Status of the COSINE-100 Experiment and Beyond

ISAPP Summer School 2024

26th September 2024

Yujin Lee

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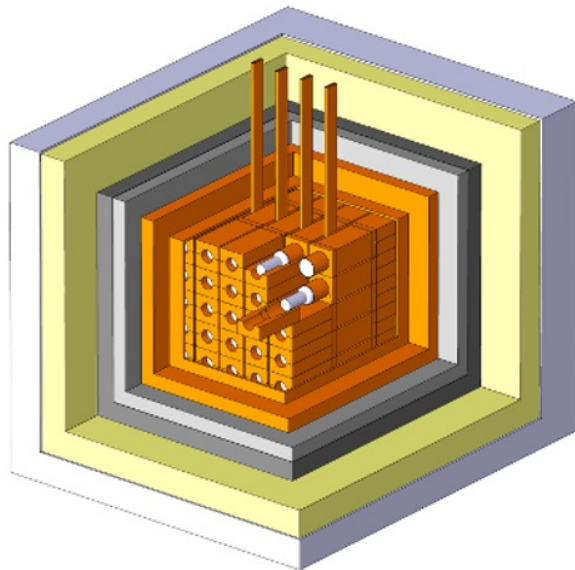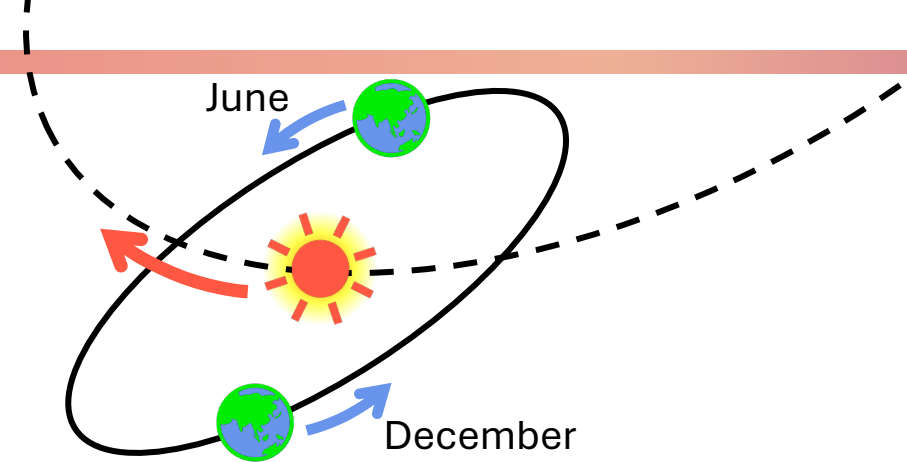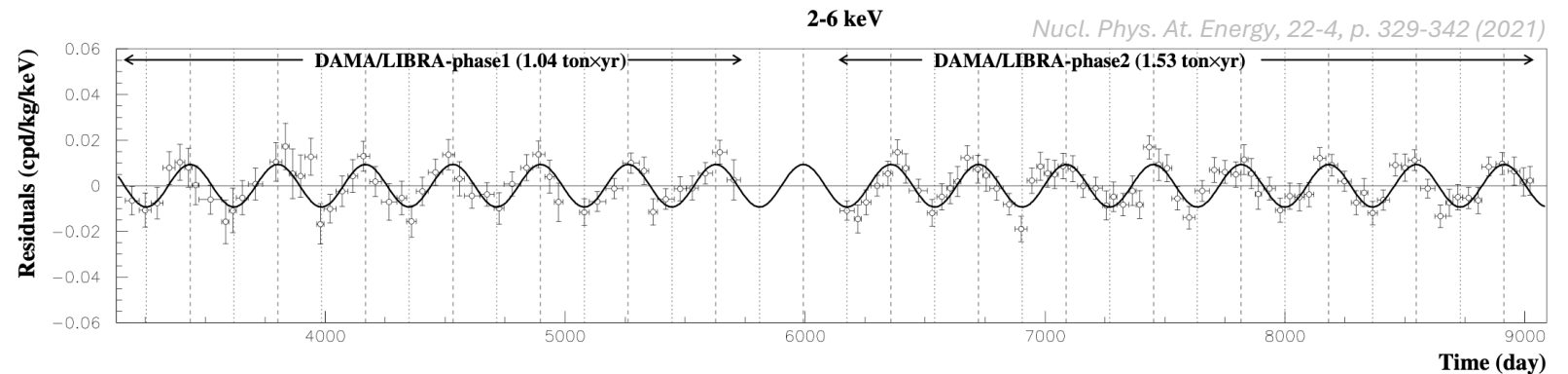
On behalf of COSINE Collaboration

Motivation
Tests of DAMA/LIBRA Results

- DAMA/LIBRA Experiment
  - Search for the annual modulation of Dark Matter in the Galactic halo
  - 25 × 9.7 kg NaI(Tl) detectors, 2.86 ton × yr (DAMA/NaI + DAMA/LIBRA)
  - Claims the detection of the Dark Matter modulation signal at 13.7σ C.L. in the energy region (2-6 keV)
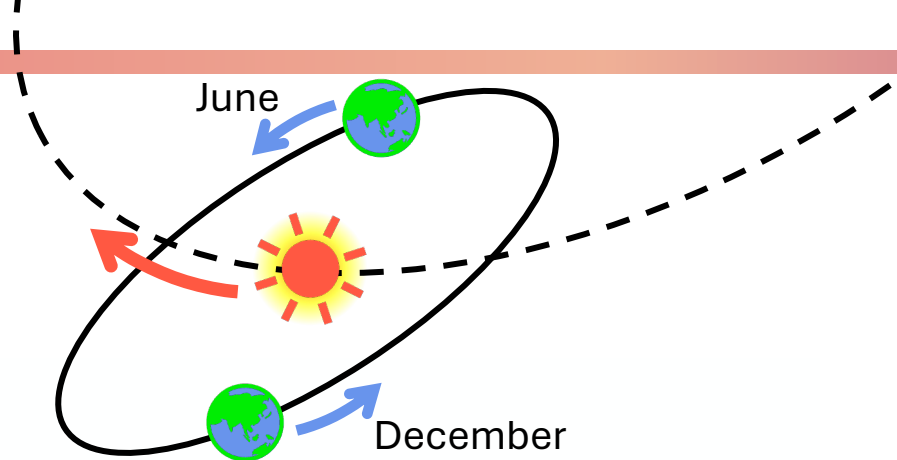
    - Modulation amplitude: (0.01014 ± 0.00074) cpd/kg/keV
      - Phase = (142.4 ± 4.2) days
   - Period = (0.99834 ± 0.00067) year

Nucl. Phys. At. Energy, 22-4, p. 329-342 (2021)

Motivation
Tests of DAMA/LIBRA Results

- DAMA/LIBRA Experiment
  - Search for the annual modulation of Dark Matter in the Galactic halo
  - 25×9.7 kg NaI(Tl) detectors, 2.86 ton×yr (DAMA/NaI + DAMA/LIBRA)
  - Claim the detection of the
    in the energy region (2-6 ke
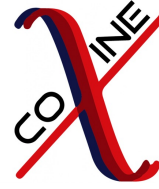   - Modulation
      - Phase =
      - Period =

June

December

Rep. Prog. Phys. **85** 056201 (2022)
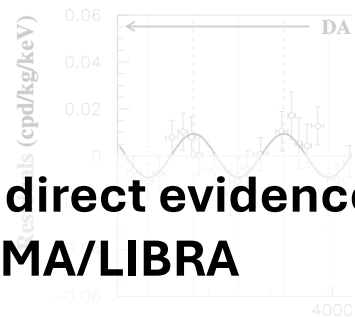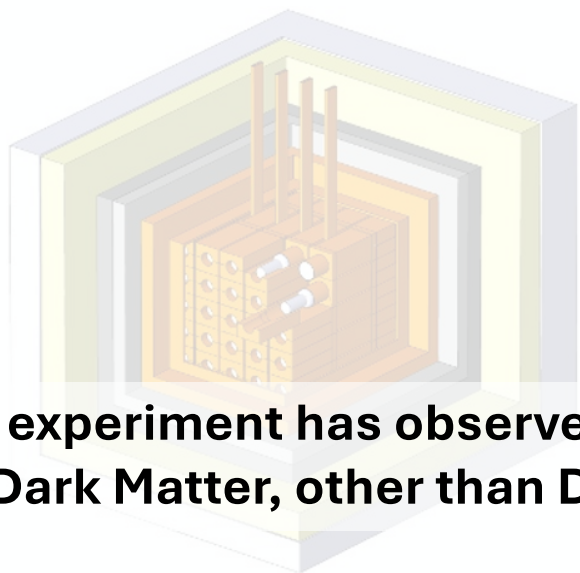
No experiment has observed direct evidence of Dark Matter, other than DAMA/LIBRA
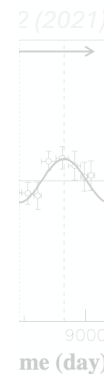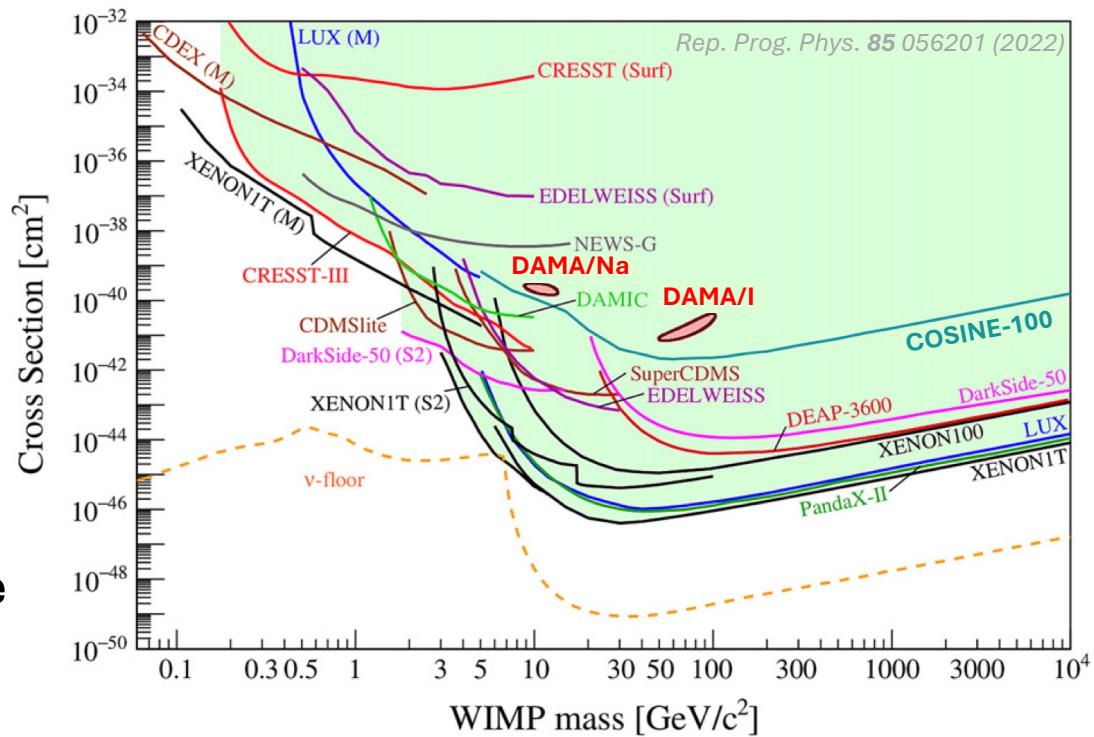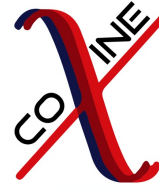
COSINE-100 Experiment

Collaboration & Experimental Site

- Collaboration of DM-ICE and KIMS
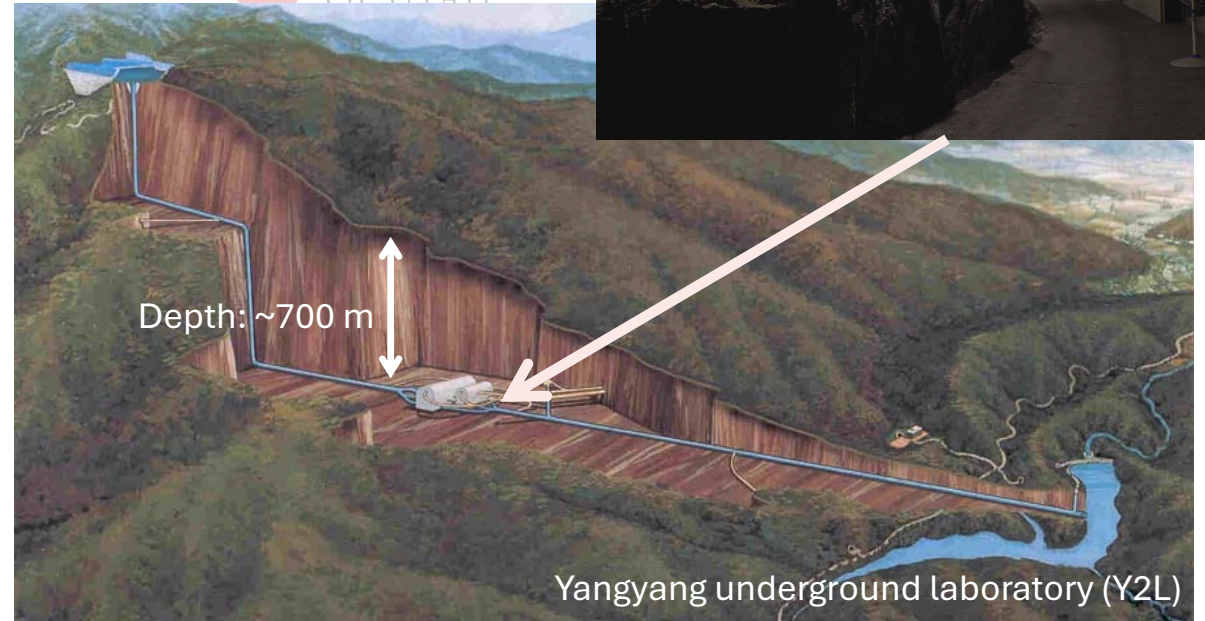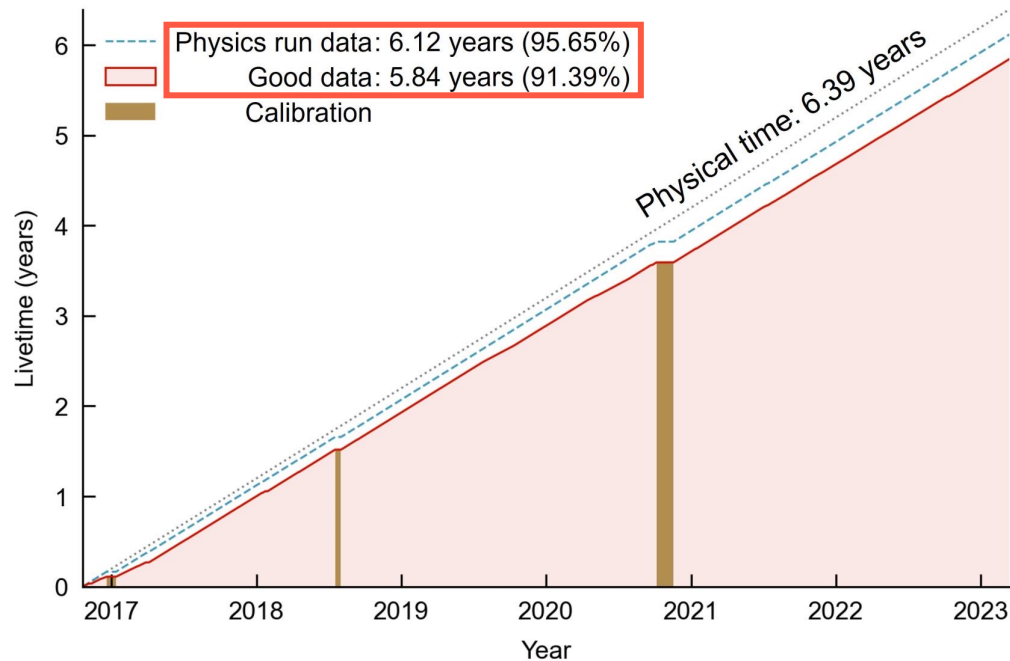
- 17 institutes, ~60 members

COSINE-100 Experiment
Collaboration & Experimental Site

- Collaboration of DM-ICE and KIMS

- 17 institutes, ~60 members

- Data taking from Oct. 2016 to Mar. 2023

  in Yangyang underground laboratory (Y2L), Korea

COSINE / AMoRE
Since 2014

Depth: ~700 m

Yangyang underground laboratory (Y2L)

COSINE-100 Experiment

Experimental Setup

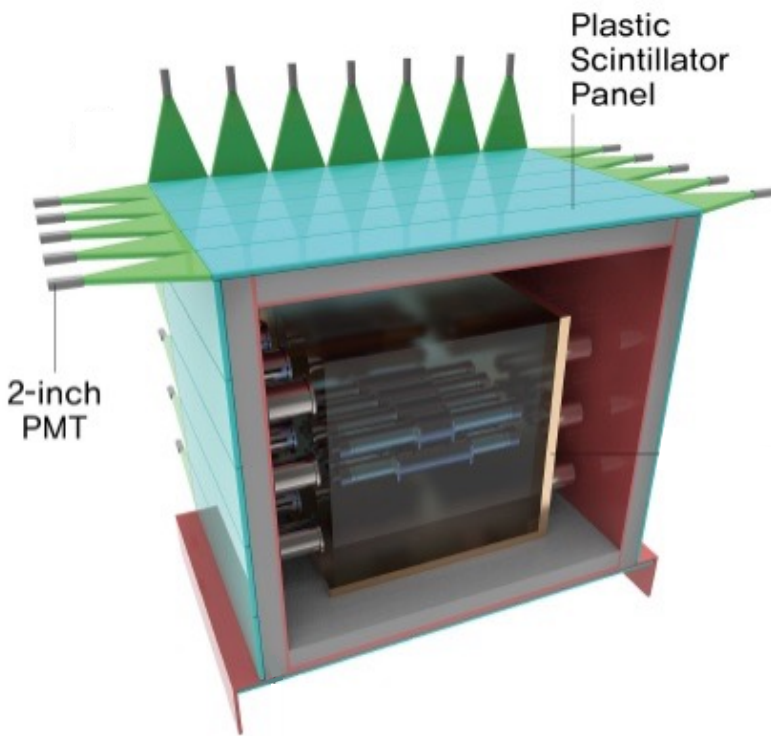# COSINE-100 Experiment

Experimental Setup

JINST 13, T02007 (2018)

4π Muon Counter
37 Plastic scintillator panel
2-inch H7195 PMTs

Plastic Scintillator Panel

2-inch PMT

COSINE-100 Experiment

Experimental Setup

JINST 13, T02007 (2018)

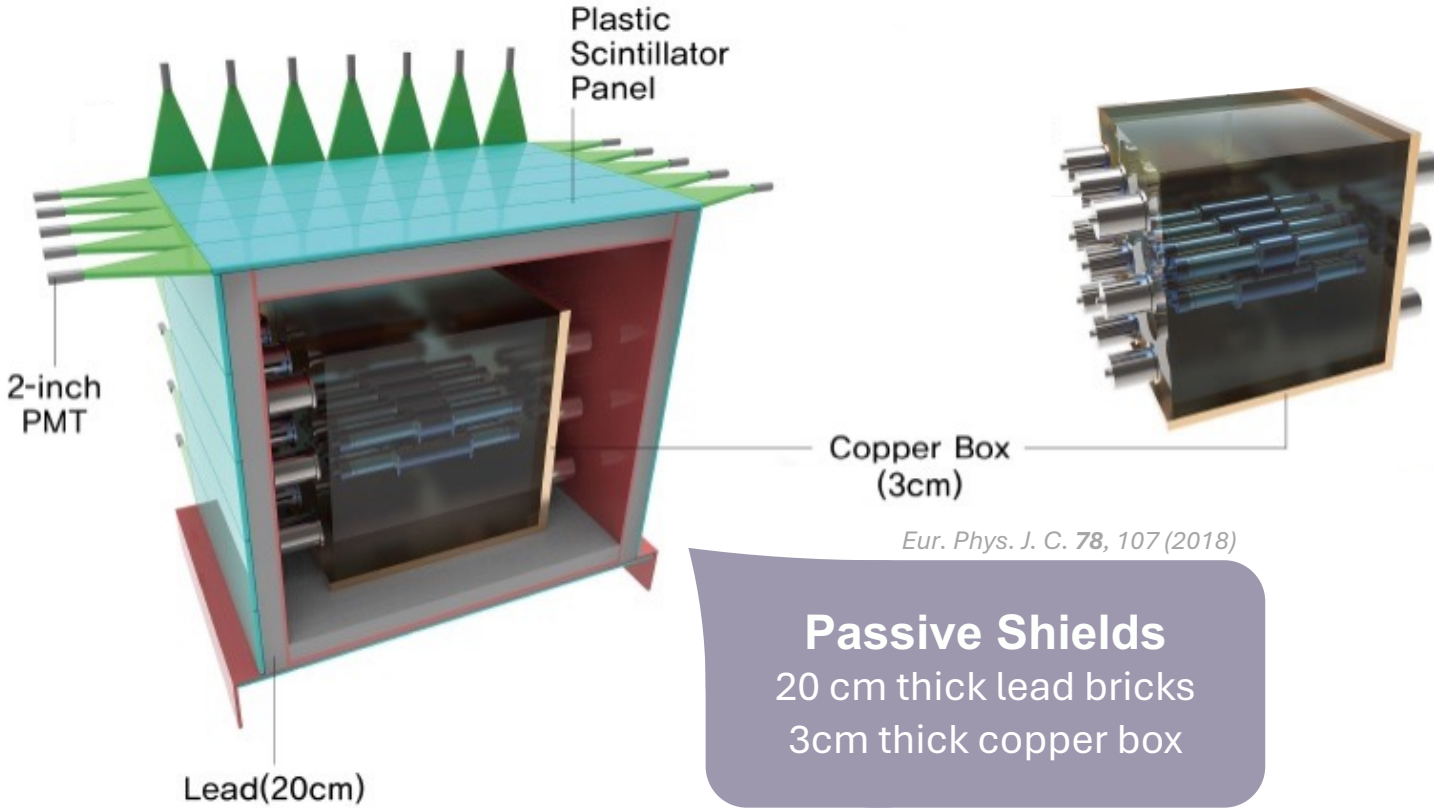**4π Muon Counter**
37 Plastic scintillator panel
2-inch H7195 PMTs

Plastic Scintillator Panel

2-inch PMT

Copper Box (3cm)

*Eur. Phys. J. C. **78**, 107 (2018)*

Passive Shields
20 cm thick lead bricks
3cm thick copper box

Lead(20cm)

COSINE-100 Experiment

Experimental Setup

JINST 13, T02007 (2018)

4π Muon Counter
37 Plastic scintillator panel
2-inch H7195 PMTs

Plastic Scintillator Panel

5-inch PMT

Liquid Scintillator

2-inch PMT

Copper Box (3cm)

Lead(20cm)

Nucl. Instrum. Meth. A 1006, 165431 (2021)

Liquid Scintillator
2200 L LAB-based LS
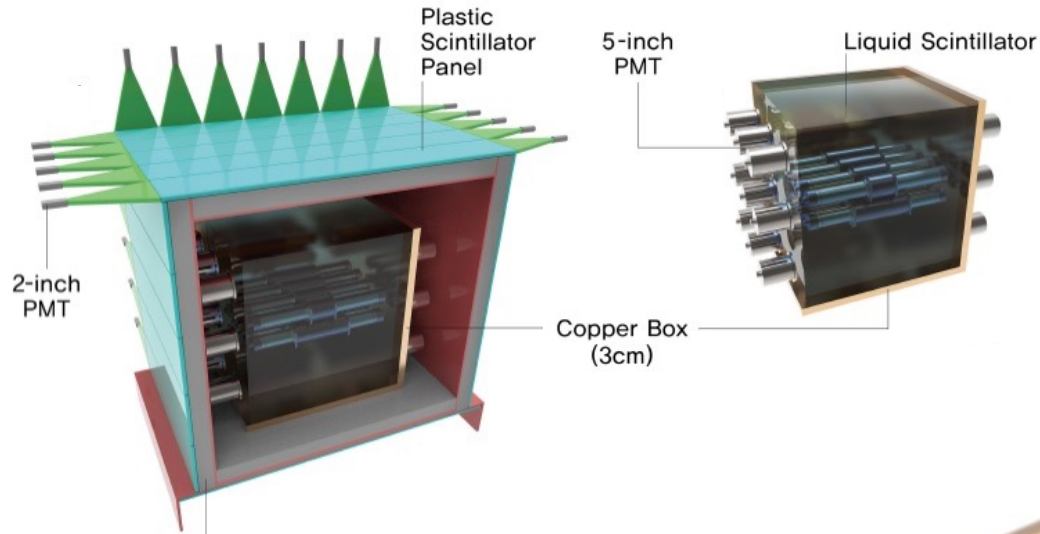18 5-inch R877 PMTs
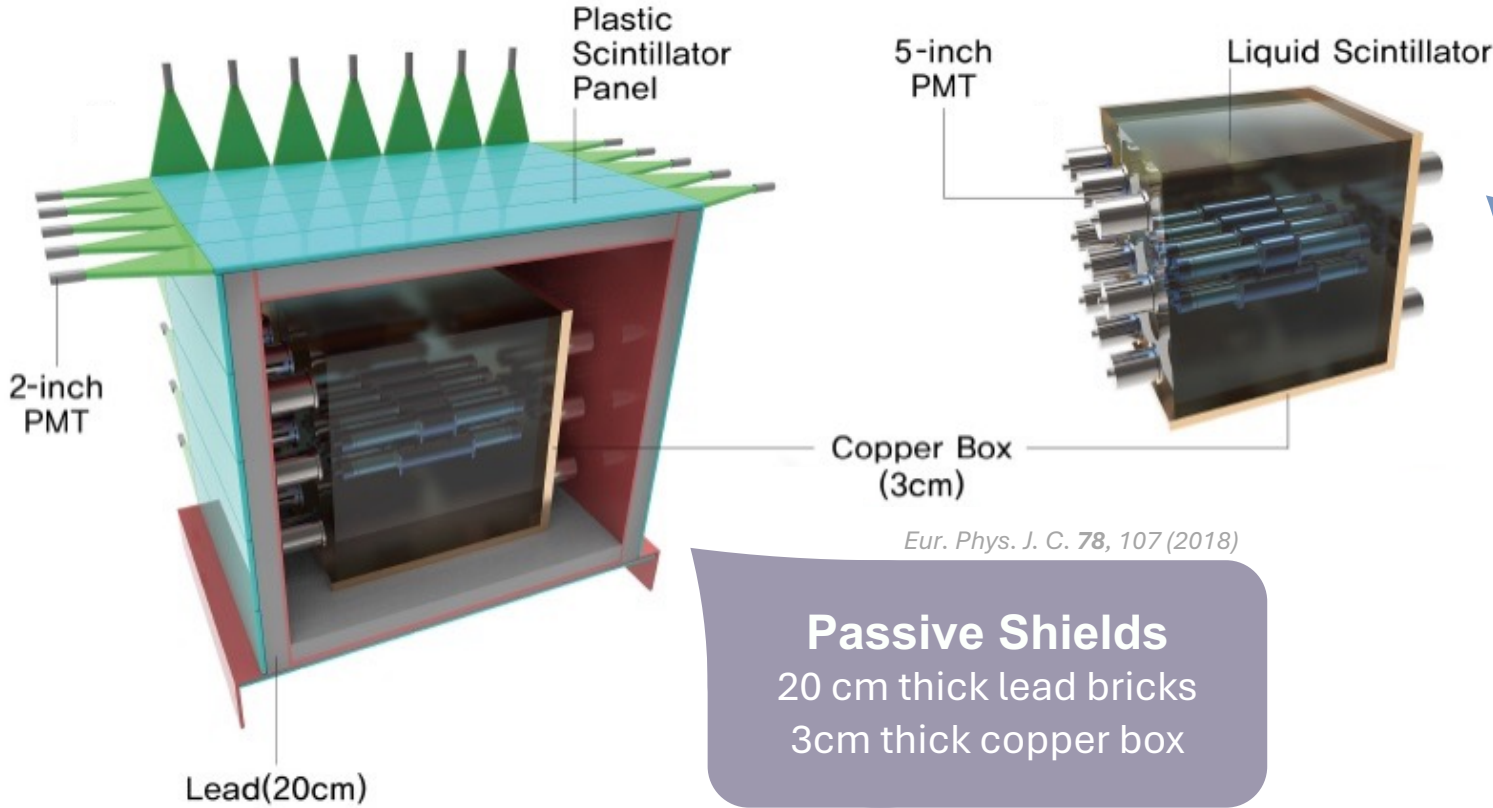
*Eur. Phys. J. C. **78**, 107 (2018)*

Passive Shields
20 cm thick lead bricks
3cm thick copper box

COSINE-100 Experiment
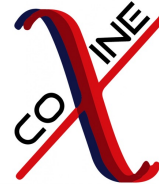
Experimental Setup

NaI(Tl) Detector
8 low-background crystals
3-inch R12669SEL PMTs
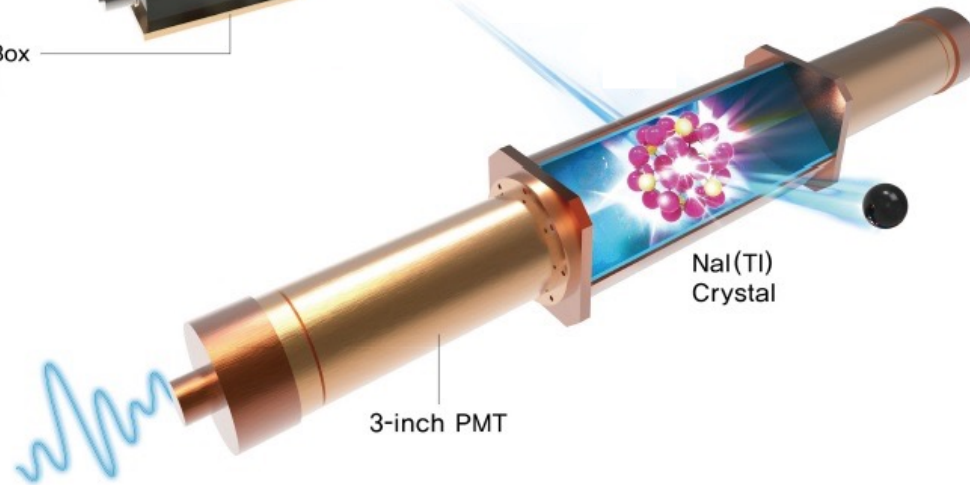in copper encapsulation

COSINE-100 Experiment

Experimental Setup

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

NaI(Tl) Detector
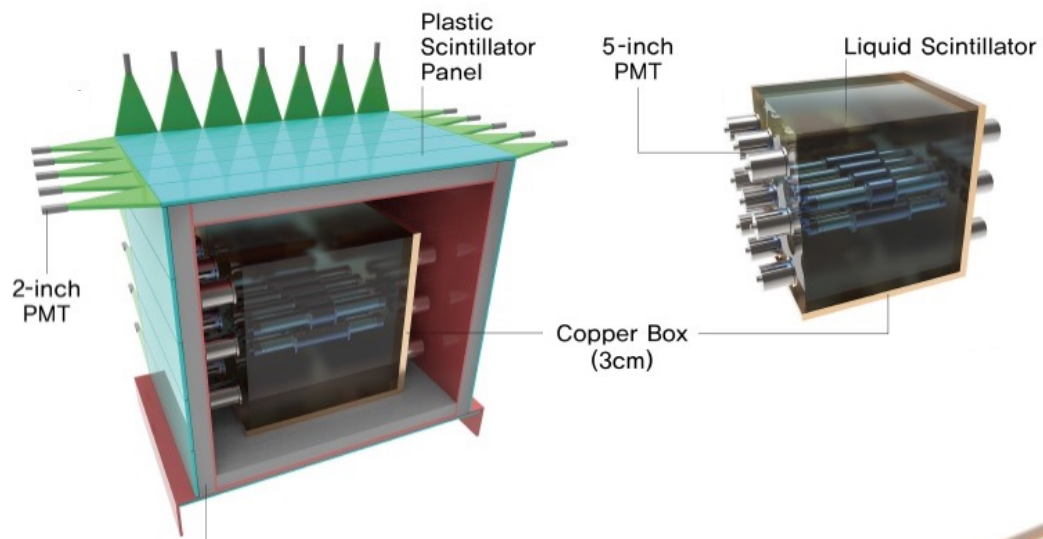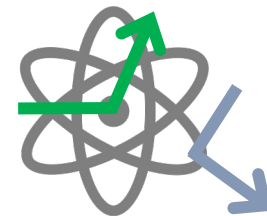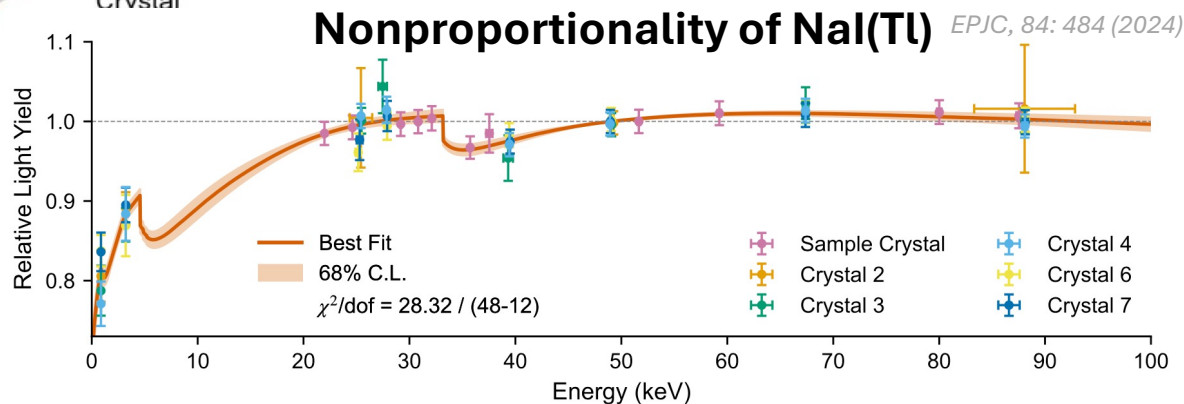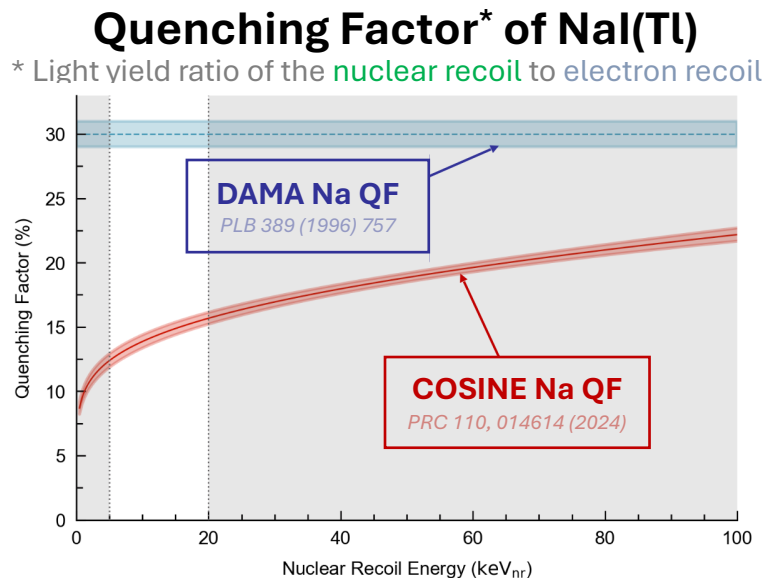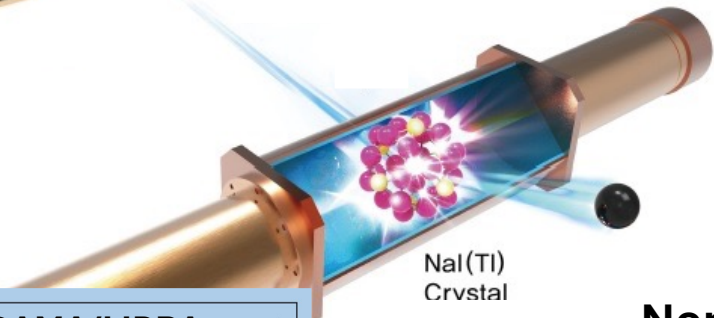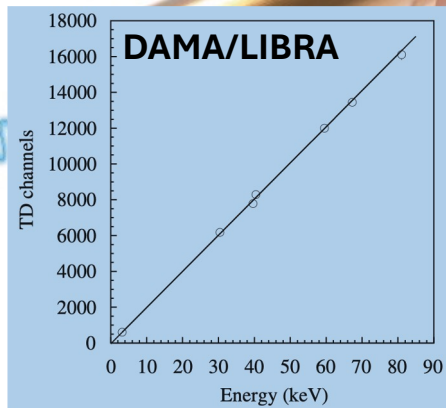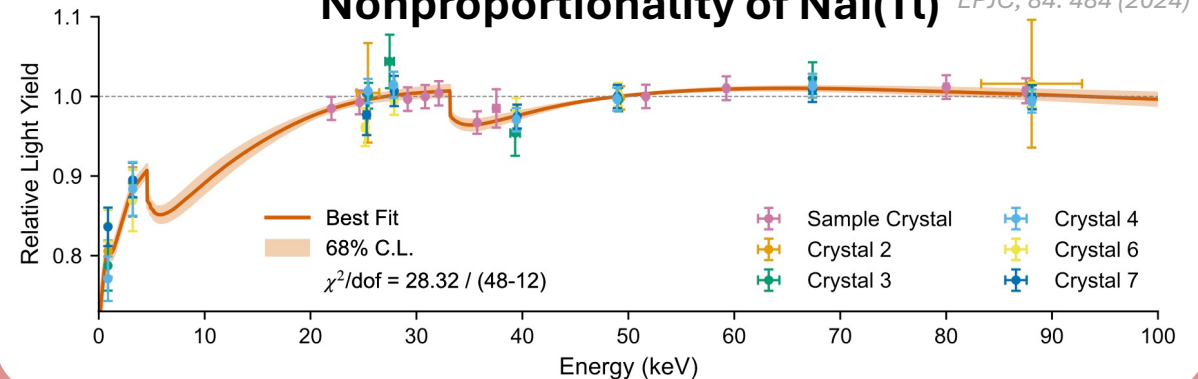8 low-background crystals
3-inch R12669SEL PMTs
in copper encapsulation

Quenching Factor* of NaI(Tl)
* Light yield ratio of the nuclear recoil to electron recoil

DAMA Na QF
PLB 389 (1996) 757

COSINE Na QF
PRC 110, 014614 (2024)

Nonproportionality of NaI(Tl) *EPJC, 84: 484 (2024)*

Best Fit
68% C.L.
χ^2/dof = 28.32 / (48-12)

Sample Crystal | Crystal 4
Crystal 2 | Crystal 6
Crystal 3 | Crystal 7

Improvement of detector understanding !

Improvement of Detector Understanding

Detector Response

Quenching Factor of NaI(Tl)

DAMA Na QF
PLB 389 (1996) 757
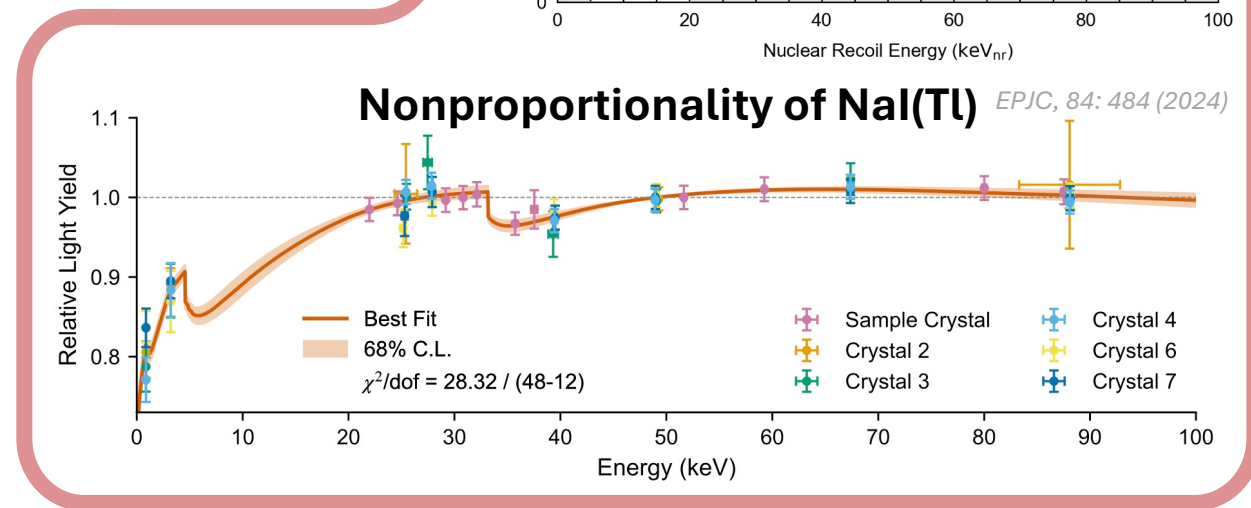
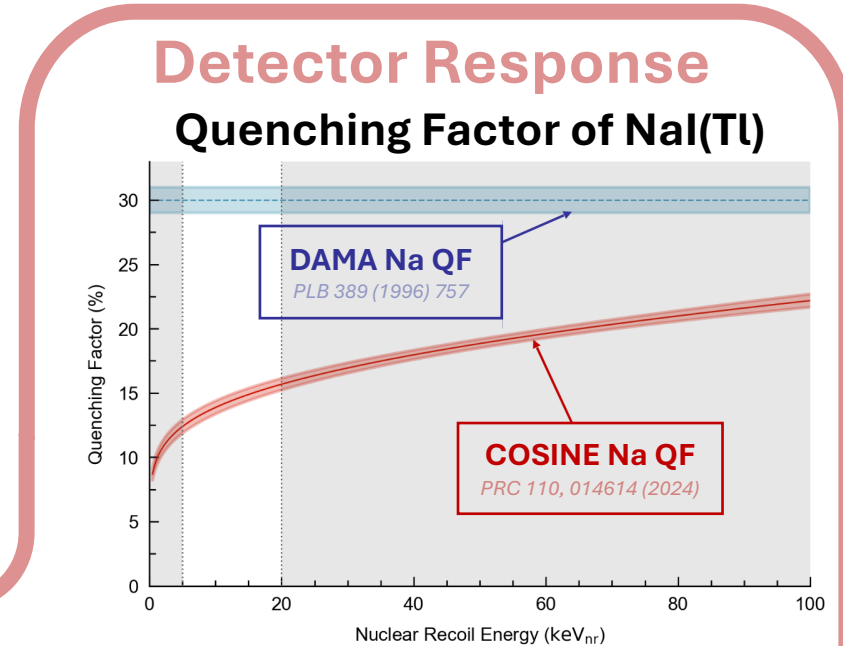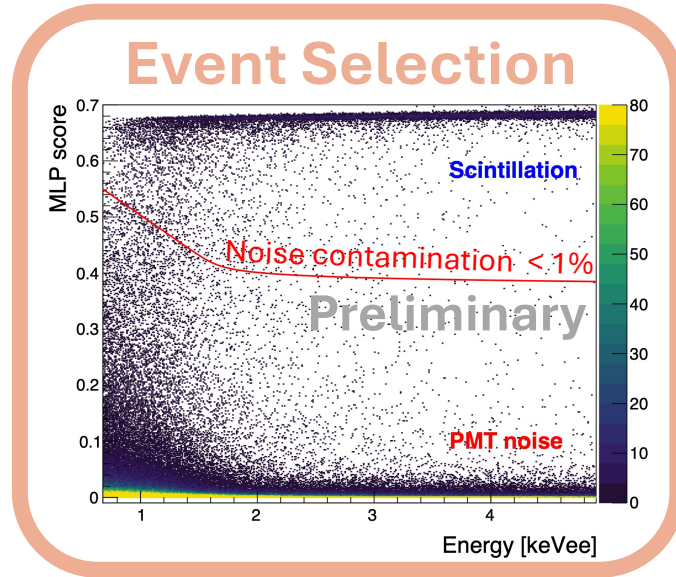**COSINE Na QF**
PRC 110, 014614 (2024)
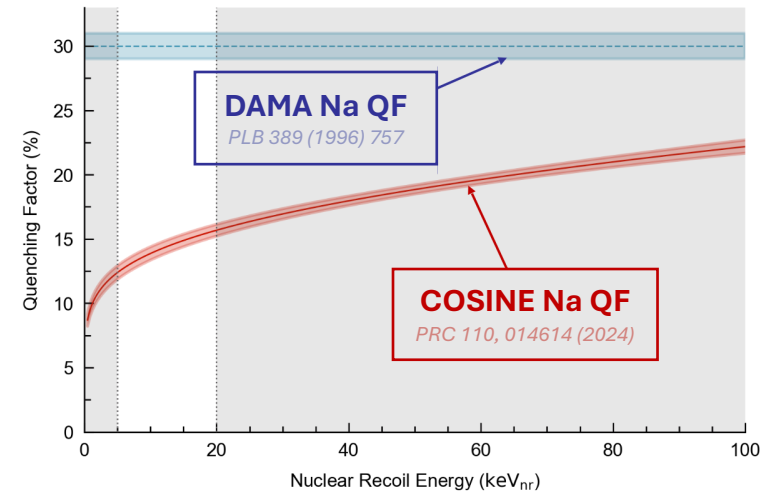
Nonproportionality of NaI(Tl) *EPJC, 84: 484 (2024)*

Improvement of Detector Understanding

Event Selection

Energy threshold: 1 keV$_{ee}$ → **0.7 keV$_{ee}$**

Detector Response

Quenching Factor of NaI(Tl)

Nonproportionality of NaI(Tl) *EPJC, 84: 484 (2024)*
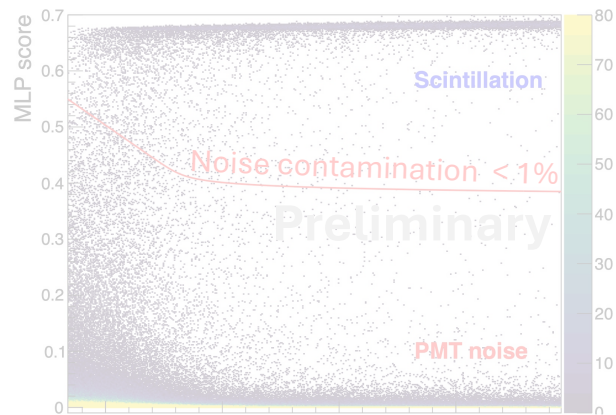
Improvement of Detector Understanding

Background Modeling

Modeling with SET3 (2.82 years) data
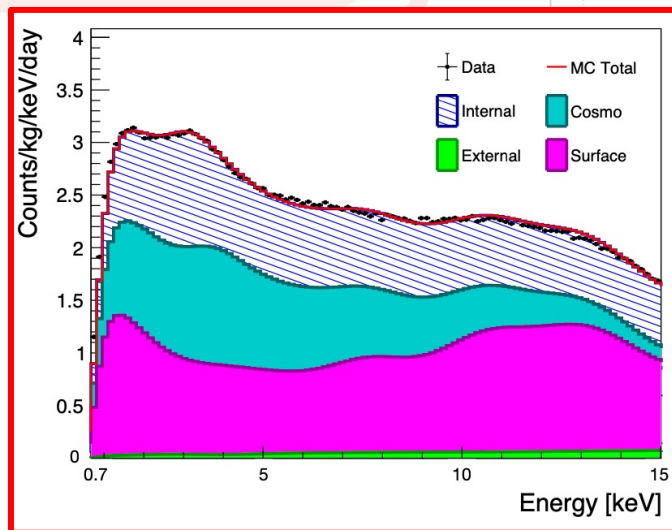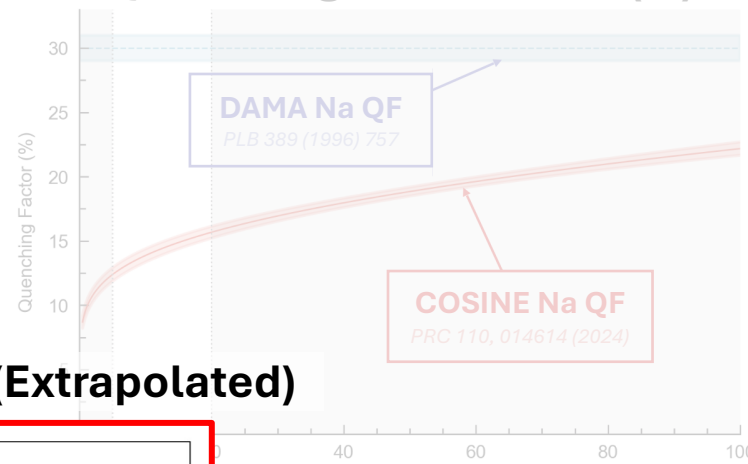Energy range of NaI(Tl) backgrounds is improved: **0.7 – 4000 keV**
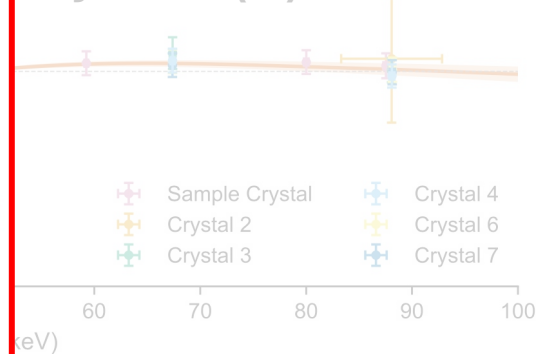

Event Selection

Detector Response
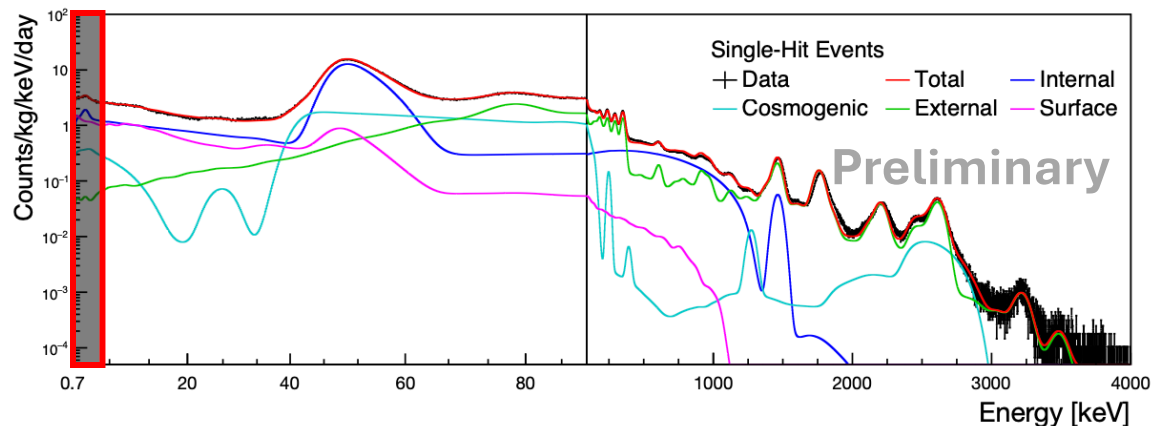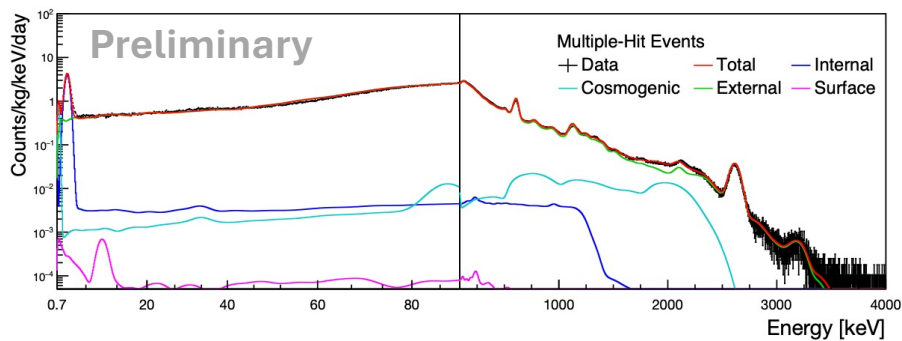
Quenching Factor of NaI(Tl)

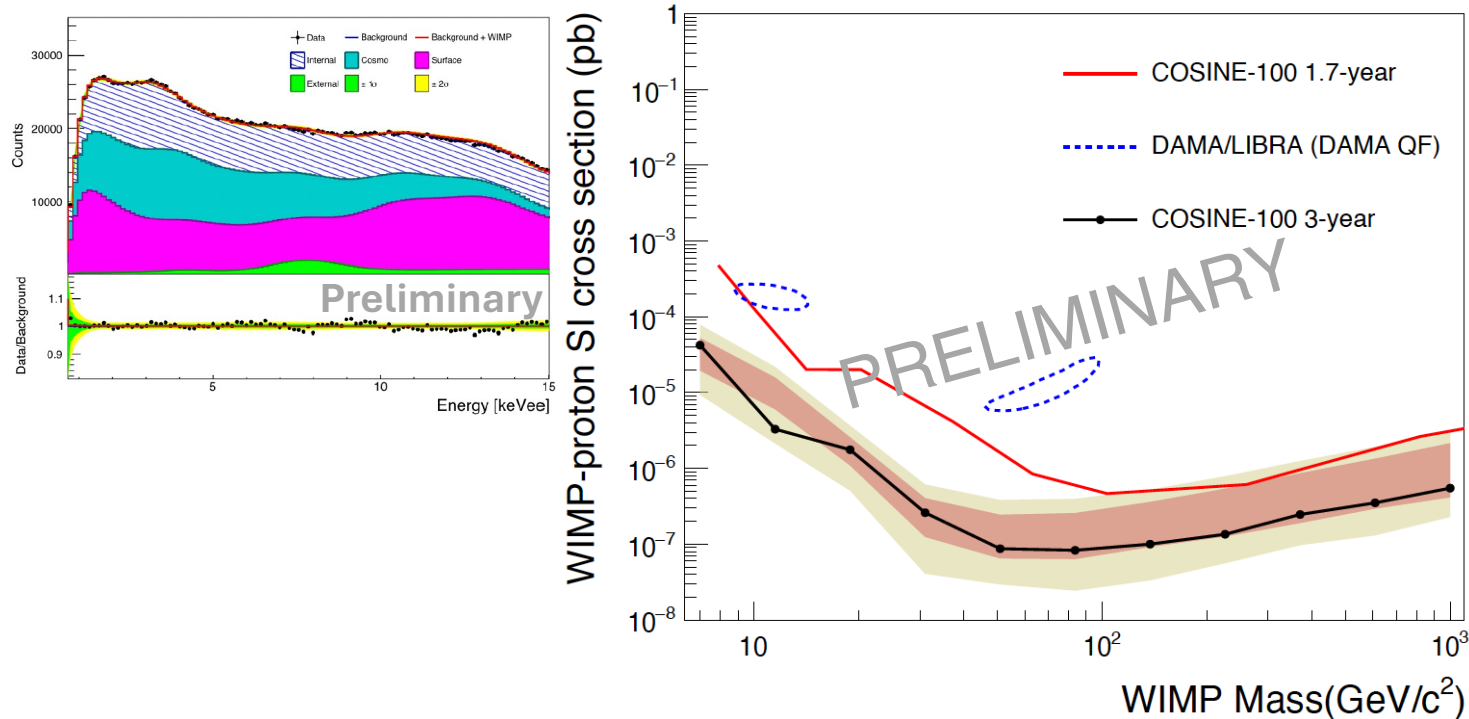**WIMP Region of Interest (Extrapolated)**

WIMP Extraction
Spectral Analysis with 3-year Data

WIMP Extraction
Spectral Analysis with 3-year Data
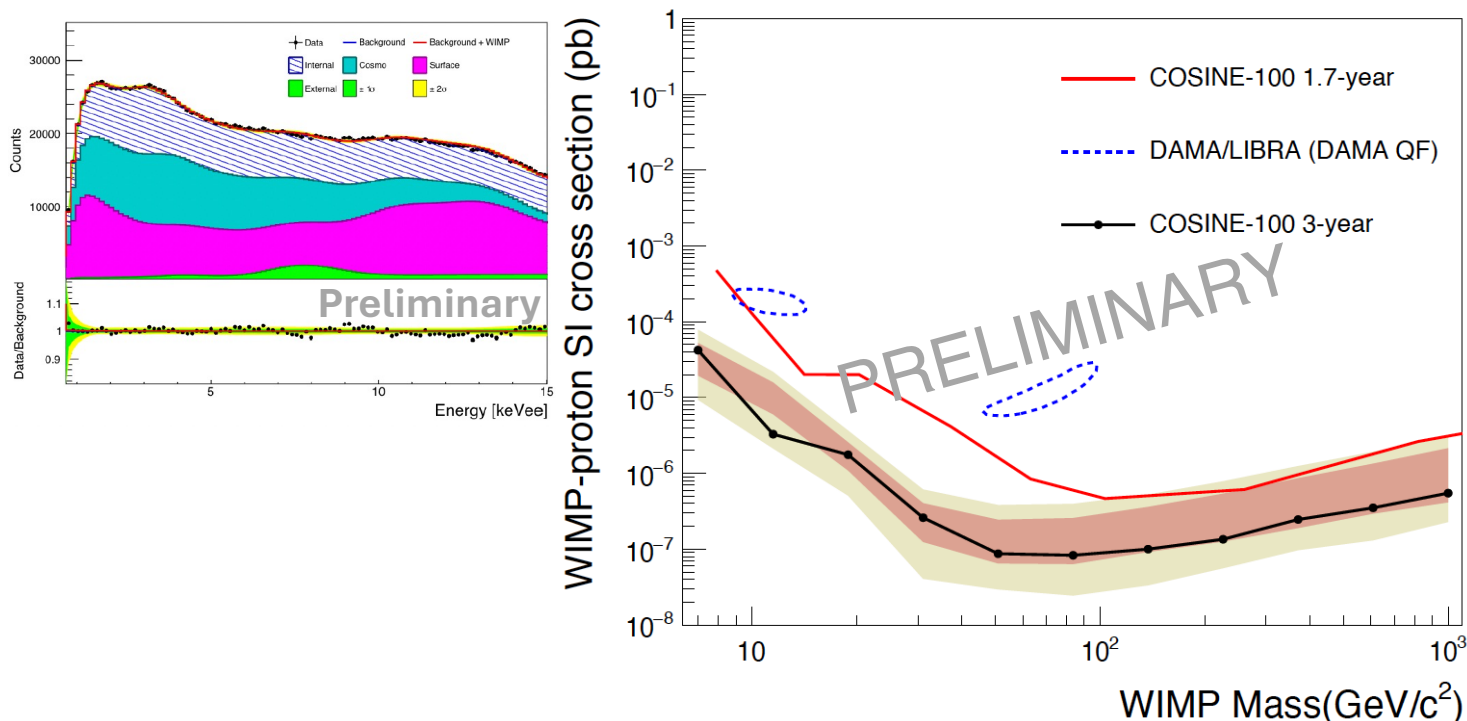
Spin-Independent (SI) Interaction

Disfavor DAMA/LIBRA's claim (3 σ)
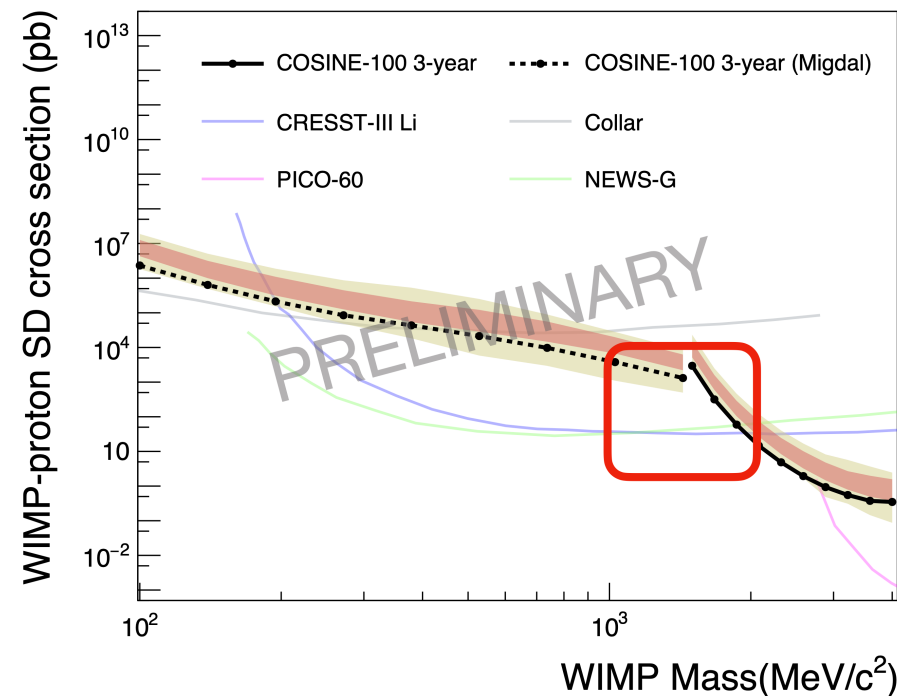
WIMP Extraction

Spectral Analysis with 3-year Data

Spin-Independent (SI) Interaction

Spin-Dependent (SD) Interaction

with Na (Z = 11) & I (Z = 53)

- Proton-odd targets
  → Sensitive in SD model
- Na Low-mass target
  → Sensitive in low-mass WIMP search

Disfavor DAMA/LIBRA's claim (3 σ)
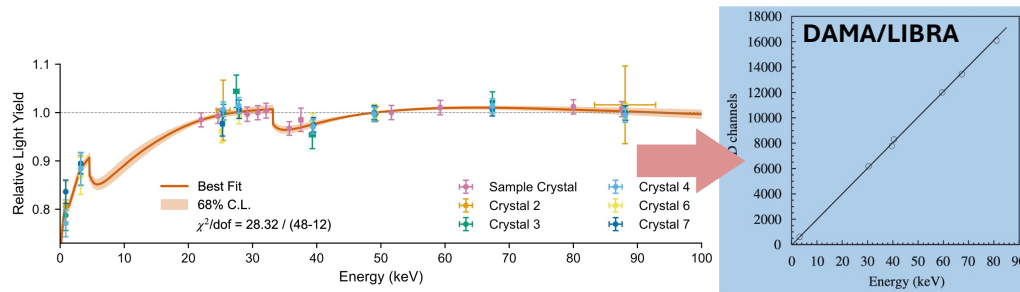
Annual Modulation Analysis
with Full COSINE-100 Dataset (~6 years)
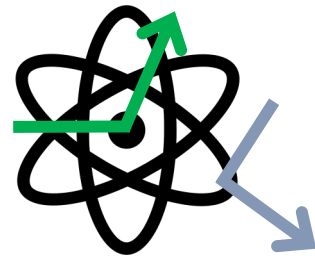
Annual Modulation Analysis

with Full COSINE-100 Dataset (~6 years)

Calibration to Test DAMA's Claim

Linear Calibration for Electron Recoil

Calibration for Nuclear Recoil

WIMP signal: 6.7 – 20 keV$_{nr}$

➡ DAMA/LIBRA: 2 – 6 keV$_{ee}$

➡ **COSINE-100**: 0.85 – 3.12 keV$_{ee}$
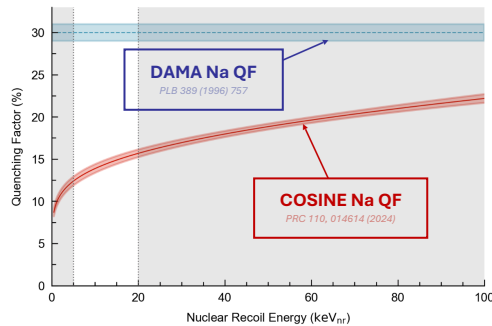
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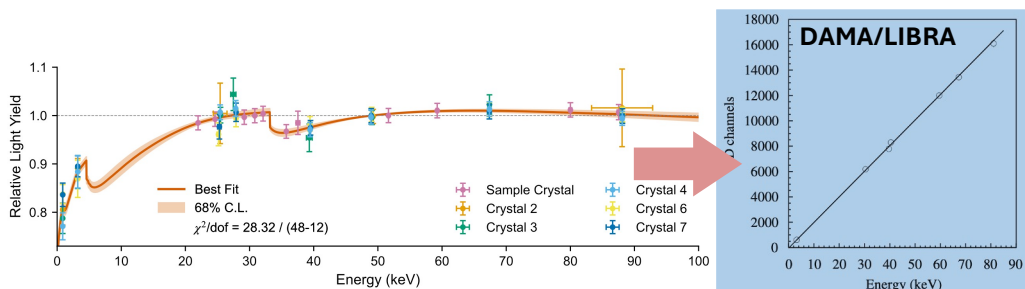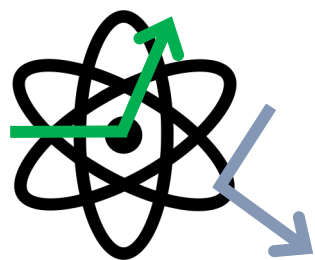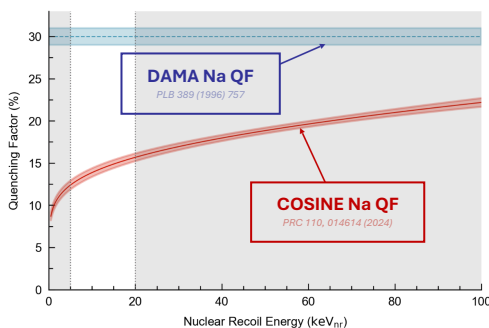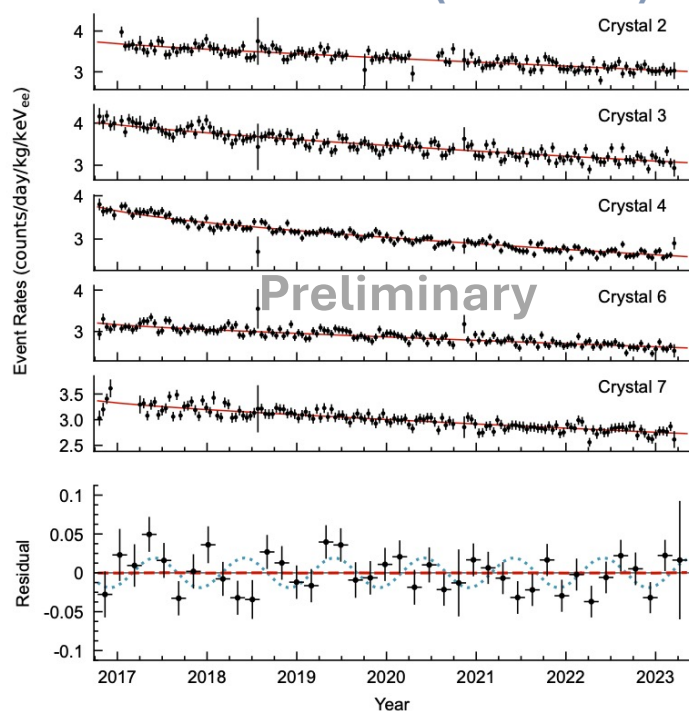WIMP signal: 6.7 – 20 keVnr

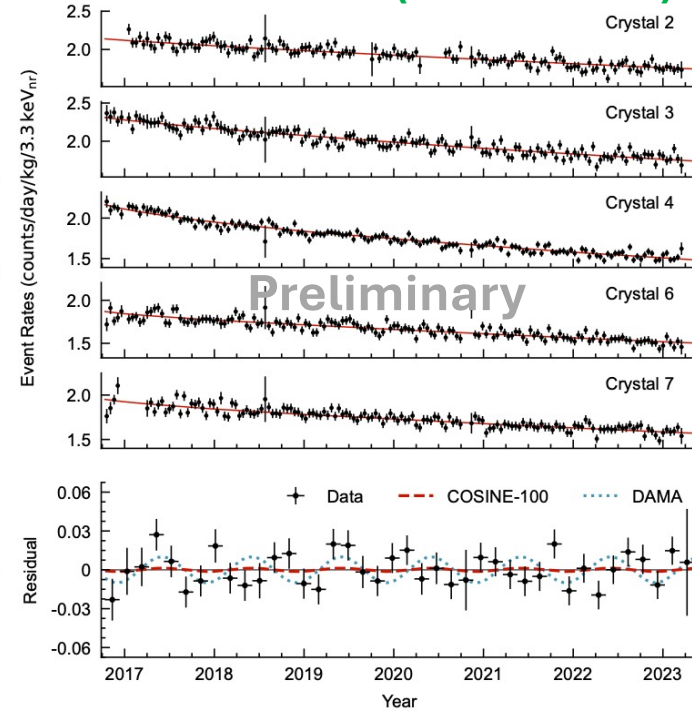➡ DAMA/LIBRA: 2 – 6 keVee

➡ **COSINE-100**: 0.85 – 3.12 keVee

Event Rates and Modulation Fit

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

Background   Modulation

Electron Recoil (1-3 keVee)
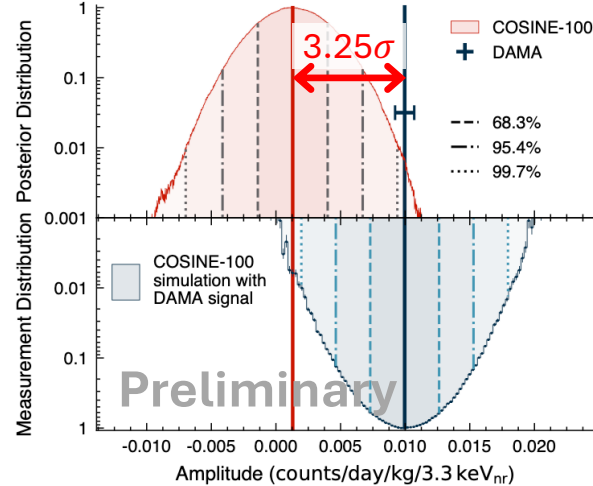

Nuclear Recoil (6.7-20 keVnr)

Annual Modulation Analysis

with Full COSINE-100 Dataset (~6 years)

Electron Recoil (1-3 keV$_{ee}$)   Nuclear Recoil (6.7-20 keV$_{nr}$)

Phase-fixed Fit

E (keV$_{ee}$)	A (counts/day/kg/keVee)	
	COSINE-100	DAMA/LIBRA
1-3	0.0004 ± 0.0050	0.0191 ± 0.0020
1-6	0.0017 ± 0.0029	0.0105 ± 0.0009
2-6	0.0053 ± 0.0031	0.0100 ± 0.0007

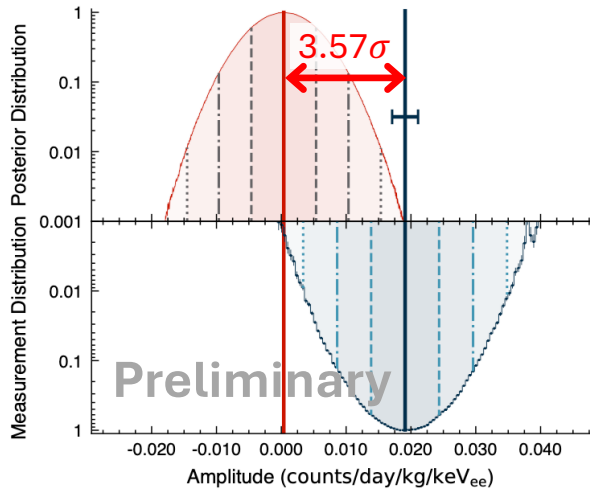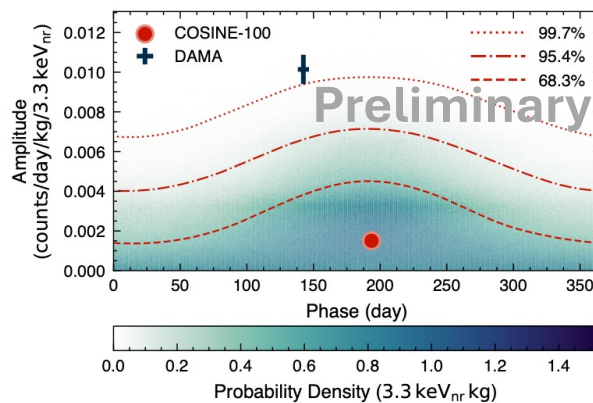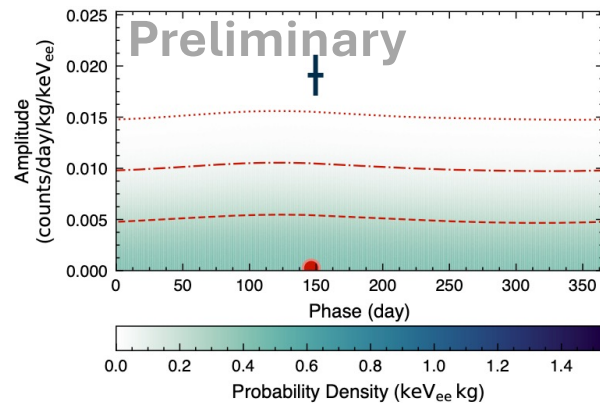| E (keV$_{nr}$)	A (counts/day/kg/3.3 keVnr)	
	COSINE-100	DAMA/LIBRA
6.7-20	0.0013 ± 0.0027	0.0100 ± 0.0007

Annual Modulation Analysis
with Full COSINE-100 Dataset (~6 years)

Electron Recoil (1-3 keV$_{ee}$)   Nuclear Recoil (6.7-20 keV$_{nr}$)
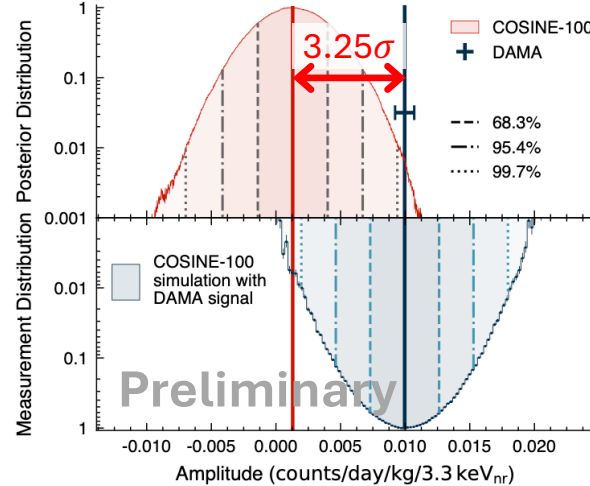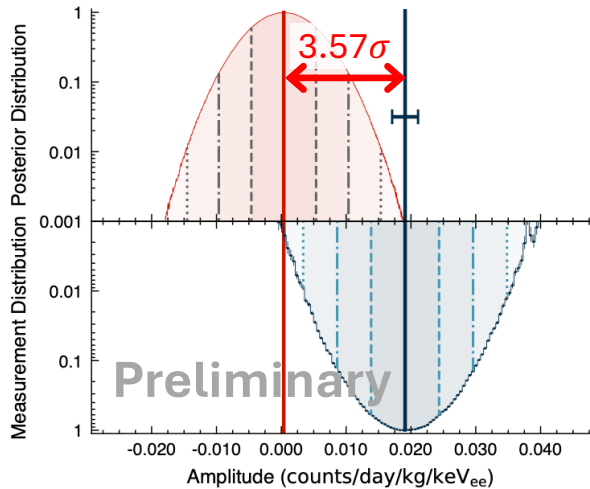
Phase-fixed Fit

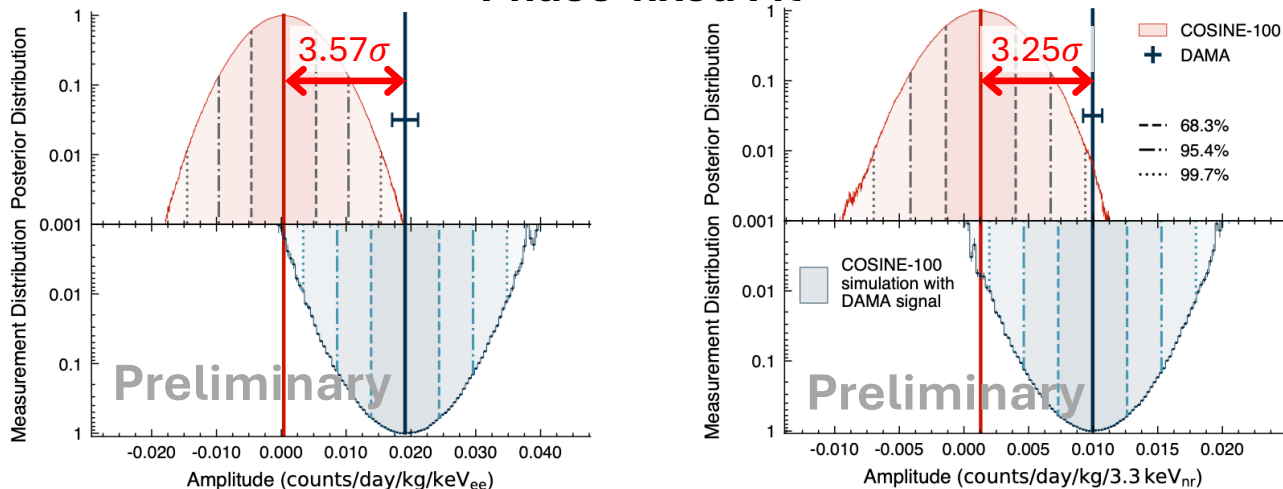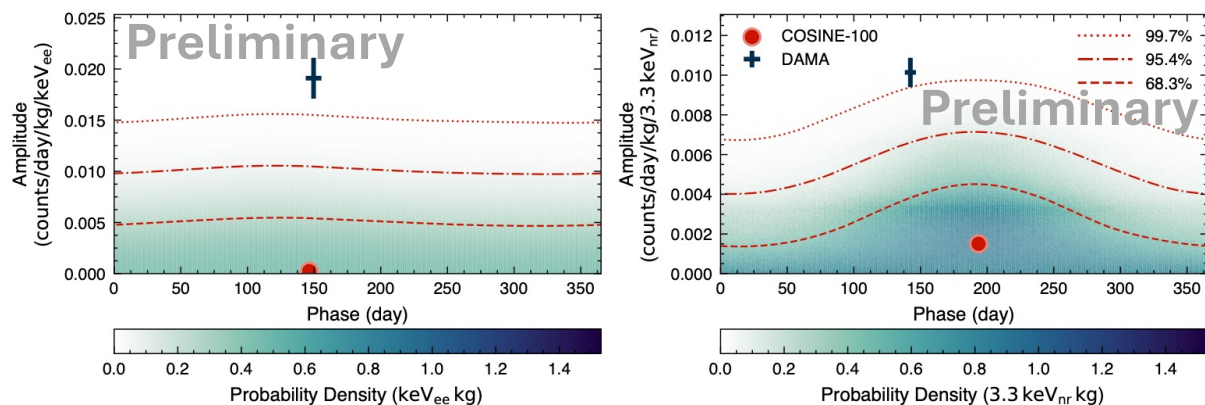### Phase-floated 2D Fit

Disfavors DAMA's result (> 3σ)

Annual Modulation Analysis

with Full COSINE-100 Dataset (~6 years)

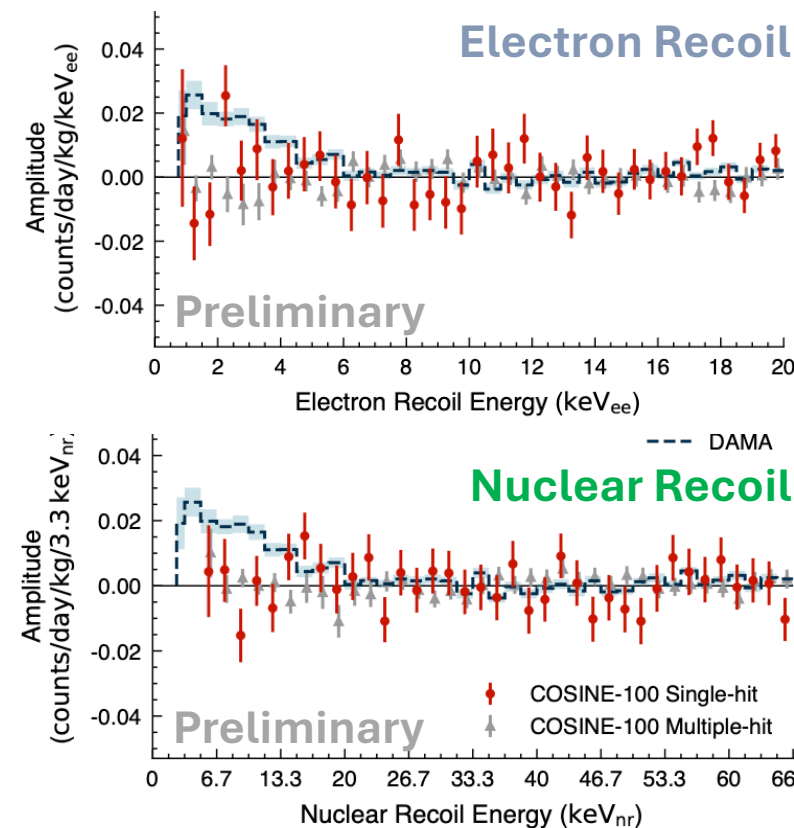**Electron Recoil (1-3 keV$_{ee}$)   Nuclear Recoil (6.7-20 keV$_{nr}$)**

Modulation Amplitude

Phase-fixed Fit

Phase-floated 2D Fit

Disfavors DAMA's result (> 3σ)
No modulation detected

Pulse Shape Discrimination of NaI(Tl) Crystals
Electron Recoil & Nuclear Recoil

- WIMP Extraction – Extracting WIMP-proton interaction in the data
- Annual Modulation – Finding sinusoidal modulation in event rates
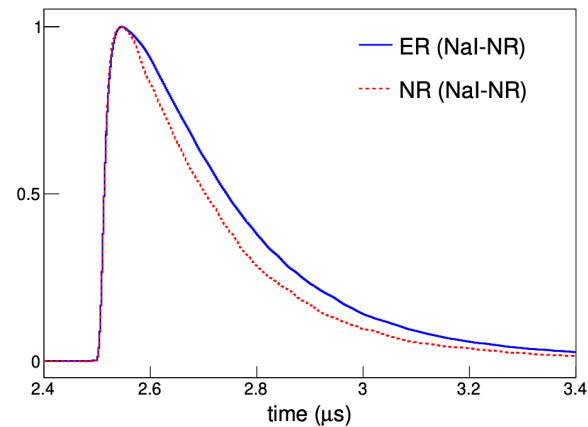
Pulse Shape Discrimination of NaI(Tl) Crystals

Electron Recoil & Nuclear Recoil

COSINE-100 WIMP Search
- WIMP Extraction – Extracting WIMP-proton interaction in the data
- Annual Modulation – Finding sinusoidal modulation in event rates
- **Pulse Shape Discrimination (PSD) – Searching nuclear recoil (WIMP-like) signals using differences of pulse shapes between nuclear recoil and electron recoil**
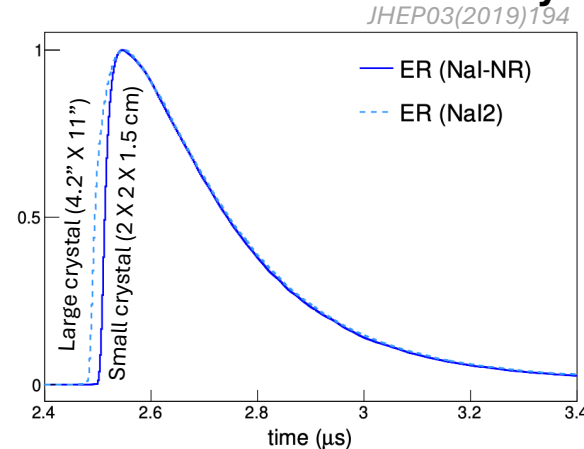
Accumulated Waveform (2-10 keV)
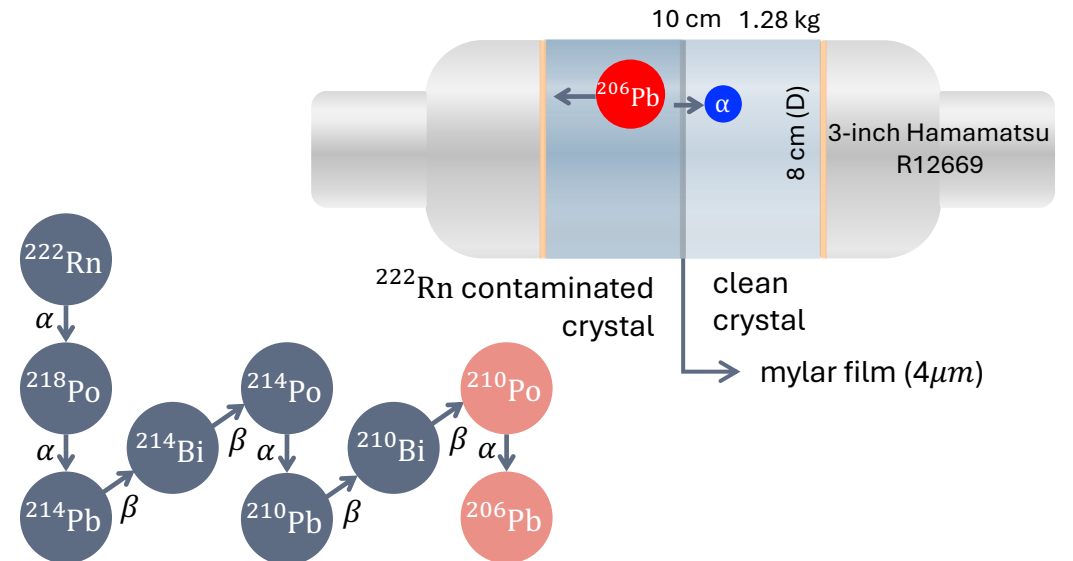
ER and NR in the same crystal

→ Different decay time

ER in the different size of crystal

JHEP03(2019)194

→ Different rise time
Same decay time

Surface Recoil due to the Contamination

^{222}Rn contaminated crystal

clean crystal

mylar film ($4\mu m$)

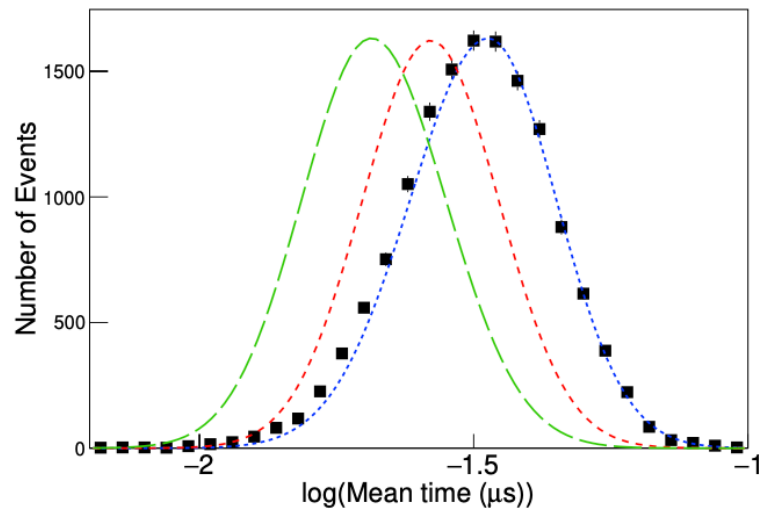# Pulse Shape Discrimination of NaI(Tl) Crystals

Electron Recoil & Nuclear Recoil

COSINE-100 WIMP Search

- WIMP Extraction – Extracting WIMP-proton interaction in the data
- Annual Modulation – Finding sinusoidal modulation in event rates
- **Pulse Shape Discrimination (PSD) – Searching nuclear recoil (WIMP-like) signals using differences of pulse shapes between nuclear recoil and electron recoil**
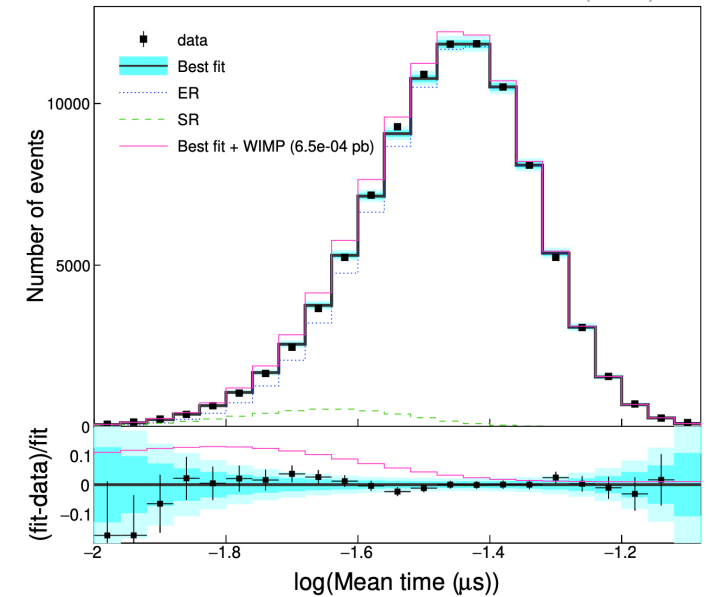
PSD Using Log Meantime Parameter

LMT Fit *JHEP03(2019)194*

Log Meantime (LMT) Distribution (3-4 keV)

RMS of LMT
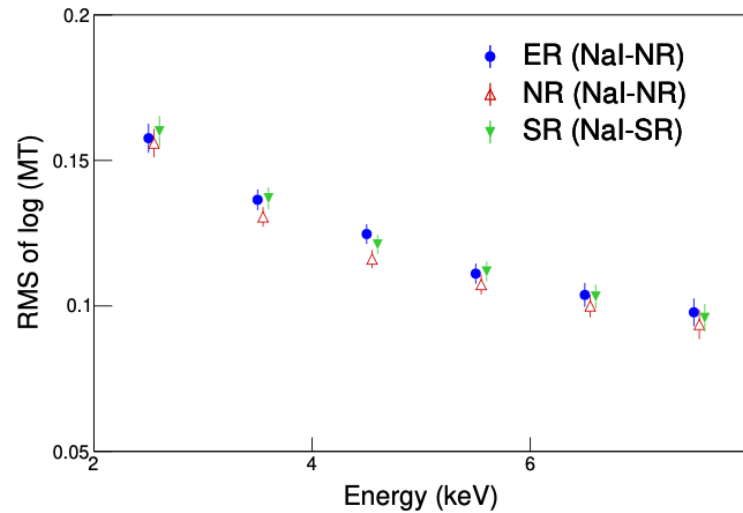
Pulse Shape Discrimination of NaI(Tl) Crystals
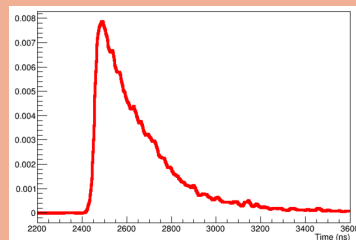
Electron Recoil & Nuclear Recoil

Pulse Shape Discrimination of NaI(Tl) Crystals
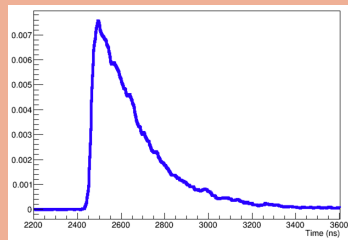
Electron Recoil & Nuclear Recoil

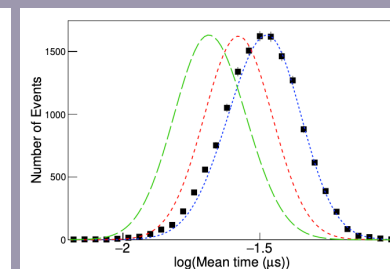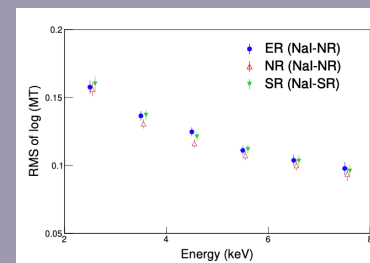**Neutron Data**

(Crystal: 2 cm X 2 cm X 1.5 cm)

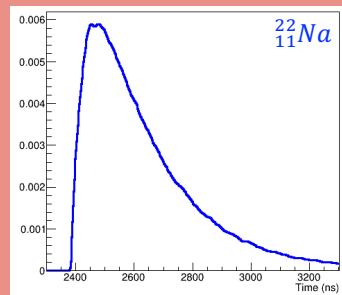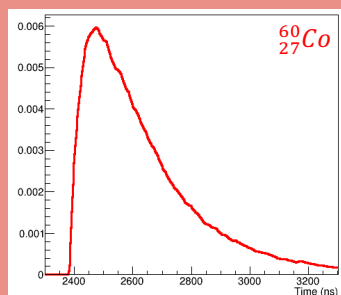Neutron waveform   Gamma waveform

Surface Recoil Data

(^{222}Rn contaminated crystal: 8 cm (D) X 10 cm (H))

COSINE-100 Physics Data (Single)

COSINE-100 Calibration Data

(Source: ^{60}Co, ^{22}Na)

$^{60}_{27}Co$ $^{22}_{11}Na$

COSINE-100 Physics Data (Multiple)
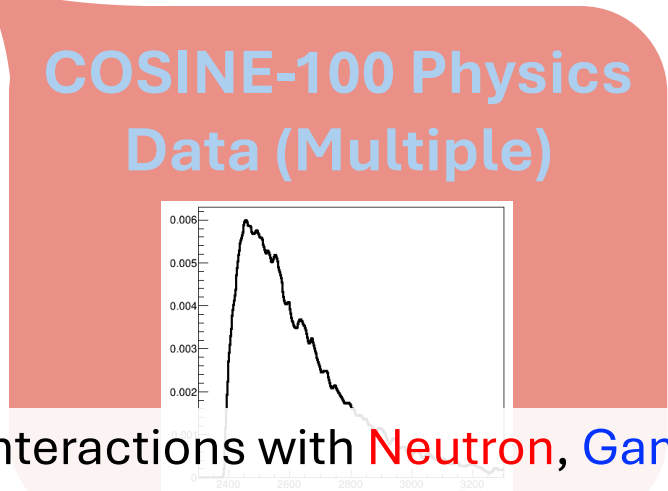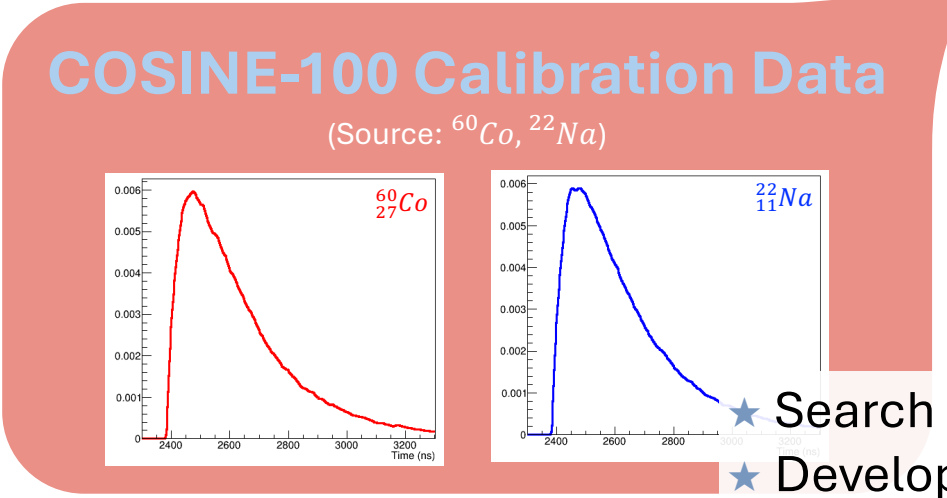
★ Search for WIMP-nucleus interactions with Neutron, Gamma, SR Model
★ Develop Parameter and use waveform simulation to enhance PSD

COSINE-100Upgrade

Move to New Deeper Site - Yemilab

Fridge room

Shield installation
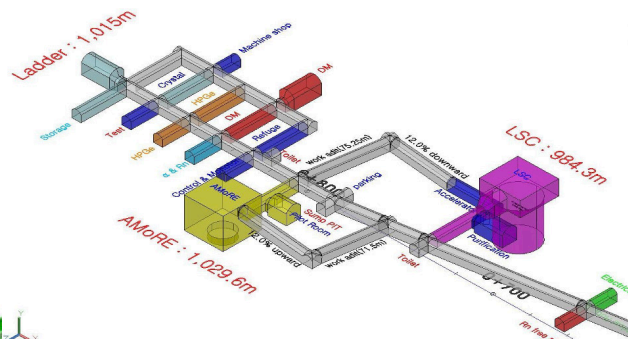
COSINE-100Upgrade

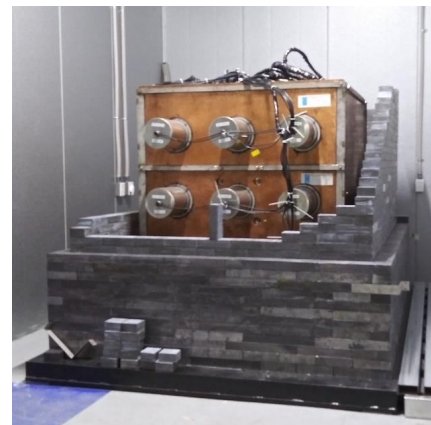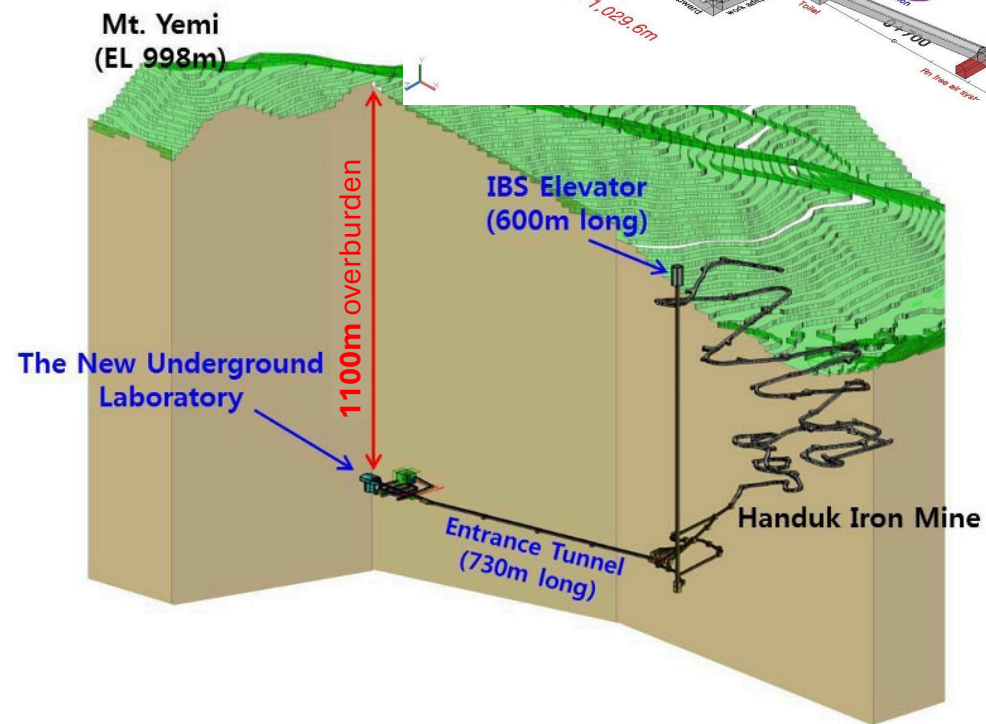## Move to New Deeper Site - Yemilab
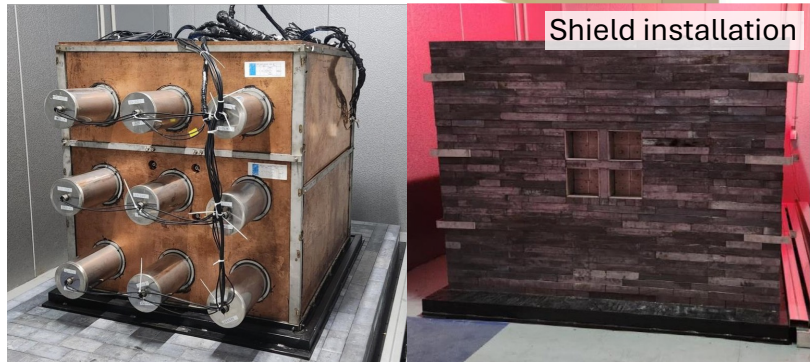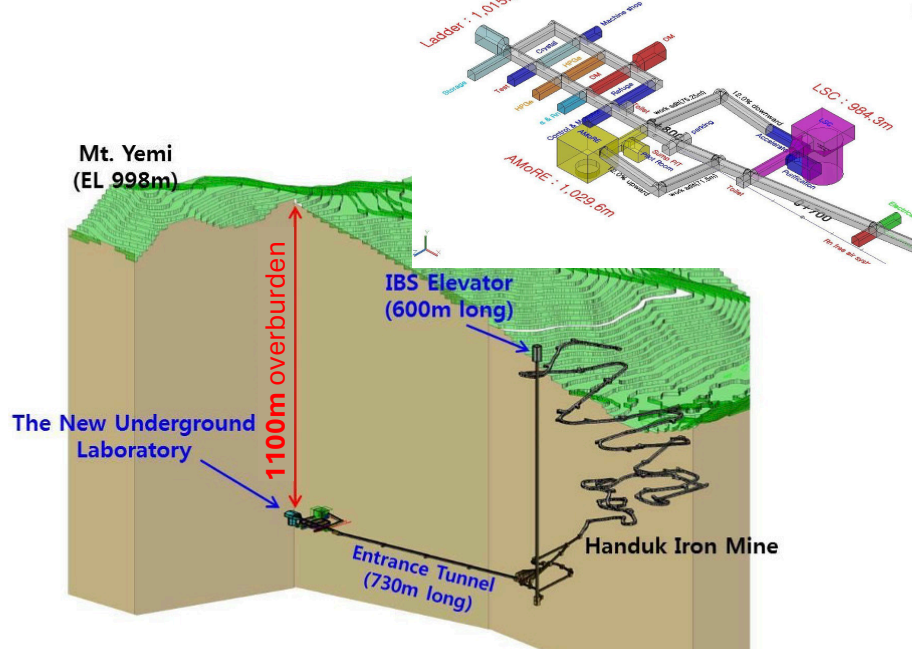
Detector Upgrade
Low temperature operation (-35℃)

Astroparticle Physics 141 (2022) 102709

Fridge room

Shield installation
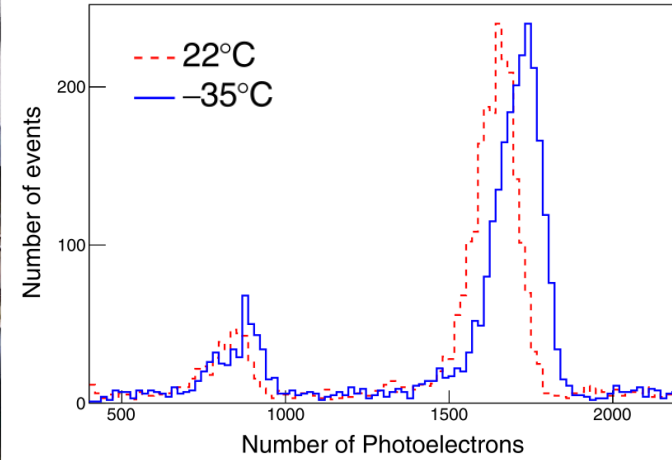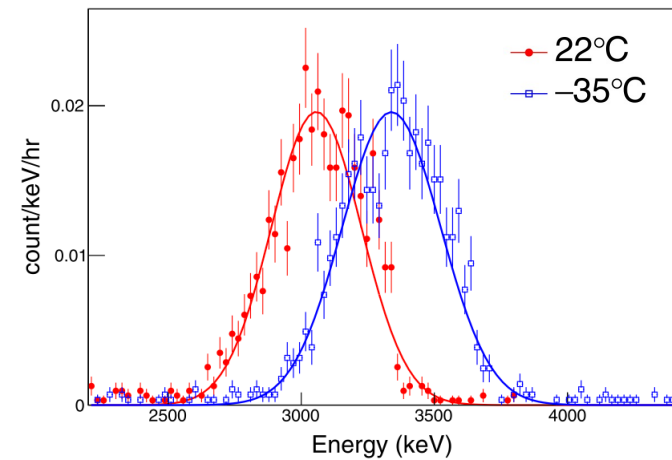
Light yield ~5%⬆

α quenching ~9%⬆

COSINE-100Upgrade

Move to New Deeper Site - Yemilab

Light yields

Preliminary

COSINE-100
New encapsulation

Resolution

Preliminary
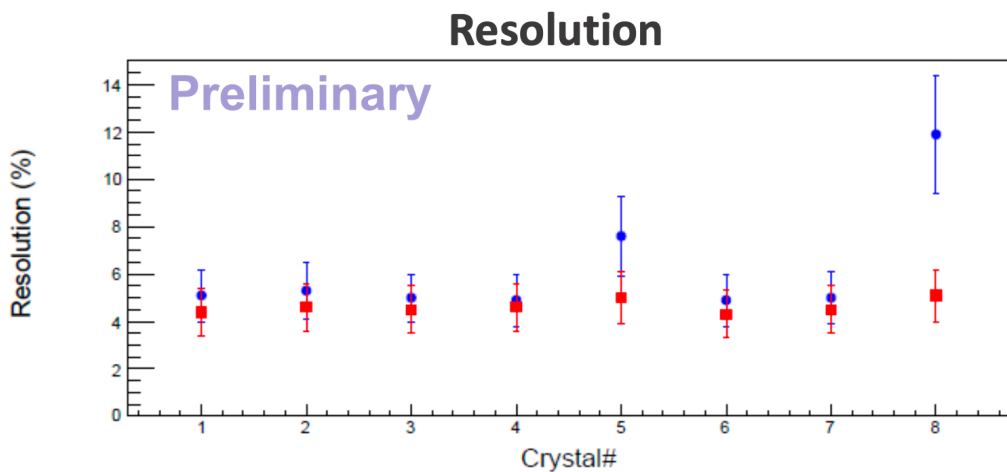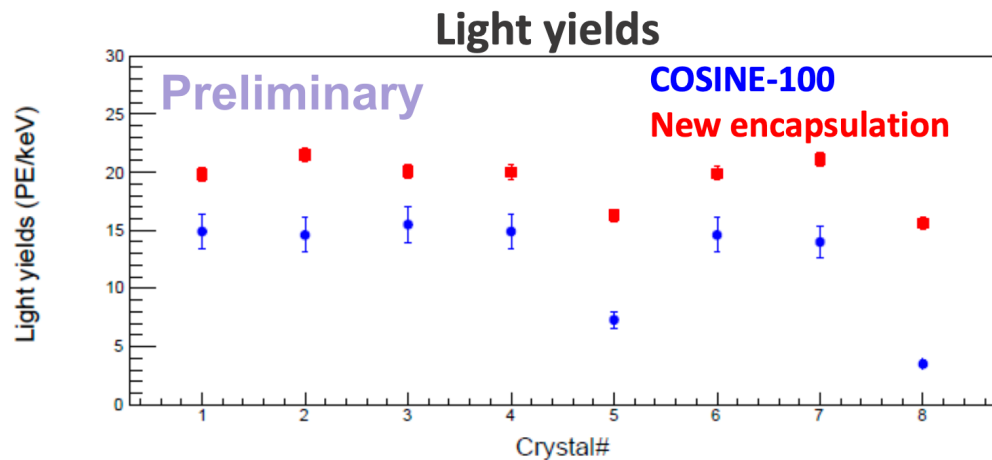
Detector Upgrade

New crystal encapsulation

Preliminary

Light yield ↑

Preliminary
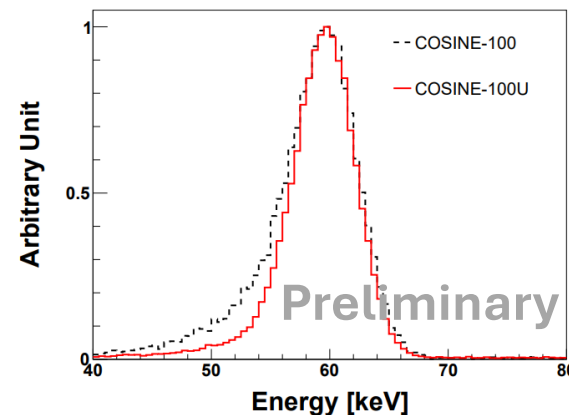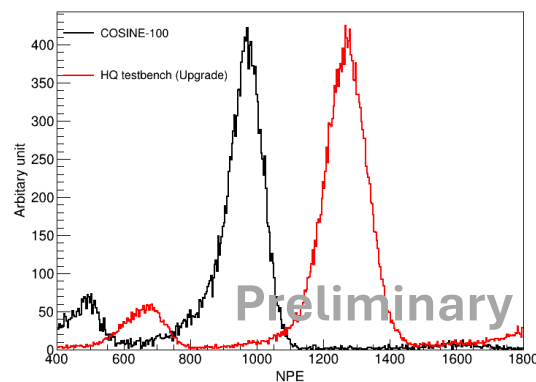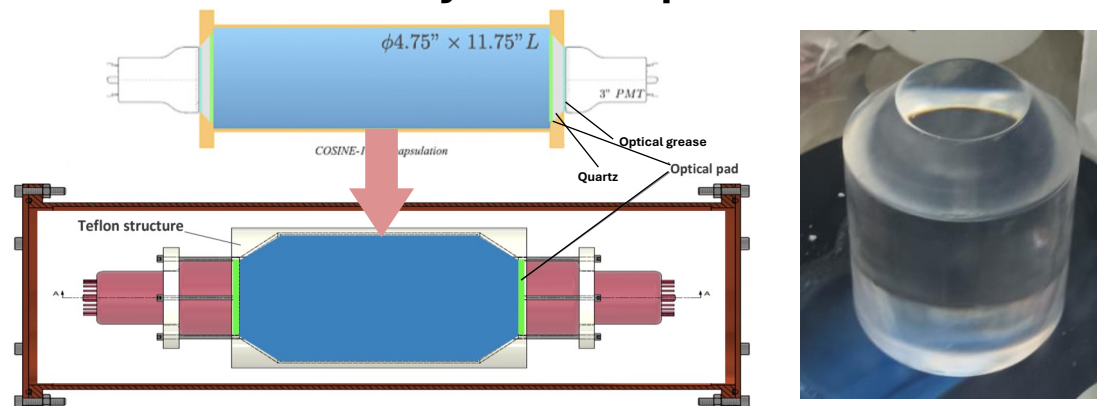
Resolution ↑

The physics operation will start in October !

COSINE-200

Ultra-pure NaI(Tl) Development

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

- For lowering background compared to DAMA

- ~400 kg of low background NaI powder has been produced

- 0.7 kg crystal with 0.2 counts/keV/kg/day achieved

Purification factory
~70 kg powder load

Test grower
~1 kg ingot

(a) (b) (c) (d)
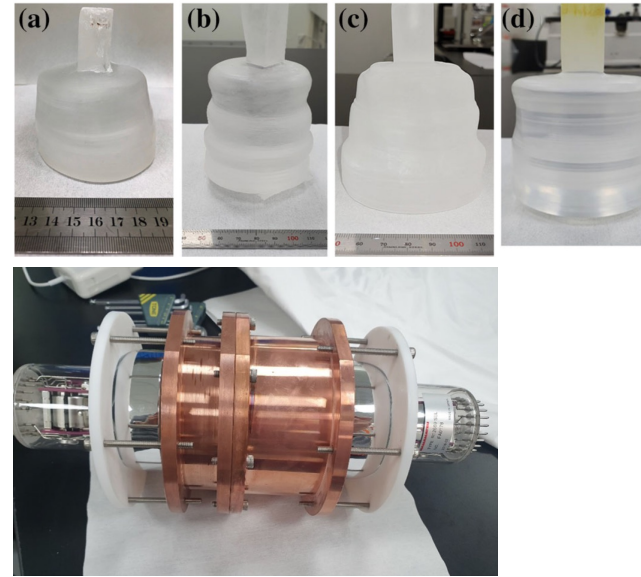
Expected Background Spectrum

Eur. Phys. J. C 80, 814 (2020)

Internal
Cosmogenic
External

Counts/keV/kg/day

Energy (keV)
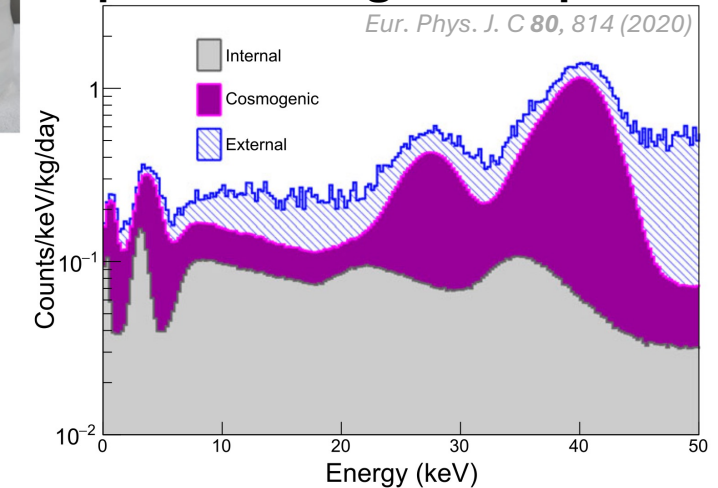
J. Rad. Nucl. Chem. 317, 1329 (2018)
JINST 15, C07031 (2020)
Front. Phys. 11, 1142849 (2023)

R&D to grow large crystals is going on !

Summary

- COSINE-100 tests DAMA/LIBRA's results with NaI(Tl) detectors

- Data were collected from Oct. 2016 to Mar. 2023 at Y2L

- Detector response and event selection analysis improved understanding of the detector

- Searching dark matter using three methods:

  1. WIMP Extraction: Finds WIMP-proton interaction

  2. Annual Modulation: Searches WIMP modulation in event rates } Disfavored DAMA/LIBRA's results by over 3 σ

  3. Pulse Shape Discrimination: Differentiates nuclear and electron recoil to find WIMP-like signals

- COSINE-100U is being prepared with enhanced detector performance

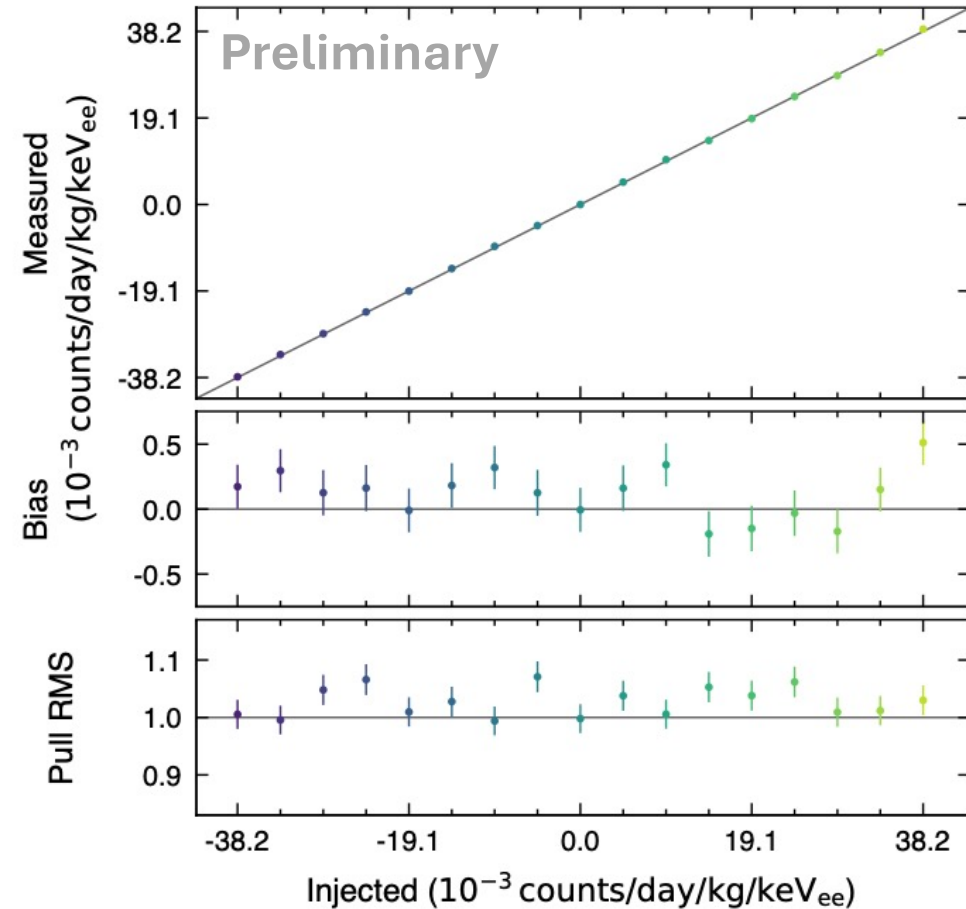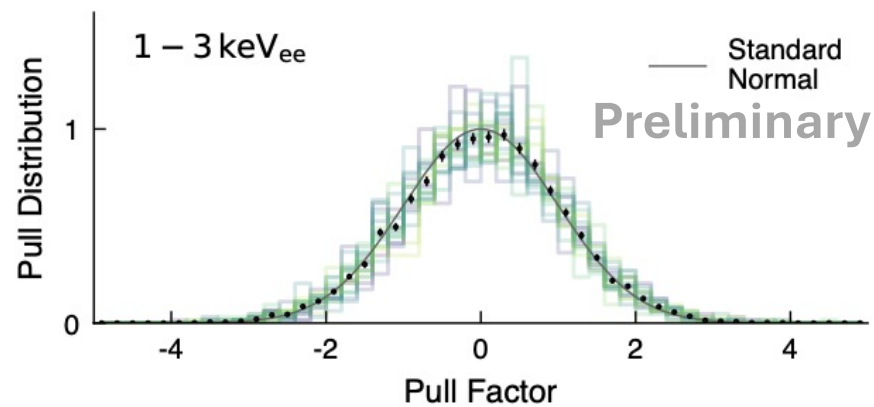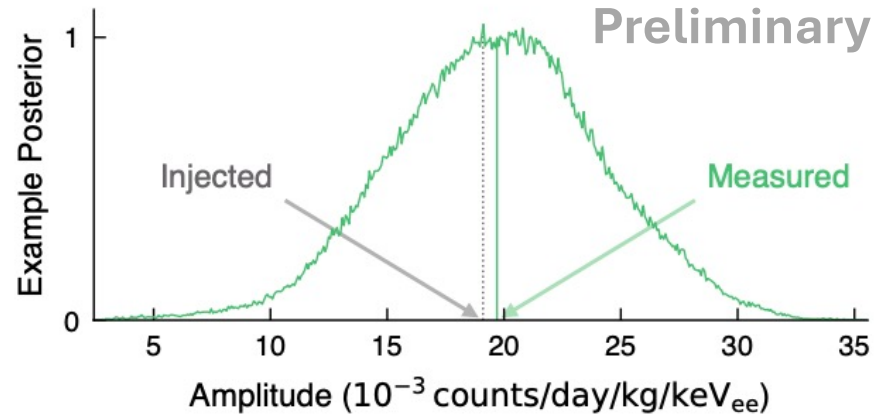- Low-background NaI(Tl) crystals are being developed for COSINE-200
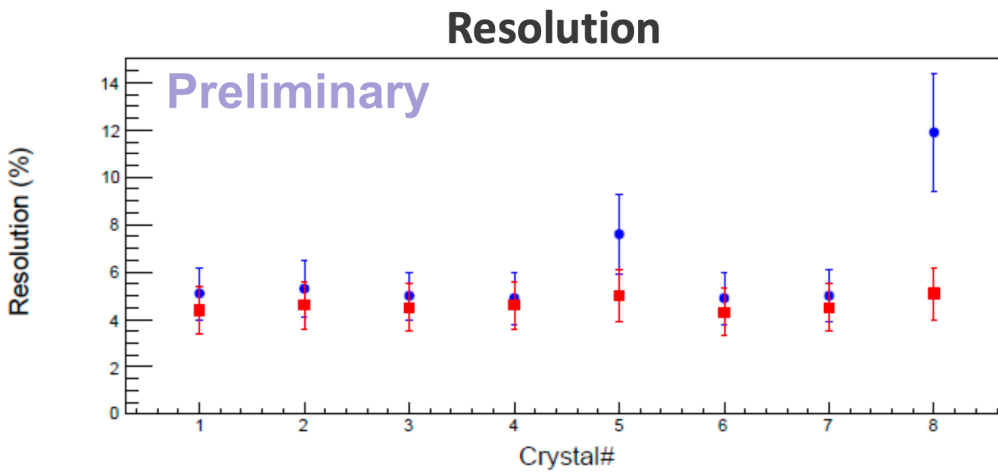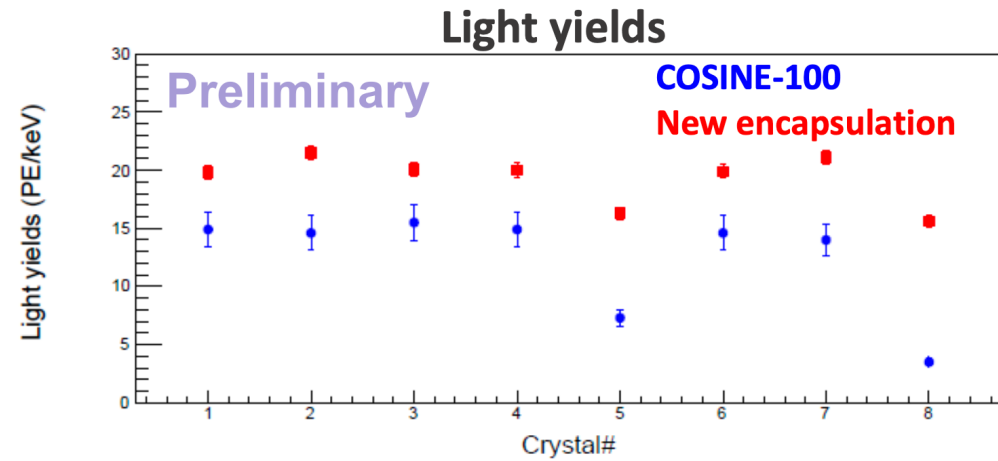
Backup

Annual Modulation Analysis

with Full COSINE-100 Dataset (~6 years)

Fitter Test in 1-3 keV$_{ee}$

No bias attributed to the fitter

COSINE-100Upgrade

Light yields

Resolution

Crystals	Mass (kg)	Light Yield (p.e./keV)	
	106.3 → 99.1	COSINE-100	COSINE-100U
C1	8.3 → 7.1	14.9 ± 1.5	22.4 ± 0.5
C2	9.2 → 8.7	14.6 ± 1.5	20.1 ± 0.5
C3	9.2 → 8.7	15.5 ± 1.6	20.4 ± 0.4
C4	18.0 → 16.9	14.9 ± 1.5	20.7 ± 0.4
C5	18.3 → 17.2	7.3 ± 0.7	16.8 ± 0.5
C6	12.5 → 11.7	14.6 ± 1.5	19.6 ± 0.3
C7	12.5 → 11.6	14.0 ± 1.4	20.2 ± 0.5
C8	18.3 → 17.2	3.5 ± 0.3	16.2 ± 0.4

COSINE-100Upgrade

COSINE-100U Sensitivity
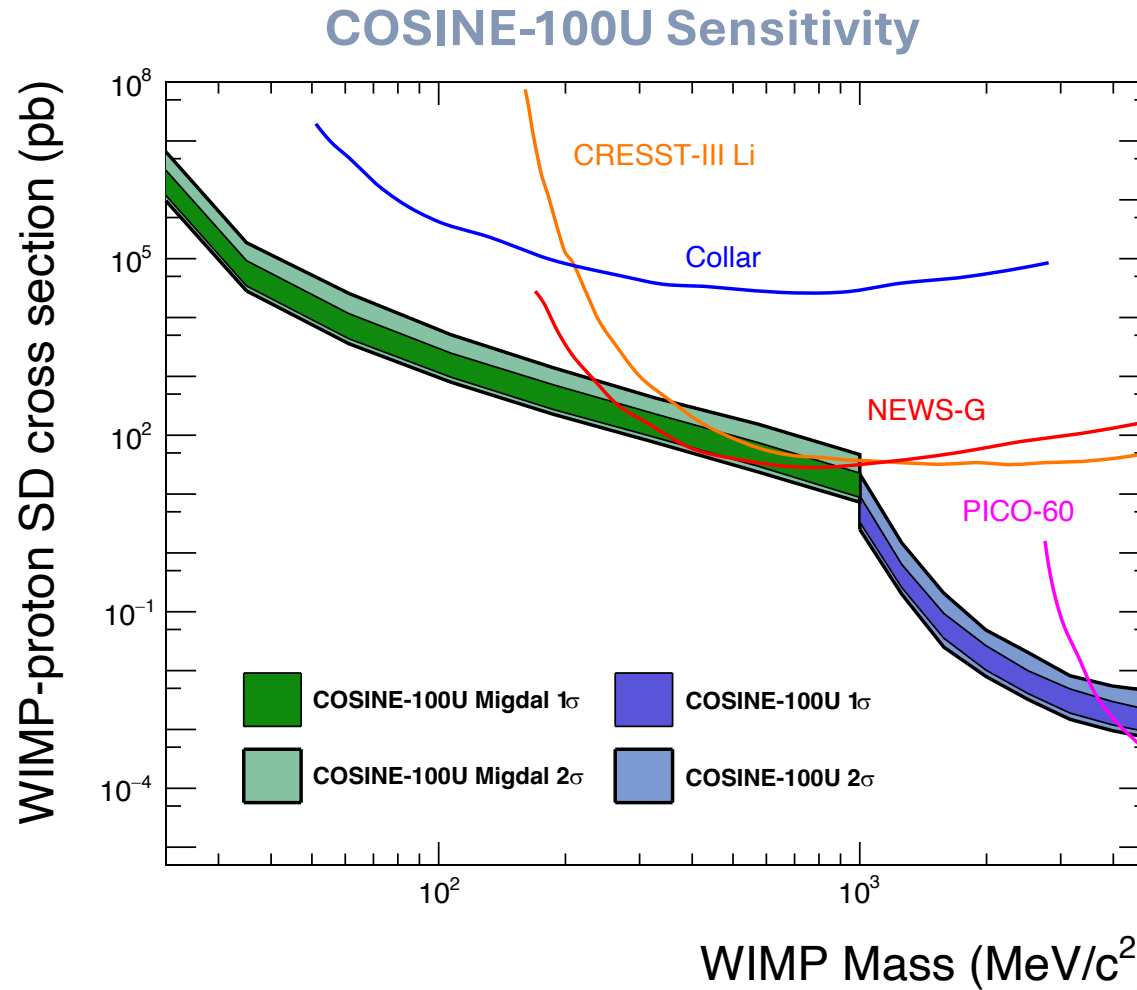
Searching for low mass WIMP !