arXiv:2603.22411

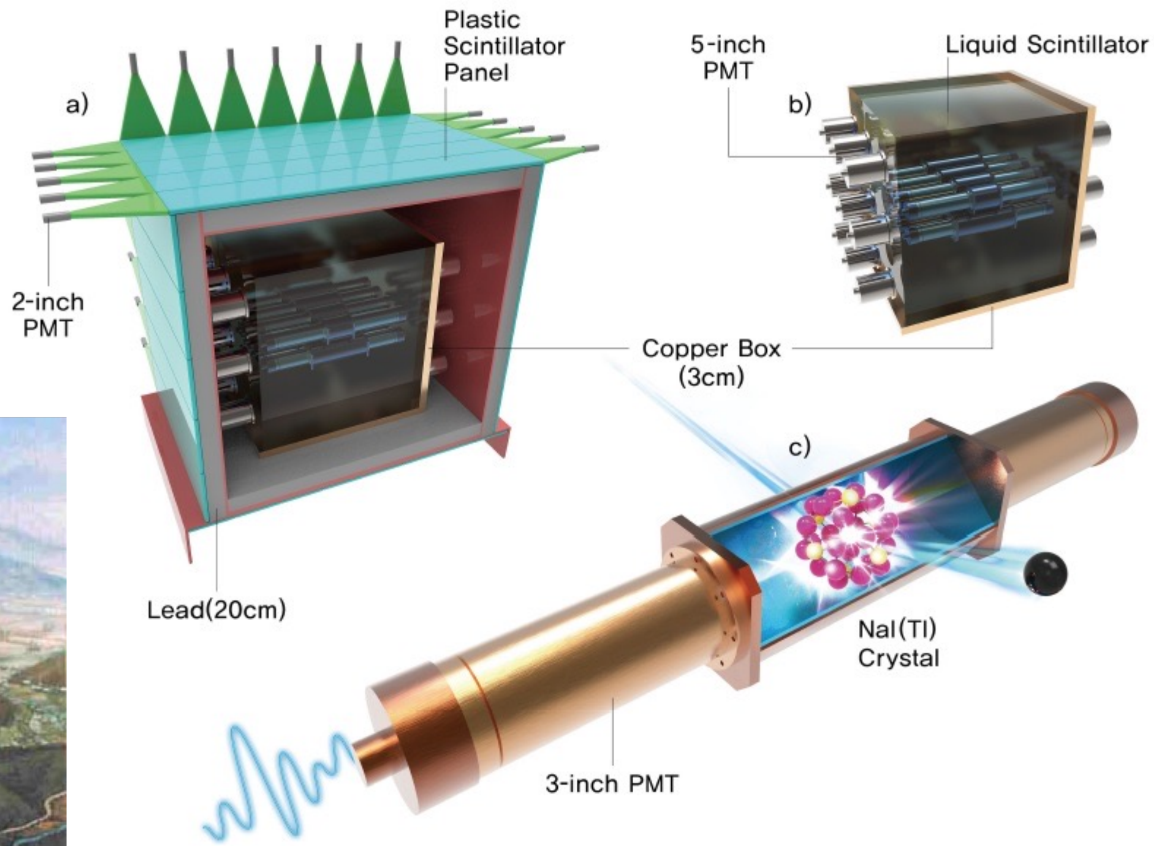
Pioneering Sub-GeV Dark Matter Limits with COSINE-100

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

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

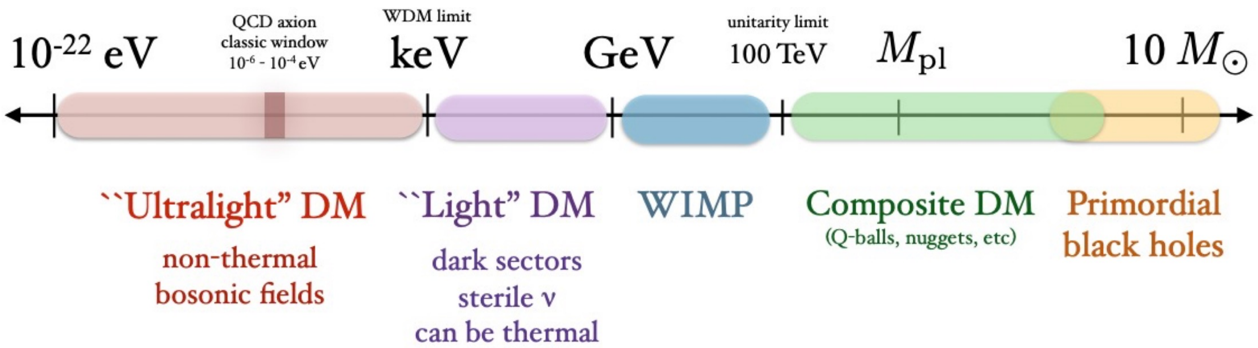
COSINE-100 Dark Matter Experiment

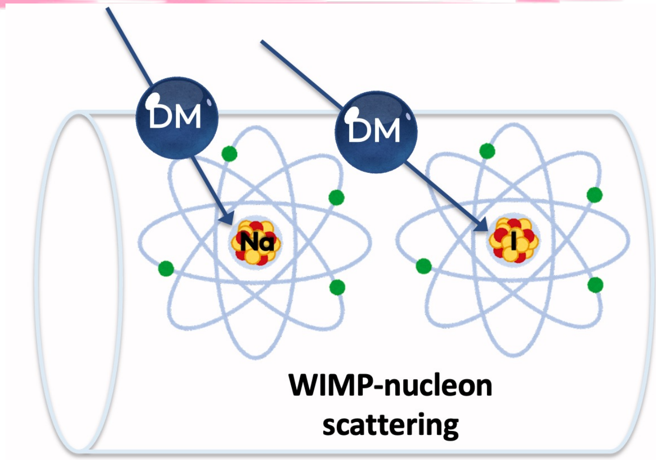
- At Yangyang underground laboratory, data taking since September 10 2016 until March 14 2023 (~6.5 years).
- COSINE-100 setup consists of 8 NaI(Tl) crystal which is coupled with two 3-inch PMTs. Those detectors are immersed in the liquid scintillator.

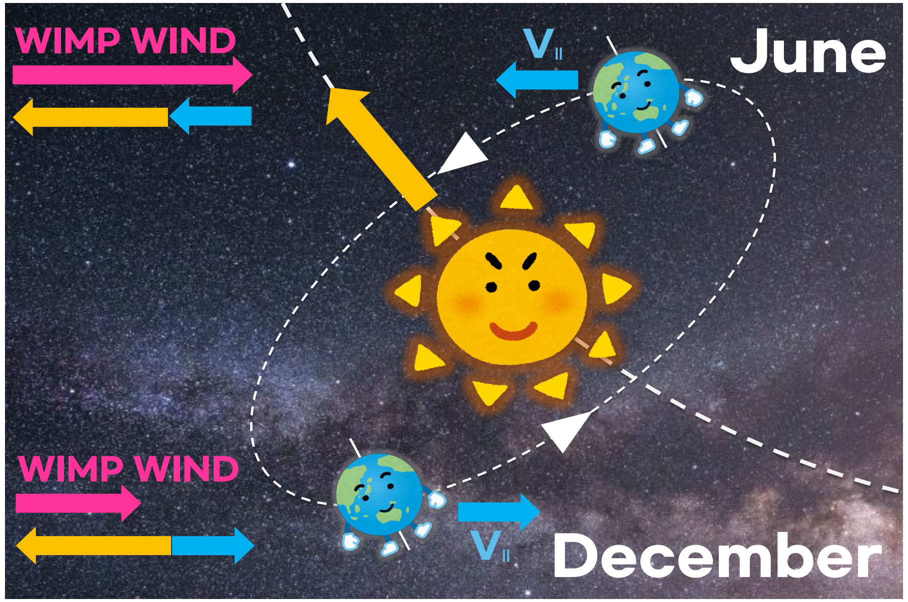


- Target material : 8 low-background NaI(Tl) crystals
- Total mass : 106 kg
- Light yield : 15 photoelectrons(NPE)/keV

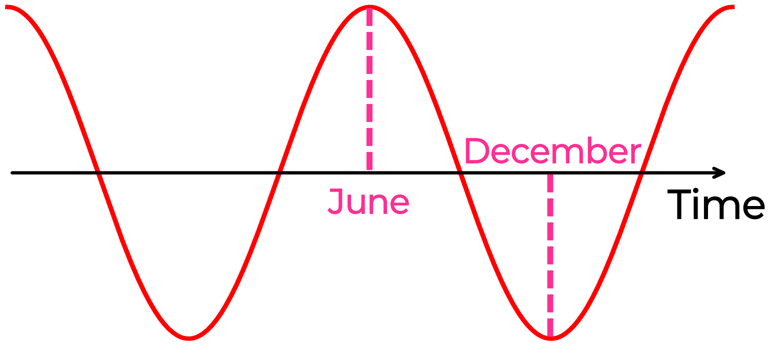
Dark Matter Landscape







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 event rate

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

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

E_{nr} : nuclear recoil energy
$f(v)$: DM velocity distribution (Maxwell-Boltzmann)
M : detector total mass
m_N : nucleus mass
m_χ : DM mass
ρ_0 : local DM density $\approx 0.3\mathrm{GeV/cm^3}$

➢ WIMP-nucleus scattering cross-section

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

Dark Matter Interactions

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

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➢ WIMP-nucleus scattering cross-section

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

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

➢ Spin-independent

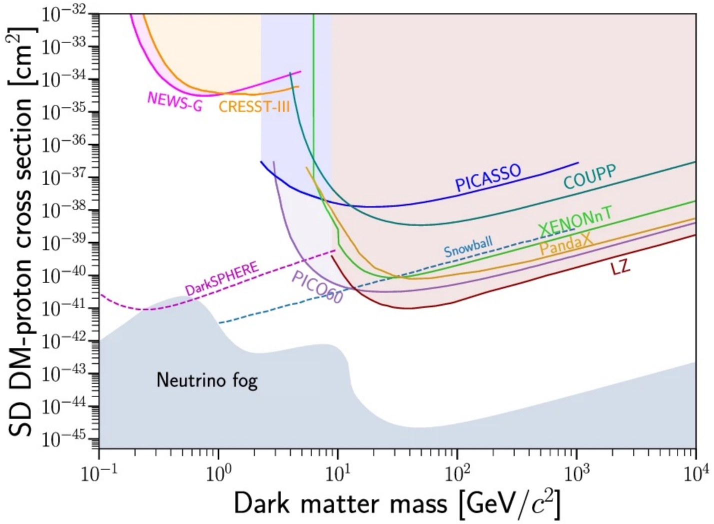
$$\sigma_{\rm SI} = \sigma_n \frac{\mu^2}{\mu_{n\chi}^2} \frac{[f_p Z + f_n(A-Z)]^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_{n\chi}^2} A^2$$

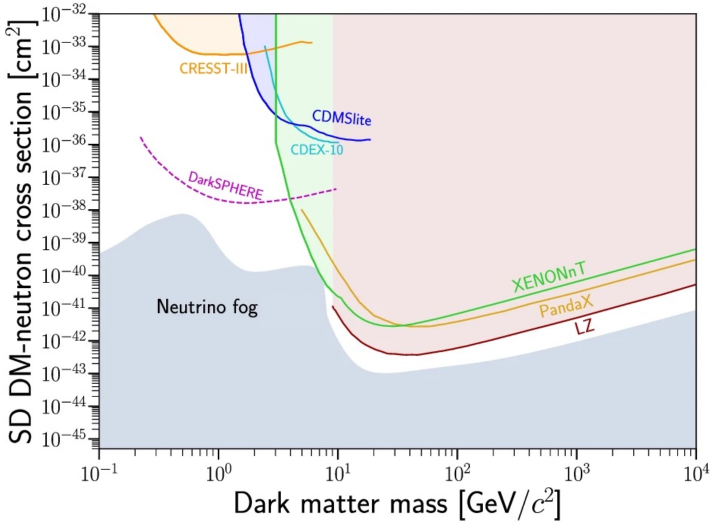
➢ Spin-dependent

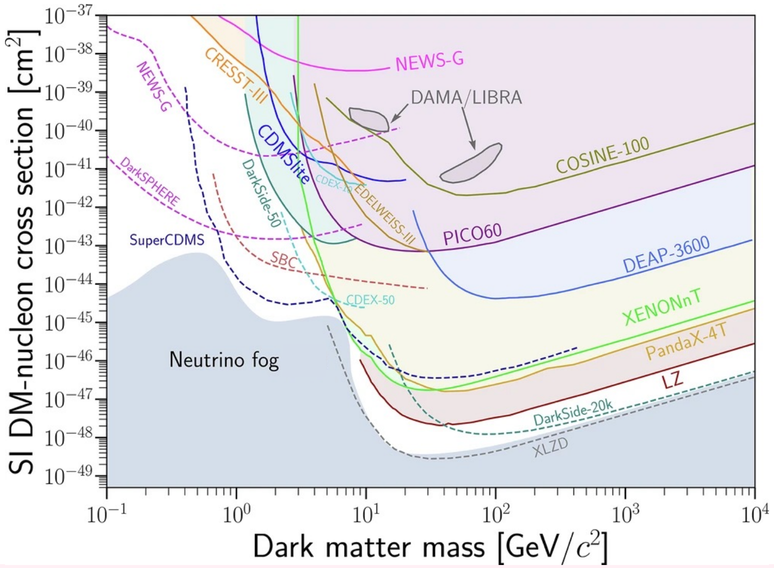
$$\frac{d\sigma_{\rm SD}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2}[a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2 \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$

- COSINE-100 used 8 NaI(Tl) crystals.
- Both **Na (*Z* = 11)** and **I (*Z* = 53)** has **odd proton** → Advantage for SD DM-proton search!

Search for Lighter Dark Matter

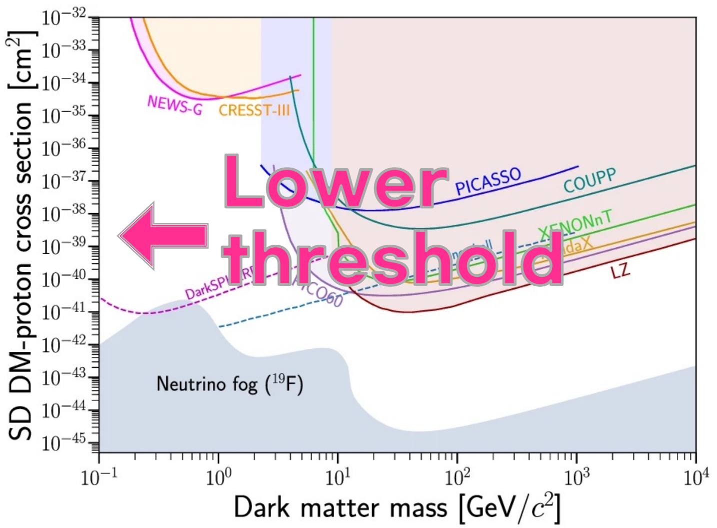


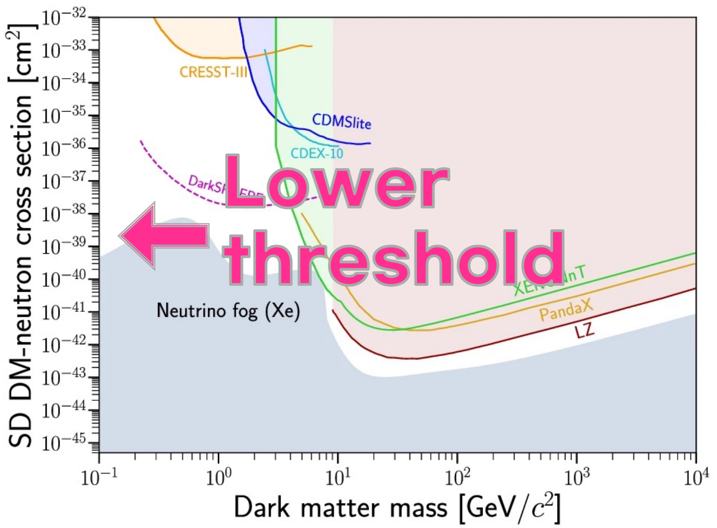


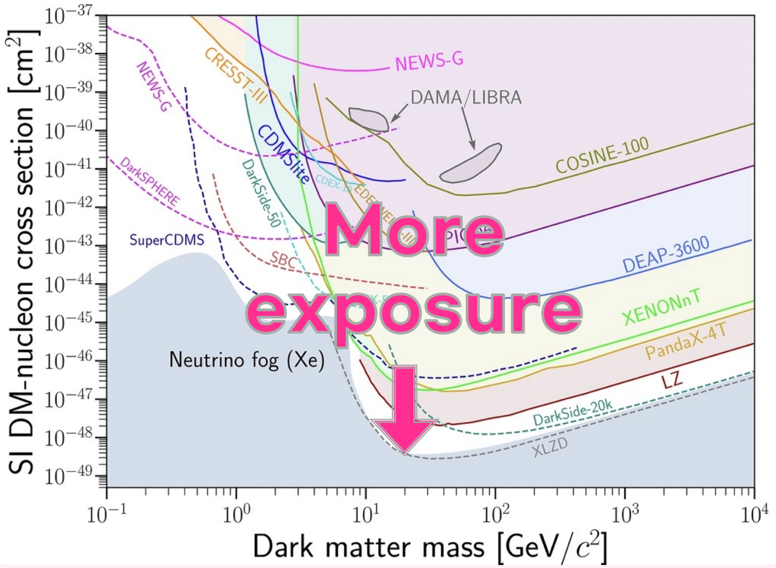


Communication Physics **9**, 105 (2026)

Search for Lighter Dark Matter

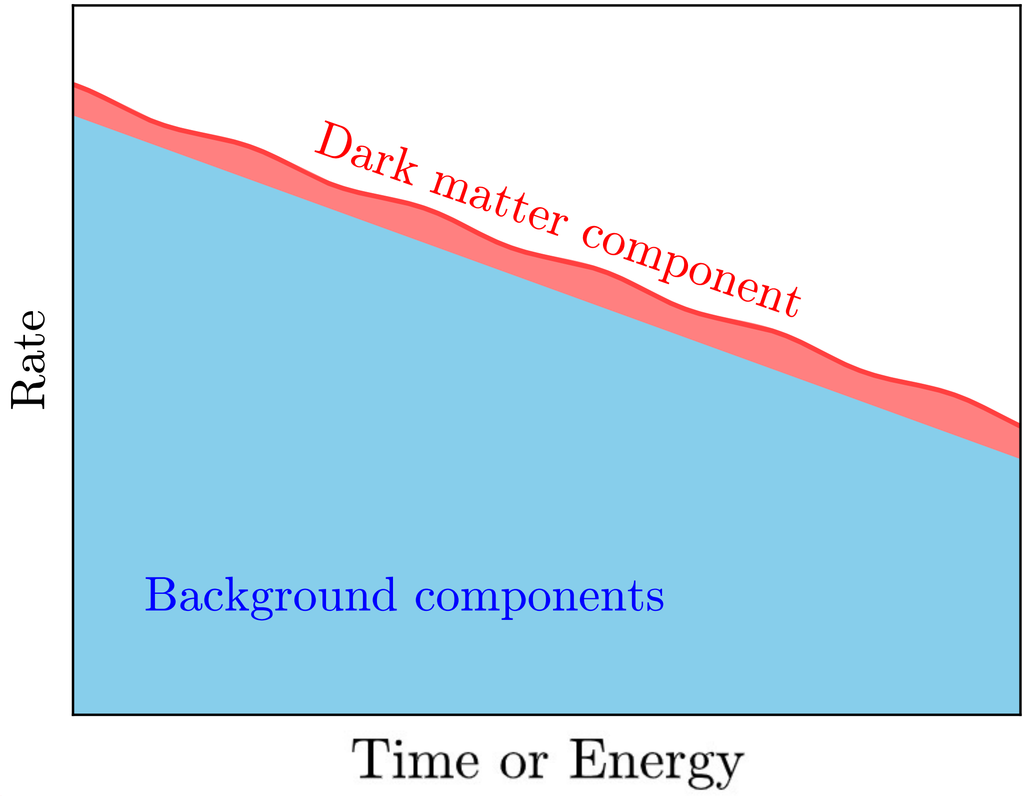






Communication Physics **9**, 105 (2026)

COSINE-100 Analysis

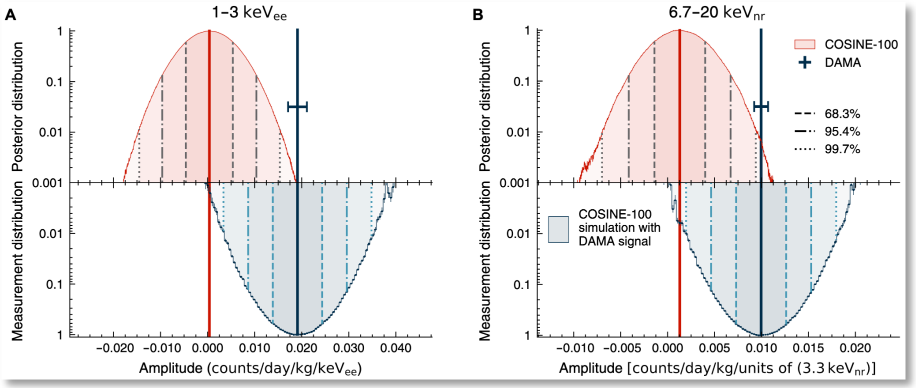


➢ COSINE-100 main analysis **(threshold : 0.49 keV)** :

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

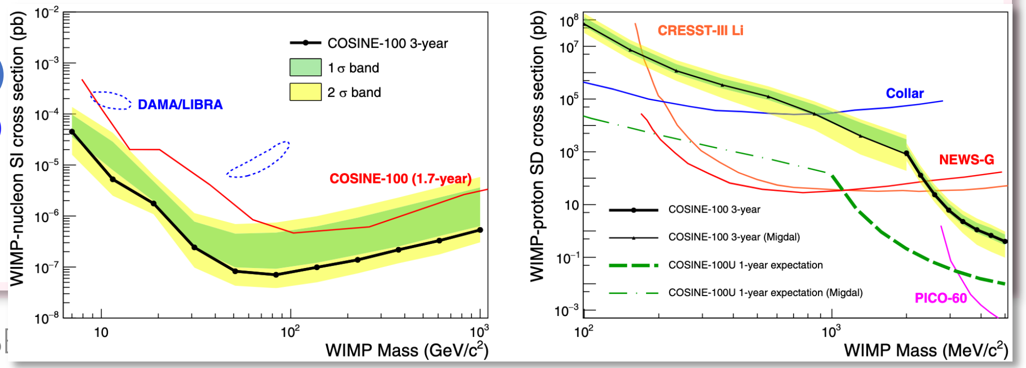
❖ **Annual modulation search to claim DAMA/LIBRA's result**

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

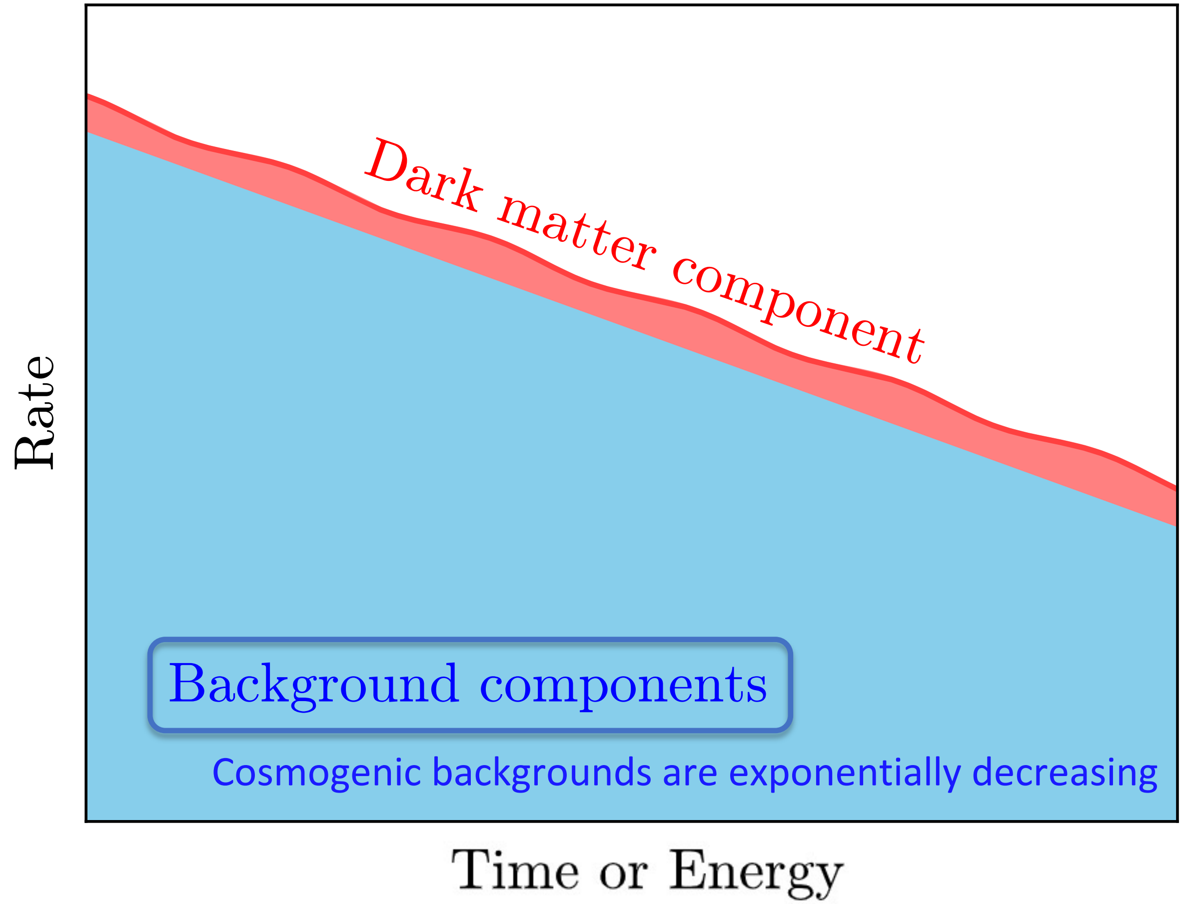


❖ **WIMP extraction analysis (WIMP-nucleon cross-section)**

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



Analysis



- COSINE-100 main analysis (threshold : 0.49 keV) :
  1. Event Selection (Signal/Noise separation).
  2. Background modeling (simulation) and mitigation.
  3. WIMP analysis.

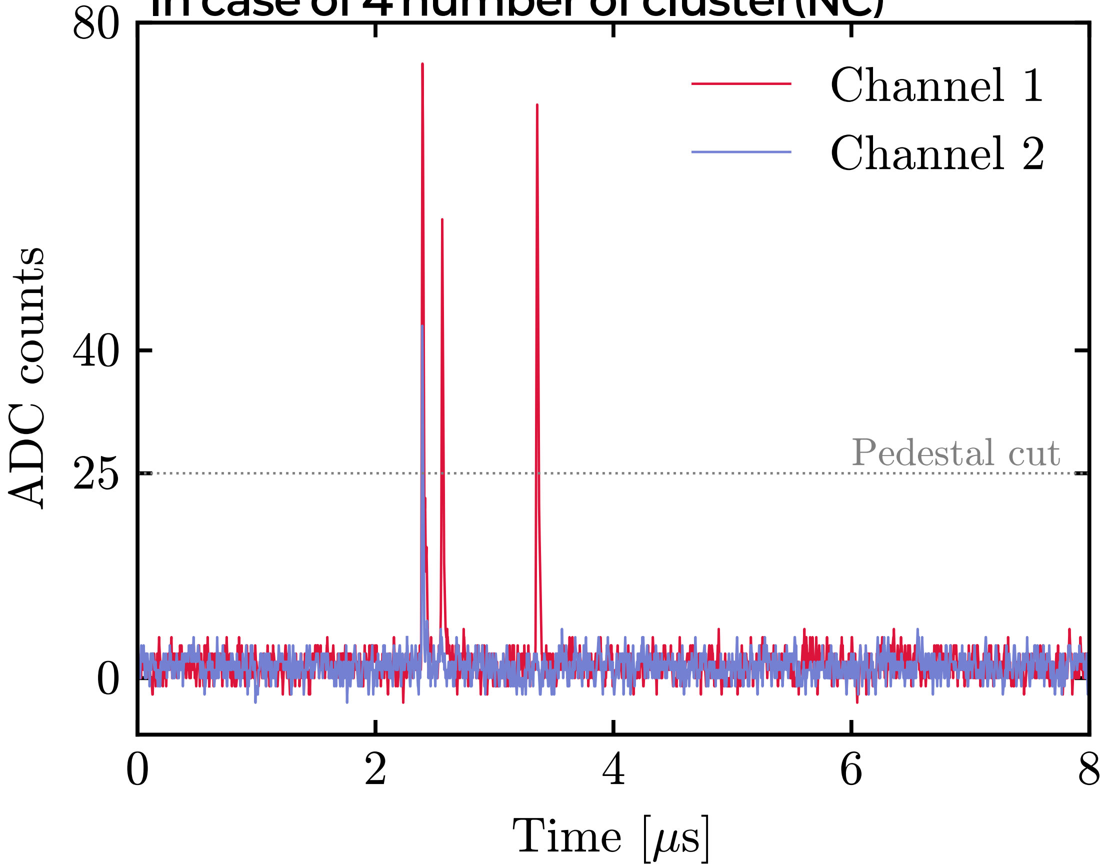
- In this study (threshold < 0.4 keV) :
  1. Event Selection (Signal/Noise separation).
  2. Phenomenological background modeling with roughly single **exponential + constant**.
  3. WIMP analysis.

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

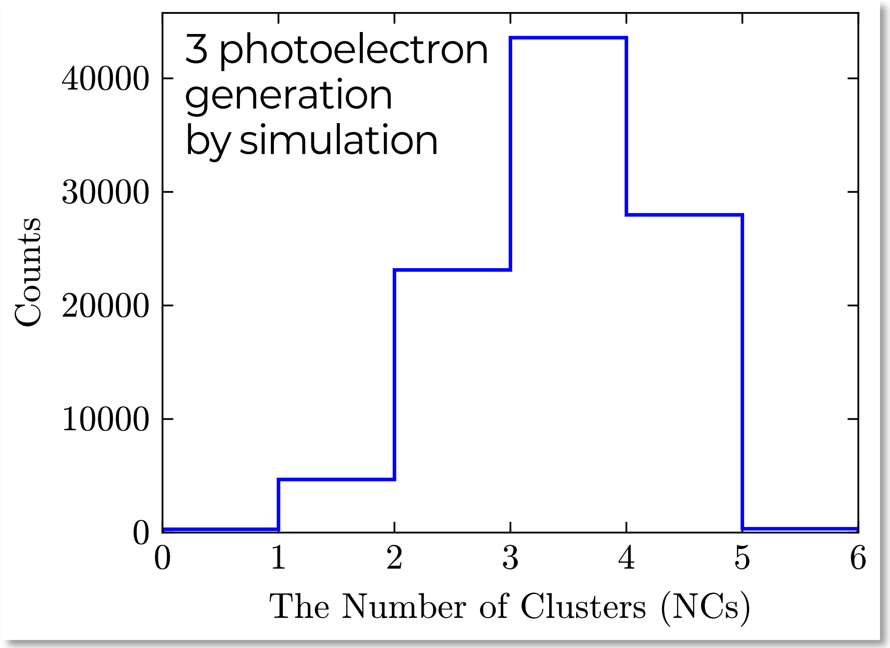
Analysis – Data Process

➢ Definition of Cluster

In case of 4 number of cluster(NC)



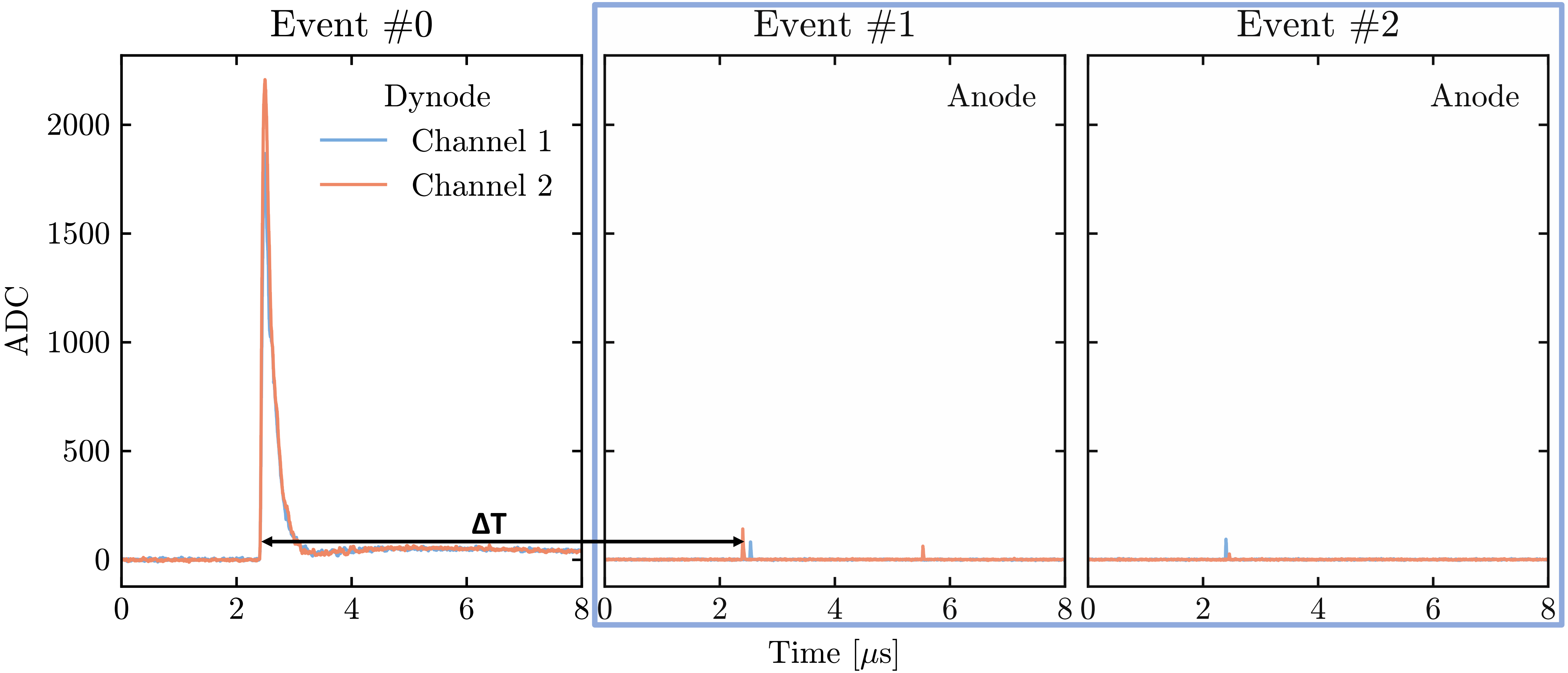
- Cluster : Isolated peak above the threshold.
- COSINE-100 event trigger condition : 2 NC
- **Used 3, 4 NC data for analysis.**
- 1 NC ≈ 1 Photoelectron ≈ 0.067 keV



Analysis – Event Selection

➢ **Deadtime cut**

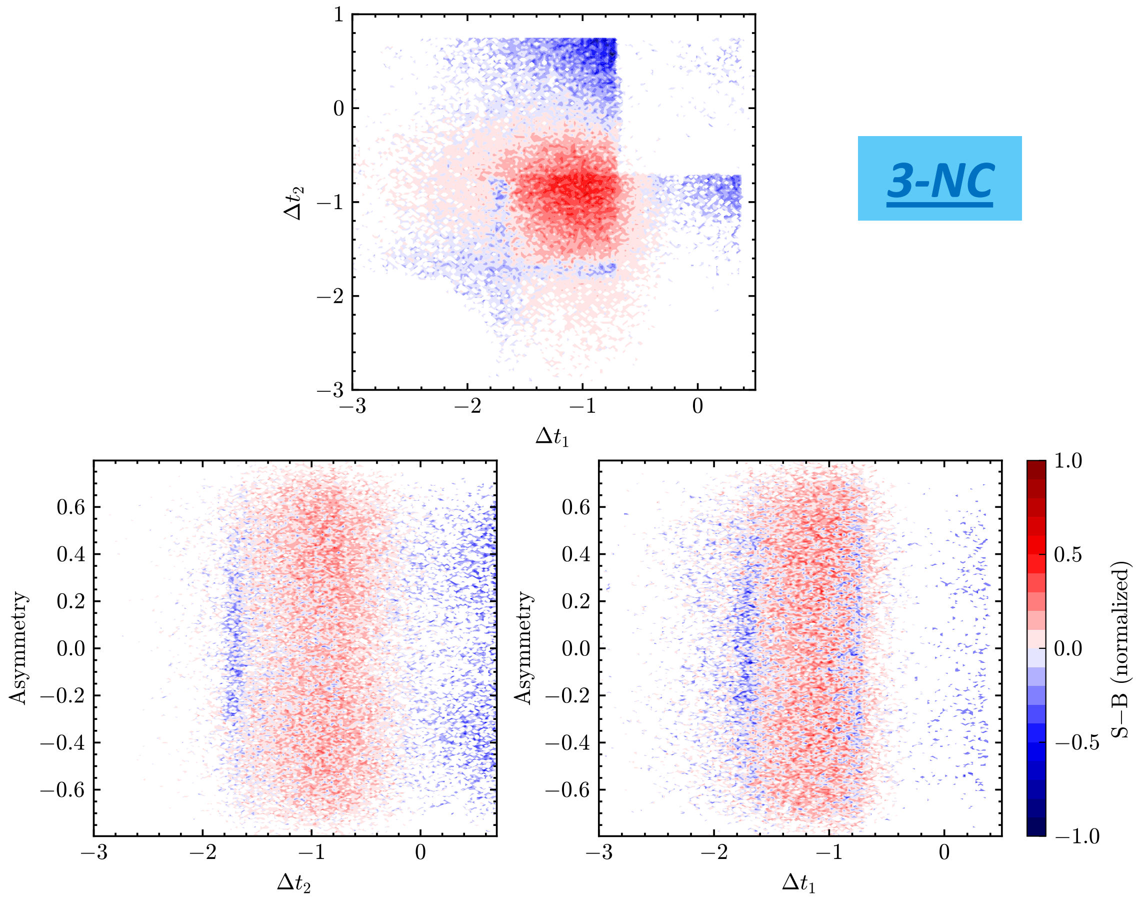
Remove afterglow events



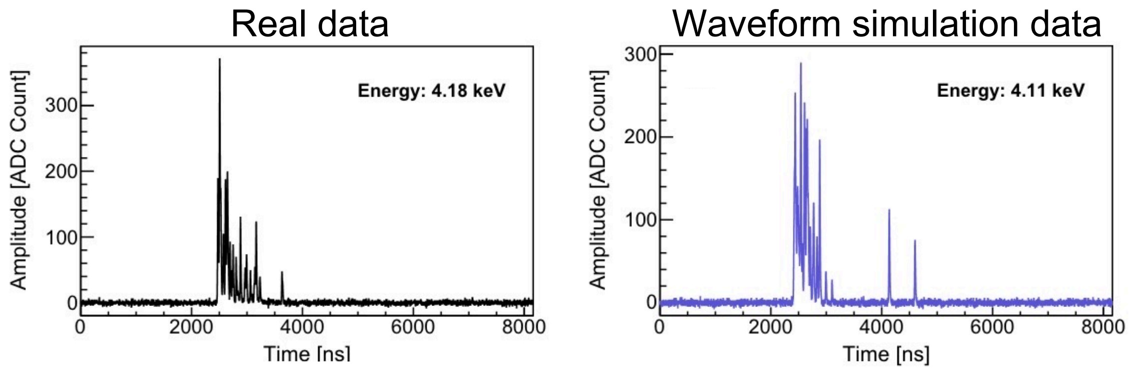
- 97% signal efficiency → ~28% noise reduction.

Analysis – Event Selection

➢ Multi-Layer Perceptron (MLP) for separation



3-NC

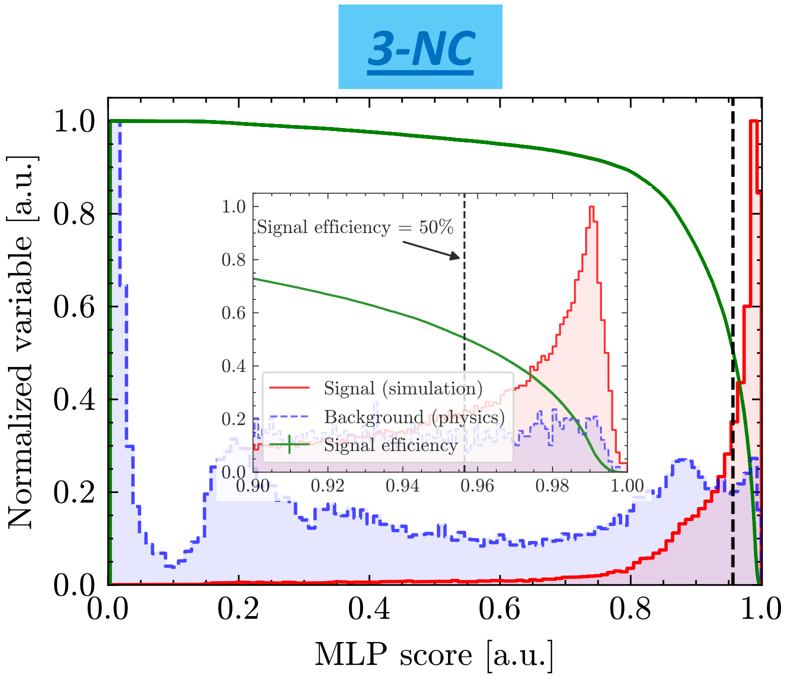


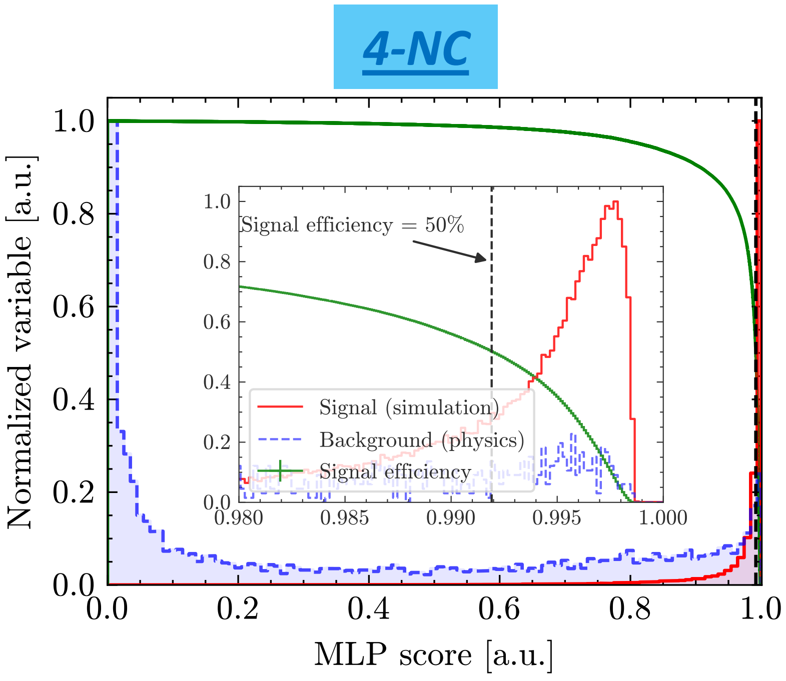
- Training Dataset :
  - Signal : Waveform simulation data
  - Background : Physics data

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

Analysis – Event Selection

➢ Multi-Layer Perceptron (MLP) for separation



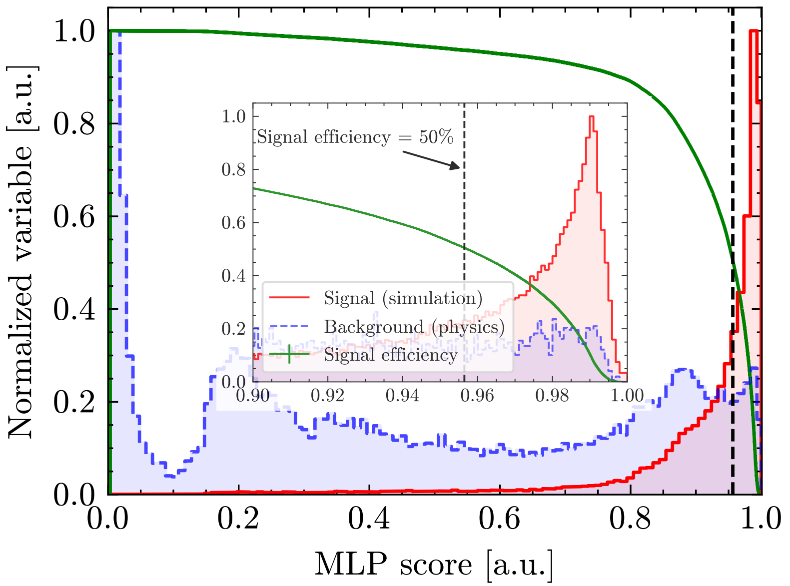


- 50% signal efficiency → noise reduction 91% for 3-NC, 97% for 4-NC.

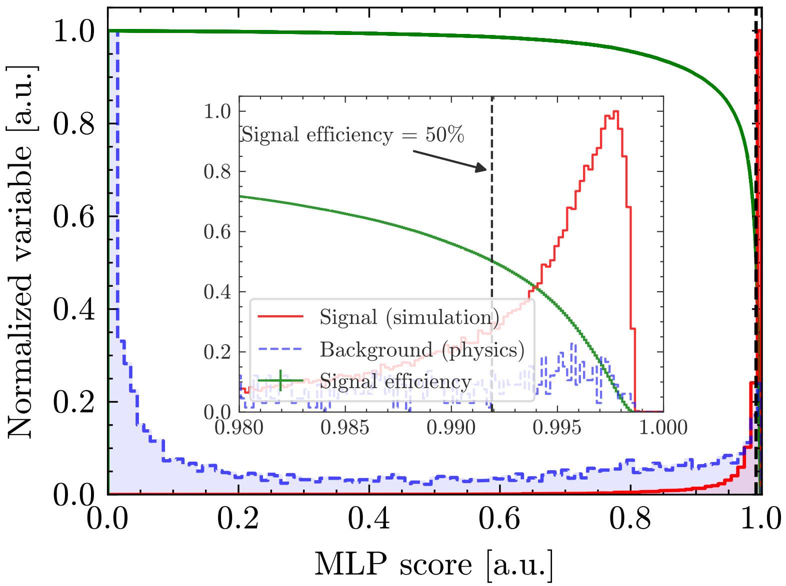
Analysis – Event Selection

➢ Multi-Layer Perceptron (MLP) for separation

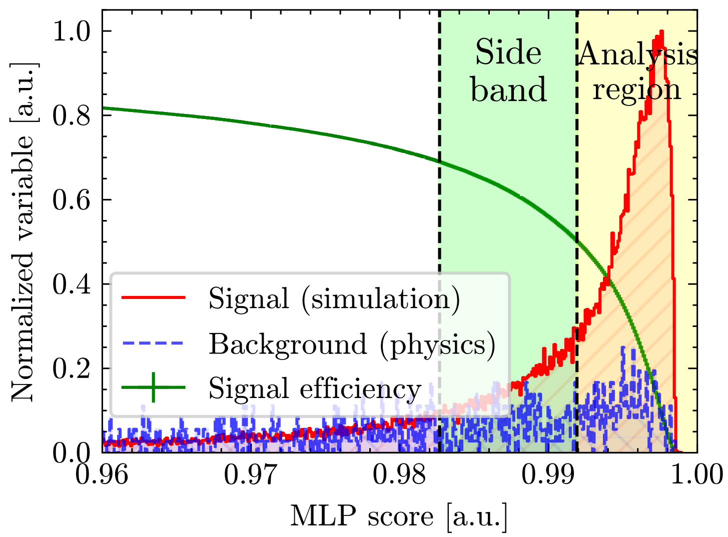
3-NC



4-NC



- For systematics

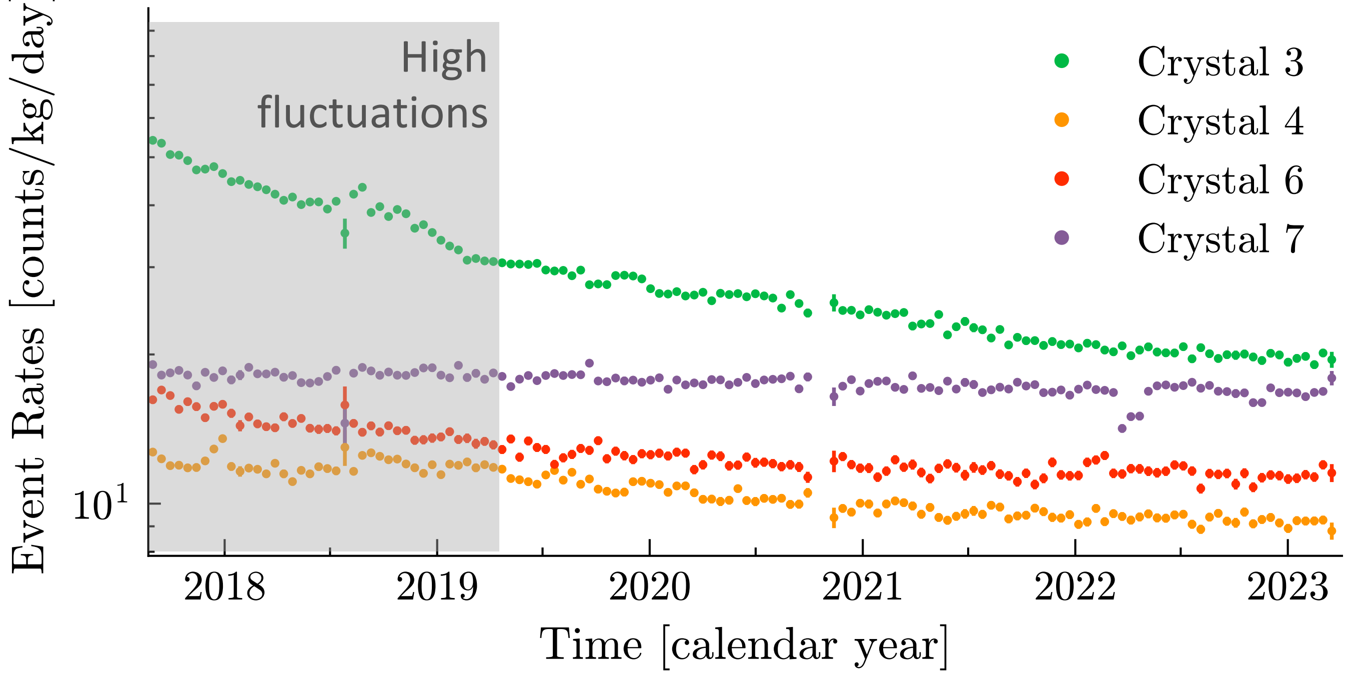


- Assume that the fluctuation from noise is similar on the side band region.
- Derive systematic uncertainty from MLP training with side band data.

Analysis – Modulation Fitting

➢ **COSINE-100 Data Simultaneous Fitting**

3-NC



- 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

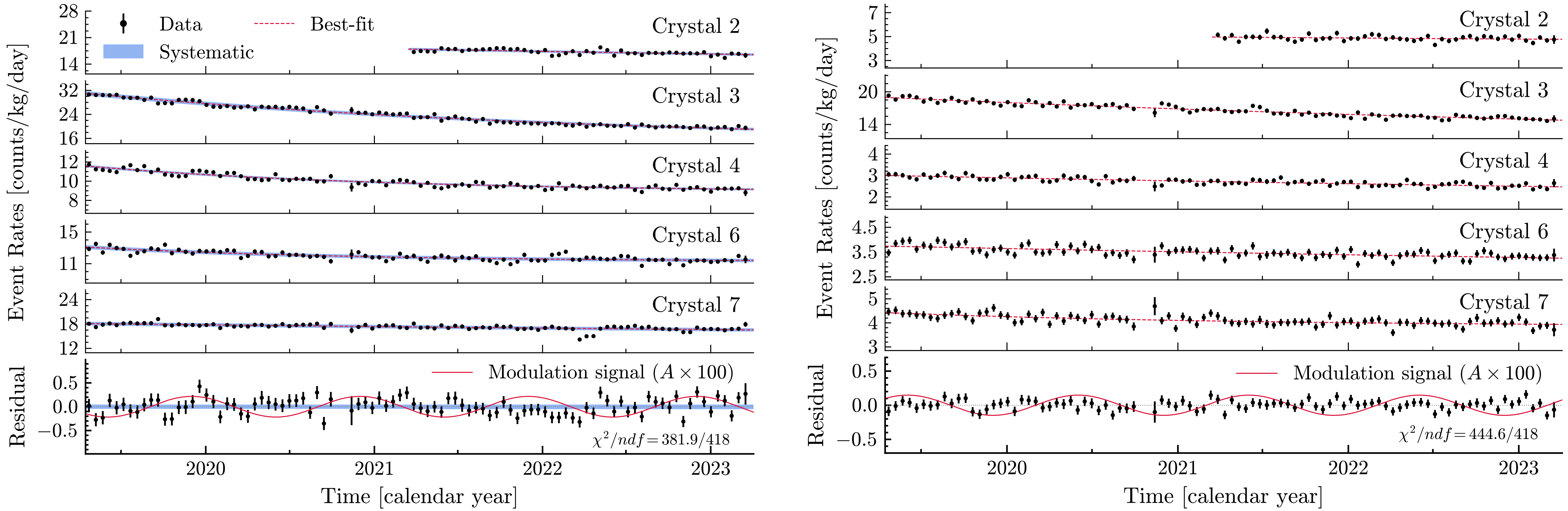
to model the background component.

Analysis – Annual Modulation

➢ **COSINE-100 Data Simultaneous Fitting**

3-NC : *Amplitude* = −0.002 ± 0.026

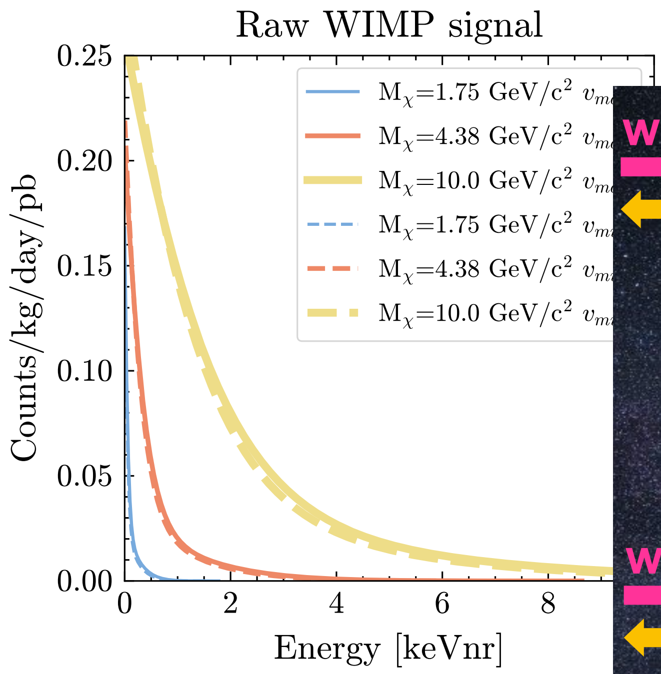
4-NC : *Amplitude* = 0.001 ± 0.001 (counts/kg/day)

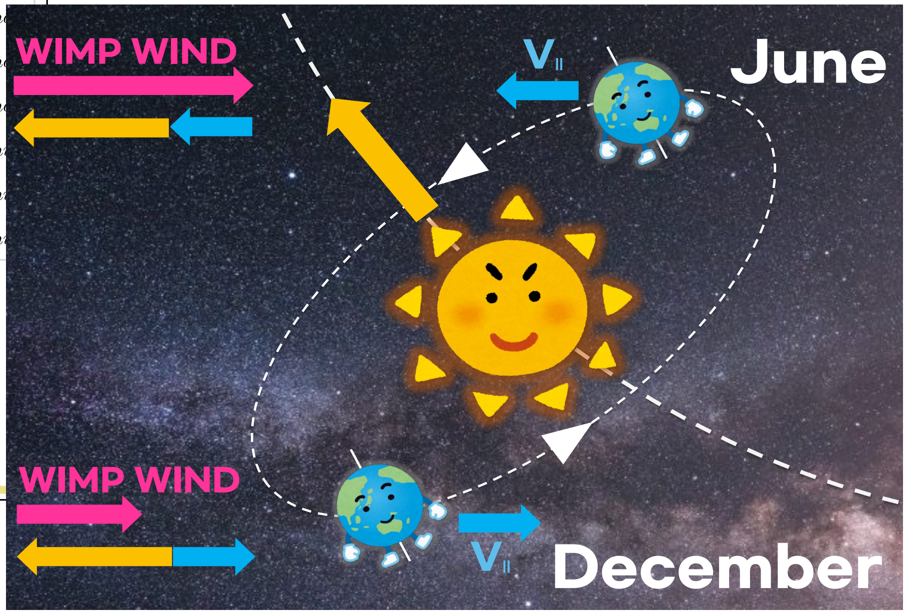


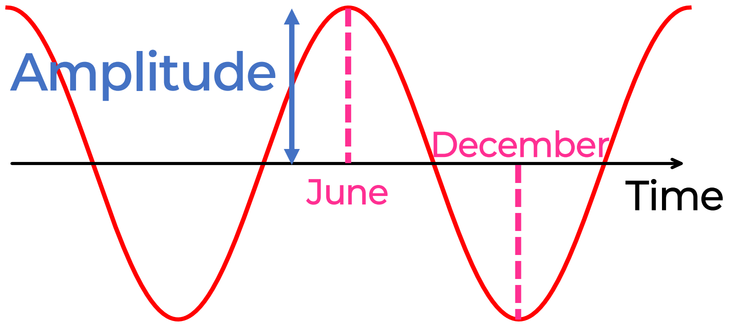
→ **Fitted results consistent with no modulation signal**

Analysis – WIMP Signal Generation

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



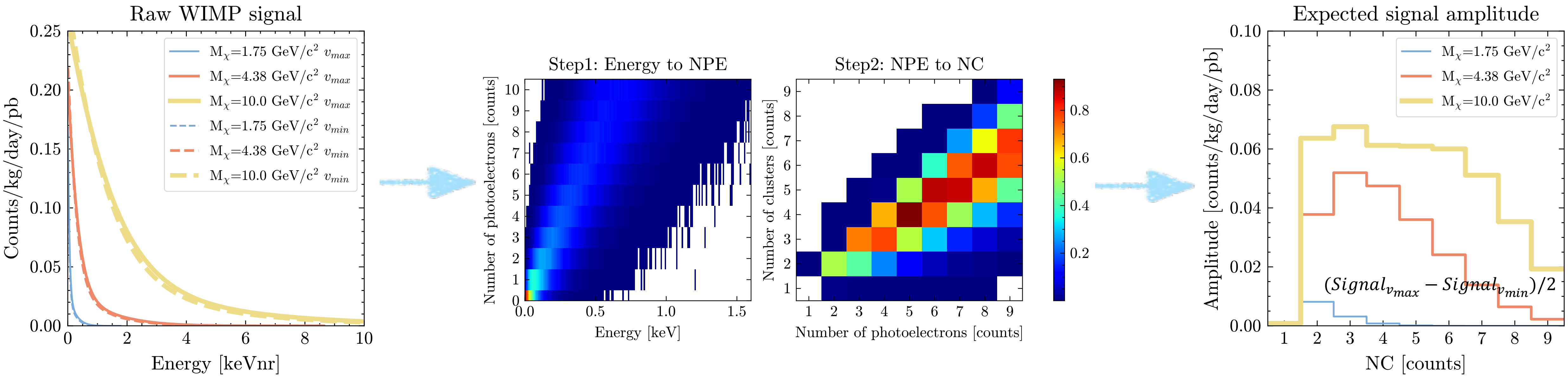




$$\text{Event Rate : } \frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\min}}^{v_{esc}} \frac{d\sigma}{dE_{nr}} v f(v) dv$$

Analysis – WIMP Signal Generation

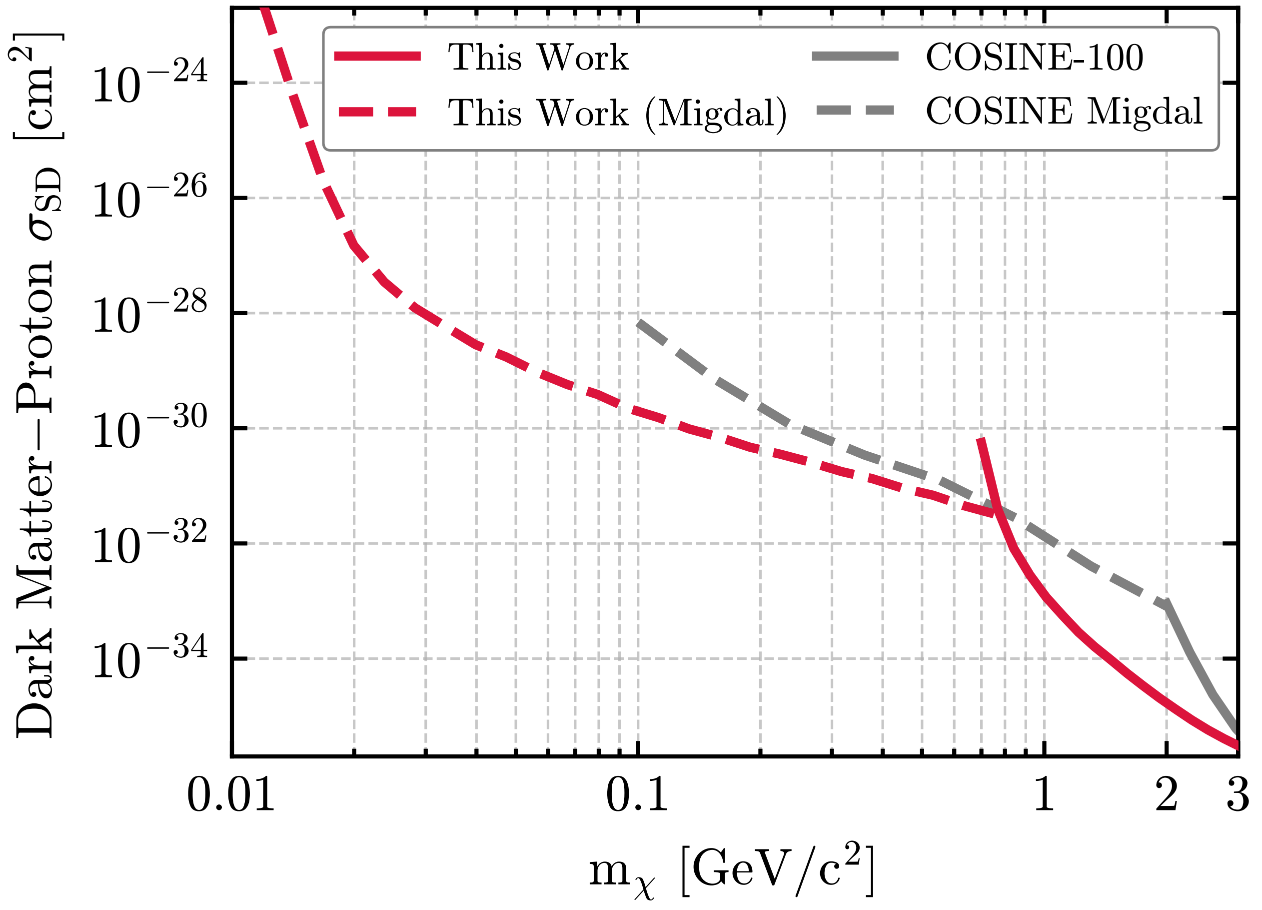
➤ **Expected WIMP signal in COSINE-100 detector**



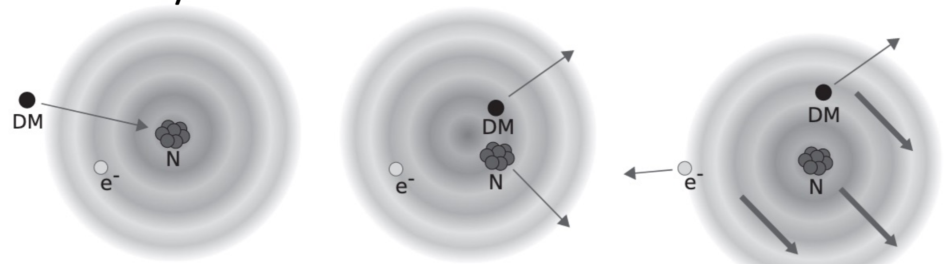
- Simulated WIMP signal for our limit determination.
- Detector response matrix and expected signal amplitude is generated for every crystals.
- Limit is determined using the likelihood ratio test method based on χ2 minimization with 90% C.L.

Result – Spin-dependent cross-section

➢ **Spin-dependent WIMP-Proton cross-section limit**



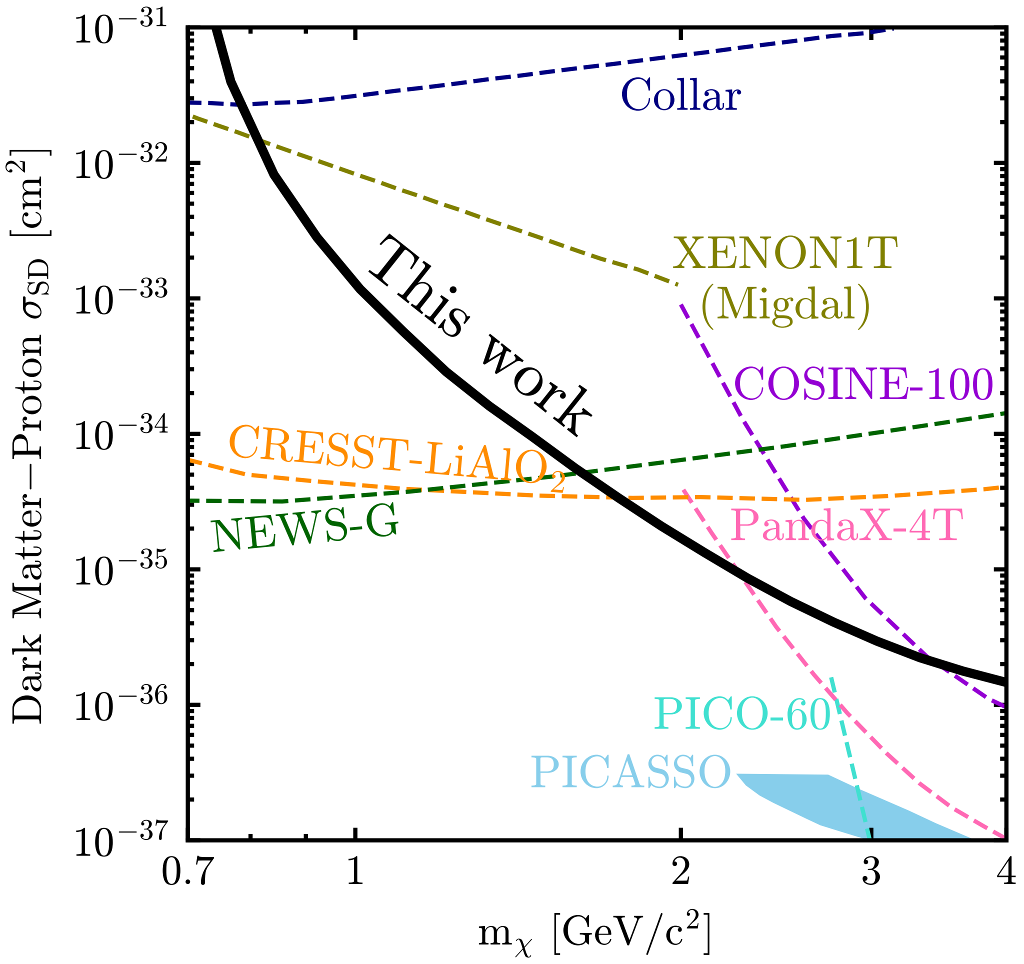
- Sodium and iodine has **odd proton number** (and even neutron number), COSINE-100 can set limits on the WIMP-proton interaction.
- Compared with COSINE-100 3 years data results, this analysis shows better limit at lower WIMP mass range.
- **Migdal effect** : When a nucleus recoils suddenly, the electron cloud cannot follow the motion instantaneously. This can lead to ionization/excitation of bound electrons.



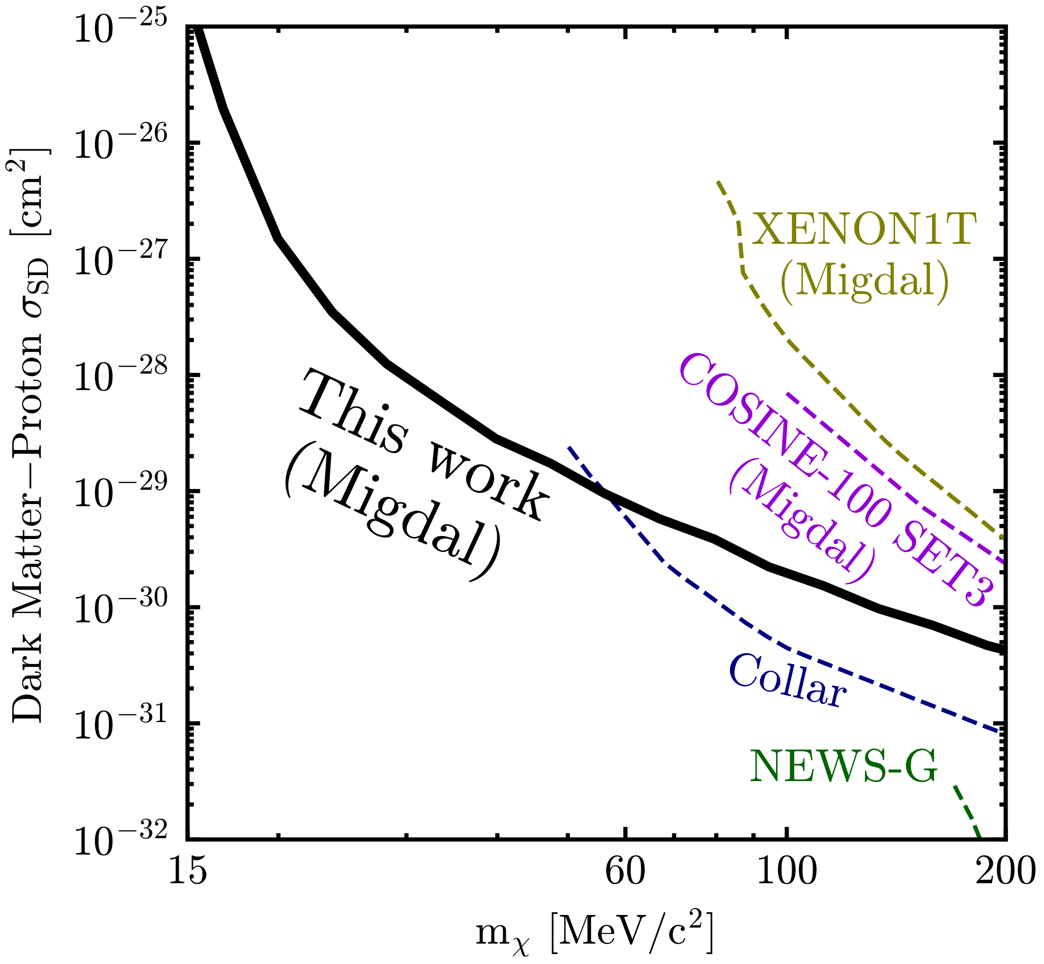
Phys. Rev. Letter **121**, 101801 (2018)

Result – Spin-dependent cross-section

➢ **Spin-dependent only**



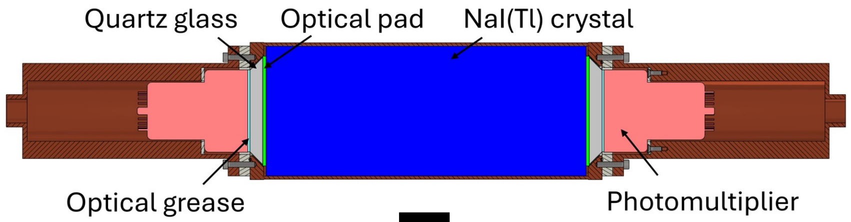
➢ **Spin-dependent with Migdal effect**



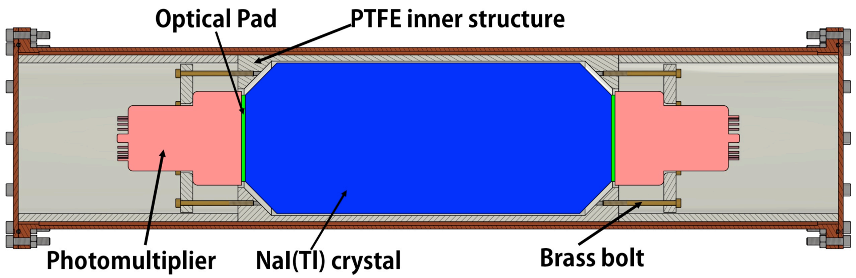
COSINE-100U

➢ Upgrade of COSINE-100 Experiment

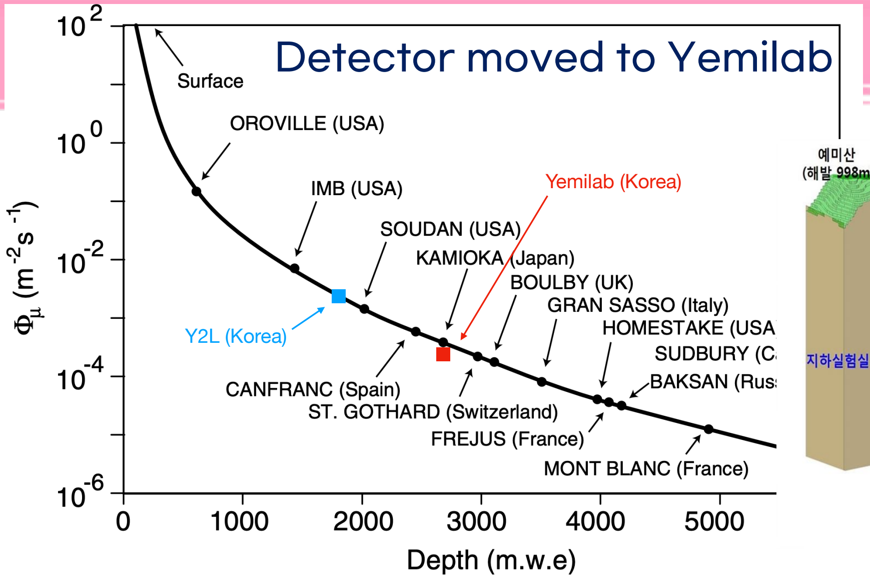
COSINE -100

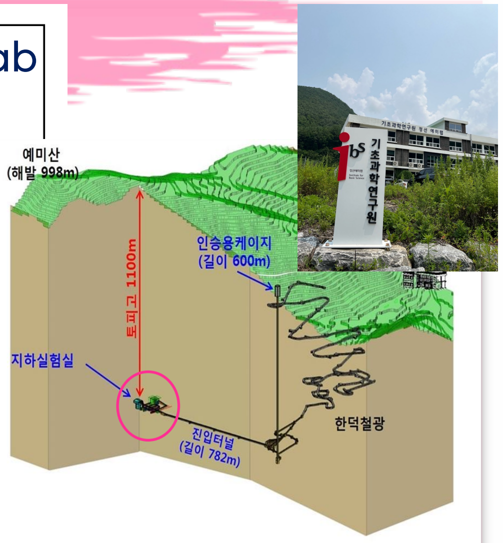


COSINE -100U



Detector moved to Yemilab





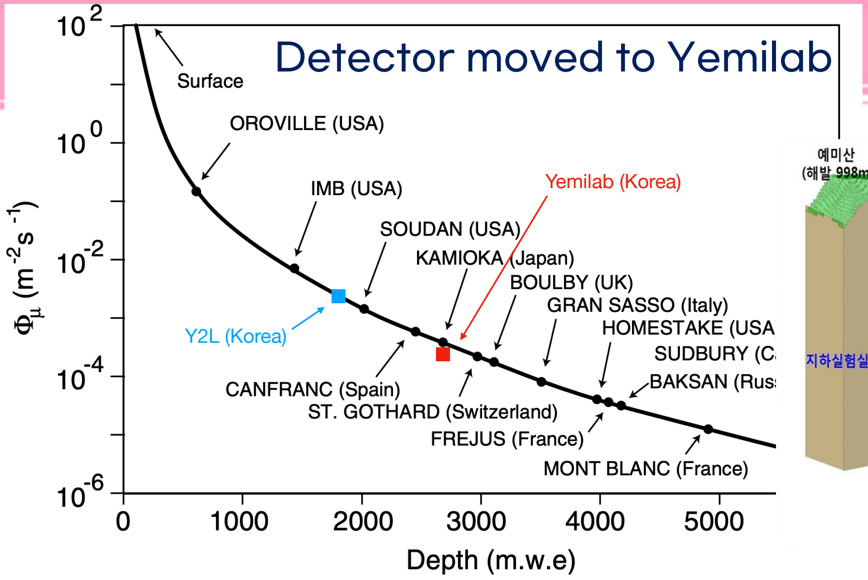
Commun. Phys. **8**, 135(2025)

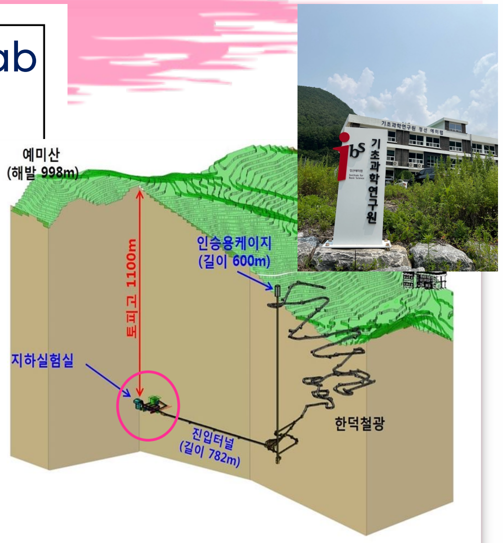
Crystal #	Mass (kg)		Light Yield (p.e./keV)	
	COSINE-100	**COSINE-100U**	COSINE-100	**COSINE-100U**
1	8.3	**7.1**	14.9 ± 1.5	**24.5 ± 0.9**
2	9.2	**8.7**	14.6 ± 1.5	**24.9 ± 0.5**
3	9.2	**8.7**	15.5 ± 1.6	**27.7 ± 0.5**
4	18.0	**16.9**	14.9 ± 1.5	**22.6 ± 0.5**
5	18.3	**17.2**	7.3 ± 0.7	**17.8 ± 0.5**
6	12.5	**11.6**	14.6 ± 1.5	**20.9 ± 0.6**
7	12.5	**11.6**	14.0 ± 1.4	**22.5 ± 0.6**
8	18.3	**17.2**	3.5 ± 0.3	**15.8 ± 0.5**

COSINE-100U

➢ Upgrade of COSINE-100 Experiment

Installation finished and started for physics data since Sep. 2025 !





Commun. Phys. **8**, 135(2025)

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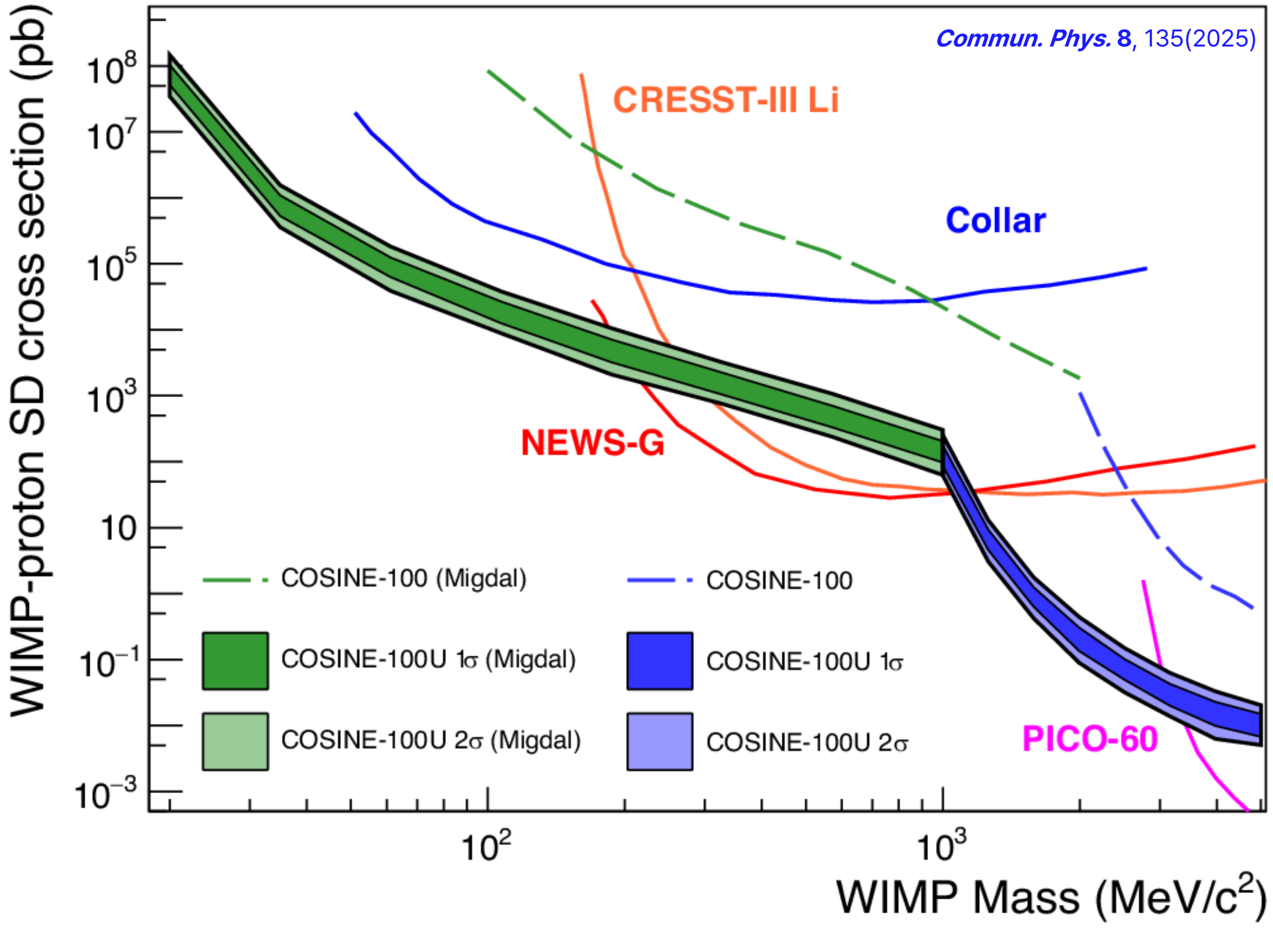
COSINE-100U

➢ **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.

Summary

Scan for this paper

- **Low-threshold data** in 4.3 years of COSINE-100 were used for explore **DM**.
- Event selection such as deadtime cut and MLP cut were applied.
- To get the **modulation amplitude value from COSINE-100 data, simultaneous fit** was conducted with modulation function, which includes phenomenological background modeling, in the form of,

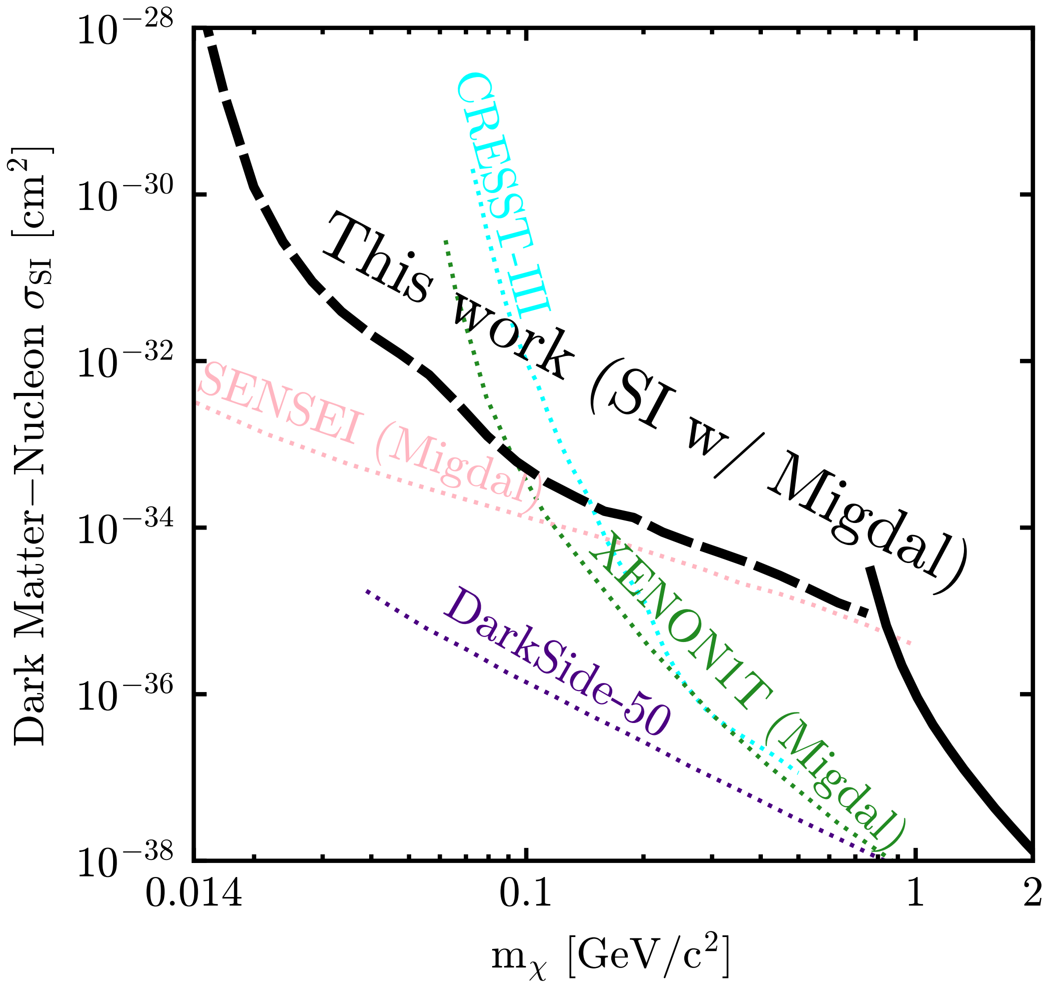
$$f(t) = A\cos\left(\frac{2\pi}{T}(t-\phi)\right) + e^{p_0+p_1 t} + C.$$

- **No significant modulation signal** were observed.
- **Spin-dependent DM-proton cross-section** was investigated and we could **reach new regions of the low-mass DM parameter space.**
- From the COSINE-100U, we can approach further lower mass DM.

Thank you for your attention!

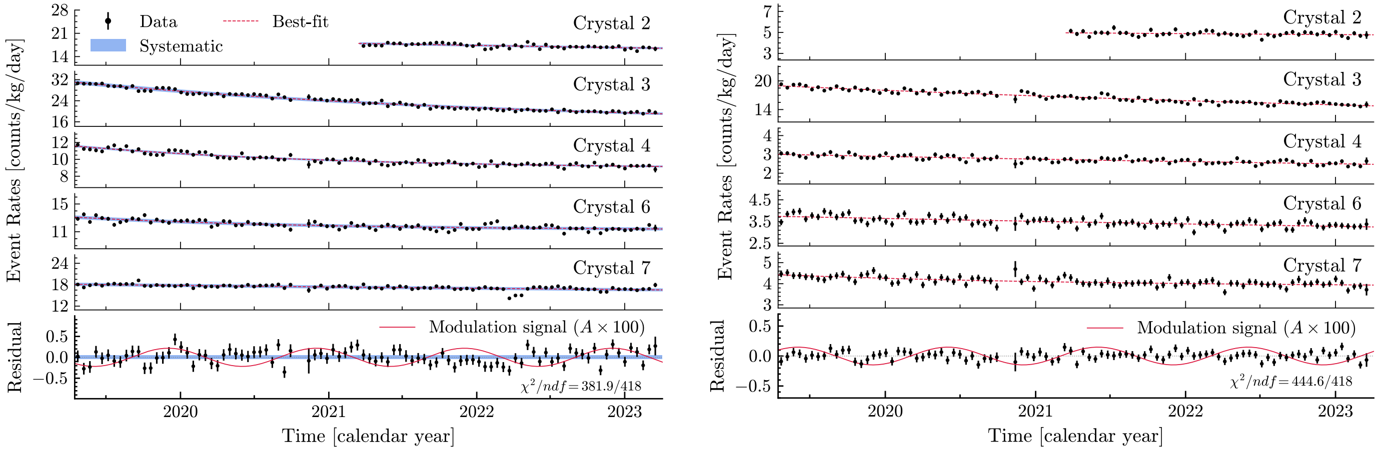
Result – Spin-independent cross section

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

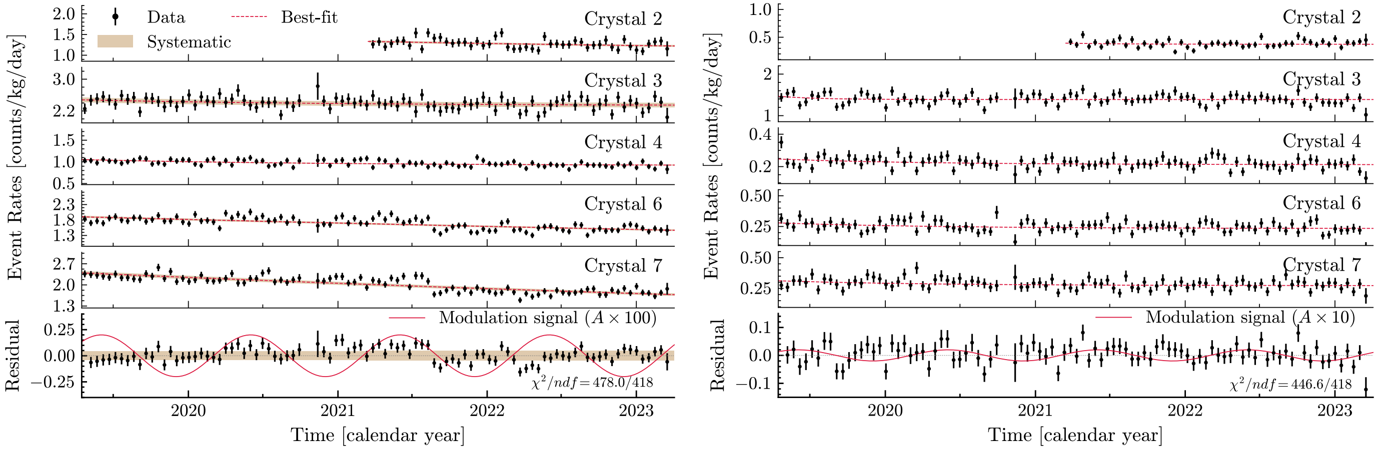


Analysis – Annual Modulation

➢ COSINE-100 Data Simultaneous Fitting



(a) Single-hit



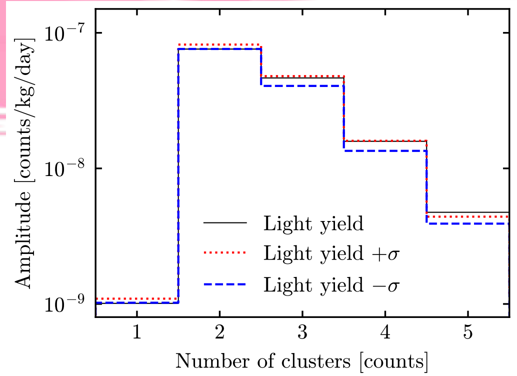
(b) Multiple-hit

- 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

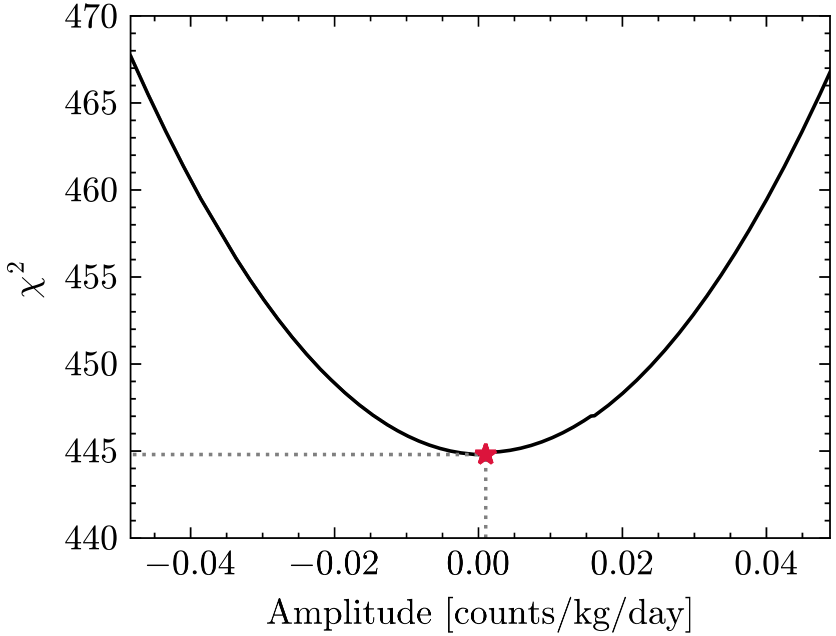
- From multiple-hit dataset, we could check the modulation signal from background component (not DM).
- No modulation signal in both data.

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

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

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