Recent Advances of Dark Matter Search from COSINE-100 Experiment

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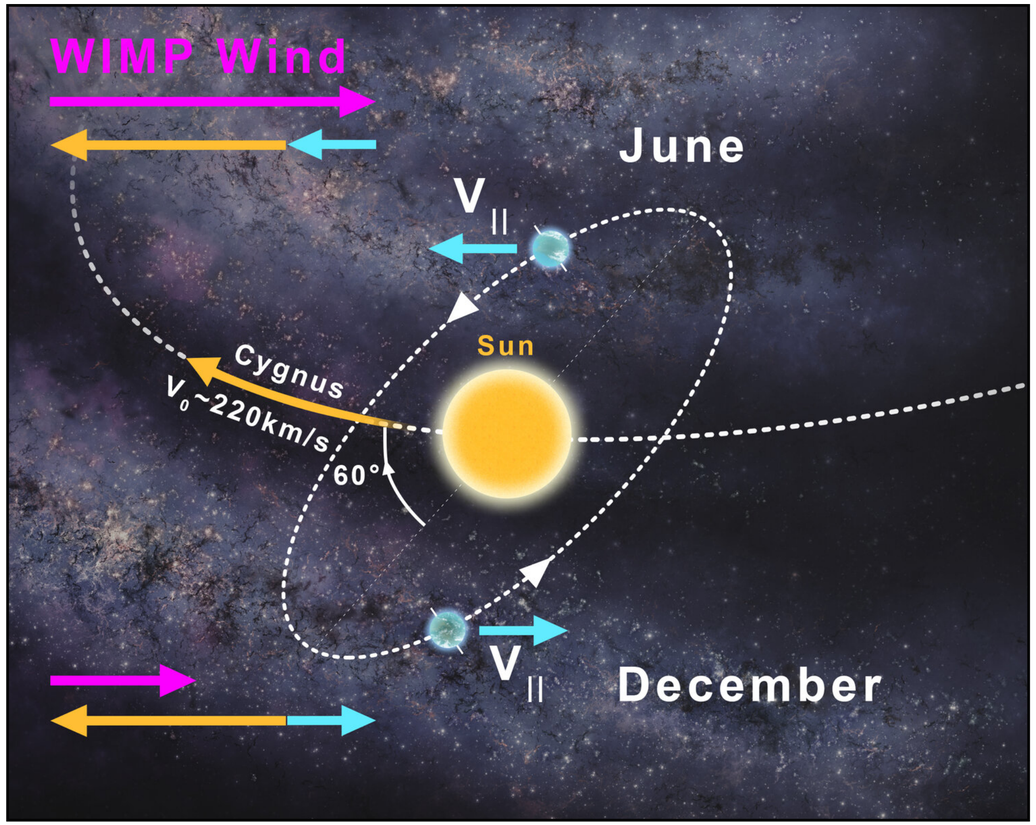
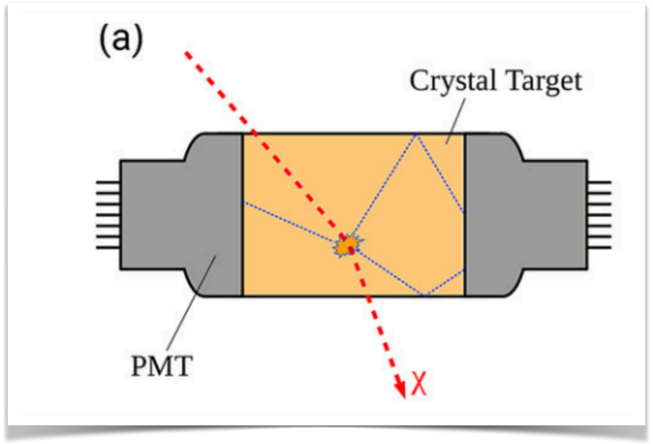
Institute for Basic Science (Center for Underground Physics)

On behalf of COSINE Collaboration

19th PATRAS Workshop on
Axions, WIMPs and WISPs

Annual modulation from DAMA/LIBRA

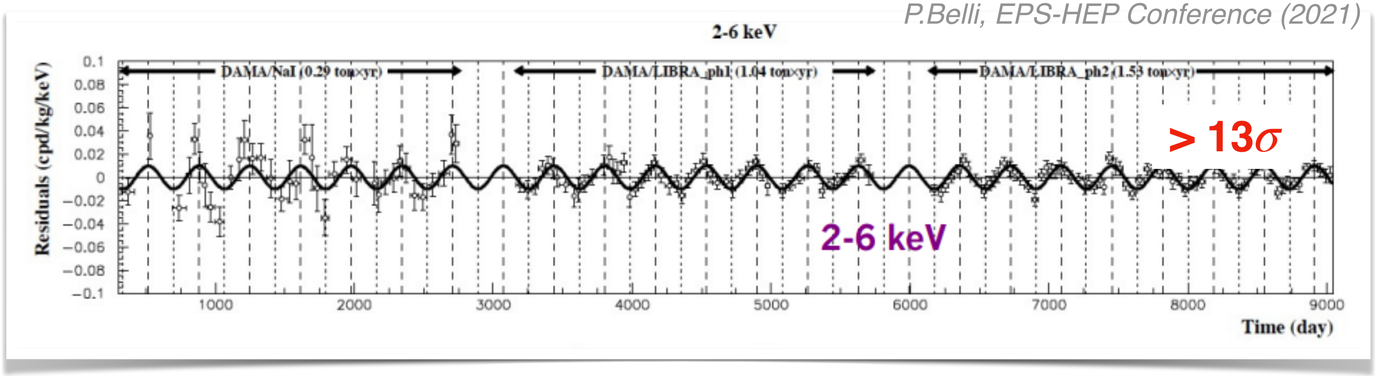




Direct DM search using NaI(TI)

DAMA/LIBRA Modulation signal

P.Belli, EPS-HEP Conference (2021)

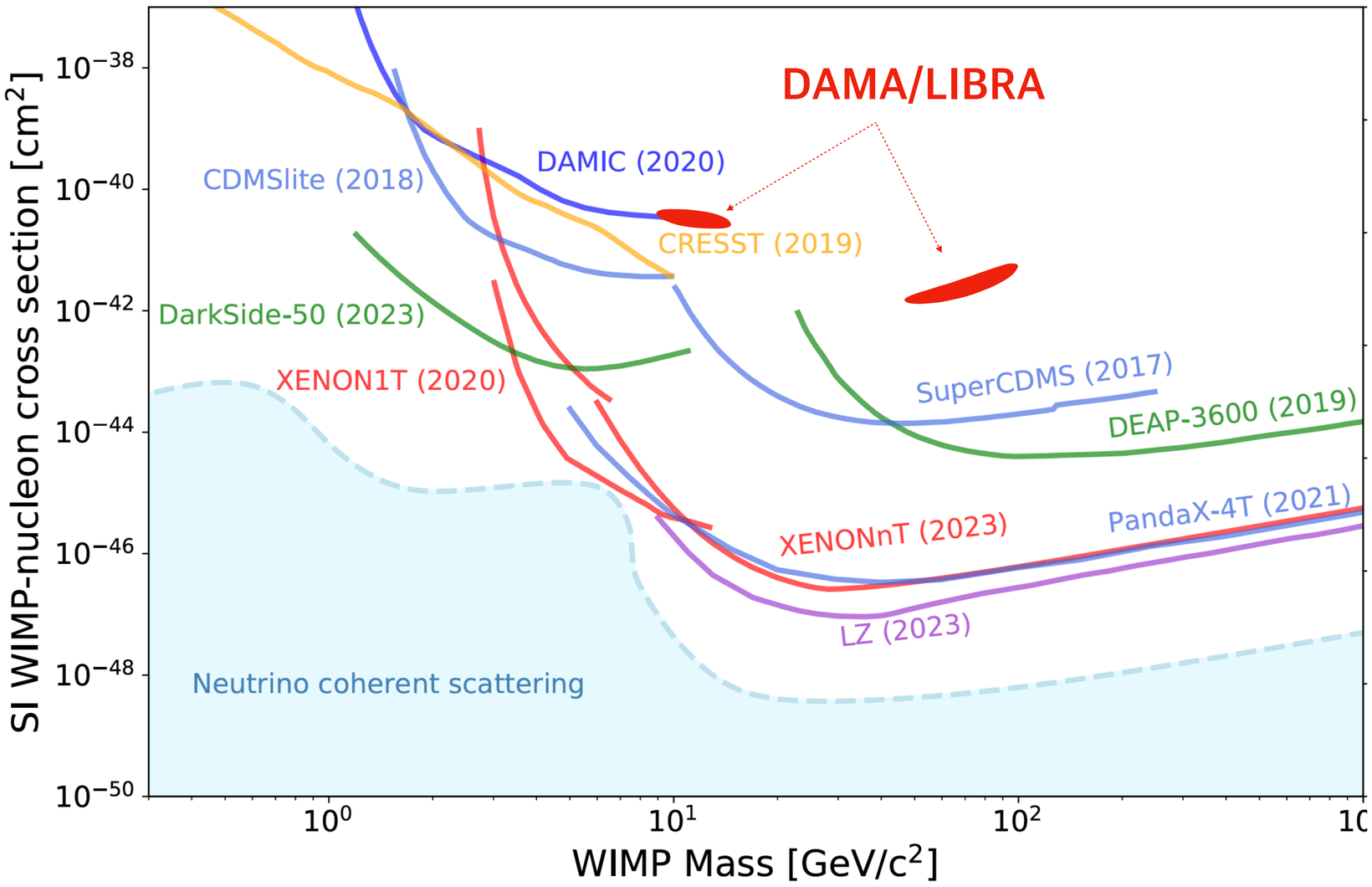


- DAMA/LIBRA claimed to find annual modulation signature by DM
- Compatible with the nature of DM candidate

A = 0.0096 ± 0.0008 counts/day/kg/keV,
ϕ = 145 ± 5 days
T = 0.9987 ± 0.0008 yr)

Annual modulation from DAMA/LIBRA

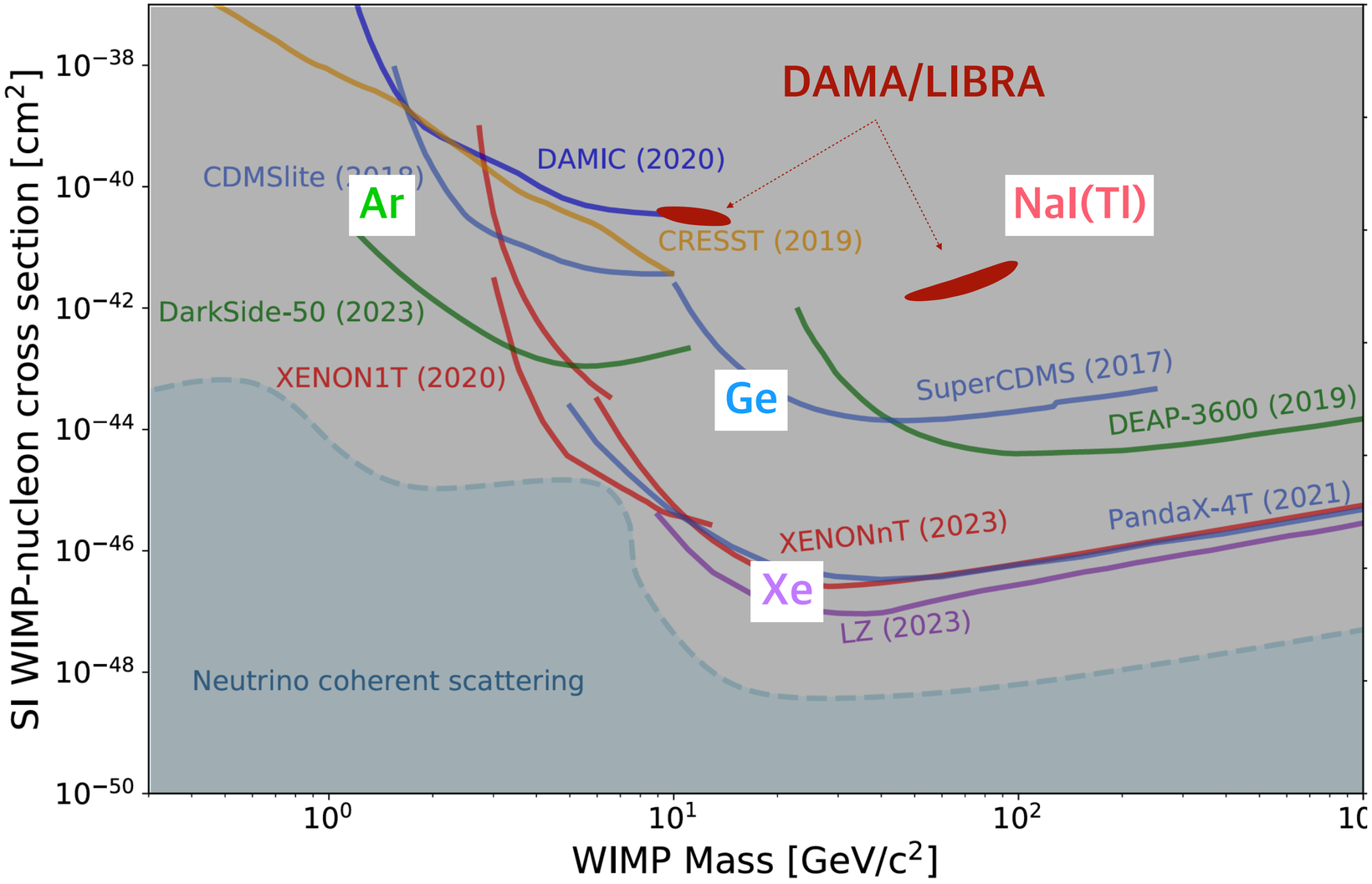
Particle Data Group : Review of Particle Physics (2024)



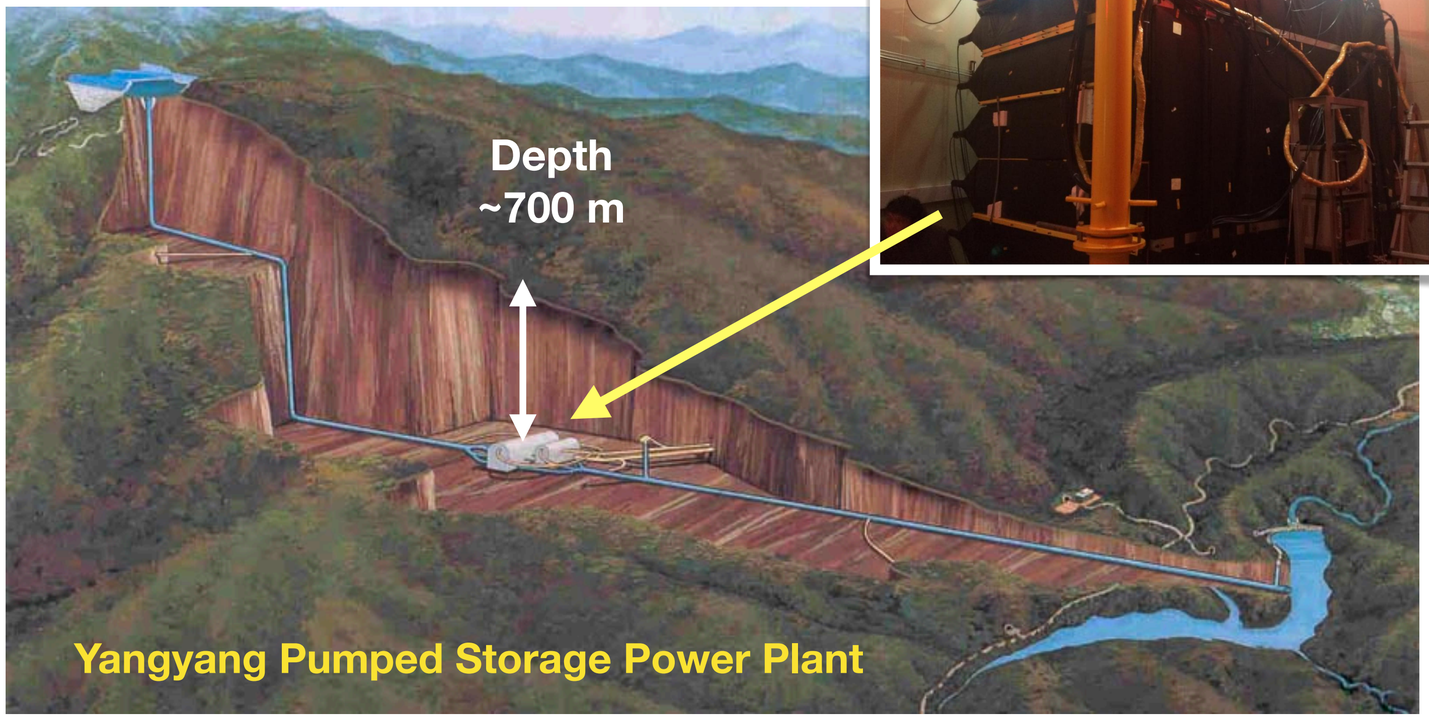
Annual modulation from DAMA/LIBRA

Particle Data Group : Review of Particle Physics (2024)

Direct test w/ NaI(Tl) target?



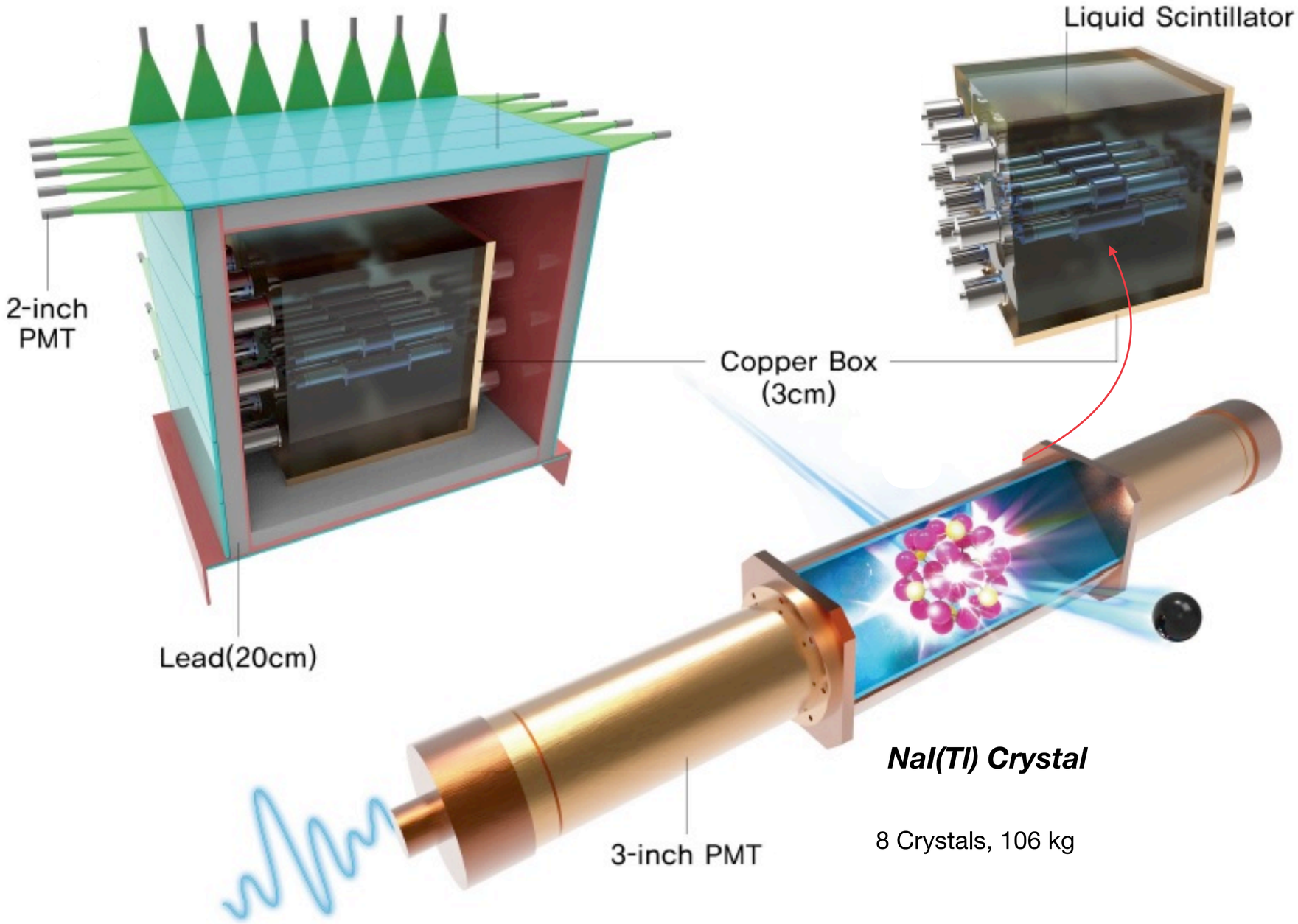
COSINE-100 experiment



- Located in Yangyang Underground Laboratory (Y2L), Korea (**Depth : ~700m**)
- **Direct test of DAMA/LIBRA using NaI(Tl).**

Muon Counter

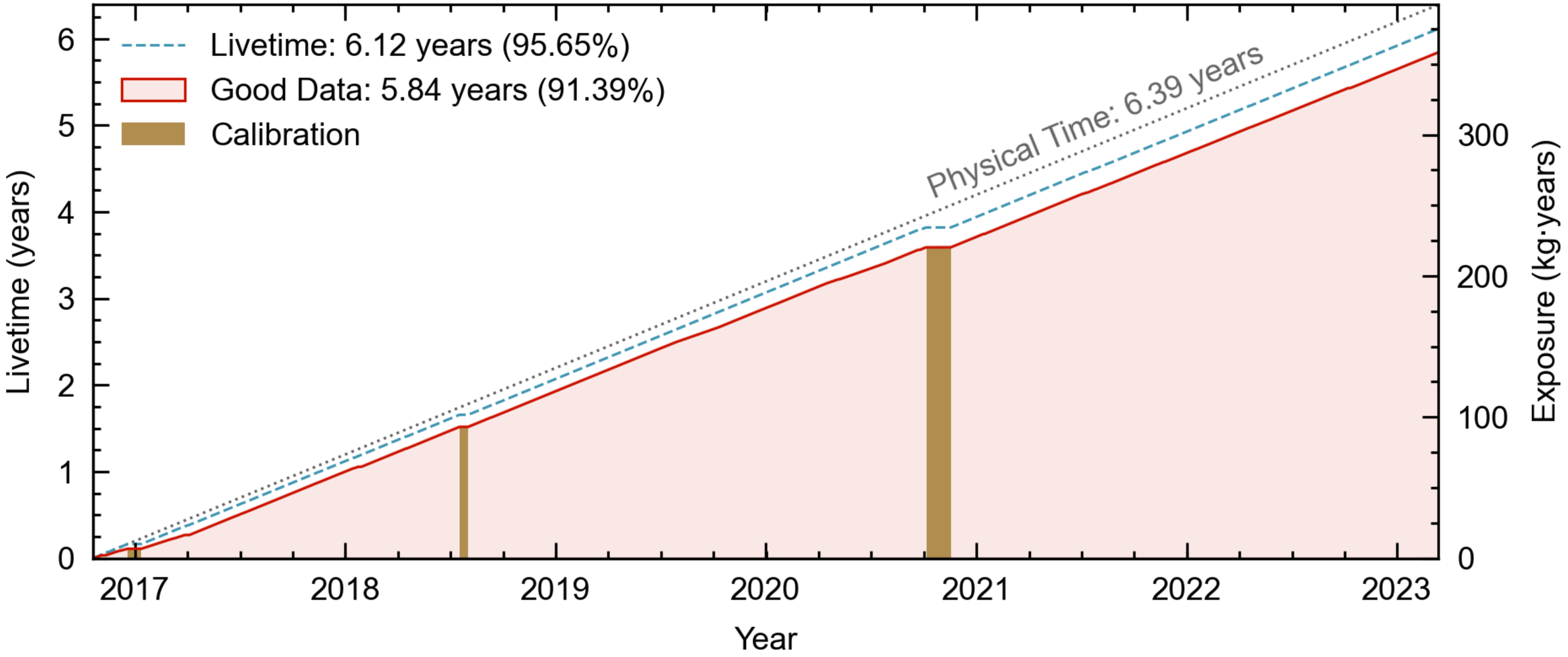
LS Veto



NaI(Tl) Crystal

8 Crystals, 106 kg

COSINE-100 experiment

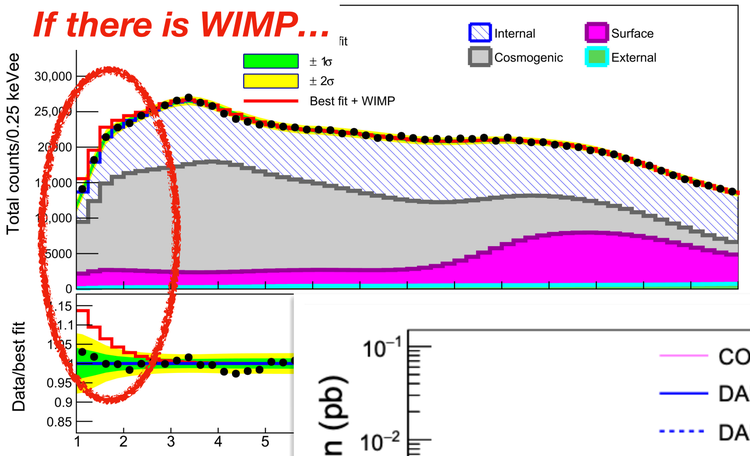


- Finished with ~6 year data taking (October 2016 ~ March 2023)

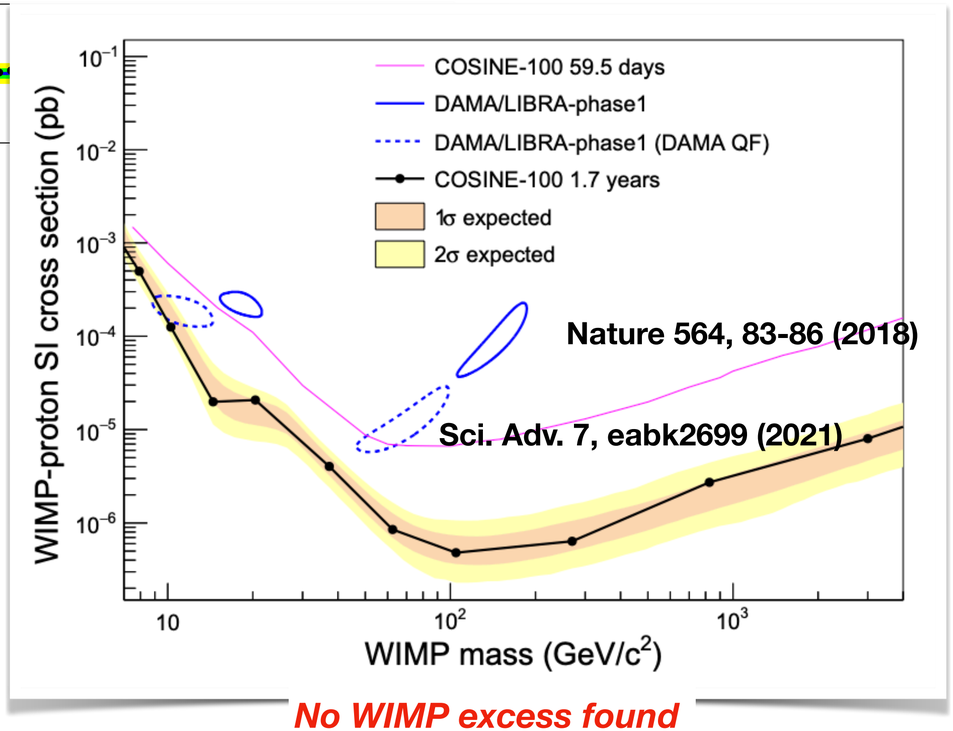
How to test WIMPs in COSINE-100?

Model Dependent
(Finding WIMP excess)

If there is WIMP…



60 days & 1.7 years analysis

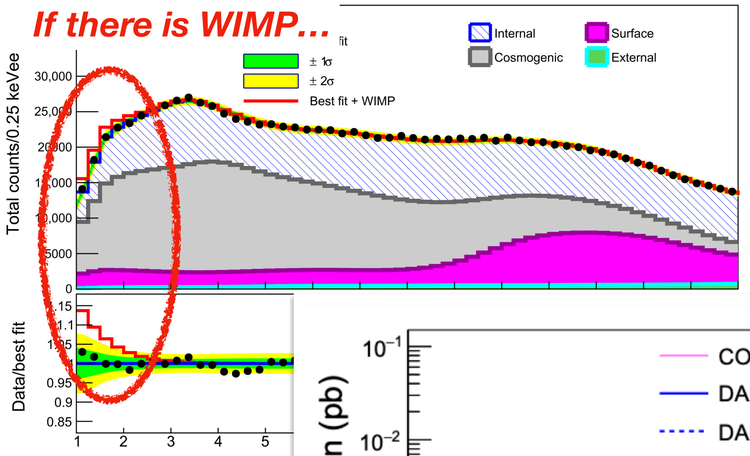


No WIMP excess found

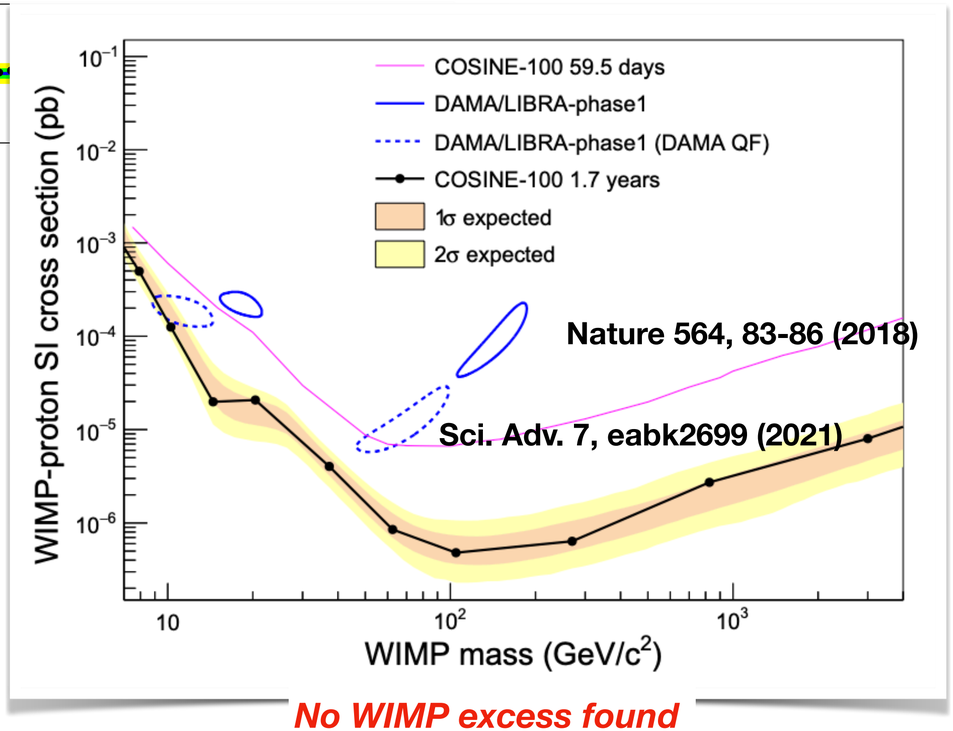
How to test WIMPs in COSINE-100?

Model Dependent
(Finding WIMP excess)

If there is WIMP…

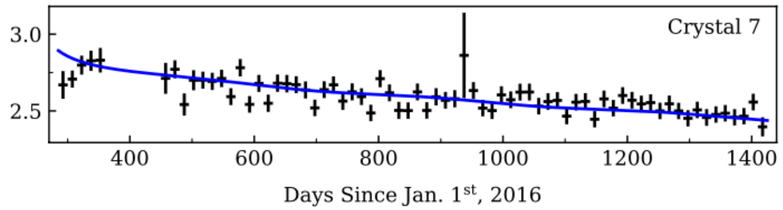


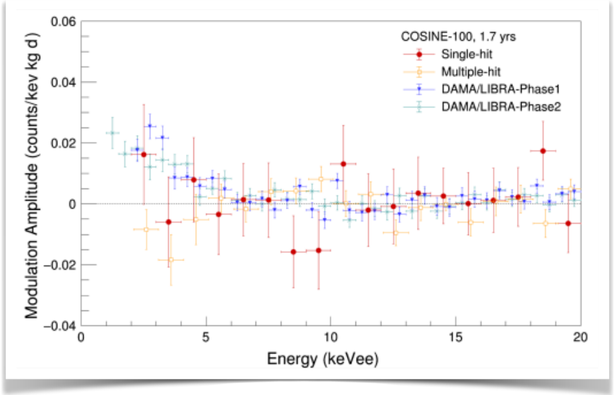
60 days & 1.7 years analysis



No WIMP excess found

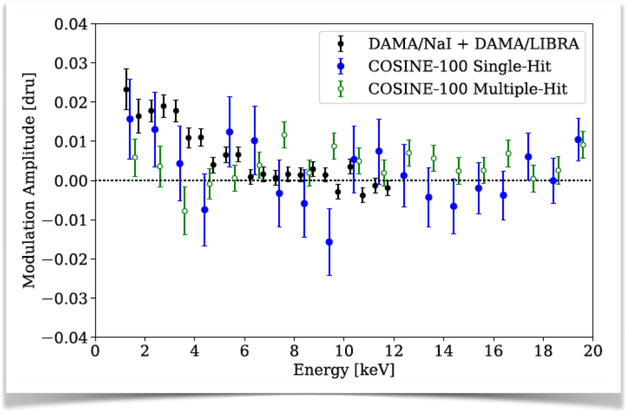
Model Independent
(Finding annual modulation)





1.7 year data analysis

PRL 122, 131802 (2019)

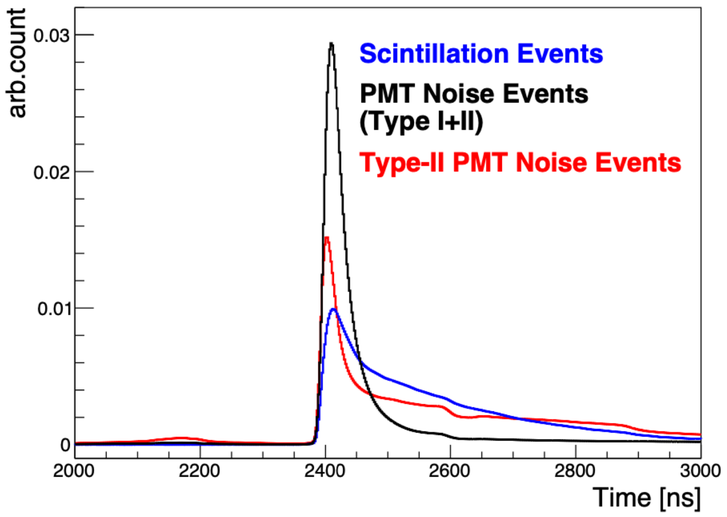


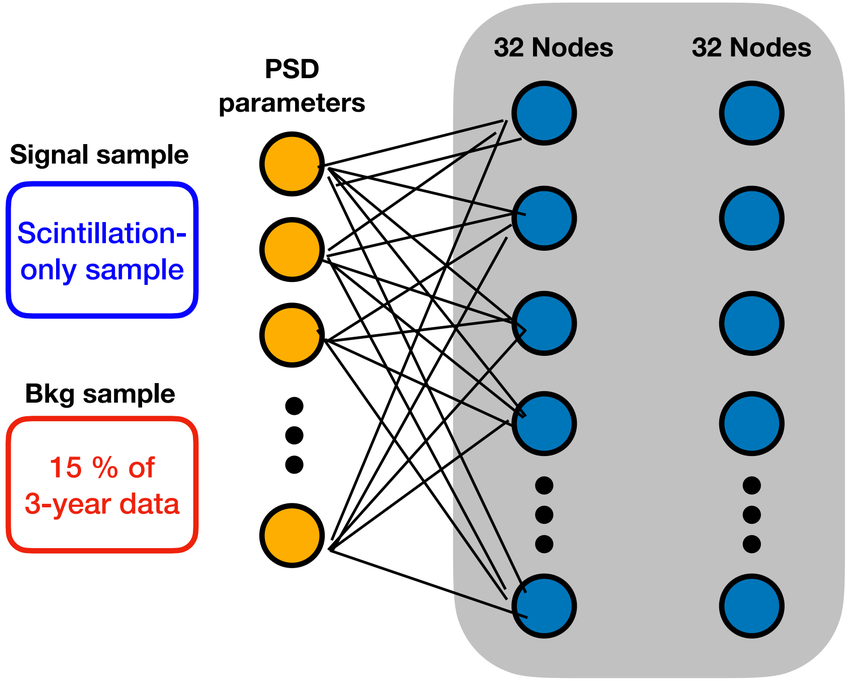
3.0 year data analysis

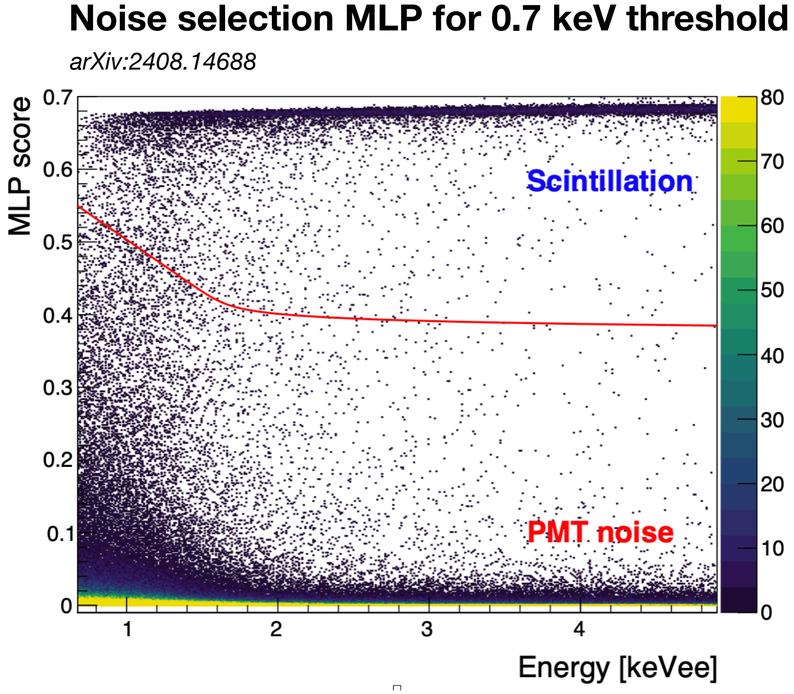
PRD 106, 052005 (2022)

Improvements on data understanding

Lowered threshold : 1 →0.7 keV





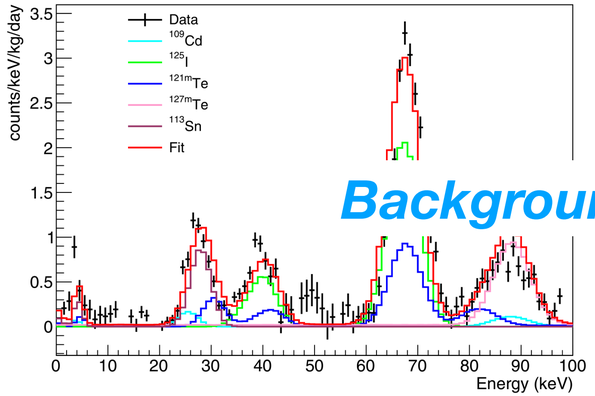


- COSINE-100 data is contaminated w/ PMT-induced noises
- MLP training using PSD parameters : 1.0 → **0.7 keV (8 P.E.) threshold** w/ ~20% efficiency

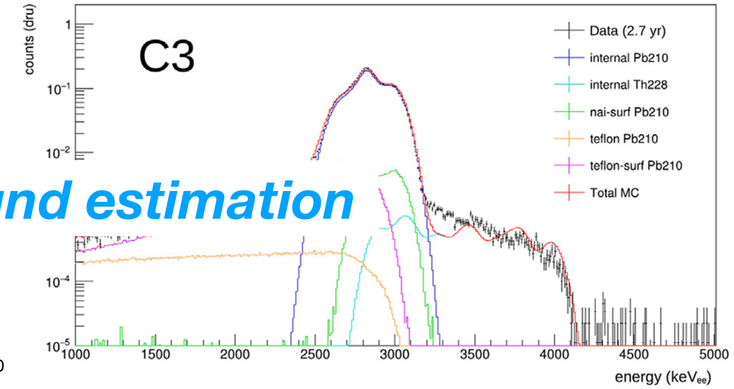
Improvements on data understanding

Background understanding

Cosmogenic background estimation
ASP 115, 102390 (2020)

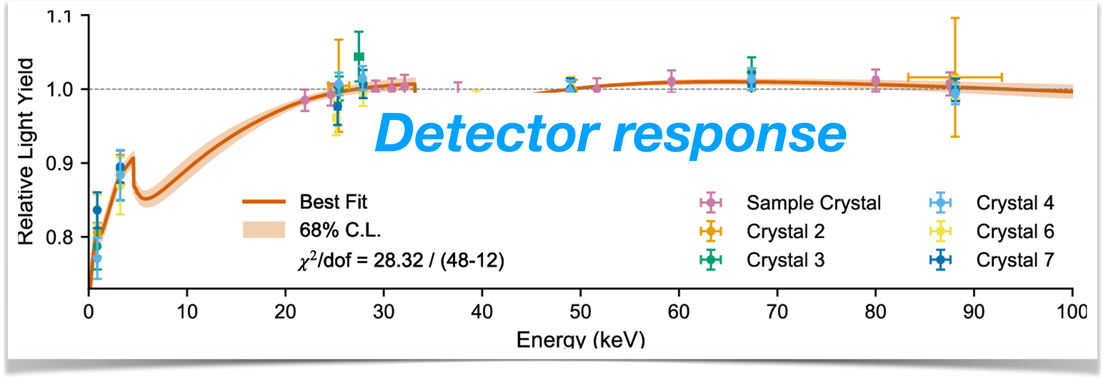


Alpha decaying background fit
ASP 158, 102945 (2024)



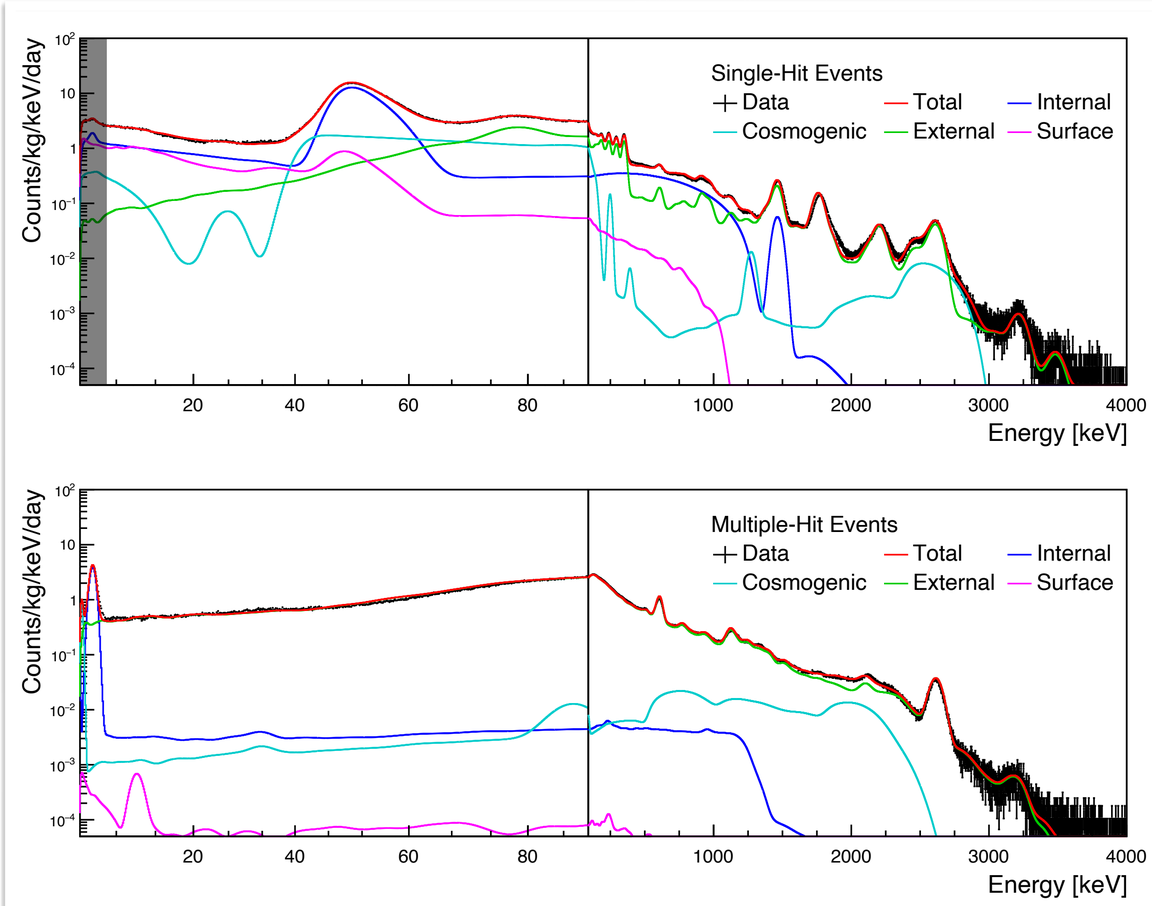
Background estimation

Detailed calibration : Non-proportional energy response
EPJC 84, 484 (2024)



Detector response

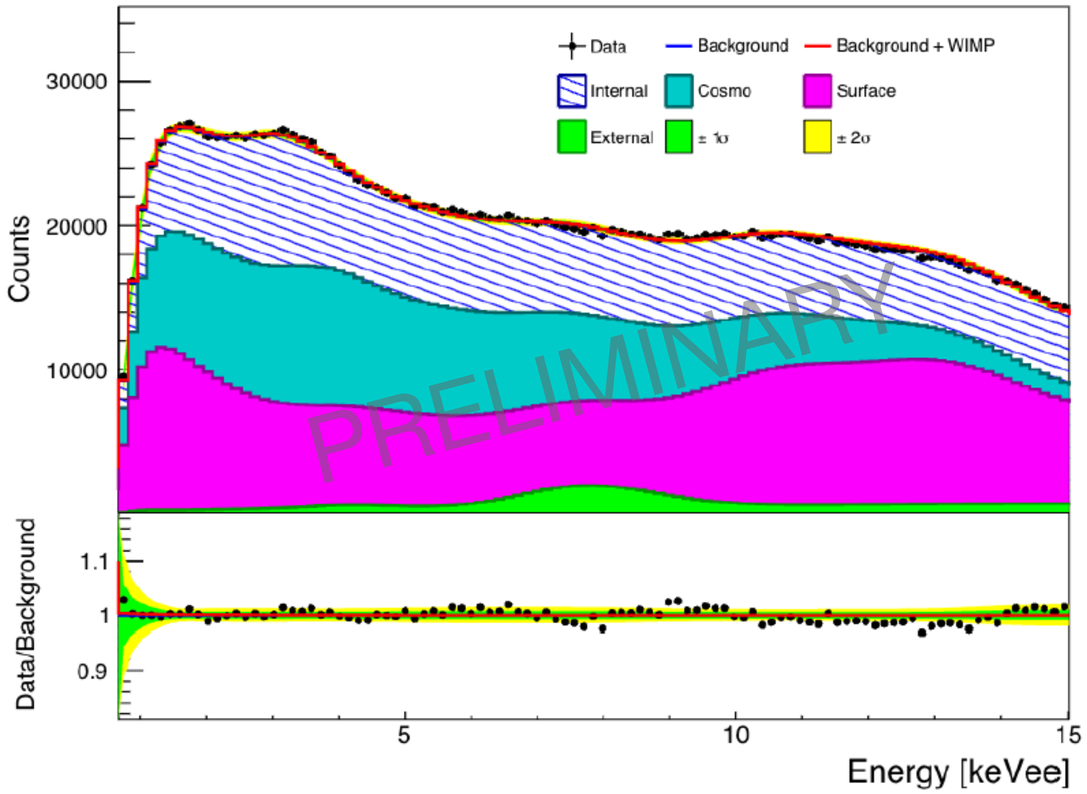
COSINE-100 background modeling w/ Geant4 MC simulation
arXiv:2408.09806

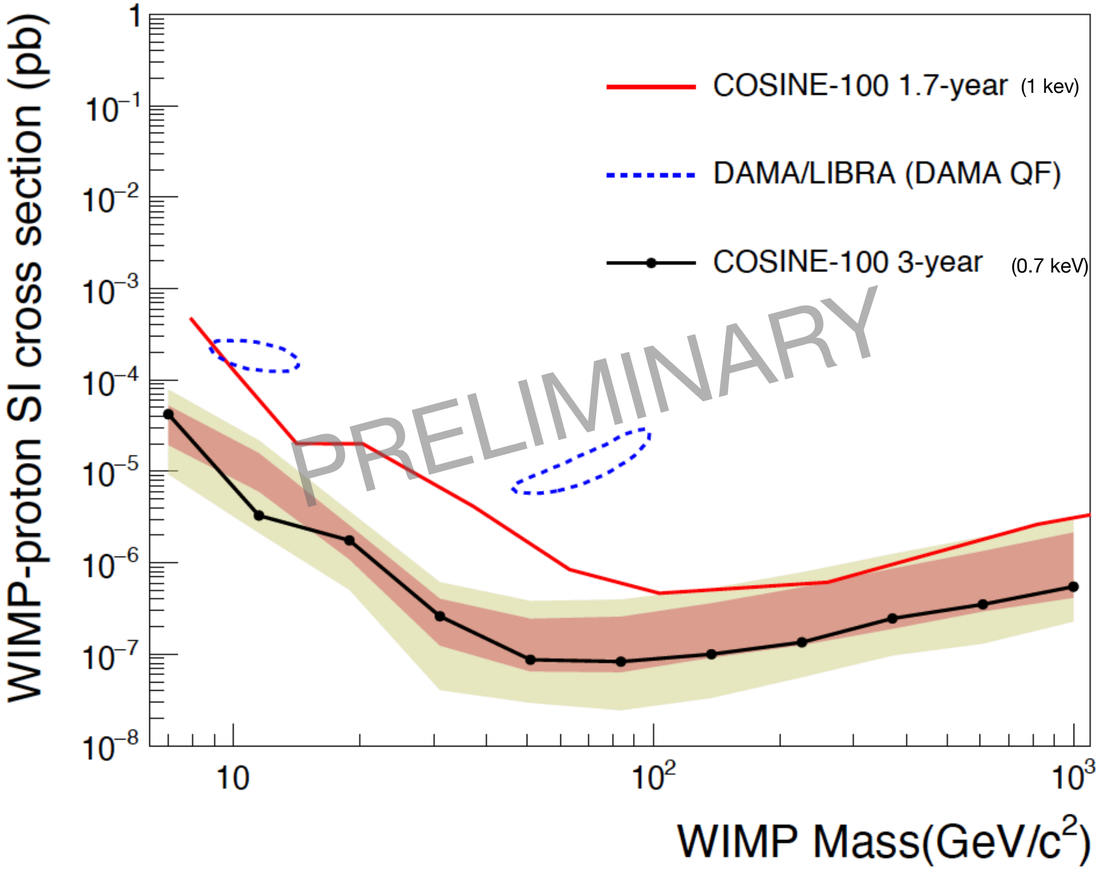


0.7 - 3000 keV background modeling

Model-Dependent WIMP search

Spectral analysis : Spin-Independent





- WIMP presence with canonical WIMP model, considering Standard Halo Model
- 3-year spectral analysis **disfavors DAMA/LIBRA**

Model-Dependent WIMP search

Spectral analysis : Spin-Dependent

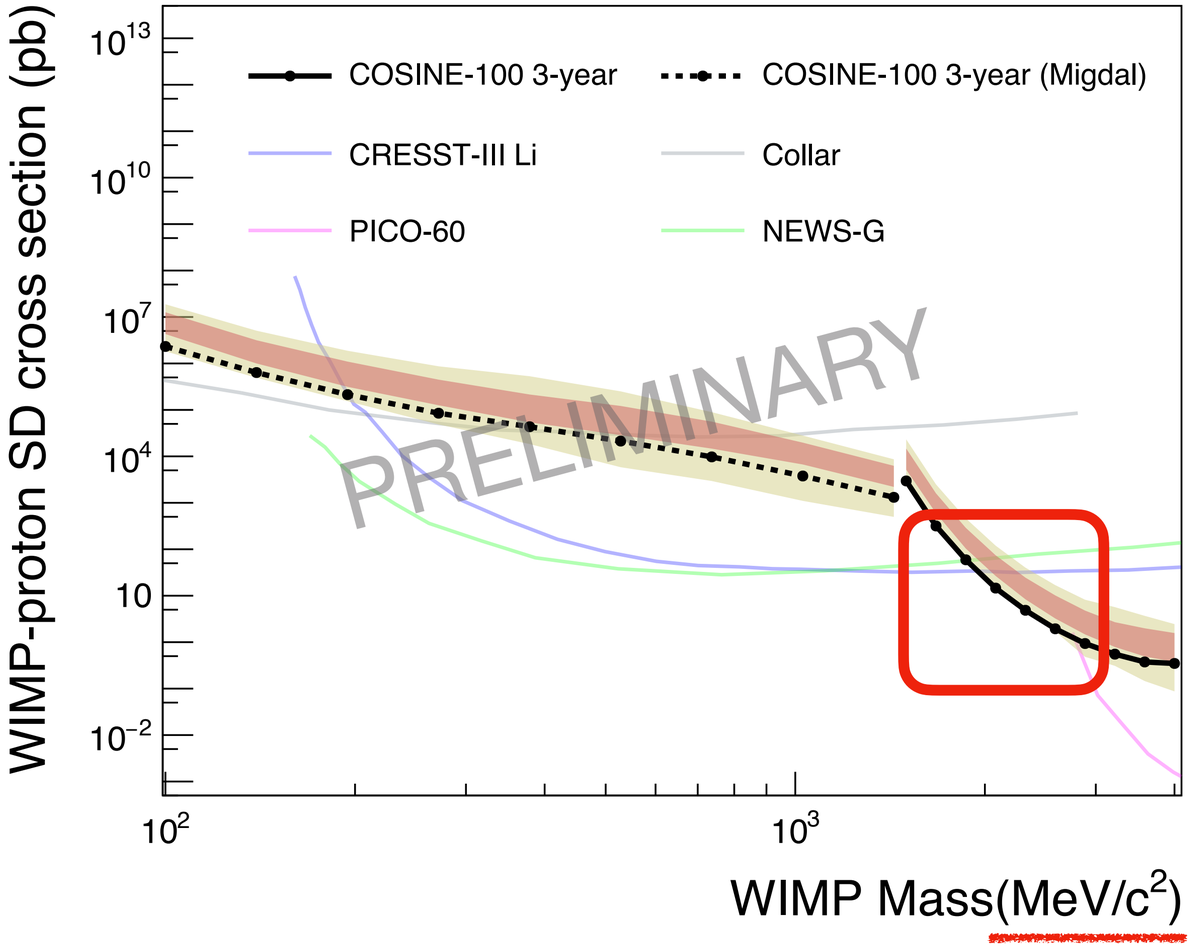
Na (Z = 11) & I (Z = 53)

- Proton-odd targets

  →sensitive in SD model

- Low-mass target (Na)

  →sensitive in low-mass WIMP search



***Best-limit** in a few-GeV mass range*

Model-Independent test

Modulation signal search

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

Rate of ith Crystal

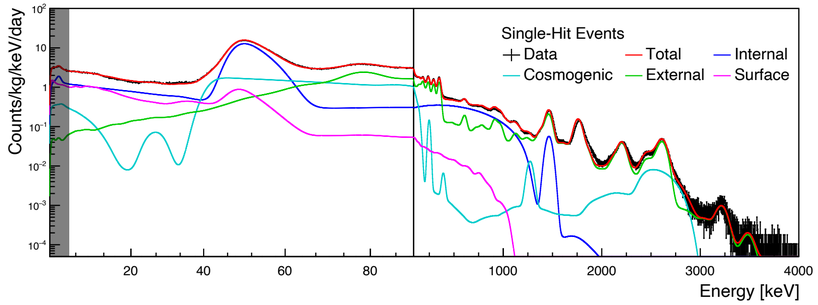
Crystal specific background components

- Constant : Long-lived
- Exponential : Short-lived
- Considers each background separately

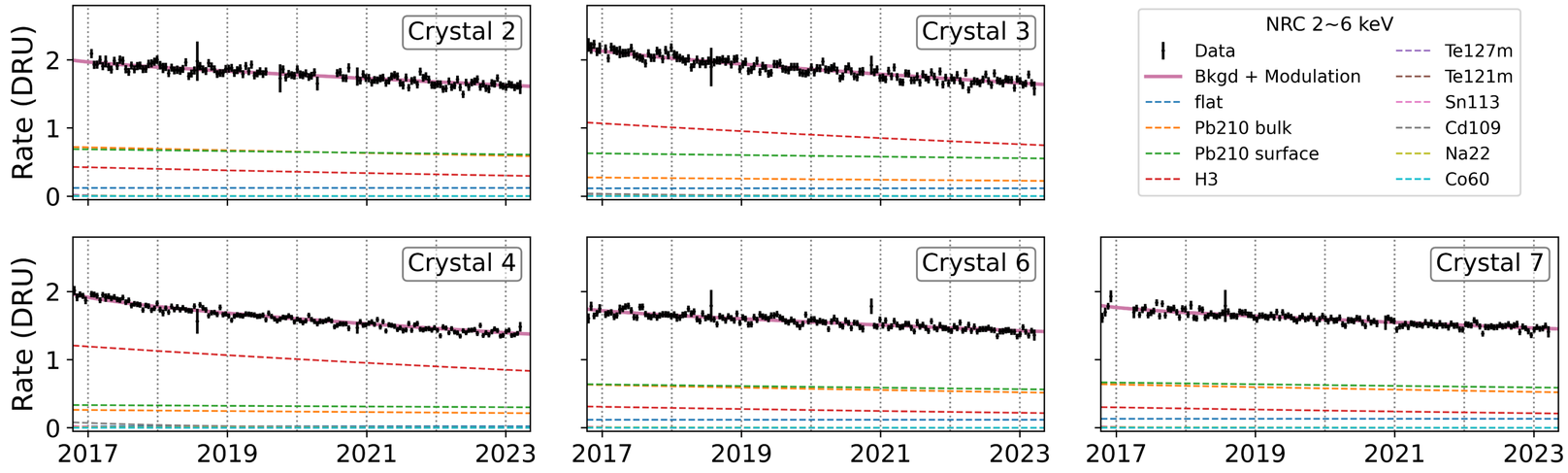
Modulation Amplitude

Fixed across crystals

Background modeling result



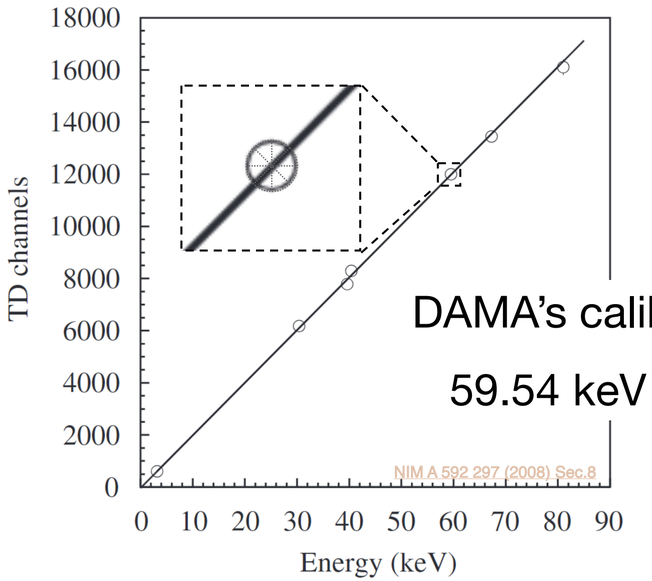
Time-dependent event rate fit on COSINE-100 6-year data



Model-Independent test

Calibration for testing DAMA

1. Electron recoil (keVee, linear calibration)



DAMA's calibration method using

59.54 keV ^{241}Am peak charge

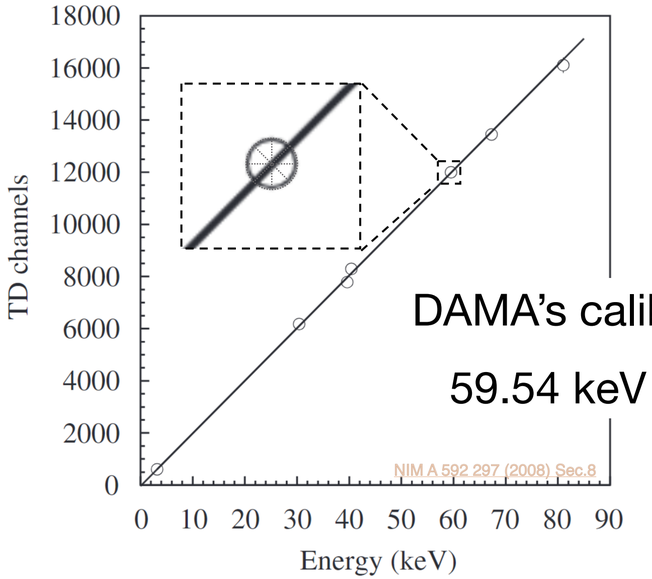
Signal region

- 1 – 3 keV_{ee}
- 1 – 6 keV_{ee}
- 2 – 6 keV_{ee}

Model-Independent test

Calibration for testing DAMA

1.Electron recoil (keVee, linear calibration)



DAMA's calibration method using

59.54 keV ^{241}Am peak charge

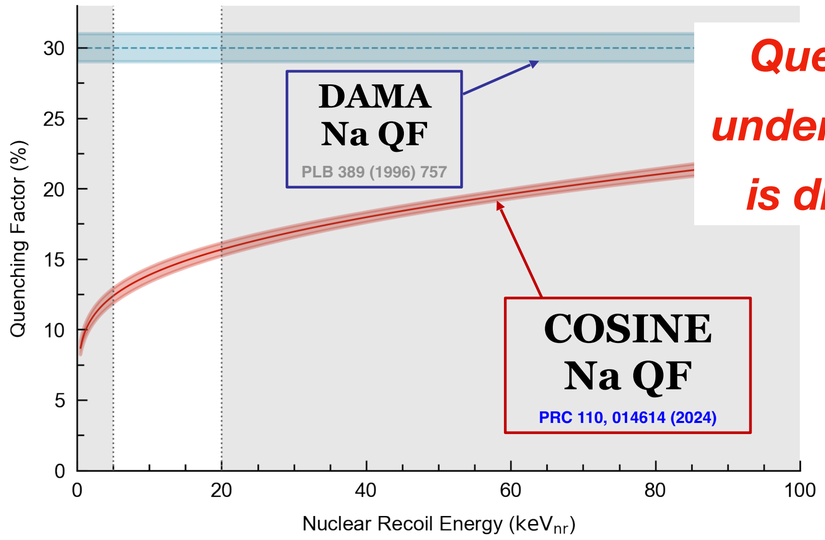
Signal region

1 – 3 keV_{ee}

1 – 6 keV_{ee}

2 – 6 keV_{ee}

2. Nuclear recoil calibration (keVnr)



Quenching understanding is different!

Different QF for DM signal interpretation

Signal region : 6.70 – 20 keV_{nr}

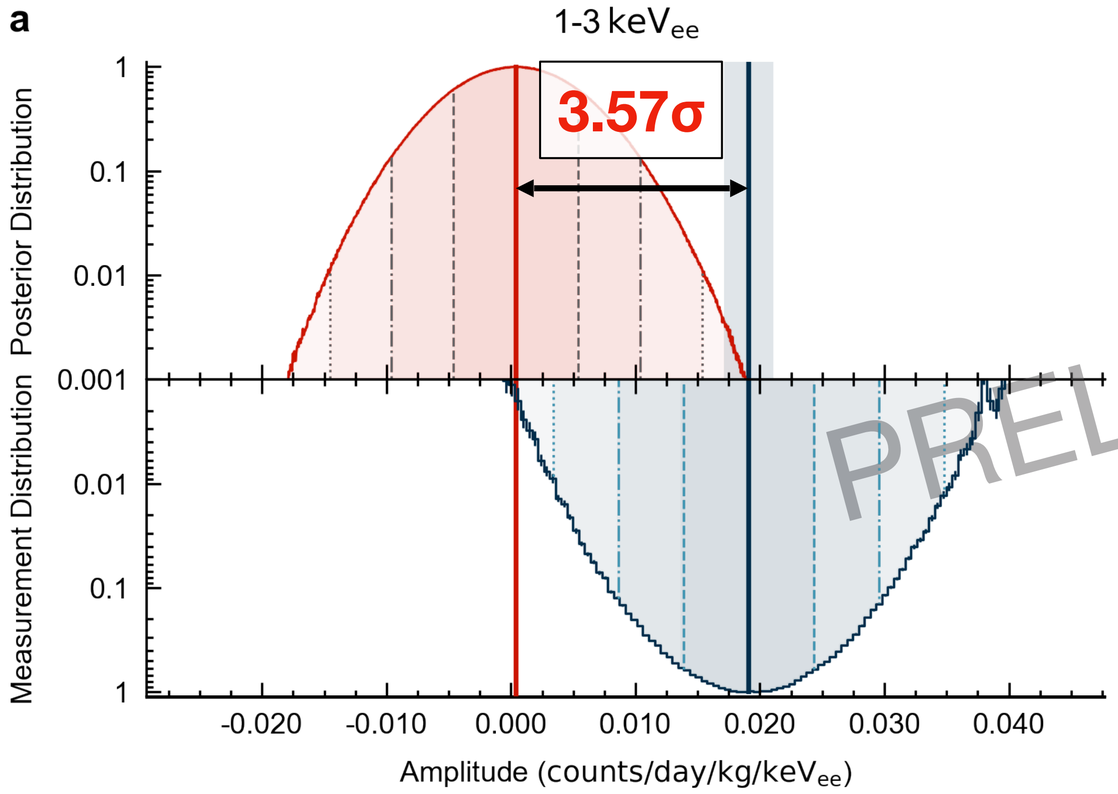
DAMA/LIBRA : 2.00 – 6 keV_{ee}

COSINE-100 : 0.85 – 3.12 keV_{ee}

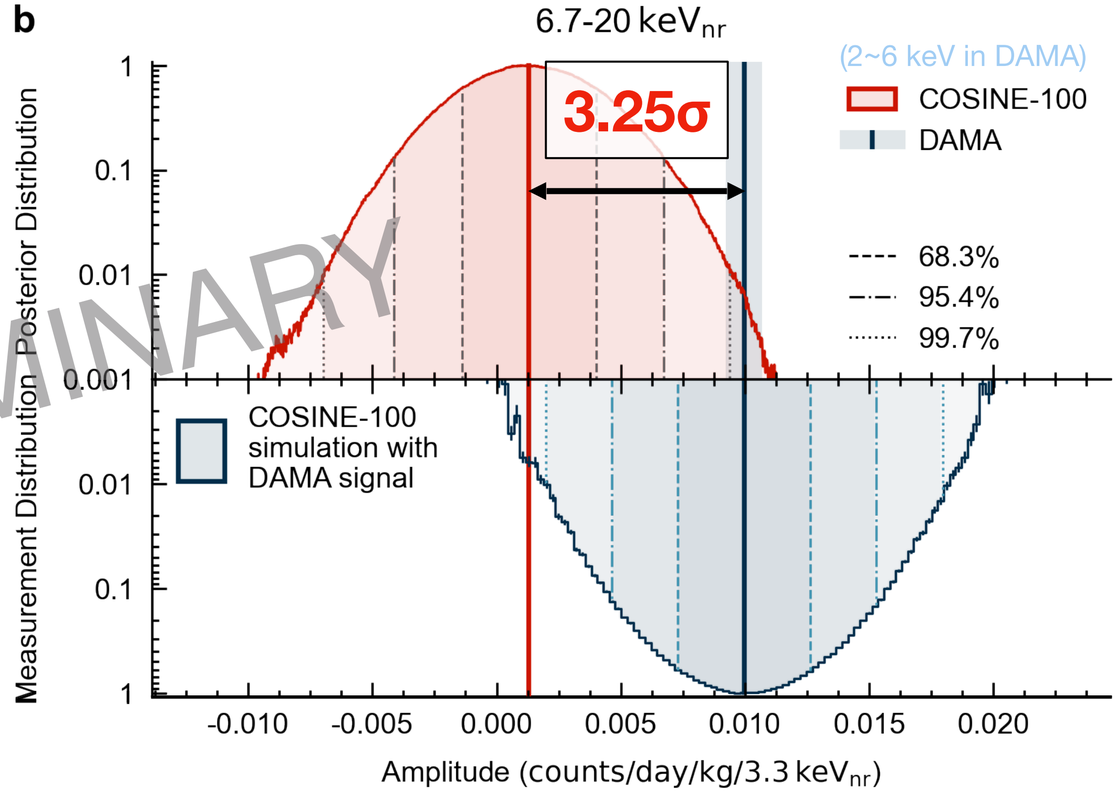
Model-Independent test

Modulation signal search : Phase fixed

1.Electron recoil (keVee, linear calibration)



2. Nuclear recoil calibration (keVnr)

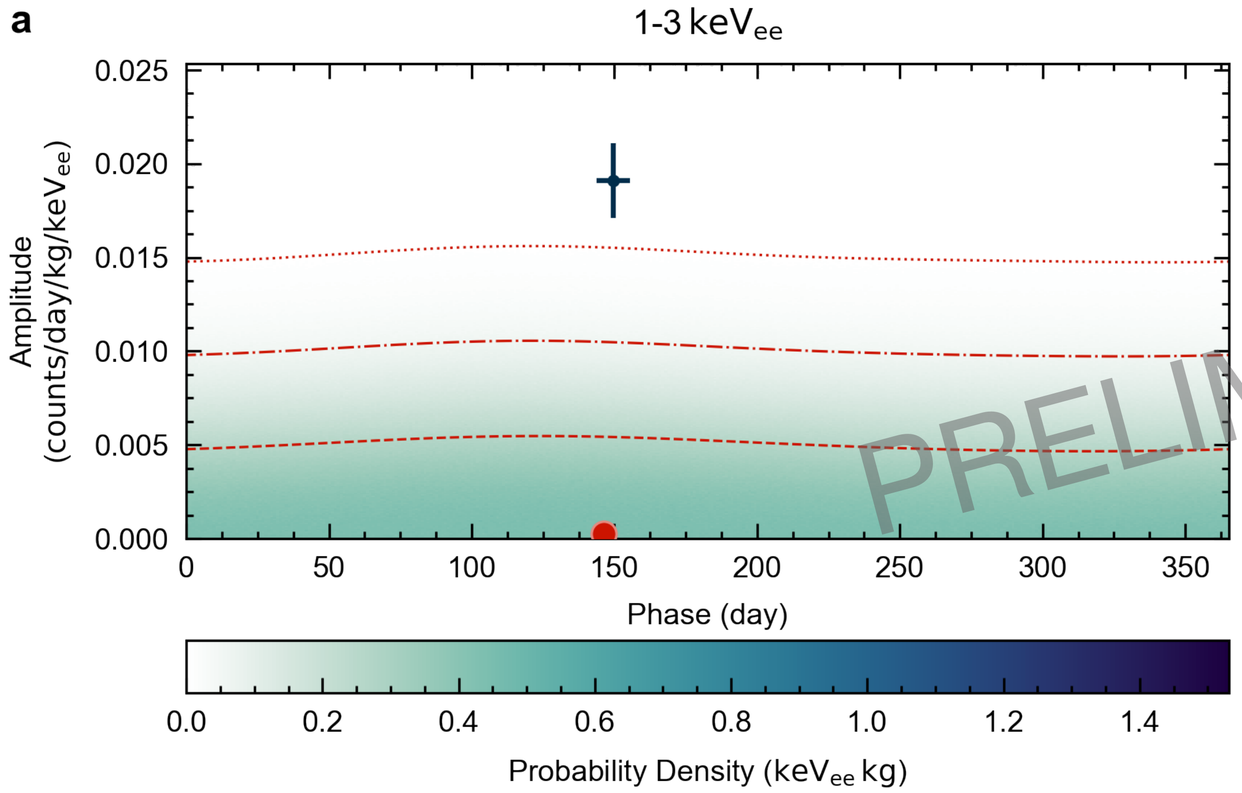


No modulation & Disfavors DAMA (> 3σ)

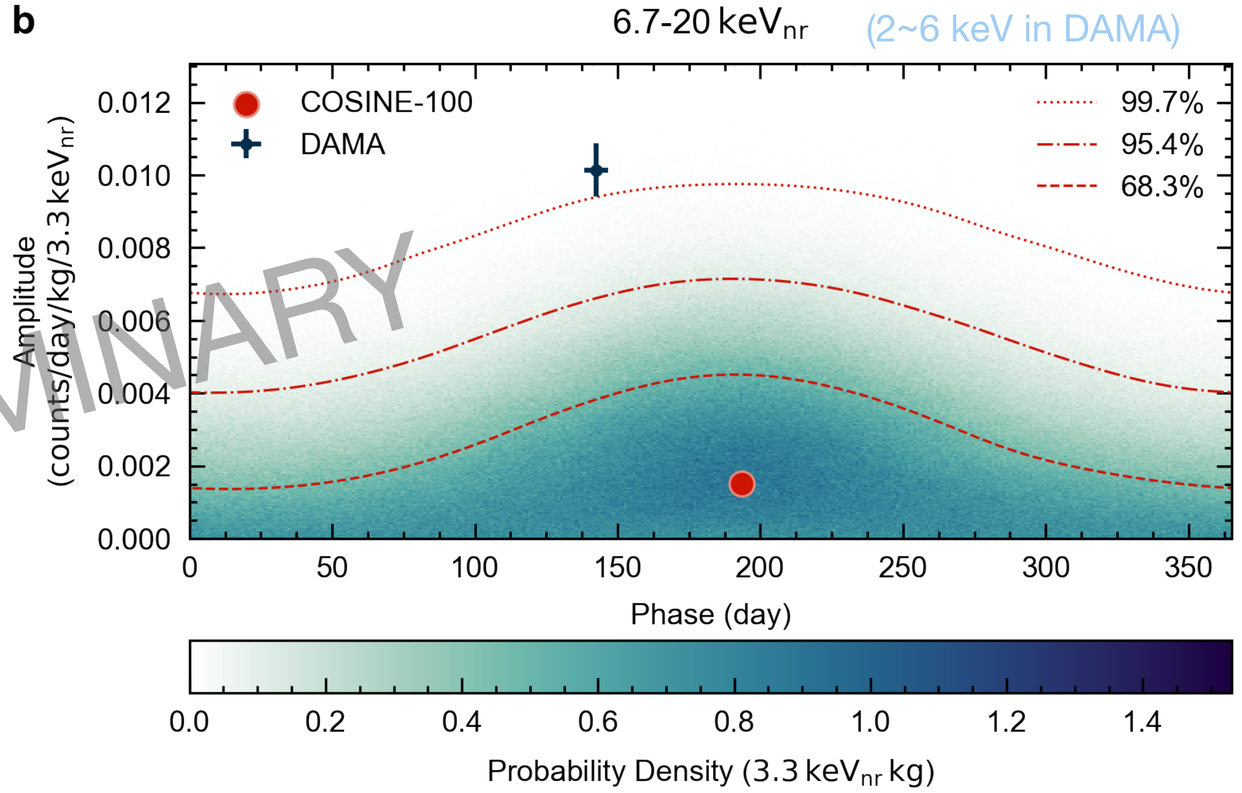
Model-Independent test

Modulation signal search : Phase floated

1.Electron recoil (keVee, linear calibration)



2. Nuclear recoil calibration (keVnr)

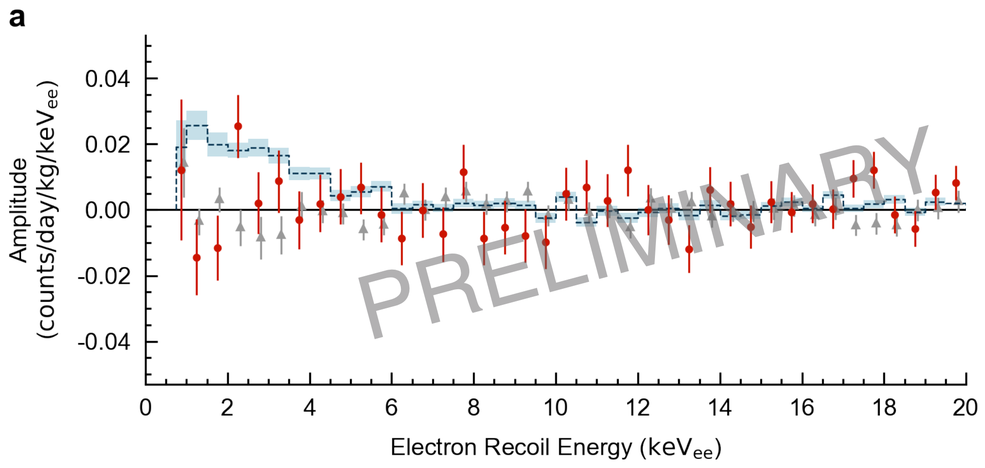


No modulation & Disfavors DAMA (> 3σ)

Model-Independent test

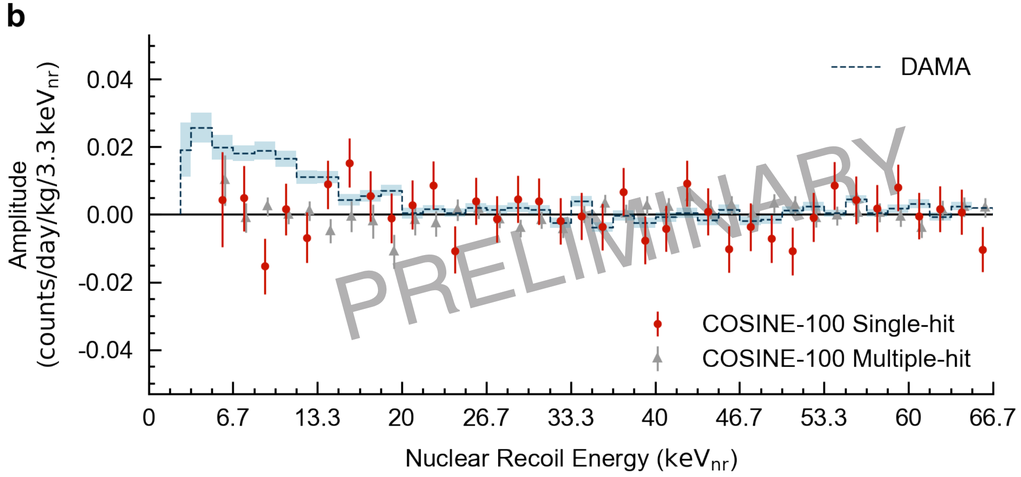
Modulation signal search : Amplitude summary

1.Electron recoil (keVee, linear calibration)



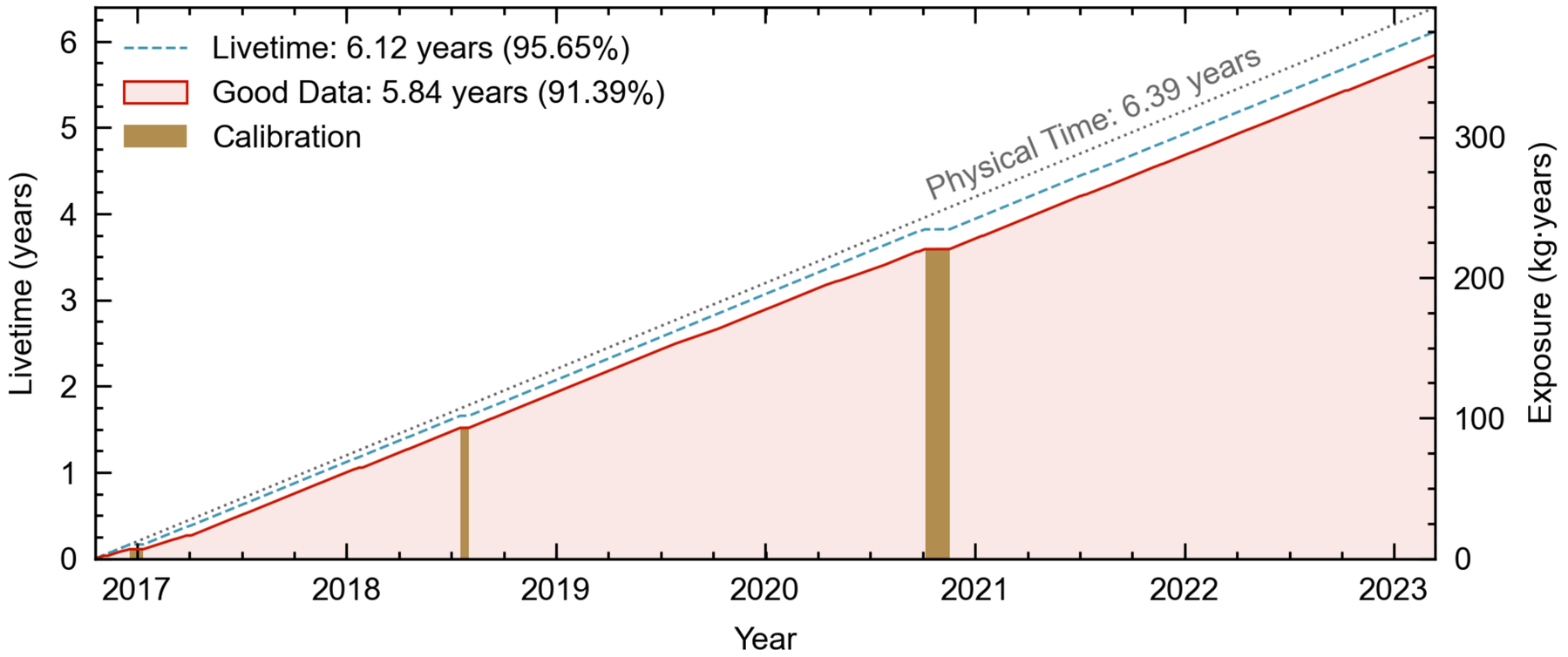
Range(KeV$_{ee}$)	Amplitude (Counts/kg/day/KeV$_{ee}$)	
	COSINE-100	**DAMA/LIBRA**
1 ~ 3	**0.001 ± 0.005**	0.019 ± 0.002
1 ~ 6	**0.002 ± 0.003**	0.010 ± 0.001
2 ~ 6	**0.005 ± 0.003**	0.010 ± 0.001

2. Nuclear recoil calibration (keVnr)



Range(KeV$_{nr}$)	Amplitude (Counts/kg/day/KeV$_{nr}$)	
	COSINE-100	**DAMA/LIBRA**
6.7 ~ 20	**0.001 ± 0.005**	0.019 ± 0.002

No modulation & Disfavors DAMA (> 3σ)



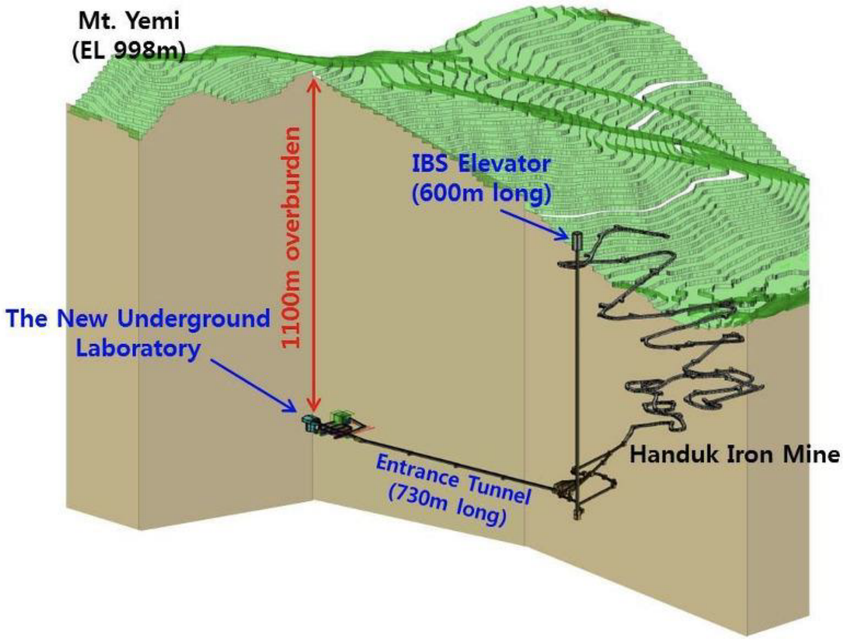
Testing DAMA & COSINE-100 operation is finished.. What's next?

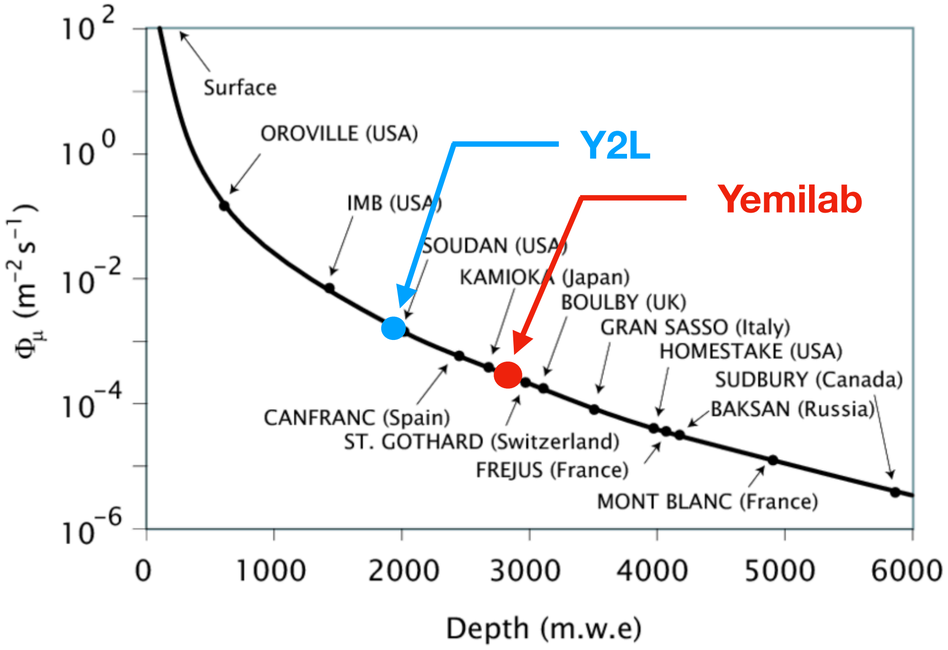
Next phase : COSINE-100Upgrade

New experimental site : Yemilab

Front. Phys. 12:1323991. (2024)

Nature News



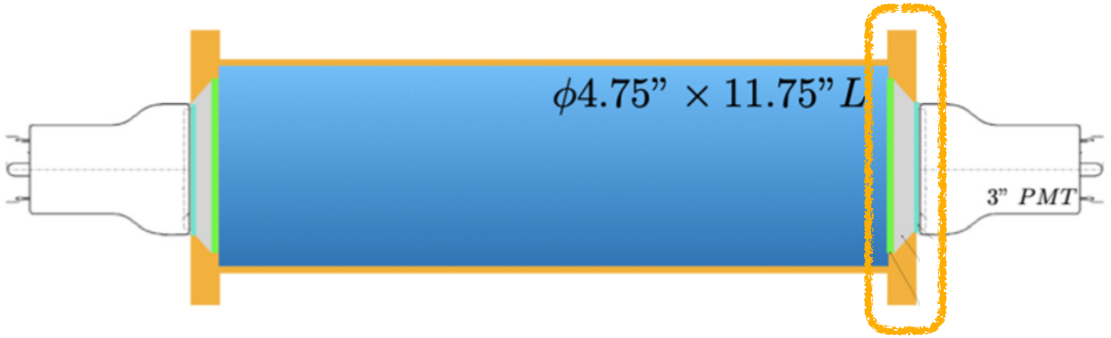


- Overburden : 700m (Y2L) → 1100m (Yemilab)
- **5 times smaller muon flux**

Next phase : COSINE-100Upgrade

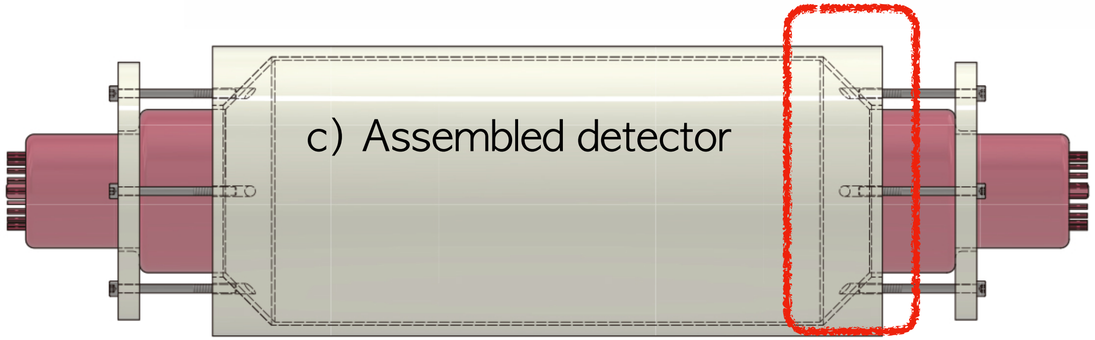
Higher light yield : New detector design

Current encapsulation design

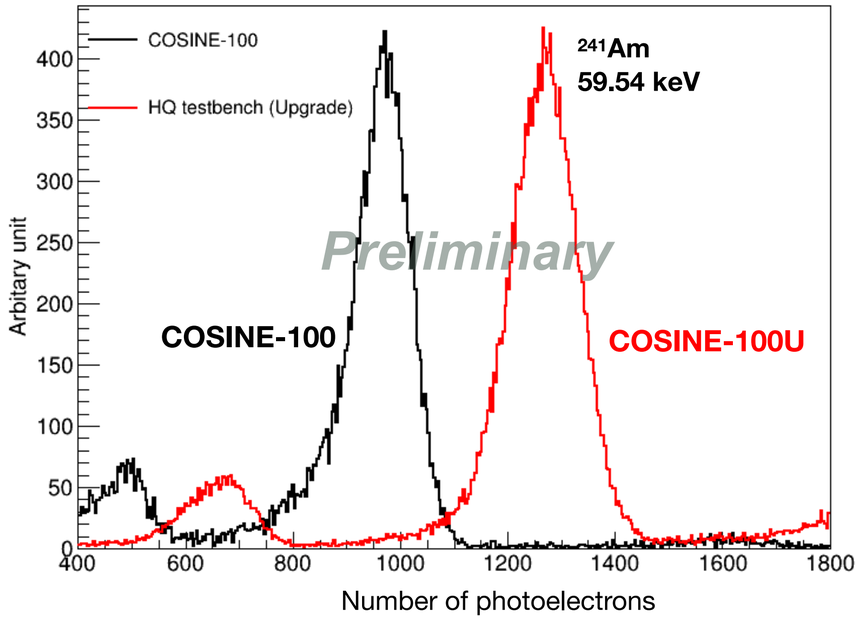


Quartz light guide
: loss in scintillation light

New encapsulation design



No quart light guide
: More efficient light collection



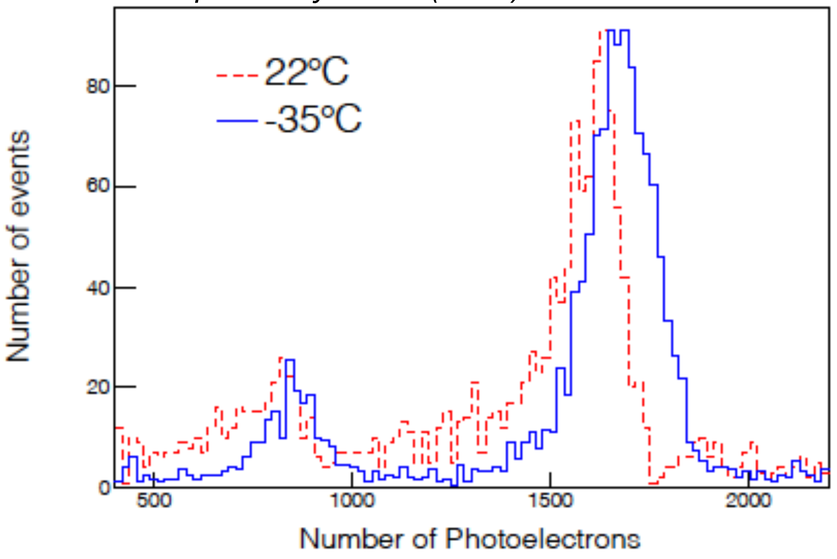
~40 % light yield improve!

Next phase : COSINE-100Upgrade

Higher light yield : Low temperature operation (-35 ºC)

NPE Measurement in -35 ºC

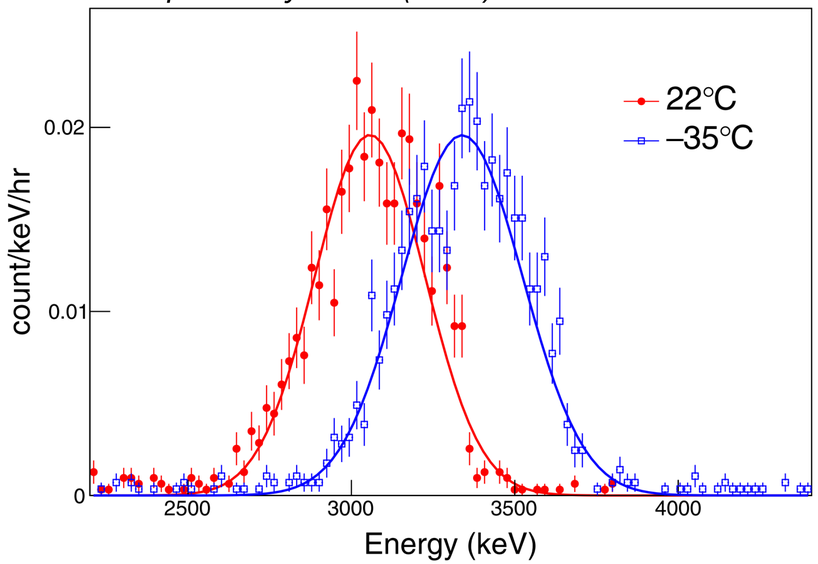
Astropart. Phys. ***141*** *(2022) 102709*



~5% increased LY for γ

Alpha spectrum using ^{210}Po in -35 ºC

Astropart. Phys. ***141*** *(2022) 102709*



~9% increased quenching (in α)

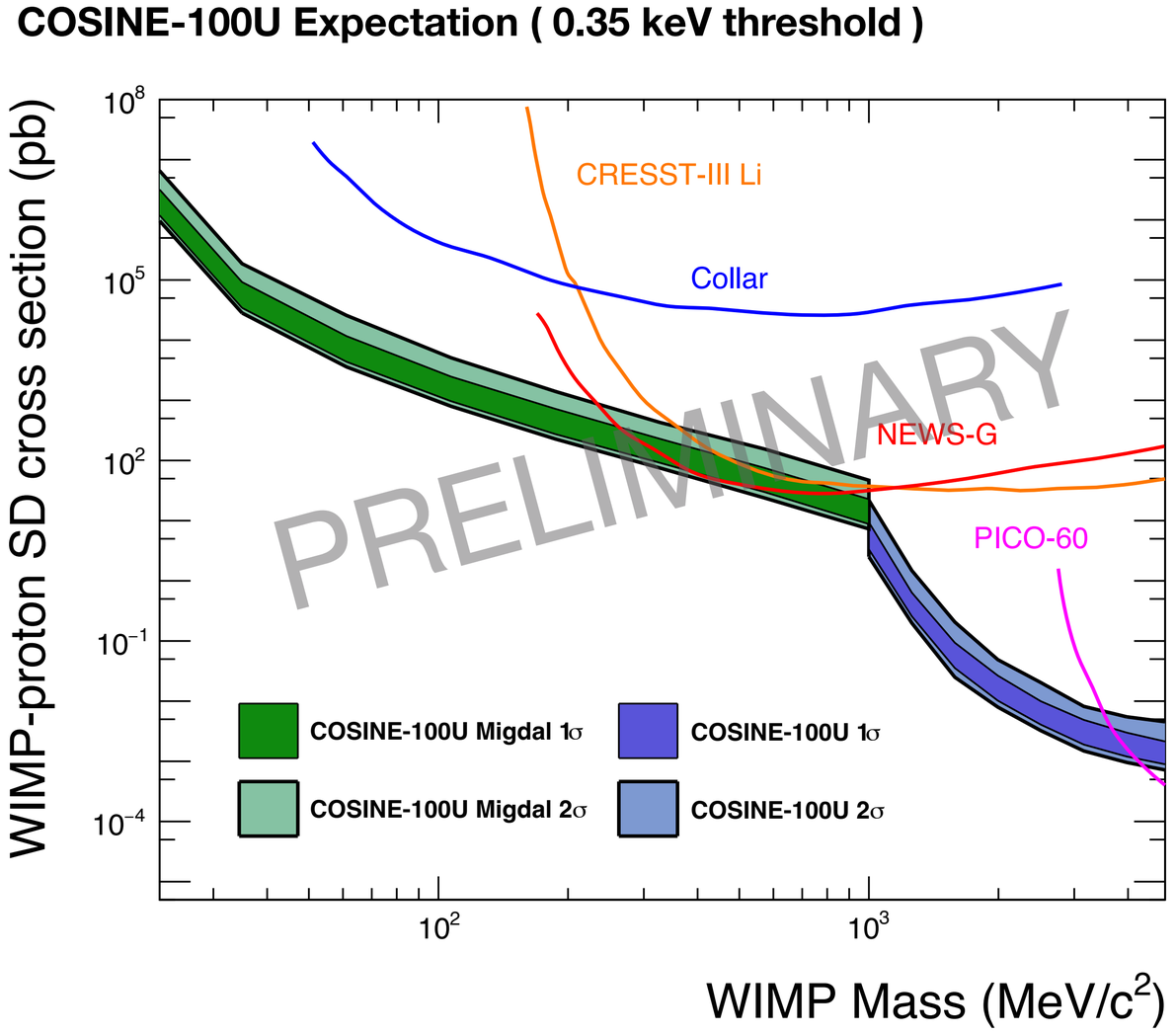
Next phase : COSINE-100Upgrade

Expectations

	2024-(1-3)	2024-(4-6)	2024-(07-08)	2024-09	2024-10	2024-11
Crystals		Assembling & Installation		TEST		
Liquid Scintillator	PMT Install LS Production		Pouring LS			
Lead Shield	Bottom	Side		Top	Operation	
Electronics		Server, HVS, Monitoring				
Muon detector		holder		PS install		

- Plan to operate in Oct.2024

- **Lowest limit sensitivity in low-mass SD** channel is expected

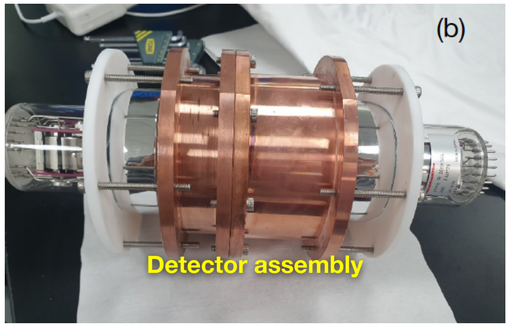


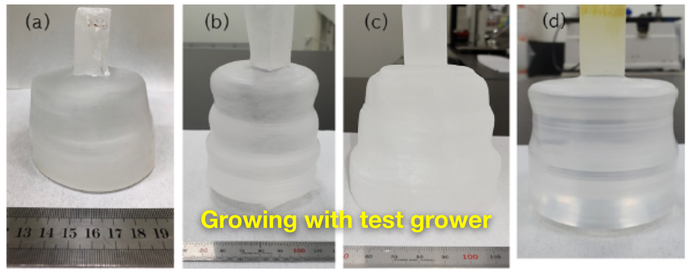
Ultra-pure crystals for COSINE-200

R&D in progress !

New Crystal development

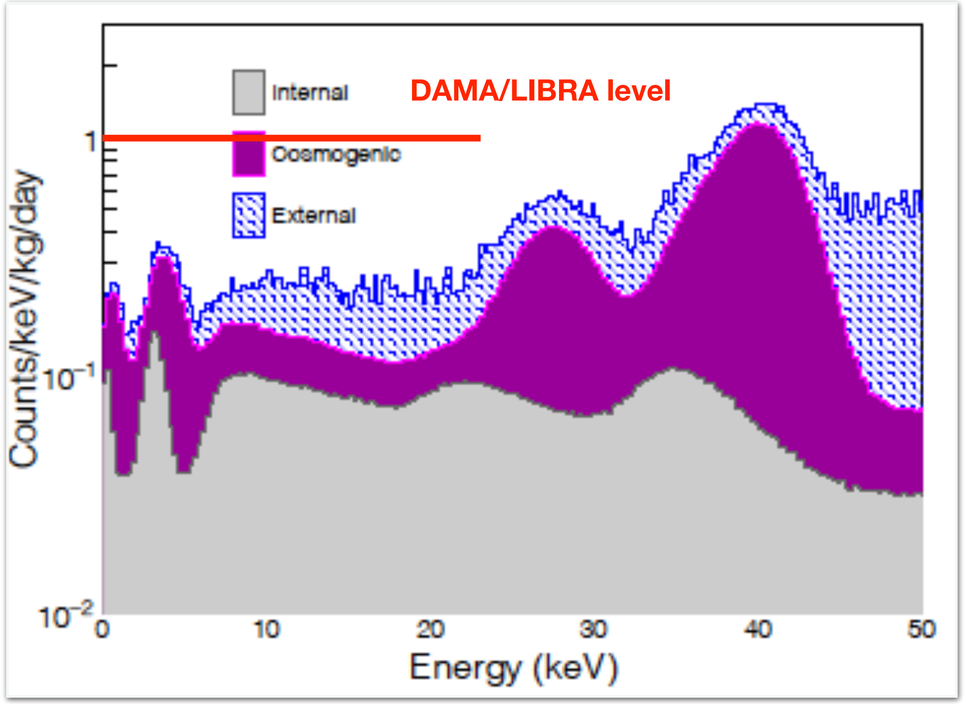
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)
K.A. Shin et al., JINST 15, C07031 (2020)
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)





Simulation of background in new crystal

*EPJC **80** (2020) 814*



- R&D for big & pure crystals are ongoing.
- Ultra-pure background is expected.

Summary

- **COSINE-100 ruled out DAMA/LIBRA**
  - -Above 3σ in model-independent analysis
  - -Perfect exclusion in model-depnednet analysis

- Spin-dependent analysis shows **competitive result in low-mass WIMP search.**
  (Best limit in a few GeV)

- **COSINE-100U will start soon**, and expected to have world competitive sensitivities for low-mass DM searches.

COSINE-100 collaboration

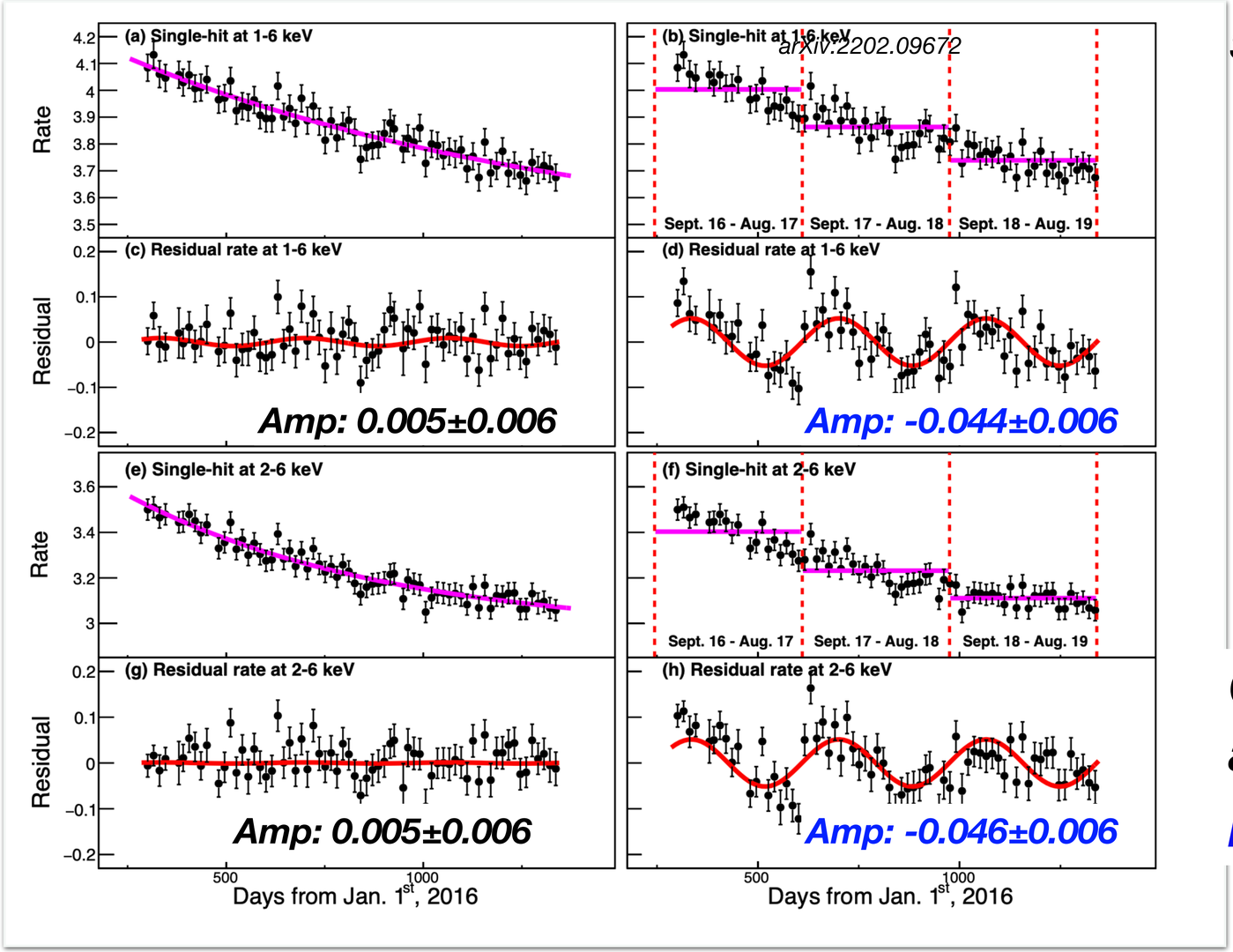
15 institutes ~60 members

DM-ICE + KIMS Korea Invisible Mass Search Experiment = COSINE

Thank you for your attention !

Possible DAMA explanation : Induced signal

Single exponential **Yearly Averaged (DAMA model)**

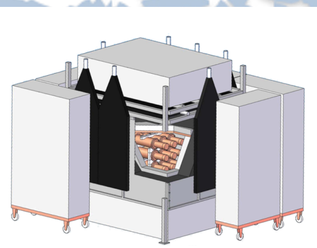


arXiv:2202.09672

Scientific Reports ***13***, *4676 (2023)*

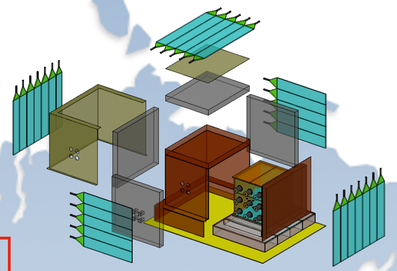
COSINE-100 data applying DAMA method gives clear modulation (~7σ, opposite phase)

NaI(Tl) experiments in the world



ANAIS
(Canfranc)

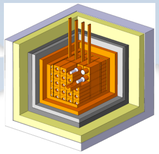
COSINUS
(LNGS)



COSINE
(YangYang)

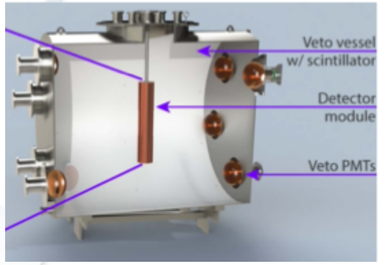
PICO-LON
(Kamioka)

DAMA
(LNGS)

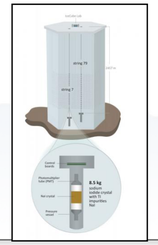


SABRE
(LNGS)

SABRE
(Stawell)



DM Ice
(South Pole)

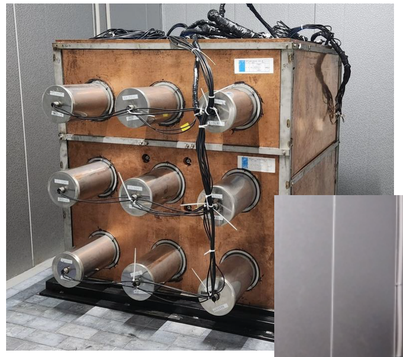


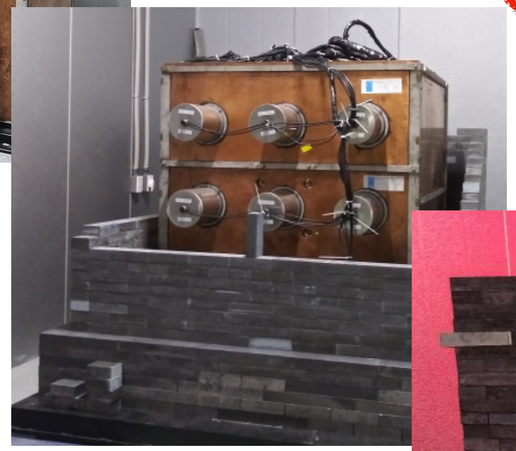
Latests results with

DAMA/LIBRA
ANAIS-112
COSINE-100

COSINE-100U

New experimental site : Yemilab

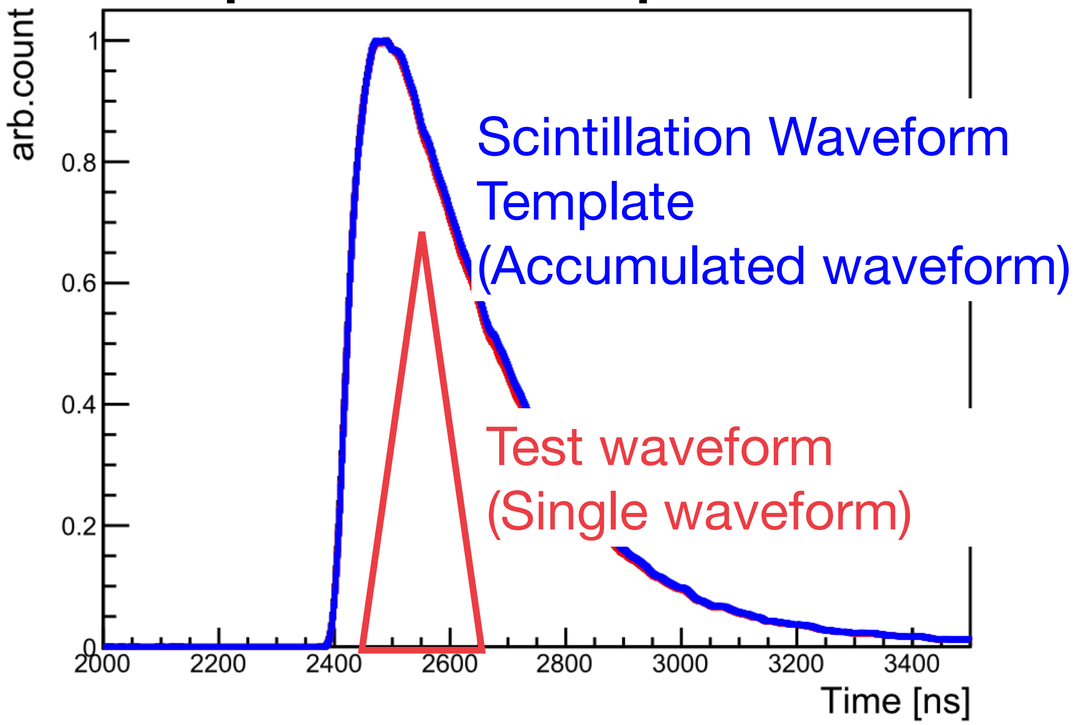




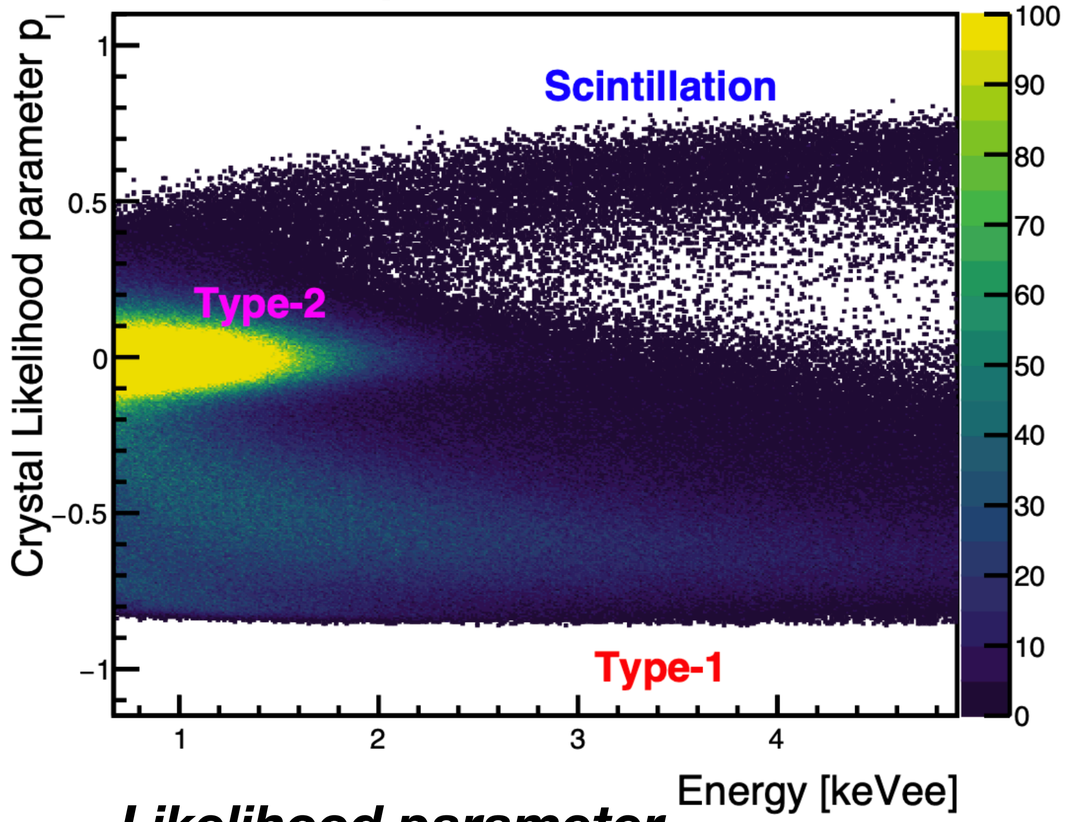
Shielding

Examples of PSD parameters

Concept of Likelihood parameter



Likelihood parameter 2D distribution



Example) Likelihood on signal waveform template

$$\ln L_s = \sum_{bin} (W_S - W_t) + W_t \times \log(W_t / W_S)$$

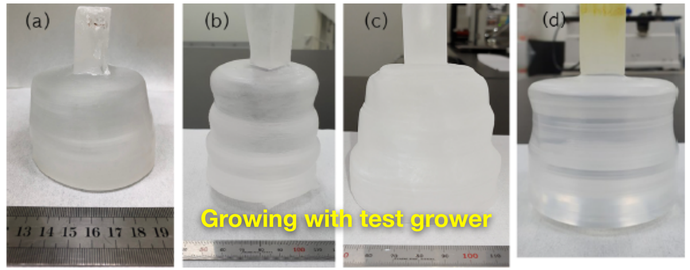
Likelihood parameter

$$p_l = \frac{\ln L_{n1} - \ln L_s}{\ln L_{n1} + \ln L_s}$$

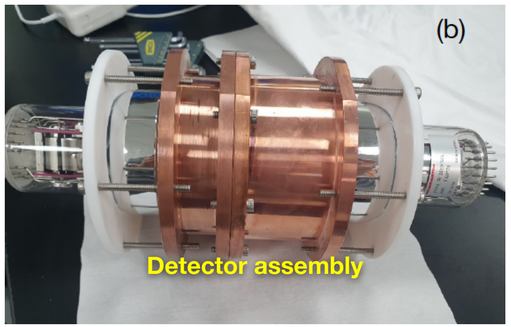
Ultra-pure crystals for COSINE-200

R&D in progress !

New Crystal development



K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)
K.A. Shin et al., JINST 15, C07031 (2020)
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)



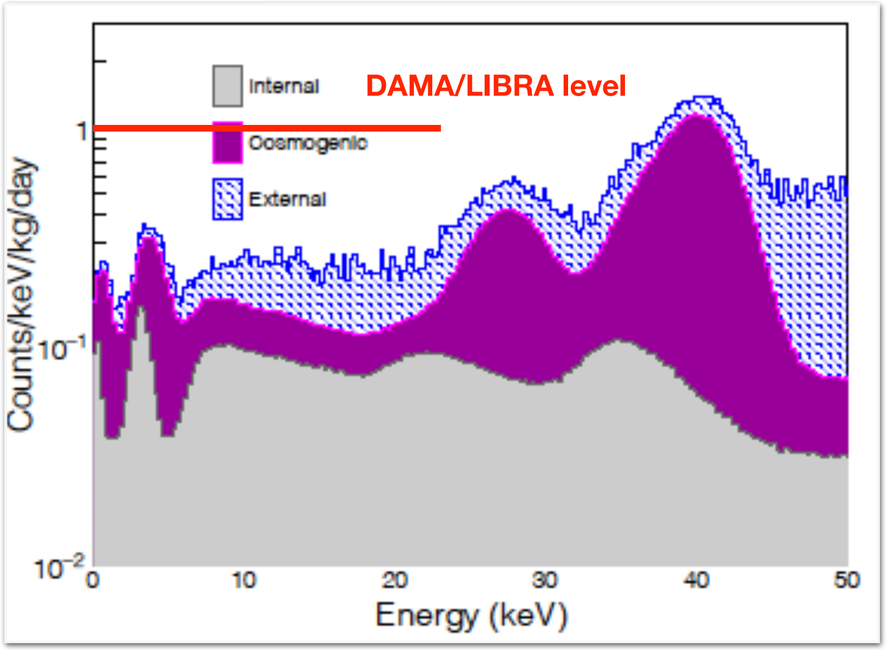
- Produced ~ 400 kg low-background NaI powder.
- 0.7kg crystal with 0.2 counts/keV/kg/day achieved
- Further R&D going on to grow large-crystals.

^{40}K & ^{210}Pb significantly reduced

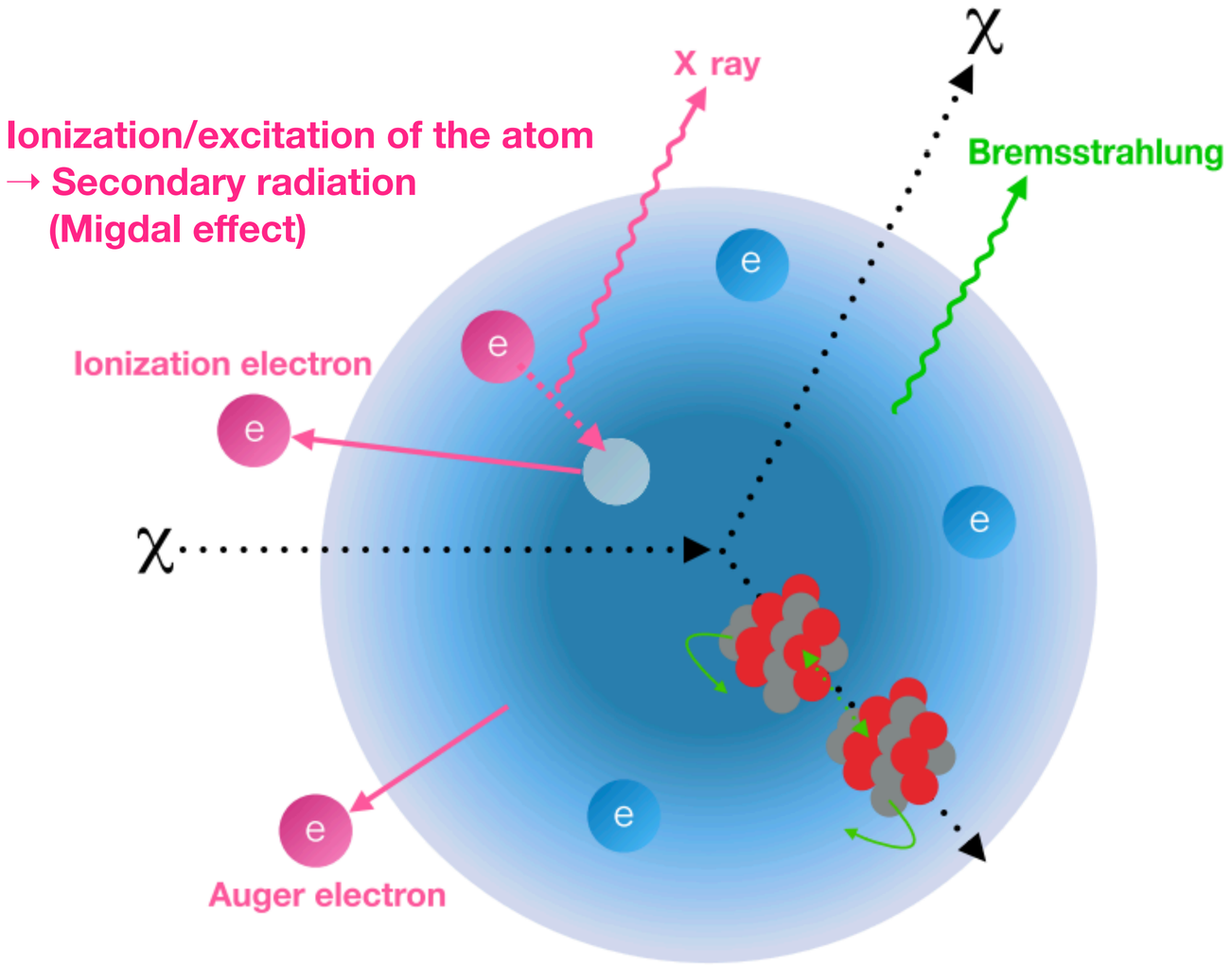
	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

Simulation of background in new crystal

*EPJC **80** (2020) 814*



Migdal Effect



- Nuclear recoil → Boost of electrons → Secondary radiation
- Large visible energy of electron recoil compared to nuclear recoil.

Reference : PRL 123, 241803 (2019) (Xenon 1T)