arXiv:2603.22411

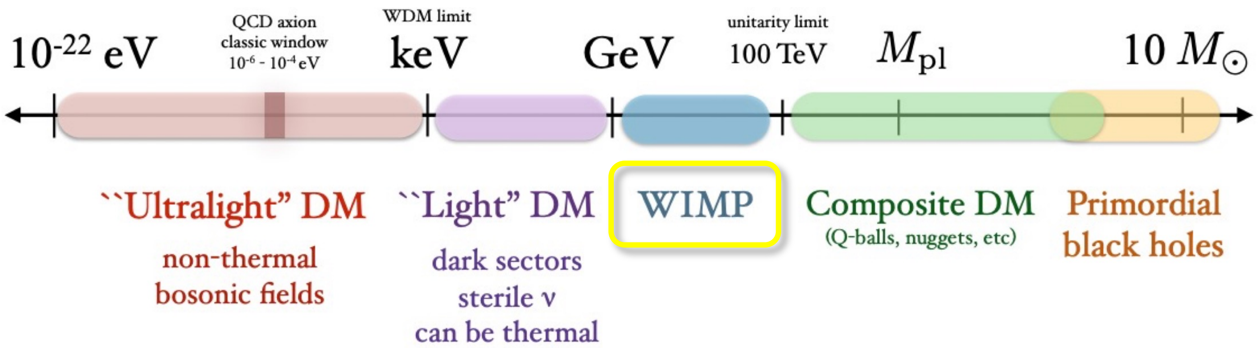
Pioneering Sub-GeV Dark Matter Limits with COSINE-100

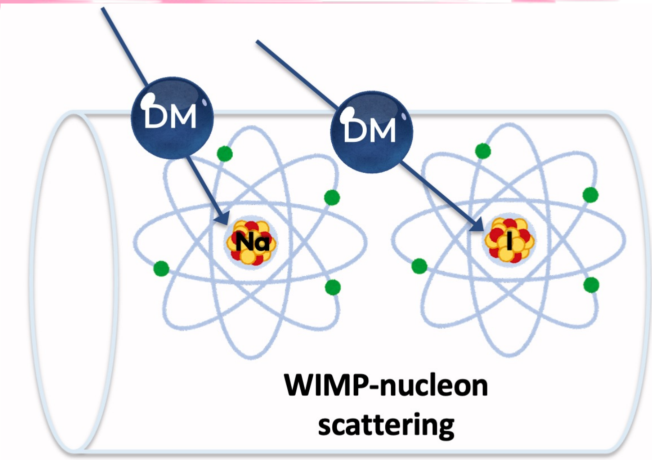
IDM2026
ZARAGOZA

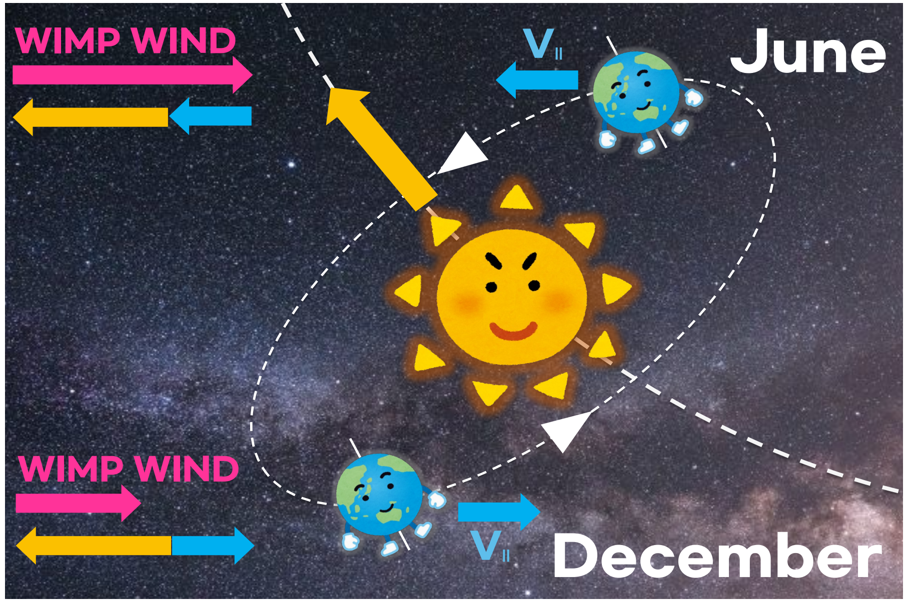
Won Kyung Kim[1,2]
On behalf of the COSINE collaboration

[1] IBS School, University of Science and Technology (UST), Daejeon, Republic of Korea
[2] Center for Underground Physics, Institute for Basic Science, Daejeon, Republic of Korea

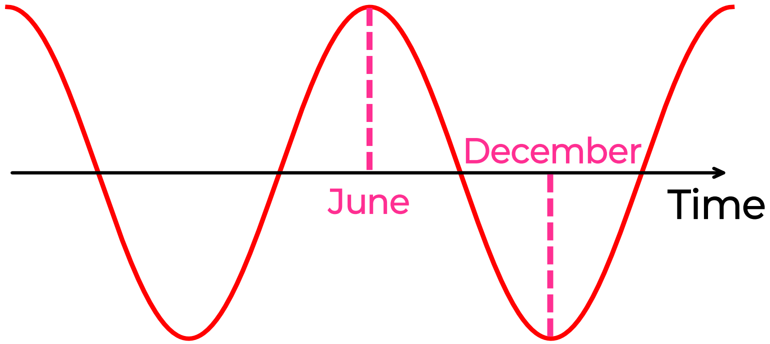
Dark Matter Landscape







$$\text{Event Rate}: \frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi}\int_{v_{\min}}^{v_{esc}} \frac{d\sigma}{dE_{nr}} v f(v) dv$$



- Assume the standard halo model (SHM), where the DM velocity follows Maxwell-Boltzmann distribution.
- Change of velocity leads to two observational sequences (Annual modulation).

Dark Matter Interactions

➤ WIMP—nucleus scattering cross-section

2019 *J. Phys. G: Nucl. Part. Phys.* **46** 103003

$$\frac{d\sigma}{dE_{\rm nr}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_{\rm SI} F^2_{\rm SI}(E_{\rm nr}) + \sigma_{\rm SD} F^2_{\rm SD}(E_{\rm nr})\right]$$

$F_{\rm SI,SD}$: Form factor
$S(|\vec{q}|)$: nuclear spin structure function
A : mass number
Z : atomic number

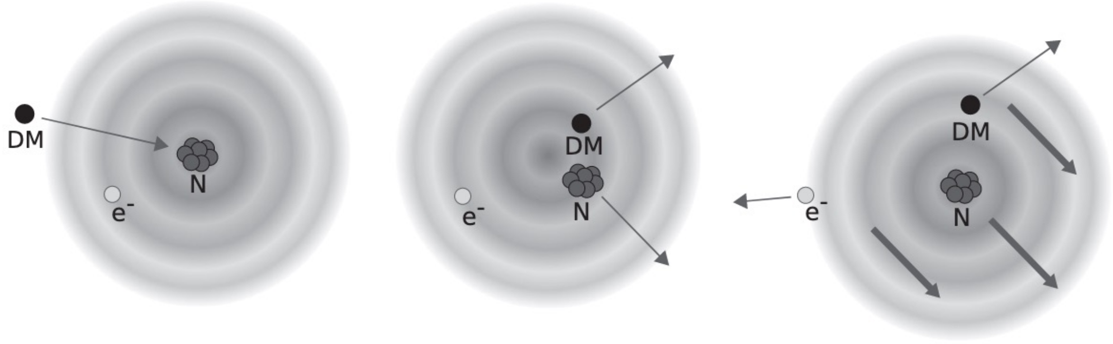
➤ Spin-independent

$$\sigma_{\rm SI} = \sigma_n \frac{\mu^2}{\mu^2_{n\chi}} \frac{[f_p Z + f_n (A-Z)]^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu^2_{n\chi}} A^2$$

➤ Spin-dependent

$$\frac{d\sigma_{\rm SD}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}\frac{S(|\vec{q}|)}{S(0)}$$

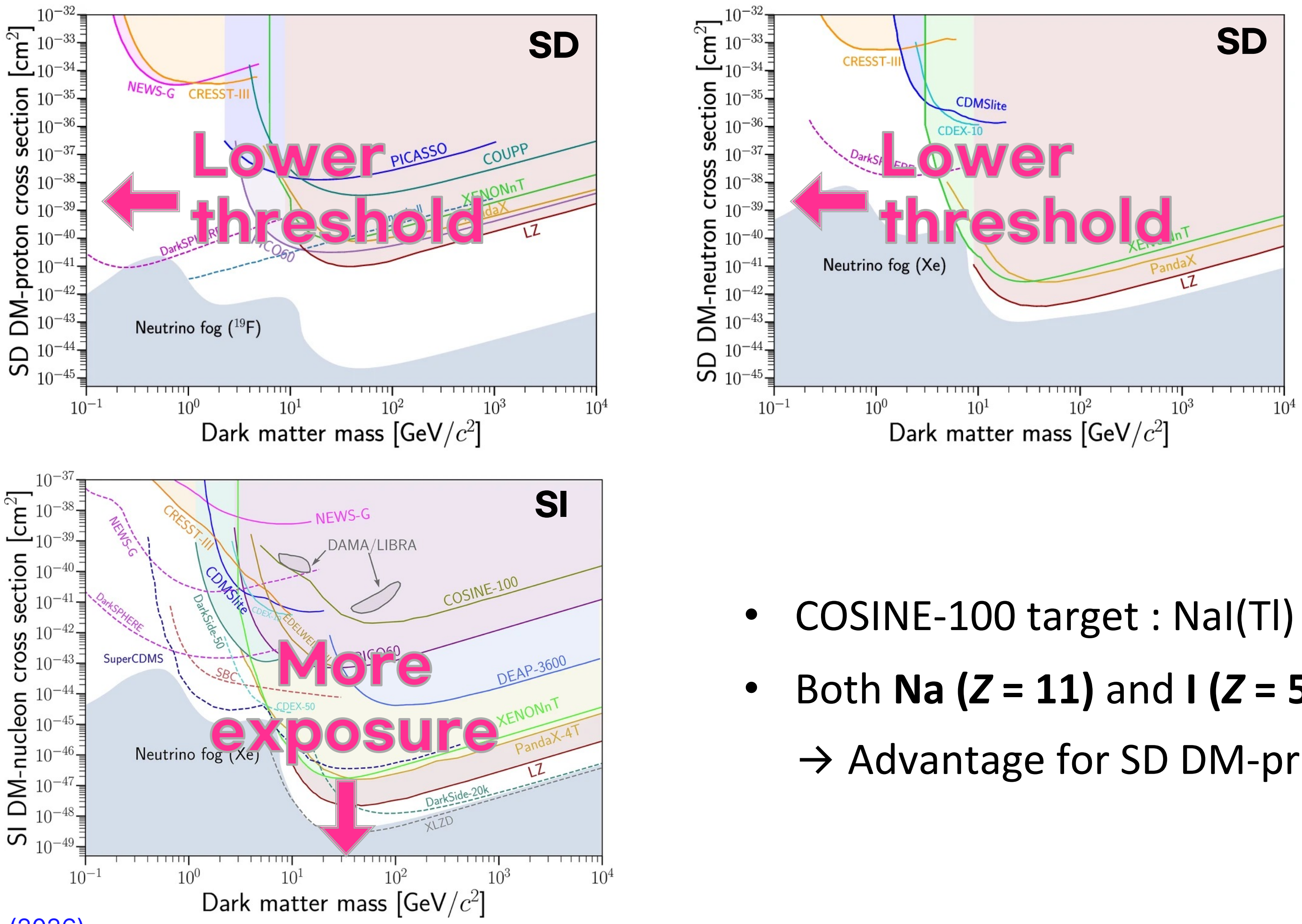
➤ Migdal effect



Phys. Rev. Letter **121**, 101801 (2018)

- When a nucleus recoils suddenly, the electron cloud cannot follow the motion instantaneously. This can lead to ionization/excitation of bound electrons.

Search for Lighter Dark Matter

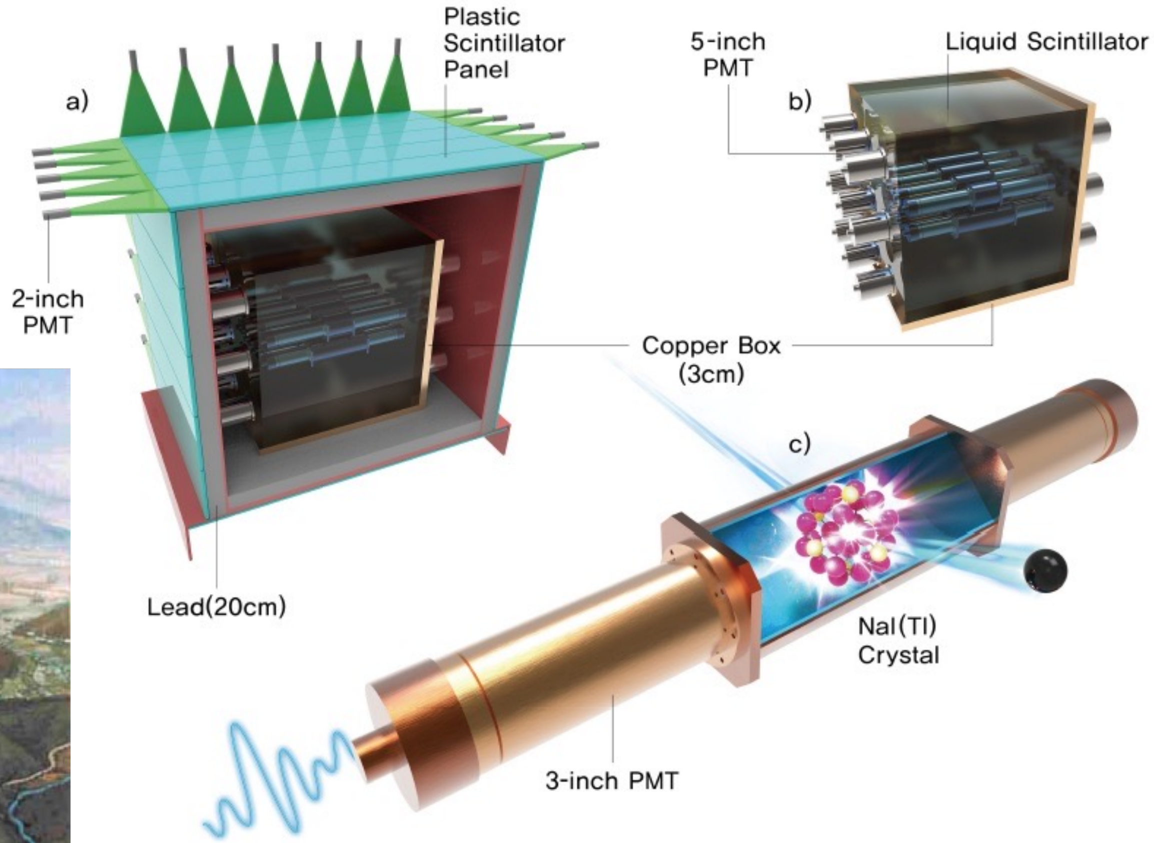


Communication Physics **9**, 105 (2026)

- COSINE-100 target : NaI(Tl)
- Both **Na (Z = 11)** and **I (Z = 53)** has **odd proton**
  → Advantage for SD DM-proton search

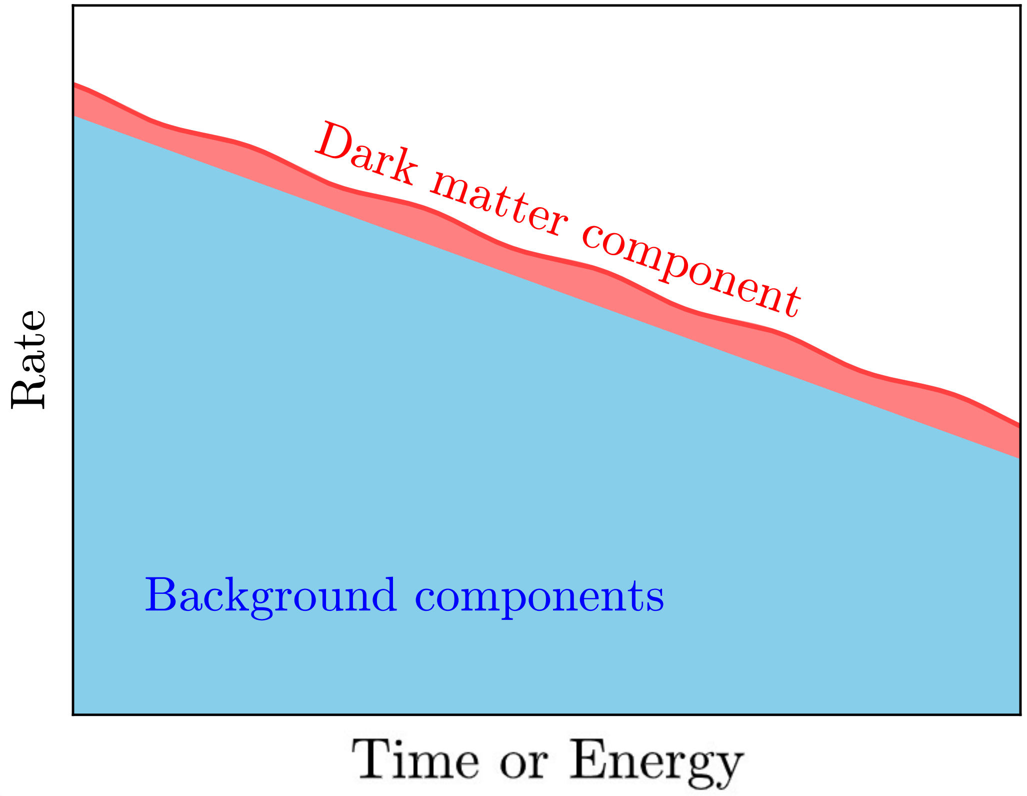
COSINE-100 Experiment

- At Yangyang underground laboratory, data taking since September 10 2016 until March 14 2023 (~6.5 years).
- Data collected from crystals, liquid scintillators, plastic scintillators.



- Target material : 8 low-background NaI(Tl) crystals
- Total mass : 106 kg
- Light yield : 15 photoelectrons(NPE)/keV

COSINE-100 Analysis

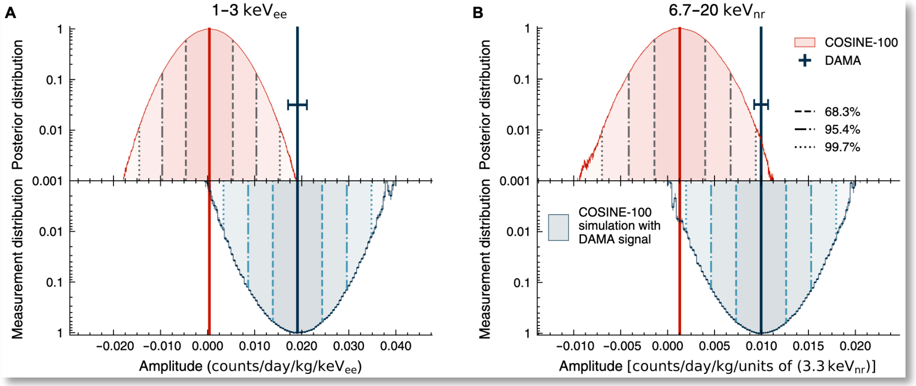


➢ COSINE-100 main analysis **(threshold = 0.49 keV)** :

1. Event Selection (Signal/Noise separation).
2. Background modeling (simulation) and mitigation.
3. WIMP analysis.

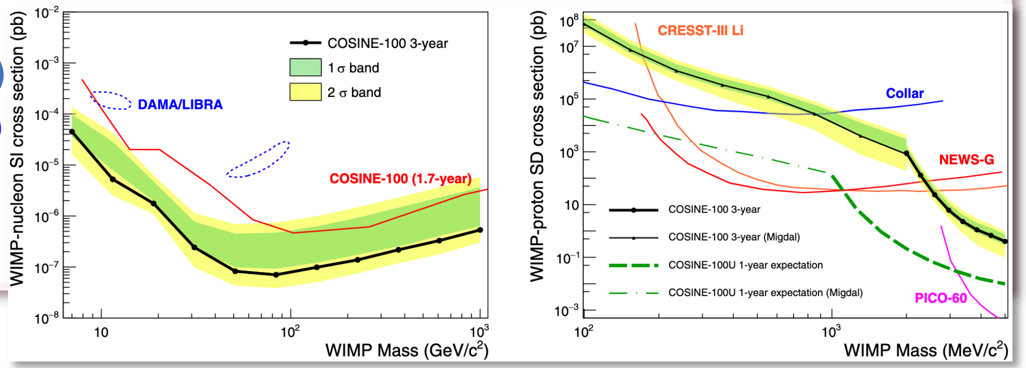
❖ **Annual modulation search to claim DAMA/LIBRA's result**

Sci. Adv. **11**, eadv6503 (2025)

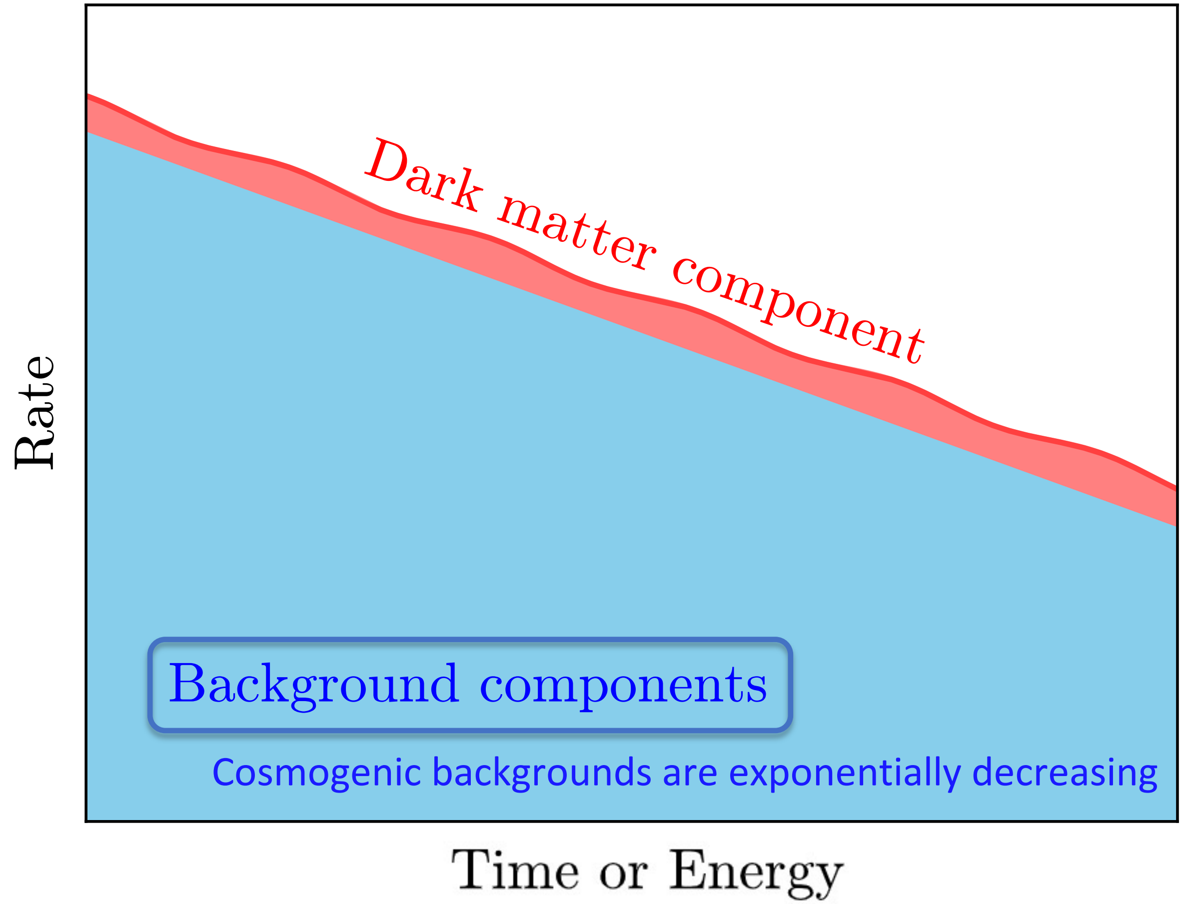


❖ **WIMP extraction analysis (WIMP-nucleon cross-section)**

Phys. Rev. Lett. **135**, 231001 (2025)



COSINE-100 Analysis



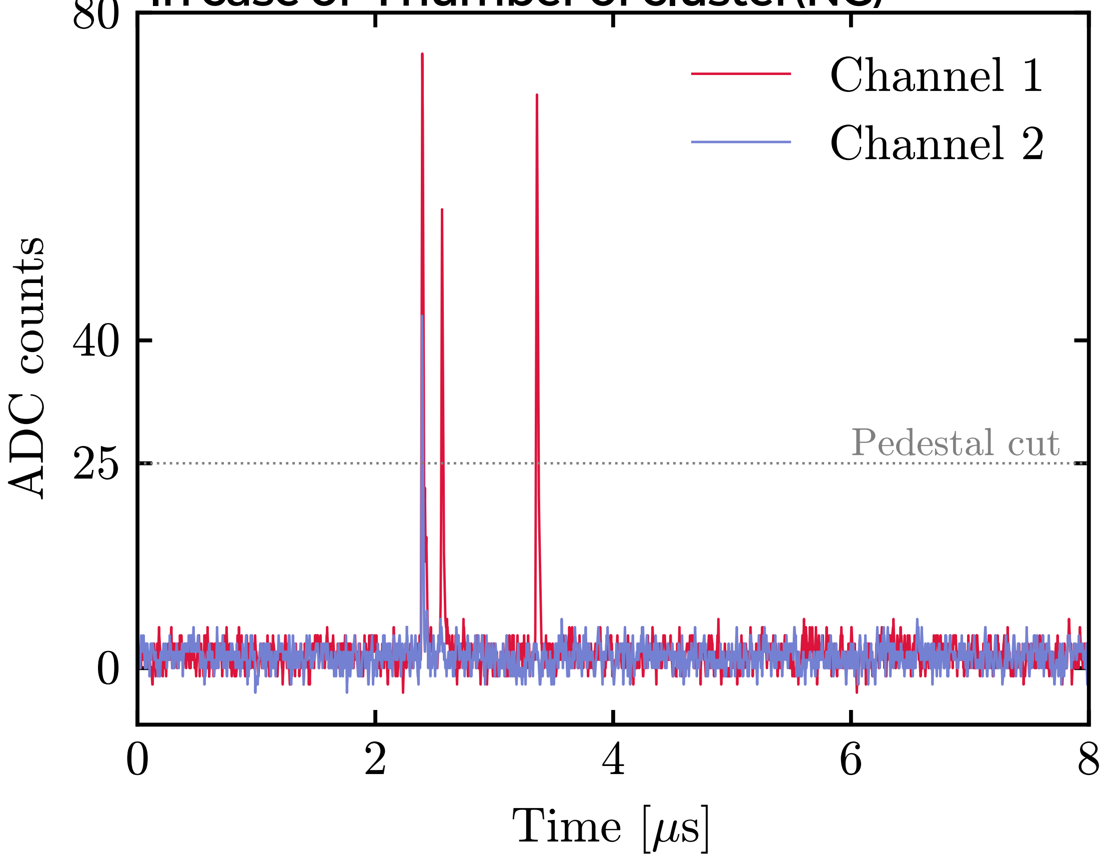
- COSINE-100 main analysis (threshold = 0.49 keV) :
  1. Event Selection (Signal/Noise separation).
  2. Background modeling (simulation) and mitigation.
  3. WIMP analysis.
- In this study (threshold < 0.4 keV) :
  1. Event Selection (Signal/Noise separation).
  2. Phenomenological background modeling with roughly single **exponential + constant**.
  3. WIMP analysis.

Even though low-threshold data contains significant noise events, we are going to use for low-mass DM search!

Analysis – Data Process

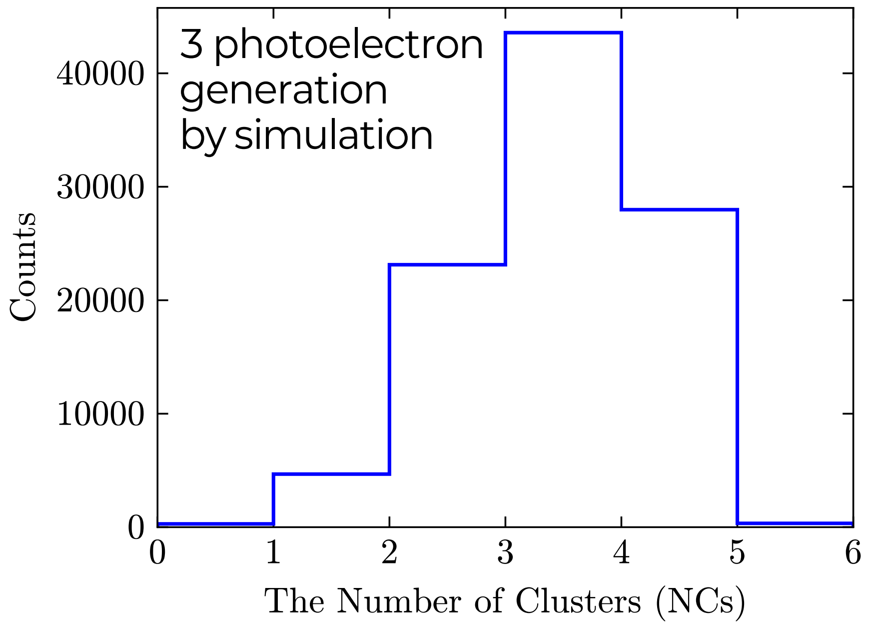
➢ Definition of Cluster

In case of 4 number of cluster(NC)



3- & 4-NC data were utilized for low-mass DM search

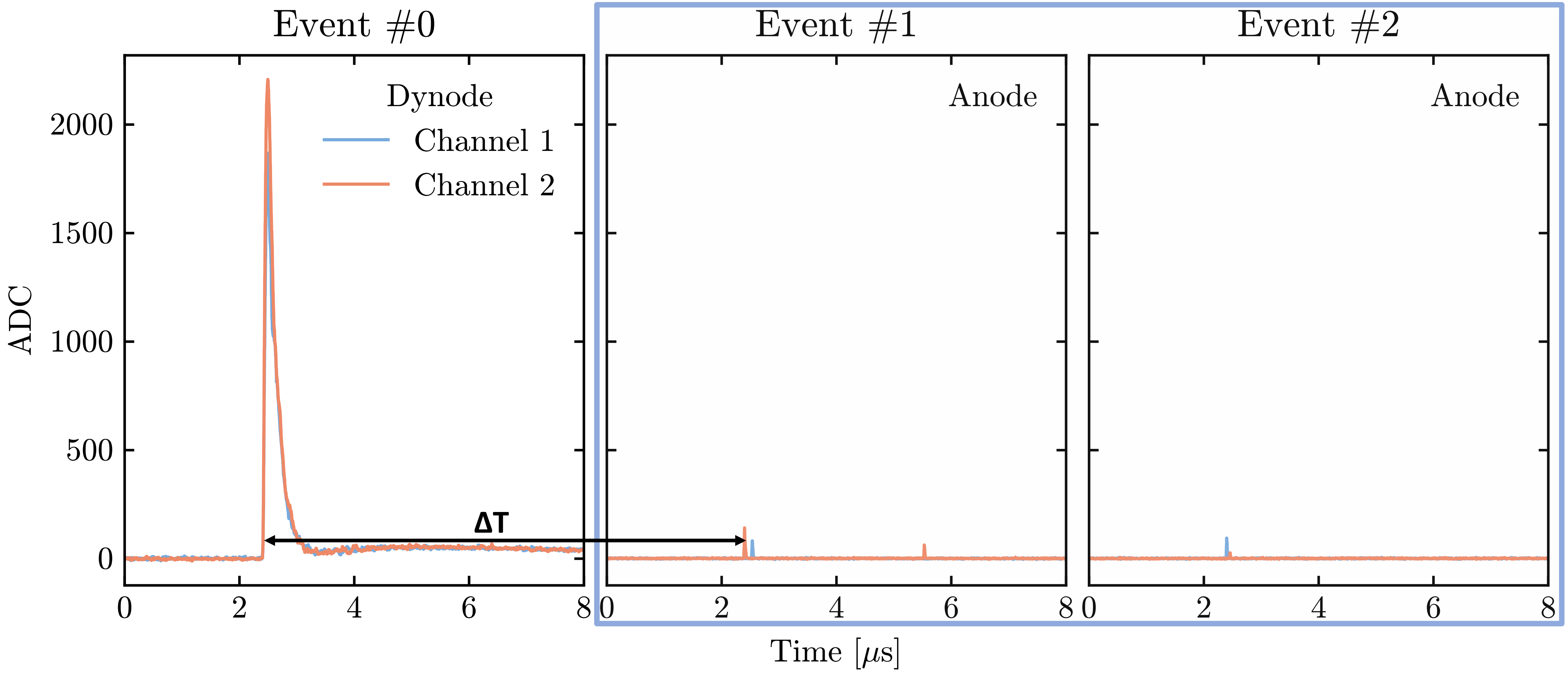
- Cluster : Isolated peak above the threshold
- COSINE-100 event trigger condition : 2 NC
- 1 NC ≈ 1 Photoelectron ≈ 0.067 keV
- Trigger efficiency : 62.5% for 3-NC and 81.0% for 4-NC



Analysis – Event Selection

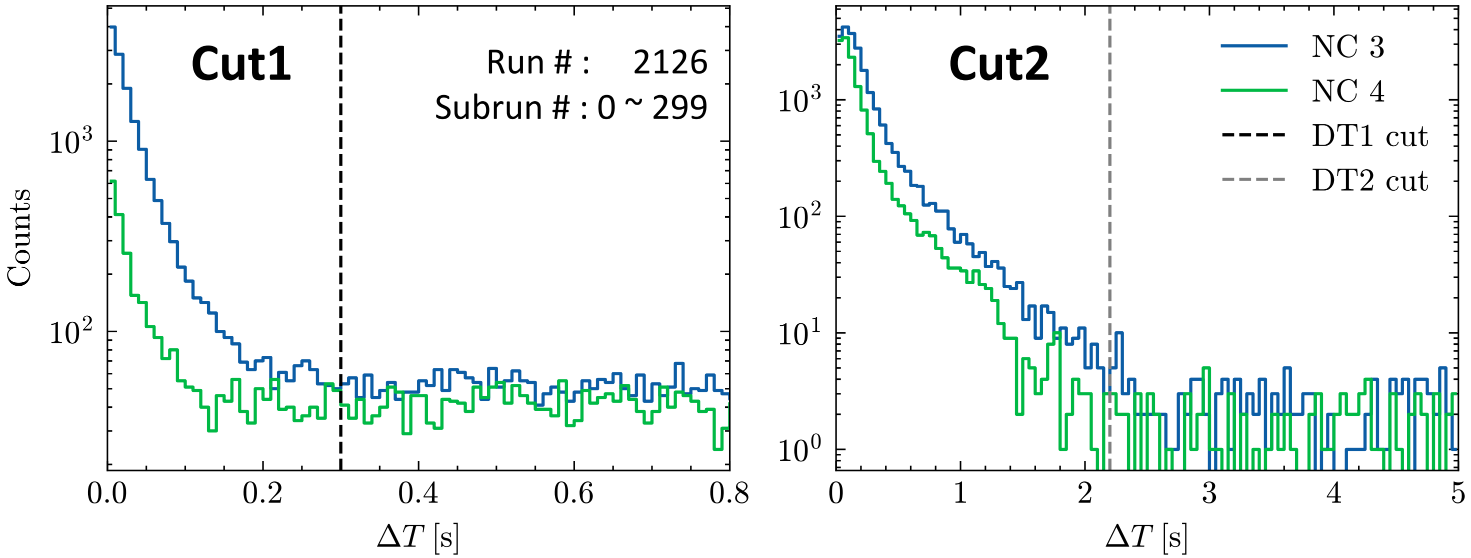
➢ **Deadtime cut**

Remove afterglow events



Analysis – Event Selection

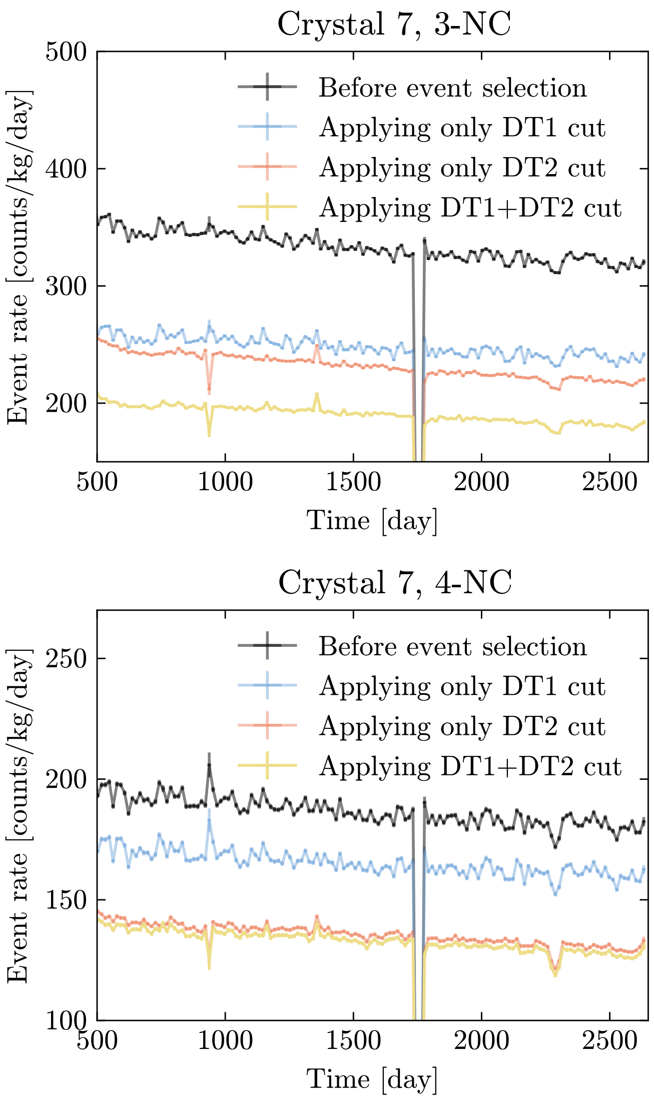
➢ Deadtime cut



Cut1 : Time difference between <u>1 MeV < Event < 3.2 MeV</u> and cluster.
Cut2 : Time difference between <u>3.2 MeV < (saturated) Event</u> and cluster.

- 97% signal efficiency (livetime)

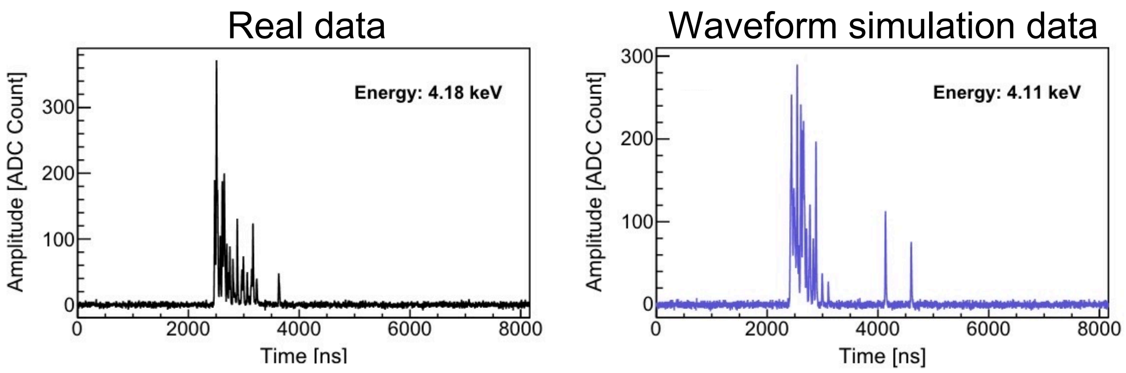
⟶ 5 crystals average 31.5% in 3-NC and 22.2% in 4-NC noise reduction.



Analysis – Event Selection

➢ **Multi-layer perceptron (MLP) for separation**

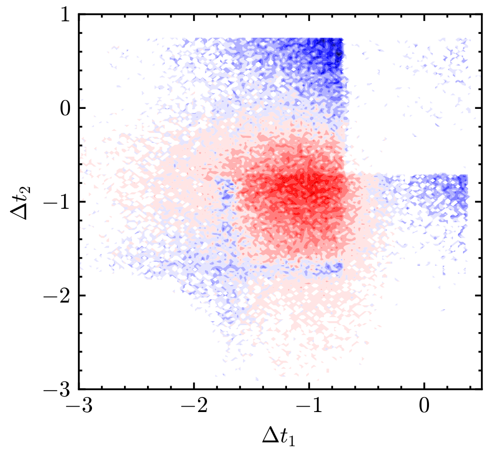
Nucl. Instrum. Methods Phys. Res. A **1065**, 169489 (2024)



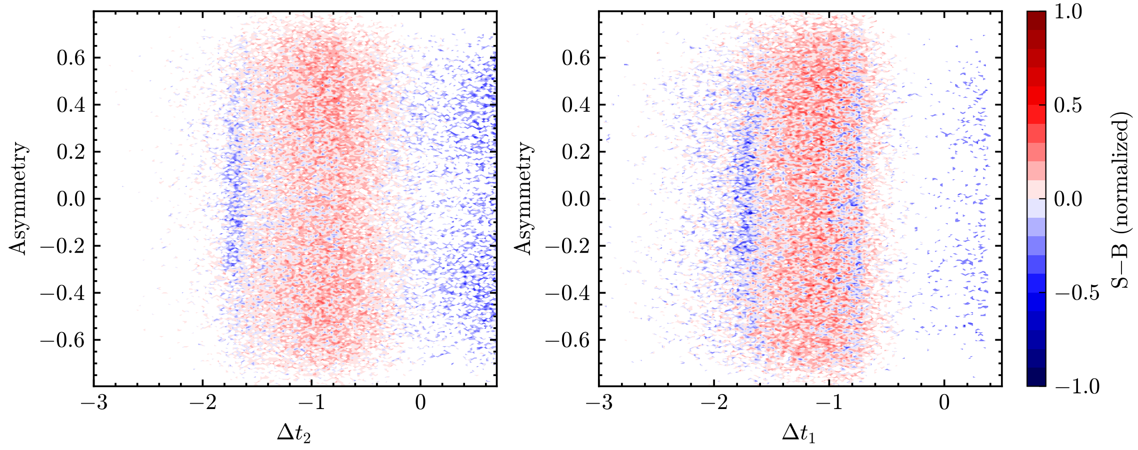
- Training Dataset :
  - Signal : Waveform simulation data
  - Background : Physics data

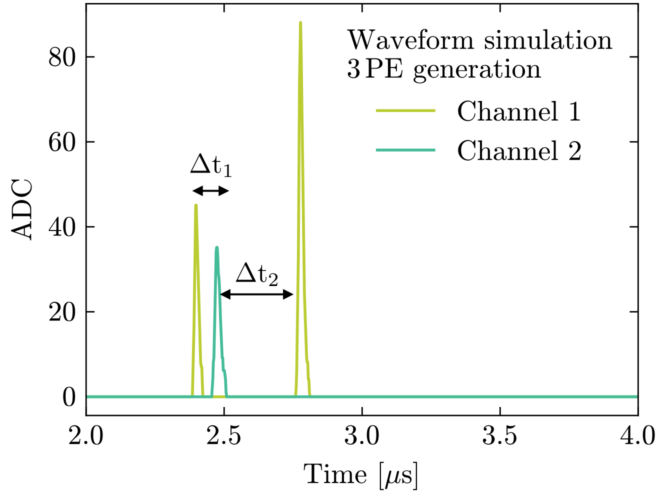
Analysis – Event Selection

➢ Multi-layer perceptron (MLP) for separation



3-NC



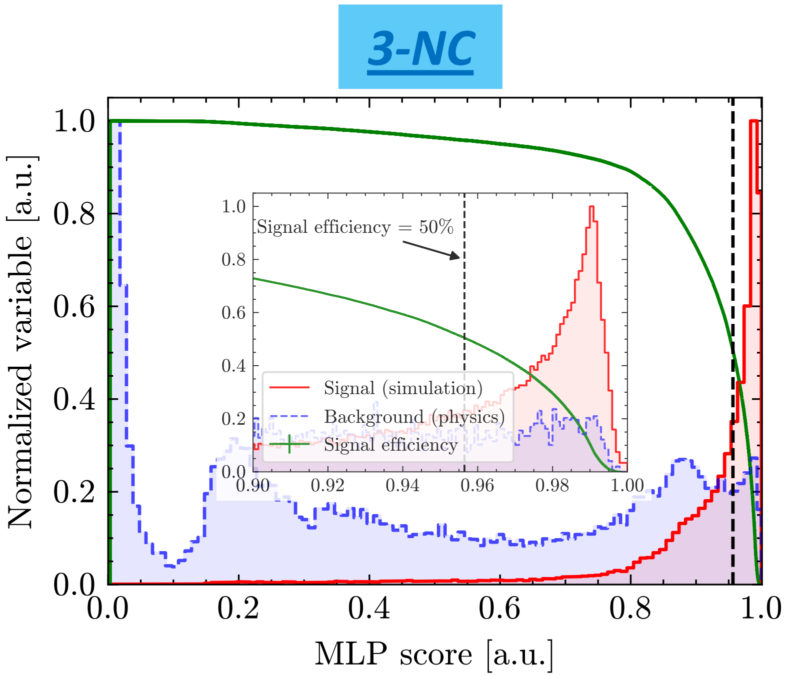


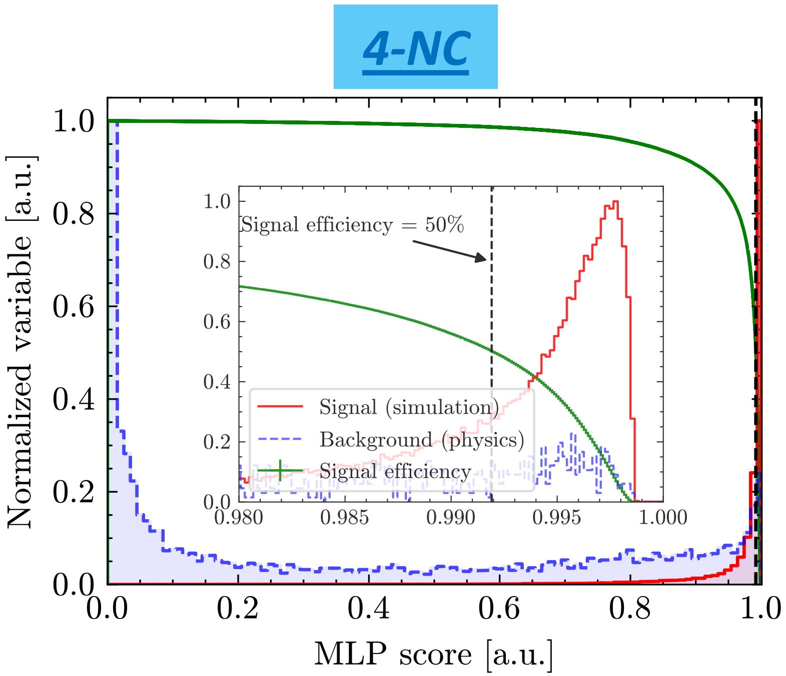
- Training Dataset :
  - Signal : Waveform simulation data
  - Background : Physics data

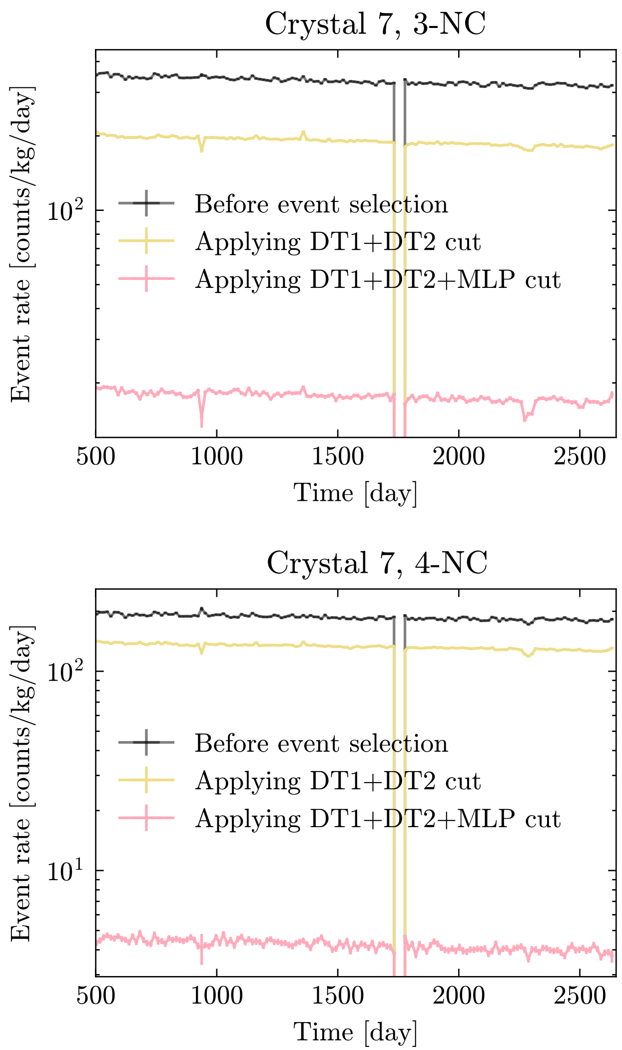
- Training Variables :
  1) Time difference between each clusters
  2) Asymmetry

Analysis – Event Selection

➢ **Multi-layer perceptron (MLP) for separation**

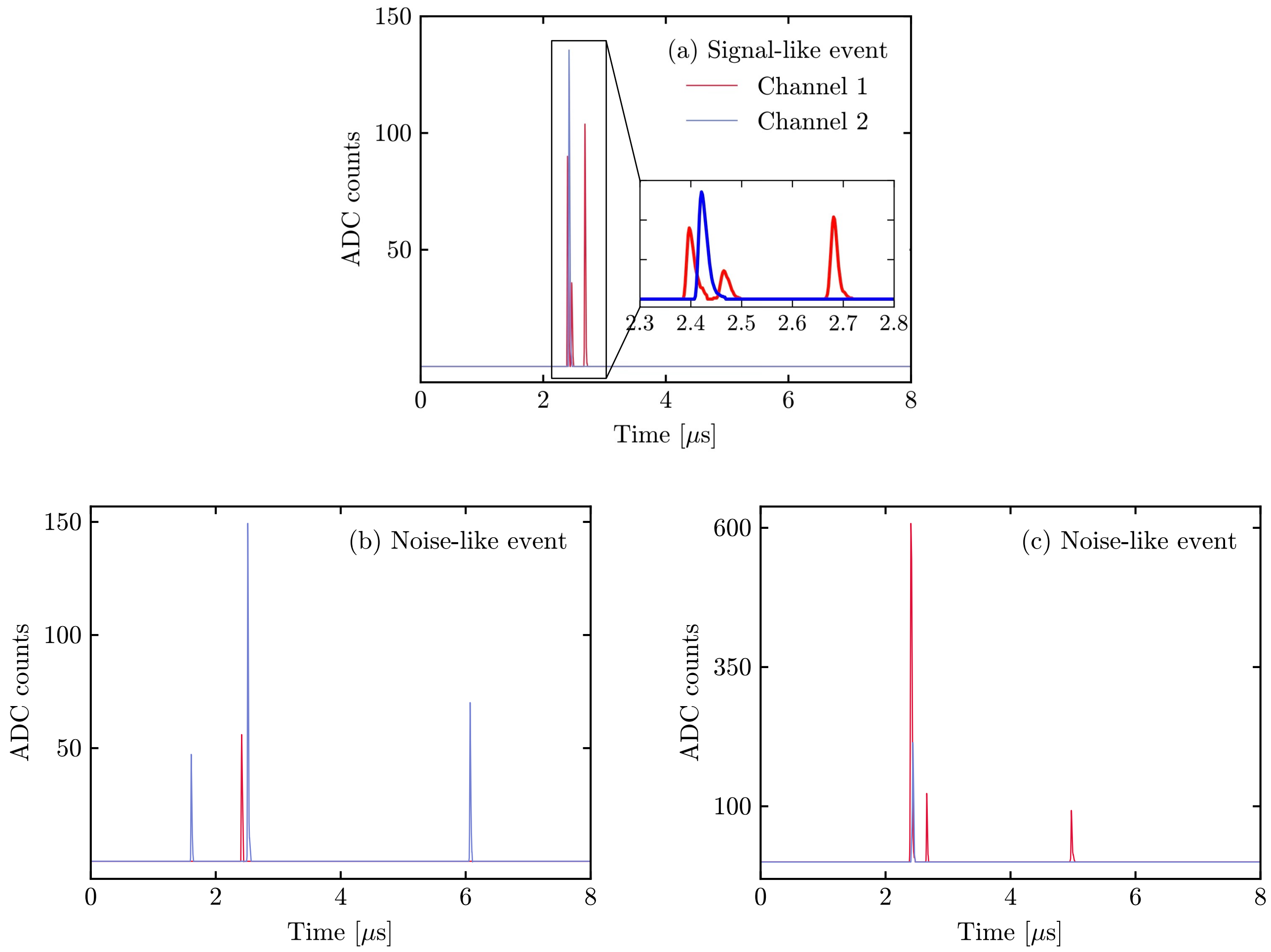






- 50% signal efficiency → noise reduction 91% for 3-NC, 97% for 4-NC.

Analysis – Event Selection

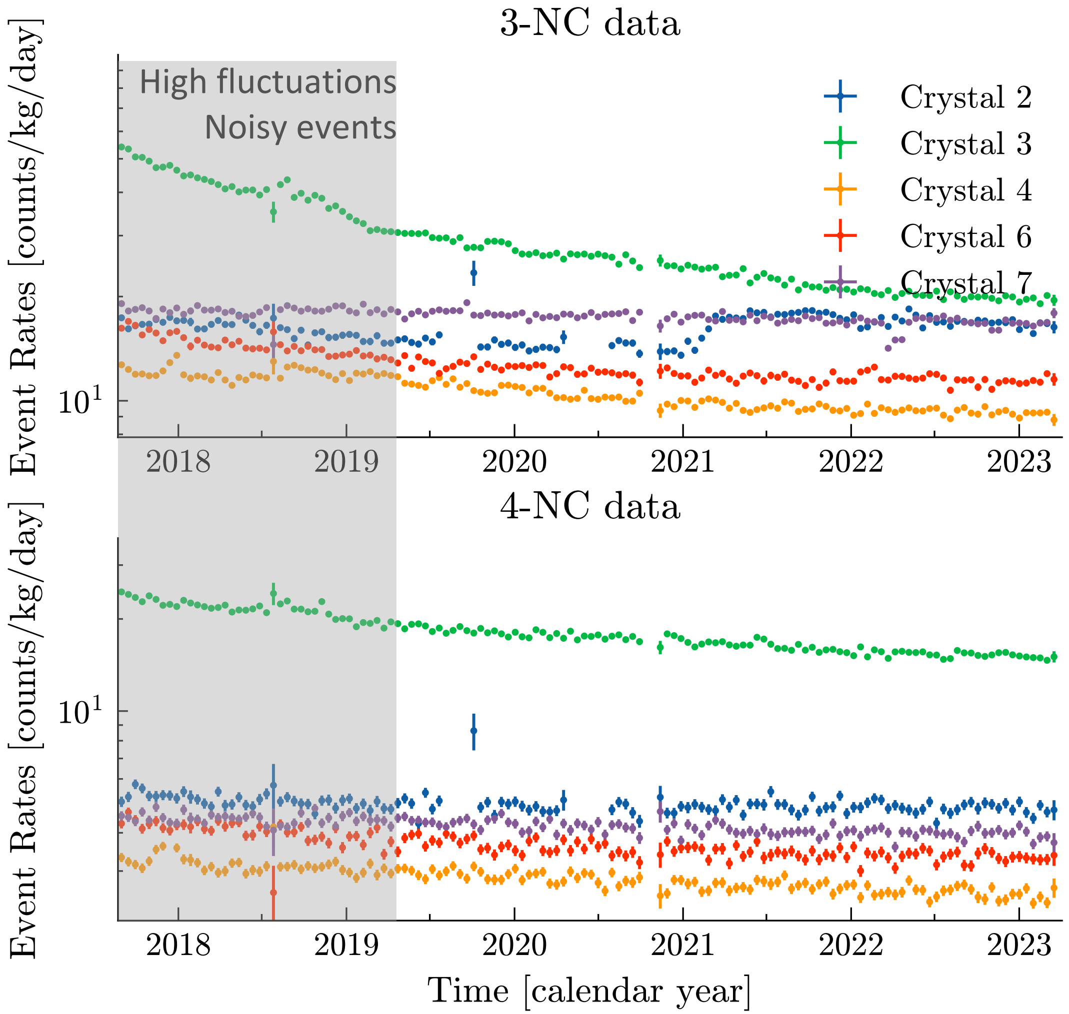


➢ Summarization of event selection

Cut	Signal efficiency (%)	Noise rejection (%)		Mitigation
		3-NC	4-NC	
Deadtime	97	32	22	(b)
MLP	50	91	97	(b) & (c)

Analysis – Annual Modulation

➤ COSINE-100 data simultaneous fitting



- Modulation fit with,

$$F(t;A) = A\cos\left[\frac{2\pi}{T}(t-\phi)\right] + \exp(p_0 + p_1 t) + C$$

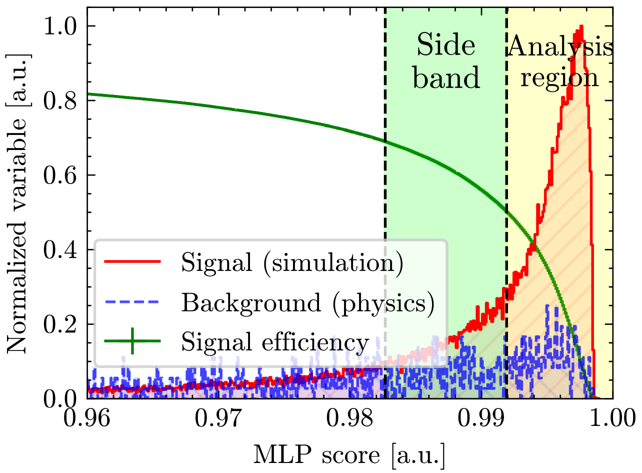
  - A : modulation amplitude
  - t : time
  - p_0, p_1 : background (exponential component)
  - ϕ : phase (fixed : 152.5 day)
  - C : constant baseline
  - T : 1 year = 365.25 days

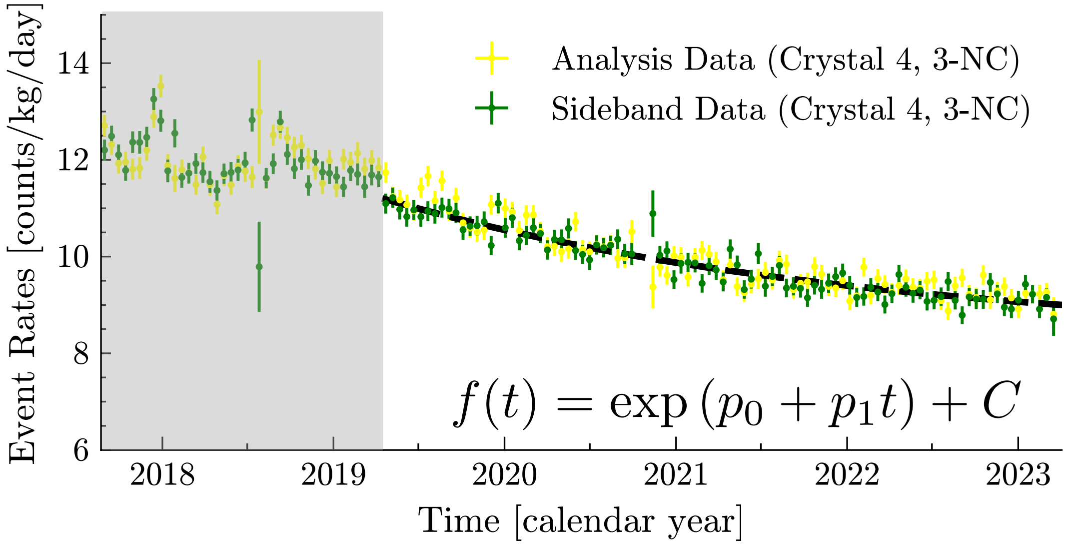
  to model the background component.

- Utilized latest **4.3 years of data** because of the cosmogenic backgrounds.

Analysis – Systematic

➤ Systematic uncertainties from MLP training (for 3-NC)





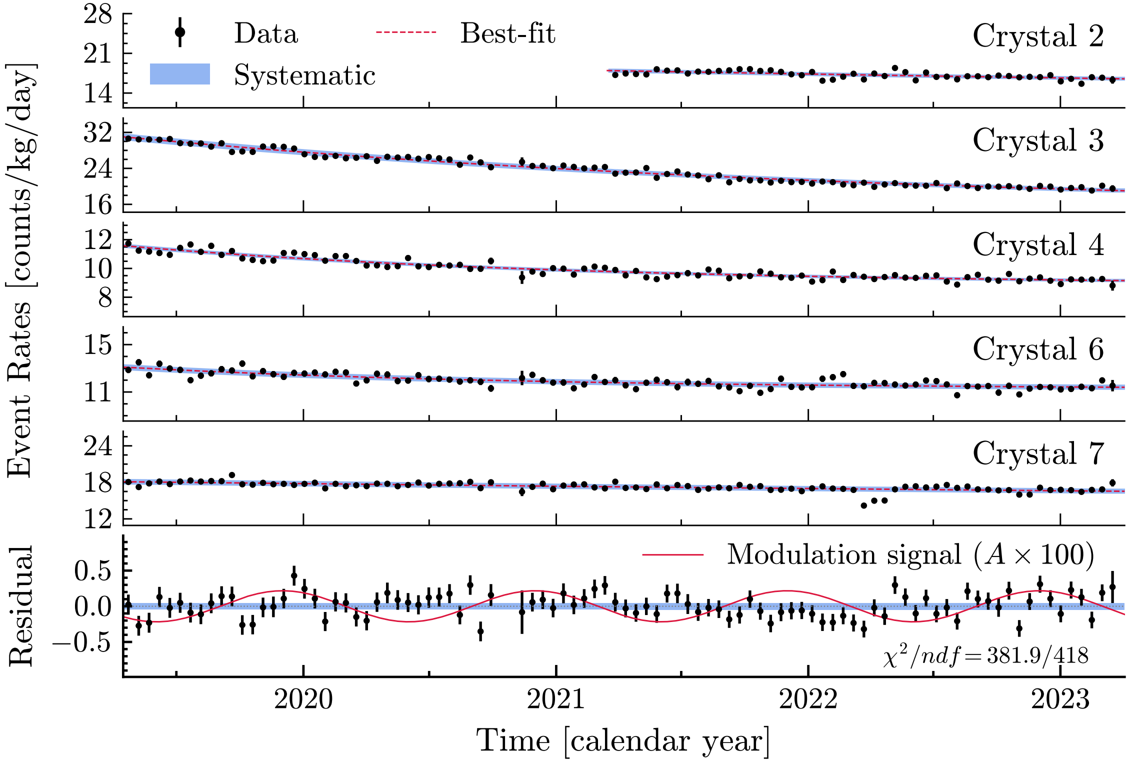
Crystal	Systematic Uncertainty (%)	Averaged Statistical Uncertainty (counts/kg/day)
2	2.02	0.36
3	2.45	0.44
4	1.25	0.20
6	1.93	0.26
7	2.53	0.32

- Assume that the fluctuation from noise is similar on the **side band** region.
- Derive systematic uncertainty from MLP training with side band data.
- Idea : Scale errors until $\chi^2/\mathrm{ndf} = 1$

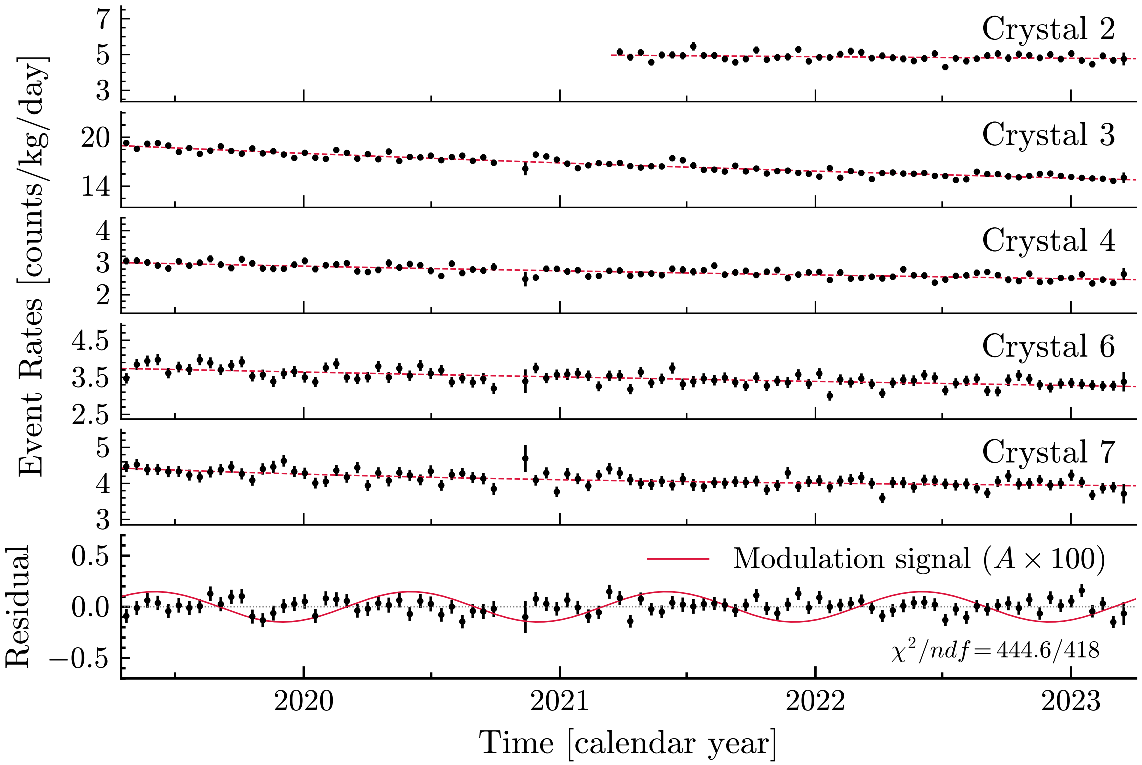
Analysis – Annual Modulation

- COSINE-100 data simultaneous fitting

3-NC : *Amplitude* = −0.002 ± 0.026



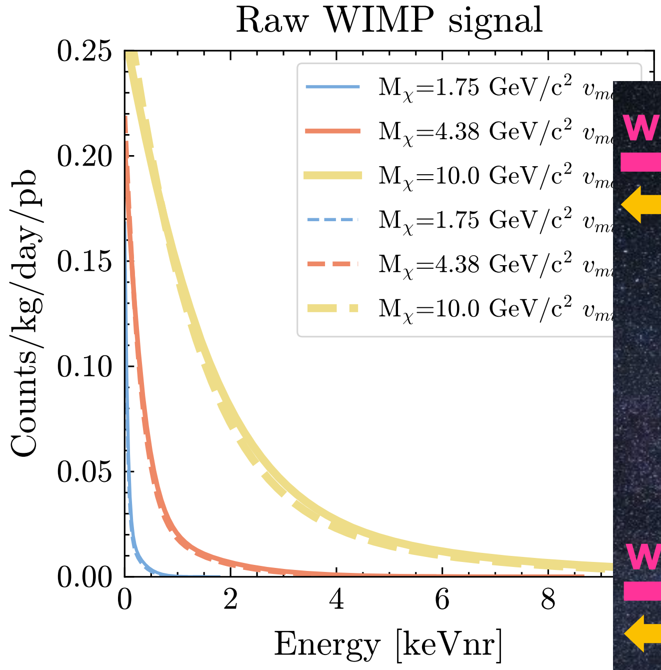
4-NC : *Amplitude* = 0.001 ± 0.001 (counts/kg/day)

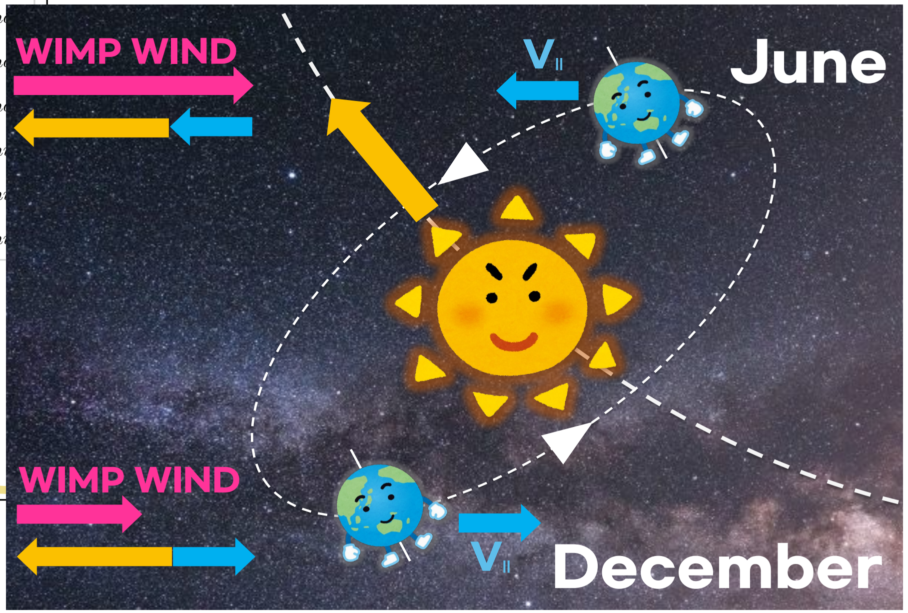


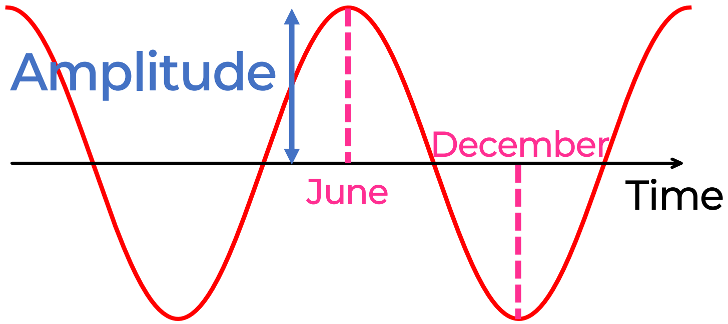
→ **Fitted results consistent with no modulation signal**

Analysis – WIMP Signal Generation

➢ **Expected WIMP signal in COSINE-100 detector**



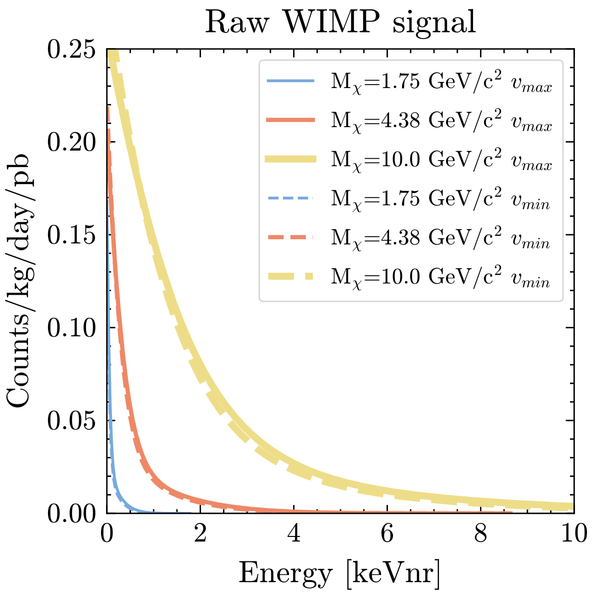


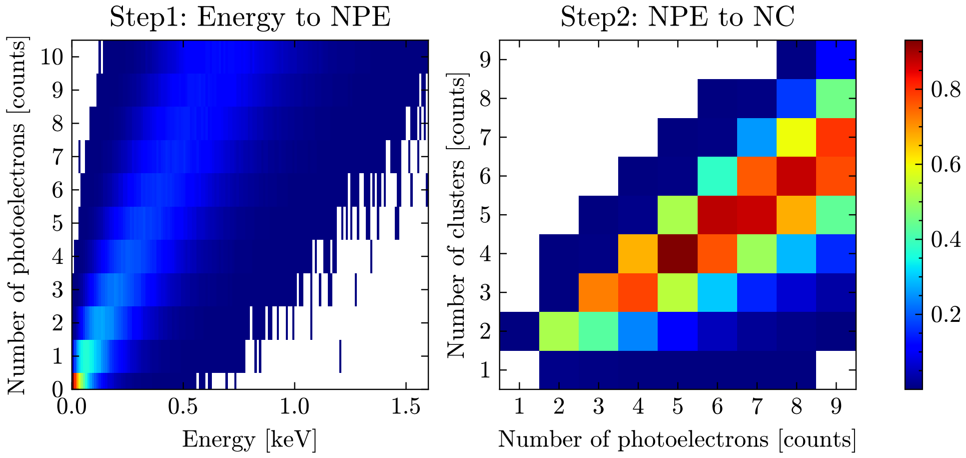


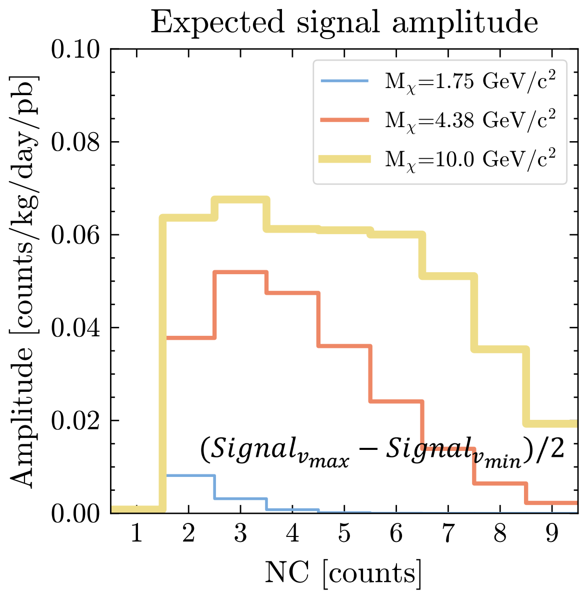
Event Rate : $\frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\min}}^{v_{esc}} \frac{d\sigma}{dE_{nr}} v f(v) dv$

Analysis – WIMP Signal Generation

➢ Expected WIMP signal in COSINE-100 detector



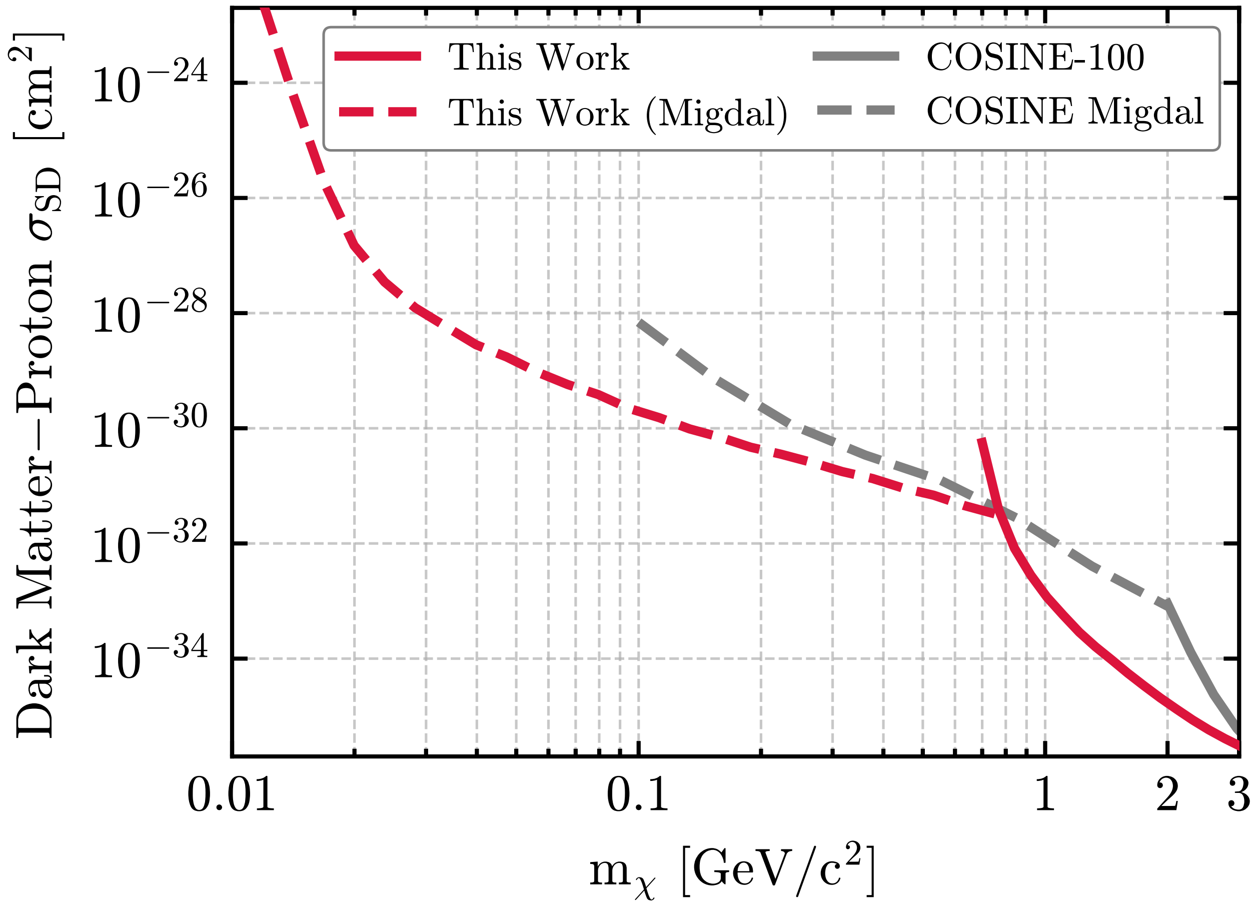




- Simulated WIMP signal for our limit determination.
- Detector response matrix and expected signal amplitude is generated for every crystals.
- Limit is determined using the likelihood ratio test method based on χ2 minimization with 90% C.L.

Result – Spin-Dependent Cross Section

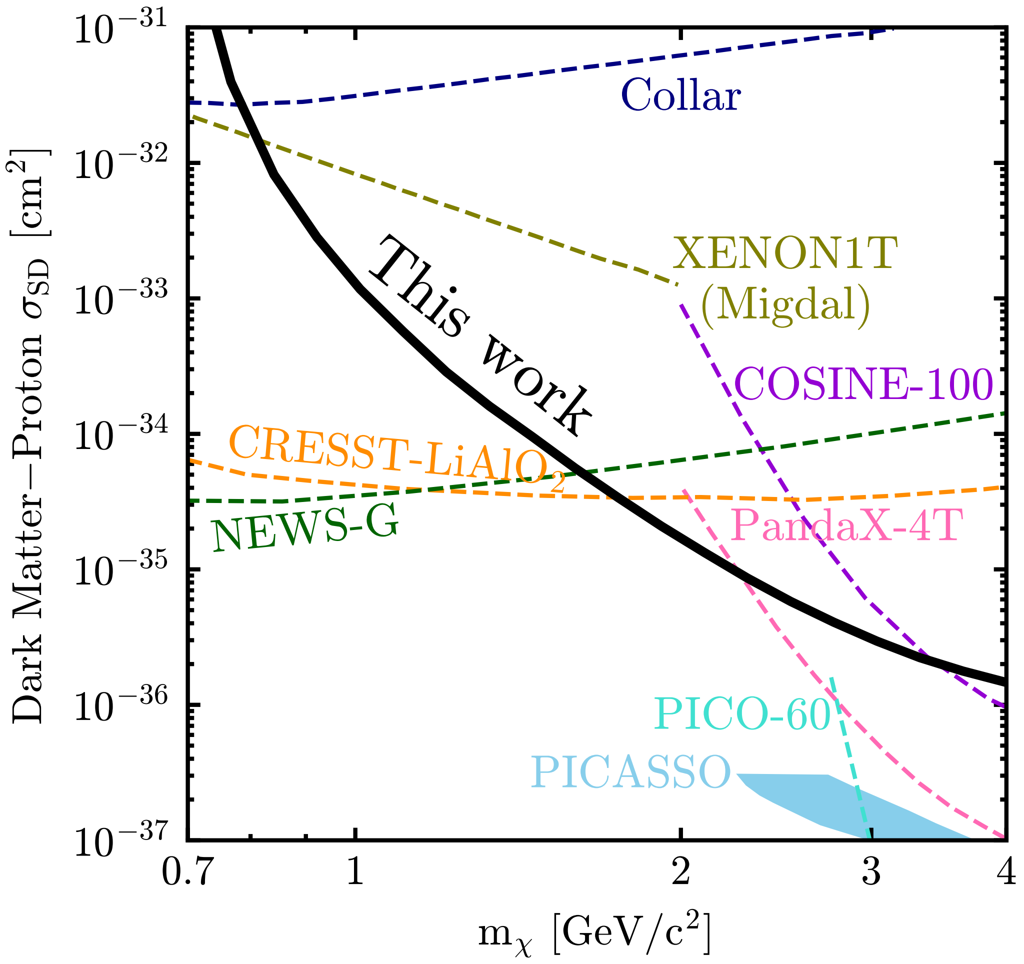
➢ Spin-dependent WIMP—Proton cross-section limit



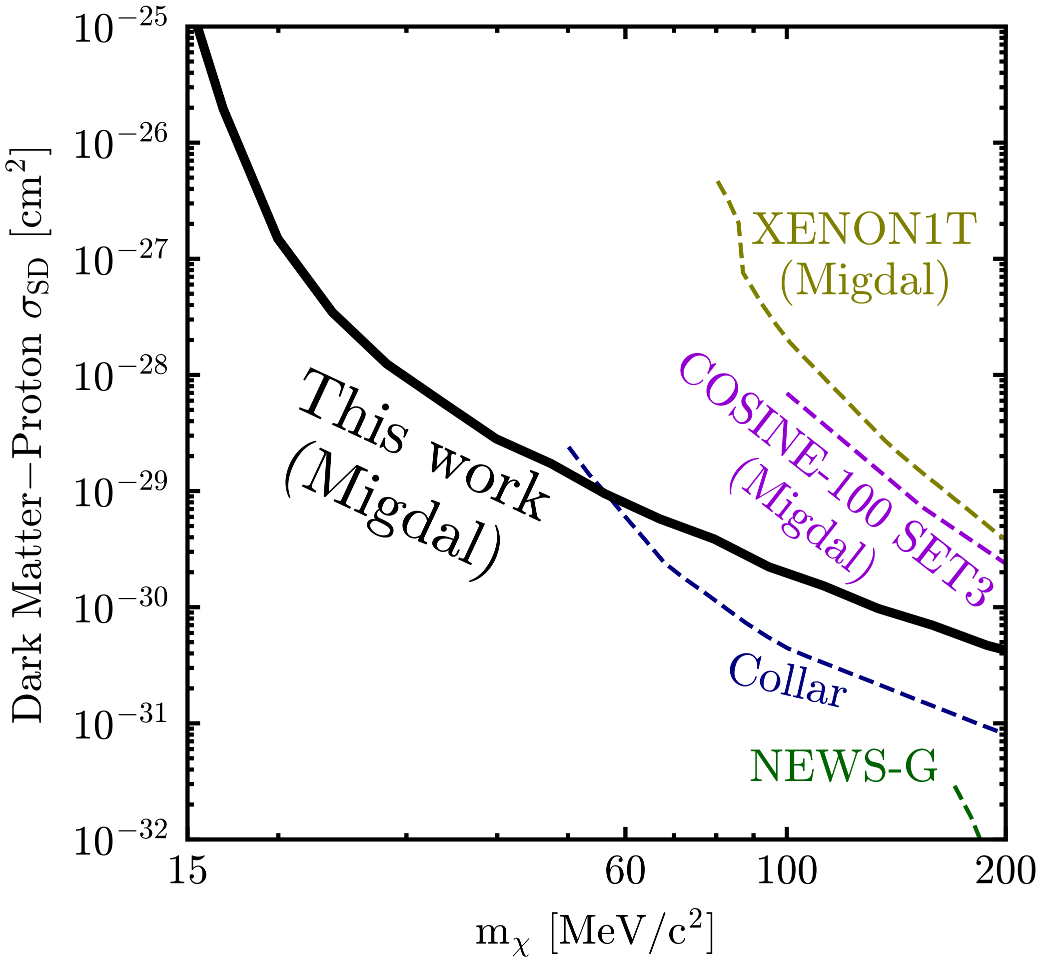
- Sodium and iodine has **odd proton number** (even neutron number), COSINE-100 can set limits on the WIMP-proton interaction.
- Compared with COSINE-100 3 years data results, **this analysis method can extends to lower WIMP mass region.**

Result – Spin-Dependent Cross Section

➢ **Spin-dependent only**



➢ **Spin-dependent with Migdal effect**



Summary

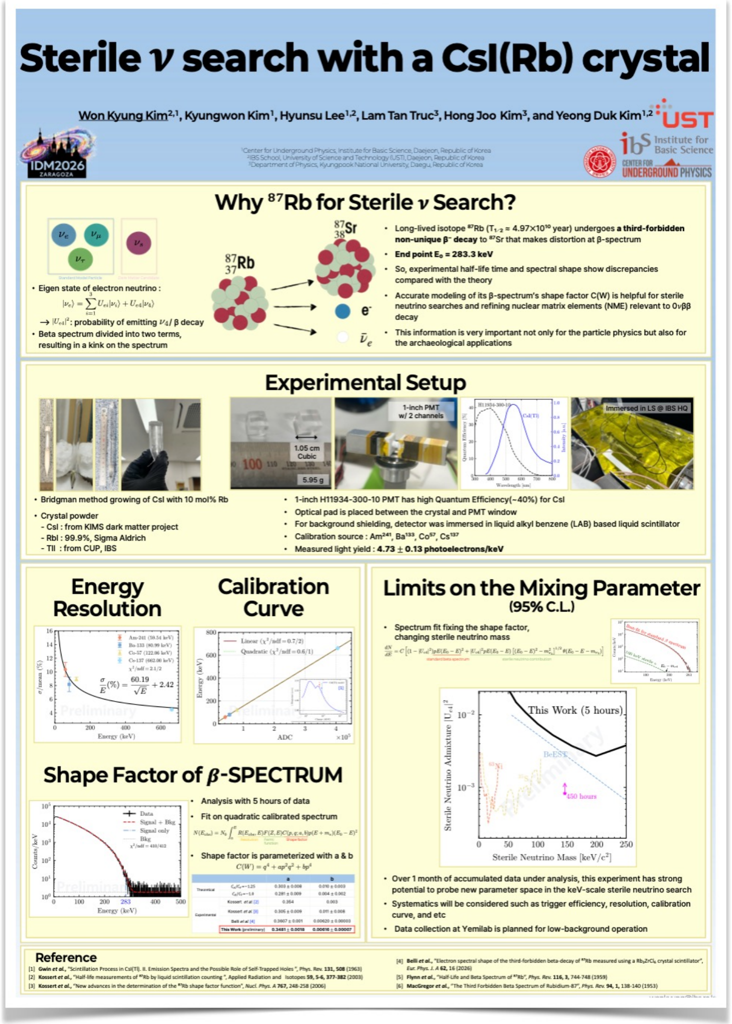
Scan for this paper

arXiv:2603.22411

- **Few-PE** (3 and 4 cluster level events) **analysis** were developed using COSINE-100 data.
- For Event selection, deadtime cut and MLP cut were applied.
- To get the **annual modulation amplitude from COSINE-100 data, simultaneous fit** was conducted with modulation function, which includes phenomenological background modeling.
- **No statistically significant modulation signal** were observed.
- New 90% C.L. limits were set on SD DM−proton interactions in the previously unexplored **1.75–2.25 GeV/c^2** and, via the Migdal effect, in the **15–58 MeV/c^2 DM mass** region.
- These results motivate future experiments such as COSINE-100U and **indicate that crystal scintillator–based detectors remain a powerful approach for exploring previously unexplored MeV scale DM parameter space.**

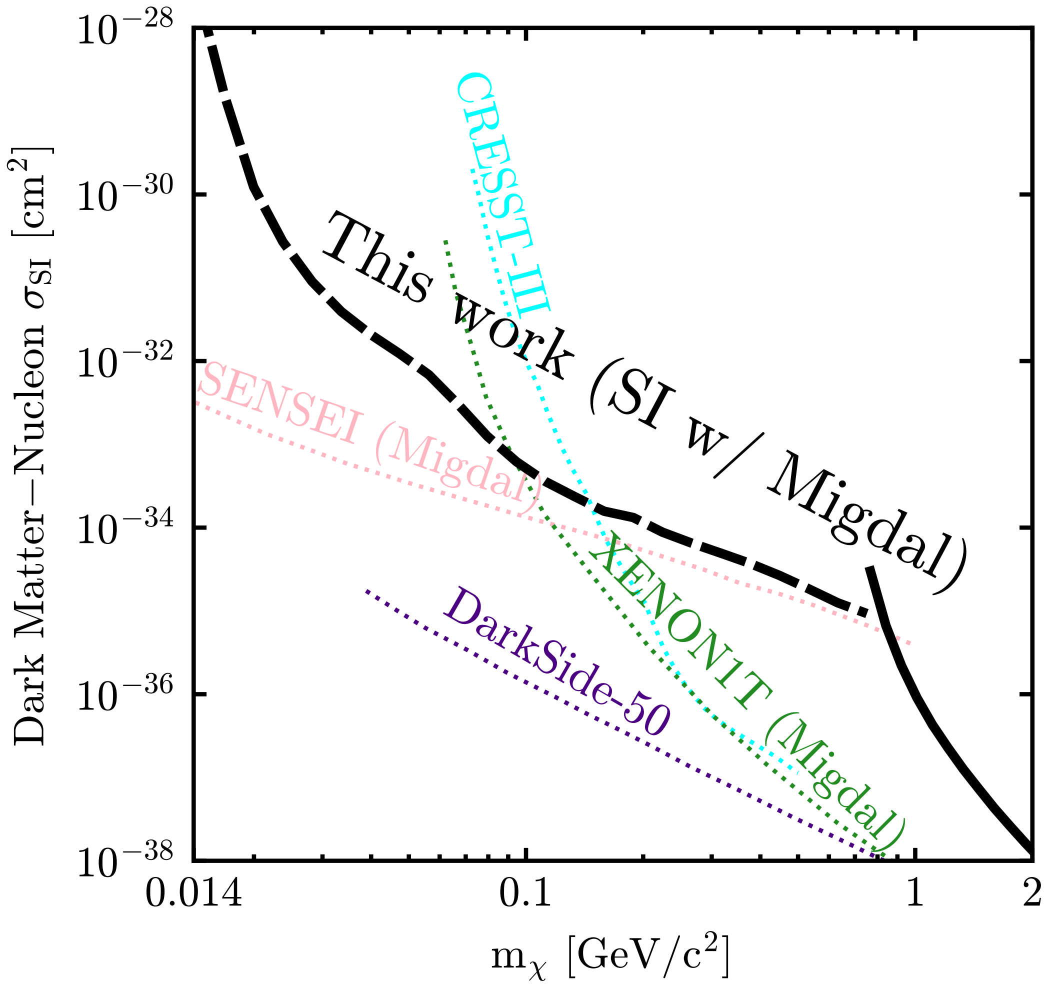
Thank you for your attention!

Questions and discussions are welcome
Please stop by my poster
during the poster session



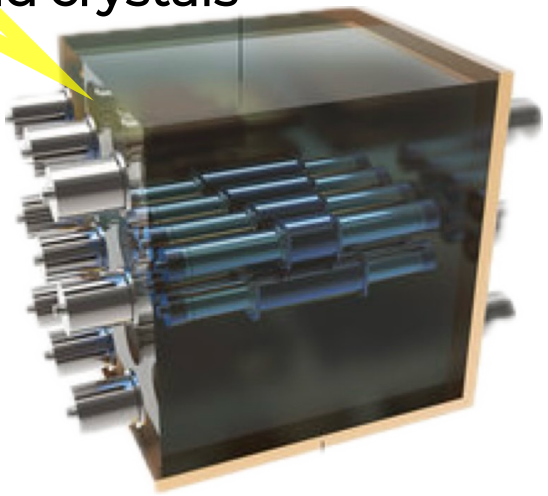
Result – Spin-Independent Cross Section

➢ **Spin-independent WIMP—Nucleon with Migdal Effect**

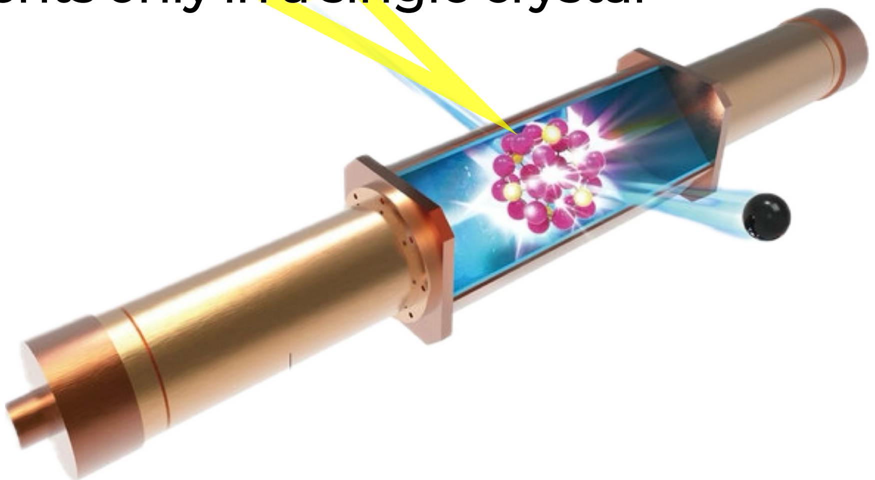


COSINE-100

Multiple-hit;
events on 2 or more crystals/
events on both LS and crystals

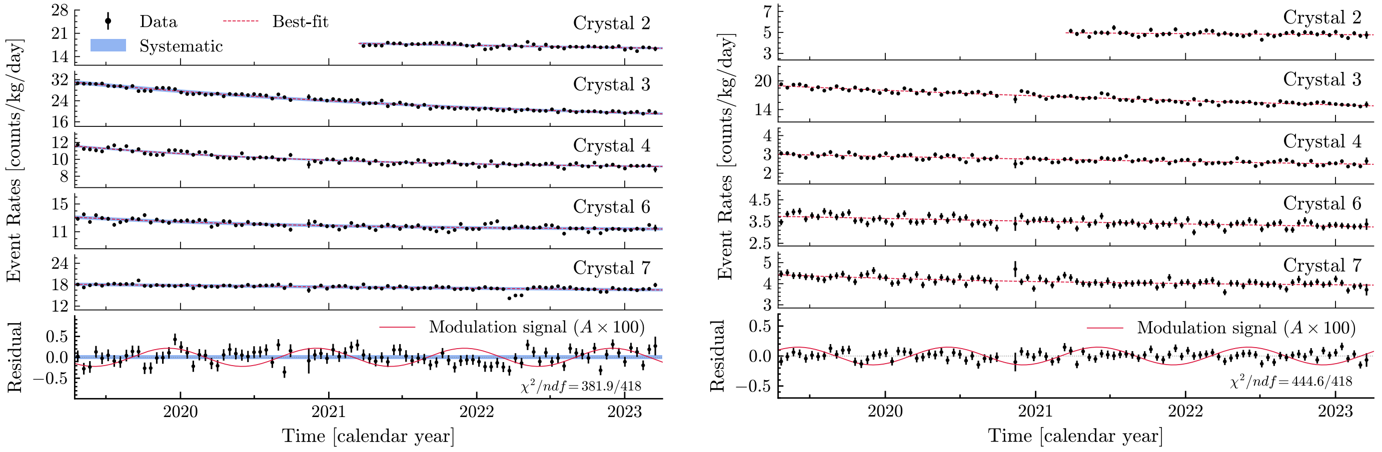


Single-hit;
events only in a single crystal

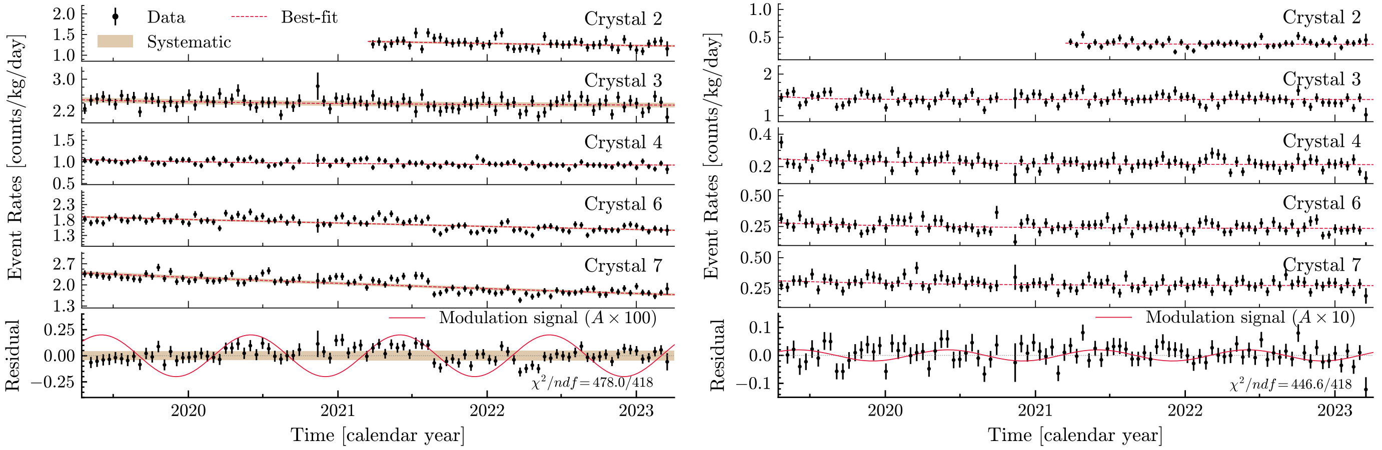


Analysis – Annual Modulation

➢ COSINE-100 Data Simultaneous Fitting



(a) Single-hit



(b) Multiple-hit

- Single-hit : Event triggered in only a one crystal
- Multiple-hit : Event triggered multiple crystals

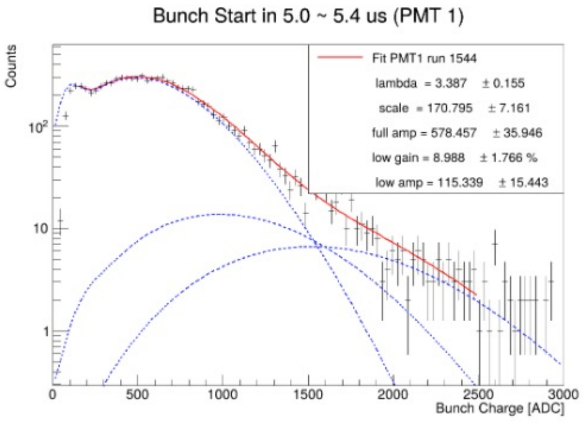
Number of clusters [NCs]	Amplitude [counts/kg/day]	
	Single-hit	Multiple-hit
3	−0.002 ± 0.026	0.002 ± 0.007
4	0.001 ± 0.011	0.002 ± 0.003

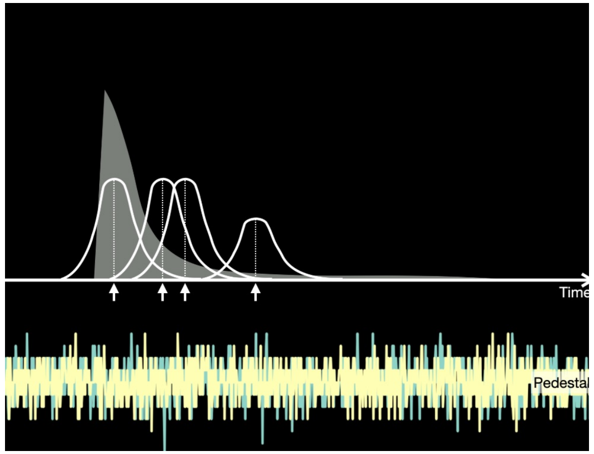
- From multiple-hit dataset, we could check the modulation signal from background component (not DM).
- No modulation signal in both data.

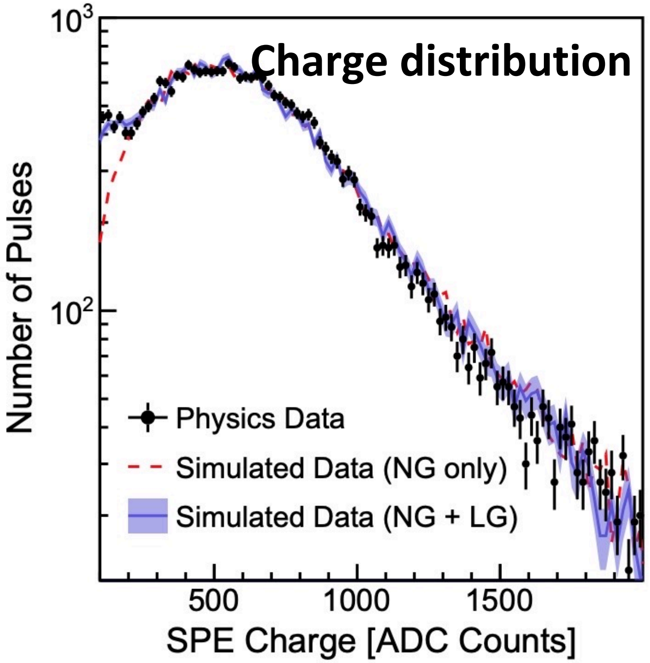
Waveform Simulation for NaI(Tl)

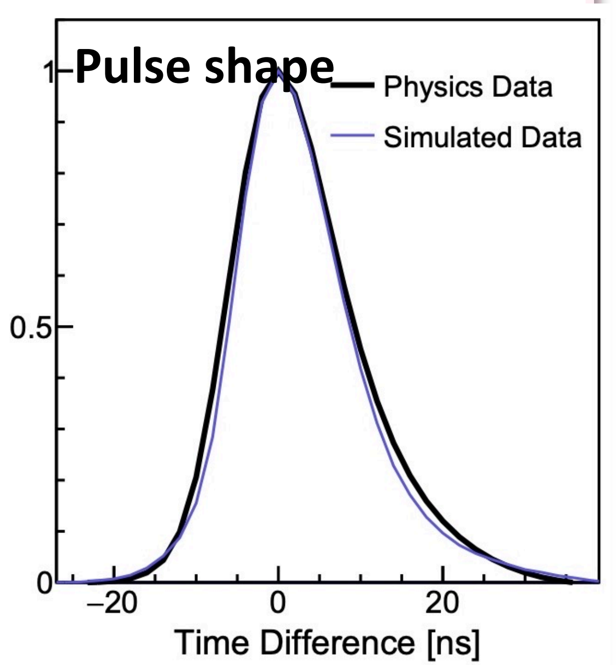
Nucl. Instrum. Meth. A **1065,**169489 (2024)

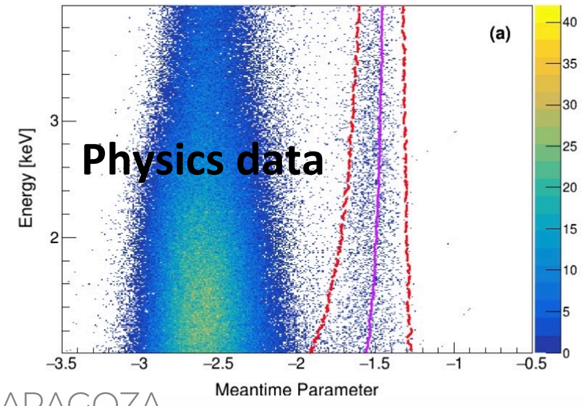
- Parameters
  - gain, low gain fraction, SPE height : from SPE fitting
  - random pulse rate : from prepulse counting in data
  - pedestal mean and rms

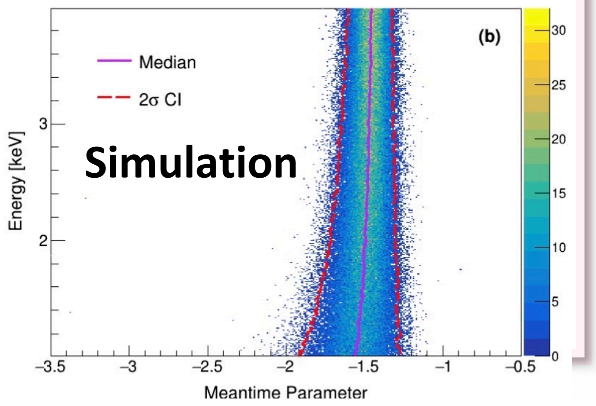




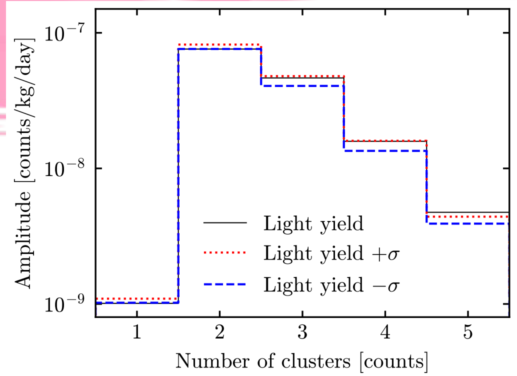






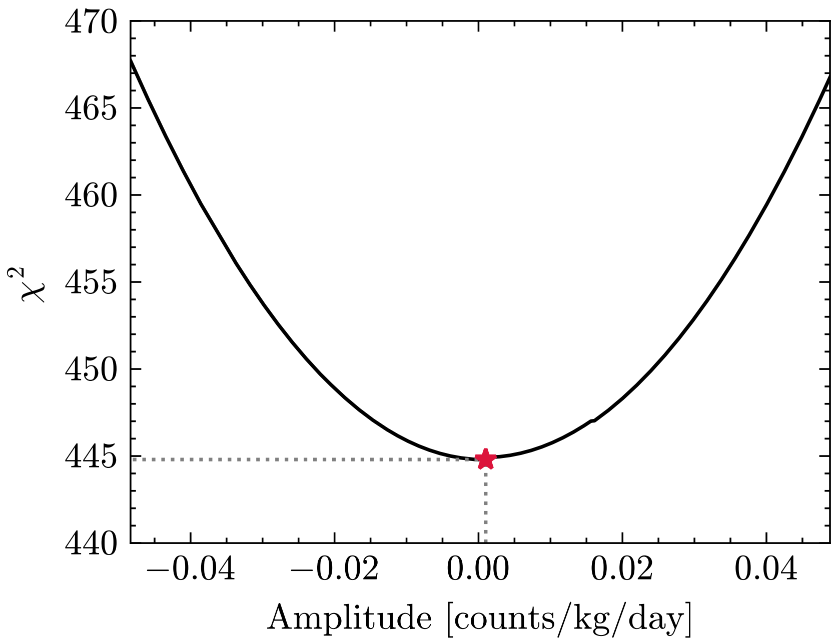


χ^2 and Systematic Errors



➤ Modulation analysis

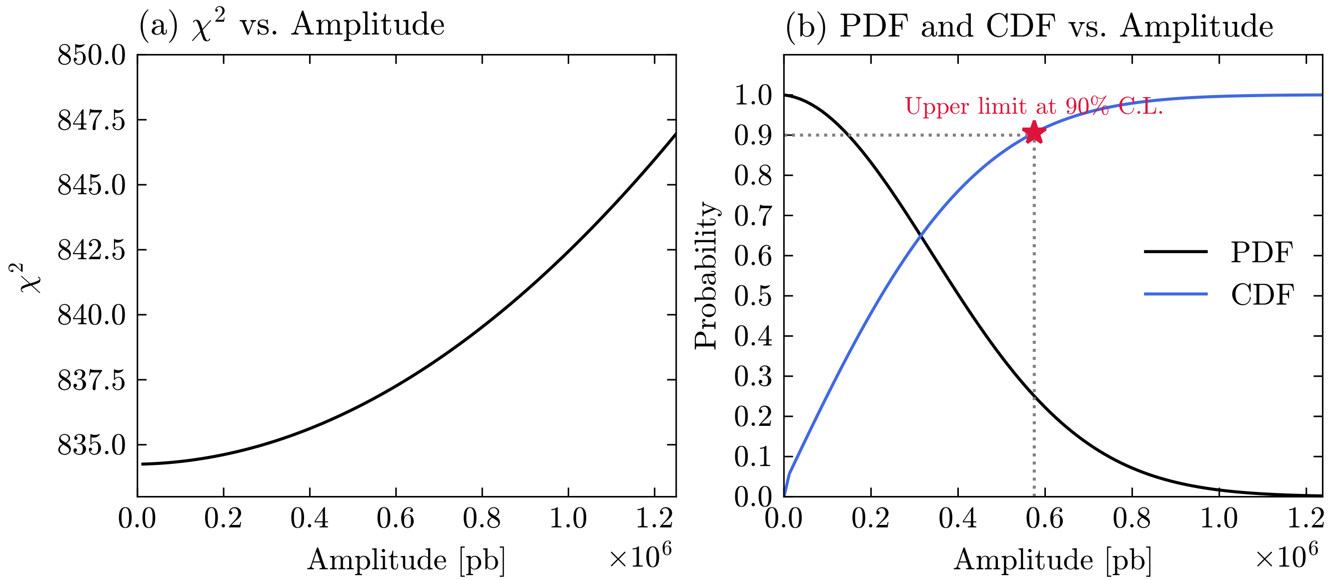
$$\chi^2 = \sum_{i}^{N_{\text{crystal}}} \sum_{j}^{N_{\text{time}}} \frac{[M_{ij} - F_i(t_j; A)]^2}{M_{ij} + \delta u_i^2 M_{ij}^2}$$



➤ Cross-section analysis

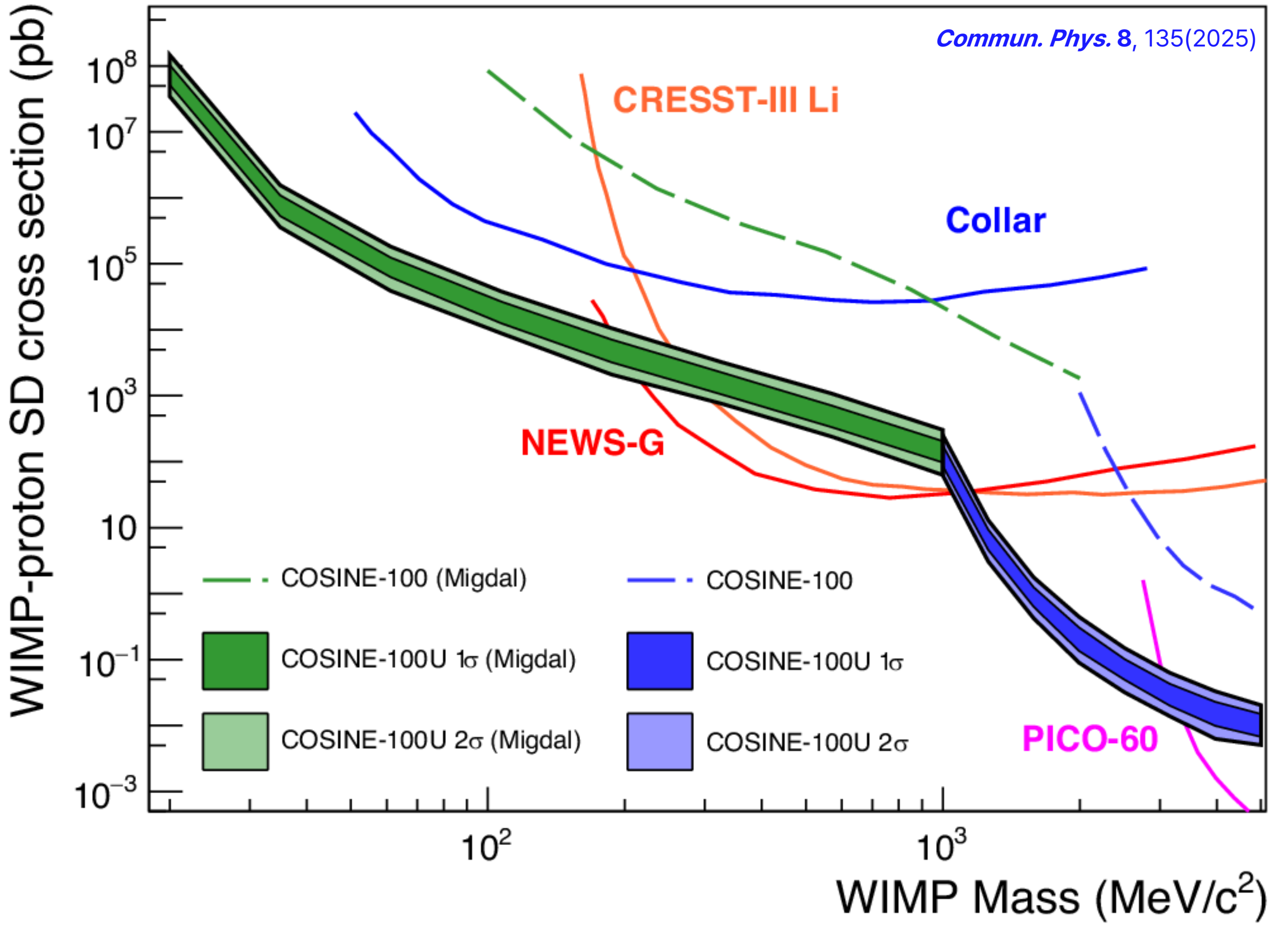
$$\chi^2(\sigma_{\text{DM}}) = \sum_{i}^{\text{NC}} \sum_{j}^{N_{\text{crystal}}} \sum_{k}^{N_{\text{time}}} \frac{[M_{ijk} - F_{ij}(t_k; A')]^2}{M_{ijk} + \delta u_{ij}^2 M_{ijk}^2} + \left(\frac{\alpha_{ij}}{\delta c_{ij}}\right)^2$$

$$A'(\sigma_{\text{DM}}) = (1 + \alpha_{ij}) f_{ij}(m_{\text{DM}})\, \sigma_{\text{DM}}$$



COSINE-100U

➤ Expected SD cross-section sensitivity (from the main analysis method)



- Increased light yield (~ 20 p.e./keV)
- 8 crystals (~100 kg)
- 1-year exposure
- 5 NPE threshold (~ 0.25 keV)
- Expected background (COSINE-100U)

If they apply the low-threshold data analysis method, we are more sensitive to much lower DM mass.