Dark Matter Searches with COSINE-100, present and perspectives

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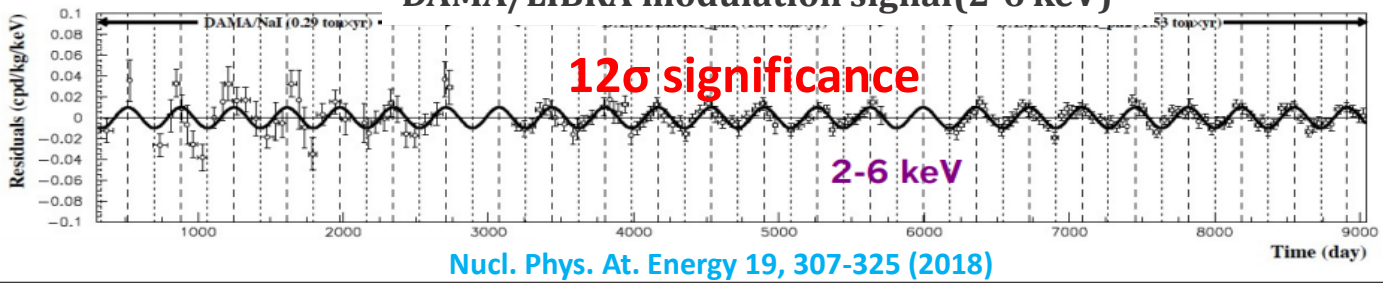
On behalf of the COSINE-100 collaboration

March 7th, 2023

Motivation-DAMA/LIBRA

- **DAMA/LIBRA experiment**
  - Search for **Dark matter (DM)** annual modulation signature
  - Using 25 × 9.7 **NaI(Tl)** detectors
  - **Claim an observation** of the DM (WIMP modulation signal) at **12σ C.L.** (2-6 keV, 2.17 ton · year)
  - **Amplitude** : 0.0096 ± 0.0008 counts/day/kg/keV
    - Phase = 145±5 days
    - Period = 0.9987± 0.0008 year

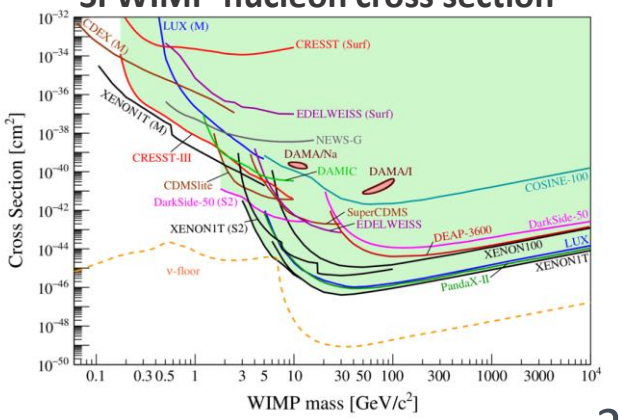
DAMA/LIBRA modulation signal(2-6 keV)



Nucl. Phys. At. Energy 19, 307-325 (2018)

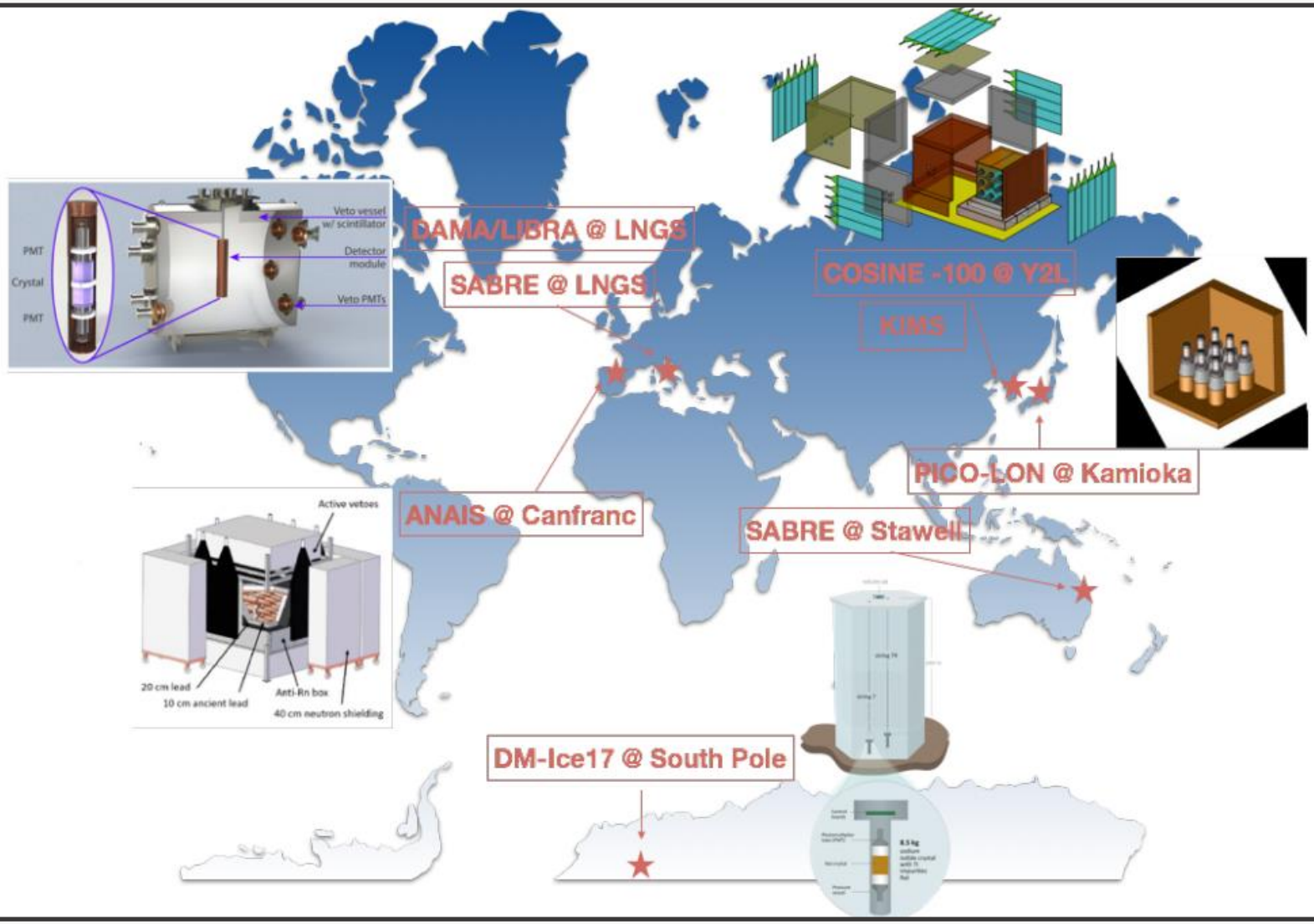
- **No other experiment** has succeeded direct detection of DM except for **DAMA/LIBRA.**
  - **Is NaI(Tl) special** for DM interaction?

SI WIMP-nucleon cross section



Rep. Prog. Phys. 85 056201 (2022)

NaI(Tl) Dark matter search

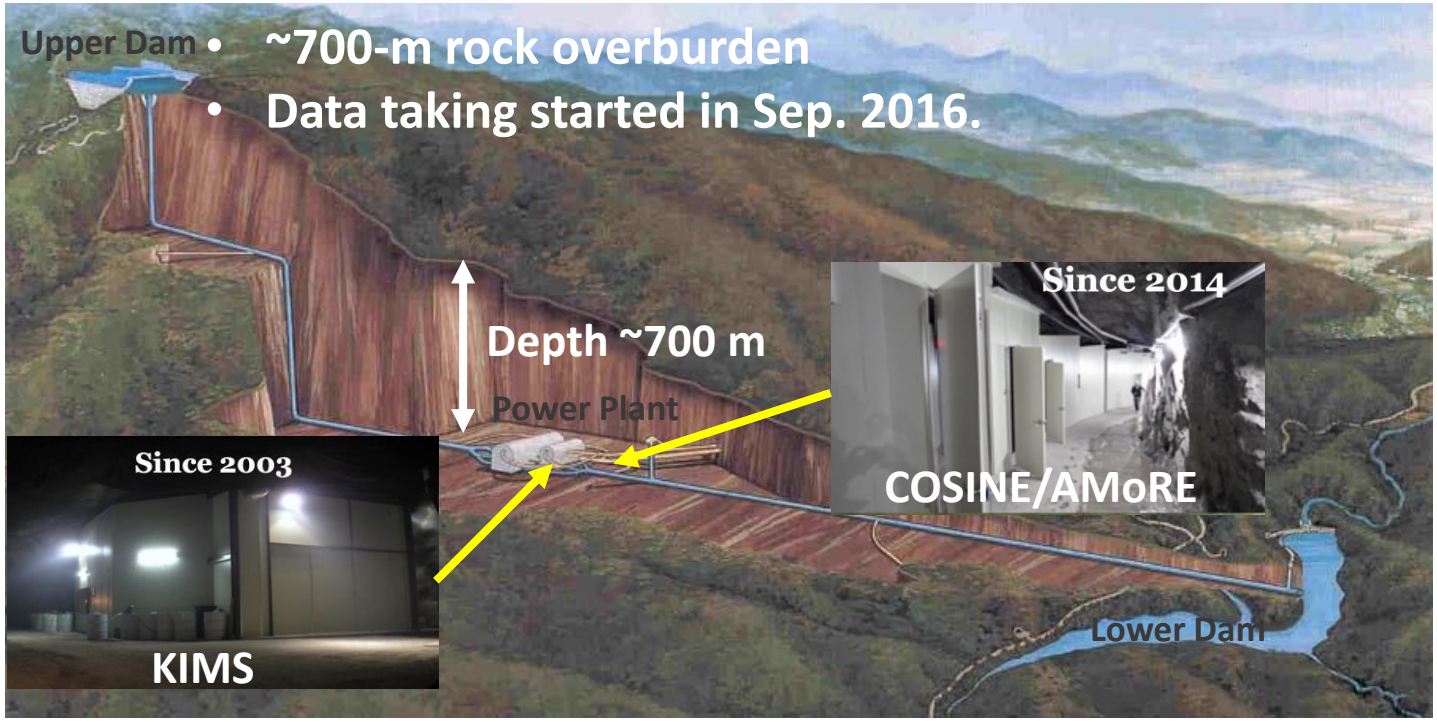


COSINE-100 experiment

DM-ICE + KIMS = COSINE

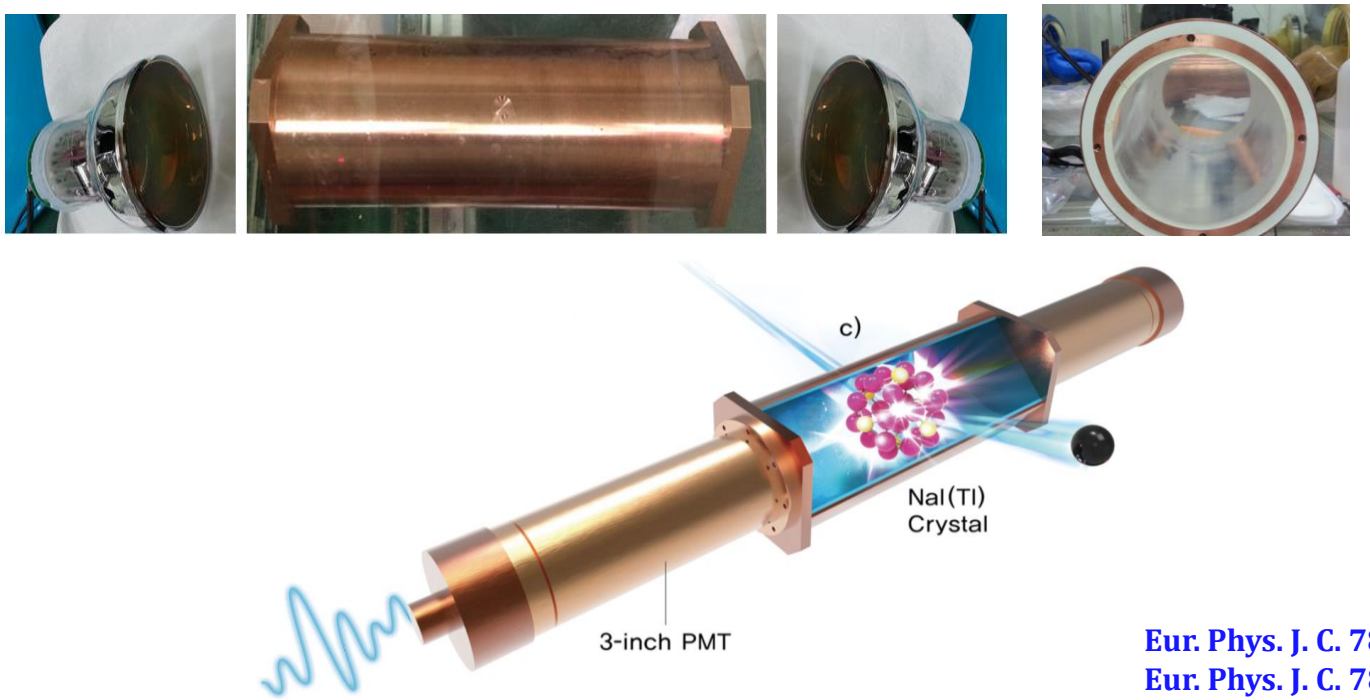
- Joint collaboration of **DM-ICE** & **KIMS**
- **~50 collaborators** in **17 institutes**
- To confirm **DAMA/LIBRA's claim** using same target material, **NaI(Tl)**

Yangyang underground laboratory (Y2L), Korea



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

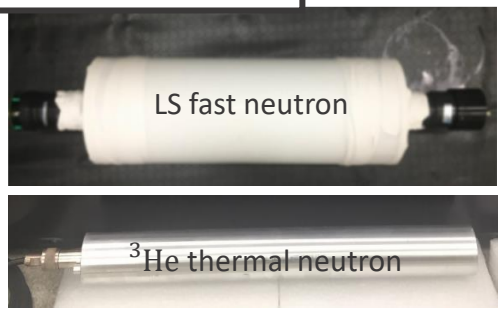


Eur. Phys. J. C. 78 107 (2018)
Eur. Phys. J. C. 78 490 (2018)

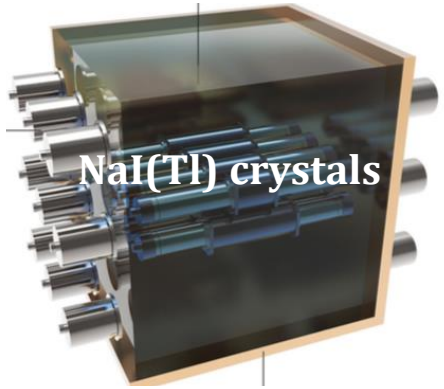
COSINE-100 experiment-Shielding

- **Active veto**
  - **Liquid scintillator (LS)**
    - **2200-L LAB-based** LS
    - **5-inch PMT(R877)** for LS detector
  - **4π Muon counter**
    - **37 plastic scintillator** panels
    - **2-inch PMT(H7195)** for muon counter
- **Passive veto**
  - **3-cm** thick **copper box**
  - **20-cm** thick **lead castle**
- **Neutron monitoring**
  - **Fast neutron** detector (**Liquid Scintillator**)
  - **Thermal neutron** detector (**^{3}He gas** detector)

Neutron monitoring — **JINST 13 T06005(2018)**

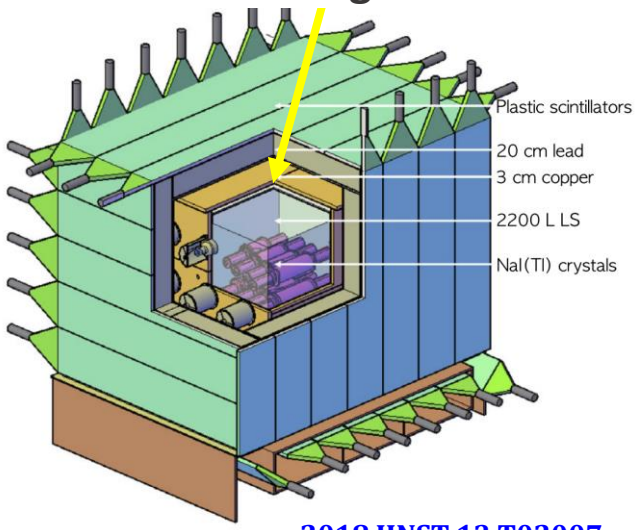


Liquid scintillator



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

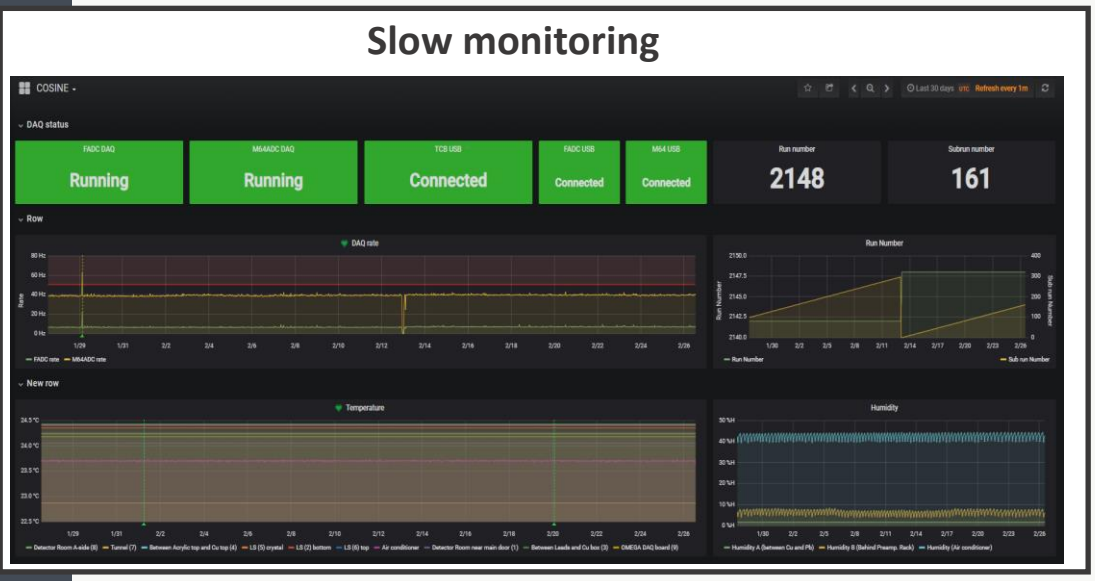
COSINE shielding structure



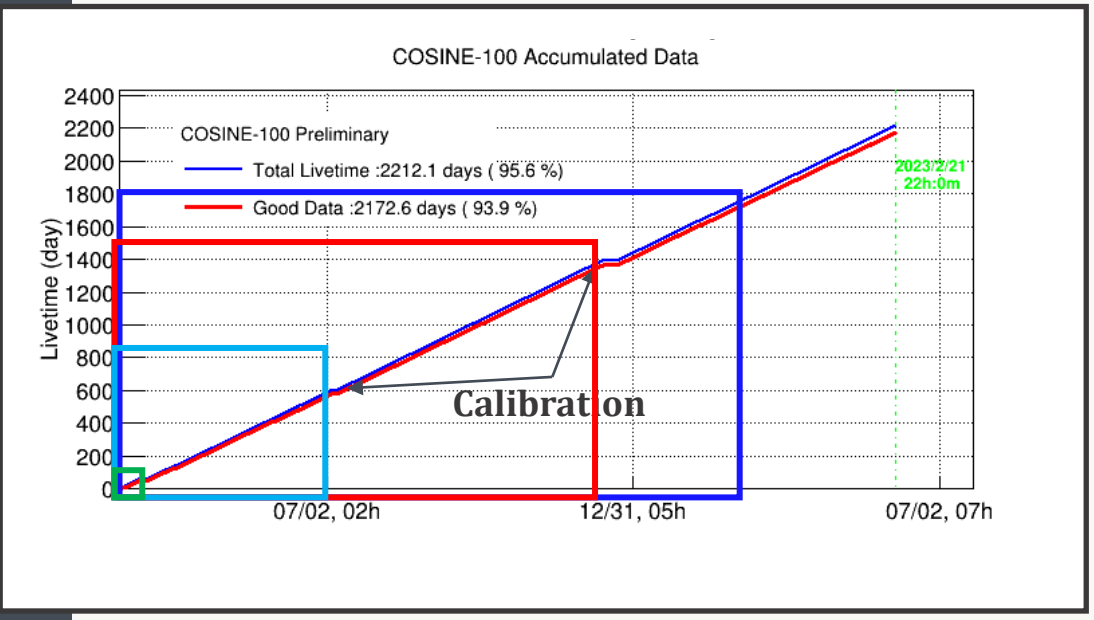
2018 JINST 13 T02007
Eur. Phys. J. C 78, 107 (2018)

Operation & slow monitoring

JINST 17 T01001 (2022)



- **Slow monitoring system**
  - **> 200 parameters**
  - DAQ system trigger rate
  - Electronics status
  - Environmental parameters
  - Neutron rate



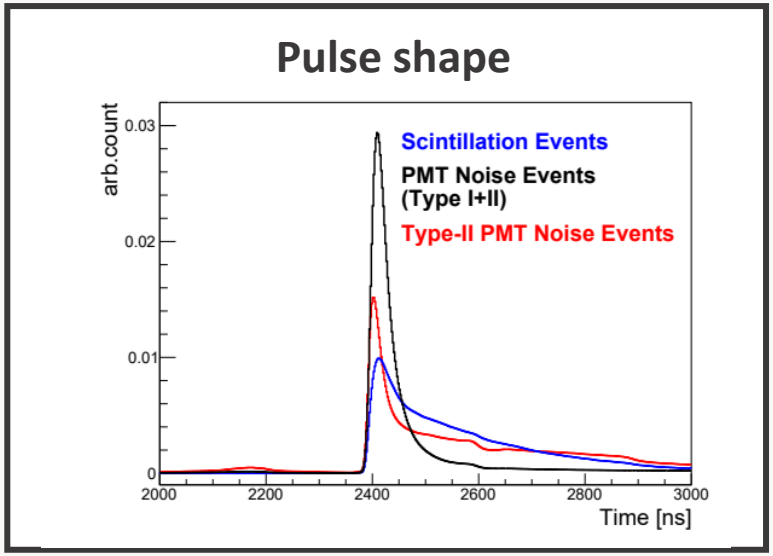
- **Stable run** from **Sep. 2016**
  - **DAQ efficiency > 96%** (calibration runs, power outage)
  - **Exposure time > 6 years**

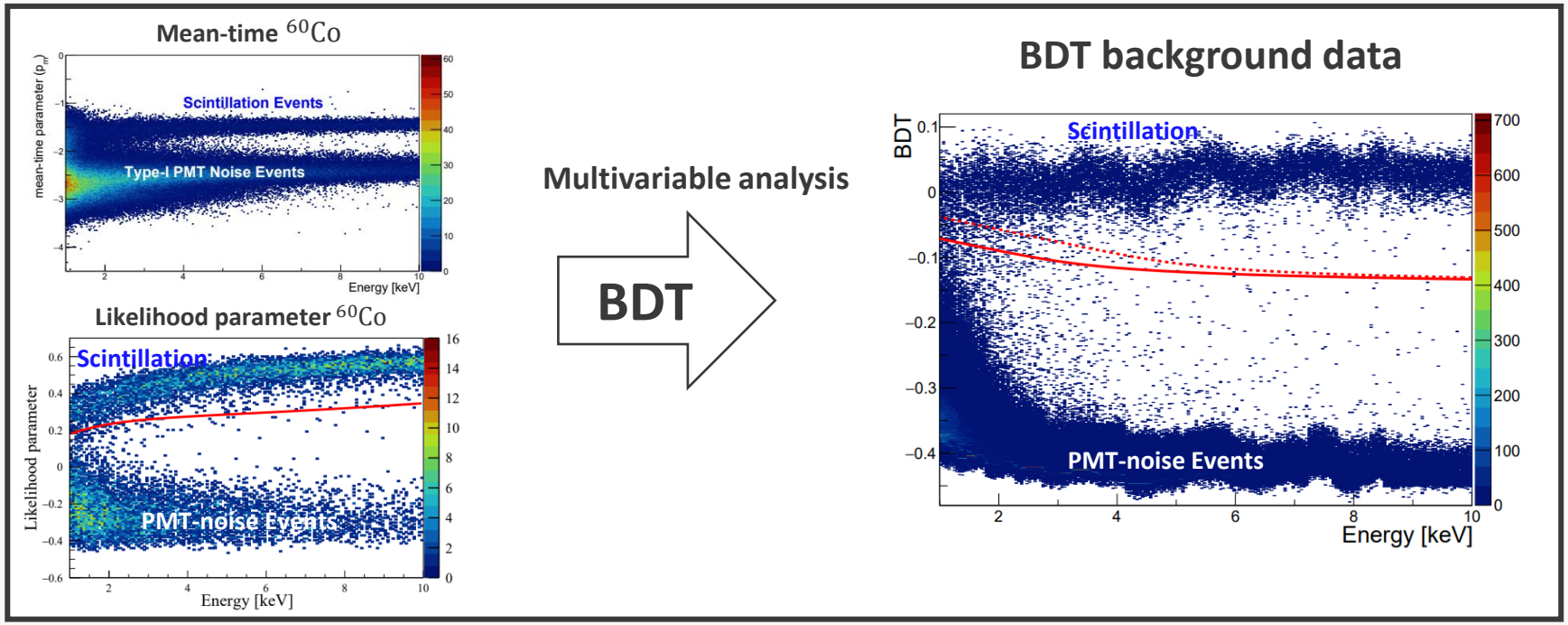
SET 1 : 59.5 days
SET 2 : ~1.7 years
SET 3 : ~3.0 years
SET 4 : ~4.5 years

Event Selection

Astropart. Phys 130, 102581 (2021)

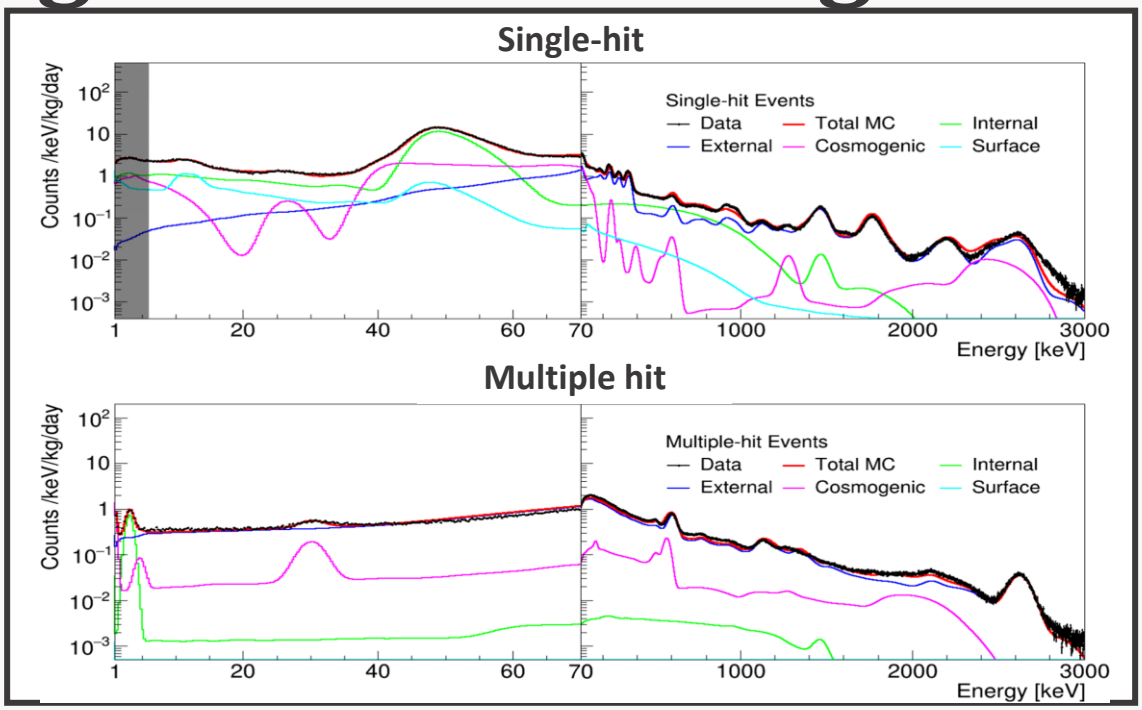
- Use Set 2 (1.7 year) data
- Use pulse-shape parameters to select NaI scintillation signals
  - Meantime, likelihood parameters
- Use Boosted decision tree (**BDT**) to separate PMT-noise from scintillation signal
- Achieve **1 keV threshold**





Background Modeling

EPJC 81, 837 (2021)
Astropart. Phys. 126, 102528 (2021)



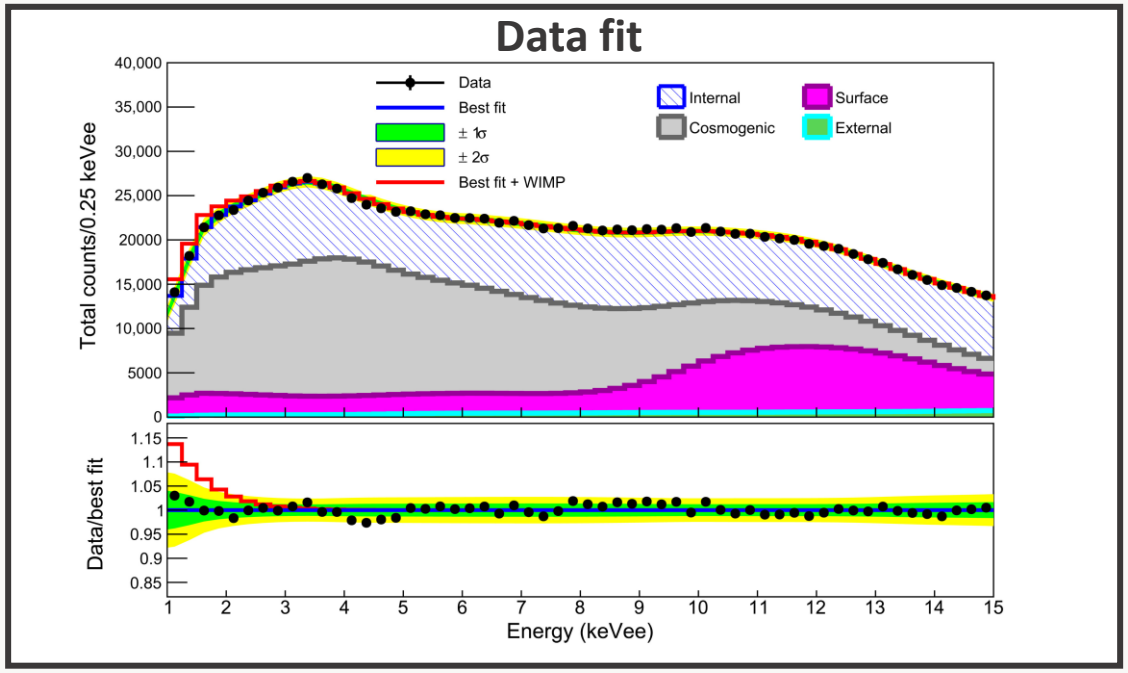
- **SET2 1.7-year** data with 1 keV Threshold
- Use detector simulation based on **GEANT4**
- Single (Multiple) Hit : Time coincidence w/o (w/) other crystal or LS
- Exclude **WIMP ROI** (<6keV single hit) in the fitting
- **Background** in low energy region
  - Cosmogenic activation (**mostly** ^{3}**H**)
  - Contamination of ^{210}Pb
  - Contamination of crystals from **K/U/Th**

} Main background

WIMP extraction

Science Advances. 7, 46 (2021)

- **Spin-independent(SI) WIMP Search with SET2 data**
  - **1.7 years** data with **1 keV** threshold
  - Fit background + WIMP signal data in [1, 15] keV

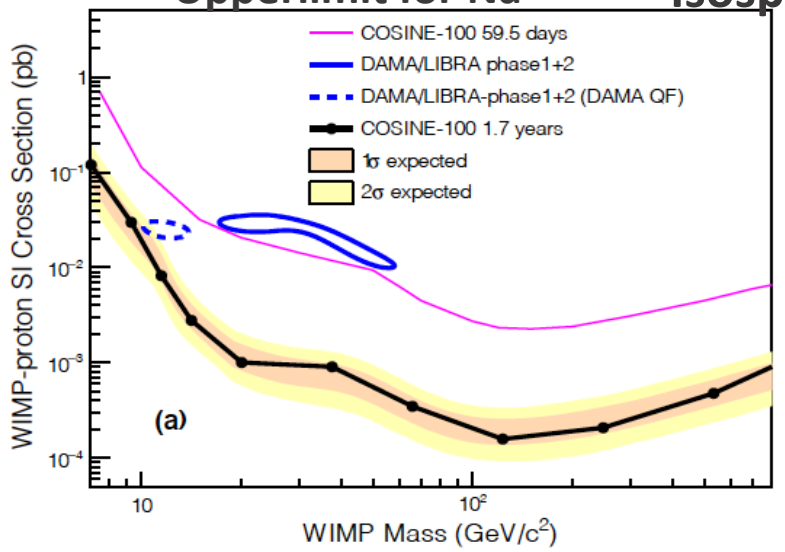


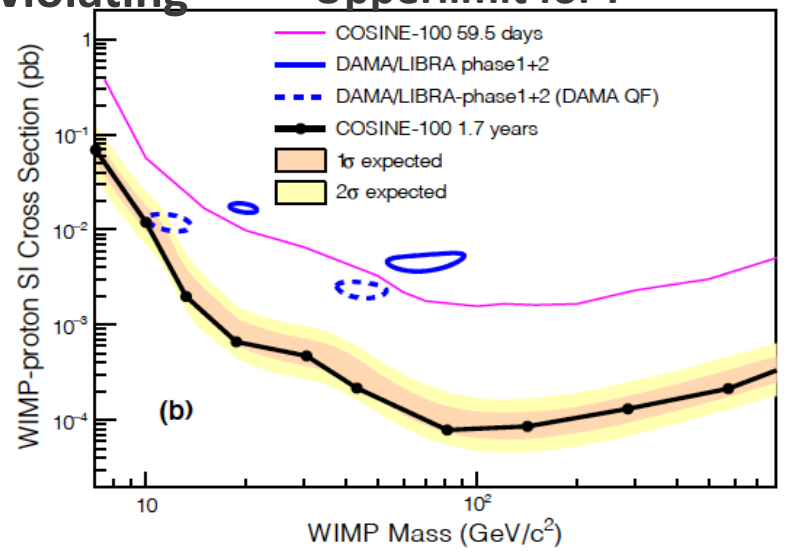
- No WIMP signal in 1 keV threshold

WIMP extraction

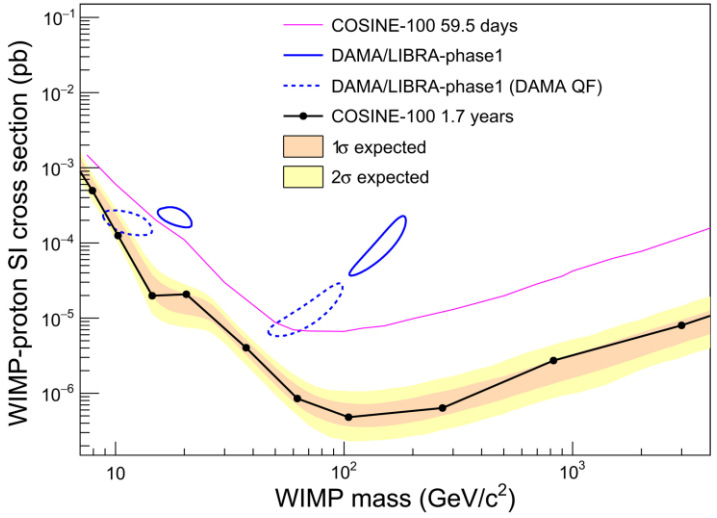
Science Advances. 7, 46 (2021)

Isospin violating





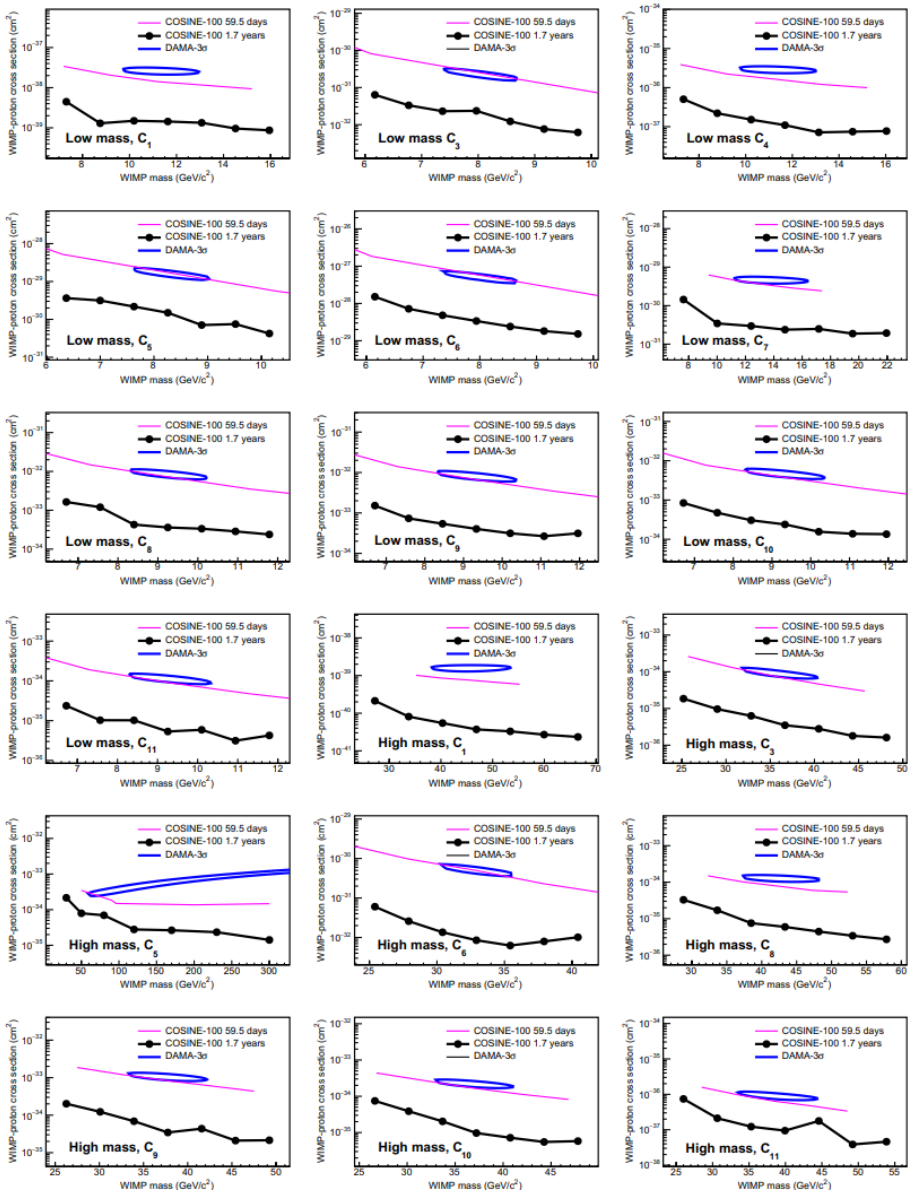
Isospin conserving



- **Exclude DAMA/LIBRA** phase 1 considering quenching factor.

WIMP extraction

Science Advances. 7, 46 (2021)

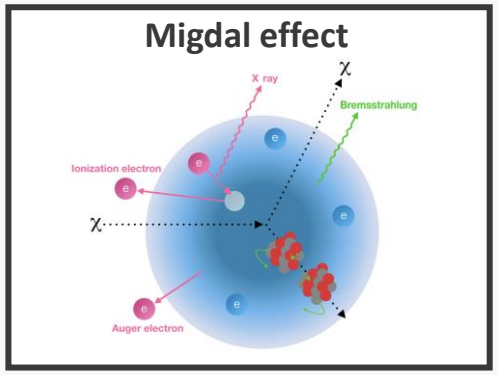


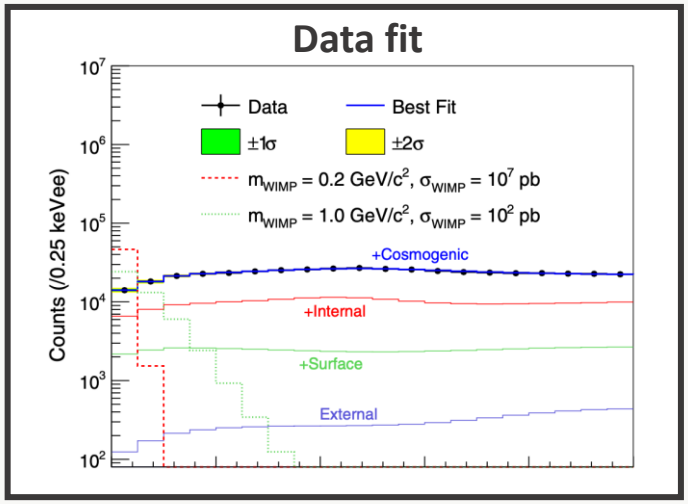
- **Exclude possible EFT operators.**

WIMP extraction using Migdal effect

- Nuclear recoil → **Boost of electrons → Secondary radiation**

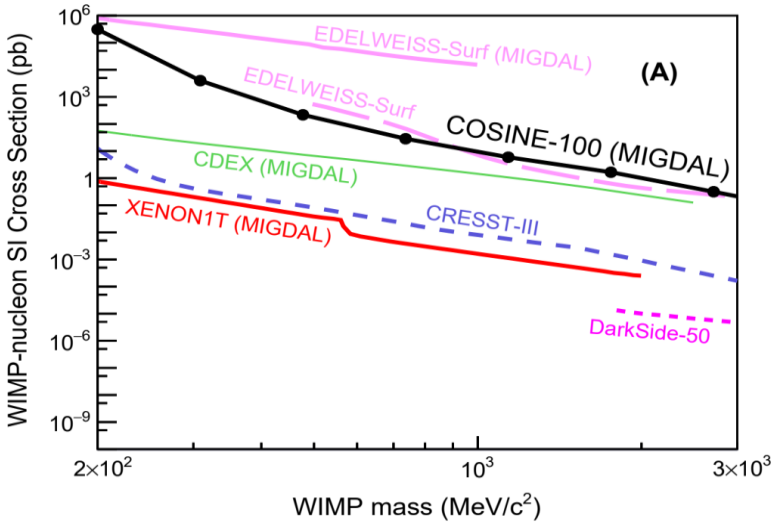
Phys. Rev. D 105, 042006

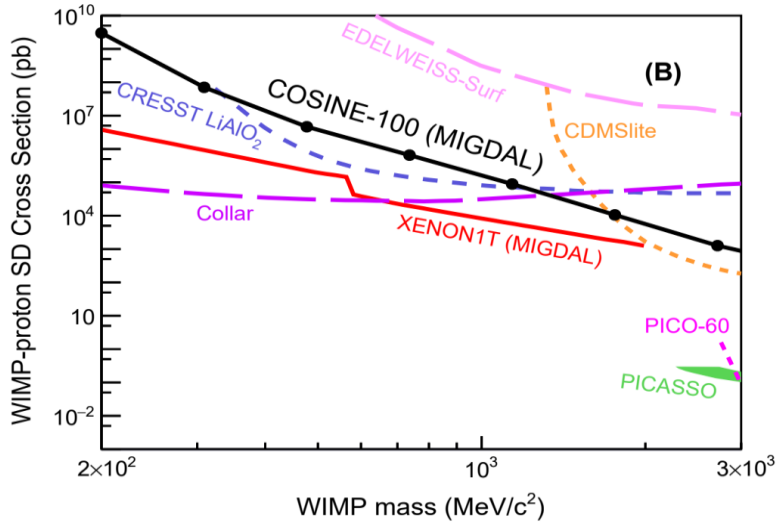




- **Large visible energy** of **electron recoil** compared to nuclear recoil.

→ Enables to search **low mass WIMP** (100 MeV Scale)





Annual modulation analysis (3 years data)

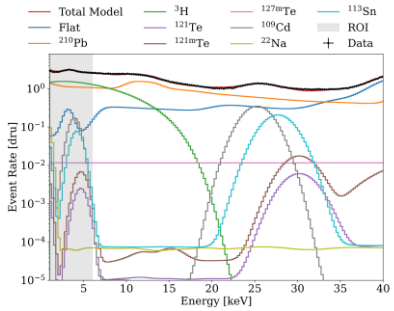
Phys. Rev. D 106, 052005 (2022)

- **Full model** of time dependent background components

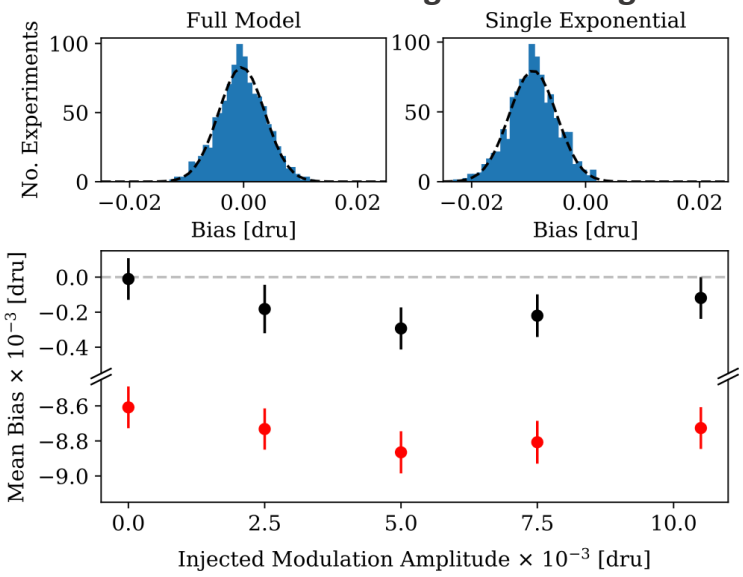
$$R^i(t|S_m,\alpha^i,\beta_k^i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t-t_0))$$

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

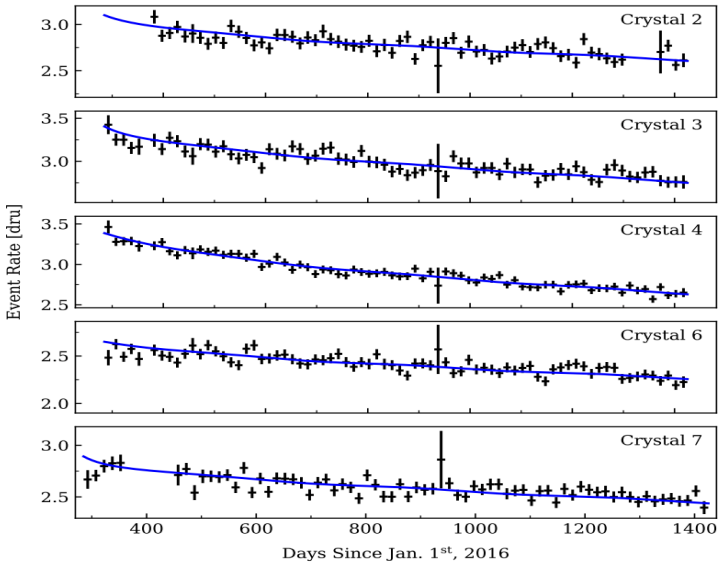
Background modeling



Bias check according to modeling



Time dependent rate fitting



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Phys. Rev. D 106, 052005 (2022)

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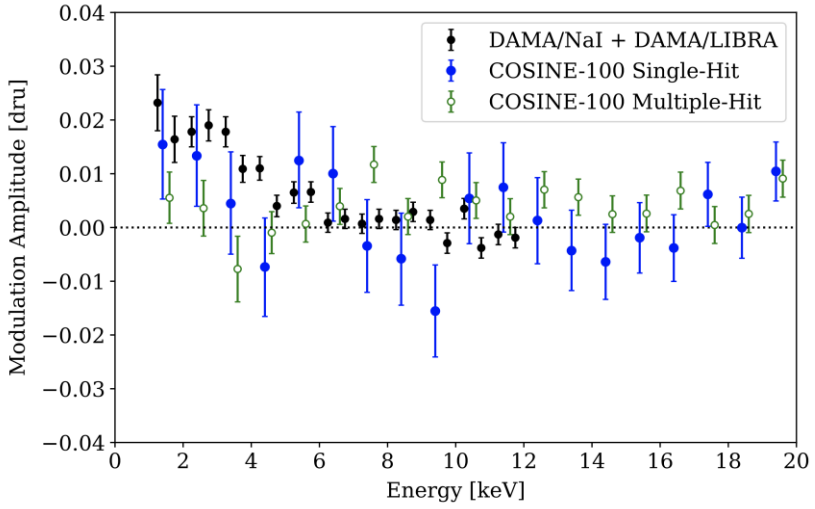
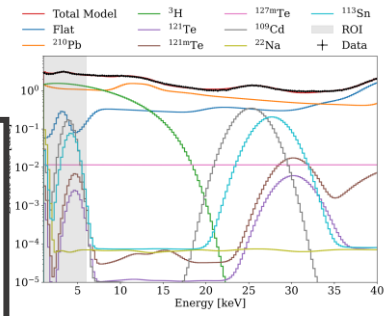
Constant fr
Exponentia
Modulatio

Modulation amplitude 1-6 keV

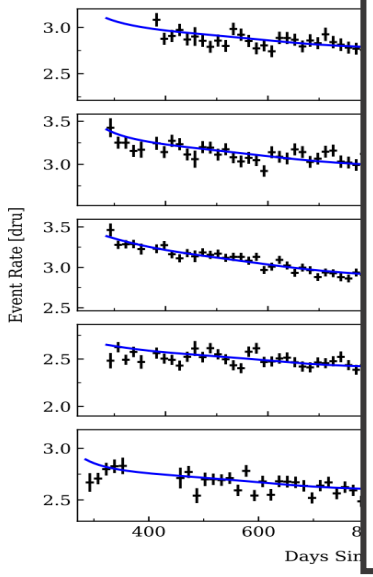
COSINE-100	0.0067±0.0042
DAMA/LIBRA	0.0105±0.0011
ANAIS-112	-0.0034±0.0042



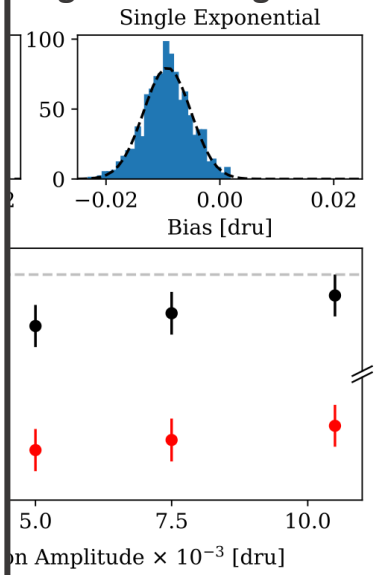
Background modeling



Time depend



ding to modeling



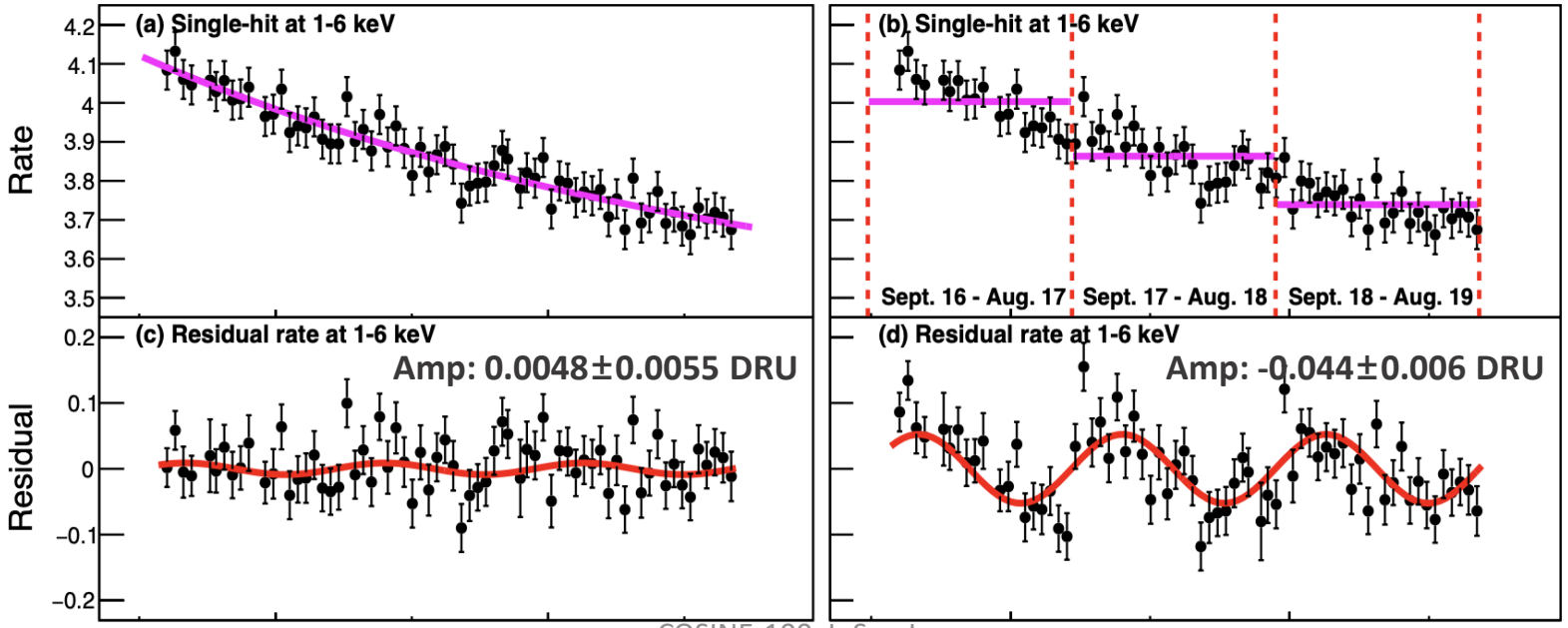
Annual modulation w/ DAMA/LIBRA method

arXiv:2208.05158

- **Test DAMA/LIBRA method in COSINE-100 data**
  - Apply similar **DAMA/LIBRA event selection**
    - No LS Veto
    - No Muon Veto
    - DAMA parameter for event selection
    - 600 ns waveform integration window.
  - Test **DAMA/LIBRA background modeling**

COSINE : $C + p_0 e^{-\frac{\ln 2 t}{p_1}} + A\cos\frac{2\pi(t-t_0)}{T}$ Single exponential

DAMA/LIBRA : $C + A\cos\frac{2\pi(t-t_0)}{T}$ Yearly average



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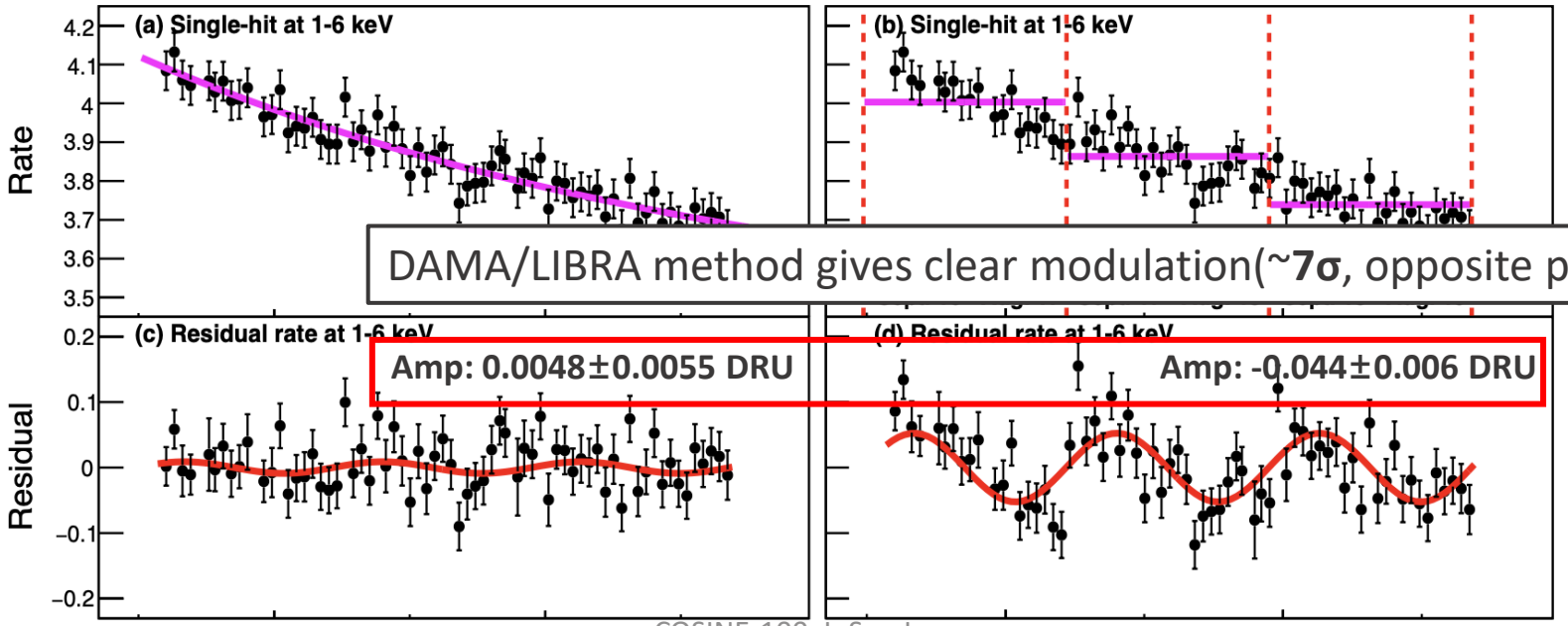


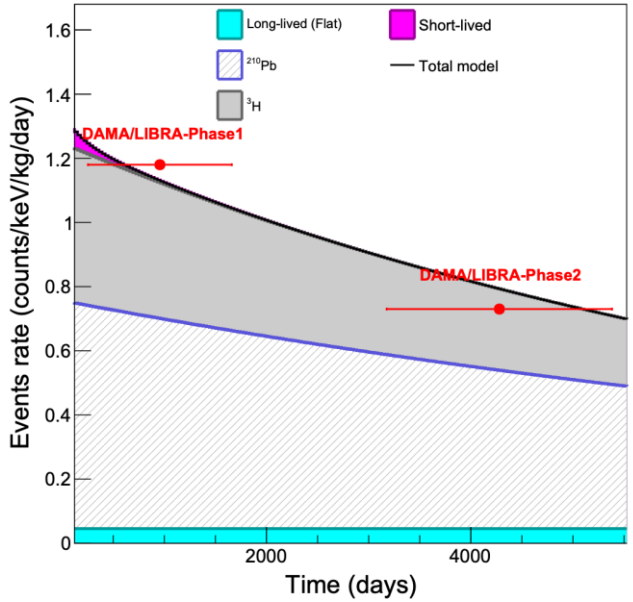
DAMA/LIBRA method gives clear modulation(~**7σ**, opposite phase)

Annual modulation w/ DAMA/LIBRA method

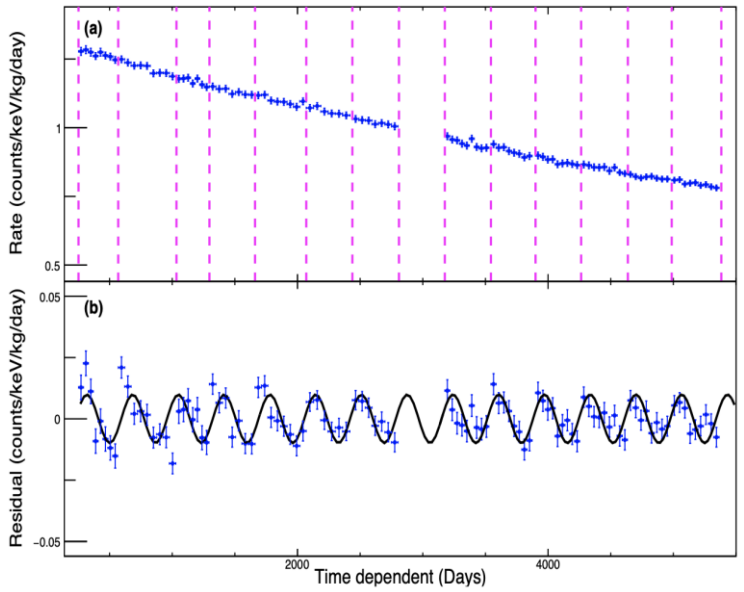
arXiv:2208.05158

- **Background model** for DAMA/LIBRA using the **COSINE-100 background compositions**

Composing DAMA/LIBRA Background, using COSINE-100 background component



13 years pseudo-data

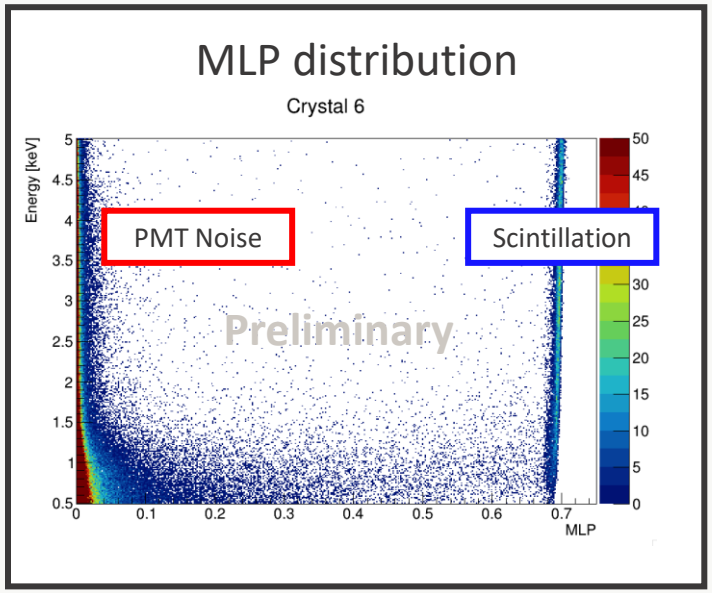


- **Similar modulation amplitude** in 1000 pseudo-experiment (**Opposite phase**)

Pseudo data	-0.0098 ± 0.0008
DAMA/LIBRA	0.0105 ± 0.0011

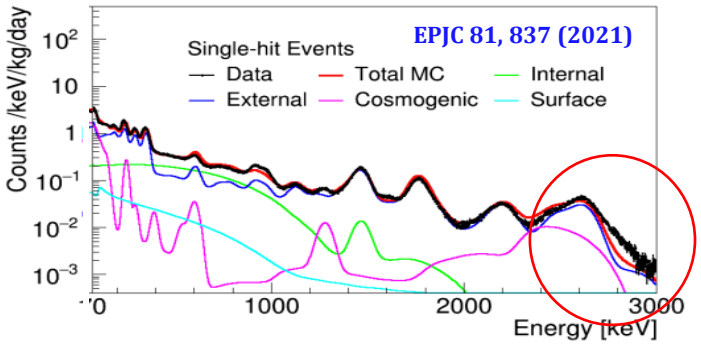
On going works

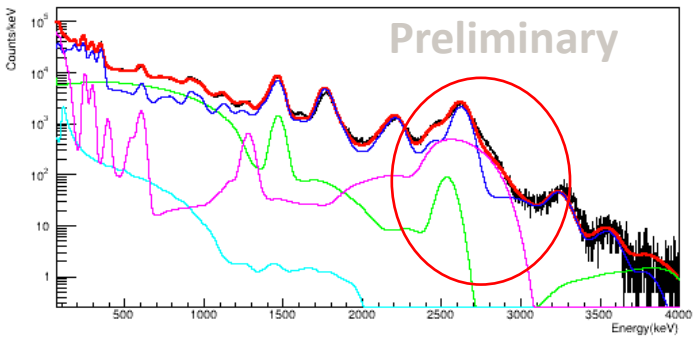
- Event selection improvement
  - Aim to 0.5 keV threshold
  - Deep learning (MLP) method



- Background modeling
  - Non-Proportionality update
  - Extended modeling range 6-3000keV →6-4000 keV

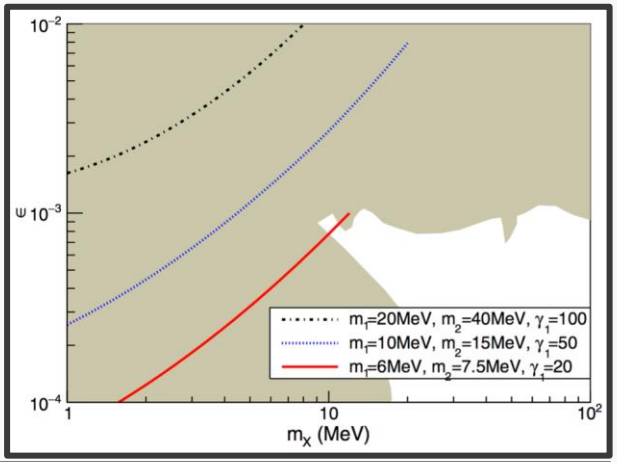
1.7-year background modeling

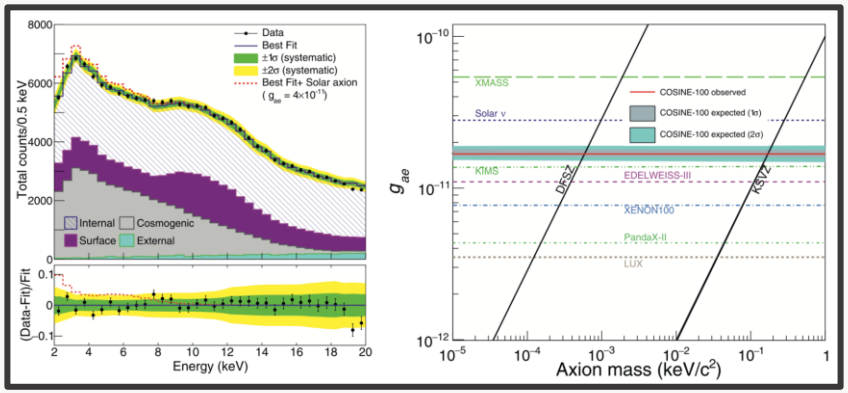


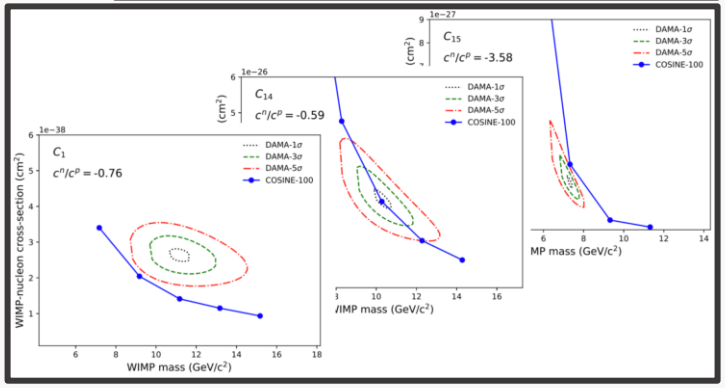


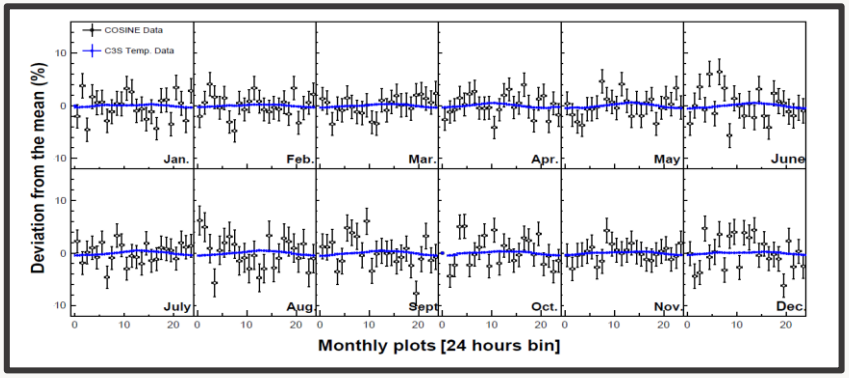
Exotic DM interaction

- Inelastic Boosted Dark Matter
- Solar Axions
- Several effective operators
- Inelastic WIMP-^{127}I interaction
- Cosmic-ray Boosted Dark matter









JCAP 06, 048 (2019)
Astropart. Phys. 114 101 (2019)
Phys. Rev. Lett. 122 131802 (2019)

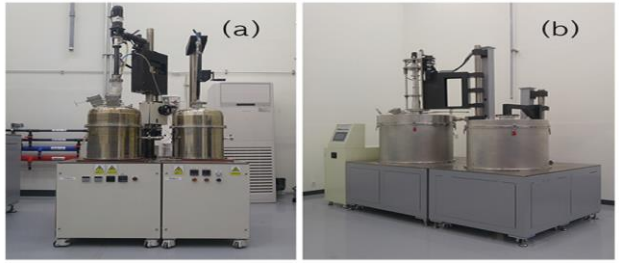
Effort for next phase

- 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)
  - Prepare COSINE-200 crystal by end of 2024

Powder purification facilities

JINST 15 (2020) C07031

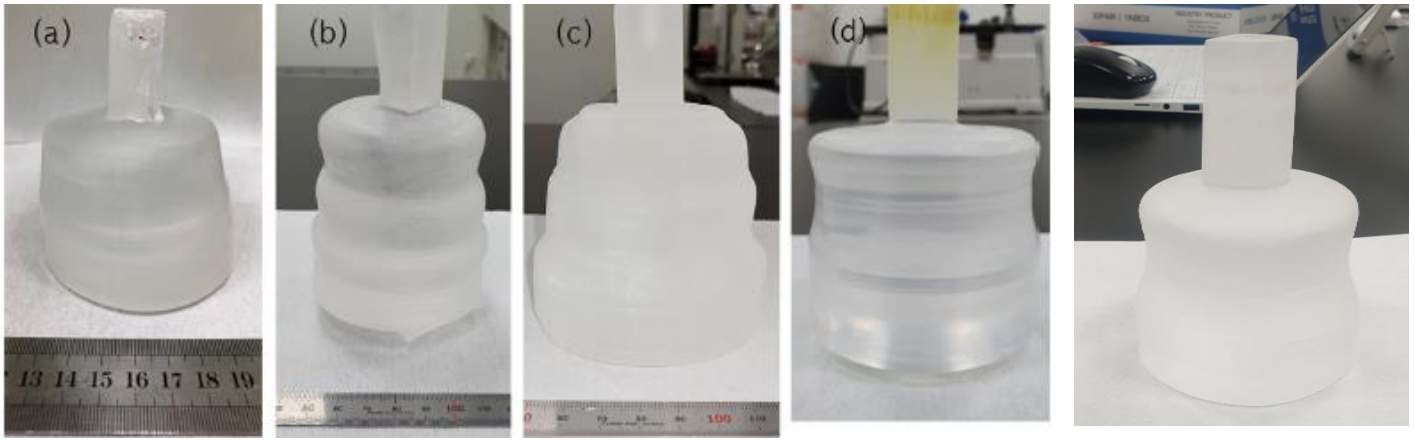
Crystal grower



J. Phys. Conf. Ser. 1468 012144

CUP Grown R&D crystals

Eur. Phys. J.C. 80 814 (2020)
Frontiers in Physics 11 (2023)



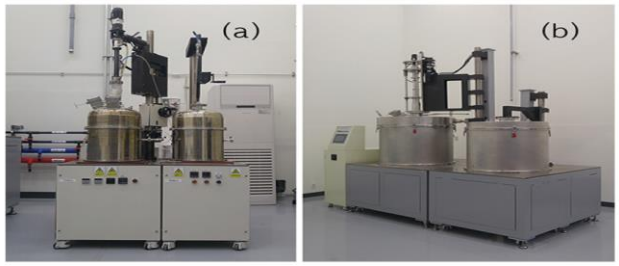
Effort for next phase

- 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** crystal
    - Expect **~0.2 DRU background level for COSINE-200 crystal**
  - On going development for full size crystal growing (~100 kg)
  - **Prepare COSINE-200** crystal by **end of 2024**

Powder purification facilities

JINST 15 (2020) C07031

Crystal grower



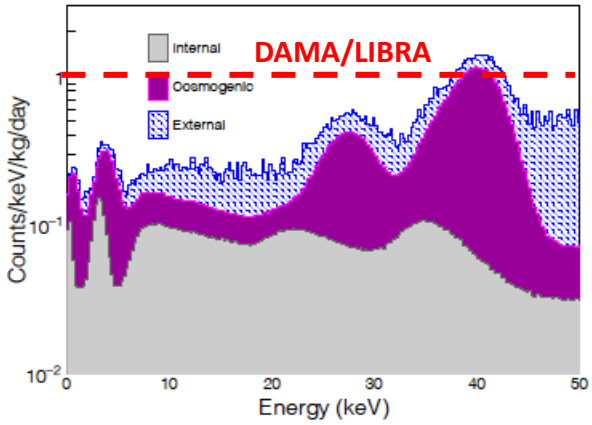
J. Phys. Conf. Ser. 1468 012144

Background level in R&D crystals

Eur. Phys. J.C. 80 814 (2020)
Frontiers in Physics 11 (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

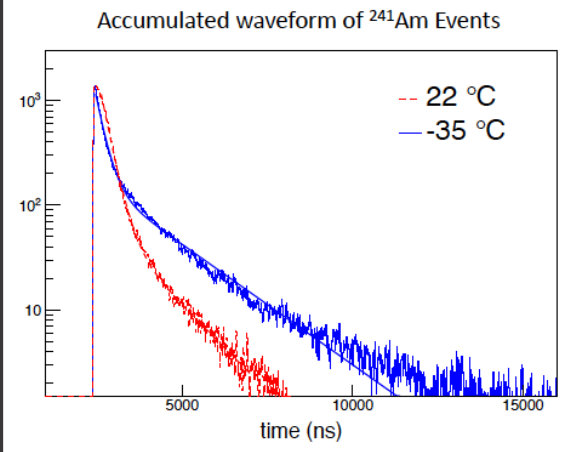


Effort for next phase

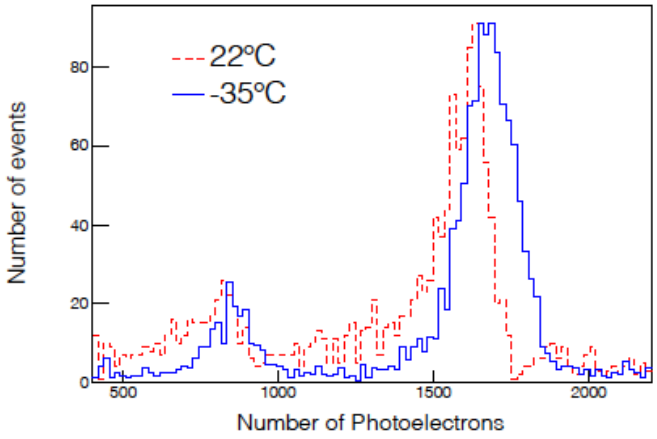
JINST 17 P02027 (2022)

- **Low temperature** operation (**at -35°C**)
  - **~5 %** increased **Light yields**
  - **~9%** increased **alpha quenching**

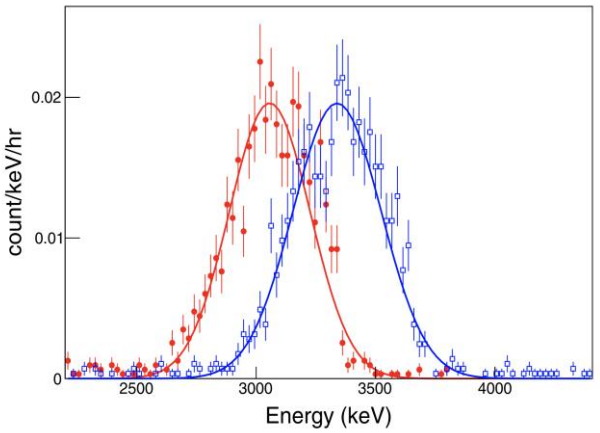
Accumulated waveform



NPE Measurement

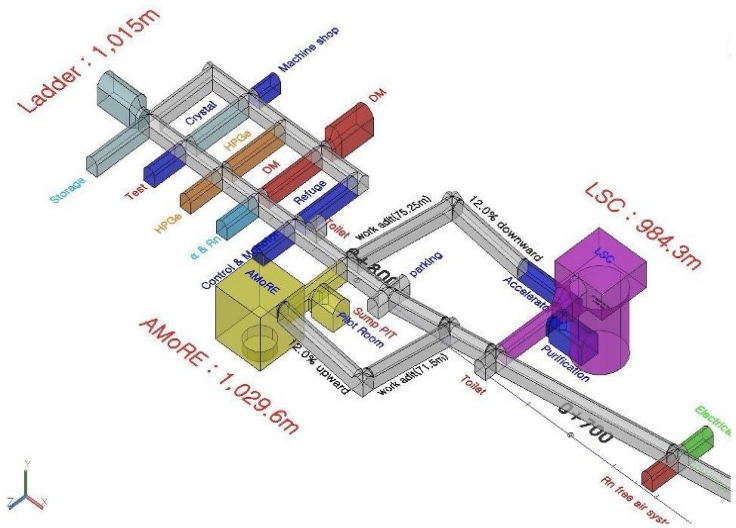


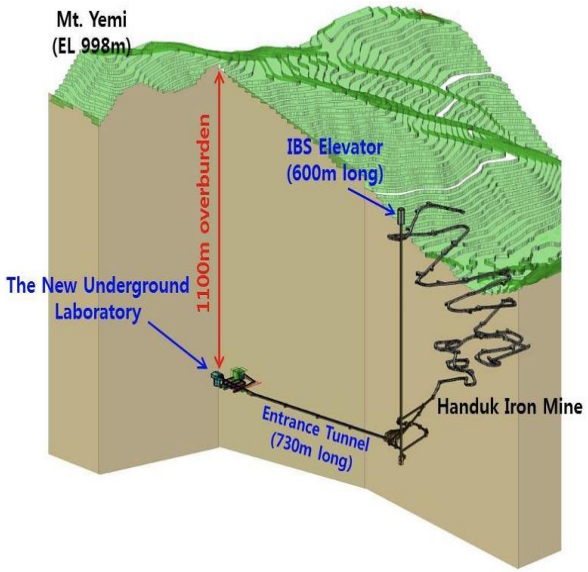
Alpha response using ^{210}Po

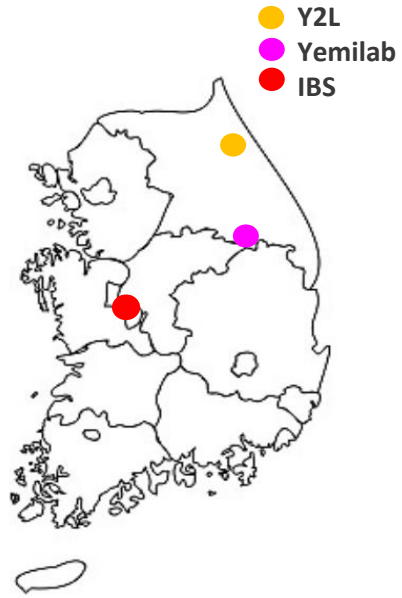


- **COSINE-200** will operate at **-35°C**

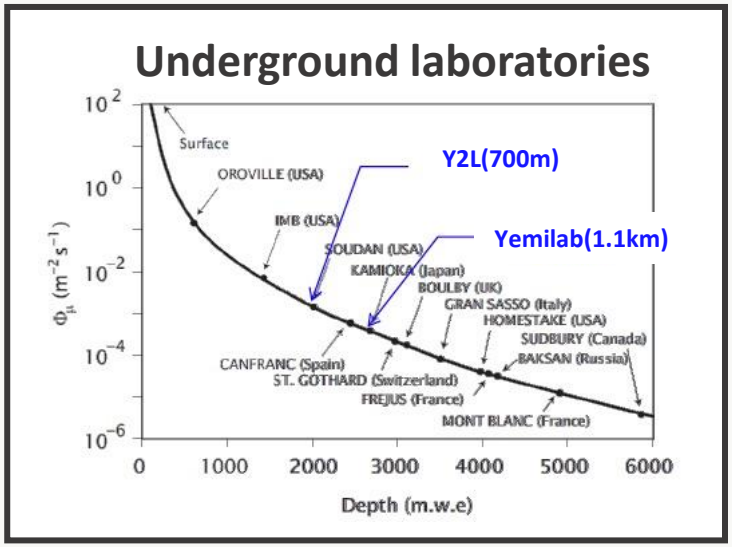
Yemilab @ Jeonseon





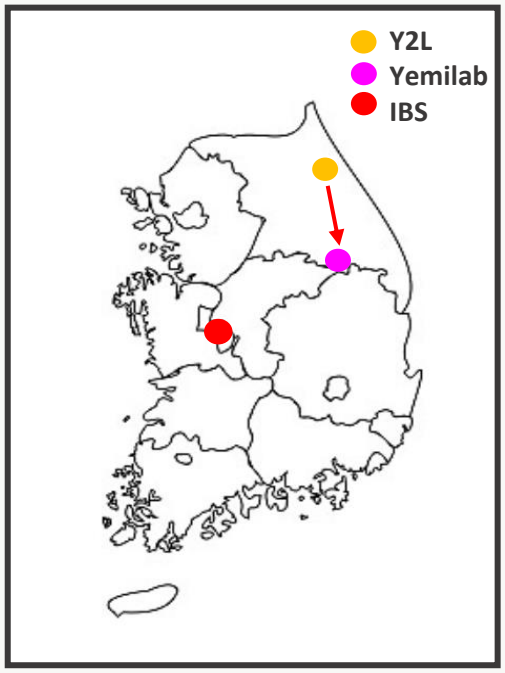


- **Newly** constructed underground laboratory at **Jeongseon in 2022**
  - **1.1 km** rock overburden
- Move to Yemilab in 2023



Upgrade COSINE-100

- **Move COSINE-100** to **Yemilab** in **2023**
- As an **intermediate experiment** of the **COSINE-200 @ Yemilab**
  - Use **COSINE-100 crystal**
  - Use **new encapsulation** method
    - **Improve light yields** >20 P.E./keV
  - Operate at **-35°C environment**
- Operate **upgrade COSINE-100** until COSINE-200 crystal preparation

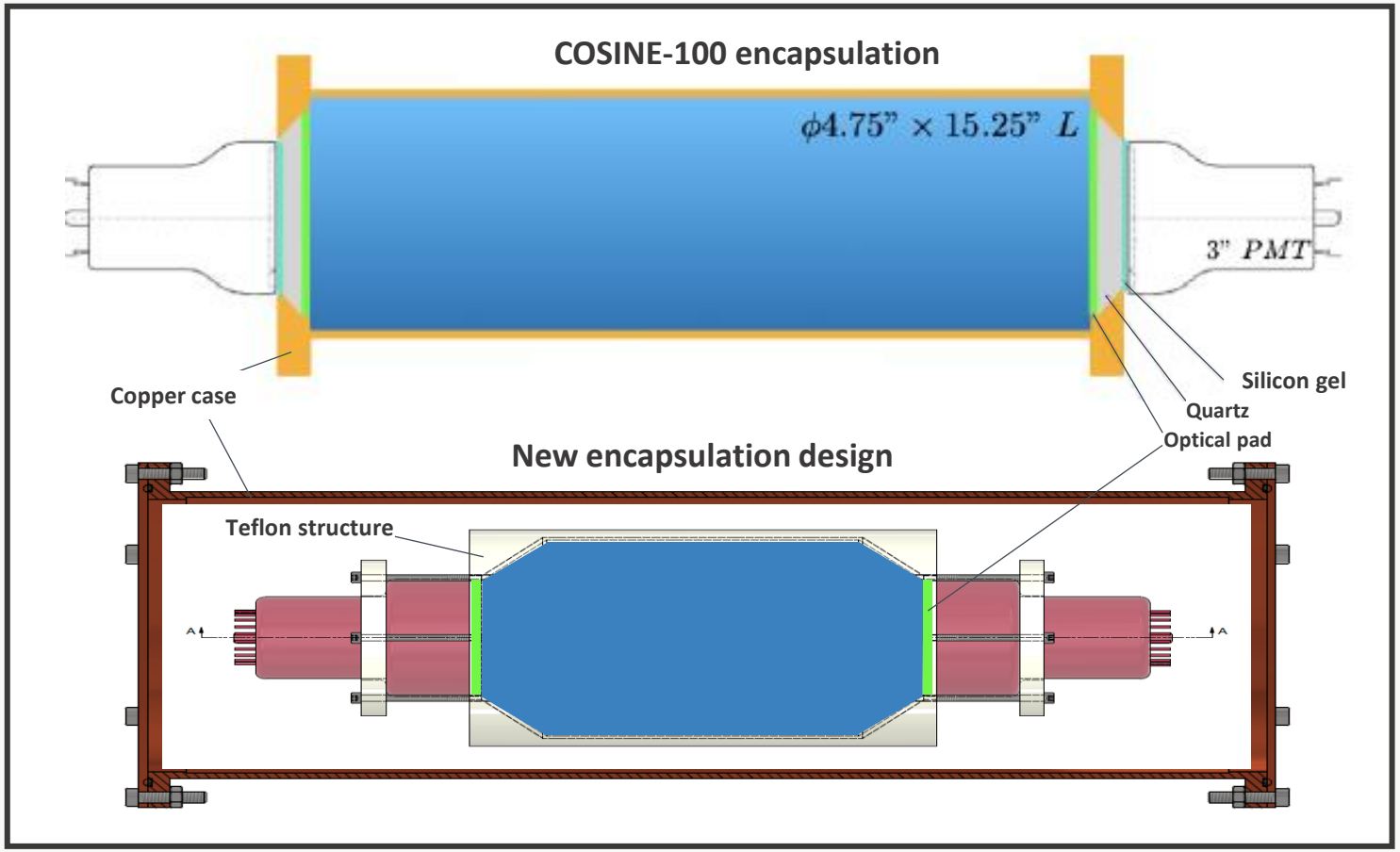


COSINE detector fridge room @Yemilab

Effort for next phase

- New encapsulation technique
  - **Direct attachment** of PMT to crystal
  - **~50% increased light Yield**
    - **15 P.E. → 22 P.E.**

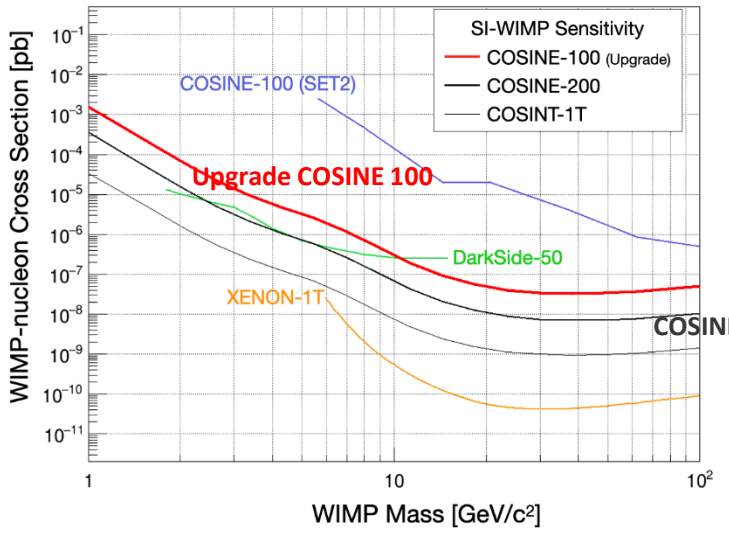
Nucl. Instrum. Meth. A 981, 164556 (2020)



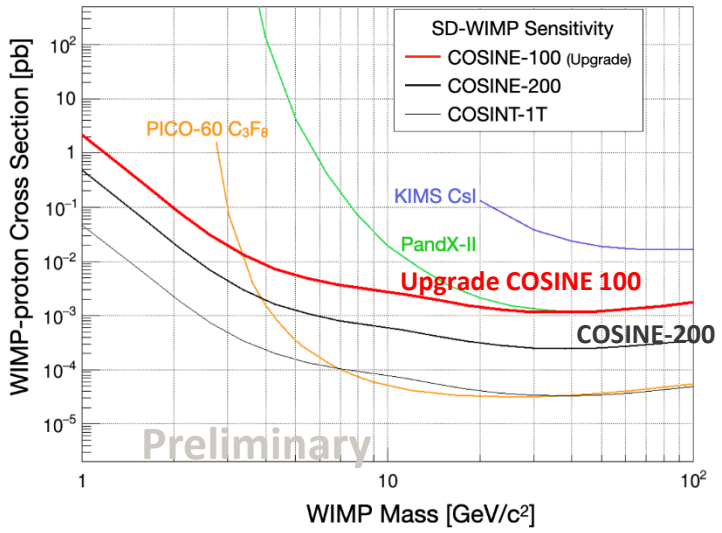
Sensitivity estimation

- **Condition for upgrade COSINE-100 (COSINE-200)**
  - 1 year
  - Light yields **22 P.E./keV**
  - COSINE-100 (R&D crystal) background
  - No systematics

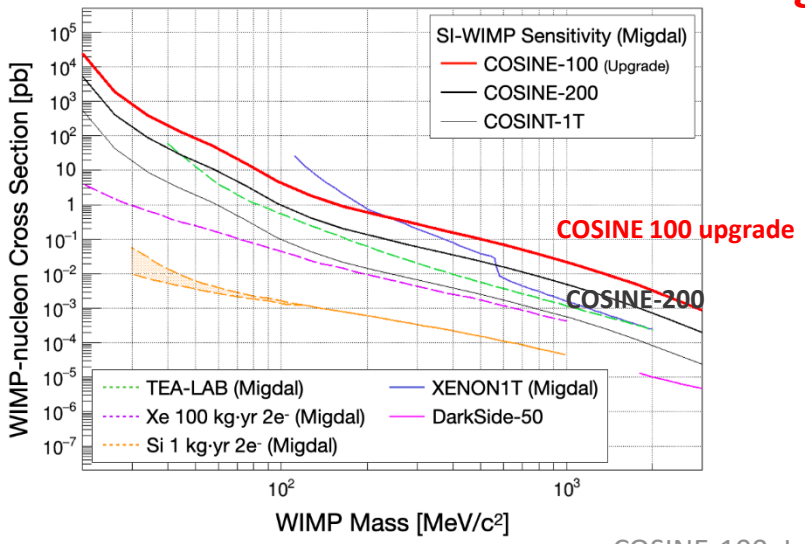
SI WIMP interaction



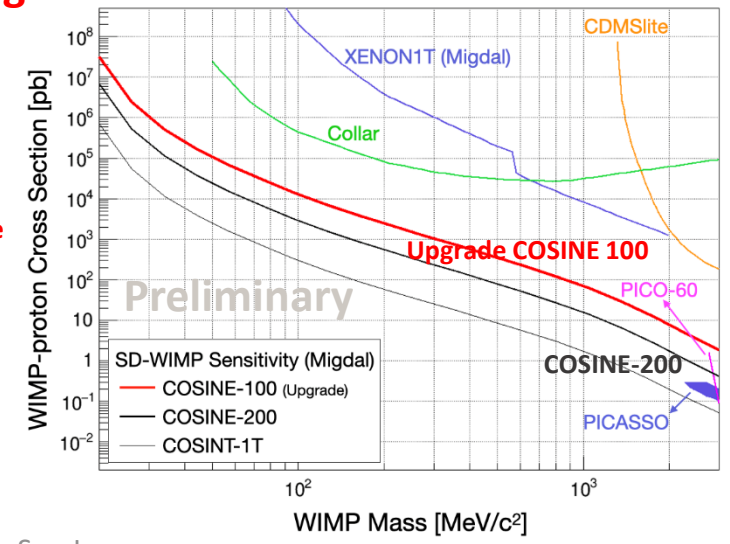
SD WIMP interaction



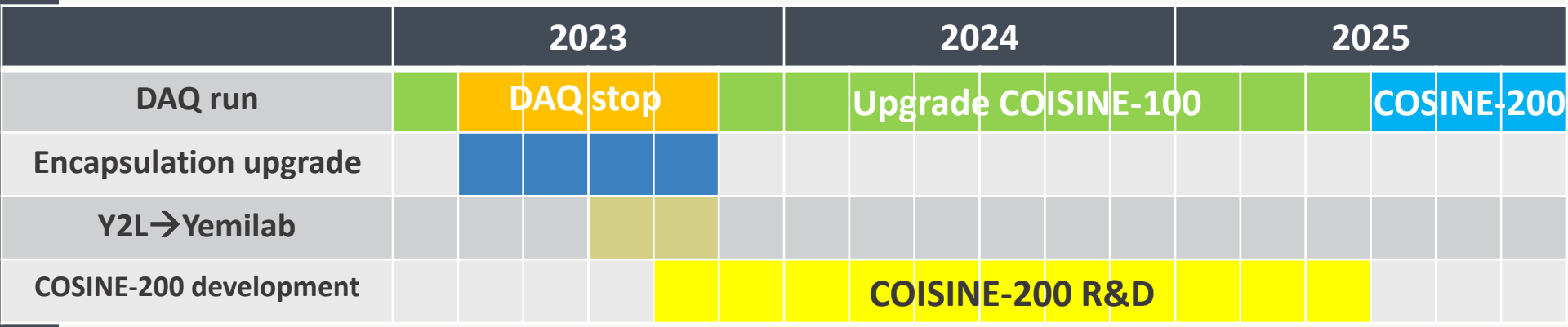
With Migdal



No systematics



Schedule for COSINE-100&200



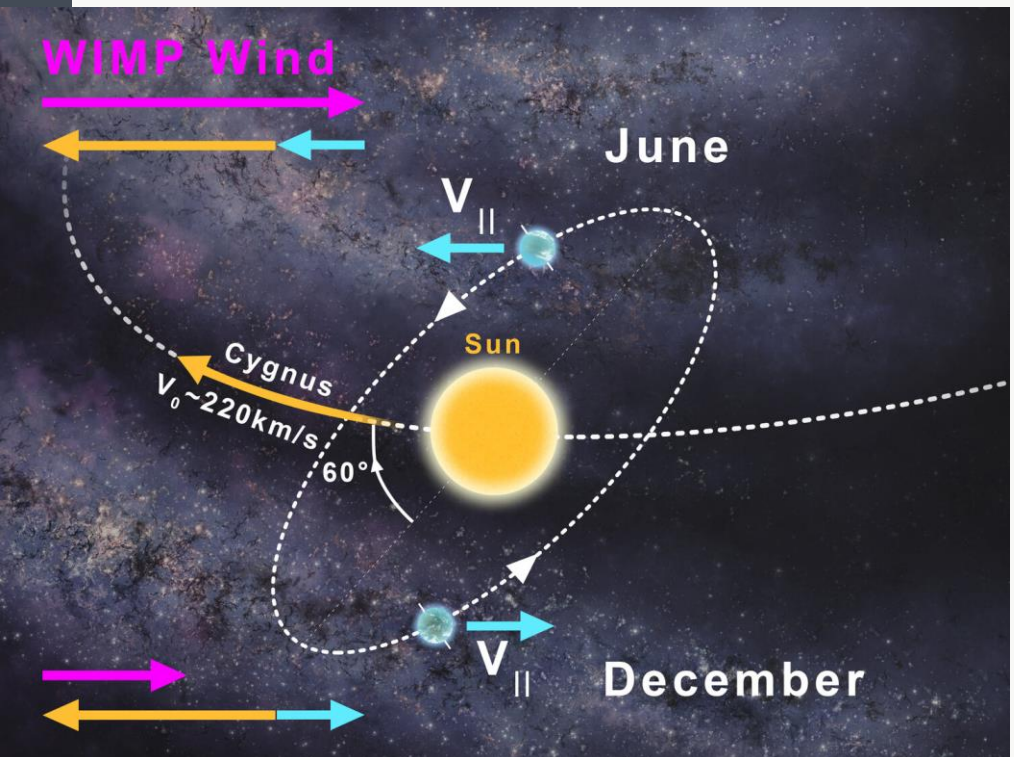
- **Stop COSINE-100** DAQ in **Mar. 2023**
- **Start** DAQ run after **6 months** encapsulation upgrade at Yemilab (~Oct. 2023)
- **Movement Y2L→Yemilab** in Aug. 2023
- Operate **upgrade COSINE-100** until COSINE-200 crystal preparation
- Start **COSINE-200** in middle of 2025

Summary

- COSINE-100 is an experiment to reproduce the DAMA/LIBRA signal via the same target material, NaI(Tl).
- Spectral Analysis
  - **Exclude** DAMA/LIBRA **signal** using 1.7 data
  - **Low mass WIMP** region was checked considering **Migdal Effect.**
- Modulation analysis
  - Could **not make clear decision** about DAMA/LIBRA modulation signal using **3 years data**
  - **Negative amplitude** using DAMA/LIBRA modeling method
- Preparations are ongoing for next phase, **COSINE-200.**
  - In-house development of **entire crystal growing process** at IBS , Korea
    - R&D NaI(Tl) crystals with **~0.2 count/day/kg/keV of background level**.
  - **50% light yields** improvement with **new encapsulation technique**.
  - Tested the properties of NaI(Tl) **at -35°C**
- We are planning an **intermediate experiment** of the **COSINE-200.**
  - Upgrade COSINE-100 **encapsulation** for **higher light yield**
  - Start upgrade COSINE-100 **DAQ** after 6-month **upgrade period (~Oct.2023)**

Back up

Annual modulation signal



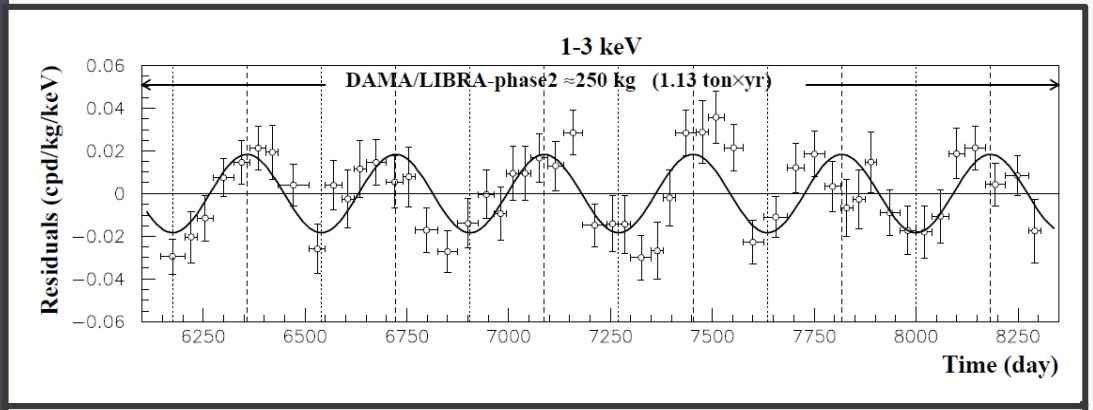
- Spherical halo of dark matter in our galaxy is expected to make dark matter flux to Solar system (WIMP Wind)
- Speed of WIMP wind changes according to seasonal rotation of the Earth.
- Changing WIMP speed induces changing interaction rate.

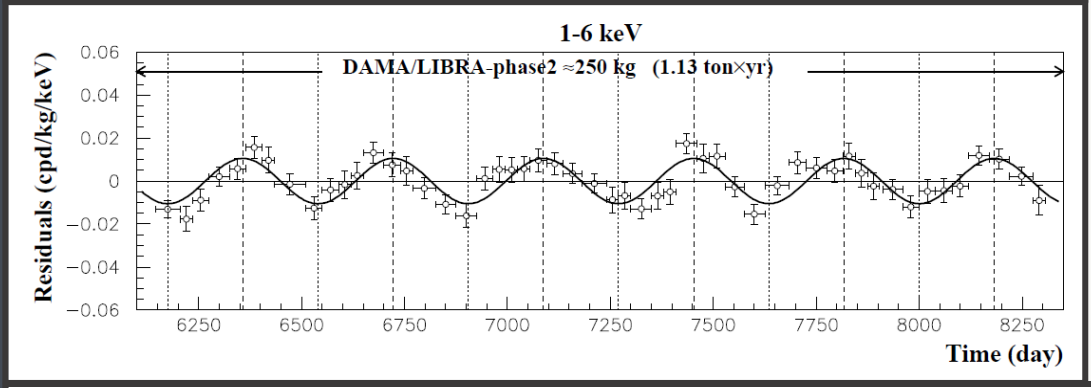
Rate of WIMP elastic scattering

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

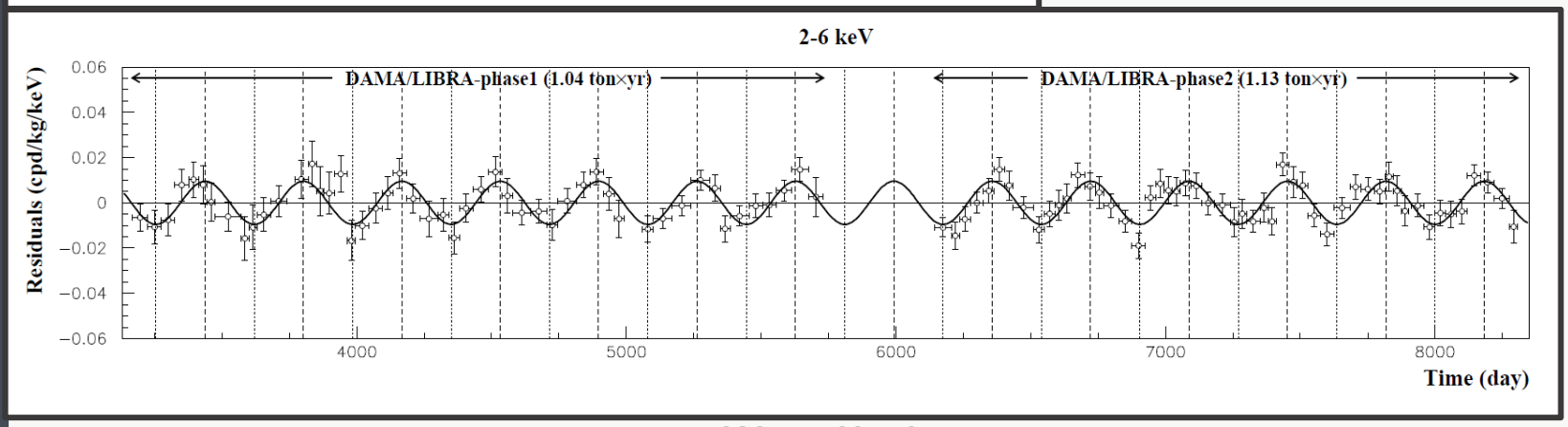
$f(v)$: WIMP velocity distribution
v_{min} : minimum velocity for interaction
ρ_χ : local WIMP density
m_χ : WIMP mass

DAMA/LIBRA result



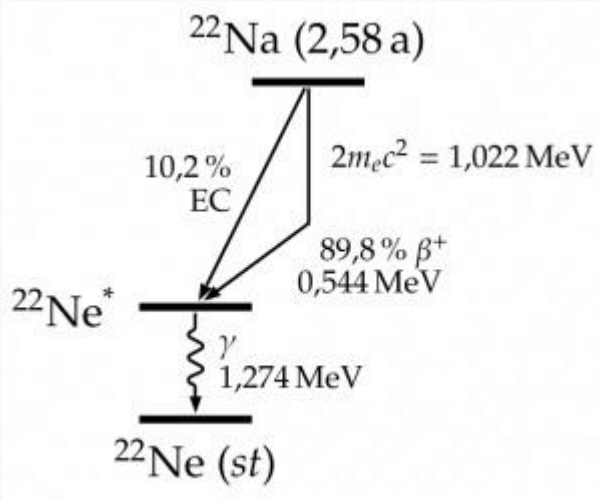


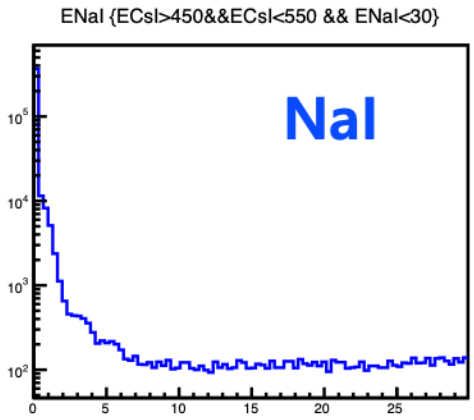
		A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/LIBRA–phase2:					
	1-3 keV	(0.0184±0.0023)	1.0	152.5	8.0 σ
	1-6 keV	(0.0105±0.0011)	1.0	152.5	9.5 σ
	2-6 keV	(0.0095±0.0011)	1.0	152.5	8.6 σ
	1-3 keV	(0.0184±0.0023)	(1.0000±0.0010)	153±7	8.0 σ
	1-6 keV	(0.0106±0.0011)	(0.9993±0.0008)	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

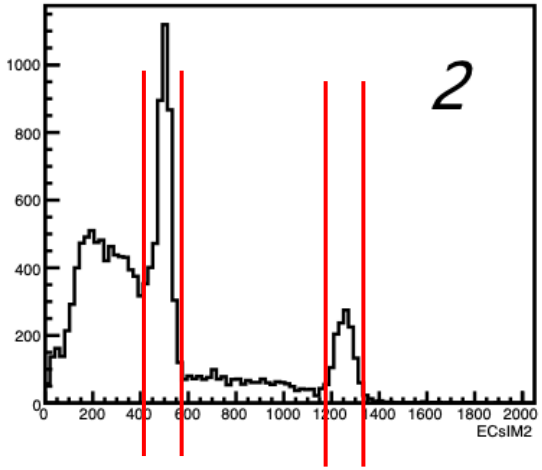


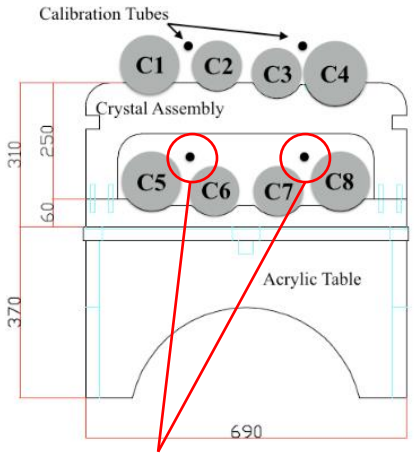
Why ^{22}Na calibration?

- To get pure low energy gamma spectrum,
  - Tagging coincidence event with other crystals' 511 keV or 1274 keV event





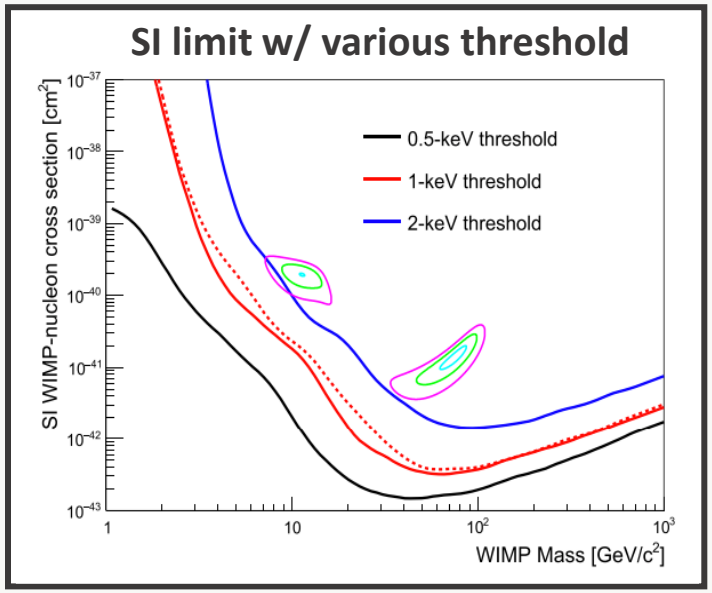




Source position

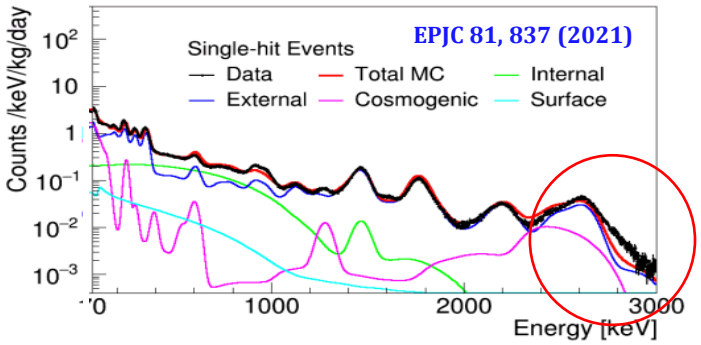
On going works

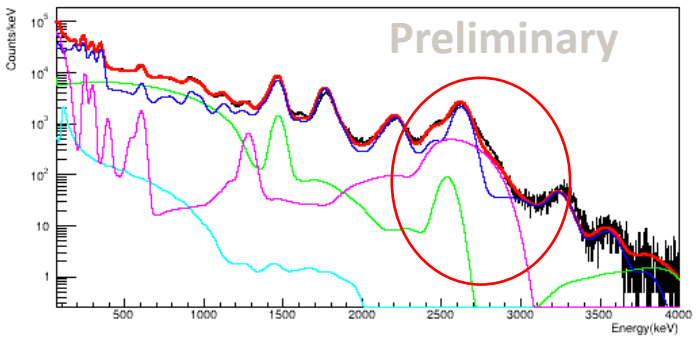
- Event selection improvement
  - Aim to 0.5 keV threshold
  - Deep learning (MLP) method



- Background modeling
  - Non-Proportionality update
  - Extended modeling range 6-3000keV →6-4000 keV

1.7-year background modeling





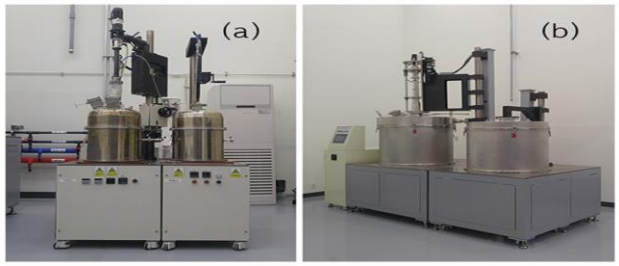
Effort for next phase

- Crystal development for **COSINE-200**
  - In-house development of entire process (at IBS , Korea)
    - NaI powder purification
    - Crystal growing
    - Detector assembly
  - **~0.7 kg** crystal w/ ~0.2 **count/day/kg/keV**
  - On going development for full size crystal (~100 kg)

Podwer purification facilities

J. Rad. Nucl. Chem. 317 1329 (2018)

Crystal grower



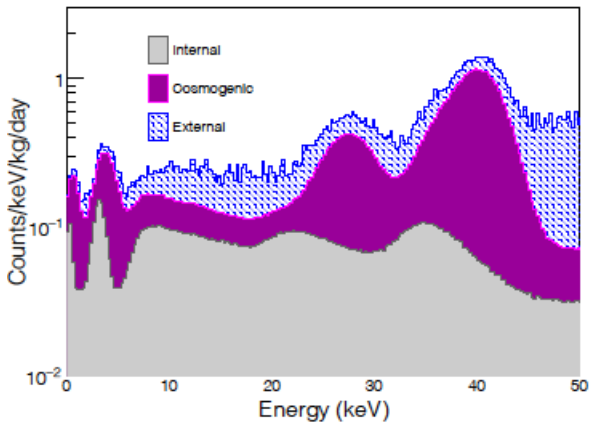
J. Phys. Conf. Ser. 1468 012144

CUP Grown crystals

Eur. Phys. J.C. 80 814 (2020)
Frontiers in Physics 11 (2023)

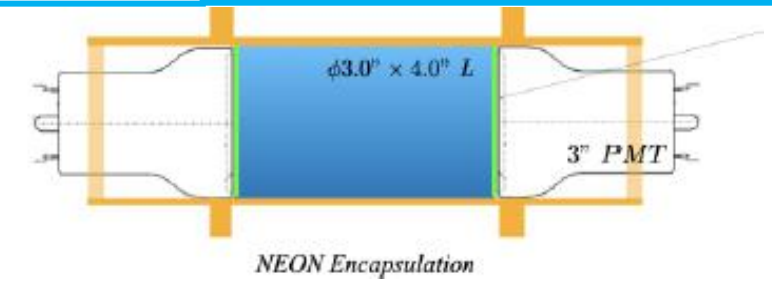
	K	^{210}Pb	^{238}U	^{232}Th
COSINE	16.8±2.5	1.87±0.09	<0.02	0.7±0.2
Powder	5	-	<20	<20
Aug.2018	<53	0.01±0.02	0.9±0.3	1.7±0.5
Sep.2019	<42	0.42±0.27	36.5±3.9	<4.9
Feb.2021	8.3±4.6	0.38±0.10	<2.0	<0.8
DAMA	<20	0.01~0.03	0.7-10	0.5-7.5

Background level

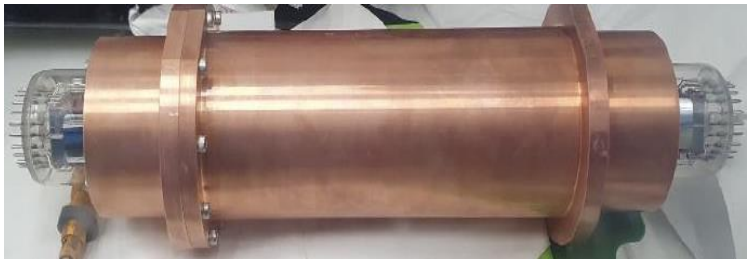


NEON-Phase 2 upgrade

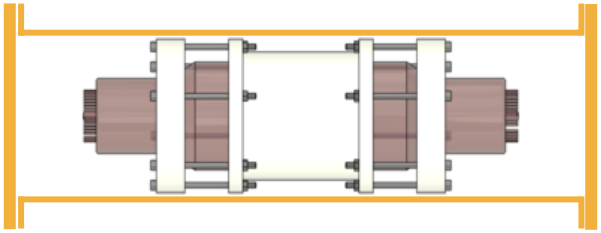
Phase 1

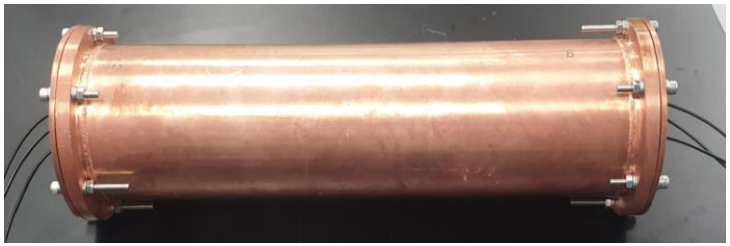


NEON Encapsulation



Phase 2



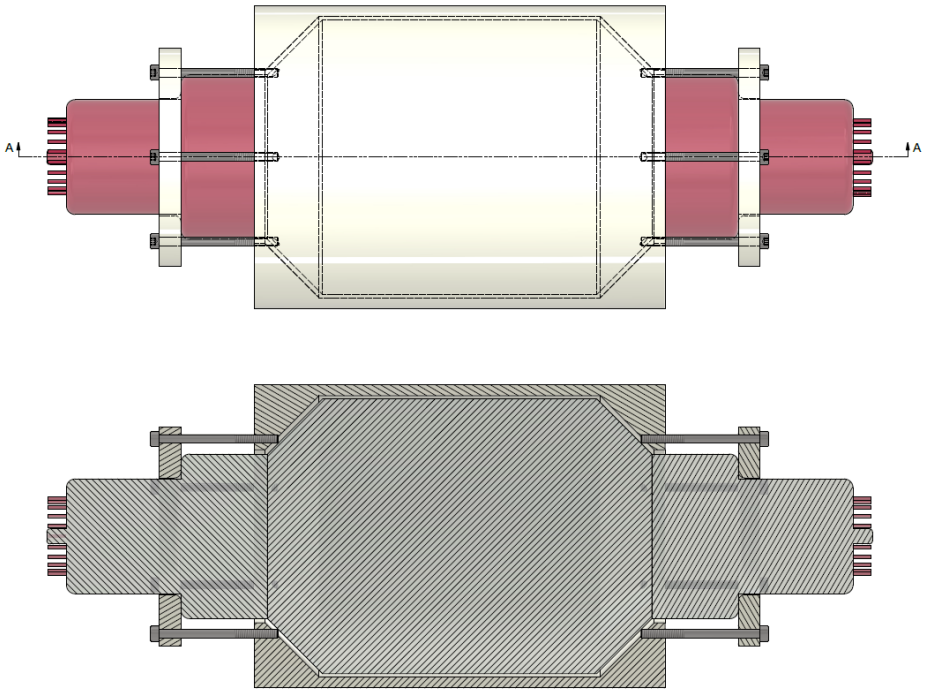


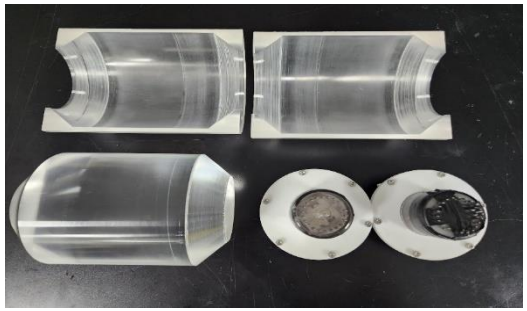
- Upgrade encapsulation (**Apr. 2022**)
  - Fix mechanical instability (Air or LS leak)
  - Achieve **higher light yields**
  - Add more mass : **13.6→ 16.3 kg**
- Exclude two high background crystals
- Include two **8" length crystals**

Crystal #	Size (dia x length)	Light yields(PE/keV)	
		Phase 1	Phase 2
1	3" x 4"	20.5 ± 0.9	Excluded
2	3" x 4"	19.3 ± 0.9	Excluded
3	3" x 4"	21.8 ± 0.9	23.9 ± 0.8
4	3" x 8"	22.4 ± 1.0	24.5 ± 0.7
5	3" x 8"	21.8 ± 0.9	22.9 ± 0.4
6	3" x 4"	21.7 ± 1.0	20.2 ± 0.4
7	3" x 8"	-	22.0 ± 0.5
8	3" x 8"	-	26.7 ± 0.8

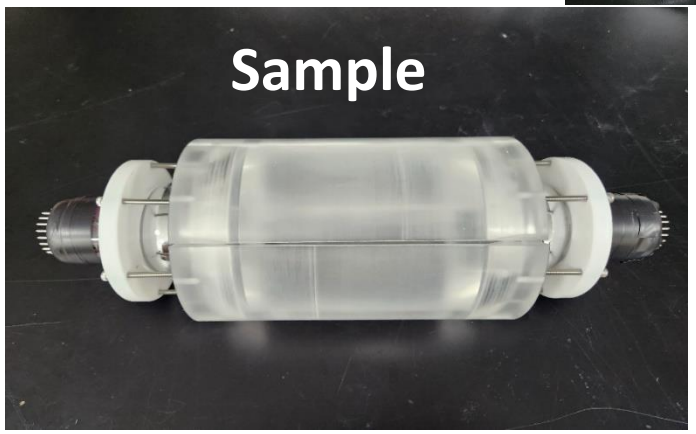
Encapsulation

- **Inner** structure for PMT-crystal connection
  - Direct contact PMT and crystal with optical pad
  - **PTFE** body, **Brass** bolt
  - PMT base shield (PTFE)



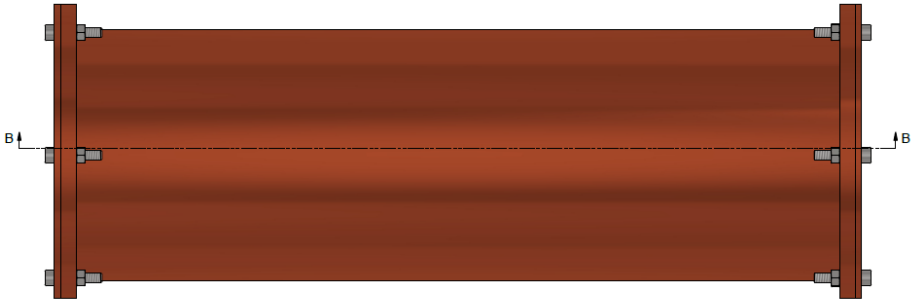


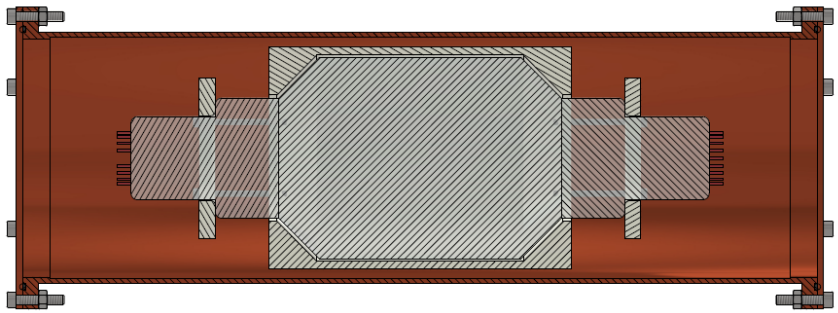
PMT base shield

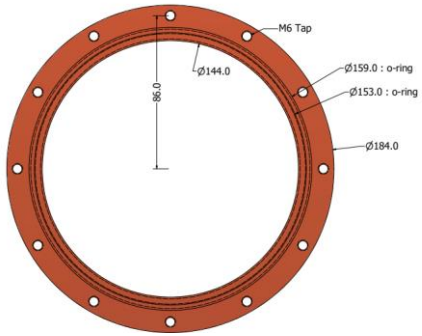


Encapsulation cont'd

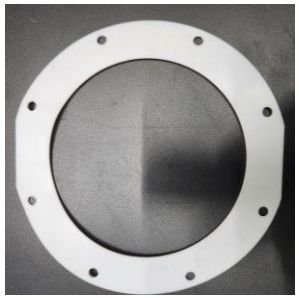
- **Copper case**
  - Same as **NEON** experiment
  - To prevent LS & air leak
    - **PTFE** Gasket
    - Cable gland







PTFE gasket



cable gland

NaI(Tl) Crystal

- 8 ultra low-background NaI(Tl) crystal with 106 kg in total
- U/Th/K level is less than DAMA, but total alphas (~210Pb) are higer than DAMA.
- Higher light yield (15 p.e/keV) than DAMA
  - Easier to reach lower threshold
- Total background is 2-3 times that of DAMA

Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS Ⅱ	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS Ⅱ	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WS Ⅲ	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS Ⅲ	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
Crystal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

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

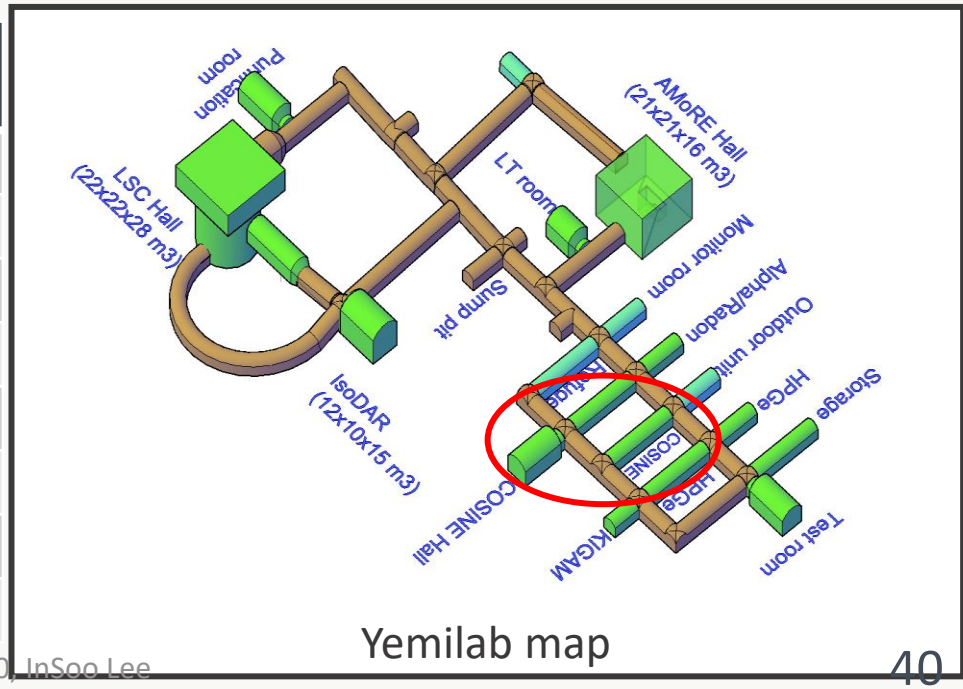
Upgrade plan for COSINE-100

Review

- COSINE-100 @ Yemilab
  - Crystals used in COSINE-100
  - Recover un-used crystals(# 1, 5, 8)
  - With **new** technique of **encapsulation** (Light yields >20 PEs/keV) Nucl. Instrum. Meth. A 981 (2020) 164556
  - At -35°C environment JINST 17 P02027 (2022)

COSINE-100 crystals

Crystal #	Size (diameter x length)	Light yield(PEs/keV)
1	5.0” x 7.0”	14.9 ±1.5
2	4.2” x 11.0”	14.6 ±1.5
3	4.2” x 11.0”	15.5 ±1.5
4	5.0” x 15.3”	14.9 ±1.5
5	5.0” x 15.5”	7.3 ±0.7
6	4.8” x 11.8”	14.6 ±1.5
7	4.8” x 11.8”	14.0 ±1.4
8	5.0” x 15.5”	3.5 ±0.3



Yemilab map