COSINE experiment
A WIMP dark matter search experiment with NaI(Tl) detectors

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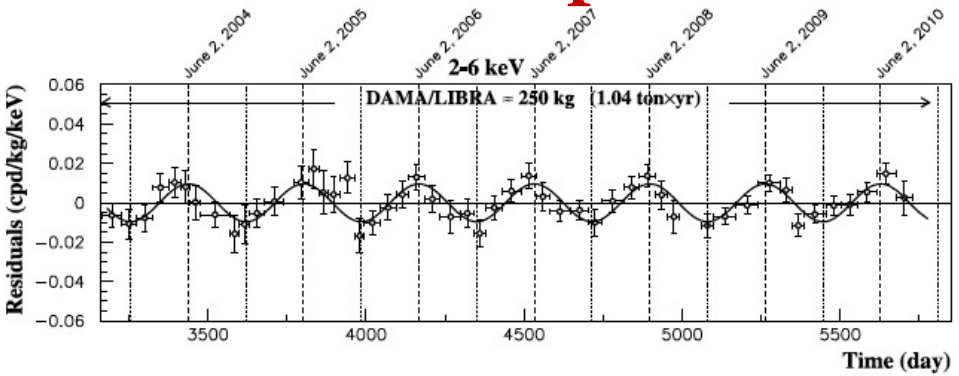
Institute for Basic Science (IBS)

Dark World to Swampland 2021 (The 6th IBS-IFT-Multidark Workshop)

November/16th 2021

Annual modulation signal from DAMA/LIBRA

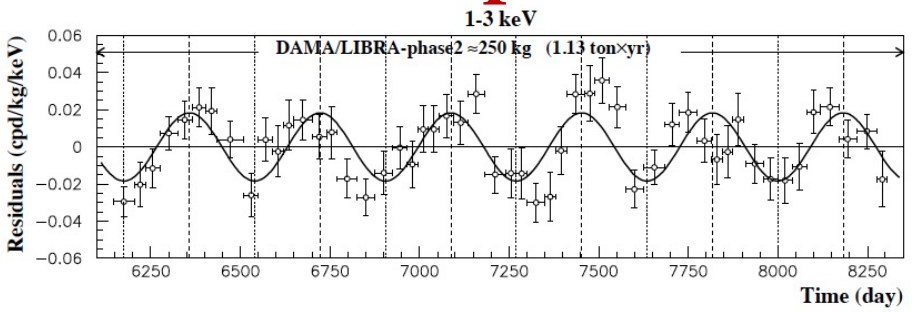
Phase1 experiment



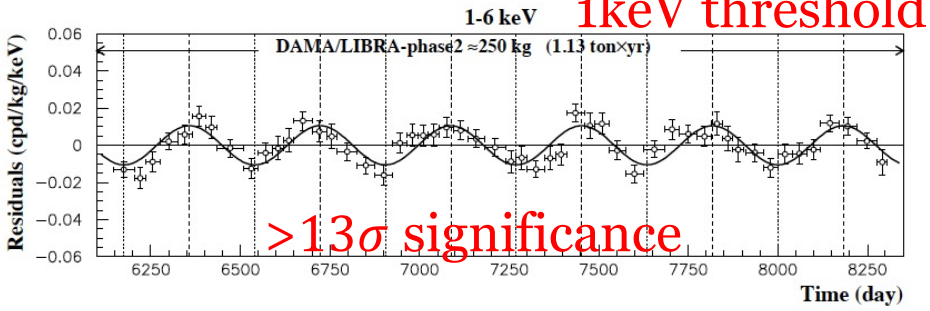
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



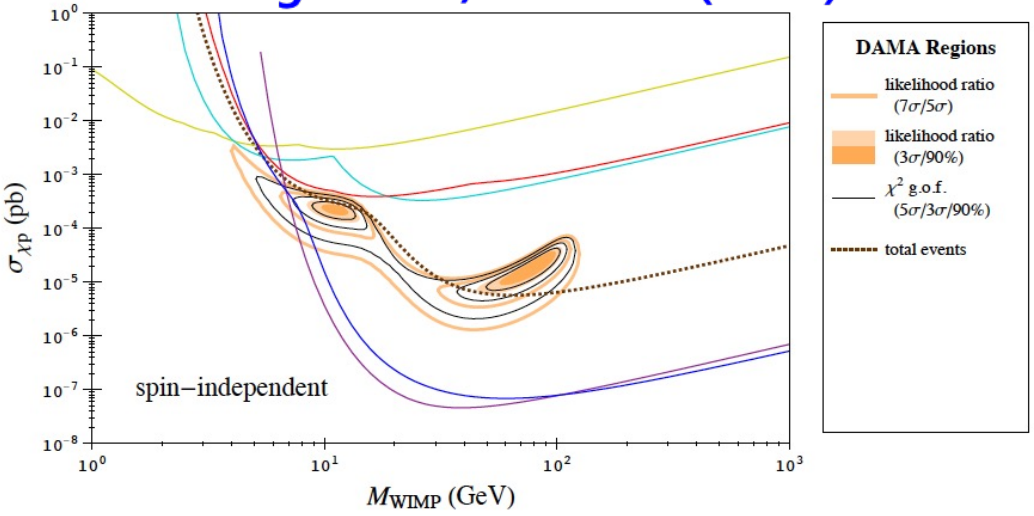
Nucl. Phys. At. Energy 19, 307 (2018)



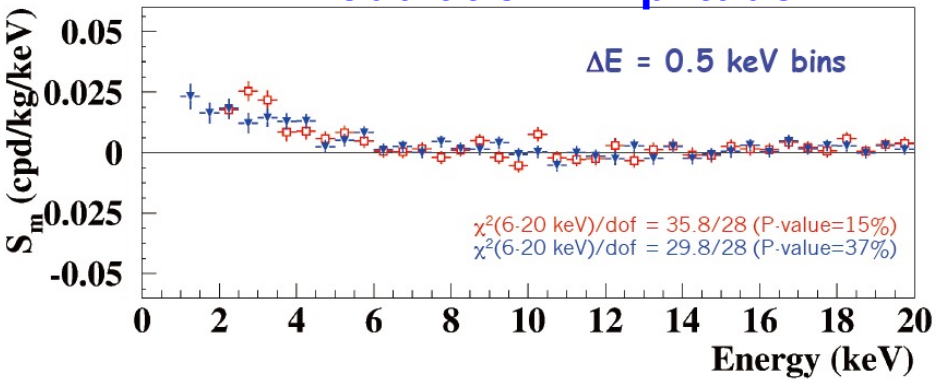
1keV threshold

>13σ significance

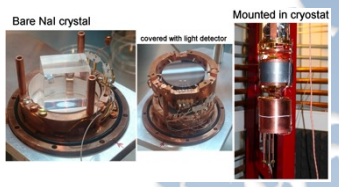
C. Savage *et al.*, JCAP 04 (2009) 010



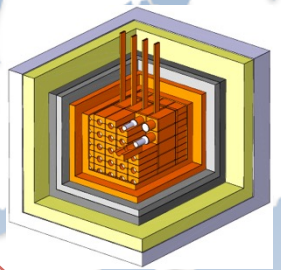
Modulation Amplitude



Global NaI(Tl) efforts

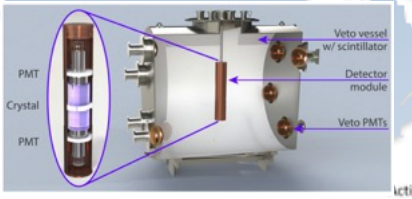


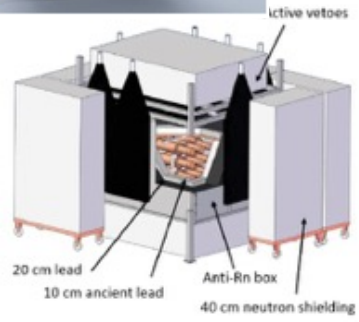
COSINUS @ LNGS



DAMA @ LNGS

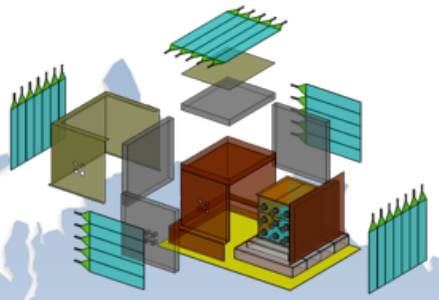
SABRE @ LNGS





ANAIS @Canfranc

In Data-taking

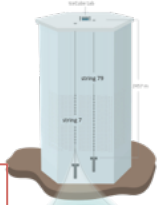


KIMS/COSINE @ Yangyang

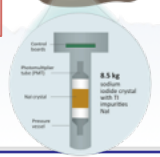
In Data-taking

PICO-LON @ Kamioka

SABRE @ Stawell



DM-Ice @ South Pole

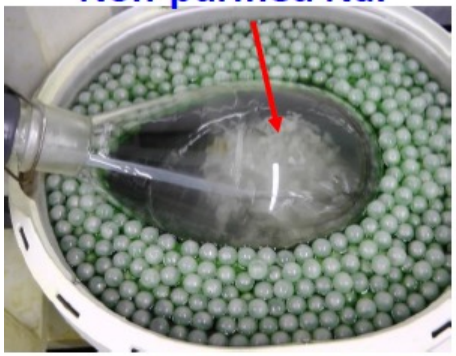


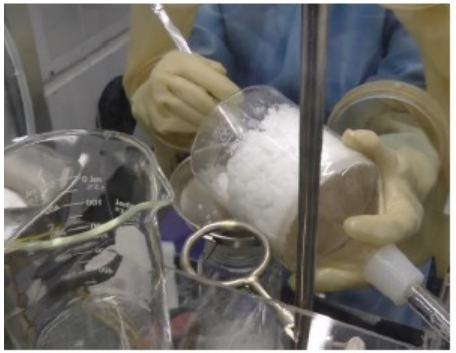
PICO-LON

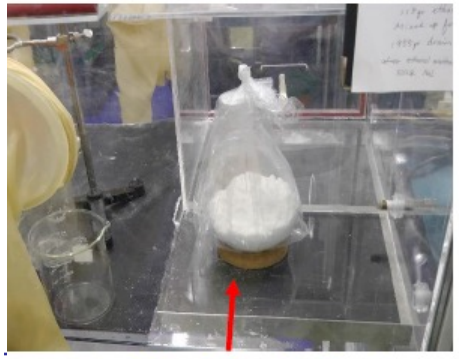
- Development of low-background NaI(Tl) crystals in Japan

A. Kozlov @ VCI 2019

Non-purified NaI



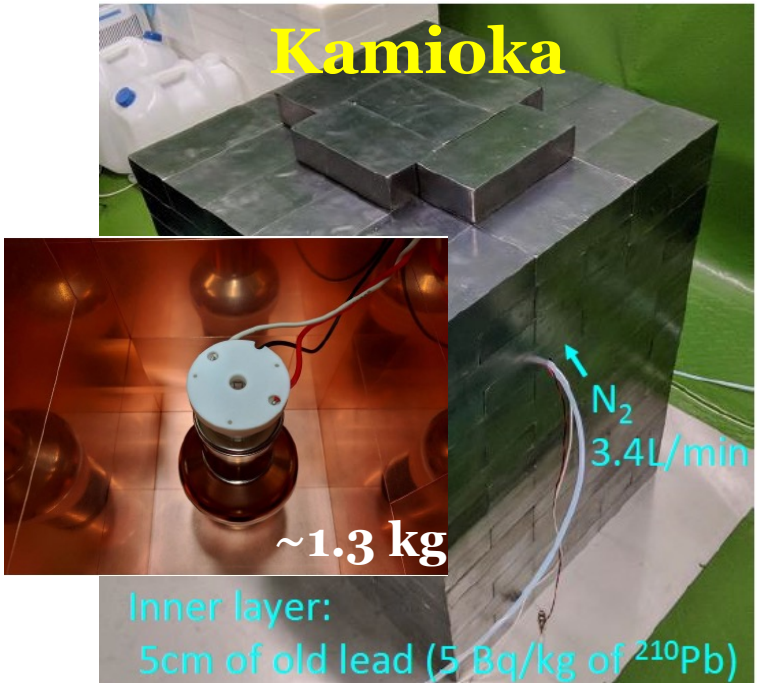




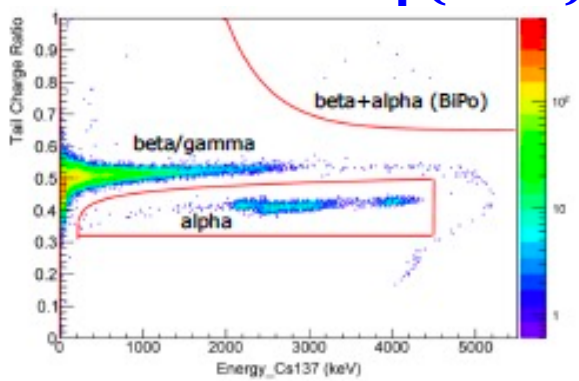
Purified NaI·2$H_2$0

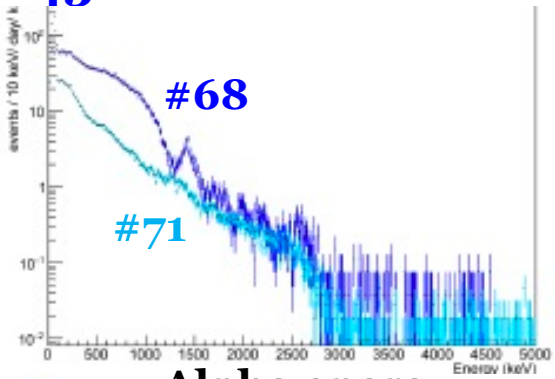
Machine cutting

PICO-LON : Background

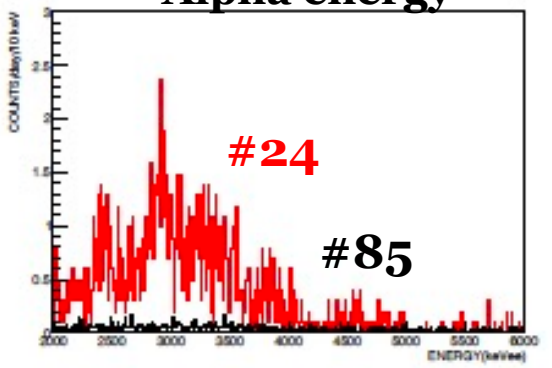


PTEP 4 (2021) 043F01





Alpha energy



Unit : μBq/kg

ID of NaI/group	^{nat}K	^{226}Ra	^{210}Pb	^{232}Th
#68	120	57 ± 7	7500	8.4 ± 2.4
#71	< 20	120 ± 10	1500	6.8 ± 0.8
#73	< 30	44 ± 7	1300	7.2 ± 0.8
#85	–	13 ± 4	< 5.7	1.2 ± 1.4
Our goal	< 20	< 100	< 10	< 10
COSINE[10]	< 42	$8 \sim 60$	$10 \sim 420$	$7 \sim 35$
DAMA[18]	< 20	$8.7 \sim 124$	$10 \sim 30$	$2 \sim 31$

Plan

- Phase1 @ 2021 spring with 23.4 kg
- Phase2 : 100 kg
- Phase3 : 250 kg

SABRE

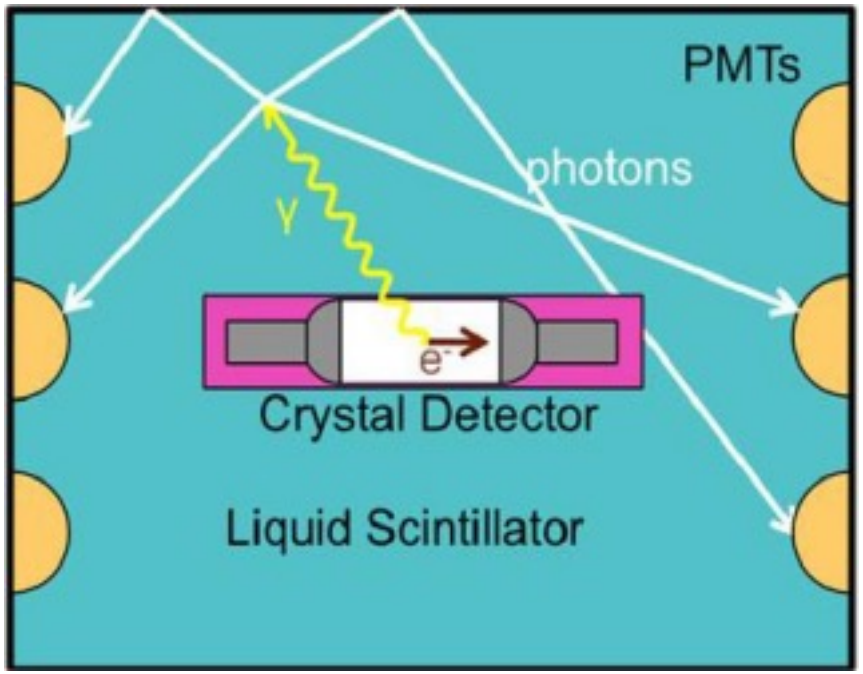
4 key features:

S. Copello@ NDM2018

1. High purity crystals: High purity powder and clean crystal growth method
2. Active background rejection: active veto of liquid scintillator
3. Low energy threshold: High QE Hamamatsu PMTs, directly coupled to the crystals
4. Double location: both in Northern and Southern hemispheres

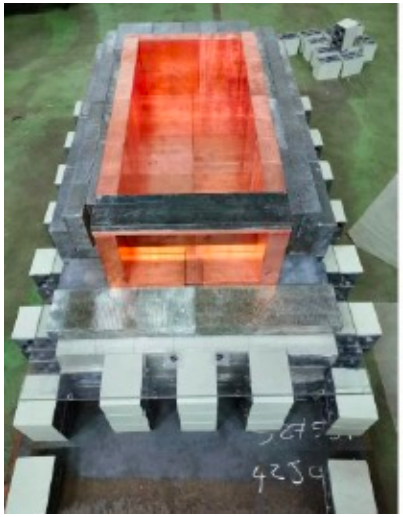
Gransasso **Stawell**

4”(D) X 8”(H) ingot (2018)

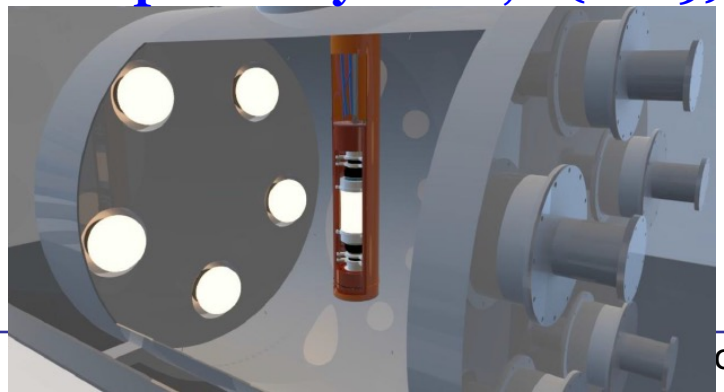


SABRE

3.4 kg



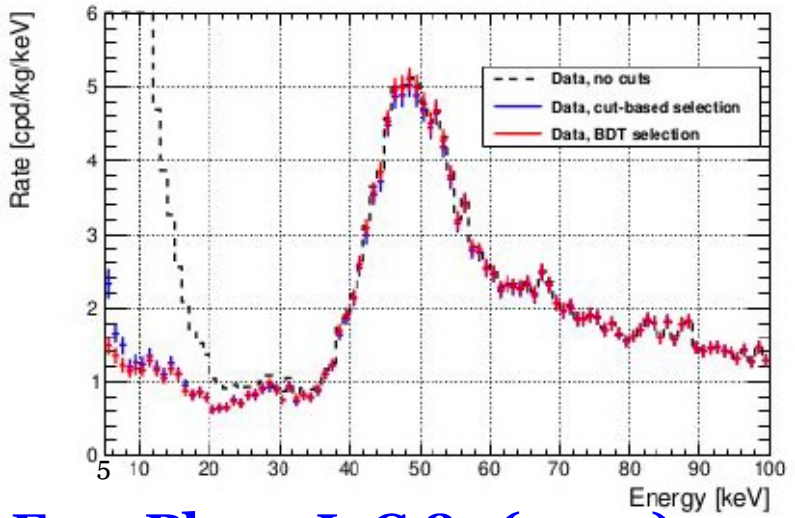
Astropart. Phys. 106, 1 (2019)



^{40}K (ICP-MS) ~ 4.3 ppb (DAMA ~ 20ppb)

^{210}Pb ~ 0.5 mBq/kg (DAMA < 0.03 mBq/kg)

1 counts/kg/keV/day @ 5-10 keV



Eur. Phys. J. C 81 (2021) 299

SABRE-PoP with liquid scintillator completed at July 2020

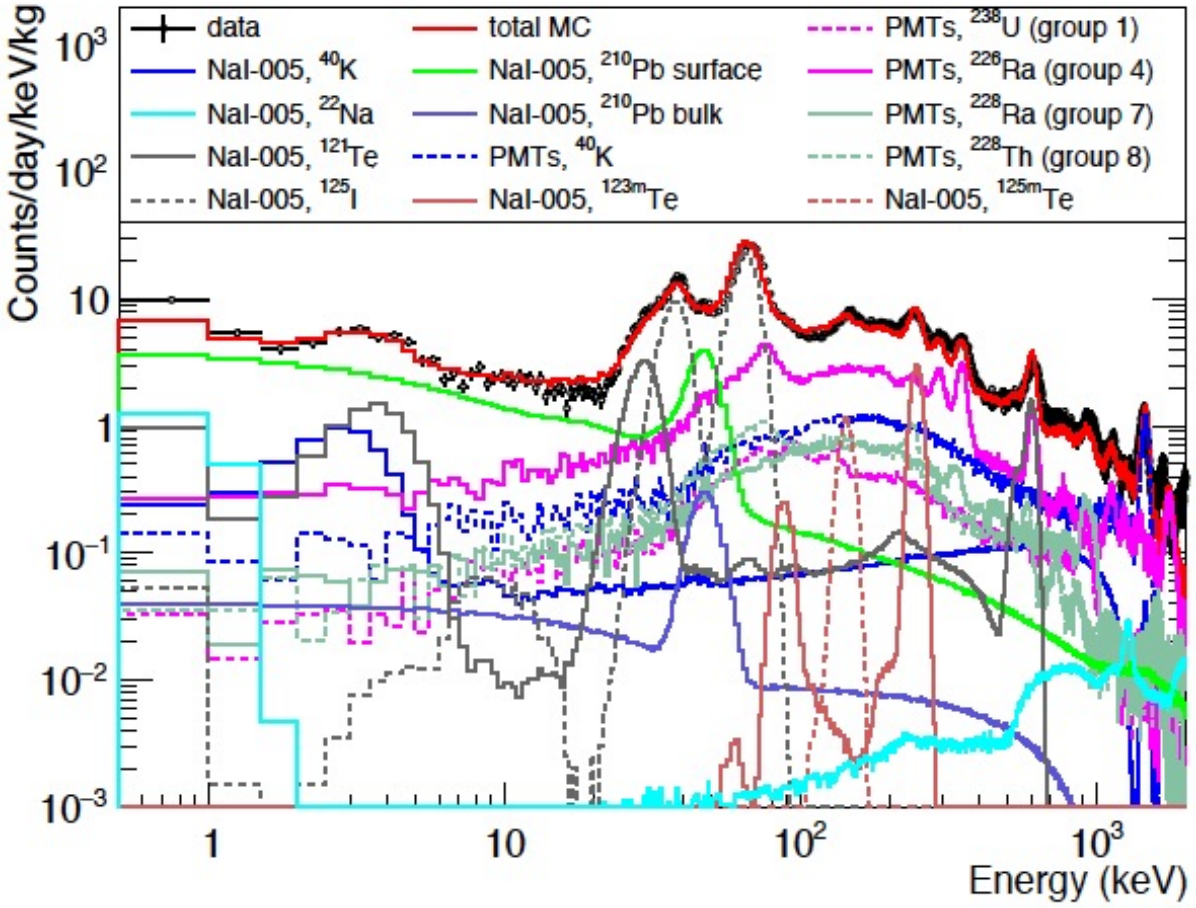
Start measurements from August 2020

Goal : 0.1 cpd/kg/keV, 50 kg each Granssaso & Stawell

NaI(Tl) development with Alpha Spectra (AS)

- Joints R&D between three (ANAIS, DM-Ice, and KIMS) collaborations and Alpha Spectra company since 2013

High light yield ~ 15 PE/keV

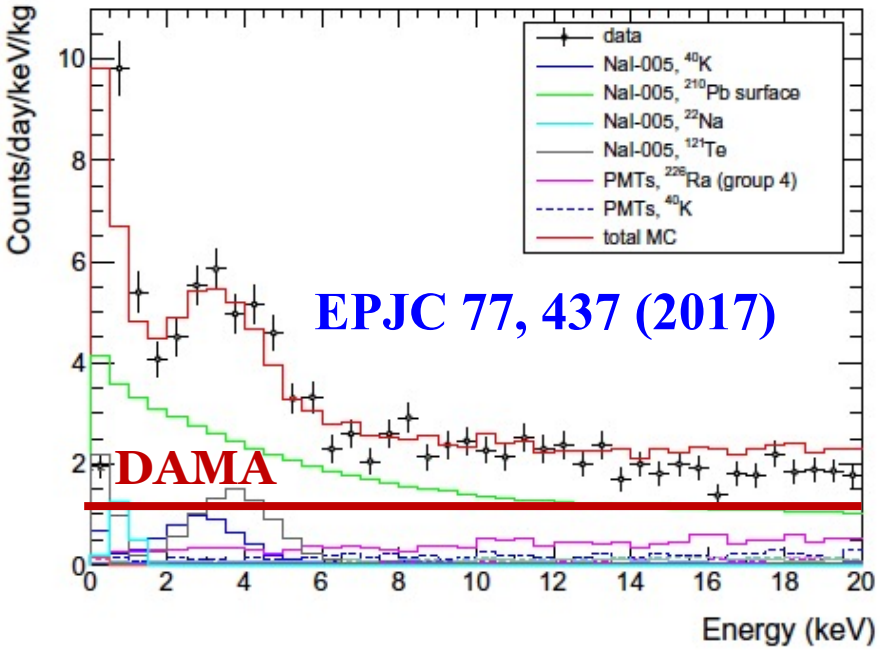


Astropart. Phys. 62, 249 (2015)
EPJC 76, 185 (2016)
EPJC 77, 437 (2017)
NIMA 103, 851 (2017)

NaI(Tl) development with Alpha Spectra (AS)

- Joints R&D between three (ANAIS, DM-Ice, and KIMS) collaborations and Alpha Spectra company since 2013

High light yield ~ 15 Photoelectrons/keV



DAMA :5~10 photoelectrons/keV

2-4 times larger than DAMA

COSINE-100

- Reduced ^{40}K but, still contribute significantly
- ^{210}Pb is the most significant contribution
- Cosmogenic activation is unexpected problem from AS
  - ❖ AS is located in Grand Junction, Colorado (~1,000 m altitude)

COSINE collaboration (Since 2015)

KIMS and DM-Ice joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals.
(Goal to **test DAMA/LIBRA experiment**)

YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

1000m

700m

(Power Plant)

KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

Minimum depth : 700 m / Access to the lab by car (~2km)

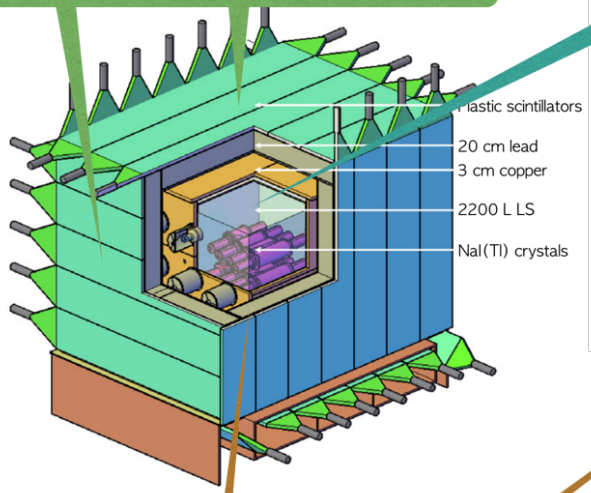
COSINE-100 detector configuration

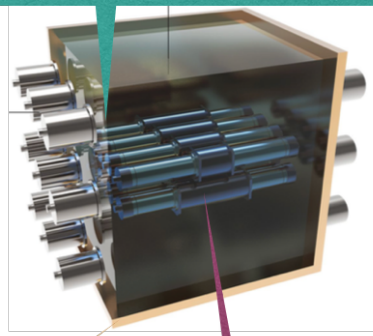
JCAP 02, 013 (2021) , JINST 13 T02007 (2018)

4π Muon Counter
37 plastic scintillator panels
2-inch PMT(H7195)s for muon counter

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

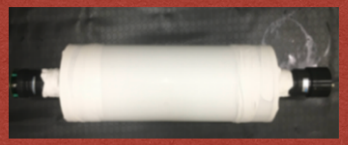
Liquid Scintillator
2200-L LAB-based LS for veto
5-inch PMT(R877)s for LS detector



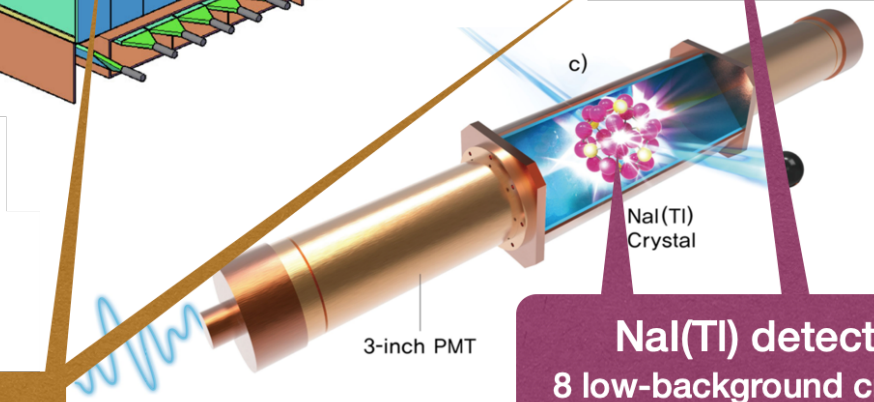


JINST 13 T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)



Thermal neutron detector
(^{3}He gas detector)



Shields
3-cm thick copper box
20-cm thick lead shielding

NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3-inch PMTs

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

Eur. Phys. J. C. 78, 490 (2018)
Eur. Phys. J. C. 81, 837 (2021)

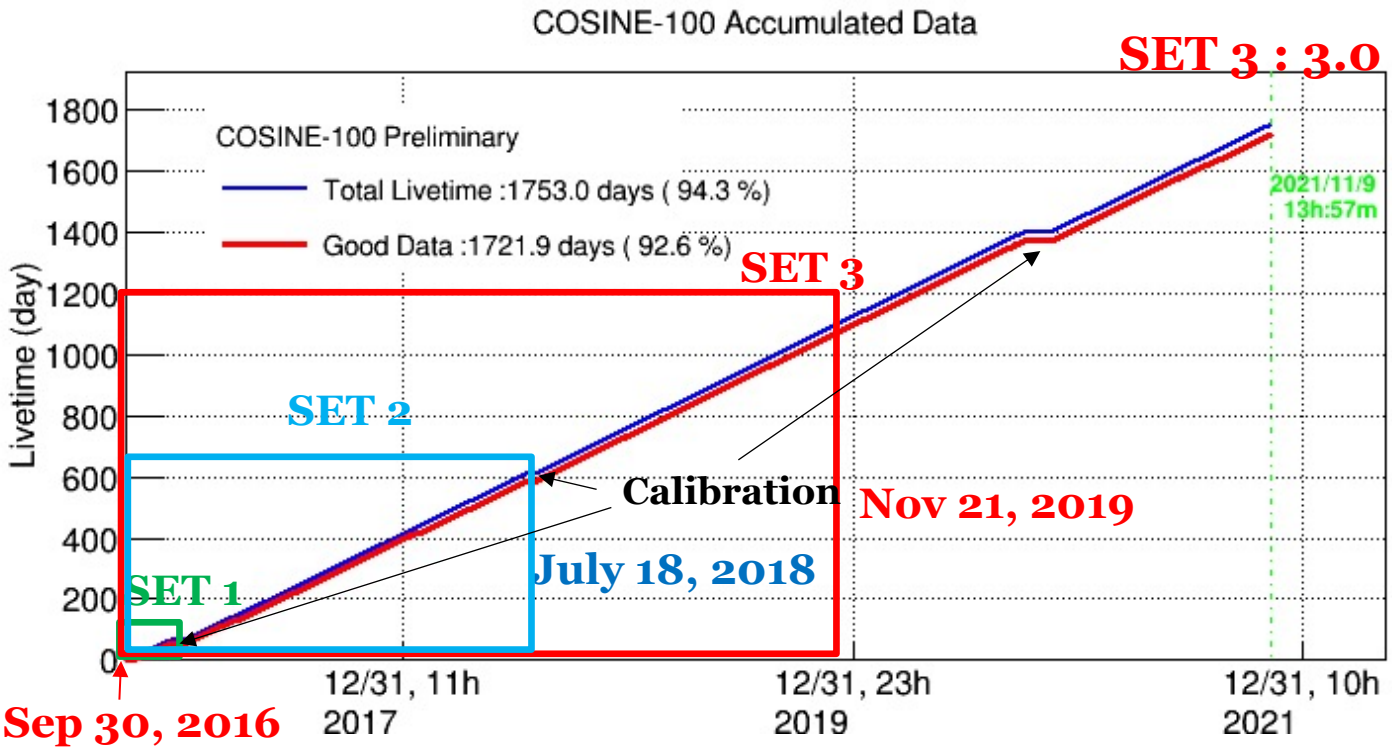
COSINE-100 operation

- **Total Exposure of COSINE-100**

SET 1 : 59.5 days

SET 2 : 1.7 years

SET 3 : 3.0 years



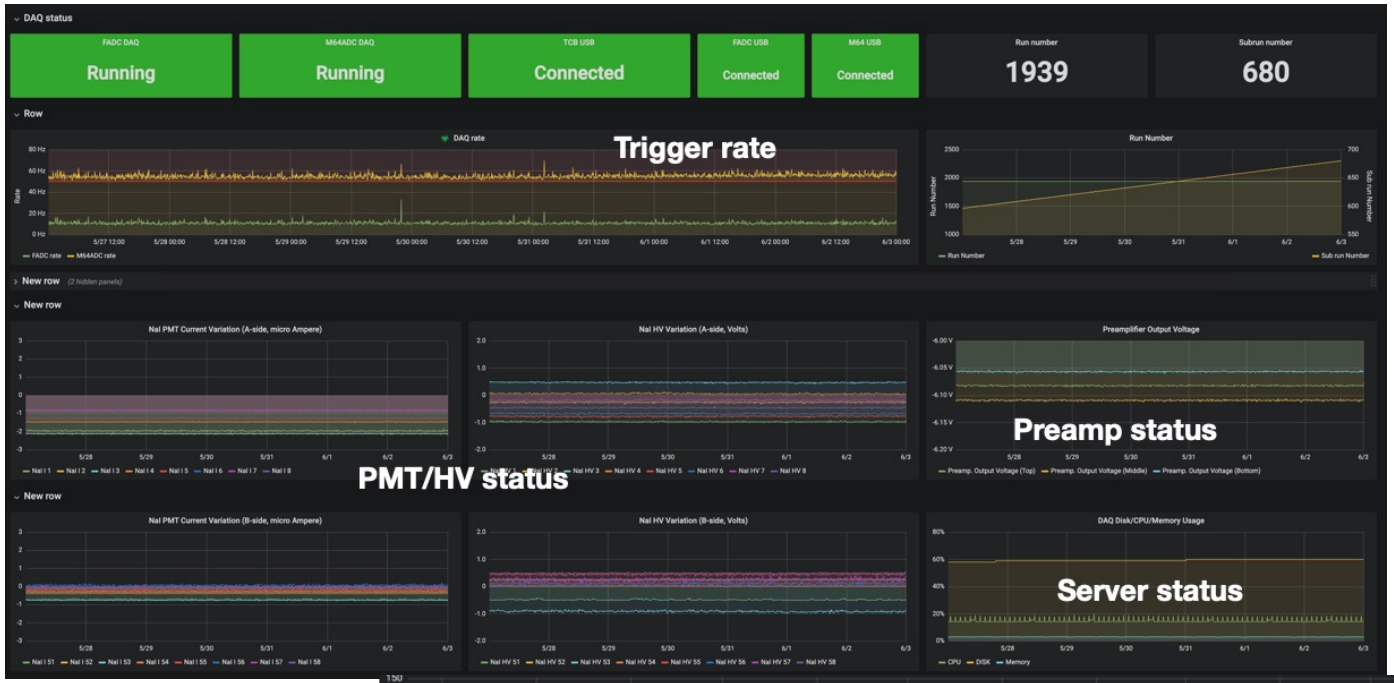
- **Stable operation from Sep. 2016 for about 5 years**
  - **~94 % physics data**
  - **~93 % good quality data**

Operation & Slow monitoring

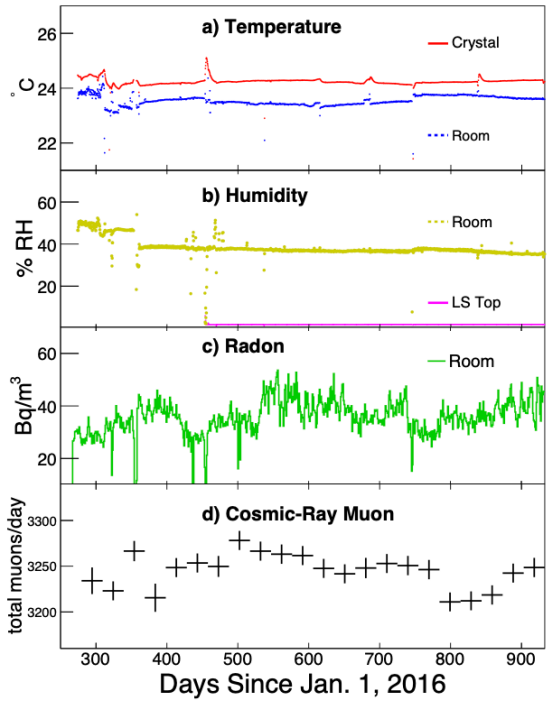
- Monitoring >200 parameters

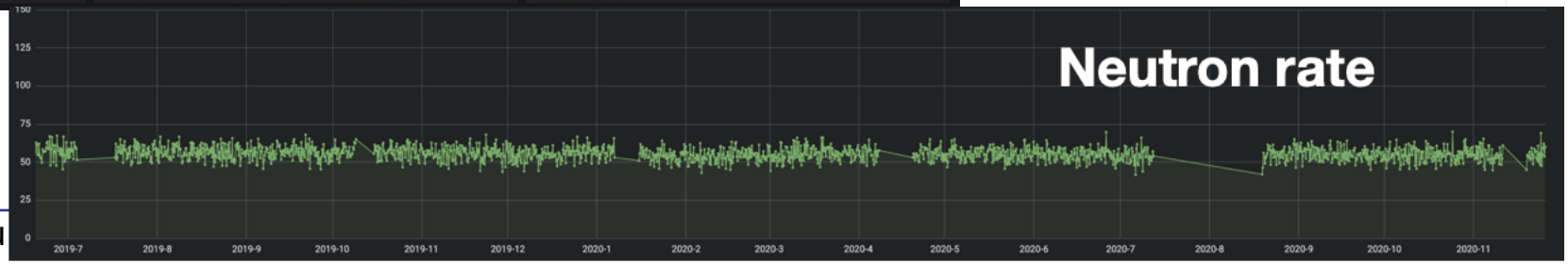
arXiv:2107.07655

  - ❖ DAQ system : Trigger rate, electronics status
  - ❖ Environmental parameters : Temperature, humidity
  - ❖ Neutron rate, muon rate etc



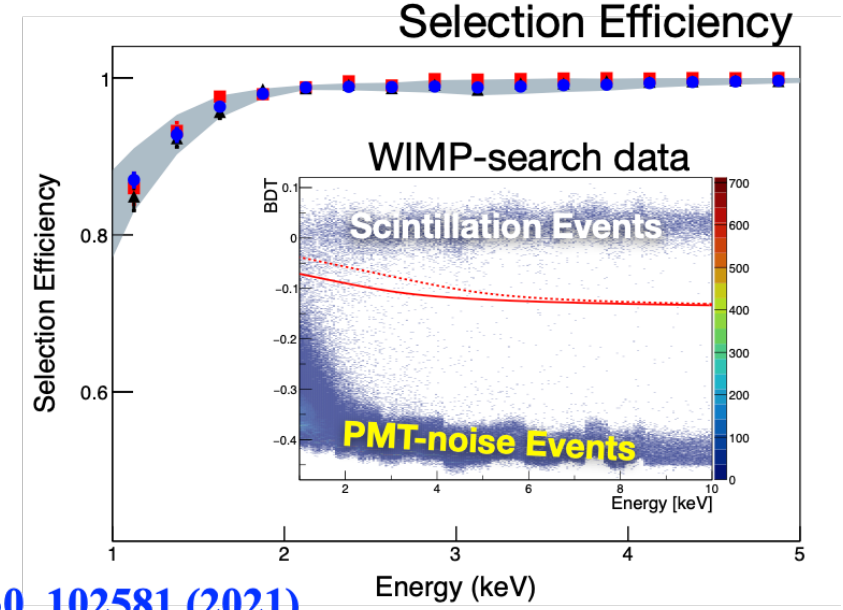
Phys. Rev. Lett. 123 031302 (2019)



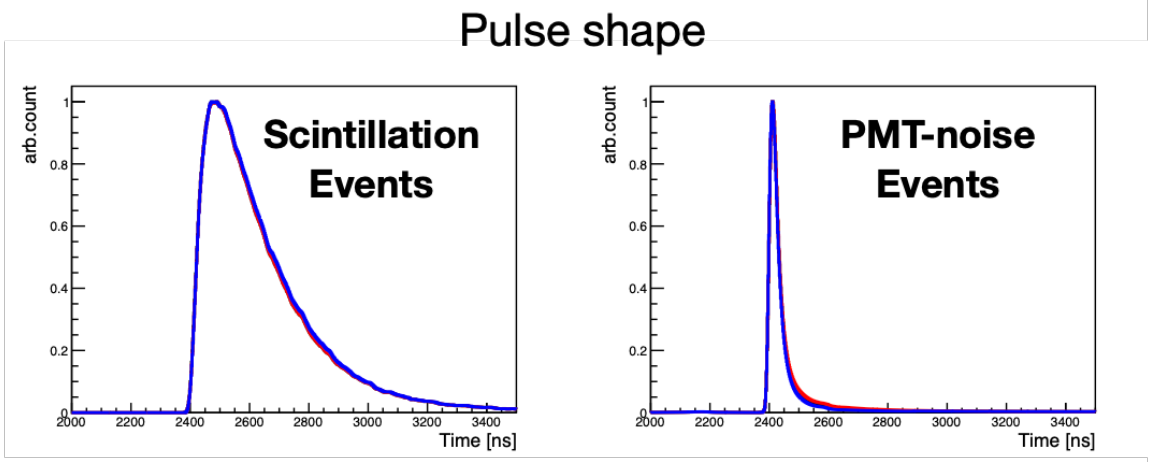


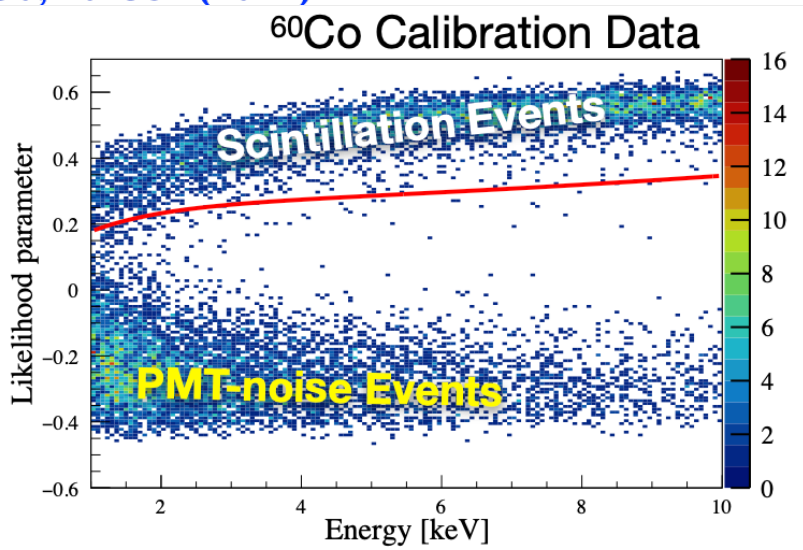
Event selection

- Lowering threshold 2 → 1 keV
  - Development of a new likelihood parameter based on pulse shape
  - Boosted decision tree (BDT) is used to separate the signals from the noises.
  - Further studies are ongoing
    - Improved multi-variable technique
    - Deep learning



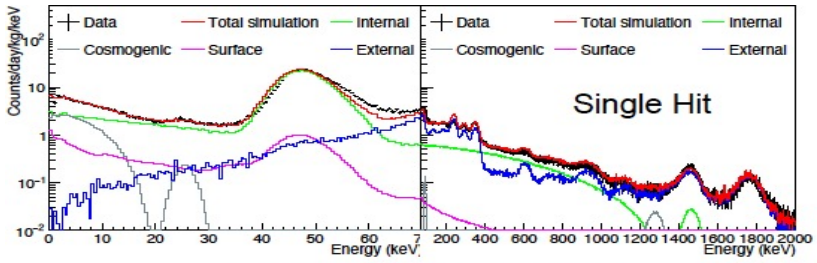
Astropart. Phys 130, 102581 (2021)



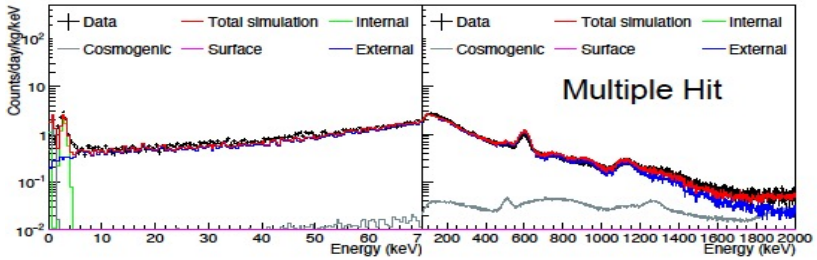


Background modeling

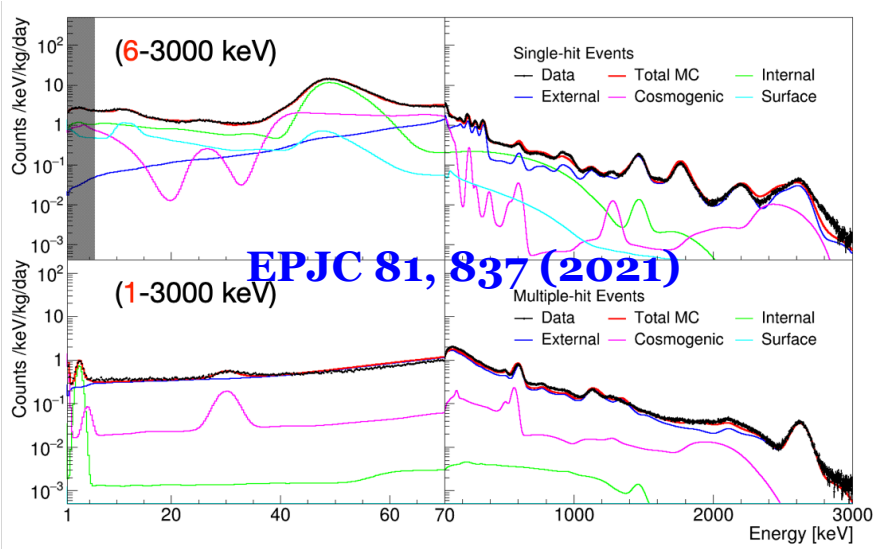
- SET1 (59.5 days) data with 2keV threshold
  - ❖ 2-6 keV single hit (signal region) was not used for the modeling
  - ❖ Demonstrate a good understanding of NaI(Tl) background



EPJC **78** 490 (2018)



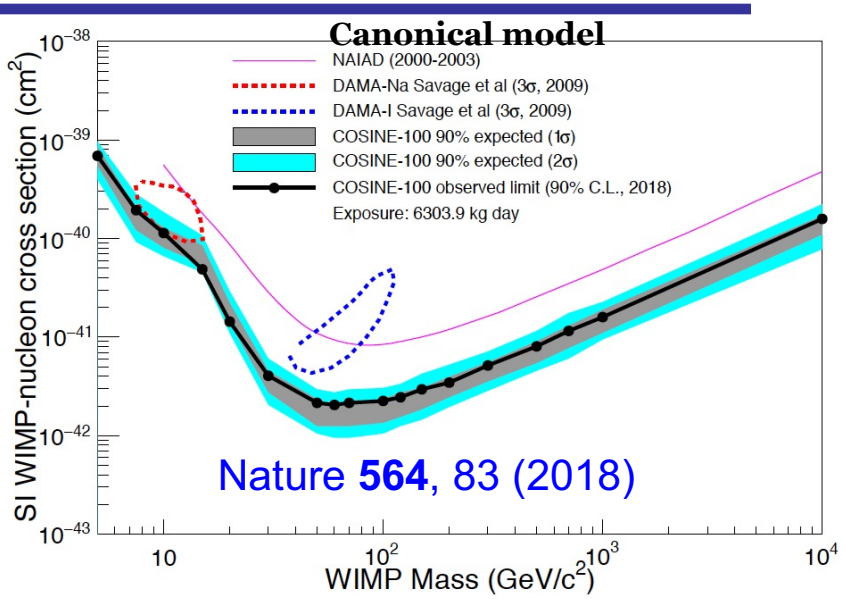
- SET2 (1.7 years) data with 1keV threshold
  - ❖ 1-6 keV single hit (signal region) was not used for the modeling
  - ❖ Extended energy range 1-3000 keV
  - ❖ Better understanding of ^{210}Pb on the surface (Astropart. Phys. **126** 102528(2021))
    - ^{129}I, rock-gamma (^{208}Tl) are added



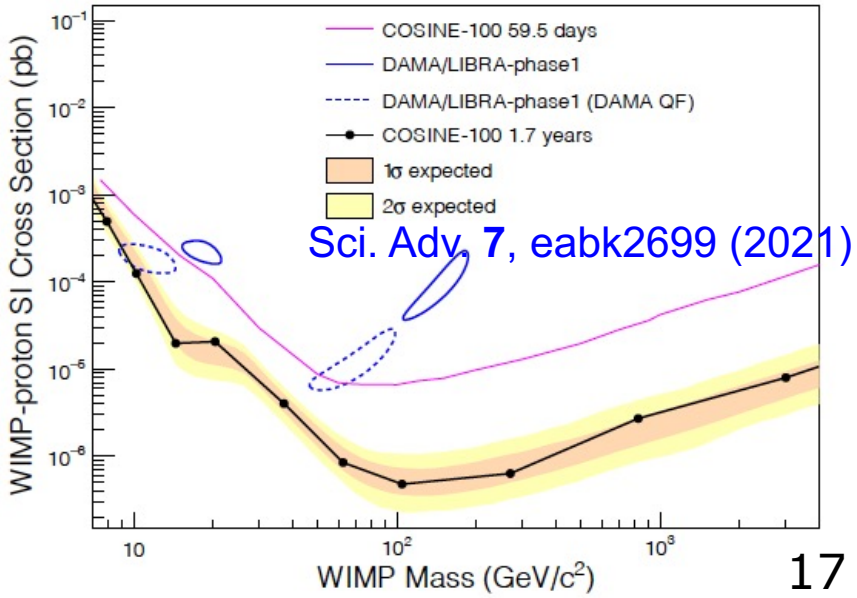
EPJC 81, 837 (2021)

WIMP extraction

- SET1 (59.5 days) data with 2keV threshold
  - ❖ **DAMA/LIBRA-phase1** is not compatible with spin-independent WIMP in the context of standard halo model
  - ❖ This is the first exclusion of DAMA using same NaI(Tl) crystals



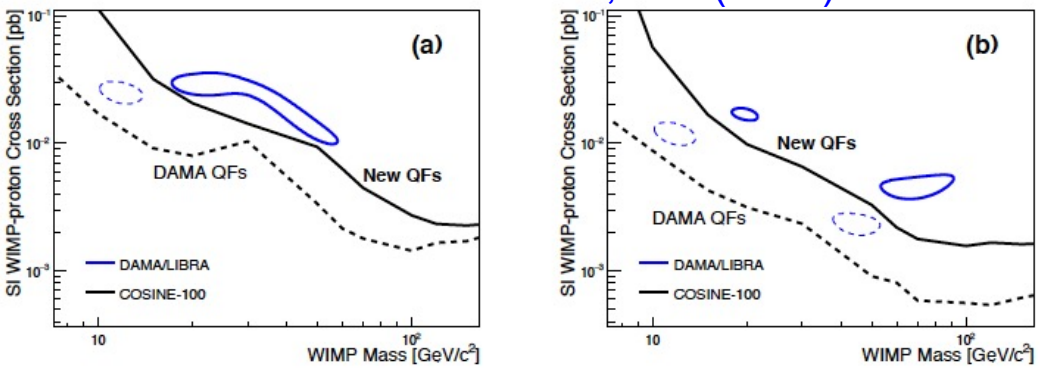
- SET2 (1.7 years) data with 1keV threshold
  - ❖ An order of magnitude improved limits
  - ❖ Exclude different quenching factor scenario



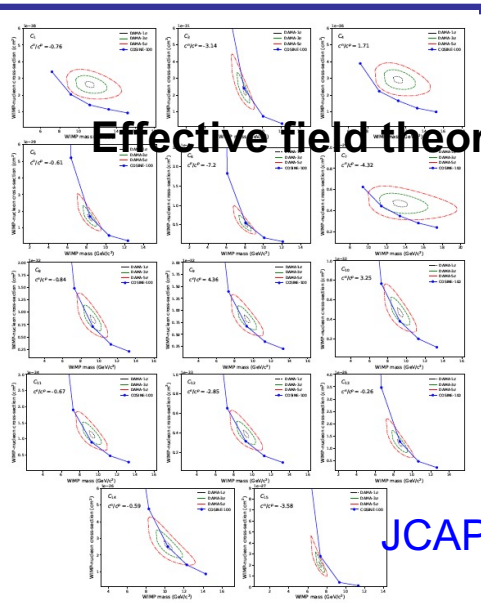
Other models

Isospin-violating interaction

JCAP 06, 048 (2019)



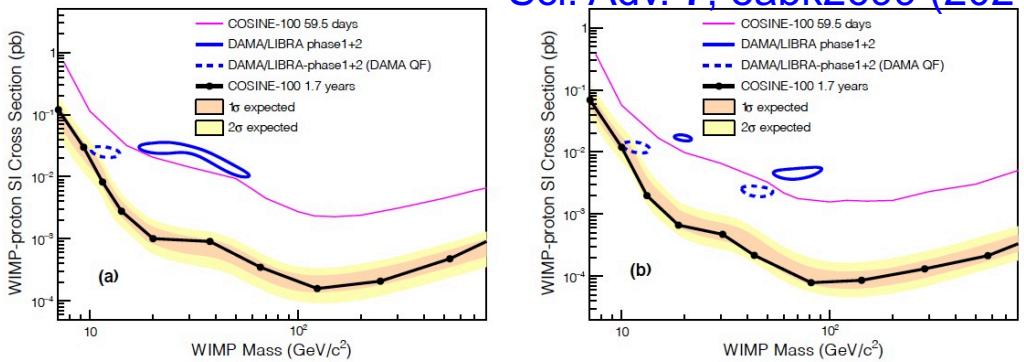
Effective field theory

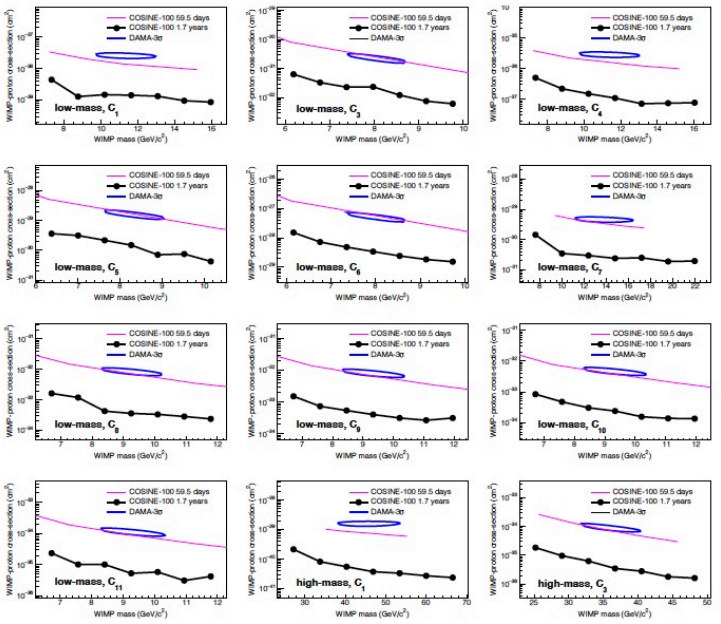


JCAP 11, 008 (2019)

DAMA/LIBRA-phase1+2

Sci. Adv. **7**, eabk2699 (2021)





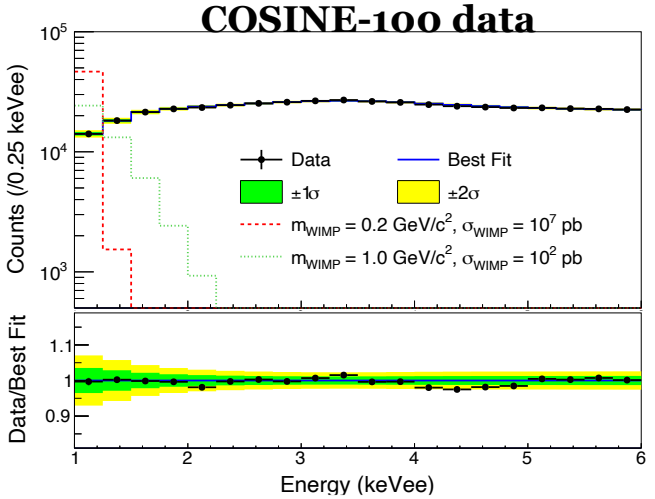
- Fully cover alternative scenarios
  - ❖ Quenching factors, EFT operators..

Low-mass dark matter with Migdal effect

- Migdal effect
  - ❖ Nuclear recoil → Boost of electrons → Secondary radiation
  - ❖ Differential rate & visible energy

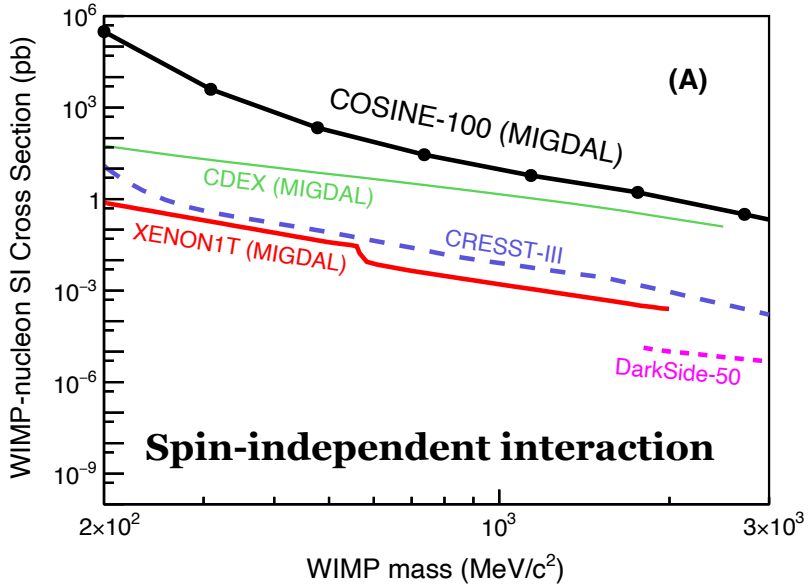
$$\frac{dR}{dE_{\rm ER}} \simeq \int dE_{\rm NR}\, dv\, \frac{d^2R}{dE_{\rm NR}dv} \frac{1}{2\pi} \sum_{n,l} \frac{d}{dE_{\rm ER}} p^c_{q_e}(n,l \to E_{\rm ER} - E_{nl})$$

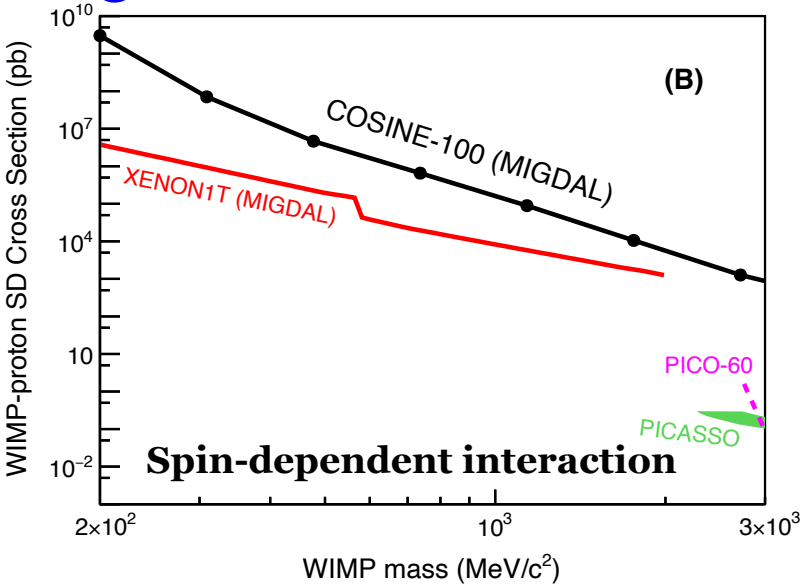
JHEP 2018, 194 (2018)



  - ❖ Possible to search low-mass dark matter
    - ❑ Sub-GeV DM as low as 0.2 GeV/c²

arXiv:2110.05806

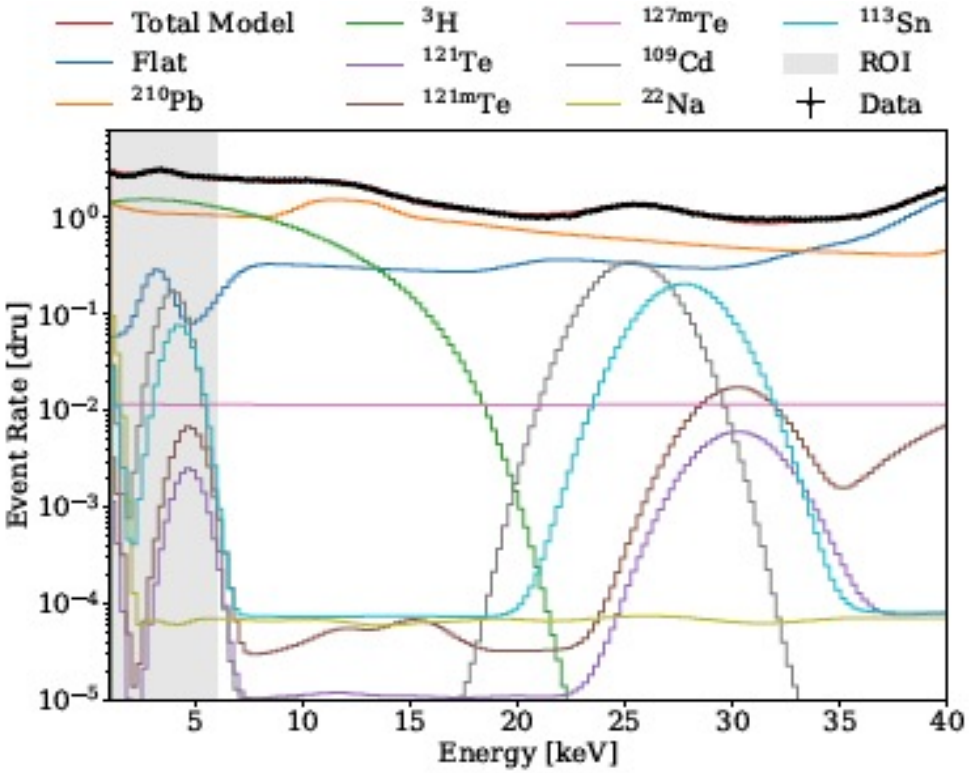




Annual modulation search

Oct/21 (2016) ~ Nov/21 (2019) ~3 year

Time dependent background modeling



Astropart. Phys. **115** (2020) 102390

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

$$R(t) = \sum_i \left[C^i + \sum_j^8 A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Crystal specific

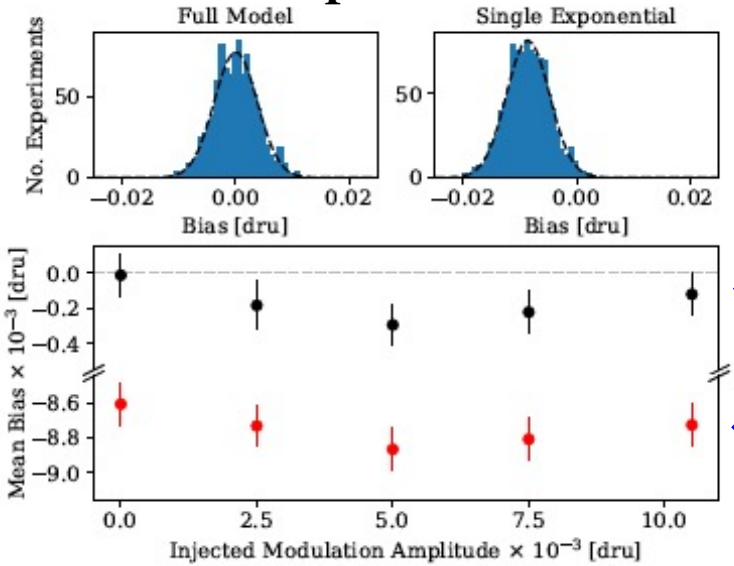
Fixed across crystal

Total rate

Background components:
Constant (long-lived backgrounds)
Exponential (short-lived backgrounds)

Modulation component
S_m is modulation amplitude

Pseudoexperiment results

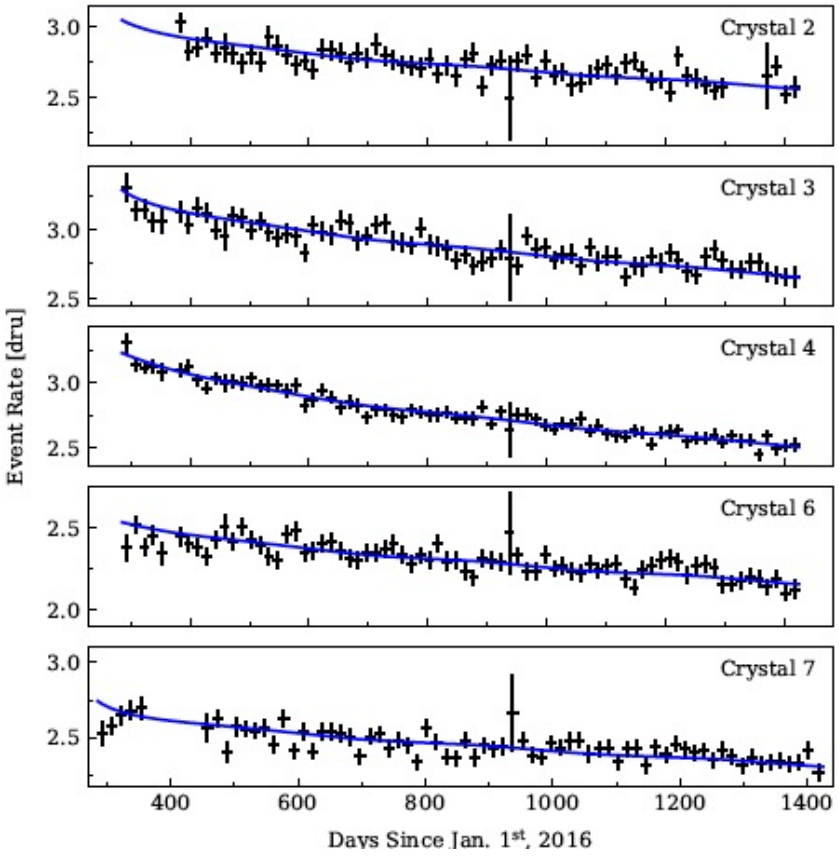


Full model

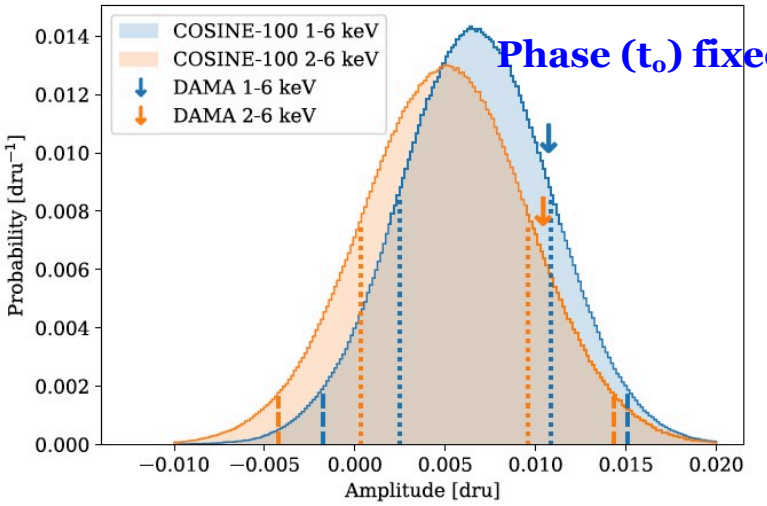
Single exponential

Annual modulation search (Data fits)

Event rate vs Time

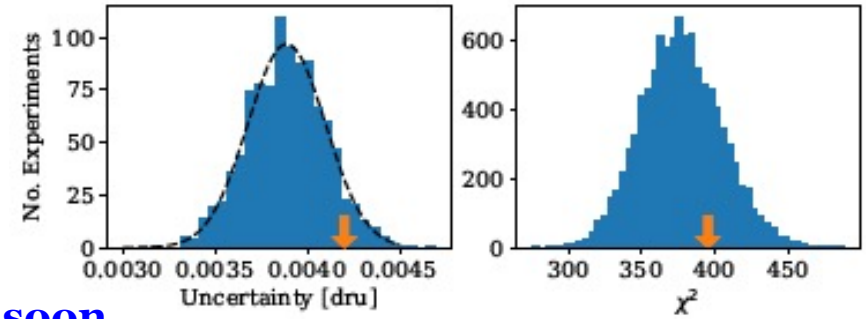


Posterior distribution with Bayesian analysis



Phase (t_o) fixed at June/2nd

Data vs pseudo data

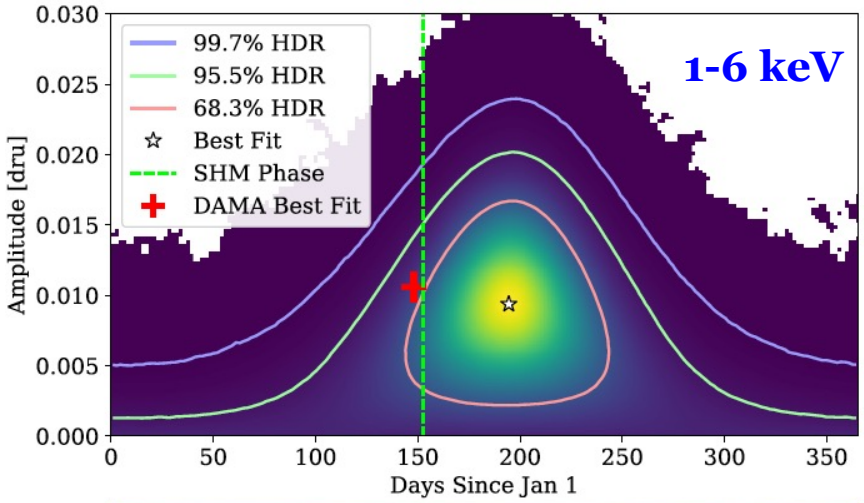


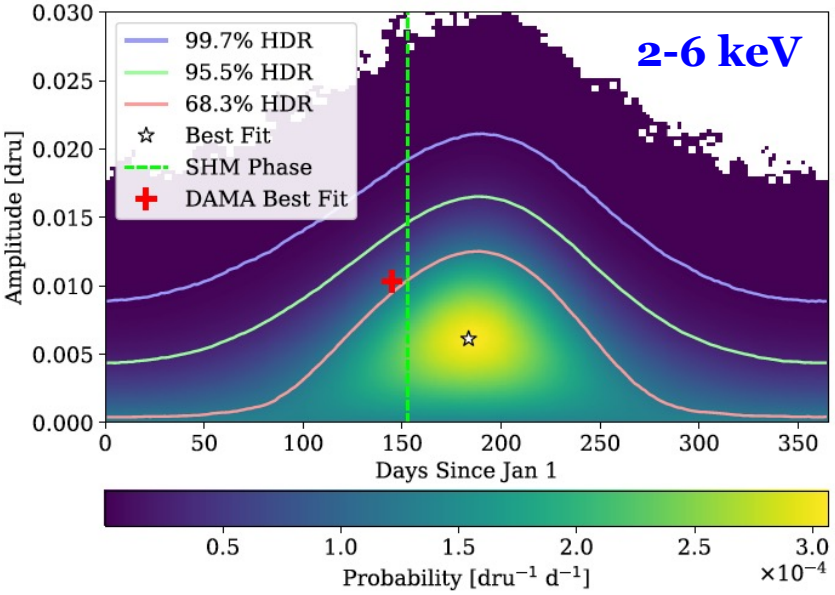
Will be appeared in arXiv soon

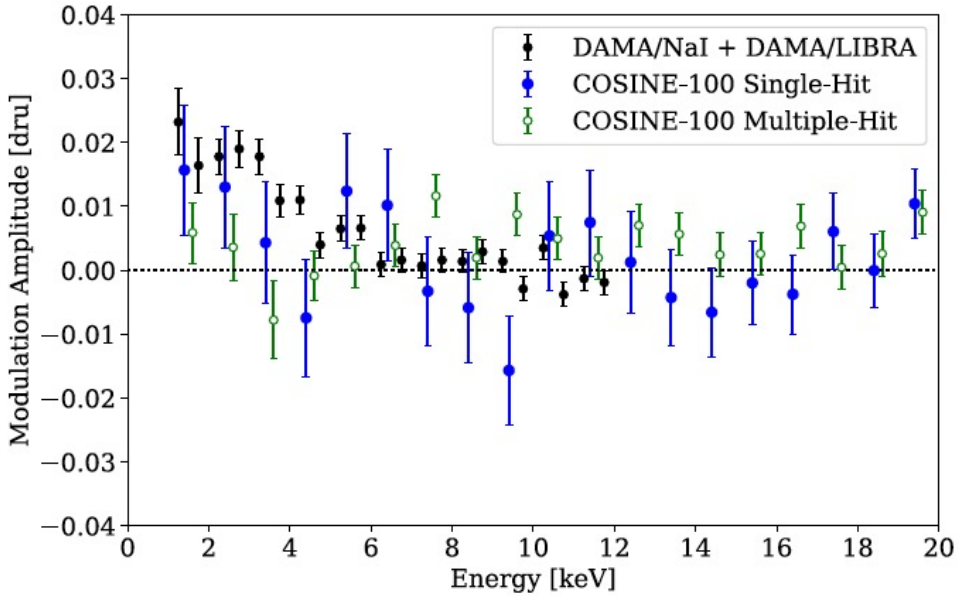
- 1-6 keV : 0.0067+/-0.0042 (DAMA : 0.0105+/-0.0011) dru
- 2-6 keV : 0.0050+/-0.0047 (DAMA : 0.0103+/-0.0008) dru

Annual modulation search (Data fits)

Phase floated (2D) fits







Will be appeared in arXiv soon

Final conclusion with model independent analysis require more data

or better quality detector

COSINE-200 crystal development

- Goal : Background less than DAMA/LIBRA (1 dru)
  - ❖ Needs a factor two or more improvement
  - ❖ Powder purification/crystal growing/detector assembly will be done at IBS, Korea

Powder purification performance

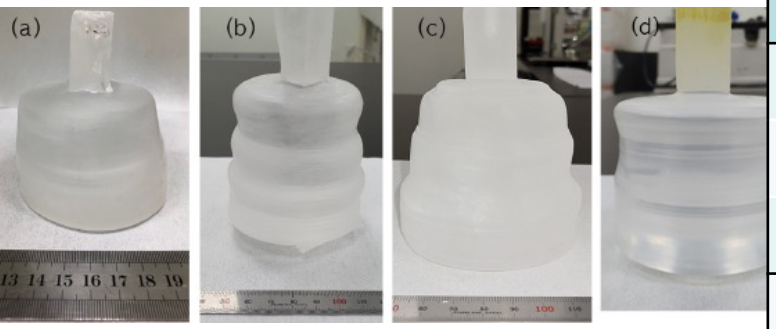
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

K.A. Shin et al., JINST 15, C07031 (2020)

	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

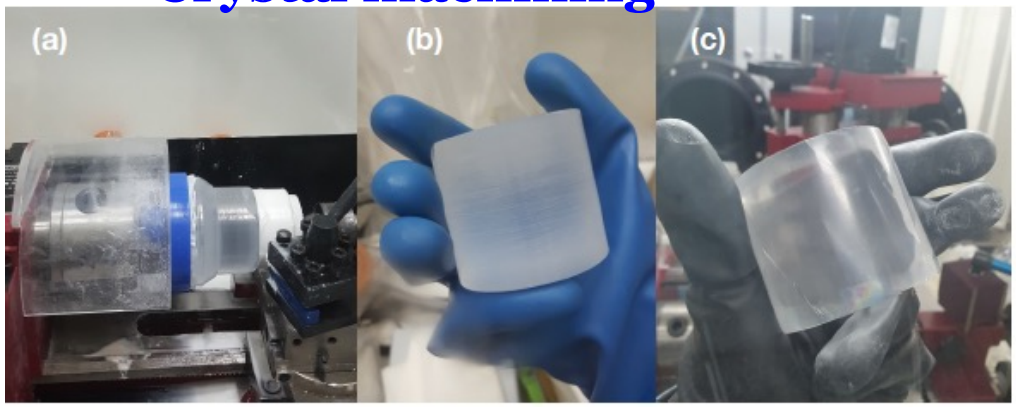
Crystal growing with test grower

Crystal ingots



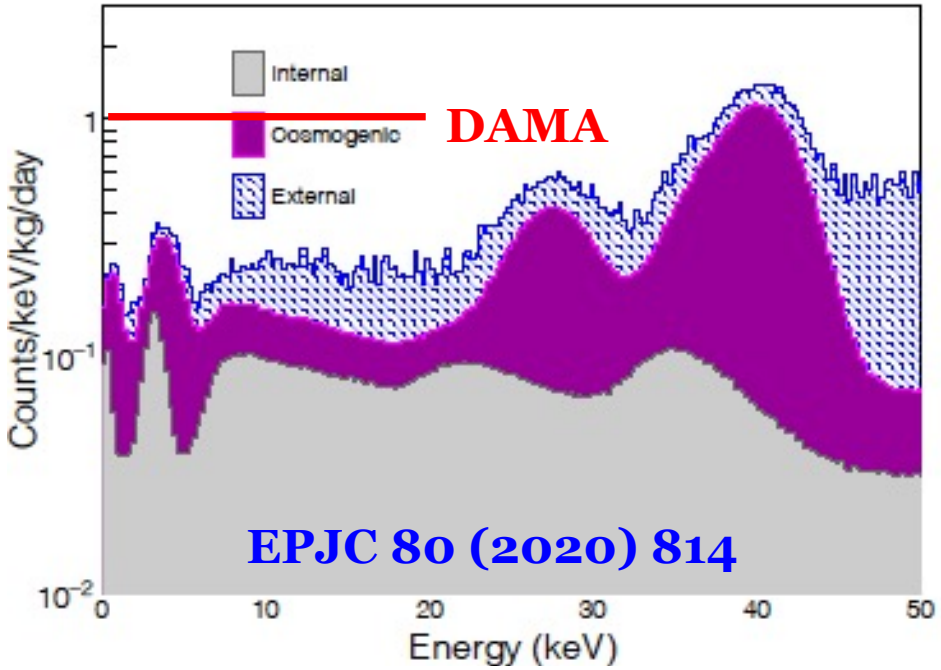
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

Expected background



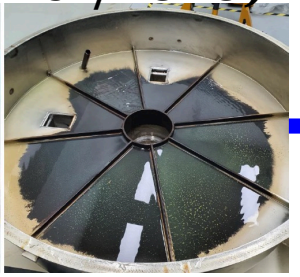
A **proof of principle** for low background NaI

Full size grower

- First test run
  - ❖ Found some issues and improved the system
- Third run
  - ❖ Successful seeding and grow ~10 cm ingot
- Goal : ~ 100 kg ingot

- Designed and built the **full size grower** based on small test grower (crystal growing & low-background)

First run (Summer/2020)



Improve the system

Third run (Aug/2021)

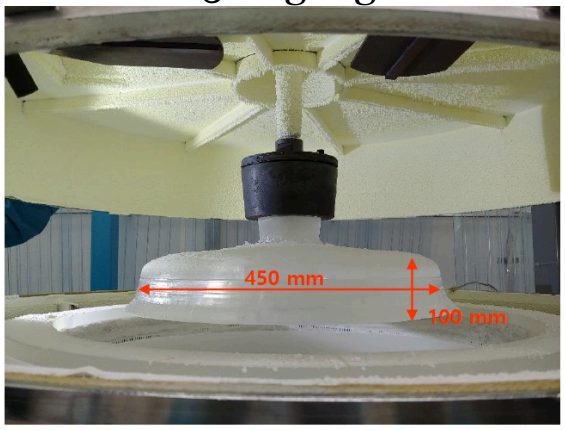
~200 kg powder

<Powder charging>

Seed holder

<Seed & holder>

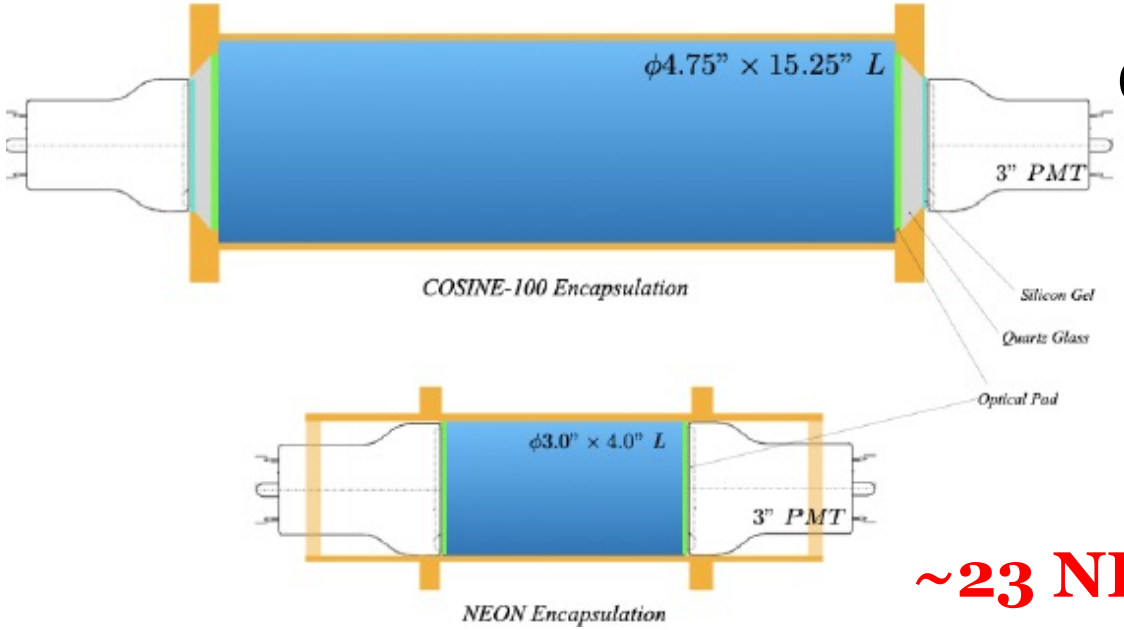
~50 kg ingot



<Crystal dimension>

Novel technique of crystal encapsulation

NIMA 981 (2020) 164556



15 NPE/keV

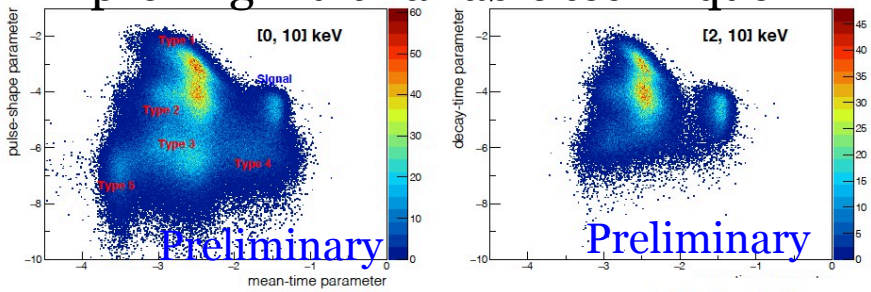
(NPE=number of photoelectrons)

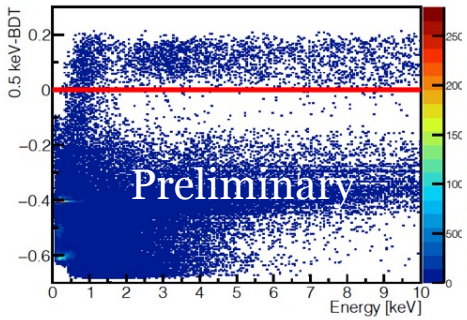
~23 NPE/keV

- Direct attachment of NaI(Tl) to PMTs
- ~50 % increased light yield was observed
- This technique can be applied for COSINE-200 detector assembly

Efforts for low-threshold NaI(Tl) detectors

Improving multivariable technique

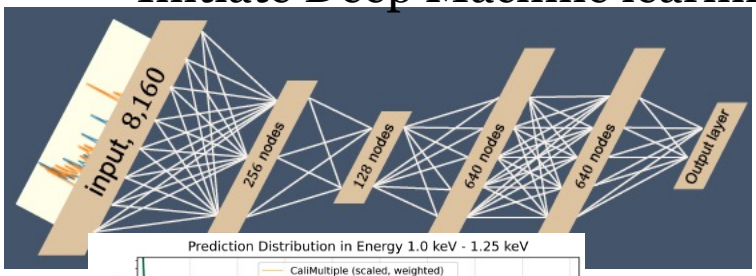


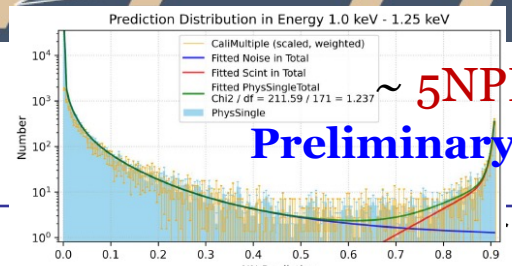


Multiple-hit

~ 0.5 keV (7 NPE) threshold achievable!!

Initiate Deep Machine learning

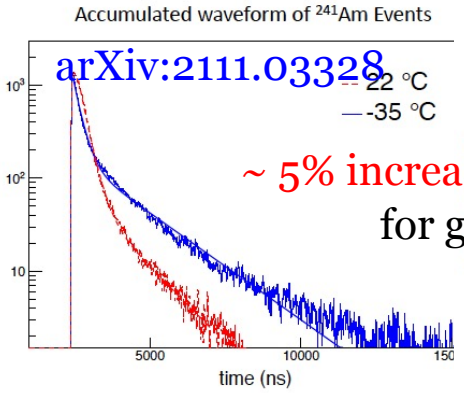




~ 5NPE threshold?

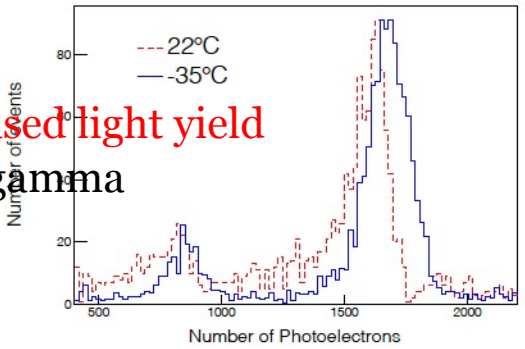
Preliminary

Low temperature measurement

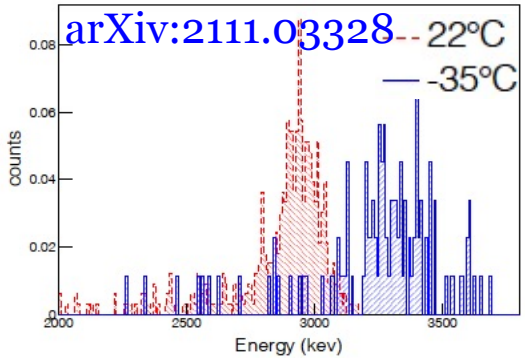


~ 5% increased light yield for gamma

Am-241 measurement



Po-210 alpha measurement



Alpha quenching increased ~ 10 %

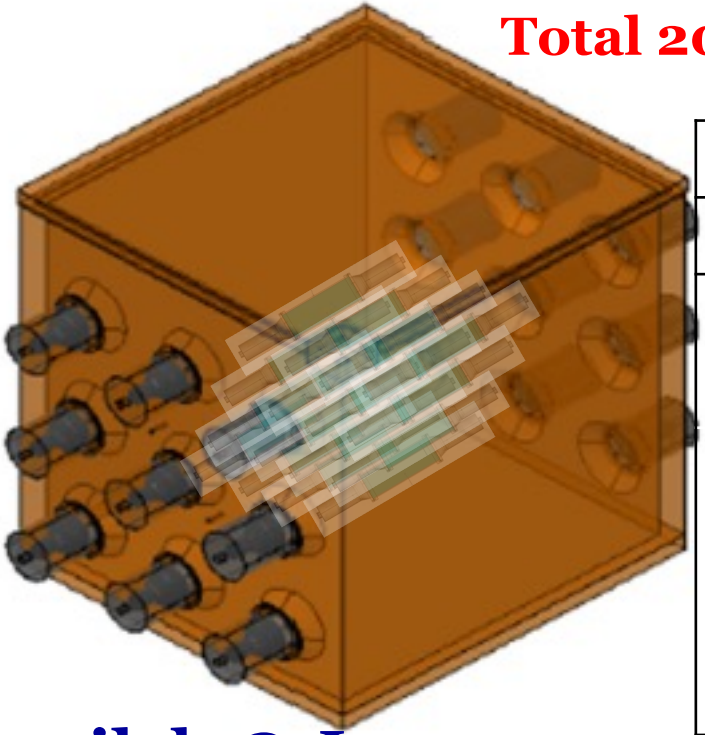
Neutron quenching measurement is under preparation

Consider -30°C operation for COSINE-200

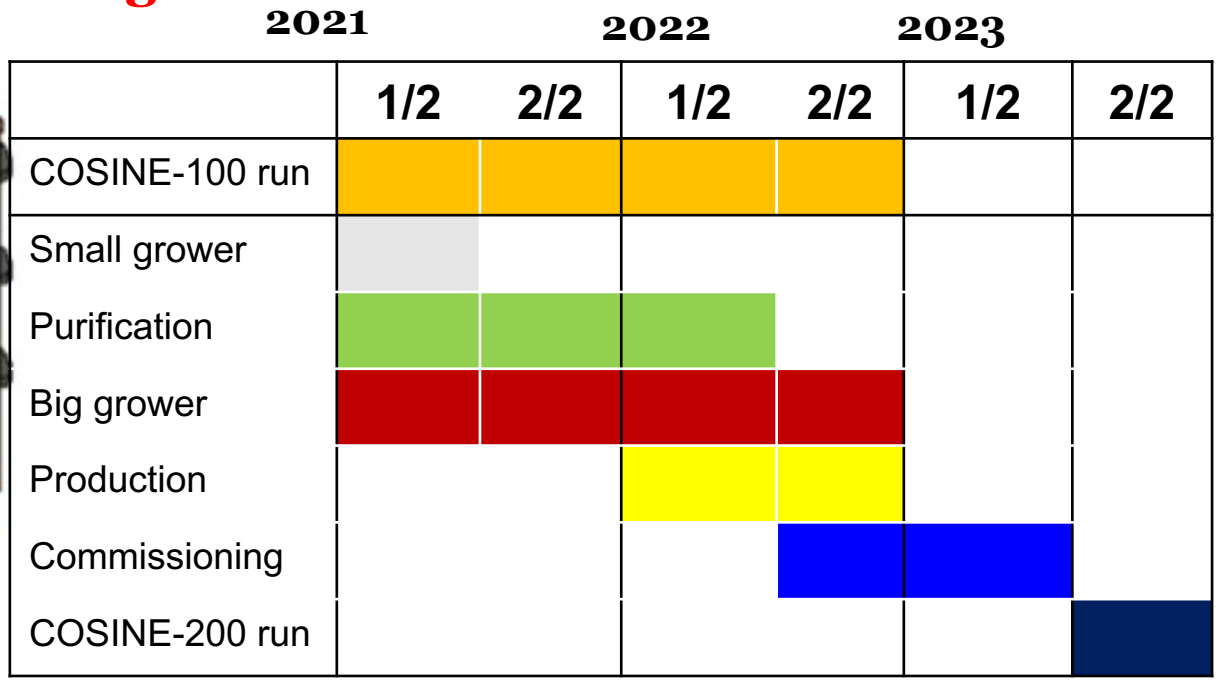
COSINE-200

- **Current COSINE-100 shield designed to accommodate 16 of 12.5 kg crystals = 200 kg**

Total 200 kg



Yemilab @ Jeongsun



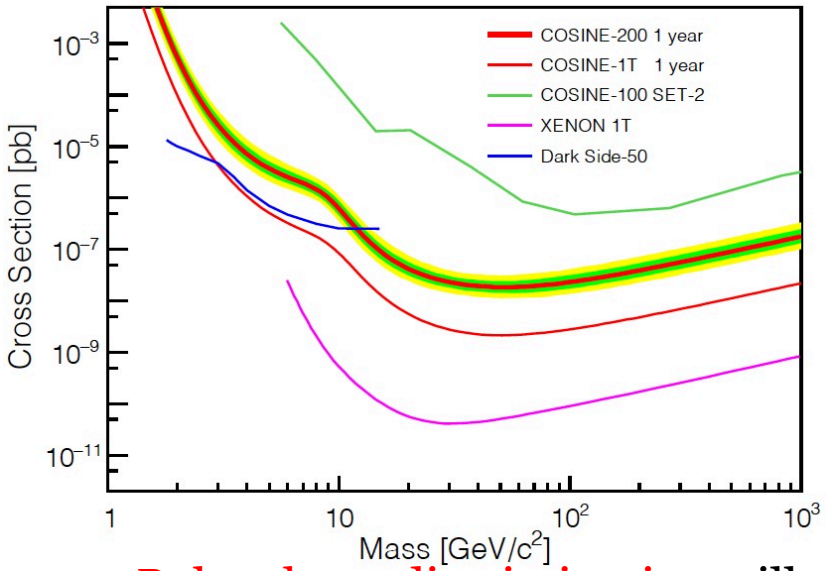
With 3 years operation, DAMA/LIBRA can be concluded with more than 7 sigma significance

- **Low temperature operation (-35°C) is under consideration**

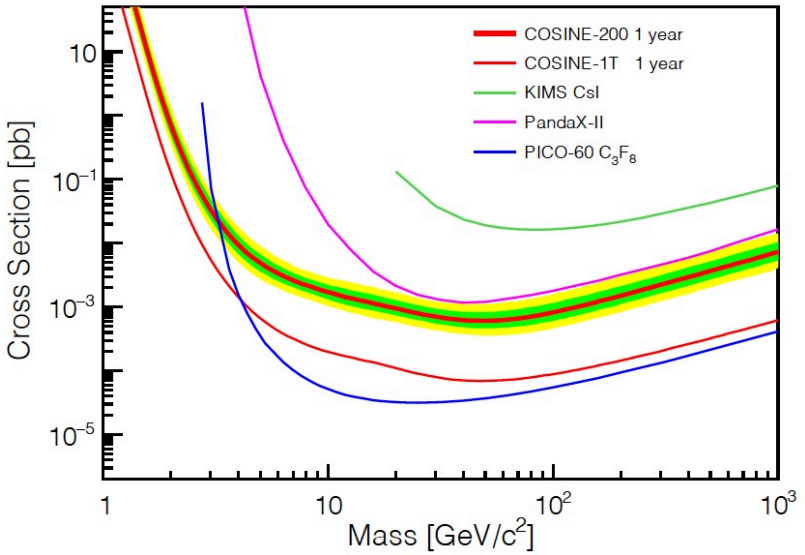
COSINE-200 as general dark matter detector

- Assuming light yield ~ 22 NPE/keV (5NPE threshold)
- 200 kg x 1 year data assumed

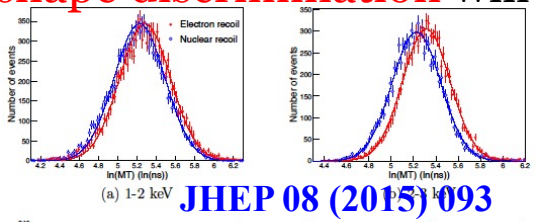
WIMP-nucleon spin-independent



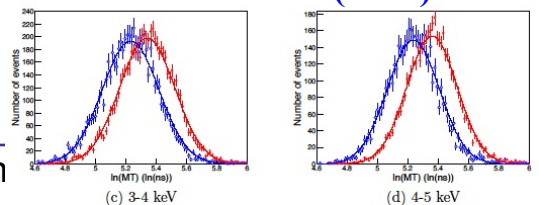
WIMP-proton spin-dependent

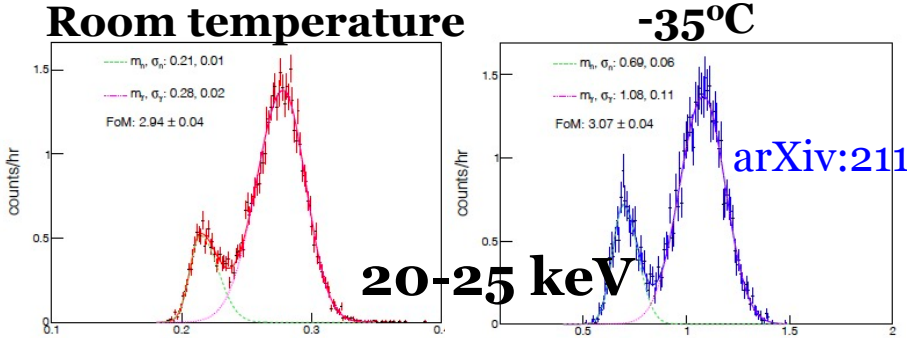


Pulse shape discrimination will enhance dark matter detection sensitivity significantly



JHEP 08 (2015) 093





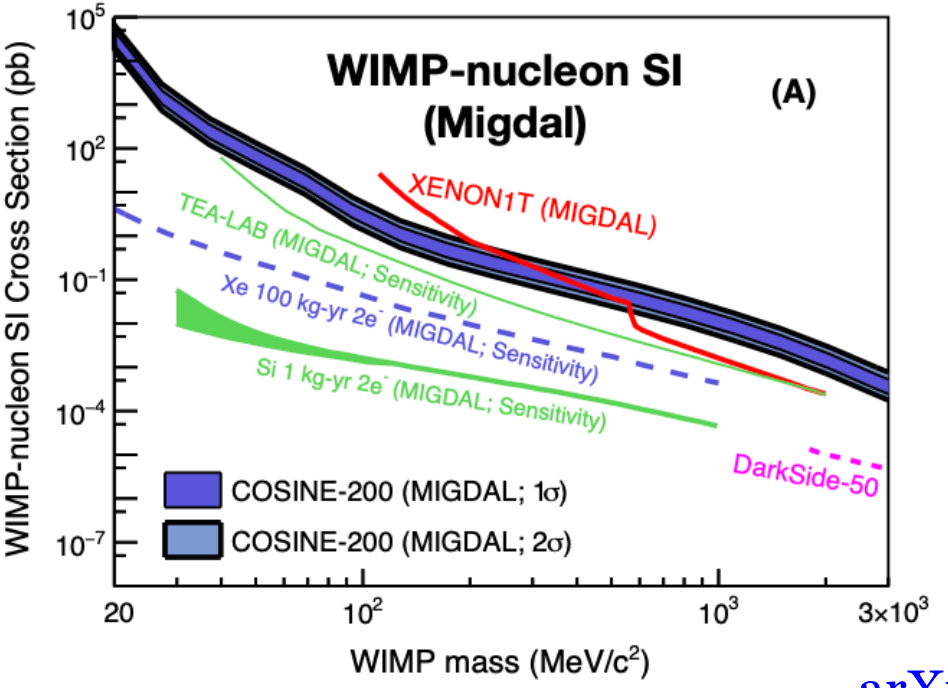
20-25 keV

arXiv:2111.03328

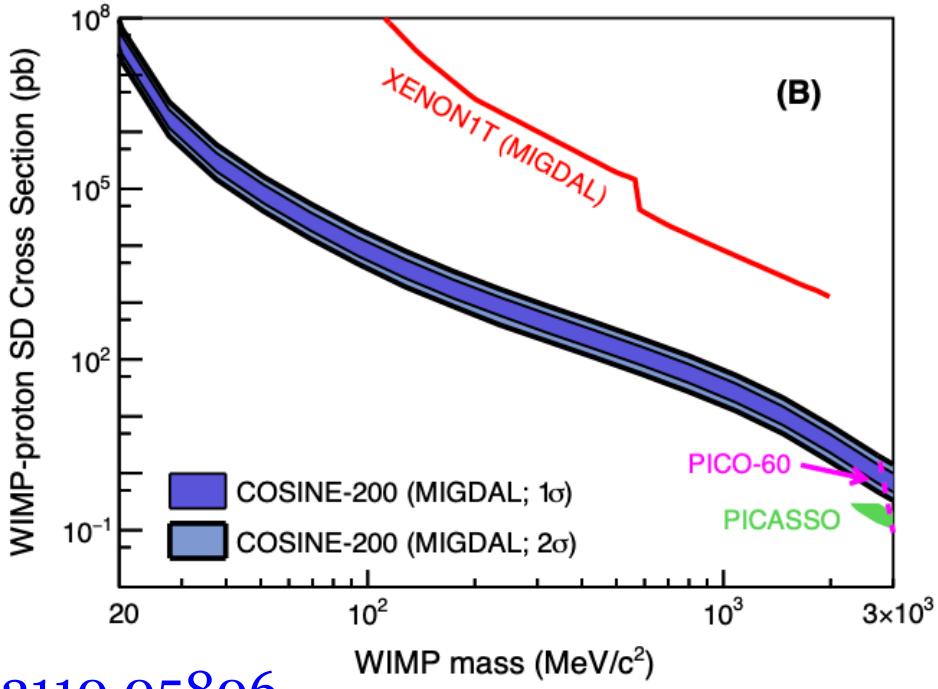
COSINE-200 sensitivity for low-mass

- Migdal process for very low-mass region

WIMP-nucleon spin-independent



WIMP-proton spin-dependent



arXiv:2110.05806

- COSINE-200 can probe unexplored parameter spaces!!

Summary

- DAMA modulation signals continue for last 20 years
- Many efforts to reproduce DAMA are ongoing
- COSINE-100 data rejects DAMA result as SI WIMP interaction for standard halo model
- Annual modulation results of COSINE-100 were updated but, still we need more data
- COSINE-200 R&D are actively ongoing
- We hope to find out the cause of DAMA modulation with lower background detectors
- COSINE-200 can probe unexplored parameter space by current or future DM search experiments

Stay tuned for more exciting results to come from COSINE-experiment!