



# Dark Matter **Annual Modulation** Search in **COSINE-100** Full Dataset and **Beyond**

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Department of Physics & Astronomy, Seoul National University

Center for Underground Physics, IBS

On behalf of **COSINE** Collaboration

July 9th, 2024

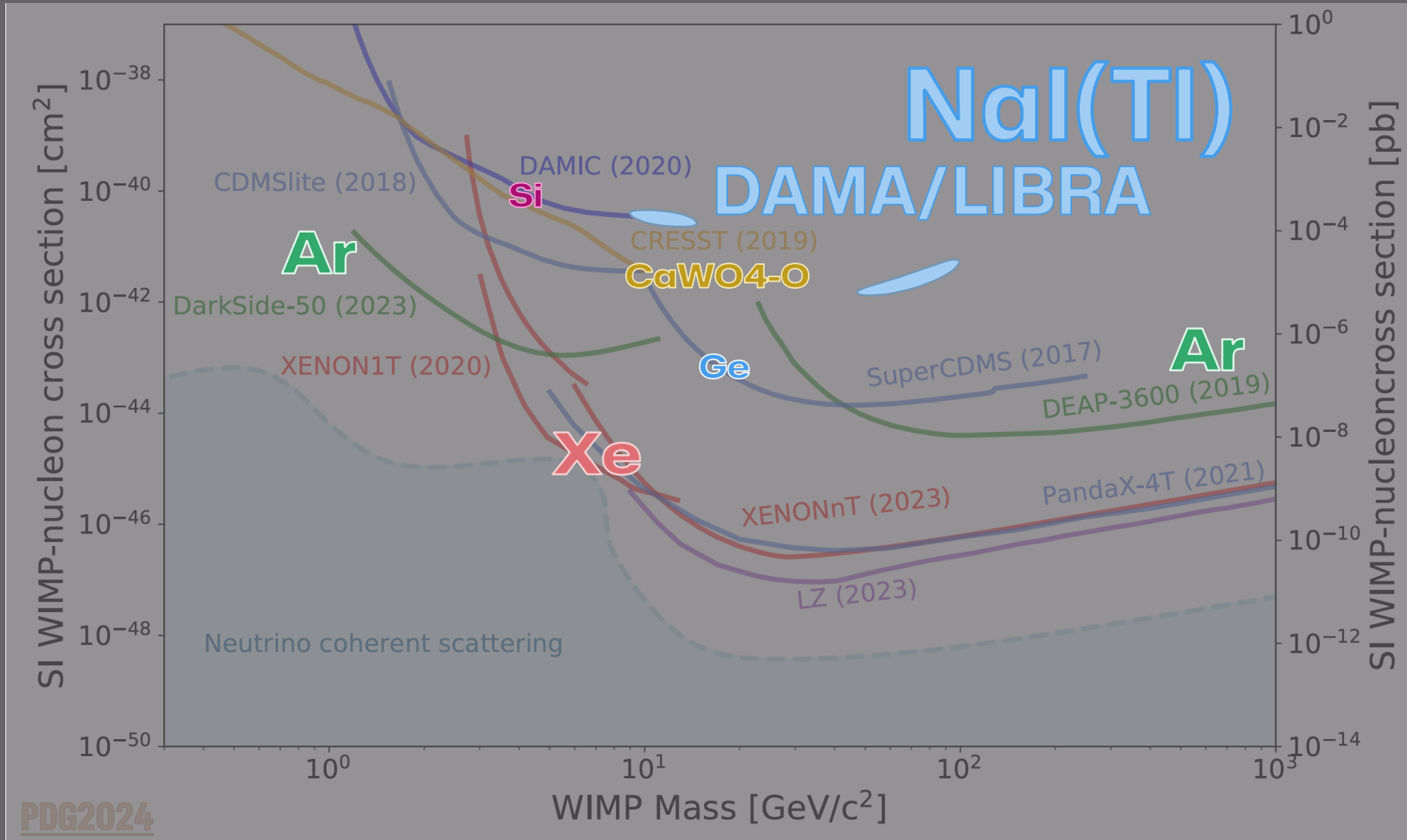
*Parallel Session 1*

Identification of Dark Matter 2024

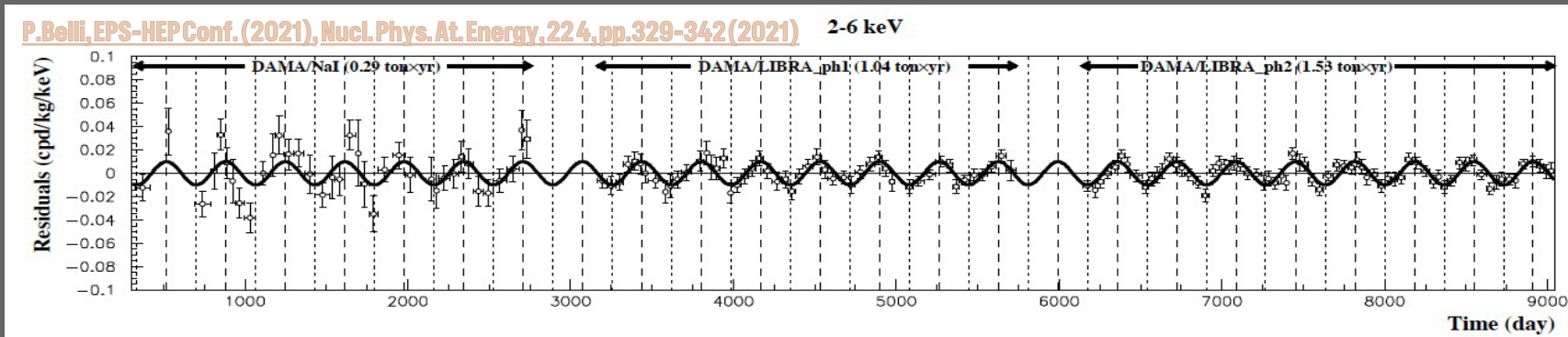
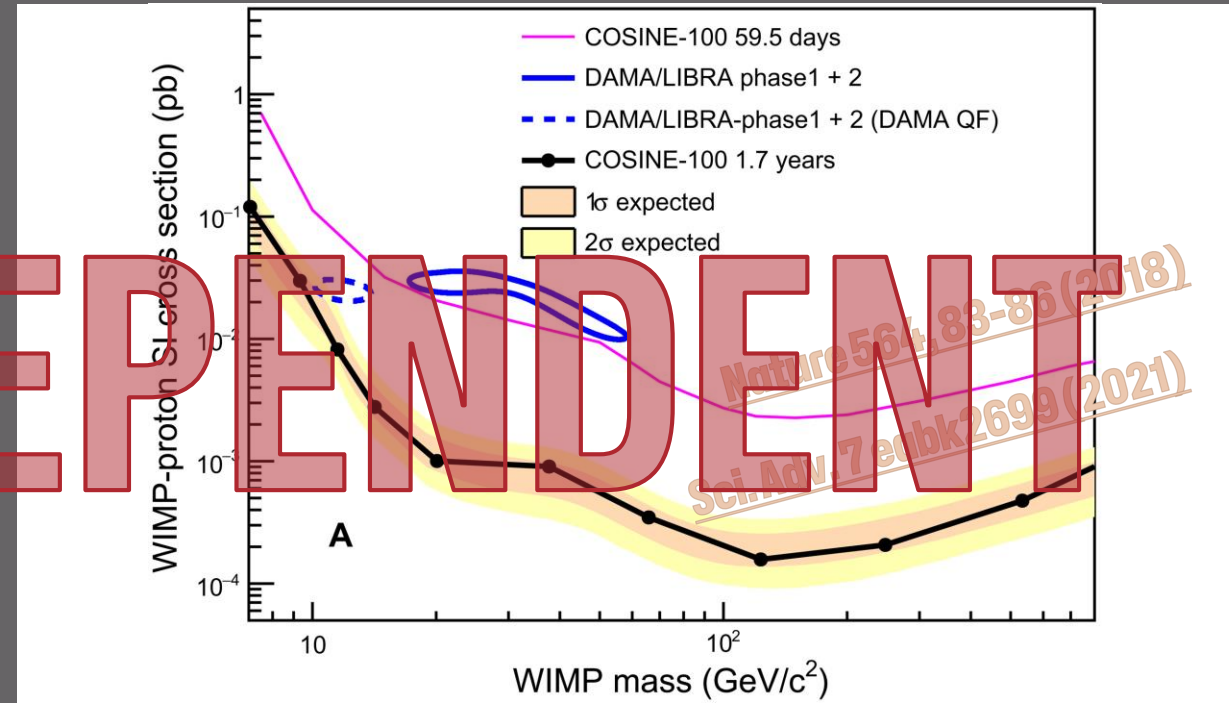
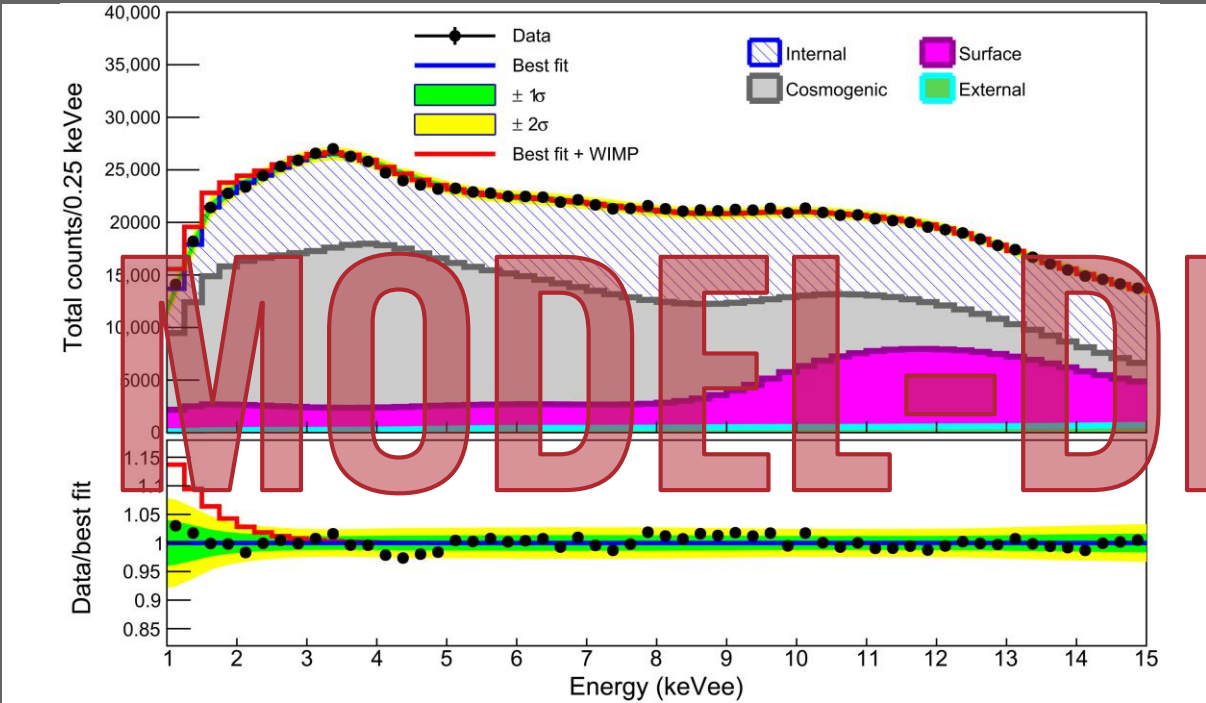
*Palazzo dell'Emiciclo, Sala Ipogea, L'Aquila, Italy*



# Check for DAMA's Signal; Target Material



# Check for DAMA's Signal; Analysis Method



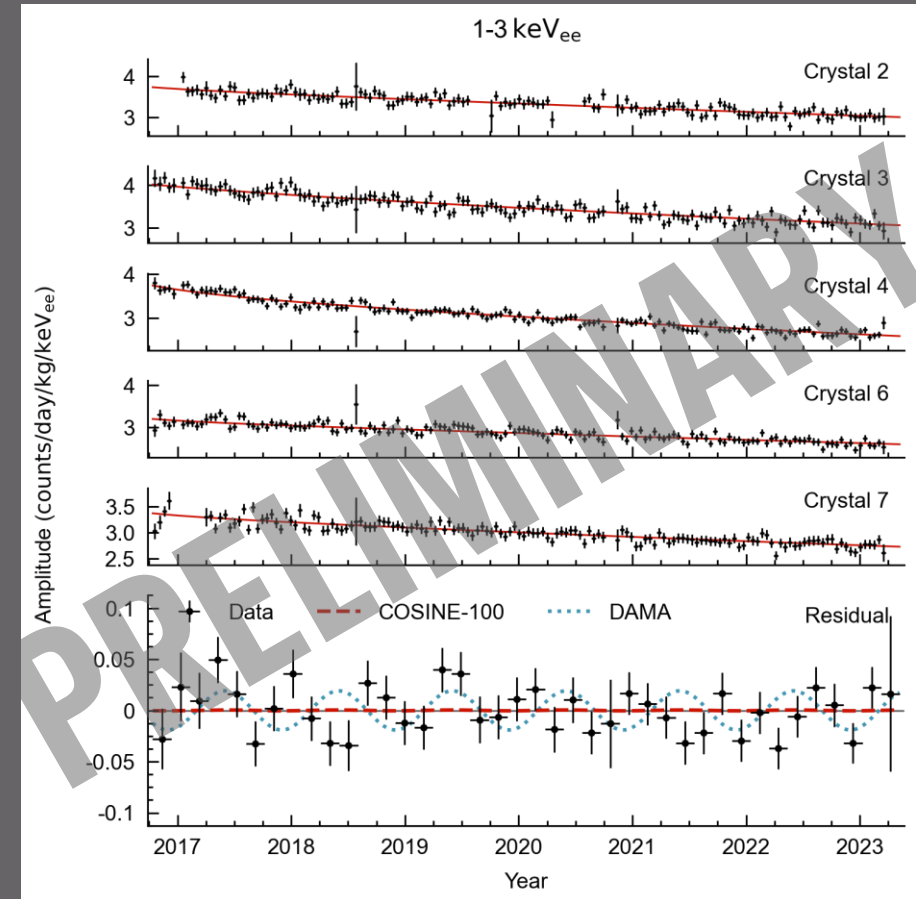


# Model-Independent Test of DAMA

## Install NaI(Tl)

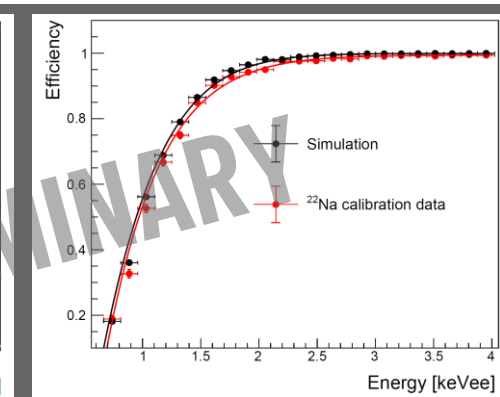
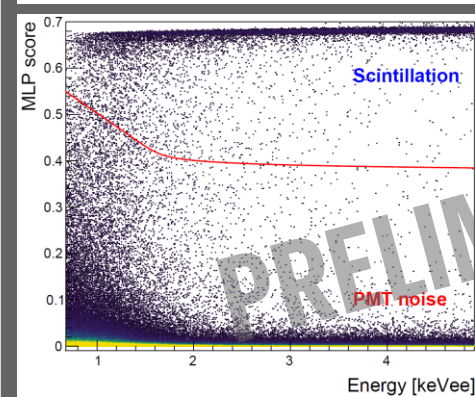
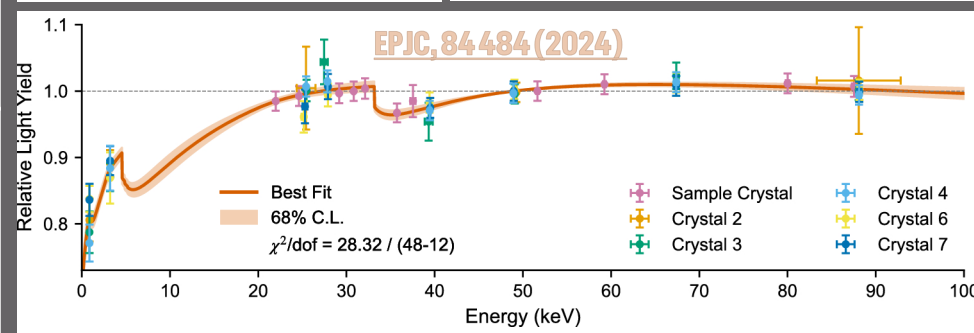
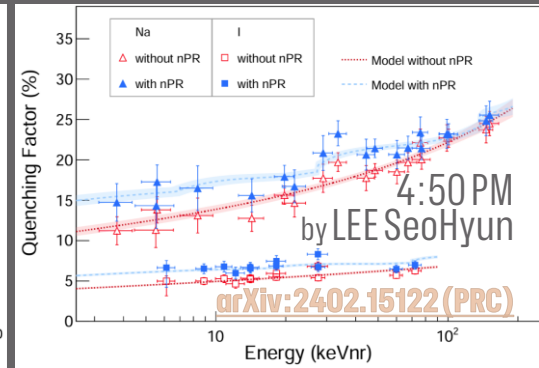
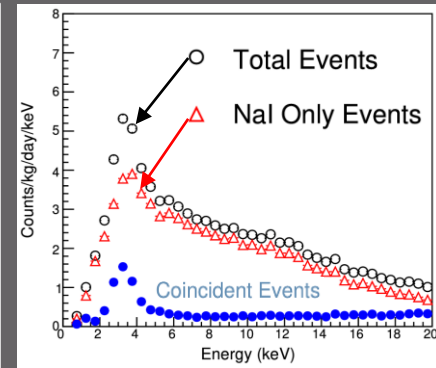
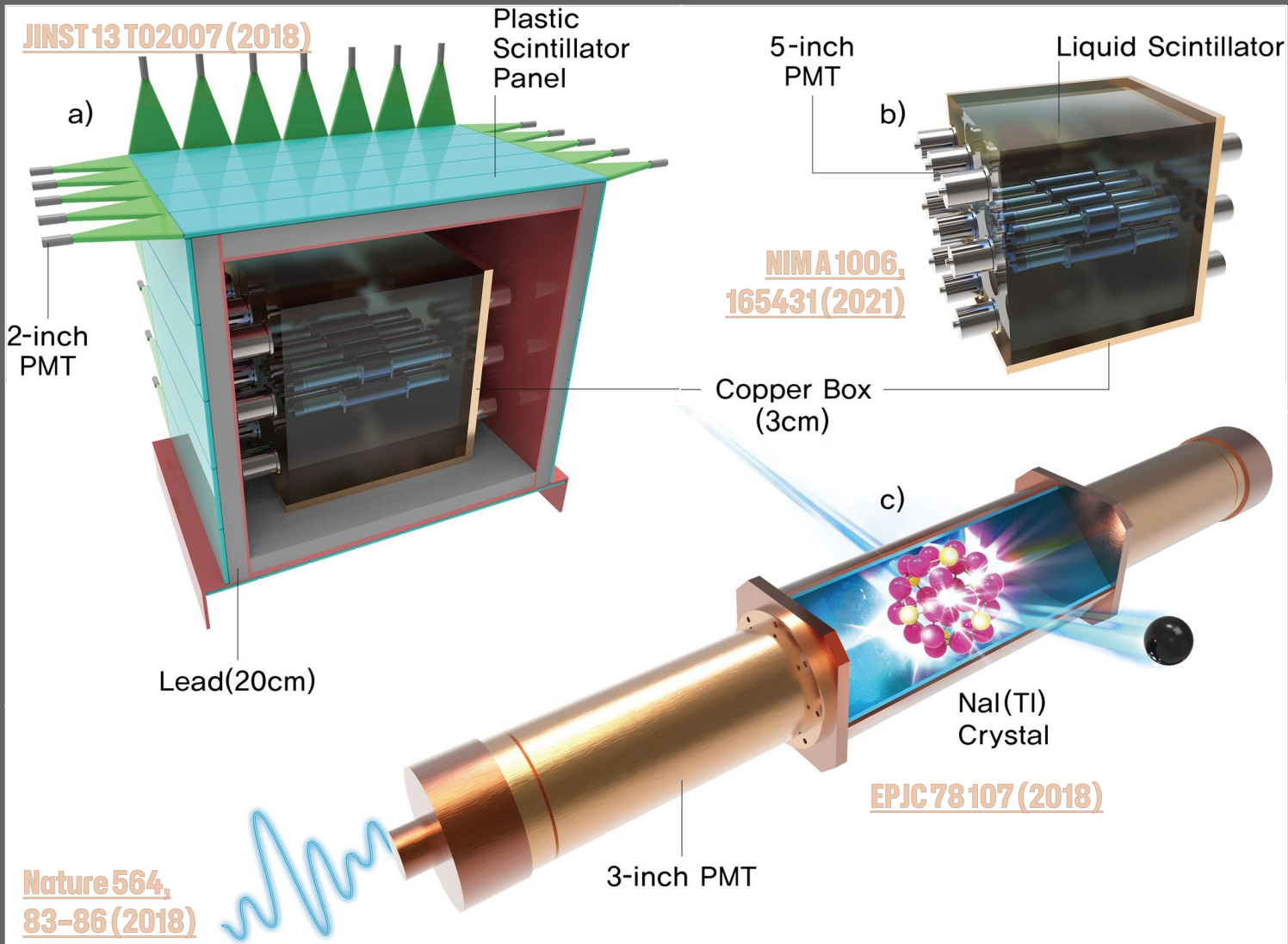


## Analyze Rate



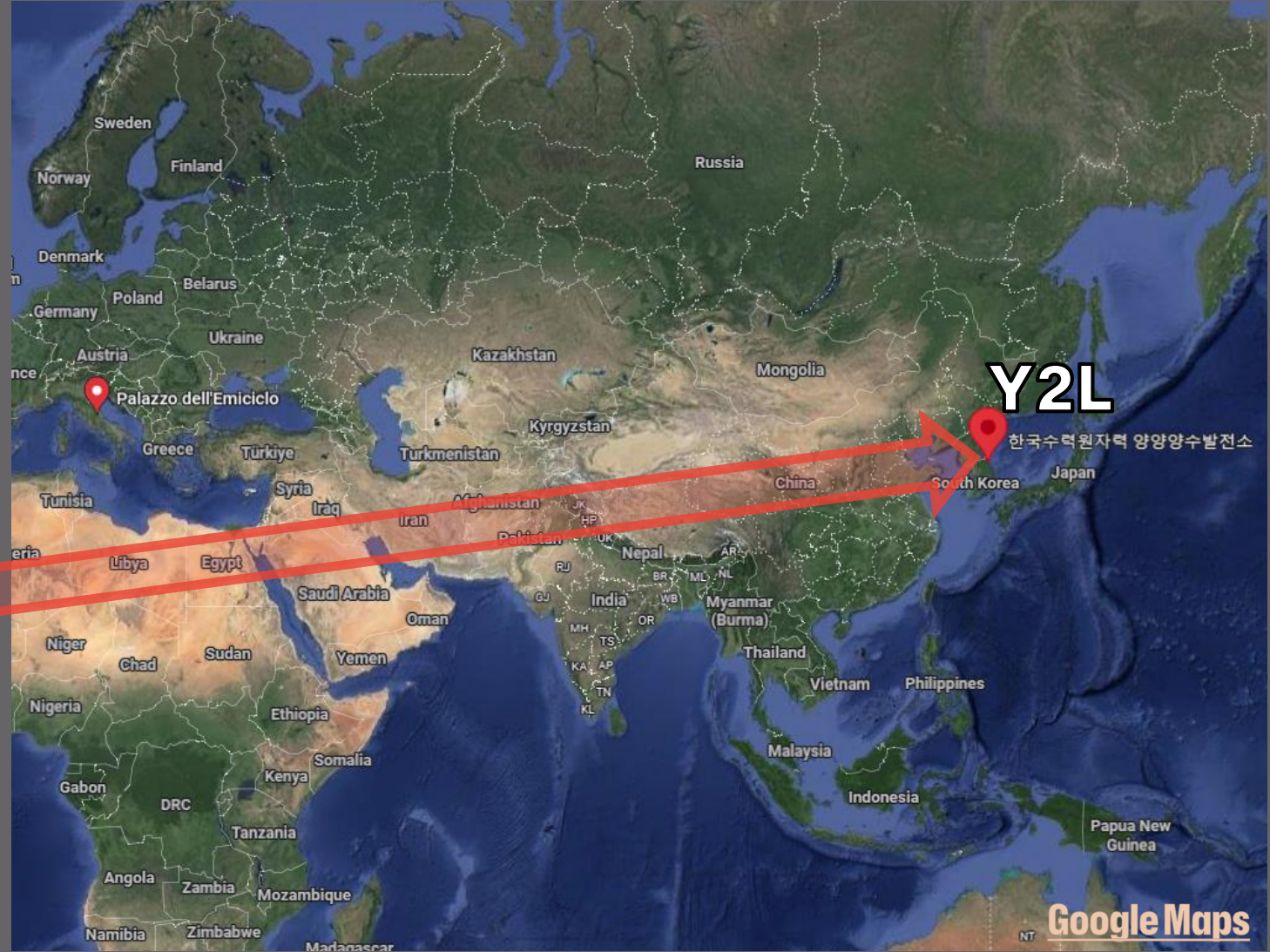


# Install NaI(Tl) – COSINE-100 Detector

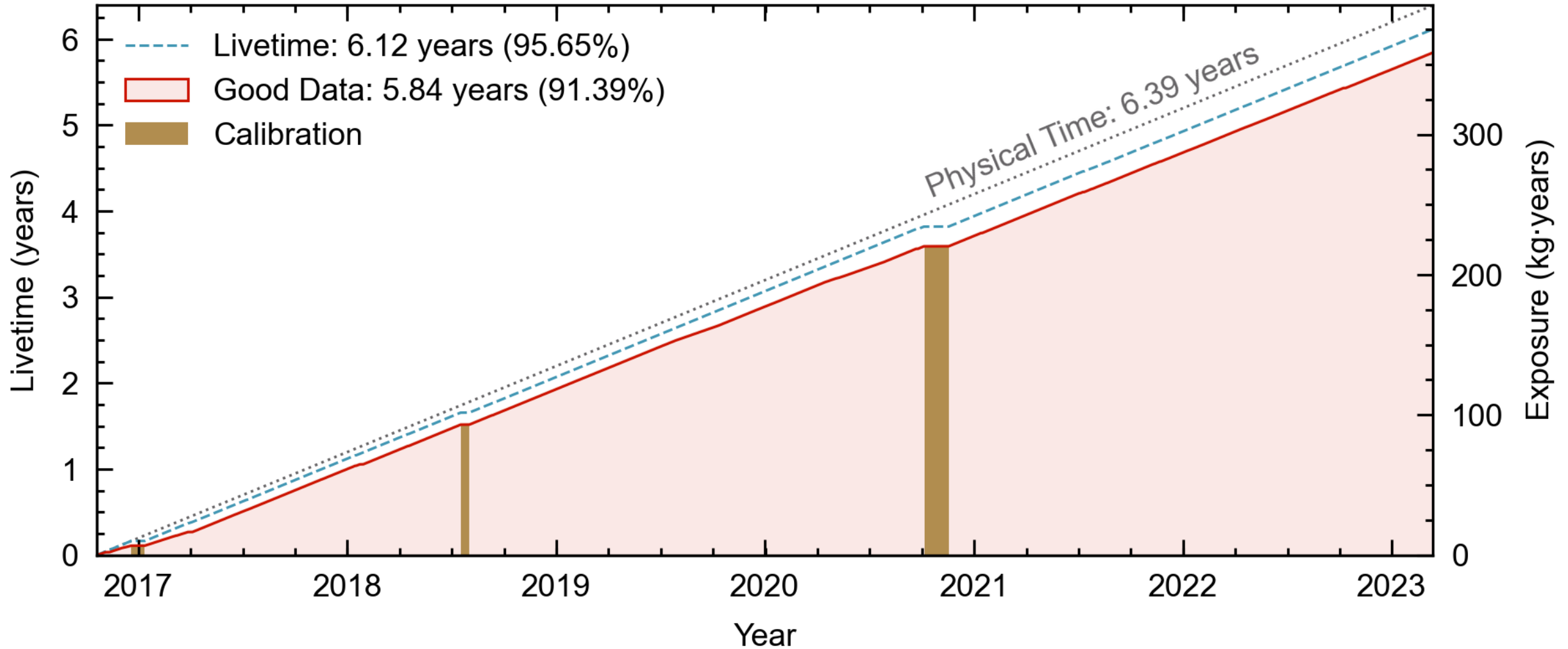




# Install NaI(Tl) – Location



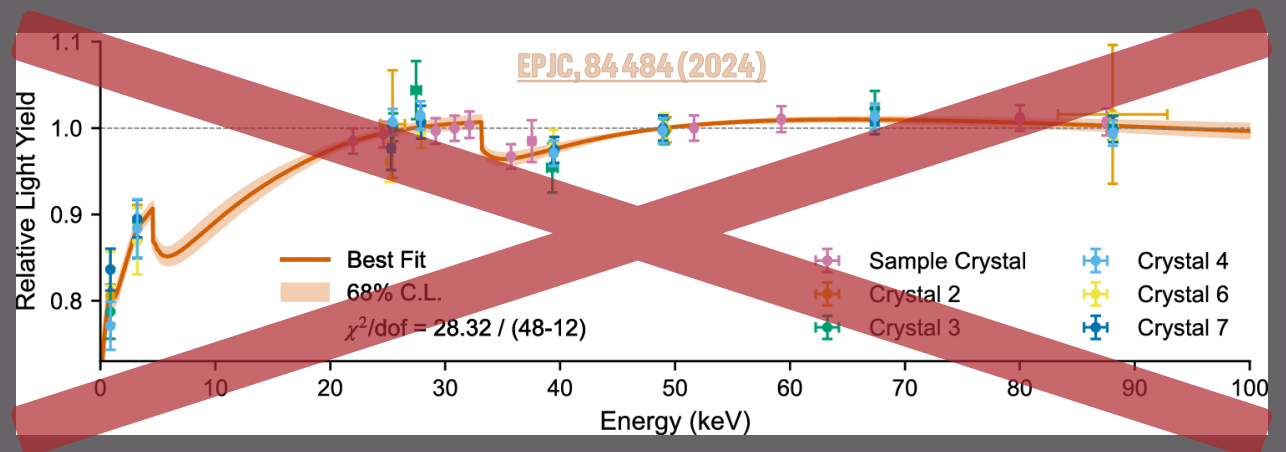
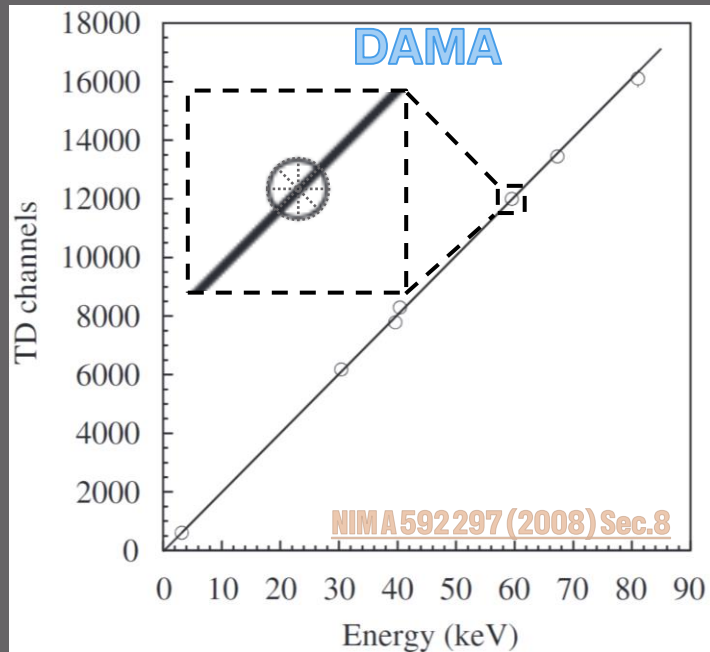
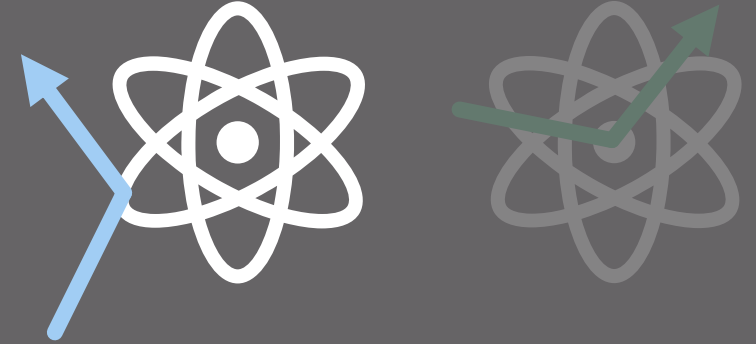
# 6 Years 4 Months 22 Days Later...





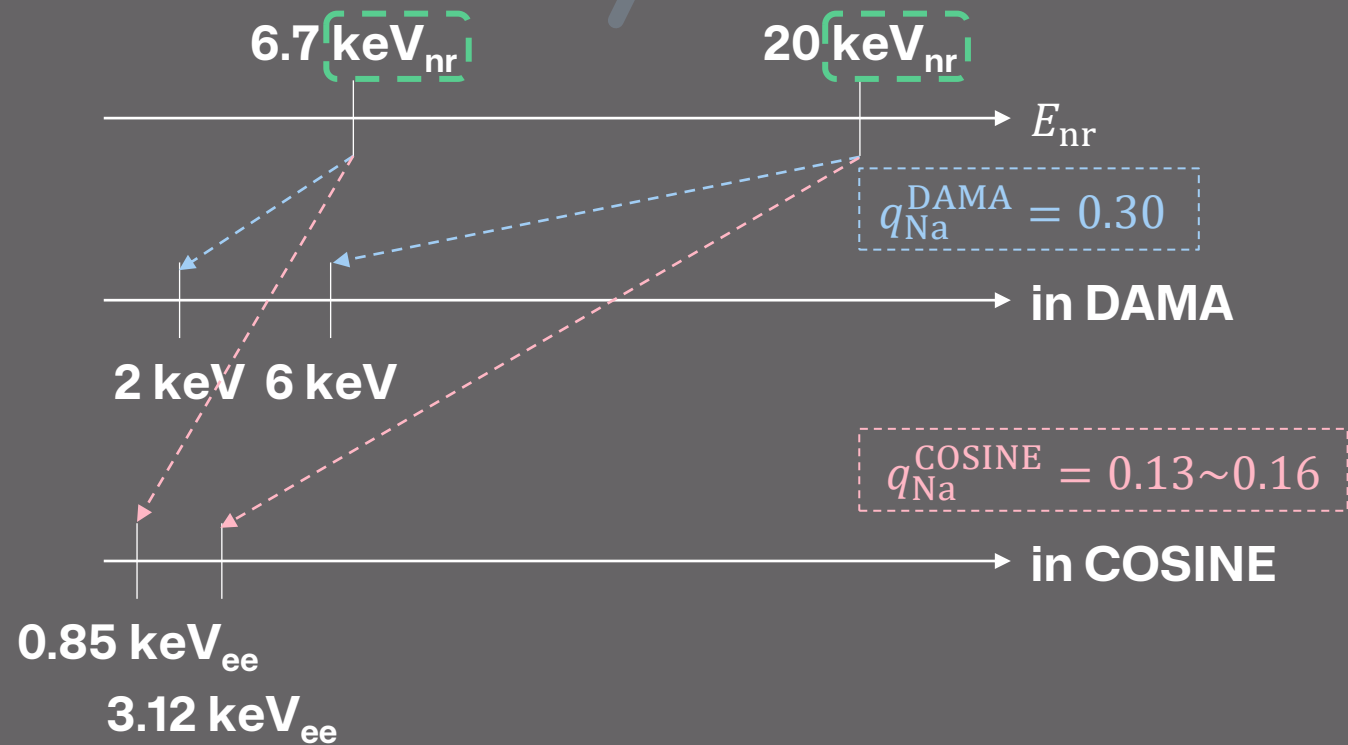
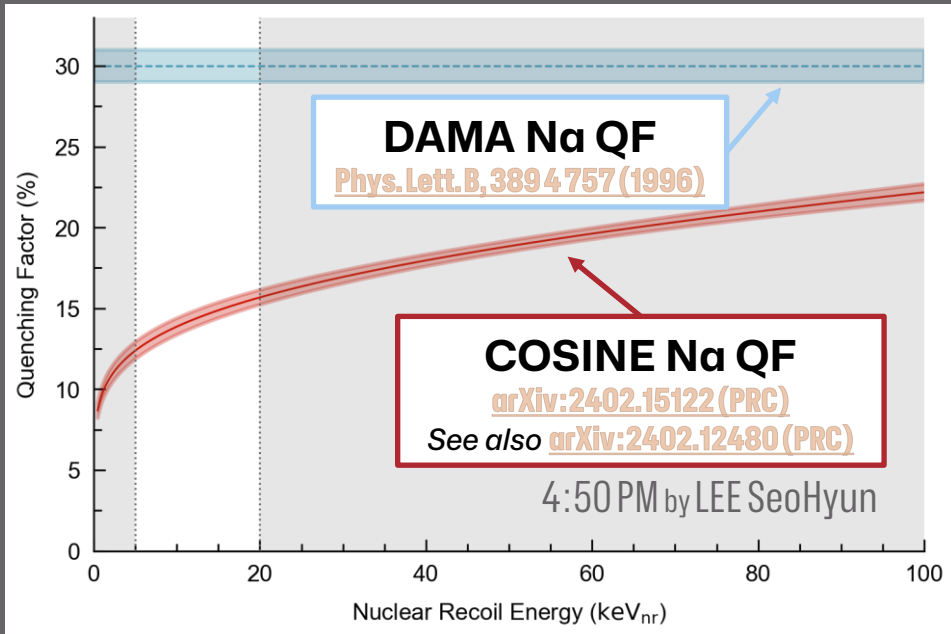
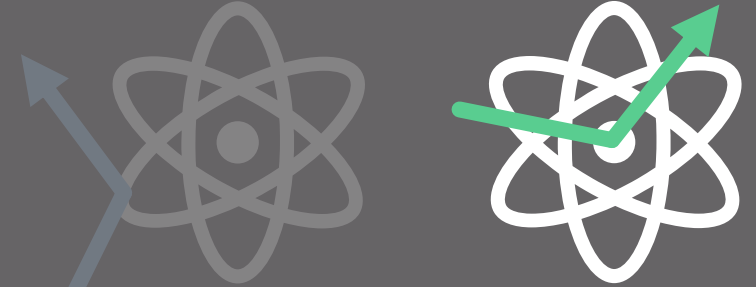
# Calibration for Testing DAMA's Claim

## 1. Linear calibration: $\text{keV}_{ee}$

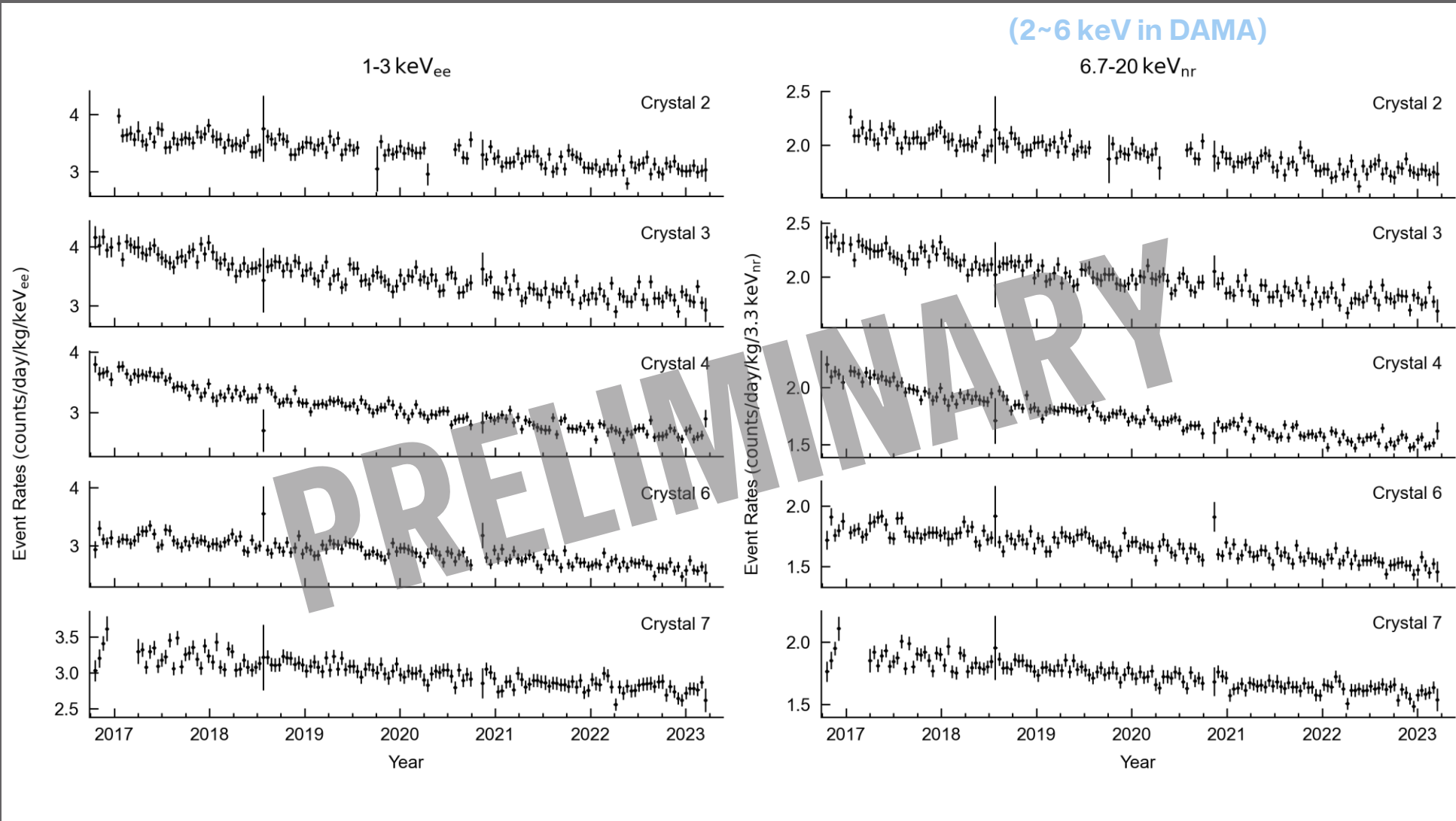


# Calibration for Testing DAMA's Claim

1. Linear calibration:  $\text{keV}_{ee}$
2. Quenching factor corrected:  $\text{keV}_{nr}$



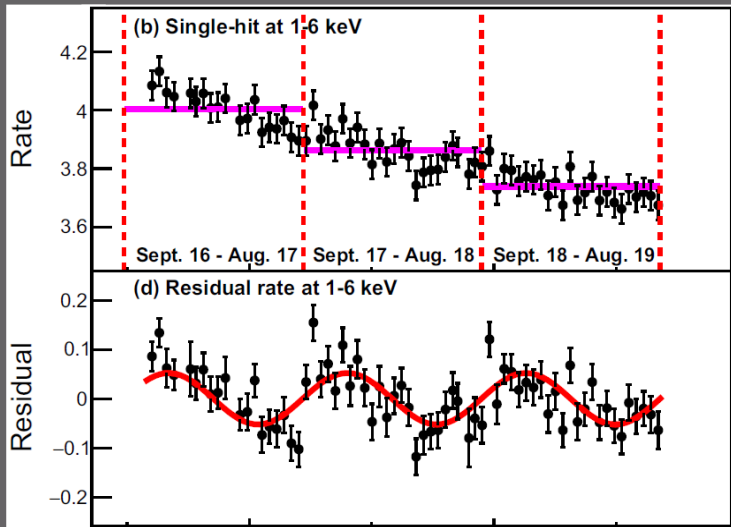
# Event Rate



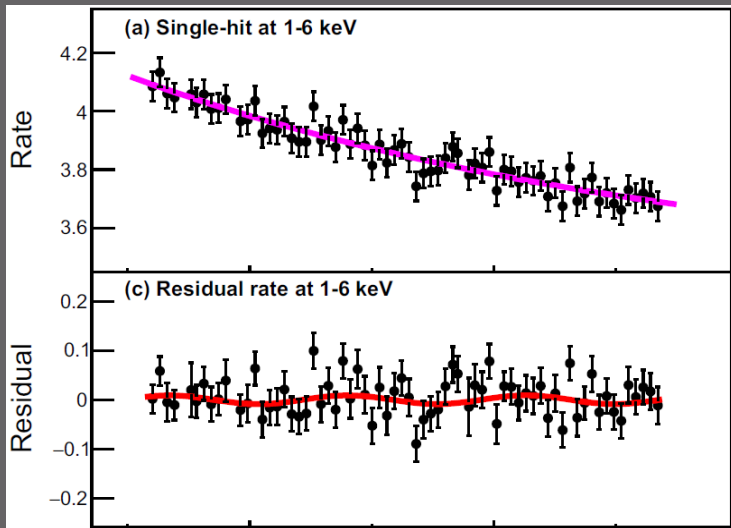


# Background Radioactive Isotopes

DAMA-like method

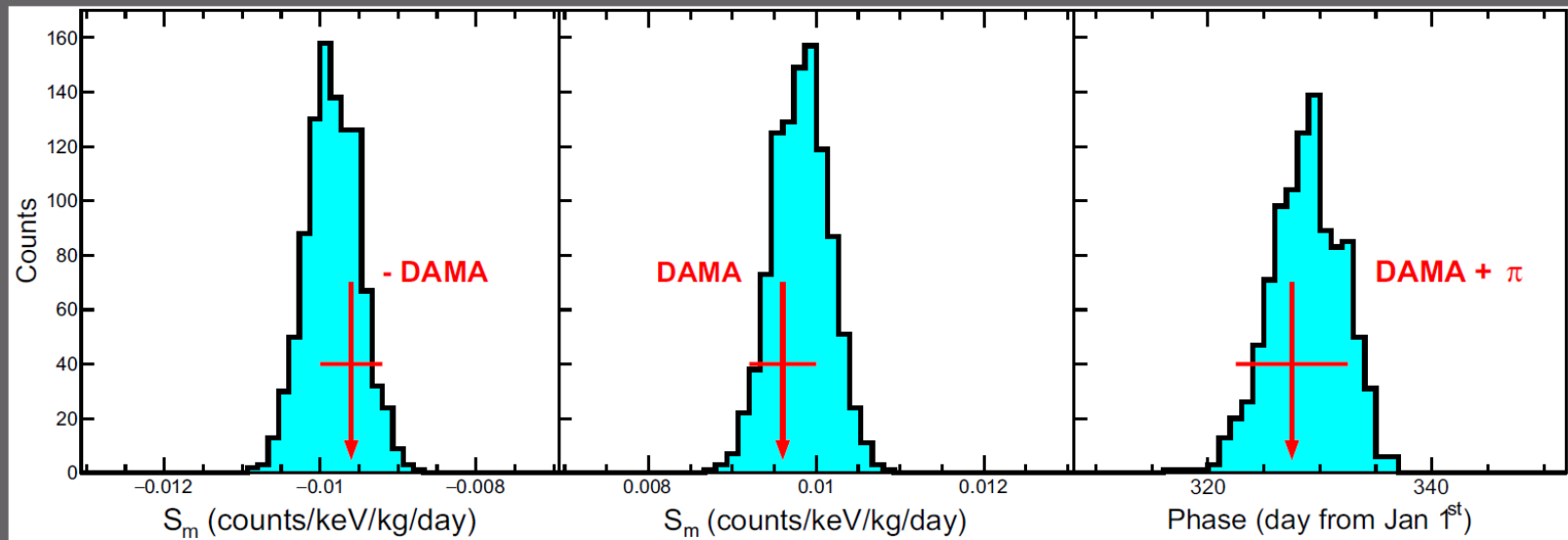


Single exponential



COSINE-100 background + DAMA method

SciRep 13, 4676 (2023) → Modulation (with reversed phase)

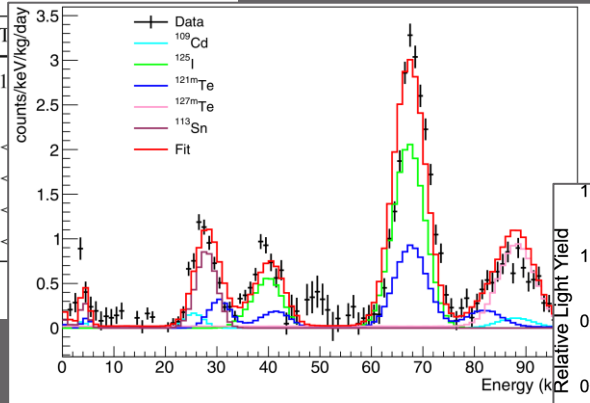


Identification of Dark Matter 2024

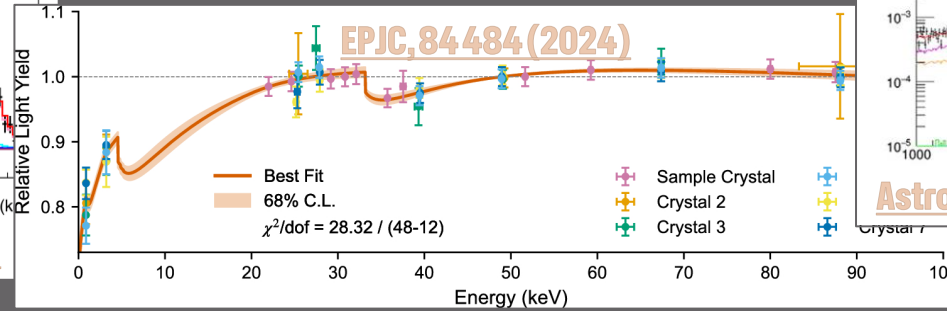
# Background Radioactive Isotopes

External source	Radioactivity <sup>a</sup>
	U ( <sup>214</sup> Bi)
PMT [1] (R12669SEL <sup>b</sup> )	25 ± 5
Quartz window	< 1.8
PTFE reflector	< 0.5
Cable ties	< 4.2
LS	< 2.7

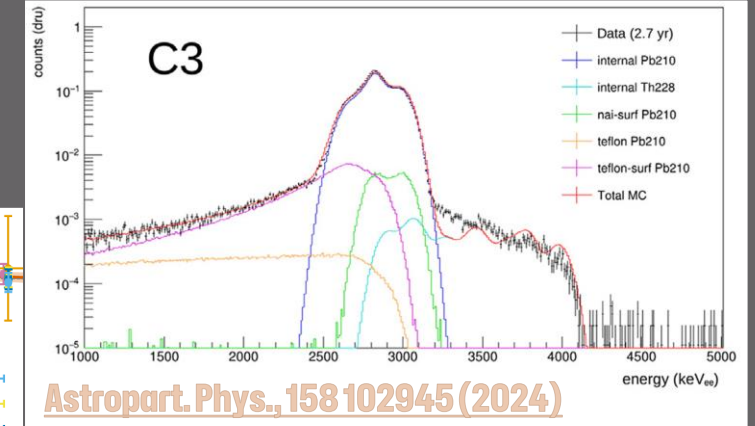
EPJC, 78 490 (2018)



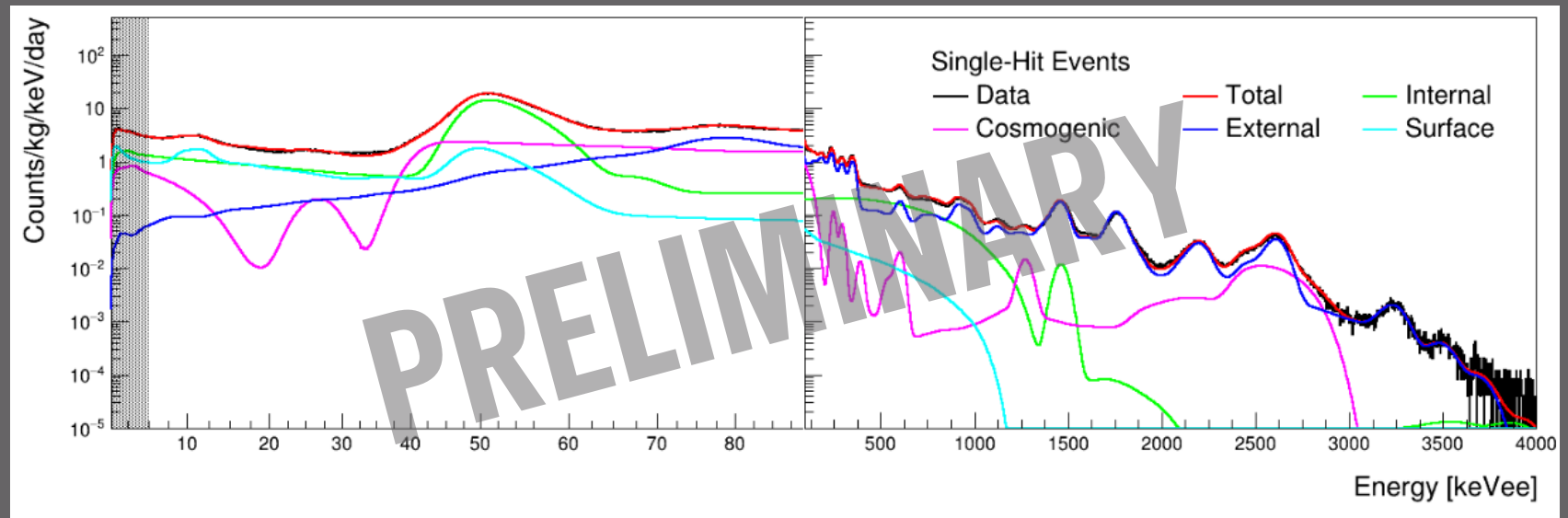
Astropart. Phys., 115 102390 (2020)



EPJC, 84 484 (2024)



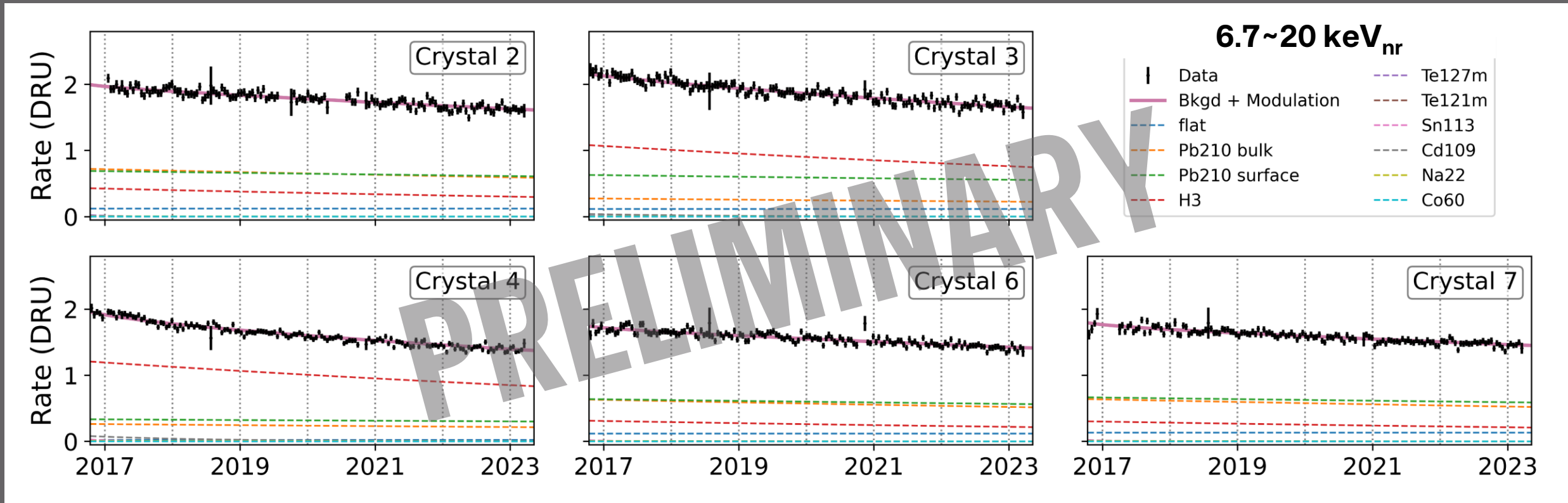
Astropart. Phys., 158 102945 (2024)



# Event Rate and Model

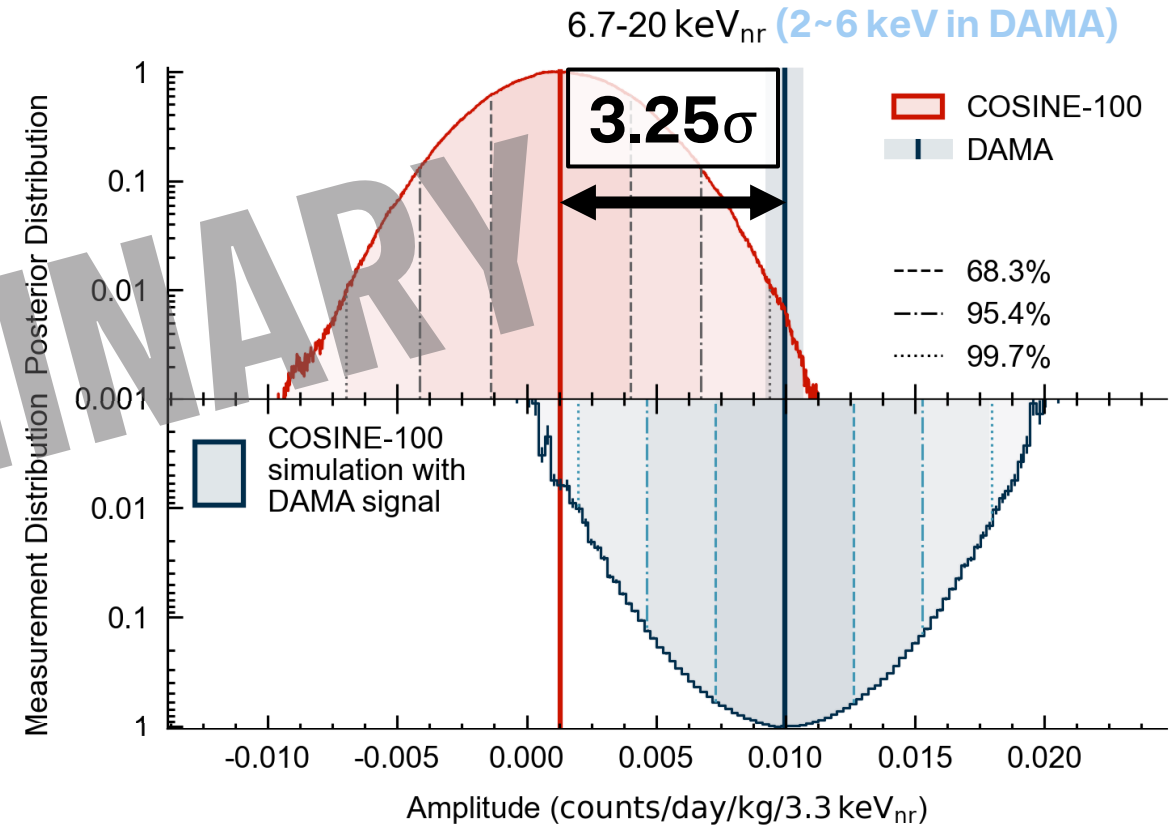
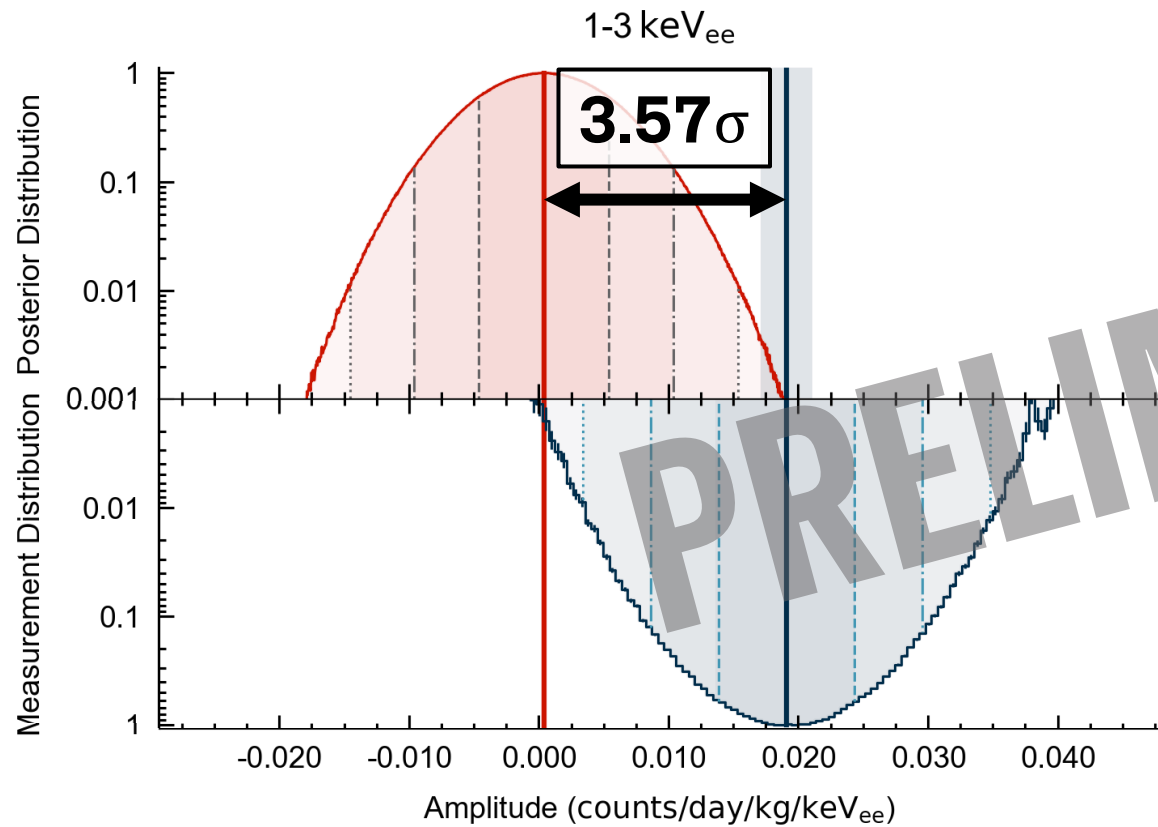
- The event rate for crystal  $i$  is modeled as

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

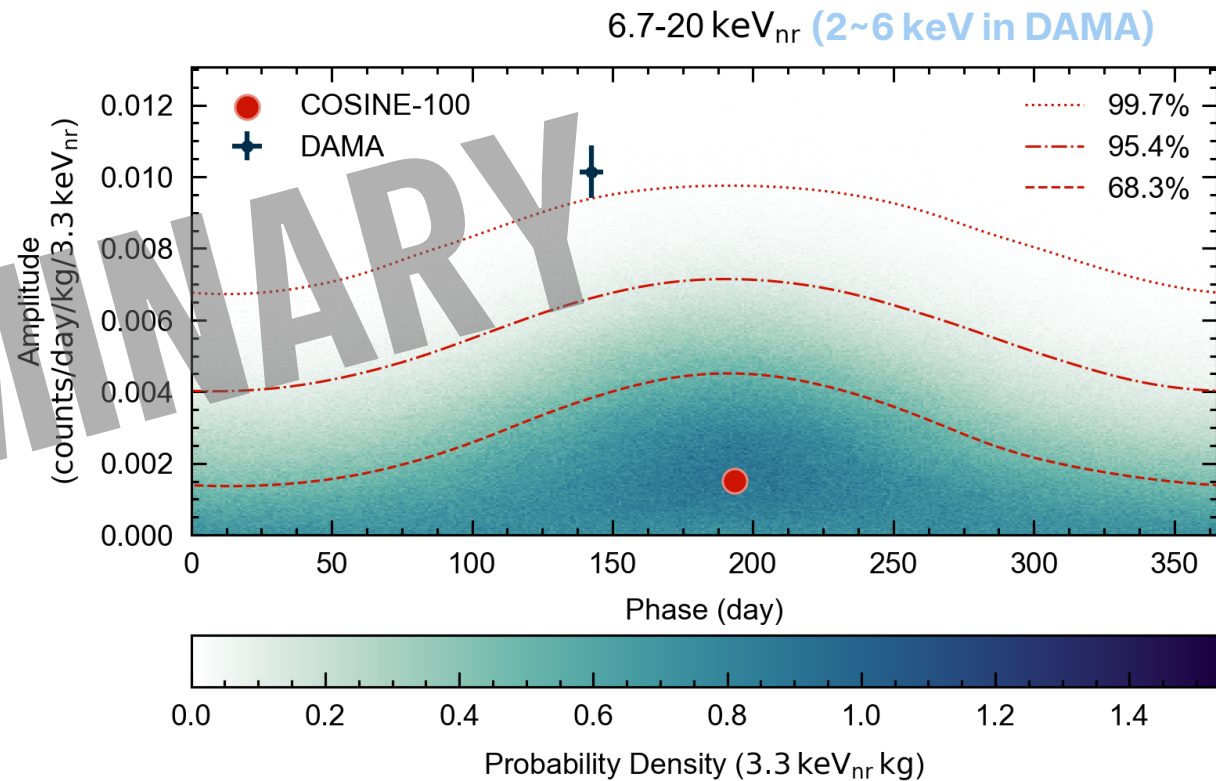
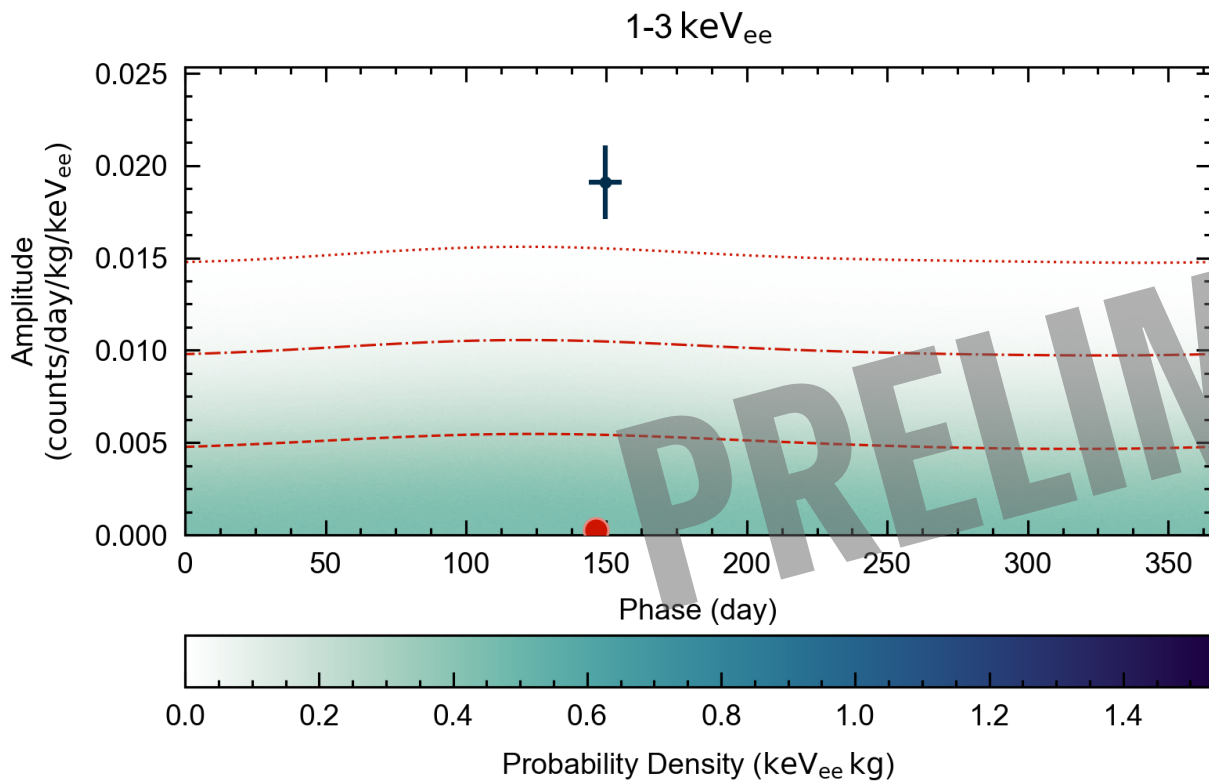




# No Modulation Detected

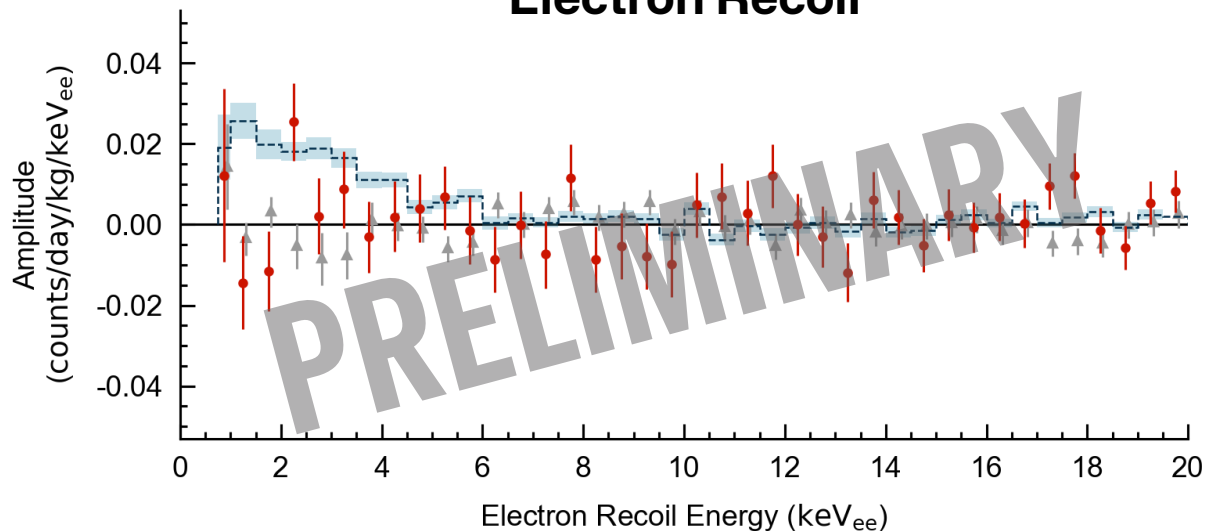


# No Modulation Detected

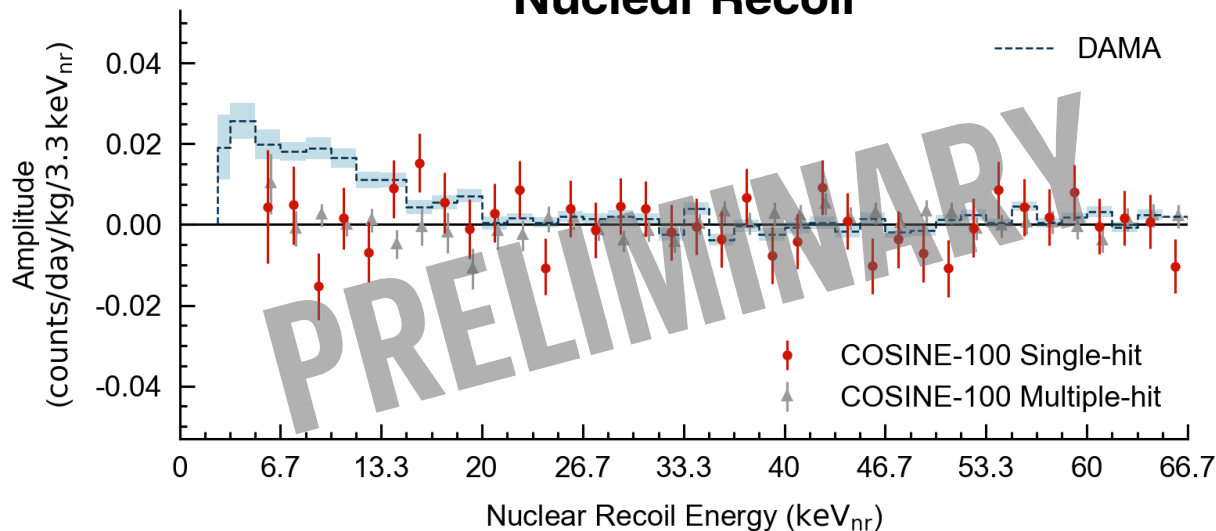


# No Modulation Detected

## Electron Recoil



## Nuclear Recoil

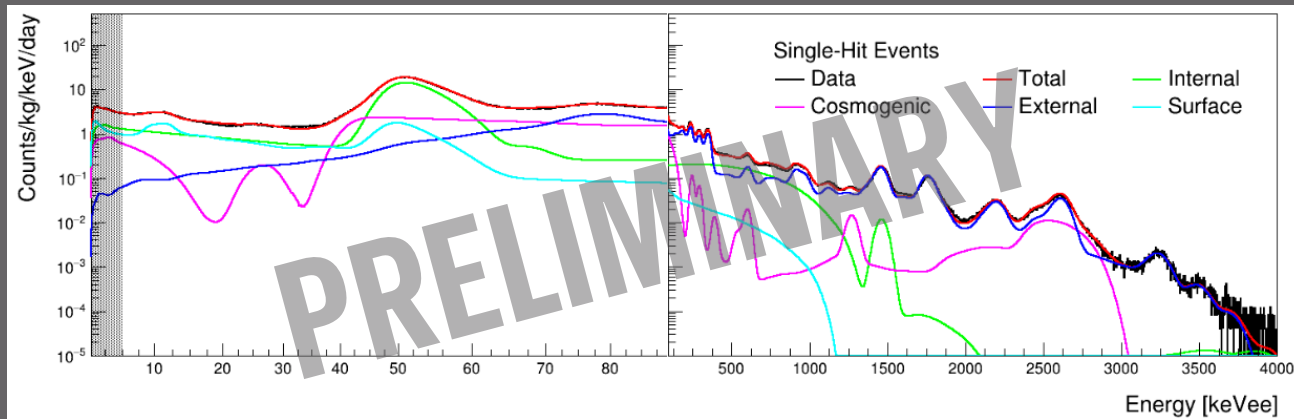
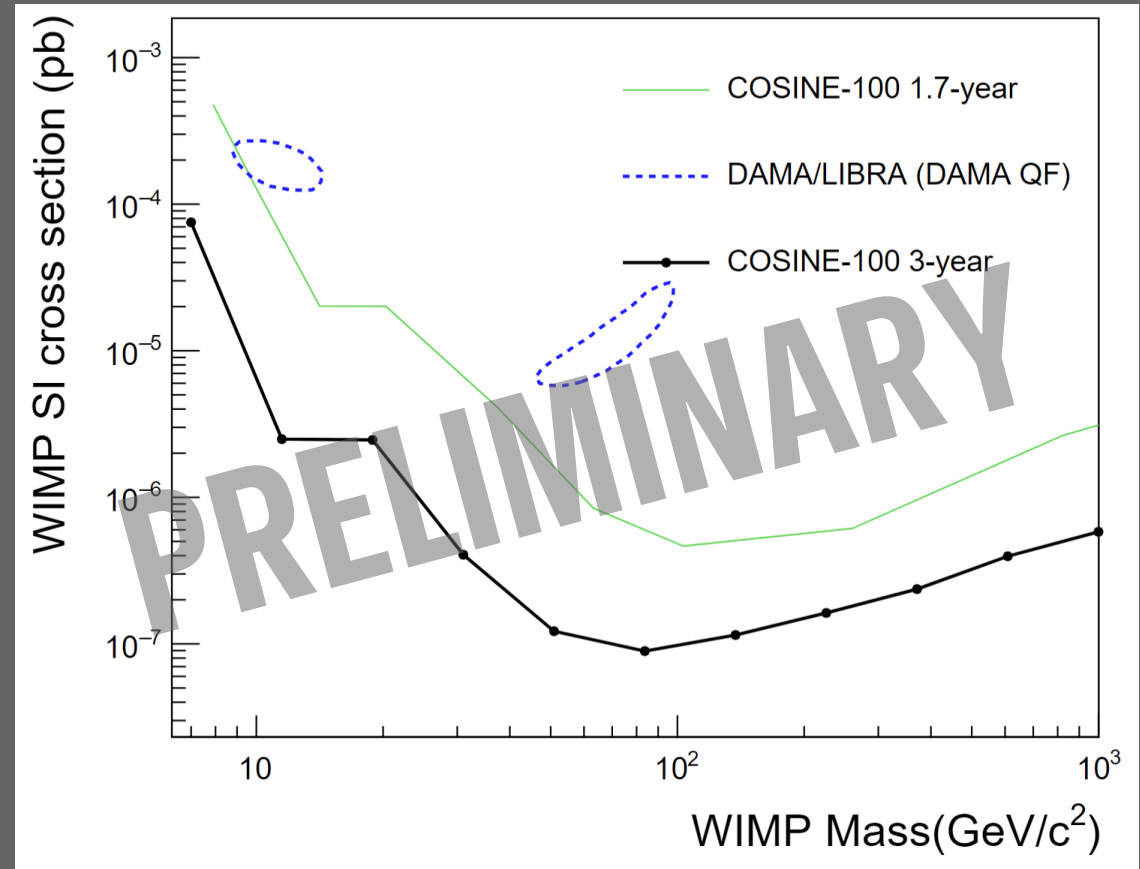
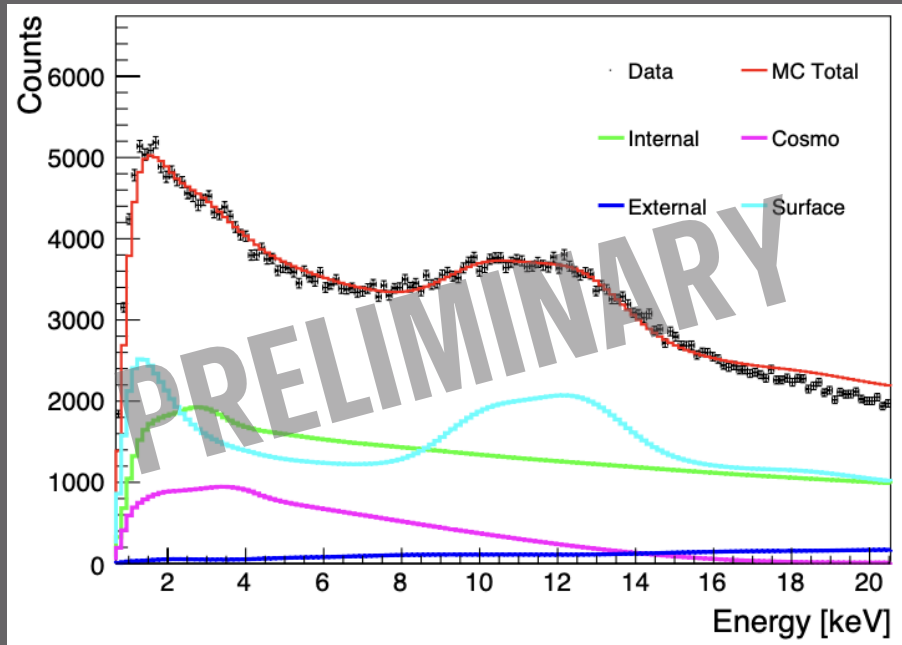


$E$ (keV <sub>ee</sub> )	$A$ (counts/day/kg/keV <sub>ee</sub> )	
	COSINE-100	DAMA/LIBRA
1~3	$0.0004 \pm 0.0050$	$0.0191 \pm 0.0020$
1~6	$0.0017 \pm 0.0029$	$0.01048 \pm 0.00090$
2~6	$0.0053 \pm 0.0031$	$0.00996 \pm 0.00074$

$E$ (keV <sub>nr</sub> )	$A$ (counts/day/kg/3.3 keV <sub>nr</sub> )	
	COSINE-100	DAMA/LIBRA
6.7~20	$0.0013 \pm 0.0027$	$0.00996 \pm 0.00074$

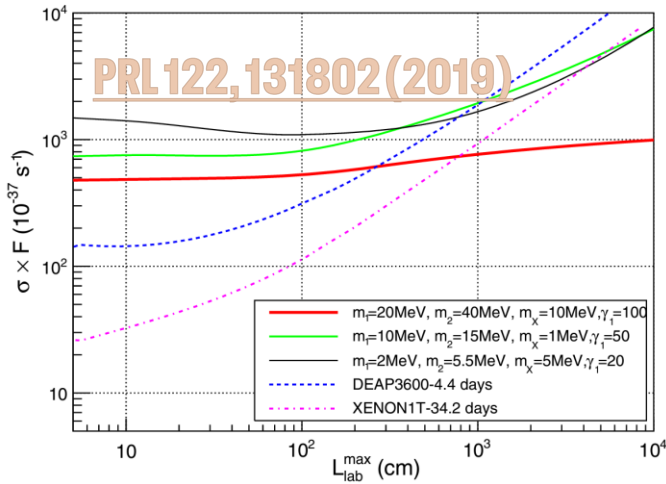


# No DAMA-like WIMPs in NaI(Tl) Spectrum

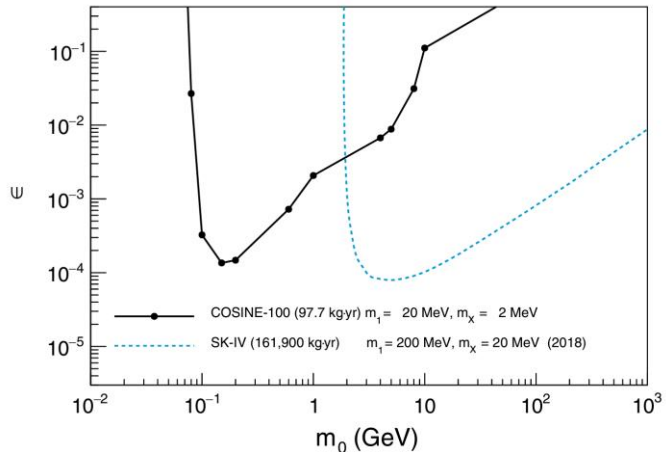


# No Dark Matter in NaI(Tl) Data

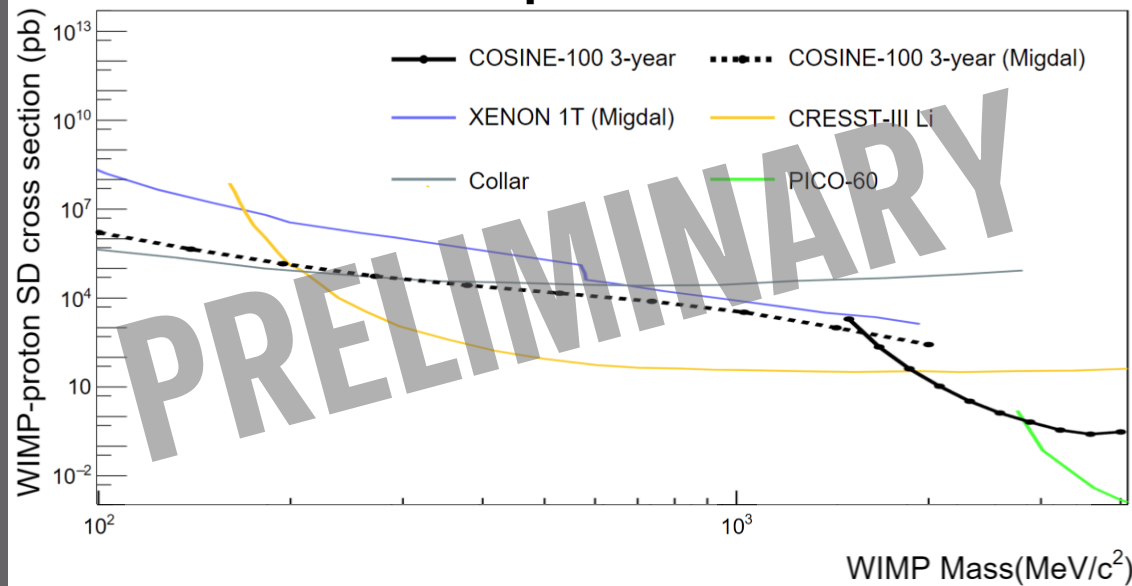
## DM Boosted from GC



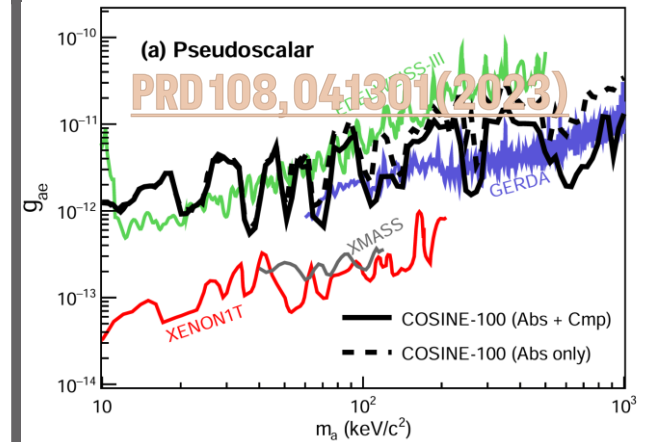
## PRL 131,201802 (2023)



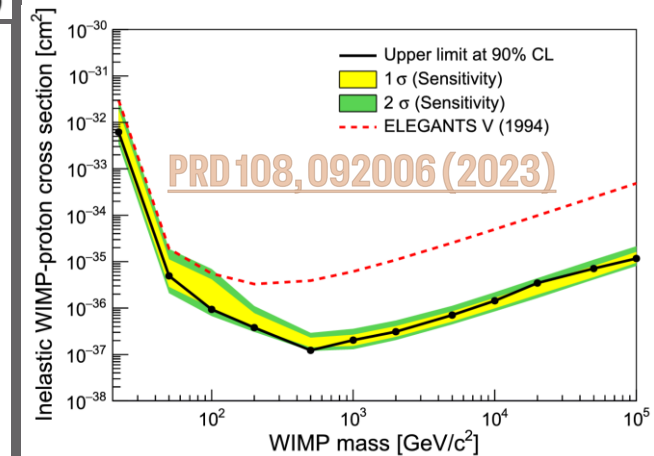
## Low Mass WIMP-proton SD Interaction



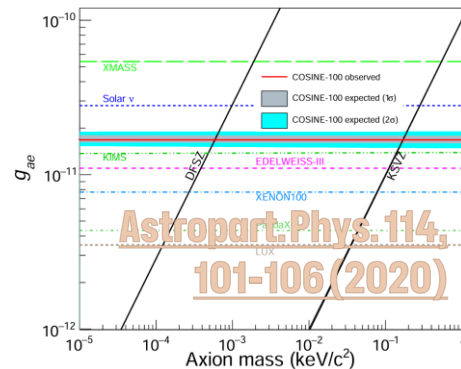
## Bosonic Super WIMP



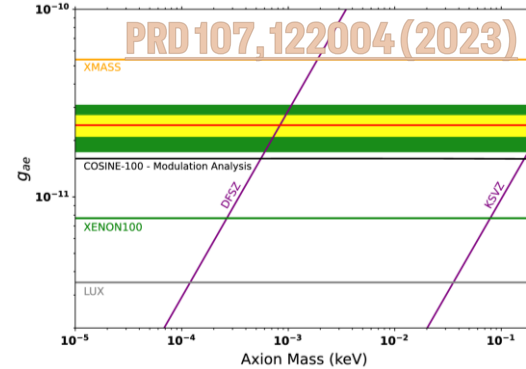
## WIMP-Iodine Inelastic Scattering



## Solar Axion



## Solar Bosonic Particles



# *COSINE-100 Upgrade*

**Lower Threshold**

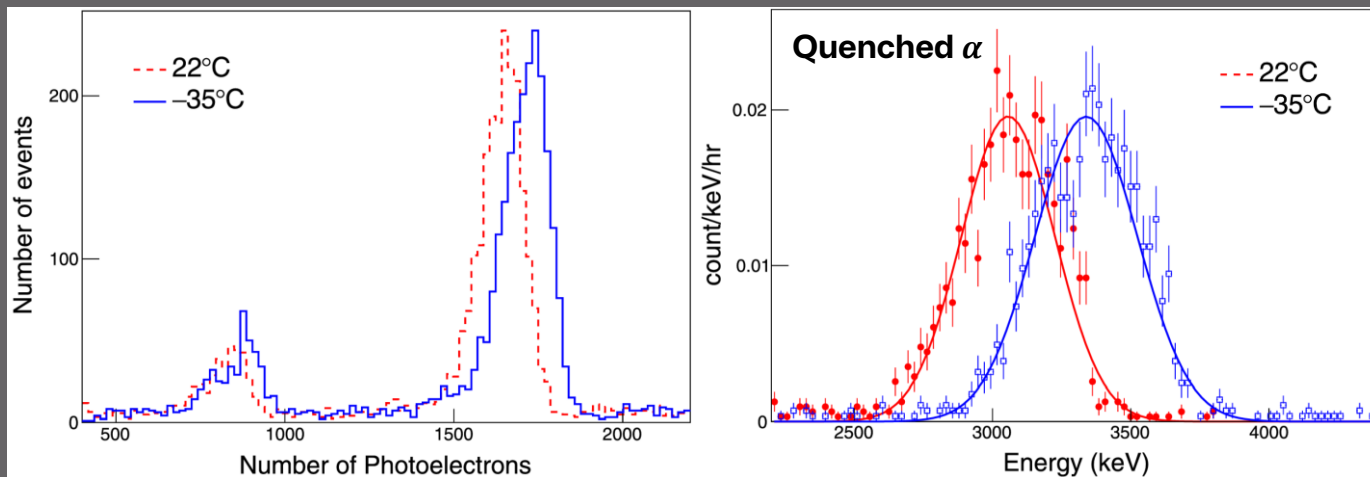
**New Deeper Site**

## Lower Threshold

New Deeper Site

Operation at  $-35^{\circ}\text{C}$

Astropart. Phys. 141102709 (2022)



Light yield +5%

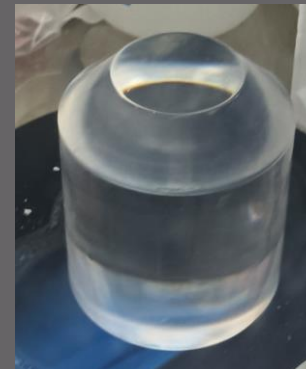
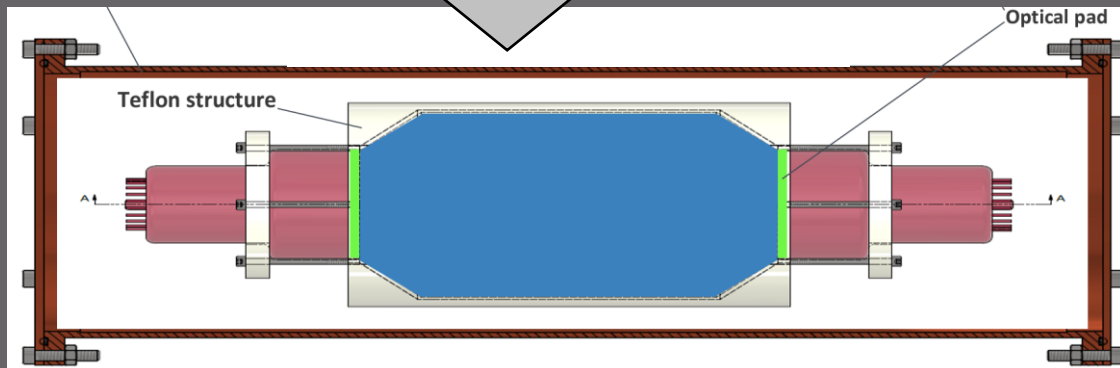
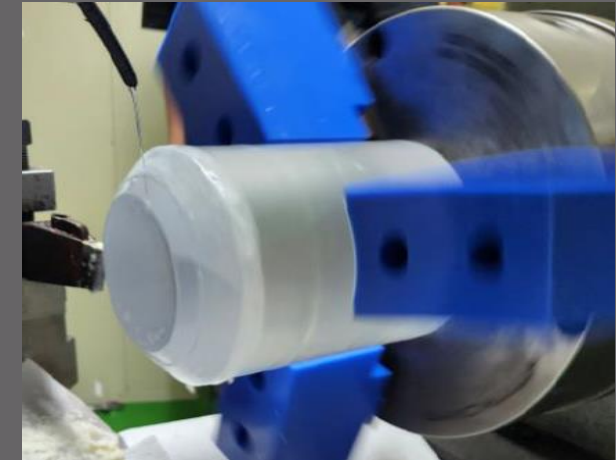
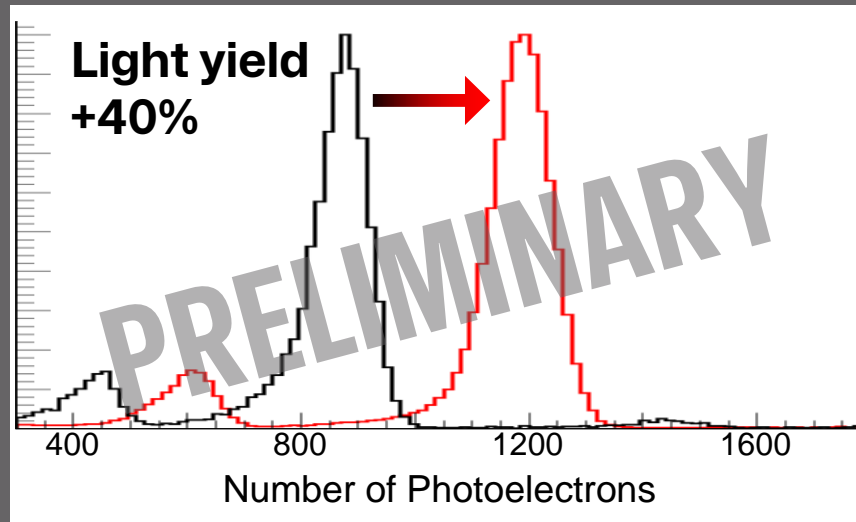
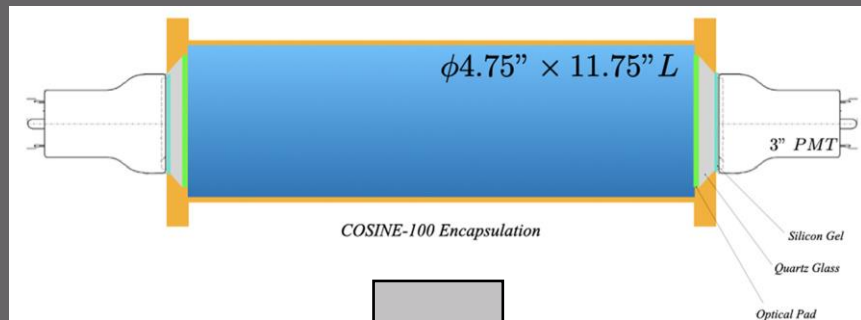
Quenching factor +9%

## Lower Threshold

New Deeper Site

Minimal Encapsulation

NIMA 981,164556 (2020), arXiv:2404.03691



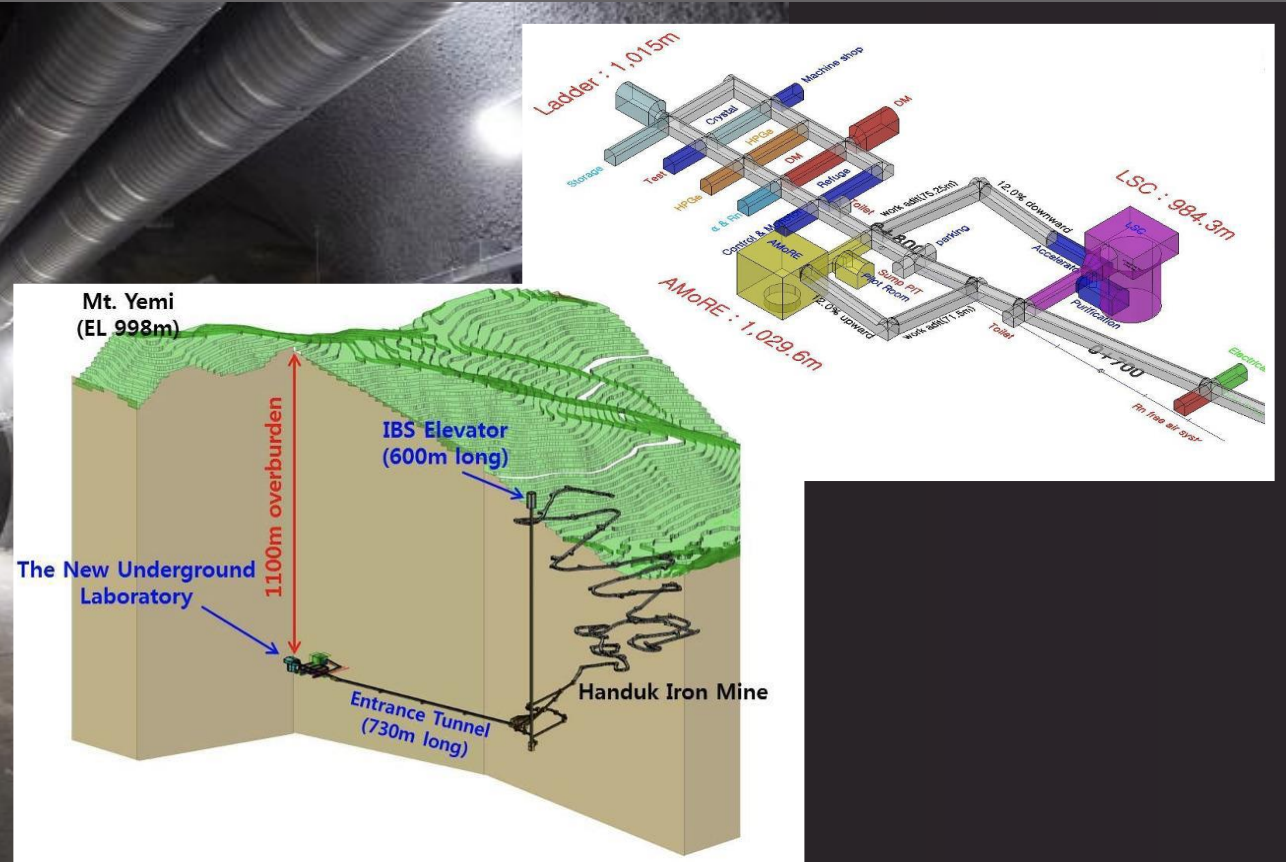
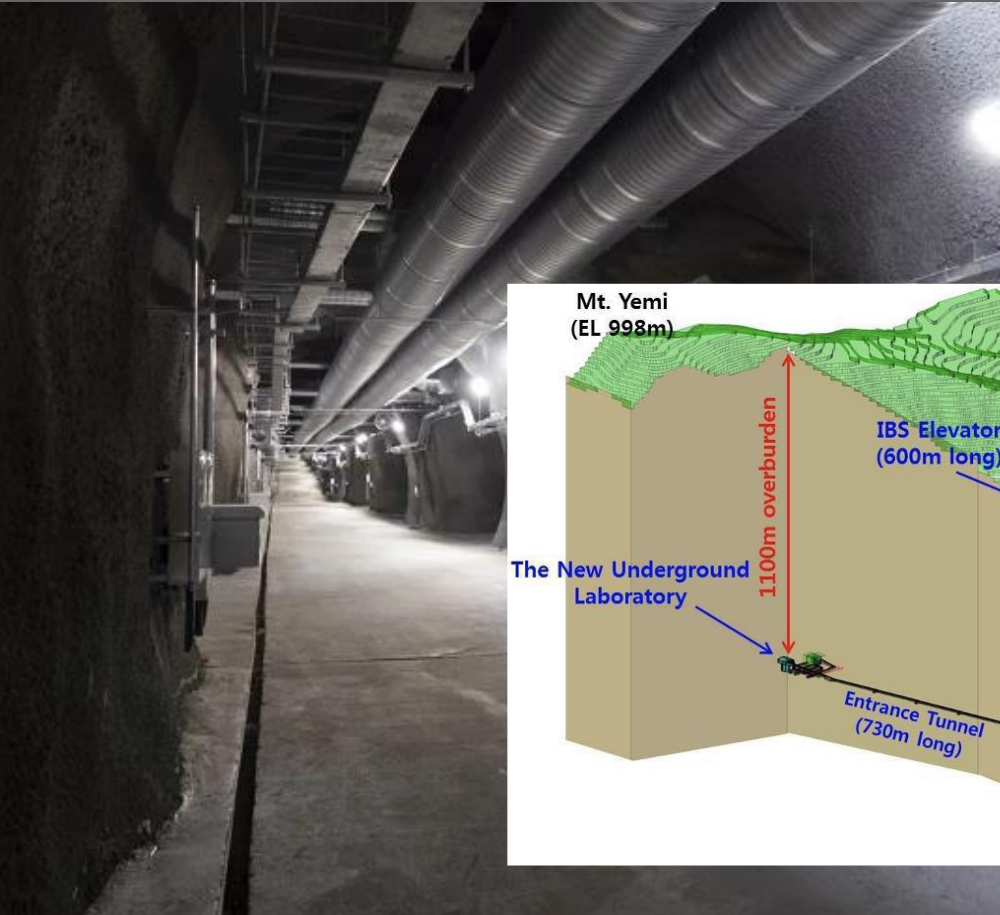


# COSINE-100 Upgrade

Lower Threshold

## New Deeper Site; Yemilab

Front. Phys. 12:1323991. (2024)

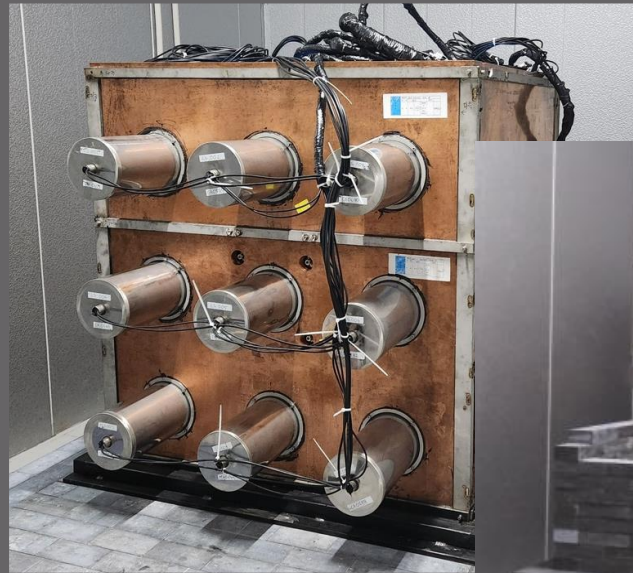


Nature News

# *COSINE-100 Upgrade*

**Lower Threshold**

**New Deeper Site; Yemilab**



# COSINE-100 Upgrade

Lower Threshold

## New Deeper Site; Yemilab

	2024-04	2024-05	2024-06	2024-07	2024-08	2024-09 ~
Crystals		#4,7	#1, 6	Install & Test		Physics run!
Lead				TOP		
LS				Install		
Muon	Others			Install		
Hardware		Preparation	Install	Test		
Software	Preparation					



# Ultra-pure NaI(Tl) Development for COSINE-200

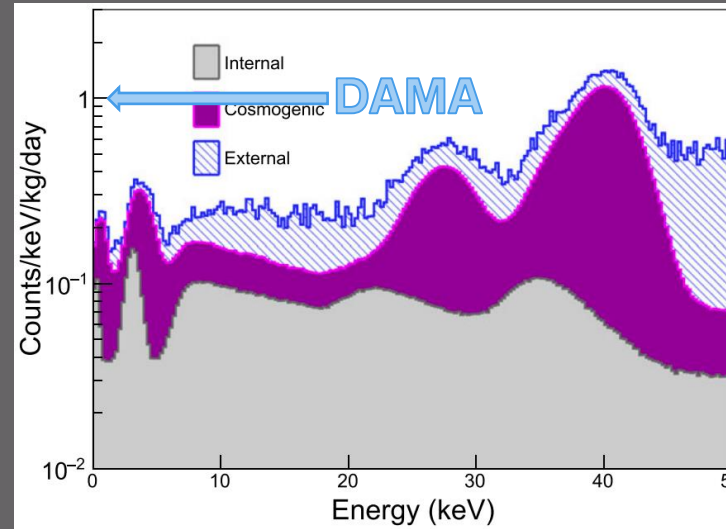
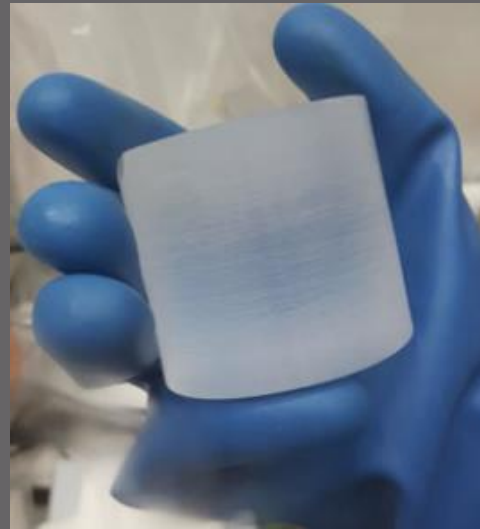
- 400 kg of ultra-pure NaI powder is ready.

- [J. Rad. Nucl. Chem. 317, 1329 \(2018\), JINST 15, C07031 \(2020\)](#)
- [EPJC 80, 814 \(2020\), Front. Phys. 11, 1142849 \(2023\)](#)

- We grew 0.7 kg of crystal with 0.2 counts/day/kg/keV.

- Further R&D to grow large crystals within the safety regulation is ongoing.

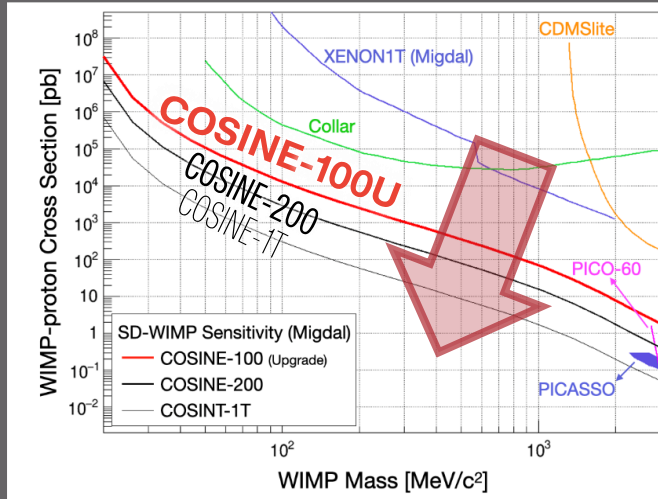
(ppb)	K	Pb	U	Th
Initial	248	19.0	<0.01	<0.01
Purified	<16	0.4	<0.01	<0.01



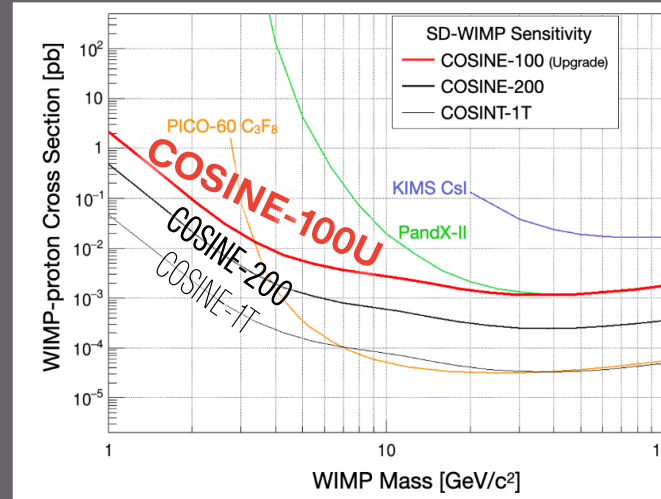
# COSINE-100 Upgrade & 200 Prospects

Spin Dependent

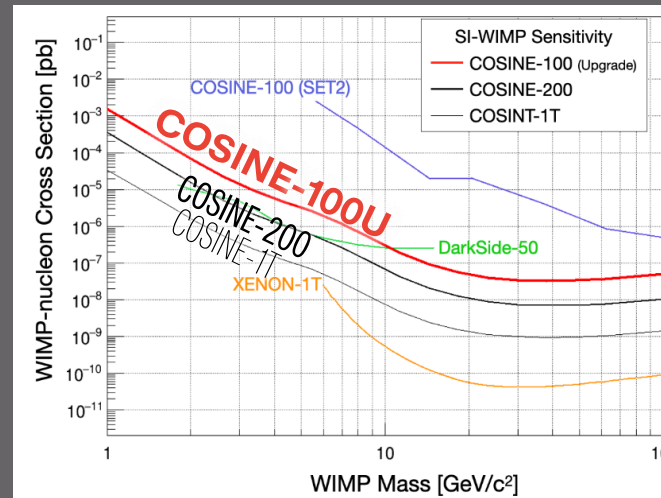
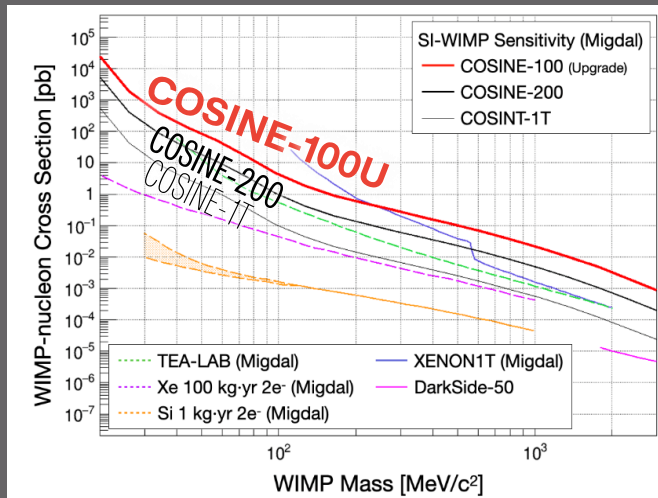
MeV Mass (with Migdal)



GeV Mass



Spin Independent



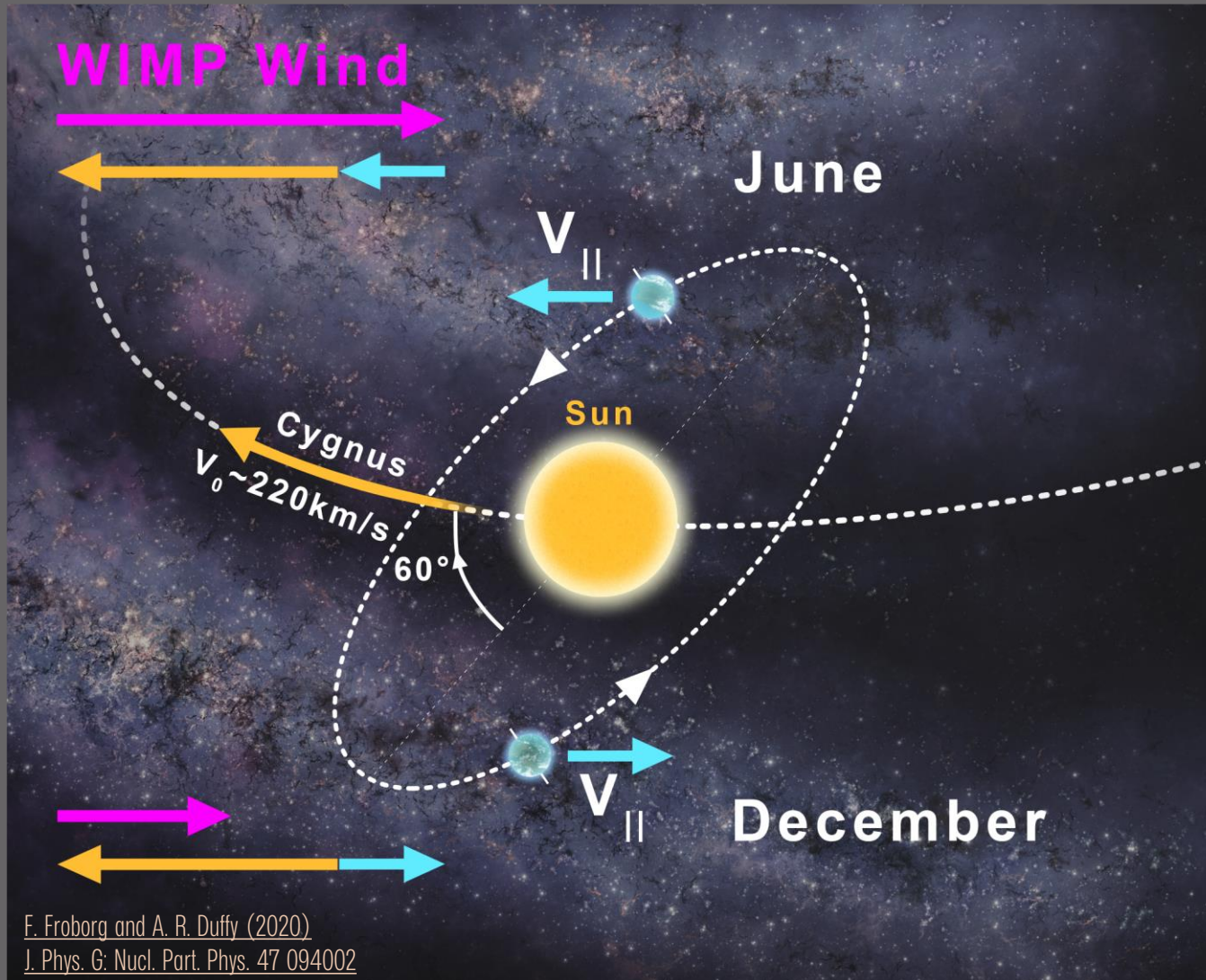




# BACK UP



# WIMP Standard Halo Model and Annual Modulation



F. Froberg and A. R. Duffy (2020)  
J. Phys. G: Nucl. Part. Phys. 47 094002

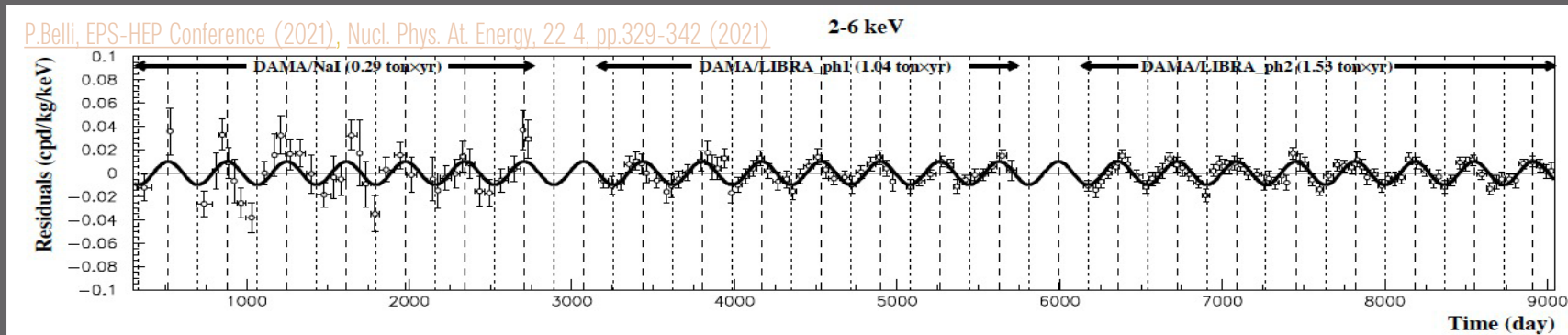
- If WIMP dark matter distribute spherically over the galaxy,
- The rotation of sun and earth makes the WIMP wind rate vary.
  - Period 1 year, maximum on 152.5 day.
- WIMP signal should have an Annual Modulation!

# Annual Modulation in DAMA Experiment

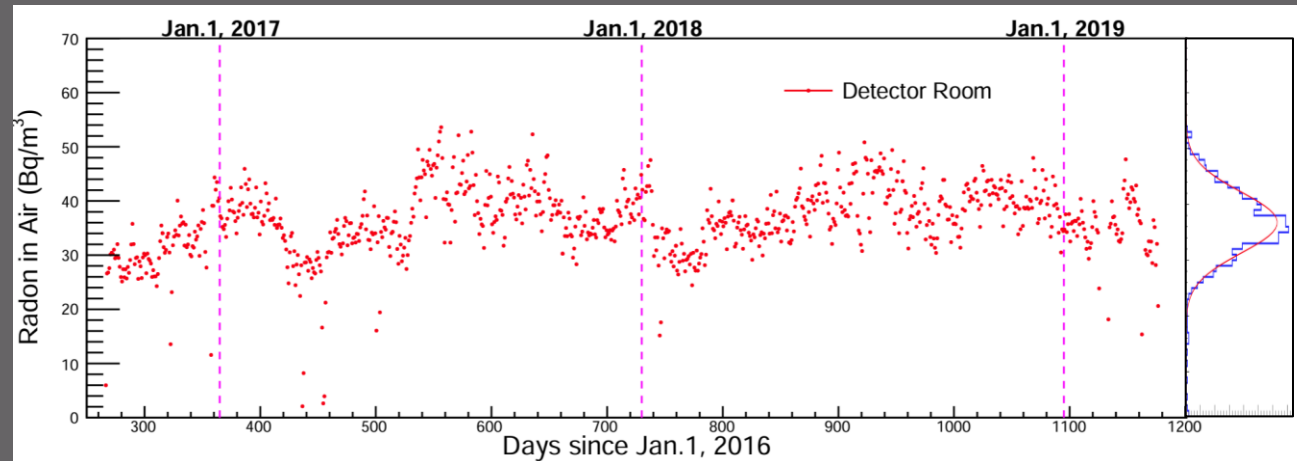
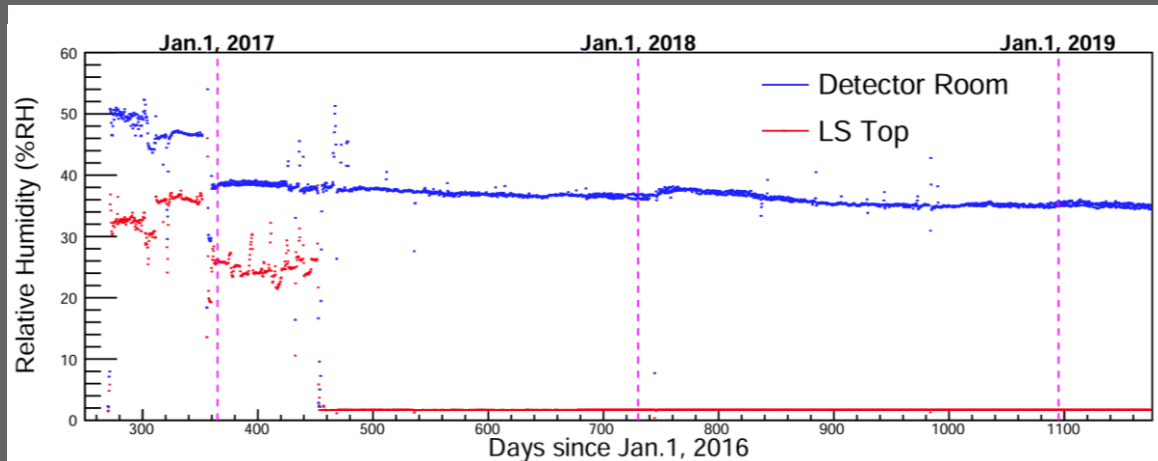
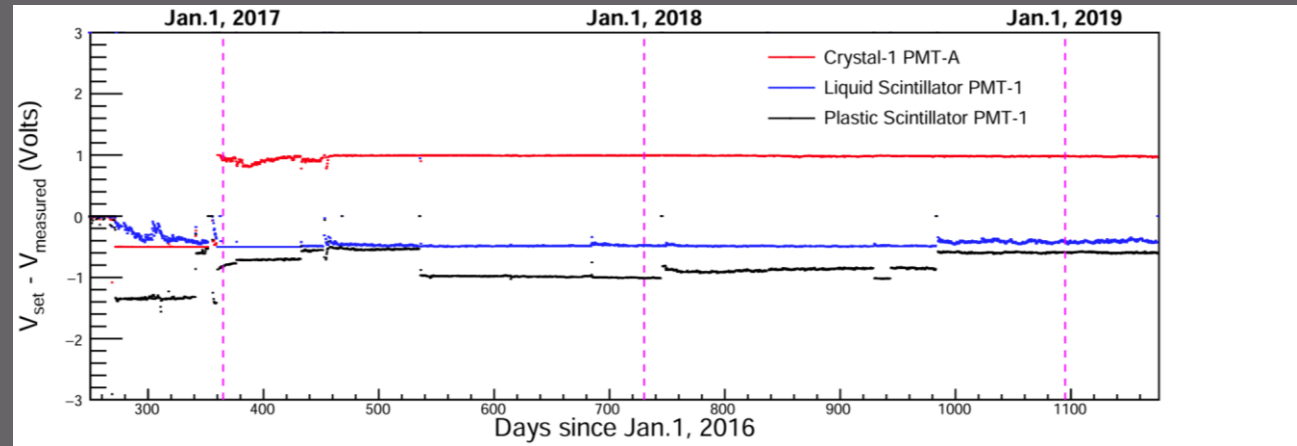
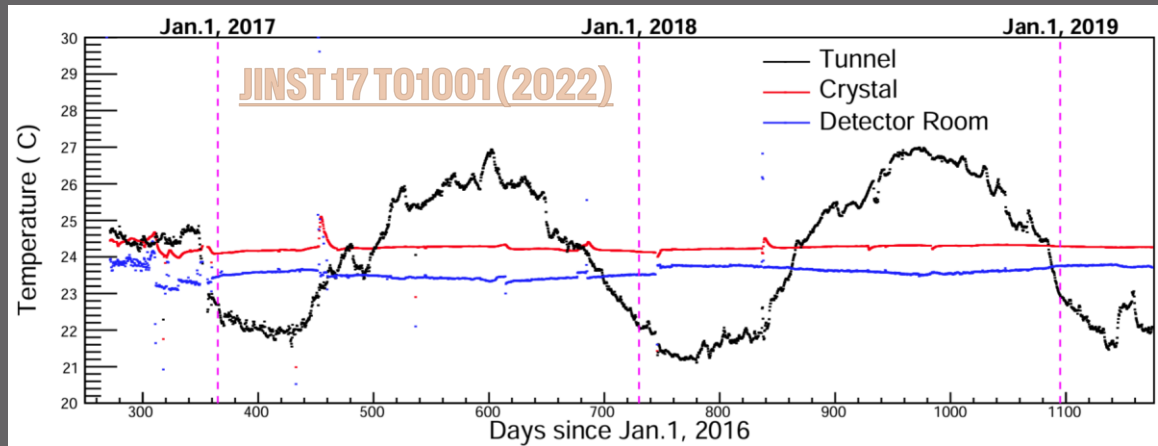


- DAMA detected the Annual Modulation!
- Using NaI(Tl) scintillator.

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



# Environment Stability





# Calibration for Testing DAMA's Claim

- If we interpret DAMA's signal as a Nuclear Recoil,
  - “the DAMA/LIBRA NaI(Tl) detectors are not the “same” as those of COSINE-100, since e.g. (...), they have different quenching factors for alpha's and nuclear recoils, etc.”
    - Quoted from DAMA's words, [SciPostPhys.Proc.12025\(2023\)](#) (Proceeding of IDM 2022).
- Then, let us consider the quenching factor difference.

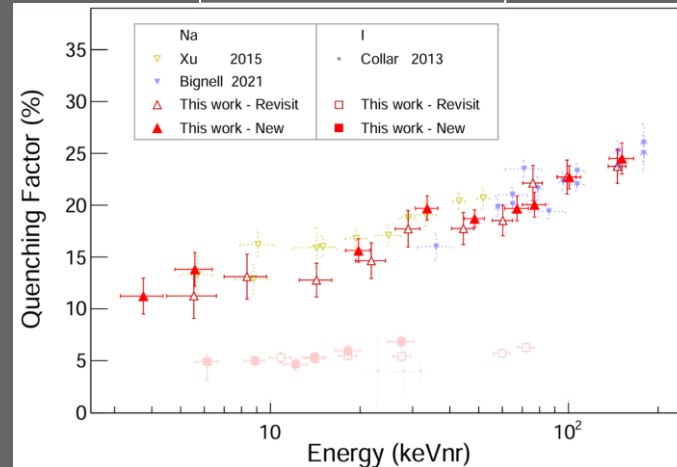
## DAMA QF

[Phys.Lett.B,389\(1996\)757](#)

The obtained quenching factors are 0.30 for Na and 0.09 for I respectively,

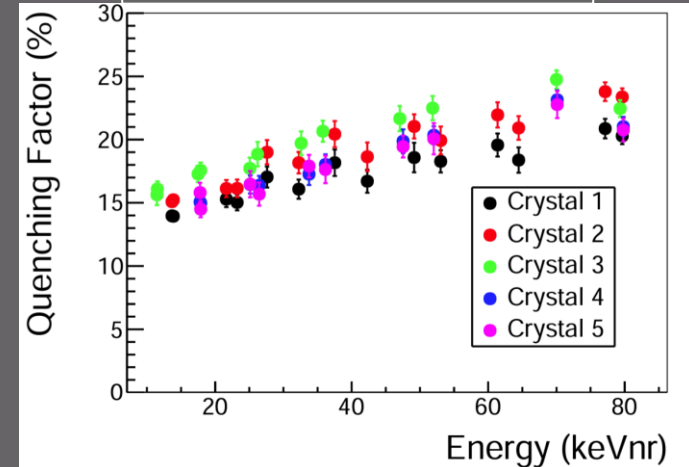
## COSINE QF

[arXiv:2402.15122\(PRC\)](#)



## COSINE & ANAIS QF

[arXiv:2402.12480\(PRC\)](#)



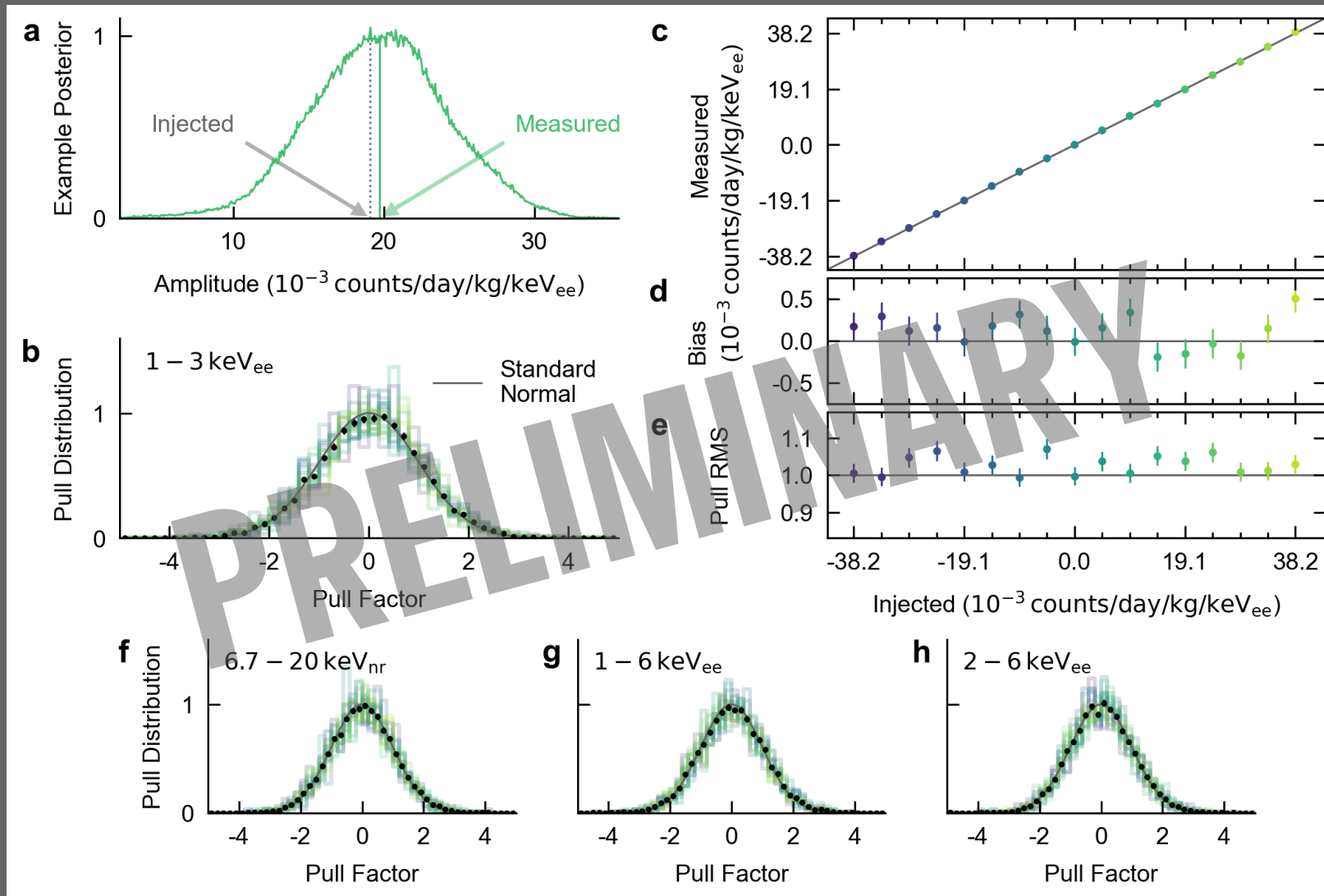
# Data and Statistical Model Detail

$$R_i(t_j) = \sum_k \alpha_{ik} e^{-\lambda_{ik} t_j} + A \cos\left(\frac{2\pi(t_j - t_0)}{T}\right)$$
$$N_{ij} = R_i(t_j) m_i \Delta E \Delta t \varepsilon_{ij}^{\text{Live}} \varepsilon_i^{\text{Selection}}, \quad D_{ij} \stackrel{\text{iid}}{\sim} \text{Pois}(N_{ij})$$

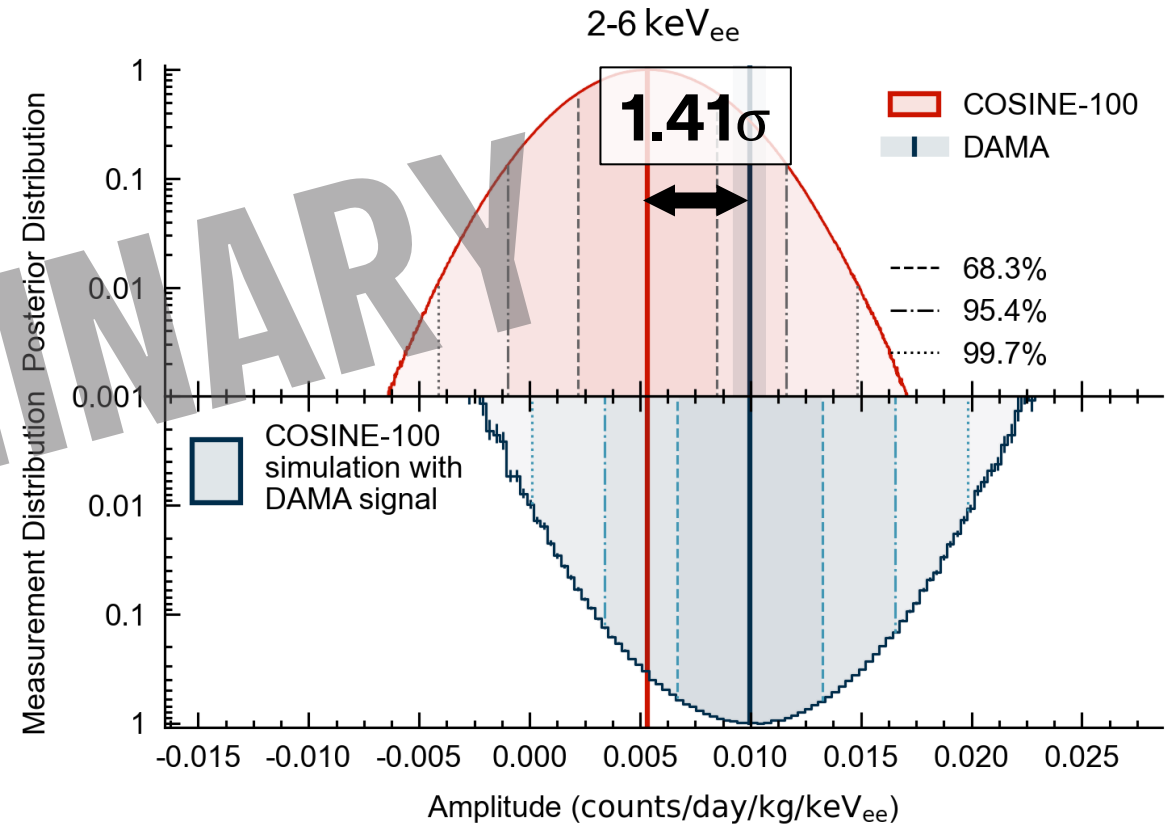
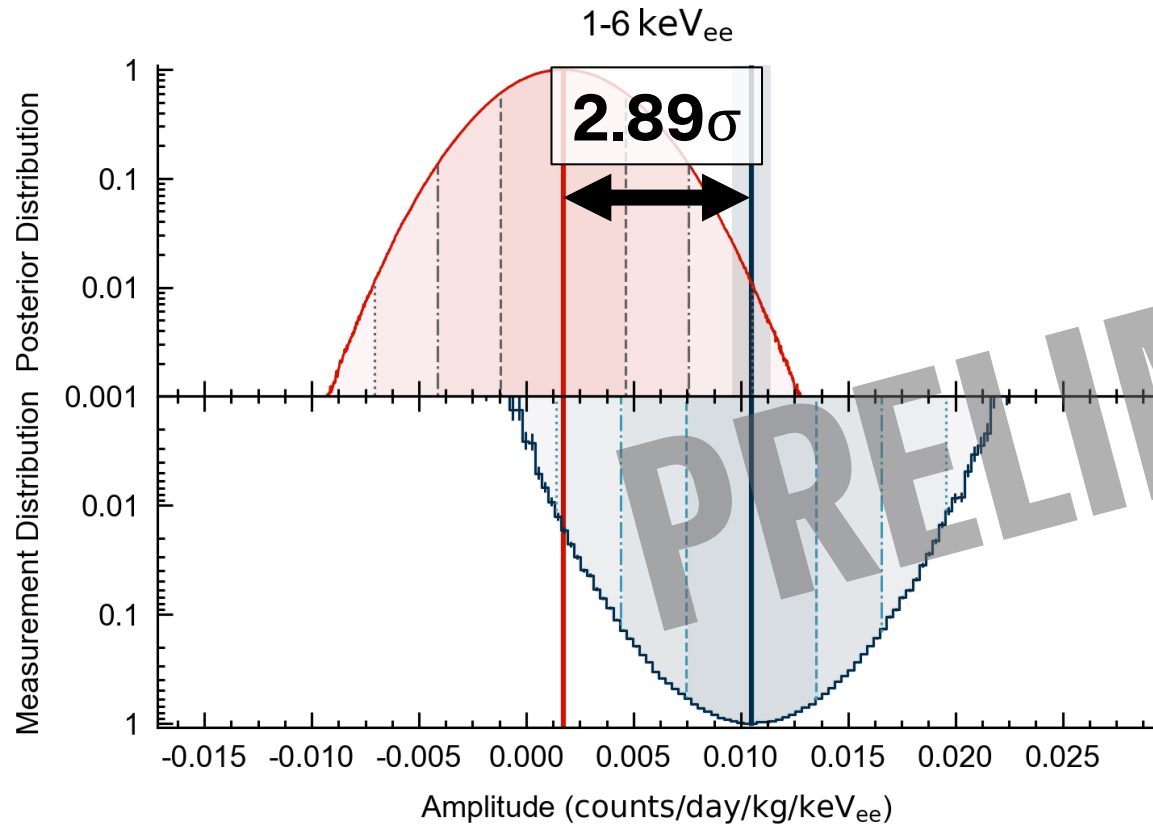
- [Indices] crystal  $i$ , time bin  $j$  (center  $t_j$ , width  $\Delta t$ ), radioactive component  $k$ .
- $\alpha_{ik}$ : initial activity for the  $k$ -th radioactive component.
- $\lambda_{ik}$ : decay constant for the  $k$ -th radioactive component.
- $\varepsilon_{ij}^{\text{Live}}$ : live time efficiency for that time bin.
- $\varepsilon_i^{\text{Selection}}$ : event selection efficiency.
- $A$ : amplitude of the modulation signal.
- $t_0$ : phase of the modulation signal.
- $T$ : period of the modulation signal.
- $m_i$ : mass of crystal  $i$ .
- $\Delta E$ : width of the energy ROI.

Constrained by  
Background Model

# Pseudo Experiment Shows No Bias

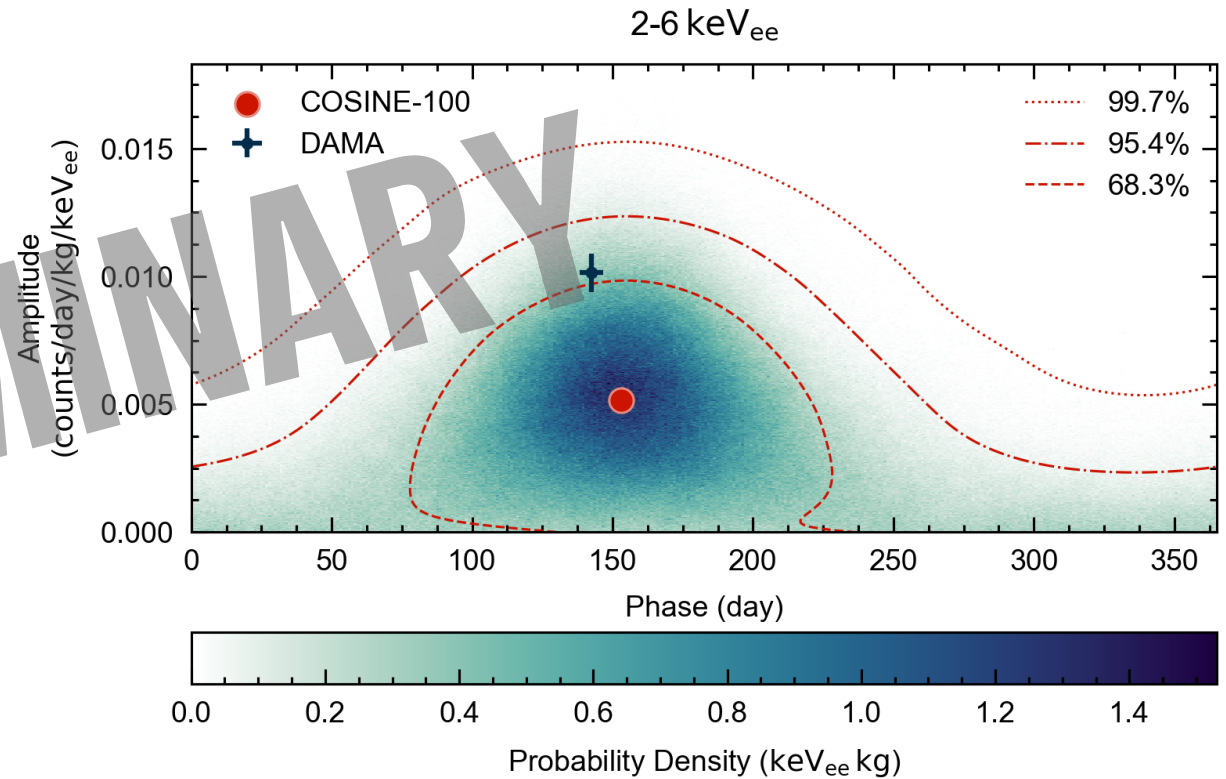
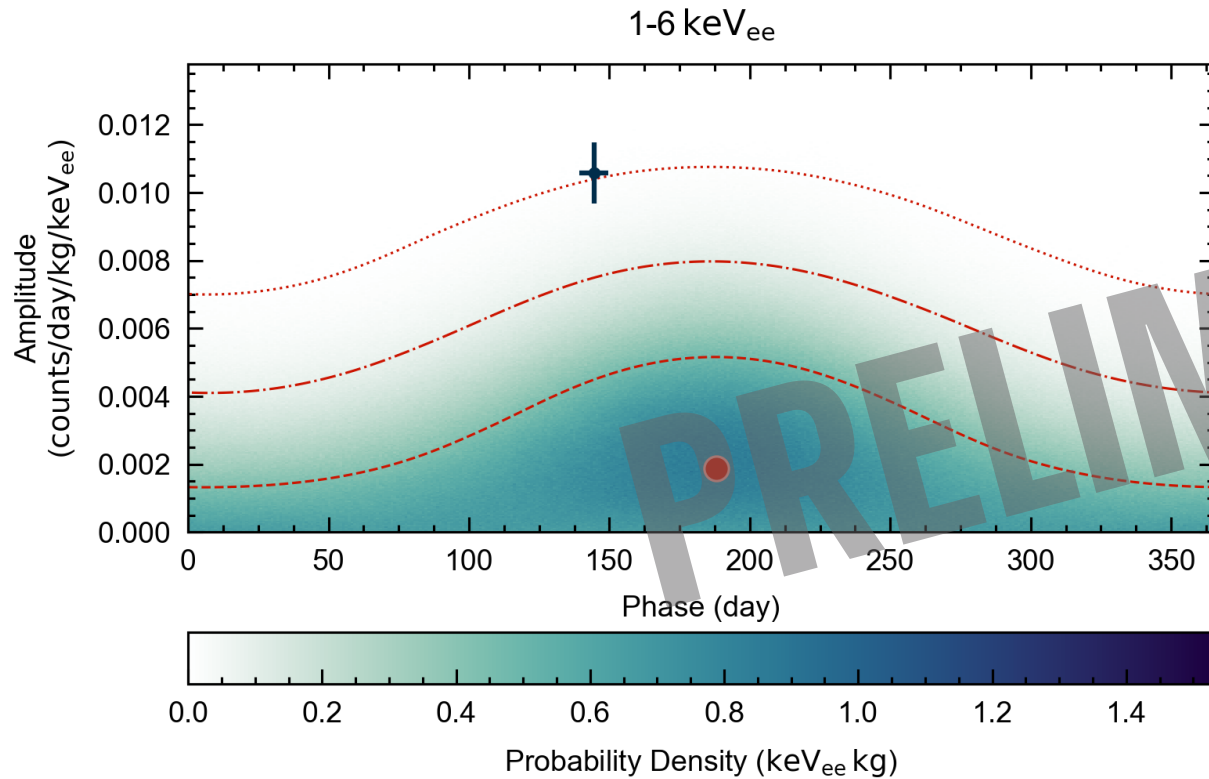


# No Modulation Detected





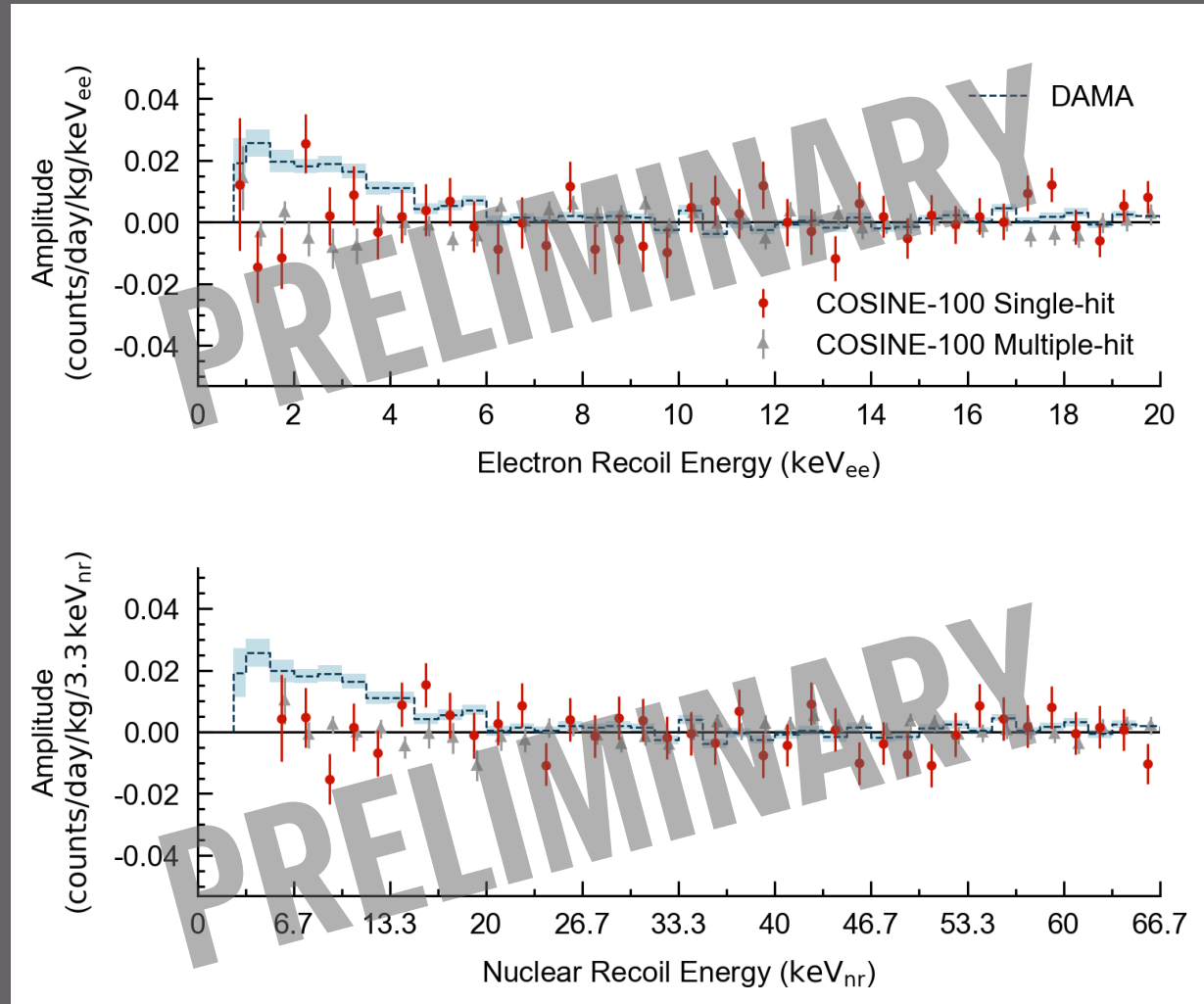
# No Modulation Detected



# No Modulation Detected

Data	Energy (keV <sub>ee</sub> )	Model	$\chi^2$	NDF	$p$ (%)
Multiple	0.75-20	Null	37.13	39	55.53
Single	6-20	Null	28.10	28	45.91
	0.75-6	Null	12.28	11	34.33
DAMA		28.03	11	0.32	

Data	Energy (keV <sub>nr</sub> )	Model	$\chi^2$	NDF	$p$ (%)
Multiple	5-66.7	Null	29.93	37	78.89
Single	20-66.7	Null	20.57	28	84.28
	5-66.7	Null	11.26	9	25.86
DAMA		30.67	9	0.03	



**END**