase 2) → 0.75 keV th.

Nucl. Phys. At. Energy 22, 329 (2021)

- However, other experiments with different targets or techniques exclude the region of parameters singled out by DAMA/LIBRA

- To be checked with independent measurements using the same NaI(Tl) crystals

Global efforts and COSINE collaboration
with NaI(Tl) crystals

Bare NaI crystal | Mounted in cryostat

COSINUS
@ LNGS

**DAMA
@ LNGS**

SABRE
@ LNGS

KIMS/COSINE
@ Yangyang

Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

In Data-taking

Veto vessel
w/ scintillator

Detector
module

Veto PMTs

PMT
Crystal
PMT

Active vetoes

20 cm lead | 10 cm ancient lead | Anti-Rn box | 40 cm neutron shielding

**ANAIS
@Canfranc**

In Data-taking

ANAIS results.
Phys. Rev. Lett. **123**, 031301 (2019)

SABRE
@ Stawell

PICO-LON
@ Kamioka

DM-Ice @ South Pole

A joint collaboration between
KIMS and DM-Ice

DM-ICE + KIMS = COSINE

~50 members from 17
institutes in 5 countries

COSINE experiments

at Yemilab

at Y2L

Plastic scintillators
20 cm lead
3 cm copper
2,200 L LS
NaI(Tl) crystals

COSINE-100U

COSINE-200

Upgraded NaI(Tl) detector

CUP grown crystal

- Lower background level < 0.5 dru
- Lower energy threshold < 0.3 keV

COSINE-100

106 kg of NaI(Tl) crystals

Crystal-1 (Sample-B)
Crystal-2 (Sample-C)
Crystal-4 (WIMPScint-II)
Crystal-6 (WIMPScint-III)

DAMA   Internal   EPJC 80 (2020), 814
Cosmogenic
External
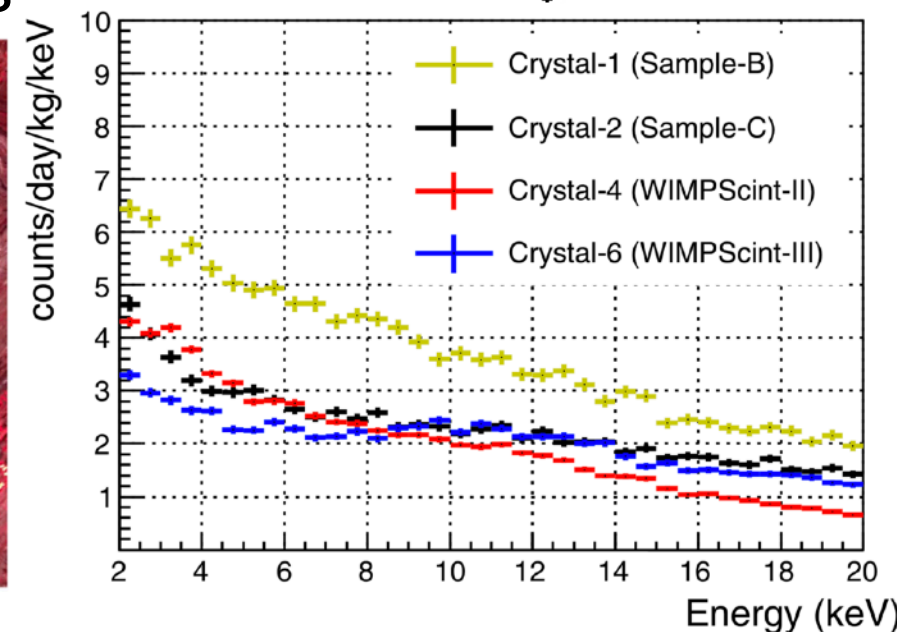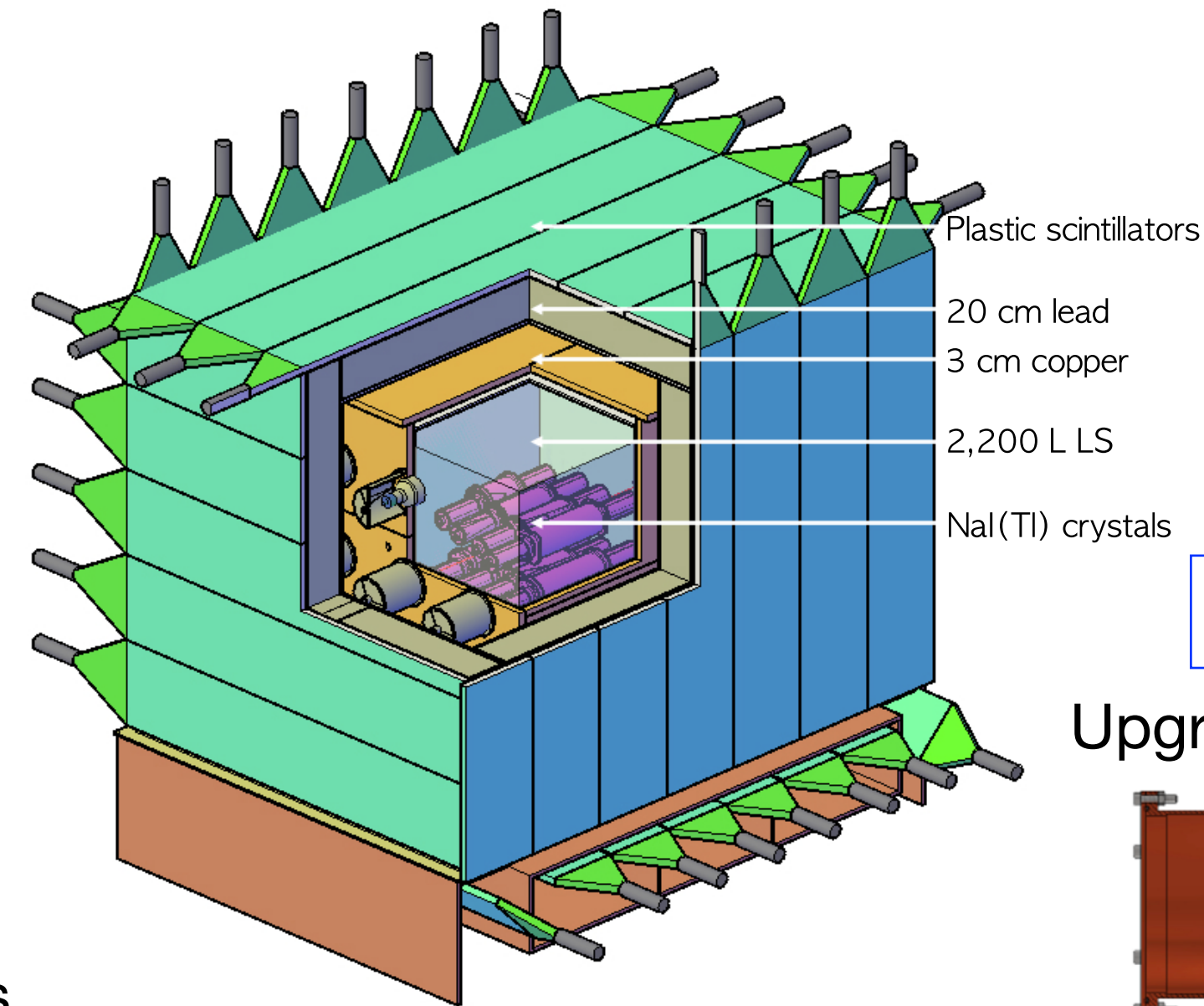
- Background level is 2-3 times higher than DAMA/LIBRA
- Extremly pure crystal development → we decided to do our own development for the entire process
- achieved 1keV energy threshold → < 0.75keV
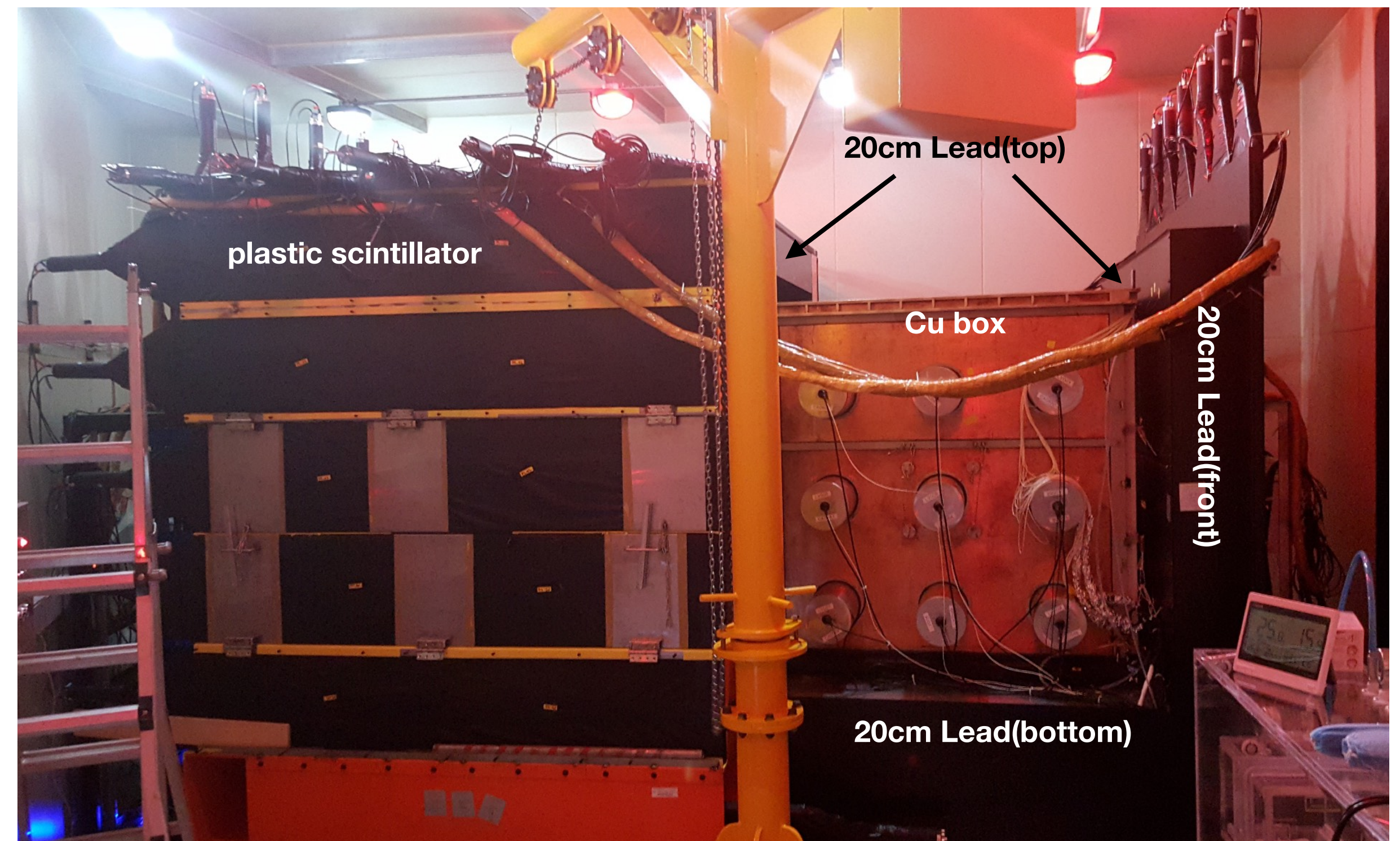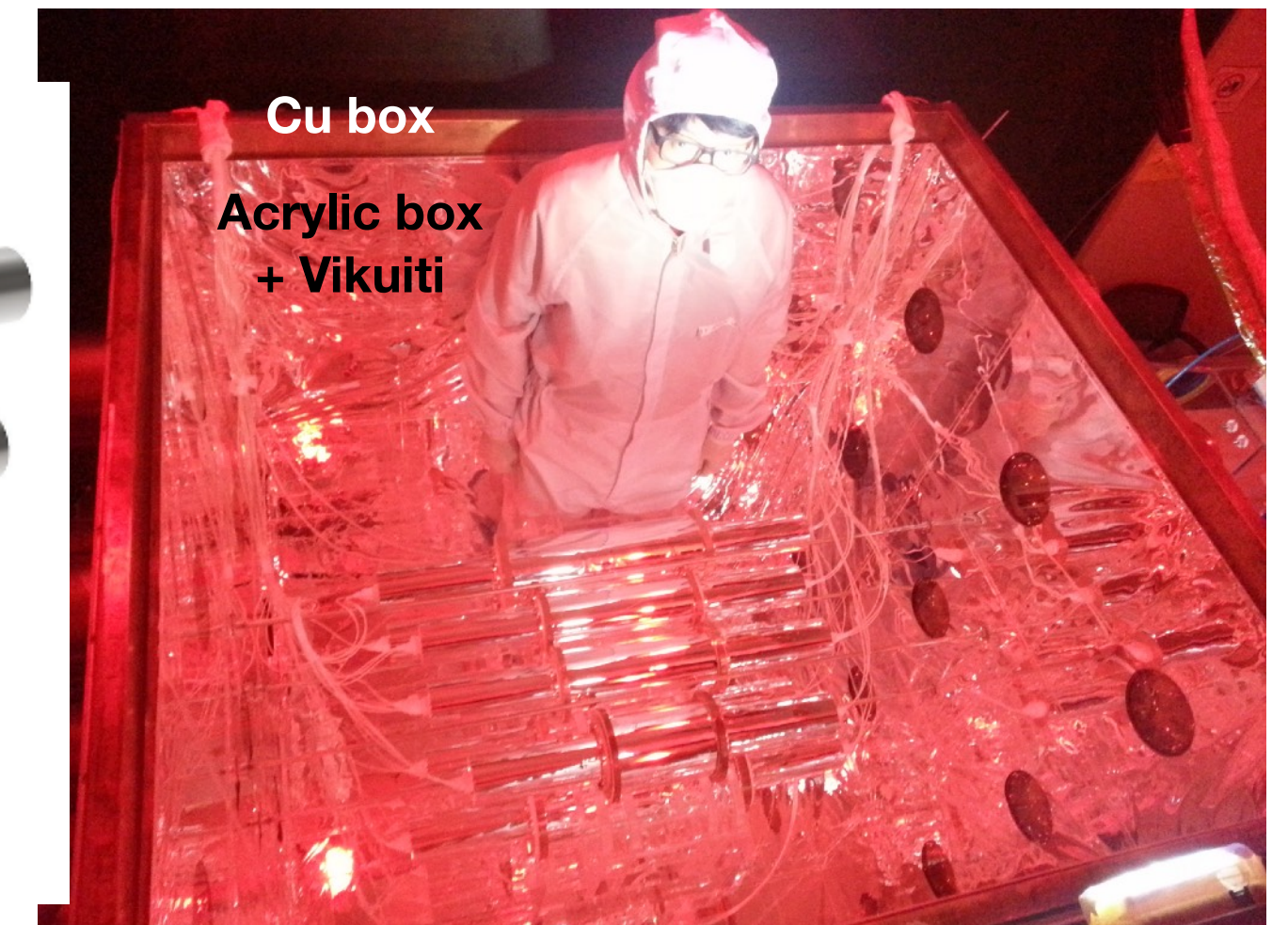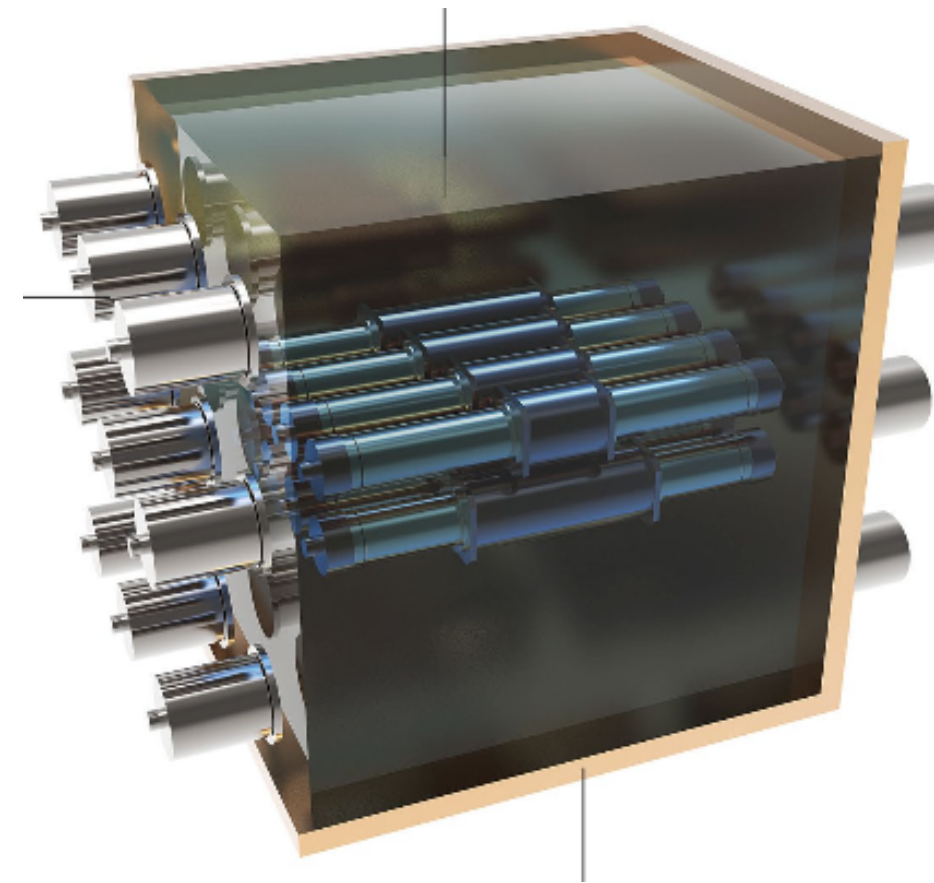
- Background level < 1 dru
- Energy threshlod < 0.3 keV

COSINE-100 (2016~2023)

- YangYang underground laboratory (Y2L)

- Started physics operation in September 2016

- Ended physics run March 2023

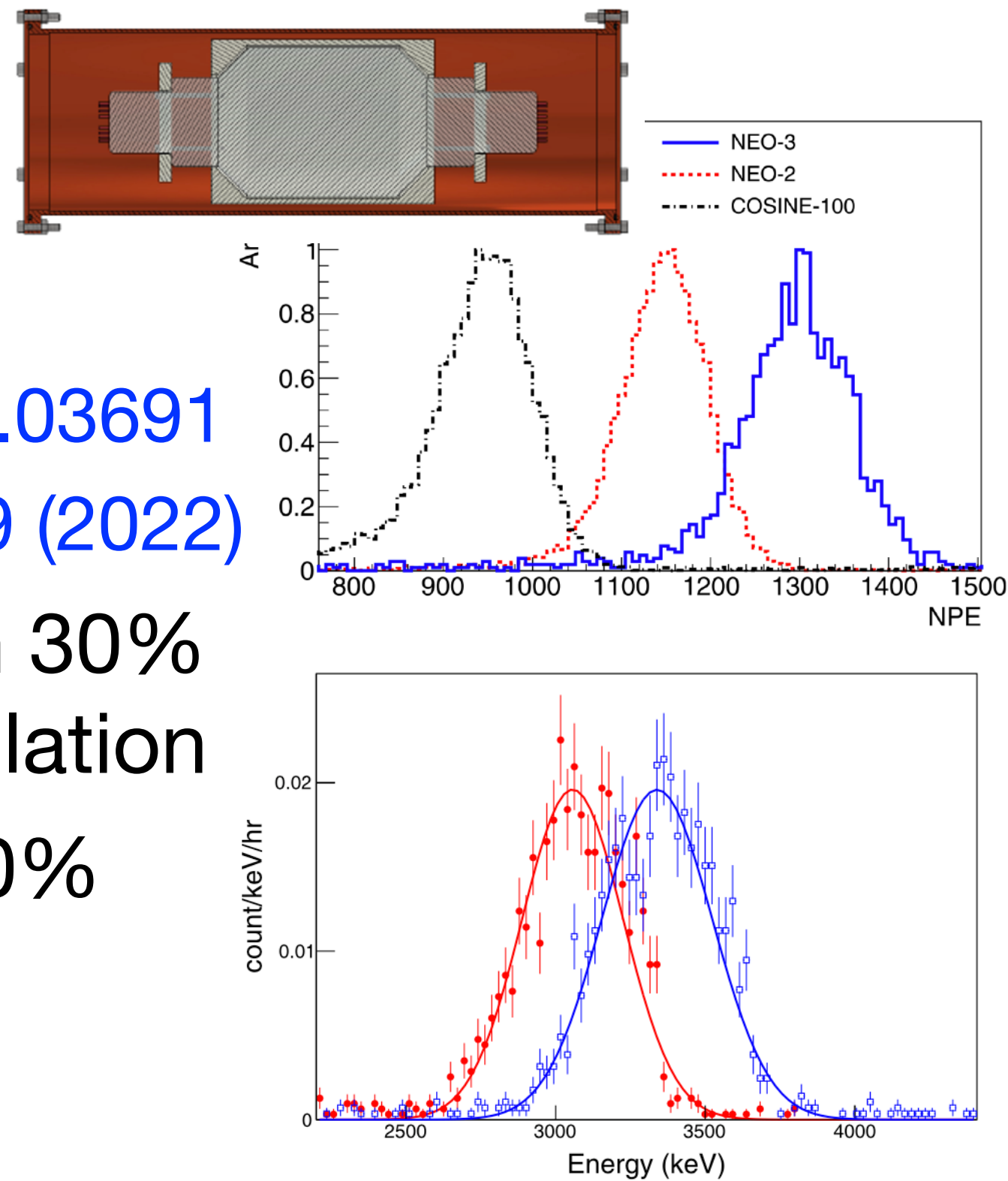- Decommissioning for upgrade and moving to Yemilab
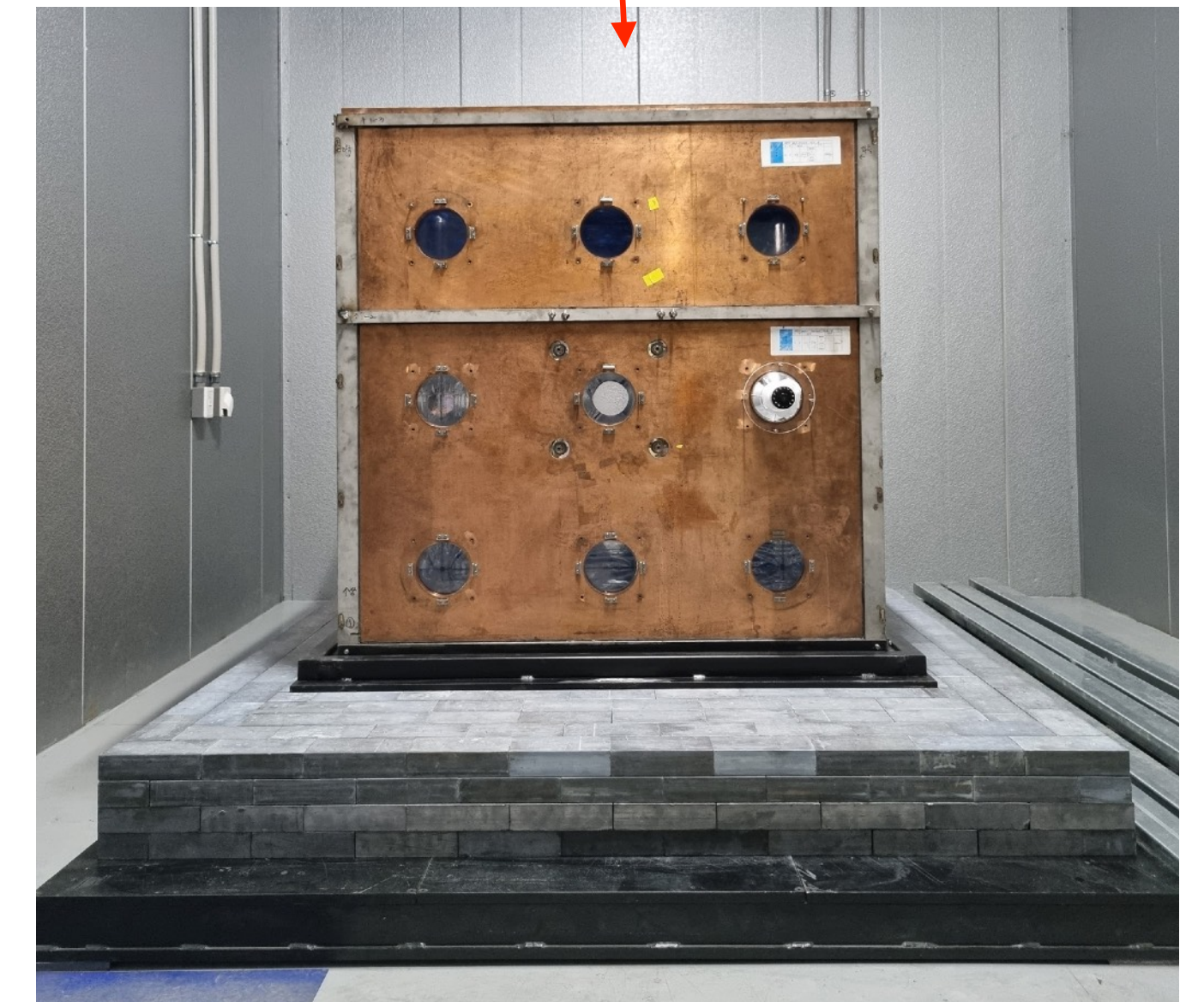
COSINE-100U

-35°C operation

arXiv:2404.03691

Astropart. Phys. 141, 102709 (2022)

- Light yield increased by more than 30% with the upgraded NaI(Tl) encapsulation

- Alpha quenching increased by ~10%

- n/γ discrimination improved

Warehouse freezer at Yemilab

Sept/25   Oct/6   Oct/10

Y2L → Yemilab

# Background of NaI(Tl) crystal developed with Alpha Spectra

- Saint-Gobain has lost the technology for producing low-background NaI(Tl) crystals

- ANAIS, DM-Ice, KIMS, and Alpha Spectra Company have been conducting R&D on NaI(Tl) since 2013

- We modeled the background spectrum of NaI(Tl) crystal used in the test arrangement

EPJC 77, 437 (2017)

DAMA
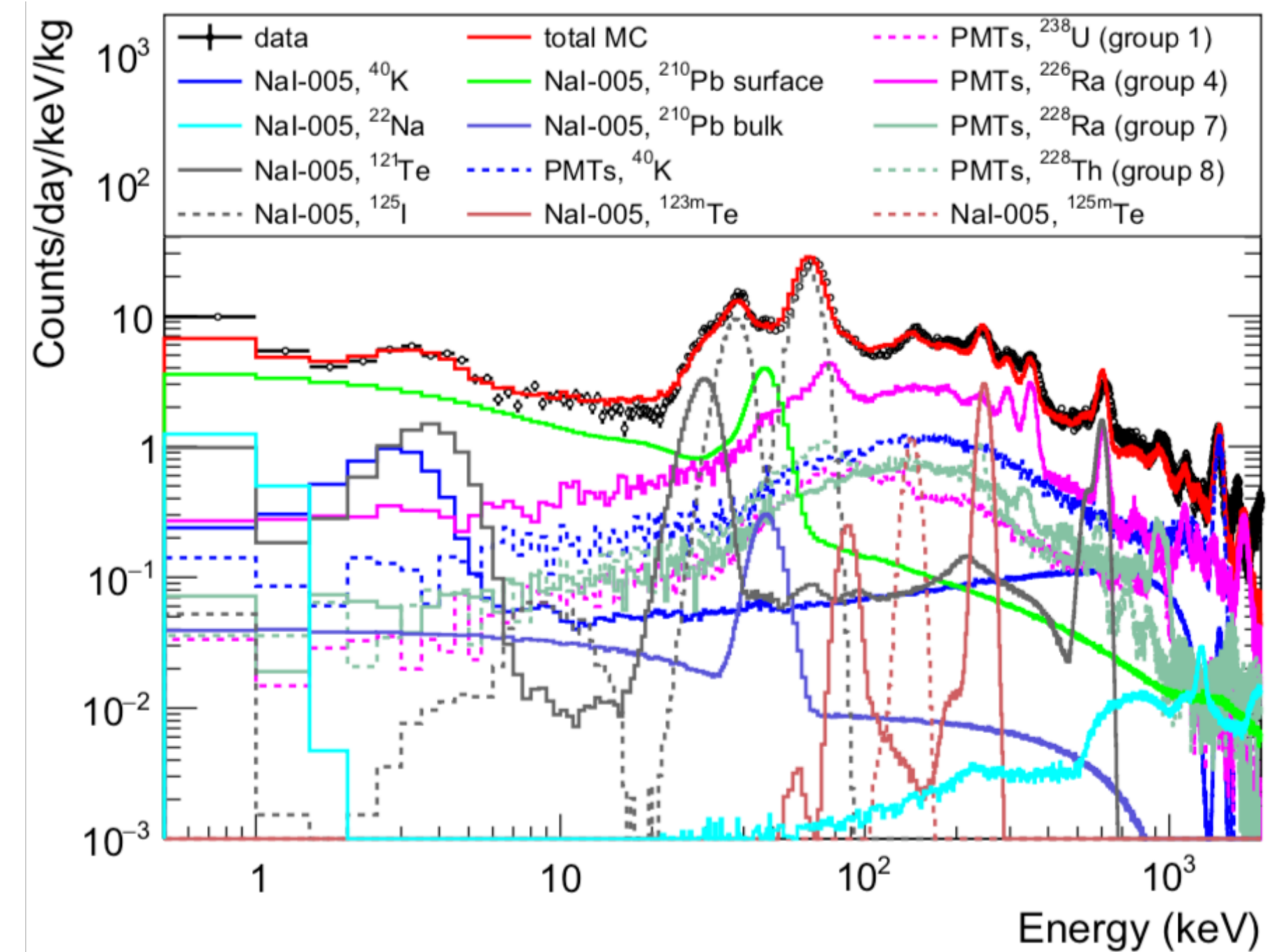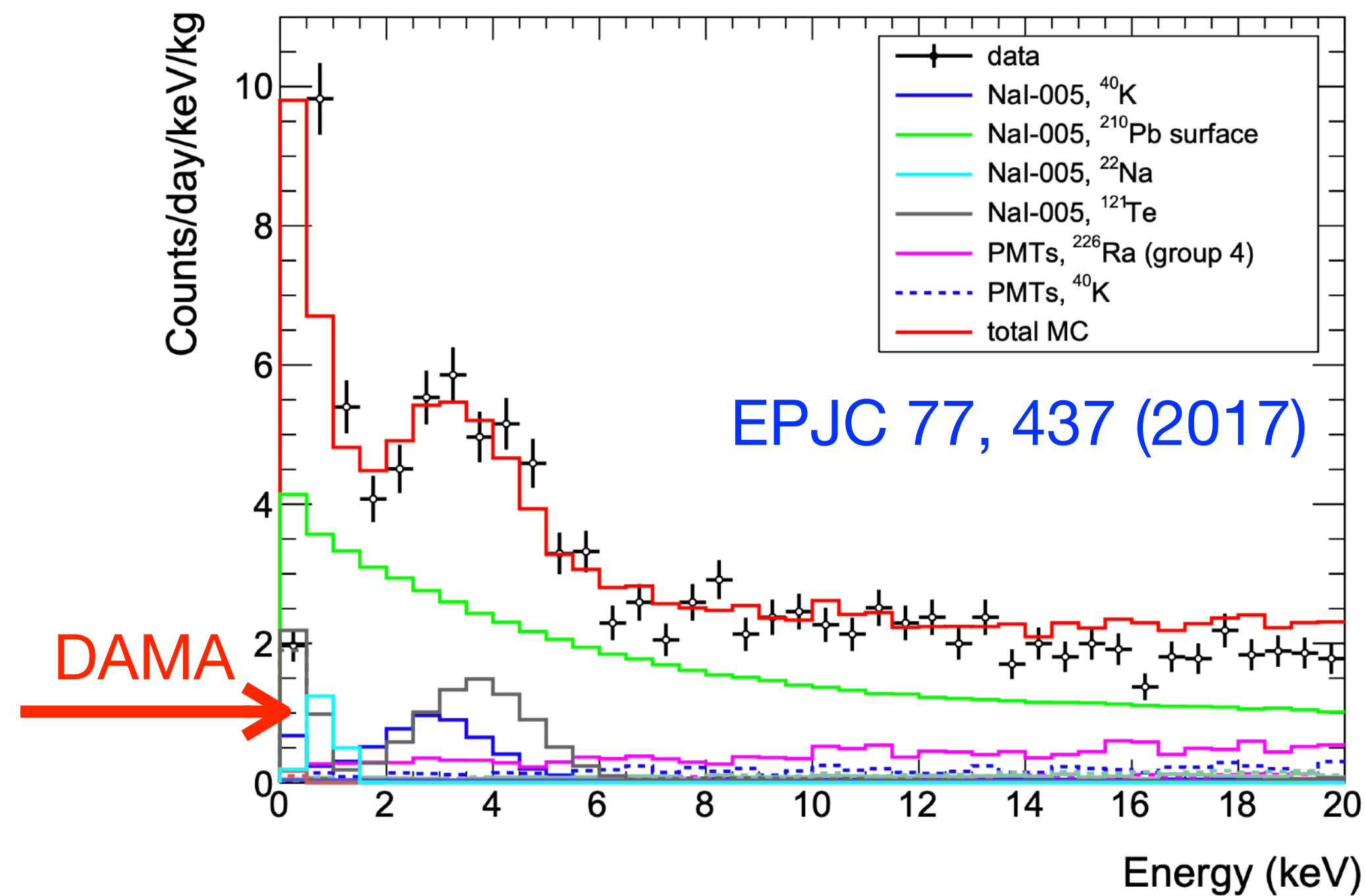
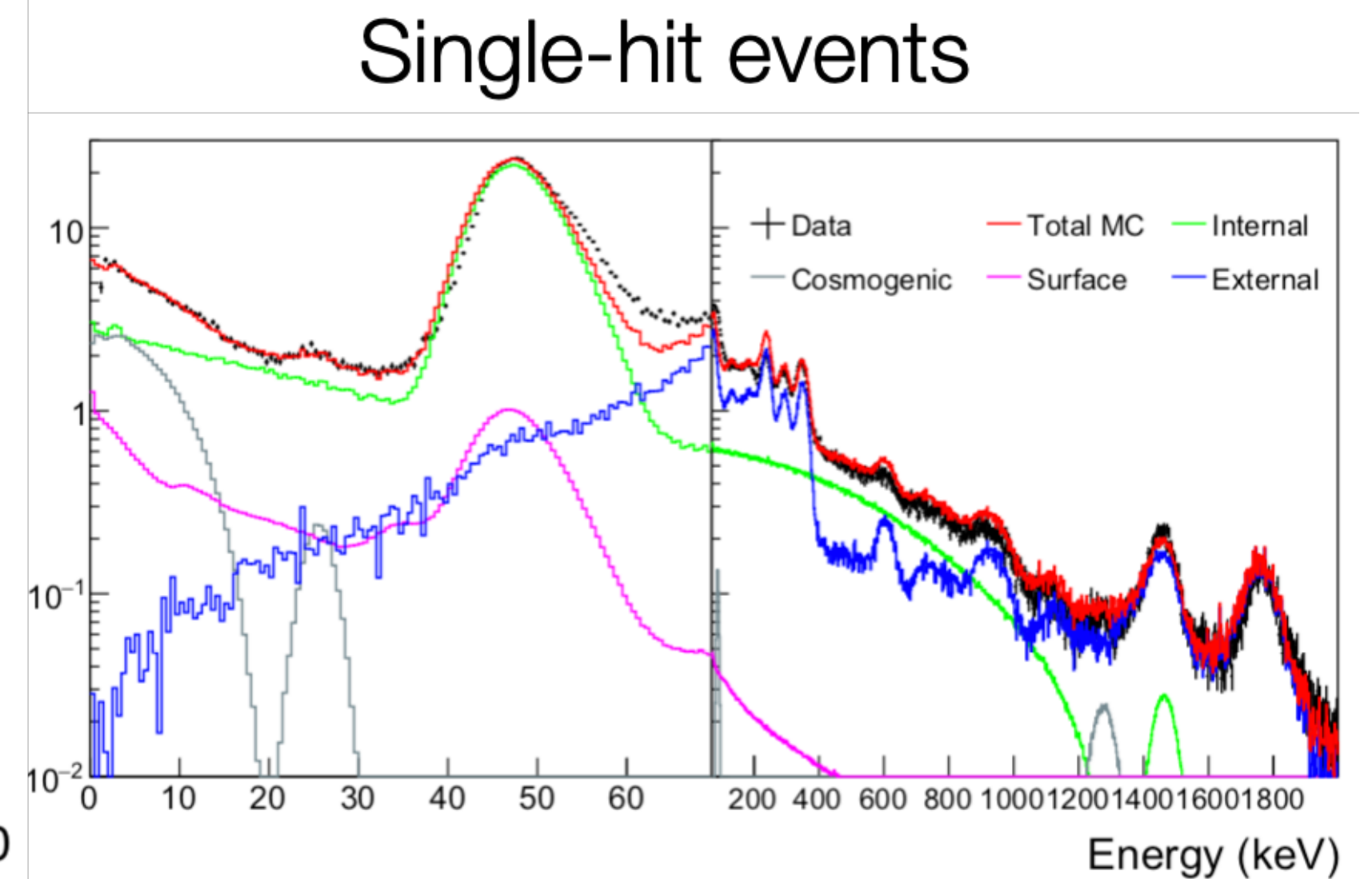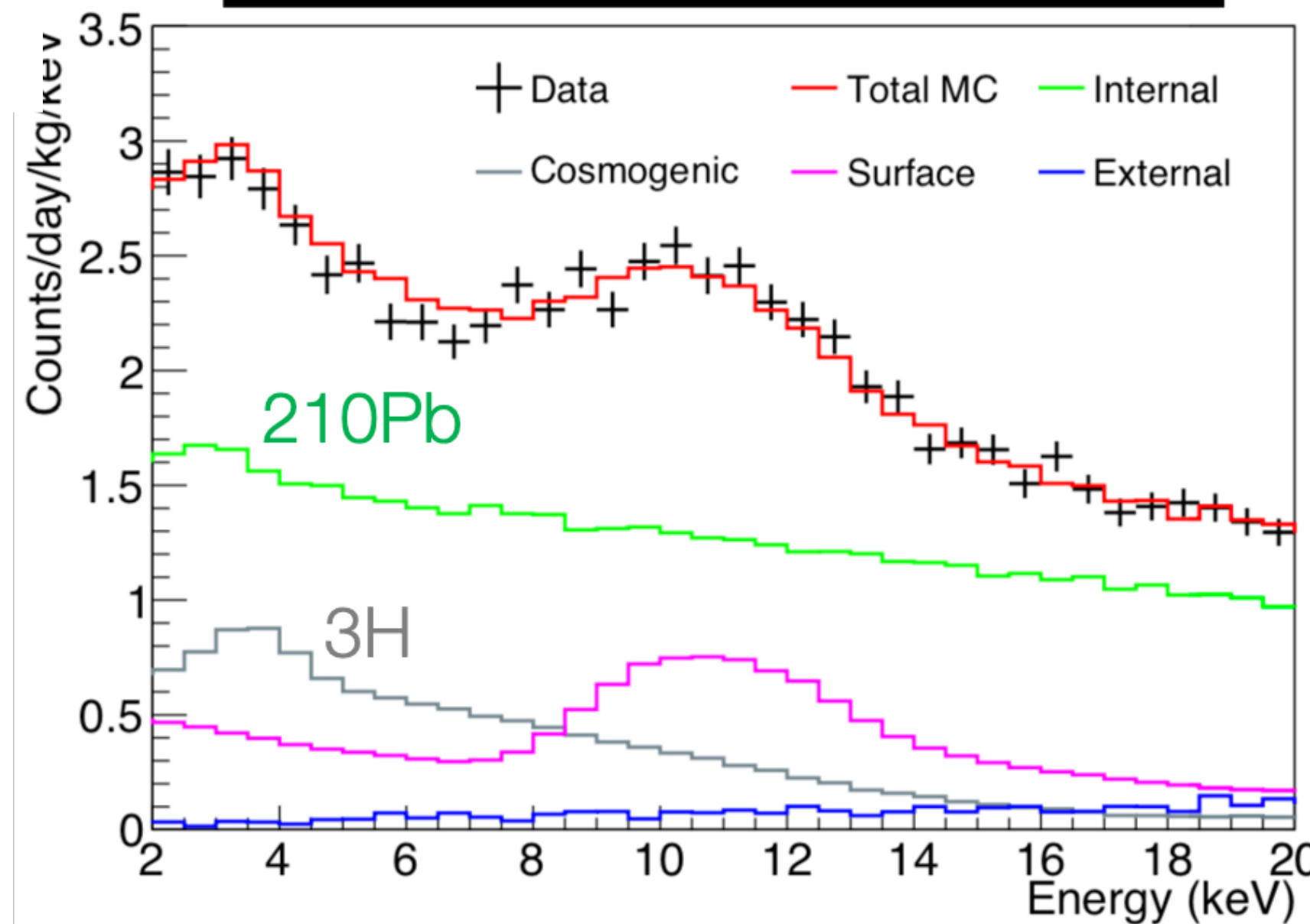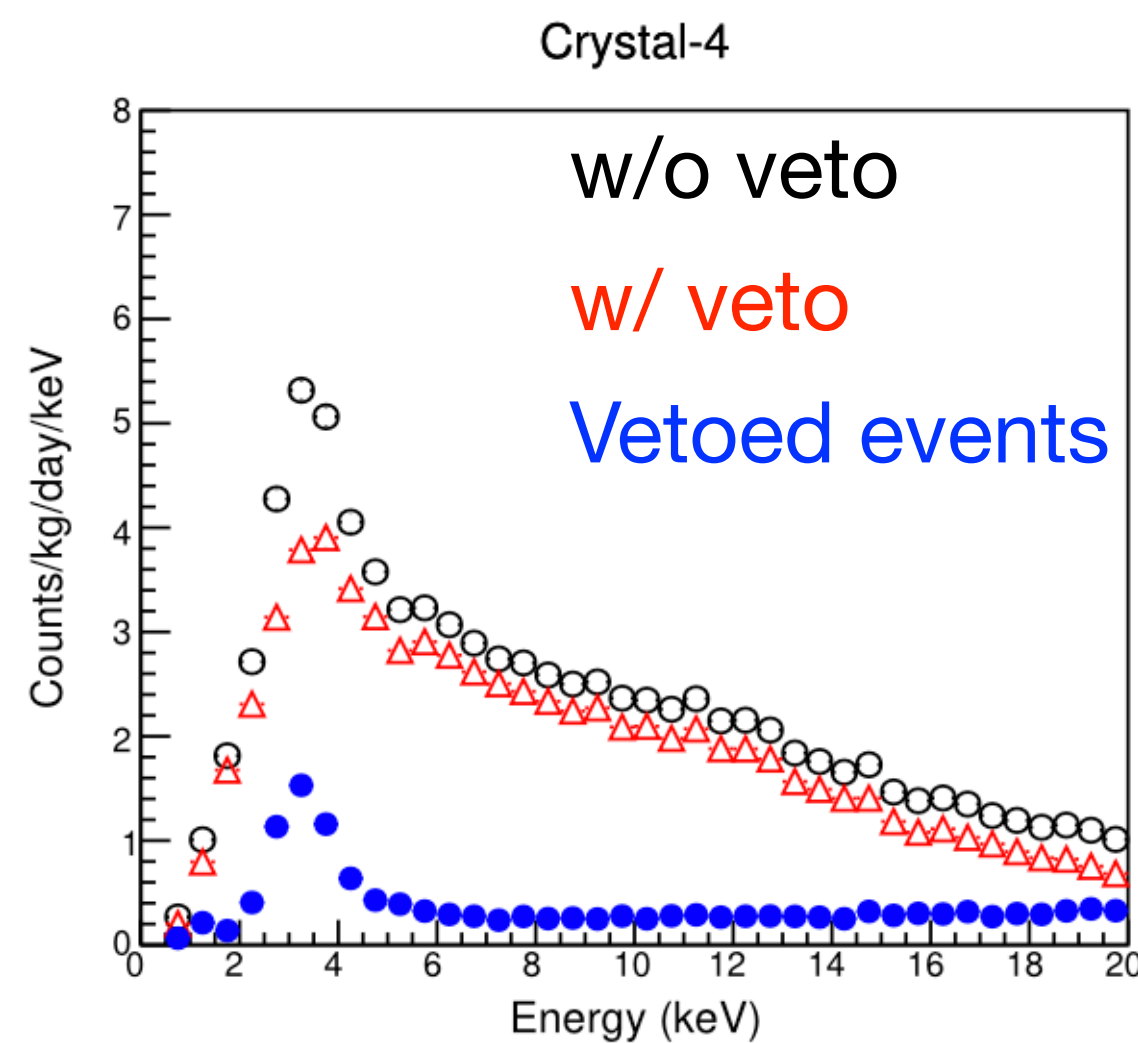- ^{40}K and ^{210}Pb are dominant contributors

Background modeling for COSINE-100

using 59.5 days data
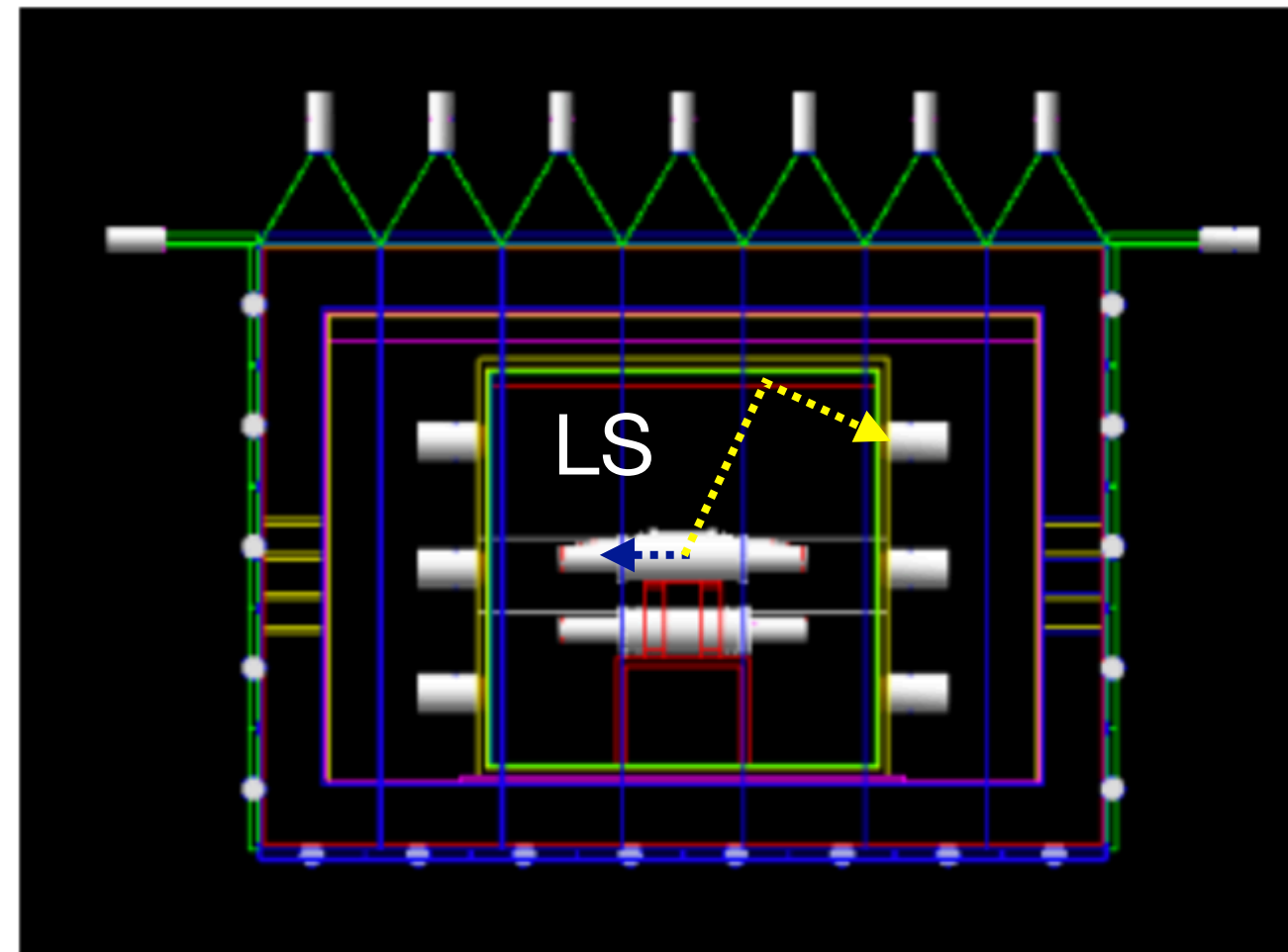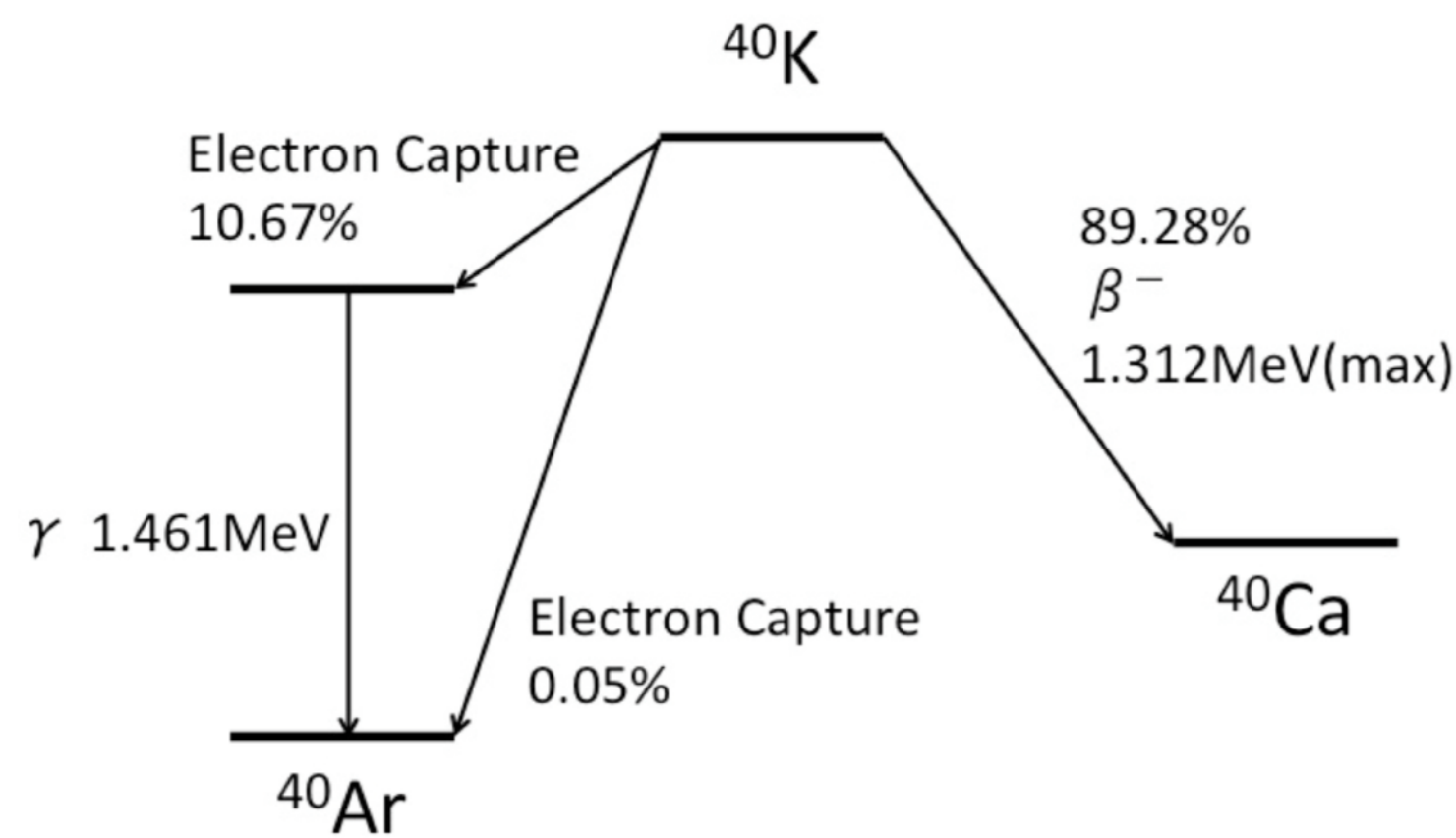
- Active background rejection with liquid scintillation (~70% veto efficiency)

Eur. Phys. J. C 78 (2018) 490

Single-hit events

Cosmogenic radioisotopes

· We measured the activities of the cosmogenic isotope produced in NaI(Tl) using the time-dependent decrease of peaks

· We estimated production rates for the cosmogenic isotopes and compared them with other experimental data and calculations using ACTIVIA and MENDL-2
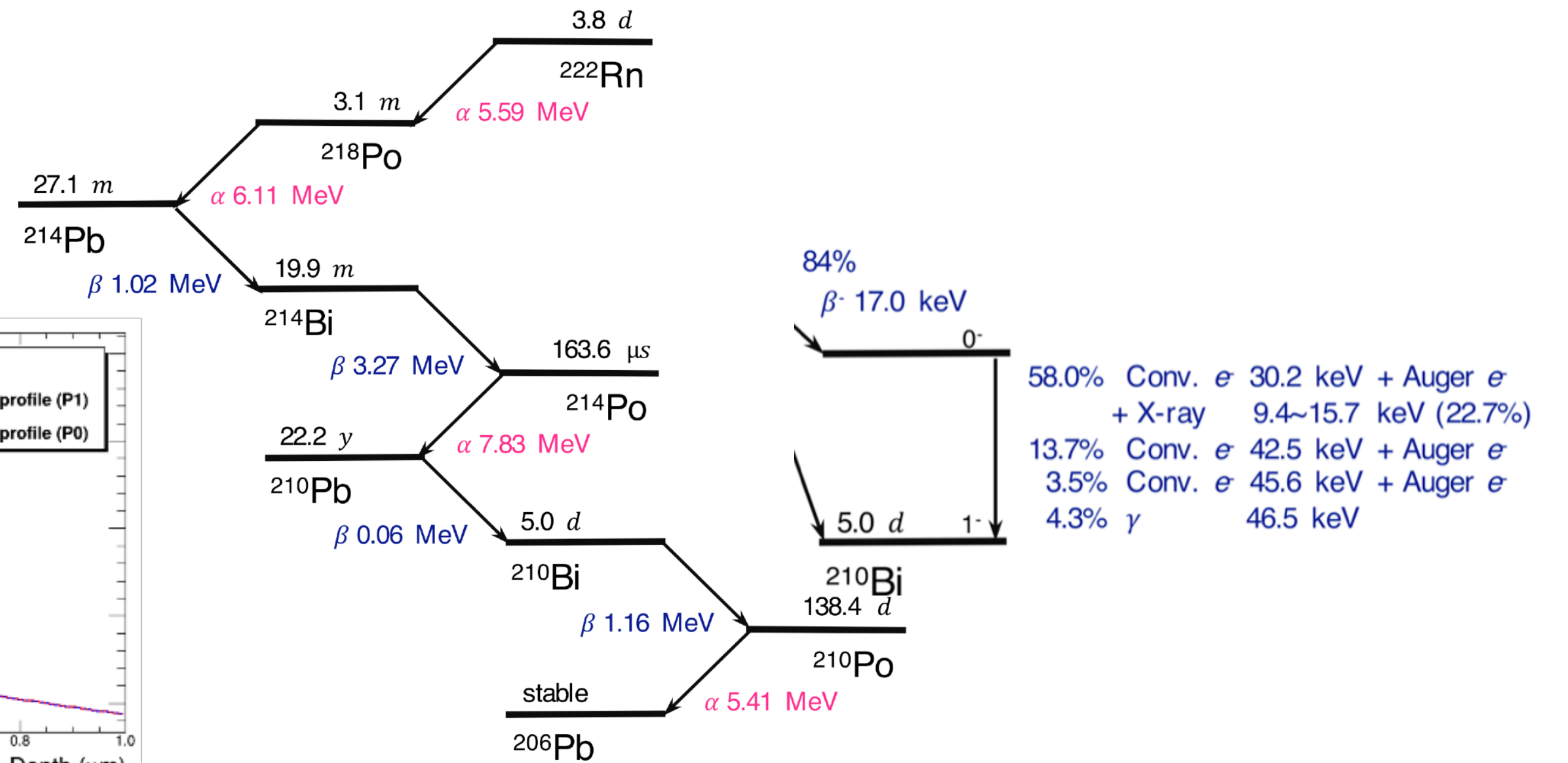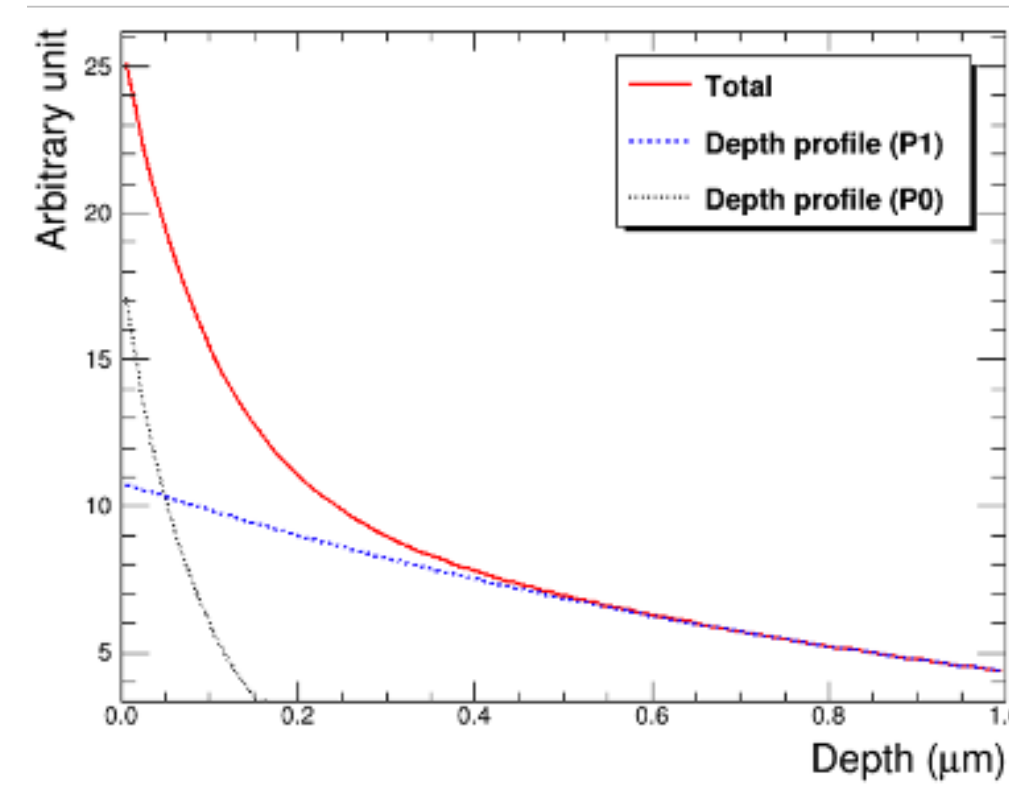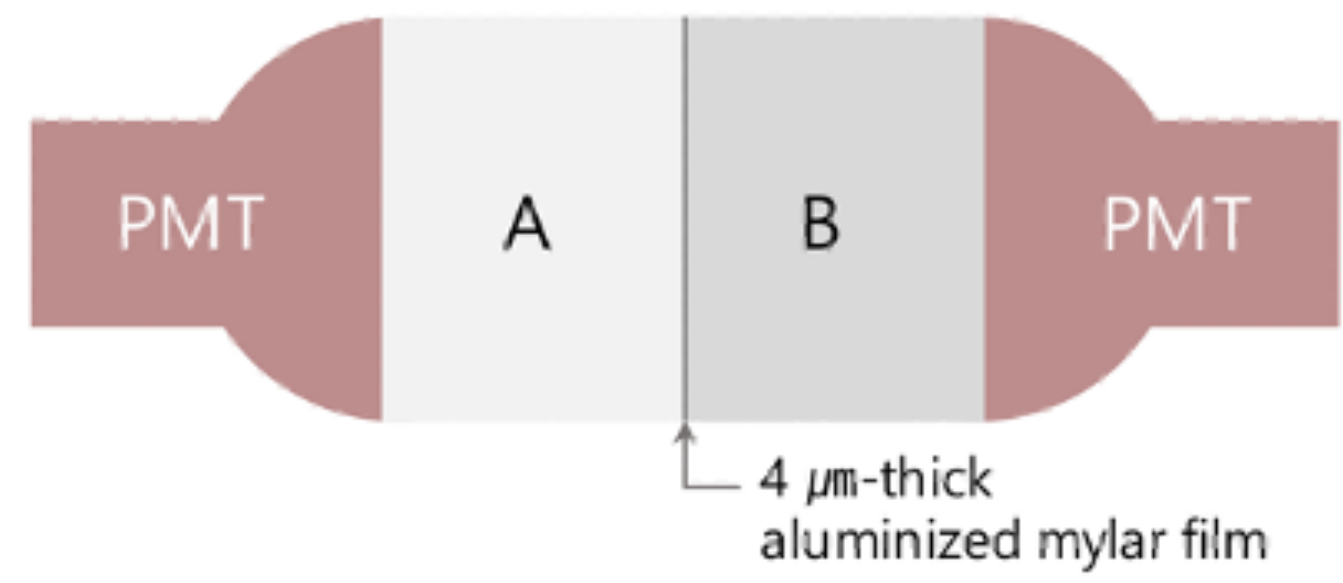
Astropart. Phys. 115 (2020) 102390
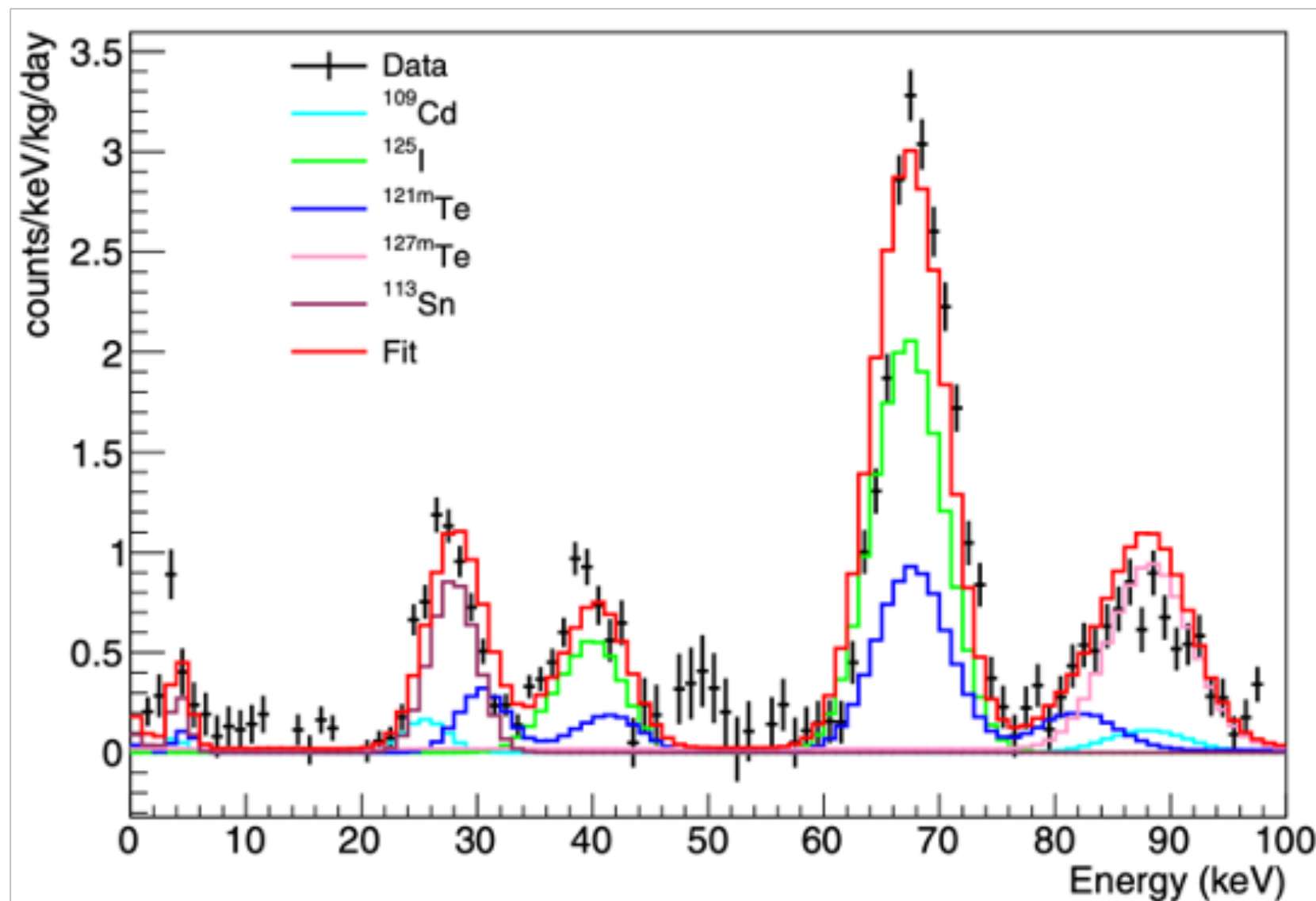
^{3}H	Crystal-1	Crystal-2	Crystal-3	Crystal-4	Crystal-6	Crystal-7
A_0 [mBq/kg]	0.38 ± 0.04	0.20 ± 0.04	0.25 ± 0.04	0.26 ± 0.04	0.11 ± 0.04	0.09 ± 0.04
Exposure time [year]	2.19	1.11	1.37	1.44	0.66	0.52

	^{22}Na	^{109}Cd	^{125}I	^{121m}Te	^{127m}Te	^{113}Sn
Crystal-1	132.0 ± 24.0	1.7 ± 1.1				
Crystal-2	148.5 ± 44.9	0.6 ± 1.2				
Crystal-3	114.5 ± 19.7	4.7 ± 0.6	280.1 ± 29.3	31.1 ± 5.5	26.9 ± 4.8	5.1 ± 1.6
Crystal-4	81.0 ± 12.7	3.7 ± 0.3	104.2 ± 3.7	24.9 ± 1.6	13.5 ± 0.7	4.1 ± 1.6
Crystal-6	144.0 ± 31.2	1.8 ± 0.8	184.7 ± 6.3	23.5 ± 3.5	16.3 ± 1.5	7.1 ± 0.5
Crystal-7	151.0 ± 52.1	1.8 ± 0.6	194.0 ± 6.3	22.3 ± 3.5	15.0 ± 1.5	5.3 ± 0.5
ACTIVIA	66	4.8	221	93	93	9
MENDL-2		4.8	208	102		
ANAIS measurement [31,32,34]	45.1 ± 1.9	2.38 ± 0.20	220 ± 10	23.5 ± 0.8	10.2 ± 0.4	4.53 ± 0.40
DM-Ice17 measurement [30]			230	25	< 9	16

NaI(Tl) crystal surface ^{210}Pb contamination

PMT | A | B | PMT

4 μm-thick aluminized mylar film

- Total
- Depth profile (P1)
- Depth profile (P0)

^{222}Rn — 3.8 d

^{218}Po — 3.1 m — α 5.59 MeV

^{214}Pb — 27.1 m — α 6.11 MeV — β 1.02 MeV

^{214}Bi — 19.9 m — β 3.27 MeV

^{214}Po — 163.6 μs — α 7.83 MeV

^{210}Pb — 22.2 y — β 0.06 MeV

^{210}Bi — 5.0 d — β 1.16 MeV

^{210}Po — stable — α 5.41 MeV

^{206}Pb

84%
β^- 17.0 keV

58.0% Conv. e^- 30.2 keV + Auger e^-
+ X-ray 9.4~15.7 keV (22.7%)
13.7% Conv. e^- 42.5 keV + Auger e^-
3.5% Conv. e^- 45.6 keV + Auger e^-
4.3% γ 46.5 keV
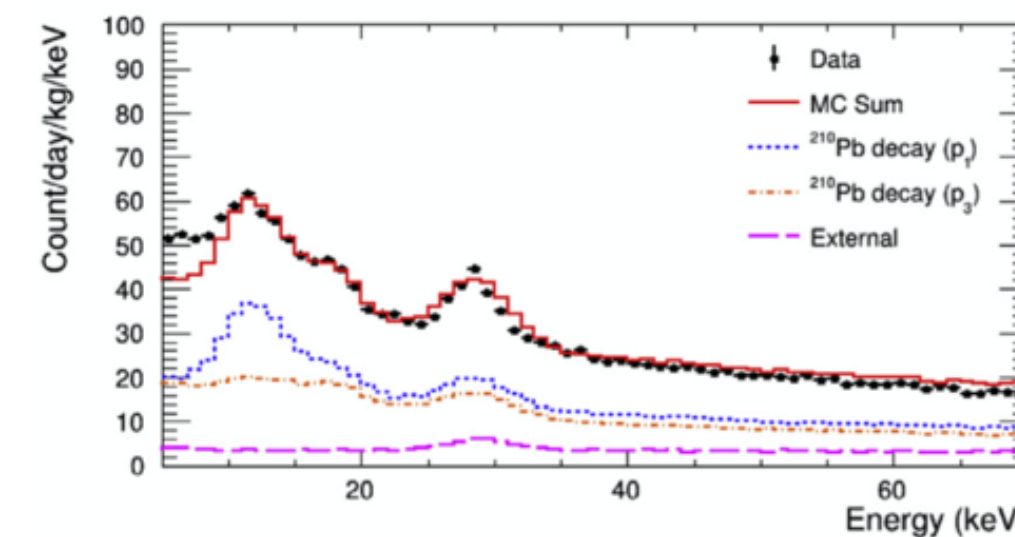
^{210}Bi 138.4 d — 5.0 d

- We used a model to estimate the depth profile of the surface contamination of ^{210}Pb by analyzing the low- and high-energy events spectra obtained from the beta decay of ^{210}Pb using a crystal-PMT detector module

- The module's crystal (B) was contaminated with ^{222}Rn and attached to a clean crystal (A)
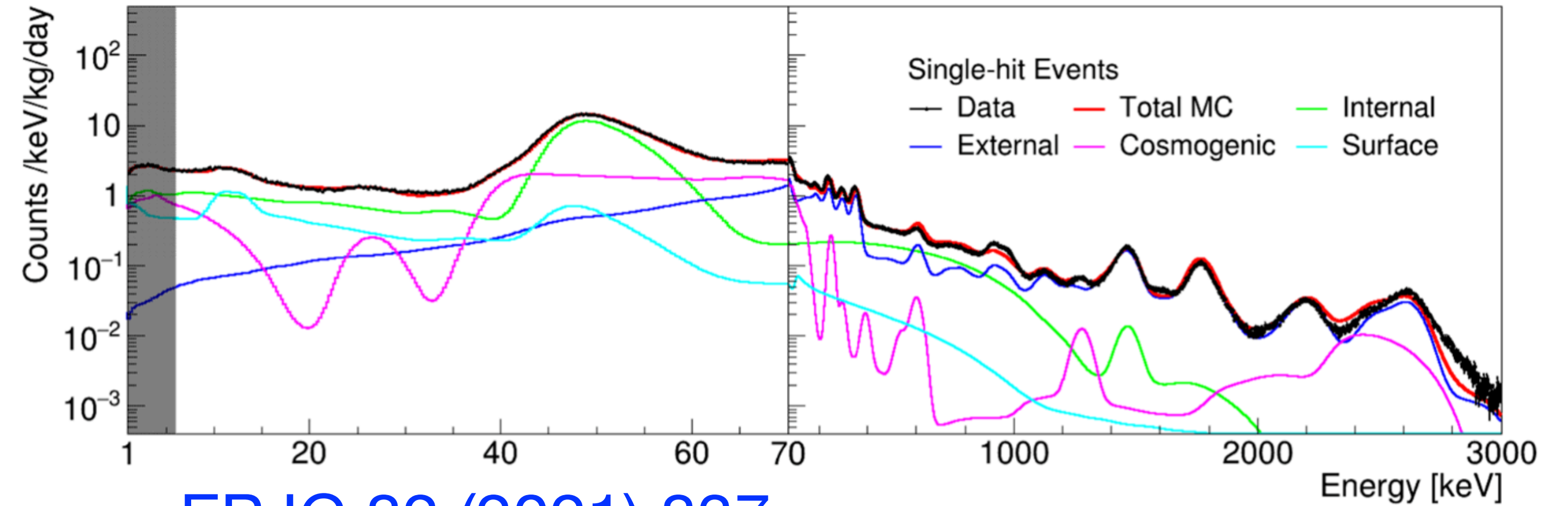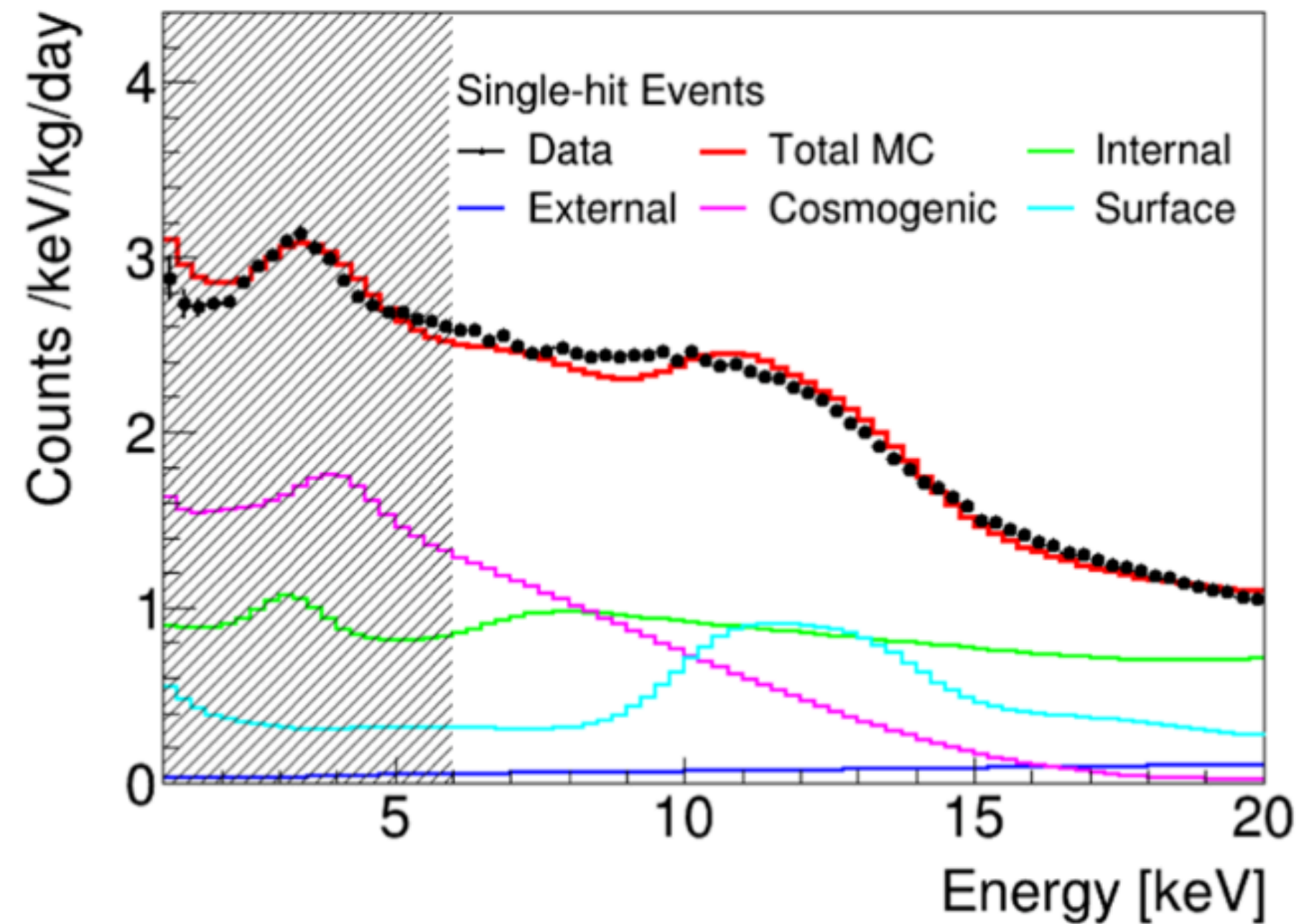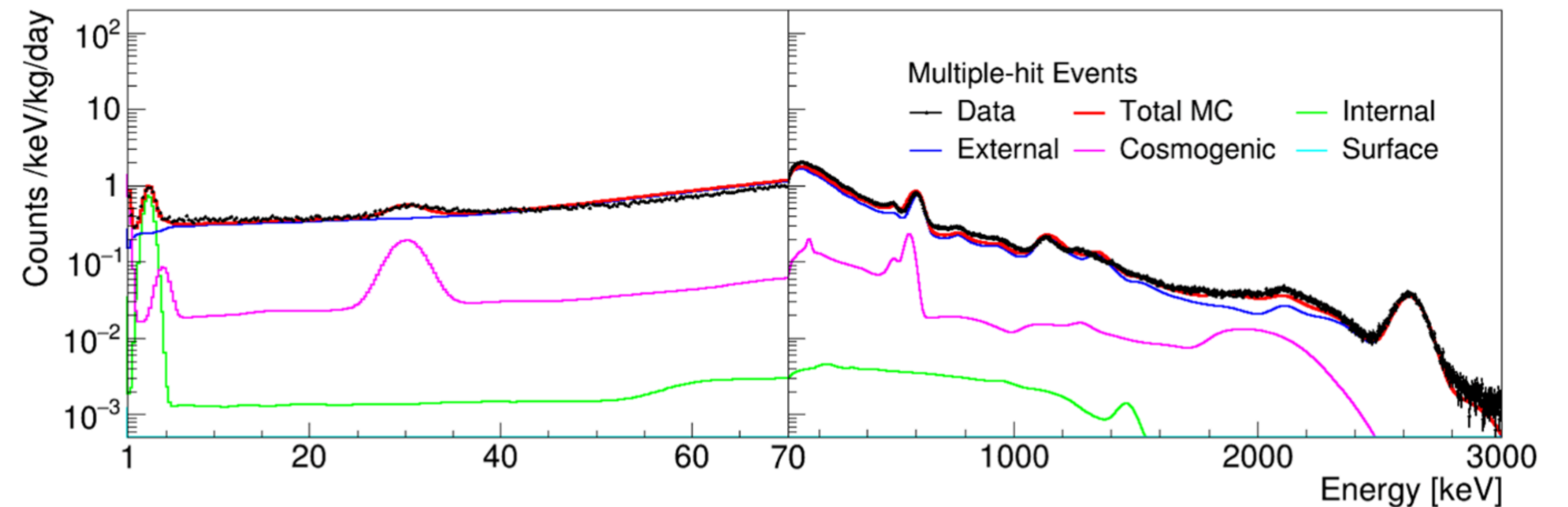
Astropart. Phys. 126 (2021) 102518
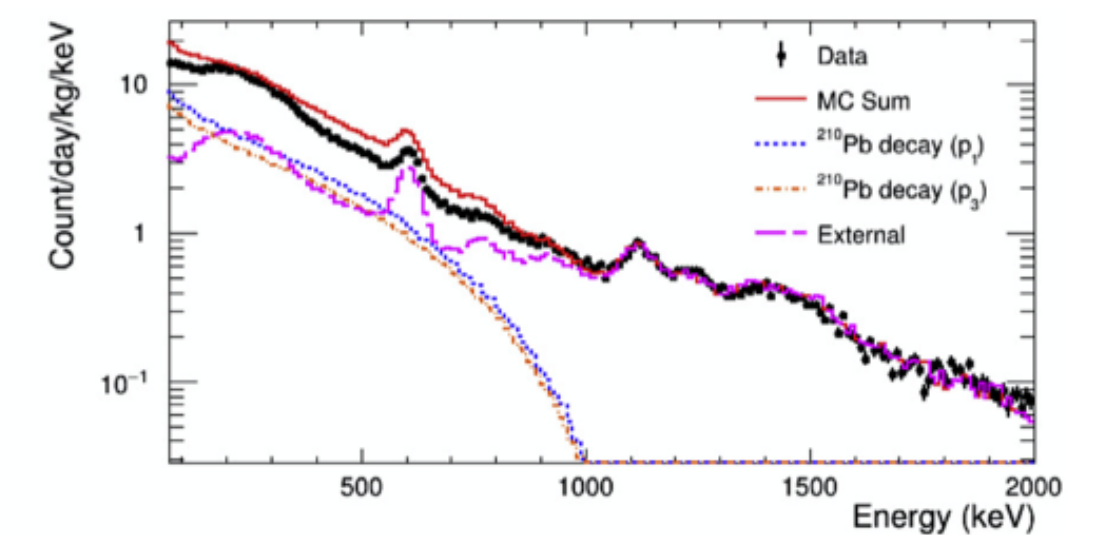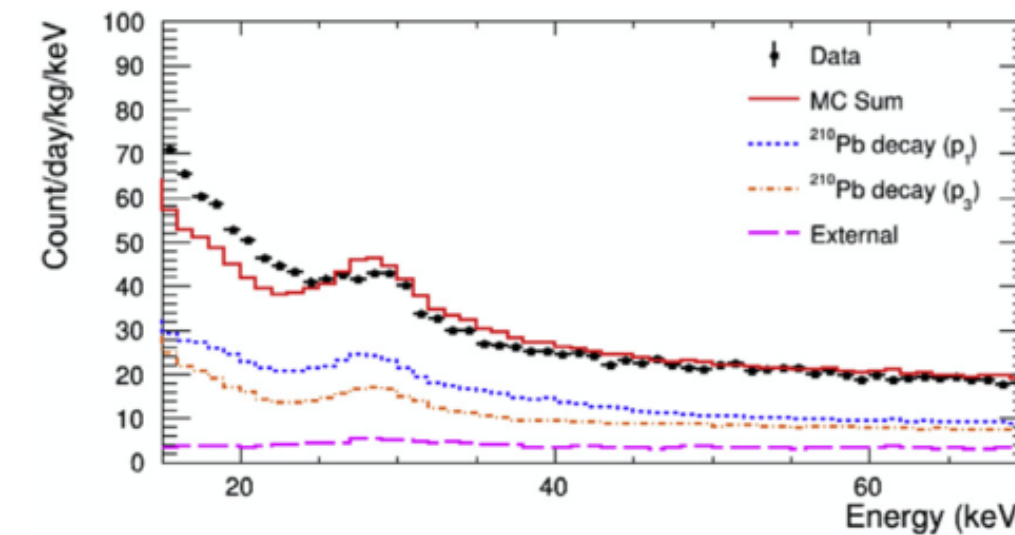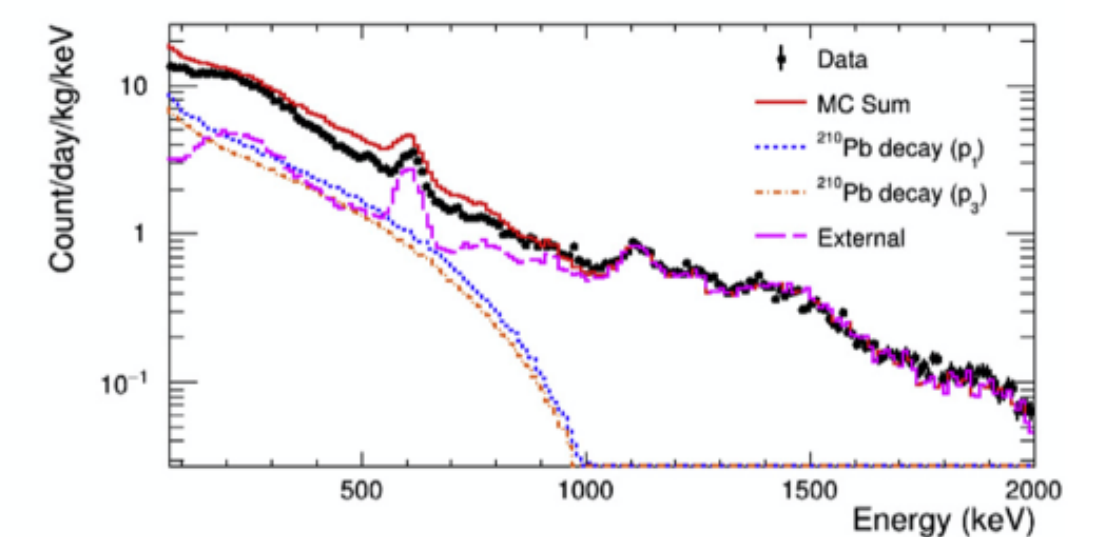
Background modeling using 1.7 years of COSINE-100 data
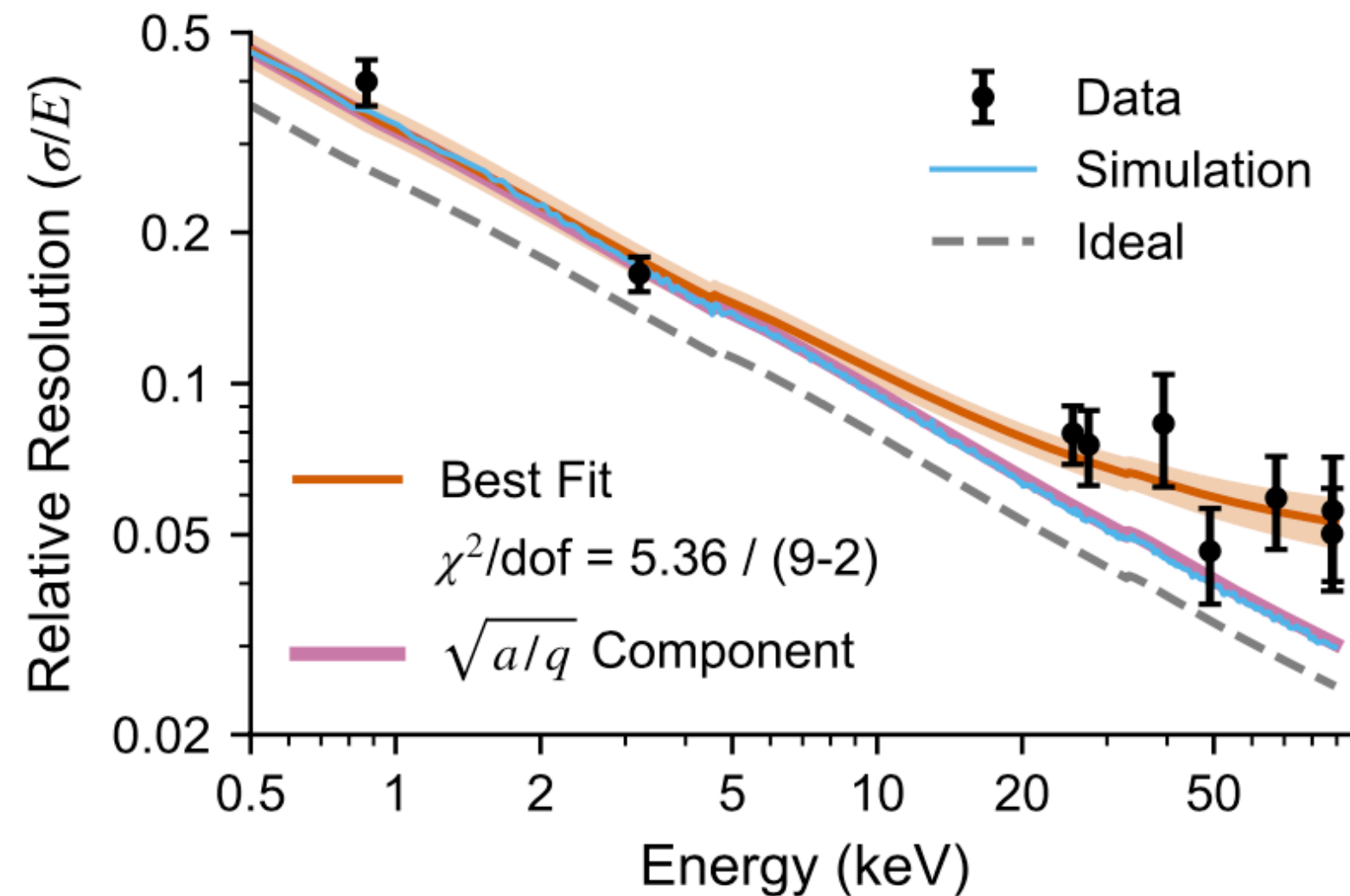
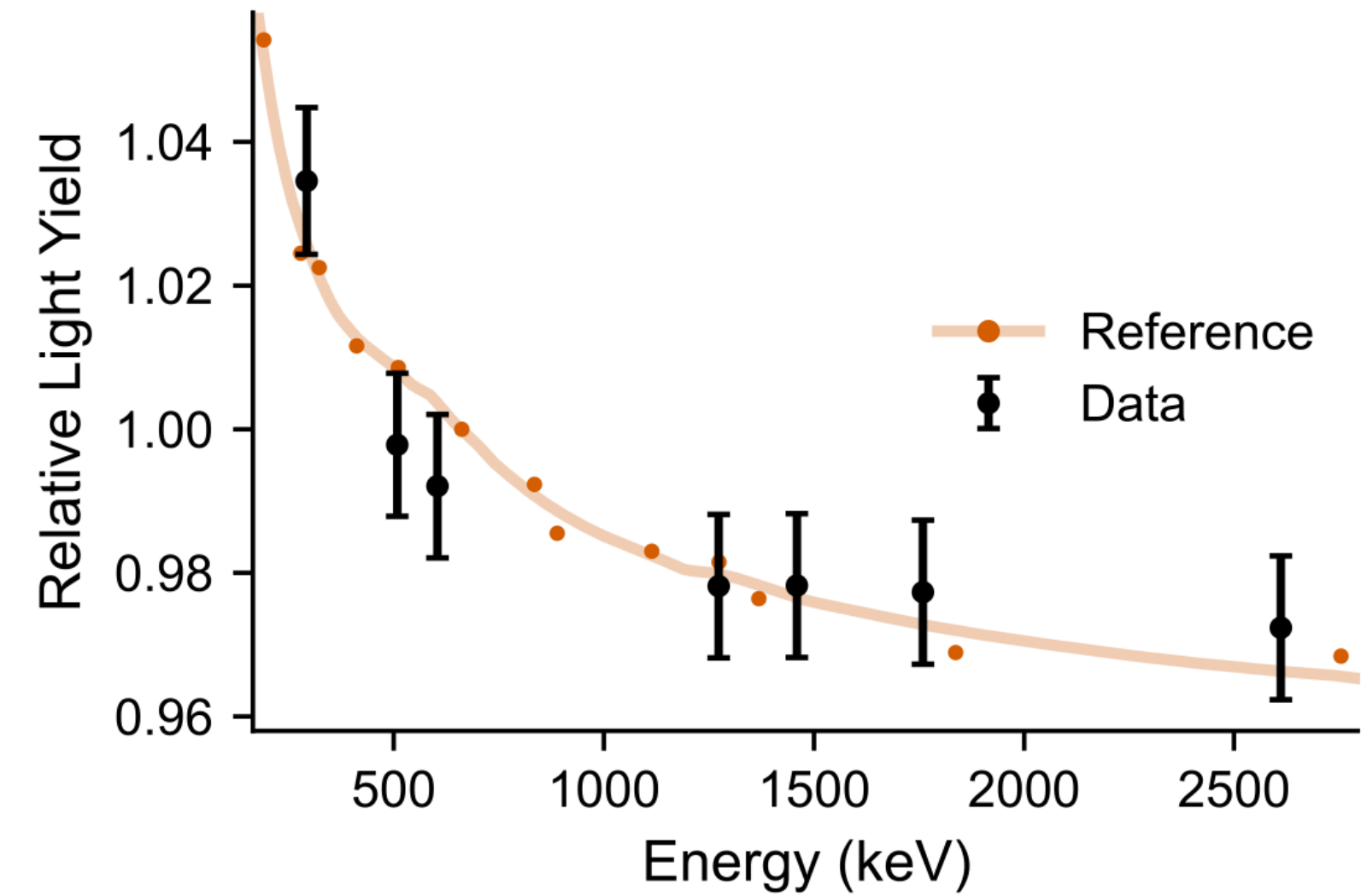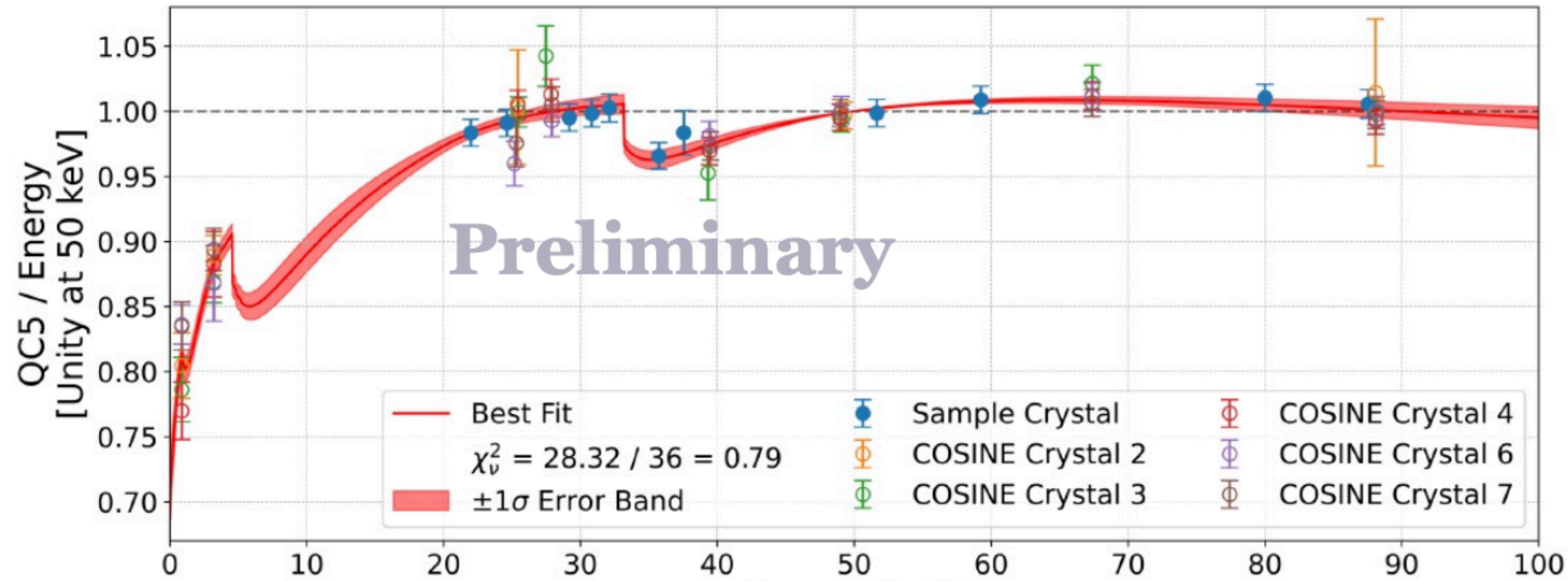## with 1 keV energy threshold
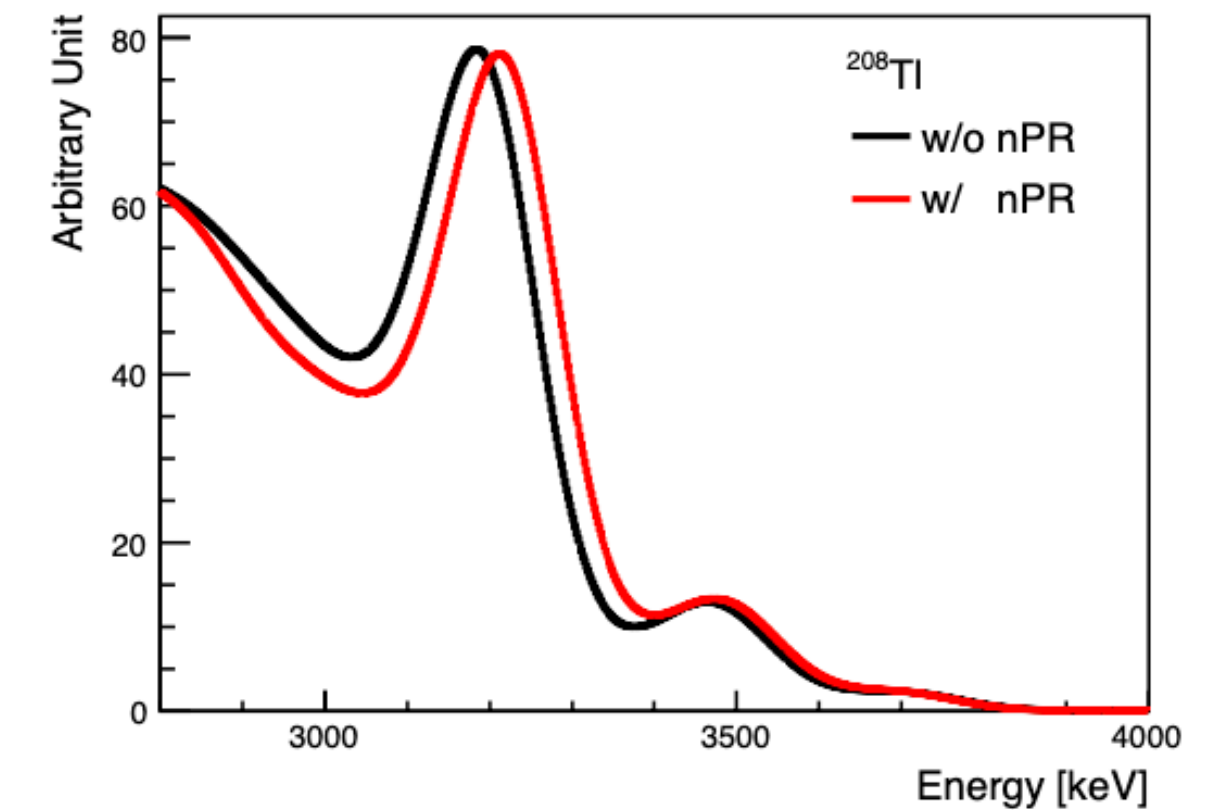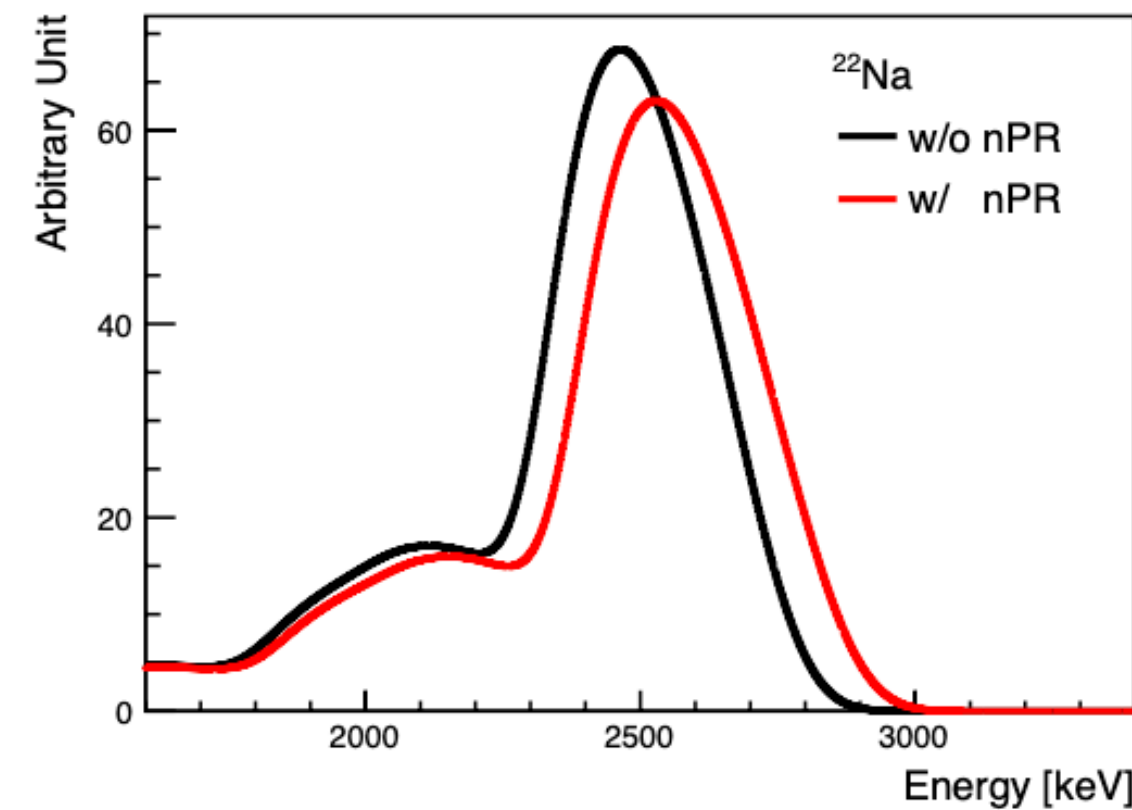

EPJC 82 (2021) 837

- ^{3}H and ^{210}Pb are dominant contributors

Nonproportionality

arXiv:2401.07462

Nonproportionality of gamma & x-rays

Preliminary

- Best Fit
- χ^2_ν = 28.32 / 36 = 0.79
- ±1σ Error Band
- Sample Crystal
- COSINE Crystal 2
- COSINE Crystal 3
- COSINE Crystal 4
- COSINE Crystal 6
- COSINE Crystal 7

- Reference
- Data

- Data
- Simulation
- Ideal
- Best Fit
- χ^2/dof = 5.36 / (9-2)
- $\sqrt{a/q}$ Component

^{22}Na: two 511 keV γs + 1274 keV γ + e$^+$(Q~545 keV)

^{22}Na
- w/o nPR
- w/ nPR

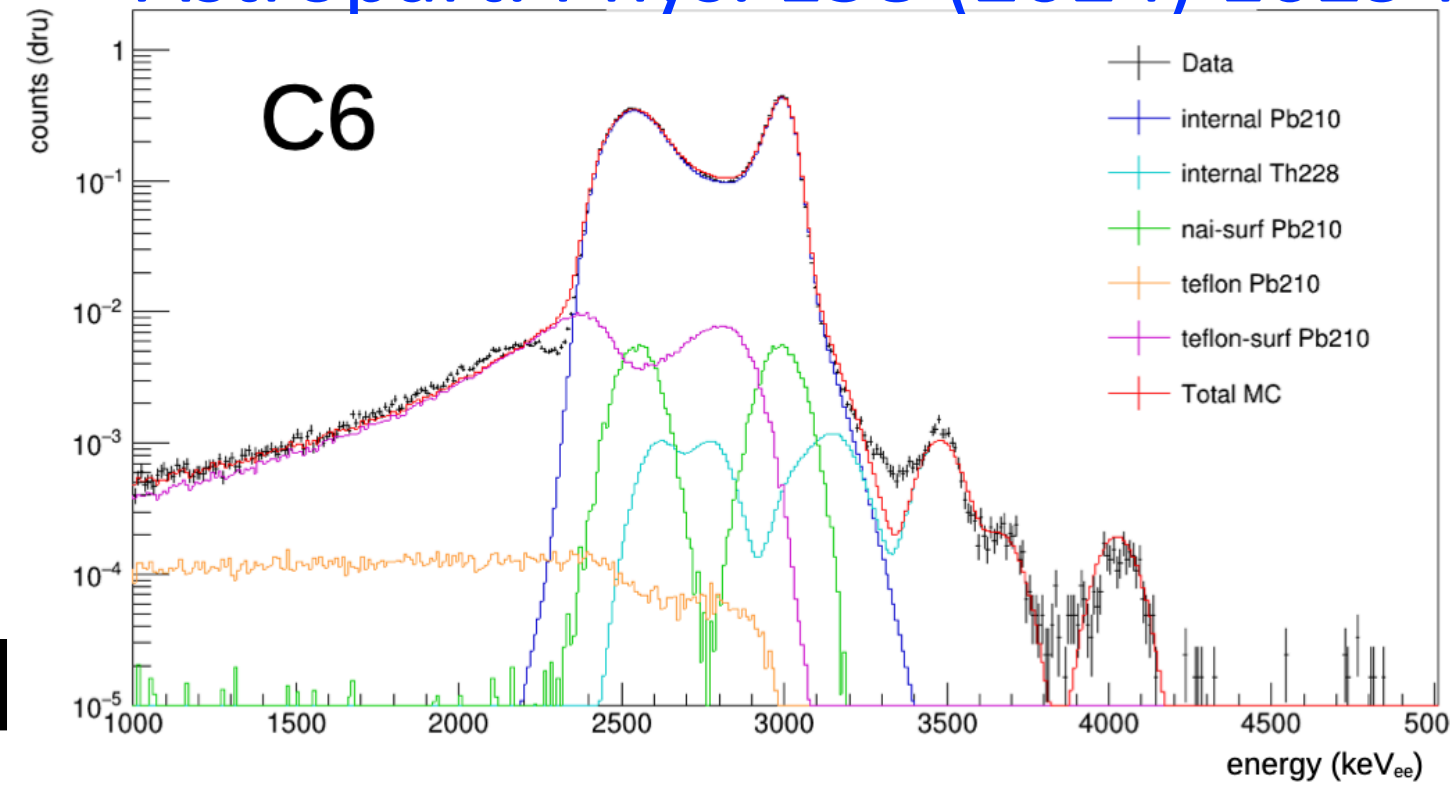^{208}Tl
- w/o nPR
- w/ nPR

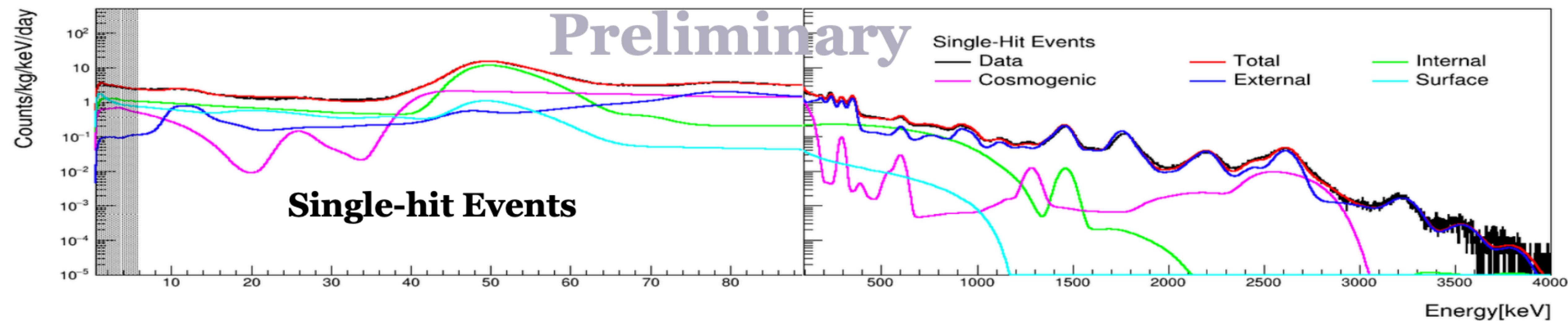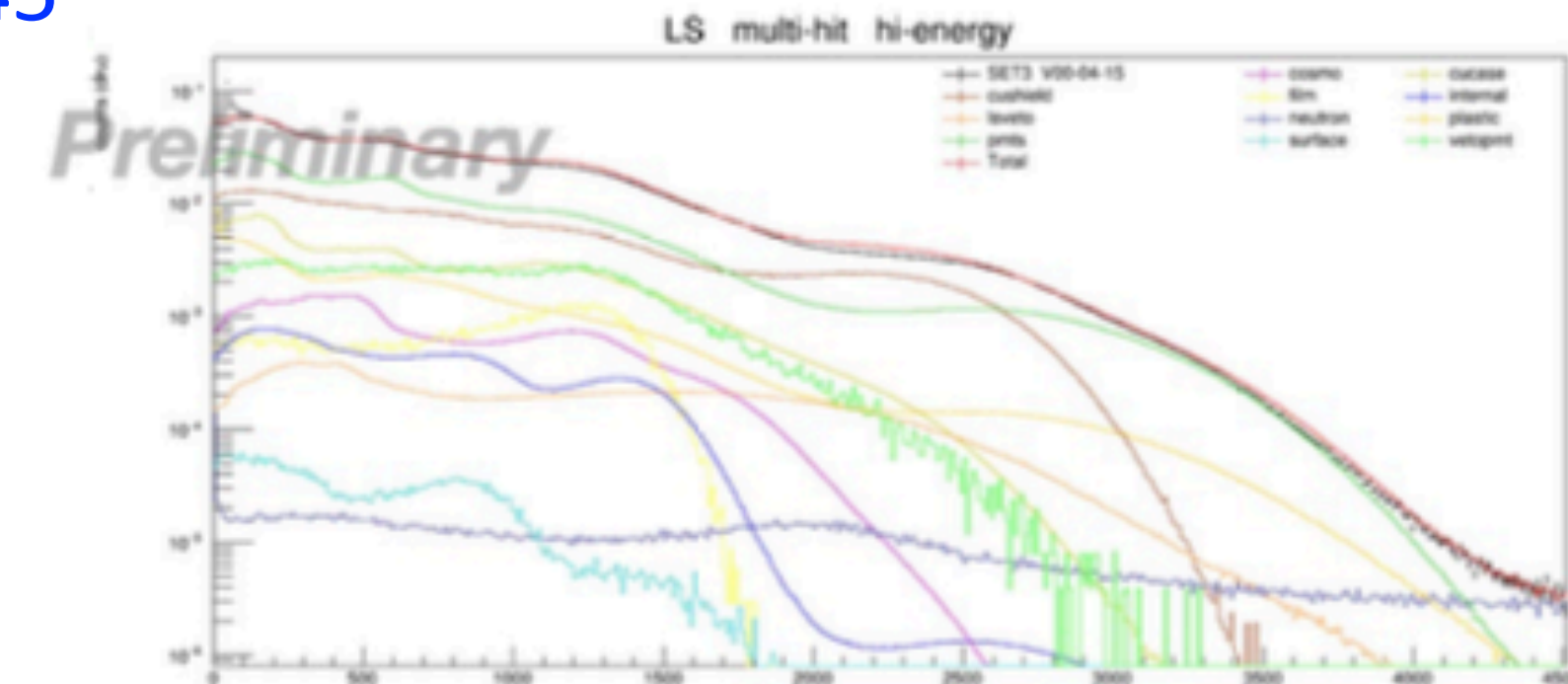# Background modeling updates for 2.8 years of data with 0.7 keV th.

- Nonproportionality applied

- Extended energy range of 0.7 keV ~ 4000 keV

- Not only β/γ but also Alpha and LS spectra are modeled

Alpha spectrum modeling
Astropart. Phys. 158 (2024) 102945


LS spectrum modeling

Nonproportionality (nPR) in the COSINE-100 simulation package

- We have measured nPR for gamma rays

- when e- and γ are emitted together, calibration becomes more challenging

- It would be ideal if nPR is included in the simulation package ➔ we embedded nPR in Geant4 (very preliminary)

  - We assumed that electron light yield is like a dotted orange line
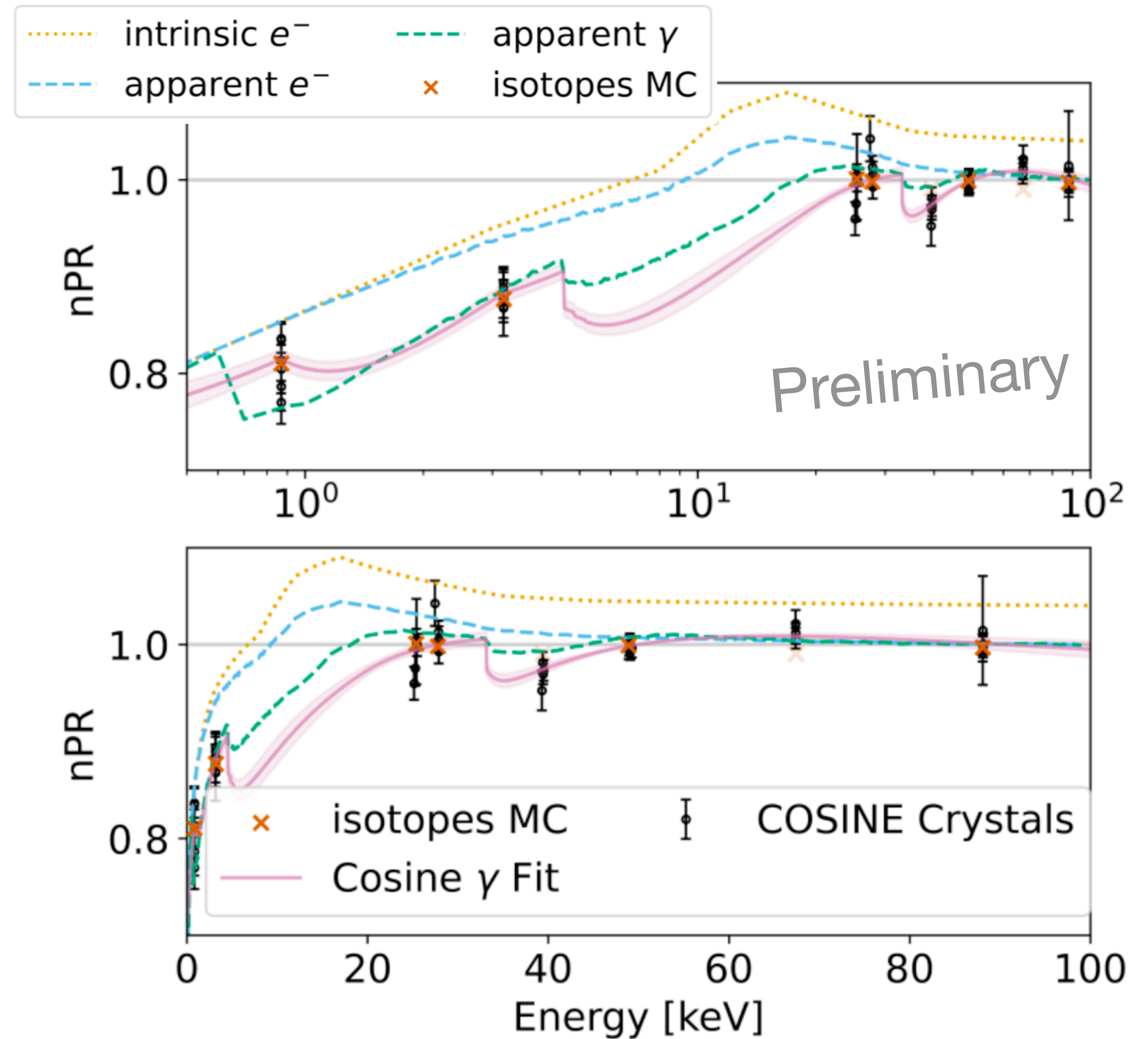
Comparison of simulation results applied by the empirical curve and using embedded in Geant4
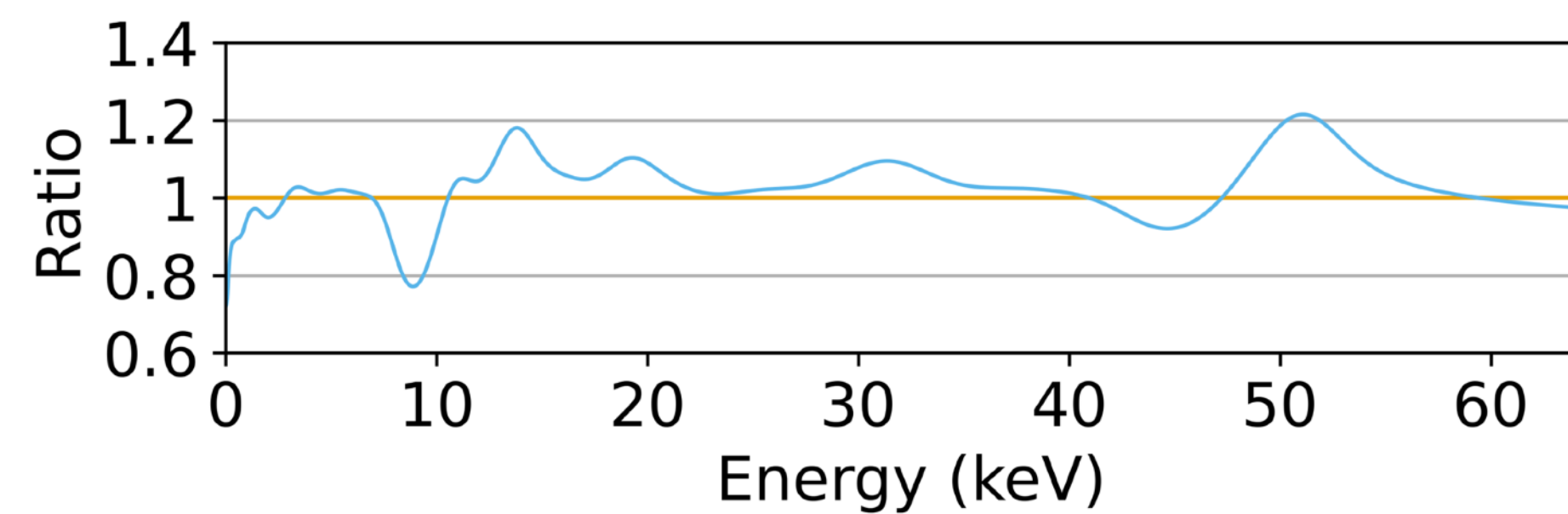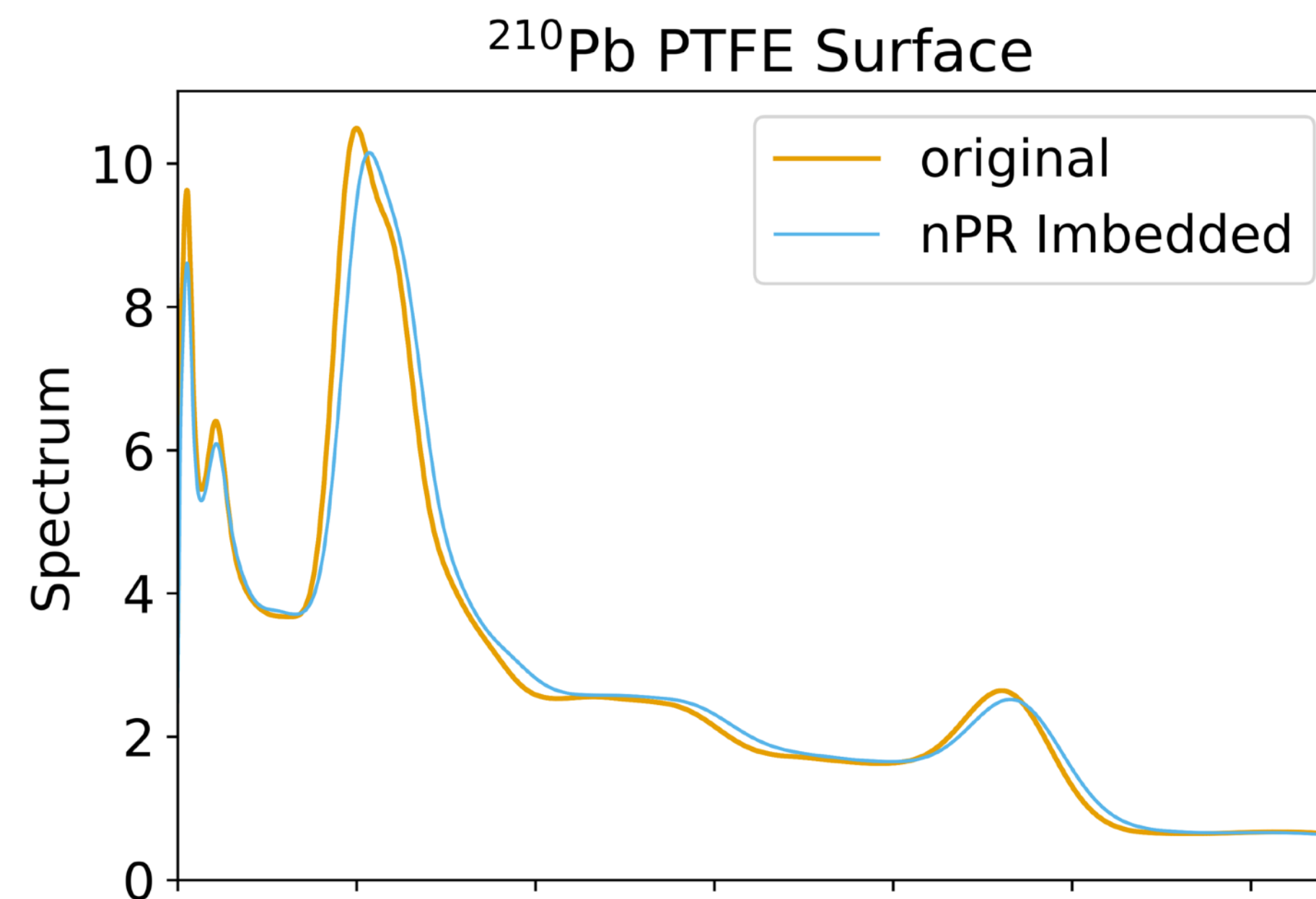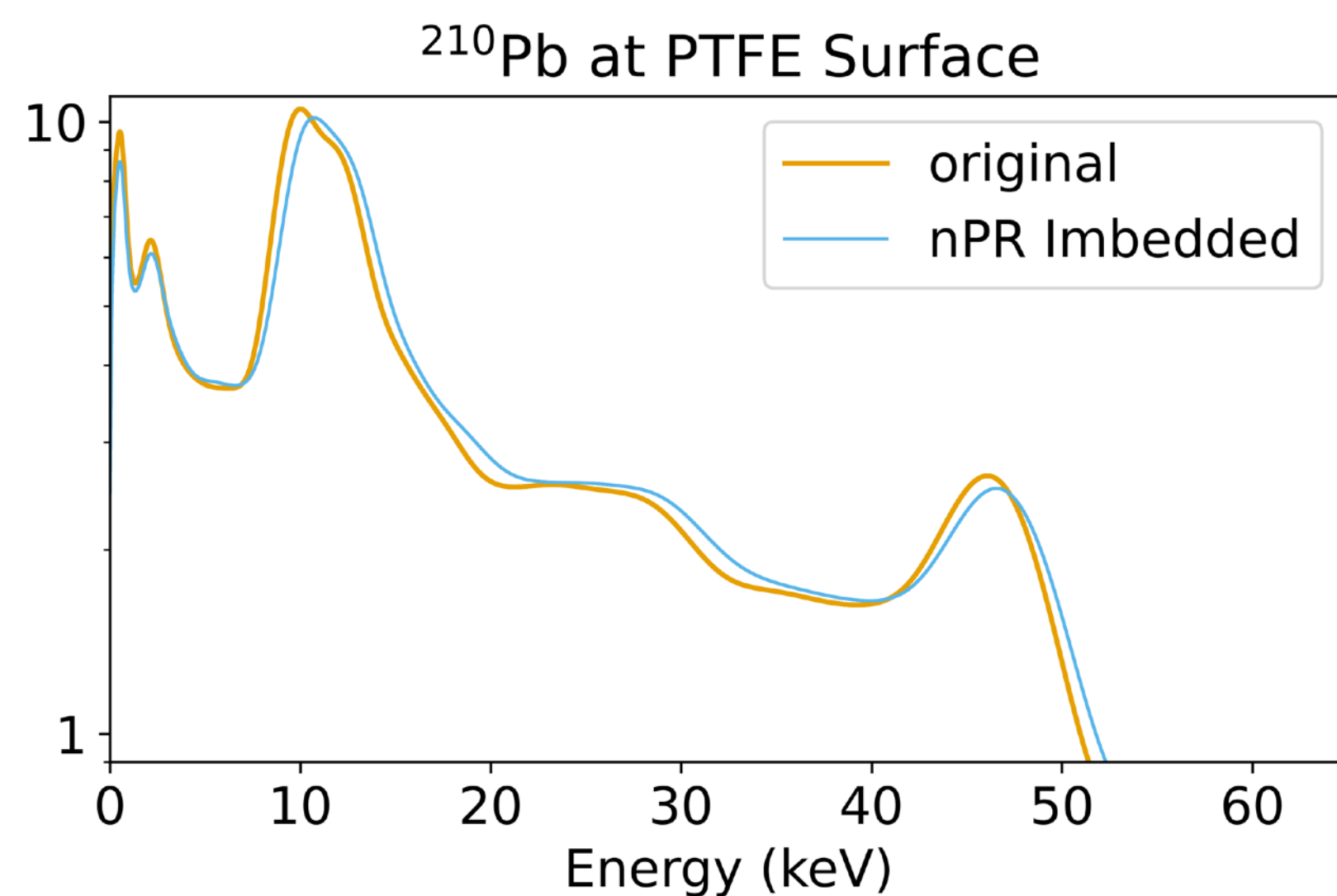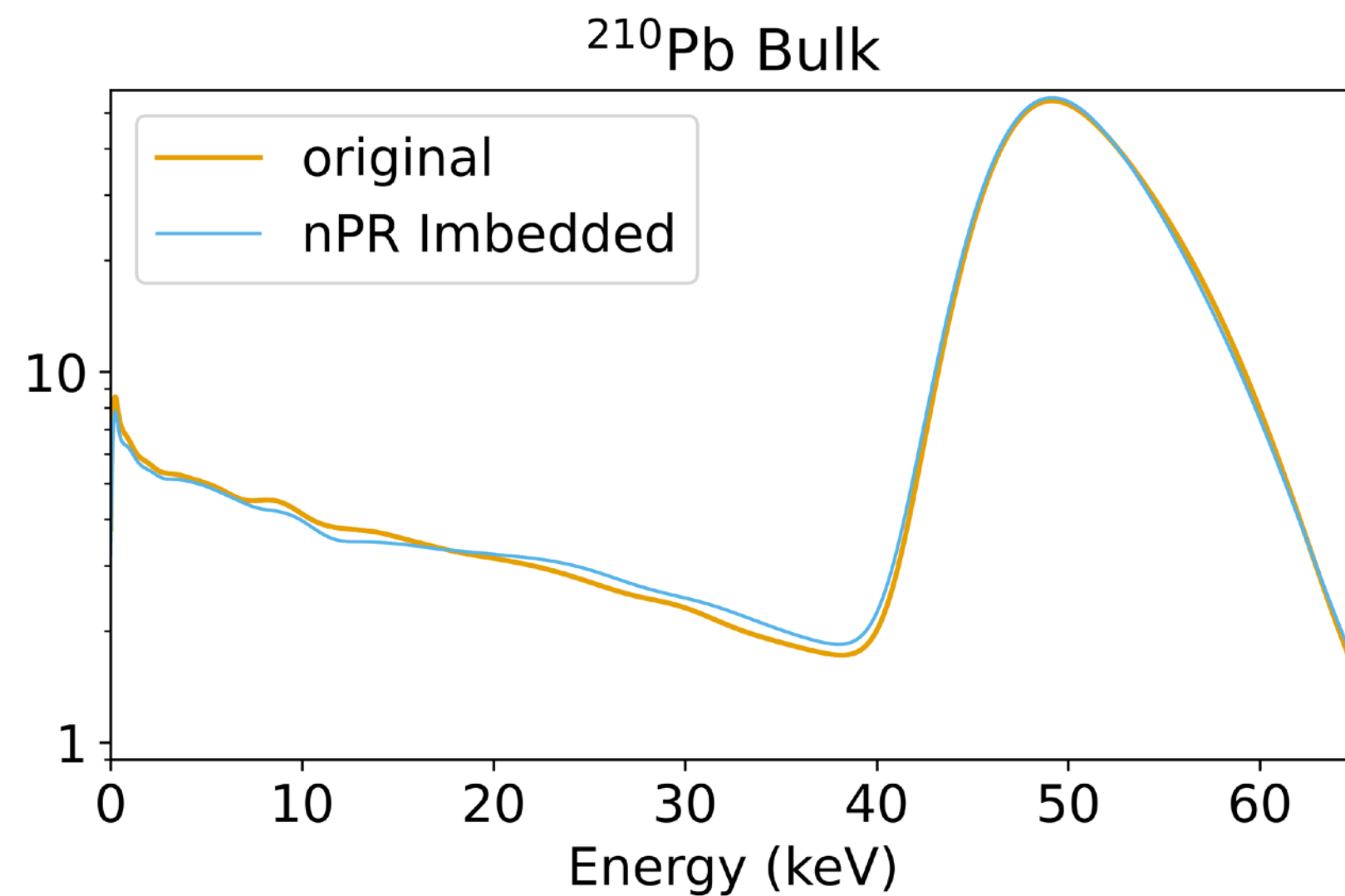
Summary

- COSINE-100 is an experiment designed to test the validity of the DAMA/LIBRA's claim for the WIMP dark matter with the standard halo model

- It is important to have a quantitative understanding of the backgrounds, even though they do not approach the level of DAMA/LIBRA

- We built the background modeling and enhanced it to accurately interpret the background spectrum while lowering the energy threshold

- We are implementing nPR in the Geant4 simulation for more accurate modeling of backgrounds, improving sensitivities for low-mass dark matter searches at Yemilab