Recent results from the COSINE-100 Experiment

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Center for Underground Physics (IBS)

On behalf of the COSINE-100 collaboration

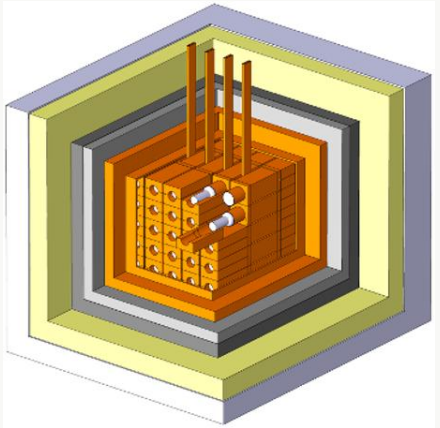
August 25, 2025

Institute for Basic Science

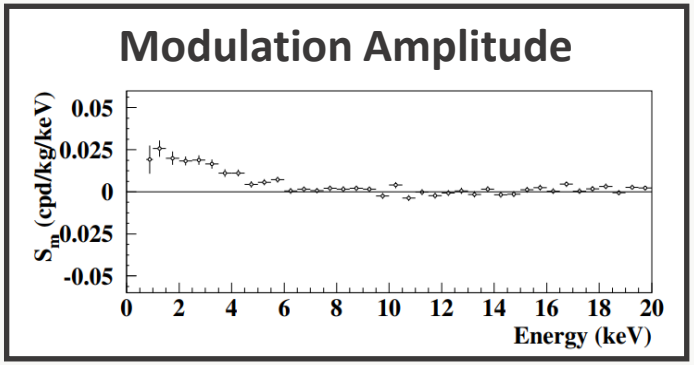
CENTER FOR UNDERGROUND PHYSICS

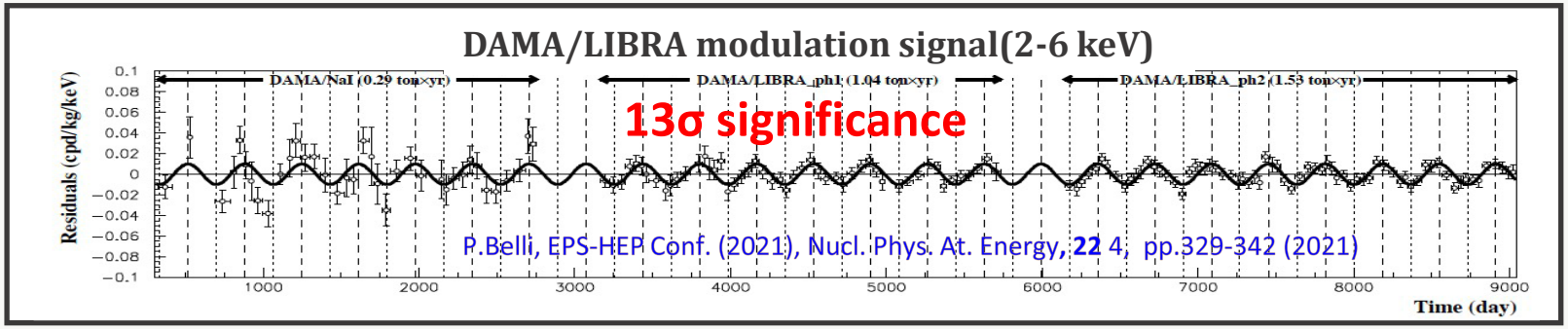
Annual modulation signal from DAMA/LIBRA

- Search for **Dark matter (DM)** annual modulation signature @ Gran Sasso in Italy
- Using 25 × 9.7 kg **NaI(Tl)** detectors
- **Claims** an **observation** of a DM signal (WIMP modulation signal) at **13σ** significance (2-6 keV)
- **Amplitude** : 0.00996 ± 0.0007 counts/day/kg/keV
  - Phase = 145±5 days
  - Period = 0.997± 0.0008 year



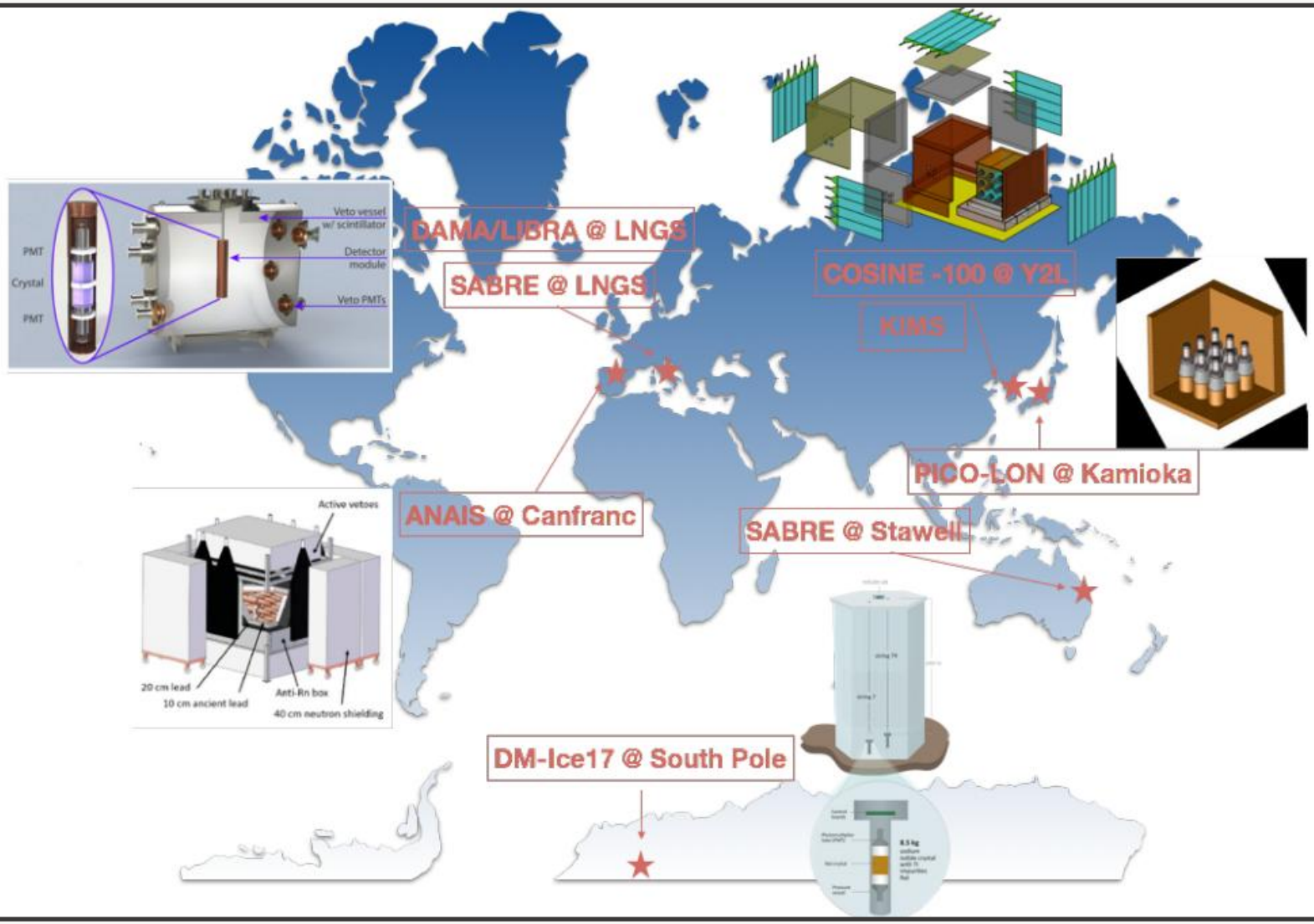
DAMA/LIBRA detector





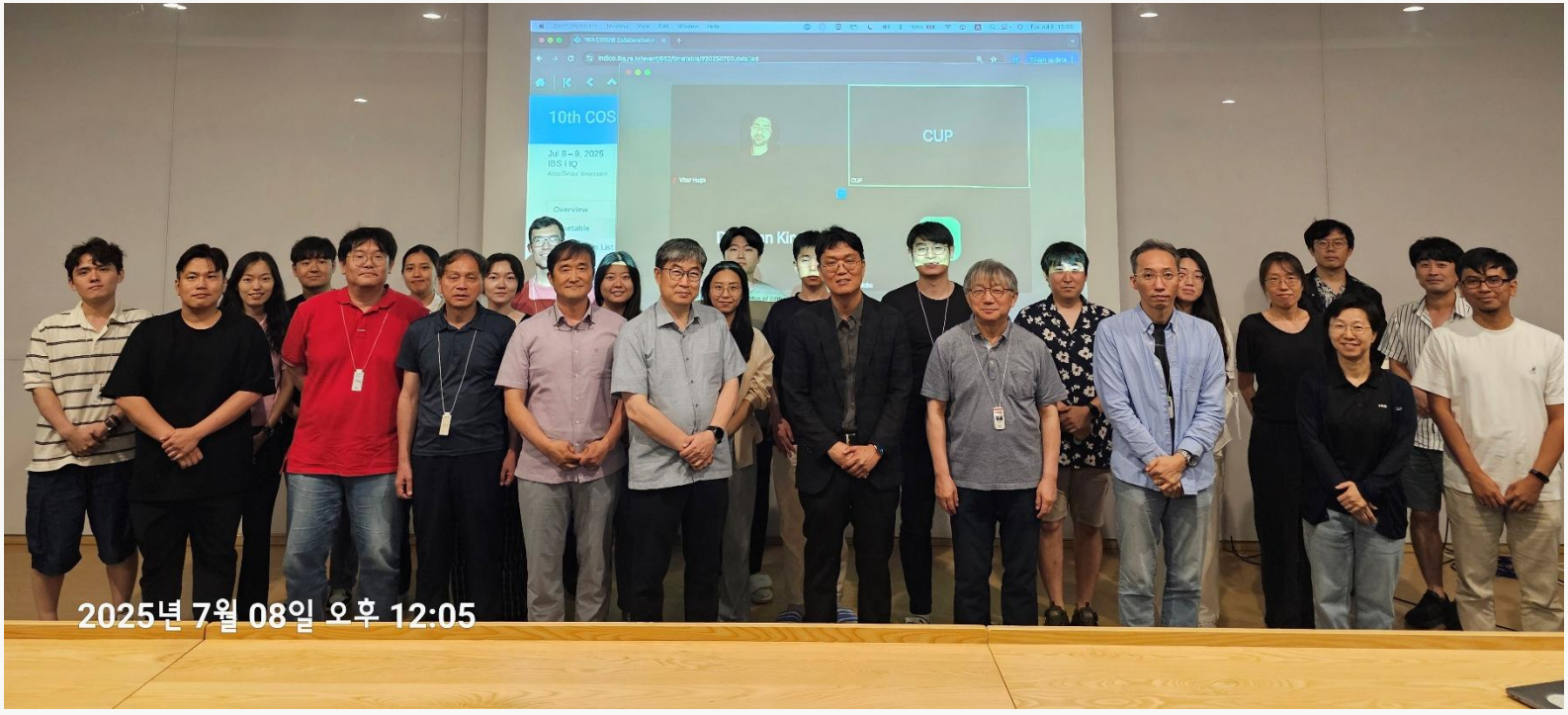
P.Belli, EPS-HEP Conf. (2021), Nucl. Phys. At. Energy, **22** 4, pp.329-342 (2021)

NaI(Tl) Dark matter search

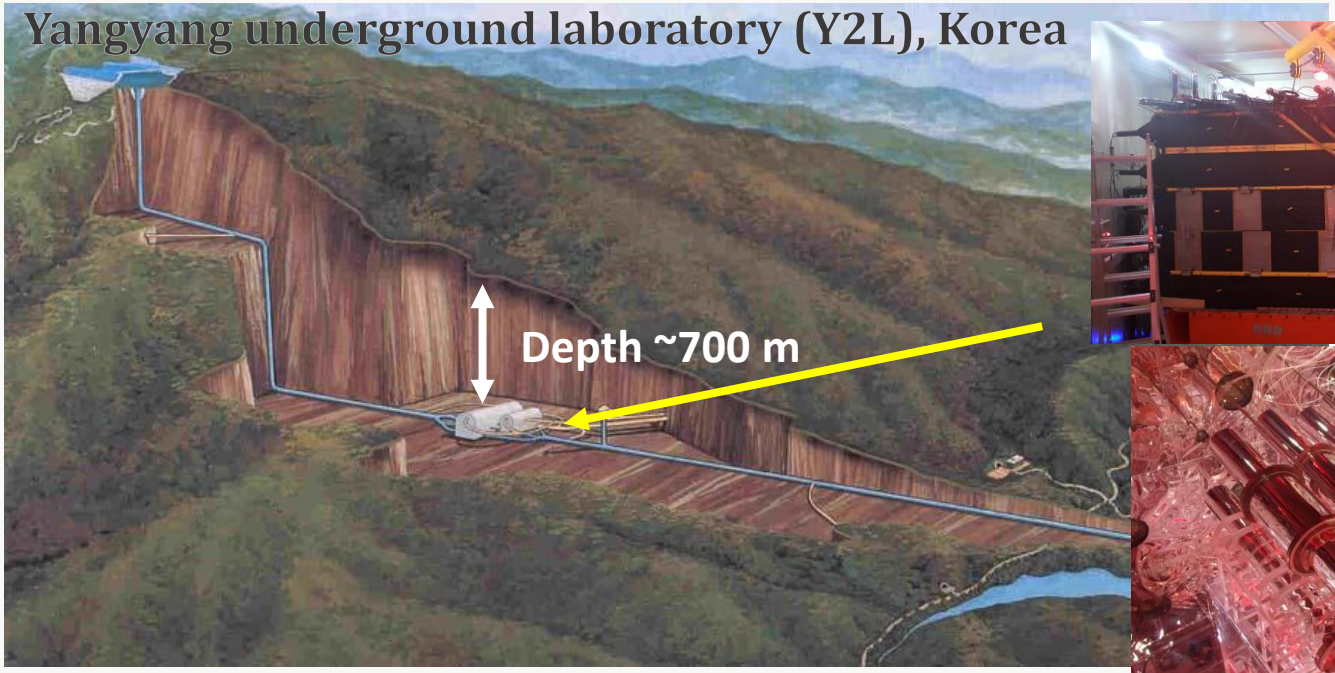


COSINE-100 collaboration

- Joint collaboration of **DM-ICE** & **KIMS**
- **~50 collaborators** in **18 institutes**



COSINE-100 experiment



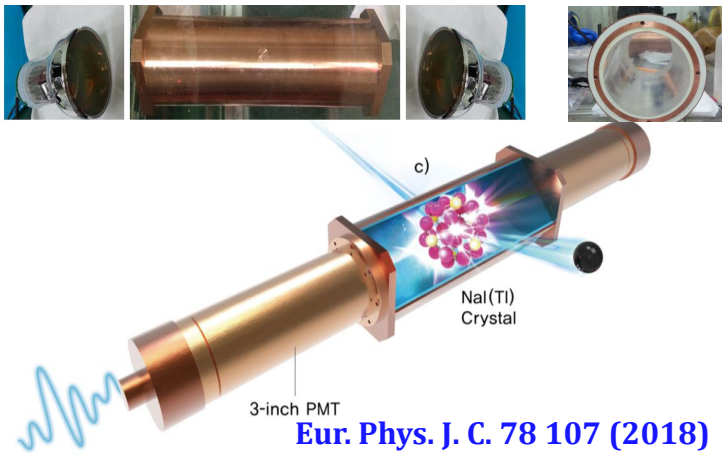
- **YangYang** underground laboratory (**Y2L**)
- **Started** physics operation since **September/2016**
- **Ended** physics run **March/2023**
- **COSINE-100U**pgrade will start at **Yemilab in early of September.**
  - **Upgrade crystal detector assembly** to improve **light yield**

Yemilab operation **Detail in JungHo's talk** **25th Aug. 14:20~14:40** **Underground Laboratories session**	**COSINE-100U** **Detail in Doohyeok's talk** **27th Aug. 16:00~16:20** **Dark matter session**

COSINE-100 Detector

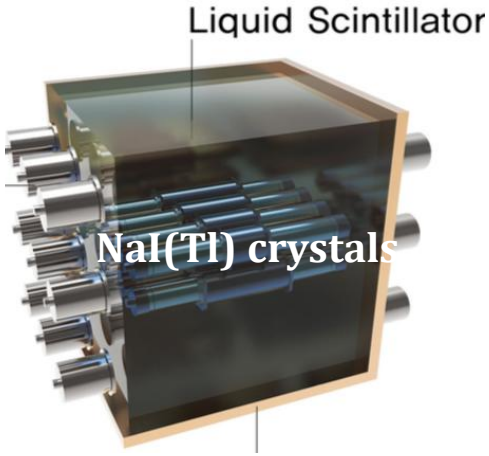
- 8 NaI(Tl) Crystals (106 kg)
  - Higher light yield (15 P.E./keV) than DAMA/LIBRA (5-10 P.E./keV)
- Shielding structure
  - Active veto
    - 2200-L LAB-based Liquid scintillator(LS)
    - 4π Muon counter
  - Passive veto
    - 3-cm thick copper box
    - 20-cm thick lead castle

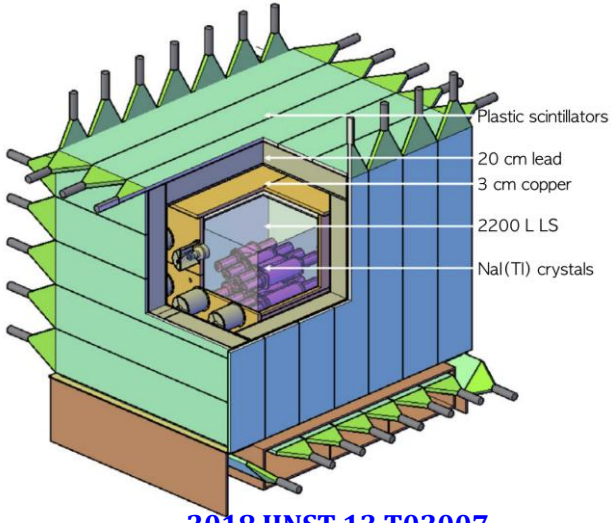
NaI(Tl) crystal



Eur. Phys. J. C. 78 107 (2018)
Eur. Phys. J. C. 78 490 (2018)

Shielding structure

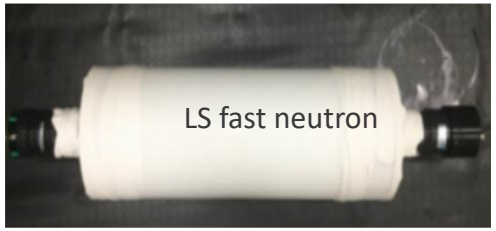


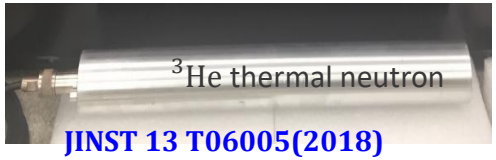


Nucl. Instrum. Meth. A 106, 165431 (2021)
Nucl. Instrum. Meth. A 851 103 (2017)

2018 JINST 13 T02007
Eur. Phys. J. C 78, 107 (2018)

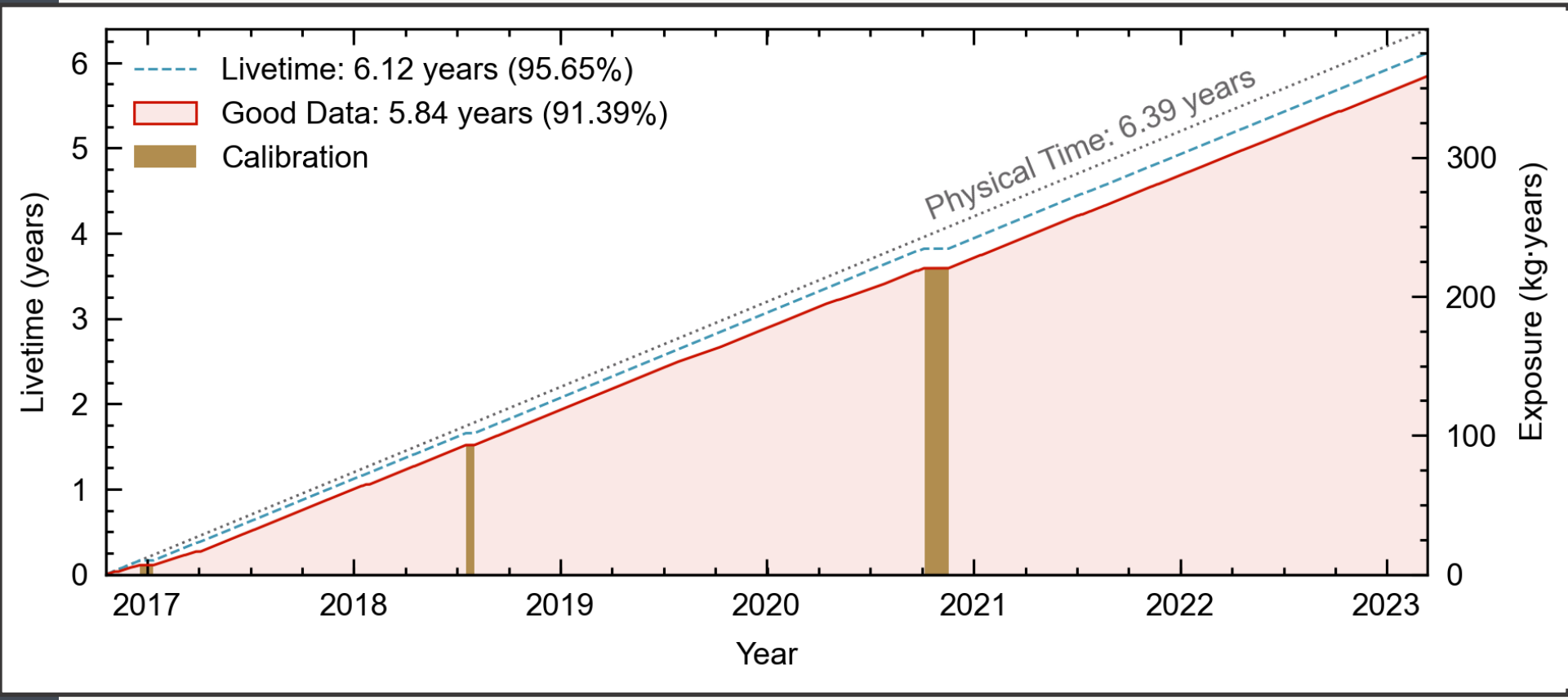
Neutron monitoring





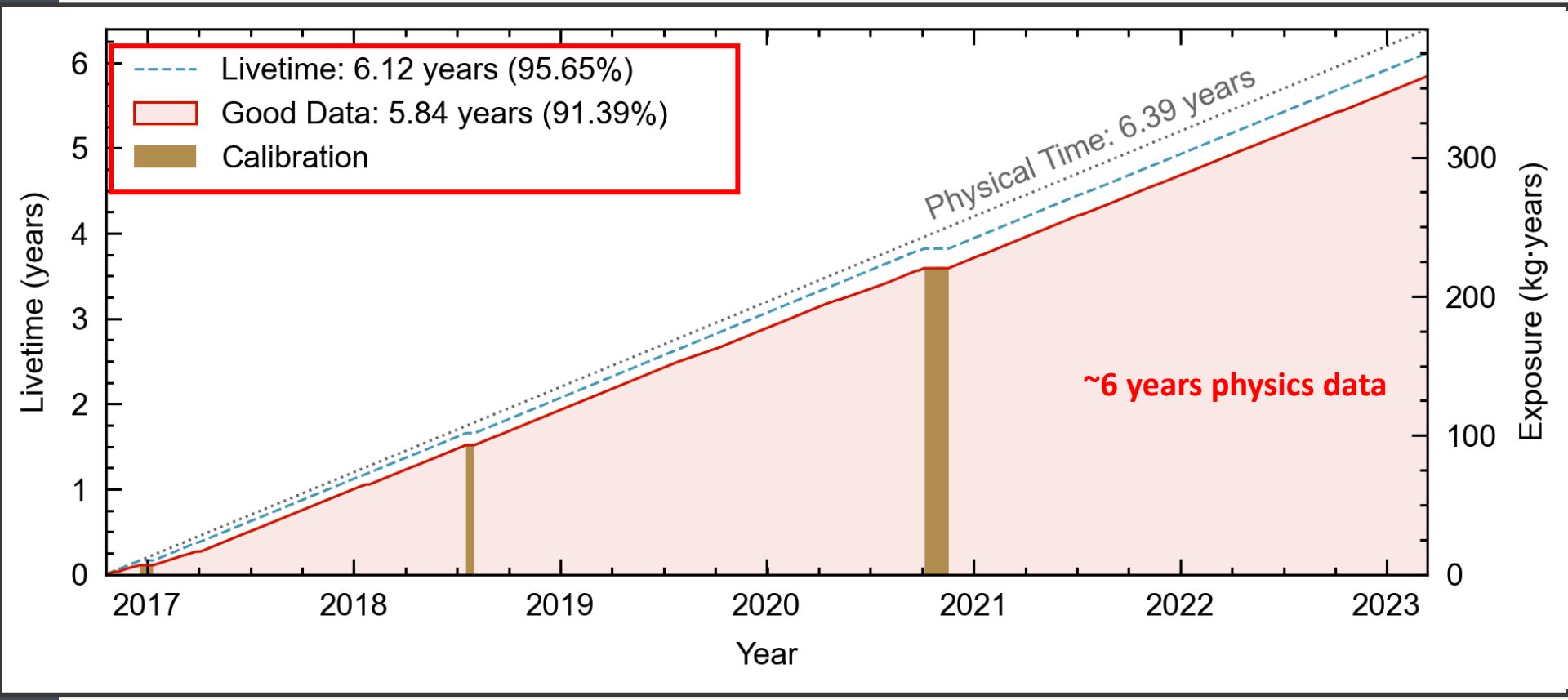
JINST 13 T06005(2018)

Data exposure



- **Operation from Sep. 2016 to Mar. 2023**
  - **Physics run : 6.12 years**
  - **Good data : 5.84 years**

Data exposure



- **Operation from Sep. 2016 to Mar. 2023**
  - **Physics run : 6.12 years**
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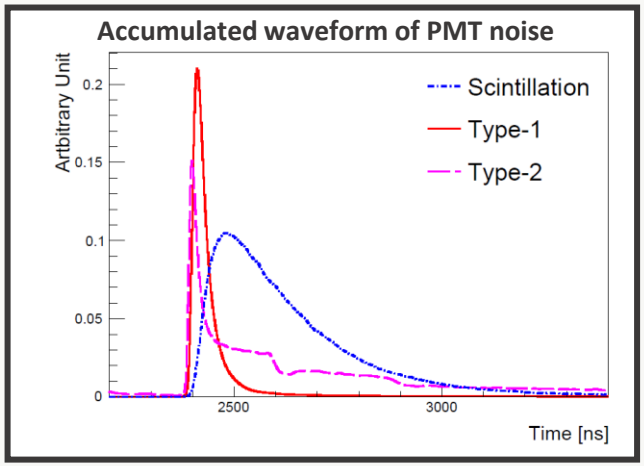
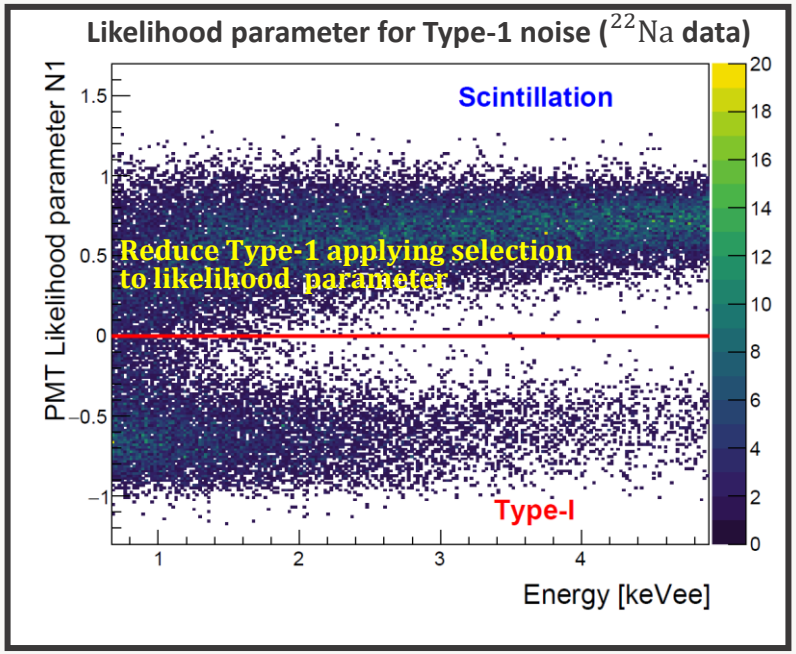
Detector understanding - Event Selection

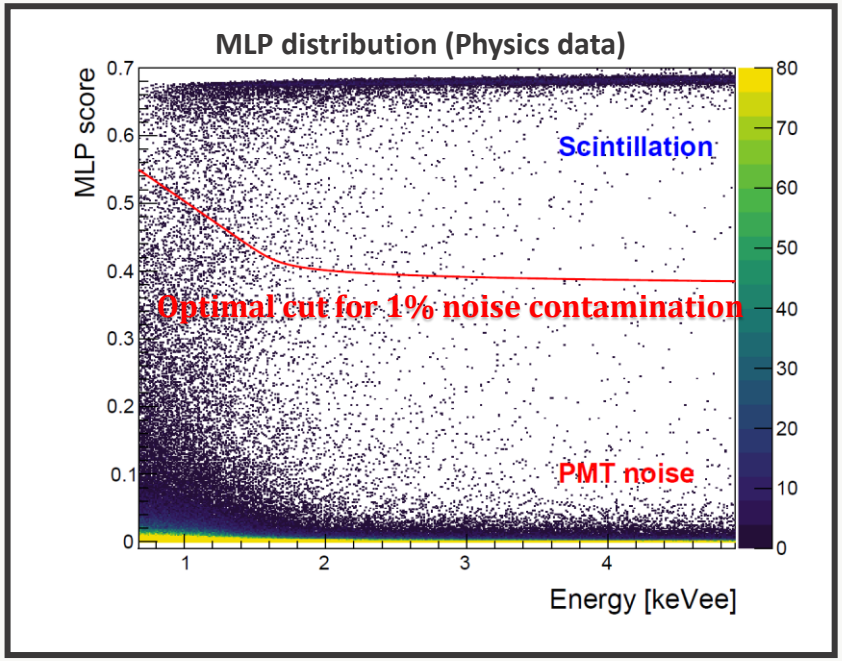


- To select **pure scintillation** from **PMT-induce noise**
  - Use **pulse-shape parameters**
    - Meantime, likelihood parameters

    + **Fast Fourier Transformation** parameter
- Multivariable analysis - **MLP**
  Multilayer perceptron
  - **Achieved 0.7 keV threshold** JINST **19** P12013 (2025)

$$F_{\mathcal{L}}^{N1} = \frac{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} - \ln \mathcal{L}_{\mathrm{FFT}}^{S}}{\ln \mathcal{L}_{\mathrm{FFT}}^{N1} + \ln \mathcal{L}_{\mathrm{FFT}}^{S}}$$



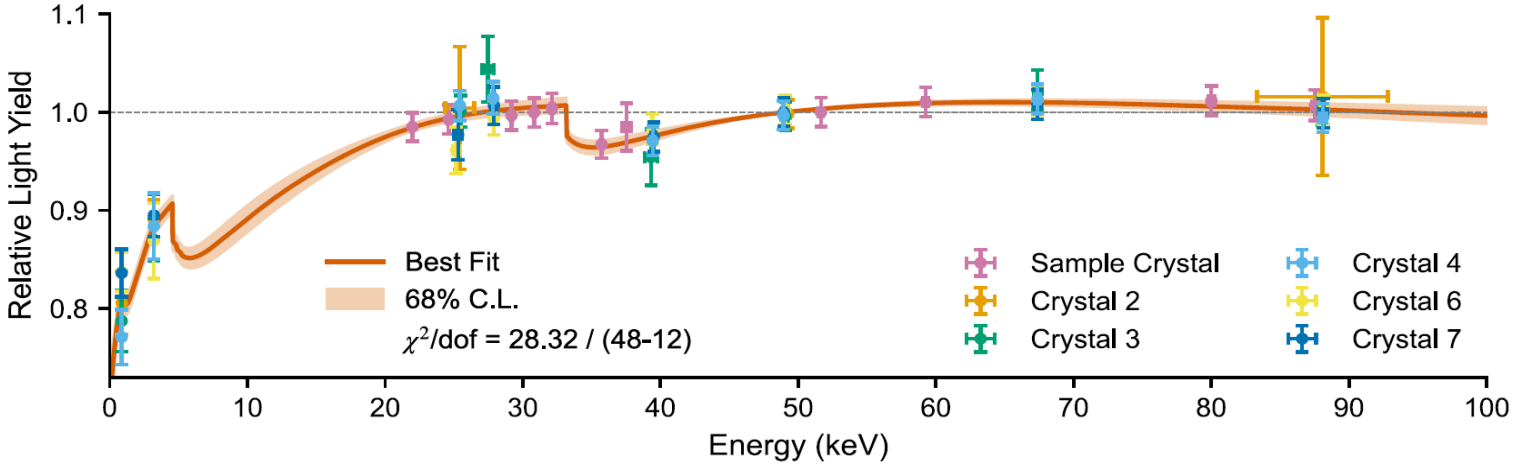


Detector understanding

Nonproportionality& Quenching factor

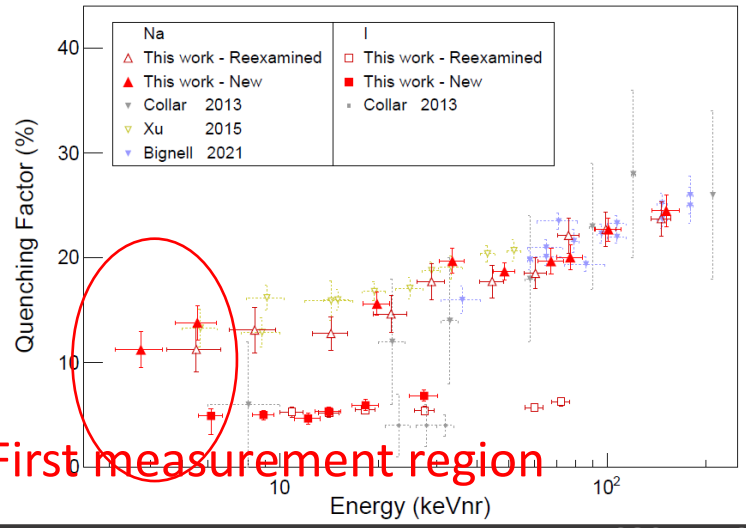
Nonproportionality(nPR) of NaI(Tl)

Eur. Phys. J. C **84** 484 (2024)

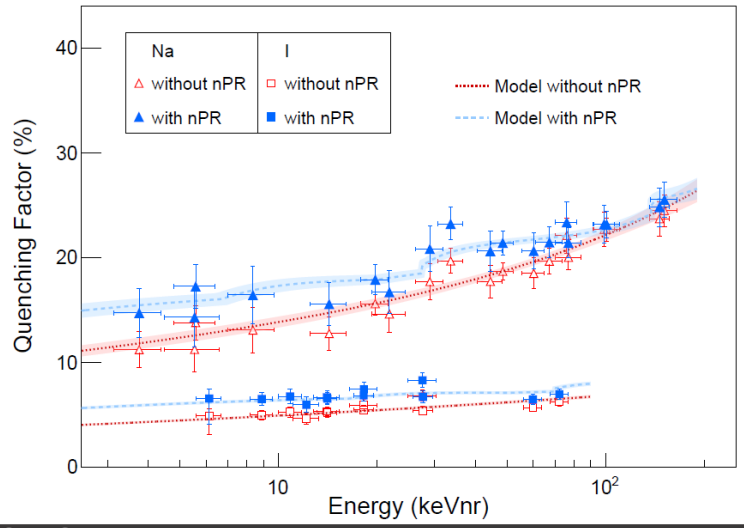


Quenching factor of NaI(Tl)

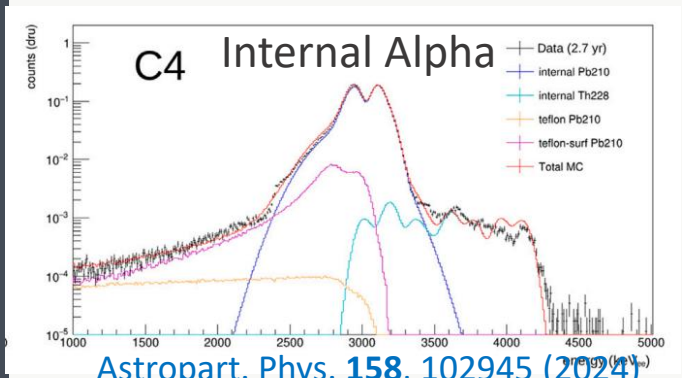
Phys. Rev. C **110**, 014614 (2024)



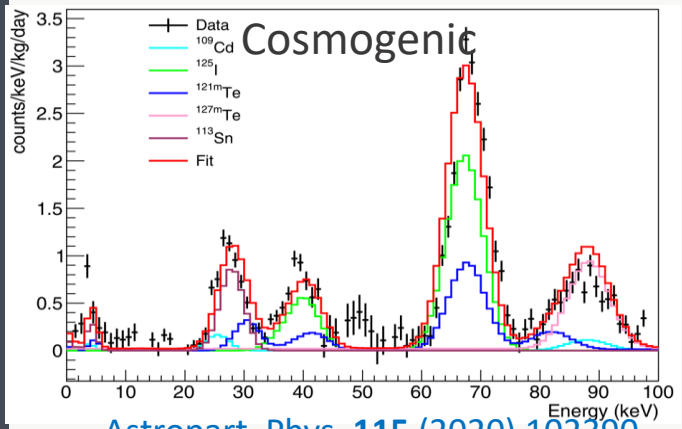
First measurement region



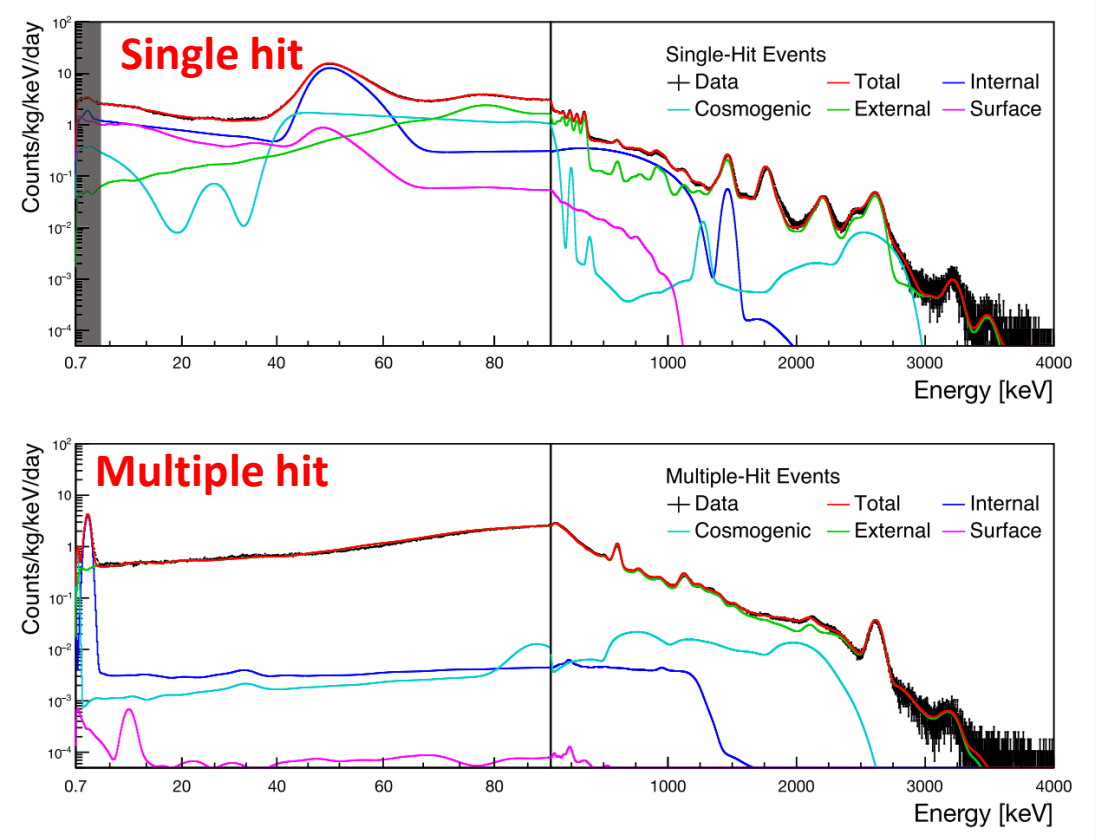
Background understanding



Astropart. Phys. **158**, 102945 (2024)



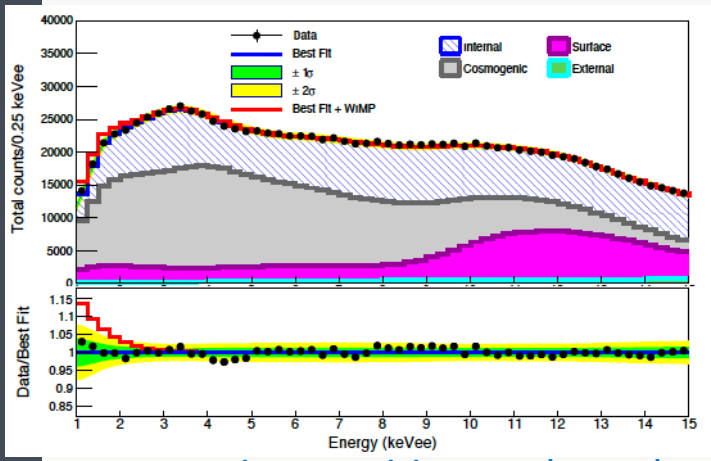
Astropart. Phys. **115** (2020) 102390



- Use 3-year data with **0.7 keV-4000 keV range.** Eur. Phys. J. C **85** 32 (2024)
  - Exclude **WIMP ROI** (<6keV single hit) in the fitting
- Improve modeling with updated **detector understanding** (nPR, Alpha modeling)

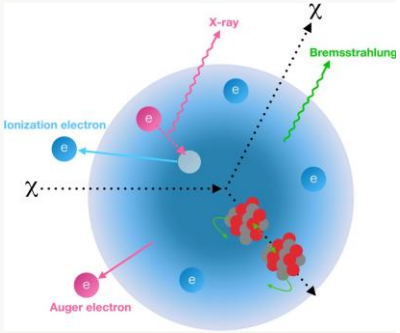
WIMP extraction analysis

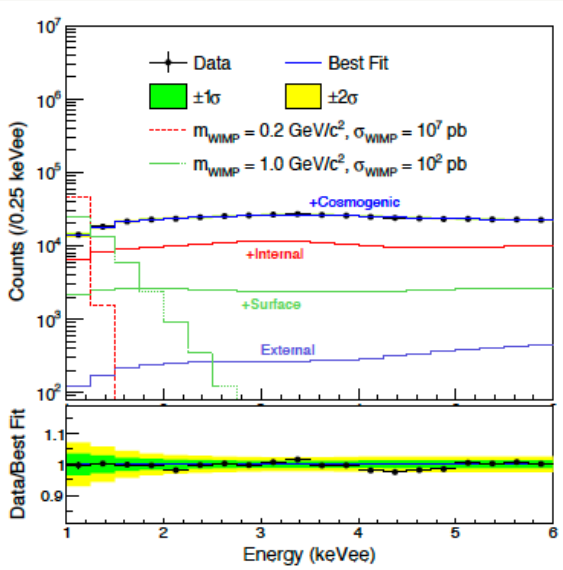
- Using **2 years data** set with **1 keV threshold**



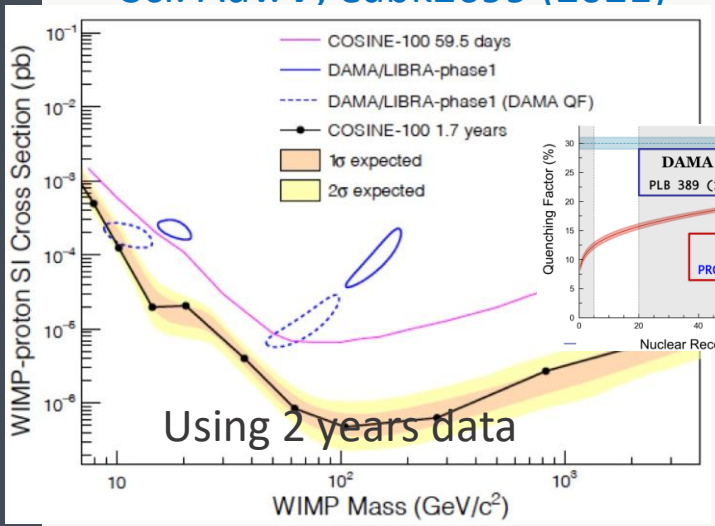
Sci. Adv. **7**, eabk2699 (2021)

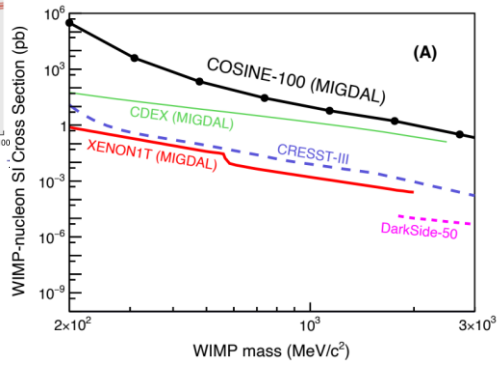
Migdal effect

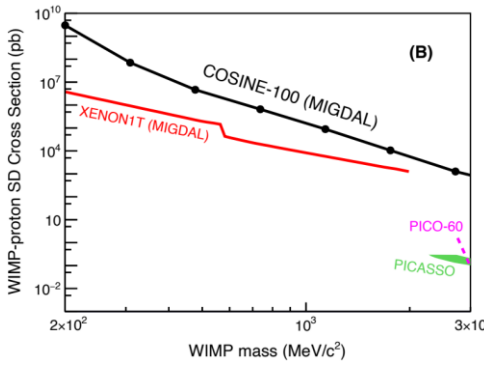




Phys. Rev. D **105**, 042006 (2022)



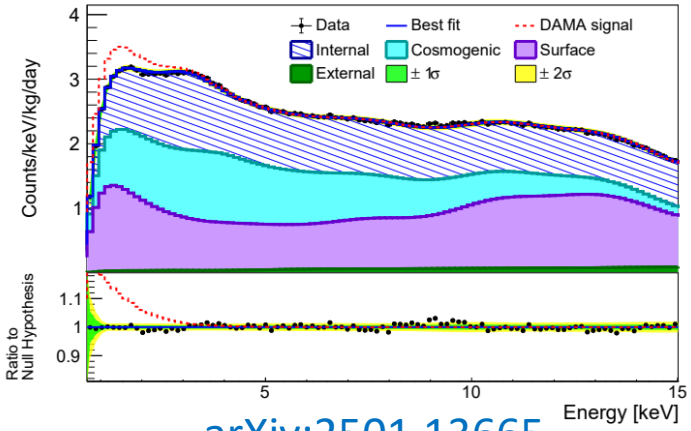




WIMP extraction analysis - 3 years data

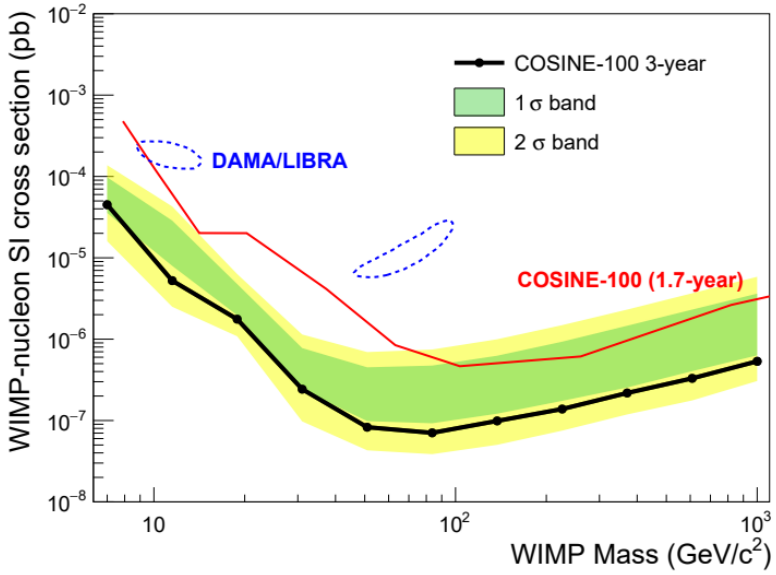
- Analyze the **3-years data** with **0.7 keV threshold** and **new background modeling**
- **An O(10) improvement** of SI WIMP-proton cross-section limit from **previous result**
- Providing **competitive cross-section** limits around 2.5 GeV/c^2 **in SD WIMP-proton** cross-section

Fit example

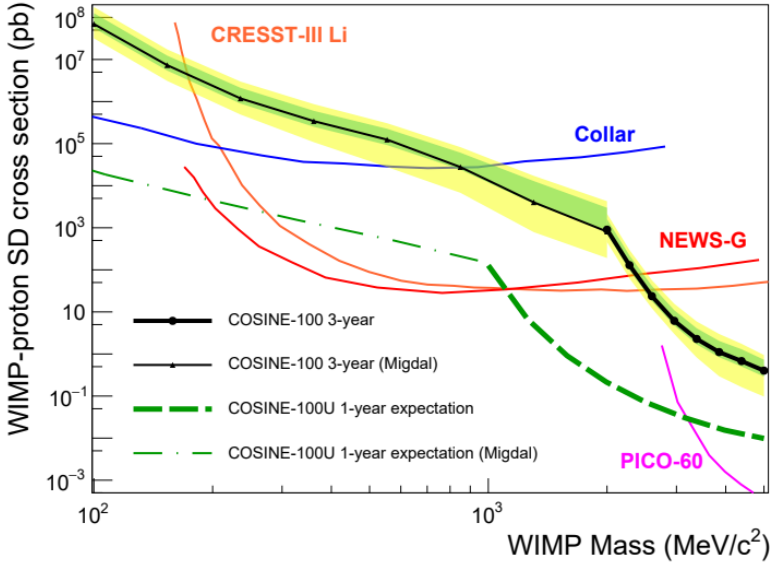


arXiv:2501.13665

SI WIMP-proton cross-section

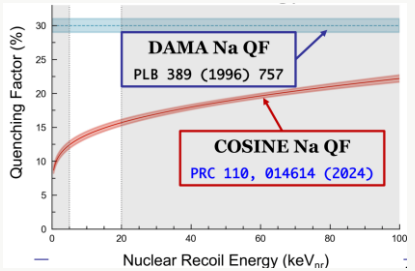


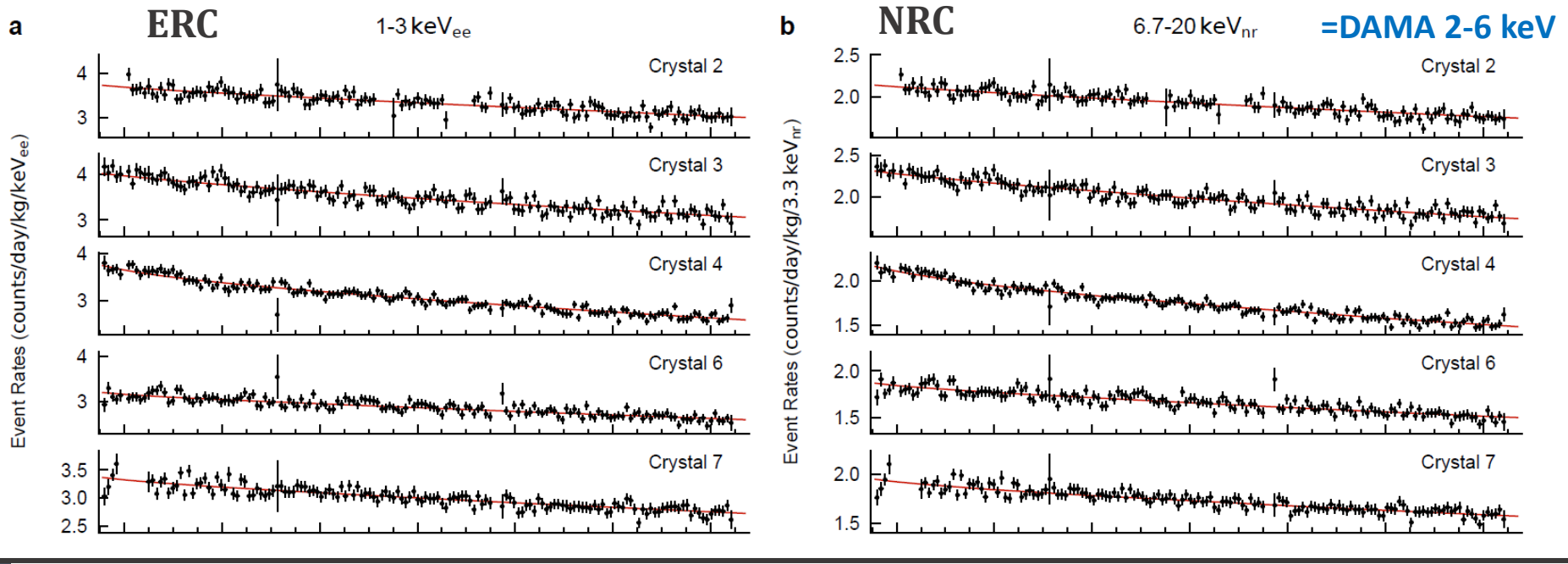
SD WIMP-proton cross-section



Annual modulation analysis

- **Updated** since result using **3 years data**(**Phys. Rev. D 106, 052005 (2022)**)
- **Using full COSINE-100** data (~6 years)
  - Using **0.7 keV threshold** and **new modeling**
  - **Calibration method to test DAMA's claim**
    - **Linear calibration** for **Electron Recoil** Comparison (ERC)
    - **Quenching factor** correction for **Nuclear Recoil** Comparison (NRC)





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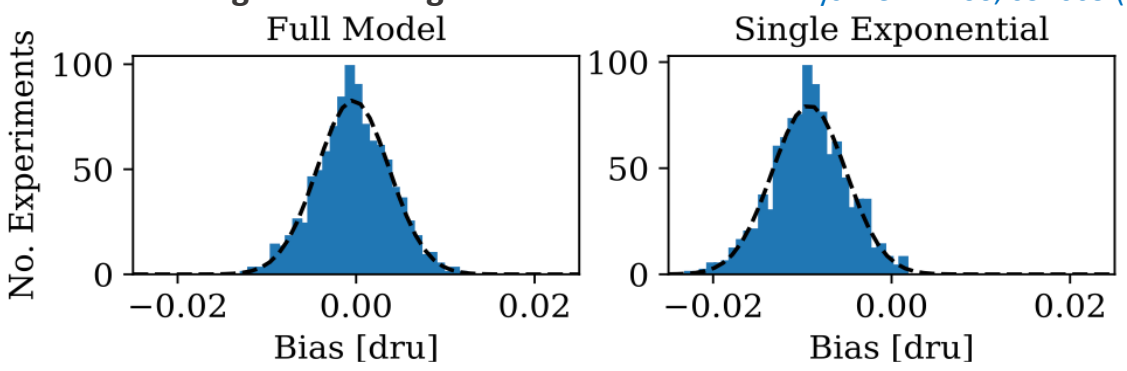
  - Applying **full model** of **time dependent background** component

$$R^i(t|S_m,\alpha^i,\beta_k^i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos\left(\omega(t-t_0)\right)$$

Constant from long-lived backgrounds
Exponential decays from short-lived
Modulation signal

Bias check according to modeling

Phys. Rev. D **106**, 052005 (2022)



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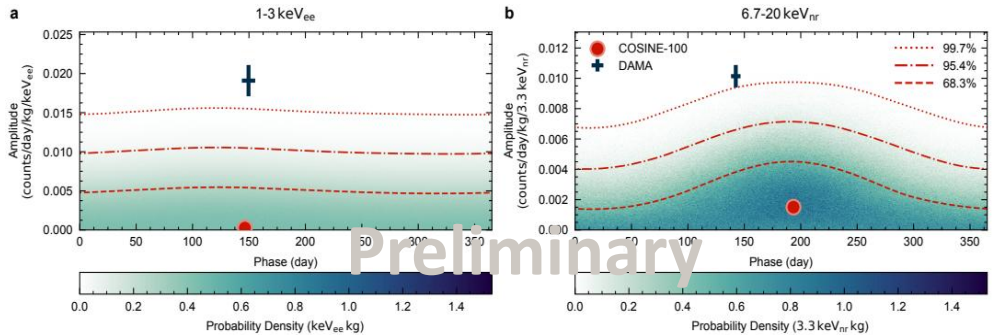
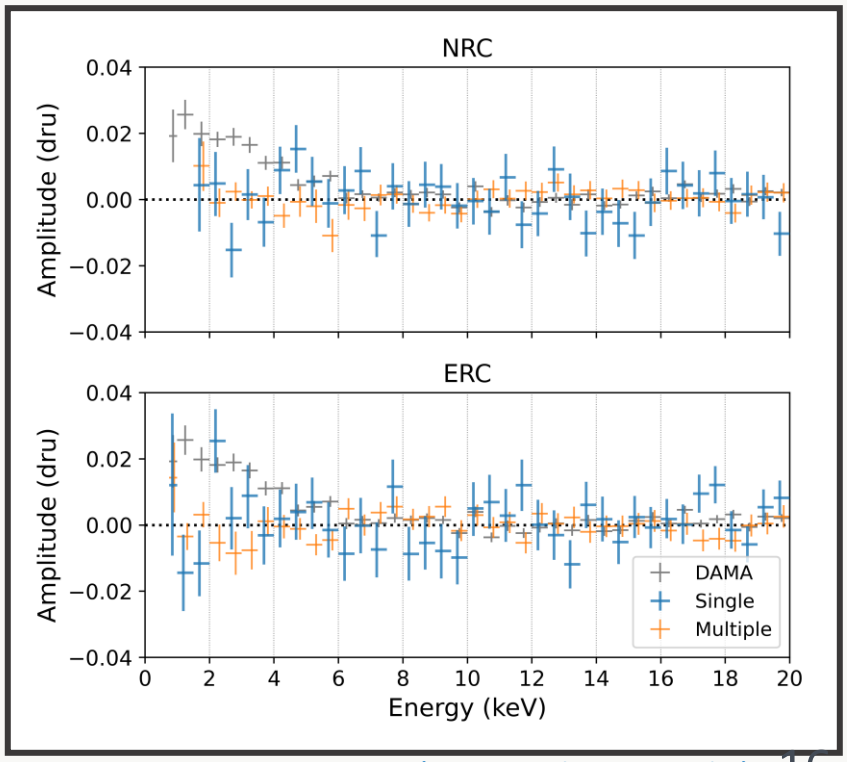
Energy (keV)		A_{COSINE} (10^{-3} DRU)	A_{DAMA} (10^{-3} DRU)	Exclusion C.L. (σ)
ERC	1-3	$0.53^{+5.00}_{-5.01}$	19.1 ± 2.0	3.57
NRC	6.7-20	$1.34^{+2.69}_{-2.68}$	9.96 ± 0.74	3.23





arXiv:2409.13226 (Accepted at Sci. Adv.)

Annual modulation analysis

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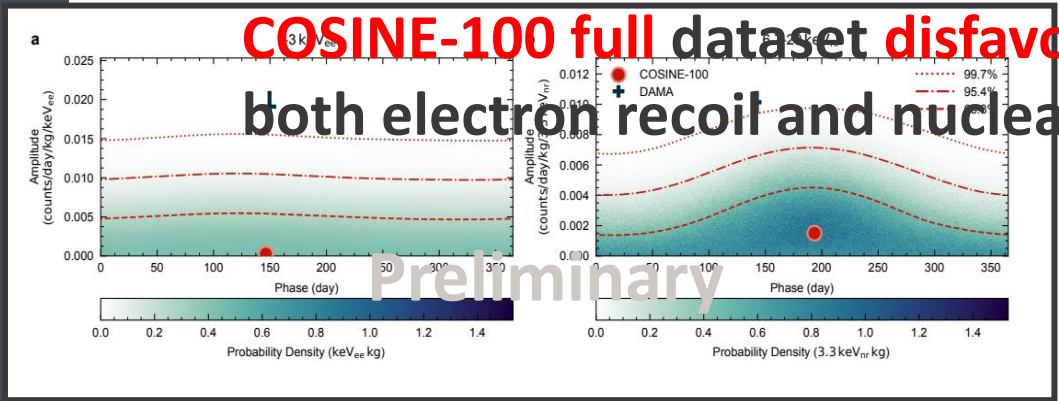
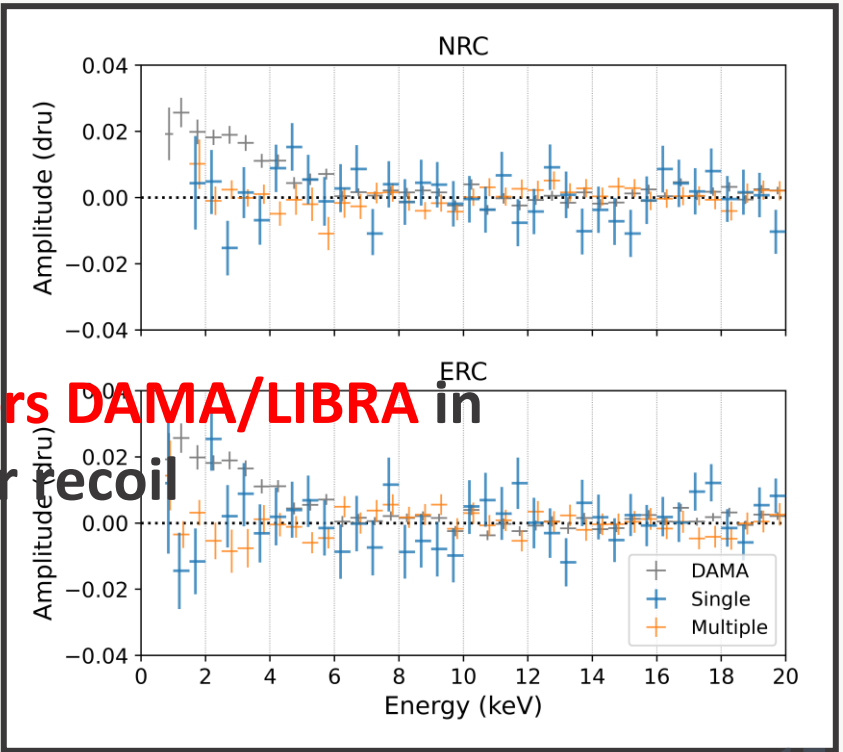
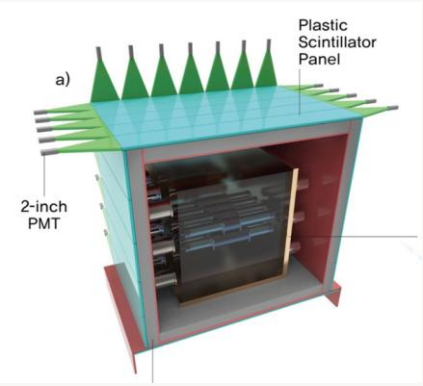


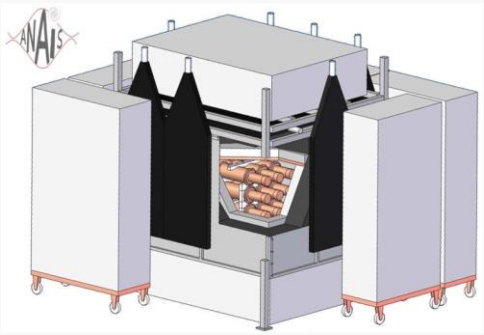


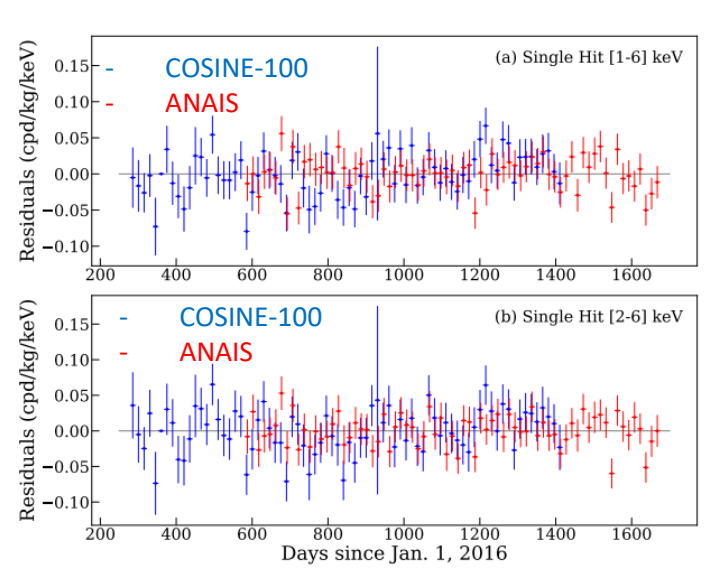
COSINE-100 full dataset disfavors DAMA/LIBRA in both electron recoil and nuclear recoil

arXiv:2409.13226 (Accepted at Sci. Adv.)

Annual modulation analysis Combined data



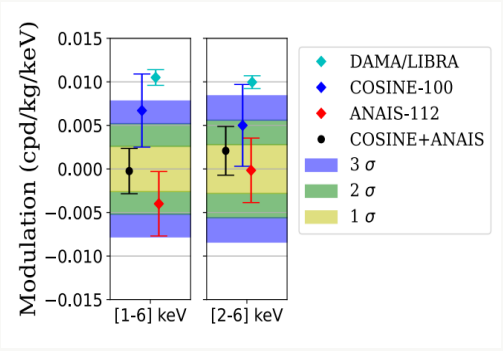




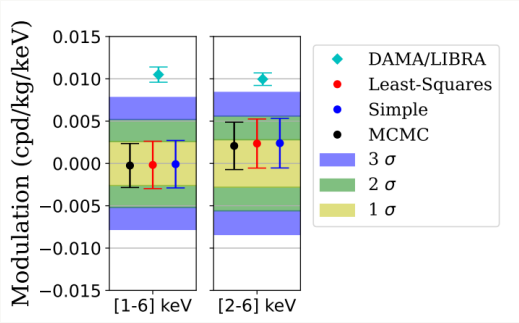
arXiv:2503.19559v1 (Accepted at PRL)

- Use COSINE100 **3 years data**+ ANAIS **3 years** data
  - **Fit to data** with full background modeling

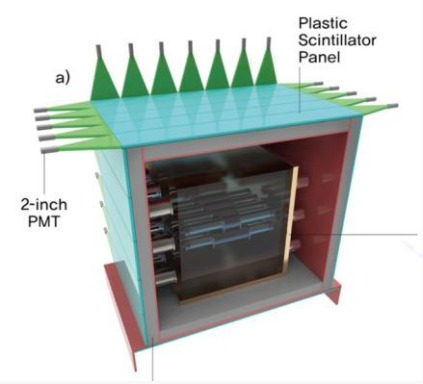
Energy (keV)	A_{Combined} $(10^{-3}$ DRU$)$	A_{DAMA} $(10^{-3}$ DRU$)$	DAMA signal Exclusion
1-6	0.2 ± 2.6	10.5 ± 1.1	$3.6\,\sigma$
2-6	2.1 ± 2.8	10.2 ± 0.8	$2.6\,\sigma$

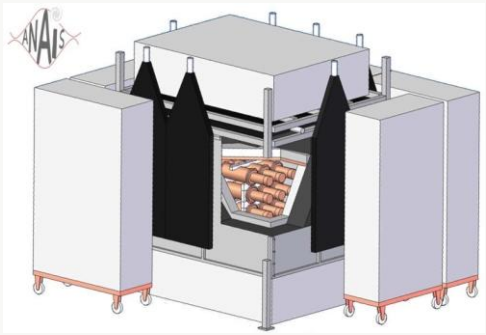


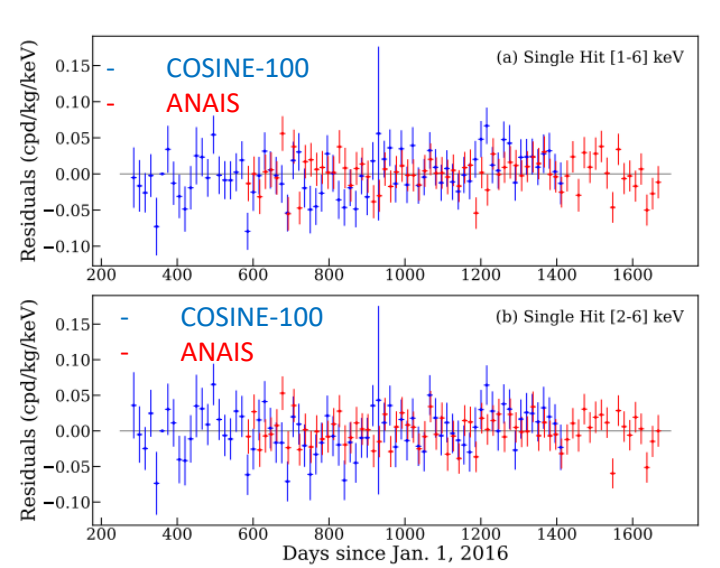
- **Test combination methods**
  - Least-Squares fit
  - Markov Chain Monte Carlo (MCMC, i.e. Bayesian)
  - Simple combination



Annual modulation analysis Combined data



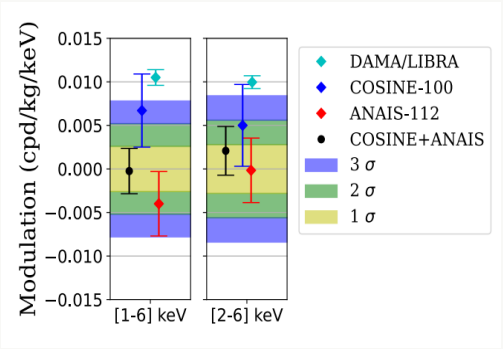




arXiv:2503.19559v1 (Accepted at PRL)

- Use COSINE100 **3 years data**+ ANAIS **3 years** data
  - **Fit to data** with full background modeling

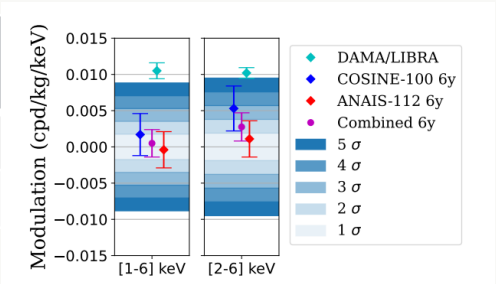
Energy (keV)	A_{Combined} (10^{-3} DRU)	A_{DAMA} (10^{-3} DRU)	DAMA signal Exclusion
1-6	0.2 ± 2.6	10.5 ± 1.1	$3.6\,\sigma$
2-6	2.1 ± 2.8	10.2 ± 0.8	$2.6\,\sigma$



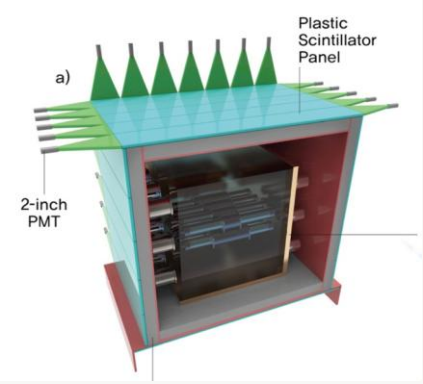
- **Simple combination** with **newly released 6 years** datasets

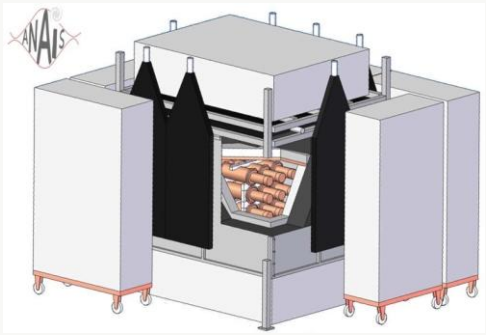
Energy (keV)	$A_{\text{COSINE 6years}}$ (10^{-3} DRU)	$A_{\text{ANAIS 6 years}}$ (10^{-3} DRU)	$A_{\text{6 year Combined}}$ (10^{-3} DRU)	A_{DAMA} (10^{-3} DRU)	DAMA signal Exclusion
1-6	1.7 ± 2.9	-0.4 ± 2.5	0.5 ± 1.9	10.5 ± 1.1	$4.7\,\sigma$
2-6	5.3 ± 3.1	1.1 ± 2.5	2.7 ± 1.9	10.2 ± 0.8	$3.5\,\sigma$

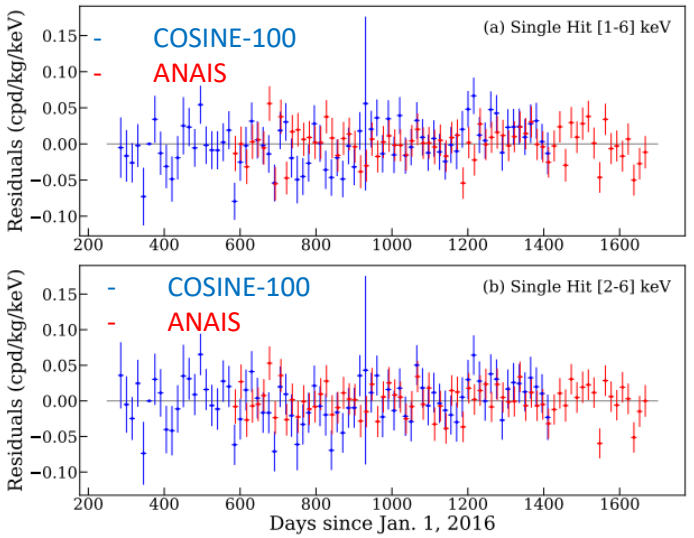
arXiv:2502.01542



Annual modulation analysis Combined data







arXiv:2503.19559v1 (Accepted at PRL)

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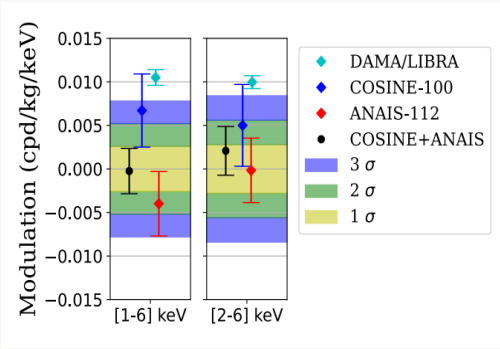

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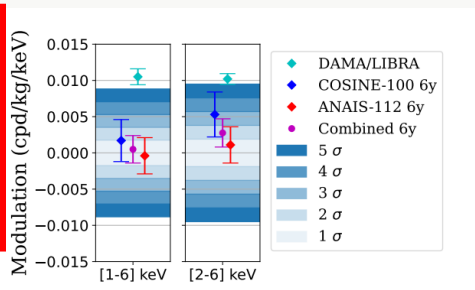
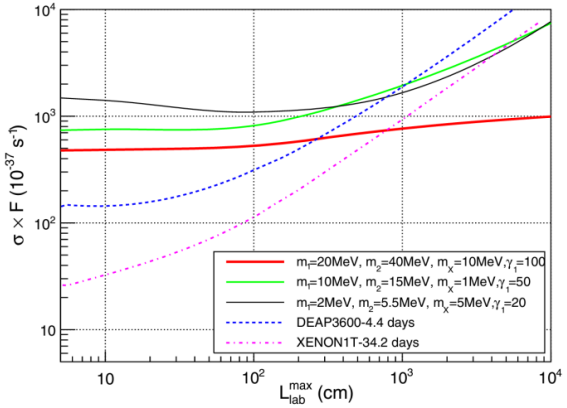


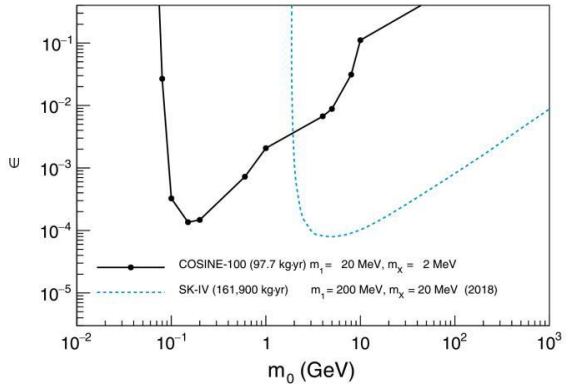
Other DM scenarios

- **Performed with 2 years data**

Boosted DM

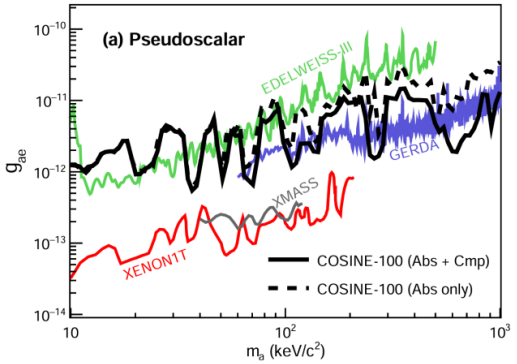


Phys. Rev. Let. **122,** 131802 (2019)



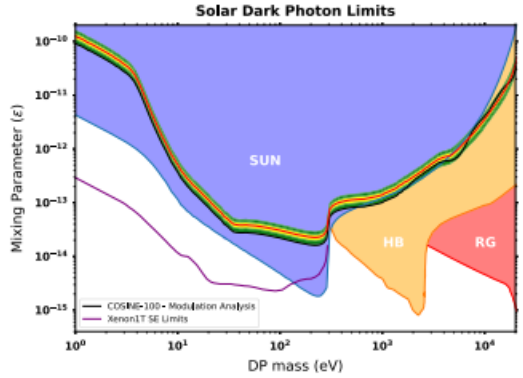
Phys. Rev. Let. **131,** 201802 (2023)

Bosonic Super WIMP



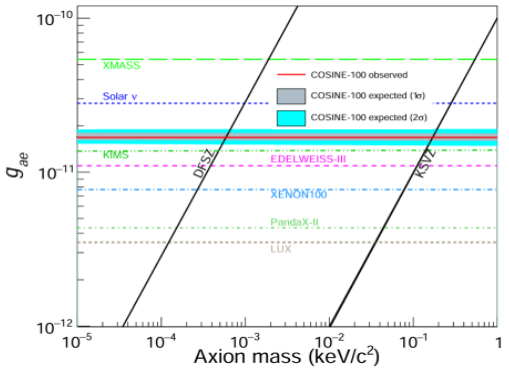
Phys Rev. D **108**, 041301 (2023)

Solar Bosonic Particles



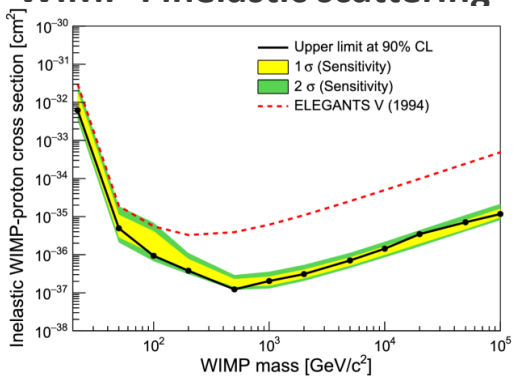
Phys. Rev. D **107**, 122004 (2023)

Solar Axion



Astropart. Phys. **114**, 101-106 (2020)

WIMP-I inelastic scattering



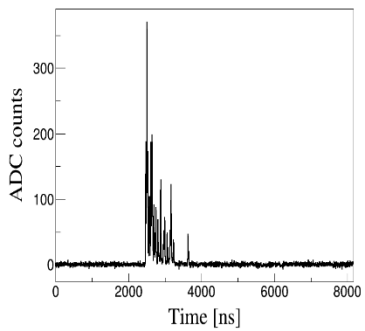
Phys. Rev. D **108**, 092006 (2023)

On going efforts : Event selection with full data

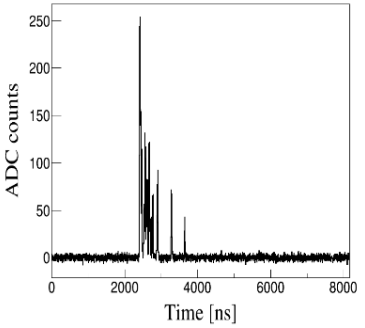
- Using **waveform simulation** for multivariable analysis

NIM A **1065** 169489 (2024)

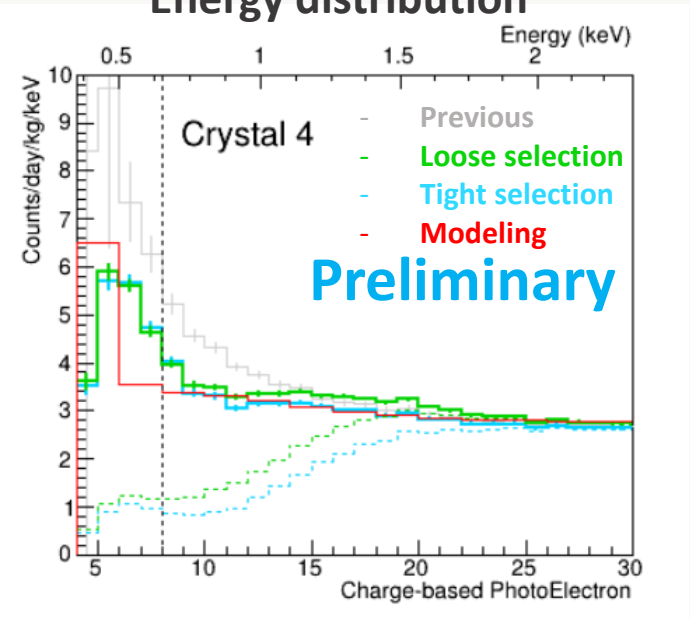
Physics waveform



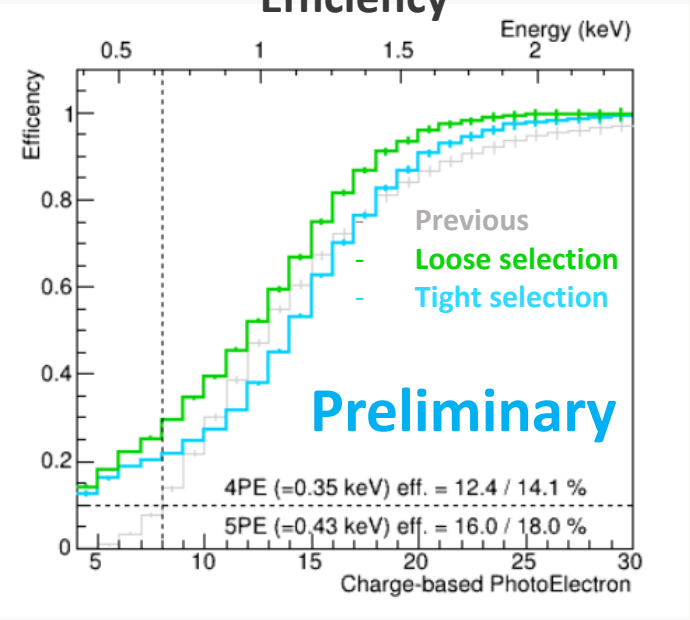
Simulation waveform



Energy distribution



Efficiency



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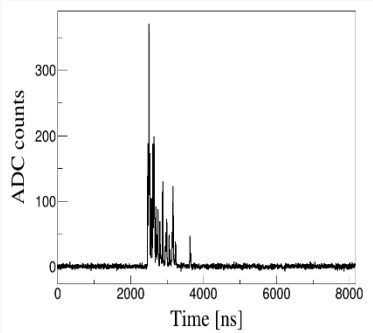
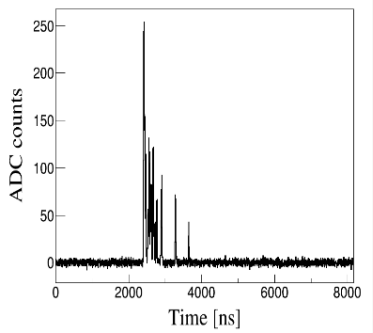
NIM A **1065** 169489 (2024)

Physics waveform

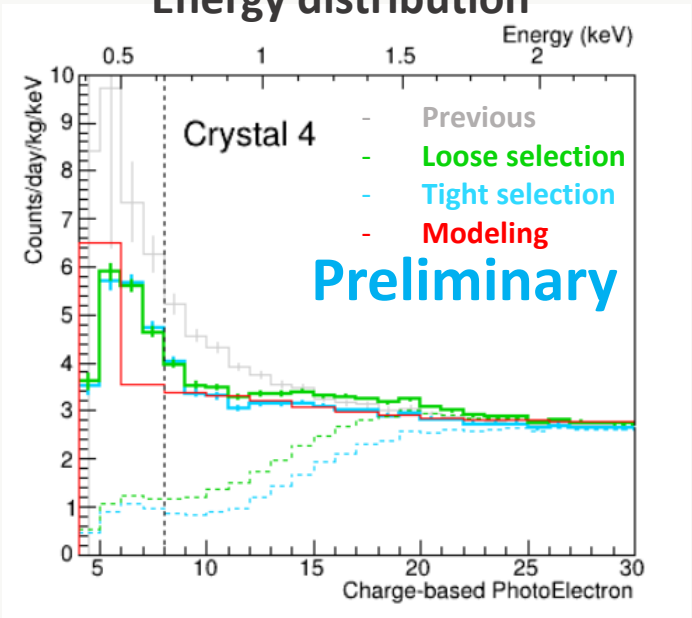


Simulation waveform

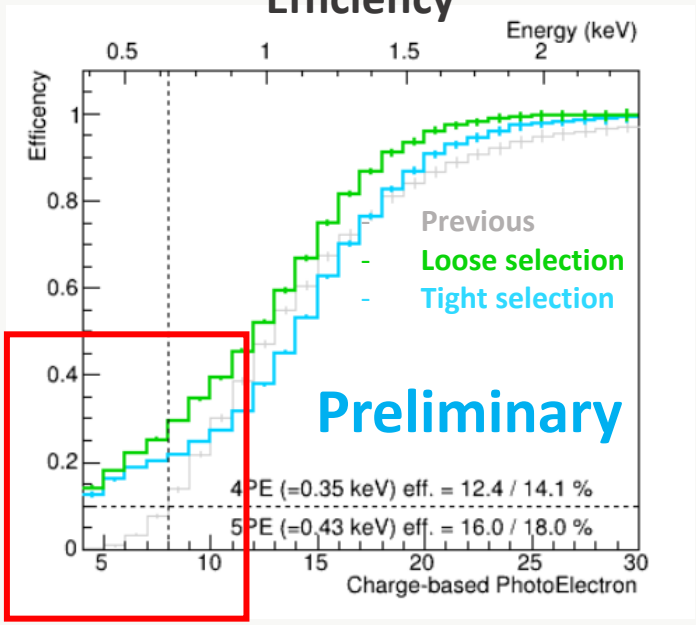


Achievable 5 PE(~0.43 keV) threshold

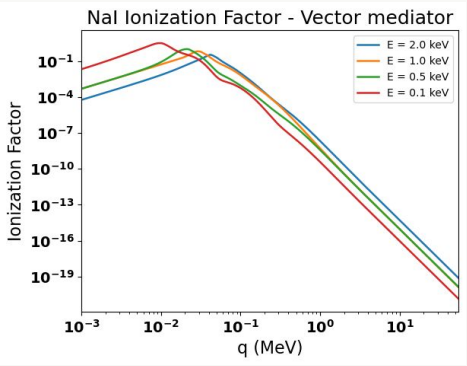
Energy distribution

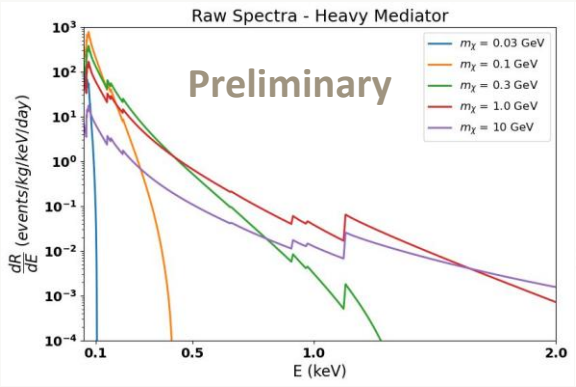


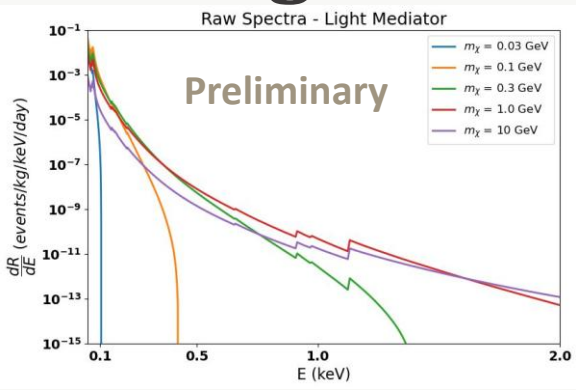
Efficiency



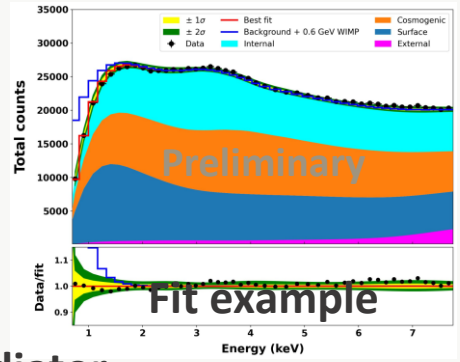
On going efforts : WIMP-e scattering



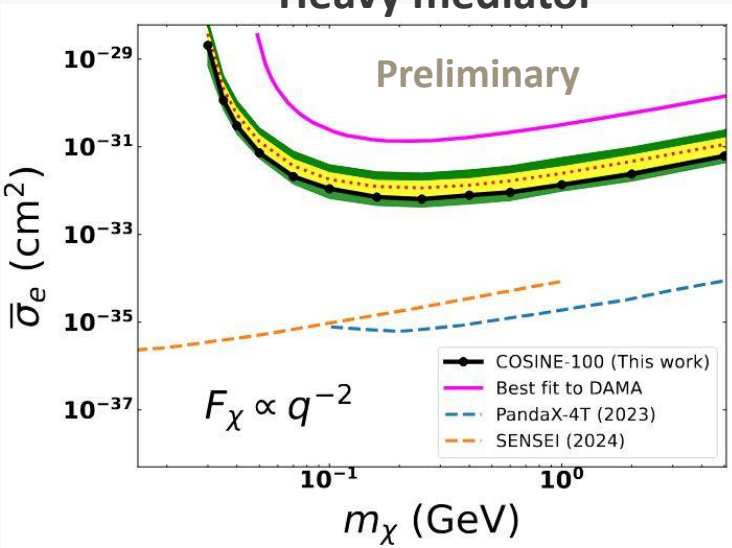




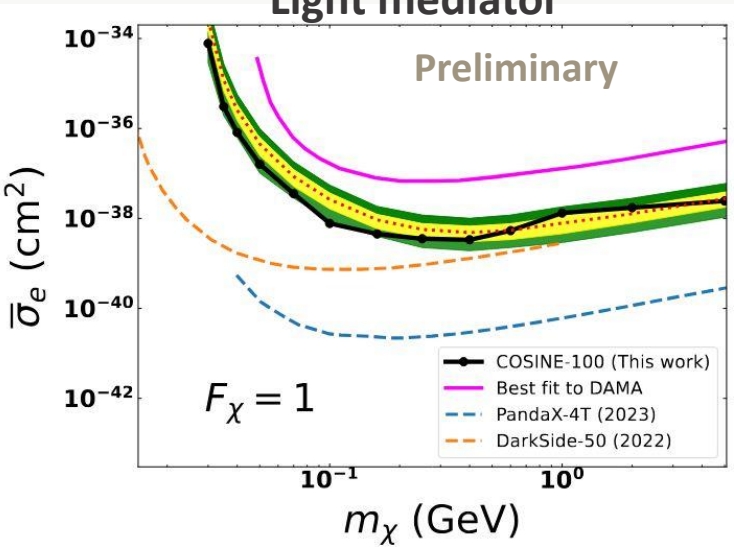
- **Using 3-years data**
  - **0.7 keV threshold with new background modeling**
- **Consider NaI ionization factor**



Heavy mediator



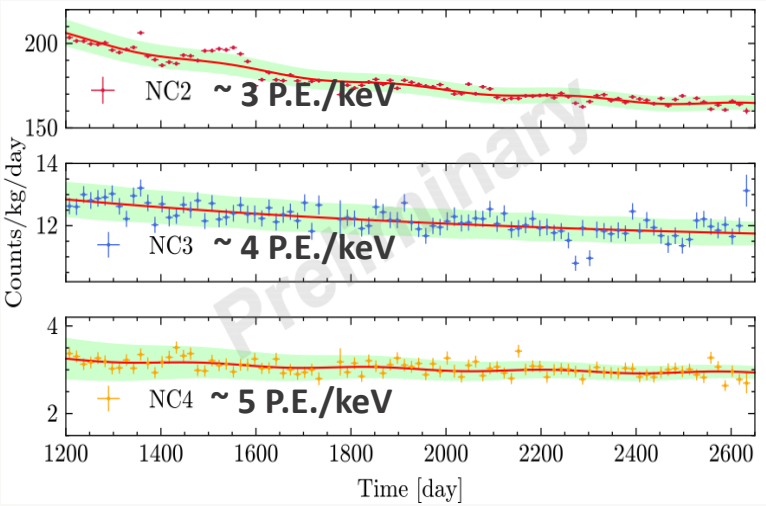
Light mediator



On going efforts: Low-mass Dark Matter Search

- **Modulation analysis** using < **6 P.E/keV** region data set
  - Using COSINE-100 full data set
  - Dead time selection after high pulse
  - Fit data with simple background model

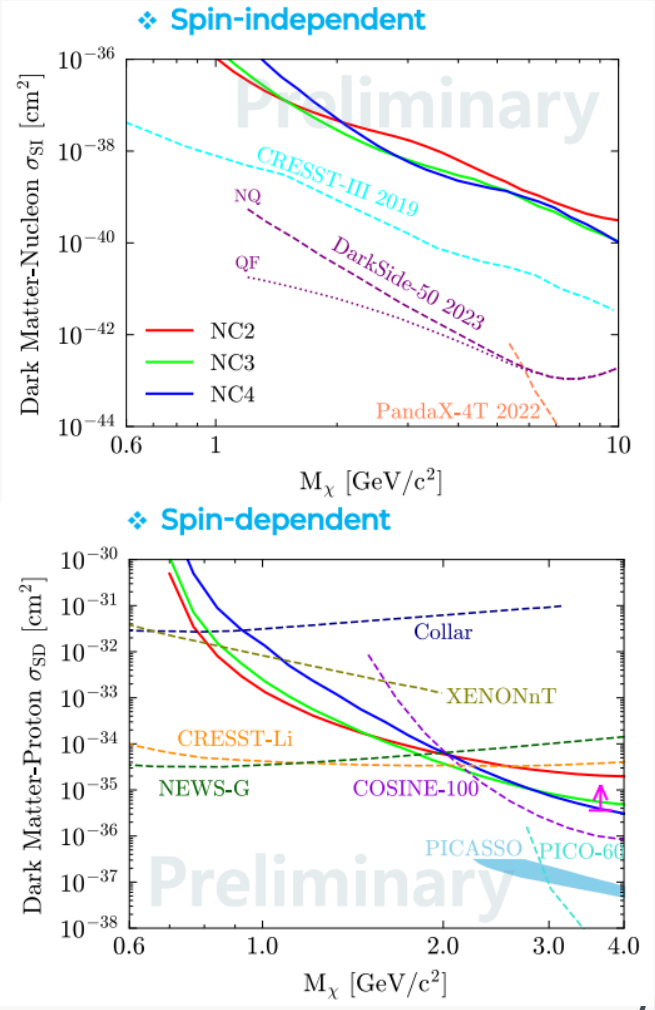
$$f(t) = e^{p_0+p_1 t} + \boldsymbol{A}\cos\left(\frac{2\pi}{T}(t-\boldsymbol{\phi})\right) + C.$$



Wonkyung's poster
Poster session
Wednesday, 27 August 19:00~20:30

Sensitivity estimation

(using pseudo-data)



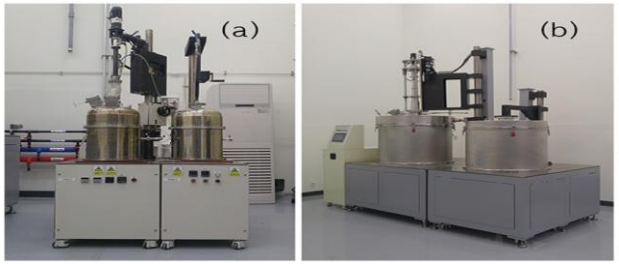
Effort for next phase

- Crystal development for **COSINE-200**
  - In-house development of **entire process** (at IBS , Korea)
    - **NaI powder purification**
    - **Crystal growing**
    - **Detector assembly**
  - Prepare ~**0.7 kg R&D** crystals
    - Expect **~0.2 DRU background level for COSINE-200 crystal**
  - On going development for full size crystal growing (~100 kg)

Powder purification facilities

JINST **15** C07031 (2020)

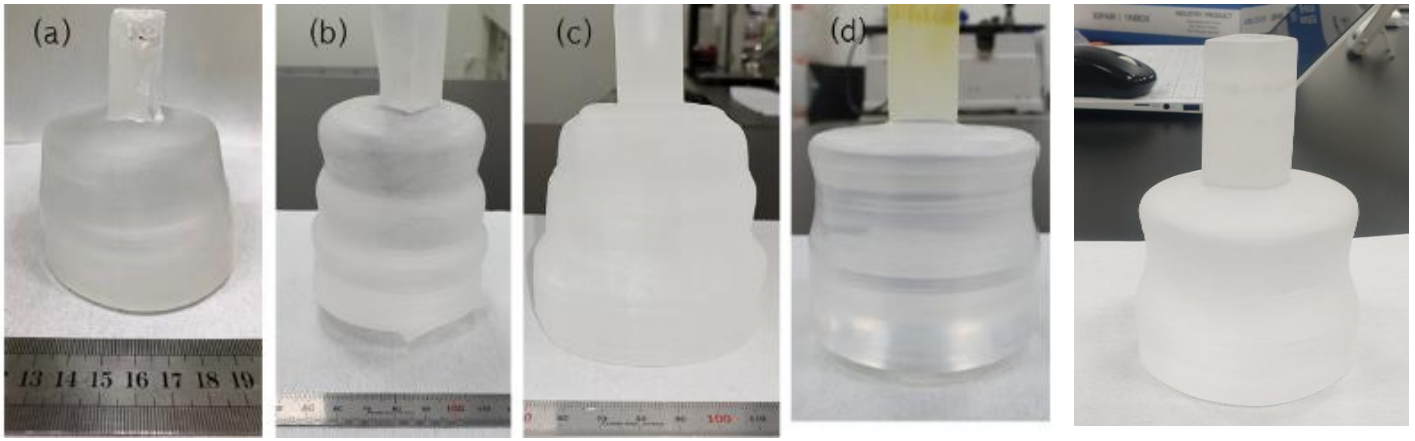
Crystal grower



J. Phys. Conf. Ser. **1468** 012144 (2020)

CUP Grown R&D crystals

Eur. Phys. J. C **80** 814 (2020)
Front Phys **11**:1142765 (2023)



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JINST **15** C07031 (2020)

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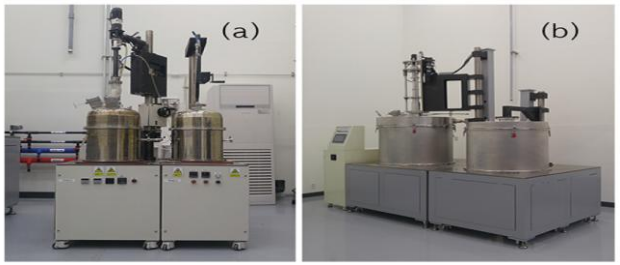


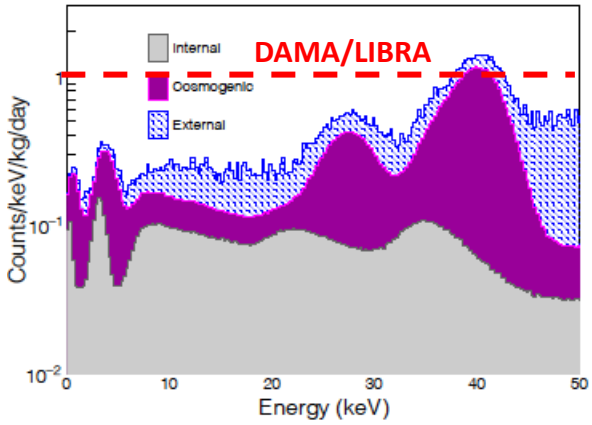
J. Phys. Conf. Ser. **1468** 012144 (2020)

Background level in R&D crystals

Eur. Phys. J. C **80** 814 (2020)
Front Phys **11**:1142765 (2023)

	K (ppb)	^{210}Pb (mBq/kg)	^{238}U(ppt)	^{232}Th(ppt)
COSINE	**16.8±2.5**	**1.87±0.09**	**<0.02**	**0.7±0.2**
Powder	5	-	<20	<20
Aug.2018	<53	0.01±0.02	0.9±0.3	1.7±0.5
Sep.2019	<42	0.42±0.27	36.5±3.9	<4.9
Feb.2021	**8.3±4.6**	**0.38±0.10**	**<2.0**	**<0.8**
DAMA	**<20**	**0.01~0.03**	**0.7-10**	**0.5-7.5**

Expected background level in COSINE-200



Summary

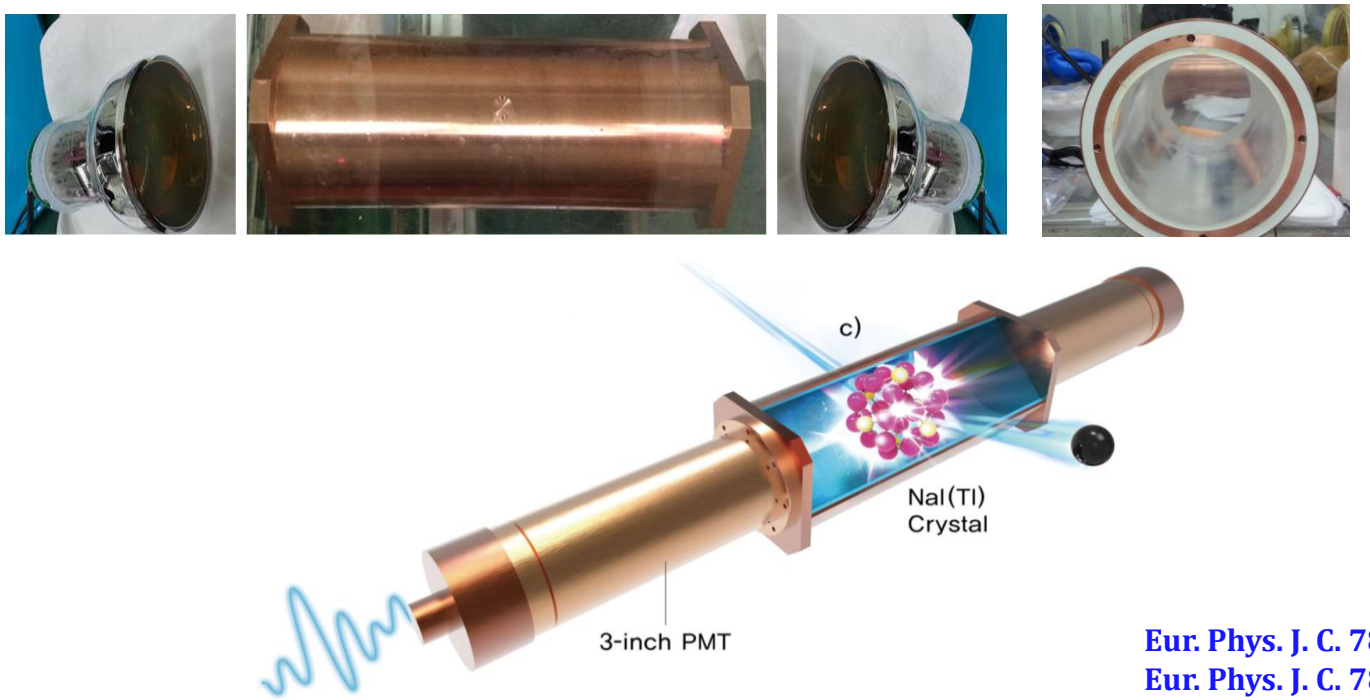
- **COSINE-100 was designed to test the DAMA/LIBRA signal using the same target material, NaI(Tl), and was operated from September 2016 to March 2023.**
  - **Spectral Analysis**
    - Improved WIMP–nucleon cross-section limits using three years of data
    - Investigated various dark matter scenarios
  - **Modulation Analysis**
    - **No DAMA-like modulation** observed, excluding DAMA's claim at more than **3σ significance** using the **full COSINE-100 dataset**
    - The **combined analysis** of COSINE-100 and ANAIS shows a **comparable result**
- **Ongoing Analyses for Improved Sensitivity**
  - Event selection update analysis for 0.5 keV threshold
  - WIMP-electron scattering analysis
  - Low-mass dark matter search analysis
- **The COSINE-100U experiment will start at Yemilab, aiming for world-leading sensitivity.**
- **Related Talks**

Progress on COSINE-100U	Low-mass Dark Matter Search
Doohyeok's talk	**Wonkyung's poster**
27th Aug. 16:00~16:20	**27th Aug. 19:00~20:30**

Back up

COSINE-100 experiment-NaI(Tl)

- **8 low-background NaI(Tl) crystals** with **106 kg** in total
  - **U/Th/K level** is less than DAMA, but total alphas (**^{210}Pb**) are higher than DAMA.
  - Total **background** level is **2-3 times that of DAMA/LIBRA.**
  - **Higher light yield (15 P.E./keV)** than **DAMA/LIBRA** (**5-10 P.E./keV**)
    - Can make the threshold lower easily
  - Each crystal is **encapsulated** in **copper and quartz windows**.
  - Two 3-inch PMTs (R12669SEL) are attached to each crystal.
    - Quantum efficiency: 35% @ 420 nm

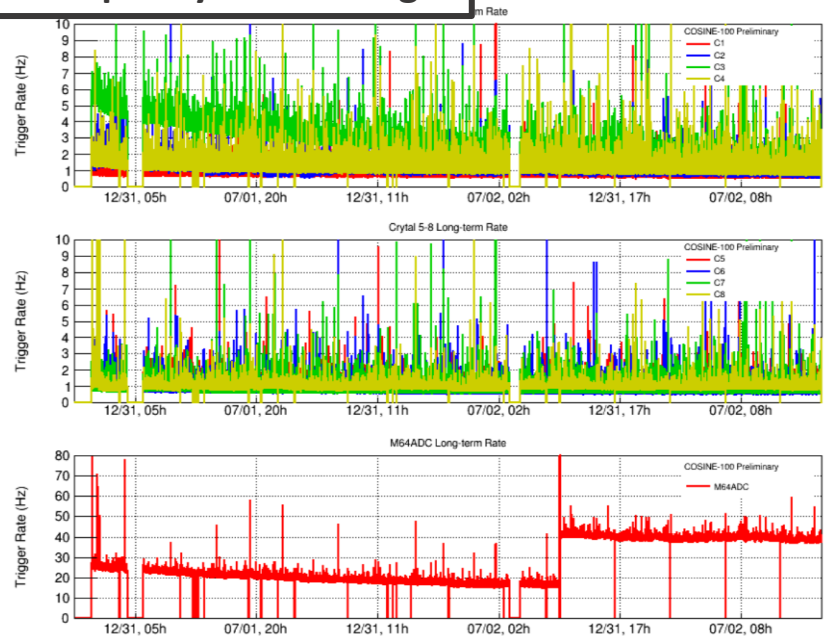


Eur. Phys. J. C. 78 107 (2018)
Eur. Phys. J. C. 78 490 (2018)

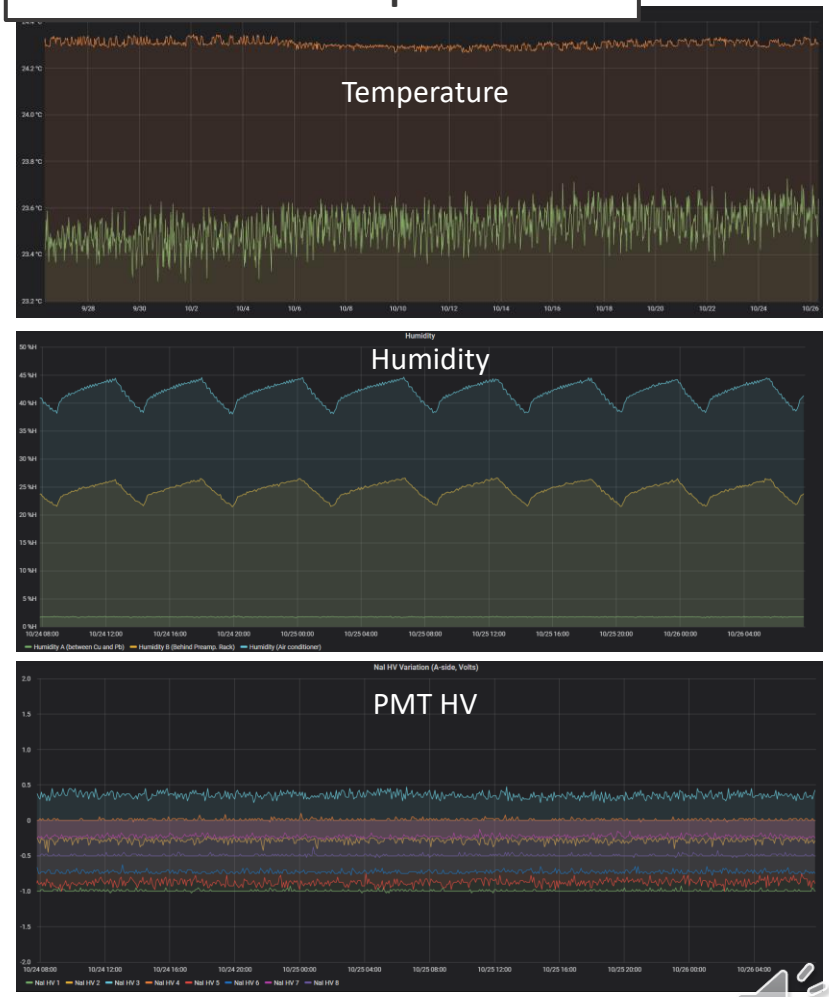
COSINE-100 operation

- **Slow monitoring system**

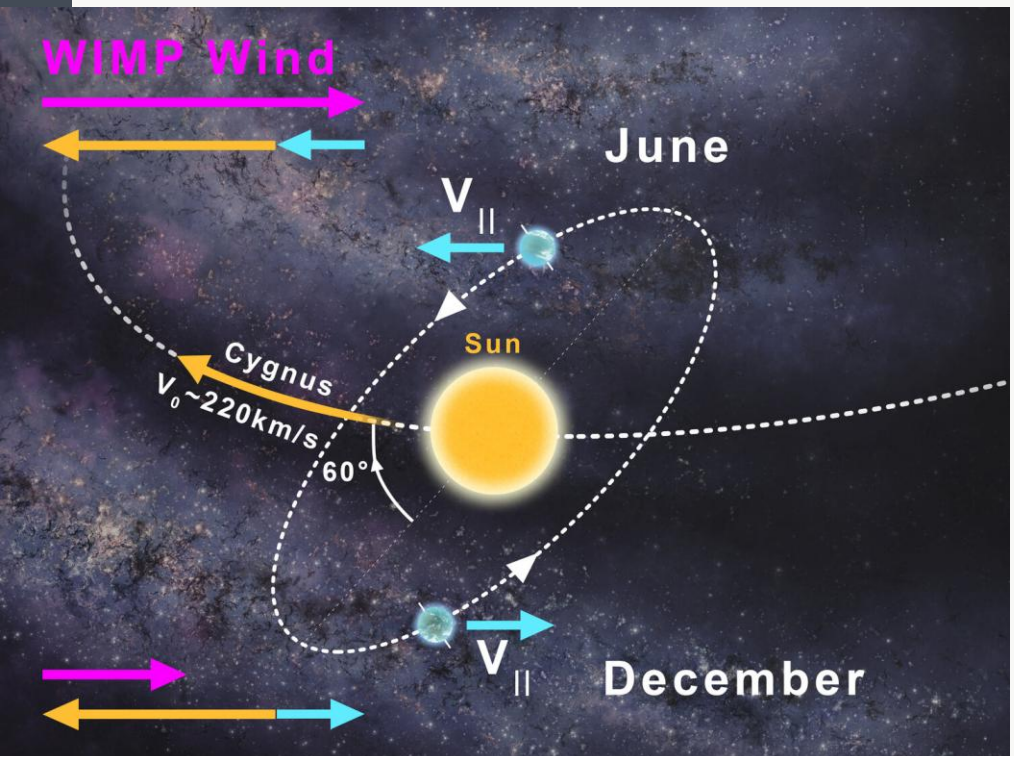
Data quality monitoring



>200 Environmental parameters



Annual modulation signal



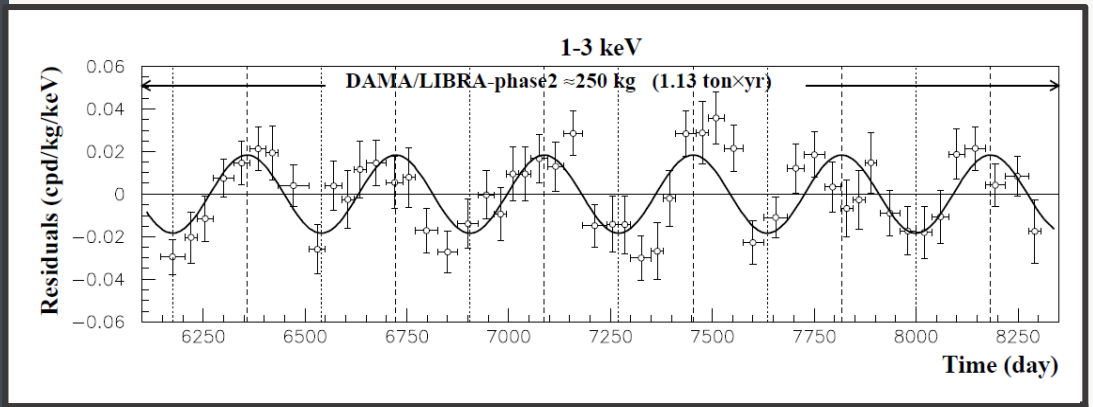
- Spherical halo of dark matter in our galaxy is expected to make dark matter flux to Solar system (WIMP Wind)
- Speed of WIMP wind changes according to seasonal rotation of the Earth.
- Changing WIMP speed induces changing interaction rate.

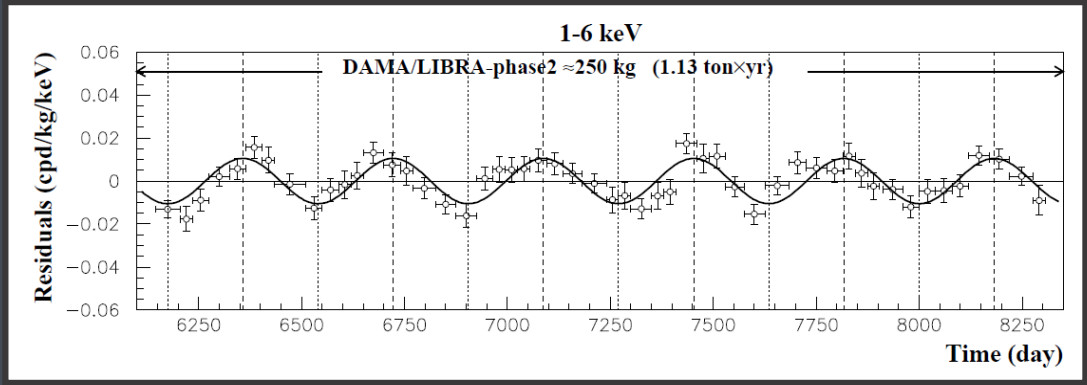
Rate of WIMP elastic scattering

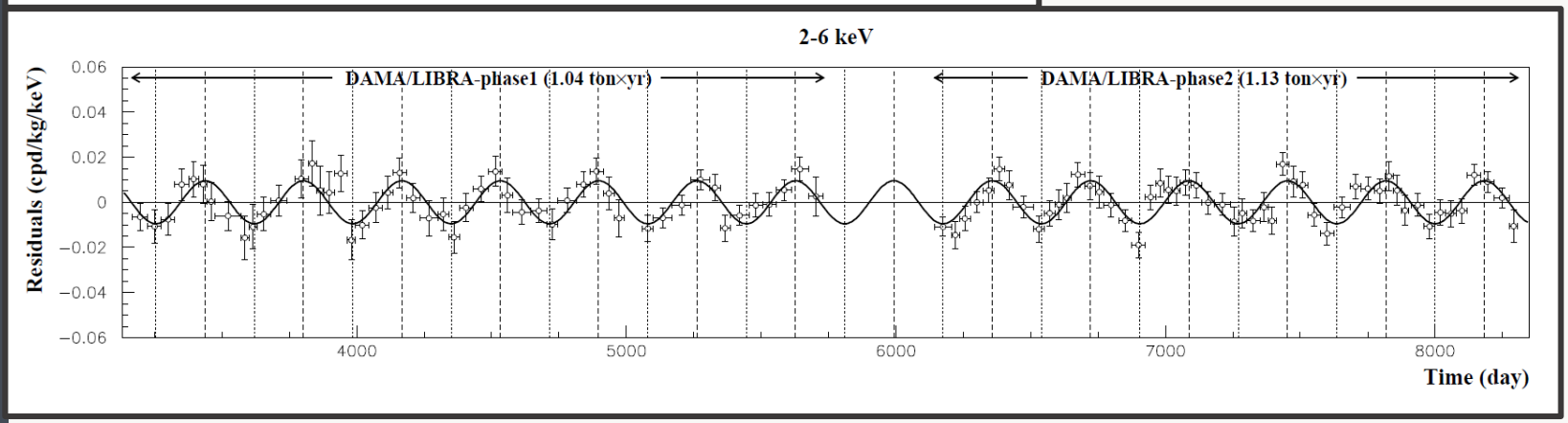
$$R \propto N_T \cdot \sigma_{\chi^N} \cdot \frac{\rho_\chi}{m_\chi} \int_{v_{min}} \frac{f(v)}{v} dv$$

$f(v)$: WIMP velocity distribution
v_{min} : minimum velocity for interaction
ρ_χ : local WIMP density
m_χ : WIMP mass

DAMA/LIBRA result





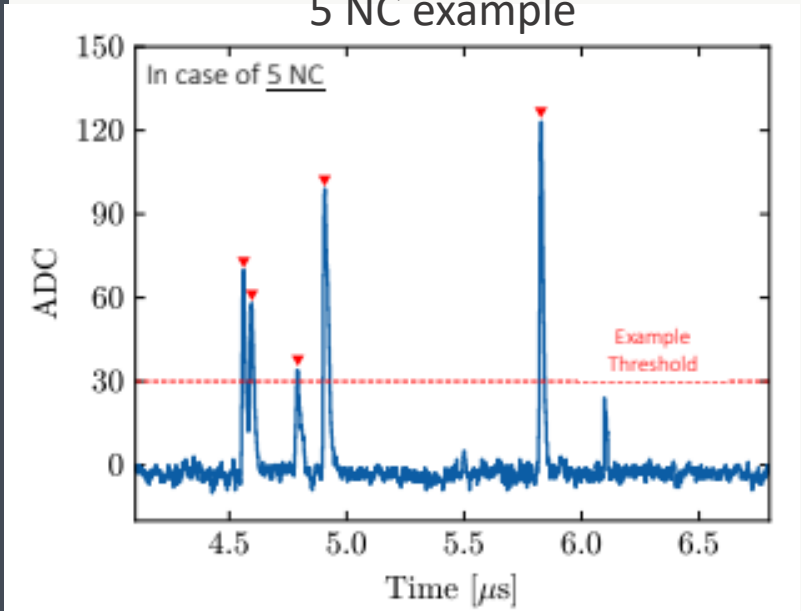


	A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/LIBRA–phase2:				
1-3 keV	(0.0184±0.0023)	1.0	152.5	8.0 σ
1-6 keV	(0.0105±0.0011)	1.0	152.5	9.5 σ
2-6 keV	(0.0095±0.0011)	1.0	152.5	8.6 σ
1-3 keV	(0.0184±0.0023)	(1.0000±0.0010)	153±7	8.0 σ
1-6 keV	(0.0106±0.0011)	(0.9993±0.0008)	148±6	9.6 σ
2-6 keV	(0.0096±0.0011)	(0.9989±0.0010)	145±7	8.7 σ
DAMA/LIBRA–phase1 + phase2:				
2-6 keV	(0.0095±0.0008)	1.0	152.5	11.9 σ
2-6 keV	(0.0096±0.0008)	(0.9987±0.0008)	145±5	12.0 σ
DAMA/NaI + DAMA/LIBRA–phase1 + phase2:				
2-6 keV	(0.0102±0.0008)	1.0	152.5	12.8 σ
2-6 keV	(0.0103±0.0008)	(0.9987±0.0008)	145±5	12.9 σ

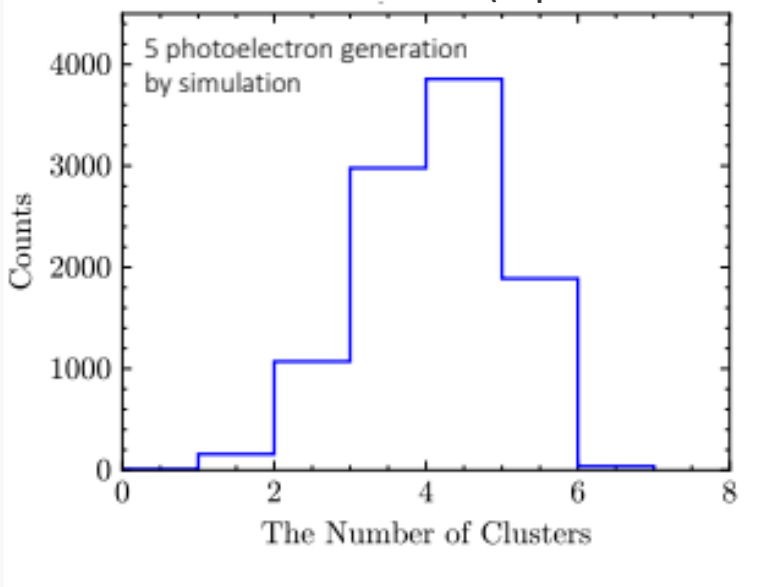
Cluster & Photo-electron

- **Cluster** : a **peak** that above the **threshold.**

5 NC example



The number of Cluster (5 photo-electron)



Event selection validation