Challenging DAMA/LIBRA and searching for WIMPs in COSINE-100

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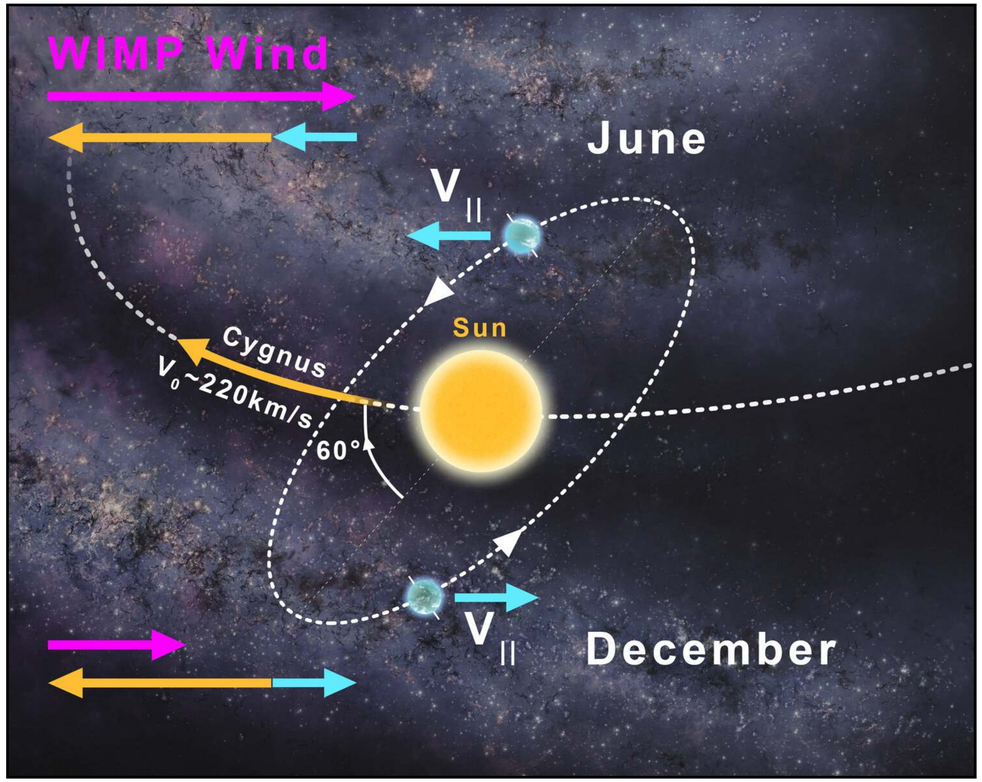
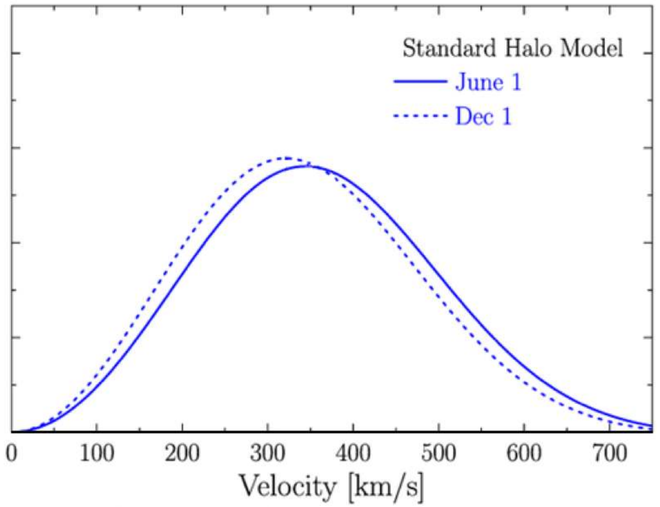
Institute for Basic Science (Center for Underground Physics)

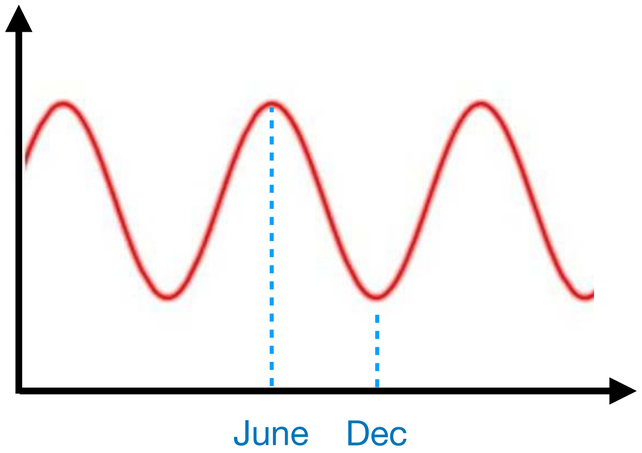
On behalf of COSINE Collaboration

59th Moriond Conference on
EW Interaction & Unified Theories

WIMP Annual modulation





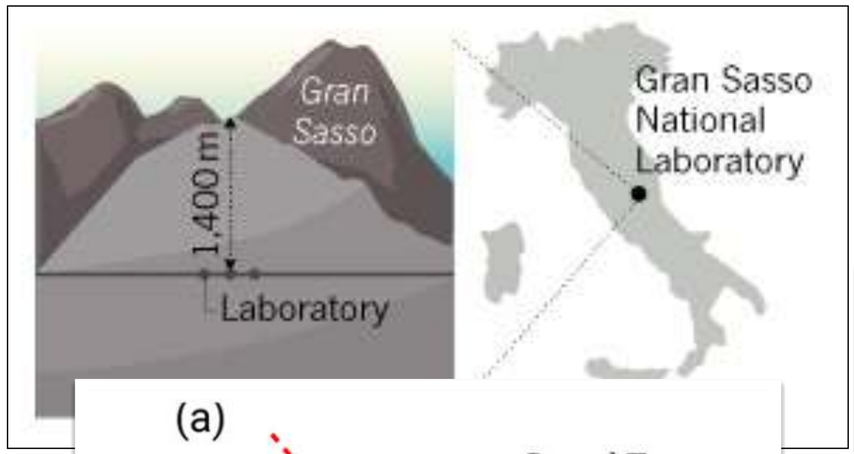


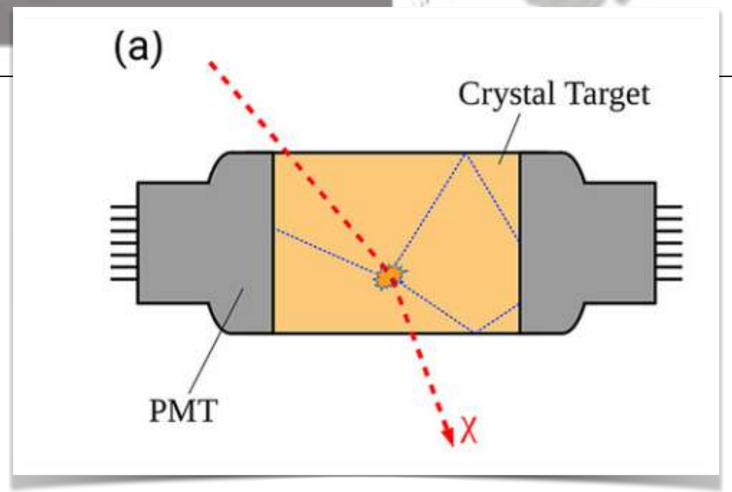
Rate of WIMP elastic scattering

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

- In Standard Halo Model (SHM), WIMP wind velocity modulates in the Earth frame.
- Modulating velocity → **Modulating WIMP scattering rate**

Dark matter signal? : DAMA/LIBRA

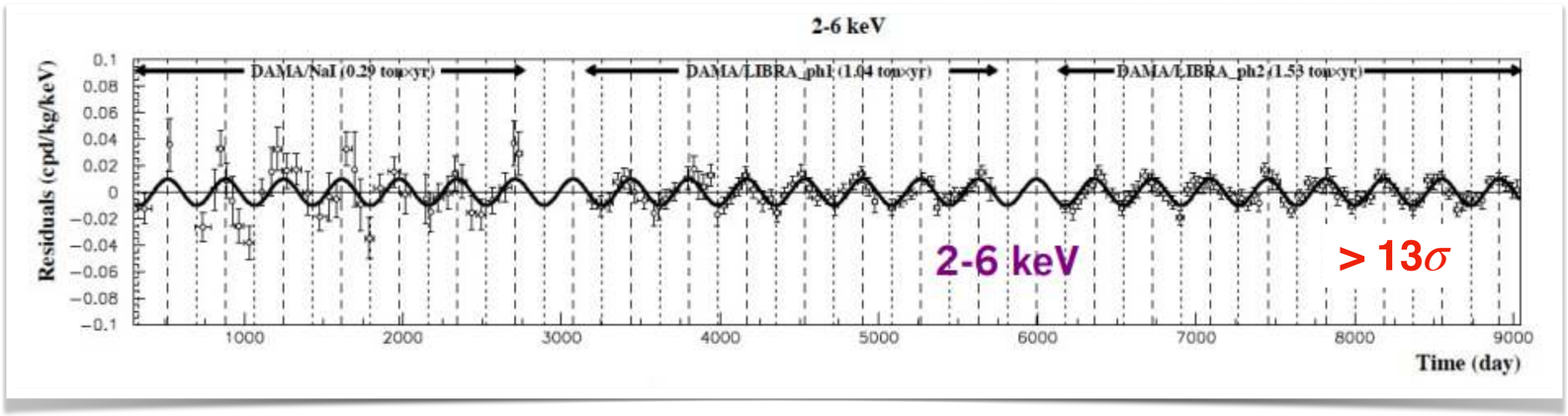




DAMA/LIBRA Modulation signal

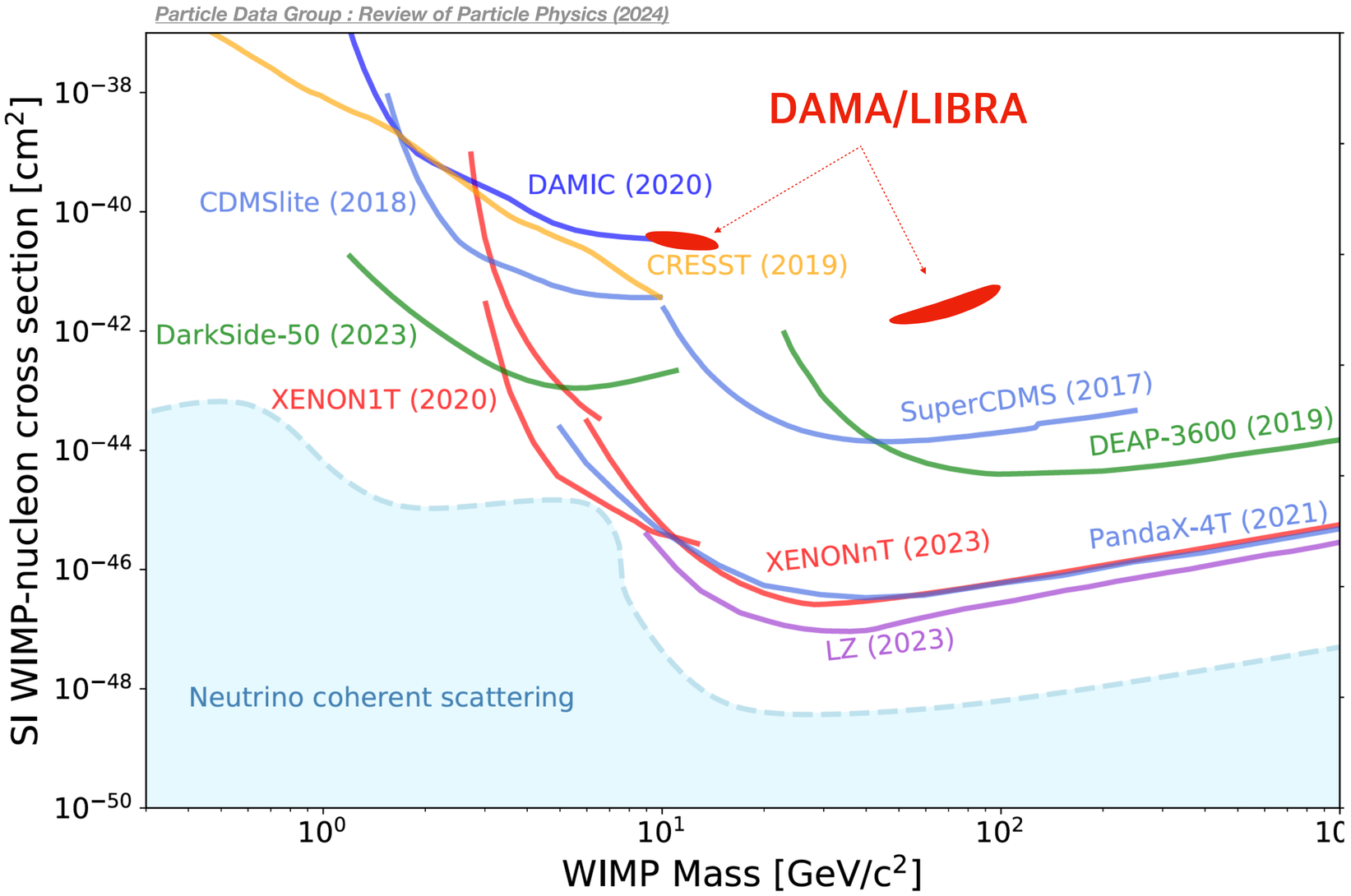
P.Belli, EPS-HEP Conference (2021)

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



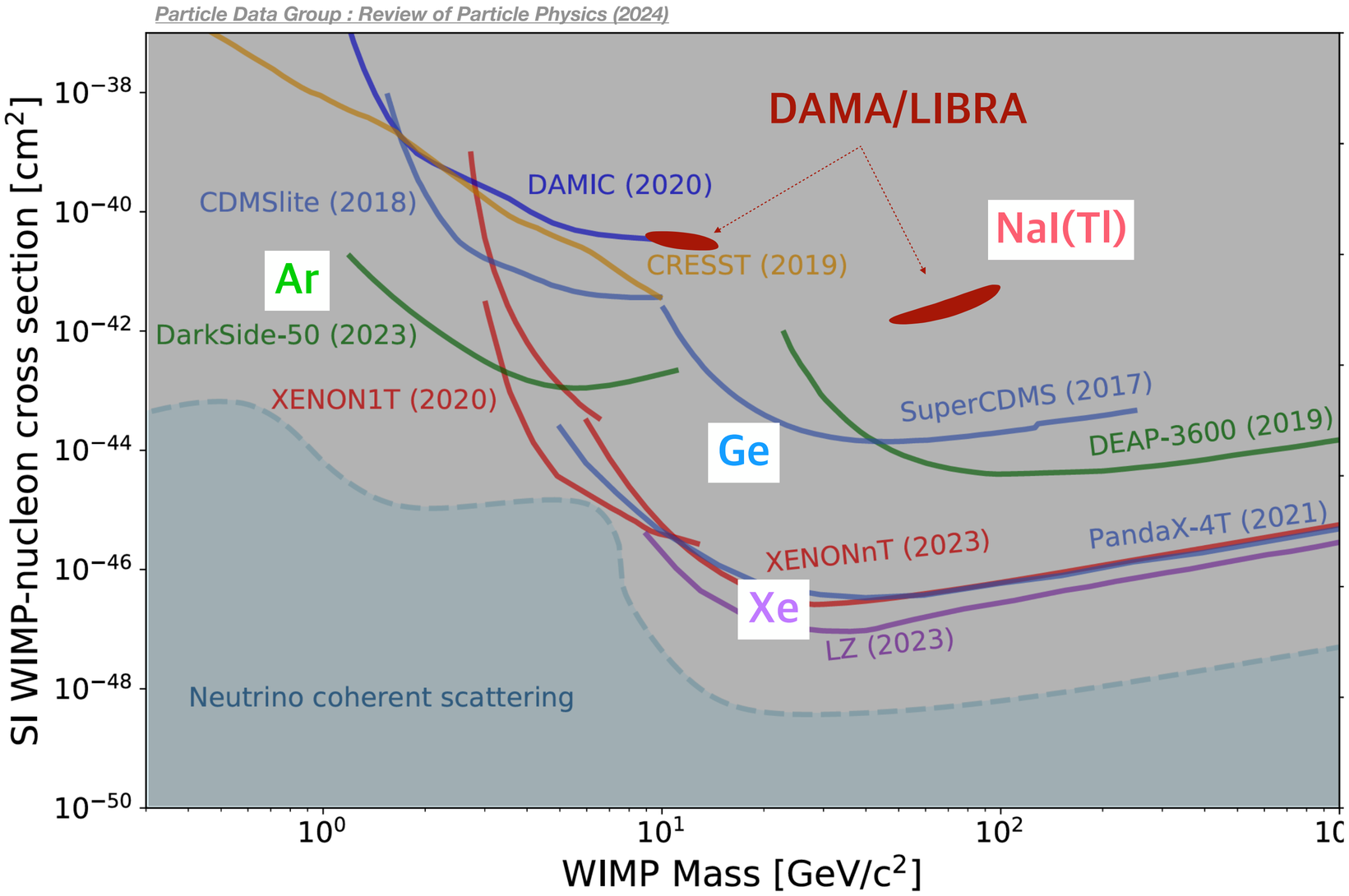
- **DAMA/LIBRA** : NaI(Tl) based direct dark matter search in Gran Sasso
- **Claimed to find annual modulation,** compatible with the nature of DM candidate

Contradictions from other experiments



Already excluded by many experiments

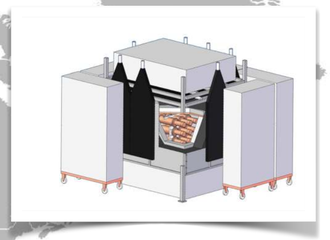
Contradictions from other experiments



Already excluded by many experiments

Maybe,, NaI(Tl) detector is something special for DM interaction?

NaI(Tl) DM searches in the world

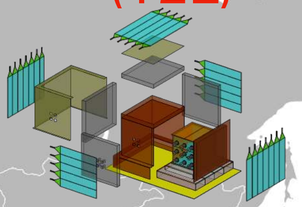


ANAIS
(Canfranc)

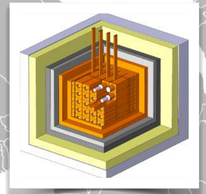
DAMA
(LNGS)

SABRE
(LNGS)

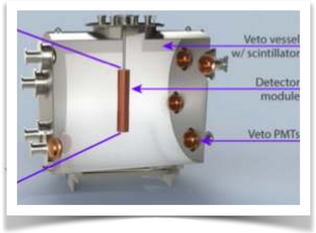
COSINE
(Y2L)



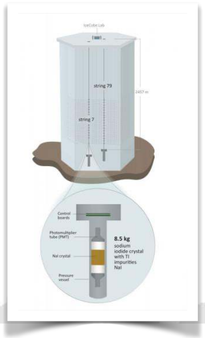
PICO-LON
(Kamioka)



COSINUS
(LNGS)



SABRE
(Stawell)



DM Ice
(South Pole)

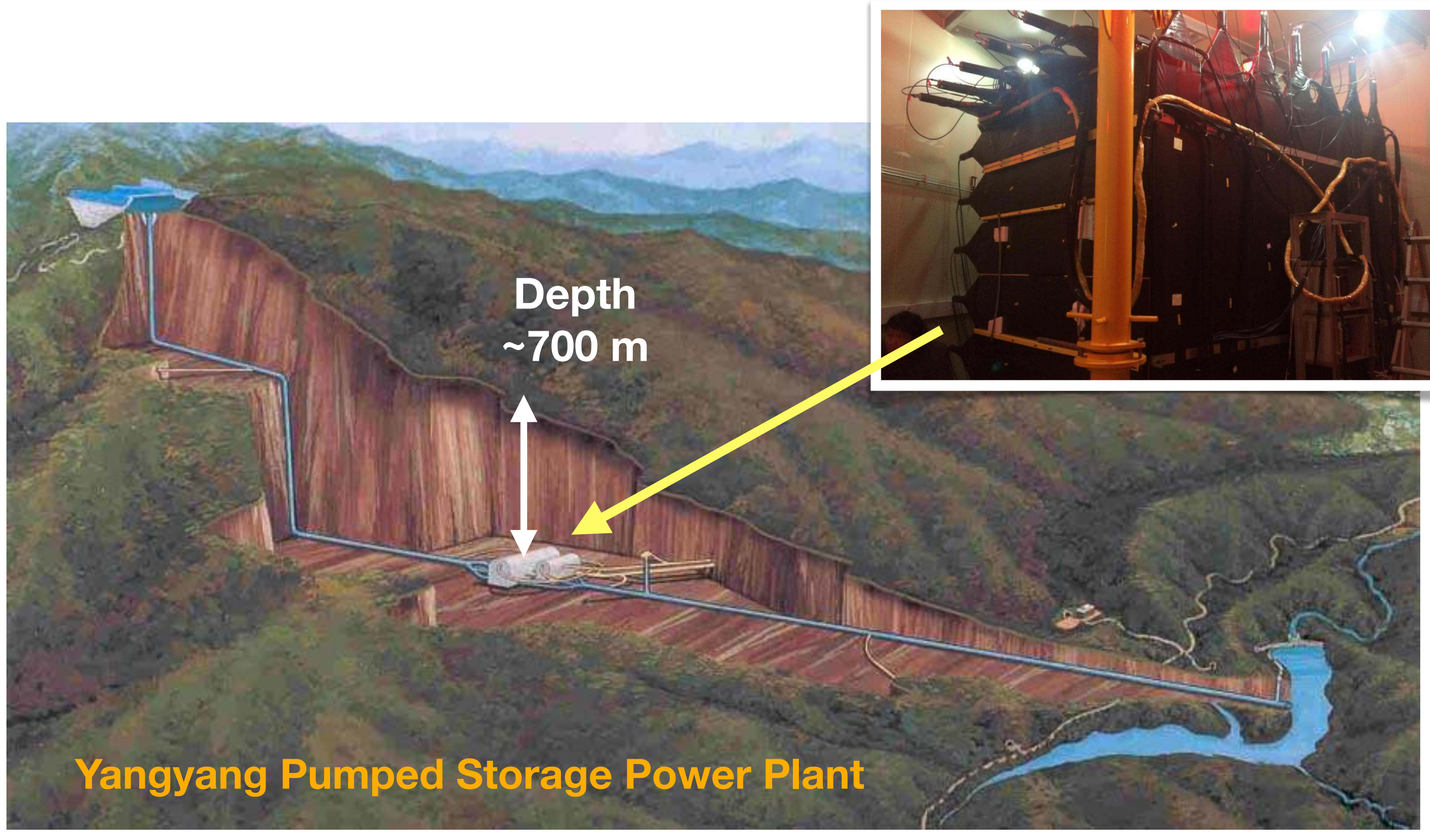
Latests results with

DAMA/LIBRA

ANAIS-112

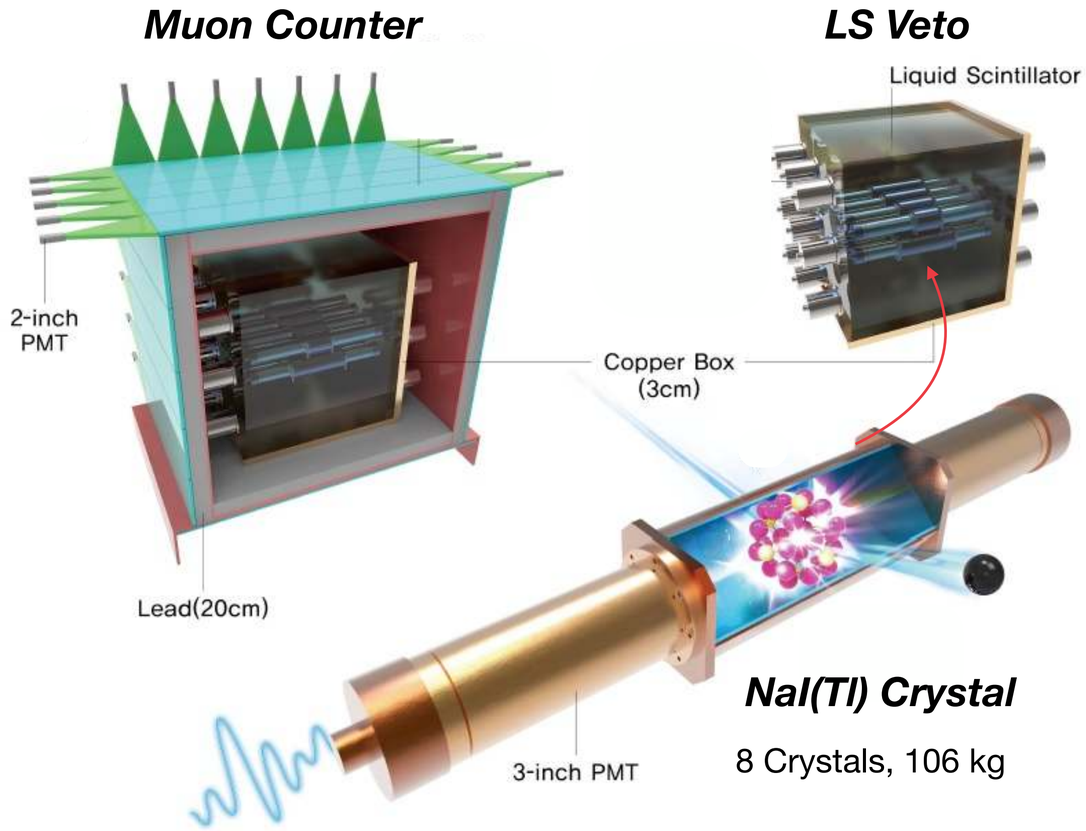
COSINE-100

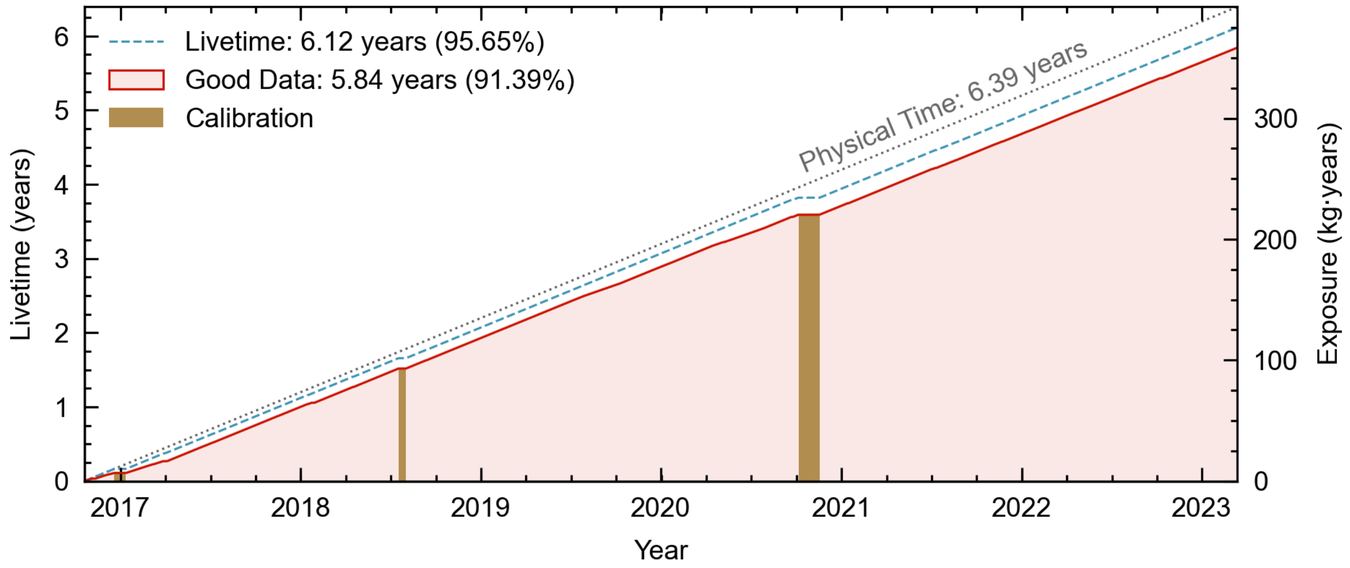
COSINE-100 experiment



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

COSINE-100 experiment

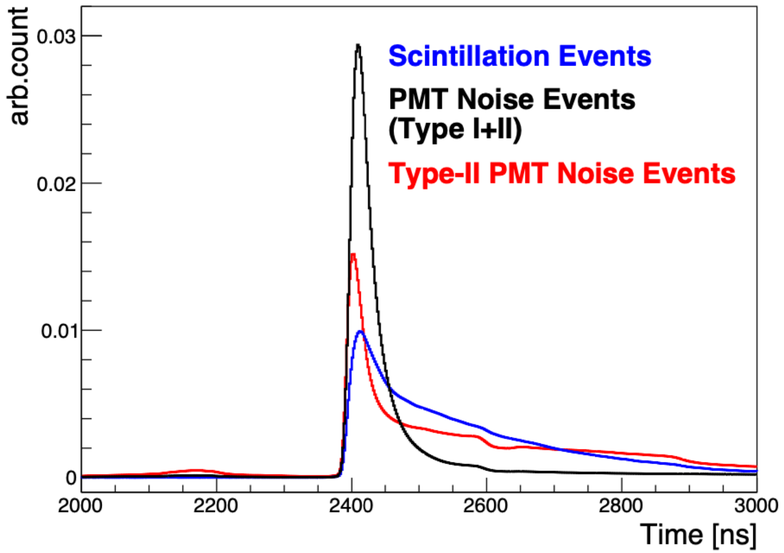




- 8 NaI(Tl) crystals (106kg), shielded with LS-veto & Lead shield & PS-veto
- **Finished with ~6 year** data taking (October 2016 ~ March 2023)

Pre-analysis 1

MLP-based PMT-induced noise selection

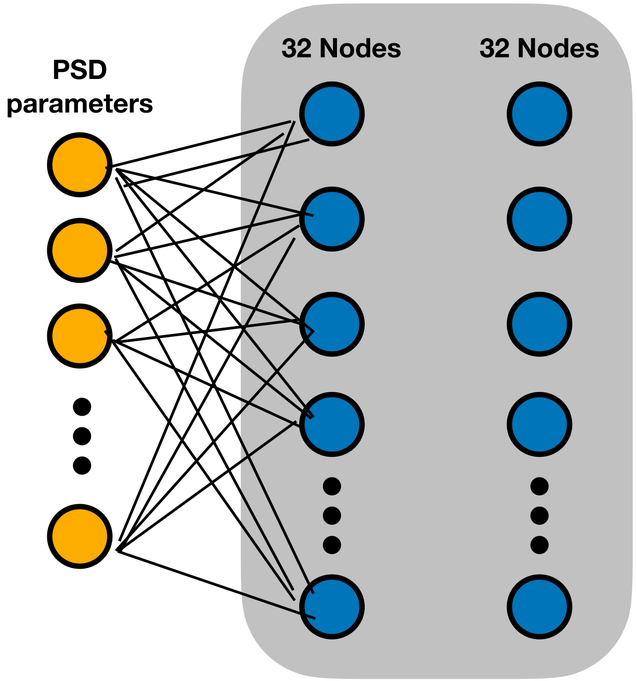


Signal sample

Scintillation sample

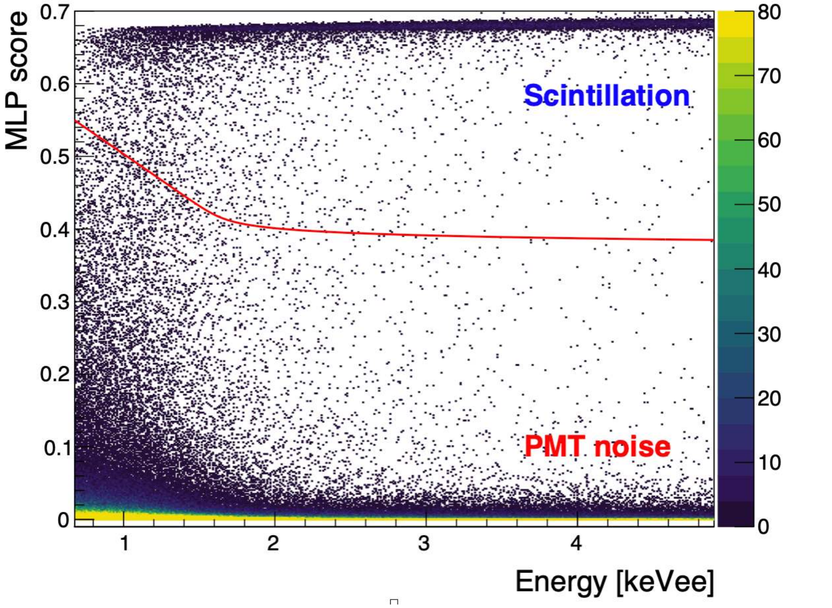
Noise sample

15 % of 3-year data



Noise selection MLP for 0.7 keV threshold

*JINST **19** P12013*

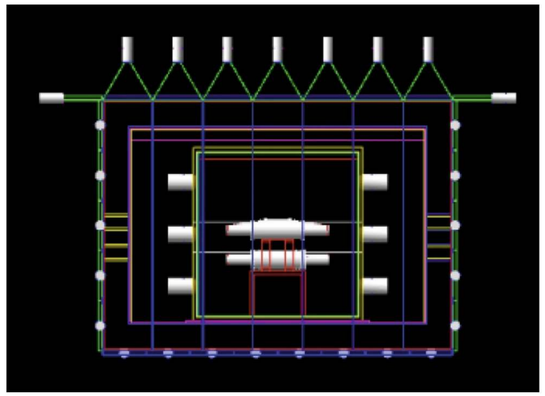


- PMT induced noised shows different pulse-shape characteristics
- PSD parameter based training: **0.7 keV (8 Photoelectrons) threshold**

Pre-analysis 2

Background modeling

Geometry of COSINE-100 In Geant4



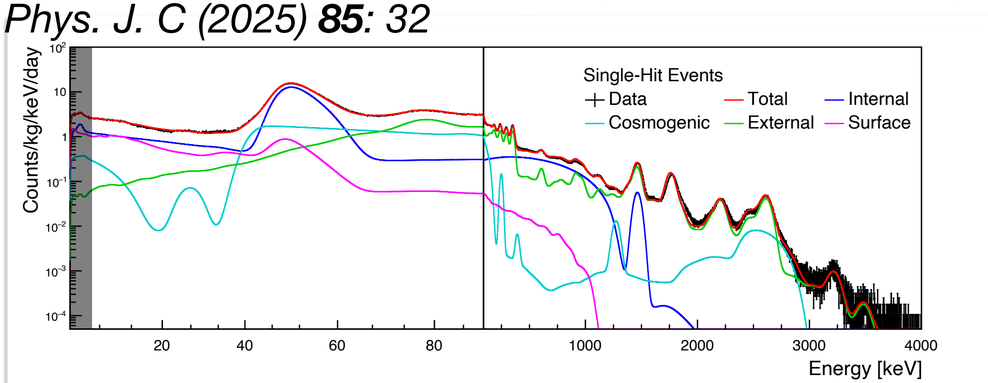
Example of background isotopes

Crystal internal	^{238}U, ^{232}Th, ^{40}K, ^{60}Co
Crystal cosmogenic	^{22}Na, ^{121m}Te, ^{129}I, ^{109}Cd, ^{3}H, ..
PMTs, Shields, ..	^{238}U, ^{232}Th, ^{40}K, ^{208}Tl, ^{235}U

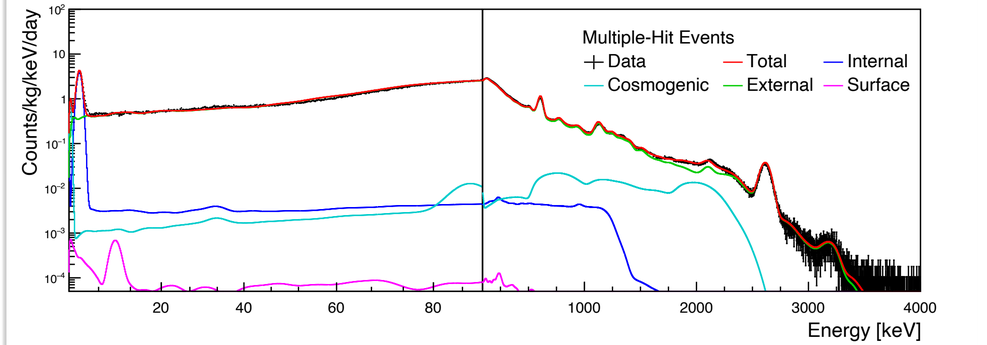
COSINE-100 3-year data background modeling

Eur. Phys. J. C (2025) ***85****: 32*

Single-hit



Multiple-hit

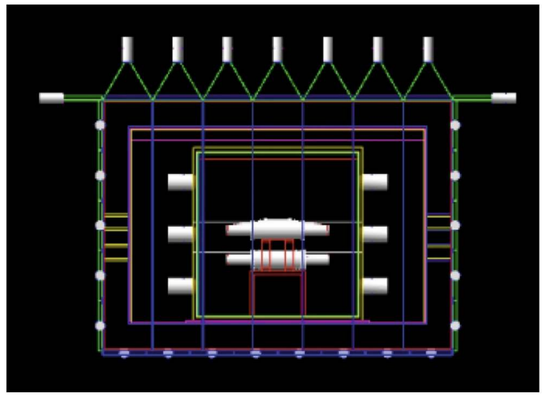


- Understand which background are existing in COSINE-100 data
- Likelihood fit of data using MC**, extrapolating WIMP ROI (Single-hit, < 6 keV) .**

Pre-analysis 2

Background modeling

Geometry of COSINE-100 In Geant4



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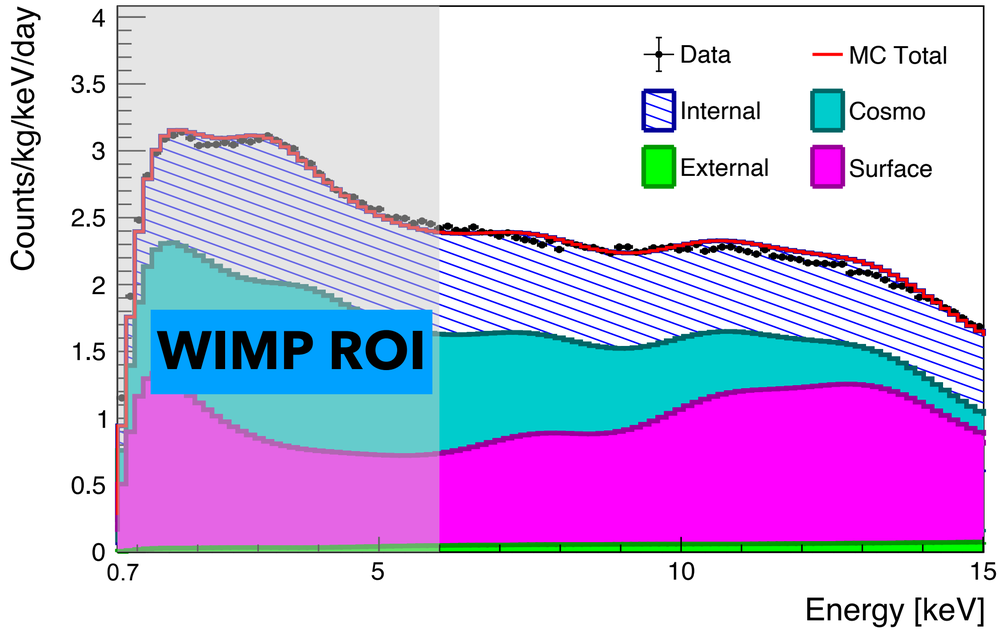
Region of interest for WIMP search



Overall data is well described by MC

- Understand which background are existing in COSINE-100 data
- Likelihood fit of data using MC**, extrapolating WIMP ROI (Single-hit, < 6 keV) .**

Model-Independent analysis

6 year data modulation fit

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

Rate of ith Crystal

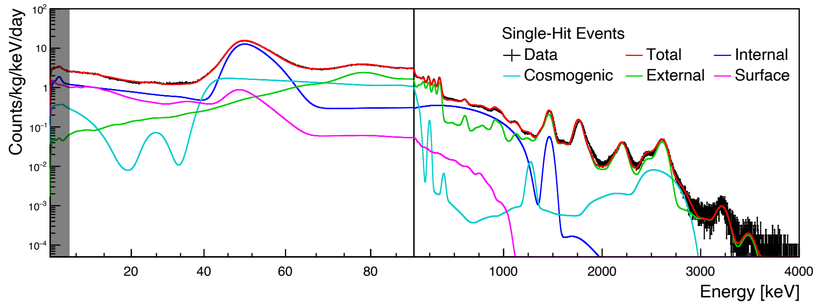
Crystal specific background components

- Constant : Long-lived
- Exponential : Short-lived

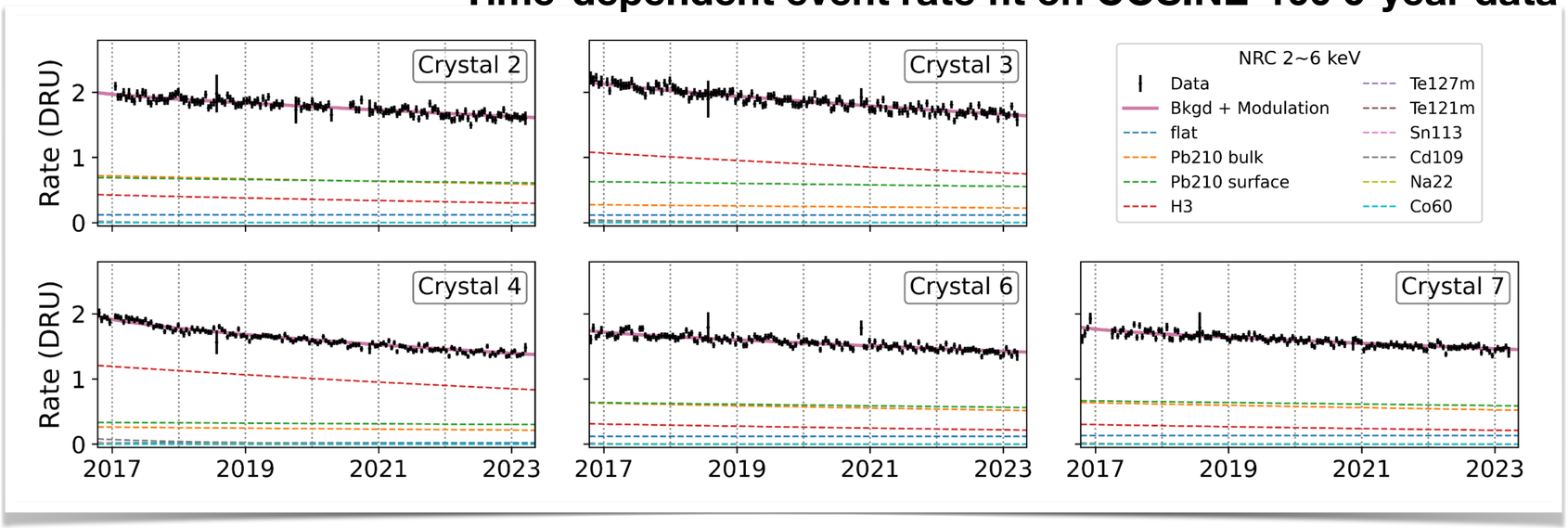
Modulation Amplitude

Fixed across crystals

Background modeling result



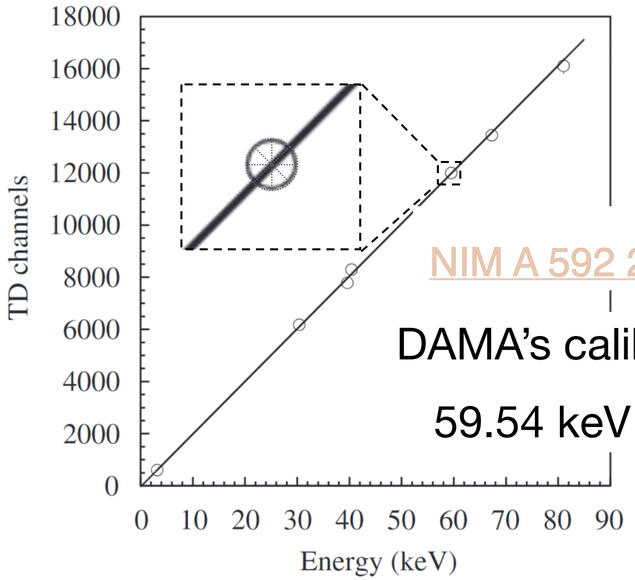
Time-dependent event rate fit on COSINE-100 6-year data



Model-Independent analysis

Precise calibration for testing DAMA

1. Electron recoil (keVee, linear calibration)



NIM A 592 297 (2008) Sec.8

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 analysis

Precise calibration for testing DAMA

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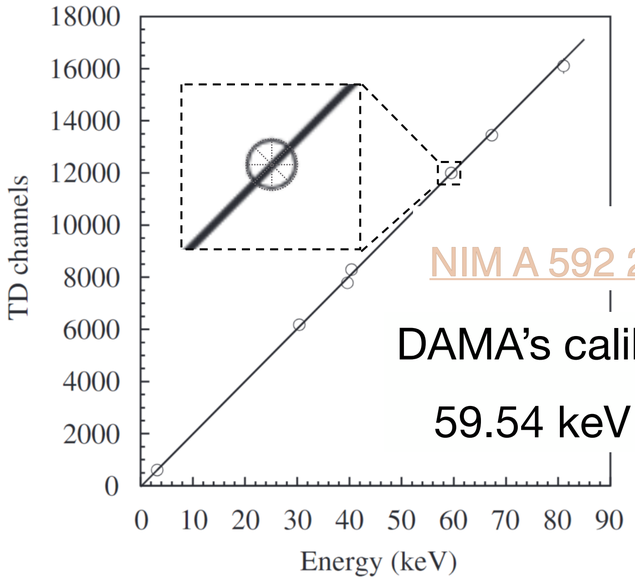

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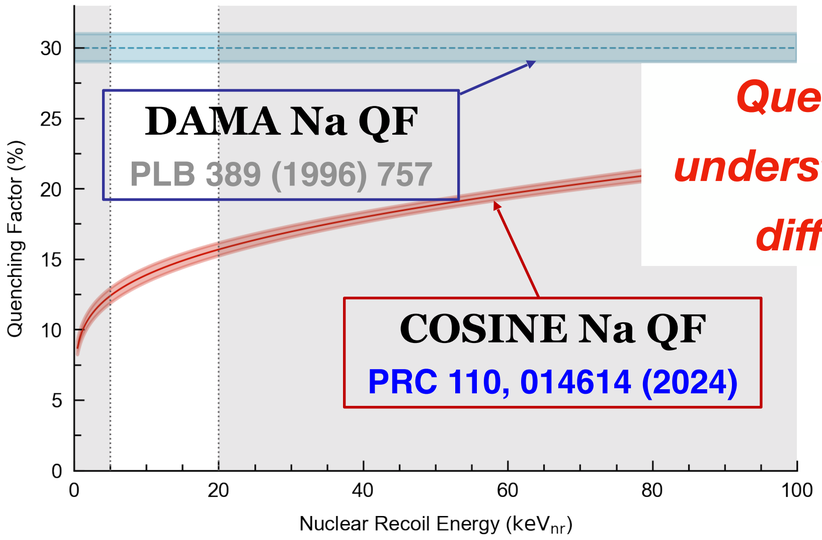
2. Nuclear recoil calibration (keVnr)



Quenching understanding is different!

Signal region : 6.70 – 20 keV_{nr}

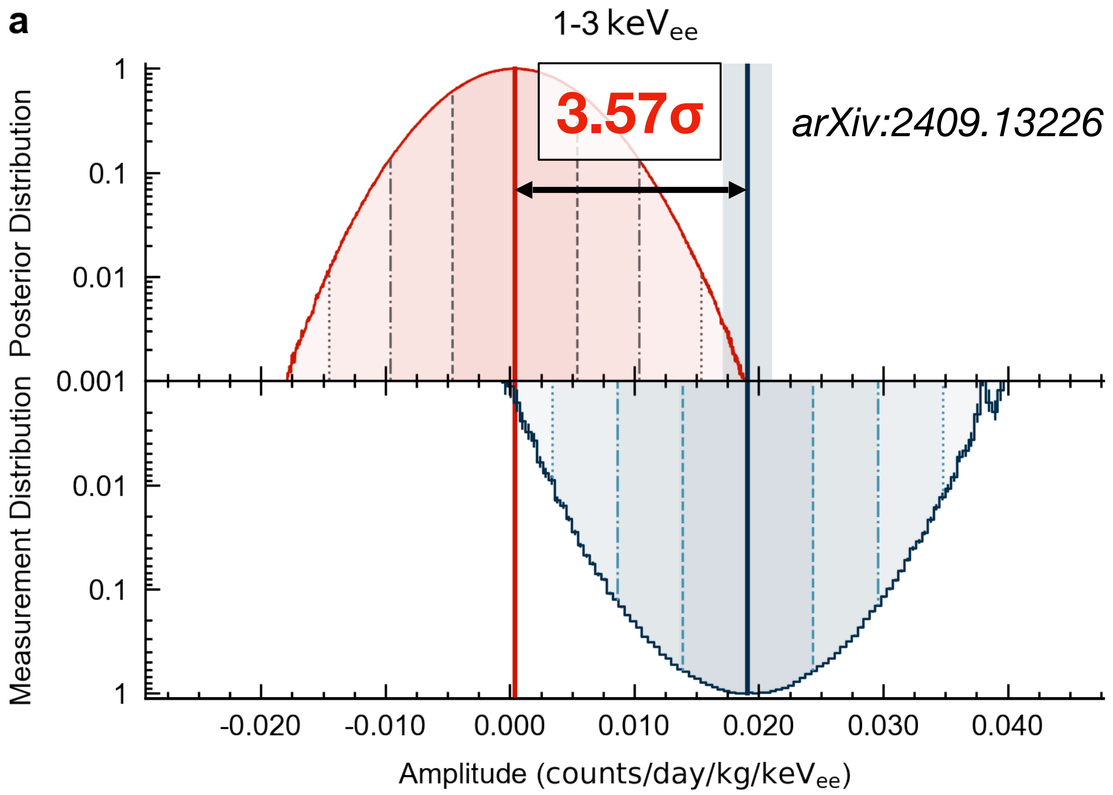
DAMA/LIBRA : 2.00 – 6 keV_{ee}

COSINE-100 : 0.85 – 3.12 keV_{ee}

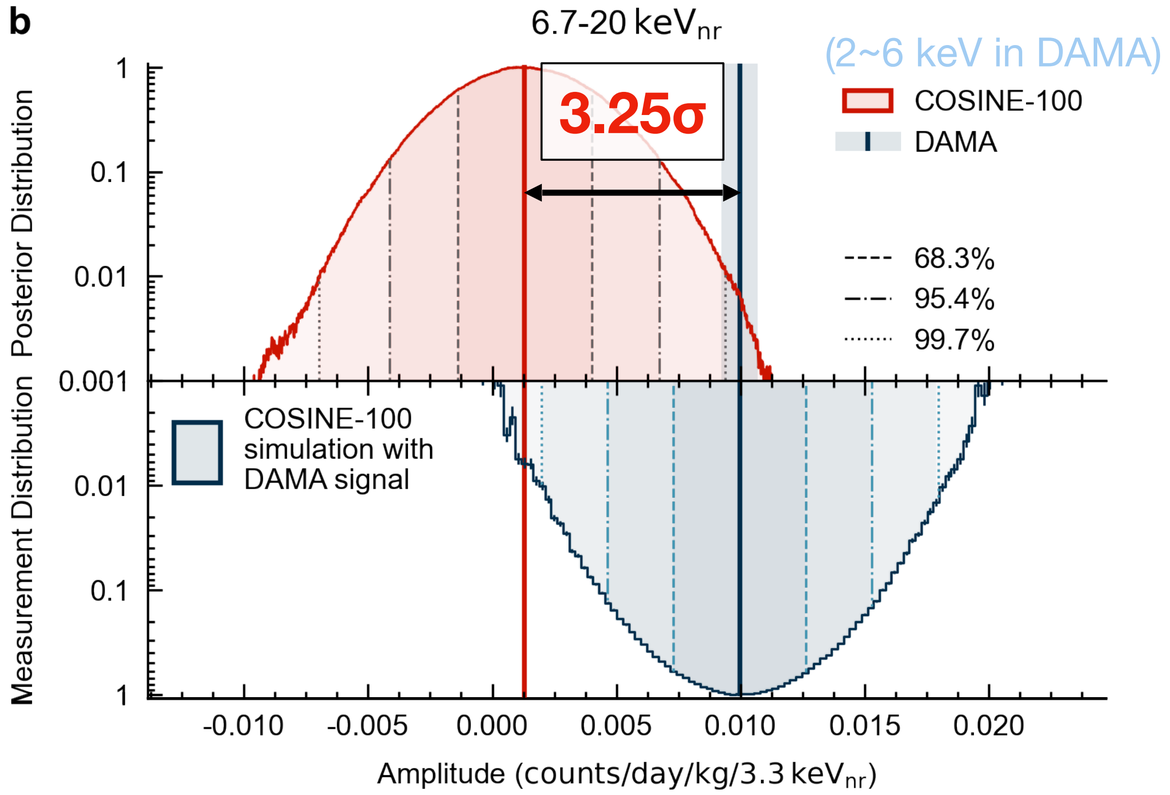
Model-Independent analysis

Annual modulation search : Phase fixed

1. Electron recoil (keVee, linear calibration)



2. Nuclear recoil calibration (keVnr)

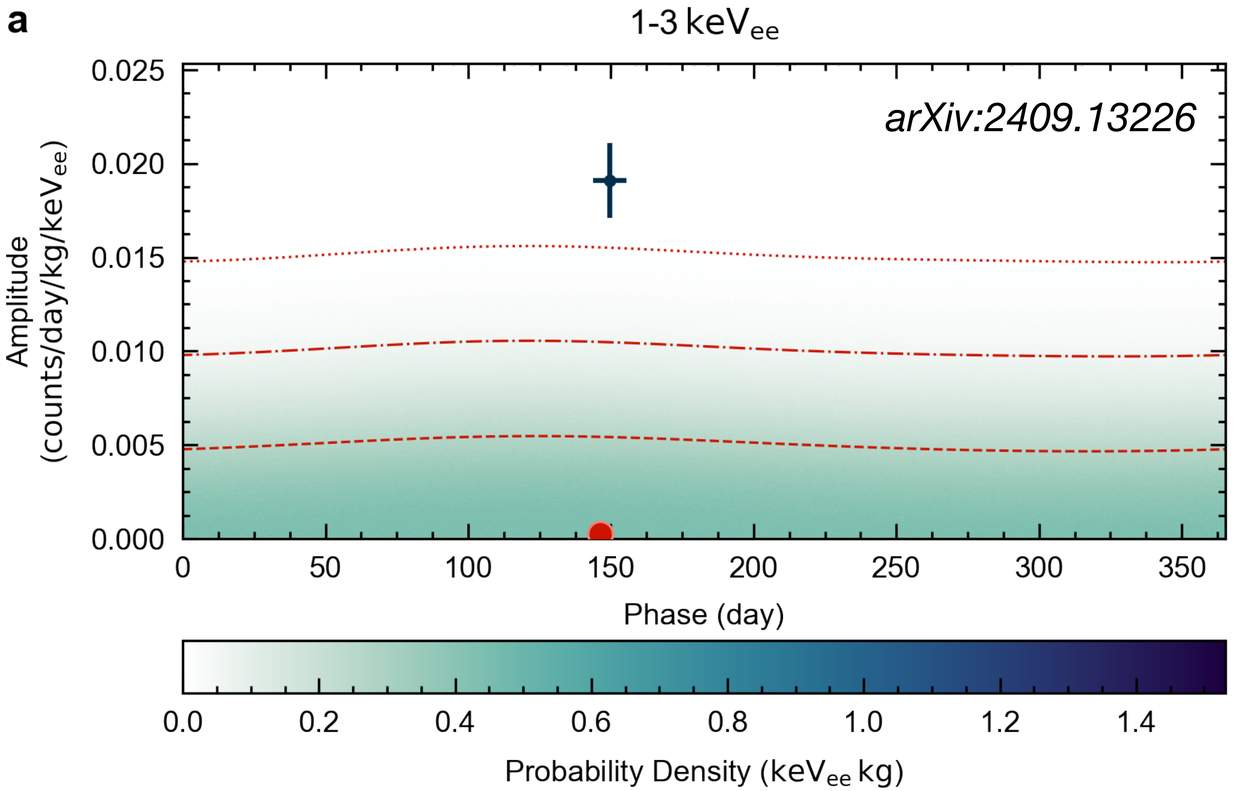


No modulation & Disfavors DAMA (> 3σ)

Model-Independent analysis

Annual modulation search : Phase floated

1. Electron recoil (keVee, linear calibration)



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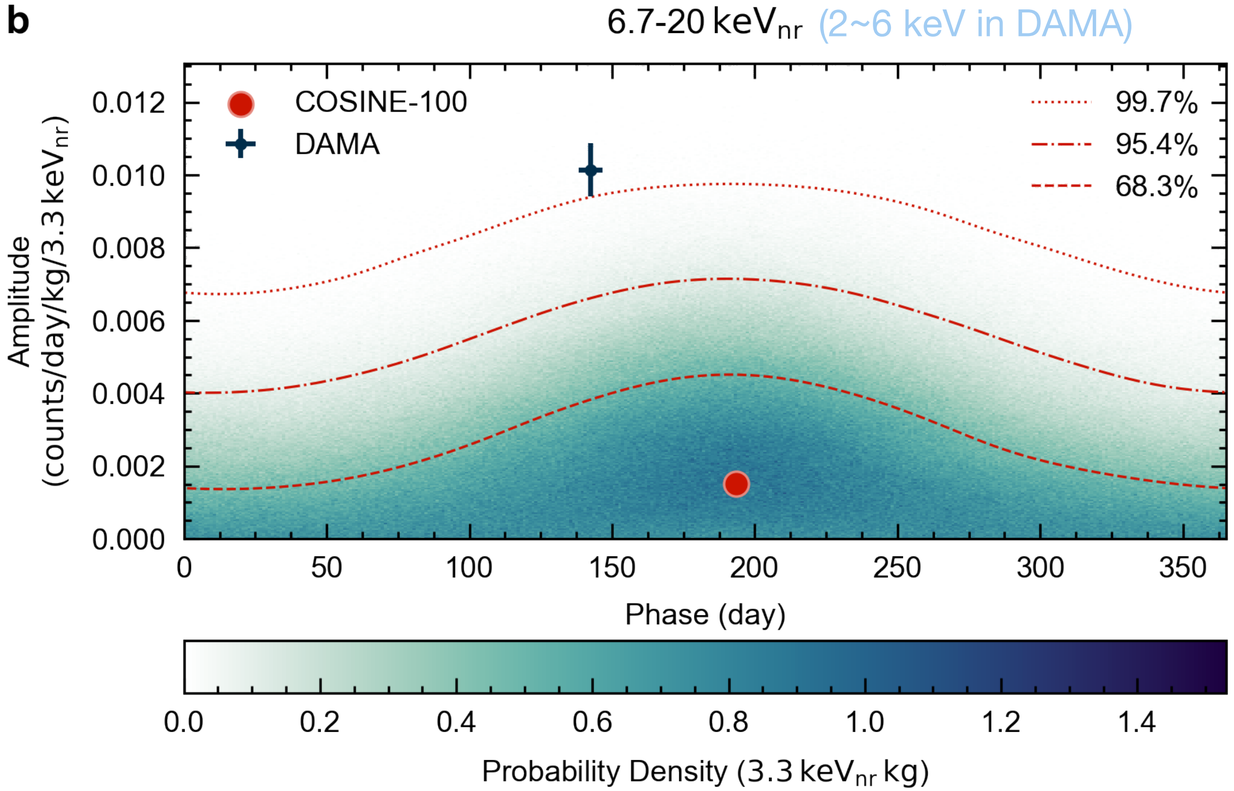
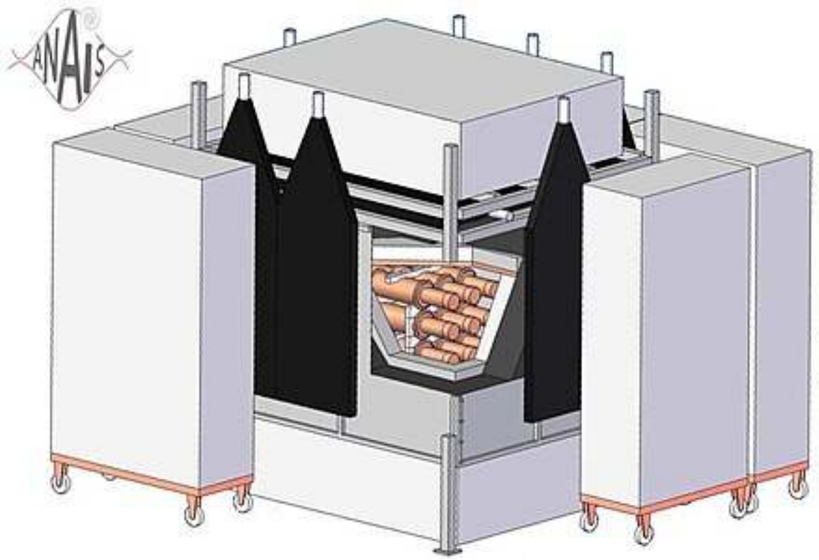


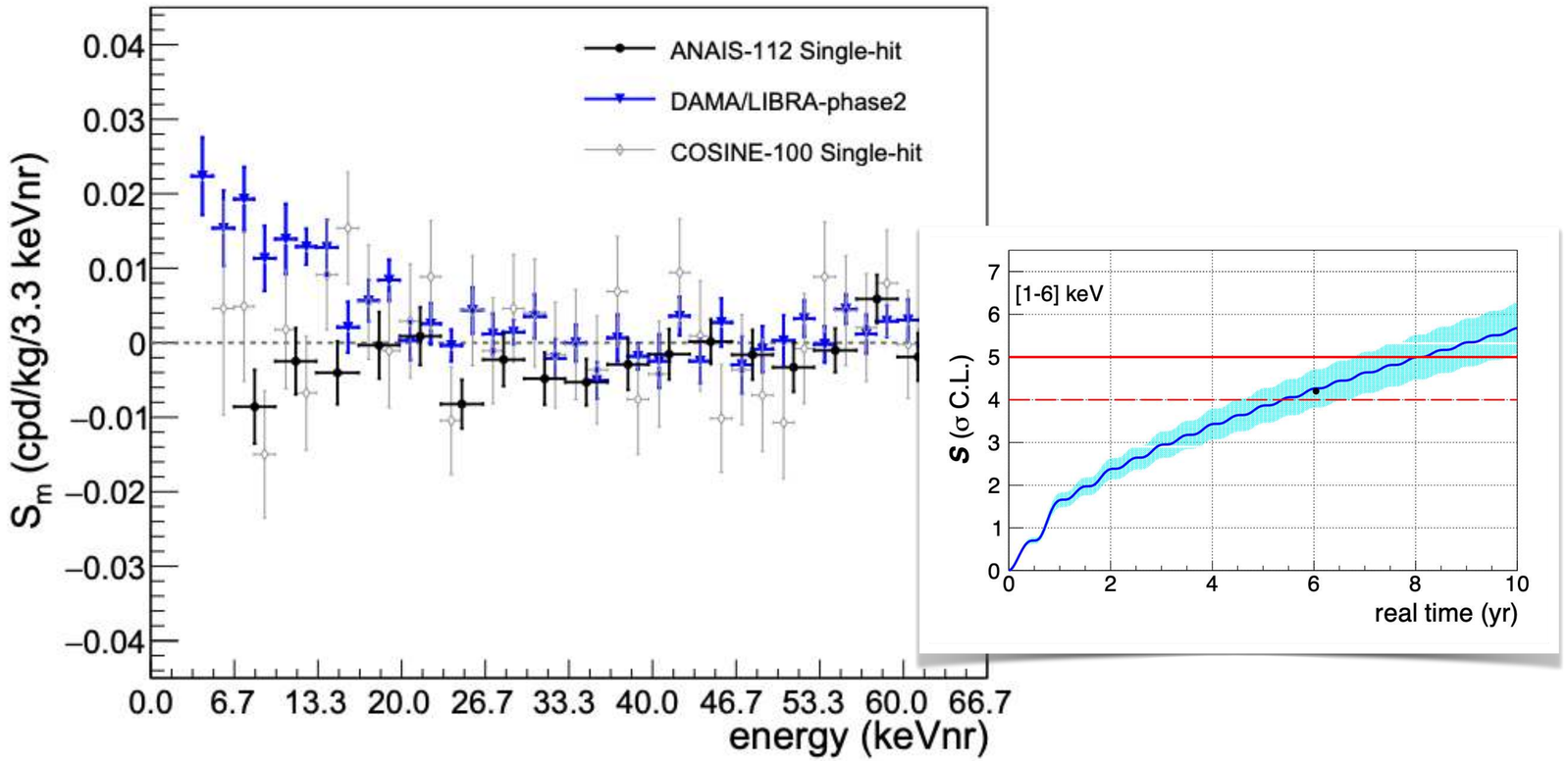
No modulation & Disfavors DAMA (> 3σ)

Consistency with ANAIS-112

Another modulation search experiment

arXiv:2502.01542





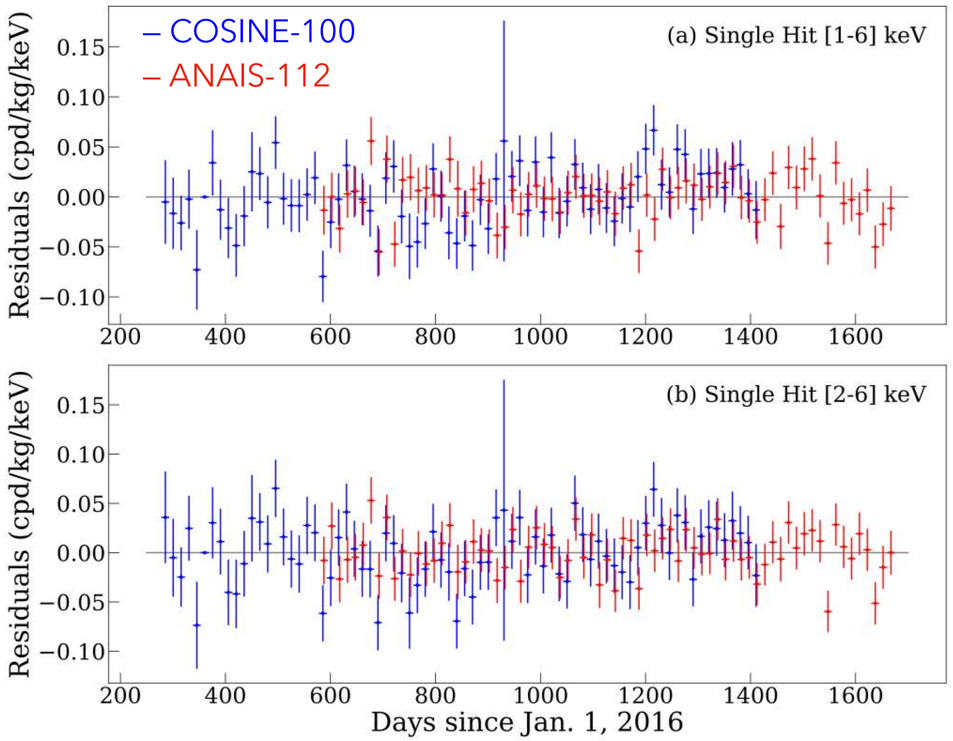
ANAIS-112 6-year analysis also disfavors DAMA in 4.2 σ C.L,

and shows **consistent result with COSINE-100**

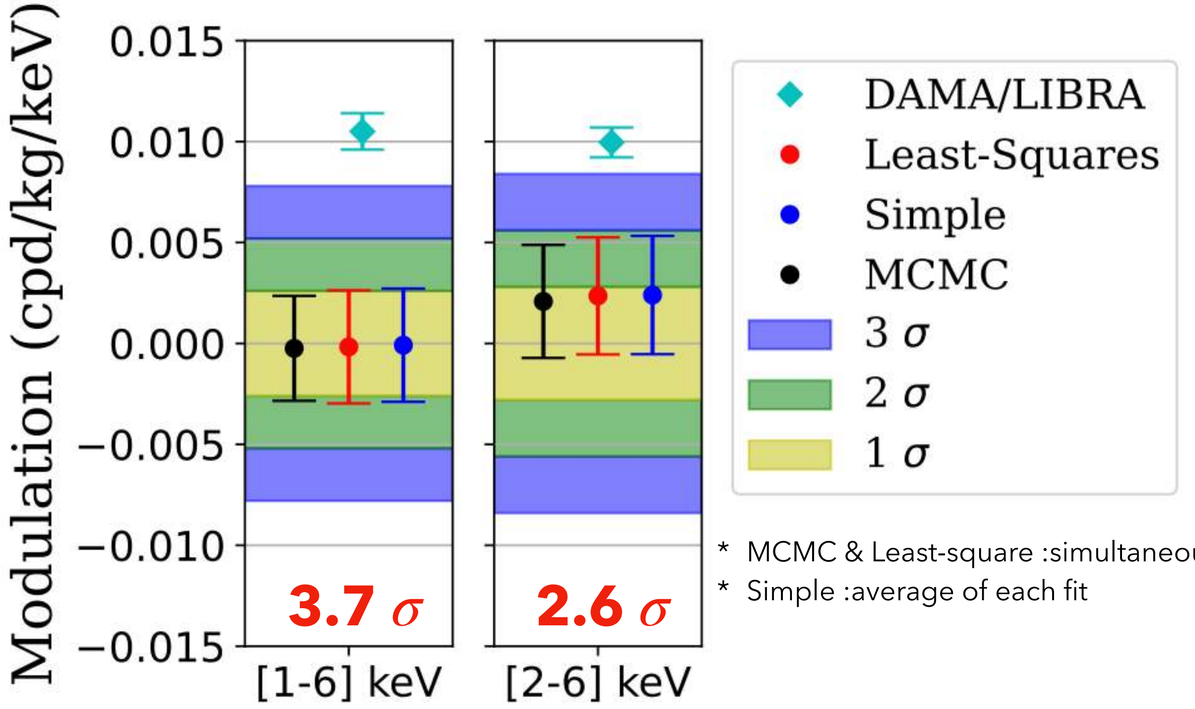
COSINE-100 + ANAIS-112

Simultaneous fit of each 3-year data

Background subtracted residuals



Modulation amplitude summary



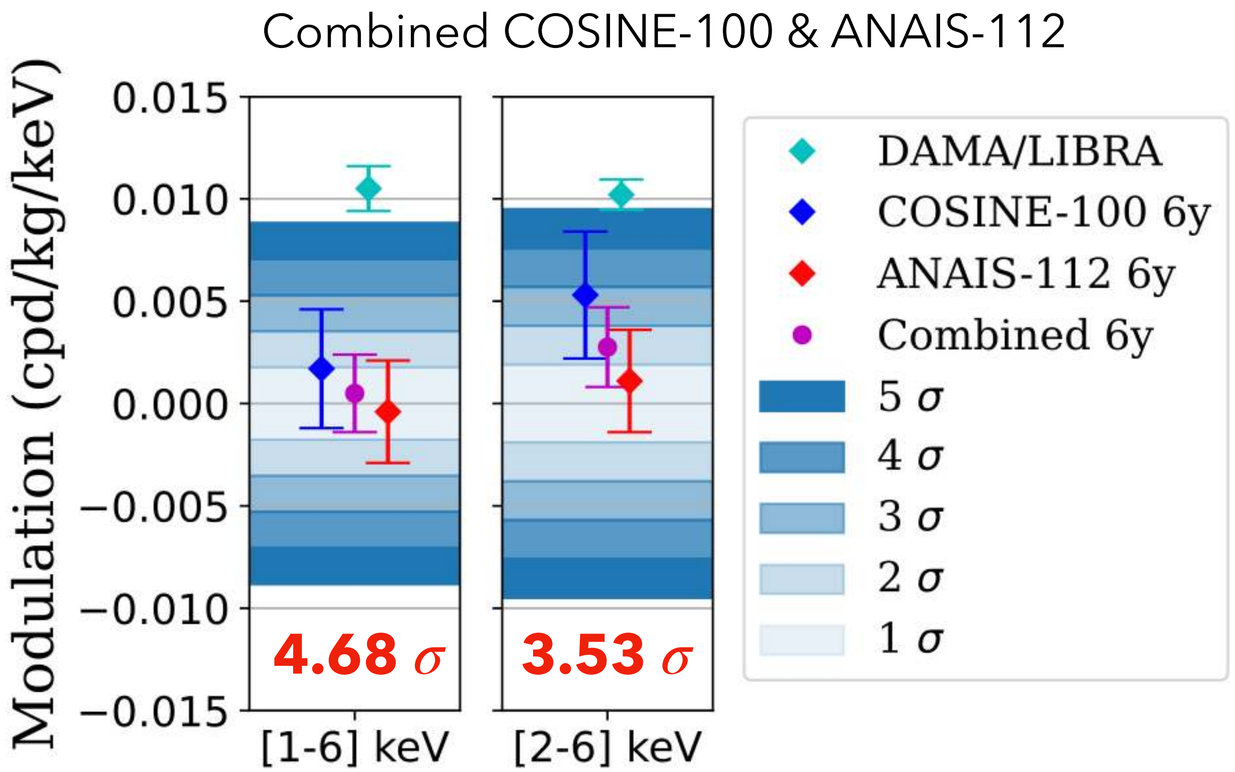
* MCMC & Least-square :simultaneous fit
* Simple :average of each fit

Used first 3-years of COSINE-100 & ANAIS-112 → disfavors DAMA

Released on arXiv this week! : https://doi.org/10.48550/arXiv.2503.19559

COSINE-100 + ANAIS-112

Average of each 6-year modulation fit

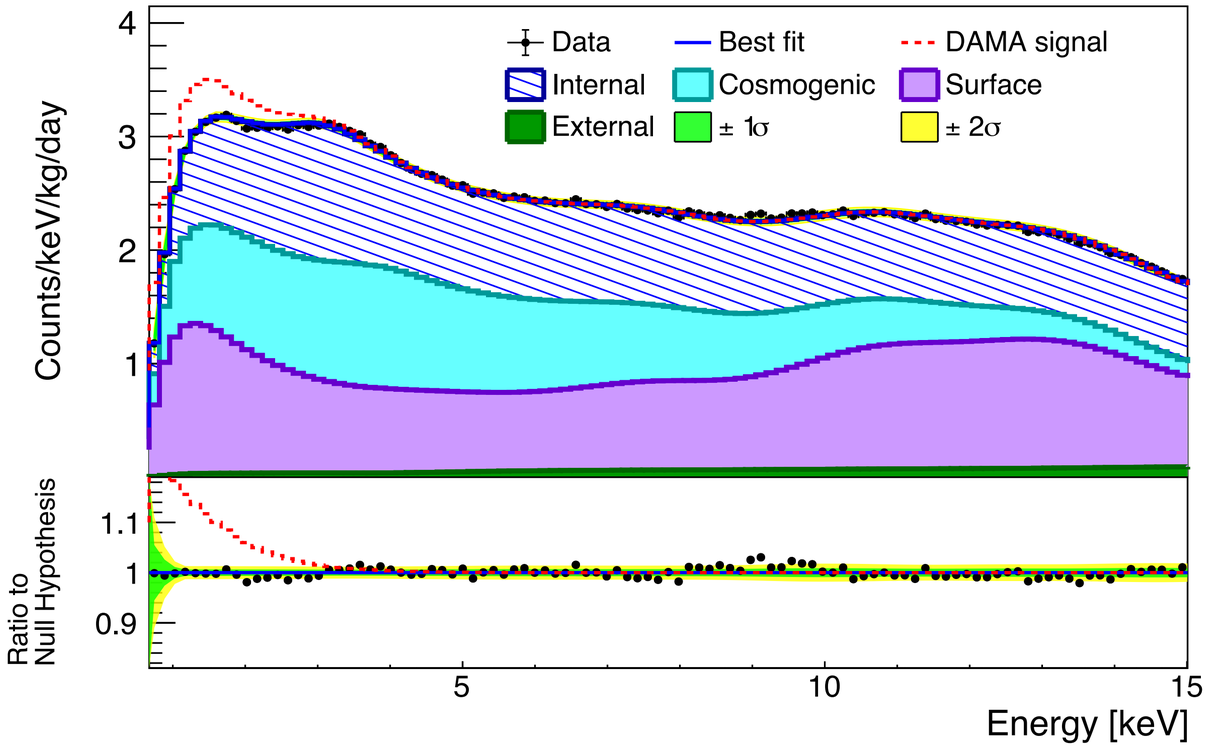


Average of each COSINE-100 & ANAIS-112 6-year result → disfavors DAMA

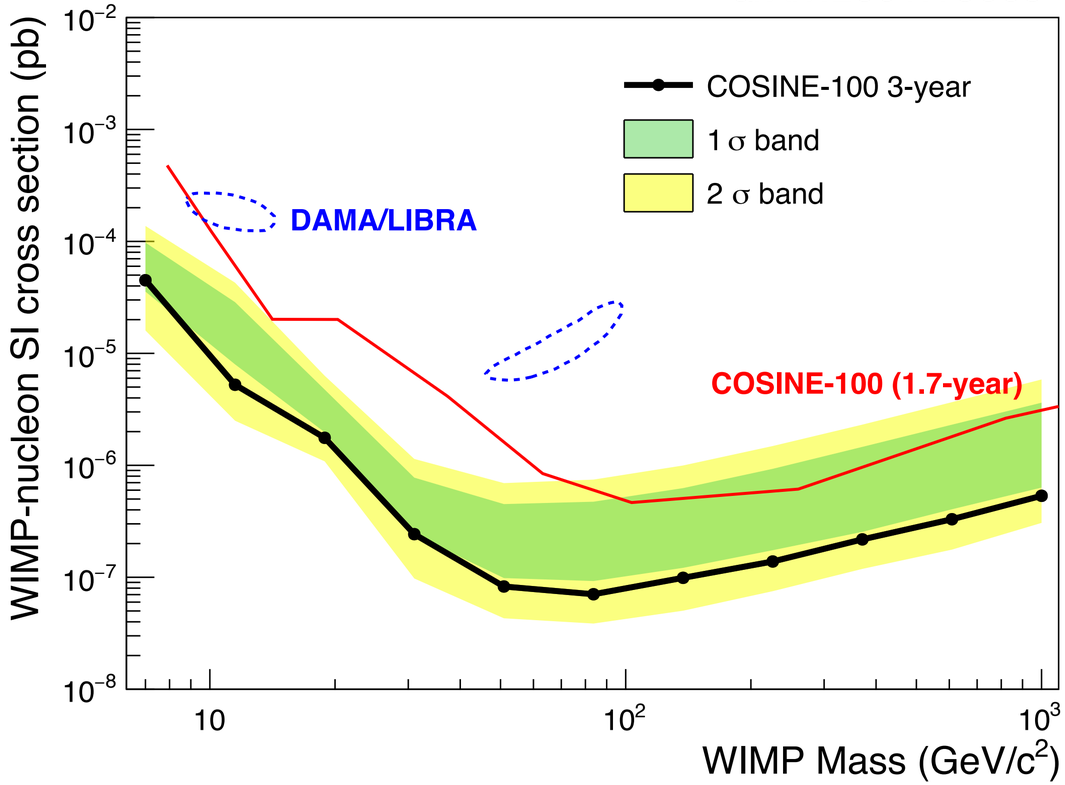
Released on arXiv this week! : https://doi.org/10.48550/arXiv.2503.19559

Model-dependent analysis

Spectral analysis in 3-year data : SI model

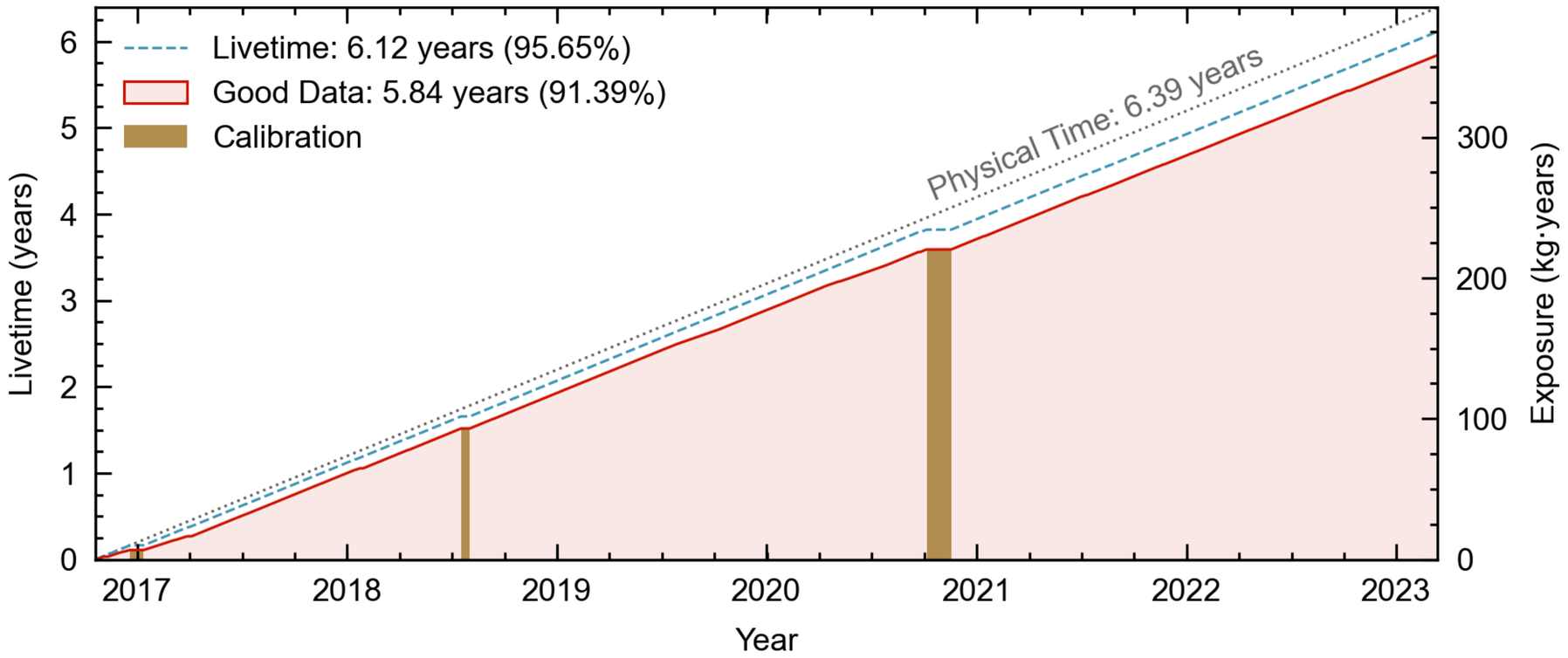


arXiv:2501.13665



Bayesian test of WIMP spectrum using MCMC fit.

Full exclusion of DAMA/LIBRA 3σ region in latest analysis

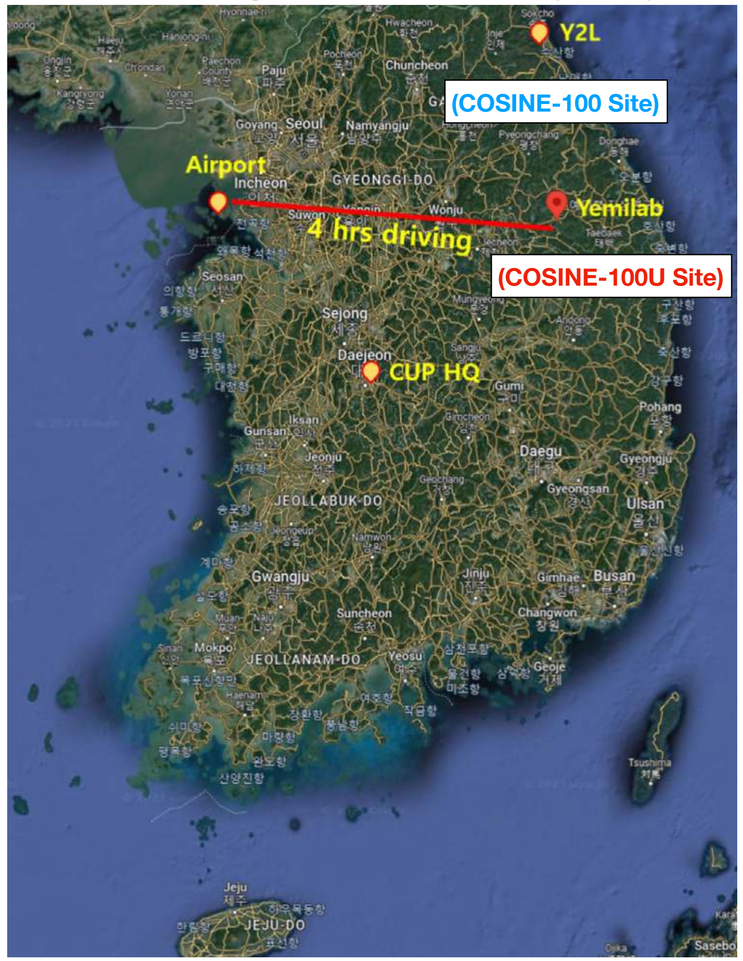


Testing DAMA & COSINE-100 operation is finished.. What's next?

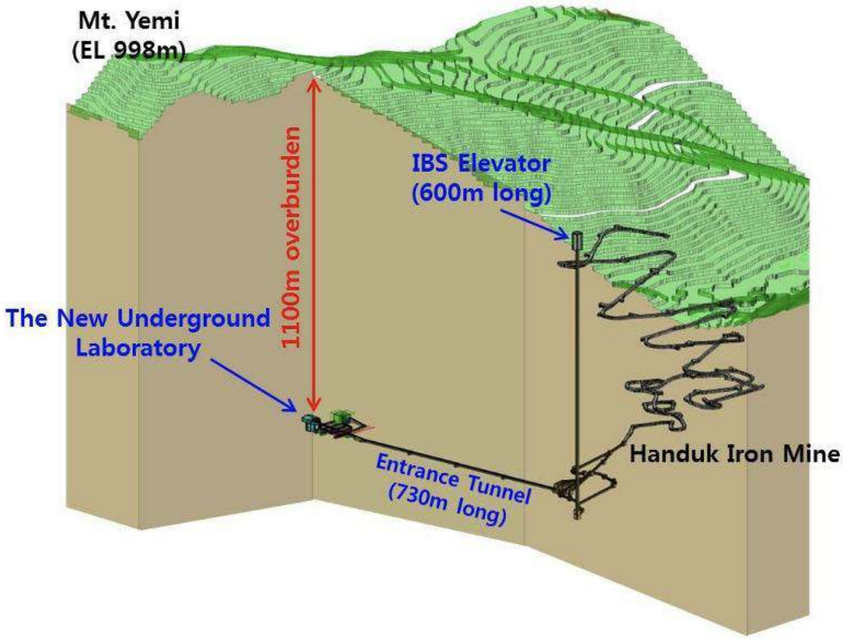
Next phase : COSINE-100U

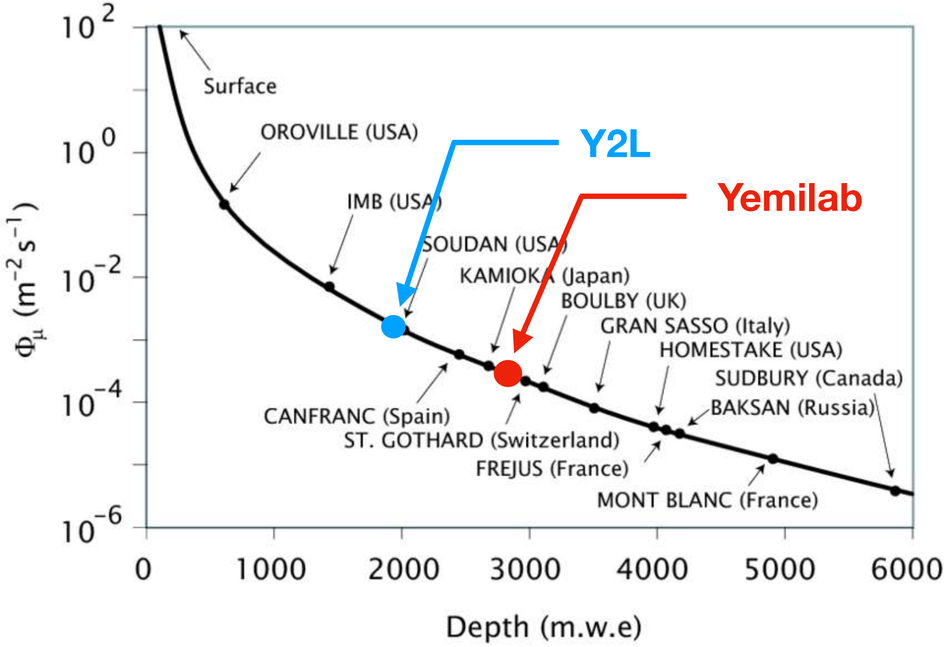
New experimental site : Yemilab

Front. Phys. 12:1323991. (2024)



Nature News



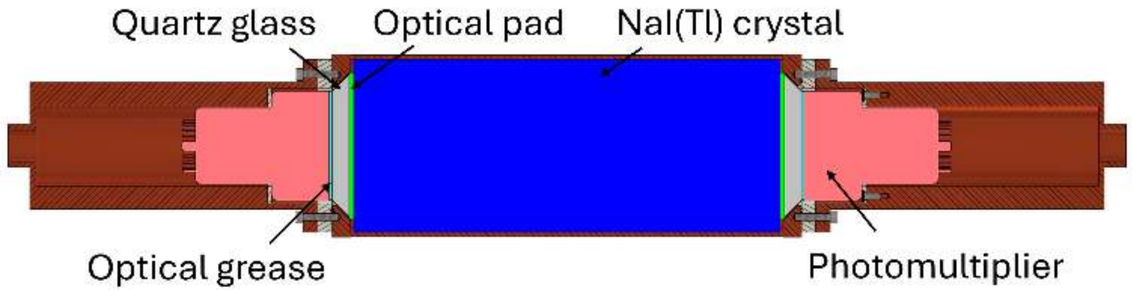


- New underground laboratory at Korea
- **700m (Y2L) → 1100m (Yemilab)**
- **5 times smaller muon flux**

Next phase : COSINE-100U

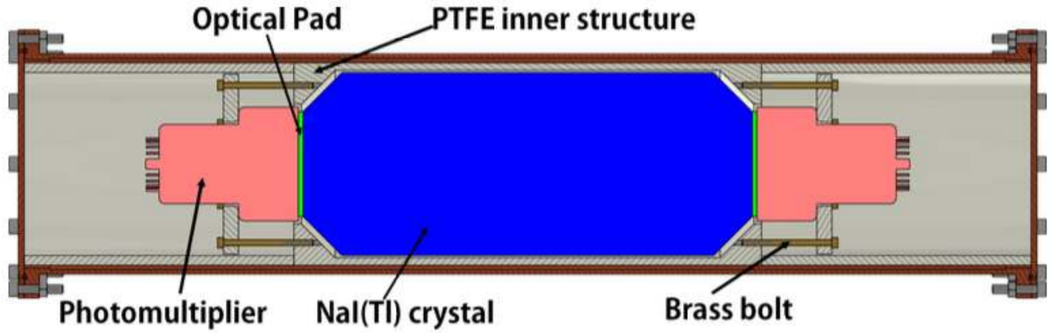
Higher light yield : New encapsulation design

Current encapsulation design



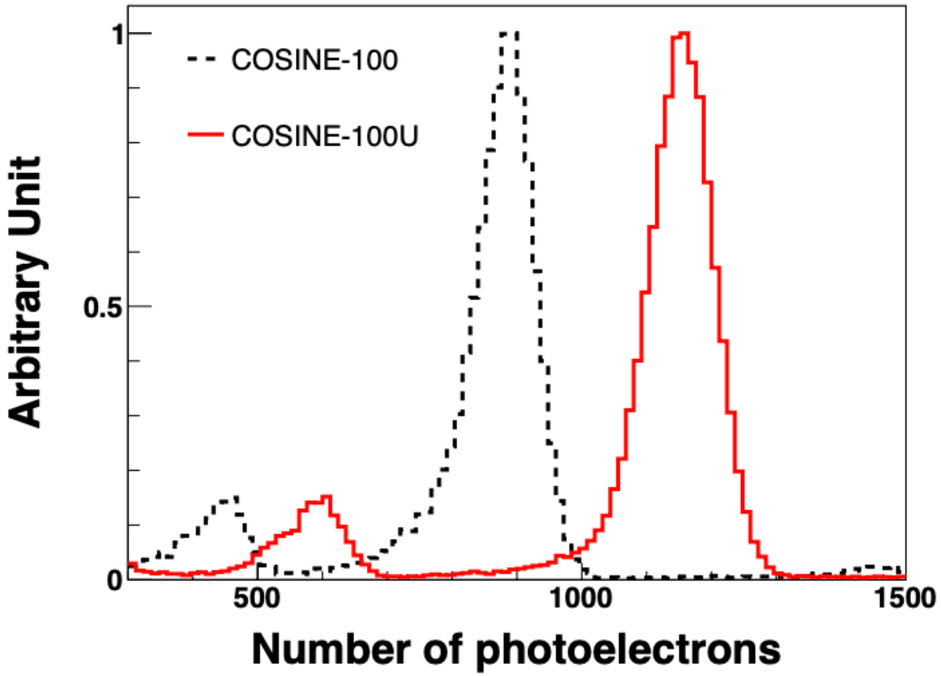
Quartz light guide
: loss in scintillation light

New encapsulation design



No quart light guide
: More efficient light collection

arXiv:2409.15748



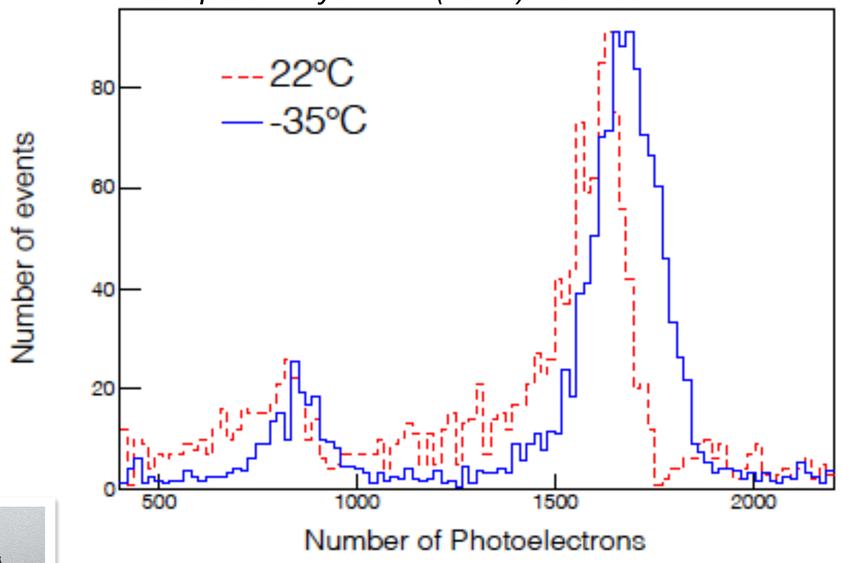
~40 % light yield improve!

Next phase : COSINE-100U

Low temperature operation : -30 ºC

NPE Measurement in -35 ºC

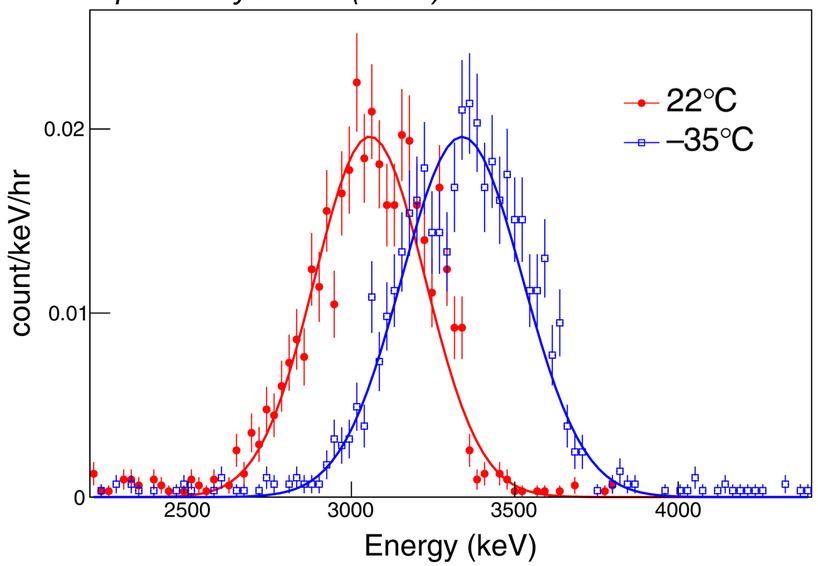
*Astropart. Phys. **141** (2022) 102709*



~5% increased Light yield

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

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

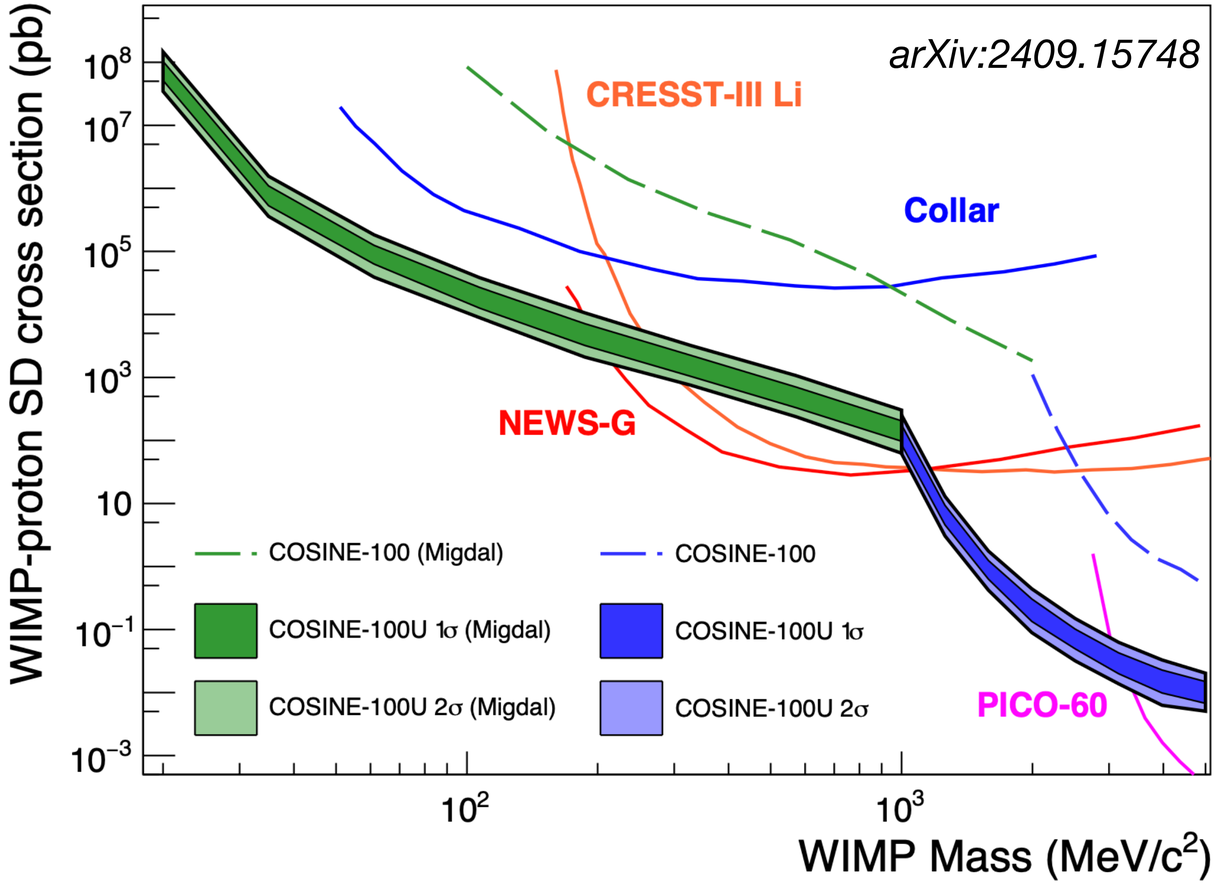


~9% increased quenching (in α)

Next phase : COSINE-100U

Expected sensitivity in SD model

COSINE-100U sensitivity : 1-year operation & 0.35 keV threshold



- **Na (Z = 11) & I (Z = 53)**
  - Proton-odd targets
  - Low-mass target (Na)

    →sensitive in **low-mass WIMP SD channel**

- Search to MeV-scale with **Migdal Effect**

- Plan to operate in May. 2025.

Stay tuned!

Summary & Outlook

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

- **COSINE-100 + ANAIS-112 combined analysis** conducted, and also rules out DAMA/LIBRA over 3σ in [1–6] keV fit.

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

Backup

Canonical WIMP scattering concept

Differential rate of WIMP scattering

$$\frac{dR}{dE_{nr}} = \frac{1}{2m_\chi \mu^2}\sigma(q)\rho_\chi \int_{v_{min}} d^3v \frac{f(\mathbf{v},t)}{v}$$

WIMP-nucleus Scattering Cross-section

WIMP Velocity requirement term

ρ_χ : local DM density = 0.3 GeV/cm^3

$f(v,t)$: time-dependent velocity distribution (SHM)

E_{nr} : Nuclear recoil energy

μ : Reduced mass

WIMP scattering total cross section : dependency on target material

$$\sigma(q) \equiv \sigma_0 F^2(q) = \sigma_{SI}F_{SI}^2(q) + \sigma_{SD}F_{SD}^2(q)$$

$F(q)$: nucleus form factor

Spin-independent

$$\sigma^{SI} = \frac{4}{\pi}\mu^2[Zf_p + (A-Z)f_n]^2$$

Spin-dependent

$$\sigma^{SD} = (\frac{32}{\pi})G_F^2\mu^2(\frac{J+1}{J})[\langle S_p\rangle a_p + \langle S_n\rangle a_n]^2$$

f_p or f_n: proton or neutron coupling constant

a_p : axial four-fermion WIMP-nucleon couplings

$\langle S_p\rangle$: average proton spin contribution

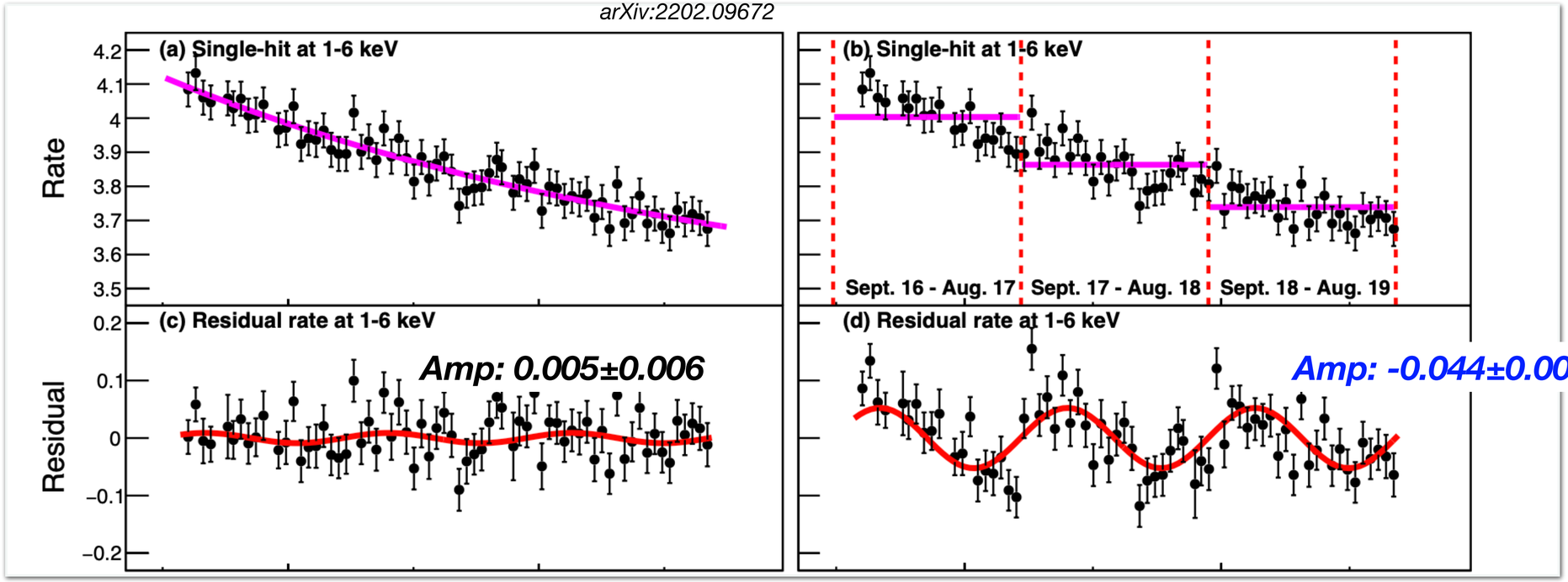
Possible DAMA explanation

Induced DM signal

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

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

arXiv:2202.09672

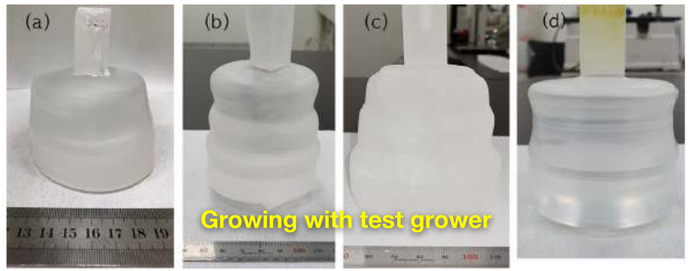


COSINE-100 data applying DAMA method gives

clear modulation (~7σ, opposite phase)

Ultra pure crystals for COSINE-200

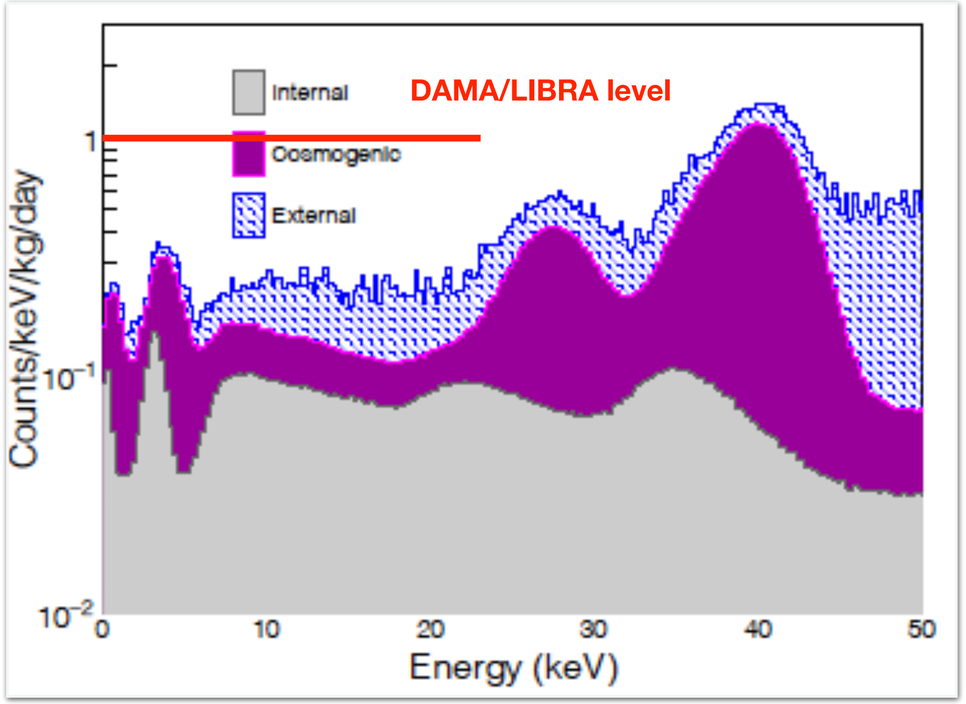
New Crystal development



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

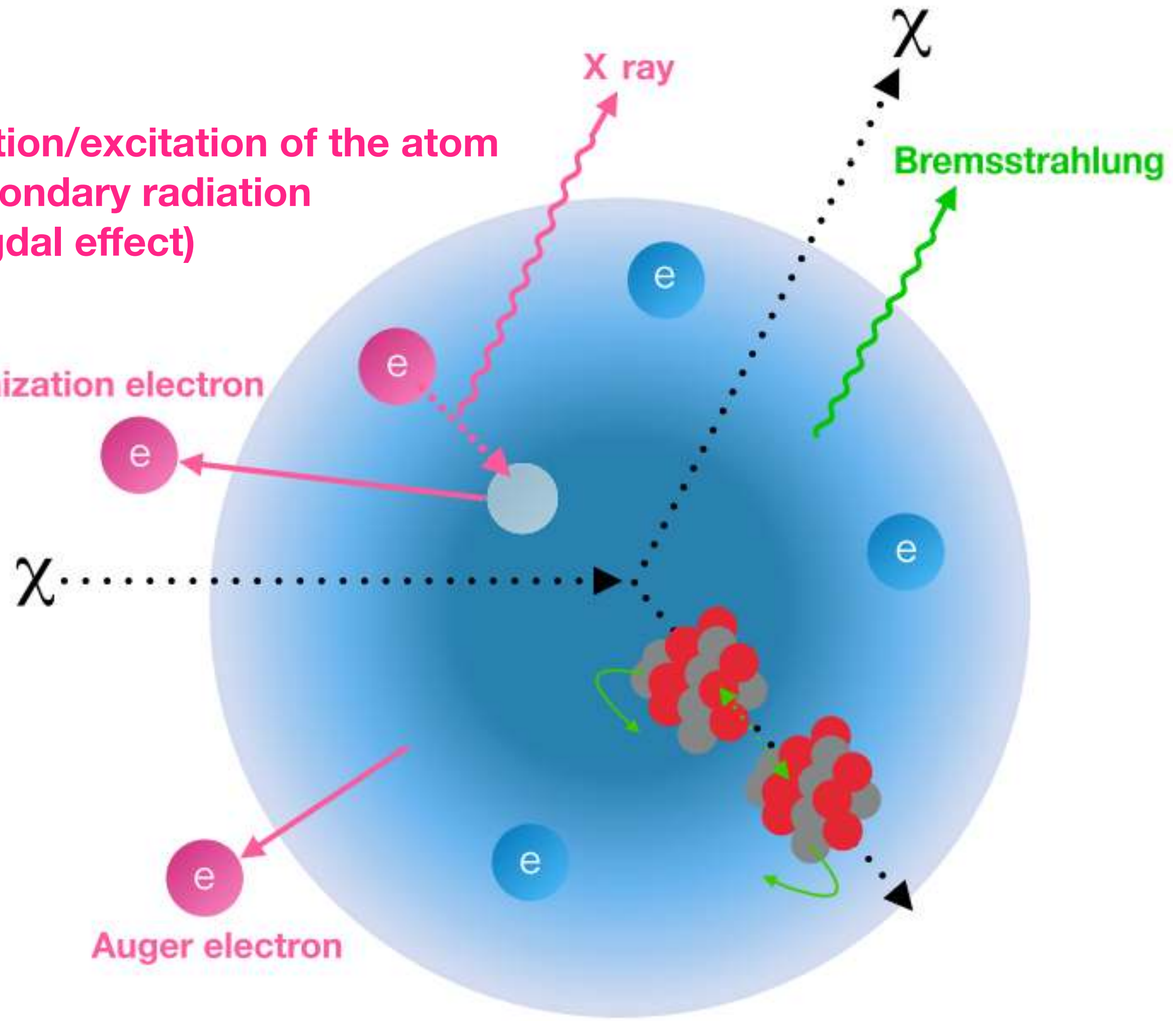
*EPJC **80** (2020) 814*



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

Migdal effect

Ionization/excitation of the atom
→ Secondary radiation
(Migdal effect)



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

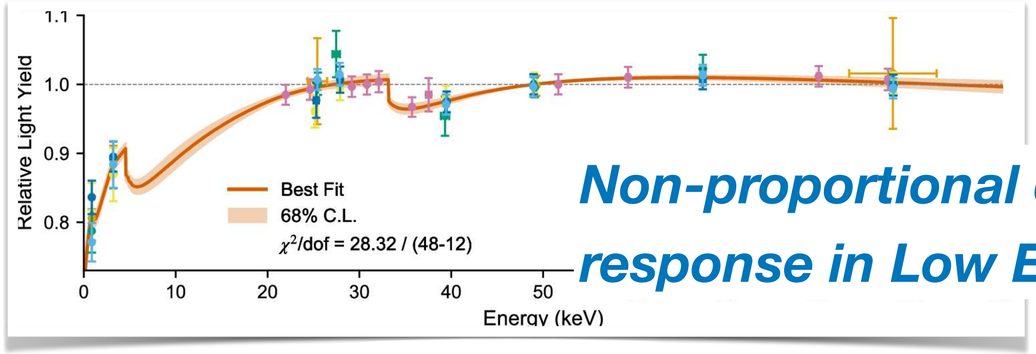
Reference : PRL 123, 241803 (2019) (Xenon 1T)

Pre-analysis 2

Updates for better understanding

Detailed calibration : Non-proportional response

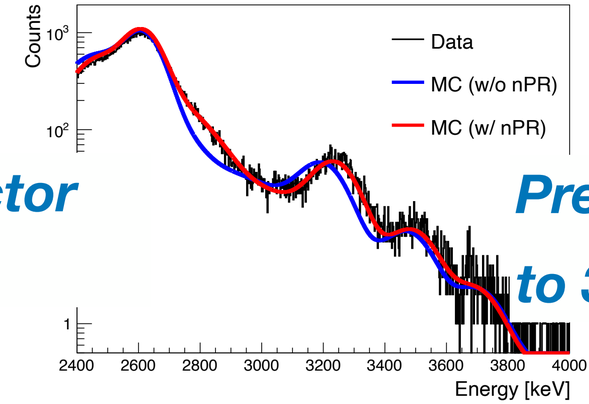
EPJC 84, 484 (2024)



Non-proportional detector response in Low E

High-energy non-proportionality correction

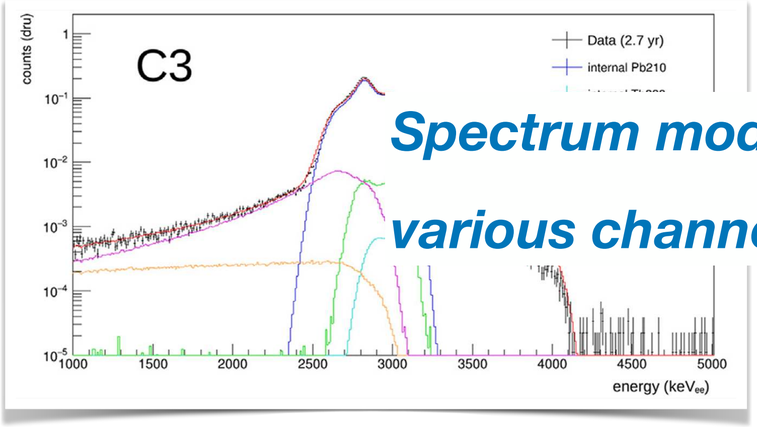
Eur. Phys. J. C (2025) ***85****: 32*



Precise calibration up to 3 → 4 MeV

Alpha decaying background fit

ASP 158, 102945 (2024)



Spectrum modeling in various channel

- 60 days → 1.7 years → **3 years data**
- Various updates in background understanding
- Better understanding on decaying components

Model-dependent analysis

Spectral analysis in 3-year data : SD model

arXiv:2501.13665

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

- Proton-odd targets

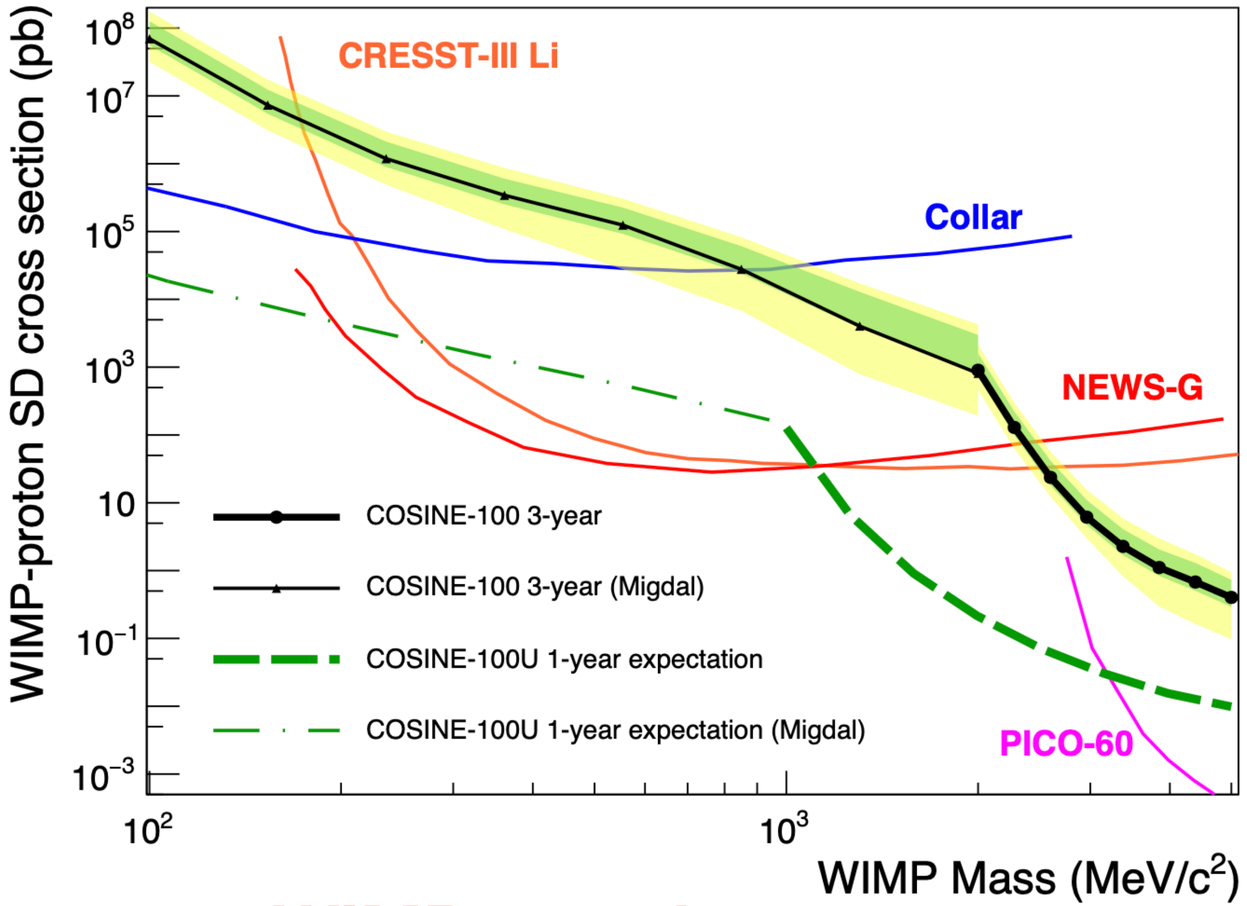
  →sensitive in SD model

- Low-mass target (Na)

  →sensitive in low-mass WIMP

Searching for Migdal effect of WIMP

→Down to sub-GeV WIMP



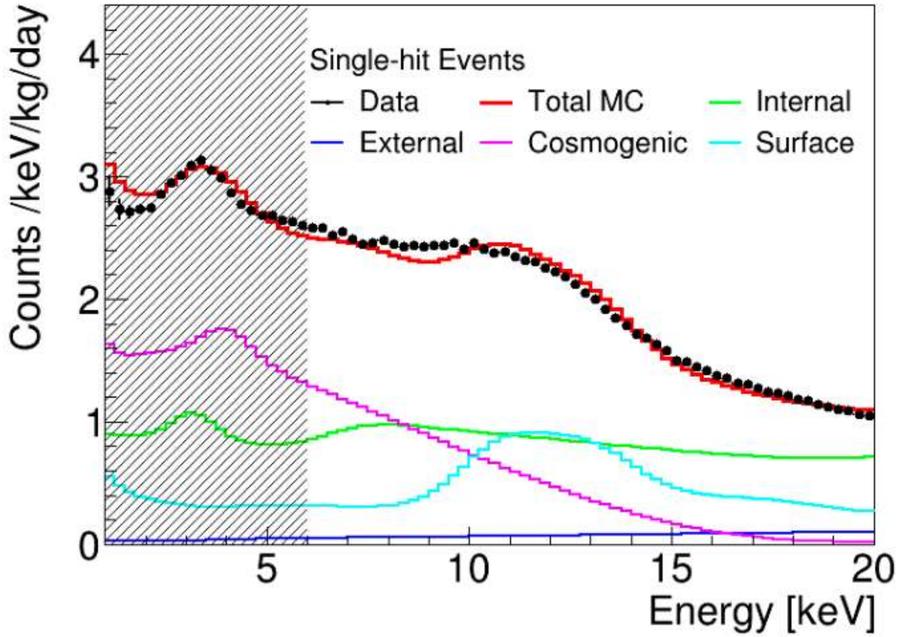
Competitive results in low-mass WIMP search

Pre-analysis 2

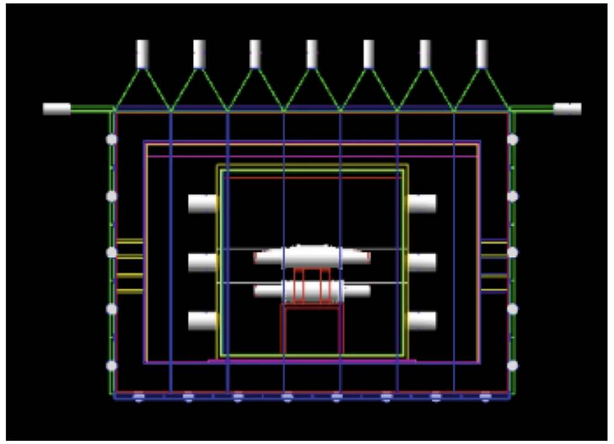
Background modeling w/ Geant4

Background study example from 1.7-year data analysis

EPJC 81, 837 (2021)



Geometry of COSINE-100 In Geant4



Example of background isotopes

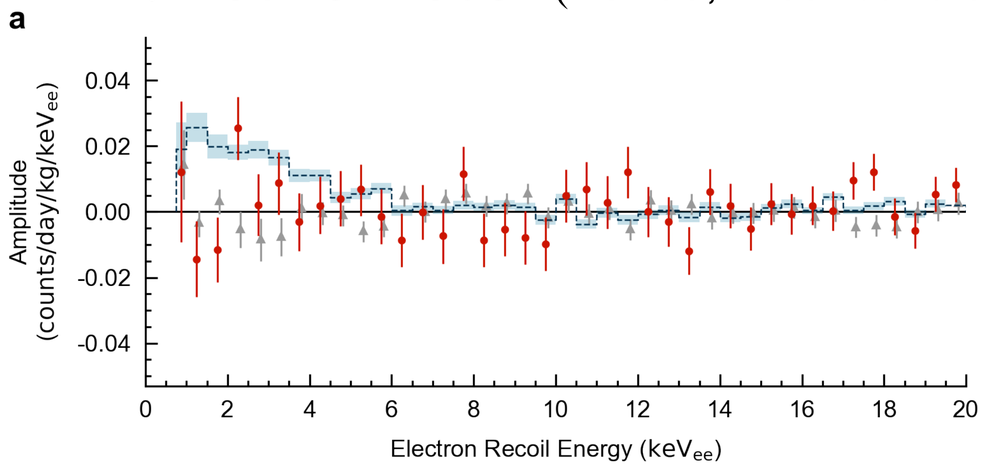
Crystal internal	^{238}U, ^{232}Th, ^{40}K, ^{60}Co
Crystal cosmogenic	^{22}Na, ^{121m}Te, ^{129}I, ^{109}Cd, ^{3}H, ..
PMTs, Shields, ..	^{238}U, ^{232}Th, ^{40}K, ^{208}Tl, ^{235}U

- Need to understand which background are existing in COSINE-100 data
- Generated MC spectrum using Geant4 and modeled the data

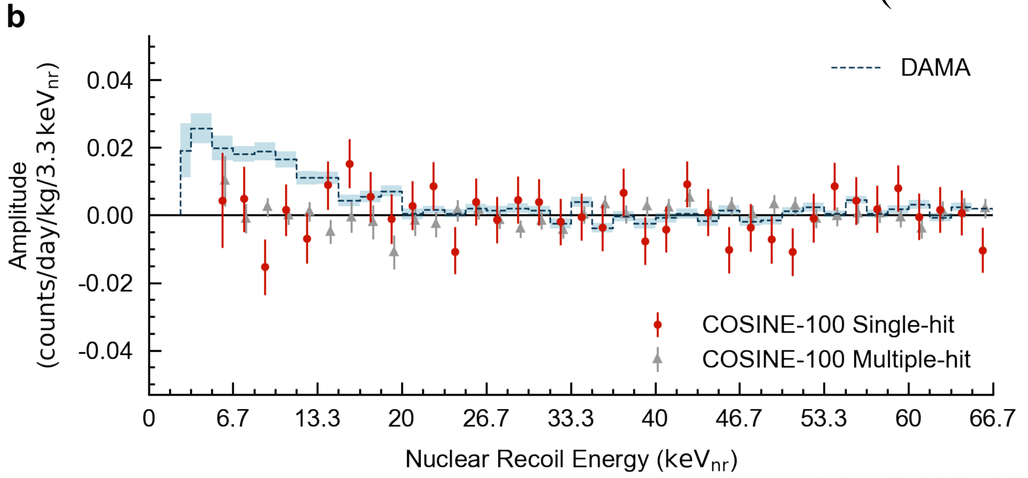
Model-Independent analysis

Annual modulation search : Amplitude summary

1. Electron recoil (keVee, linear calibration)



2. Nuclear recoil calibration (keVnr)



arXiv:2409.13226

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

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

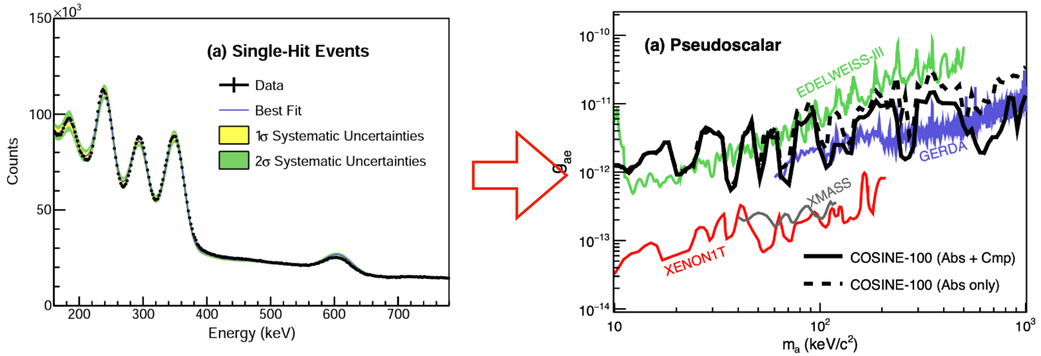
No modulation & Disfavors DAMA (> 3σ)

Other DM searches in COSINE-100

Exotic DM models

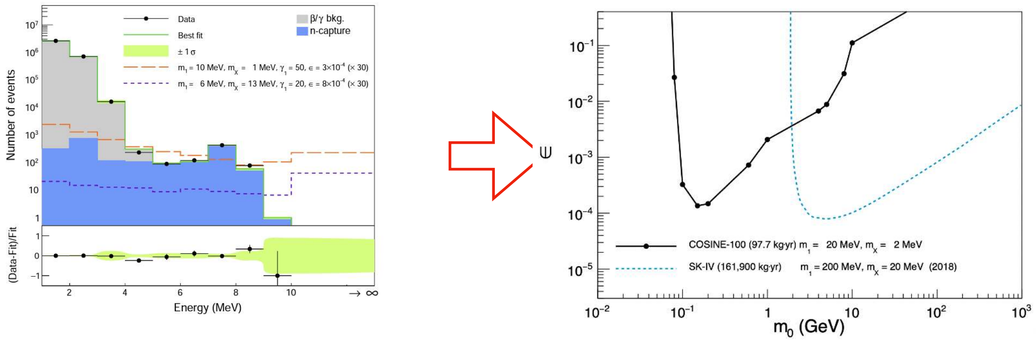
1. Bosonic super WIMP *Phys. Rev. D **108** (2023) L041301*

• Search region : COSINE-100 energy $\mathcal{O}$(100 keV)



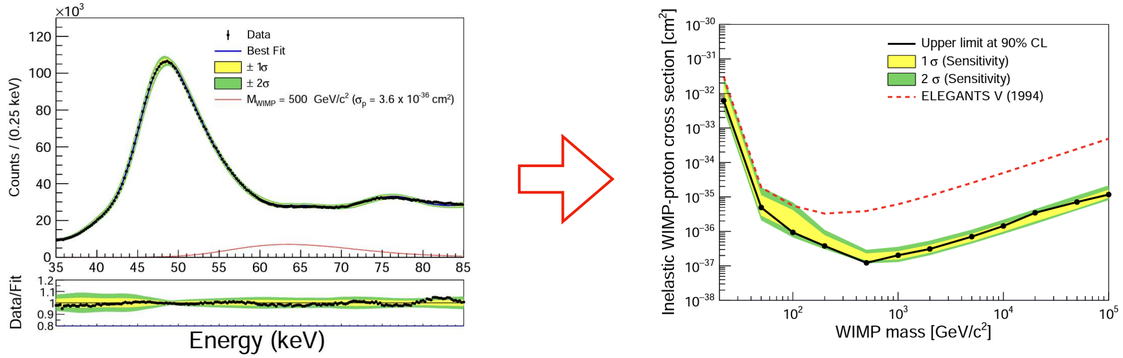
2. Boosted dark matter *Phys. Rev. Lett. **131**, 201802*

• Search region : COSINE-100 energy $\mathcal{O}$(MeV)



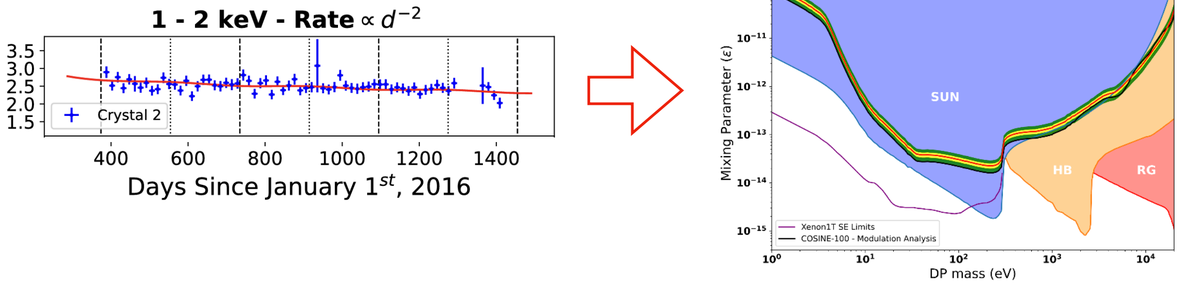
3. Inelastic ^{127}I - DM scattering *Phys. Rev. D **108**, 092006*

• Search region : COSINE-100 energy $\mathcal{O}$(10 keV)



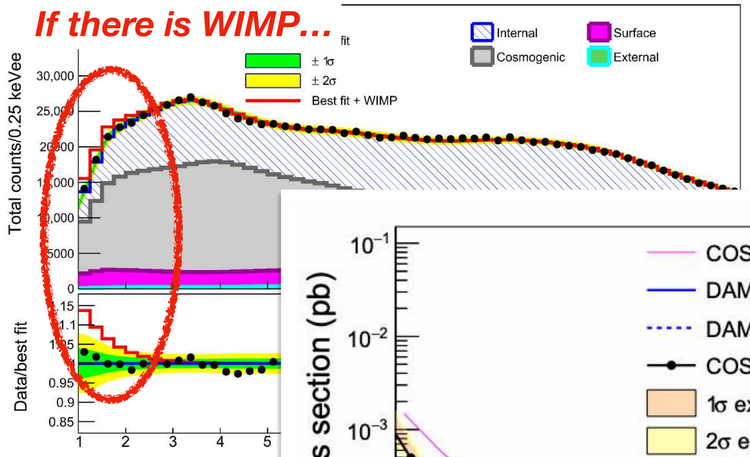
4. Solar bosonic dark matter modulation search

• Modulation search period : 3 years *Phys. Rev. D **107**, 122004*

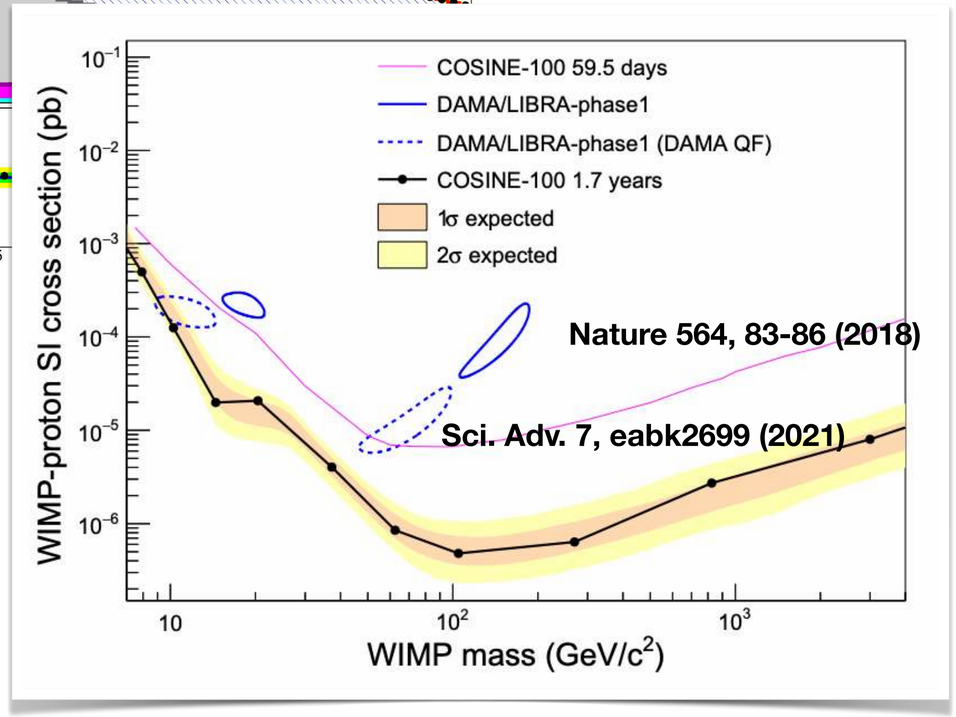


Previous COSINE-100 analysis

Model Dependent : (WIMP spectrum test)

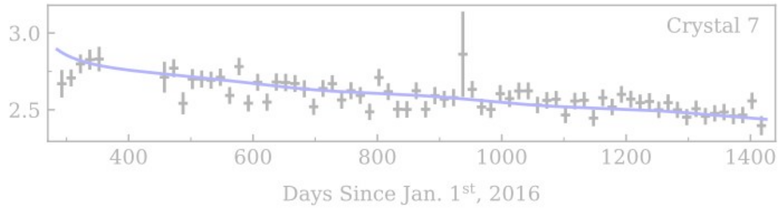


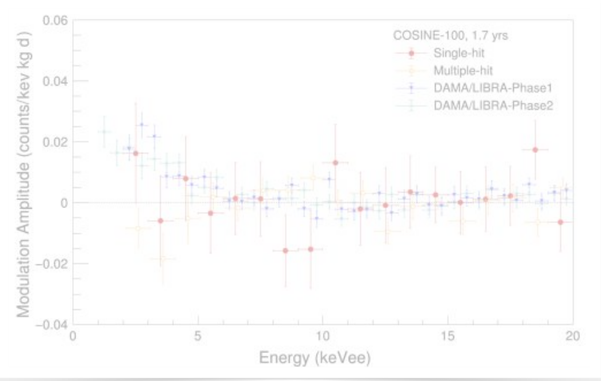
60 days & 1.7 years analysis



Excluded most of regions from DAMA/LIBRA

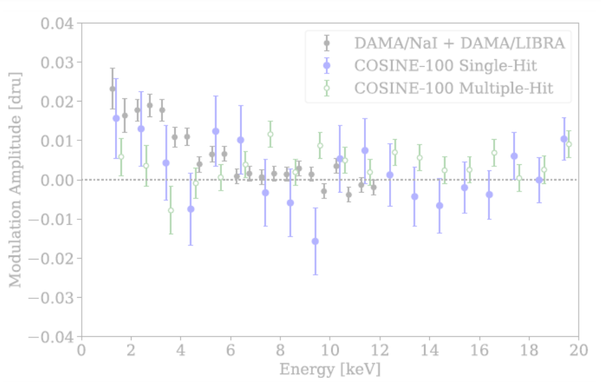
Model Independent : (Annual modulation)





1.7 year data analysis

PRL 122, 131802 (2019)



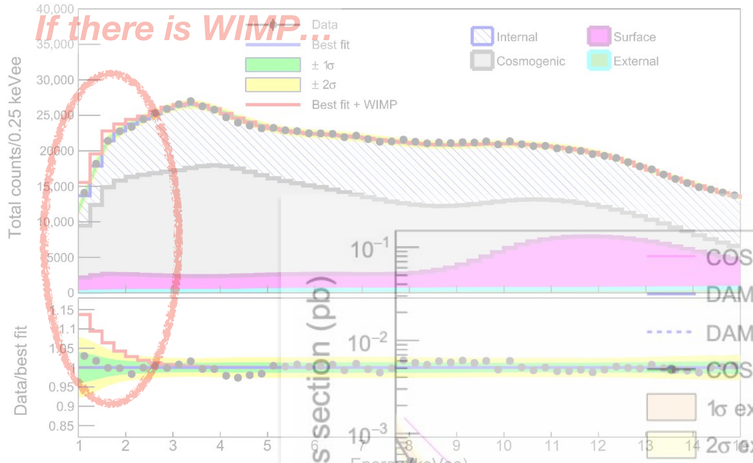
3.0 year data analysis

PRD 106, 052005 (2022)

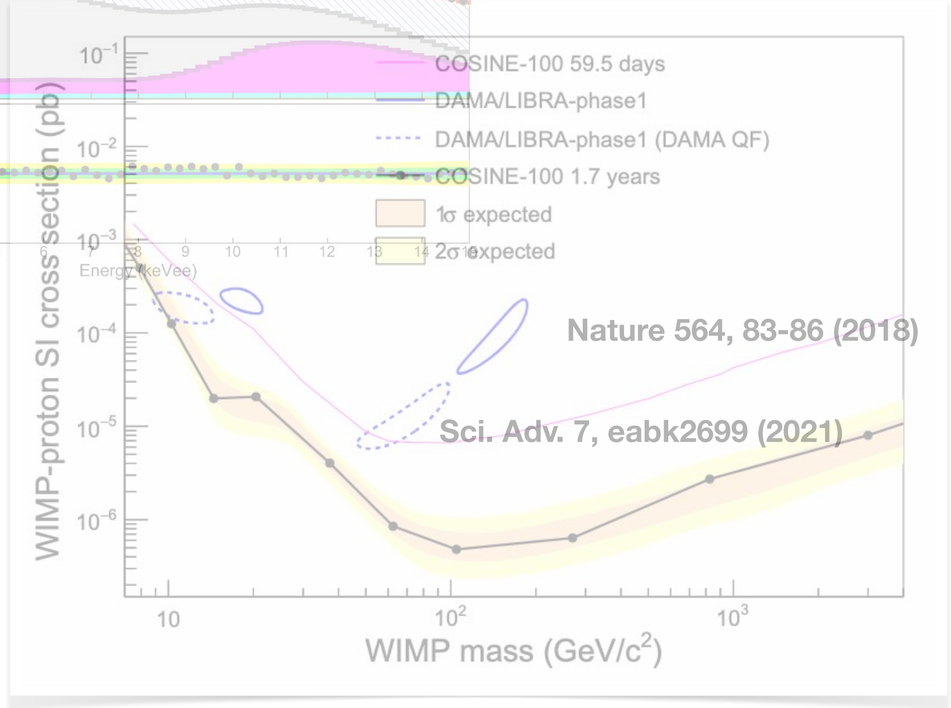
Previous COSINE-100 analysis

Model Dependent : (WIMP spectrum test)

If there is WIMP...



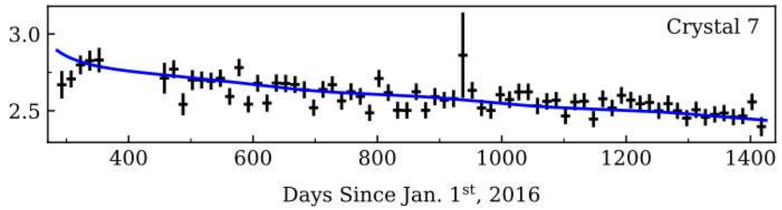
60 days & 1.7 years analysis

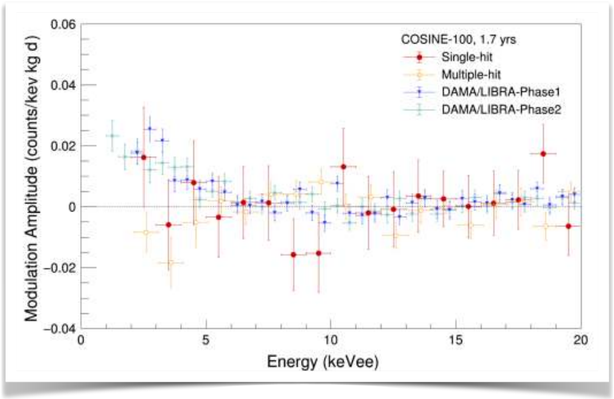


Nature 564, 83-86 (2018)

Sci. Adv. 7, eabk2699 (2021)

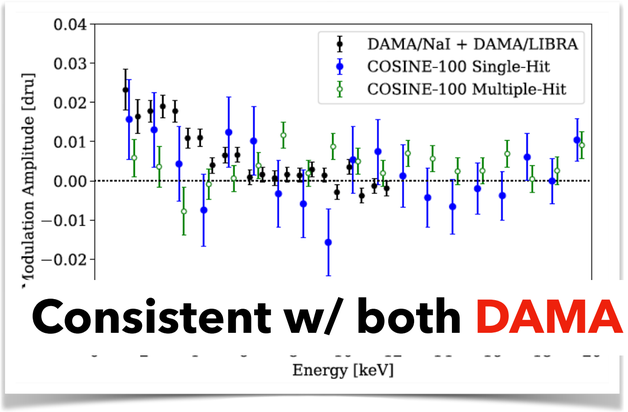
Model Independent : (Annual modulation)





1.7 year data analysis

PRL 122, 131802 (2019)



3.0 year data analysis

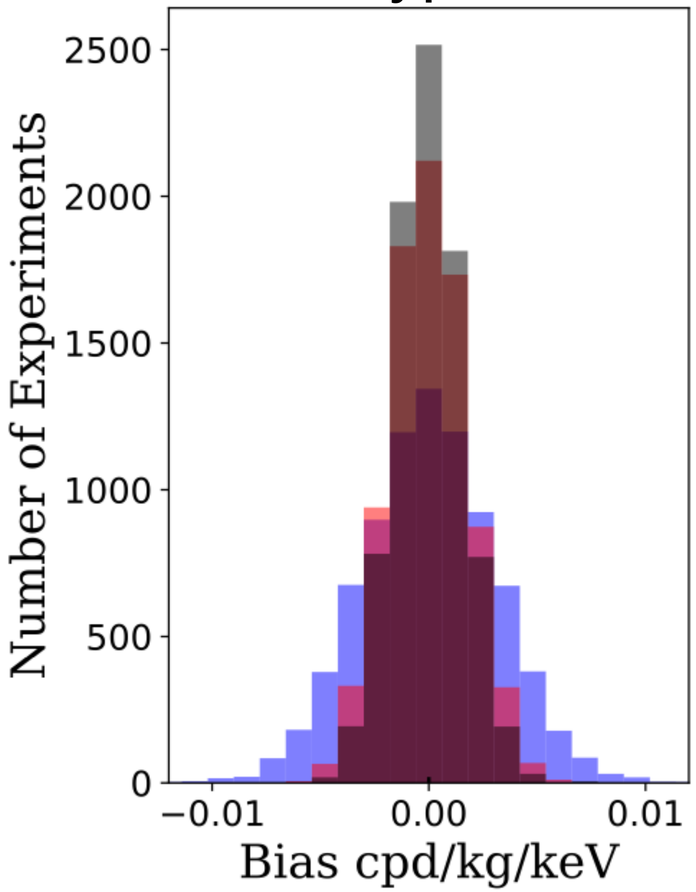
PRD 106, 052005 (2022)

Consistent w/ both DAMA & Null hypothesis

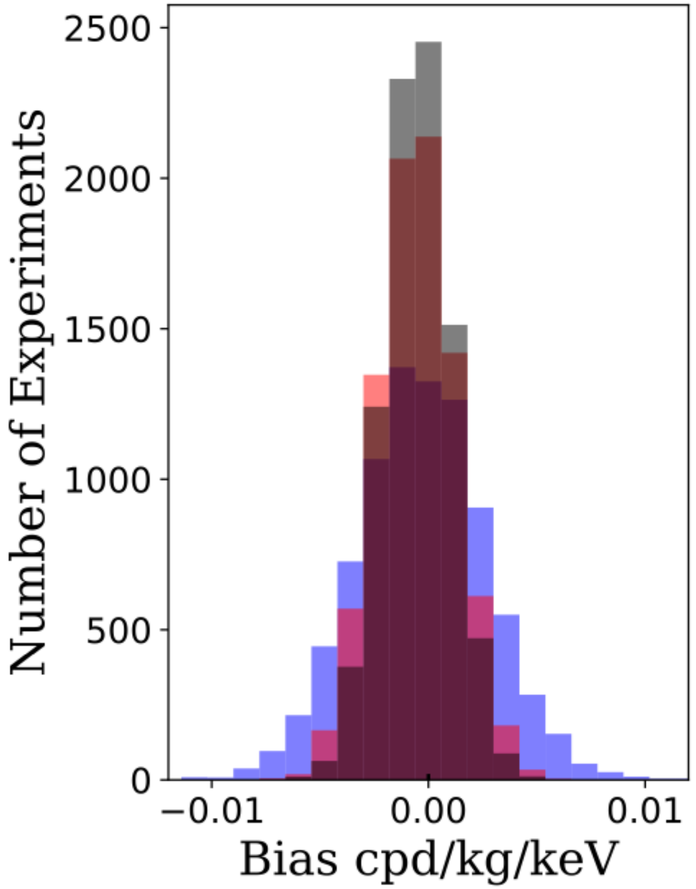
Bias check w/ simulation

COSINE-100 + ANAIS-112 3-year

Null-hypothesis



DAMA modulation



Blue : COSINE-100

Red : ANAIS-112

Black : Combined