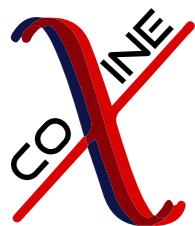


Dark matter search using NaI(Tl) at the COSINE-100 experiment

TMEX 2023

Gyunho Yu (IBS / Sungkyunkwan Univ.)

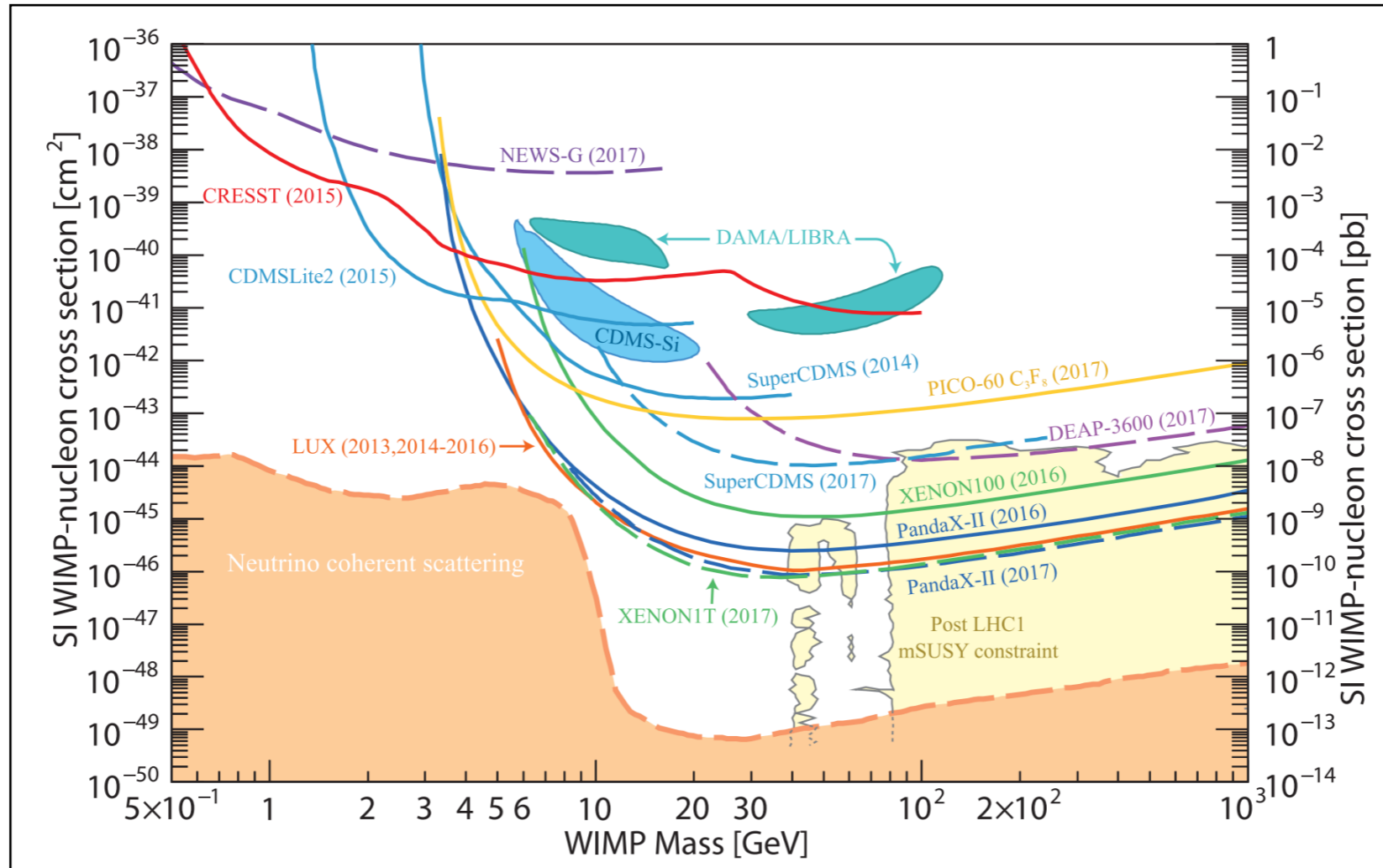
On behalf of the COSINE-100 collaboration



Motivation

DAMA/LIBRA experiment

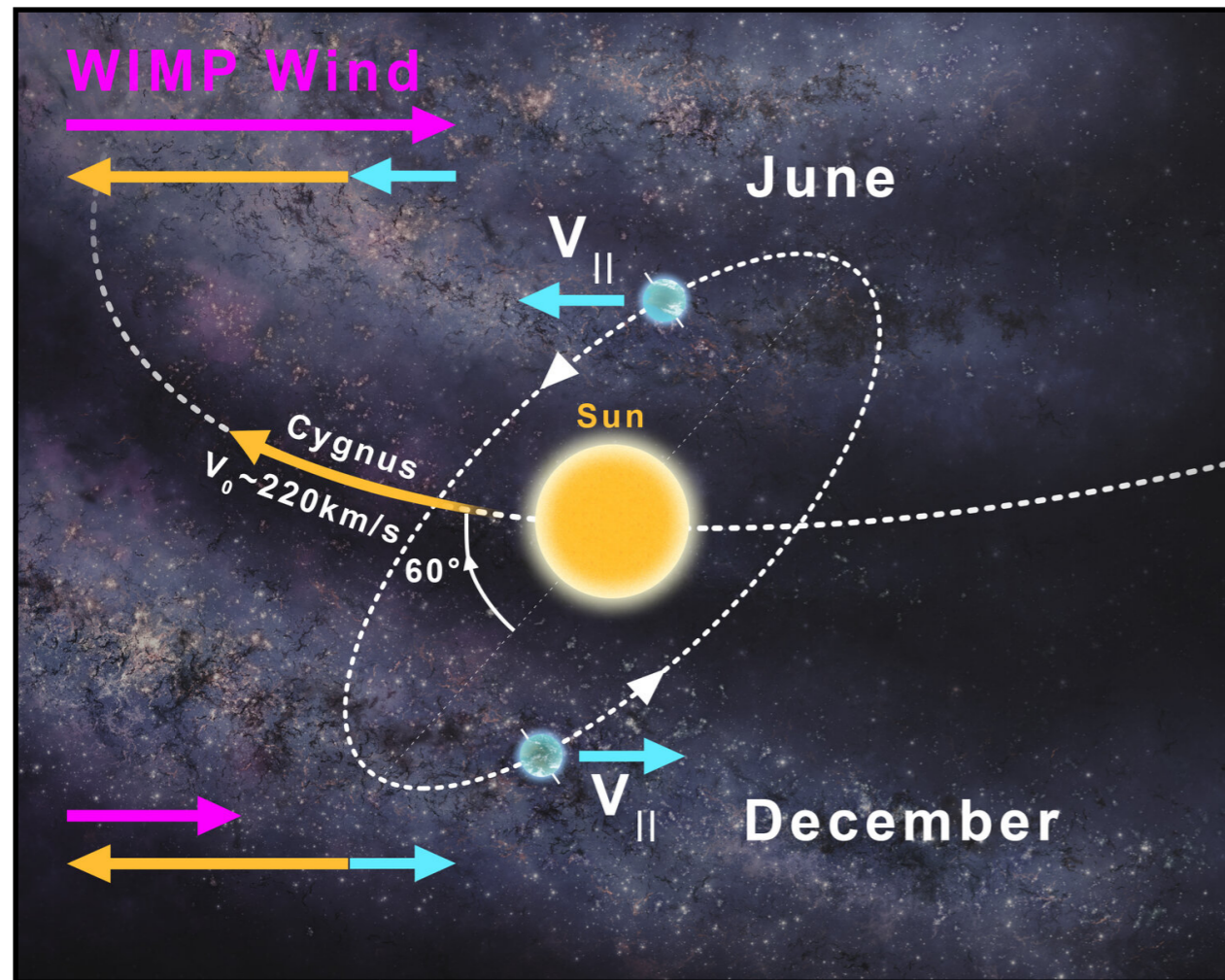
Ref : Phys. Rev. D 98, 030001 (2018)



- No other experiment has succeeded direct detection of DM, except **DAMA/LIBRA**

Motivation : WIMP Annual modulation

DAMA/LIBRA experiment



Rate of WIMP elastic scattering

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

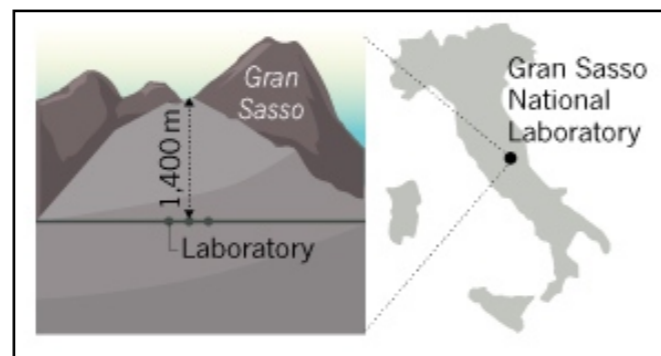
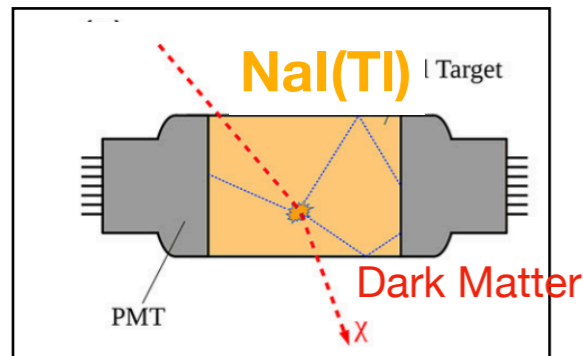
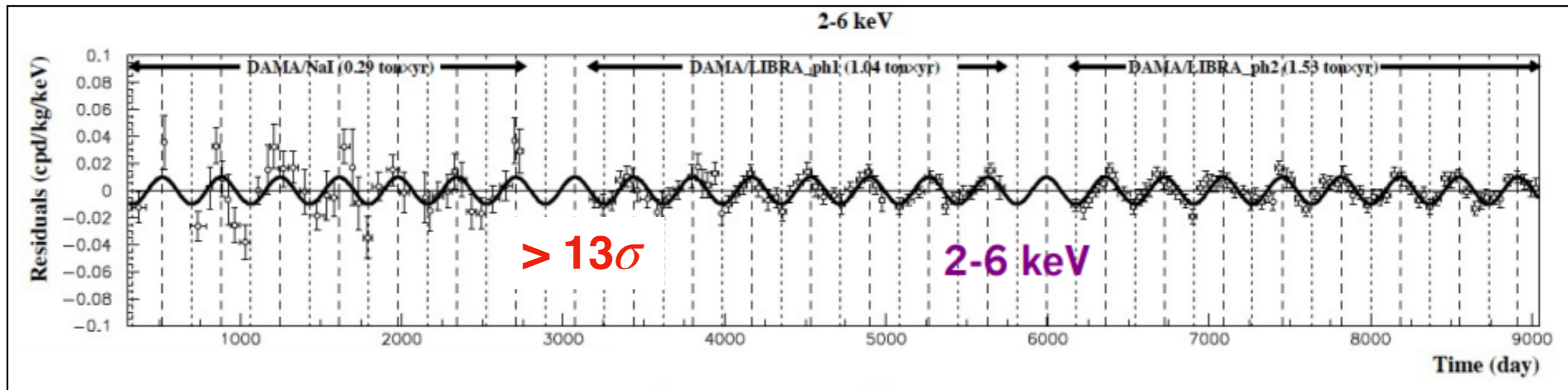
- No other experiment has succeeded direct detection of DM, except DAMA/LIBRA
- DAMA/LIBRA searches for **annual modulation signature by DM**

Motivation : WIMP Annual modulation

DAMA/LIBRA experiment

DAMA/LIBRA Modulation signal

P.Belli, EPS-HEP Conference (2021)



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- **Compatible with the nature of DM** candidate

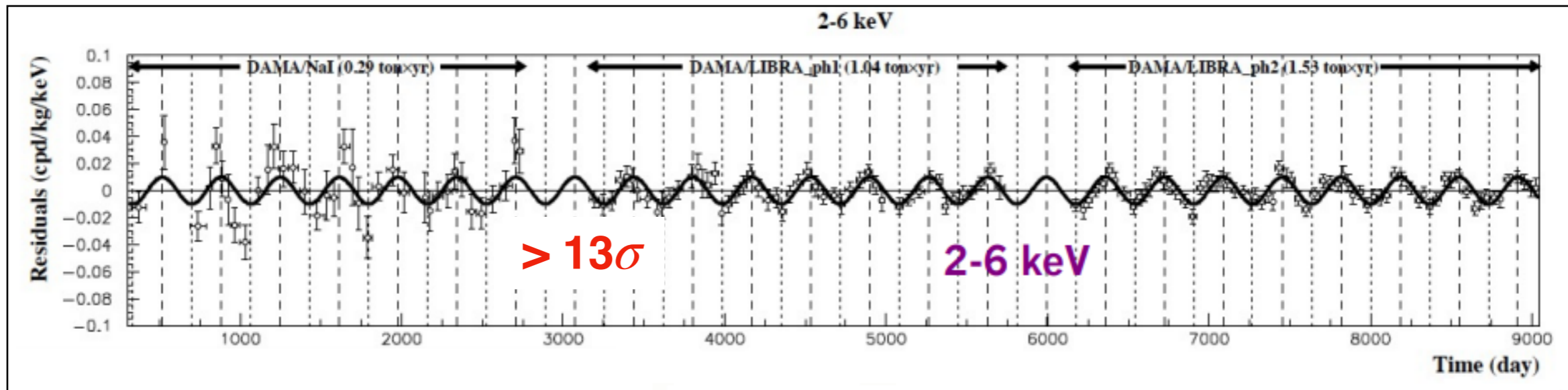
$$A = 0.0096 \pm 0.0008 \text{ counts/day/kg/keV,}$$
$$\phi = 145 \pm 5 \text{ days}$$
$$T = 0.9987 \pm 0.0008 \text{ yr)}$$

Motivation : WIMP Annual modulation

DAMA/LIBRA experiment

DAMA/LIBRA Modulation signal

P.Belli, EPS-HEP Conference (2021)



Q. Why dark matter only seen in DAMA/LIBRA ?

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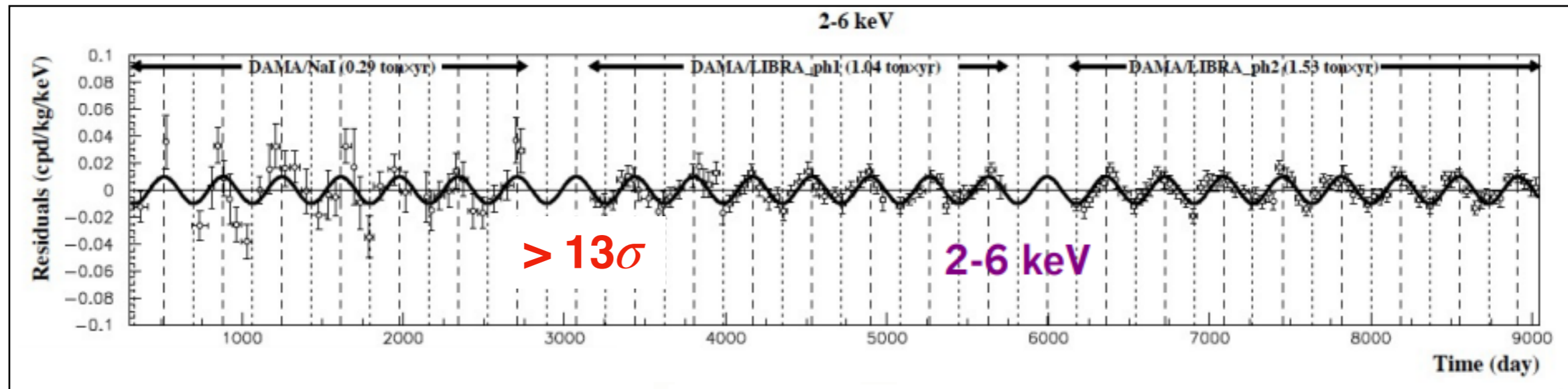
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Motivation : WIMP Annual modulation

DAMA/LIBRA experiment

DAMA/LIBRA Modulation signal

P.Belli, EPS-HEP Conference (2021)



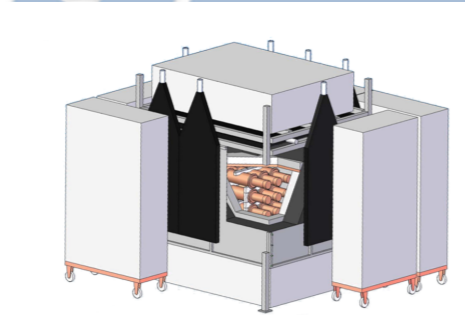
Q. Why dark matter only seen in DAMA/LIBRA ?

⇒ NaI(Tl) is special target for DM interaction?

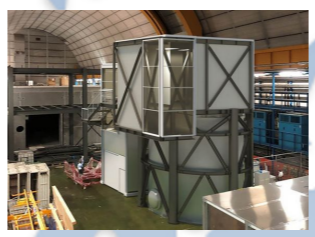
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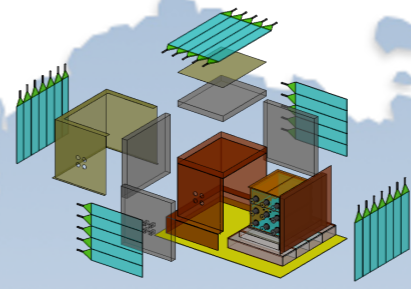
NaI(Tl) Experiments



ANAIS
(Canfranc)



COSIUS
(LNGS)



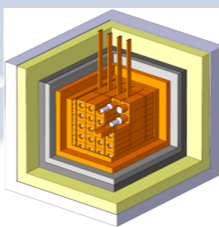
COSINE
(YangYang)



PICO-LON
(Kamioka)



DAMA
(LNGS)



SABRE
(LNGS)



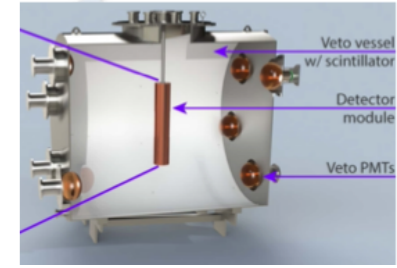
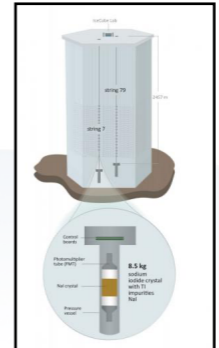
SABRE
(Stawell)



DAMA/LIBRA
ANAIS-112
COSINE-100

In data taking!

DM Ice
(South Pole)



COSINE-100

COSINE-100 Collaboration

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

DM-ICE +



=



KRISS



UST



The University of Sheffield.



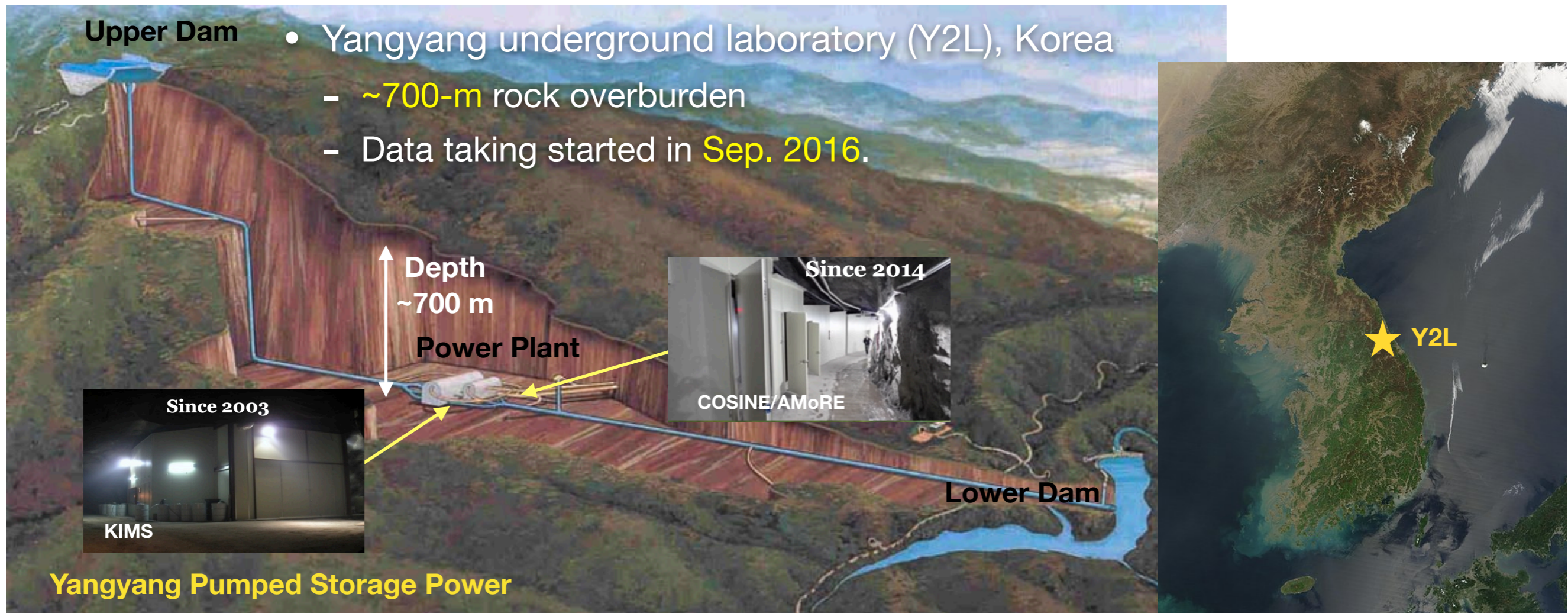
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Yale

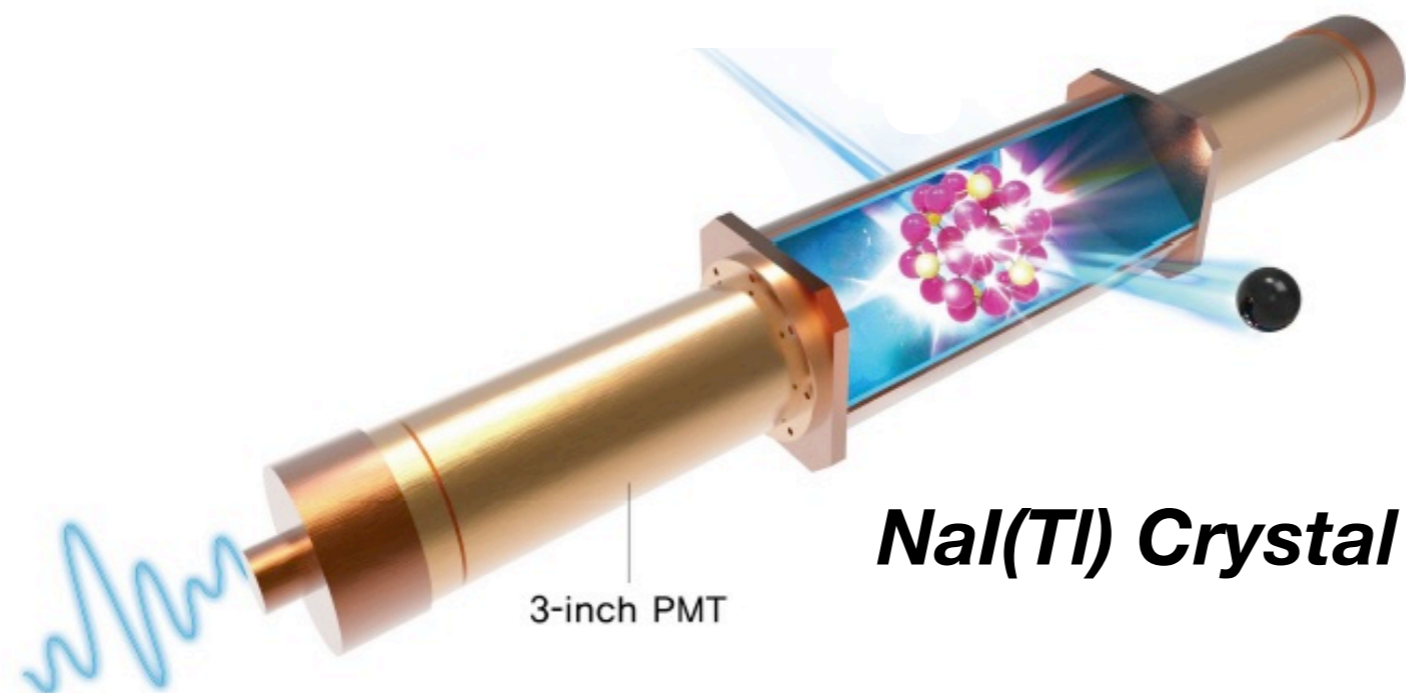
COSINE-100

COSINE-100 Collaboration & Experimental Site

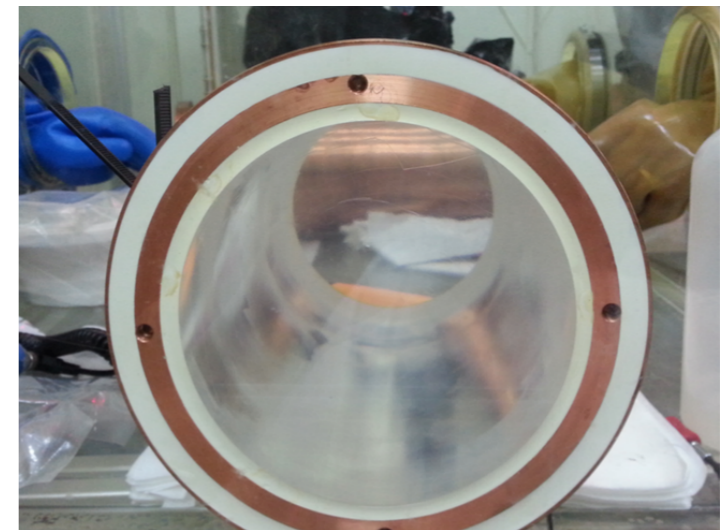
- Joint collaboration of DM-ICE & KIMS
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 - To confirm/refute DAMA/LIBRA, using same target material (NaI(Tl) Crystal)



COSINE-100 Detector



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

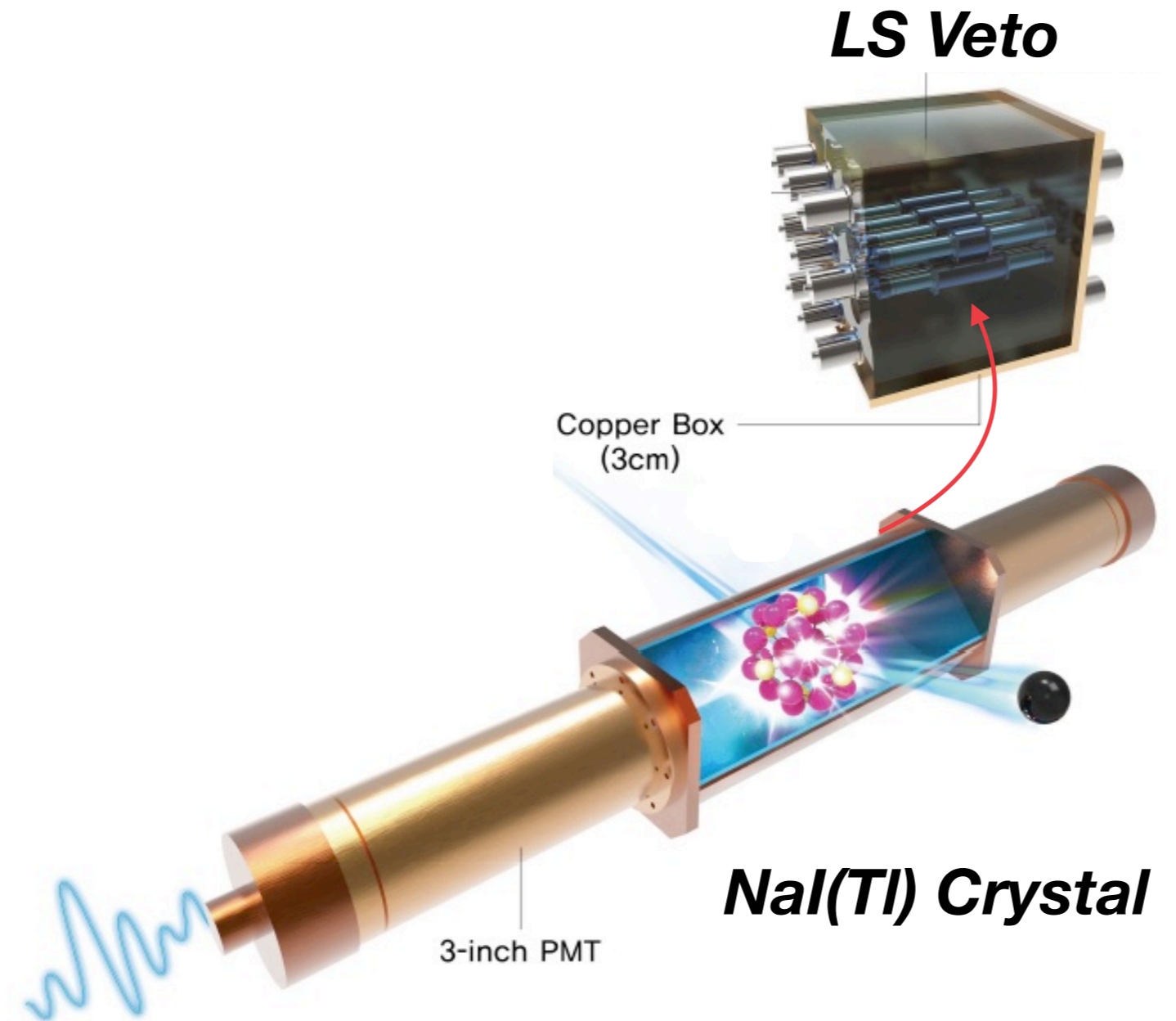


Same Target as DAMA/LIBRA experiment

- 8 Low Background NaI(Tl) Crystals with 106 kg total
- **Higher Light Yield** (15 p.e./keV) than DAMA/LIBRA (5-10 p.e./keV) *p.e. = photoelectrons
- Crystals encapsulated with copper case, attached with two 3-inch PMTs (R12669SEL)

COSINE-100 Detector

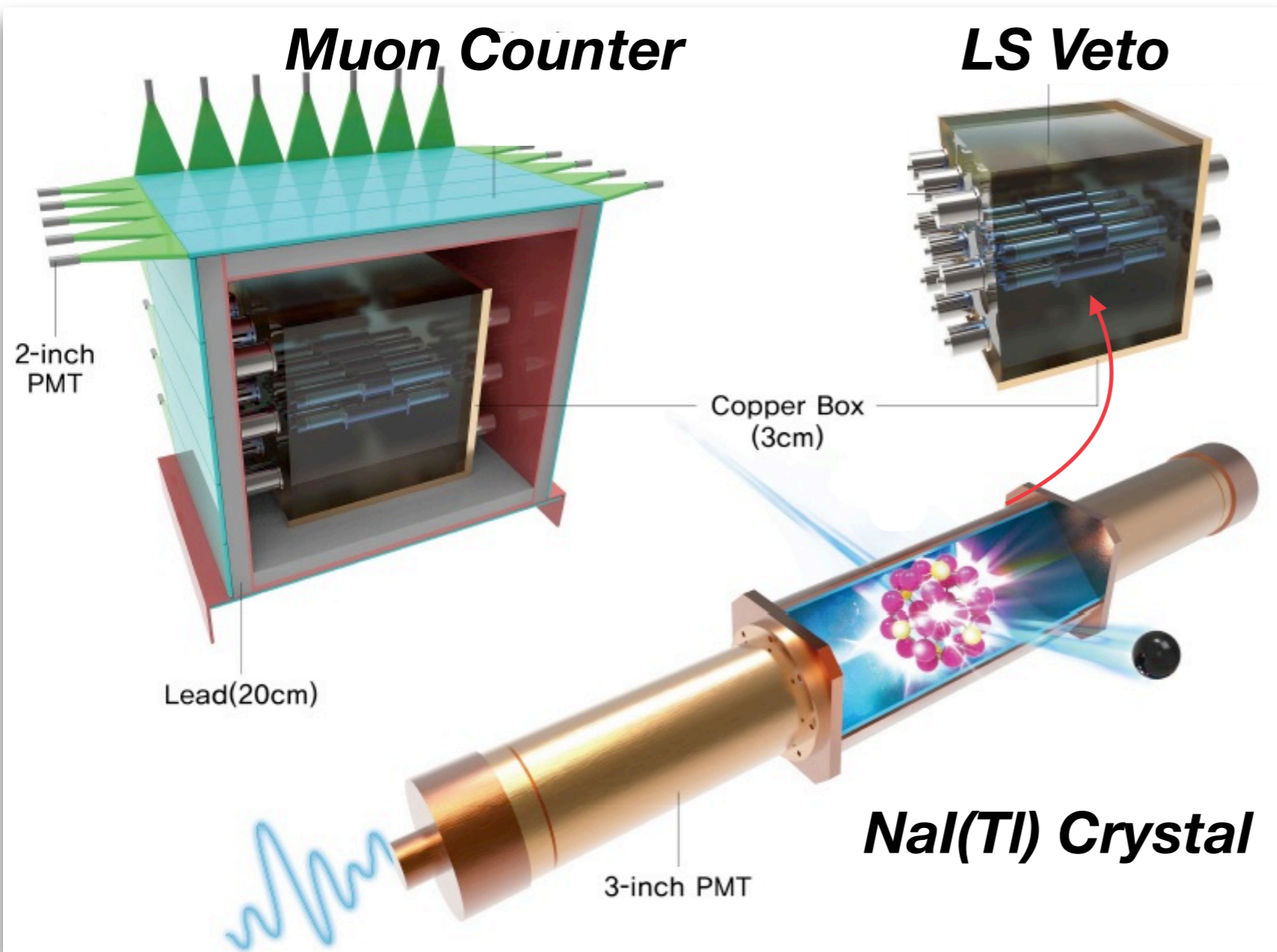
Nucl. Instrum. Methods Phys. Res., Sect. A 1006, 165431 (2021).



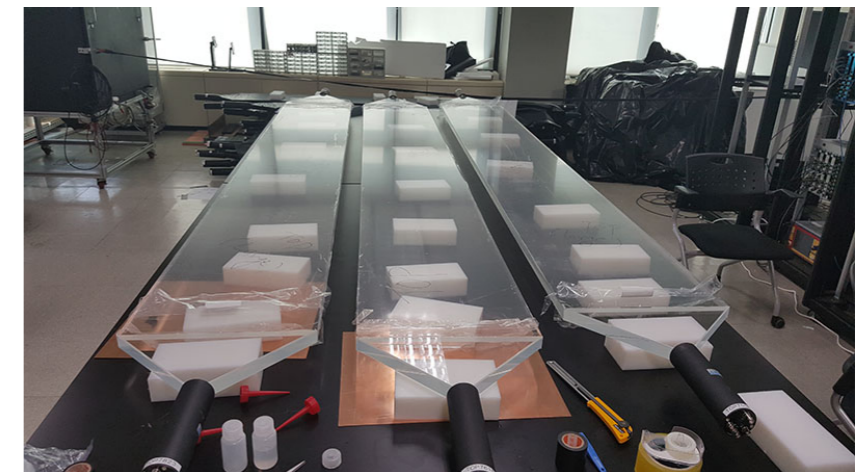
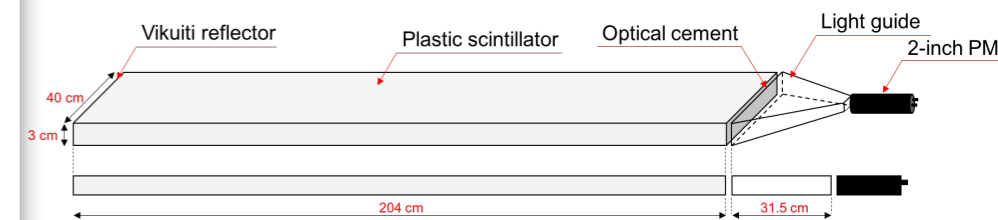
Liquid Scintillator(LS) active shield

- 2200L LAB based LS for Veto.
- 5-inch PMTs_(R877) for LS detector
- LS is contained in a 3cm thick Copper Box

COSINE-100 Detector



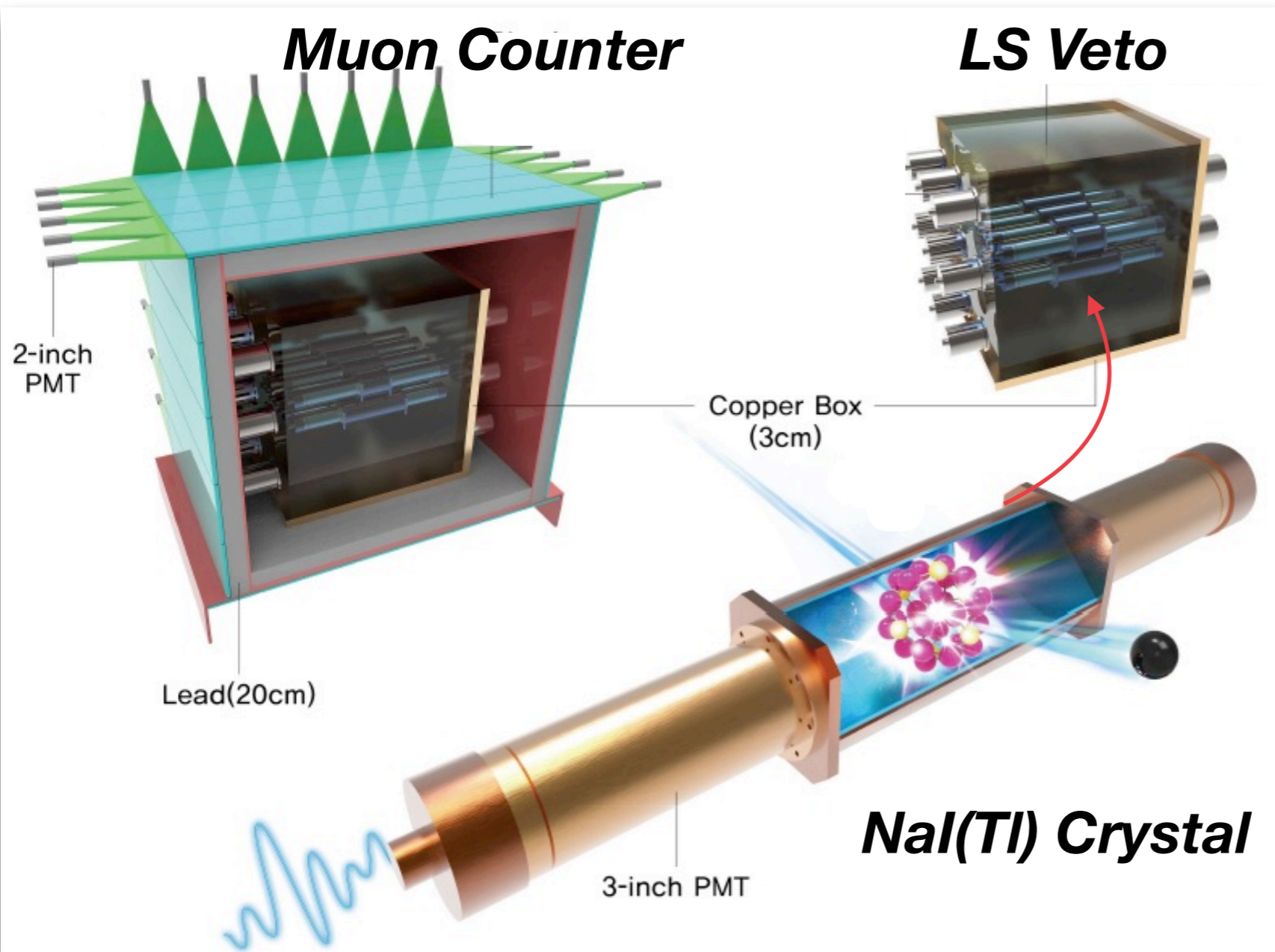
JINST 13 T02007 (2018)



Muon counter

- 37 muon counters using plastic scintillators.
- 2-inch PMT_(H7195)s for muon counters.
- Lead shield (20cm) inside muon counters.

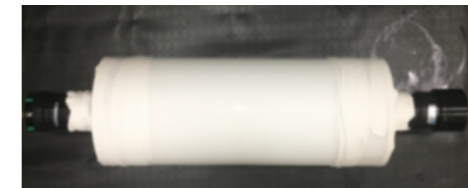
COSINE-100 Detector



JINST 13 T06005 (2018)

Neutron Monitoring Detector

Fast neutron detector
(Liquid scintillator)



Thermal neutron detector
(^3He gas detector)



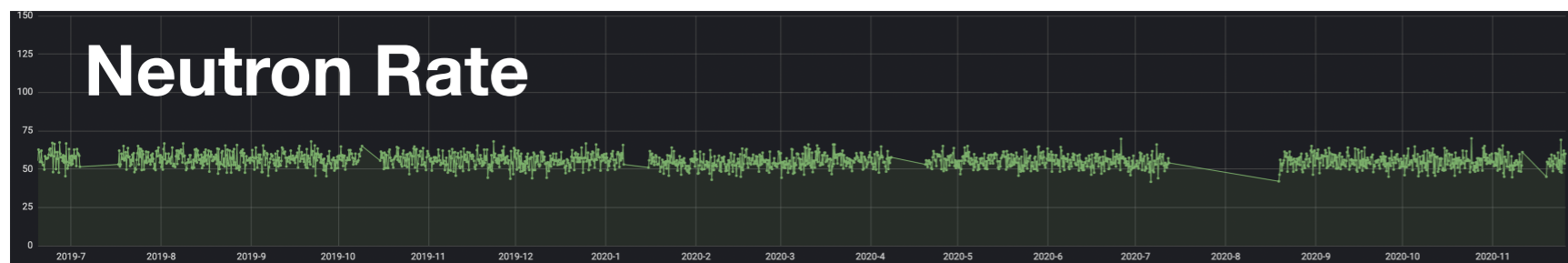
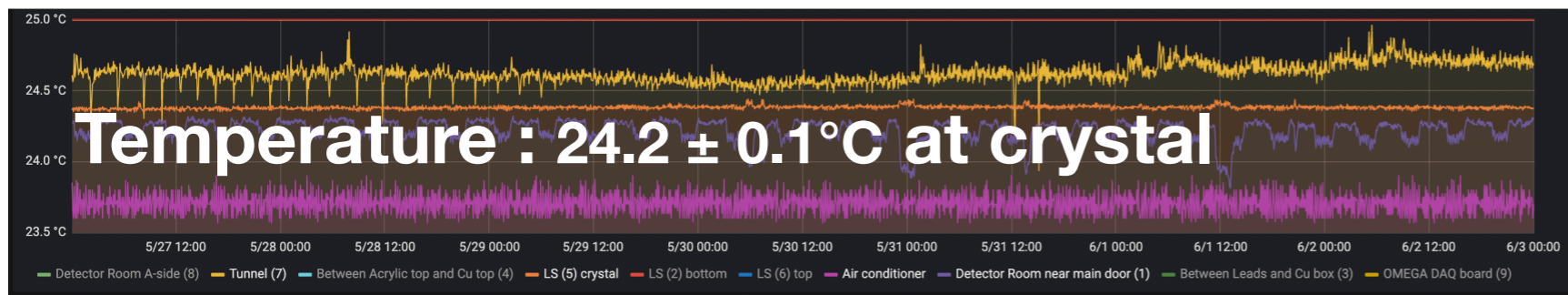
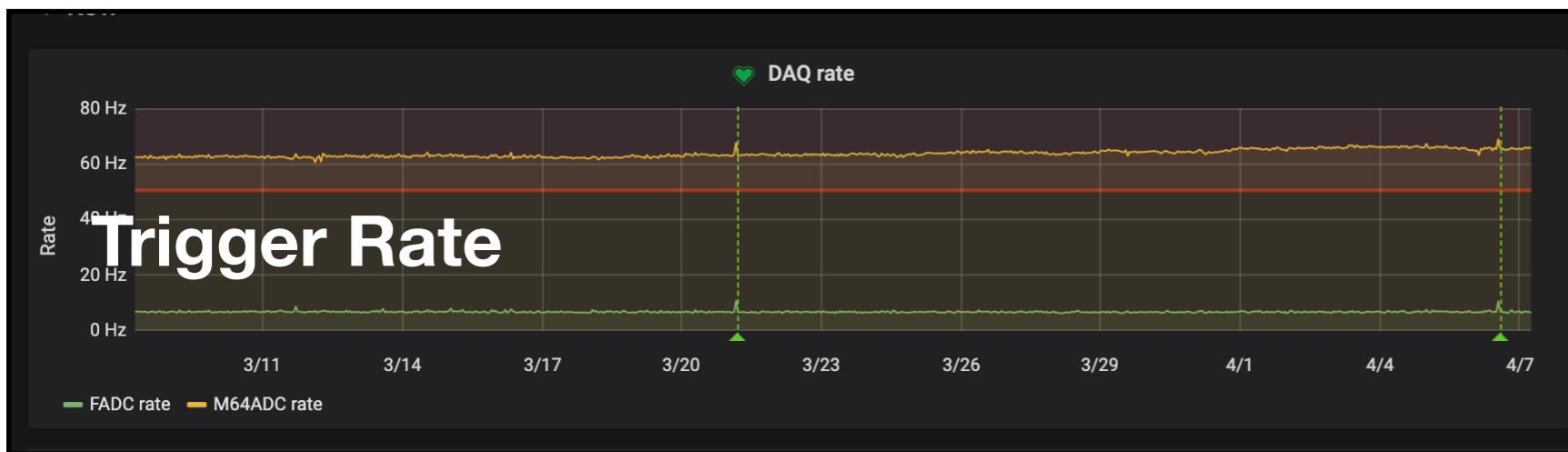
Neutron monitoring detector

- Possibility that neutron recoil events can be misunderstood as WIMP events.
- Detectors for each of Fast / Thermal neutron is installed at the detector room

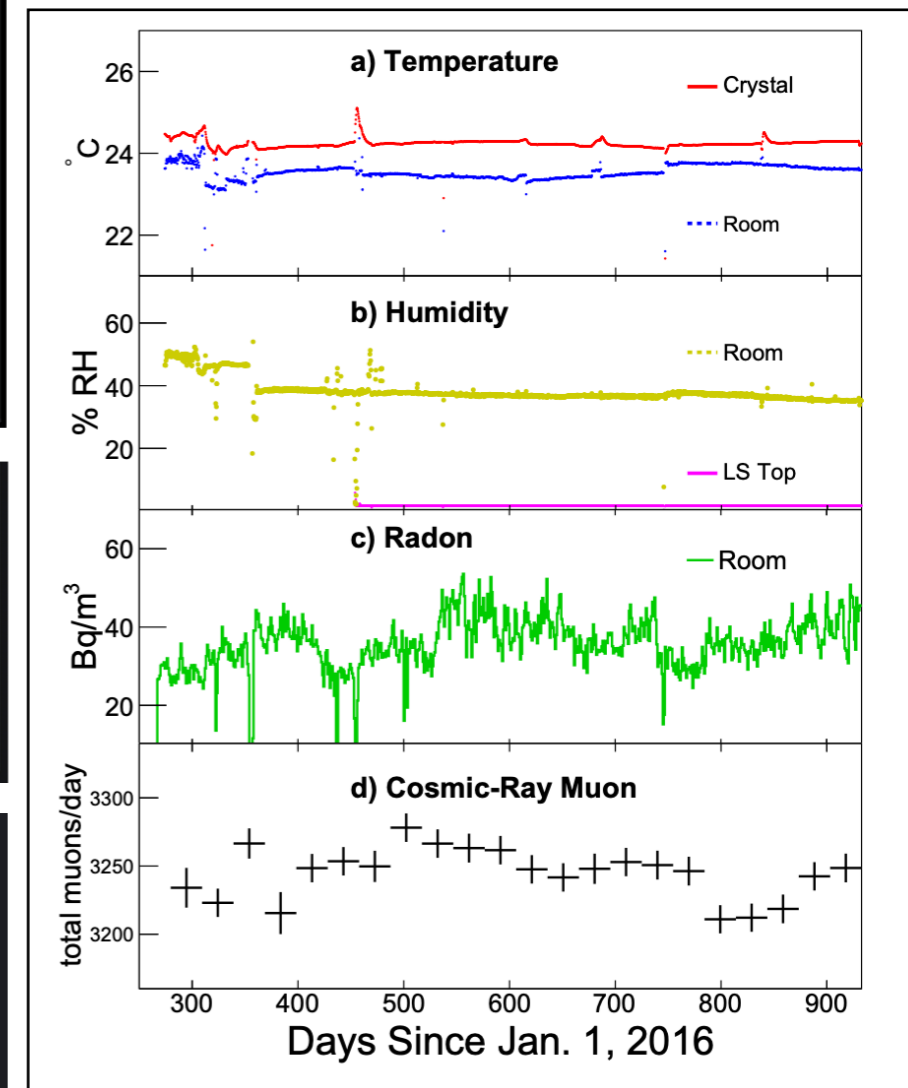
COSINE-100 Detector

Monitoring >200 parameters

- DAQ system: Trigger rate, High voltage, PMT current ..
- Stable environment parameters : Temperature, Humidity ..
- Neutron rates



Phys. Rev. Lett. **123**, 031302 (2019)



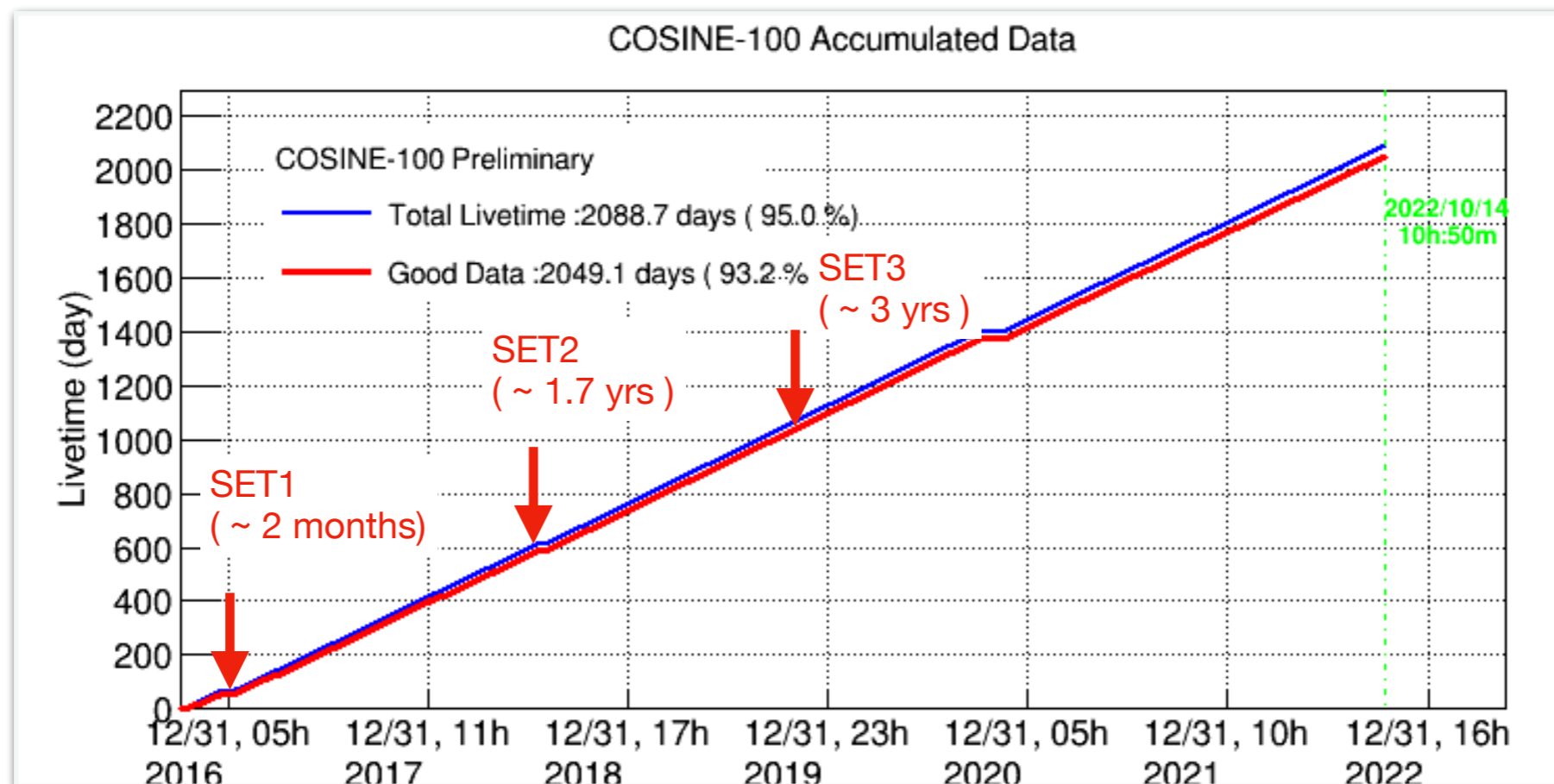
COSINE-100 Detector

Monitoring >200 parameters

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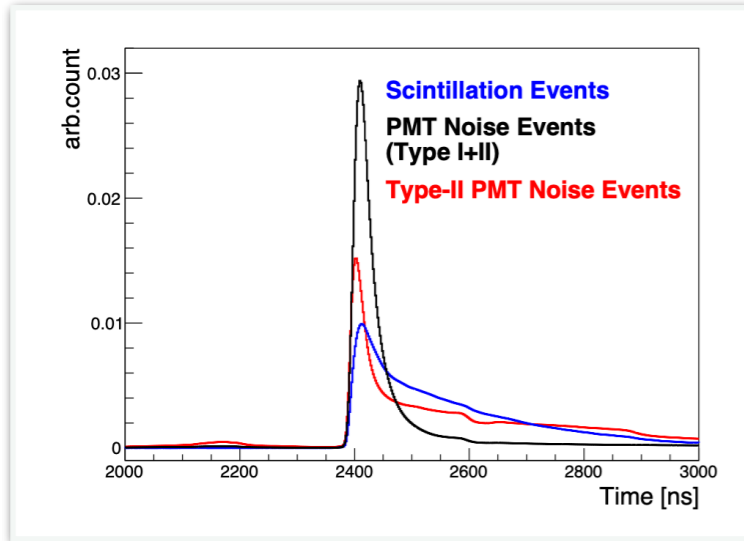
Stable runs from Sep. 30th, 2016

- DAQ efficiency: ~93% (Calibration runs, Power outage ..)
- Exposure time ~6 years.



Event selection

Waveform difference according to event types

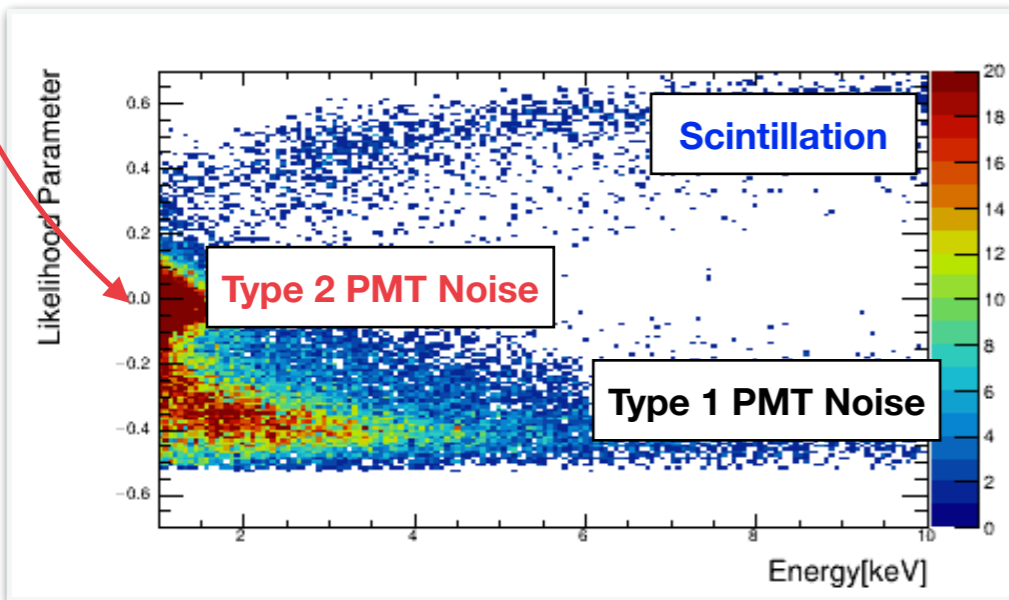


Event Selection

- Need to separate **PMT-noise** from **scintillation** events.
- **Developed effective parameters** based on characteristics of each event.

Example of effective parameters : Likelihood parameter

Astropart. Phys. 130 (2021) 102581



***Effective
Parameters***

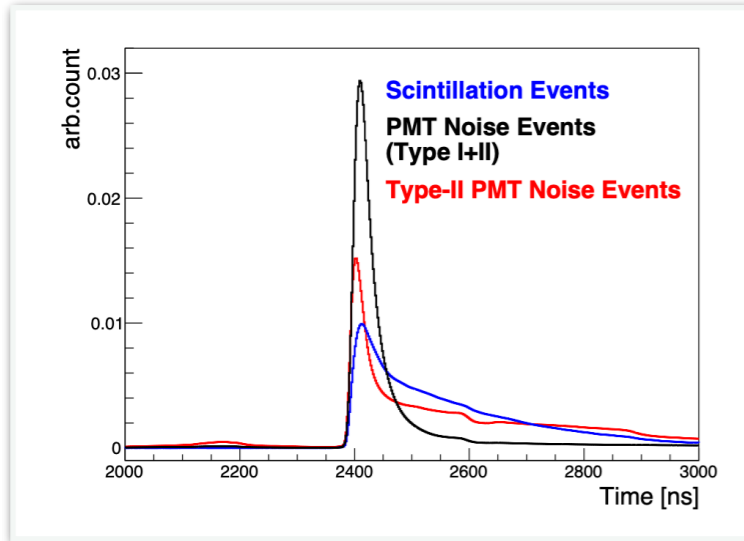
Parameter1

Parameter2

...

Event selection

Waveform difference according to event types

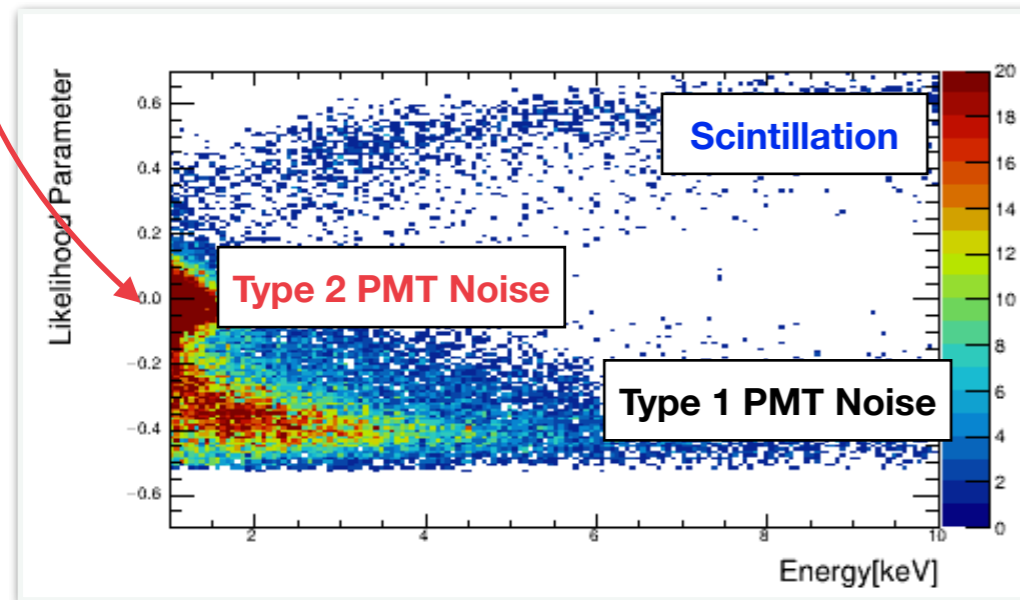


Event Selection

- Need to separate **PMT-noise** from **scintillation** events.
- **Developed effective parameters** based on characteristics of each event.
- Used **BDT Training** to achieve **1 keV** Threshold.

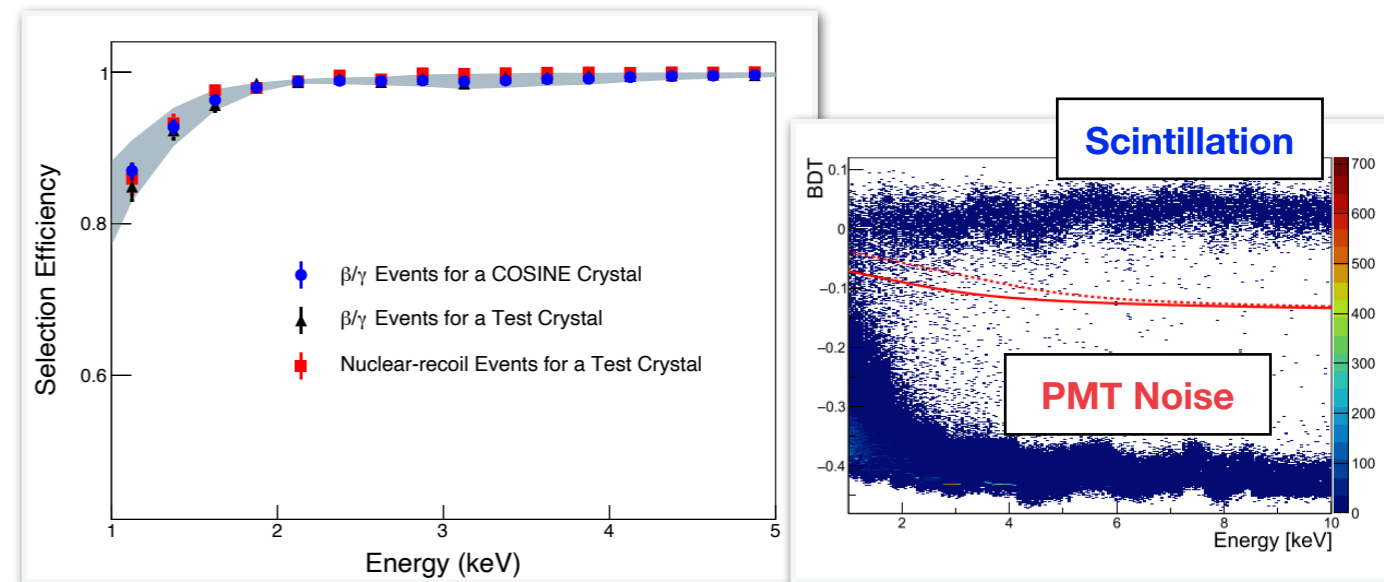
Example of effective parameters : Likelihood parameter

Astropart. Phys. 130 (2021) 102581



BDT variable and its efficiency with 1 keV threshold study

Astropart. Phys. 130 (2021) 102581



Effective Parameters

- Parameter1
- Parameter2
- ...

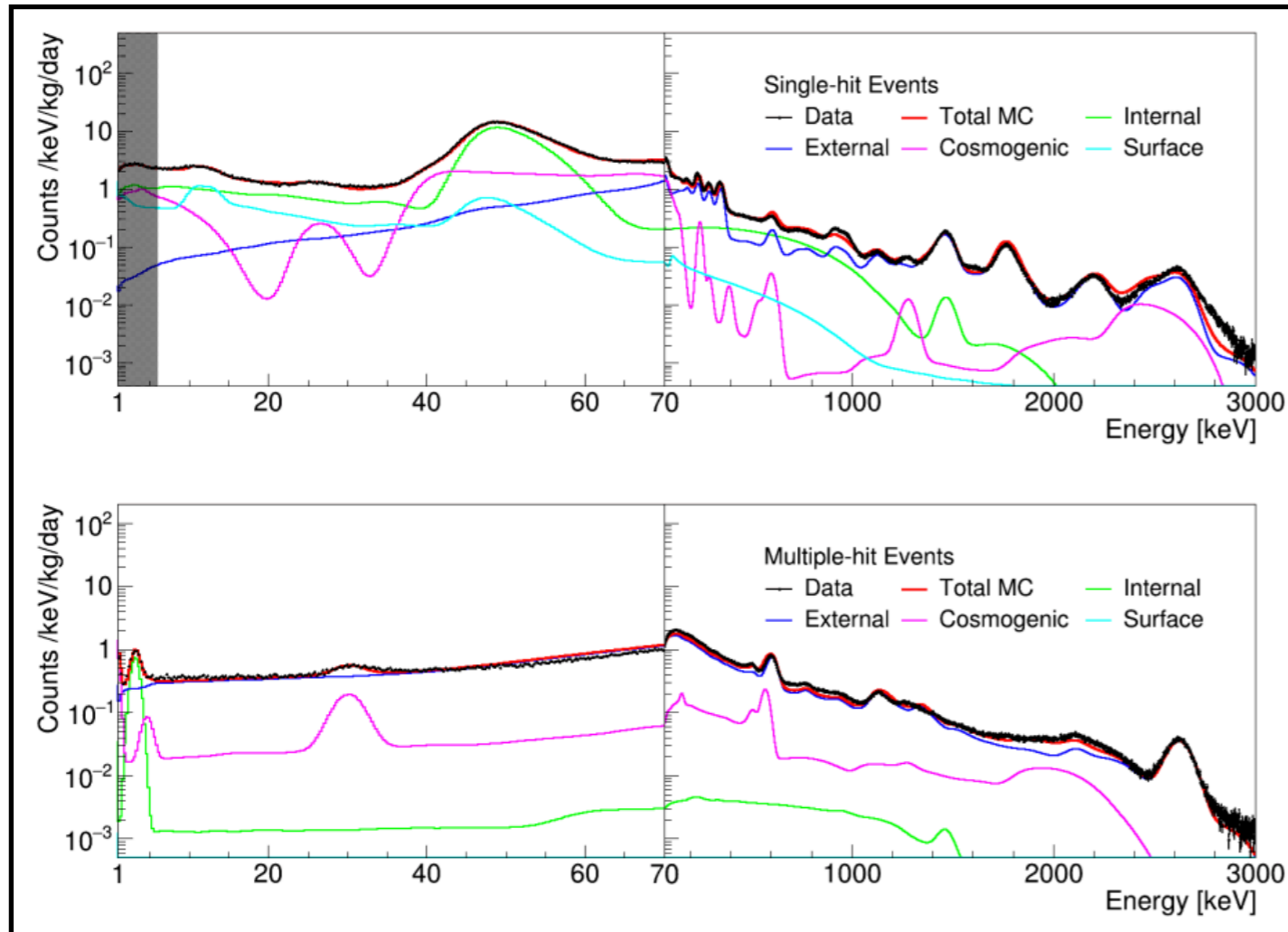
Multi variable Technique (TMVA BDT)

BDT Parameter

WIMP spectral analysis

COSINE-100 Background modeling with 1.7 years data

Eur. Phys. J. C. 81 837 (2021)



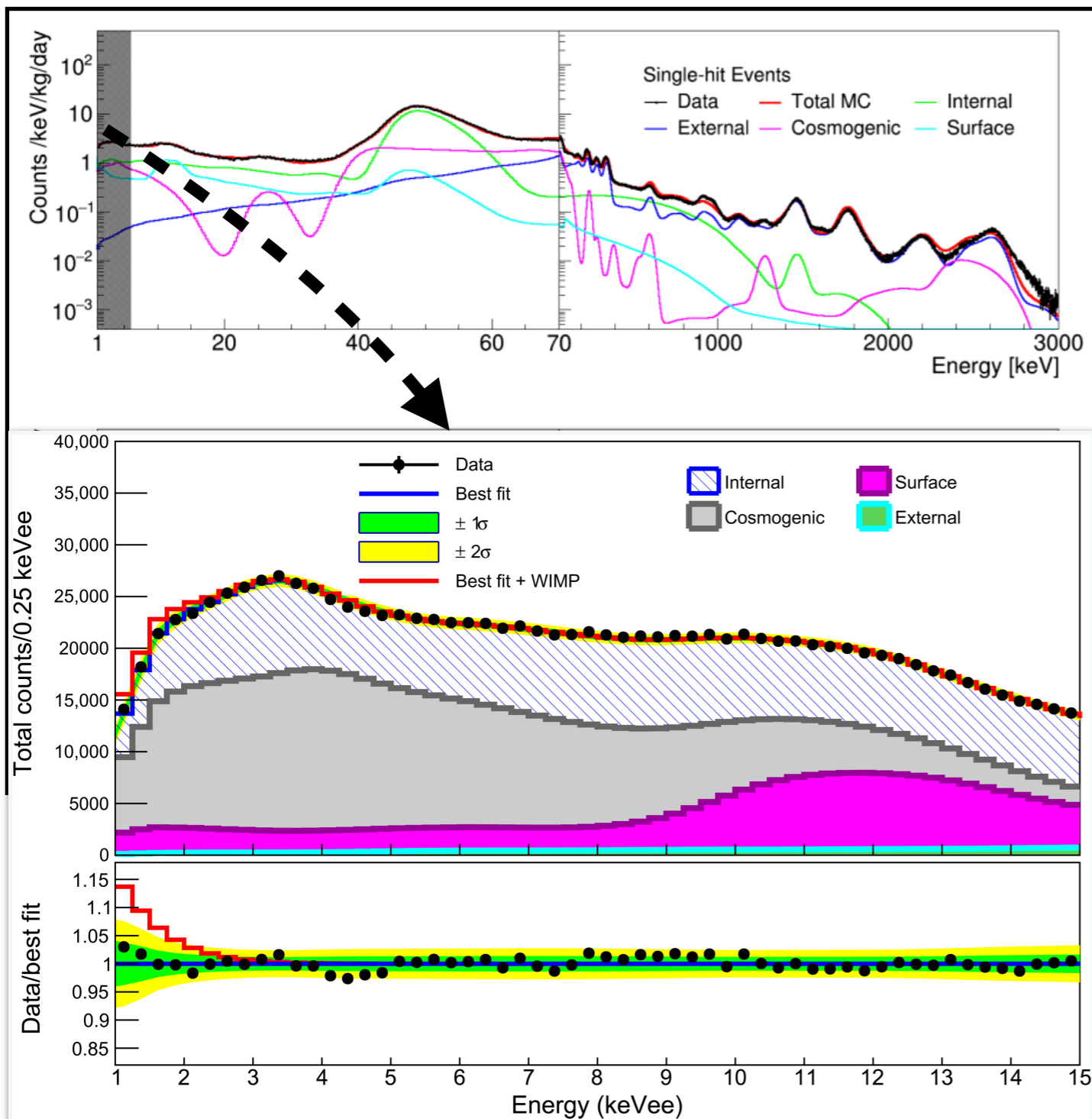
Background modeling

- Single / Multiple Hit : time coincidence w/ other crystal or LS veto's event.
- Understand data spectrum using Geant4 MC Spectrum.
- **WIMP ROI (<6 keV, shaded region) is not used** at modeling, and extrapolated from higher energy's fitting result.

WIMP spectral analysis

COSINE-100 Background modeling with 1.7 years data

Eur. Phys. J. C. 81 837 (2021)



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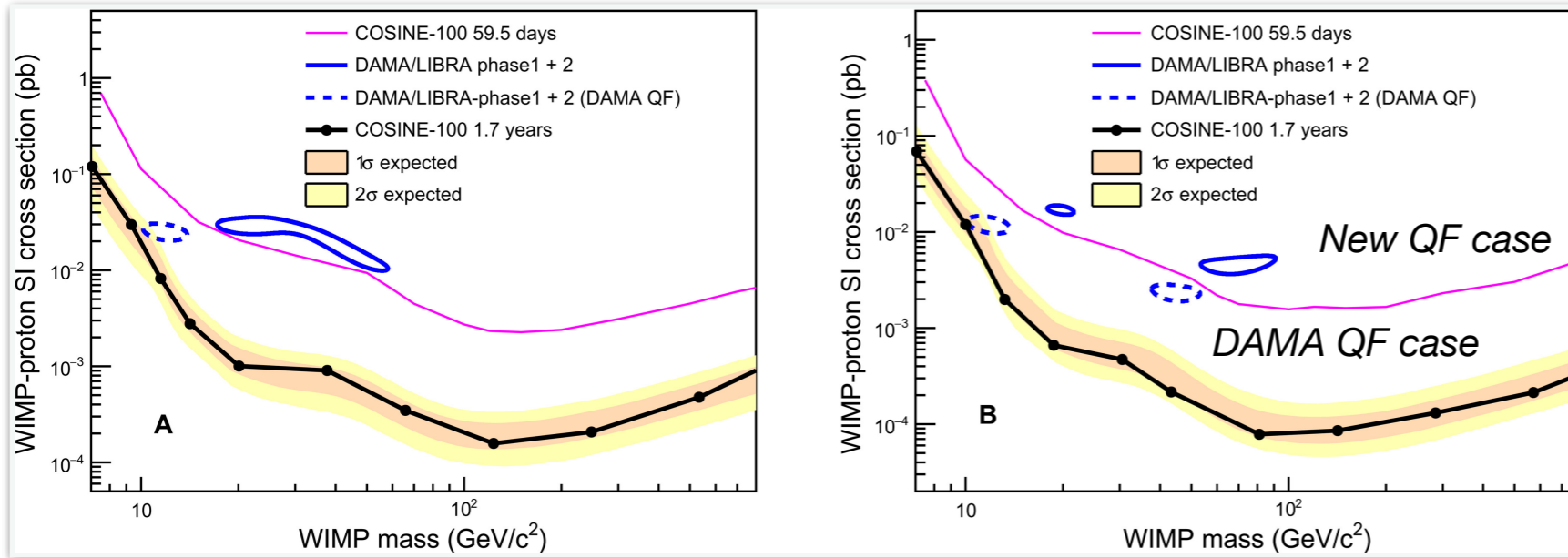
No WIMP Signal till 1 keV

WIMP Region of Interest
Science Advances. 7, 46 (2021)

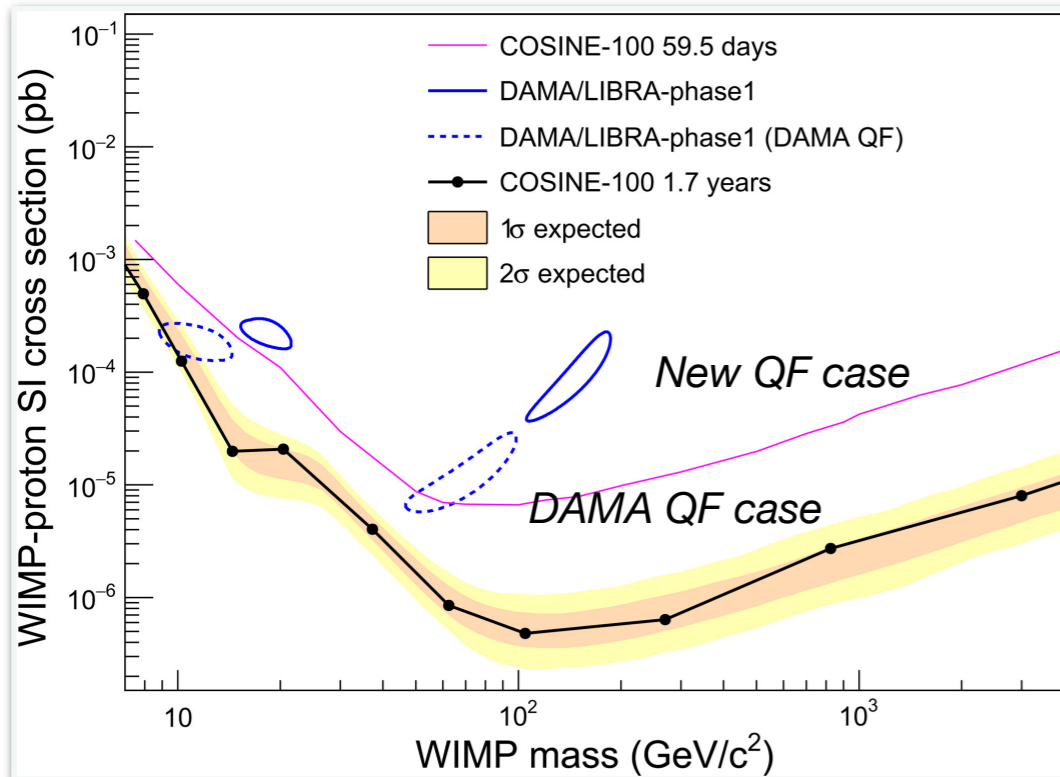
WIMP upper limit

1. Isospin violating case. 'Na' (Left) and 'I' (Right) target each

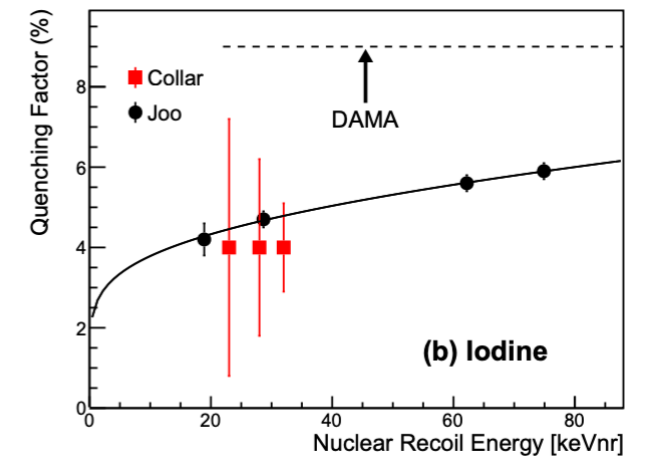
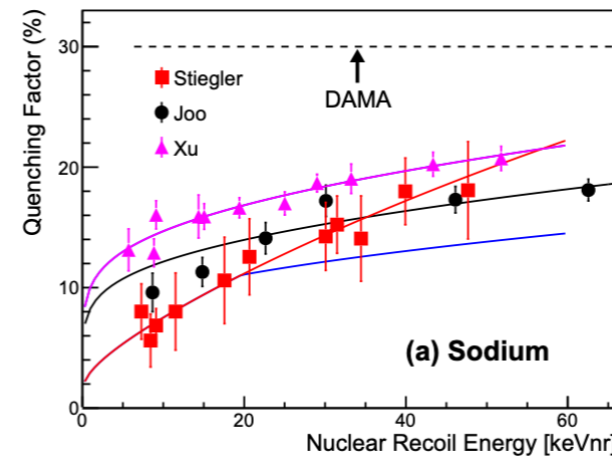
Science Advances. 7, 46 (2021)



2. Isospin conserving case.



Quenching factor comparison between New & DAMA's

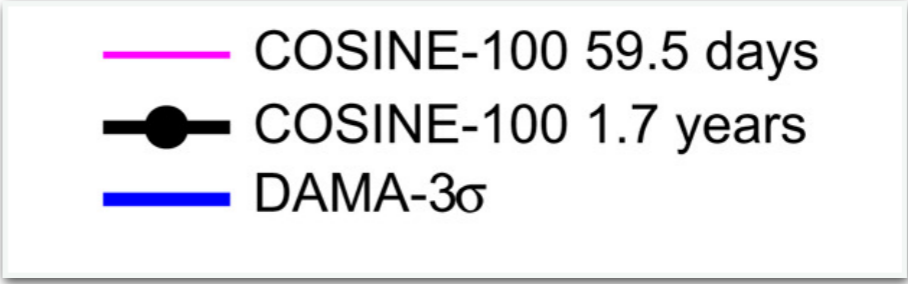
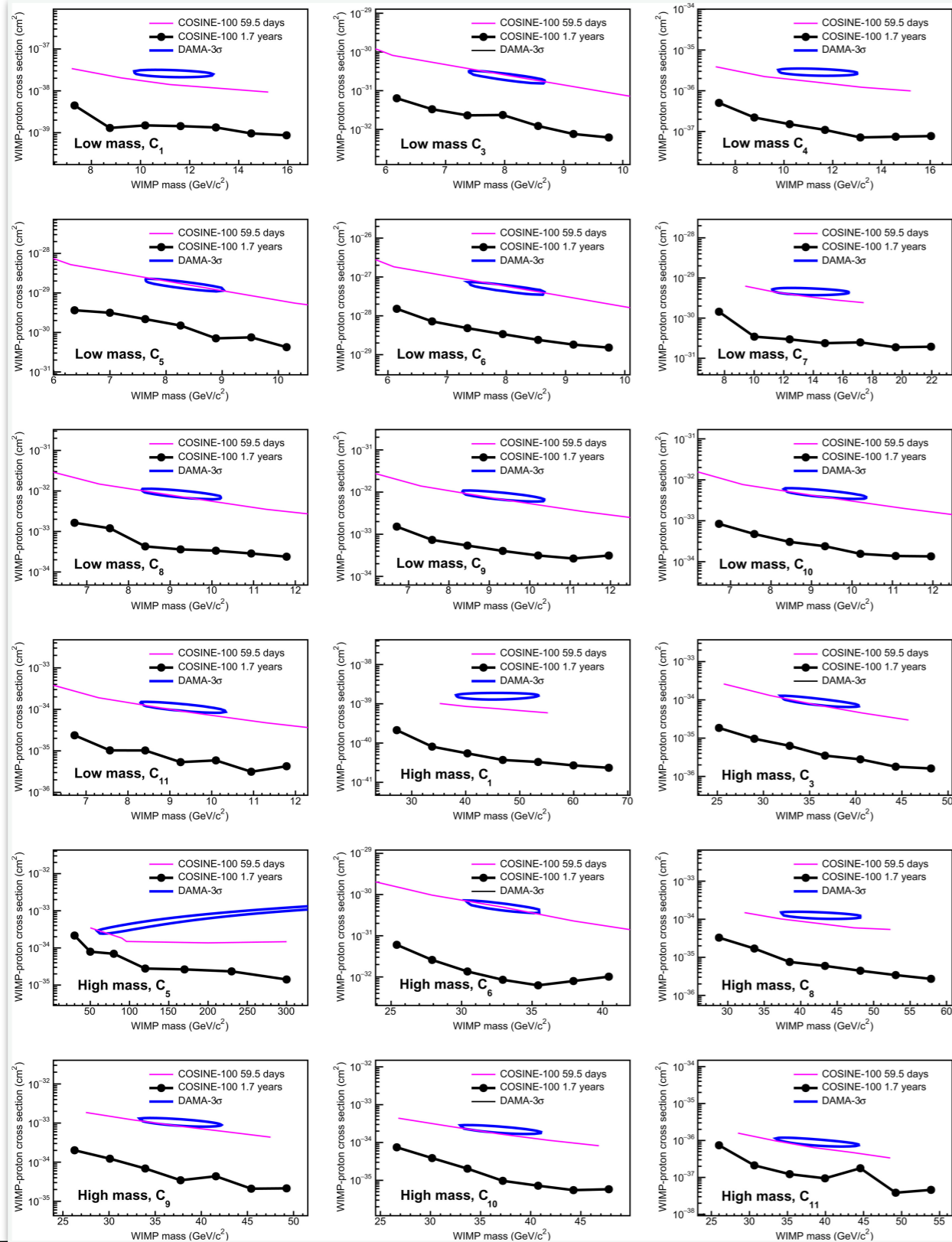


COSINE-100 1.7 years result excluded DAMA region

WIMP upper limit

3. WIMP-proton cross section for EFT operators.

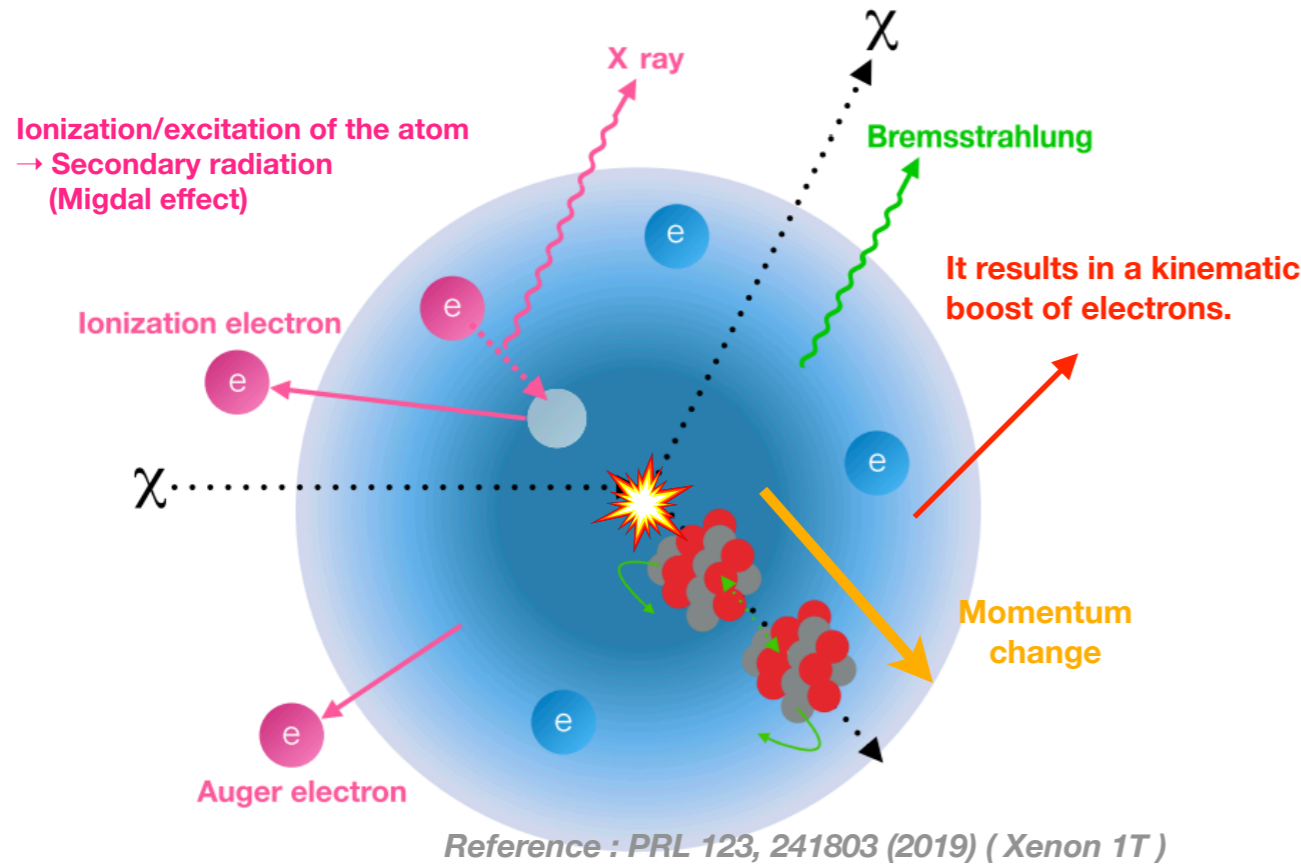
Science Advances. 7, 46 (2021)



Also excluded possible region for EFT operators.

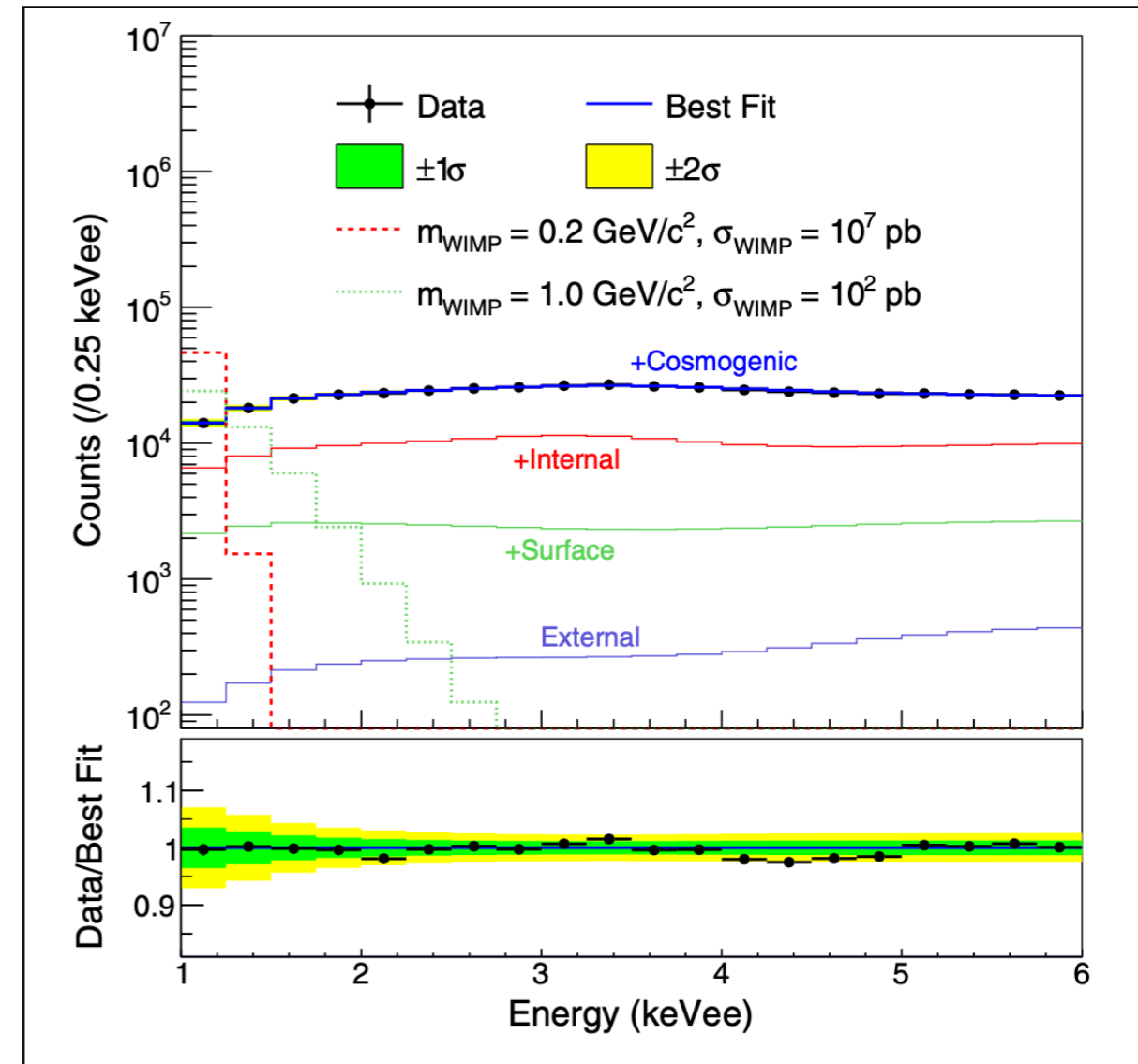
WIMP spectral analysis via Migdal Effect

Schematic diagram of Migdal effect



Migdal effect w/ WIMP mass 0.2 & 1.0 GeV/c²

Phys. Rev. D 105, 042006



No WIMP Migdal signal.

Migdal effect

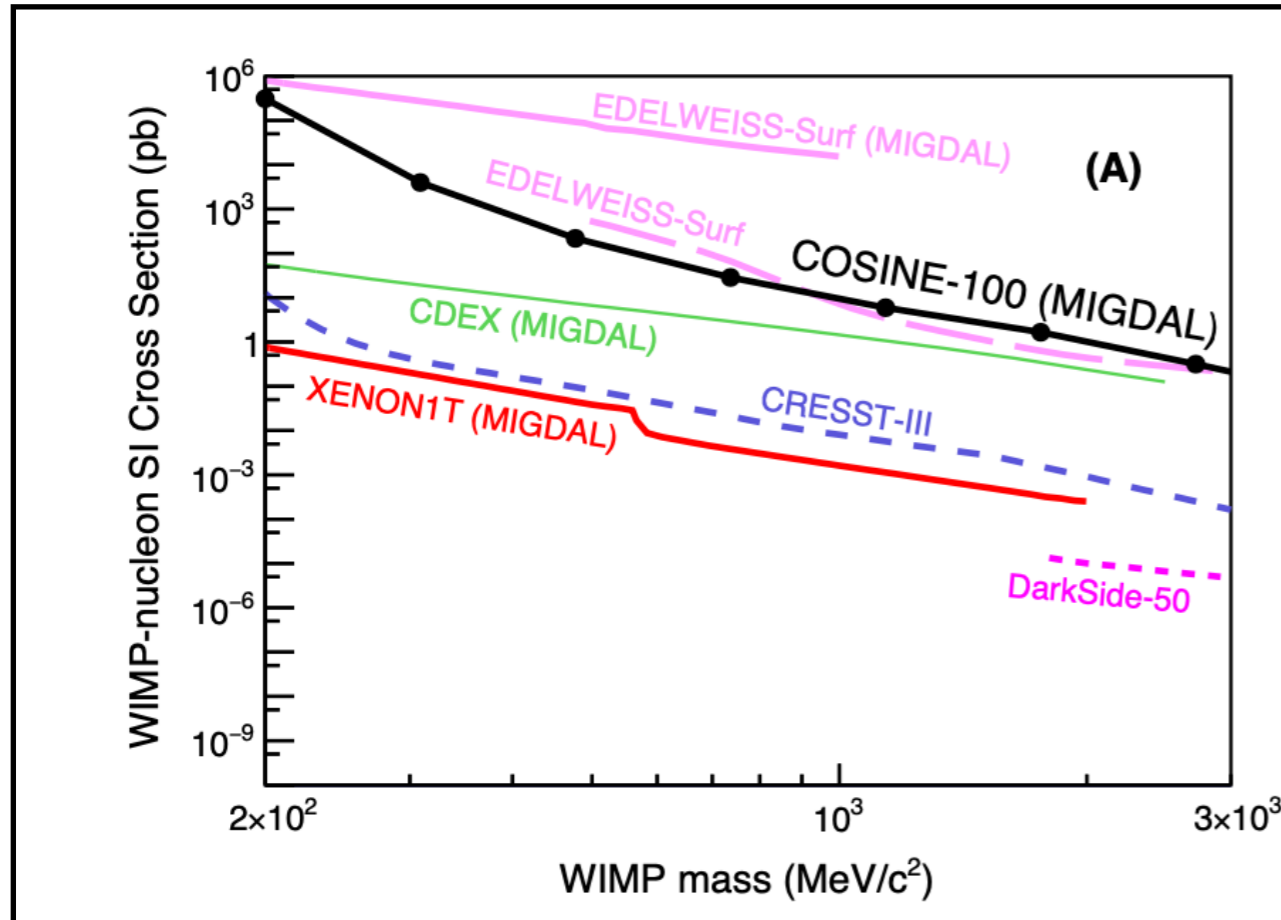
- Nuclear recoil → Boost of electrons → Secondary radiation
- Large visible energy of electron recoil compared to nuclear recoil.

→ enables to search **low mass WIMP**

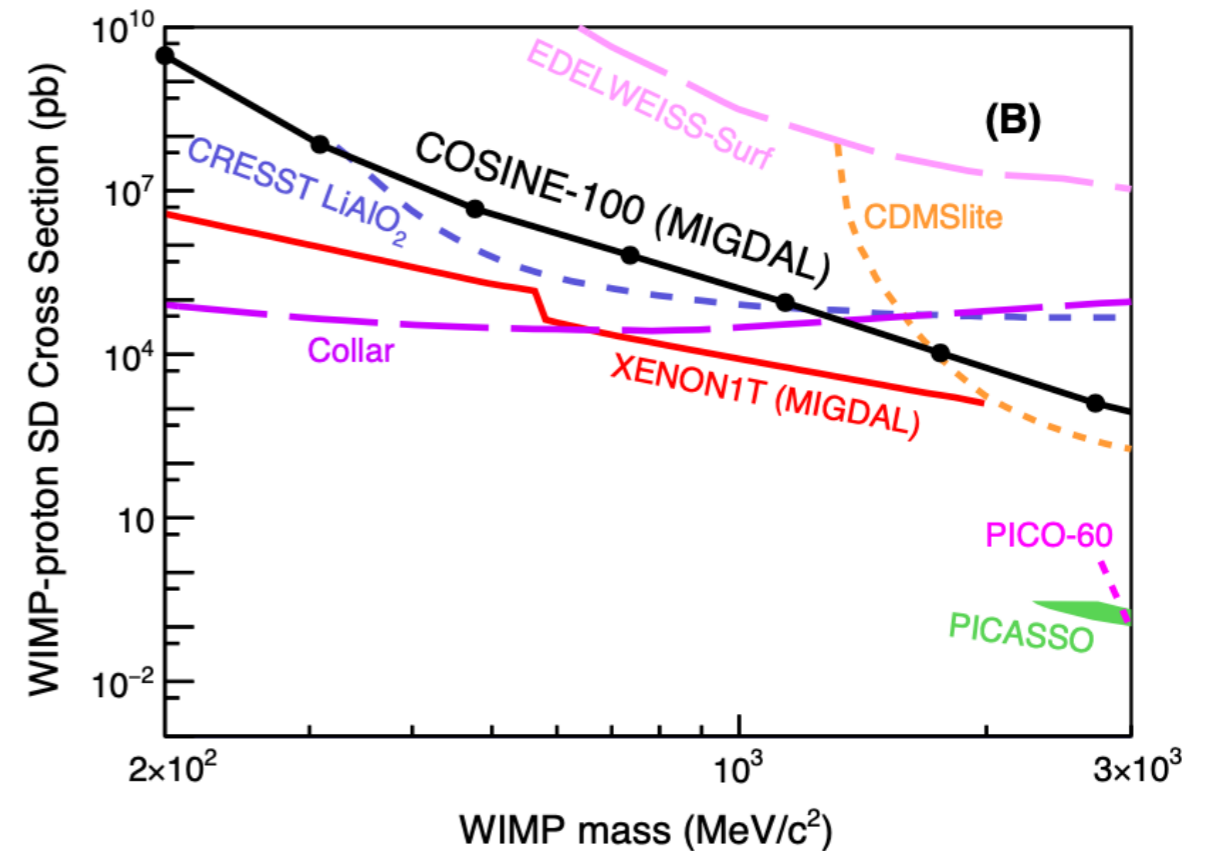
WIMP upper limit via Migdal Effect

WIMP-nucleon SI cross section w/ Migdal Effect

Phys. Rev. D **105**, 042006



WIMP-proton SD cross section w/ Migdal Effect



Migdal effect

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

→ enables to search *low mass WIMP*

Annual modulation analysis (3 years data)

Full model time dependent rate fitting

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

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

Rate of i^{th} Crystal

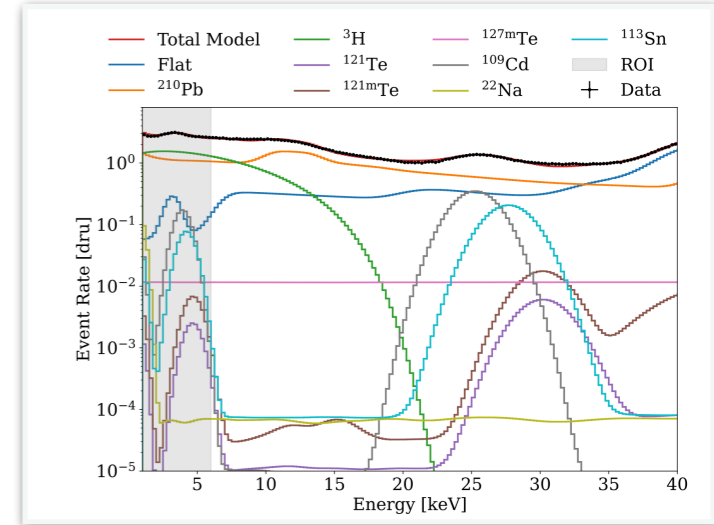
Crystal specific background components

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

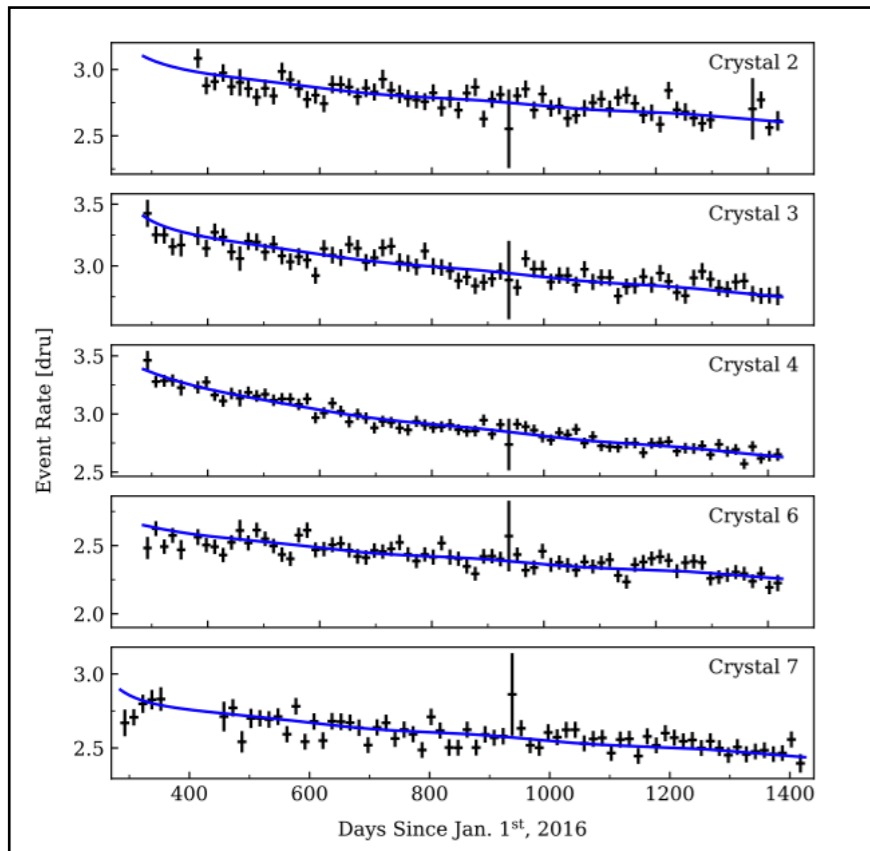
Modulation Amplitude

Fixed across crystals

Background modeling



Time dependent data rate fitting



Annual modulation analysis (3 years data)

Full model time dependent rate fitting

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

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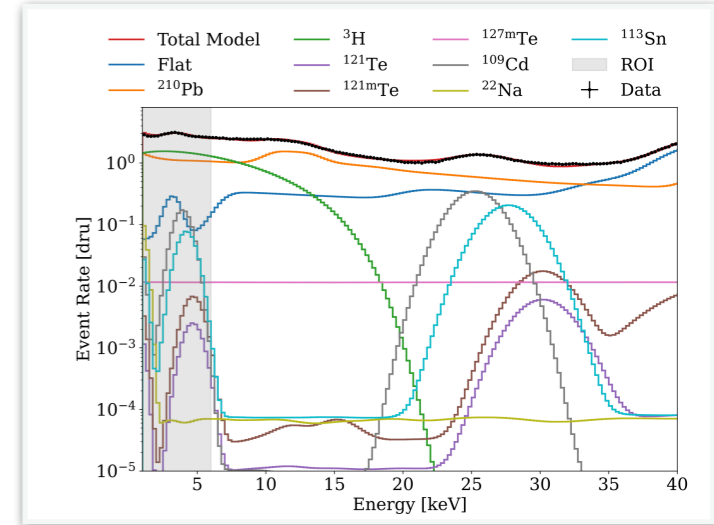
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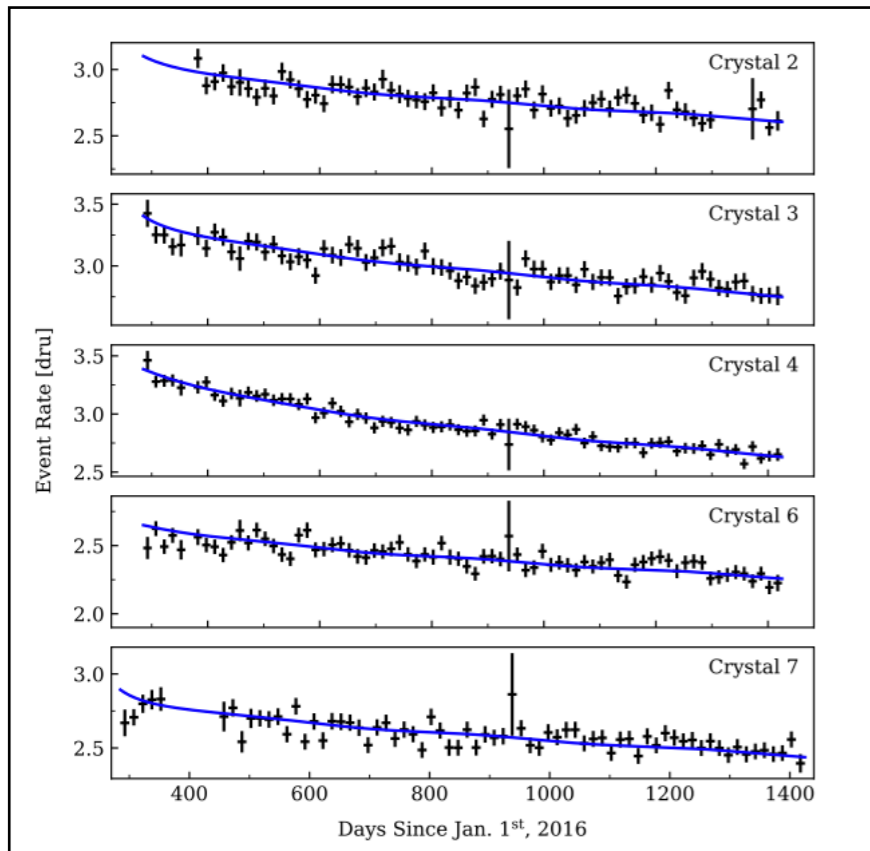
Modulation Amplitude

Fixed across crystals

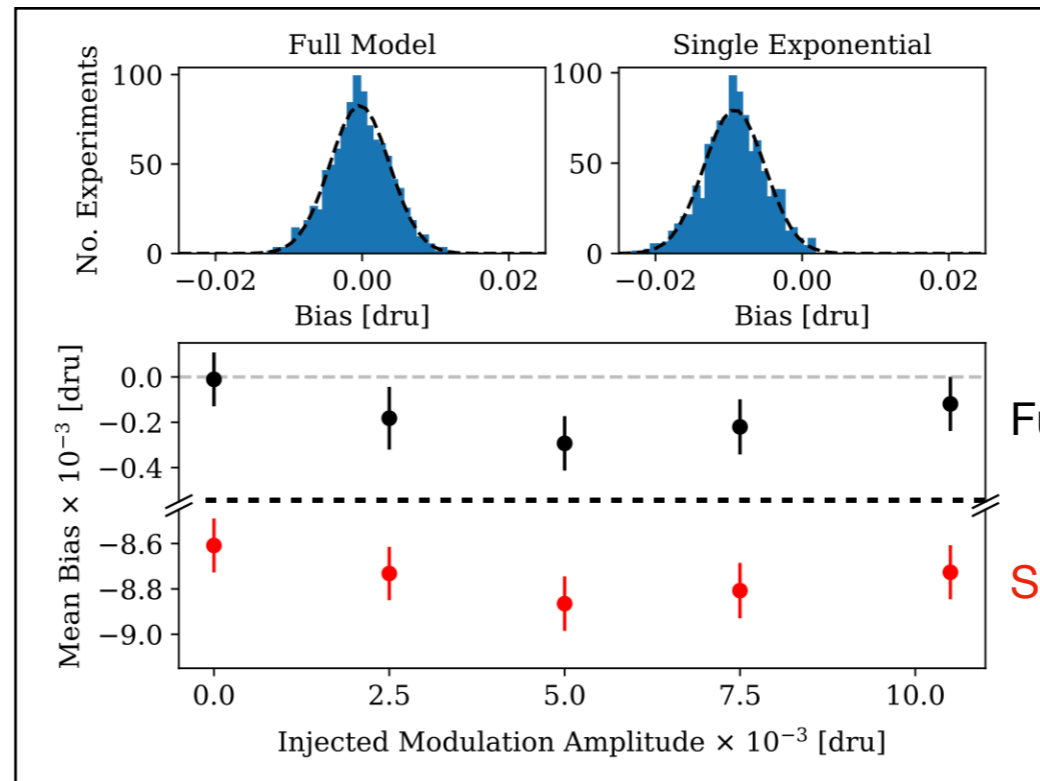
Background modeling



Time dependent data rate fitting



Bias check according to model (Pseudo data)



Precise understanding of background is important

Full Model

Single Exponential

Annual modulation analysis (3 years data)

Full model time dependent rate fitting

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

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

Rate of i^{th} Crystal

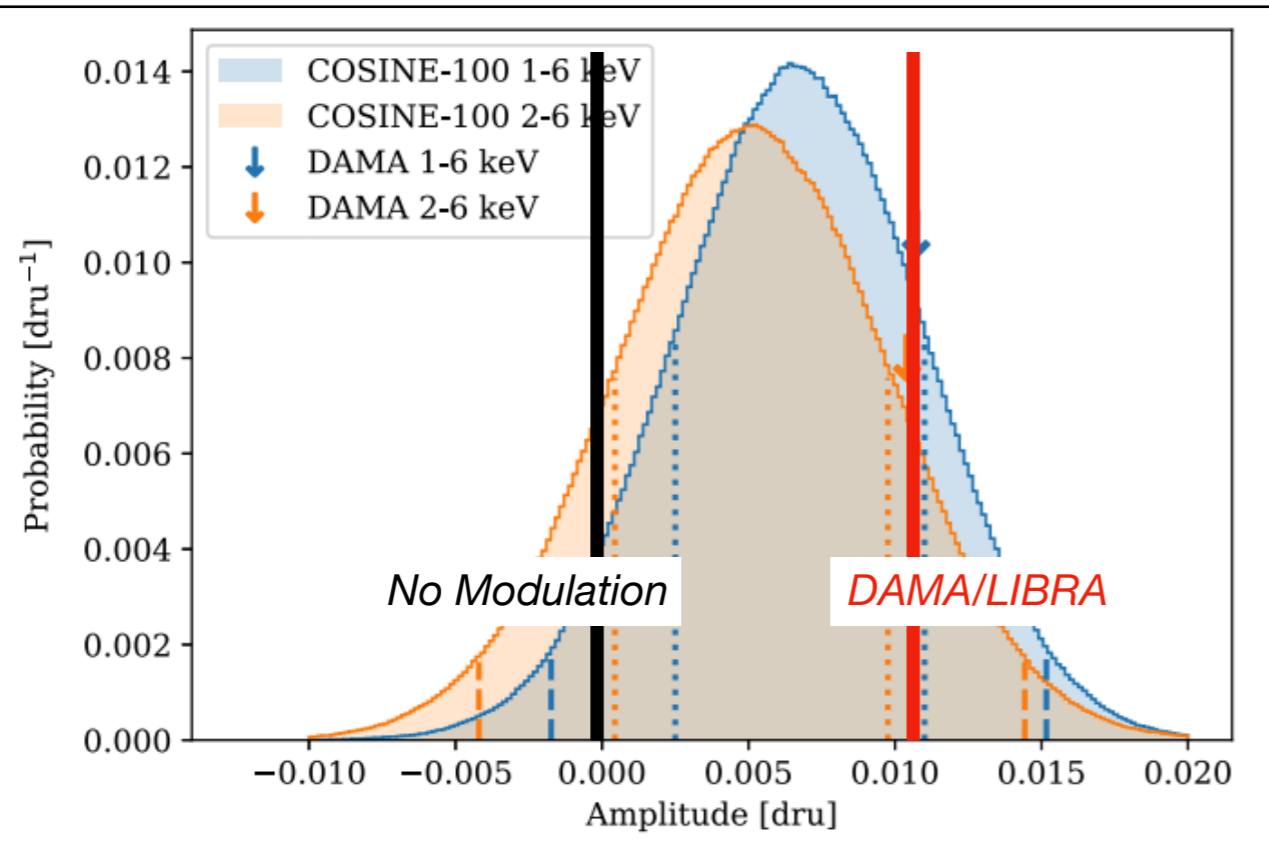
Crystal specific background components

Modulation Amplitude

Fixed across crystals

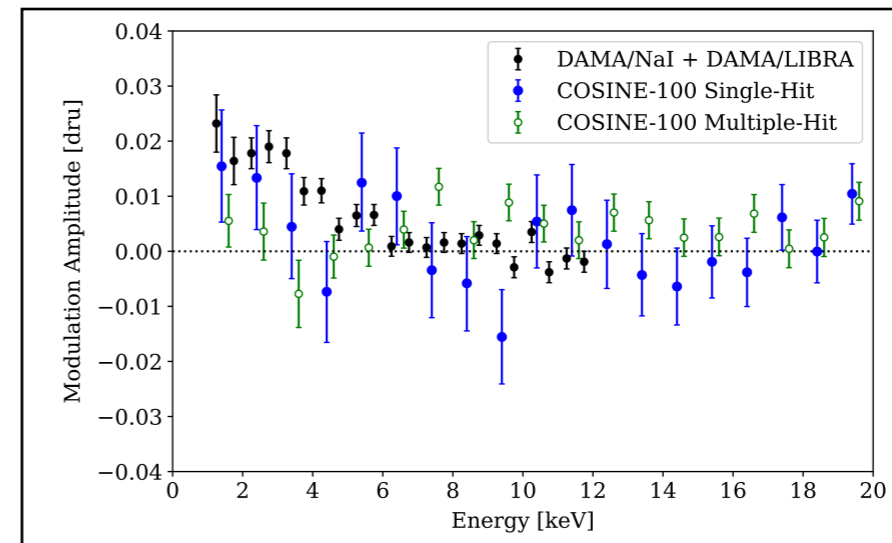
- Constant : Long-lived
- Exponential : Short-lived
- Considers each background separately

Phase fixed ($t_0 = \text{June 2, 152.5 days}$) fitting



Modulation amplitude 1 - 6 keV

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

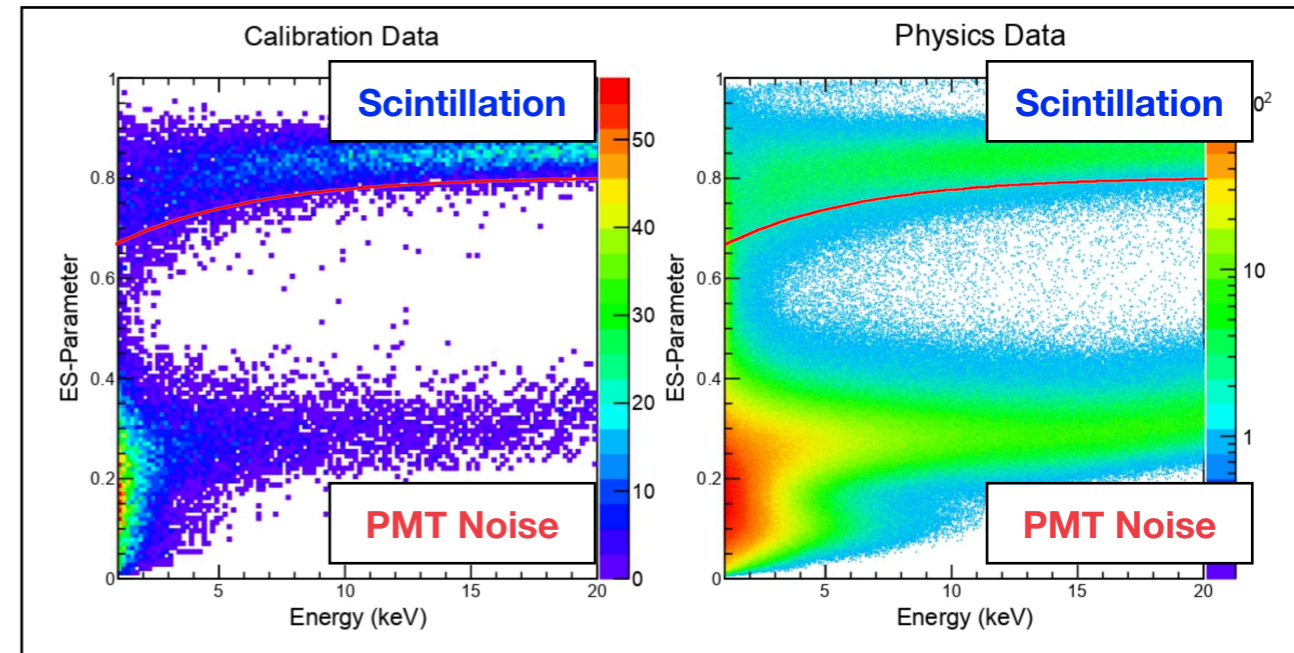


COSINE-100 on DAMA/LIBRA's method

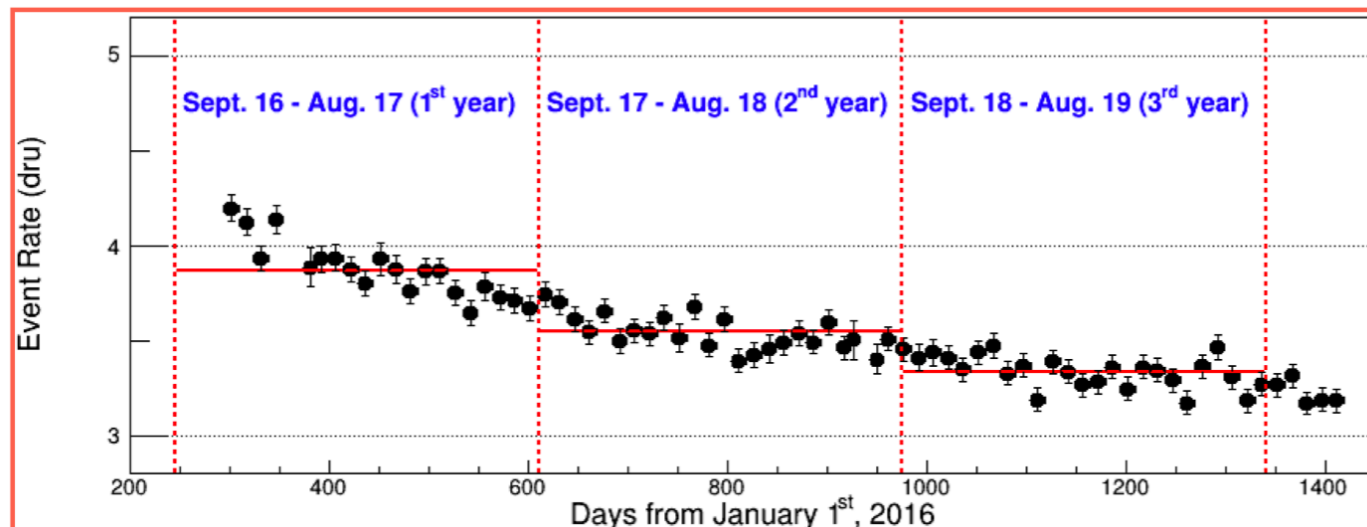
DAMA/LIBRA's analysis method

- No LS Veto
- No Muon Veto
- DAMA parameter for event selection
- 600 ns waveform integration window.
- Yearly averaged background rate model

COSINE -100 Event selection using DAMA parameter



DAMA's Rate model on COSINE-100 data : Yearly averaged



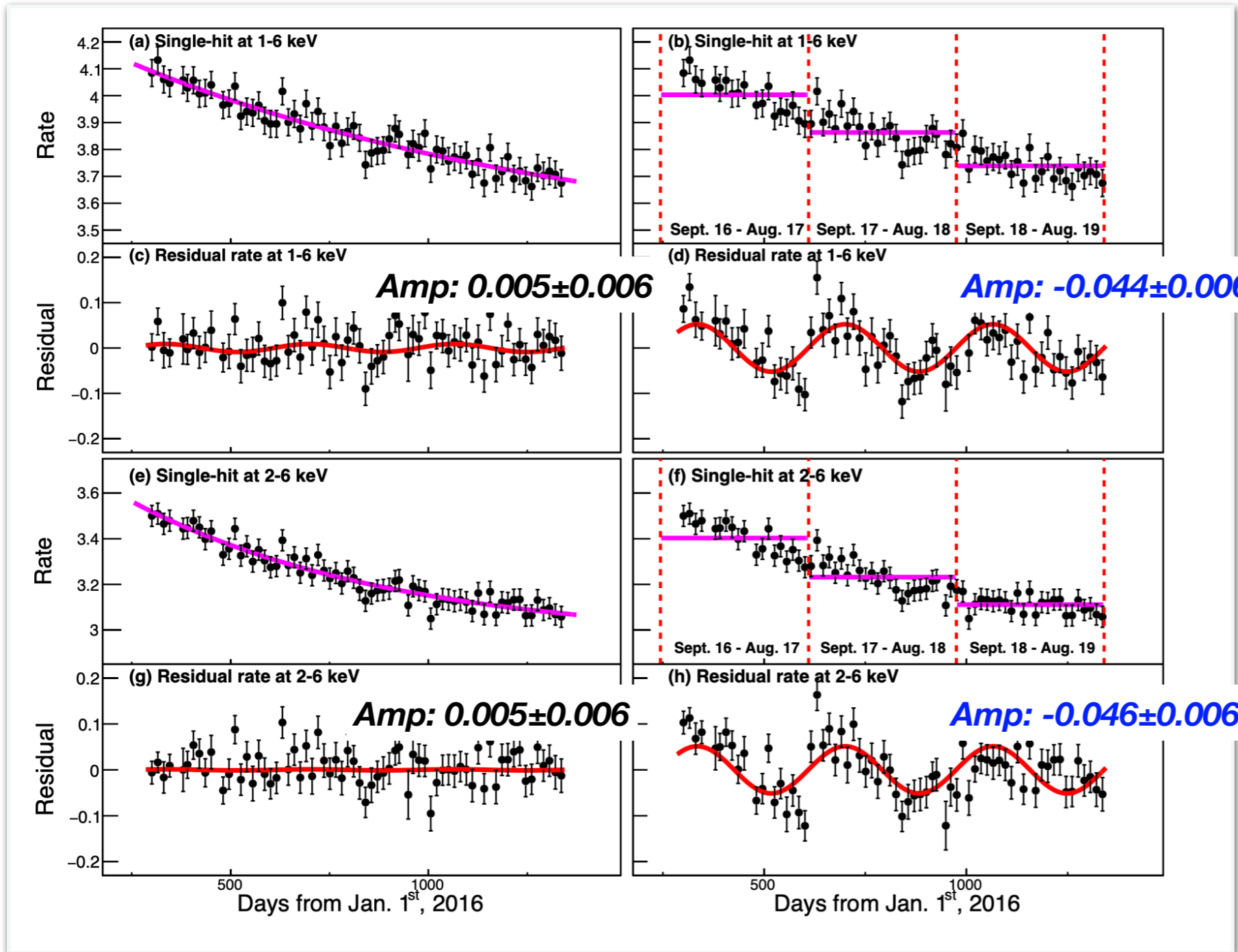
***Possible bias from rate model
suggested at JHEP 20, 137 (2020)***

COSINE-100 on DAMA/LIBRA's method

Single exponential

Yearly Averaged (DAMA model)

arXiv:2202.09672

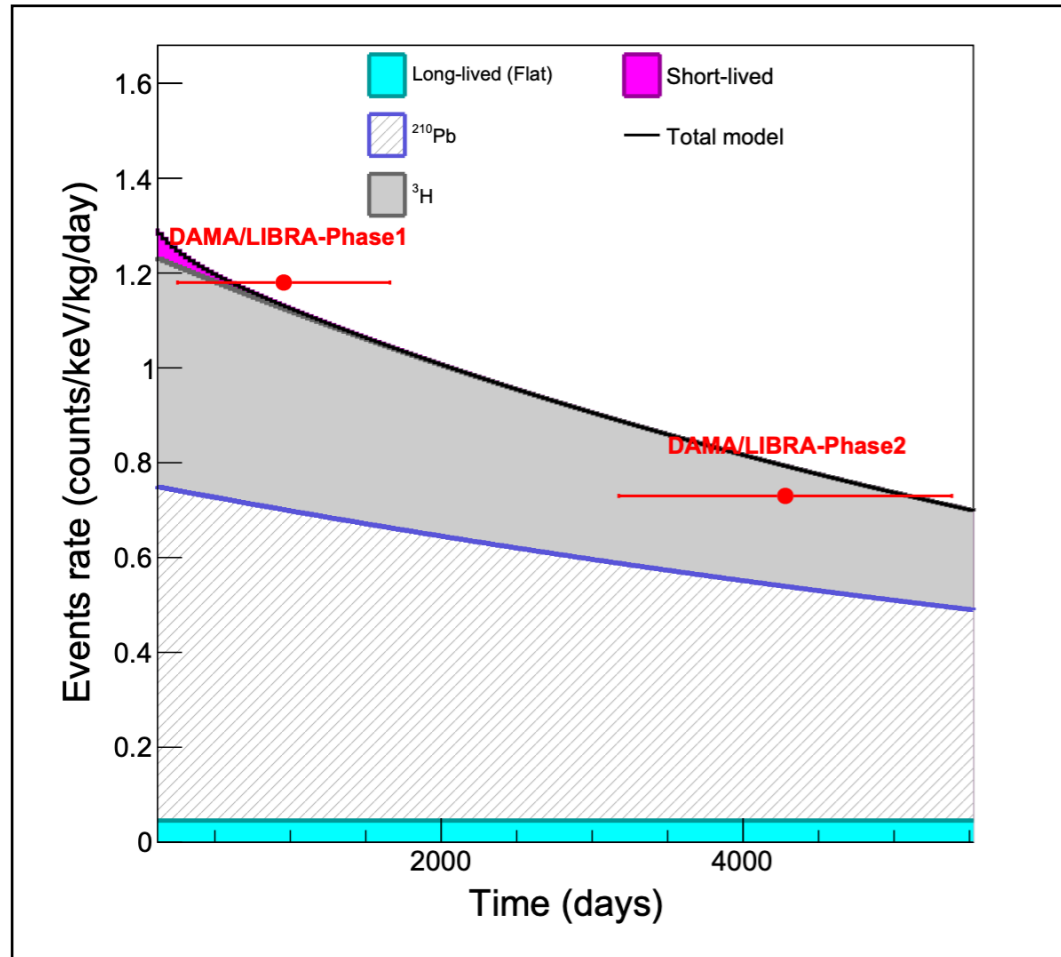


COSINE-100 data

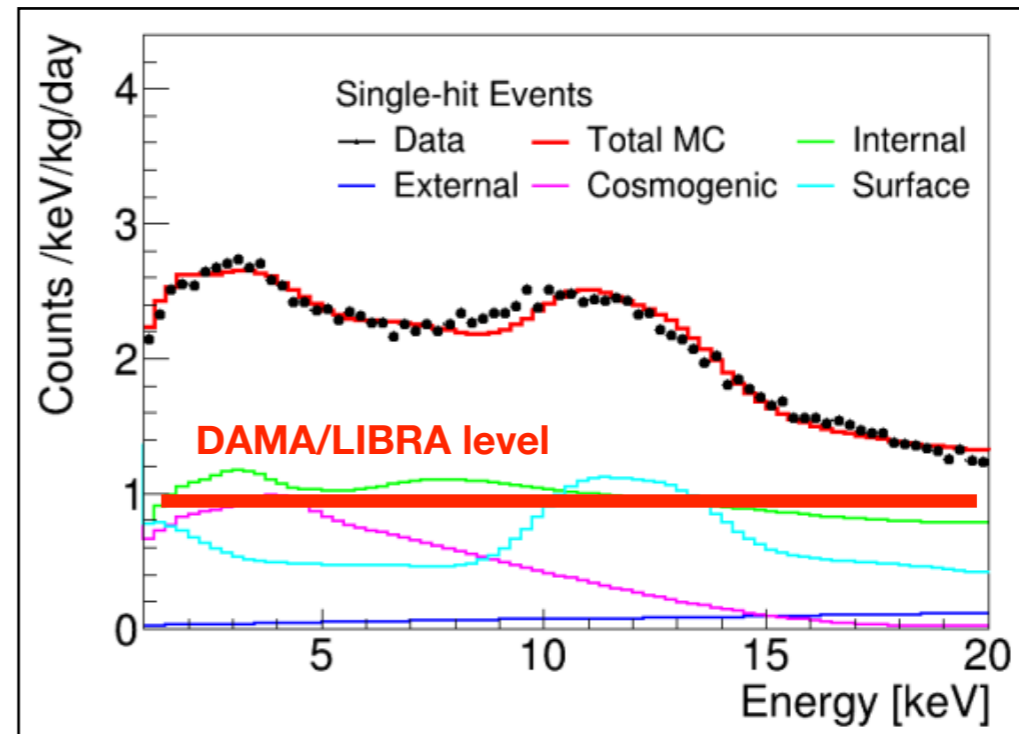
applying DAMA method gives clear modulation ($\sim 7\sigma$, opposite phase)

Bias in DAMA's Method

Composing DAMA/LIBRA, using the COSINE-100 background understanding



COSINE-100 background

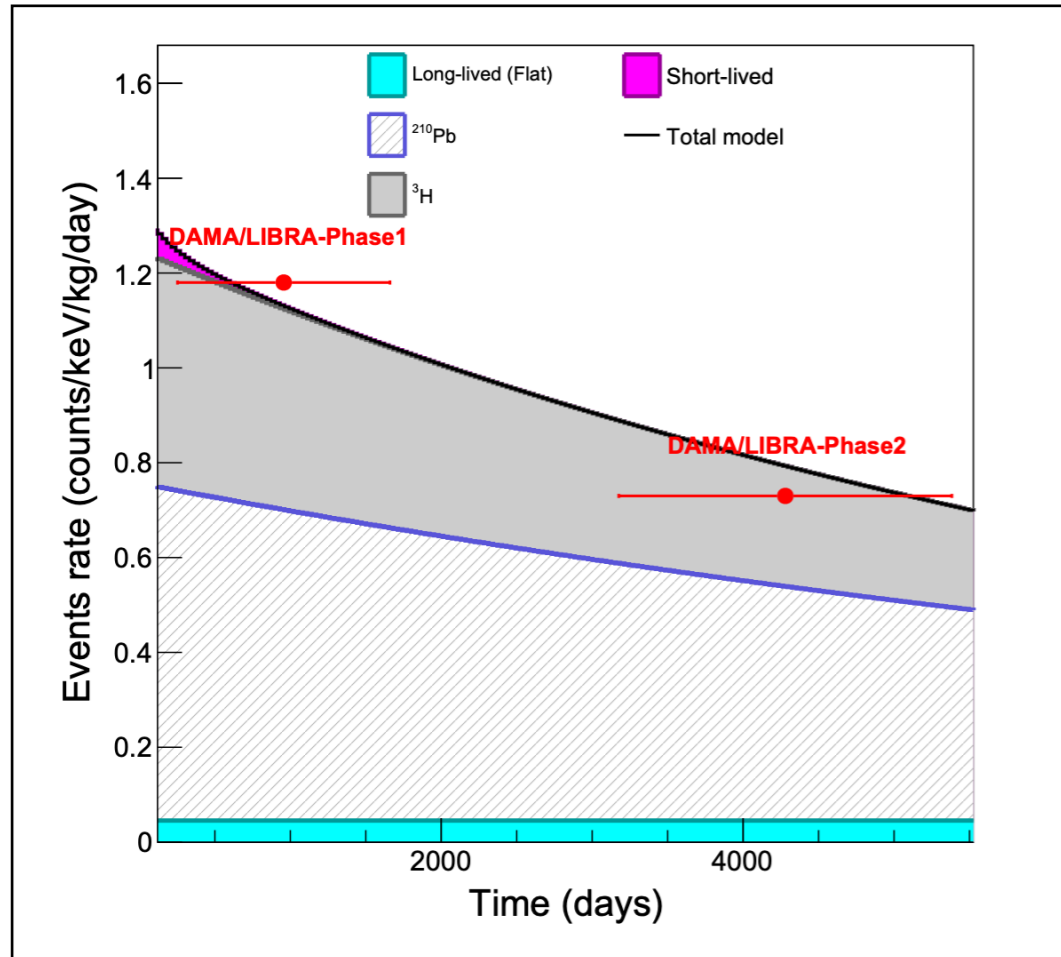


arXiv:2202.09672

- No precise understanding about DAMA background components
- COSINE-100 background composition + DAMA background level

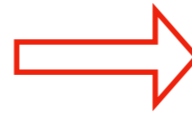
Bias in DAMA's Method

Composing DAMA/LIBRA, using the COSINE-100 background understanding

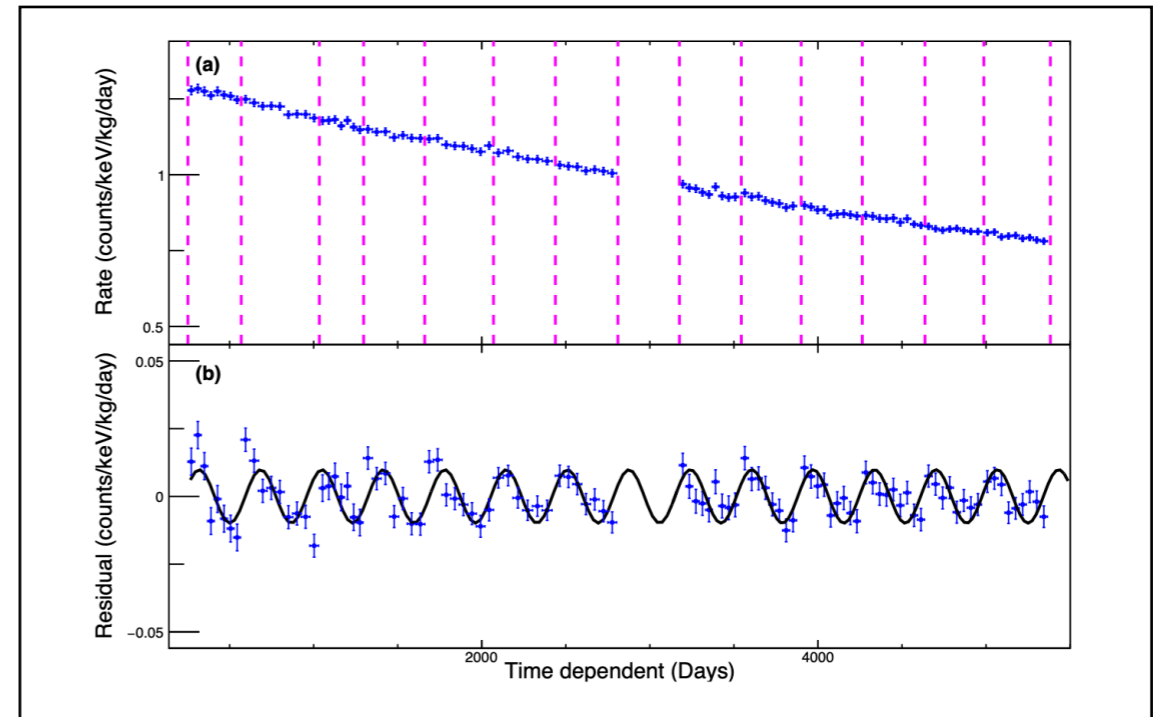


arXiv:2202.09672

Simulation



Residual of pseudo data, using DAMA method



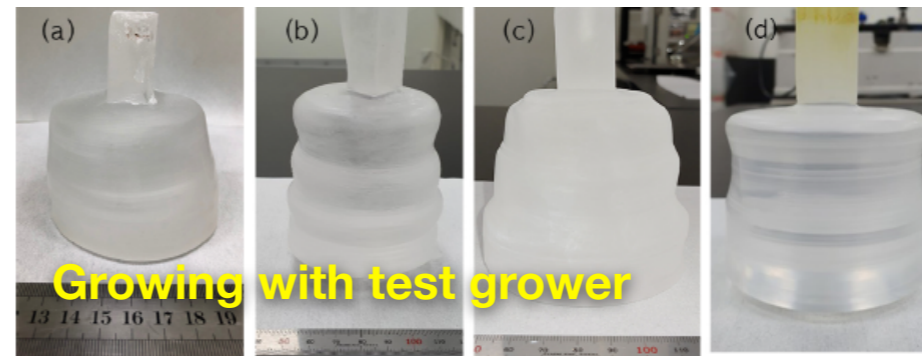
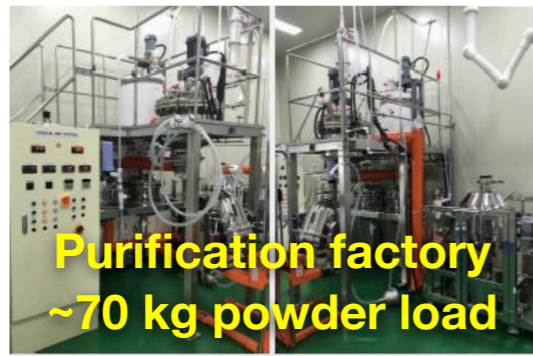
Pseudo data	-0.0098 ± 0.0008
DAMA/LIBRA	0.0105 ± 0.0011

- No precise understanding about DAMA background components
- COSINE-100 background composition + DAMA background level
- Could check similar modulation amplitude in simulation (Opposite Phase)

Plan for next phase

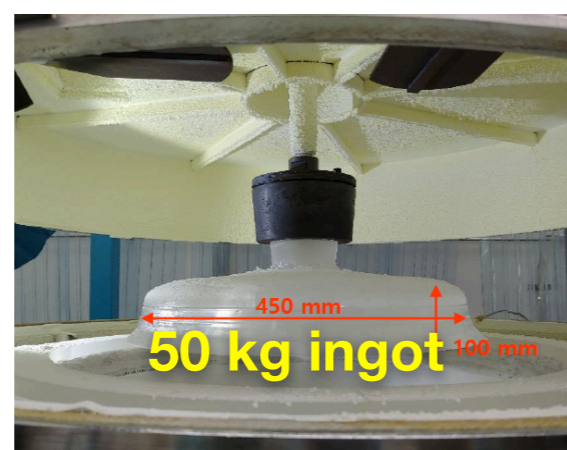
Crystal Development

- Goal: **Lower background than DAMA/LIBRA** (2~3 times higher in COSINE-100)
- In-house development of entire process (at IBS , Korea)
 - NaI Purification / Crystal growing / Detector assembly
- Full size grower 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

⁴⁰K & ²¹⁰Pb significantly reduced

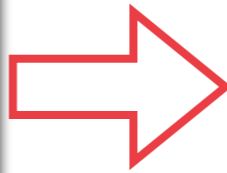
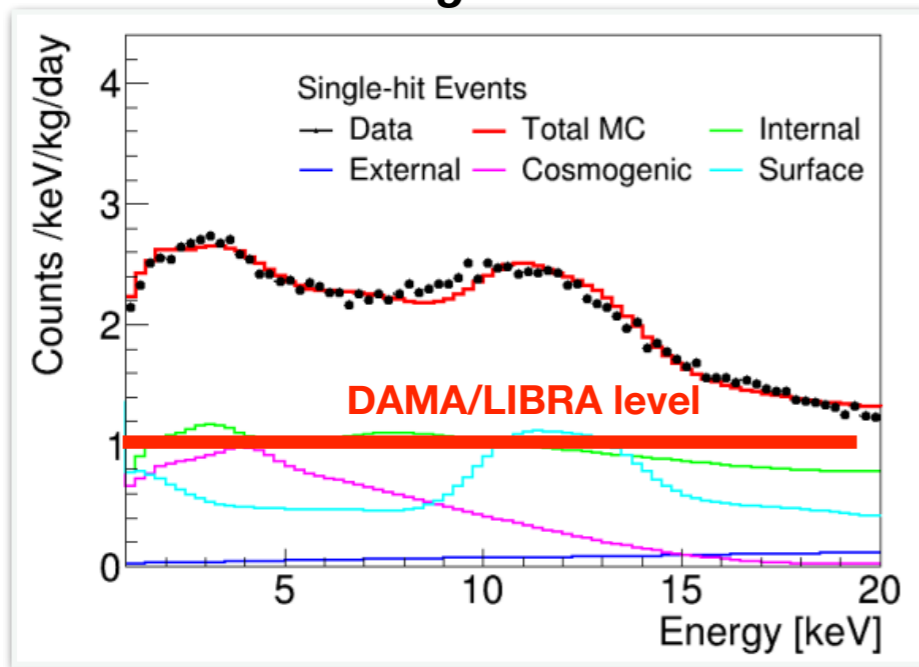


Plan for next phase

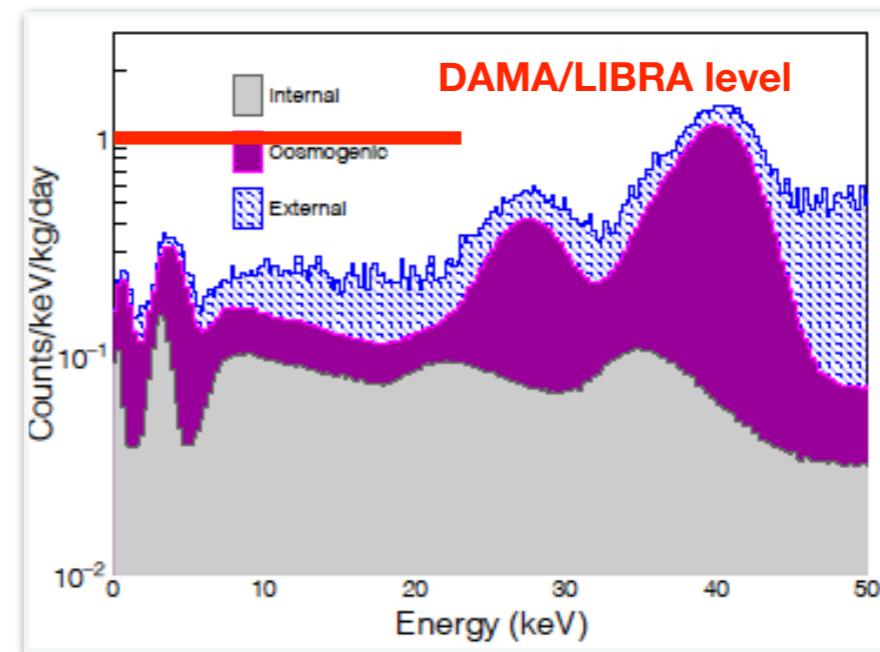
Crystal Development

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COSINE-100 background



Simulation of background in new crystal
EPJC 80 (2020) 814



	K [ppb]	²¹⁰ Pb [mBq/kg]	²³⁸ U [Bq/kg]	²³² Th [Bq/kg]
Powder	5	-	< 20	< 20
Aug., 2018	684	3.8 ± 0.3	26 ± 7	< 6
Sep., 2019	8	0.01 ± 0.02	11 ± 4	7 ± 2
DAMA	< 20	0.01 ~ 0.03	8.7 ± 124	2 ~ 31

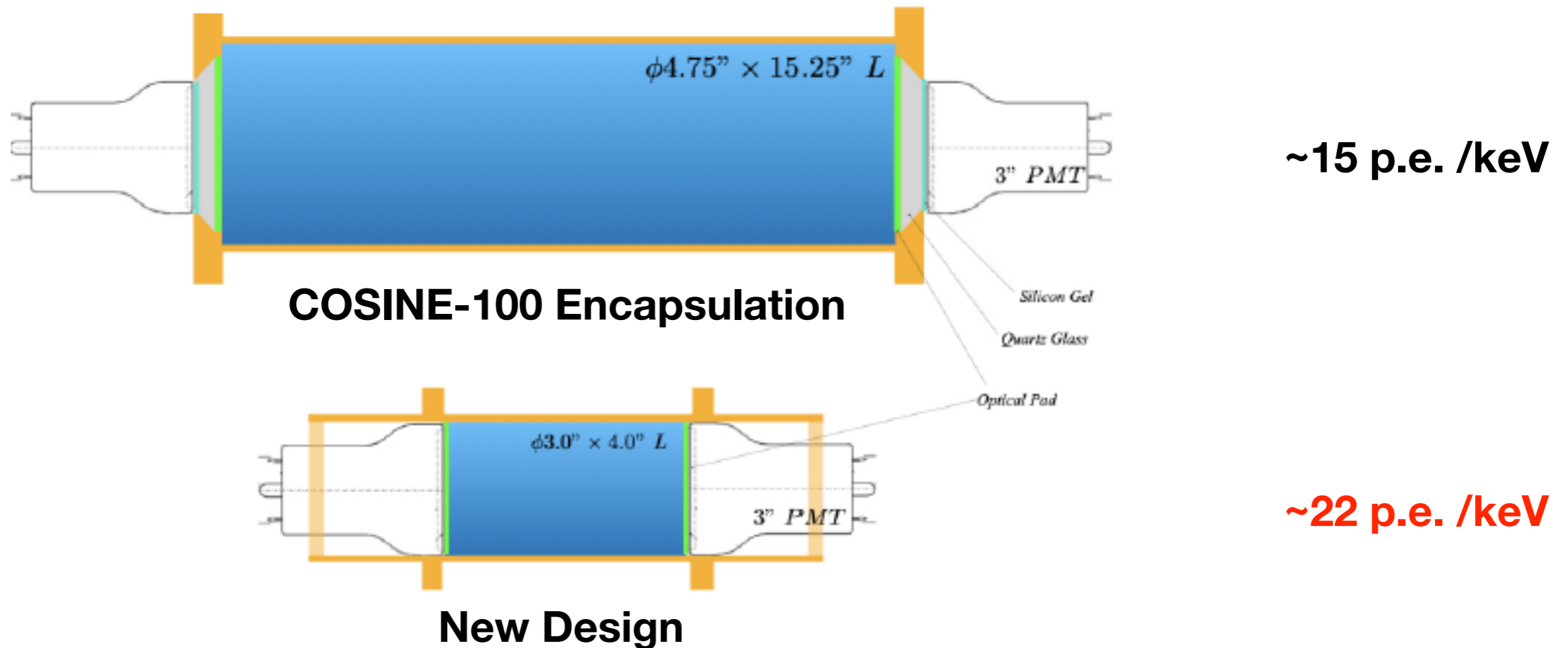
Plan for next phase

Lowering Threshold

- New Encapsulation technique
 - Direct attachment of PMT to crystal.
 - ~50 % increased Light Yield (LY)
 - Will be applied to COSINE-200 assembly

Light Yield change in new encapsulation

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

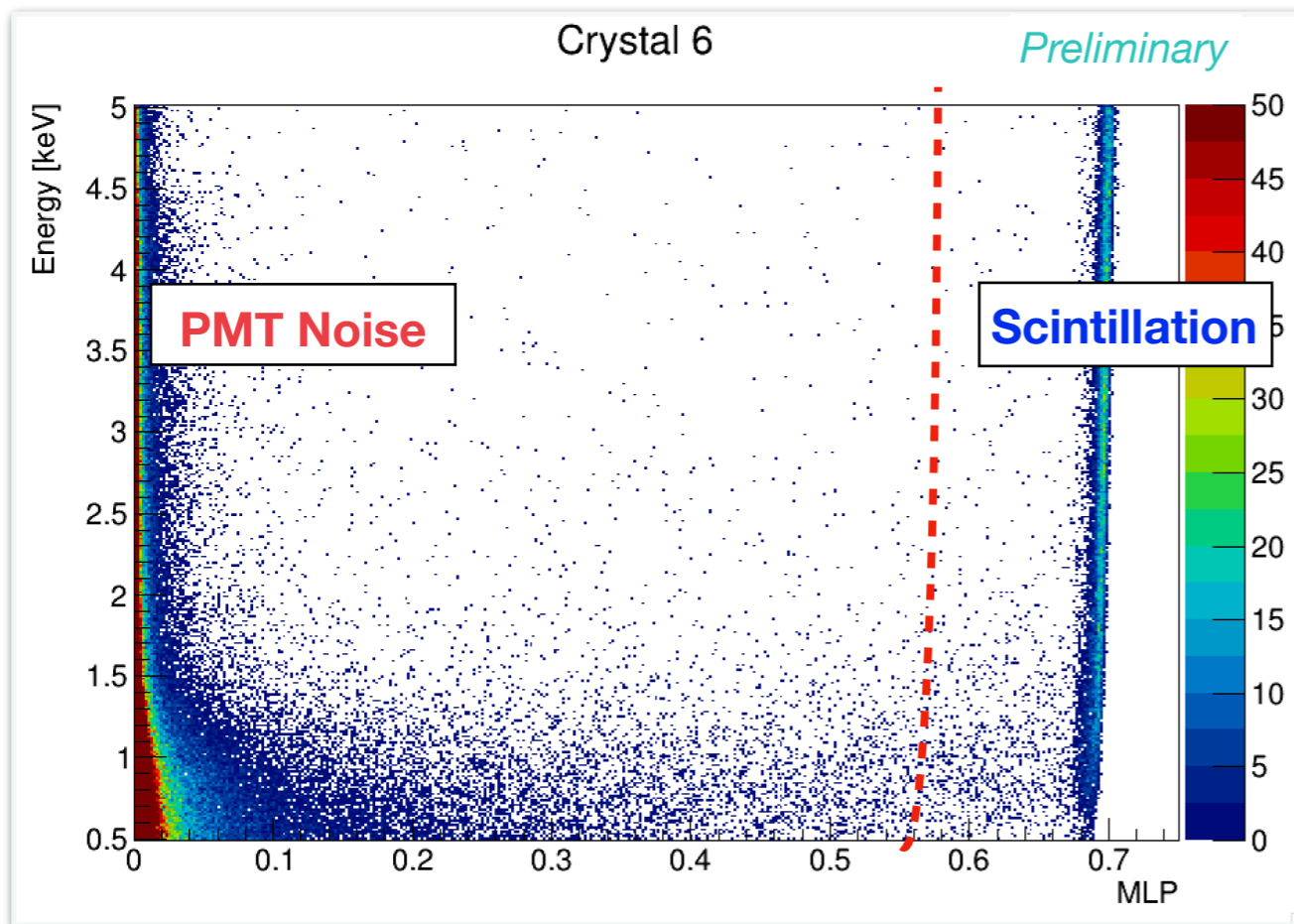


Plan for next phase

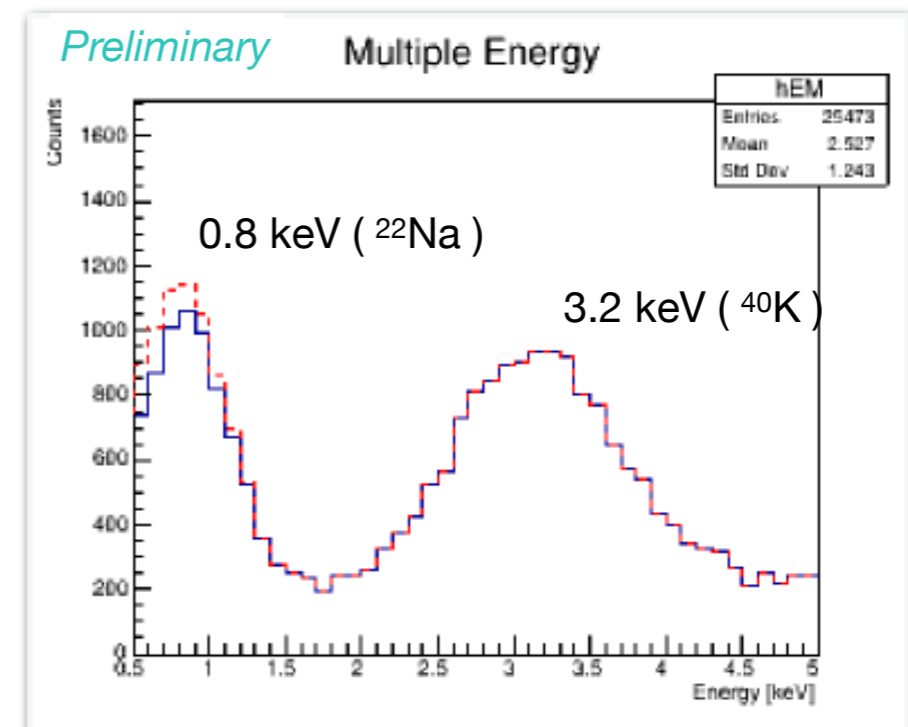
Lowering Threshold

- New Encapsulation technique
 - Direct attachment of PMT to crystal.
 - ~50 % increased Light Yield (LY)
 - Will be applied to COSINE-200 assembly
- Event selection improvement
 - Aims to achieve 1 → 0.5 keV (7 P.E.)
 - Deep learning (MLP) method
 - CNN (Waveform shape) study for COSINE-200 (5 P.E)

MLP distribution for 0.5 keV threshold in COSINE-100



0.5 keV threshold spectrum with MLP



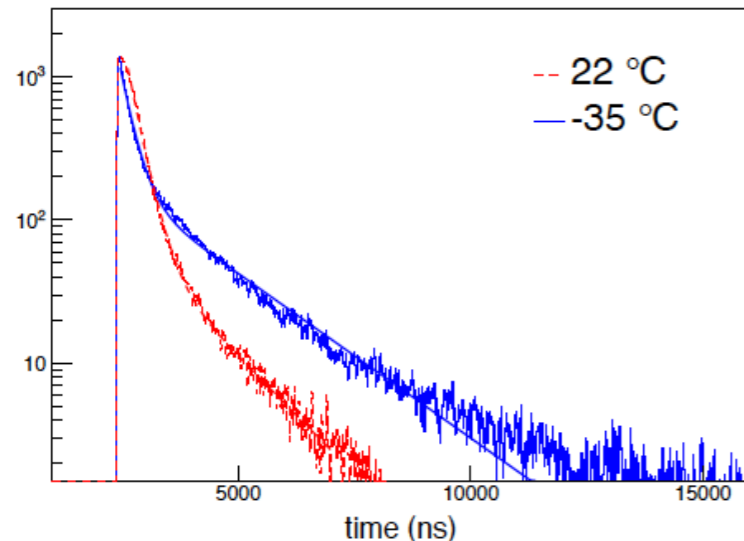
Plan for next phase

Lowering Threshold

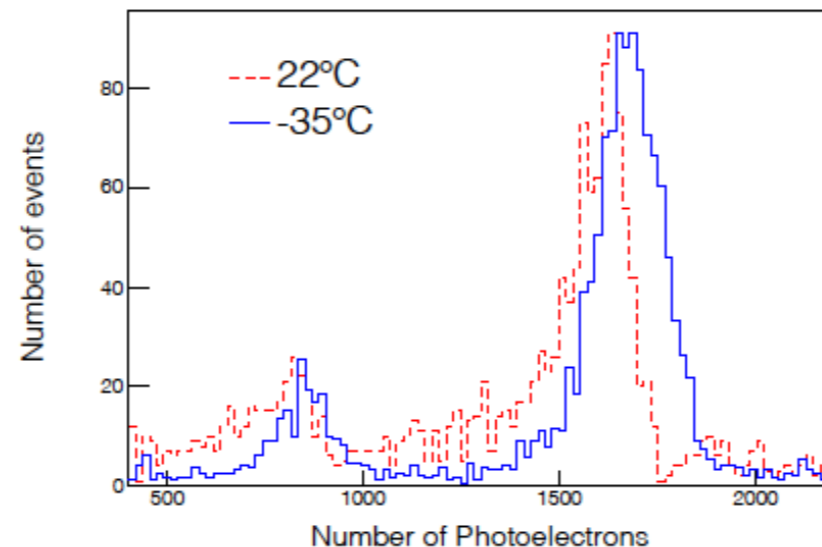
- New Encapsulation technique
 - Direct attachment of PMT to crystal.
 - ~50 % increased Light Yield (LY)
 - Will be applied to COSINE-200 assembly
- Event selection improvement
 - Aims to achieve 1 \rightarrow 0.5 keV (7 P.E.)
 - Deep learning (MLP) method
 - CNN (Waveform shape) study for COSINE-200 (5 P.E)
- Low temperature operation
 - COSINE-200 can be operated at **-35 °C**

Performance at low temperature(-35 °C) using ^{241}Am

Accumulated waveform

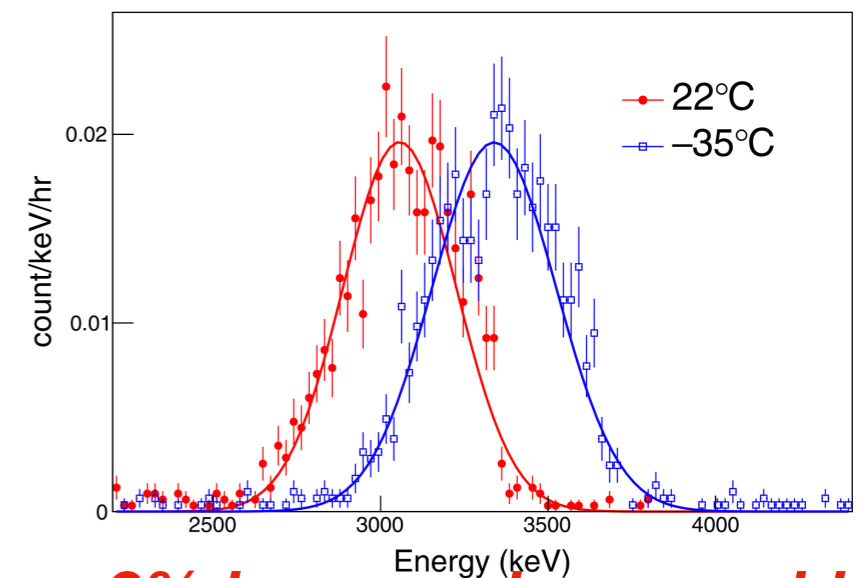


NPE Measurement



~5% increased LY for γ

Alpha response using ^{210}Po

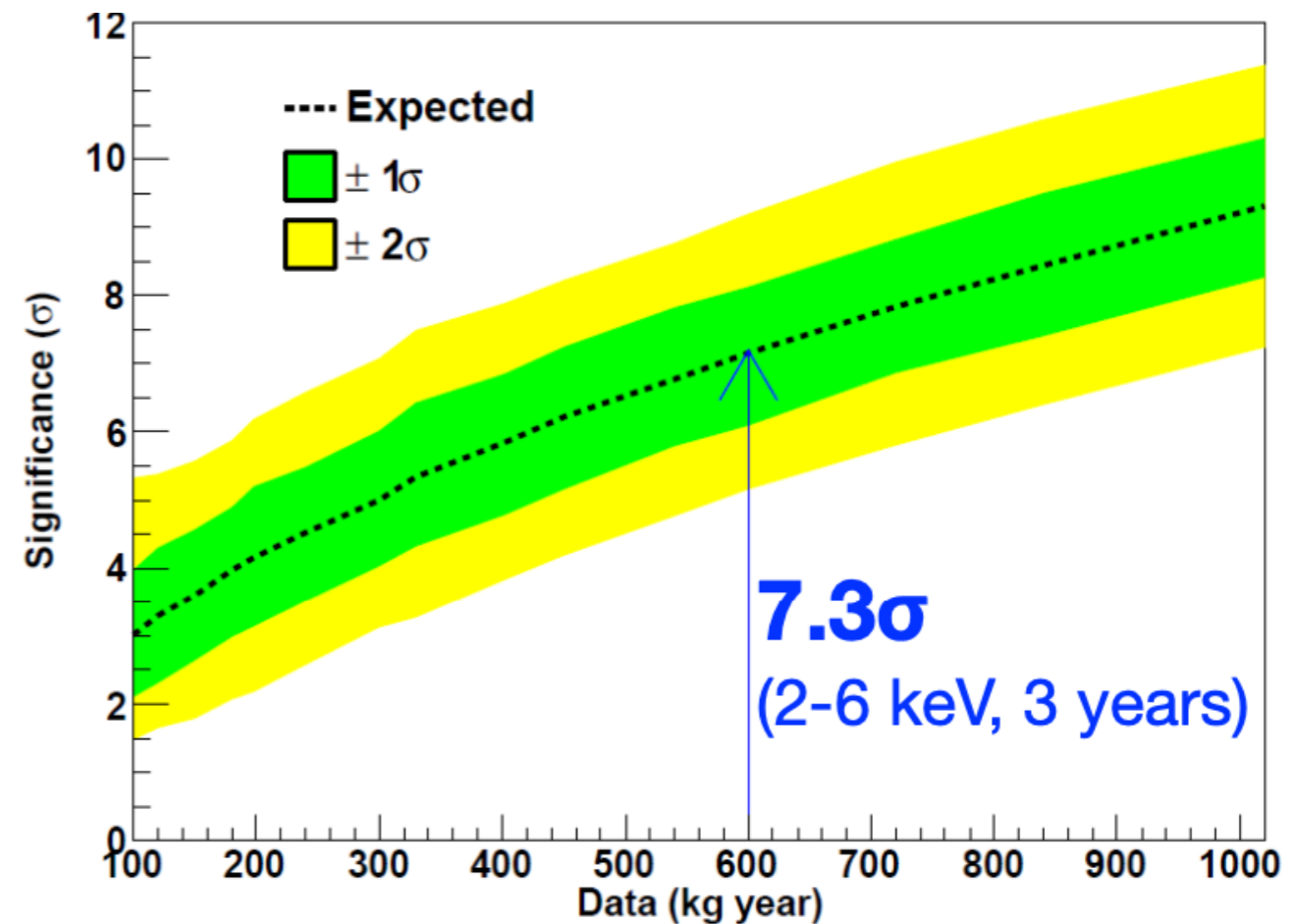
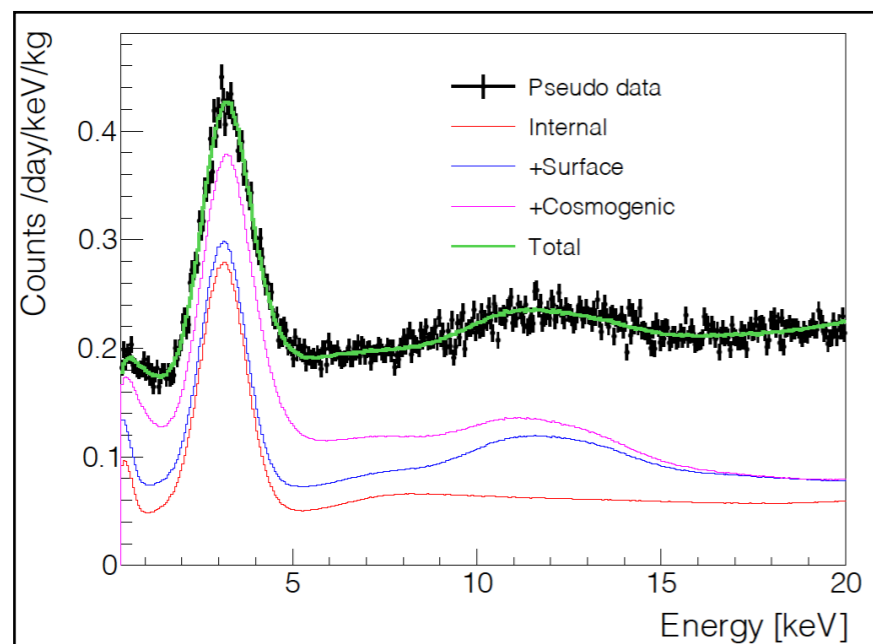


~9% increased α quenching

Sensitivity in COSINE-200 WIMP search

- Assumed profile of COSINE-200
 - 200 kg mass , ~0.2 DRU background rate *DRU = counts/kg/keV/day
 - ~22 p.e/keV light yield, with 5 p.e. threshold
 - Better performance expected after considering low-temperature operation

COSINE-200 expected background
EPJC 80, 814 (2020)

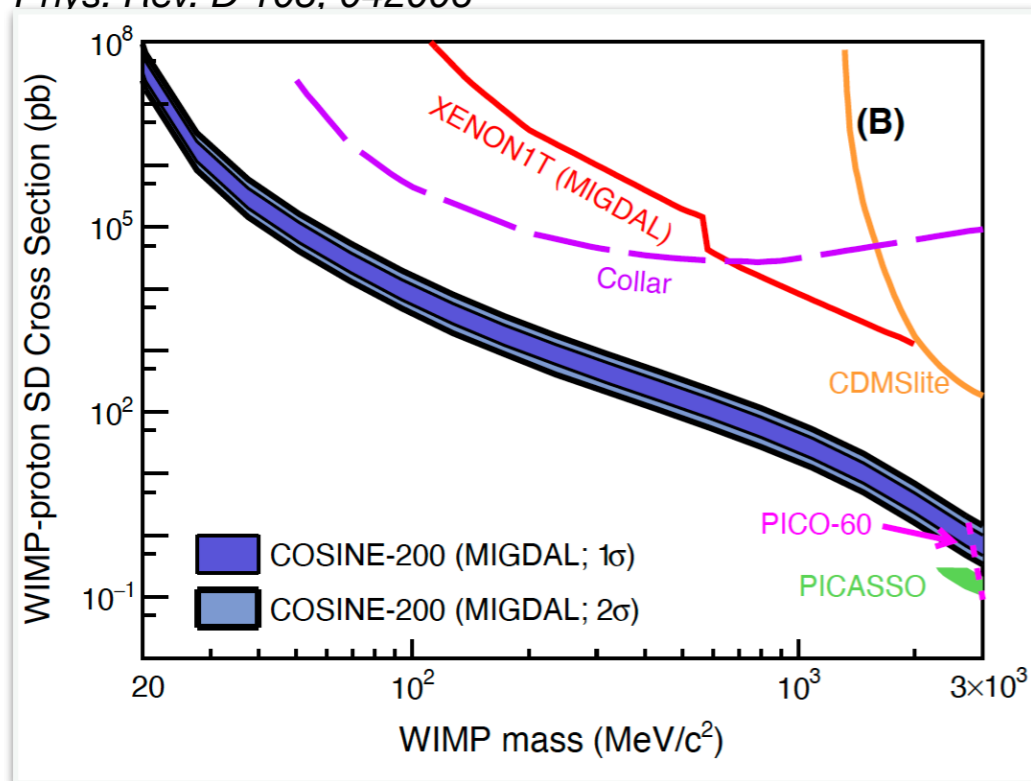


Model independent conclusion of DAMA/LIBRA in 3 years is possible

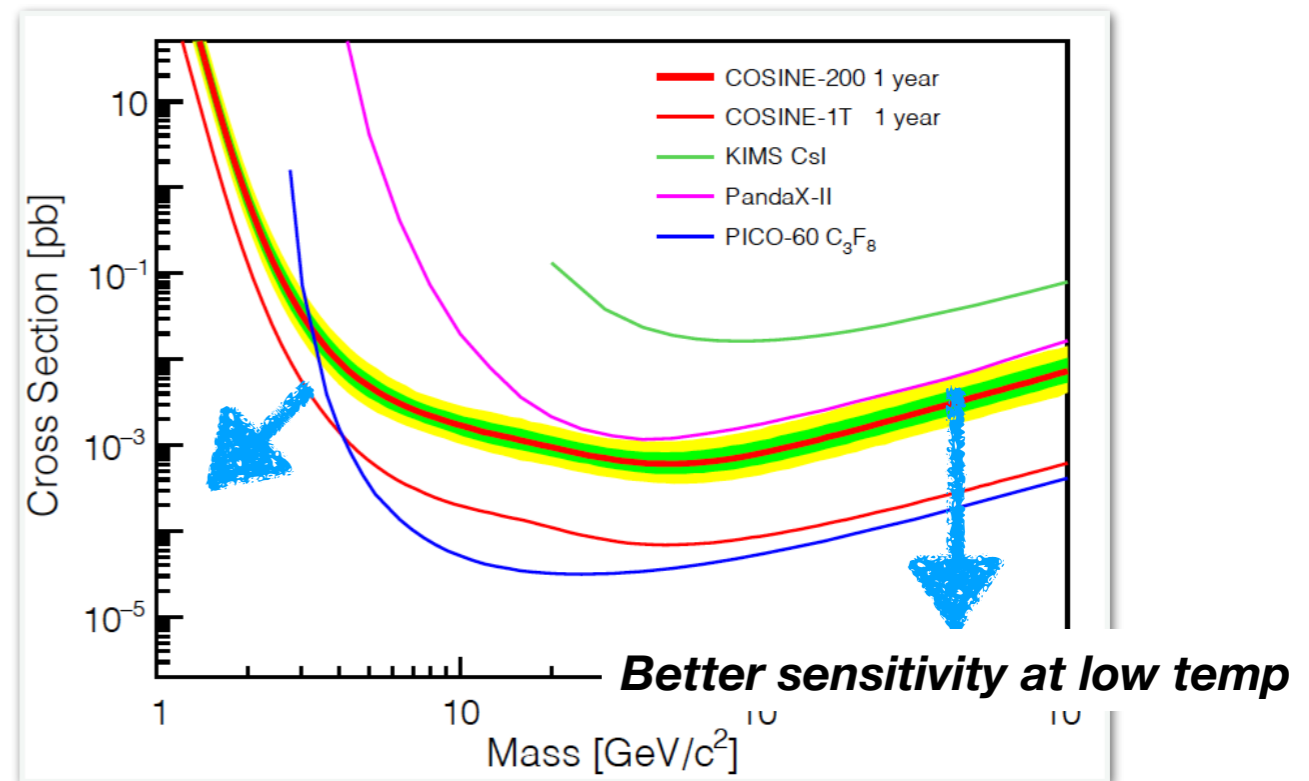
Sensitivity in COSINE-200 WIMP search

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WIMP-proton SD cross section w/ Migdal Effect
Phys. Rev. D 105, 042006



WIMP-proton SD cross section



World's best sensitivity for low mass SD WIMP-proton cross section is expected

Summary

COSINE-100 tests DAMA/LIBRA using same target material, NaI(Tl)

Spectral Analysis

- DAMA/LIBRA result is excluded by COSINE-100 spectral analysis.
- Low mass WIMP region was checked considering Migdal Effect

Modulation Analysis

- Model independent test
- Modulation analysis could not make clear decision about modulation signal
- Strong negative amplitude was found, using DAMA's method

Plan for next phase

- Lower background, lower threshold
- Preparation for COSINE-200 in ongoing



**Thank you for your
attention**