Dark Sector Particle Searches with NaI(TI) crystals

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Center for Underground Physics

CAU-PNU BSM Workshop @ Chung-Ang Univ., February 19, 2024

NaI crystals for particle detection

Pro

- High light output
  - ❖ 40,000 photons/MeV
  - ❖ >60,000 photons/MeV?
- Easy to grow
  - ❖ Cheap
  - ❖ Large size
- The most widely used scintillator
- Mixture of low and high atomic numbers

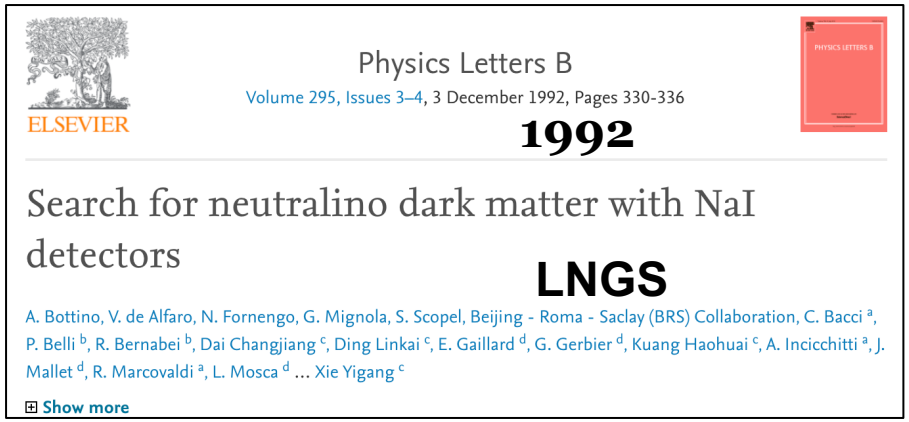
The first 32 inch diameter NaI(Tl) crystal. Pictured from left to right are Dr. Swinehart, Ed Jablon, Joe Knaus and Marko Sfilgoi.

Properties	From Saint-Gobain
Density [g/cm^3]	3.67
Melting point [K]	924
Thermal expansion coefficient [C^{-1}]	47.4 x 10^{-6}
Cleavage plane	<100>
Hardness (Mho)	2
Hygroscopic	yes
Wavelength of emission max [nm]	415
Refractive index @ emission max.	1.85
Primary decay time [ns]	250
Light yield [photons/keVγ]	38
Temperature coefficient of light yield	-0.3%C^{-1}

Con

- Huge hygroscopic materials
- Contamination of natural Potassium
  - ❖ ~ 3keV X-ray from ^{40}K
- No good identification of nuclear recoil

NaI(Tl) for rare event searches : Dark Matter



ELSEVIER

Physics Letters B

Volume 295, Issues 3–4, 3 December 1992, Pages 330-336

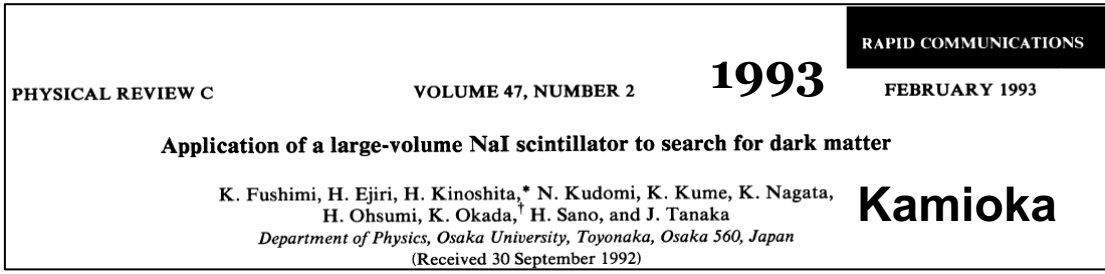
1992

Search for neutralino dark matter with NaI detectors

LNGS

A. Bottino, V. de Alfaro, N. Fornengo, G. Mignola, S. Scopel, Beijing - Roma - Saclay (BRS) Collaboration, C. Bacci [a], P. Belli [b], R. Bernabei [b], Dai Changjiang [c], Ding Linkai [c], E. Gaillard [d], G. Gerbier [d], Kuang Haohuai [c], A. Incicchitti [a], J. Mallet [d], R. Marcovaldi [a], L. Mosca [d] ... Xie Yigang [c]

Show more



PHYSICAL REVIEW C VOLUME 47, NUMBER 2 **1993** RAPID COMMUNICATIONS FEBRUARY 1993

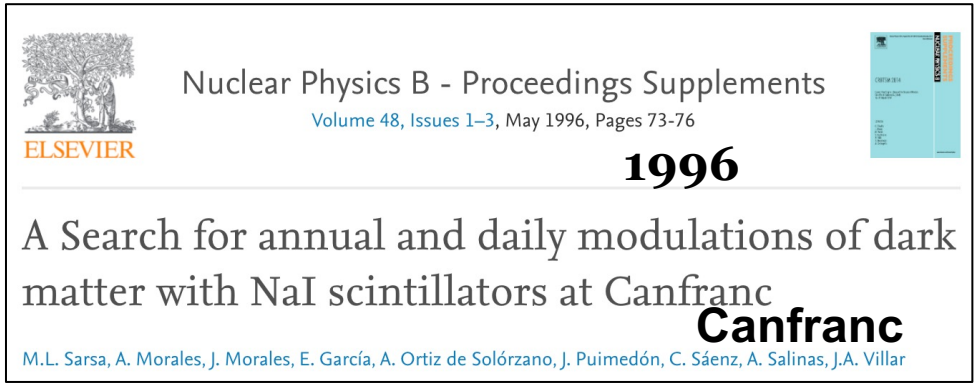
Application of a large-volume NaI scintillator to search for dark matter

K. Fushimi, H. Ejiri, H. Kinoshita,* N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada,† H. Sano, and J. Tanaka

Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan

(Received 30 September 1992)

Kamioka



ELSEVIER

Nuclear Physics B - Proceedings Supplements

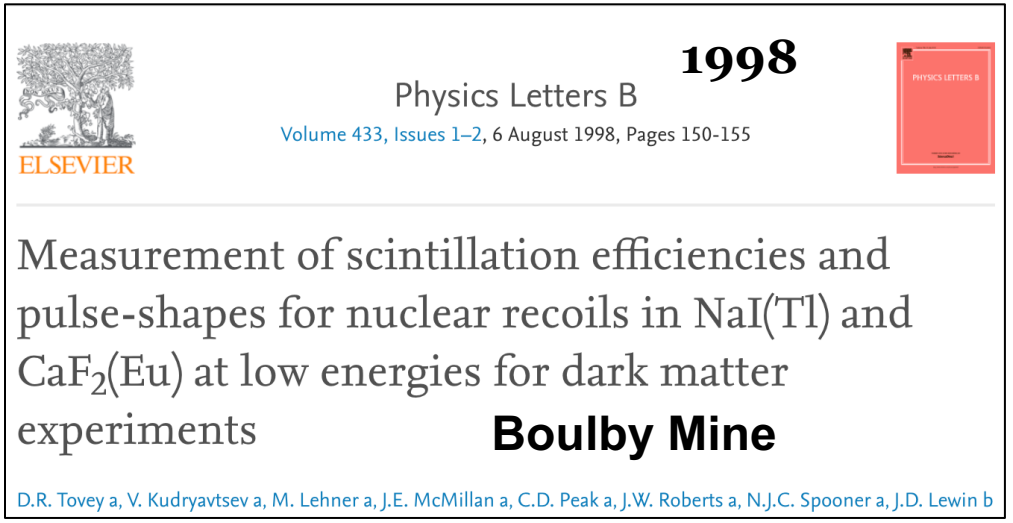
Volume 48, Issues 1–3, May 1996, Pages 73-76

1996

A Search for annual and daily modulations of dark matter with NaI scintillators at Canfranc

Canfranc

M.L. Sarsa, A. Morales, J. Morales, E. García, A. Ortiz de Solórzano, J. Puimedón, C. Sáenz, A. Salinas, J.A. Villar



ELSEVIER

1998

Physics Letters B

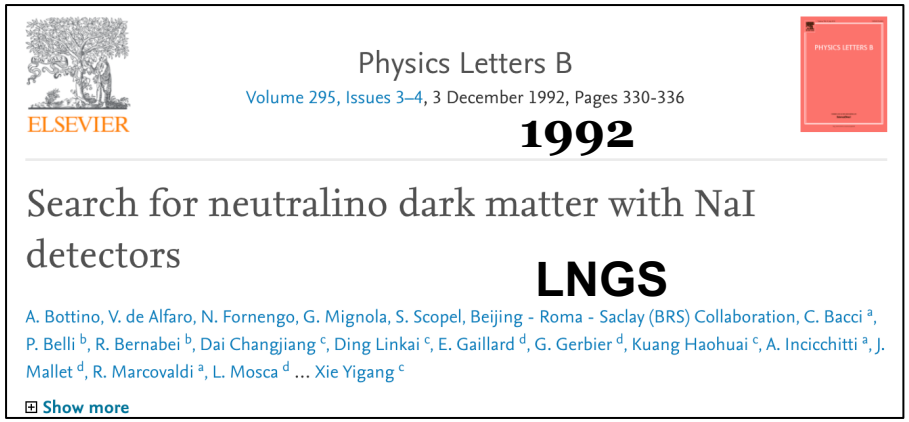
Volume 433, Issues 1–2, 6 August 1998, Pages 150-155

Measurement of scintillation efficiencies and pulse-shapes for nuclear recoils in NaI(Tl) and $CaF_2(Eu)$ at low energies for dark matter experiments

Boulby Mine

D.R. Tovey a, V. Kudryavtsev a, M. Lehner a, J.E. McMillan a, C.D. Peak a, J.W. Roberts a, N.J.C. Spooner a, J.D. Lewin b

NaI(Tl) for rare event searches : Dark Matter



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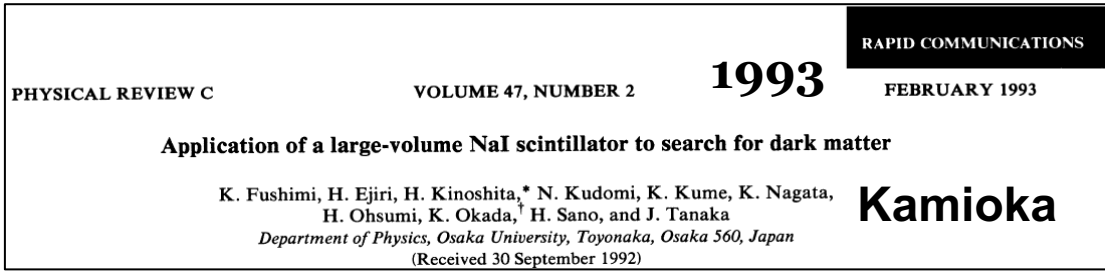
DAMA/LIBRA



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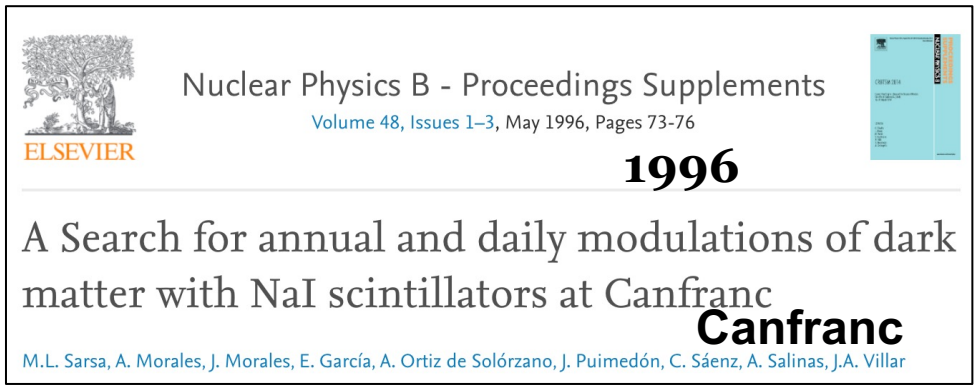

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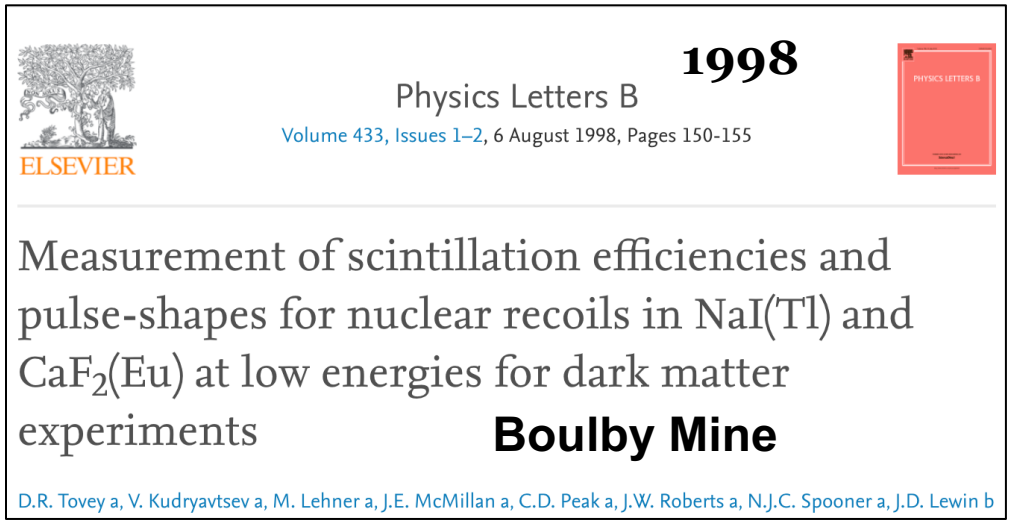
ANAIS



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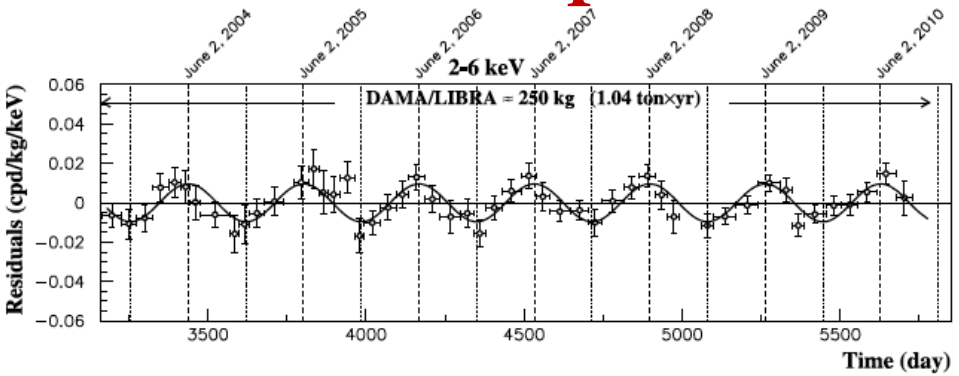
COSINE

Annual modulation signal from DAMA/LIBRA

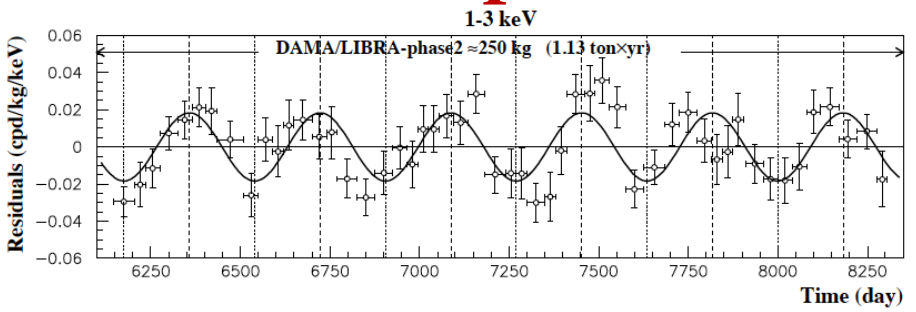
Phase1 experiment



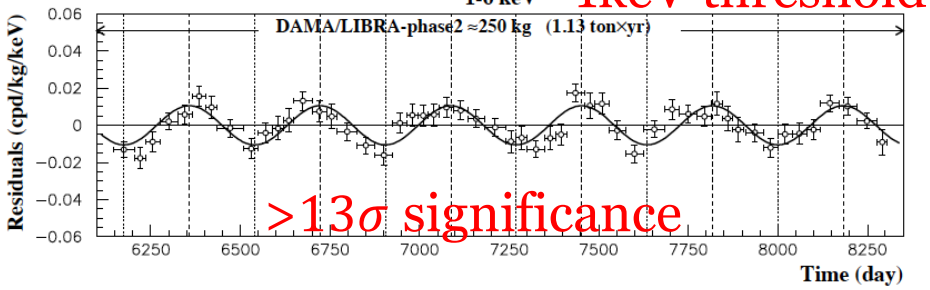
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



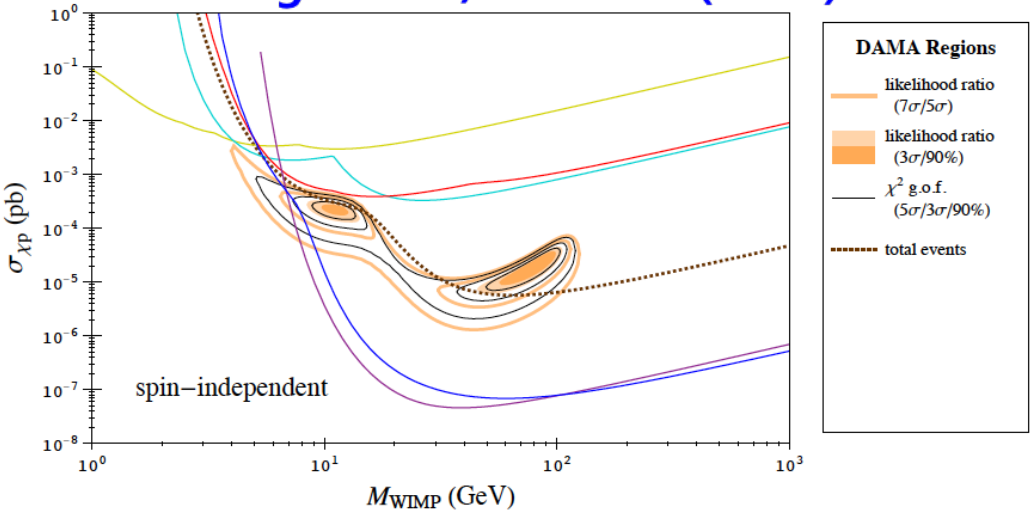
Nucl. Phys. At. Energy 19, 307 (2018)



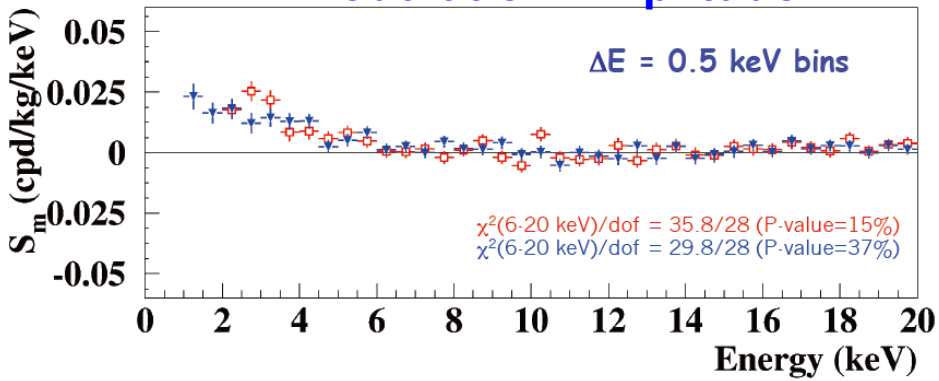
1keV threshold

>13σ significance

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



Modulation Amplitude



Annual modulation signal from DAMA/LIBRA

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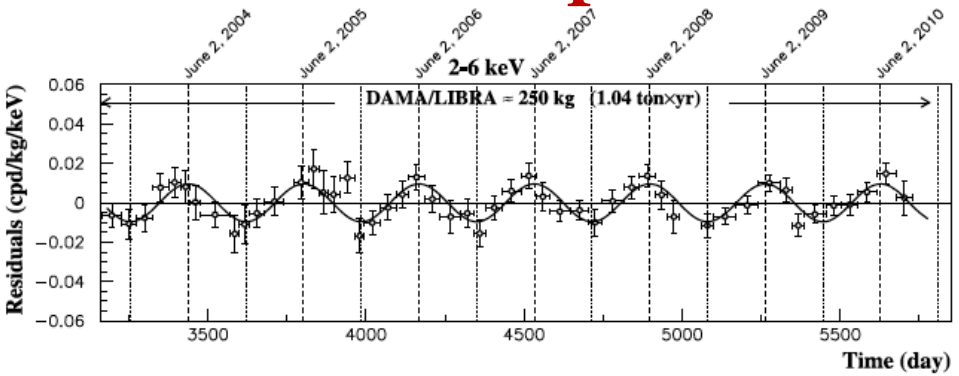

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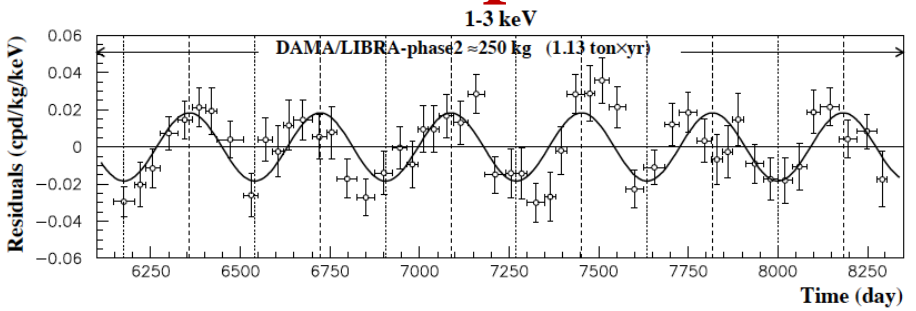

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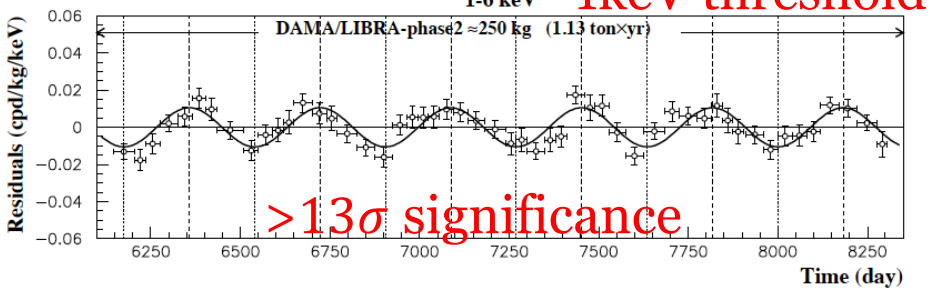

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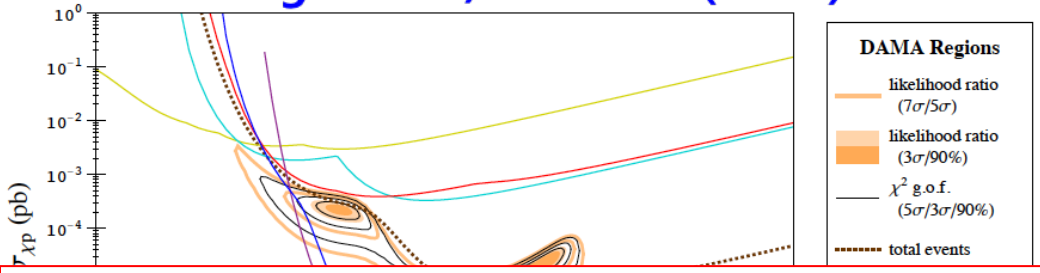

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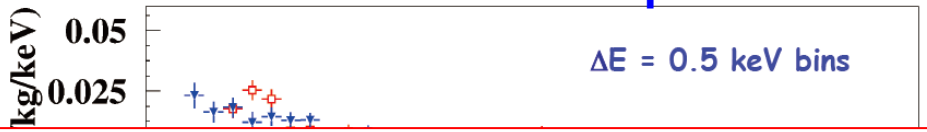


Although proving DAMA/LIBRA is main purpose of NaI(Tl)-based dark matter search experiments, **this talk** will focus on the **general dark sector particle searches** with NaI(Tl) crystals

COSINE collaboration

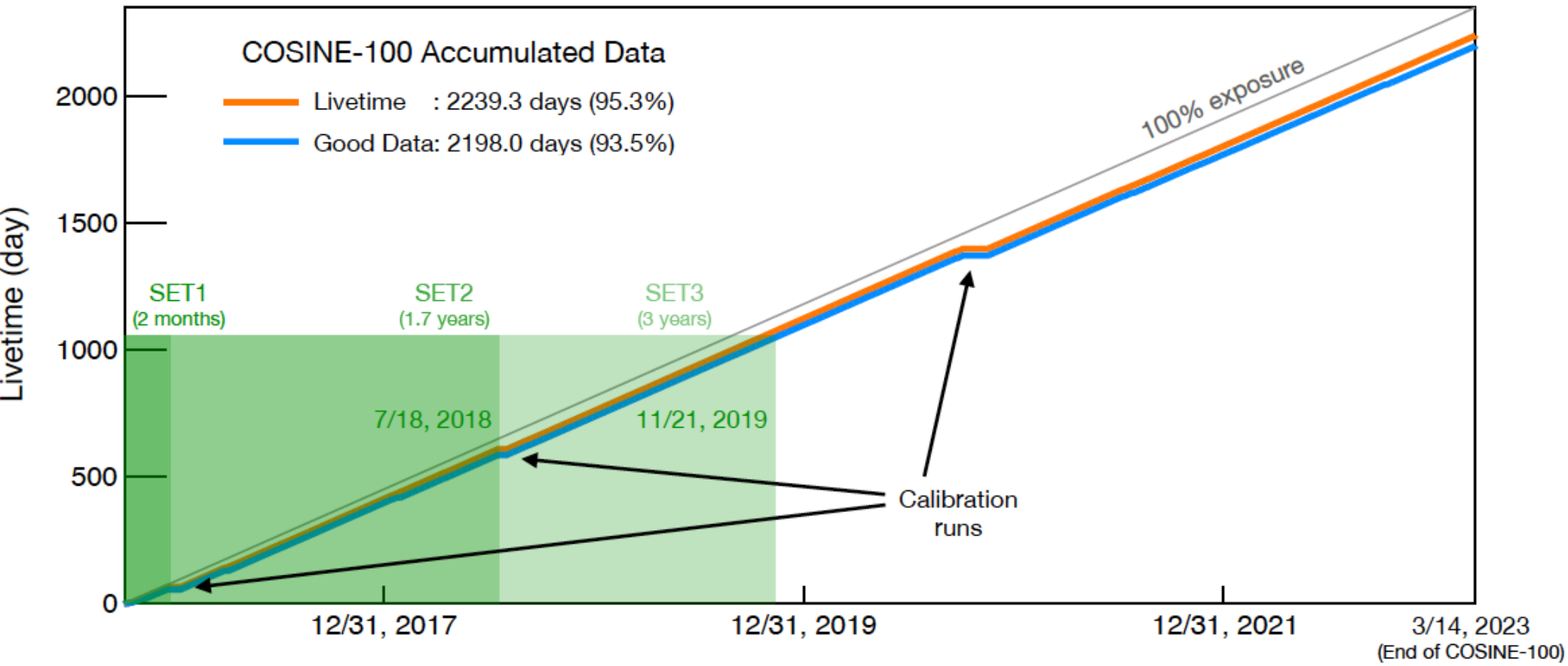
15 institutes
~60 members

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

COSINE-100 experiment (2016~2023)

- YangYang underground laboratory (Y2L)
- **Started** physics operation since **September/2016**
- **Ended** physics run **March/2023**
- Decommissioning for upgrade and moving to **Yemilab**
  - ❖ Plan to **restart COSINE-100 upgrade** by **early 2024** at Yemilab

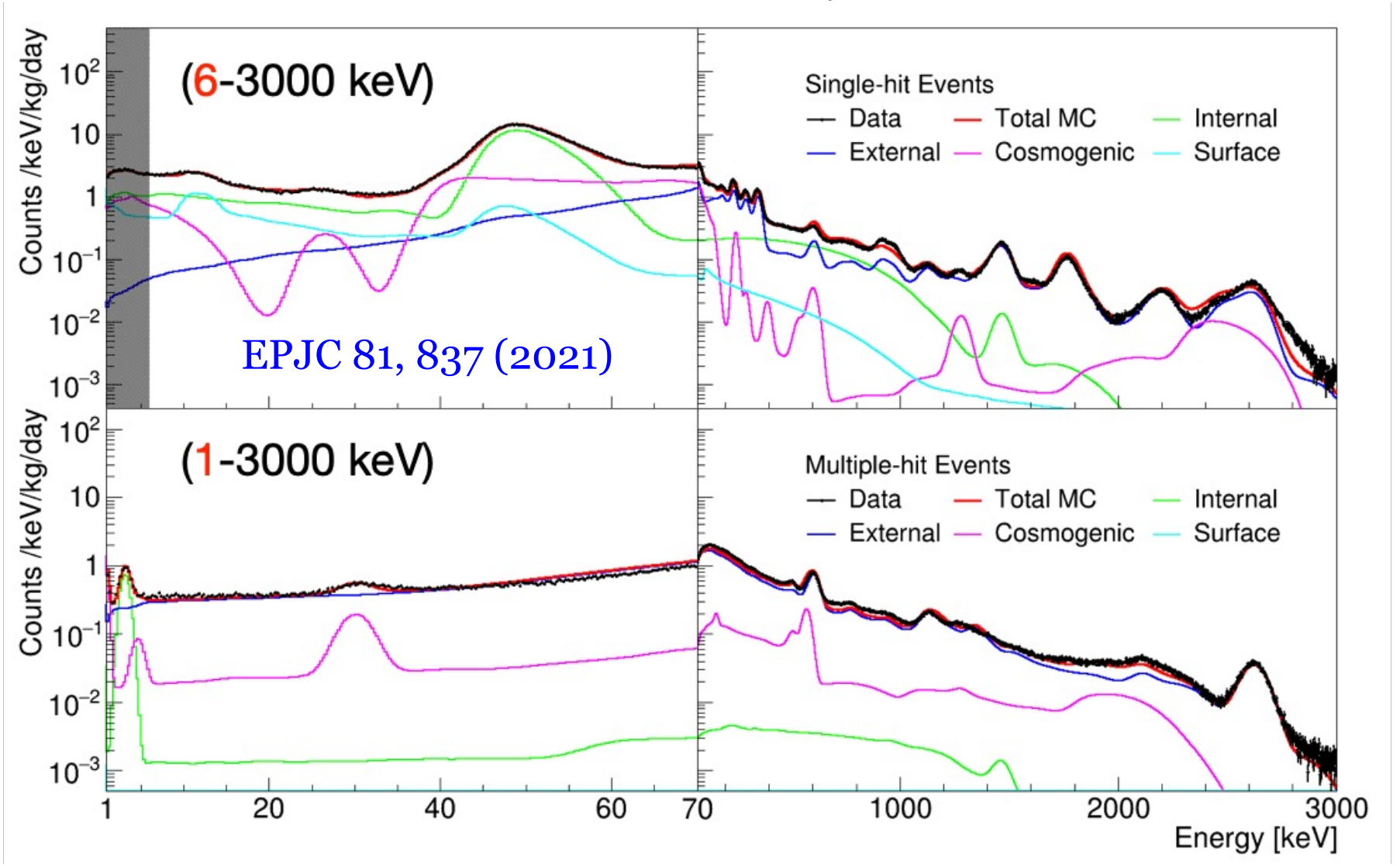
COSINE-100 data exposure



- **Stable operation Since Sep. 2016 for about 6.4 years**
  - **~95 % physics data**
  - **~94 % good quality data (6.0 years data)**

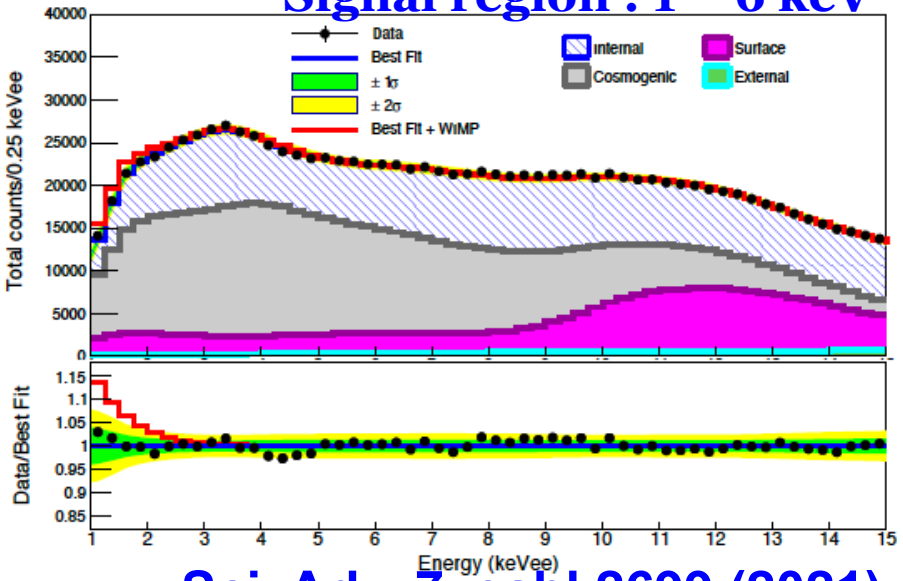
Detector background understanding

Background modeling **1.7 years data**

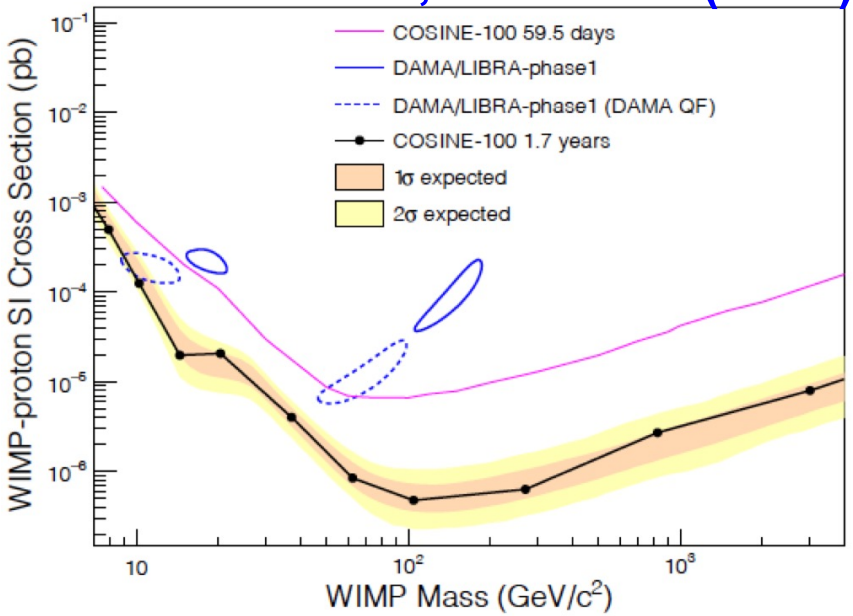


Dark matter search with spectral shape fit

Signal region : 1 – 6 keV



Sci. Adv. 7, eabk2699 (2021)



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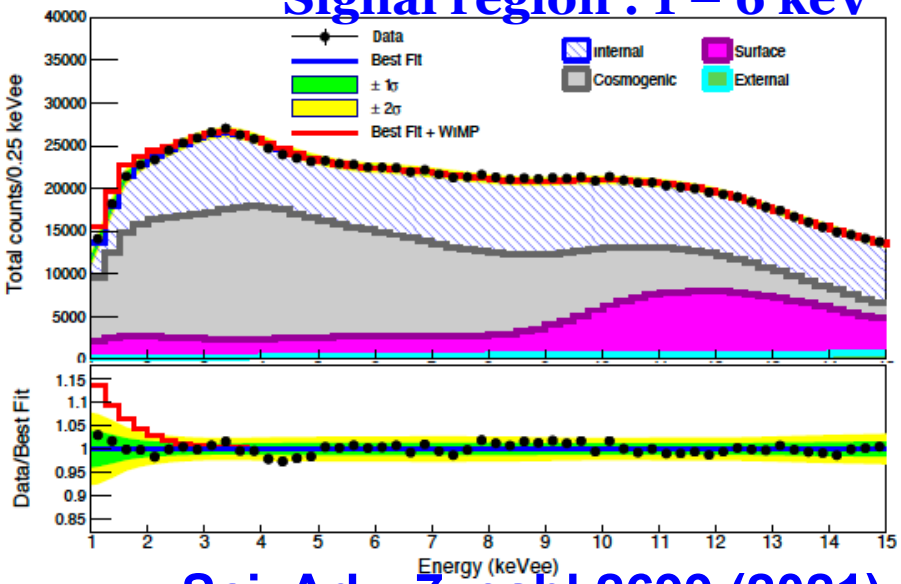
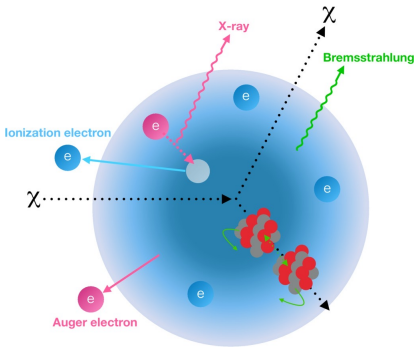
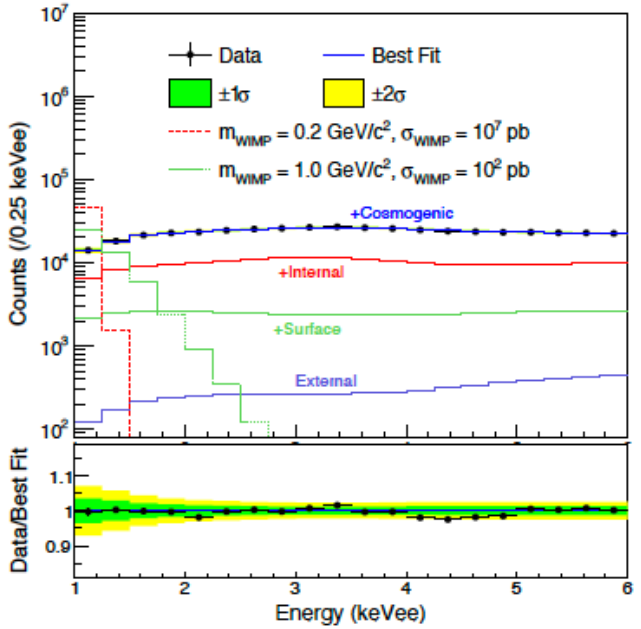


Migdal effect





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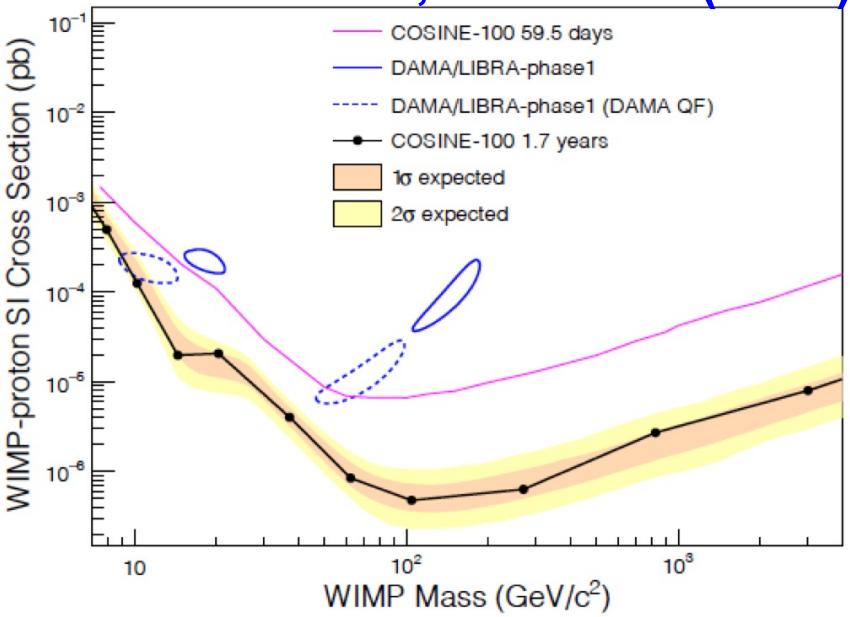
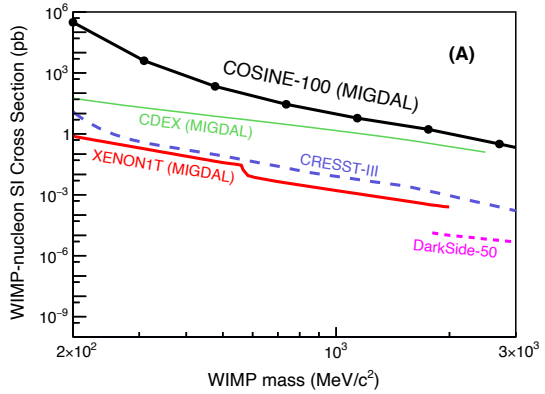
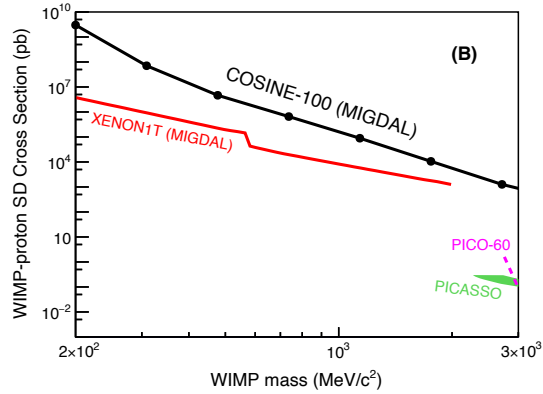
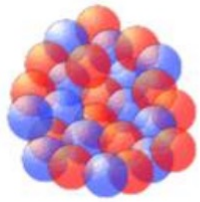


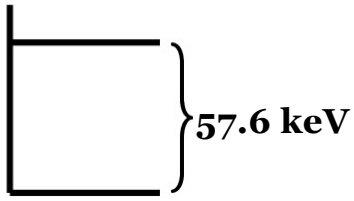
PRD 105, 042006 (2022)





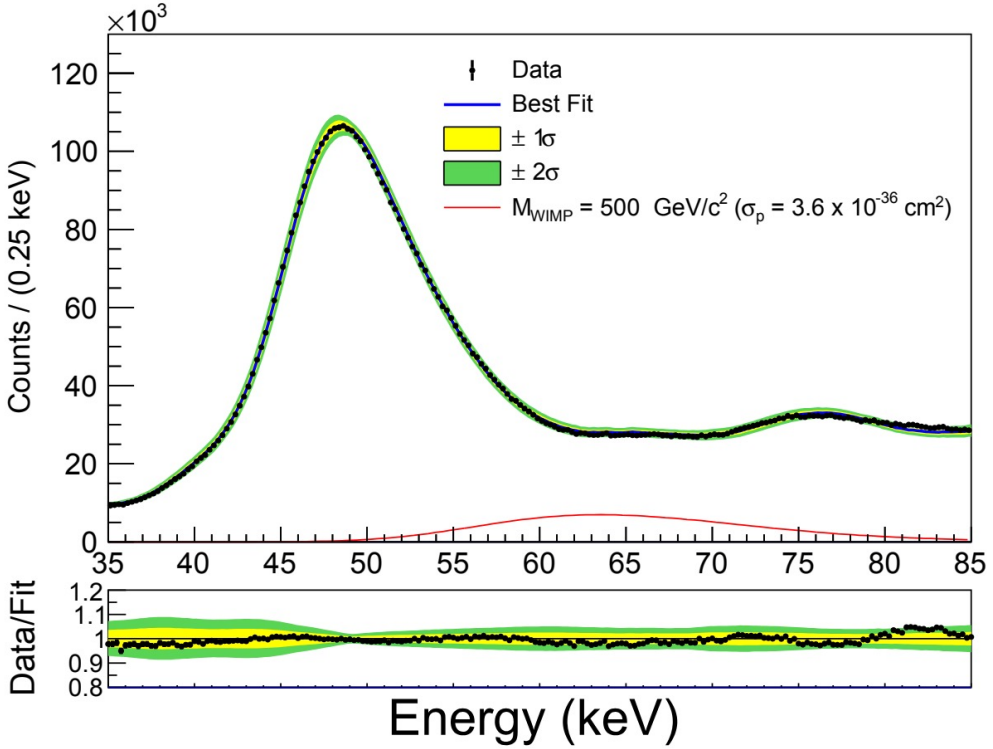
WIMP-^{127}I inelastic interaction

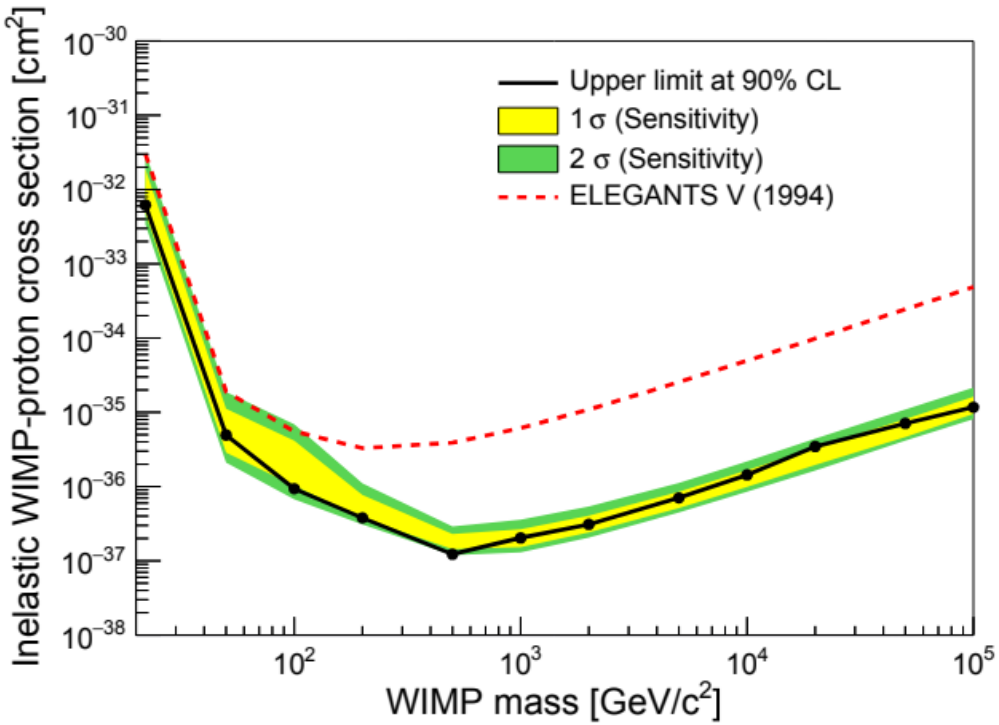




^{127}I

- Signal : 57.6 keV gamma + nuclear recoil
- 1.7 years data
- Search for energy 35 keV – 85 keV



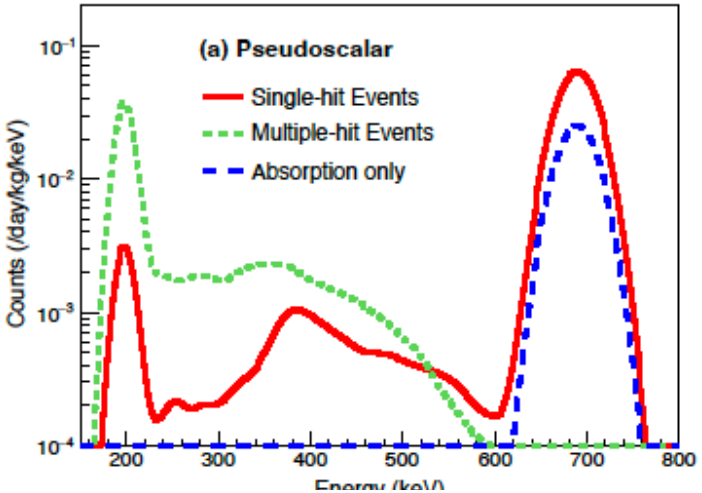


Phys. Rev. D 108, 092006 (2023)

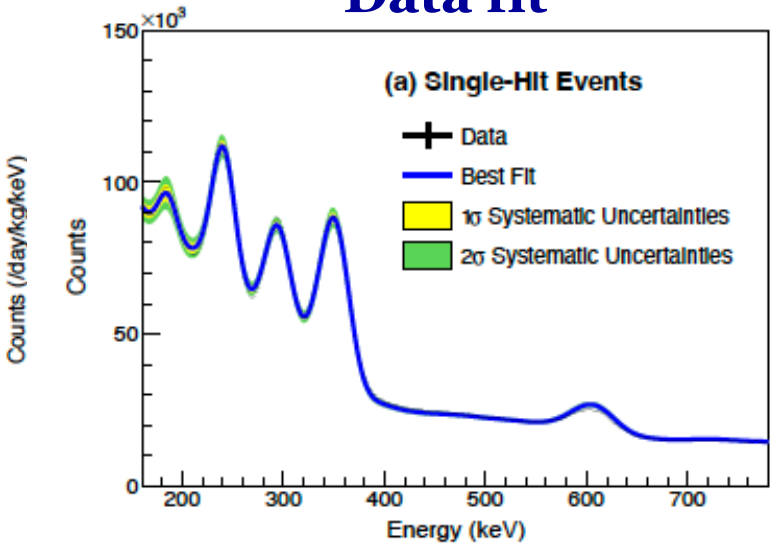
Bosonic super-WIMP (BSW)

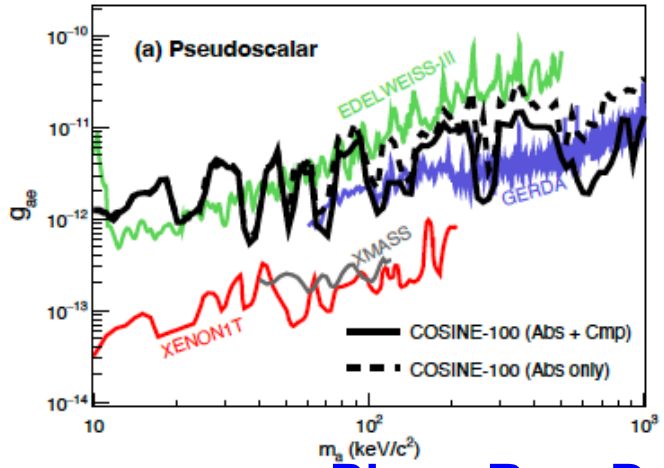
- Bosonic dark matter with mass 10 keV – 1 MeV

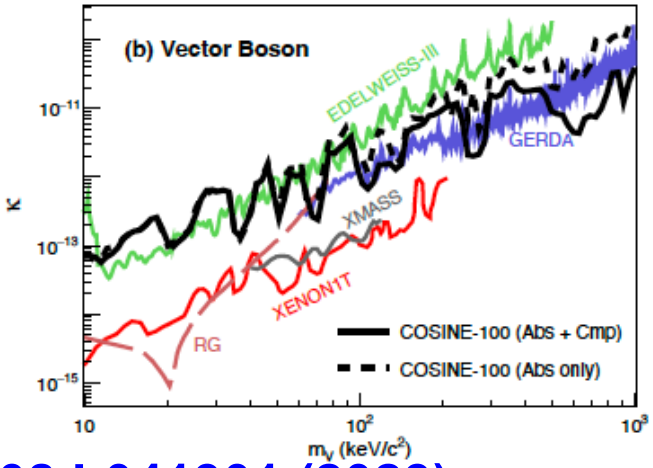
Expected Signal (690 keV BSW)



Data fit

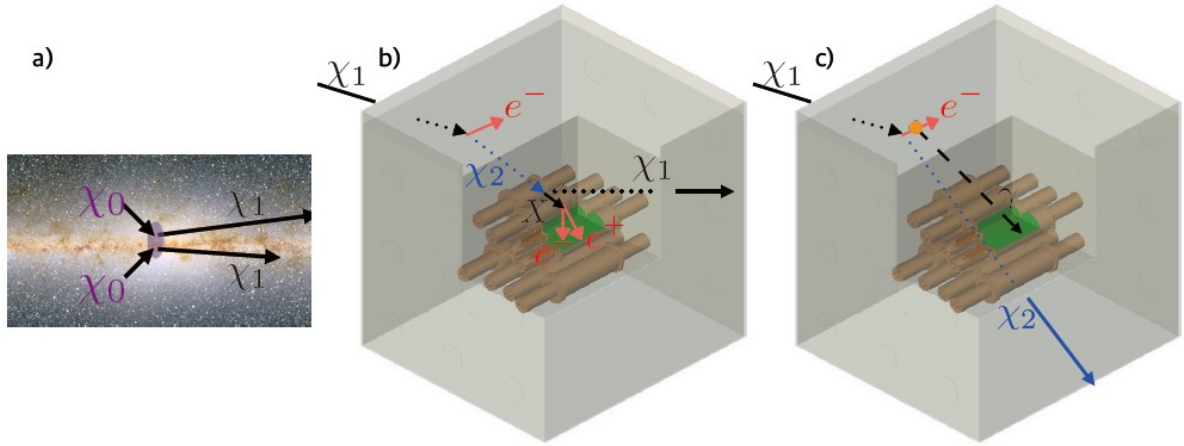




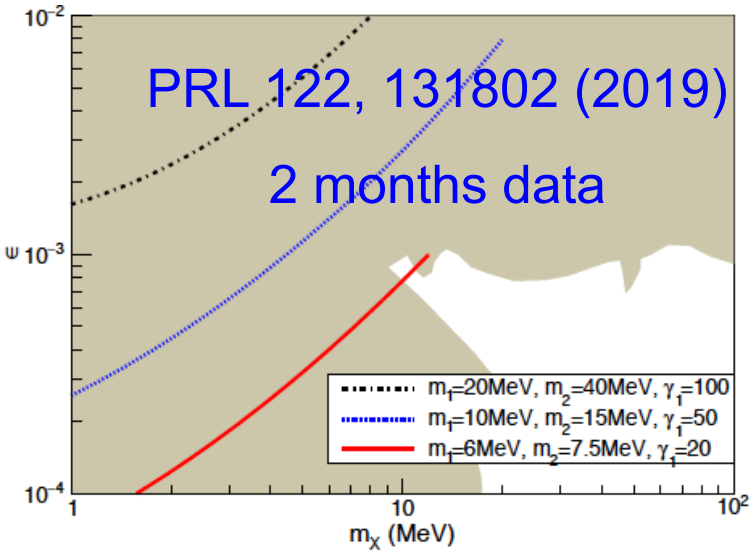


Phys. Rev. D 108,L041301 (2023)

Boosted dark matter with extended energy (~10 MeV)

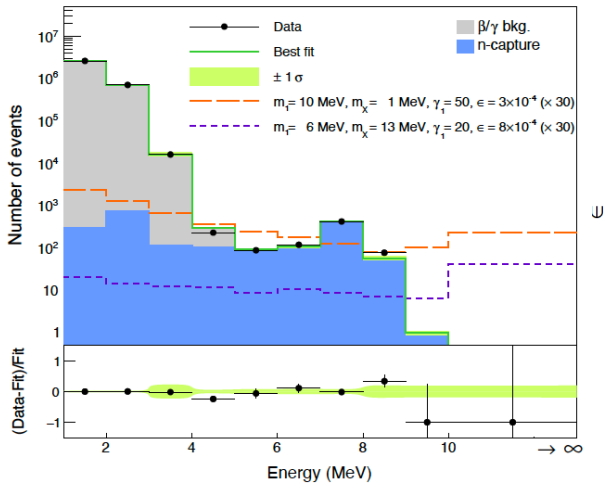


Inelastic interaction

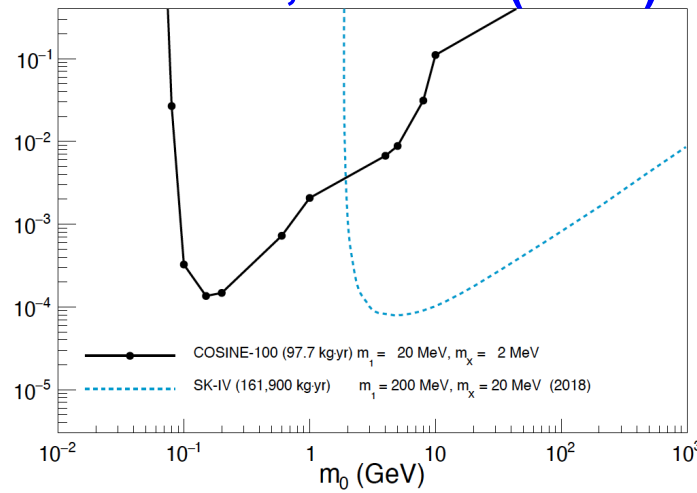


Elastic interaction

1.7 years data



PRL 131, 201802 (2023)

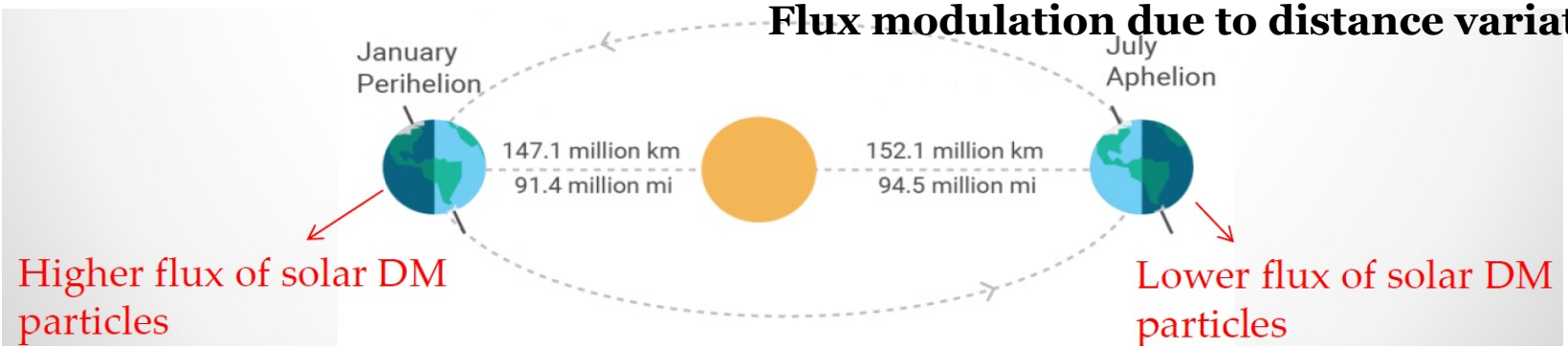


- Search for energy 1 MeV – 10 MeV

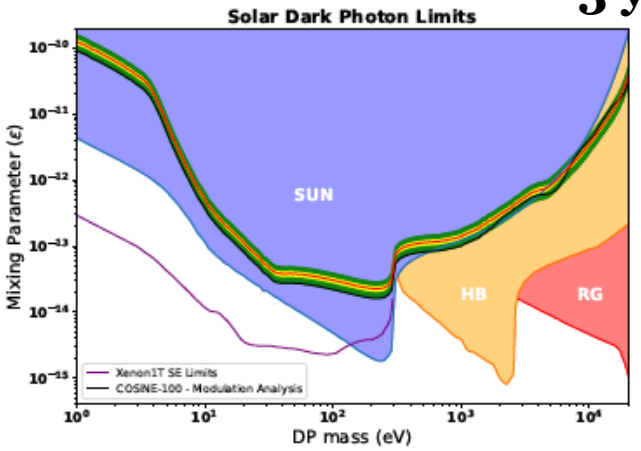
Solar bosonic dark matter annual modulation

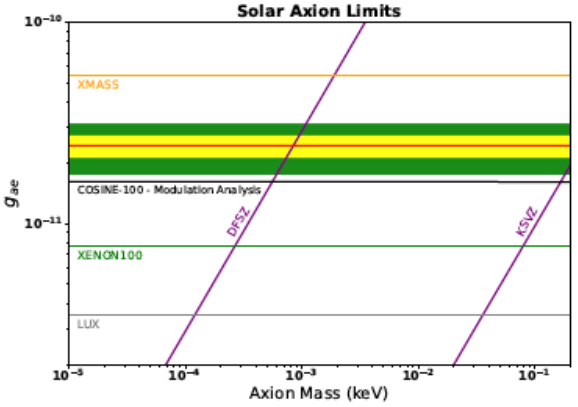
- Sun is the strong source of gamma
  - ❖ Conversion to dark sector bosonic particle is possible

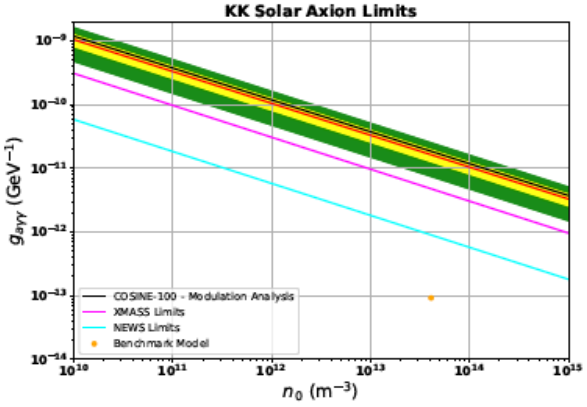
Flux modulation due to distance variation



3 years data for the modulation search





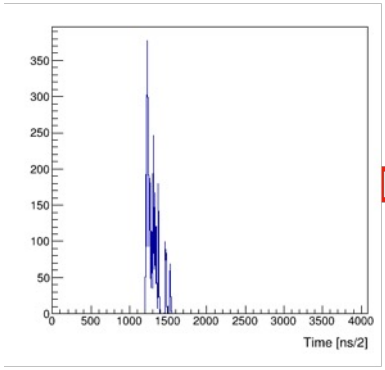


Phys. Rev. D 107, 122004 (2023)

Ongoing works : Event selection update

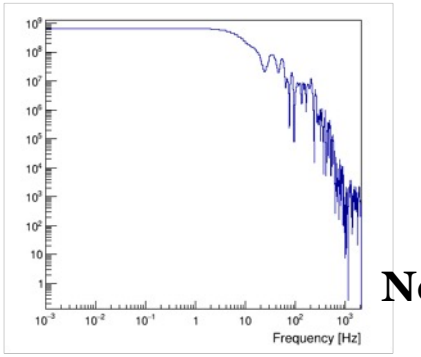
- Multivariable machine learning training

New parameter development example



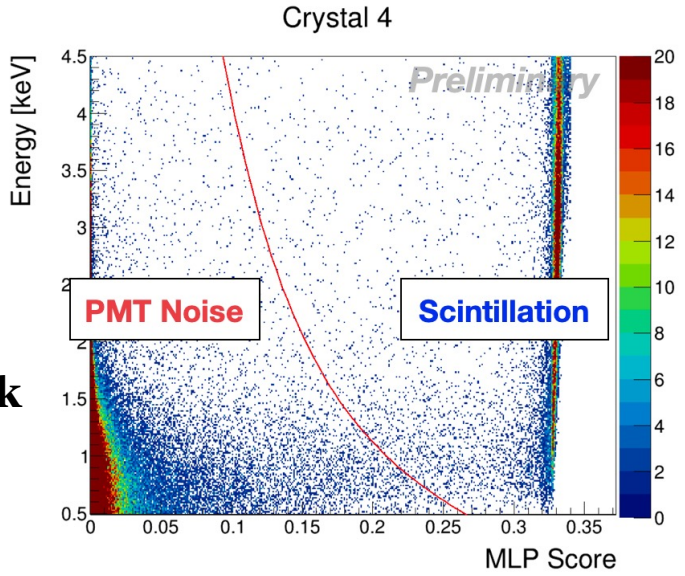
Waveform example of COSINE-100 data

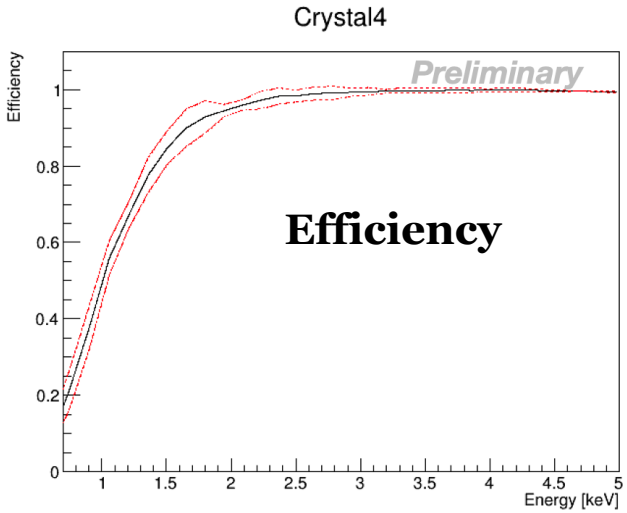
FFT



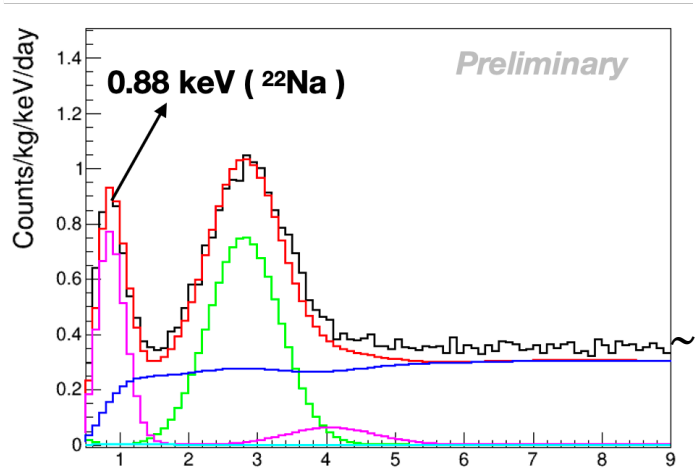
Fourier transformed waveform

Neutral network training





Efficiency



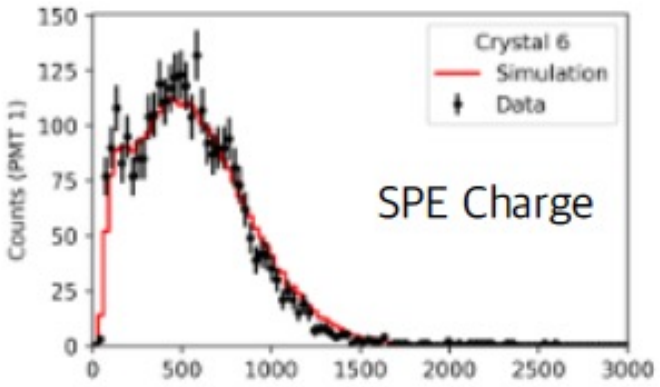
8 NPE threshold

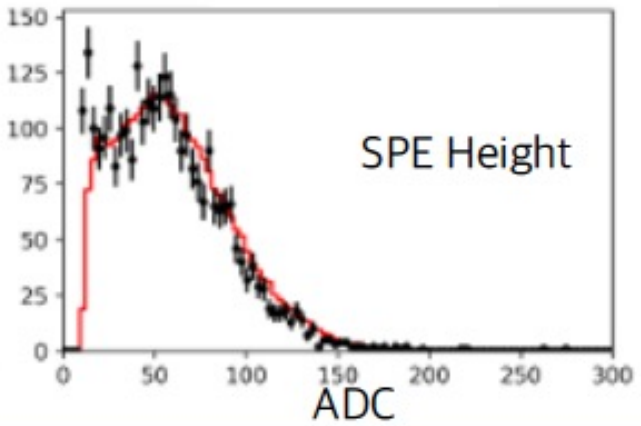
NPE (number of photoelectrons)

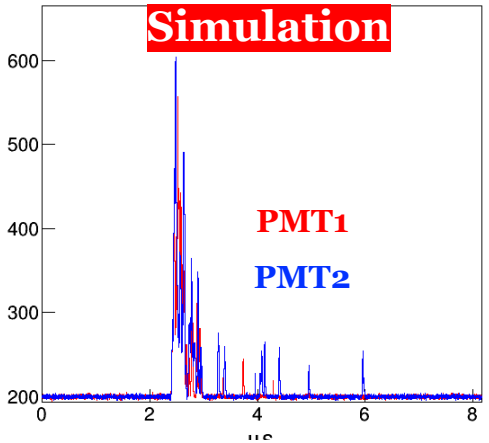
~ 15 NPE/keV light yield @ 59.54 keV

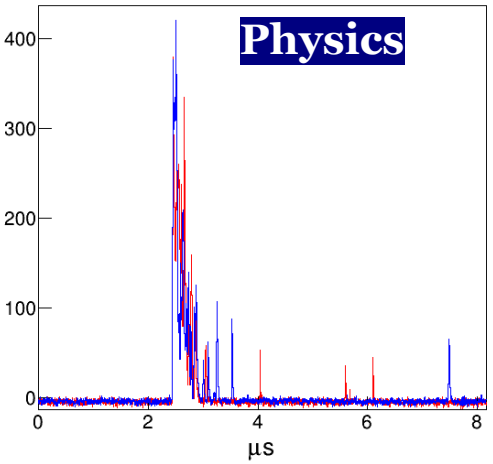
Ongoing works : Waveform simulation

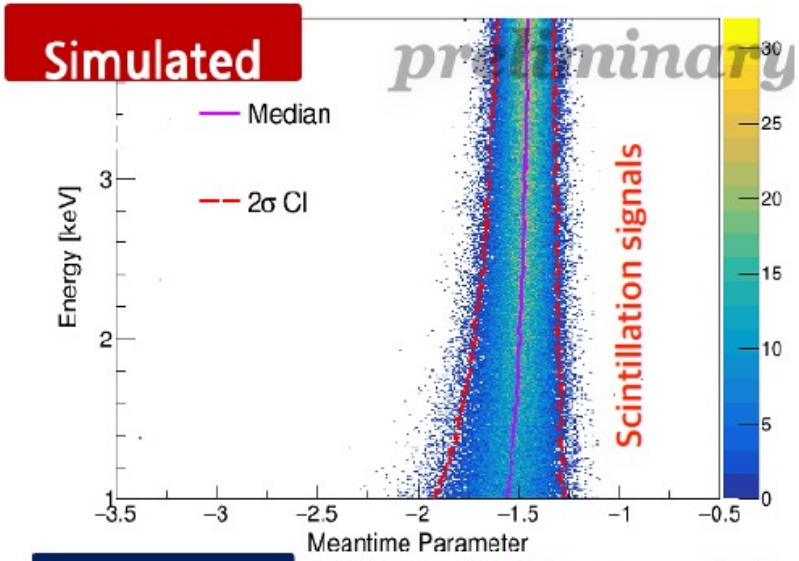
Single photoelectron tuning

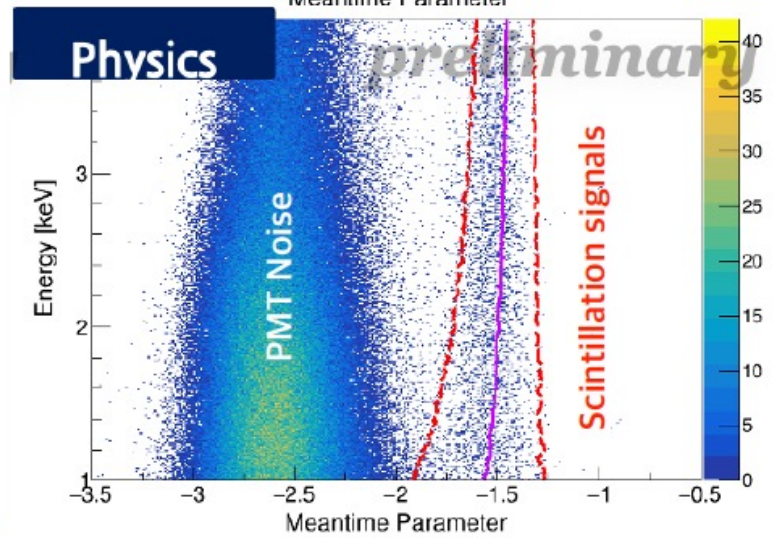










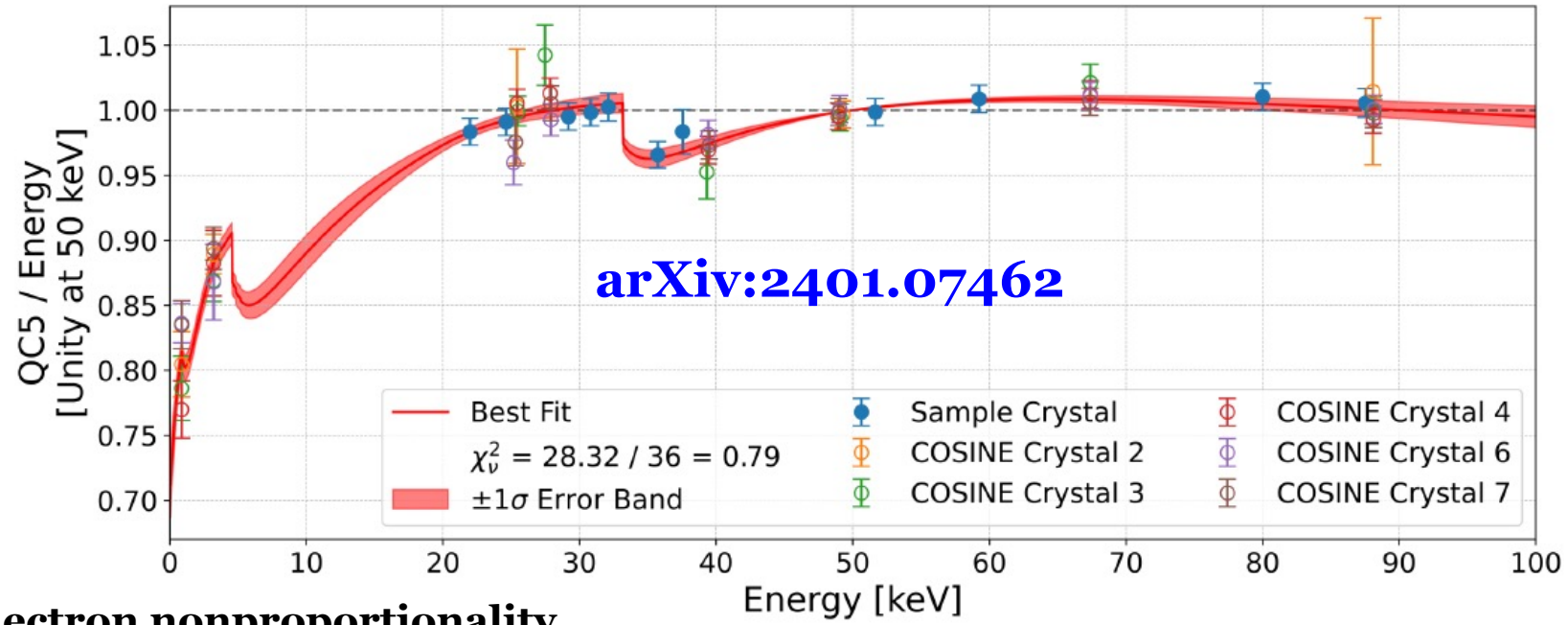


- **Waveform simulation** is developed to **describe** low-energy events (**sub-keV**)
- Simulation describe the data reasonably well
- Currently, the waveform simulation cross checked the trigger/selection efficiencies
- The waveform simulation will be used as signal sample of the multivariable analysis

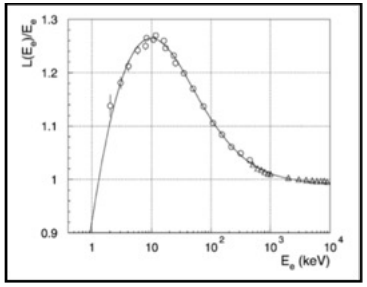
Ongoing works : Nonproportionality of NaI(Tl) crystals

- Internal background of COSINE-100 + external sources

Nonproportionality of gamma & x-rays



Electron nonproportionality

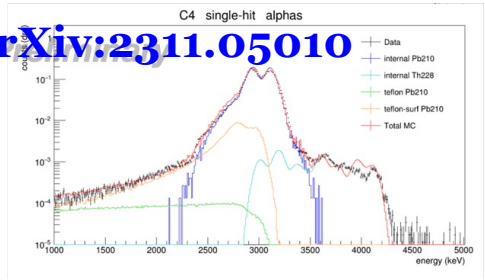


Nuclear Instruments and Methods in Physics Research Section A ,430, 2–3,(1999)

- **Gamma & x-rays calibration** updated
- Electron can have different nonproportionality in low energy
- High energy nonproportionality

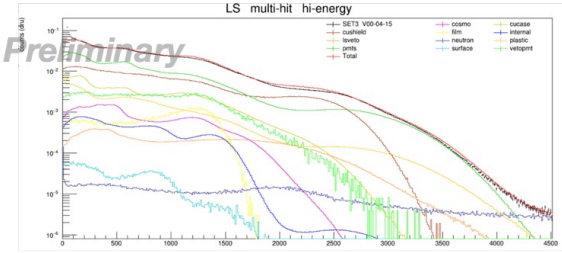
Ongoing works : Background modeling update

Alpha spectrum modeling

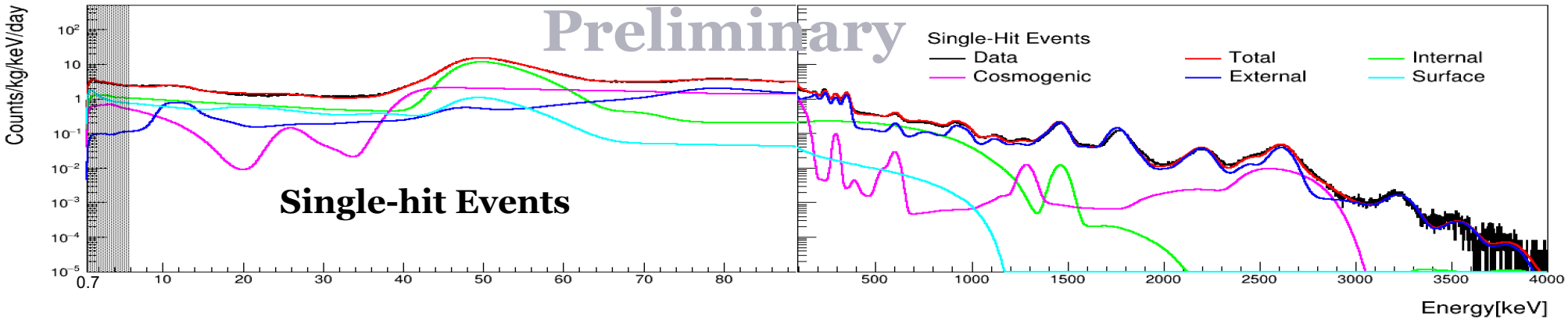


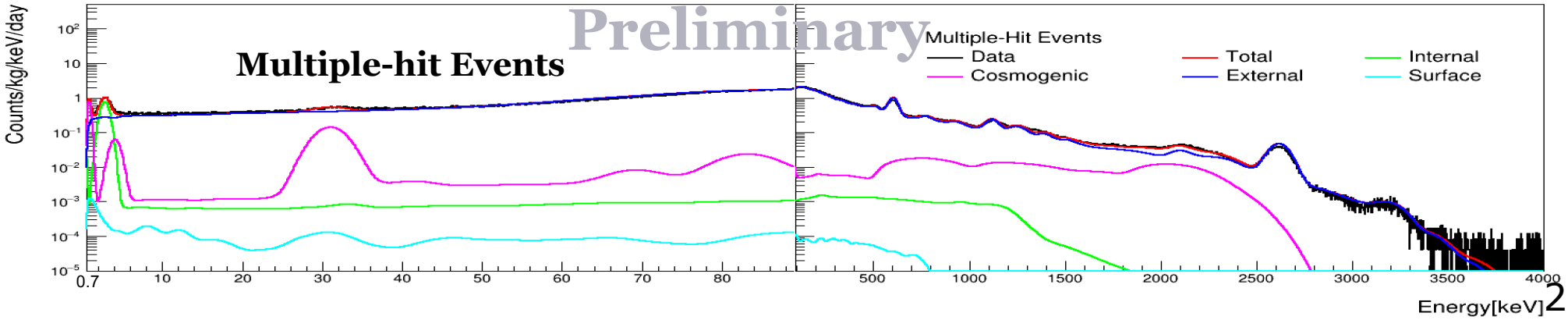
arXiv:2311.05010

LS spectrum modeling



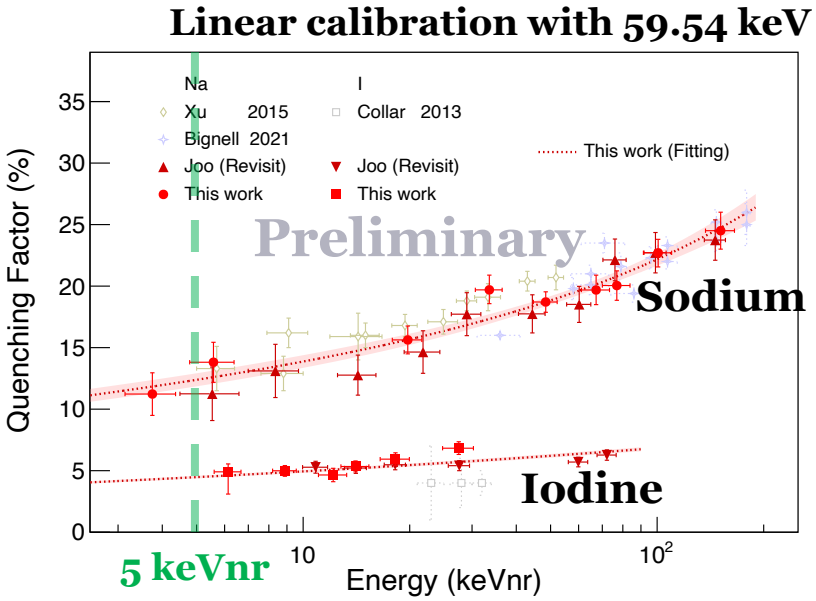
- Detector calibration (nonproportionality)
- Better understanding of internal (alpha) & external (LS) backgrounds
- Extended energy modeling between 0.7 – 4000 keVee (considering nonproportionality)

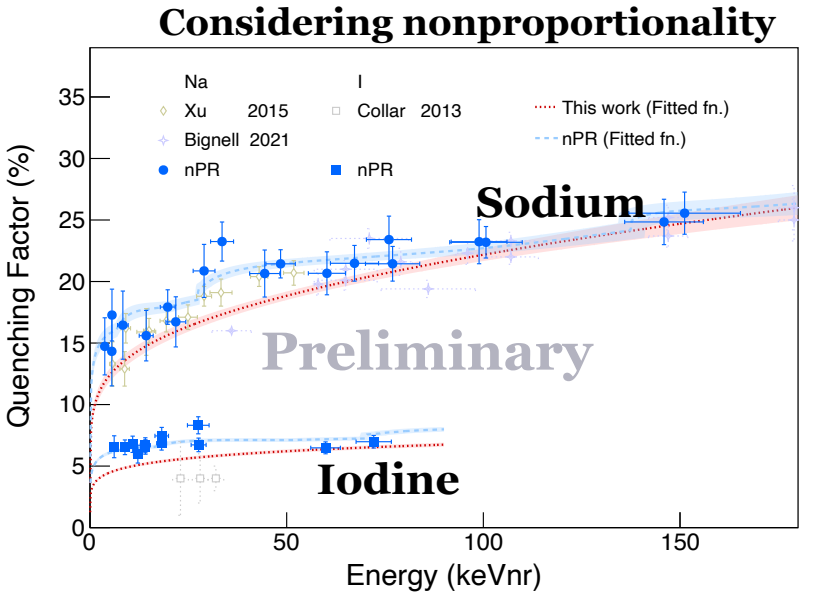




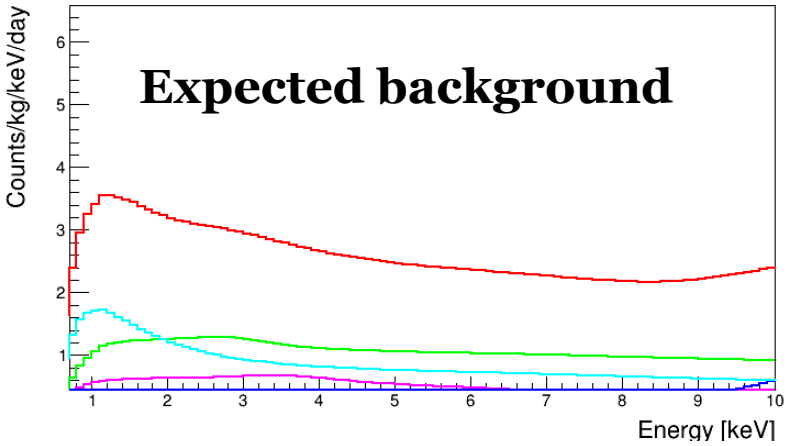
Ongoing works : Calibration of the nuclear recoils

- Update previous measurement with improved understanding of incident neutron energy and low-energy event selection
  - ❖ Consistent with other group's measurements
- New measurement including the lowest energy point (3.8 keVnr)
  - ❖ Modified Lindhard model describe the measured data well
- Complete feature including detector's nonproportionality



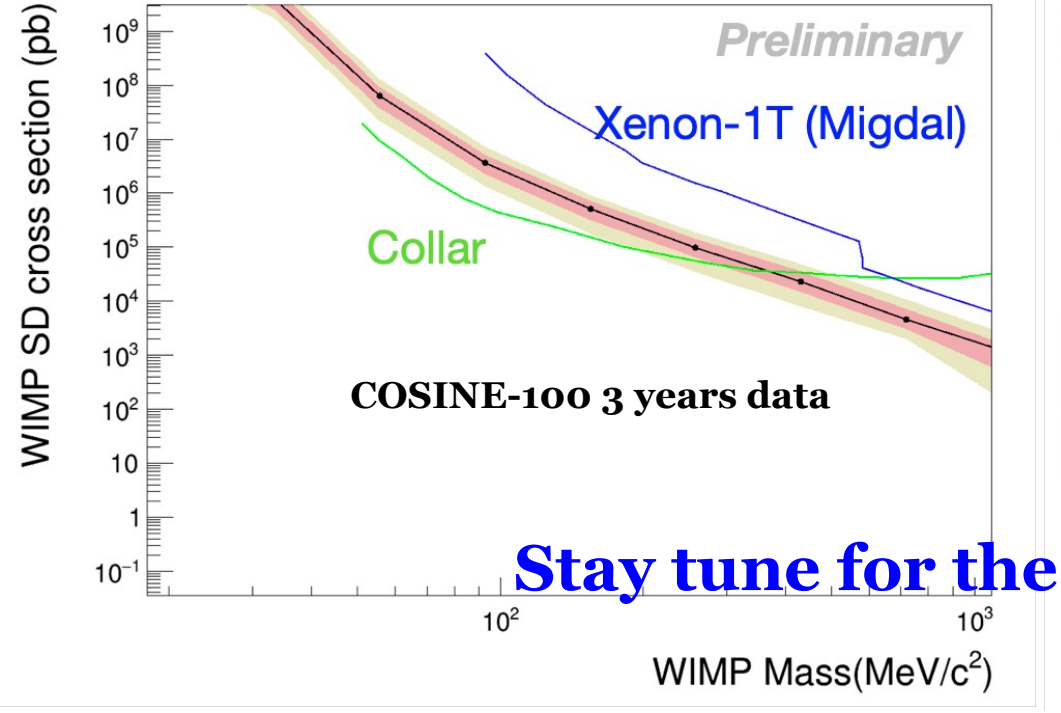


Ongoing works : Dark matter sensitivities

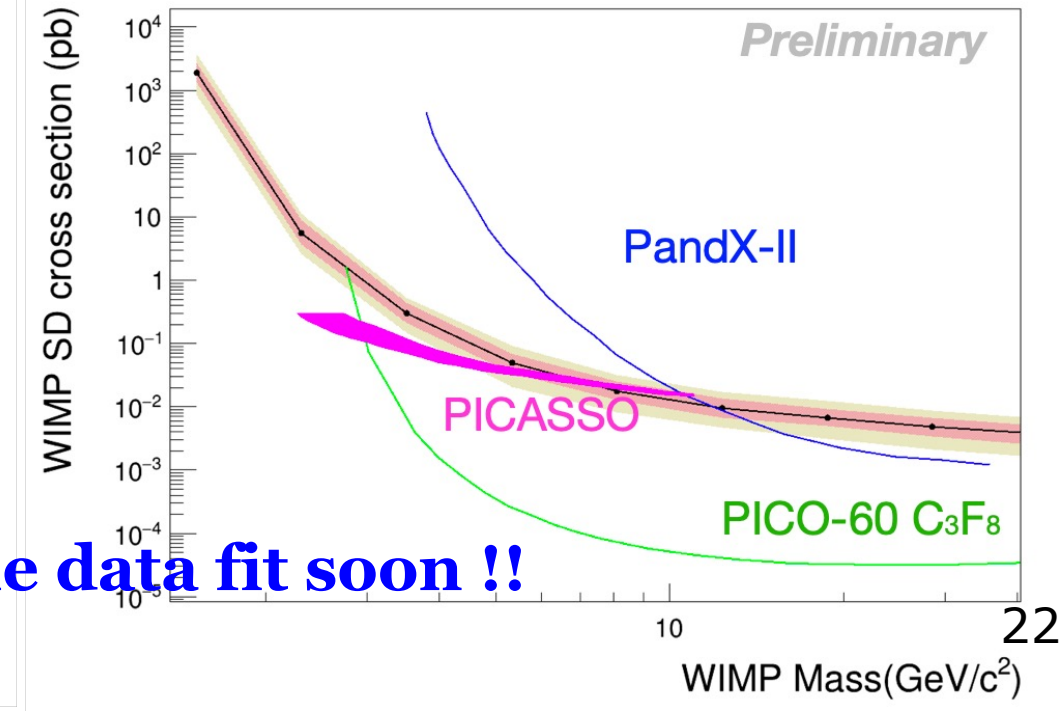


- With reduced energy threshold about 0.7 keV, we can do the world best search for the low-mass dark matter in the spin-dependent WIMP-proton interaction

W/ Midgal Effect (No systematics)



W/O Midgal Effect (No systematics)

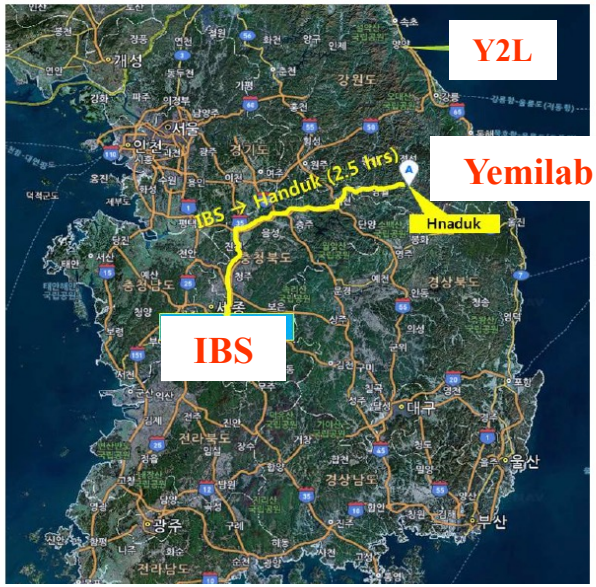


Stay tune for the data fit soon !!

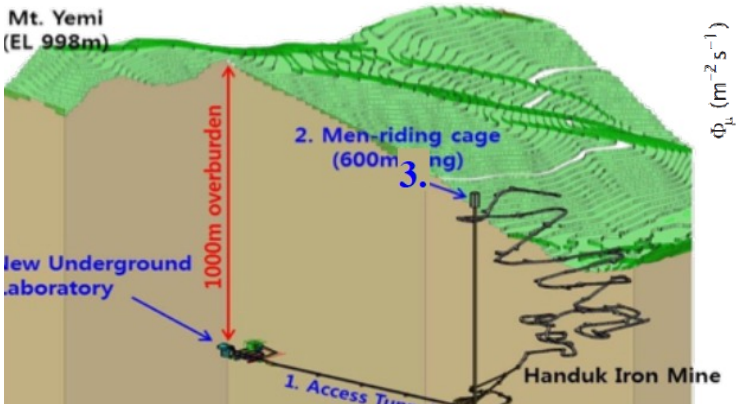
Yemilab for new discoveries

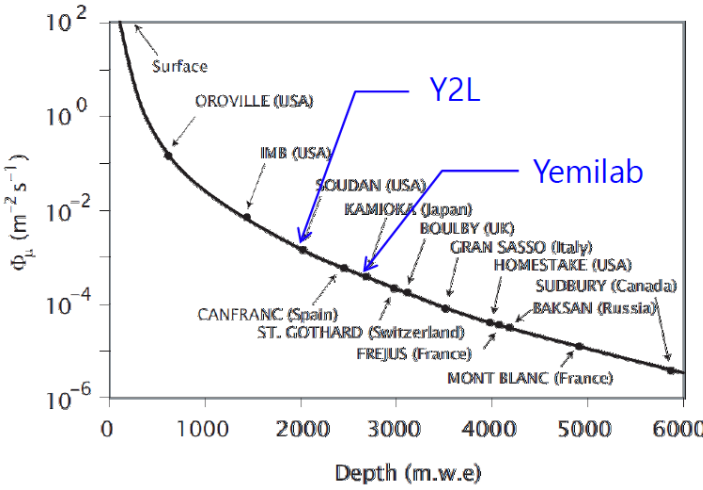
- New underground laboratory in Korea is one of the most important milestone of the **CUP/IBS** – 10 years journey

Handeok iron mine, Jeongseon, Gangwon, Korea



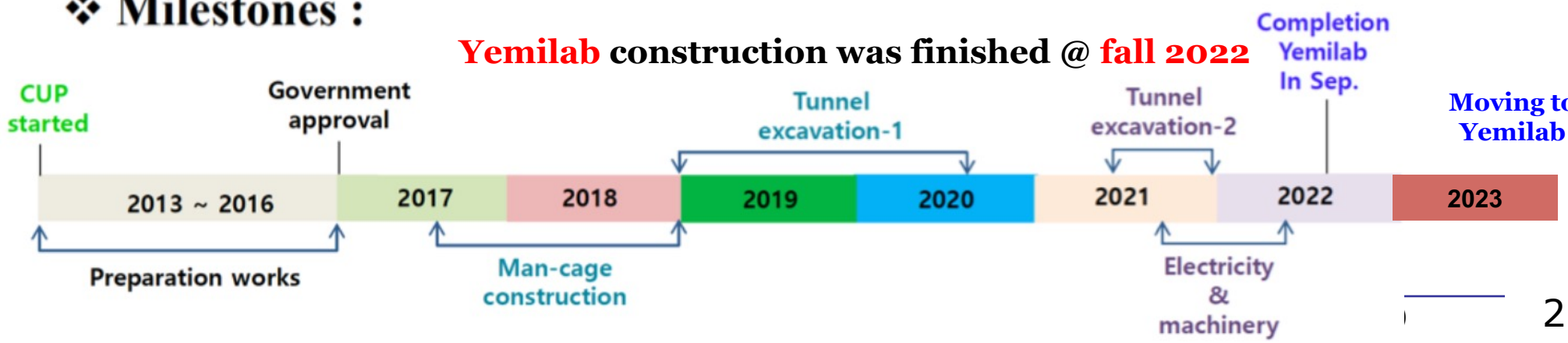
- 1000 meter underground.
- Construction cost ~30 M$
- 2018-2022





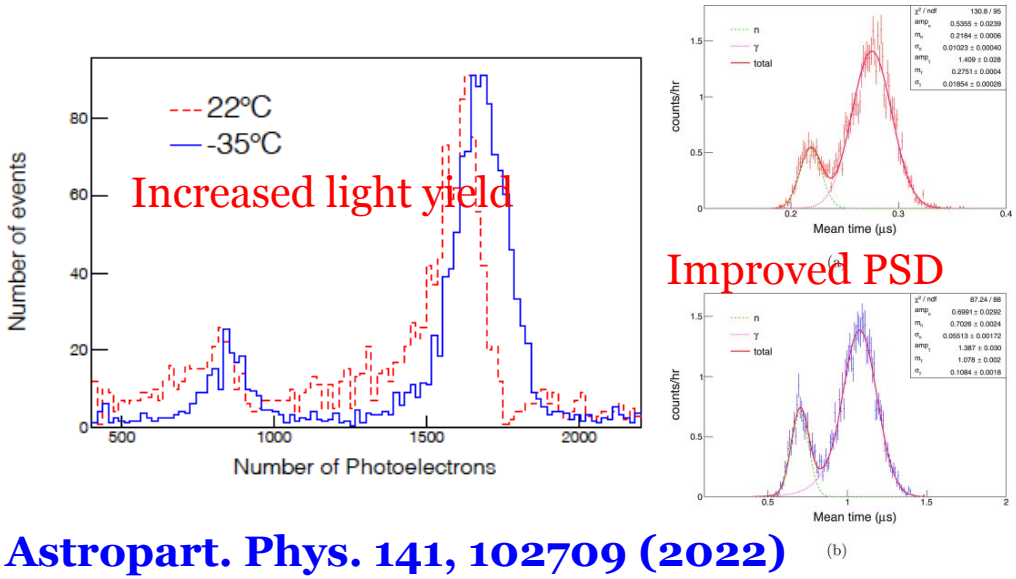
❖ Milestones :

Yemilab construction was finished @ fall 2022



COSINE-100U @ Yemilab

-35°C operation

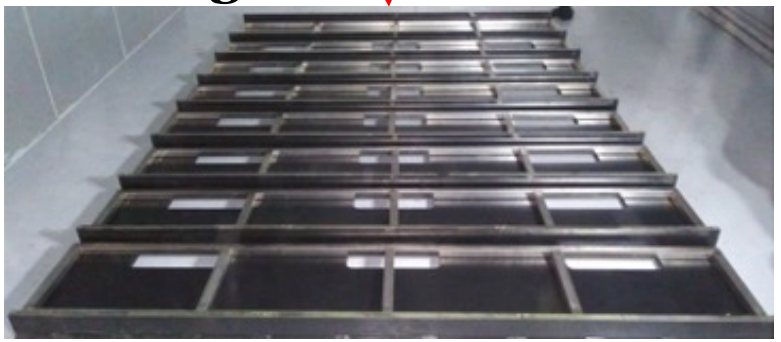


Astropart. Phys. 141, 102709 (2022)

- 5% gamma light yield increase
- 10% alpha quenching increase
  - ❖ Will measure nuclear recoil quenching
- Pulse shape discrimination is significantly improved

Warehouse freezer at Yemilab

Shielding base for muon detector



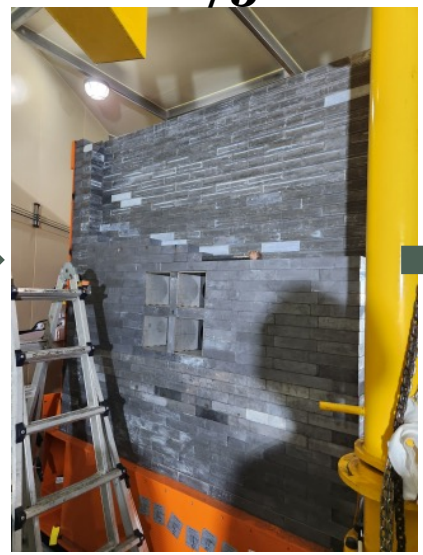
To start COSINE-100U at Yemilab May/2024

Decommissioning of the COSINE-100 detector @ Y2L

Sept/25

Sept/27

Oct/5



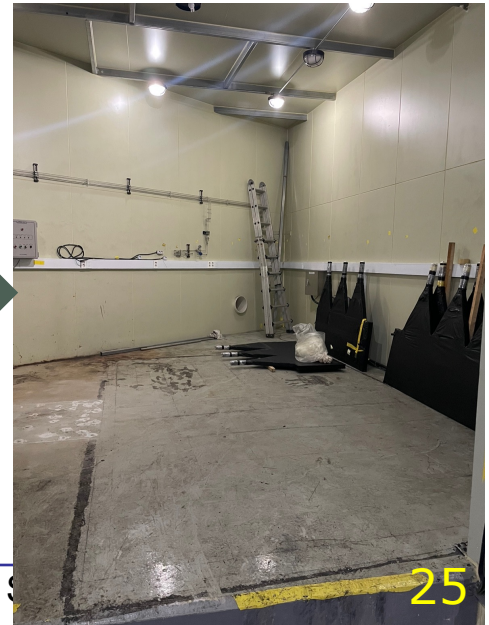
Oct/6

Oct/10

Oct/12

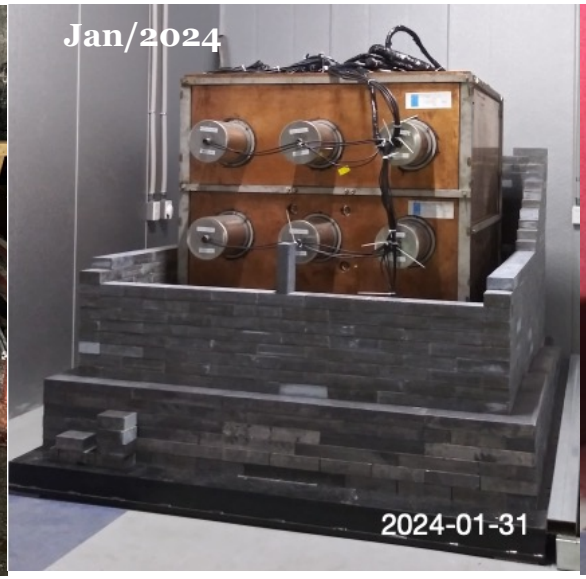
Oct/16

Oct/30



Installation @ Yemilab

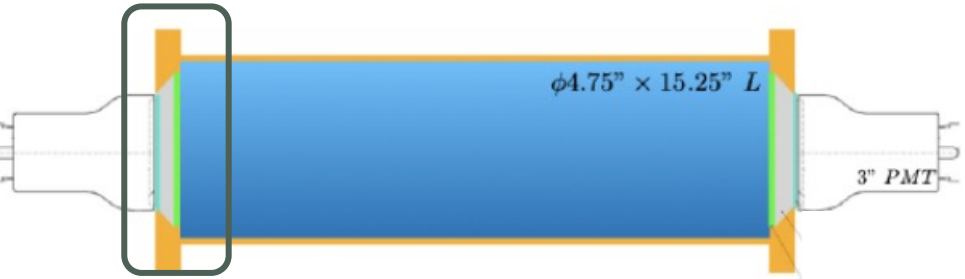
Y2L to Yemilab

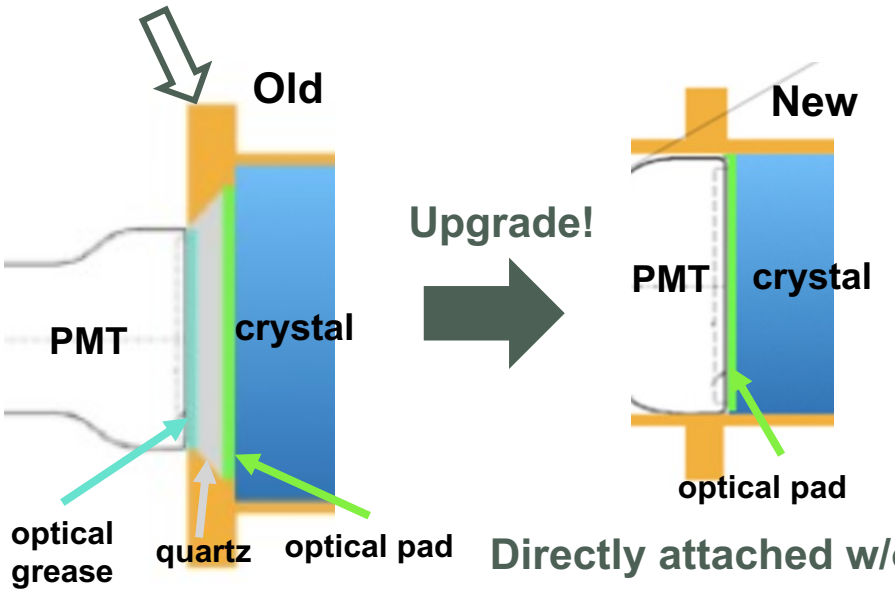


- All COSINE-100 materials were delivered to Yemilab
- Shield installation is ongoing
- Preparing upgrade of NaI(Tl) crystals

COSINE-100 Upgrade : New encapsulation

COSINE -100

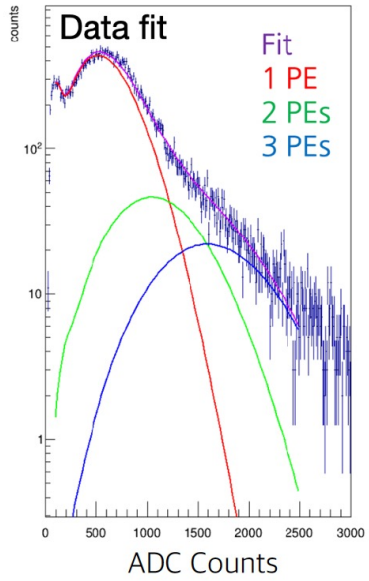


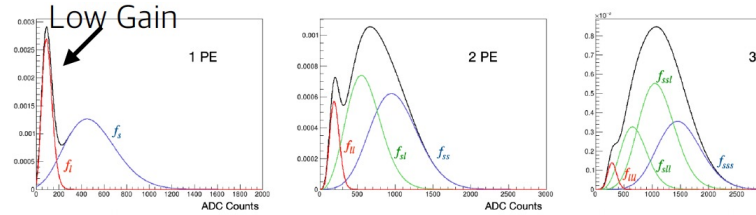


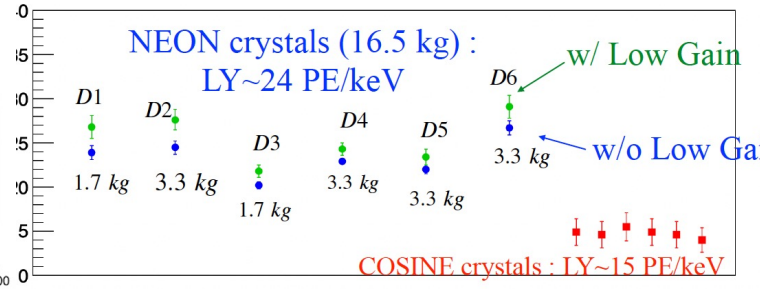
Directly attached w/o quartz!

We achieved ~ 50% increased light yield

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

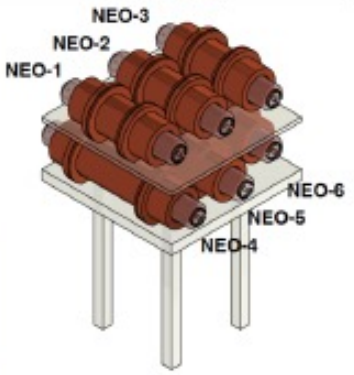






High light yield (24 NPE/keV) and long-term stability has been proved by NEON experiment

Eur. Phys. J. C 83, 226 (2023)



COSINE-100U : Detector upgrade

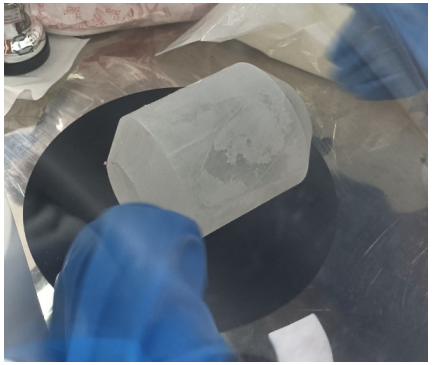
COSINE-100U for high light yield

Remove the copper case

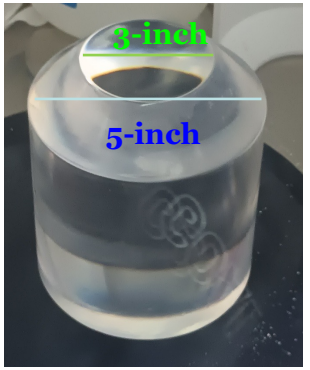
Crystal machine

Mass : 8.26 kg → 7.19 kg

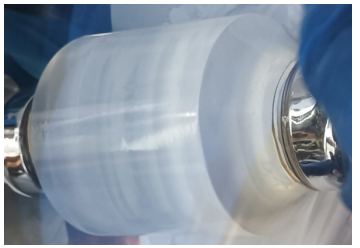
Deliver to glove box

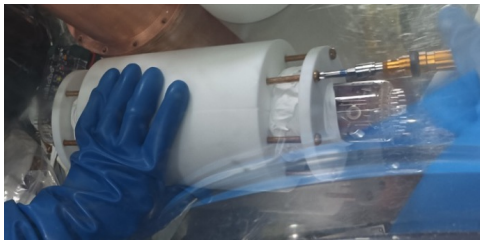


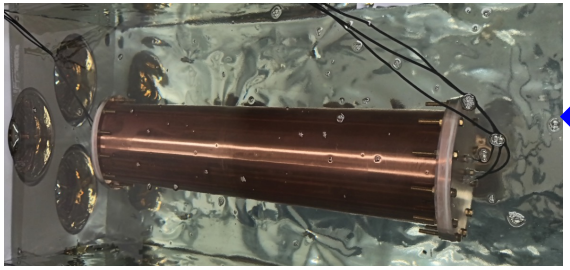
Polishing



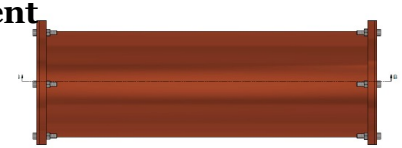
COSINE crystal-1

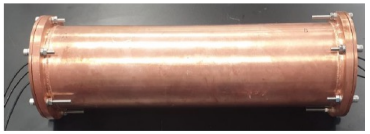




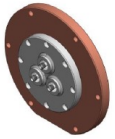


Above ground measurement





Cover design

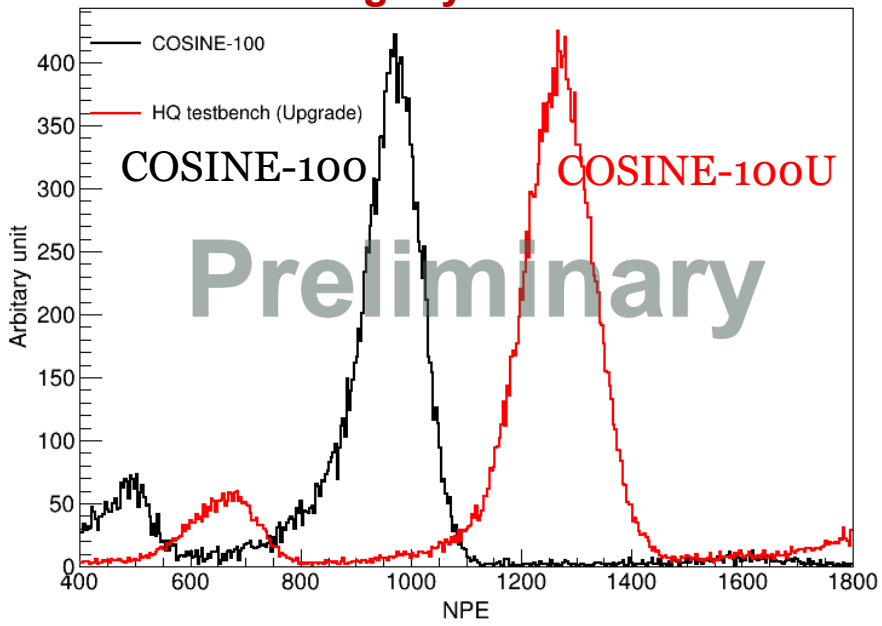


COSINE-100U : Detector upgrade

- Light yield @ 59.54 keV

^{241}Am 59.54 keV

~45% light yield increase!!!



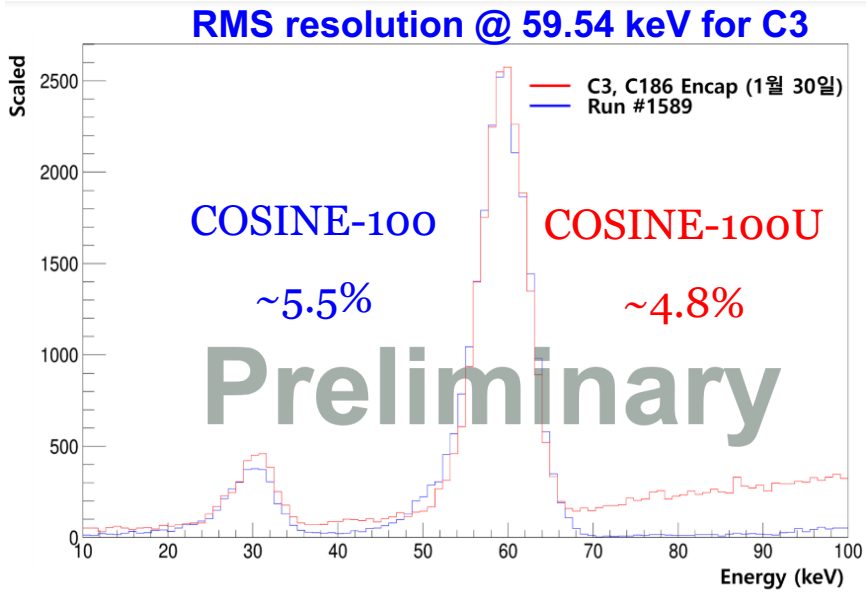
NPE = Number of photoelectrons

14.9 ± 1.5 ⟶ **21.5 ± 0.6 NPE/keV**

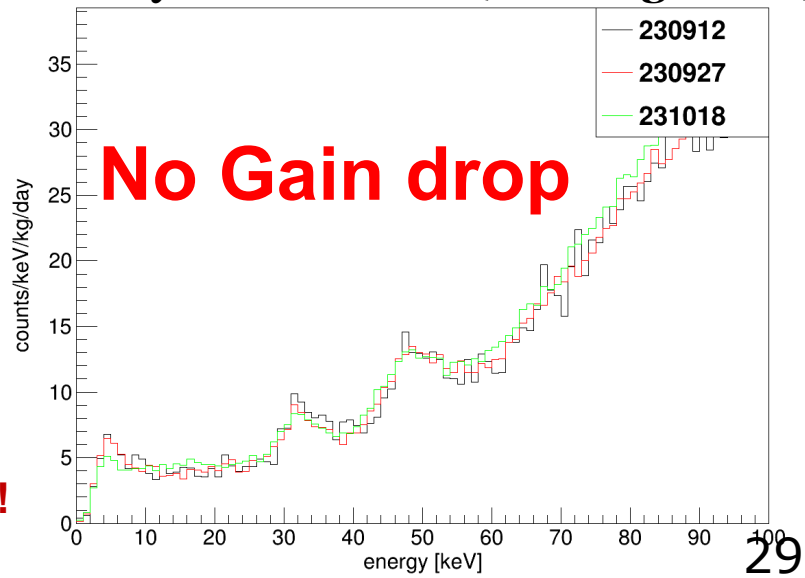
COSINE-100 C1 COSINE-100U C1

C2 and C3 were assembled with similar improvement!!

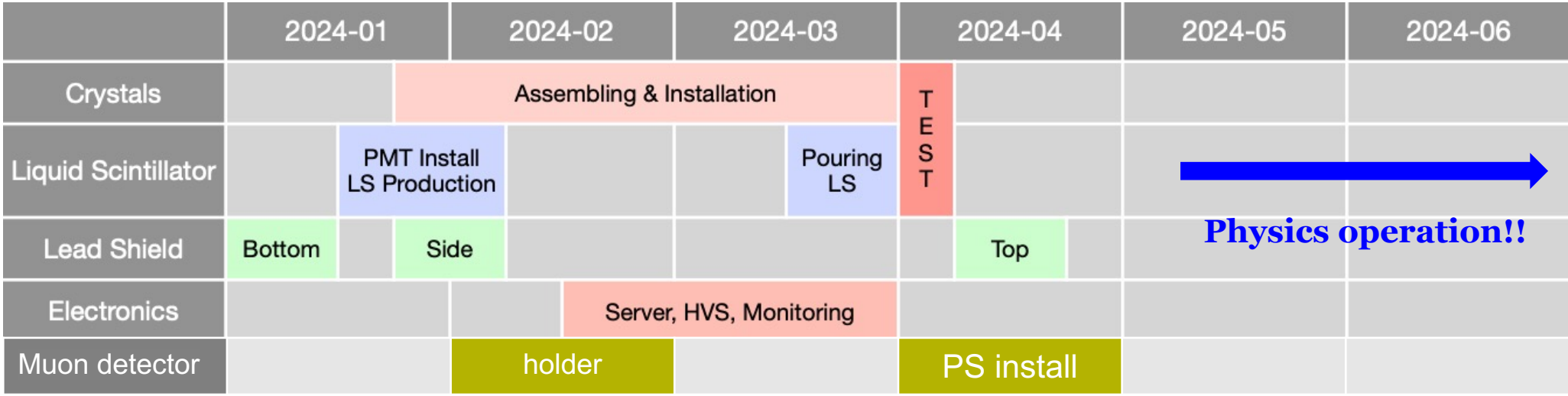
RMS resolution @ 59.54 keV for C3



Stability of ~ 1 month (Above-ground)



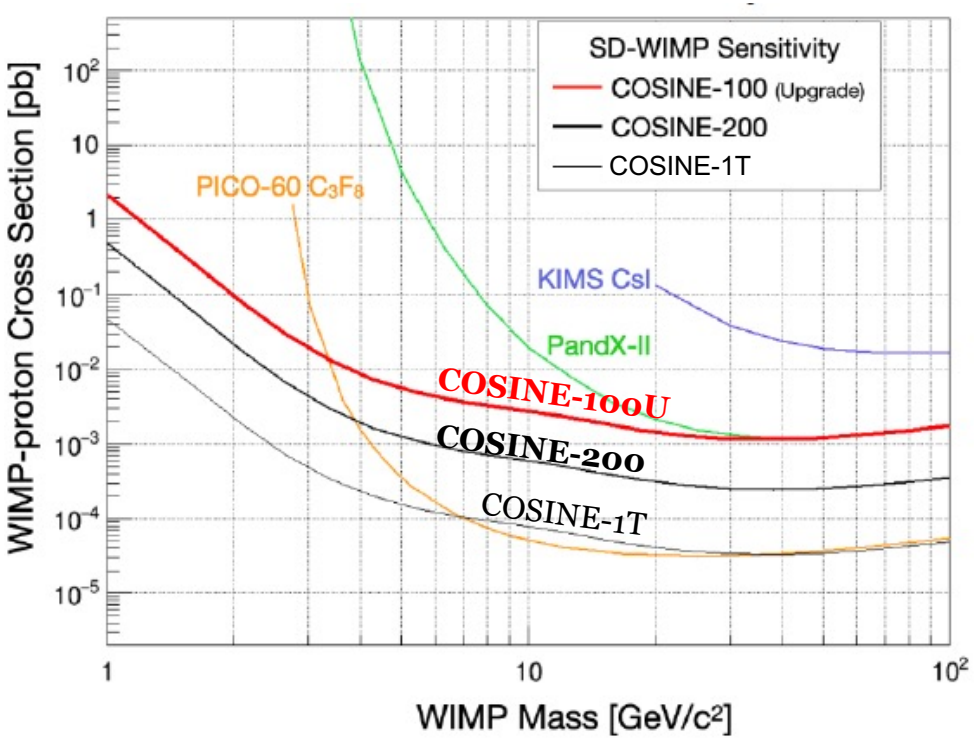
COSINE-100U schedule



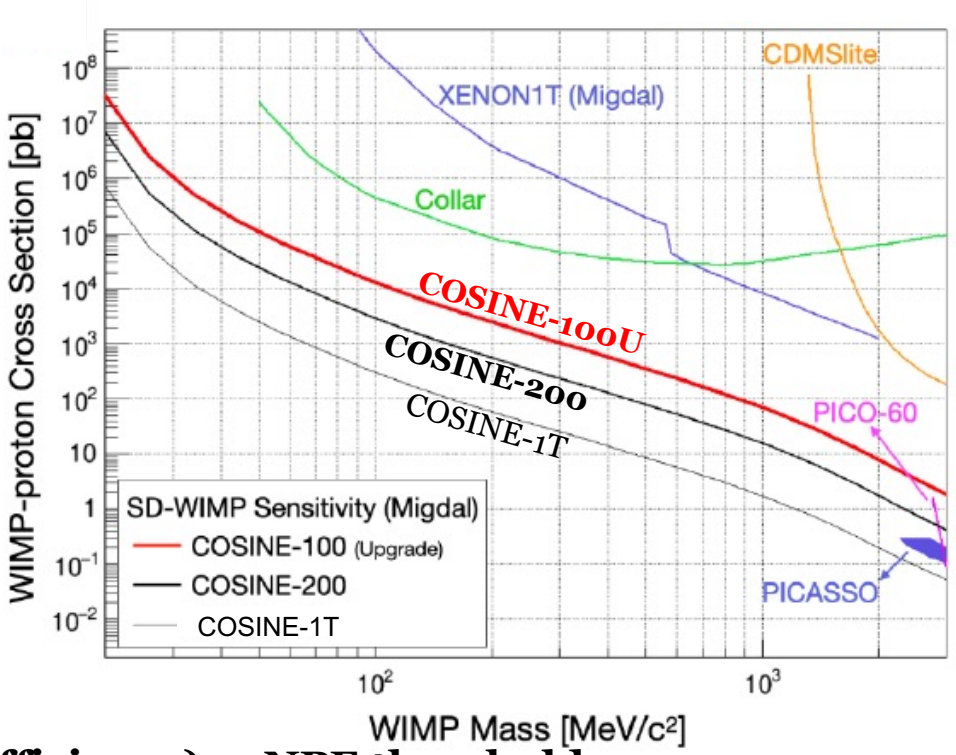
- We already prove the high light yield crystal (C1,C2,C3 assembled)
- Production for other crystals are on the way
- Moving from Y2L to Yemilab was done and shielding was prepared
- We plan to start COSINE-100U in May/2024

Low-mass sensitivities for spin-dependent limit

WIMP-proton spin-dependent



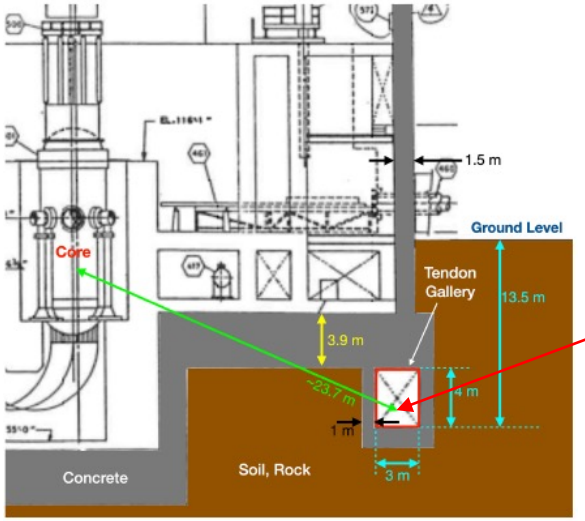
Low mass search with Migdal



22 NPE/keV, 1 year operation (100% efficiency), 5 NPE threshold

- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test for the COSINE-200 & 1T experiments

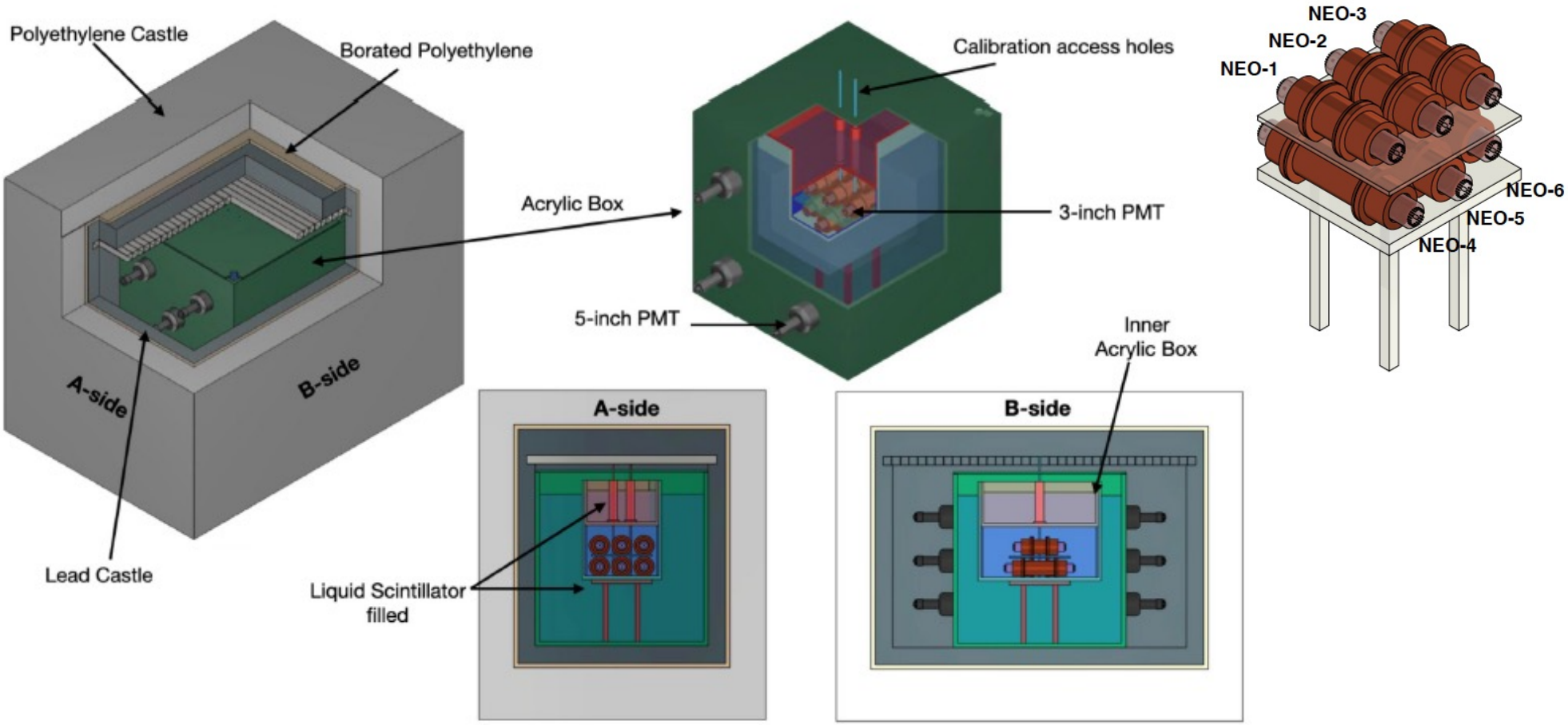
Neutrino Elastic scattering Observation with NaI



~20 members, 5 institutes, since 2019 IBS, SNU, CAU, KAERI, Sejong

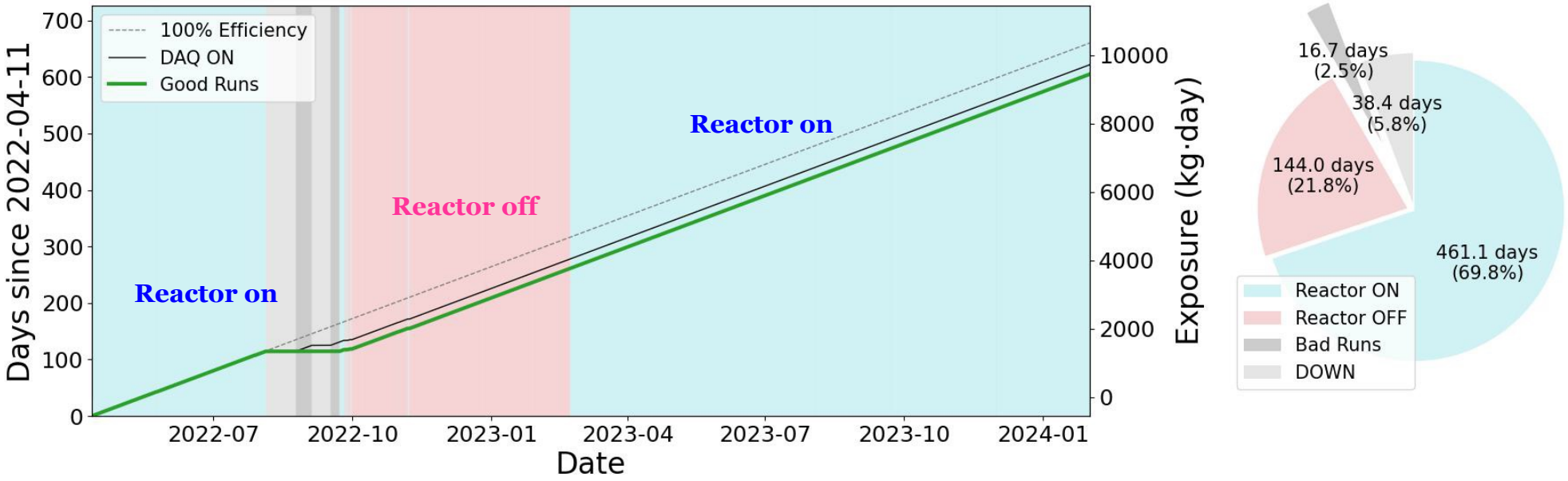
- NEON aim to **observe** coherent elastic neutrino-nucleus scattering (CEvNS) using reactor antielectron neutrino
- 16.6 kg high light yield (**~24 photoelectrons/keV**) NaI(Tl) crystals were deployed at tendon gallery (~24 m from reactor core) of Hanbit nuclear power plant
- Stable physics data acquisition **since April/2022**

NEON detector



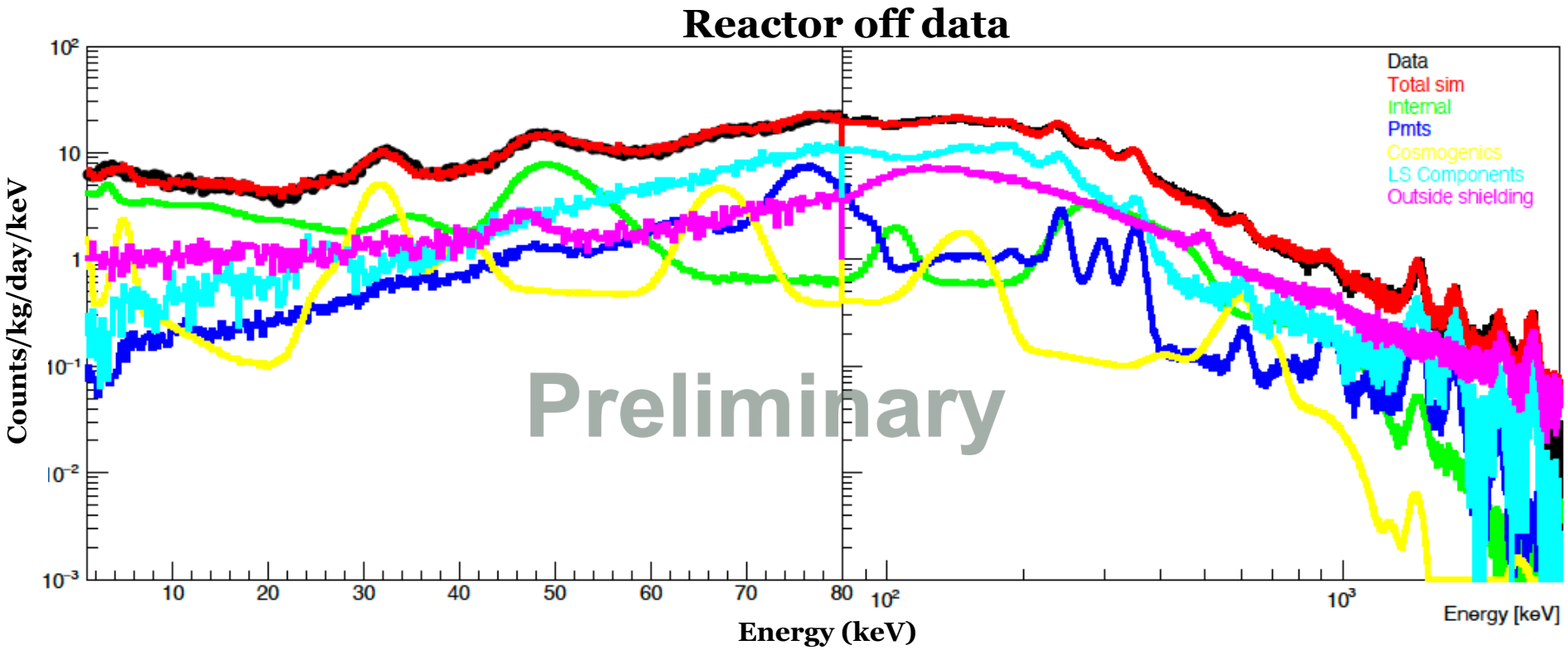
- 16.6 kg NaI(Tl) crystals immersed in **800 L liquid scintillator**

NEON operation



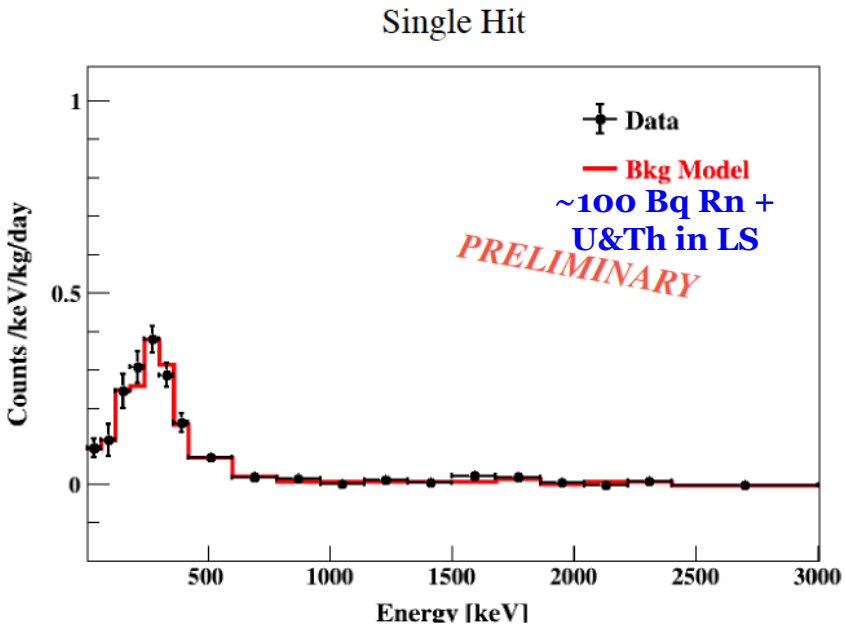
- Reactor on data : 461 days
- Reactor off data : 144 days
- Total exposure ~ 10,000 kg days
  - ❖ The largest exposure between reactor CEvNS experiments

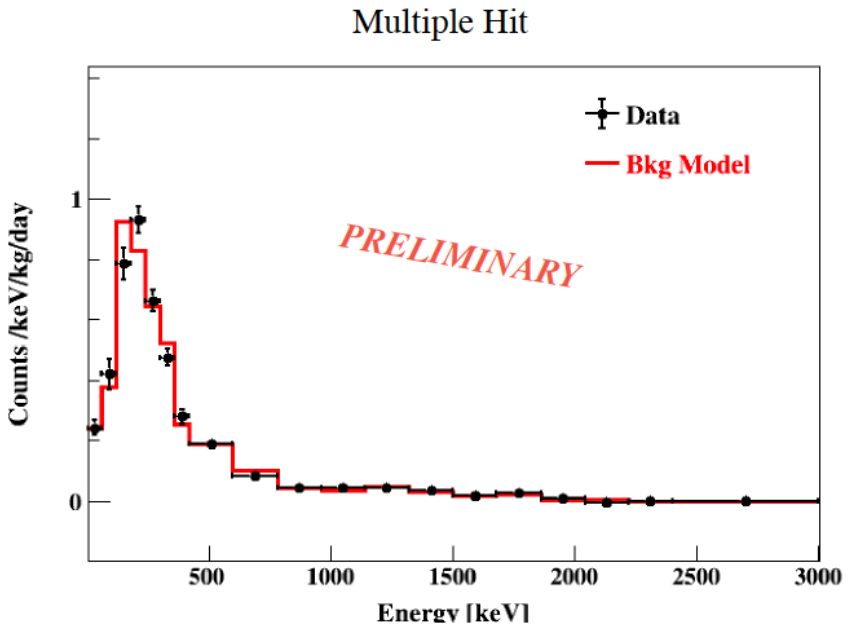
Background understanding

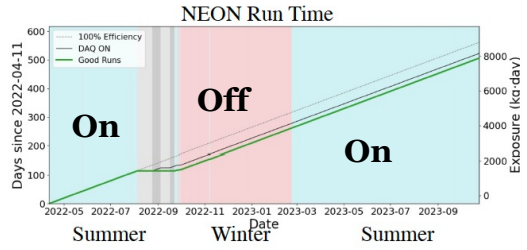


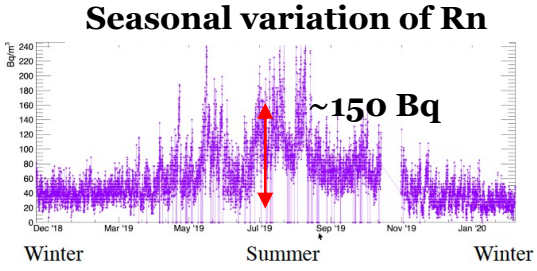
- Reasonable understanding of background contributions
- ~7 counts/kg/day/keV background level **below 10 keV**
  - ❖ Comparable with CONUS experiment

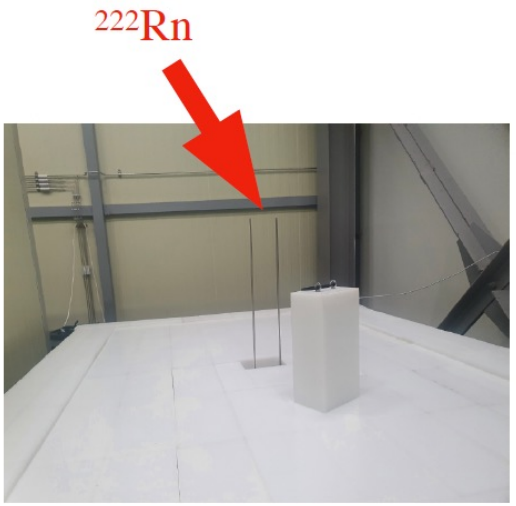
Reactor on minus off modeling





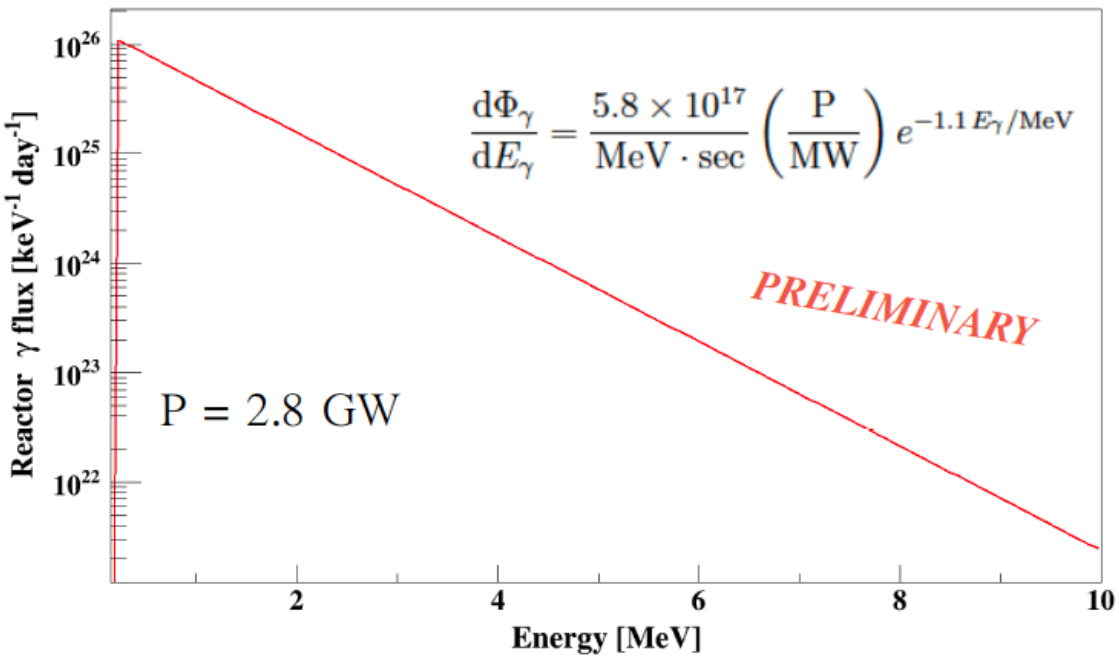




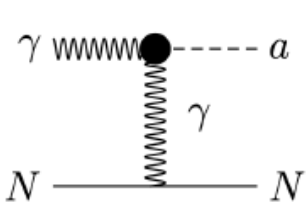


- Time-dependent background from Rn and dust describes on minus off background properly

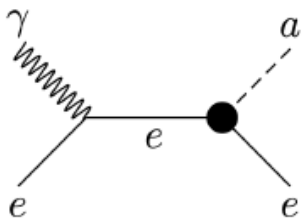
Reactor is the most intense source of MeV energy γ



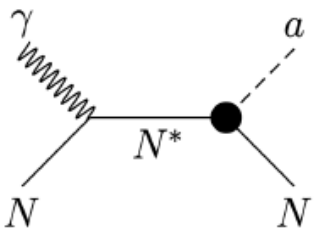
- Dark sector bosonic particle such as dark photon or axion-like particle (ALP) may produced with the SM photon interaction
- Reactor is the stringent source of MeV mass dark photon or ALP



Primakoff



Compton-like

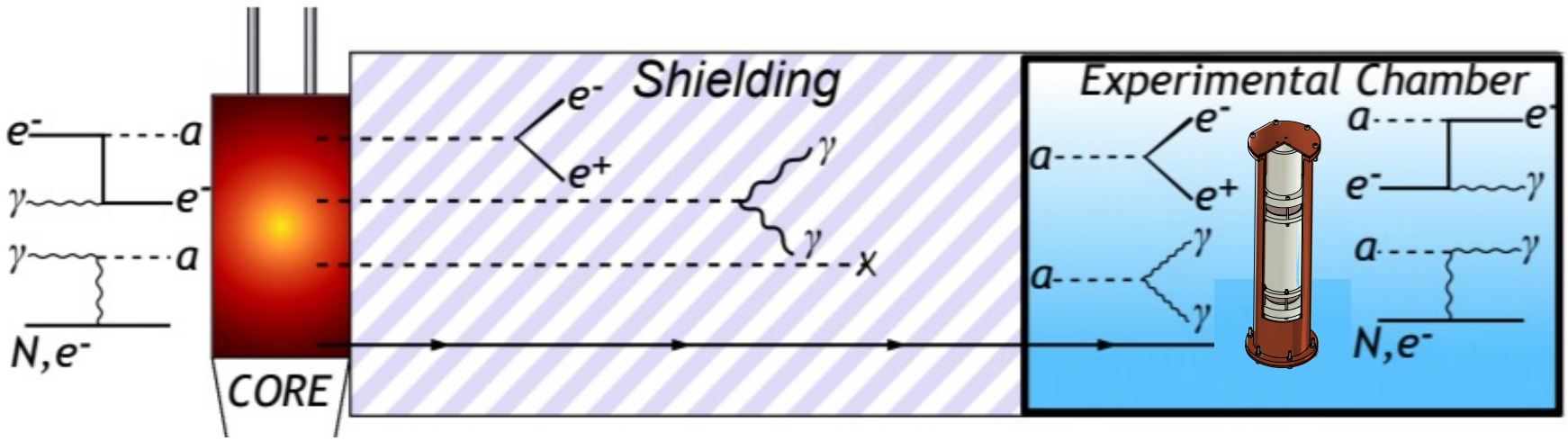


Nuclear deexitation

ALP production @ reactor

Compton-like process can produce dark photon

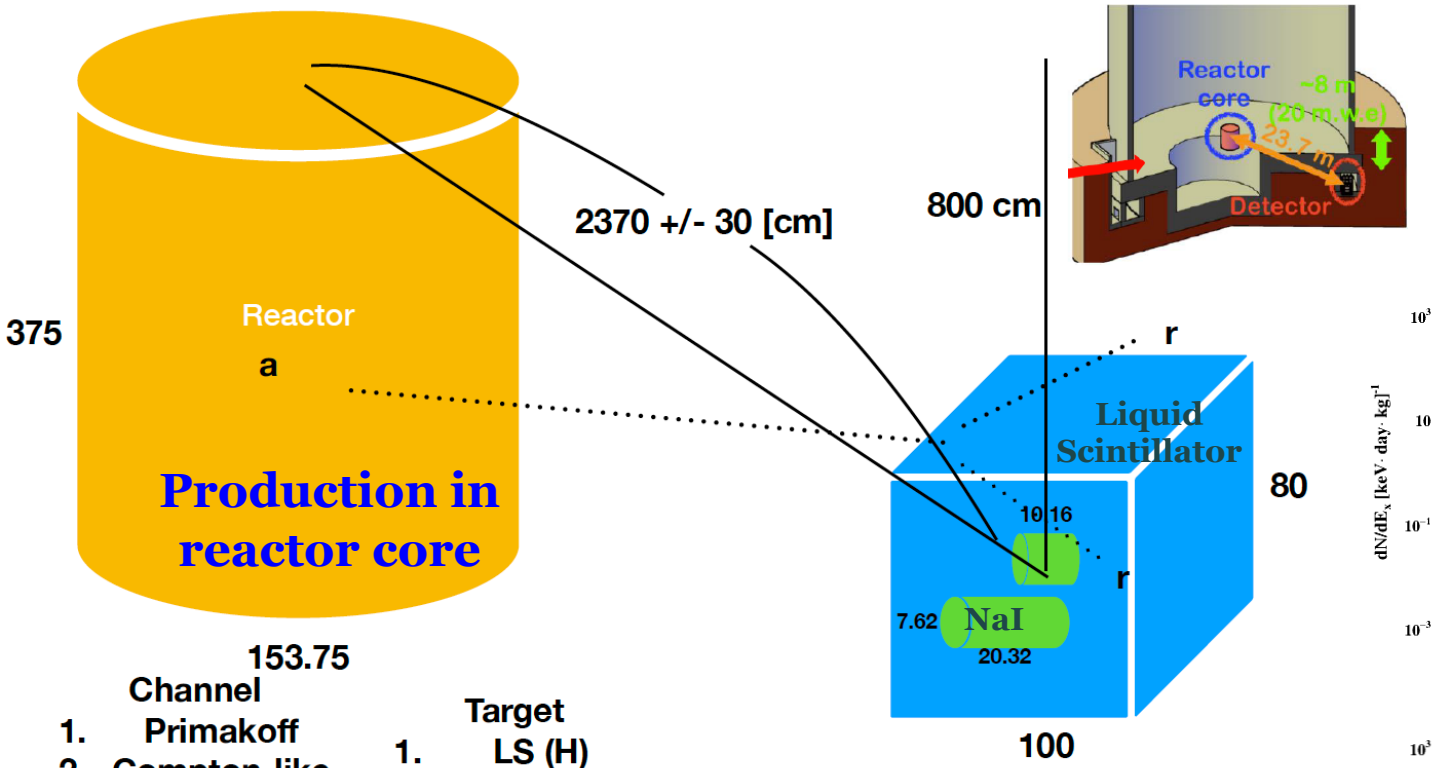
ALP production & detection



PRL 124, 211804 (2020) & JHEP 03, 294 (2021)

Production	Detection	Coupling
Primakoff Process	Inverse Primakoff Decays to two photons	$g_{a\gamma\gamma}$
Compton-like scattering	Inverse Compton-like Decays to e^+–e^- pair Axio-electric process	g_{aee}
Nuclear de-excitation	Nuclear absorption	g_{ann}

ALP simulation



Channel

1. **Primakoff**
2. **Compton-like**
3. Axioeletric
4. **A->rr**
5. A->ee

Target

1. **LS (H)**
2. **LS (C)**
3. **Crystal (Na)**
4. **Crystal (I)**

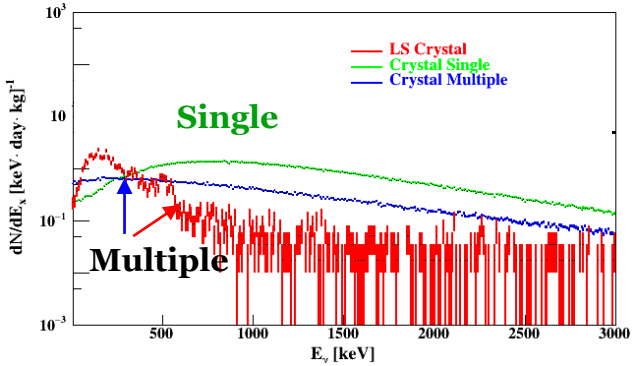
Calculated momentum Using generated signal (Energy, position)

Scattering or decay in detector

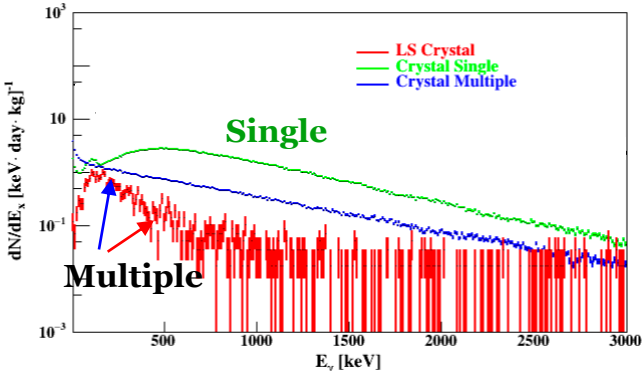
(NaI and LS)

Fast simulation of axion production, flight, and detection + Geant4 simulation for detector responses

Primakoff

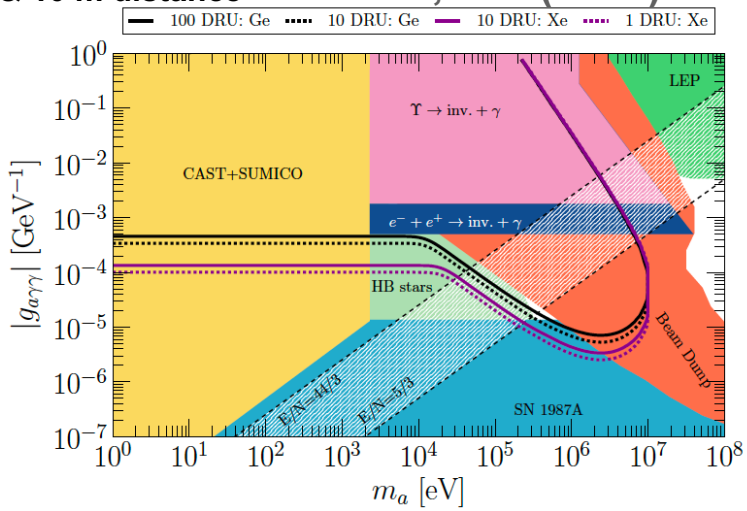


$a \rightarrow \gamma\gamma$

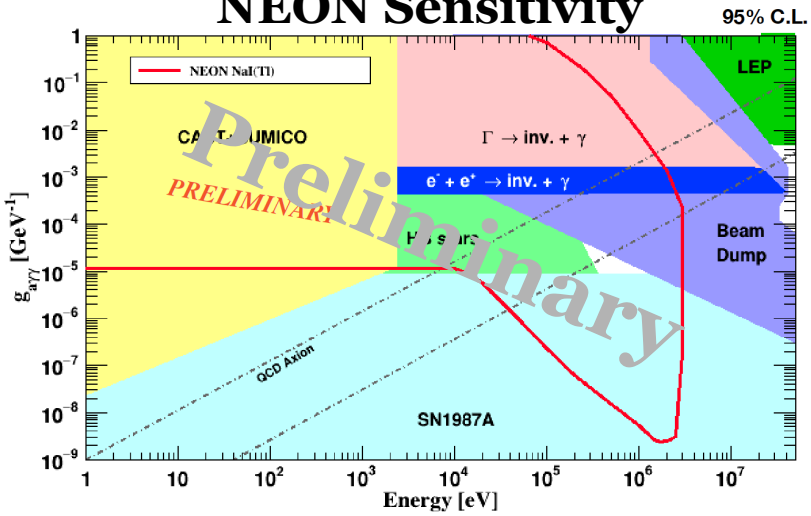


Sensitivity

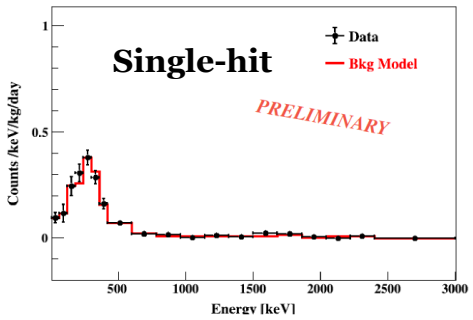
4 GW & 10 m distance JHEP 03, 294 (2021)

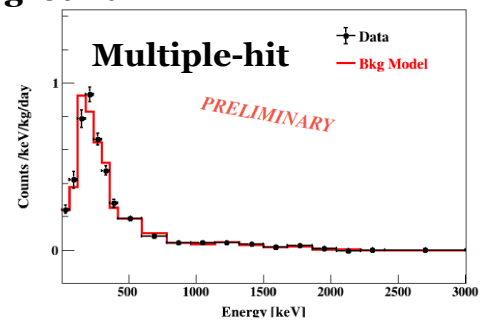


NEON Sensitivity



NEON background





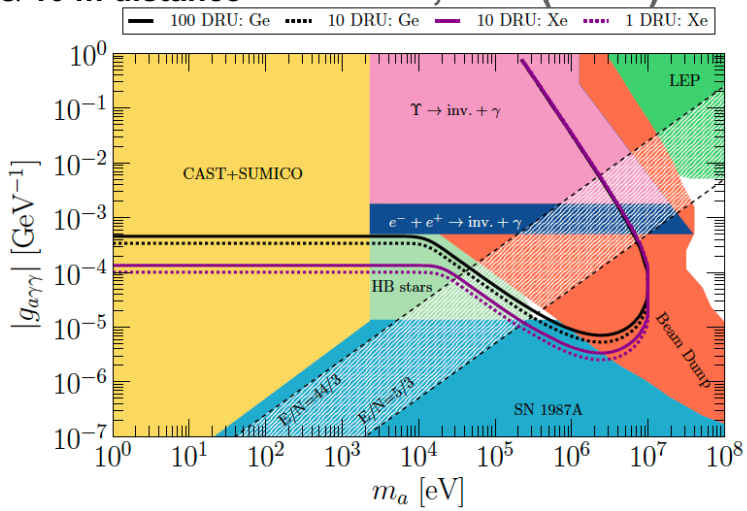
Background levels were much smaller than 1 dru especially for energy above 1 MeV

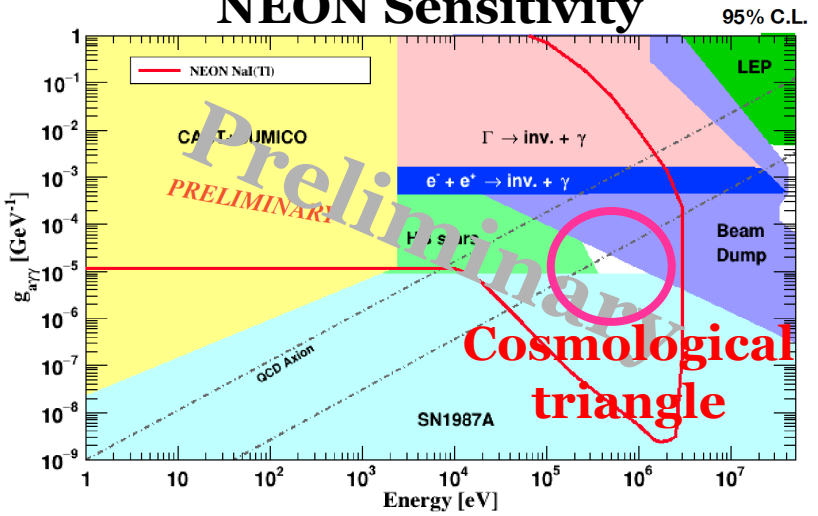
Multiple hit events enhance sensitivities for photon coupling (can use LS as active target)

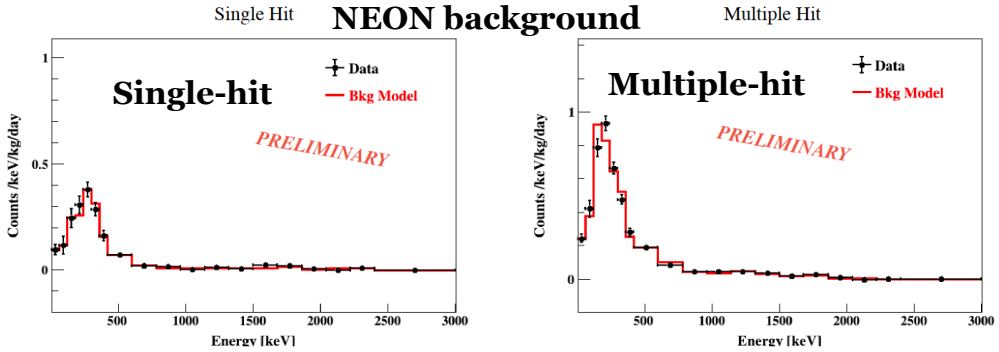
- NEON data will provide best direct search results for MeV mass ALP (both photon coupling and electron coupling)

Sensitivity

4 GW & 10 m distance JHEP 03, 294 (2021)







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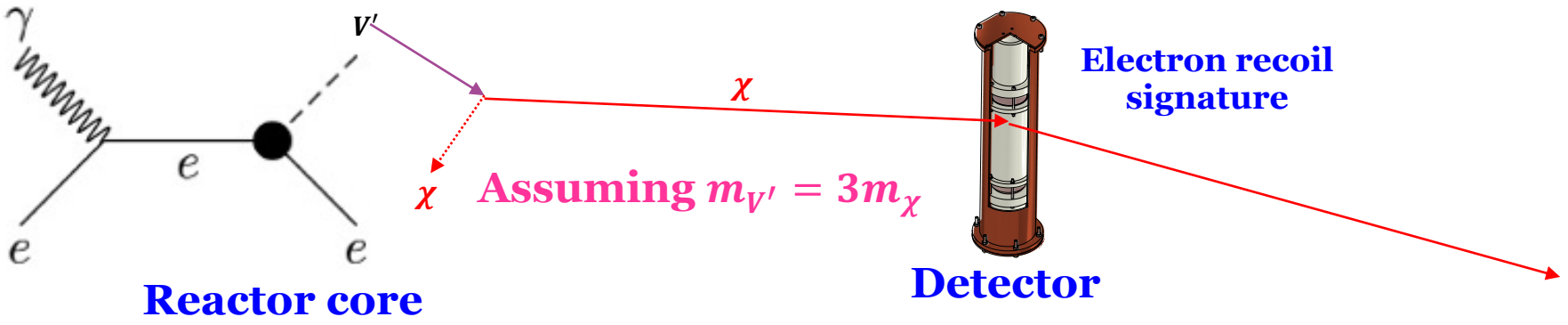
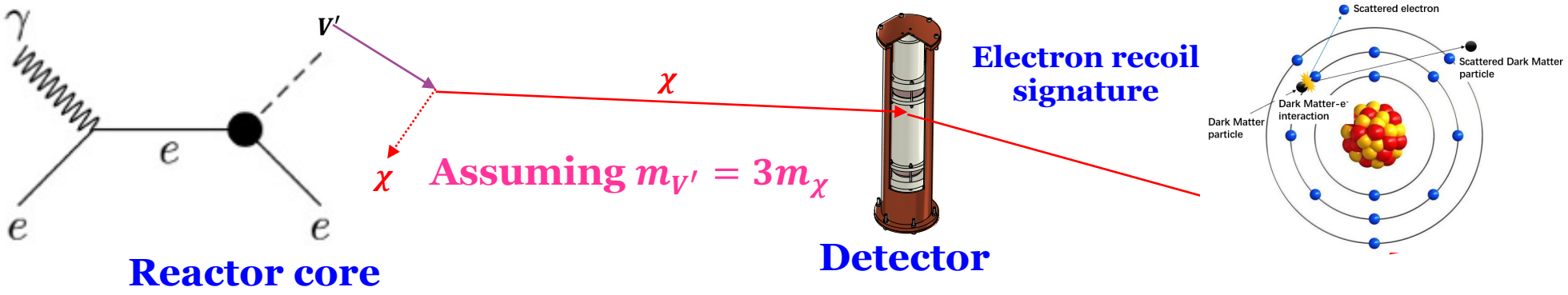
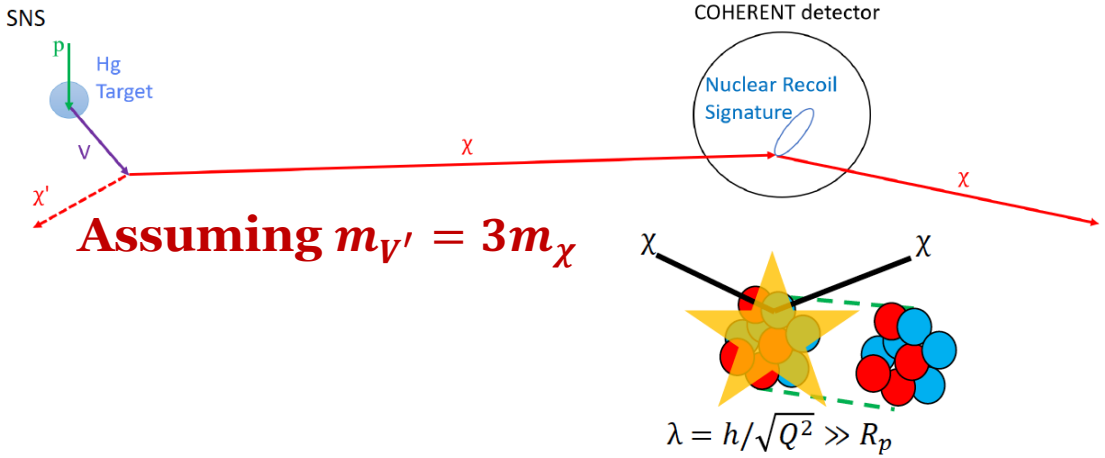
Dark photon production & decay to dark matters



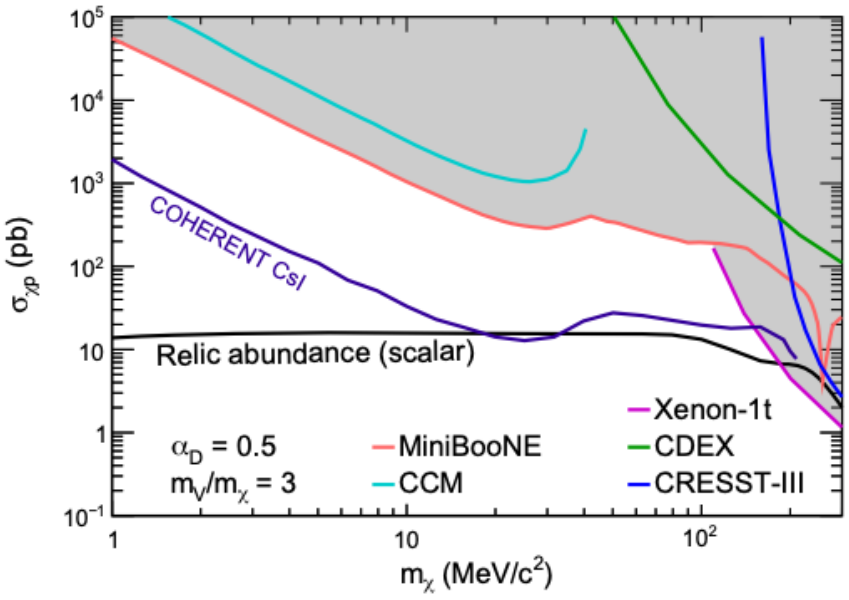
Dark photon production & decay to dark matters



COHERENT reported similar search results in nuclear recoils



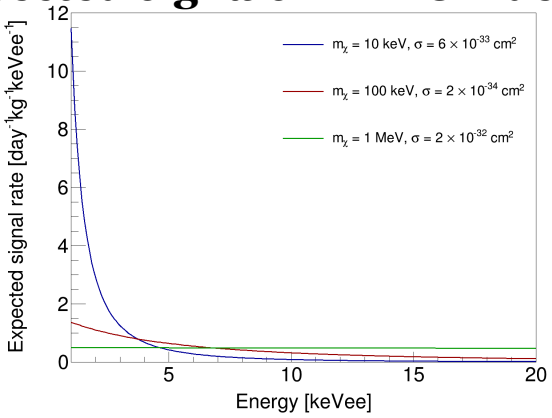
PRL 130, 051803 (2023)



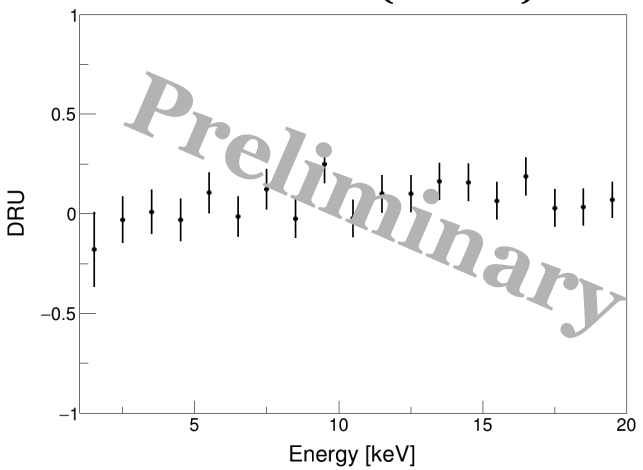
NEON sensitivity

JHEP 11, 066 (2018)

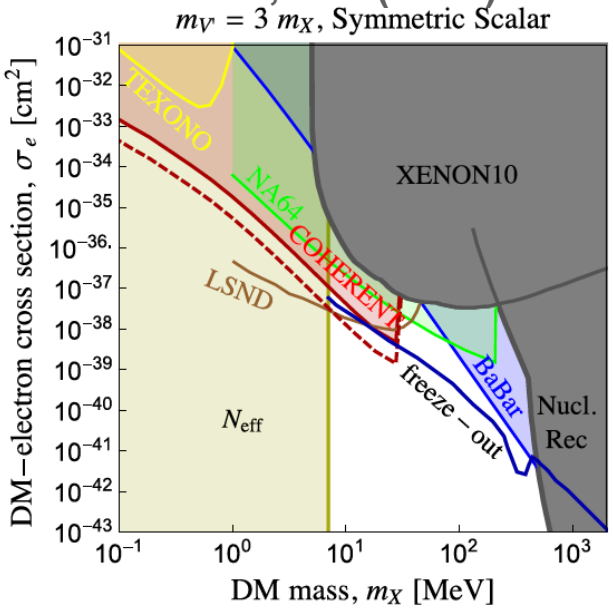
Expected signals in NEON detector



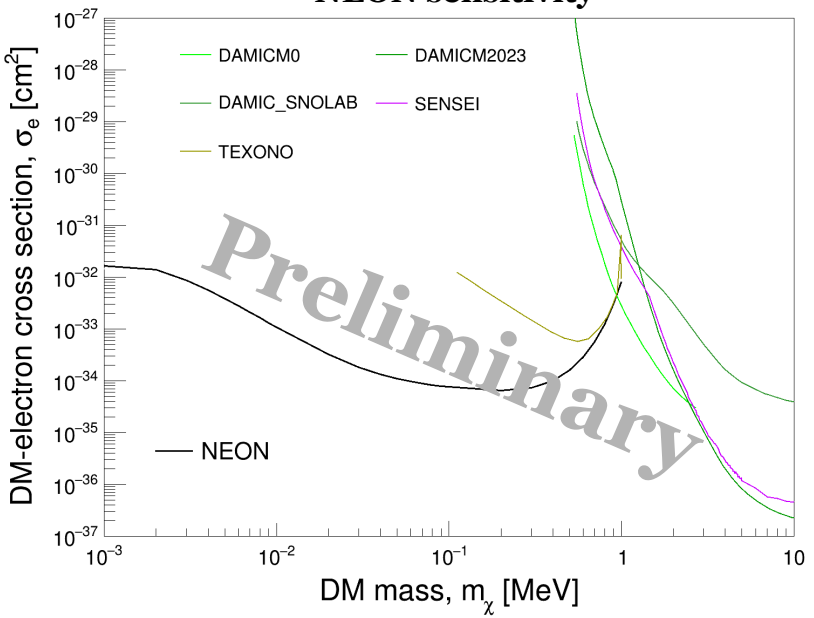
NEON data (on – off)



JHEP 11, 066 (2018)



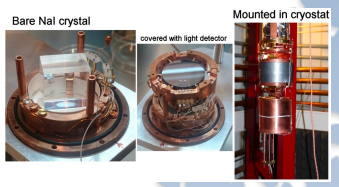
NEON sensitivity



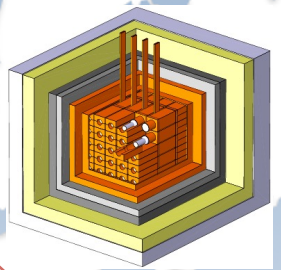
Summary

- COSINE-100 searched various dark matter candidates in wide energy ranges
- COSINE-100U and COSINE-200 have world competitive sensitivities for low-mass dark matter searches
- Reactor is the most intense MeV gamma source, therefore, the stringent source of MeV dark photon and ALP
- NEON can unveil unexplored parameter spaces for ALP and low-mass dark matter (dark photon)

Global NaI(Tl) efforts

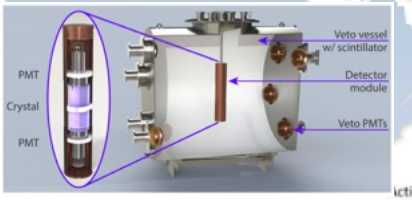


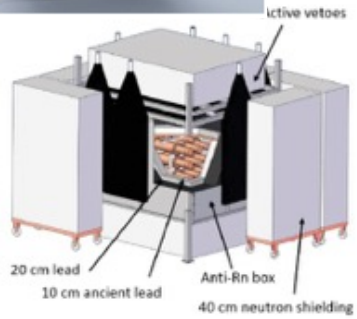
COSINUS @ LNGS



DAMA @ LNGS

SABRE @ LNGS

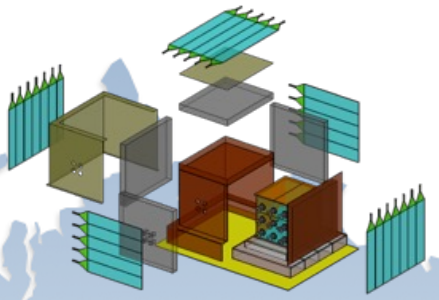




ANAIS @Canfranc

In Data-taking

ANAIS results.
Phys. Rev. Lett. **123**, 031301 (2019)



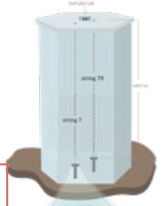
KIMS/COSINE @ Yangyang

In Data-taking

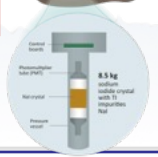
Nature 564, 83-86 (2018)
Phys. Rev. Lett. 123, 031302 (2019)

PICO-LON @ Kamioka

SABRE @ Stawell

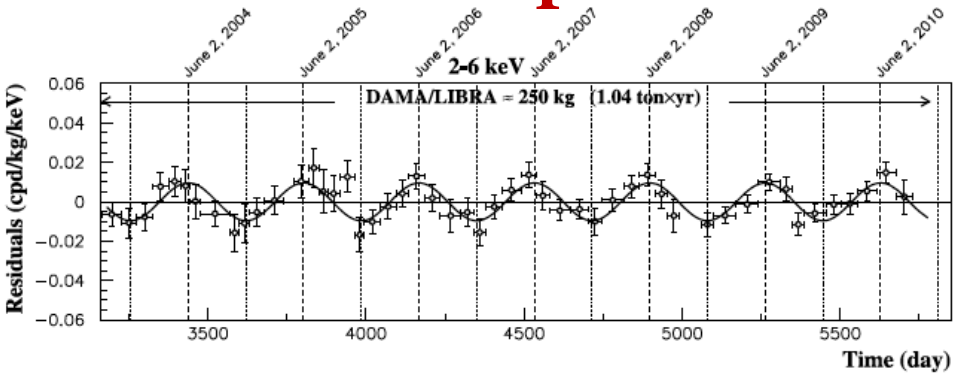


DM-Ice @ South Pole



Annual modulation signal from DAMA/LIBRA

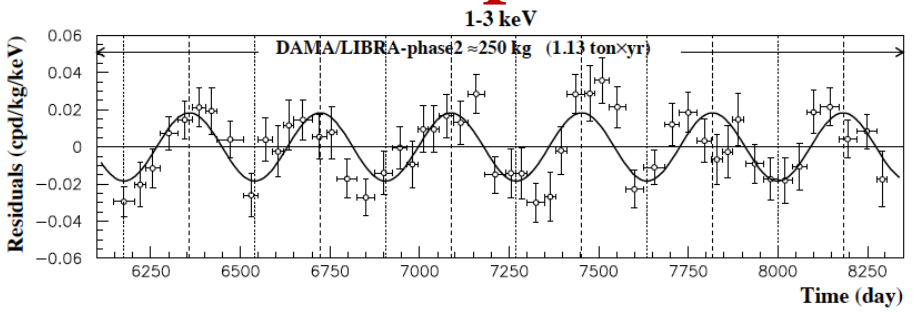
Phase1 experiment



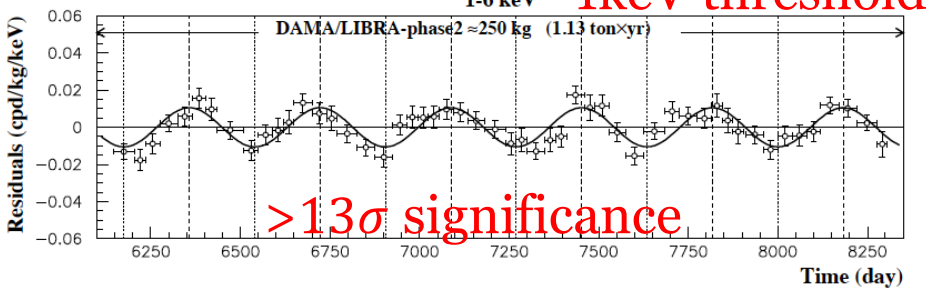
Eur. Phys. J. C 73:2648 (2013)

2keV threshold

Phase2 experiment



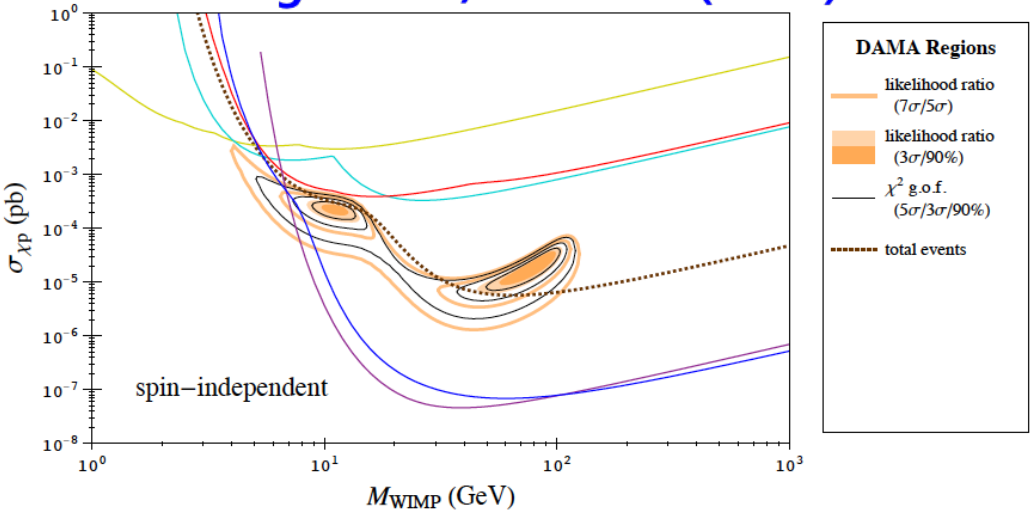
Nucl. Phys. At. Energy 19, 307 (2018)



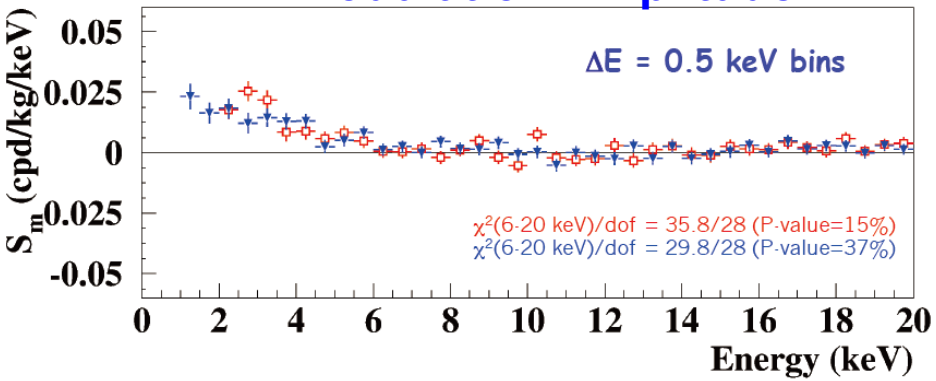
1keV threshold

>13σ significance

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

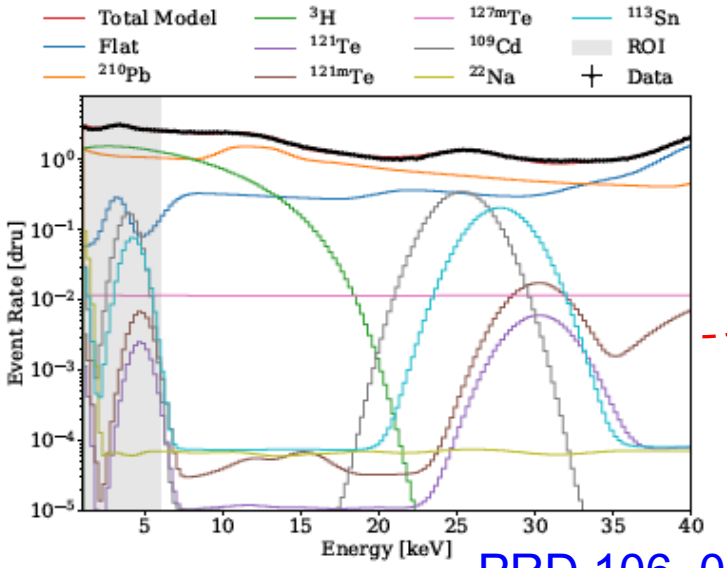


Modulation Amplitude



Model-independent annual modulation search

Time dependent background modeling



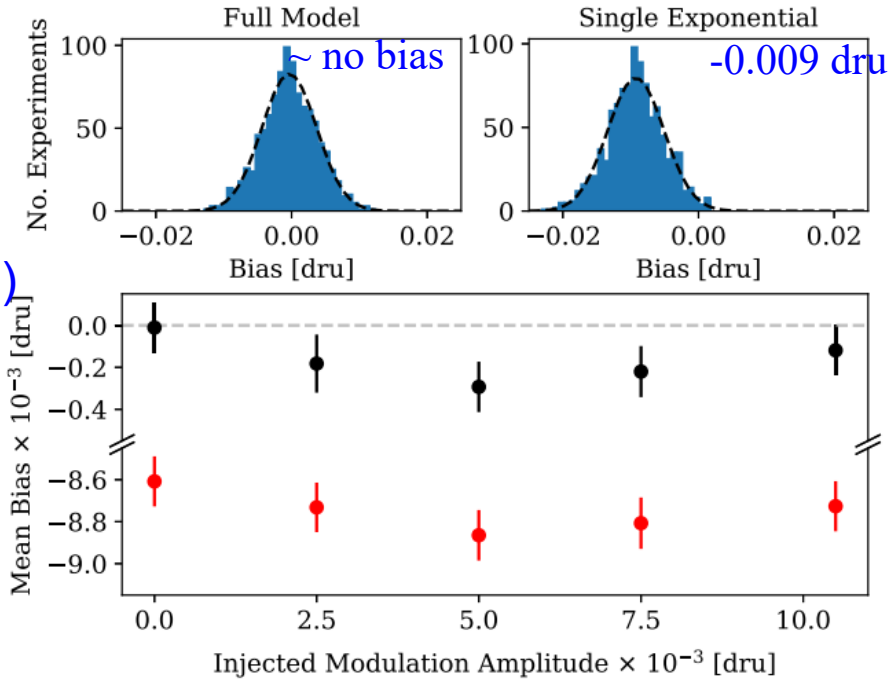
Single exponential

$$R(t) = P_0 + P_1 e^{-t/P_2} + S\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Full model (8 exponential)

$$R(t) = P_0 + \sum_{i=1}^{8} P_i e^{-t/\tau_i} + S\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$

Bias test (1-6 keV)



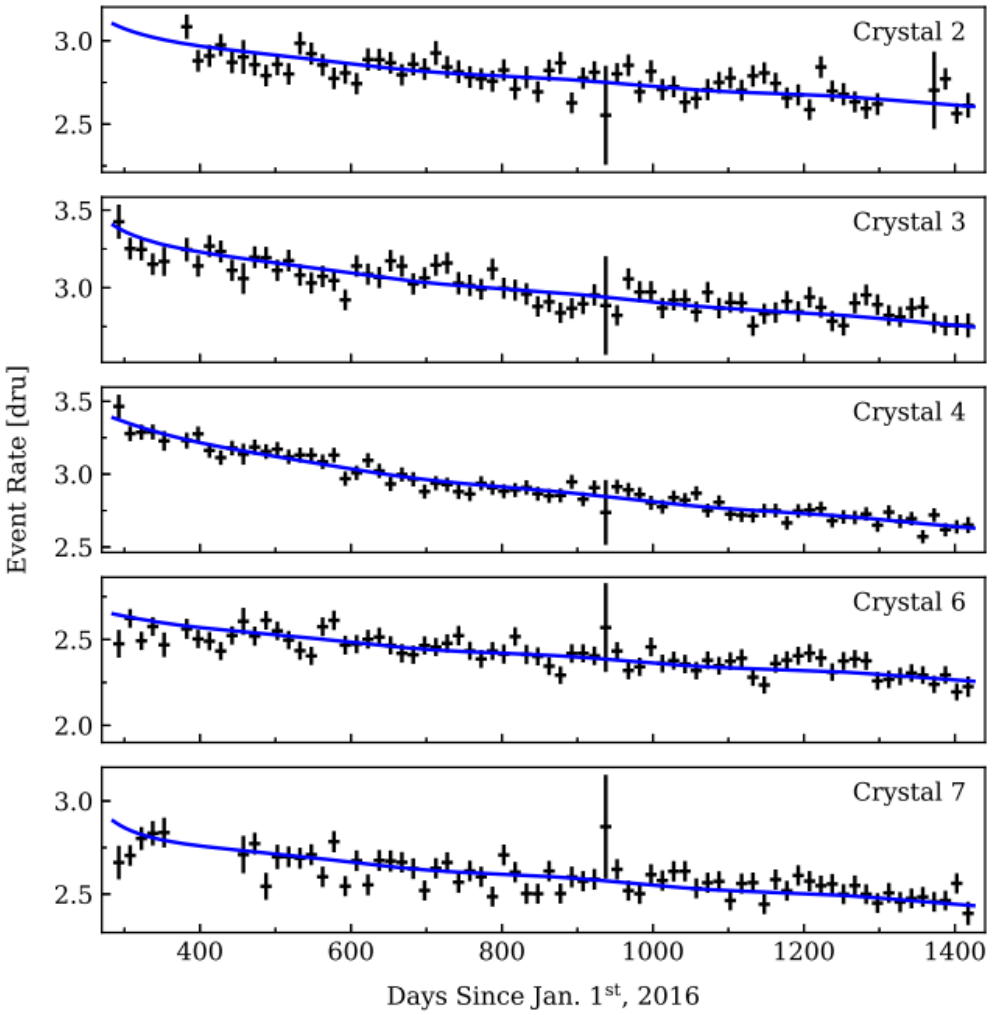
PRD 106, 052005 (2022)

Component	Half life	Average activity (dru)
Total		$(2.74 \pm 0.23) \times 10^{0}$
^{3}H	12.3 year	$(1.41 \pm 0.18) \times 10^{0}$
^{210}Pb	22.3 year	$(1.12 \pm 0.15) \times 10^{0}$
Flat		$(1.35 \pm 0.08) \times 10^{-1}$
^{109}Cd	461.4 days	$(4.13 \pm 0.39) \times 10^{-2}$
^{113}Sn	115.1 days	$(1.55 \pm 0.16) \times 10^{-2}$
^{127}Te	109 day	$(6.59 \pm 0.52) \times 10^{-3}$
^{22}Na	2.6 year	$(5.88 \pm 1.34) \times 10^{-3}$
^{121m}Te	154 day	$(1.50 \pm 0.16) \times 10^{-3}$
^{121}Te	16.8 day	$(5.07 \pm 1.23) \times 10^{-4}$

Understanding time-dependent background is crucial for the annual modulation search

Model-independent annual modulation search

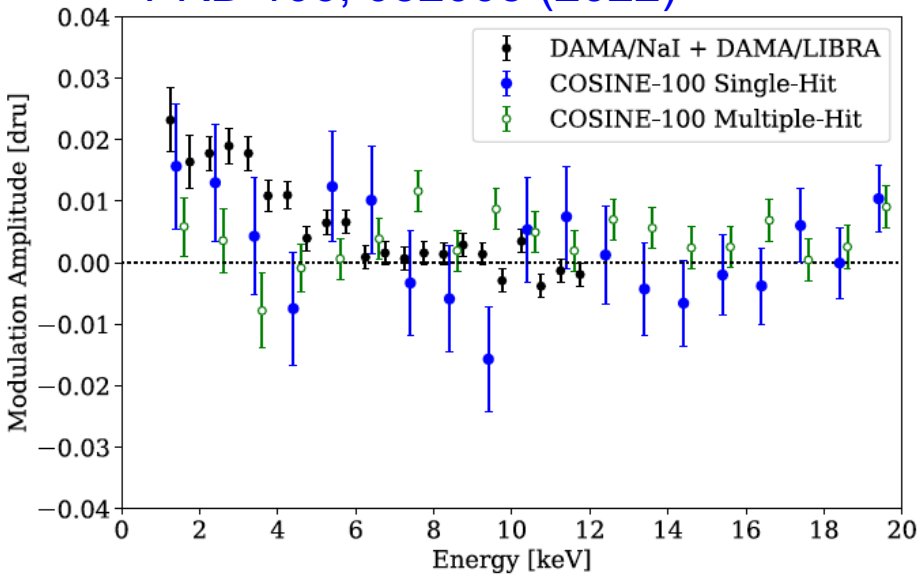
Data Fit (1-6 keV)



1-6 keV modulation amplitude

COSINE-100	$\mathbf{0.0067 \pm 0.0042}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

PRD 106, 052005 (2022)

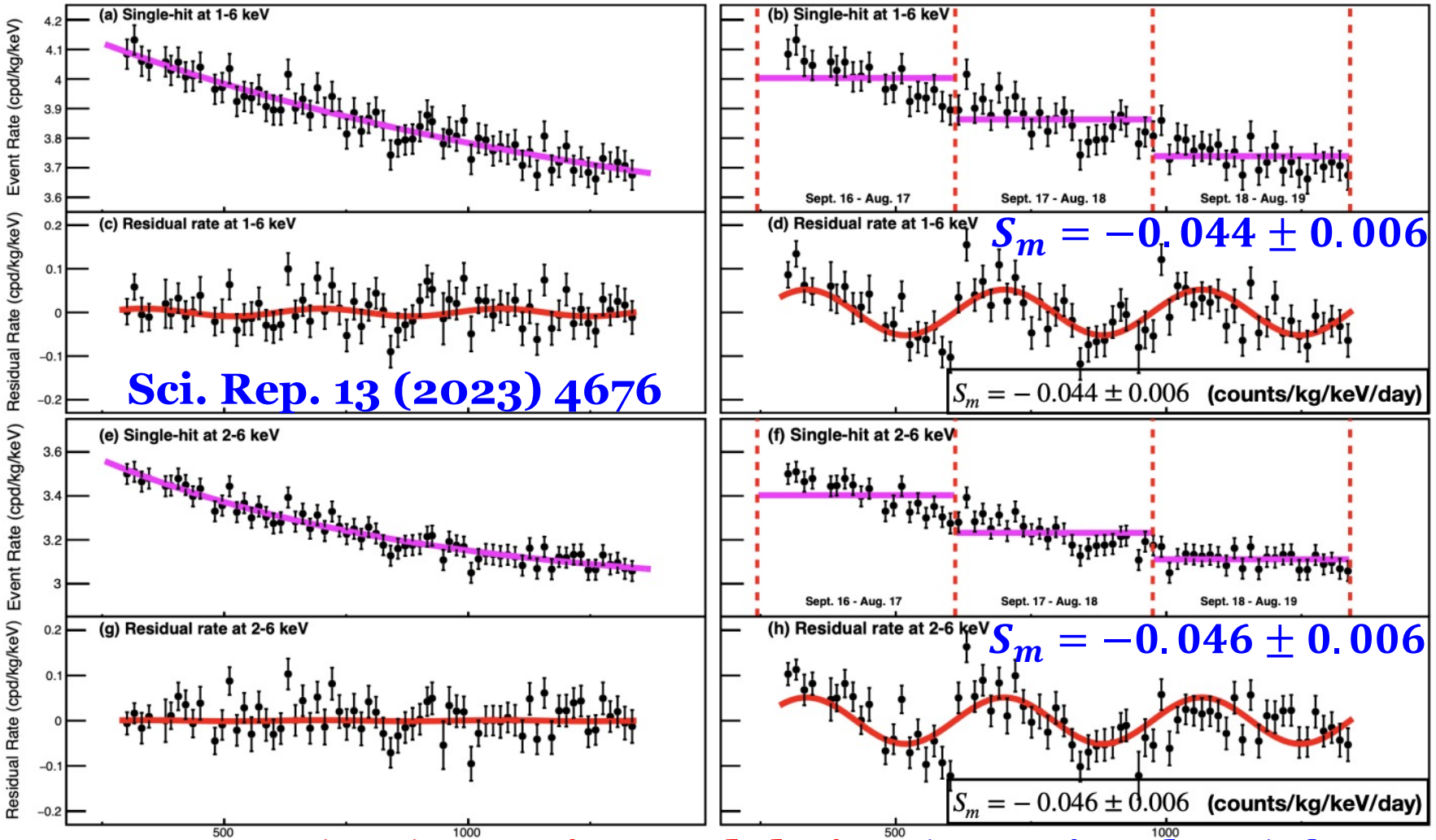


We need more data and/or better quality detector

- Full data (~2.5 times larger dataset) open soon
- COSINE-200

DAMA/LIBRA's method (induced modulation)

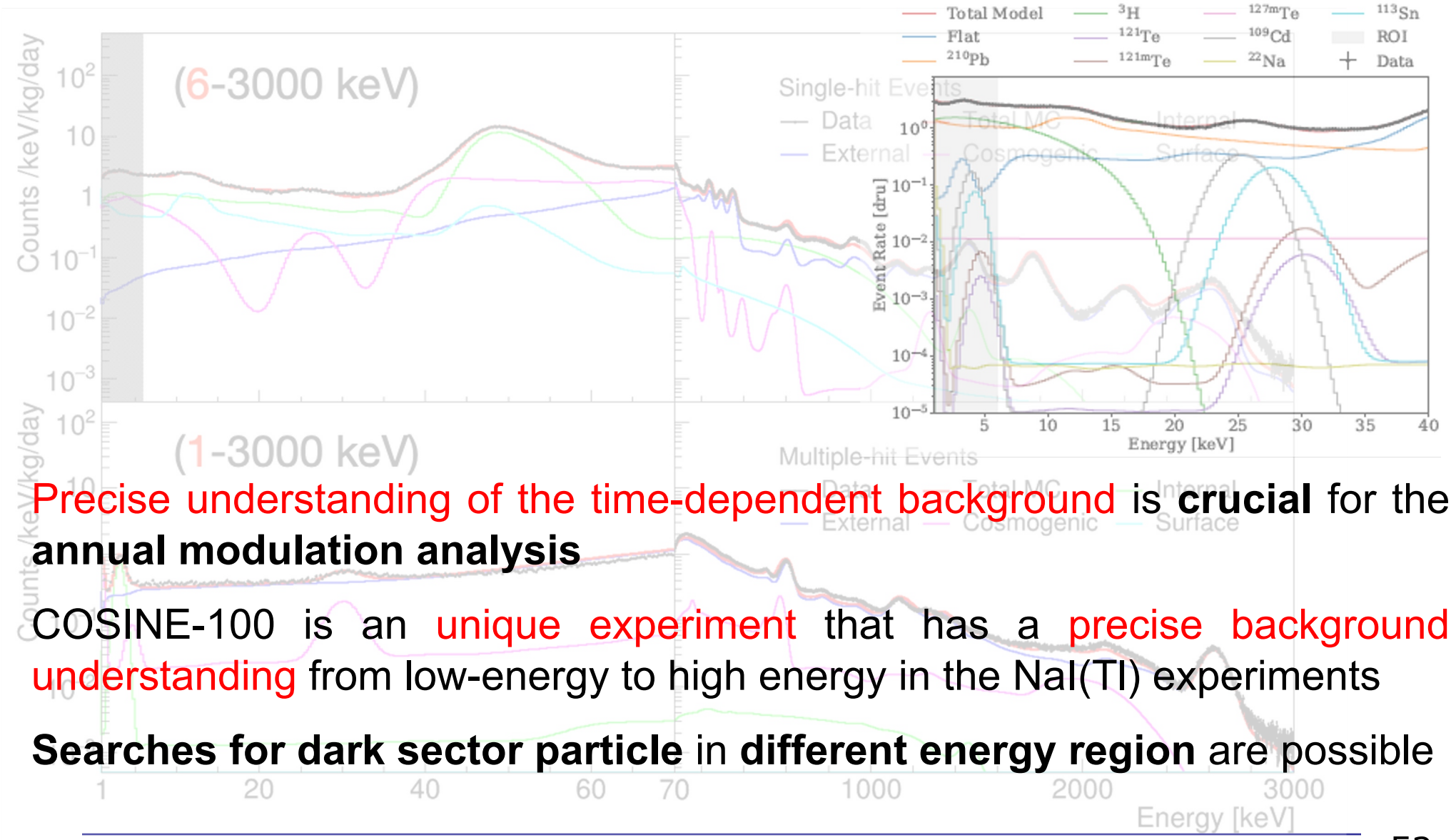
Single exponential model (reference) **DAMA/LIBRA's method**



Sci. Rep. 13 (2023) 4676

Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

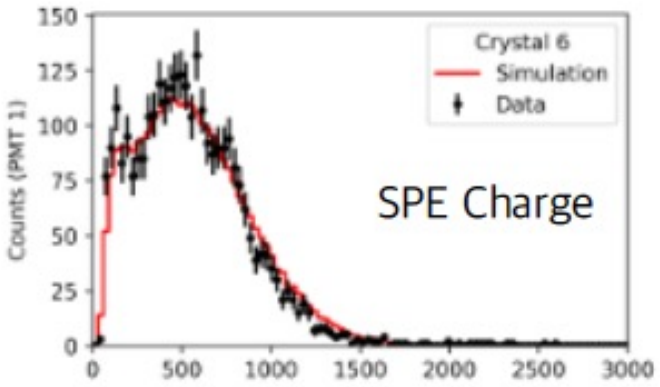
Importance of background understanding

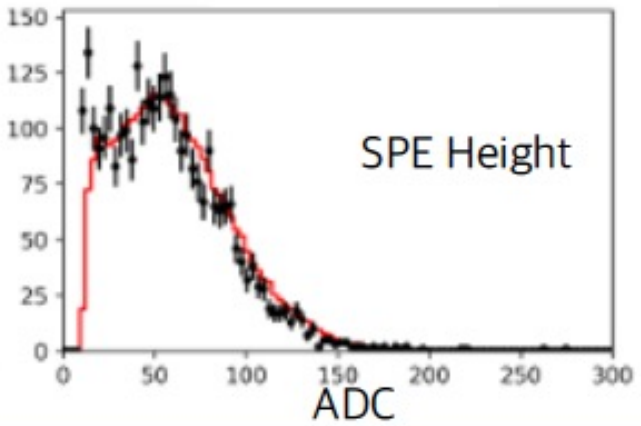


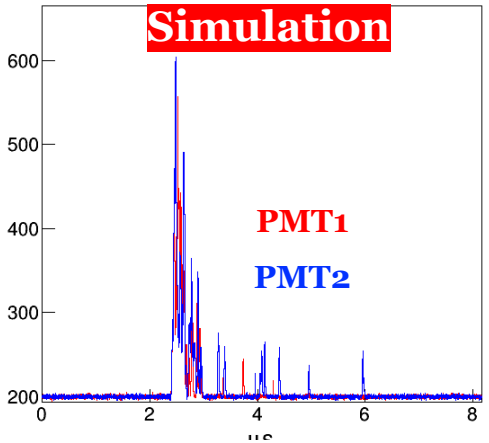
- Precise understanding of the time-dependent background is **crucial** for the **annual modulation analysis**
- COSINE-100 is an unique experiment that has a precise background understanding from low-energy to high energy in the NaI(Tl) experiments
- **Searches for dark sector particle** in **different energy region** are possible

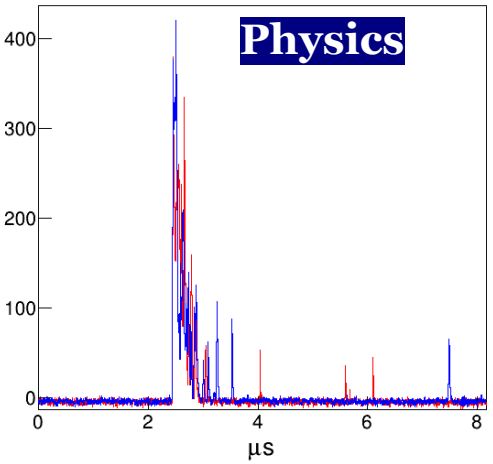
Ongoing works : Waveform simulation

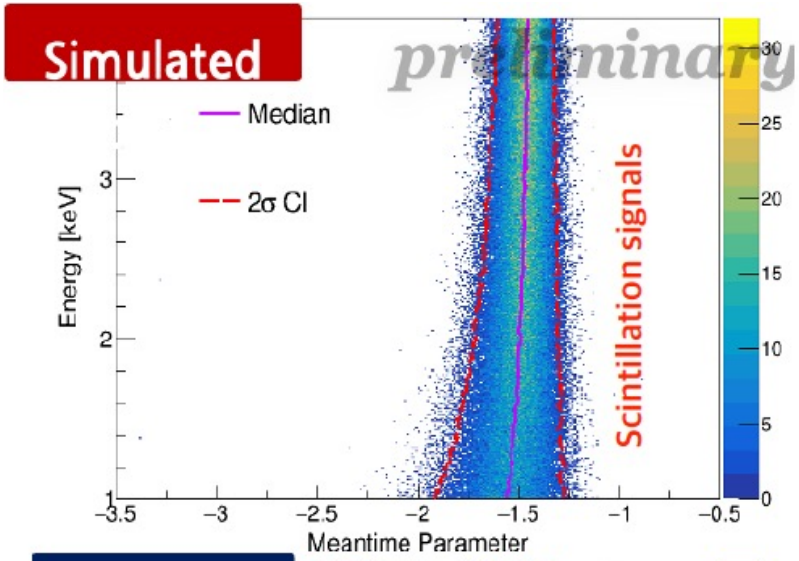
Single photoelectron tuning

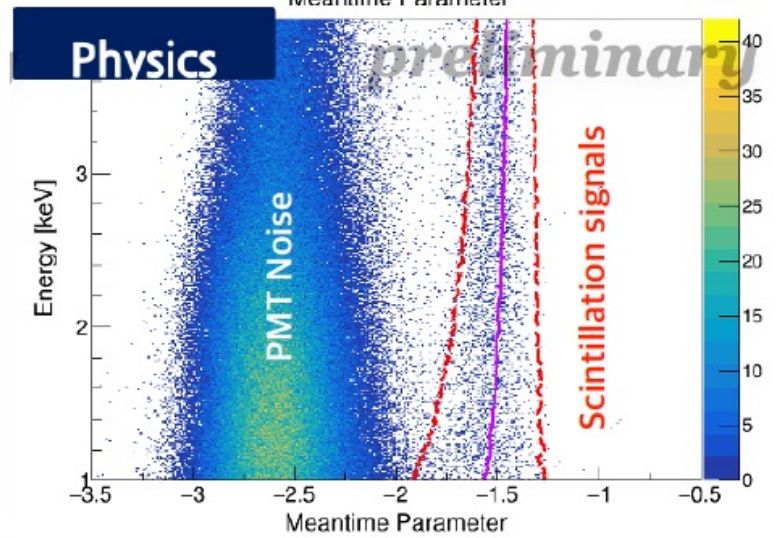












- **Waveform simulation** is developed to **describe** low-energy events (**sub-keV**)
- Simulation describe the data reasonably well
- Currently, the waveform simulation cross checked the trigger/selection efficiencies
- The waveform simulation will be used as signal sample of the multivariable analysis

COSINE-200 crystal development

Powder purification performance

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

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

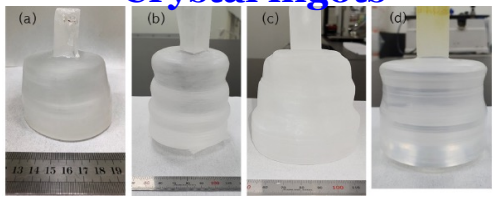
K.A. Shin et al., Front. Phys. 11, 1142849 (2023)

	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

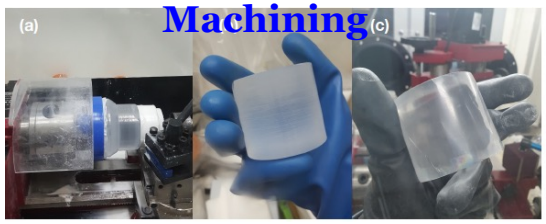
We produced ~ 400 kg low-background NaI powder

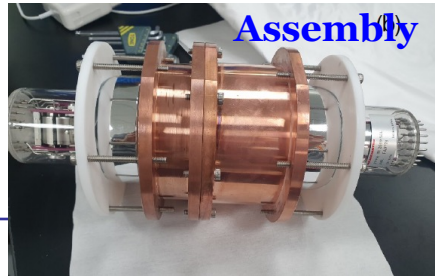
(Maximum production rate ~ 100 kg/month)

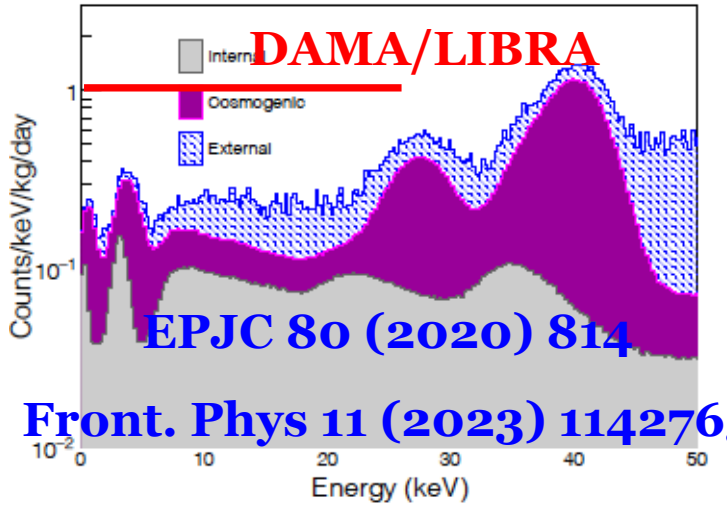
Crystal ingots



Machining





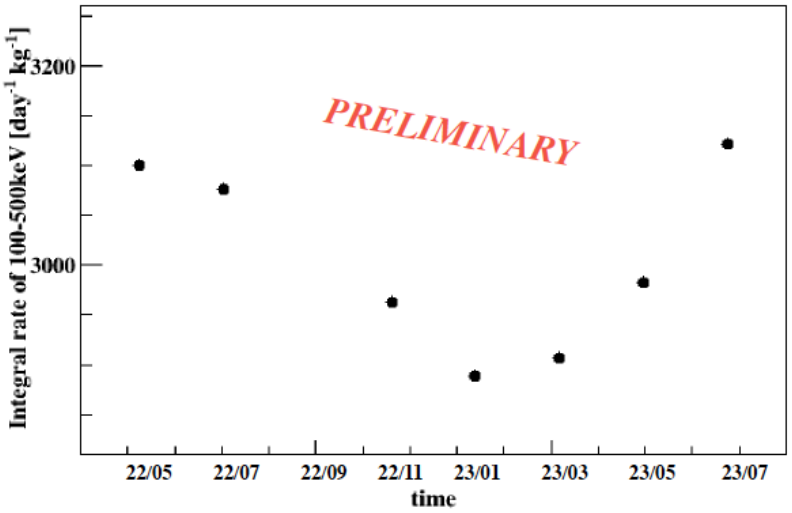


A proof of principle for low background NaI

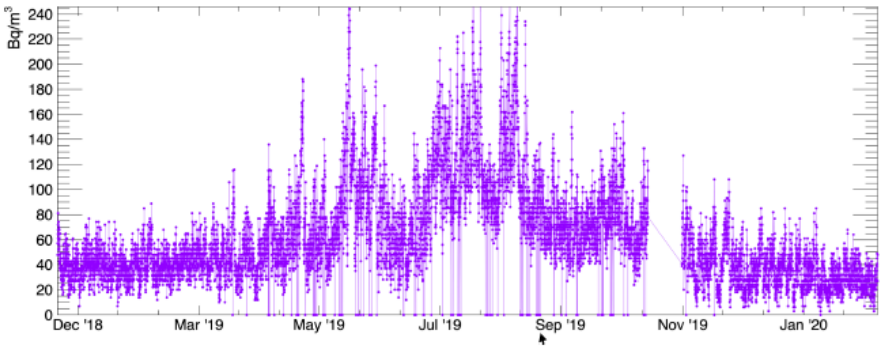
Large crystal growing is going on

NEON Event rate (100-500keV) over time

Single Hit



NEOS Rn measurement over time



Winter Summer Winter

Multiple Hit