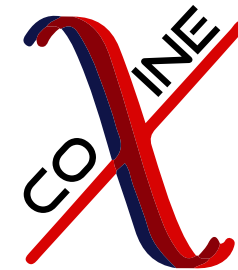


# COSINE dark matter search

## Resolving DAMA/LIBRA



**Hyunsu Lee**



Institute for Basic Science

Center for Underground Physics

*The 21<sup>st</sup> Reconstres du Vietnam (TMEX 2025)*

*January 9<sup>th</sup>, 2025*

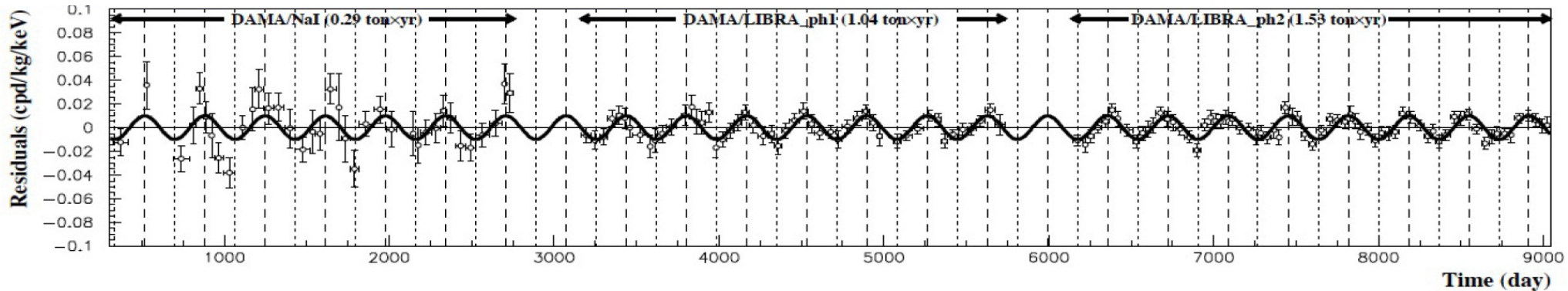
# DAMA/LIBRA

- Dark matter discovery (more than 25 years old story)?
- Annual modulation signature of relic dark matter
- 250 kg **NaI(Tl) crystal** array at Gransasso (Italy)

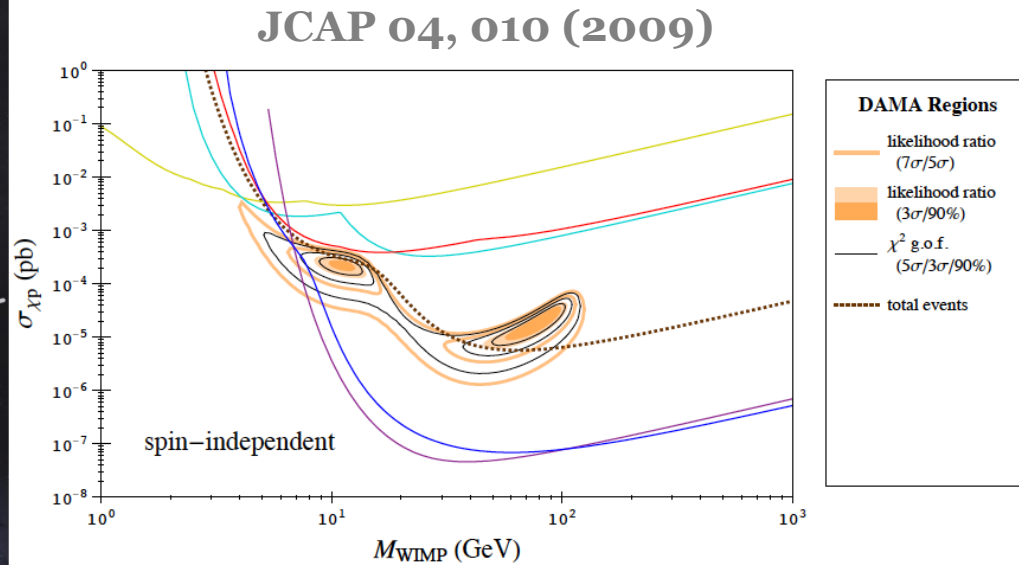
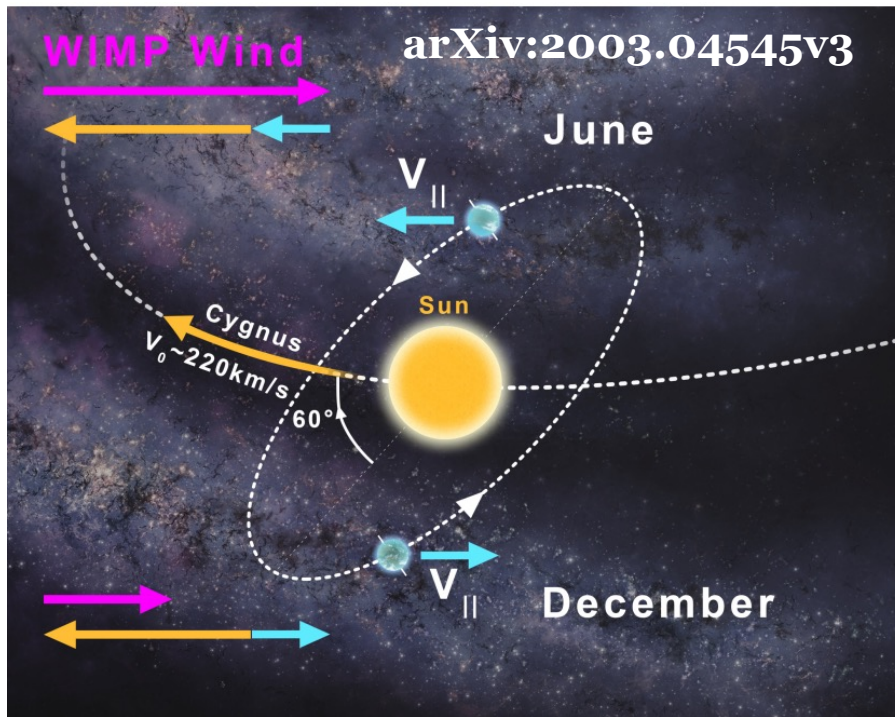


Nucl. Phys. At. Energy 22, 329 (2021)

2-6 keV



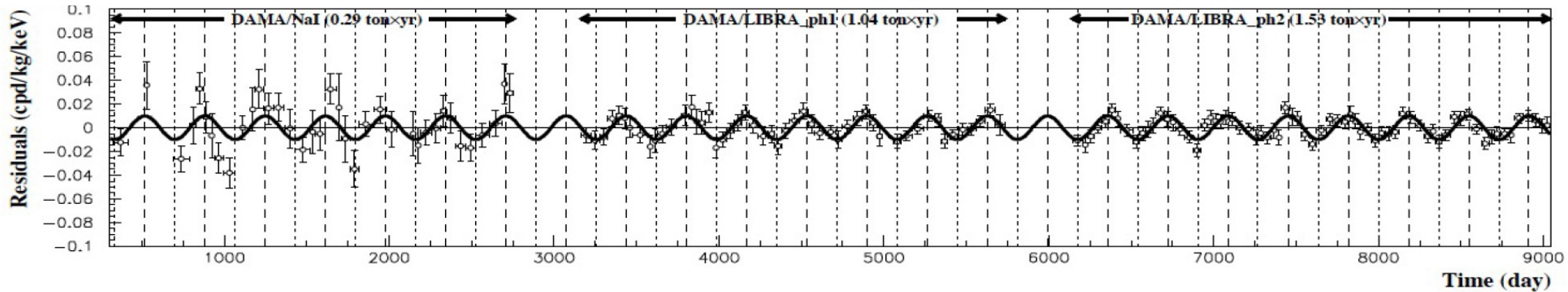
# DAMA/LIBRA



Greatly matched with **Standard-halo model** of the dark matter distribution

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

2-6 keV



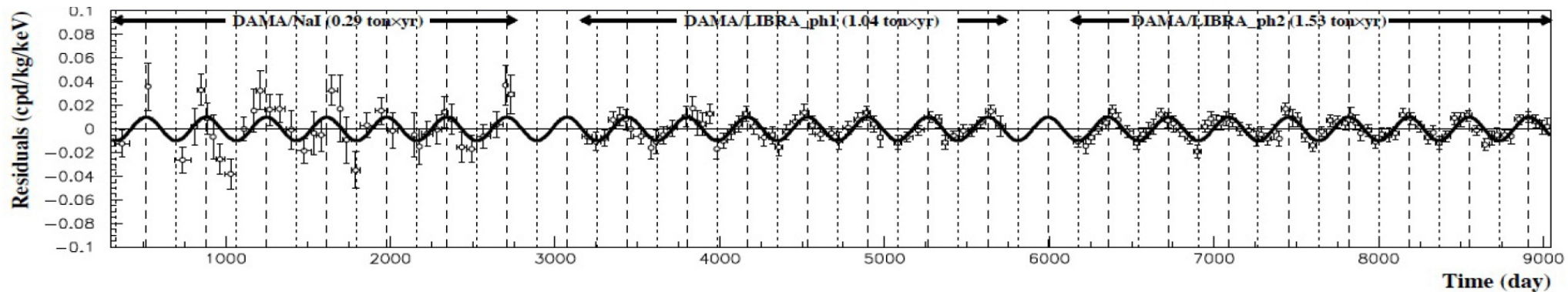


# DAMA/LIBRA

$E$ (keV)	$A$ (counts/day/kg/keV)	$\phi$ (day)	C.L.
1 ~ 3	$0.0191 \pm 0.0020$	152.5 ( <b>fixed</b> )	$9.7\sigma$
	$0.0191 \pm 0.0020$	$149.6 \pm 5.9$	$9.6\sigma$
1 ~ 6	$0.01048 \pm 0.00090$	152.5 ( <b>fixed</b> )	$11.6\sigma$
	$0.01058 \pm 0.00090$	$144.5 \pm 5.1$	$11.8\sigma$
2 ~ 6	$0.00996 \pm 0.00074$	152.5 ( <b>fixed</b> )	$13.4\sigma$
	$0.01014 \pm 0.00074$	$142.4 \pm 4.2$	$13.7\sigma$

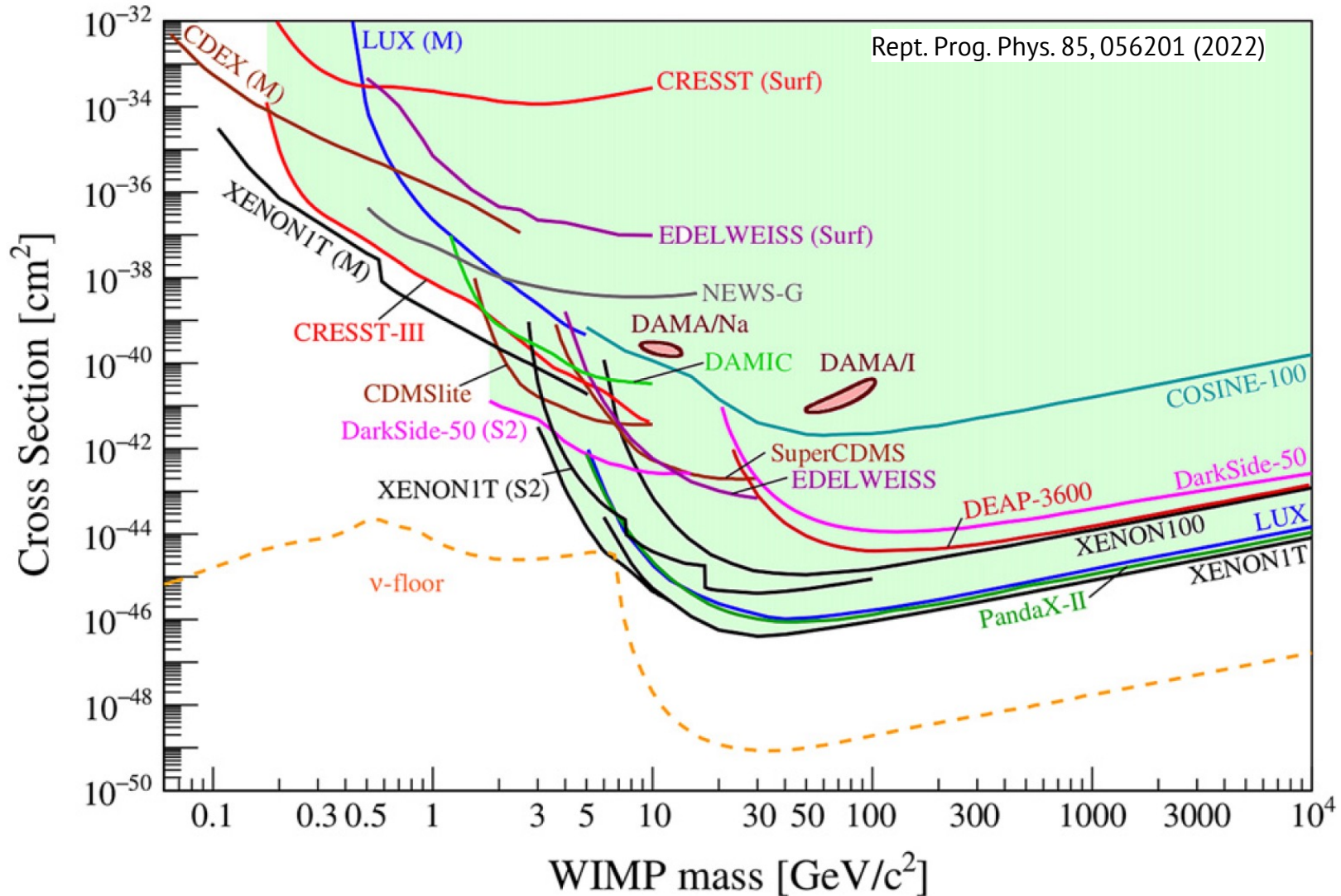
Nucl. Phys. At. Energy 22, 329 (2021)

2-6 keV



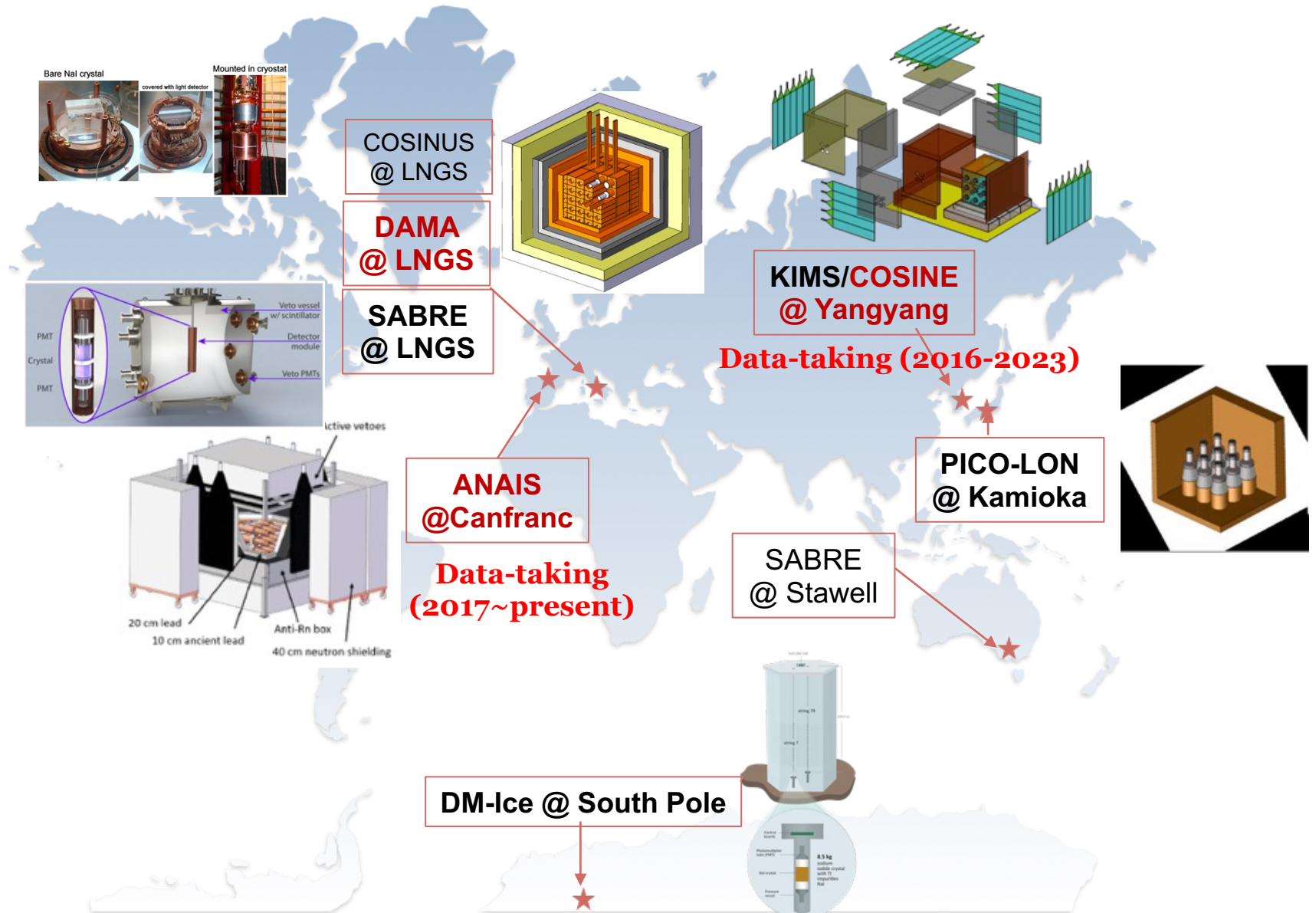


# However...



Requiring Model-independent test with same NaI(Tl) crystals

# World-wide efforts on NaI(Tl)





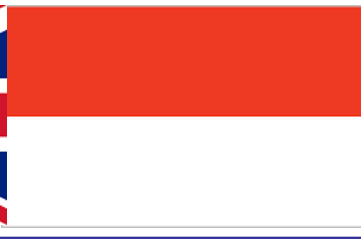
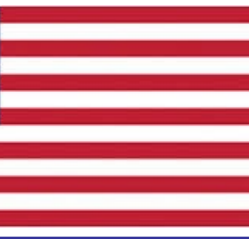
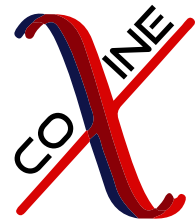
# COSINE collaboration



15 institutes  
~60 members



**DM-ICE** =



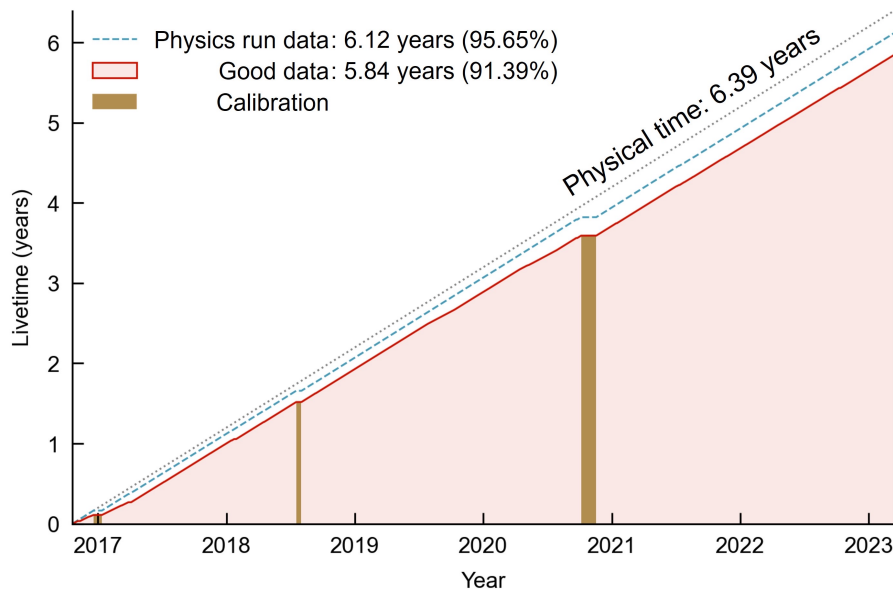
Hyun Su Lee,

Center for Underground Physics (CUP),

Institute for Basic Science (IBS)



# COSINE-100 experiment (2016~2023)

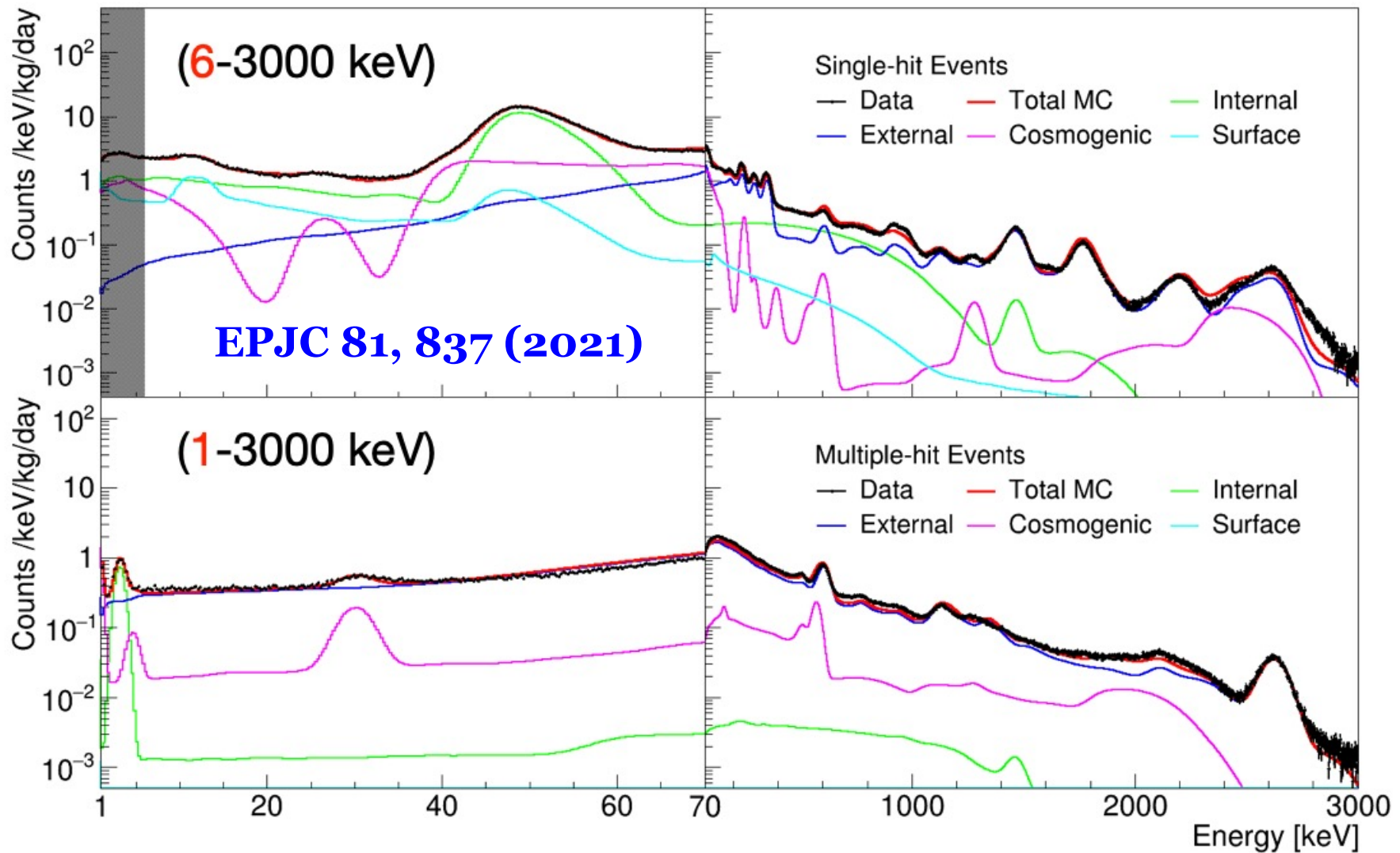


- YangYang underground laboratory
  - ❖ **October/2016 ~ March/2023**
- Decommissioning
  - ❖ **Move to Yemilab**
  - ❖ **Upgrade of detector for high light yield**

# Background understanding

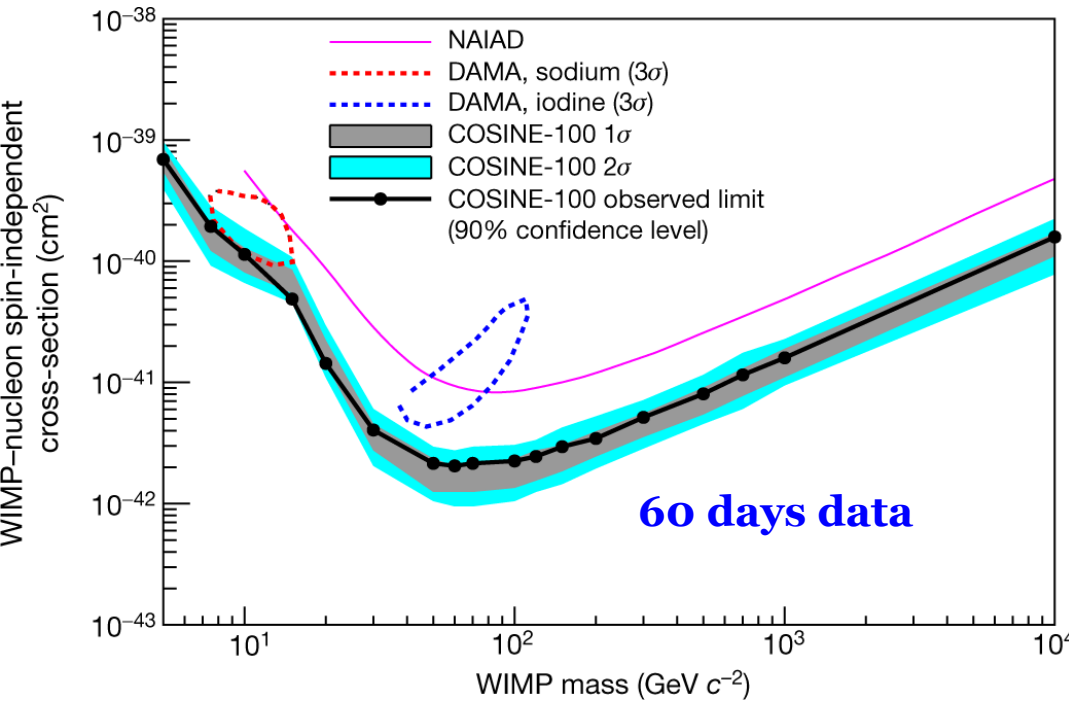
Background modeling

1.7 years data

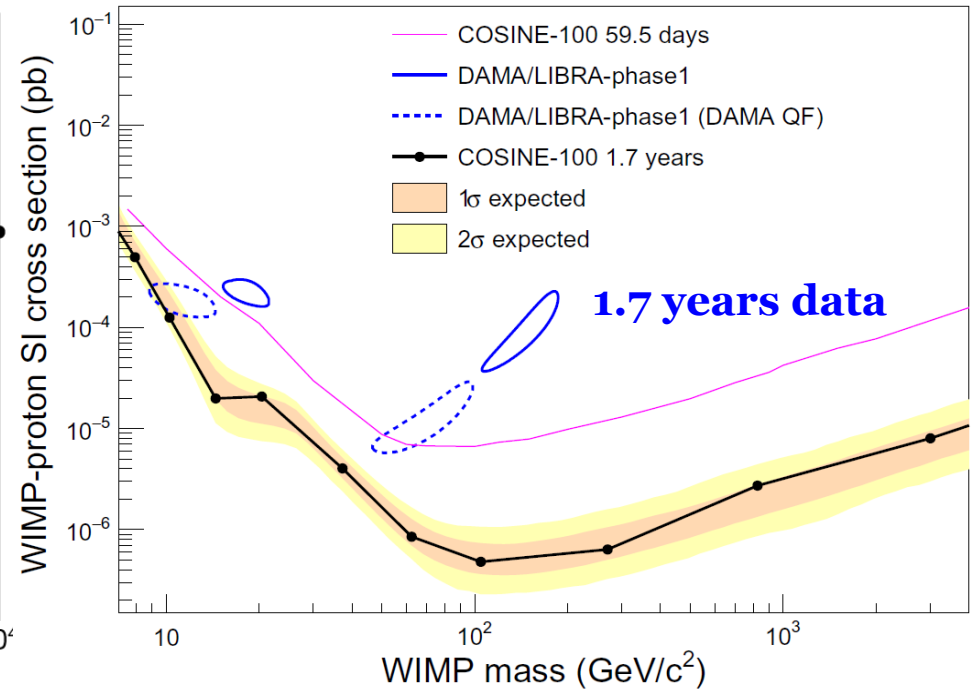


# Ruled out DAMA/LIBRA by COSINE-100

## Model-dependent comparison



Nature 564, 83-86 (2018)

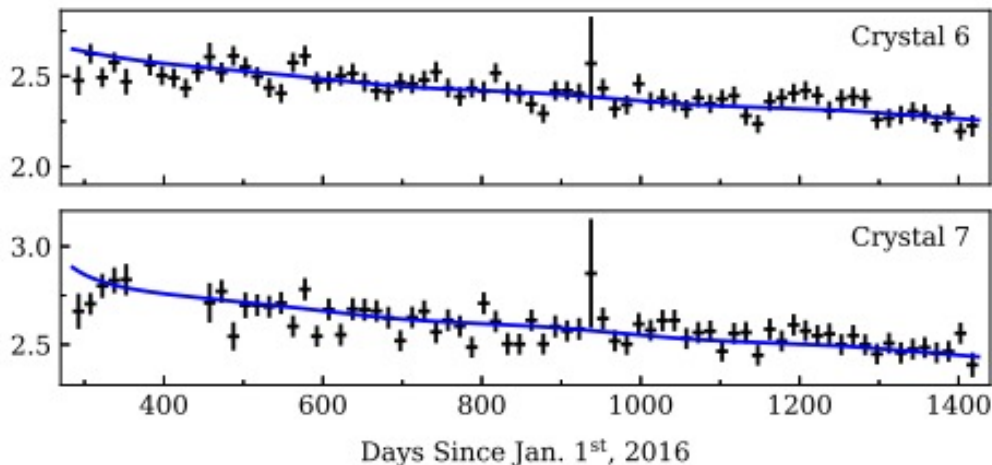


Sci. Adv. 7, eabk2699 (2021)

COSINE-100 data ruled out DAMA/LIBRA's 3 sigma contours for the canonical WIMP dark matter model

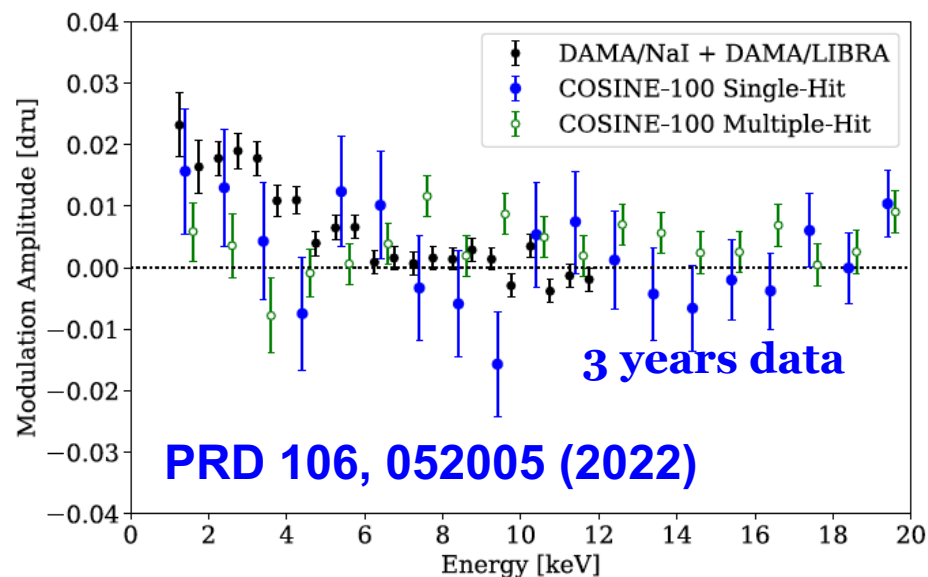
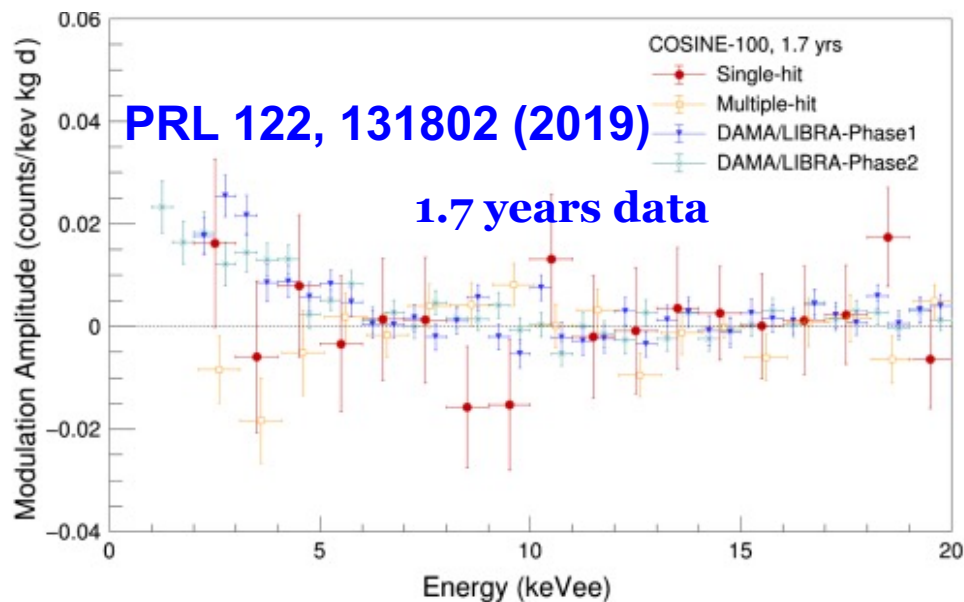


# Annual modulation searches



## 1-6 keV modulation amplitude

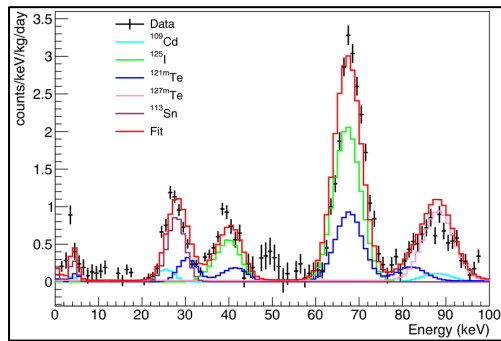
<b>COSINE-100</b>	$0.0067 \pm 0.0042$
DAMA/LIBRA	$0.0105 \pm 0.0011$
ANAIS-112	$-0.0034 \pm 0.0042$



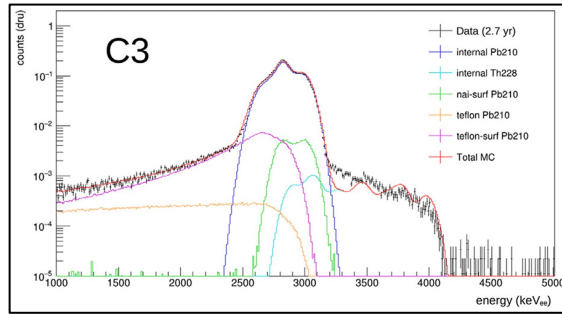
Not enough statistics but, we have full 6.4 years data

# Improvement of NaI(Tl) detector understanding

ASP 115, 102390 (2020)



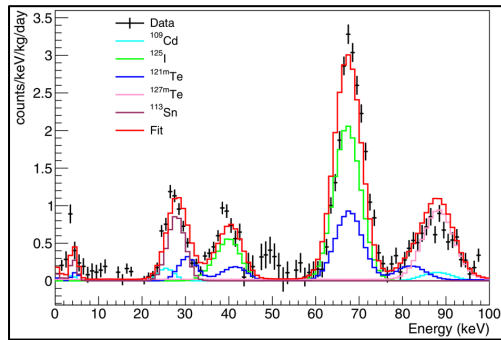
ASP 158, 102945 (2024)



**Background components**

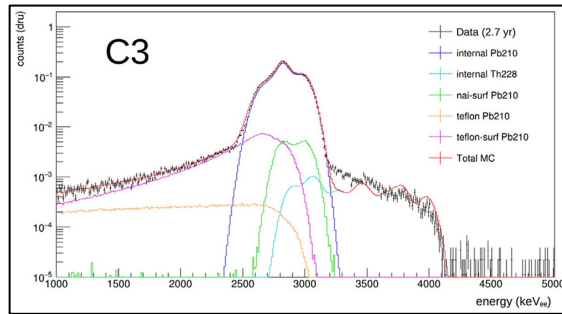
# Improvement of NaI(Tl) detector understanding

ASP 115, 102390 (2020)



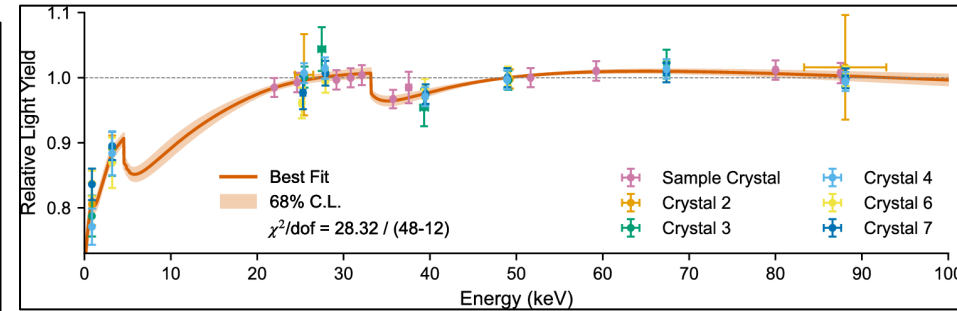
**Background components**

ASP 158, 102945 (2024)

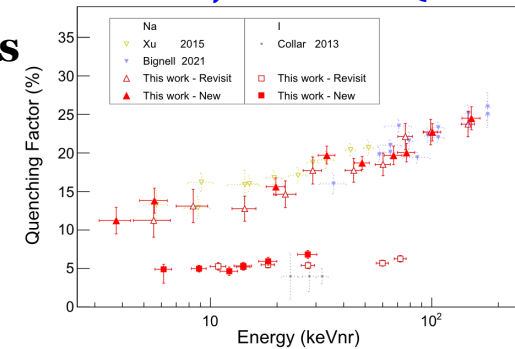


**Detector responses**

EPJC 84, 484 (2024)



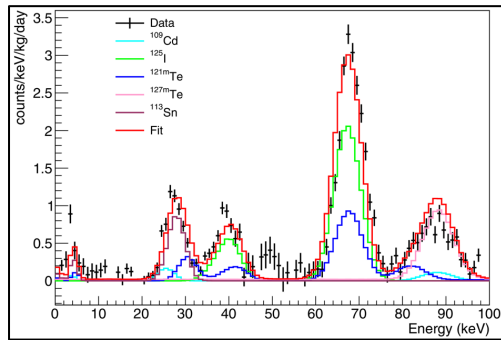
PRC 110, 014614 (2024)



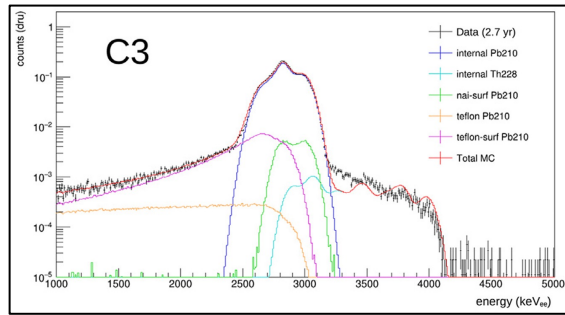


# Improvement of NaI(Tl) detector understanding

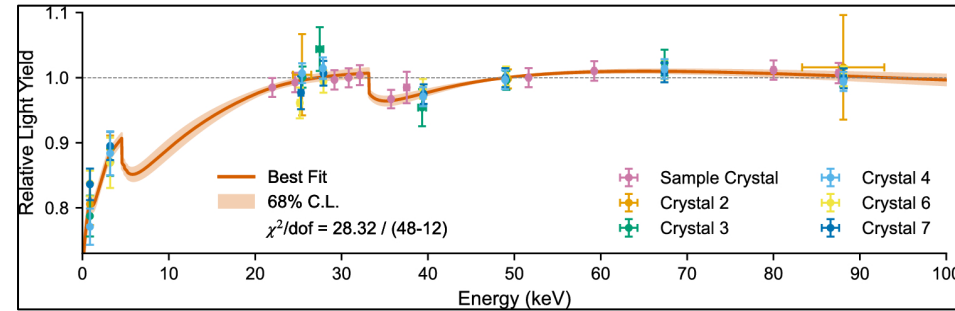
ASP 115, 102390 (2020)



ASP 158, 102945 (2024)



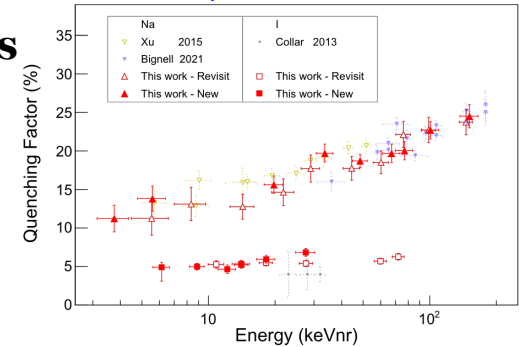
EPJC 84, 484 (2024)



## Background components

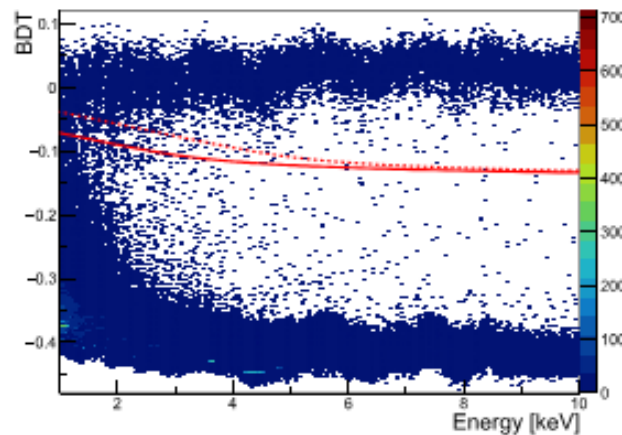
## Detector responses

PRC 110, 014614 (2024)

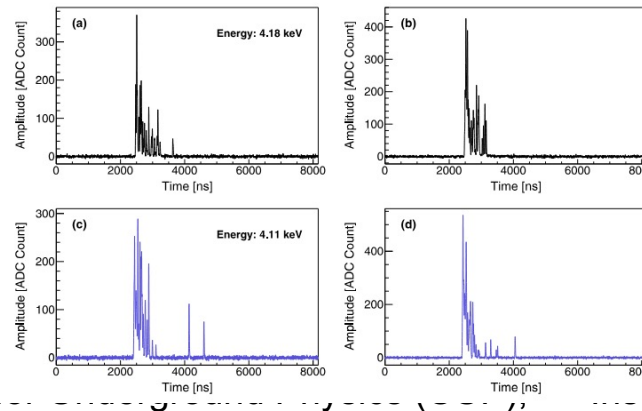


## Low energy scintillation responses

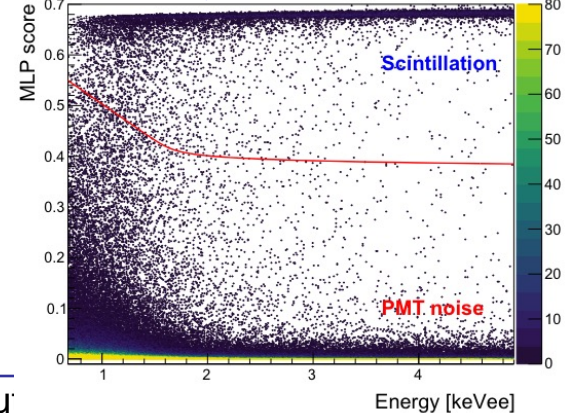
ASP 130, 102581 (2021)



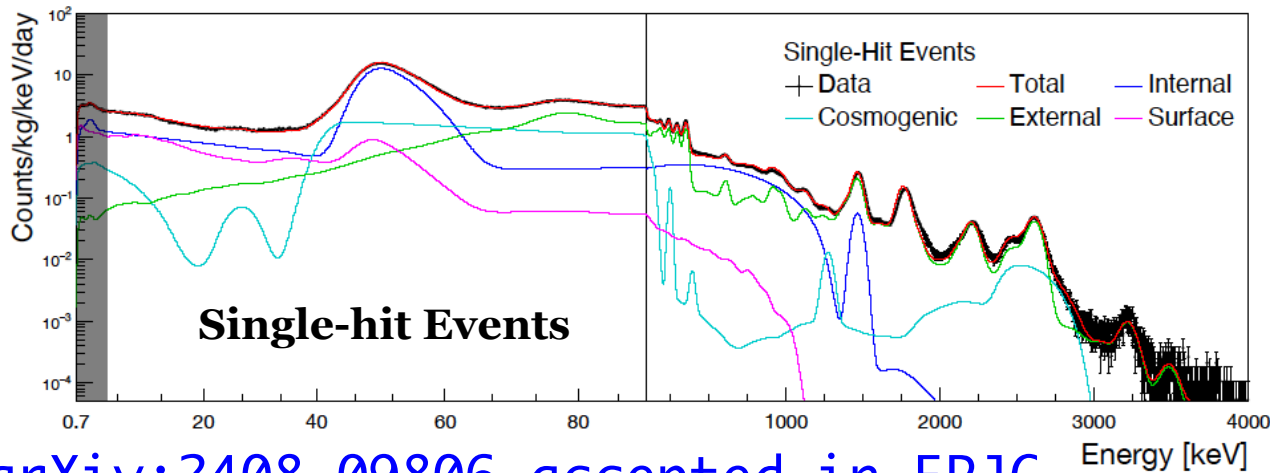
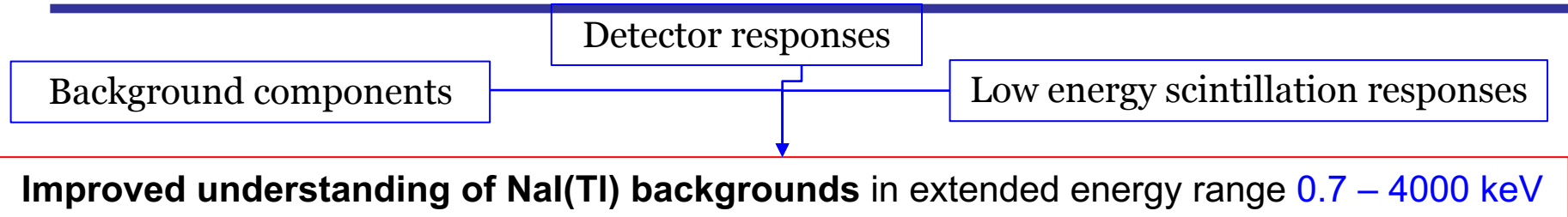
NIMA 1065, 169489 (2024)



JINST 19, P12013 (2024)

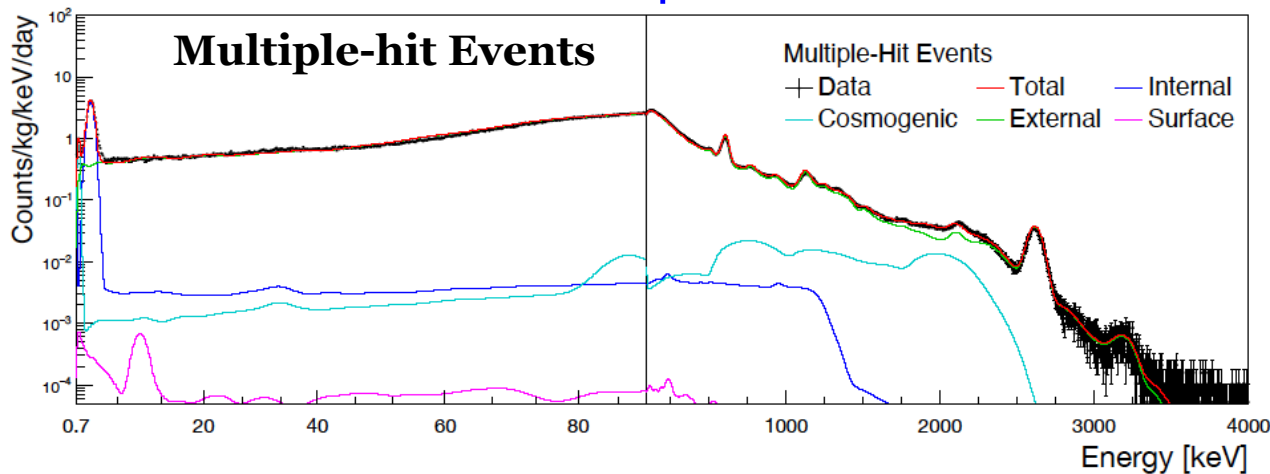


# Improvement of NaI(Tl) detector understanding



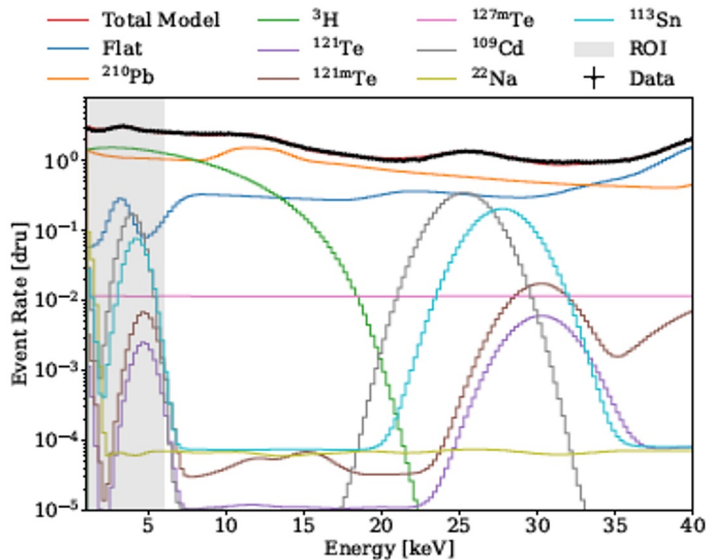
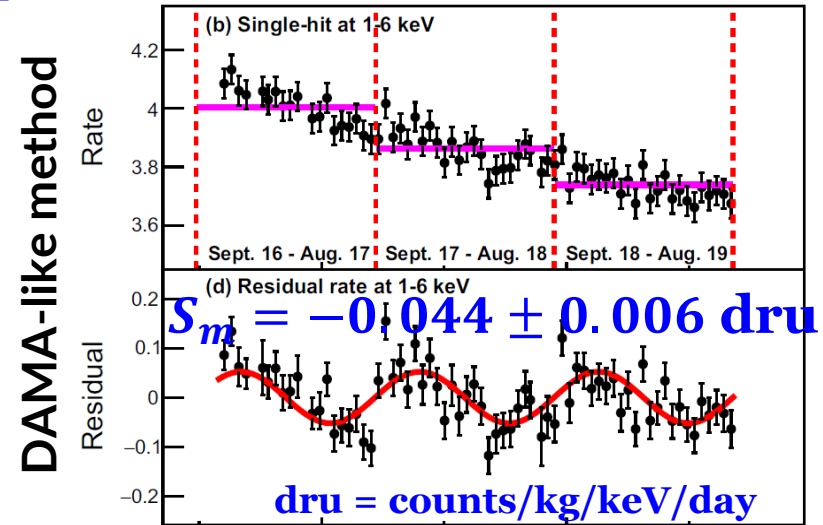
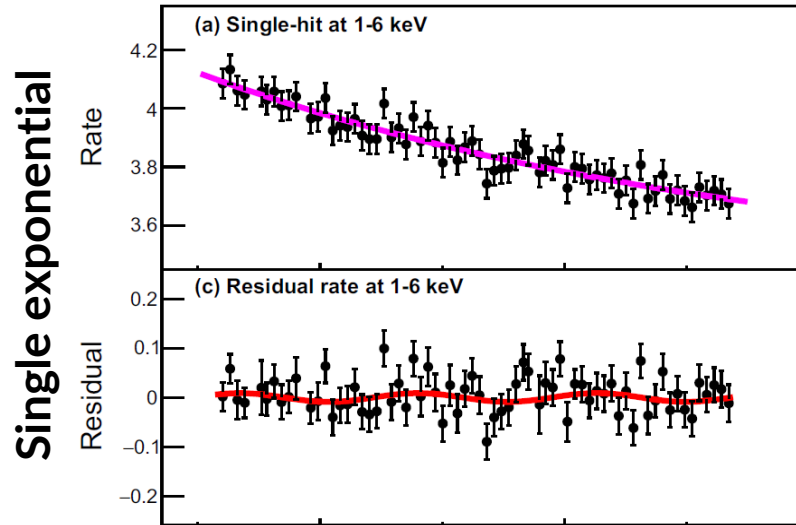
**3 years data**

arXiv:2408.09806 accepted in EPJC



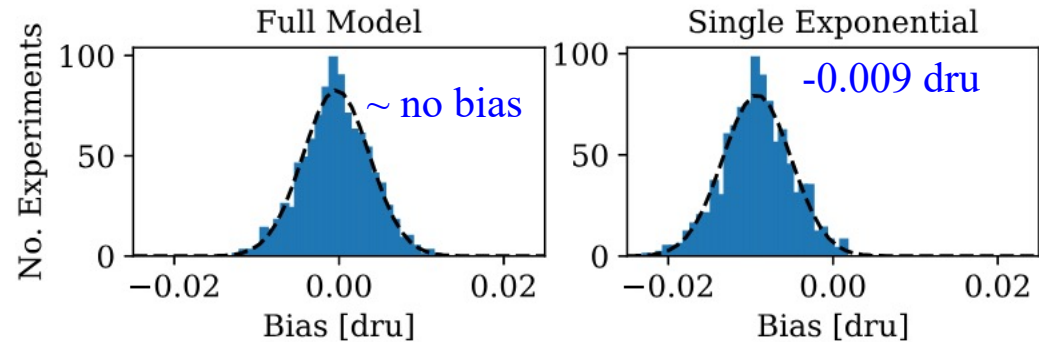
# Time-dependent background models

Sci. Rep. 13, 4676 (2023)



PRD 106, 052005 (2022) (3 years modulation search)

Full model : eight exponential components



DAMA/LIBRA :  $0.010 \pm 0.001 \text{ dru}$



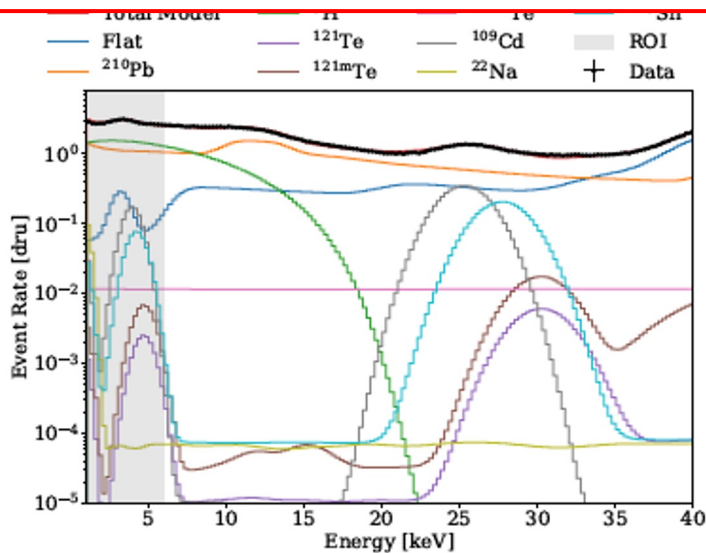
# Time-dependent background models

Sci. Rep. 13, 4676 (2023)



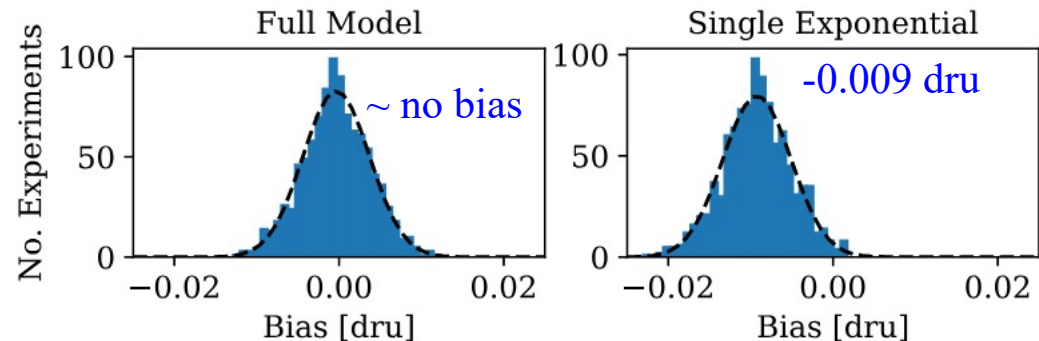
**Caveat** : Understanding of time-dependent background is crucial for the annual modulation analysis

**COSINE-100** is a unique experiment achieving precise background understanding of NaI(Tl) crystals



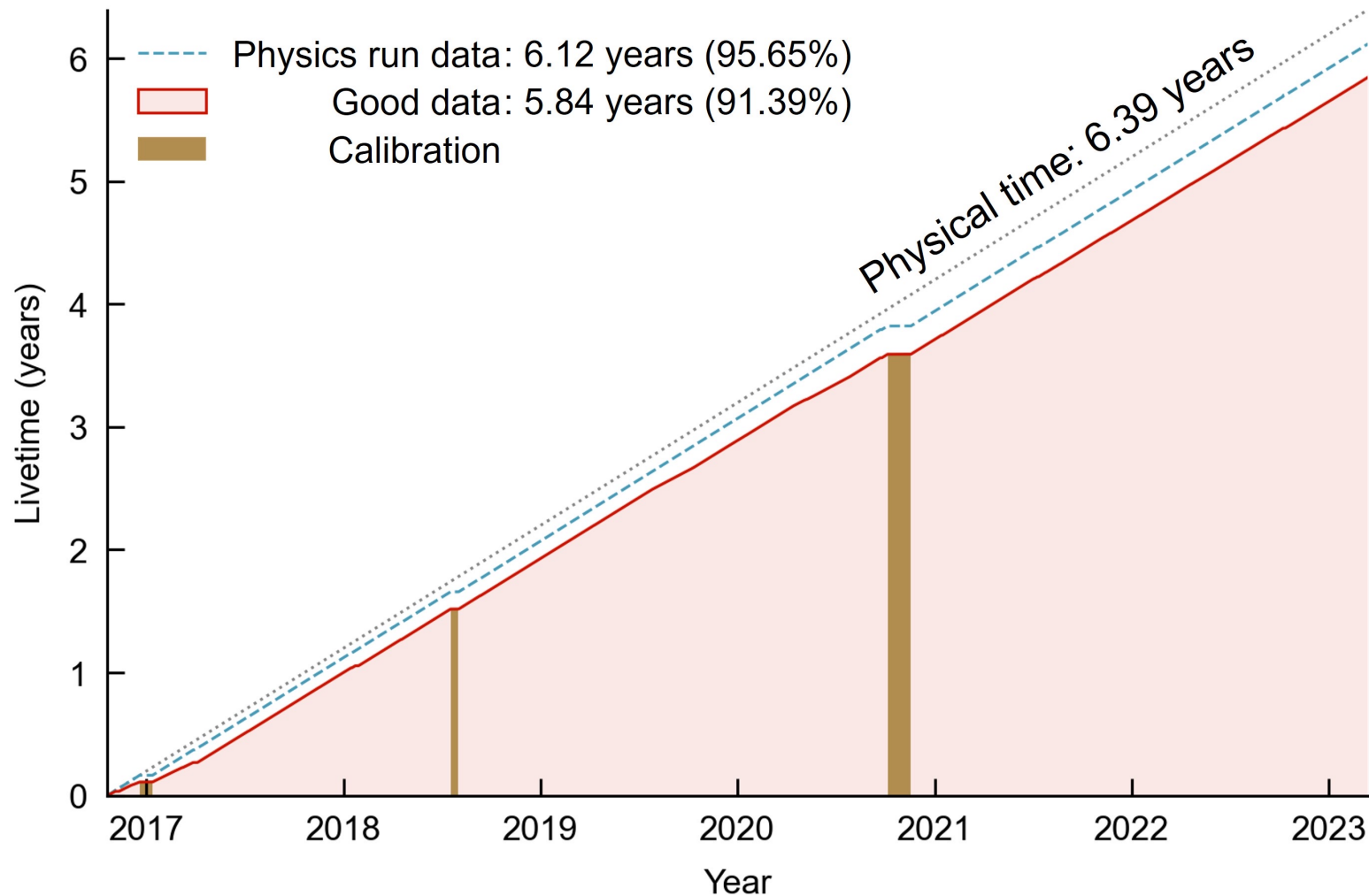
PRD 106, 052005 (2022) (3 years modulation search)

Full model : eight exponential components



DAMA/LIBRA :  $0.010 \pm 0.001$  dru

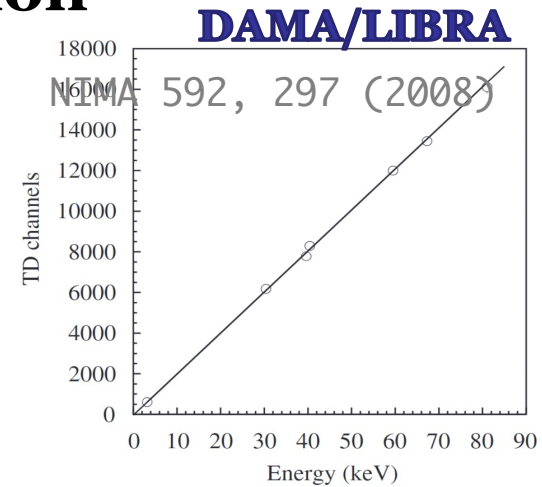
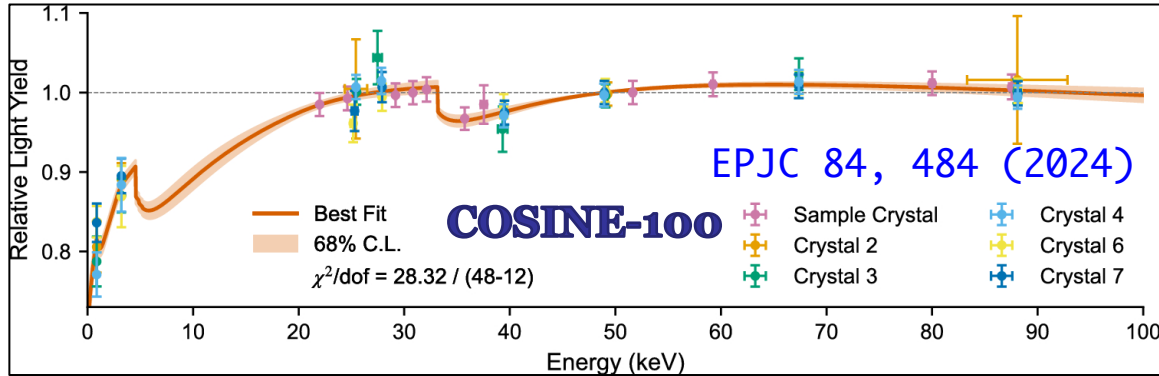
# COSINE-100 full dataset



- Importance : [Apple-to-apple](#) comparison with **DAMA/LIBRA**

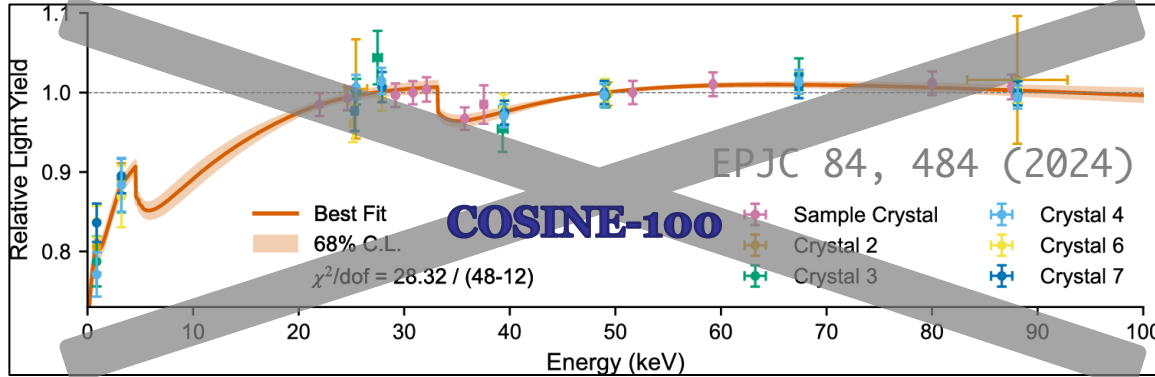
# Comparison with DAMA : Energy calibration

## Electron-recoil energy calibration

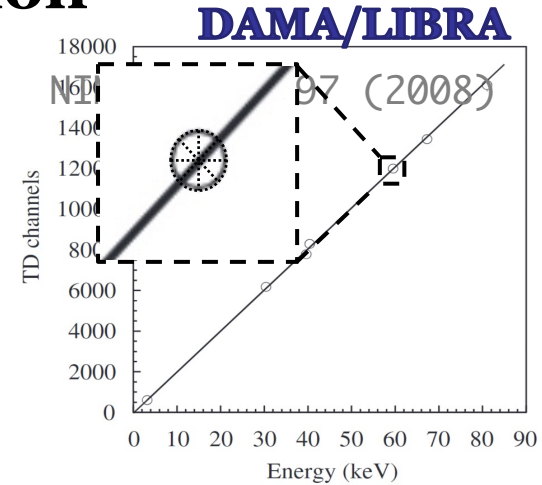


# Comparison with DAMA : Energy calibration

## Electron-recoil energy calibration

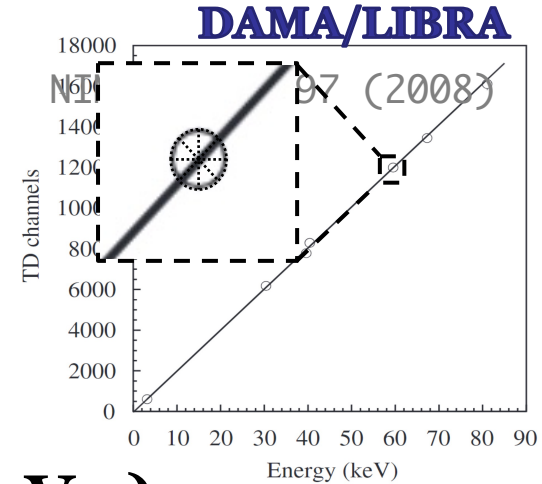
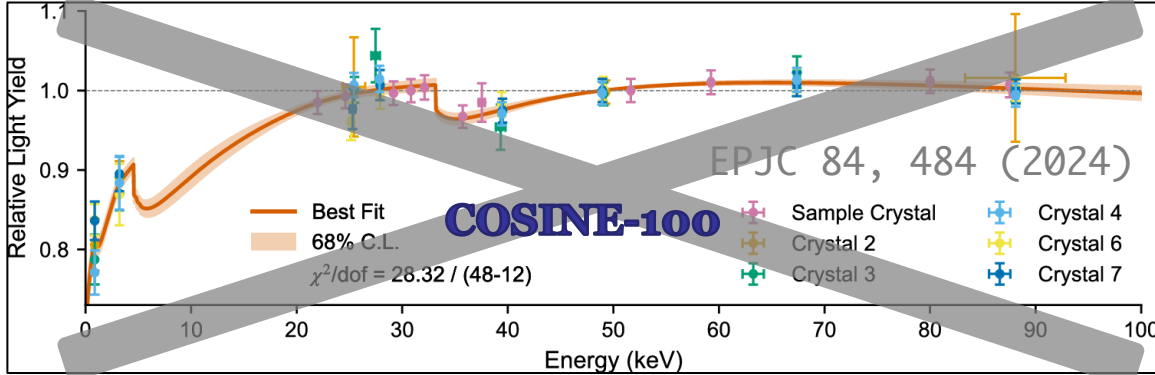


Linear calibration to 59.54 keV :  $\text{keV}_{ee}$

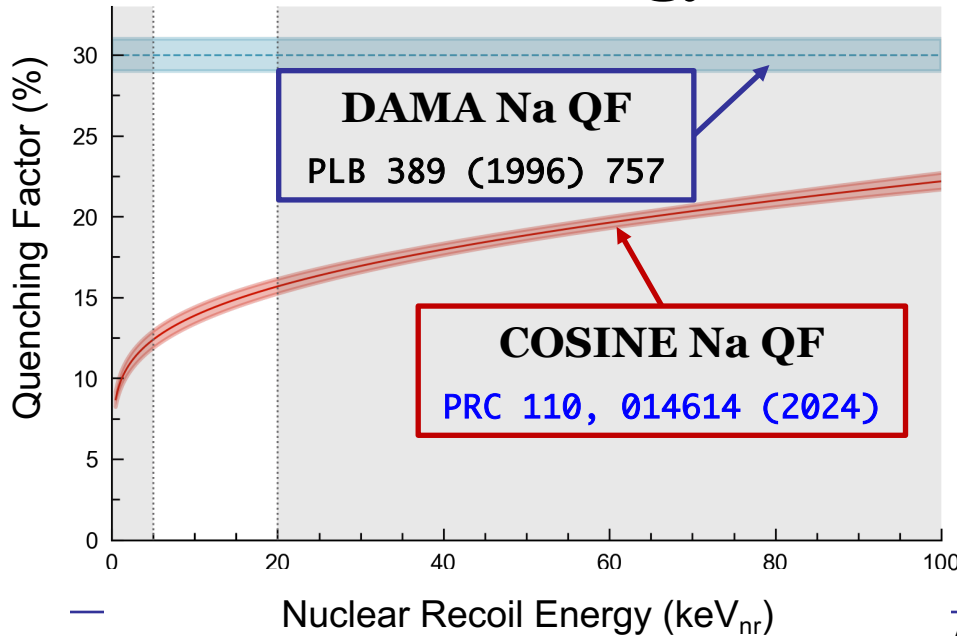


# Comparison with DAMA : Energy calibration

Linear calibration to 59.54 keV :  $\text{keV}_{ee}$



## Nuclear-recoil energy calibration ( $\text{keV}_{nr}$ )



### Quenching factor (QF)

Measured electron-equivalent energy/True nuclear recoil energy

Signal region : 6.7-20  $\text{keV}_{nr}$

DAMA/LIBRA : 2-6  $\text{keV}_{ee}$

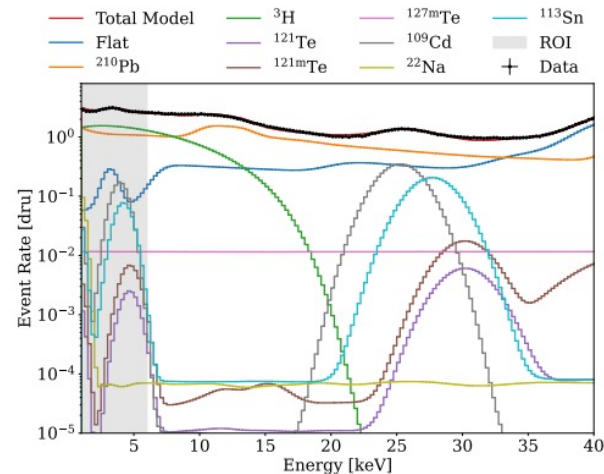
COSINE-100 : 0.85-3.12  $\text{keV}_{ee}$



# Modulation fit

$$R_i(t) = A \cos\left(\frac{2\pi(t - \phi)}{T}\right) + \sum_j C_{ij} e^{-\lambda_{ij}t}$$

Modulation signals      10 time-dependent components



## Simulated experiments

Measured signal

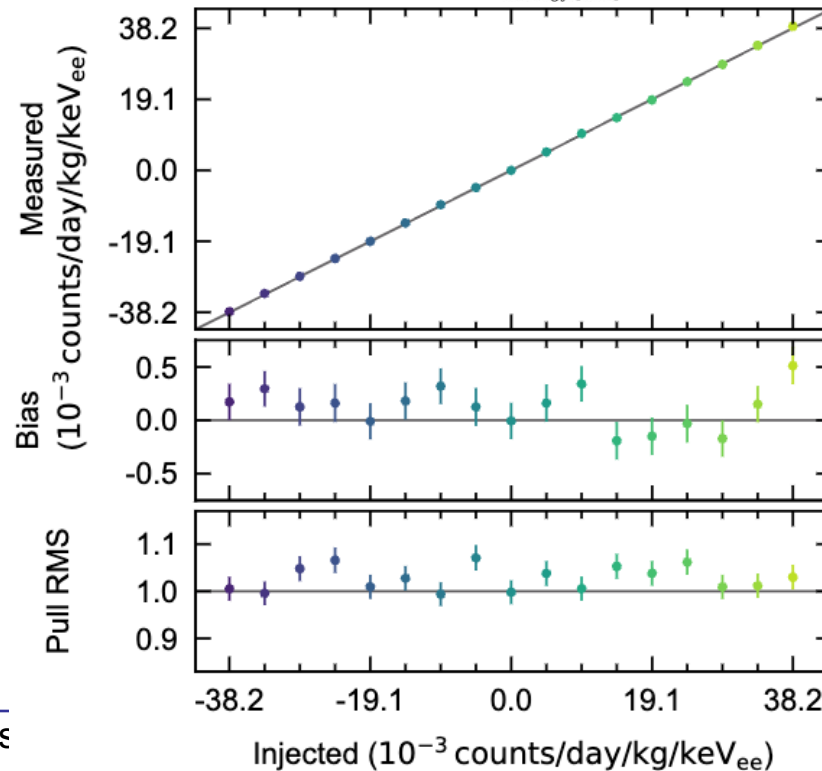
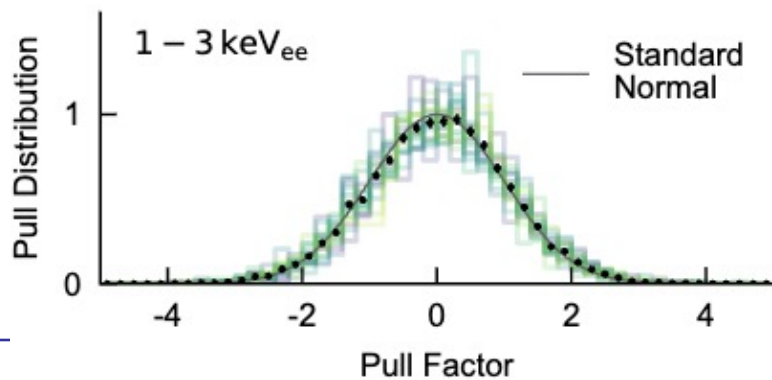
Pull Factor

$$z = \frac{m_A - I_A}{\sigma_A}$$

Input signal

Measured uncertainty

**No Bias**



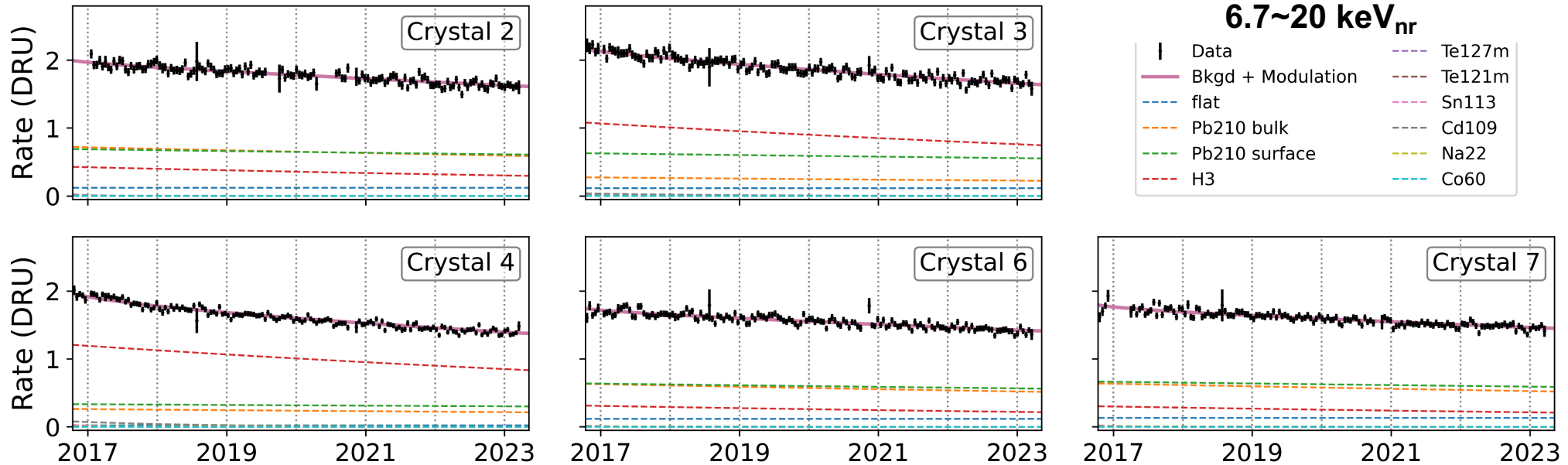
# Modulation fit

$$R_i(t) = A \cos\left(\frac{2\pi(t - \phi)}{T}\right) + \sum_j C_{ij} e^{-\lambda_{ij}t}.$$

Modulation signals      10 time-dependent components

## COSINE-100 full dataset

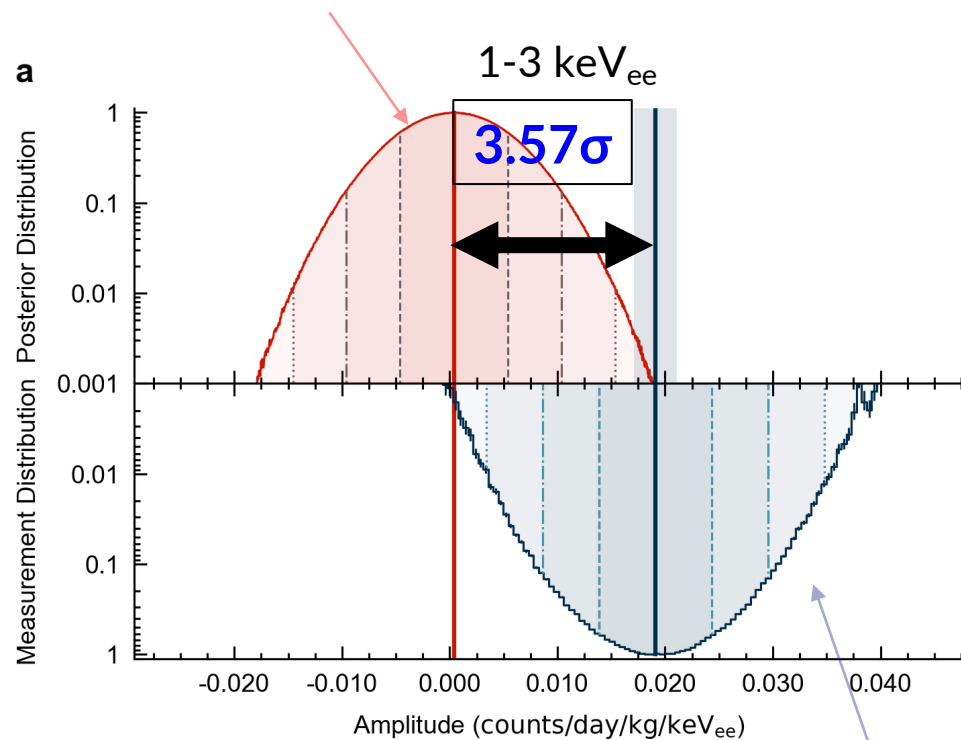
DRU = counts/kg/keV/day



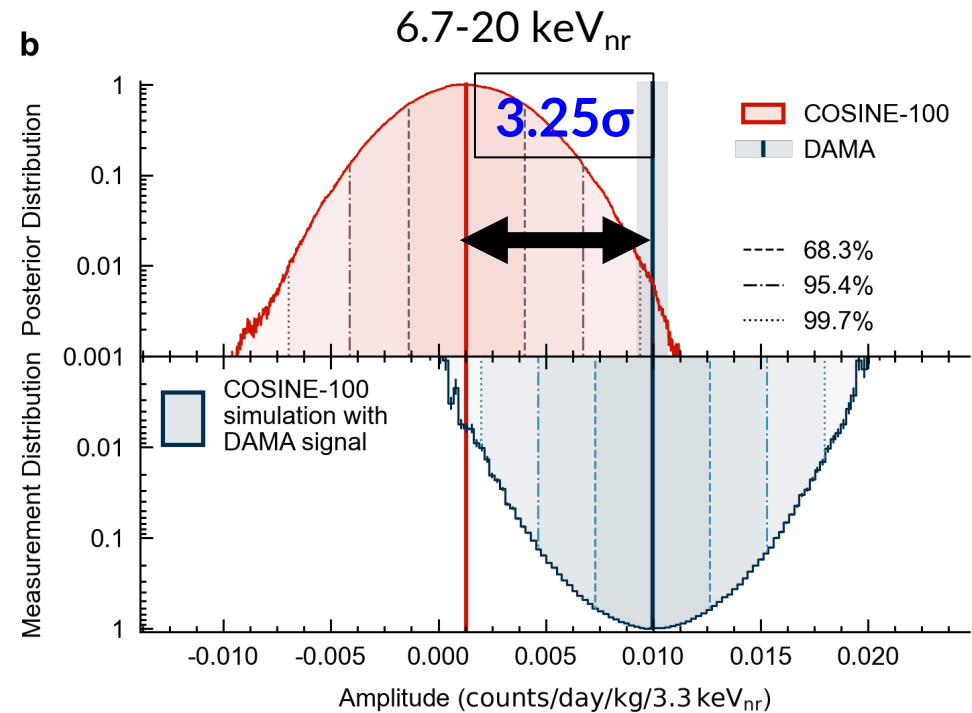
No modulation signal observed !!

# COSINE-100 full dataset fits

## Posterior of COSINE-100 full dataset



(2-6 keV<sub>ee</sub> in DAMA/LIBRA)



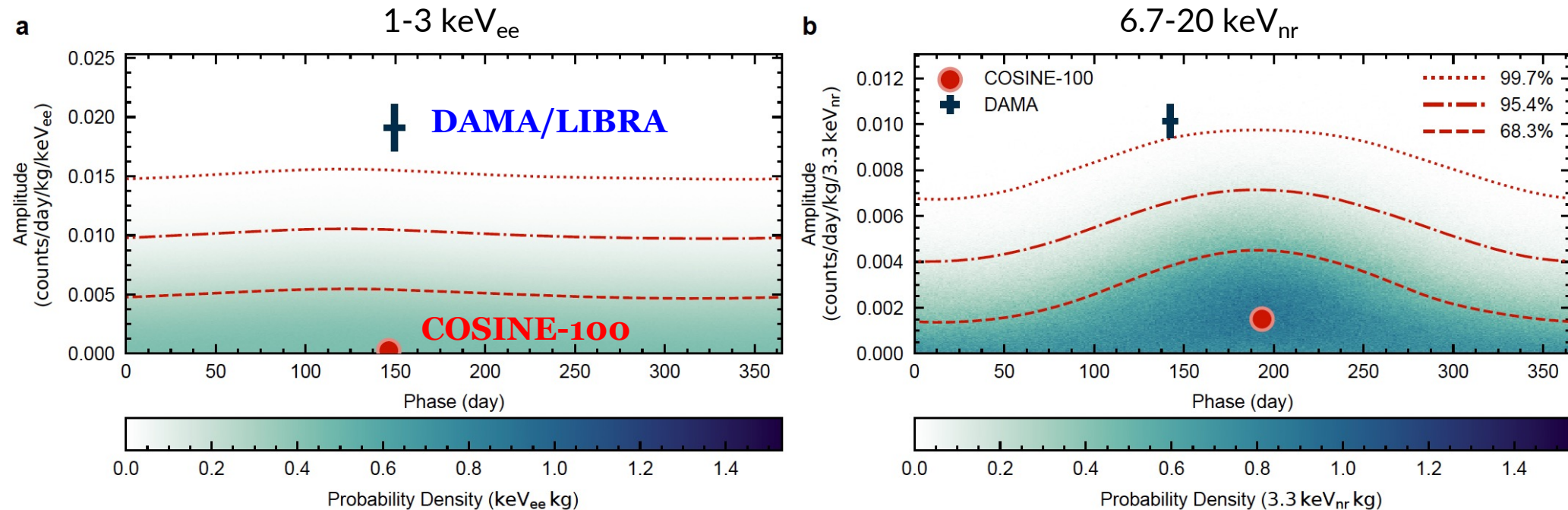
Simulated experiments (300,000) assuming  
DAMA/LIBRA modulation signals

[arXiv:2409.13226](https://arxiv.org/abs/2409.13226)

COSINE-100 full dataset disfavors DAMA/LIBRA in  
both electron recoil and nuclear recoil

# COSINE-100 full dataset fits

Phase floated 2-dimensional fit for COSINE-100 full dataset

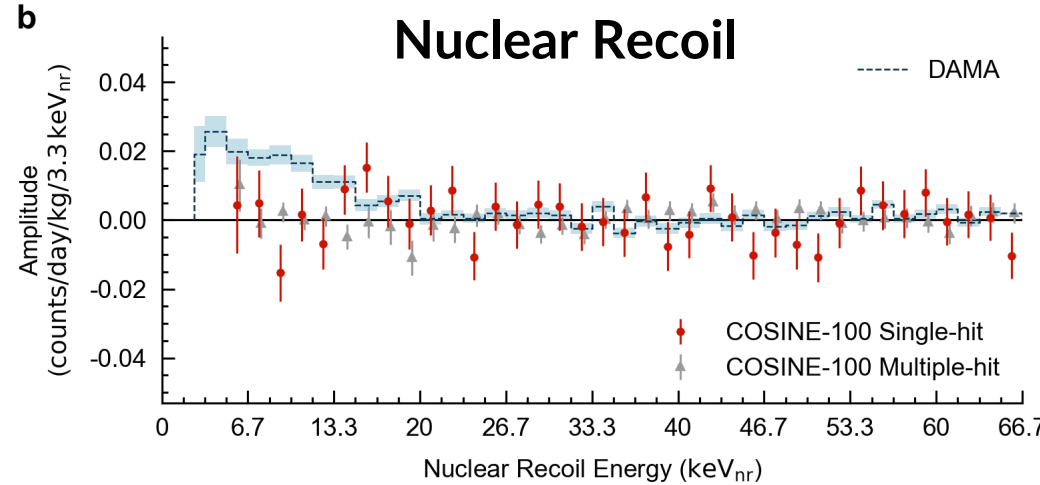
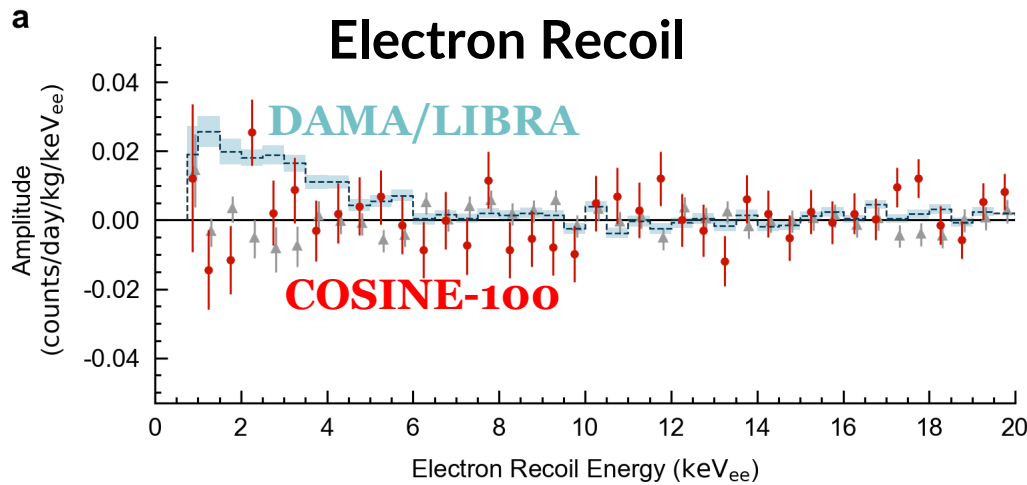


[arXiv:2409.13226](https://arxiv.org/abs/2409.13226)

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil



# COSINE-100 full dataset fits



$E$ (keV <sub>ee</sub> )	$A$ (counts/day/kg/keV <sub>ee</sub> )	
	COSINE-100	DAMA/LIBRA
1~3	$0.001 \pm 0.005$	$0.019 \pm 0.002$
1~6	$0.002 \pm 0.003$	$0.010 \pm 0.001$
2~6	$0.005 \pm 0.003$	$0.010 \pm 0.001$

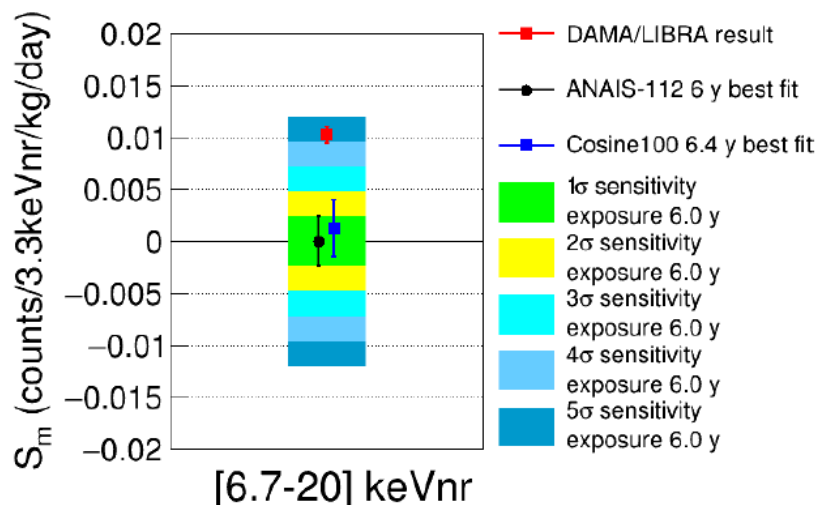
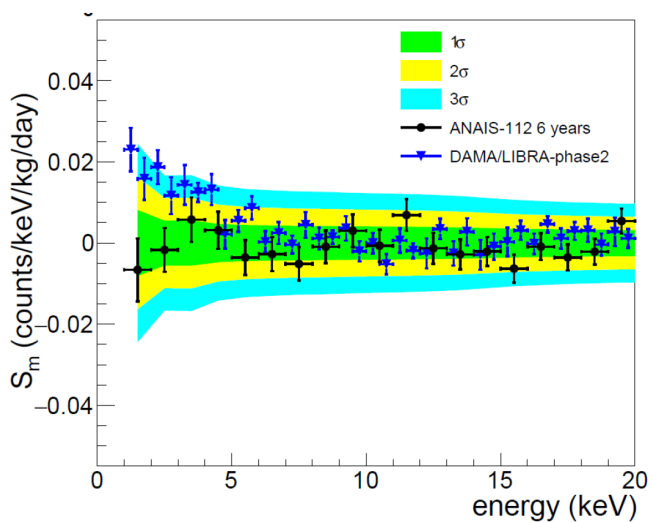
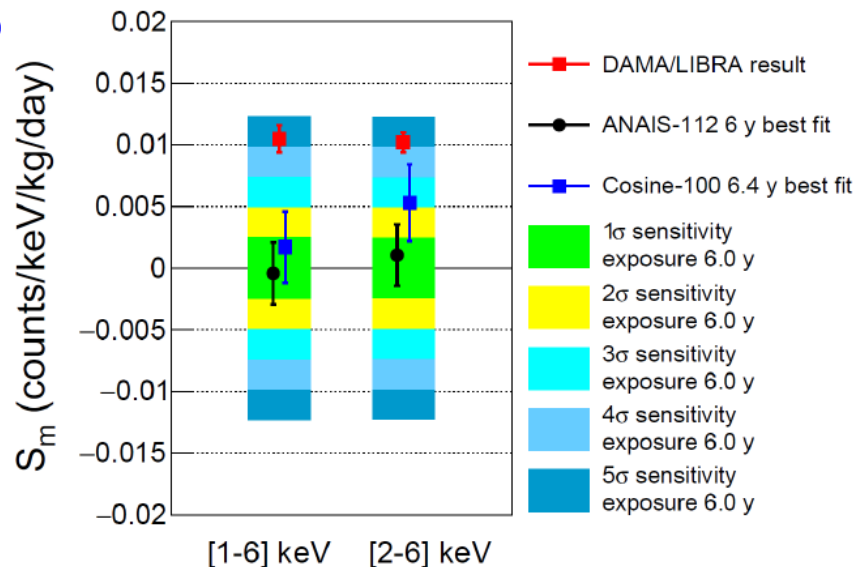
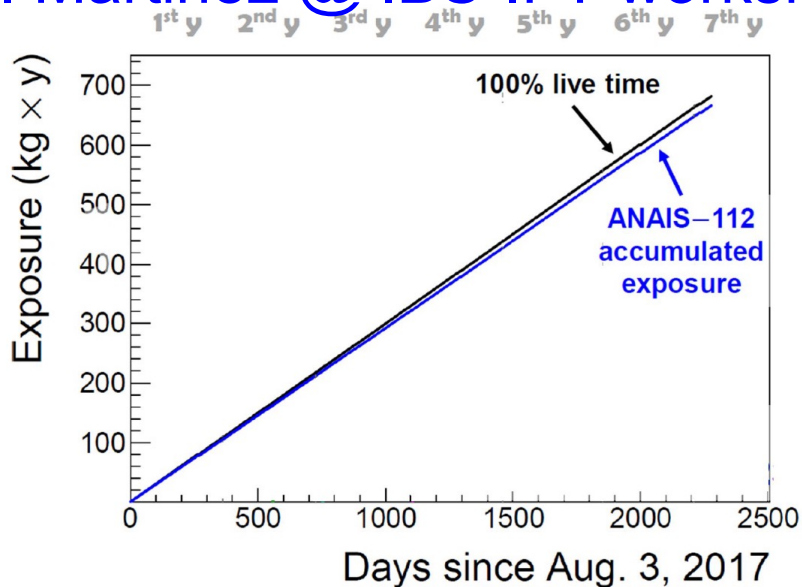
$E$ (keV <sub>nr</sub> )	$A$ (counts/day/kg/3.3 keV <sub>nr</sub> )	
	COSINE-100	DAMA/LIBRA
6.7~20	$0.001 \pm 0.003$	$0.010 \pm 0.001$

[arXiv:2409.13226](https://arxiv.org/abs/2409.13226)

COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

# ANAIS-112 (6 years data)

M. Martinez @ IBS-IFT workshop



More than **4 sigma** discrepancy

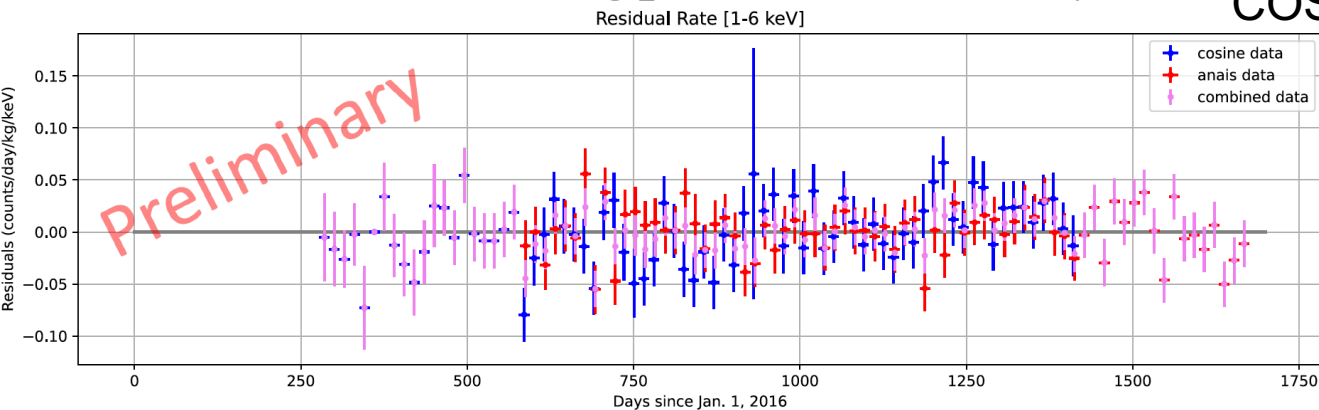
# Combined analysis between COSINE and ANAIS

S. Hollick@ IDM2024

Combining published data (~ 3 years)

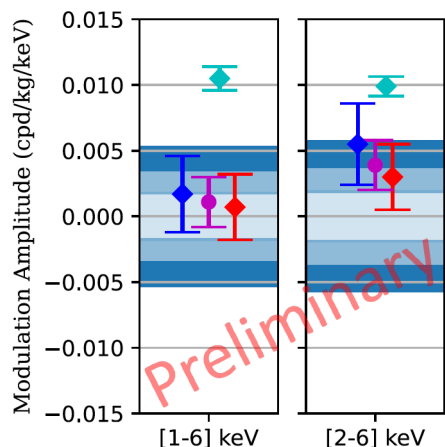
ANAIS-112: PRD 103, 102005 (2021)

COSINE-100: PRD 106, 052005 (2022)



Energy ROI	Combined Amplitude (dru) -- MCMC	DAMA Exclusion
1-6 keV	$-0.0003 \pm 0.0028$	$3.6\sigma$
2-6 keV	$0.0023 \pm 0.0029$	$2.6\sigma$

## Combining 6 years modulation sensitivity



- ◆ DAMA/LIBRA
- ◆ Prelim COSINE-100 6y
- ◆ Prelim ANAIS-112 6y
- ◆ Prelim Combined 6y

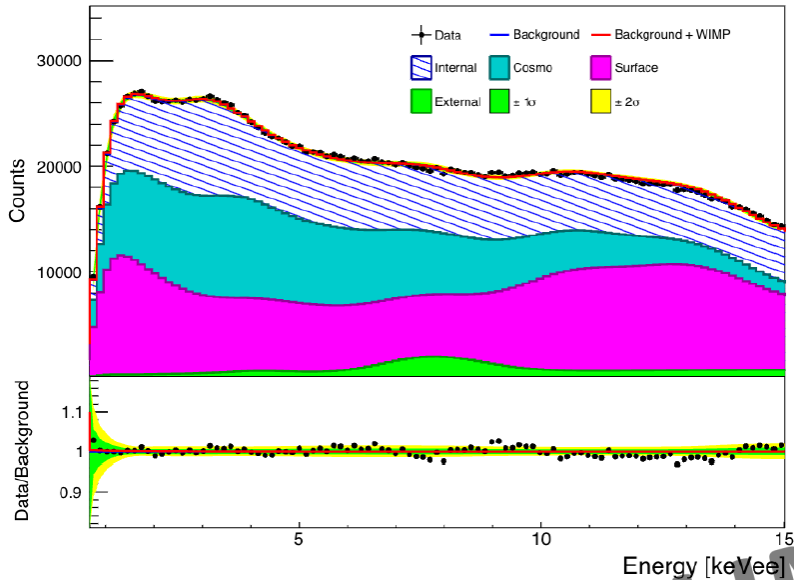
- Sensitive to DAMA at  $5.3\sigma$  in 1-6 keV and  $5.0\sigma$  in 2-6 keV

Energy ROI	*COSINE 6-year (dru)	*ANAIS 6-year (dru)	Combine Simple
1-6 keV	$0.0017 \pm 0.0029$	$0.0007 \pm 0.0025$	$0.0011 \pm 0.0019$
2-6 keV	$0.0053 \pm 0.0031$	$0.0030 \pm 0.0025$	$0.0039 \pm 0.0019$

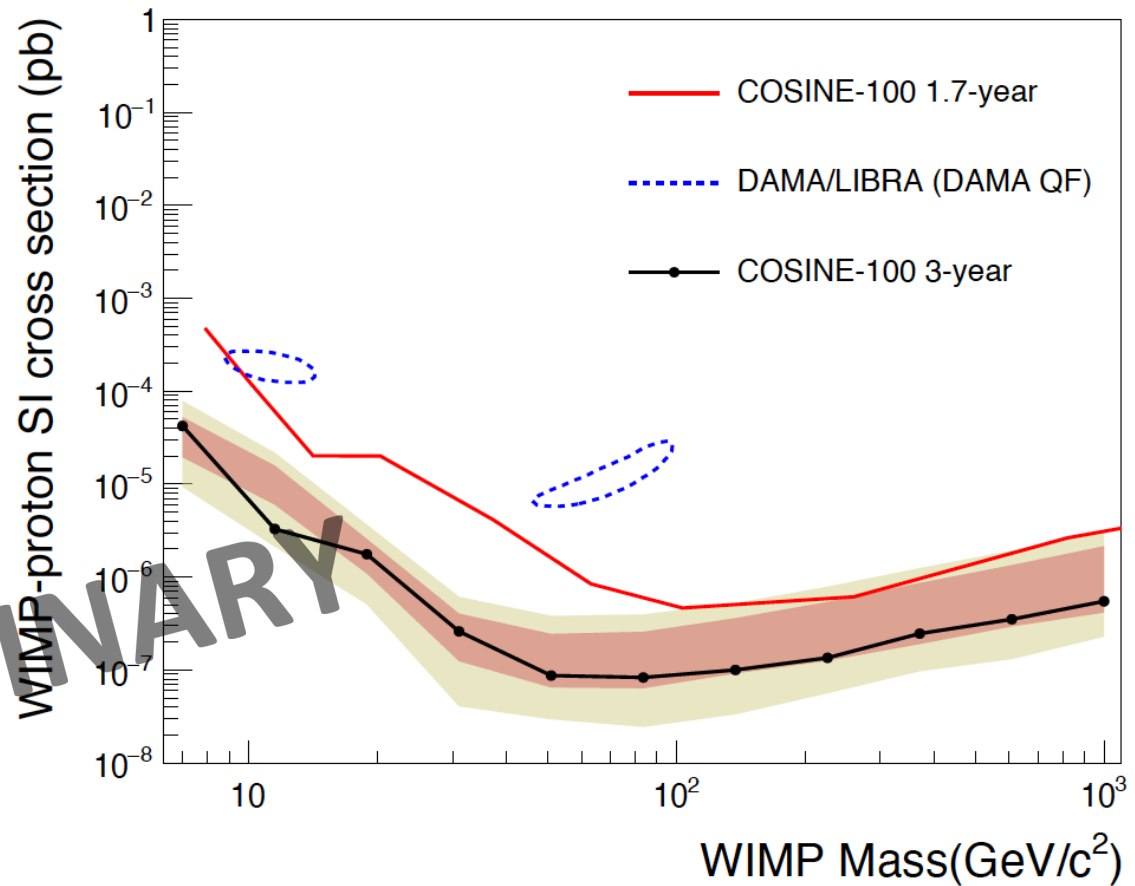
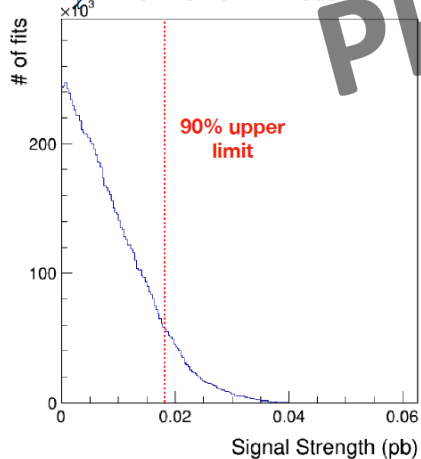
# Model-dependent searches

## COSINE-100 3 years data

Example of WIMP presence test in  $M_\chi = 12.92 \text{ GeV}/c^2$  SD model



90% upper limit of data fit in  
 $M_\chi = 12.92 \text{ GeV}/c^2$  SD model



**COSINE-100 full dataset disfavors DAMA/LIBRA** in model-dependent search

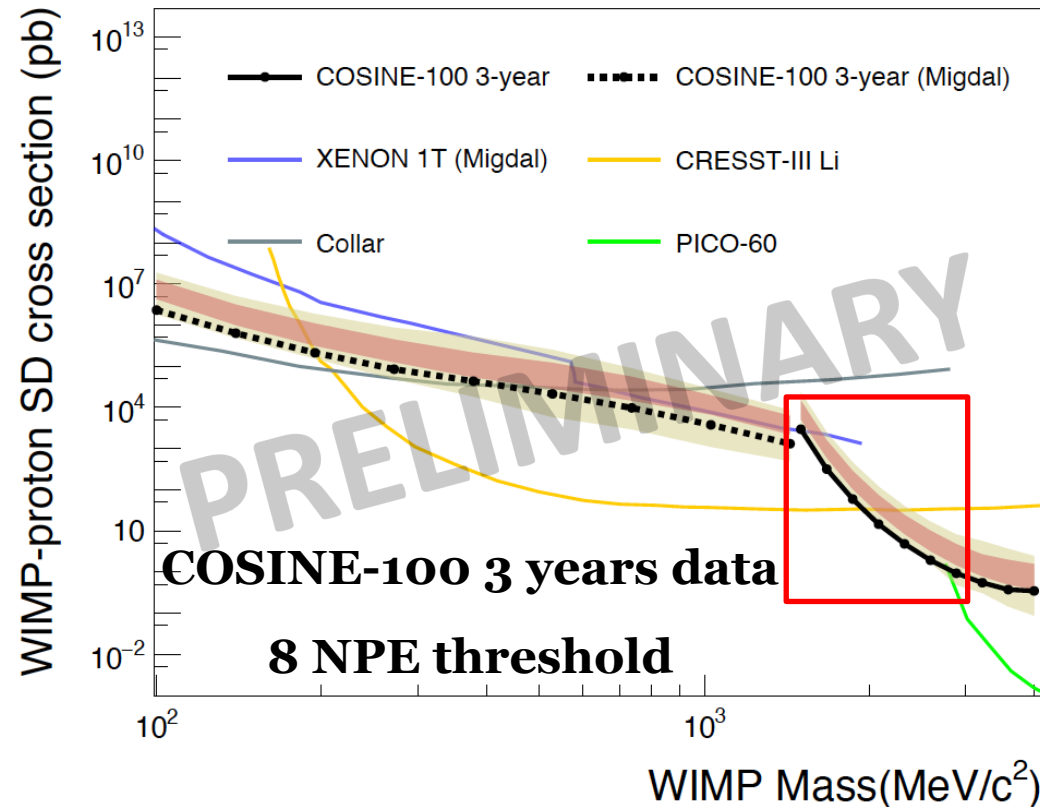


# World best limit from COSINE-100

- Na ( $Z = 11$ ) and I ( $Z=53$ )
  - ❖ Good for **spin-dependent WIMP-proton** interactions
  - ❖ Si ( $Z = 14$ ), Ge ( $Z = 32$ ), Ar ( $Z = 18$ ), Xe ( $Z = 54$ )
  - ❖ Good for **low-mass (sodium)**
- Reduced threshold?
  - ❖ Current threshold : **8 NPE** (0.7 keV)
  - ❖ COSINE-100 goal : **5 NPE** (0.5 keV)
    - Waveform simulation
    - Improving machine learning
    - Employ deep learning

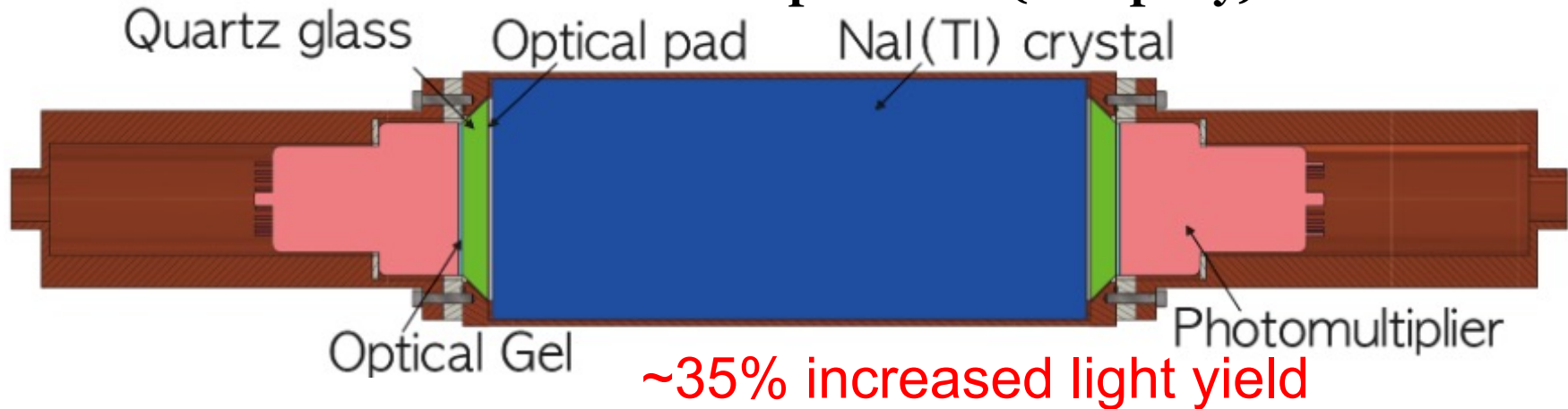
**NPE = number of photoelectrons**

## WIMP-proton spin-dependent interaction

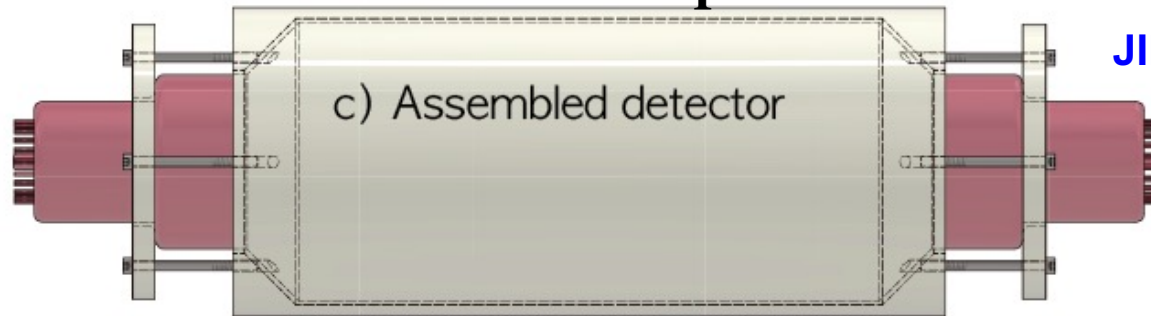


# Moving forward to COSINE-100U<sub>pgrade</sub>

## COSINE-100 encapsulation (Company)

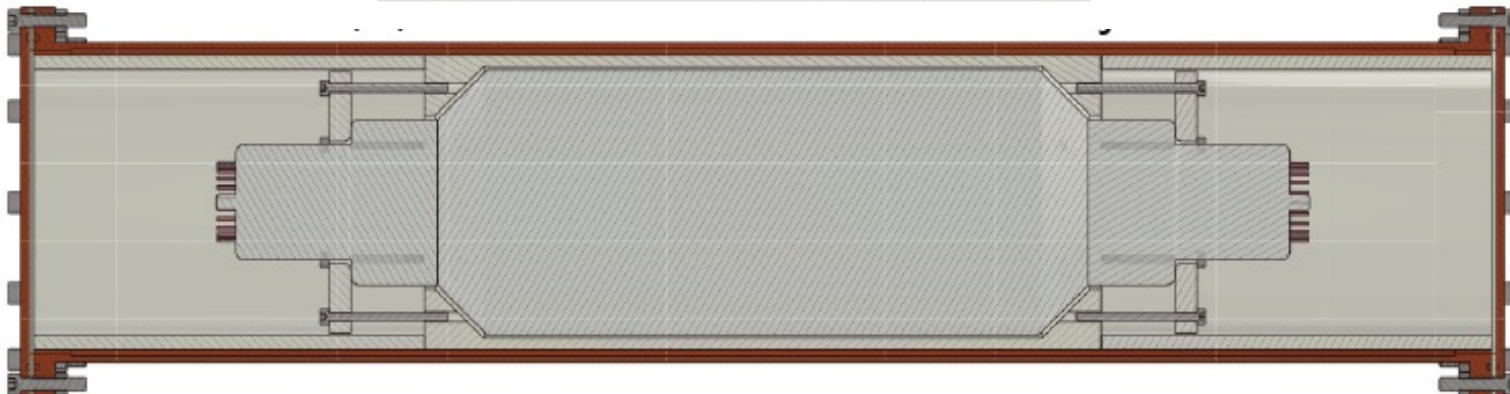


## COSINE-100U encapsulation



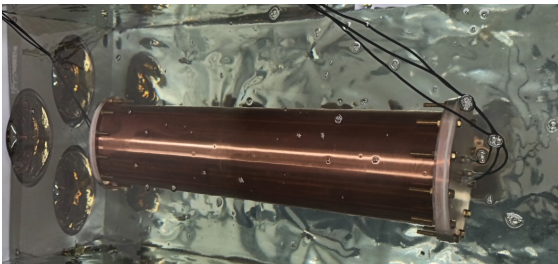
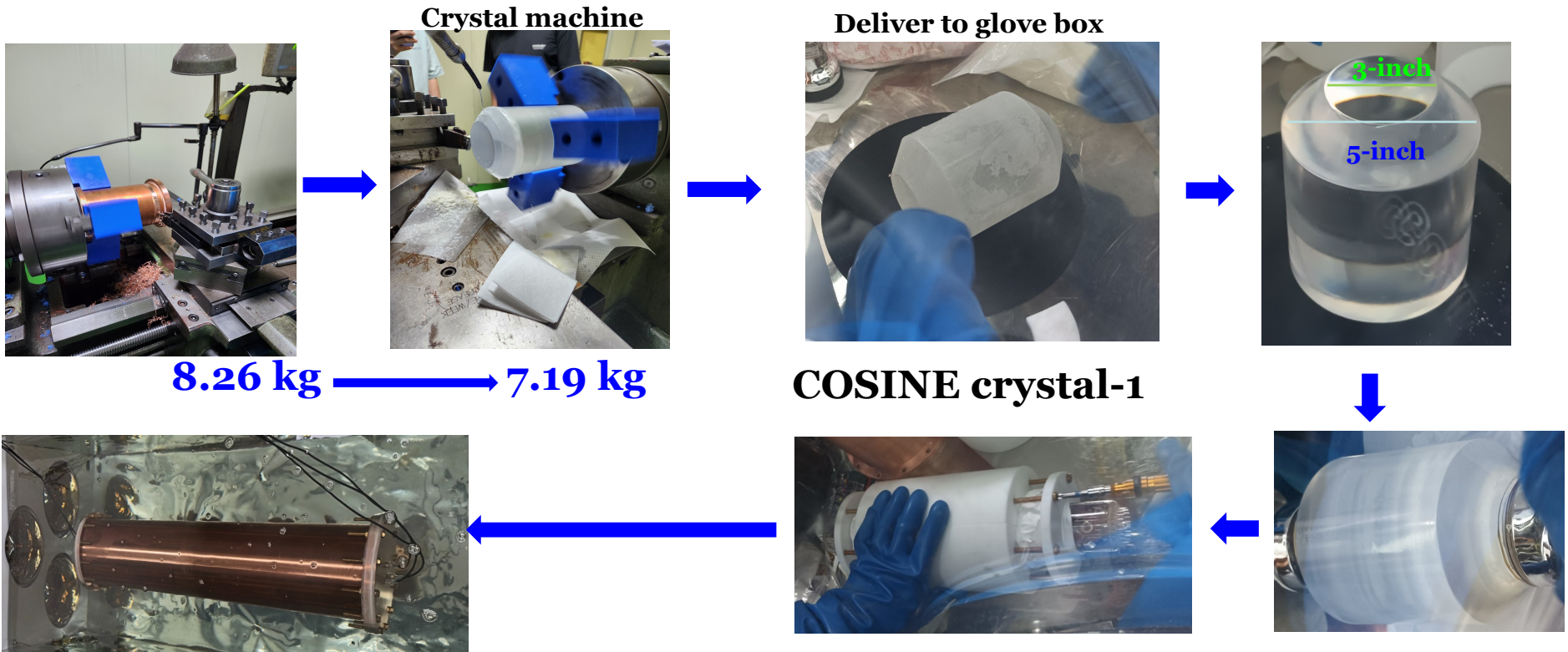
NIMA 981 (2020) 164556

JINST 19 (2024) P10020

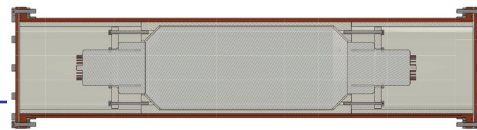
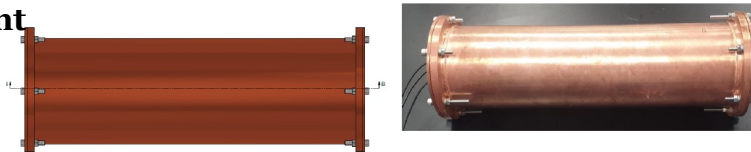


# Moving forward to COSINE-100U<sub>p</sub>grade

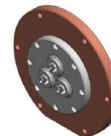
- Upgrade detector assembly for **high light yield**



Above ground measurement



Cover design



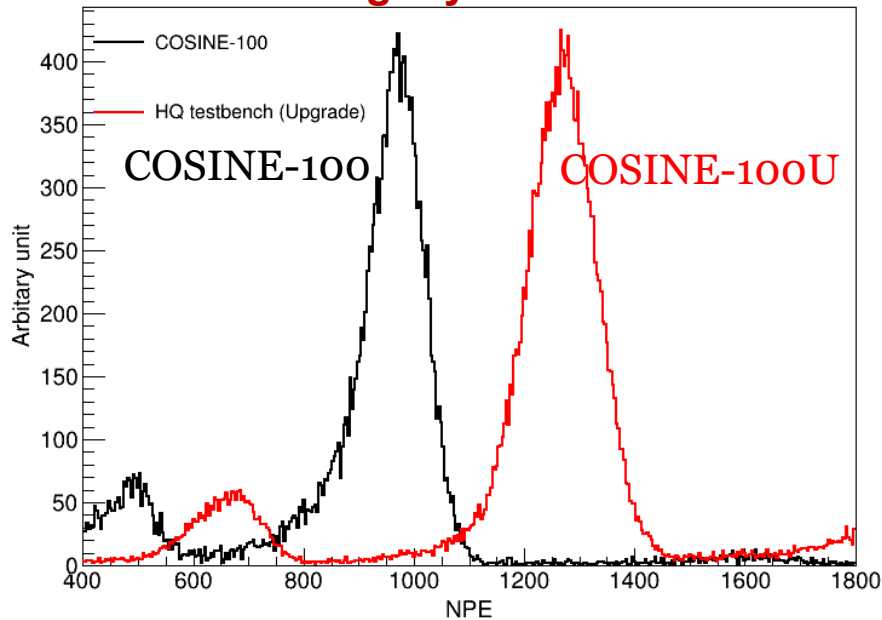
# COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

arXiv:2409.15748

$^{241}\text{Am}$  59.54 keV

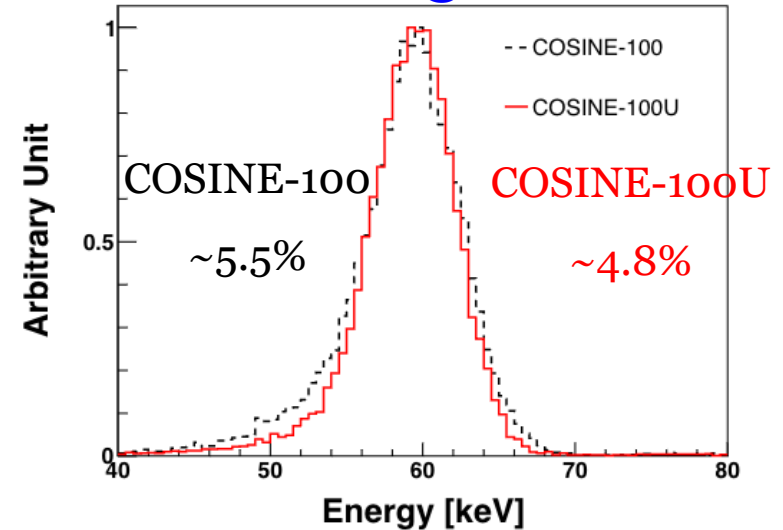
**~40% light yield increase!!!**



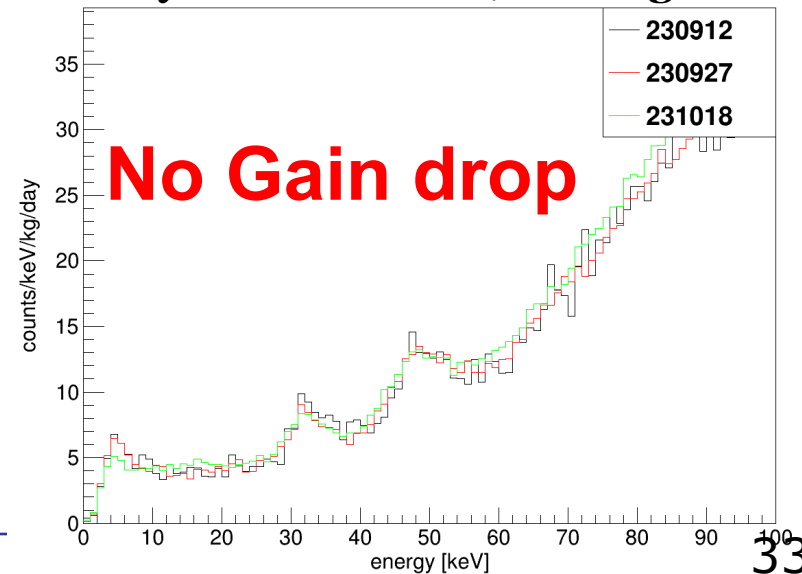
**NPE = Number of photoelectrons**

**$14.9 \pm 1.5$  →  $21.5 \pm 0.6$  NPE/keV**  
**COSINE-100 C2      COSINE-100U C2**

**RMS resolution @ 59.54 keV for C3**



**Stability of ~ 1 month (Above-ground)**



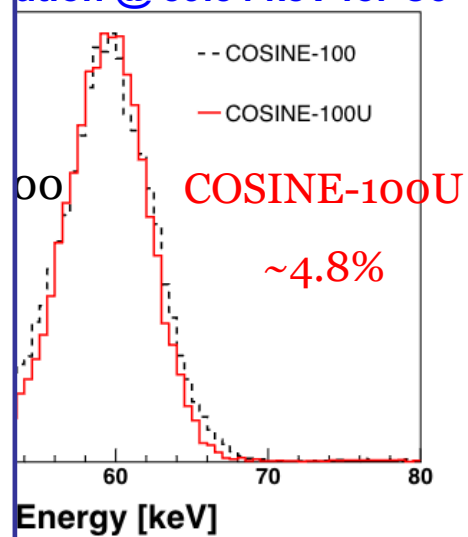
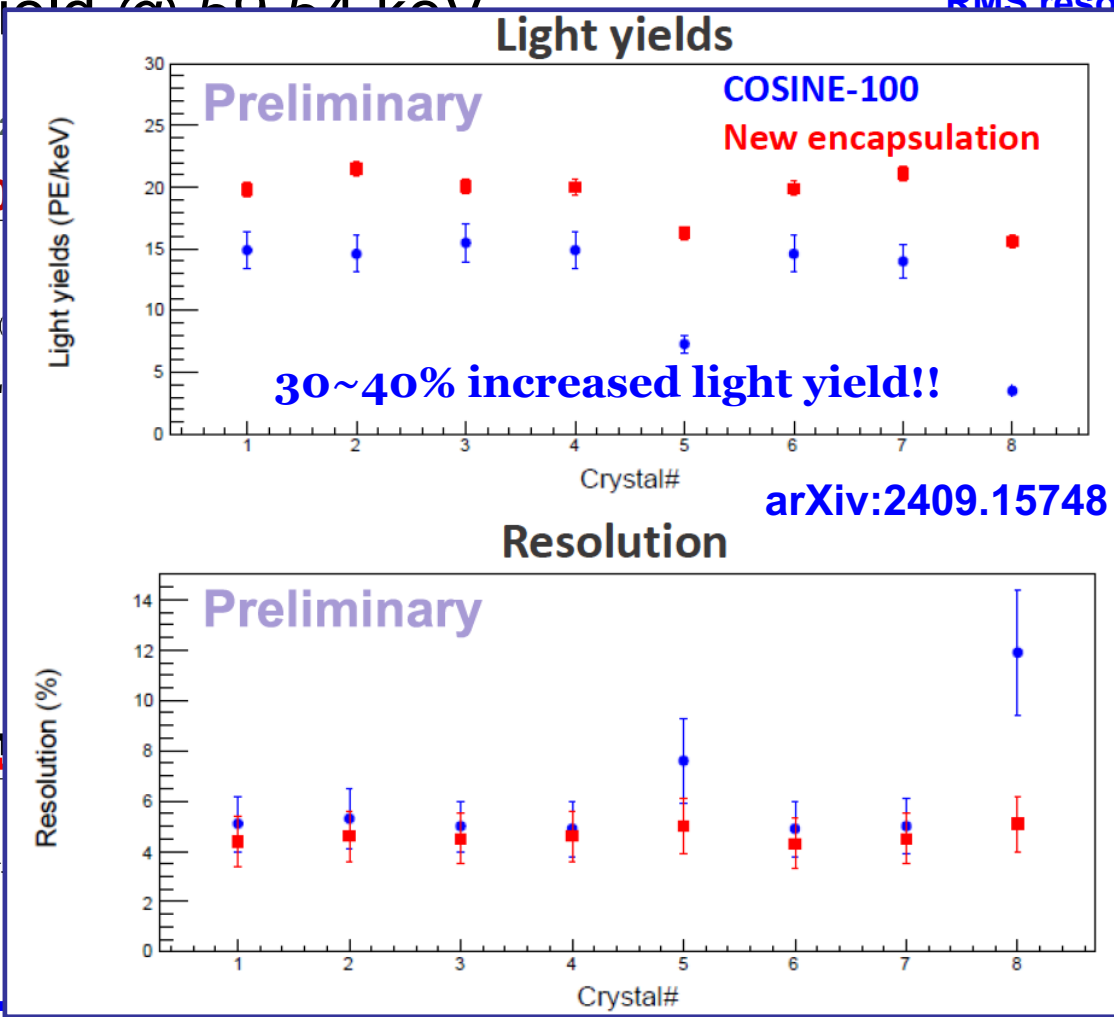
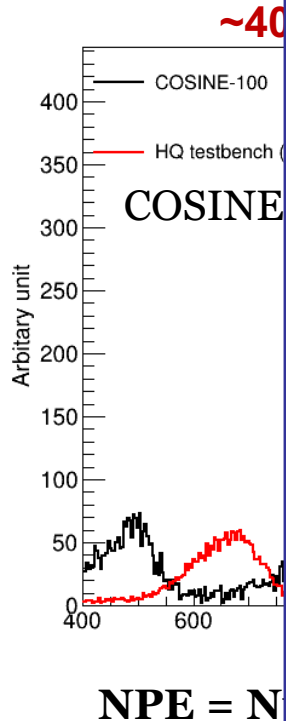
**No Gain drop**



# COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

RMS resolution @ 59.54 keV for C3



14.9 ± 1.5  
COSINE-100

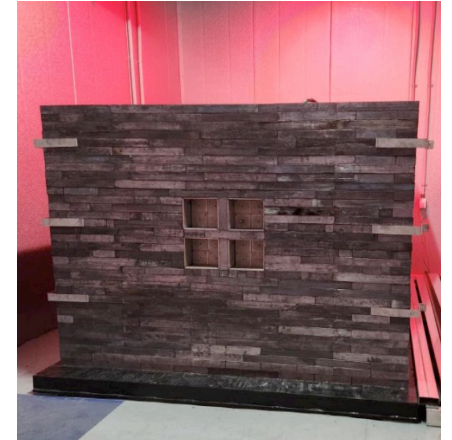
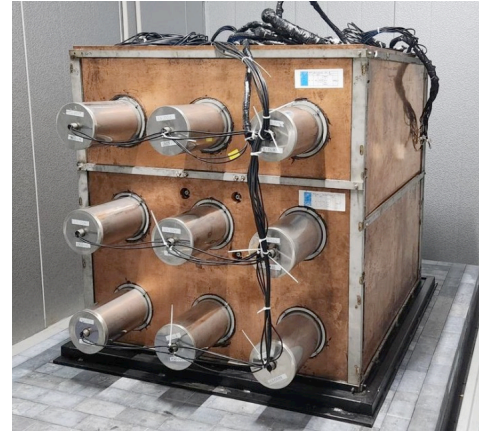
**All crystals were assembled!!**  
**Installation at Yemilab will soon be done**

# COSINE-100U : Yemilab installation

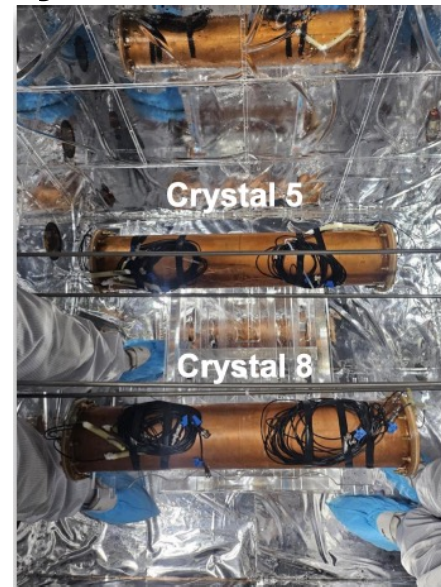
Freeze room for  $-30^{\circ}\text{C}$  operation



Liquid scintillator veto    Lead shield



Crystal installation

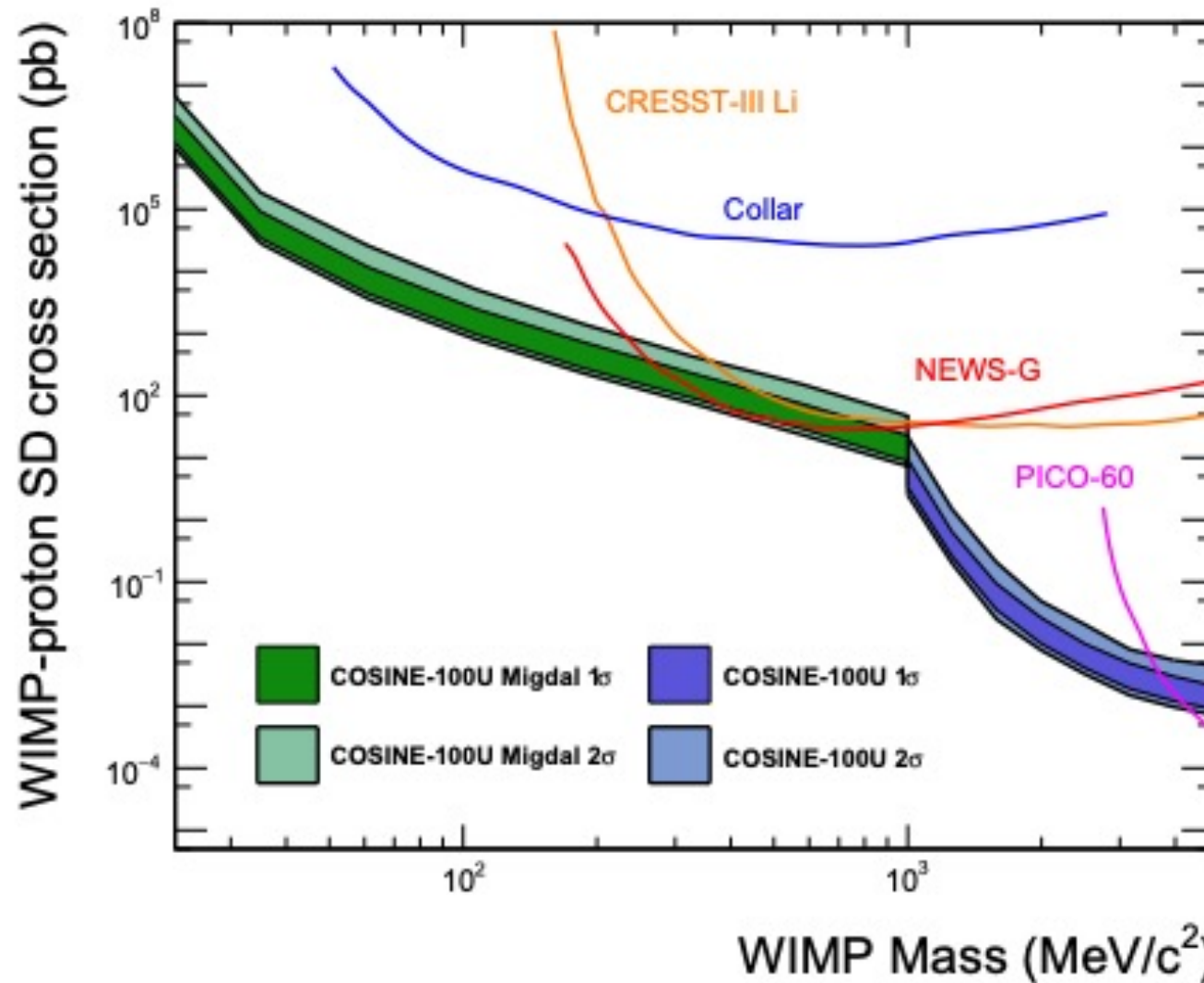


$-30^{\circ}\text{C}$  improvement : [Astropart. Phys. 141, 102709 \(2022\)](#)

- We will start **COSINE-100U** soon

# Sensitivity of COSINE-100U

## WIMP-Proton spin-dependent interaction





# COSINE-200 crystal development



**Purification  
factory ~ 70 kg  
powder load**

## Powder purification performance

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

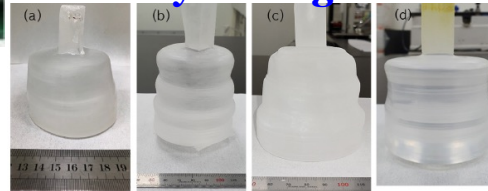
K.A. Shin et al., JINST 15, C07031 (2020)

K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

**We produced ~ 400 kg low-background NaI powder  
(Maximum production rate ~ 100 kg/month)**

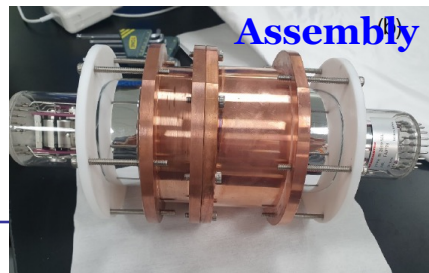
## Crystal ingots



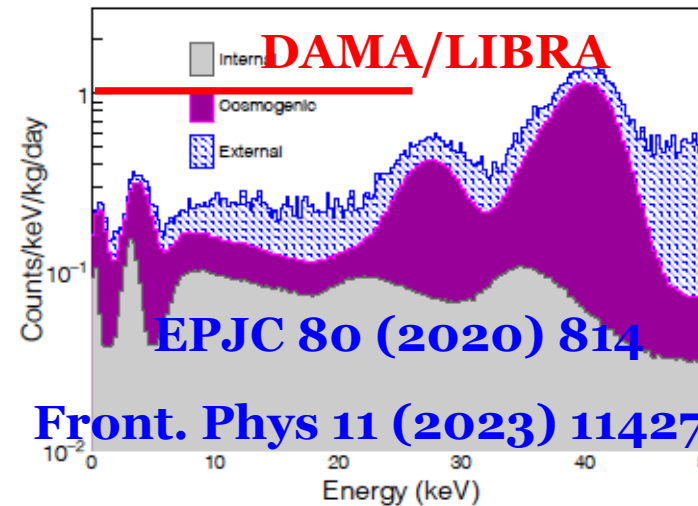
## Machining



## Assembly



**Test grower  
~ 1kg ingot**



**Front. Phys 11 (2023) 1142765**

**A proof of principle for low background NaI**

# Summary

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- COSINE-100 ruled out DAMA/LIBRA with significance above 3 sigma in model-independent analysis
- Preliminary combined analysis with ANAIS-112 reach to 5 sigma level exclusion
- COSINE-100U will have world competitive sensitivities for low-mass dark matter searches