IBS CUP activity on dark matter search

Hyunsu Lee

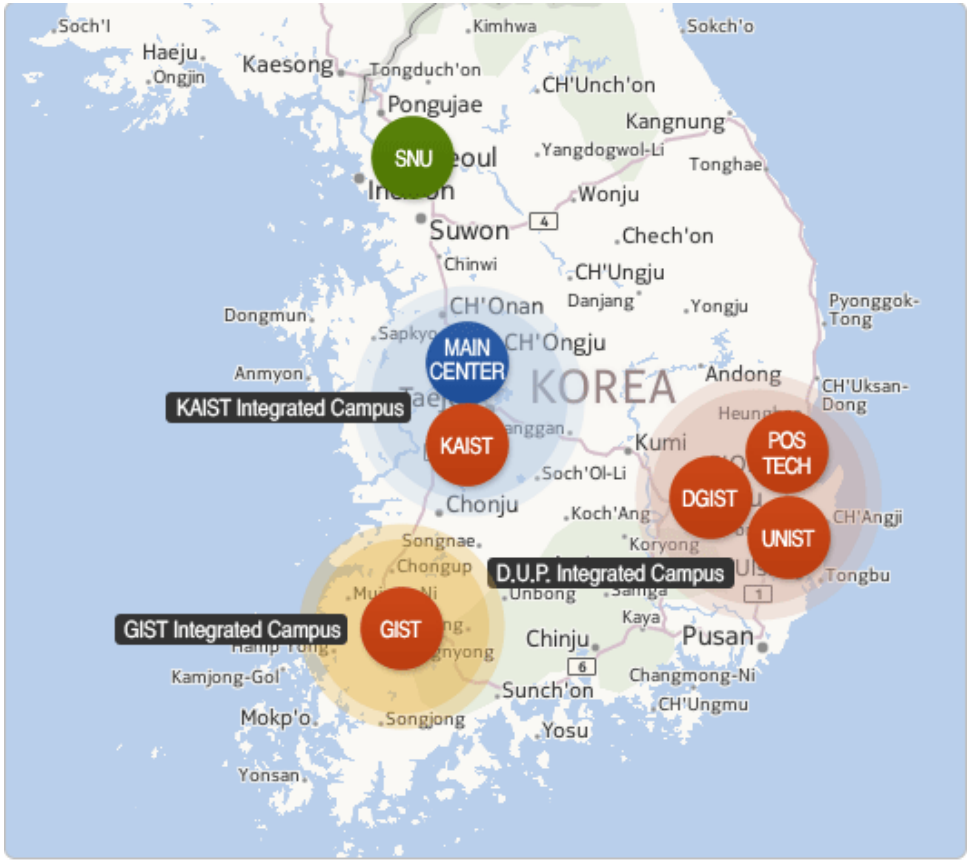
Institute for Basic Science (IBS)

Center for Underground Physics (CUP)

The 2nd DMNet International Symposium, Sep 13-15, 2022

Institute for Basic Science (IBS) in Korea

- Korea's comprehensive institute for basic science research
- Established in November 2011
  - ❖ Benchmark Max Planck Institute



Center types

HQ Centers	9
Campus Centers	13
Extramural Centers	9

Budget and Human Resources

225,425,841 USD

2,253 members

Center for Underground Physics (CUP)

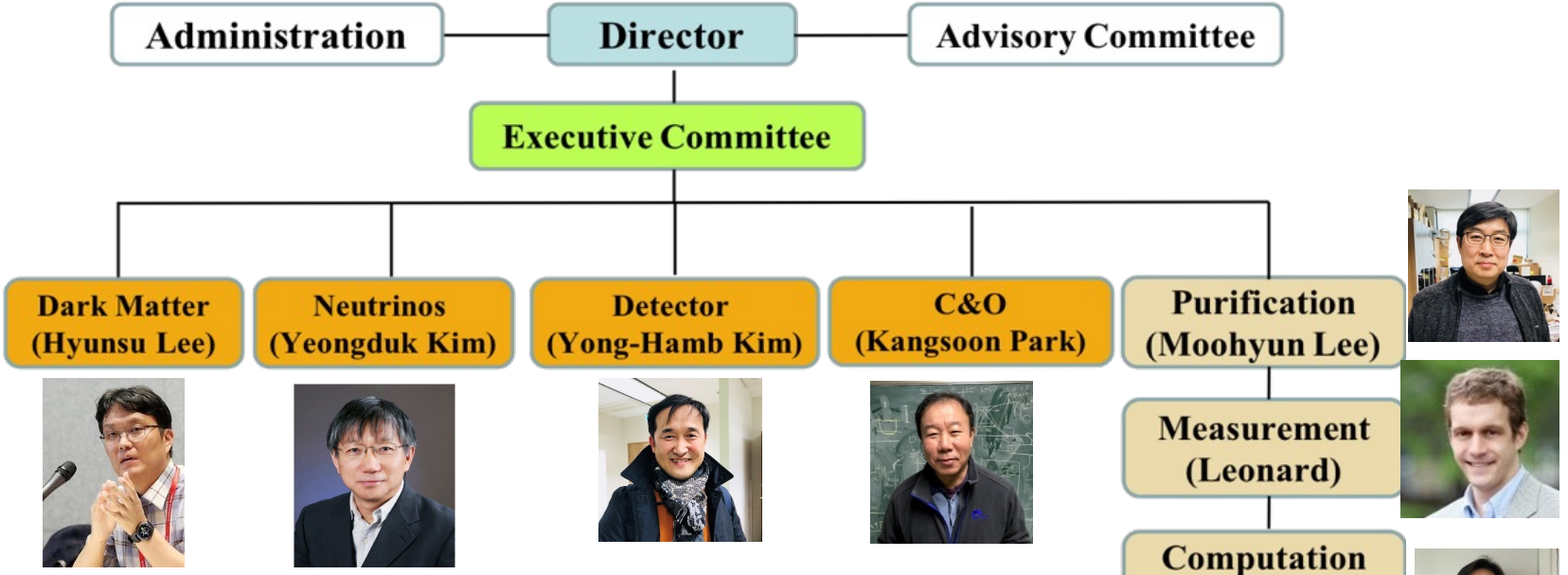
- HQ center of IBS focusing on rare event searches
  - ❖ Dark matter
  - ❖ Neutrinoless double beta decay
  - ❖ Sterile neutrino
  - ❖ Coherent neutrino nucleus scattering

Yangyang underground laboratory (2003~)

+ Yemilab (2022~)

Hanbit nuclear reactor

- ~70 members (40 researchers + 30 students)



Experimental group : COSINE, AMoRE, NEOS, NEON

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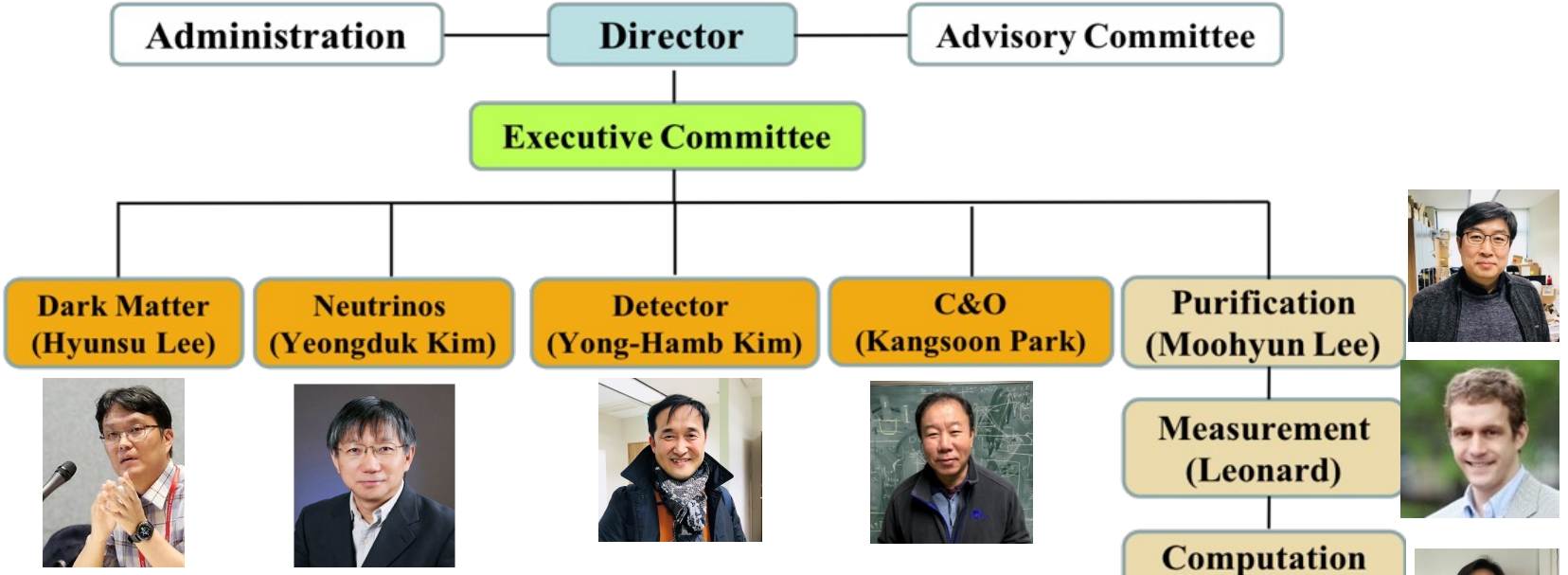


Experimental group : COSINE, AMoRE, NEOS, NEON

WIMP dark matter search with NaI(Tl) detector

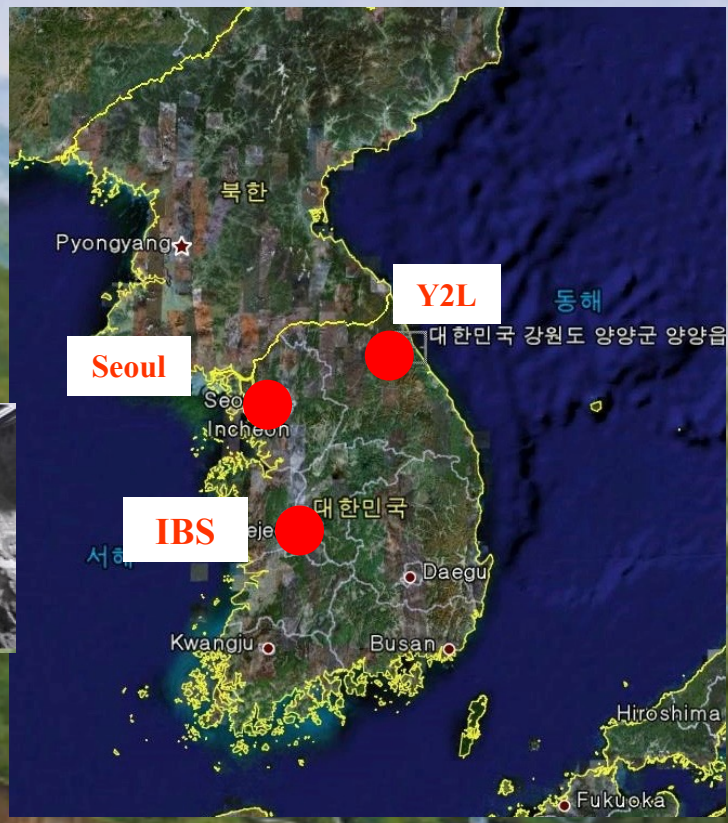
YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

1000m

700m

(Power Plant)



KIMS/COSINE (Dark Matter Search)

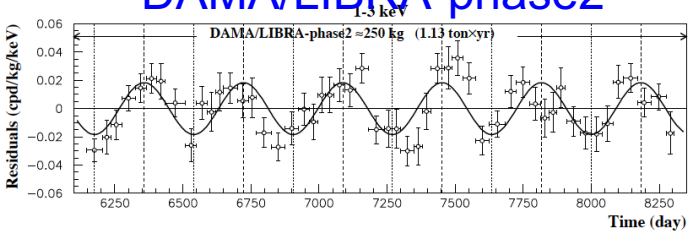
AMoRE (Double Beta Decay Experiment)

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

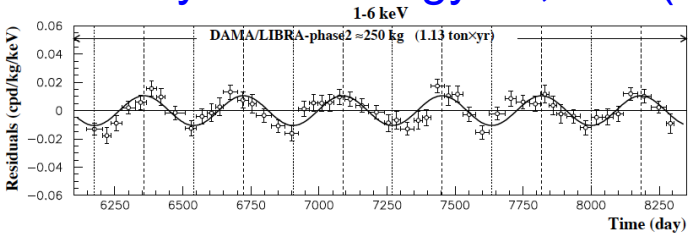
COSINE-100 dark matter search experiment

Goal : Reproducing DAMA/LIBRA with same NaI(Tl) target

DAMA/LIBRA-phase2

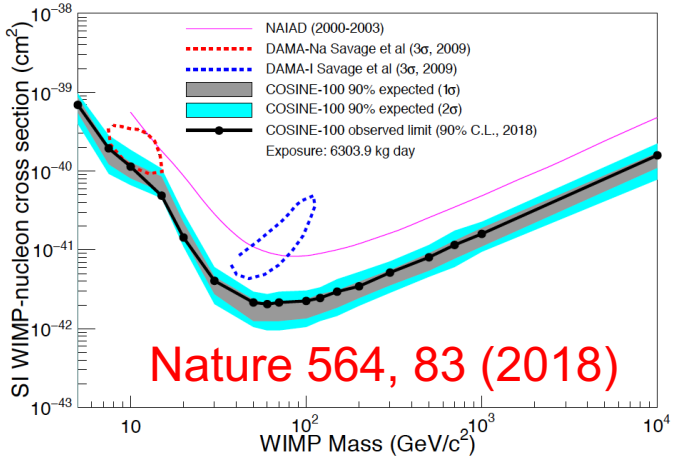


Nucl. Phys. At. Energy 19, 307 (2018)



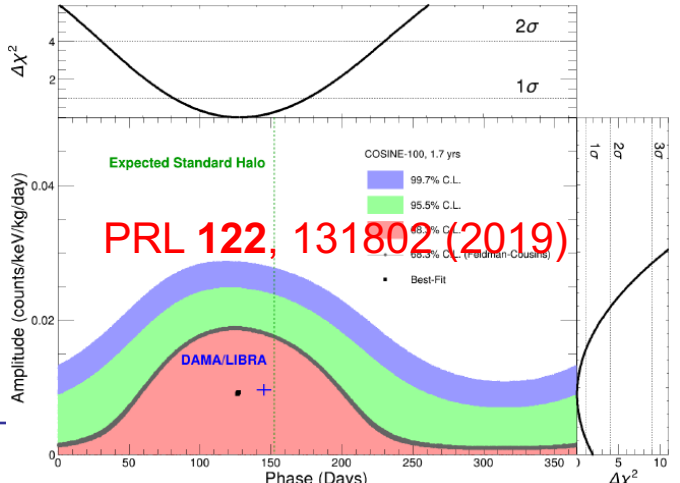
First physics results

Spectral shape fit



Nature 564, 83 (2018)

Annual modulation search

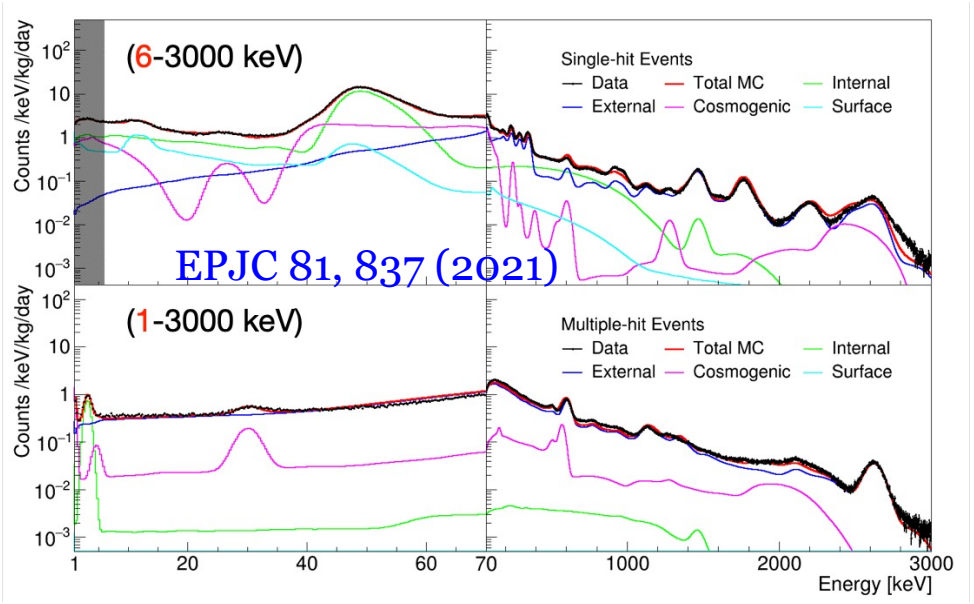


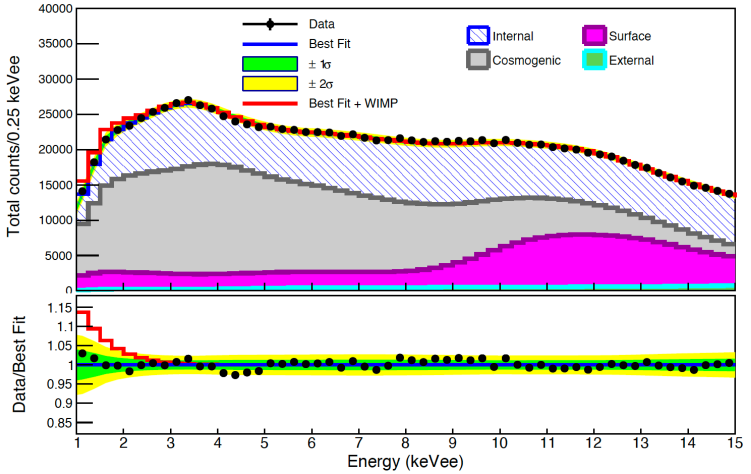
PRL **122**, 131802 (2019)

derground Physics (CUP),

Spectra shape and dark matter searches

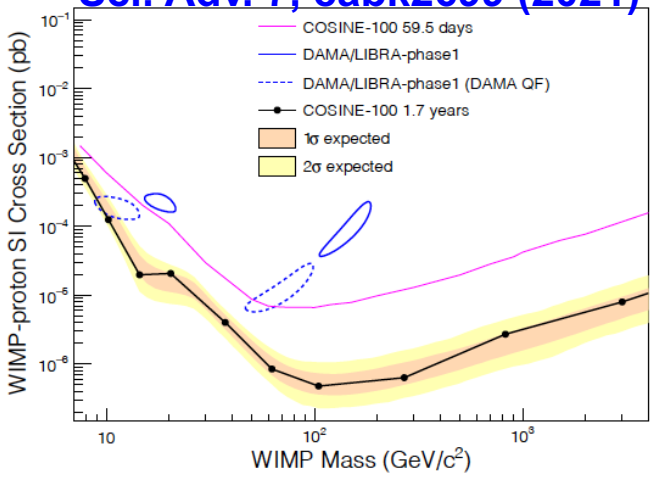
Background modeling





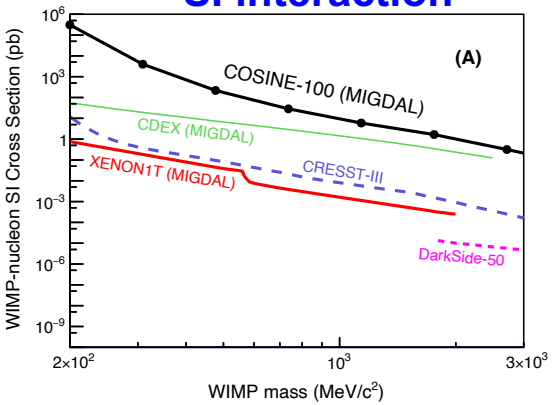
WIMP search result

Sci. Adv. 7, eabk2699 (2021)

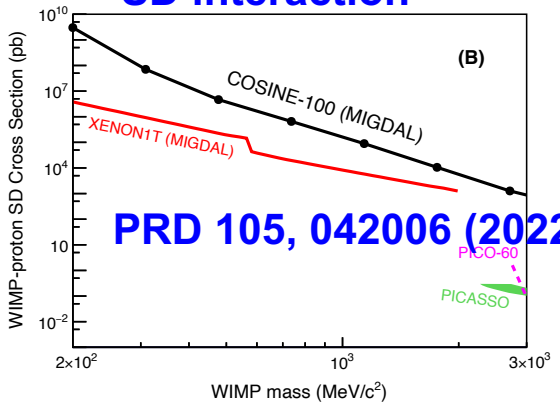


Low-mass search with Migdal effect

SI interaction



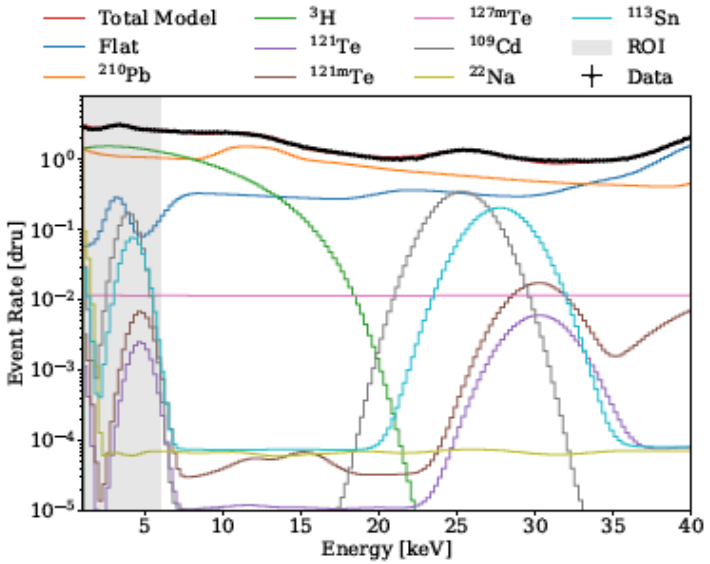
SD interaction



PRD 105, 042006 (2022)

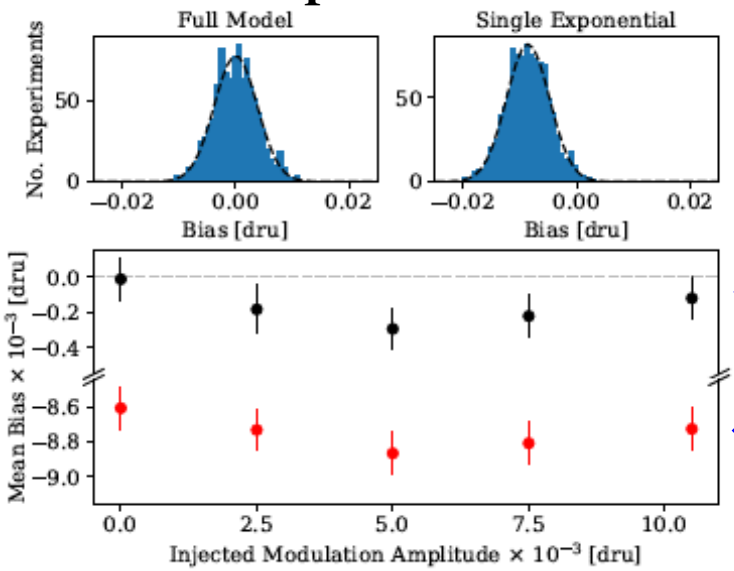
Annual modulation (3 years data)

Time dependent background modeling

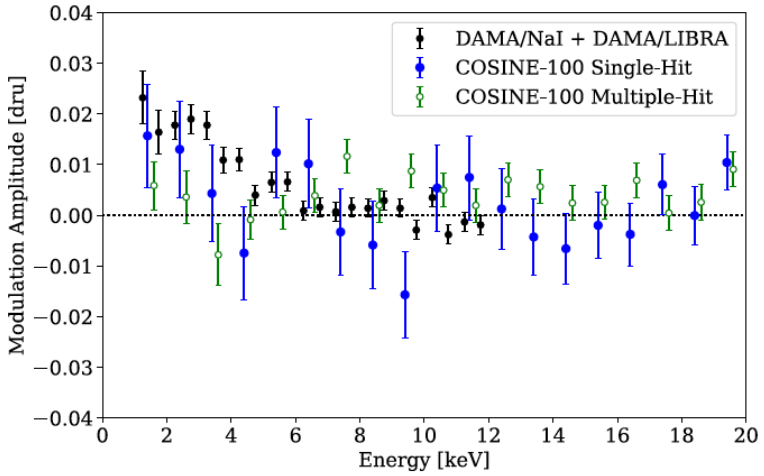


$$R(t) = \sum_i \left[C^i + \sum_j^8 A_j^i e^{-\lambda_j t} \right] + S_m \cos\left(\frac{2\pi(t - t_0)}{T}\right)$$

Pseudo experiment



PRD 106, 052005 (2022)



Precise understanding of the time-dependent backgrounds is crucial for the annual modulation searches

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

DAMA/LIBRA's method

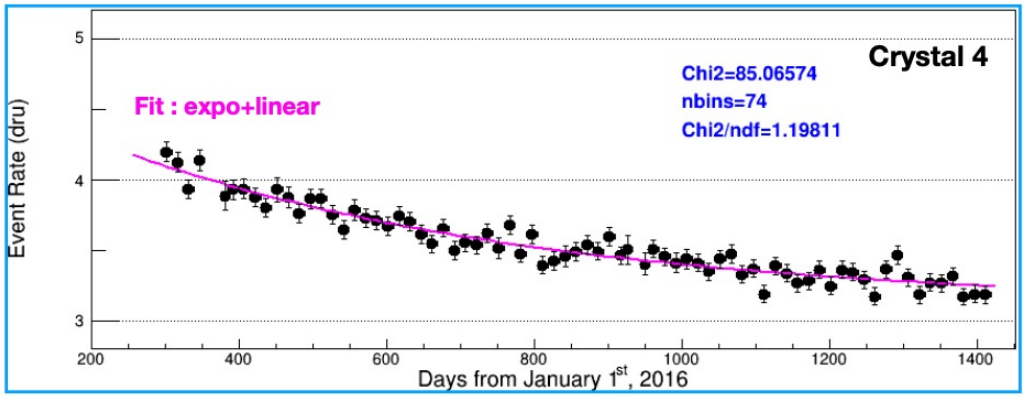
- Event selection (single parameter)
- No liquid scintillator veto
- No Muon veto
- 600 ns integration window
- Time-dependent background model
  - ❖ Yearly average to obtain residual rate

JHEP 20, 137 (2020)
Idea of time-dependent background as an explanation of DAMA signals

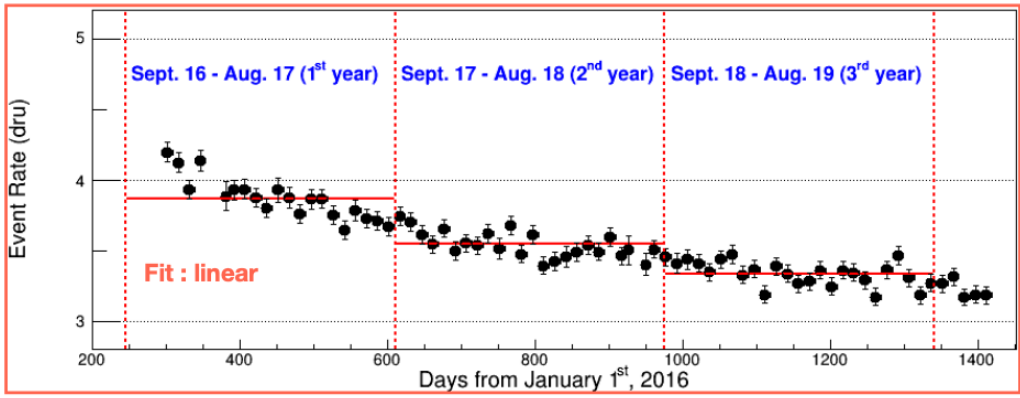
DAMA/LIBRA claimed that there is no time-dependent background in their data

Applying DAMA/LIBRA's method to the COSINE-100 data

Single exponential model (reference)

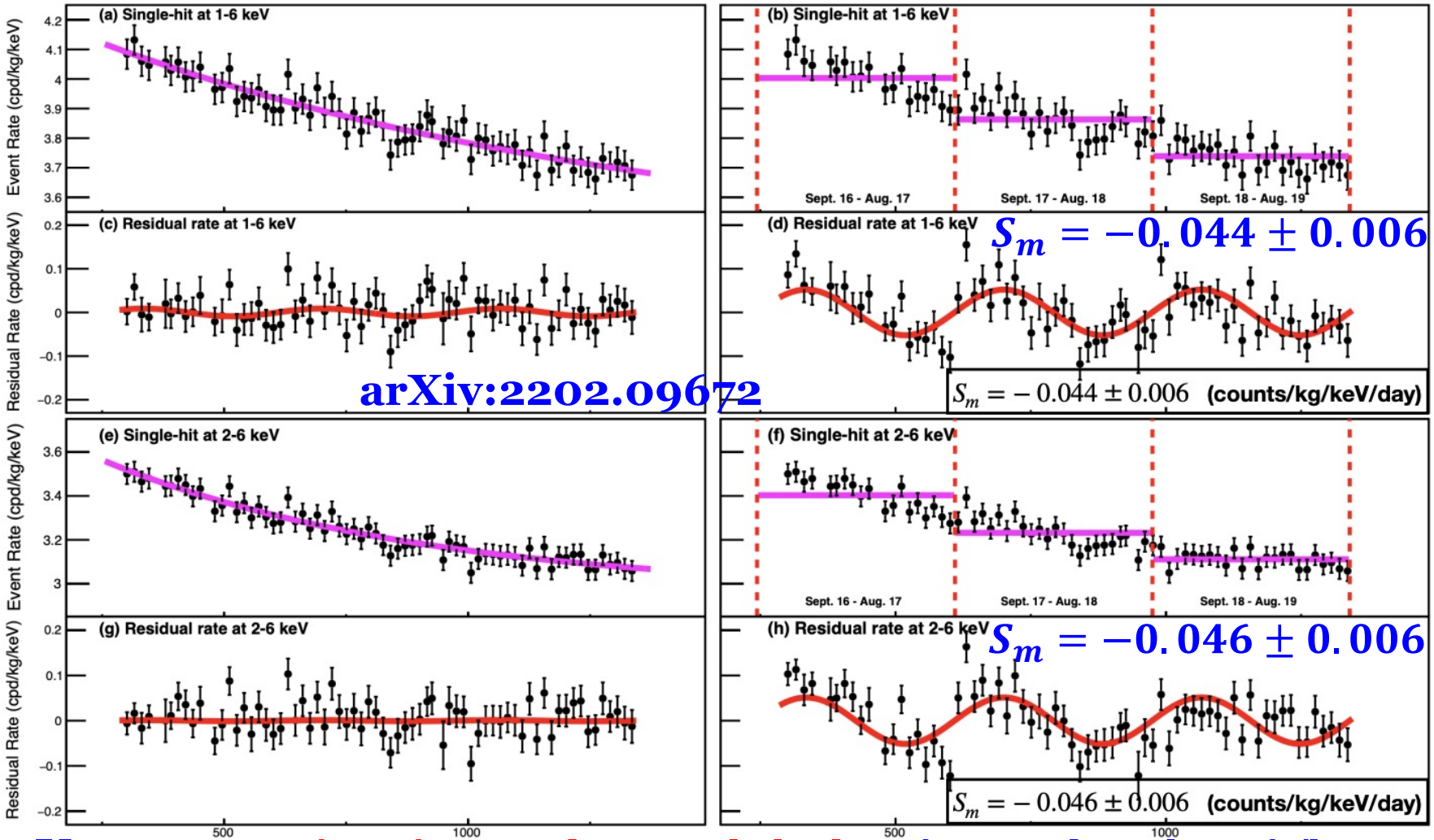


DAMA/LIBRA's method



Results from the COSINE-100 data

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

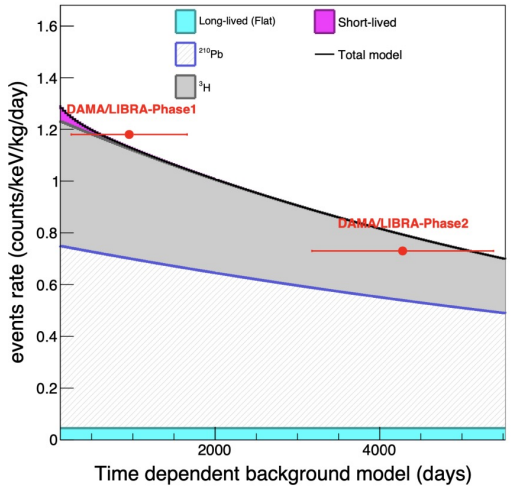


Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

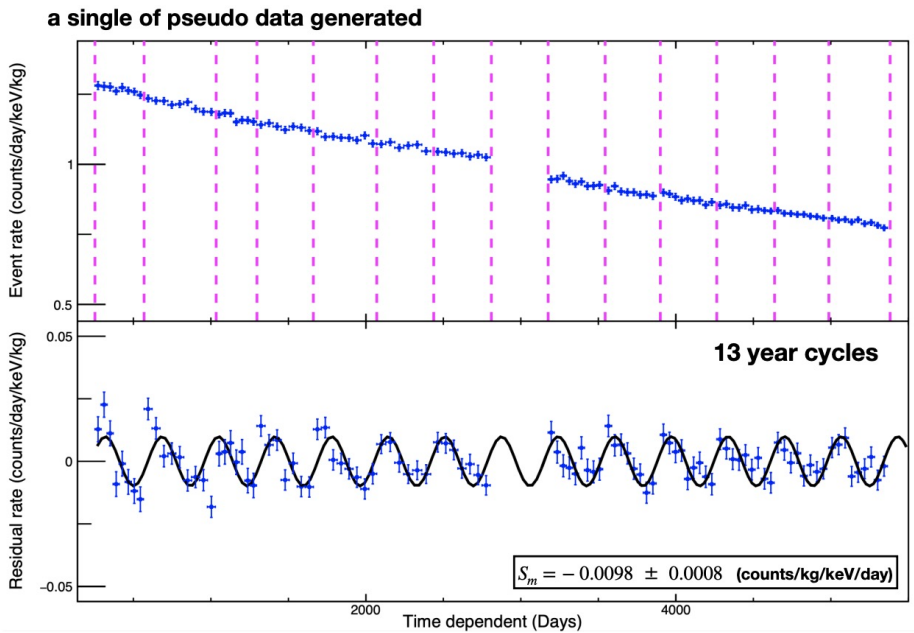
Pseudo data for the DAMA/LIBRA

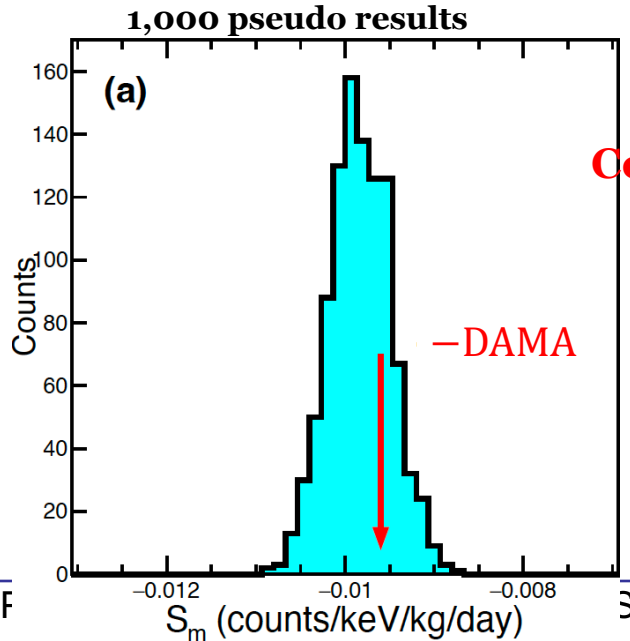
Assuming same background composition between COSINE-100 and DAMA

Component	Scaled at dru	Half life (d)
^{210}Pb	0.687	8140
^{238}U, ^{232}Th, ^{40}K (Long lived)	0.043	>10^{10}
^{3}H	0.474	4494
^{113}Sn	0.055	115.1
^{109}Cd	0.025	462
^{121m}Te	0.004	164.2
^{127m}Te	0.011	106.1
Total	1.3	



arXiv:2202.09672



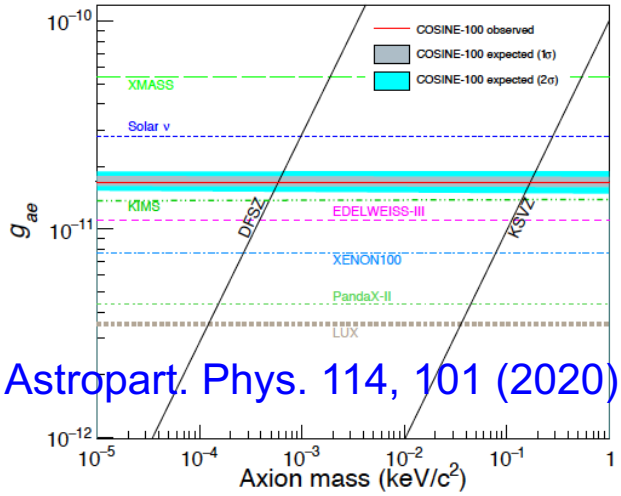


Consistent modulation amplitude

Opposite phase

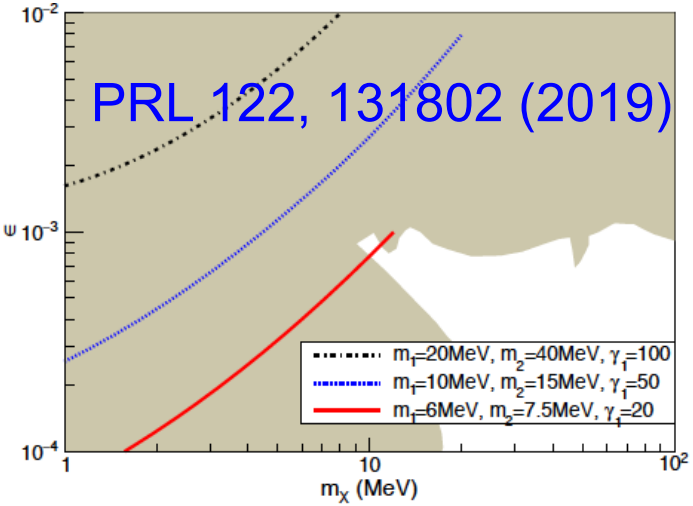
Recent COSINE-100 results

Solar Axion

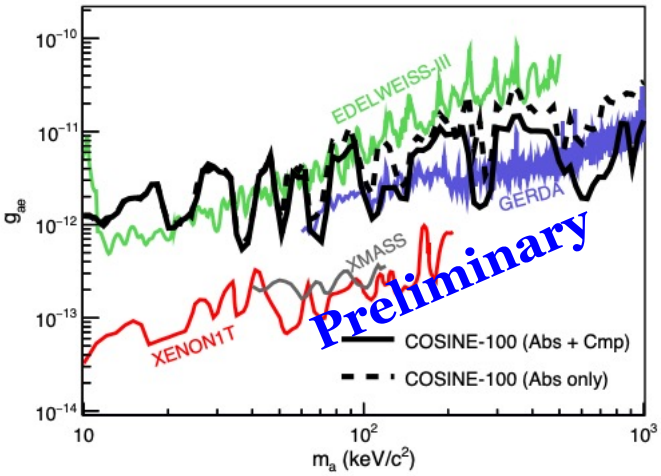


Astropart. Phys. 114, 101 (2020)

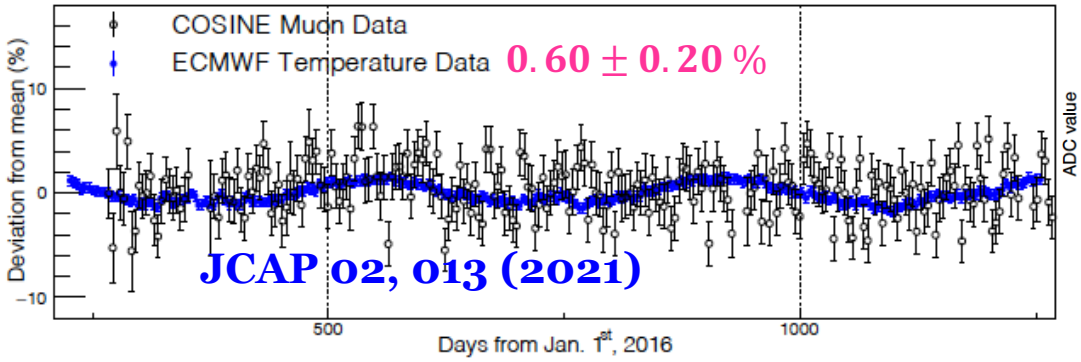
Inelastic boosted dark matter



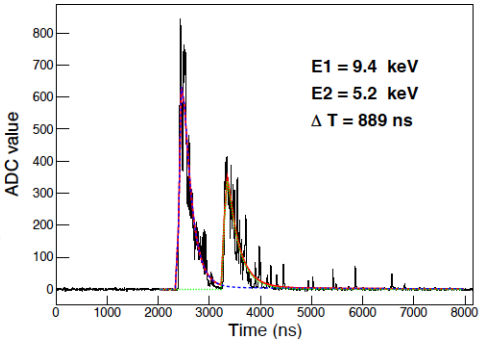
Bosonic SuperWIMP



Annual modulation of muon rate



Identification isomer state of ^{228}Ac



EPJC 81, 746 (2021)

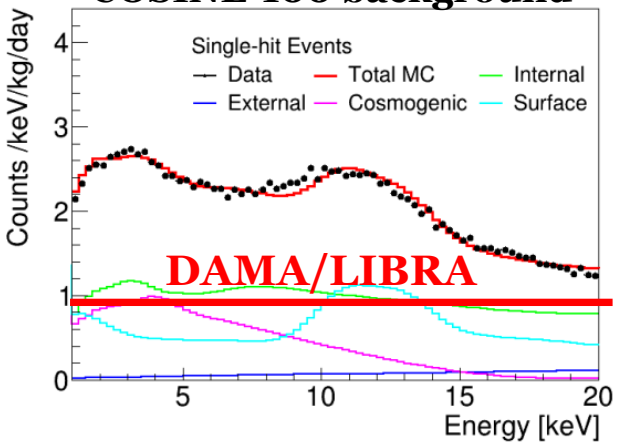
- Dark photon
- Diurnal modulation
- Boosted dark matter
- Pauli exclusion
- Inelastic dark matter
- ....

Low-background NaI(Tl) developments

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

1 dru

COSINE-100 background



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

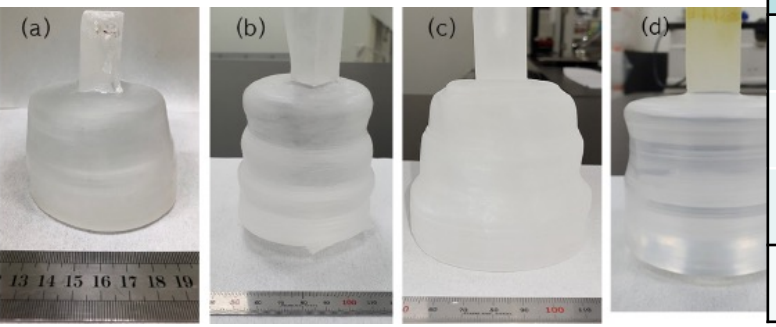
Purification factory ~ 70 kg powder load

Test grower ~ 1kg ingot

Full size grower ~ 100 kg ingot

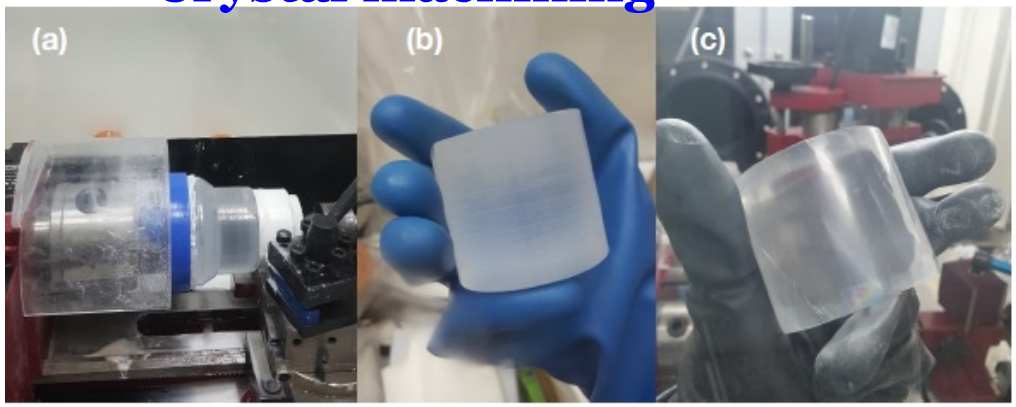
Our grown crystals

Crystal ingots



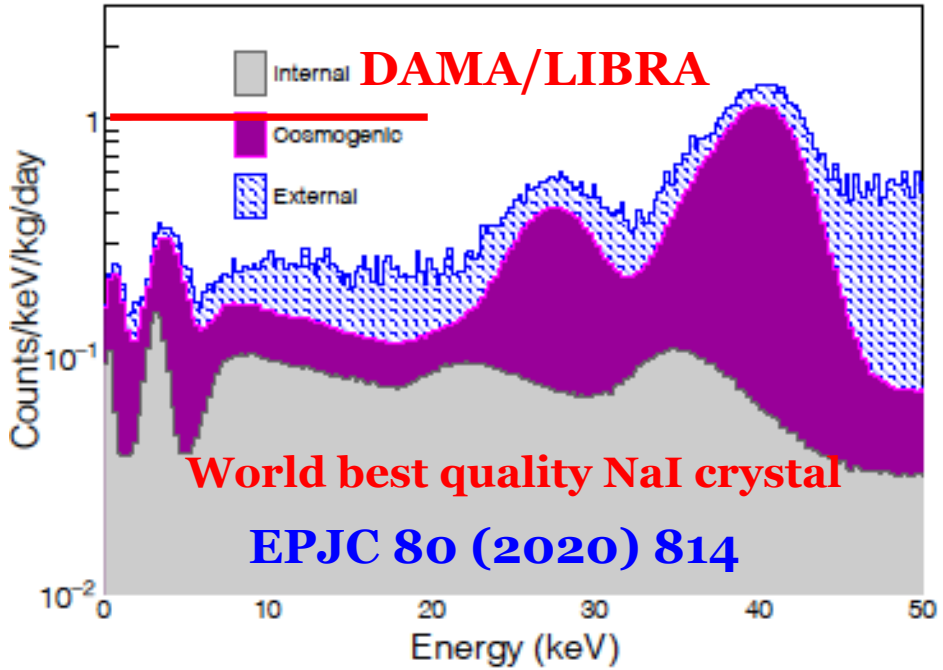
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

Expected background

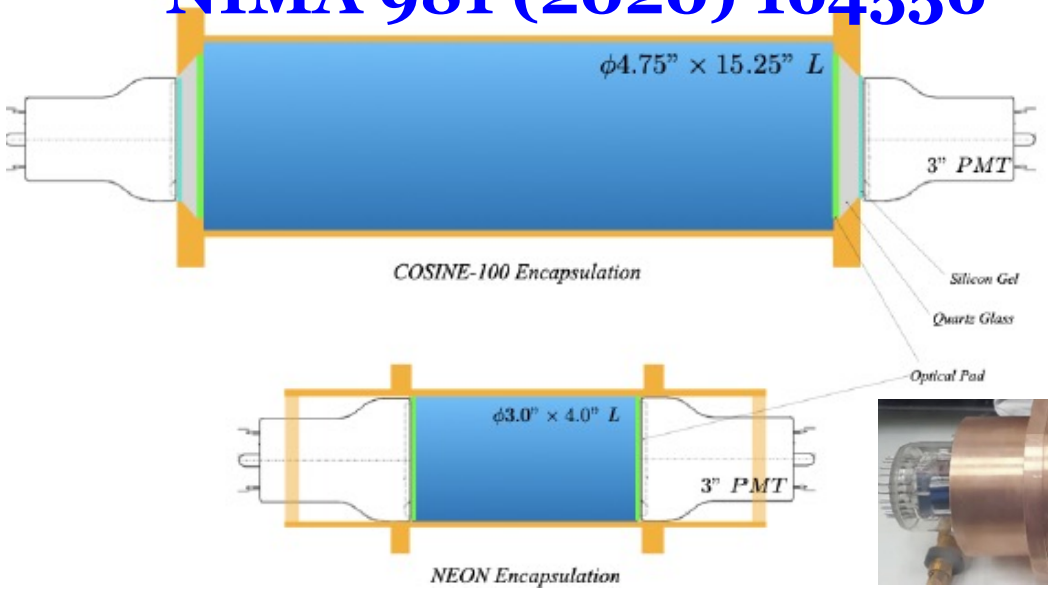


A proof of principle for low background NaI

Large crystal growing is going on

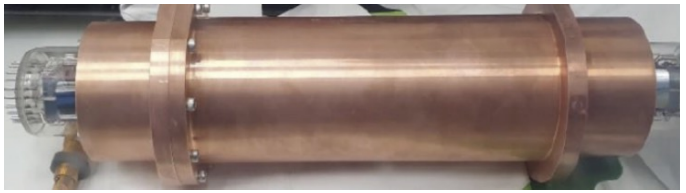
Novel technique of crystal encapsulation

NIMA 981 (2020) 164556



15 NPE/keV

(NPE=number of photoelectrons)



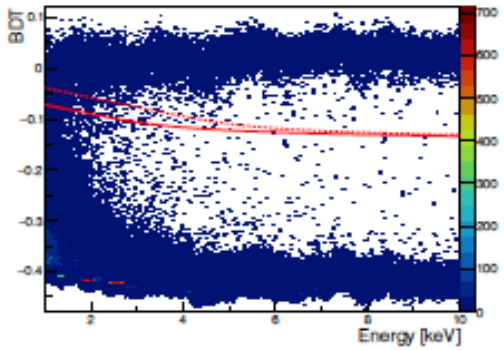
~23 NPE/keV

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

Low energy threshold of NaI(Tl)

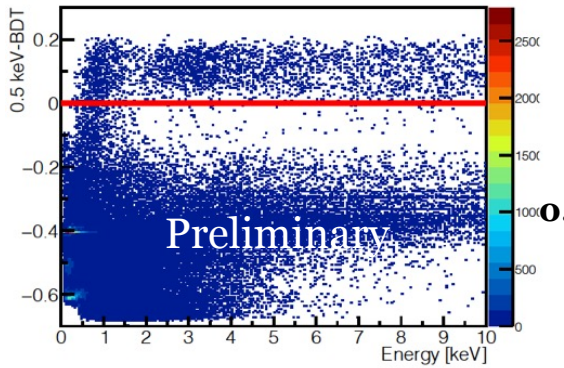
- Two-fold trigger is applied (trigger threshold : 2 NPE)
- PMT-induced noise makes difficulty to use low energy events
- 1 keV (15 NPE) threshold was achieved with multivariable technique
- 0.5 keV (7 NPE) threshold can be achieved with improved BDT

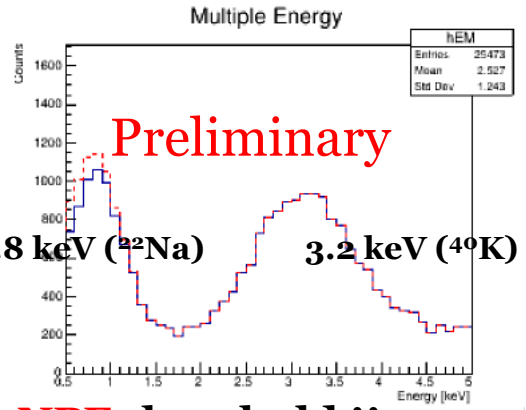
WIMP search data



Astropart. Phys 130, 102581 (2021)

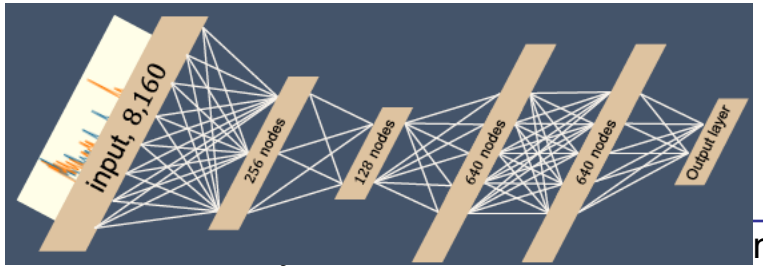
Categorizing noise type and develop new likelihood parameters

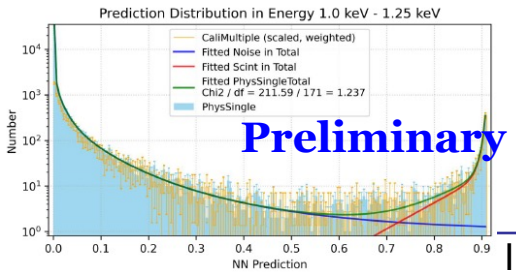




7 NPE threshold !!

Initiate Deep Machine learning

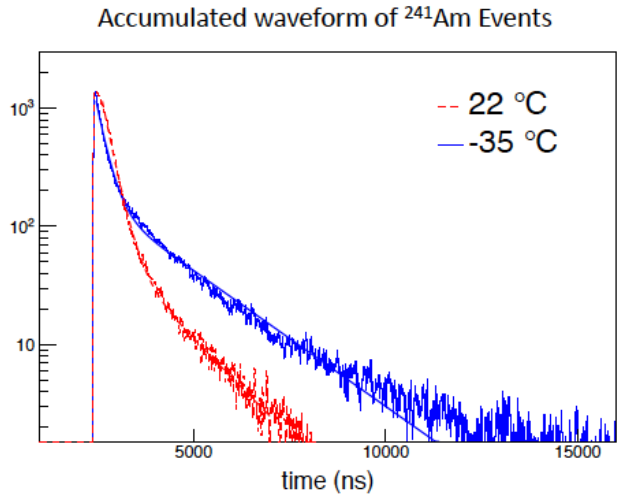




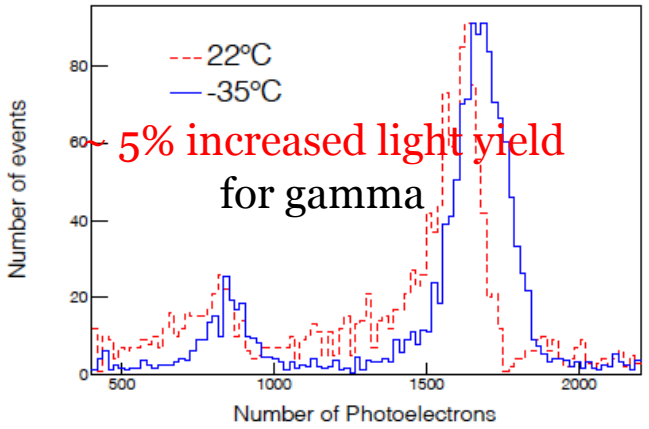
Final goal for ≤ 5NPE threshold!!

Low temperature (-30°C) response

PMT measurement

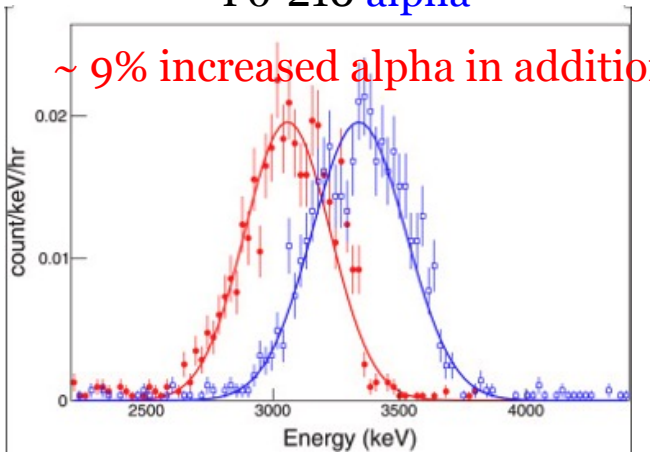


Am-241 measurement



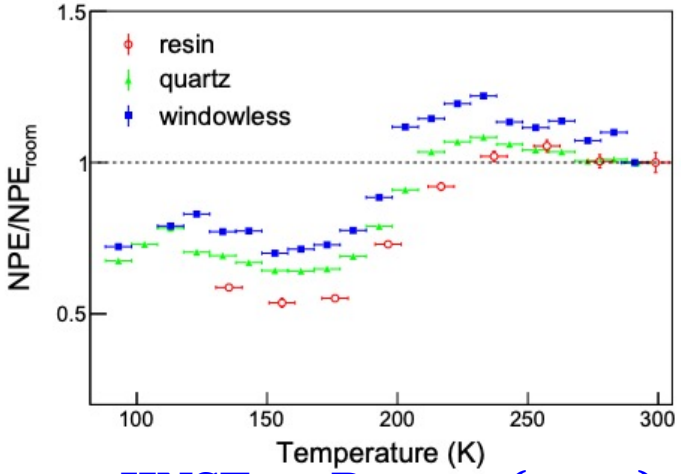
Po-210 alpha

~ 9% increased alpha in addition



Astropart. Phys. 141, 102709 (2022)

SiPM measurement



~ 5-15% increased light yield at -30°C

COSINE-200 can be operated at -30°C

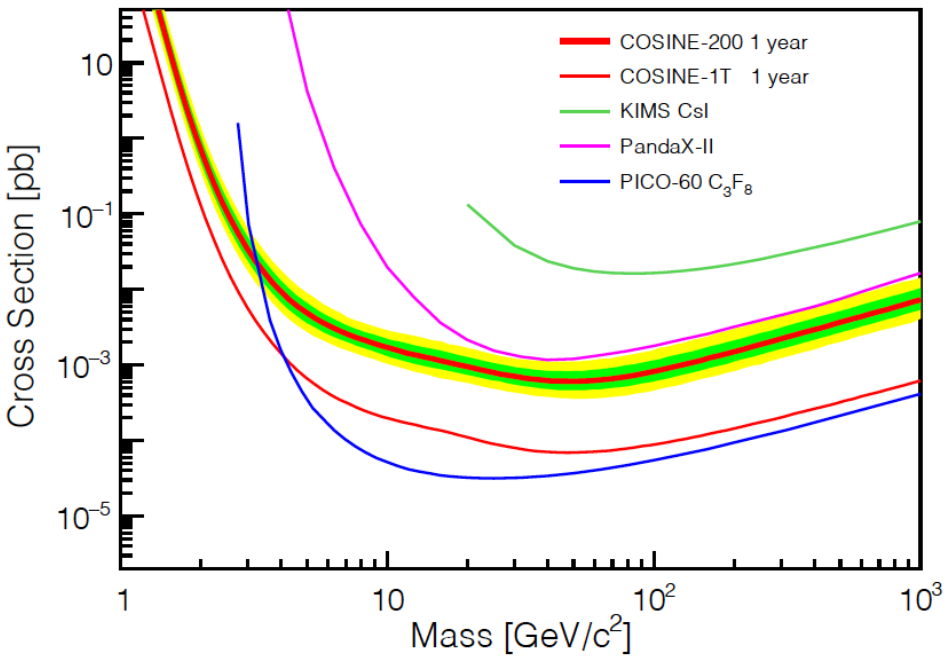
JINST 17, P02027 (2022)

COSINE-200 for low-mass dark matter

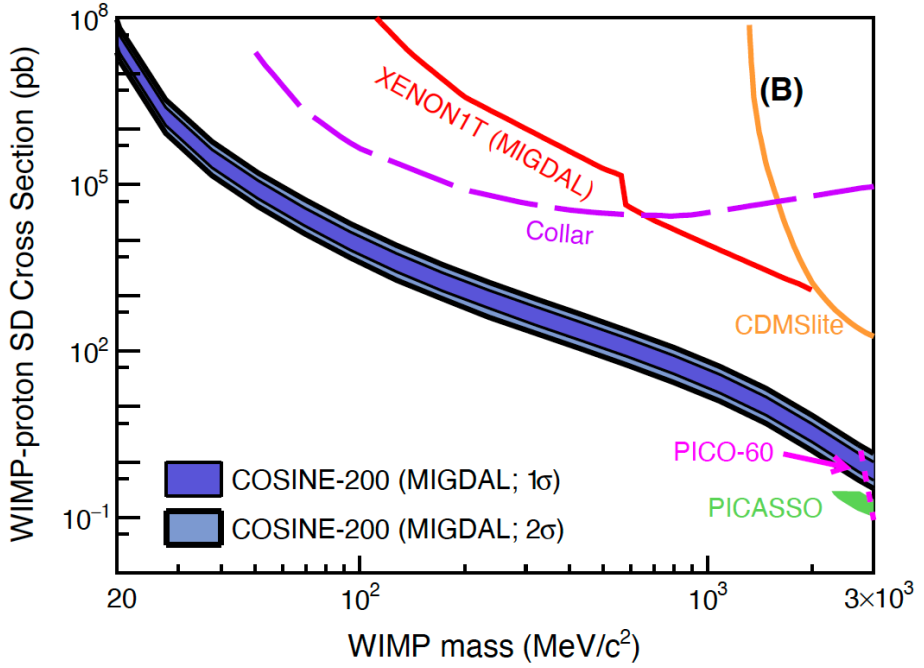
- Unambiguous conclusion on the DAMA/LIBRA's

COSINE-200 sensitivities

WIMP-proton spin-dependent

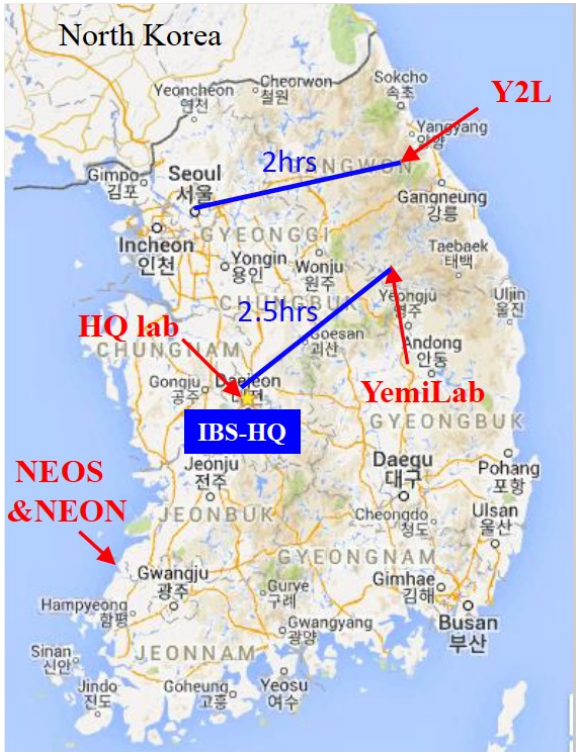


Low mass search with Migdal

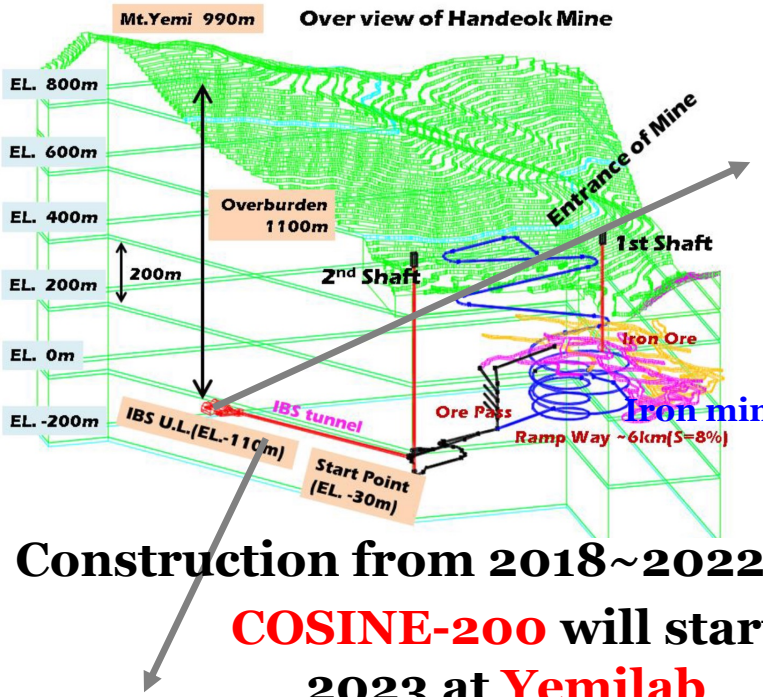


- A world best sensitive detector for low-mass WIMP-proton spin-dependent interaction
- Feasibility test of the COSINE-1T experiment

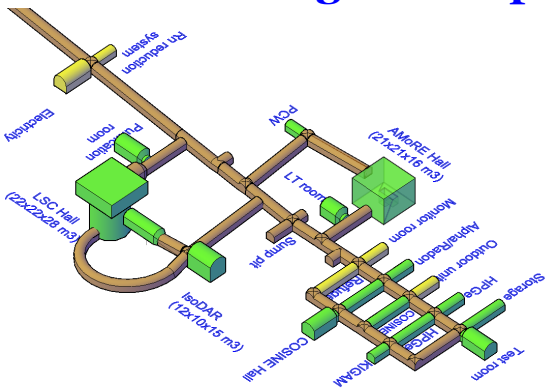
“Yemilab” New underground lab in Korea (2022~)



~ 1100 m deep underground

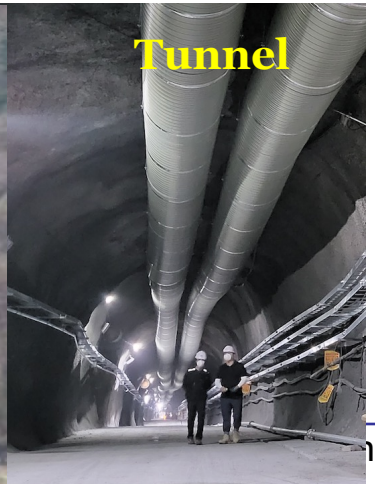


~ 2000m² underground space



Construction from 2018~2022

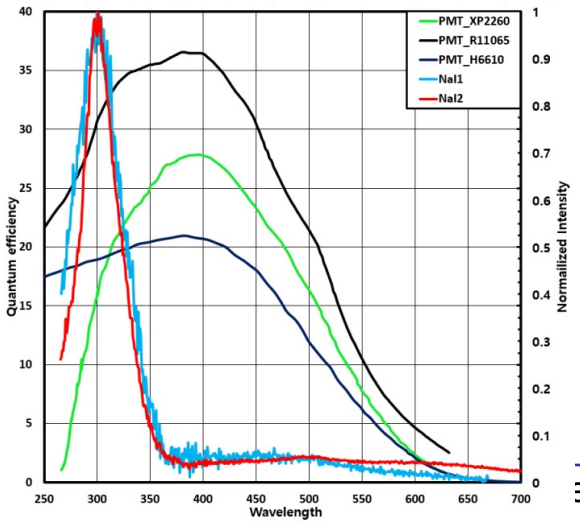
COSINE-200 will start 2023 at Yemilab



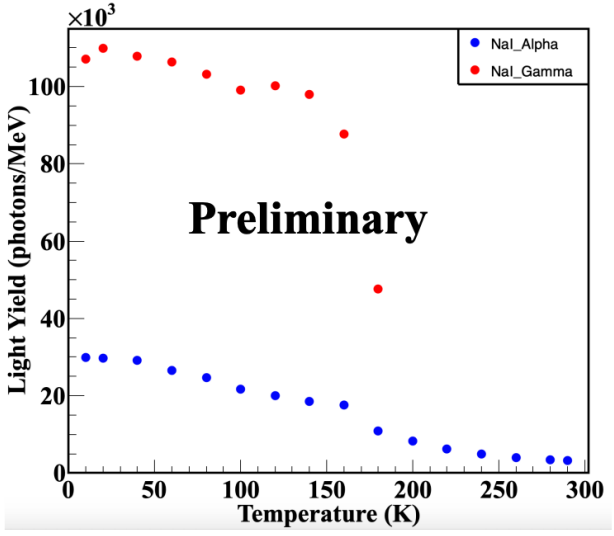
Undoped CsI and NaI with SiPM

- High measured light yield at 77 K from undoped CsI+SiPM
  - ❖ 43 NPE/keV (EPJC 82, 344 (2022)) reported by D. Keyu *et al.*
- Reported light outputs of undoped NaI and CsI are pretty similar
  - ❖ As high as 120,000 NPE/MeV @ 77 K (NaI(Tl) ~ 40,000, CsI(Tl) ~ 50,000)
- We have **low-background** NaI and CsI crystal technique
  - ❖ COSINE and KIMS experiments
- Grew small undoped NaI and CsI crystals with purified powder

Emission spectrum and NaI



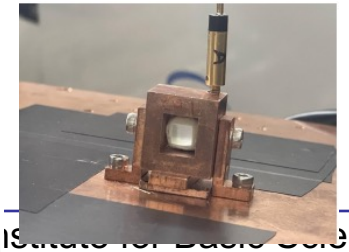
Absolute light output from NaI

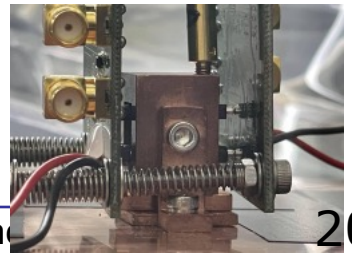


Emitted light from NaI :

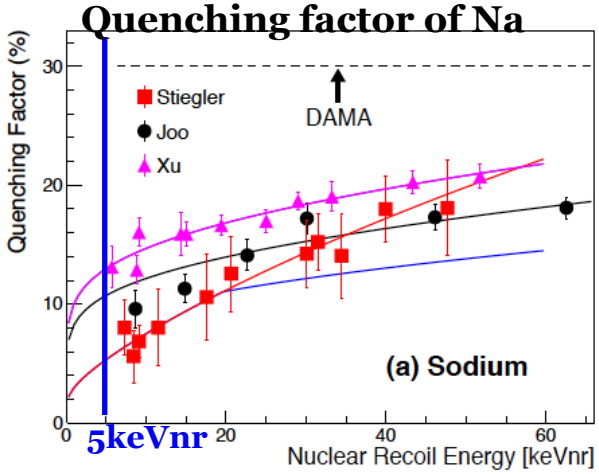
~100,000 NPE/MeV @ 77K

This crystal will be tested with SiPM





Low-energy nuclear recoil calibration

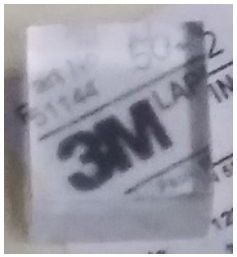


- No measurement below 5keVnr (~ 0.5 keVee)
  - PMT-induced noise
- Most of measurements were done with ~15 NPE/keVee crystals

Company encapsulation

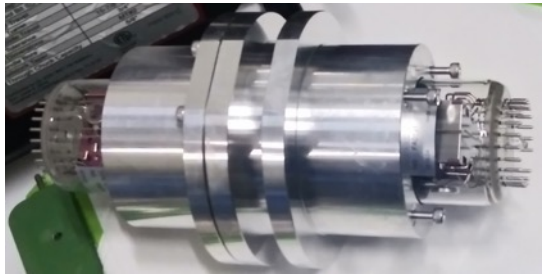
16 NPE/keV

Polishing

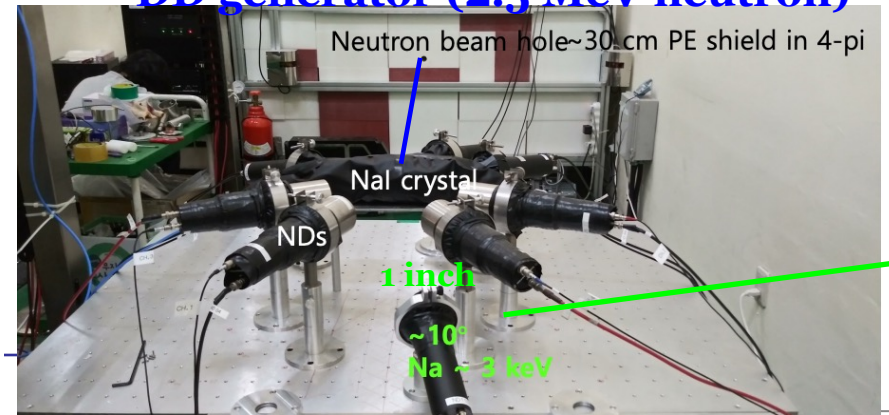


Encapsulation

25 NPE/keV

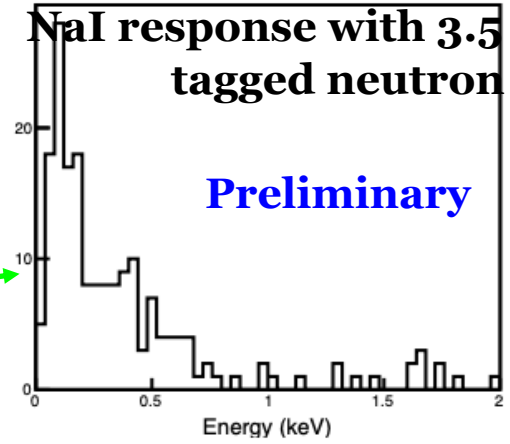


DD generator (2.5 MeV neutron)

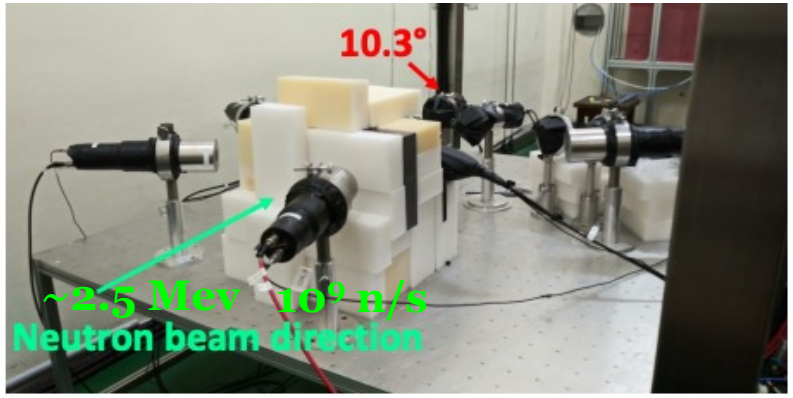


NaI response with 3.5 keVnr tagged neutron

Preliminary



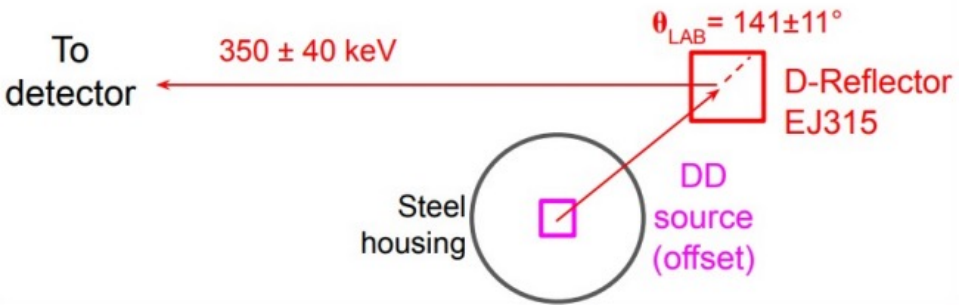
Low energy neutron calibration



- 2.5 MeV is too high for low-energy nuclear recoil calibration of Na
  - Need to put neutron tagging detector in collinear direction (<10º)
  - Small detector and small solid angle

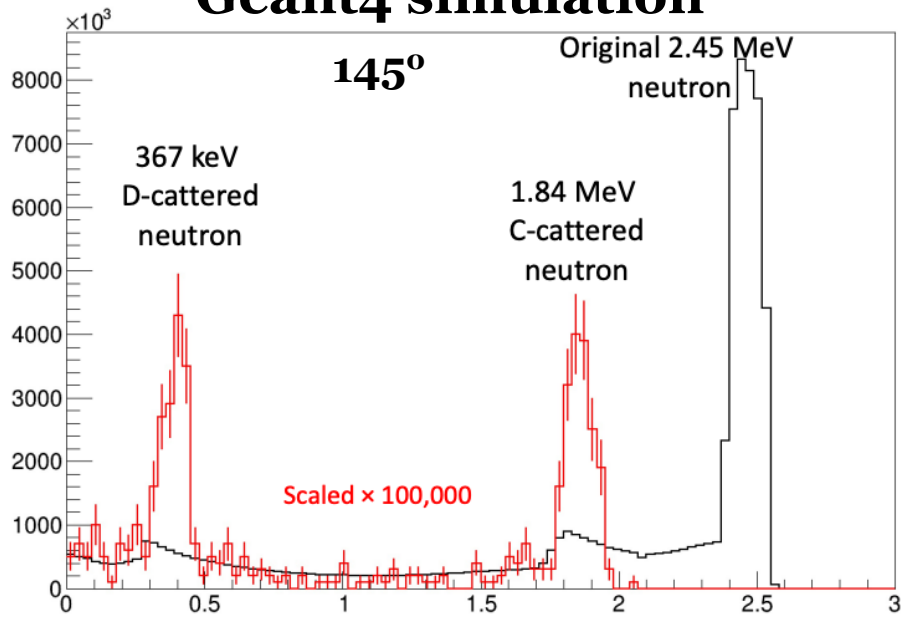
- 2.5 MeV neutron scattered off deuteron make O(300 keV) neutron

J.R. Verbus *et al.*, NIMA 851, 68 (2017)



We plan to install DD-generator and D-reflector in IBS HQ

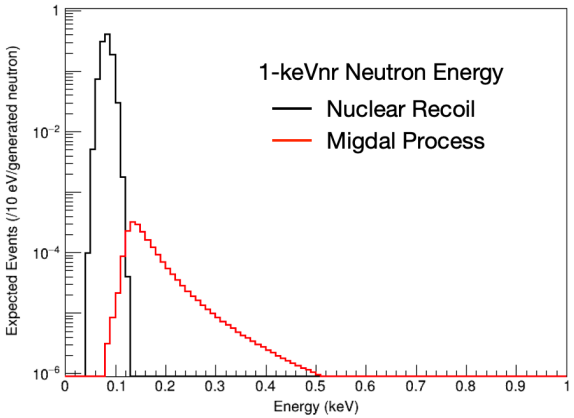
Geant4 simulation

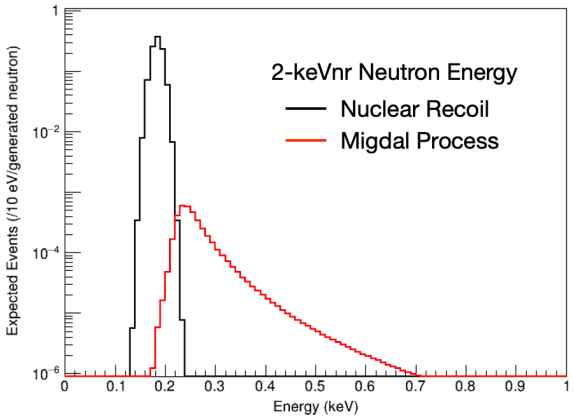


Neutron flux ~ 1/60 (~600 Hz)

Measurement of Migdal process from Na recoil ?

- Midgal process can be separated from nuclear recoil in case of 1-2 keVnr Na recoil

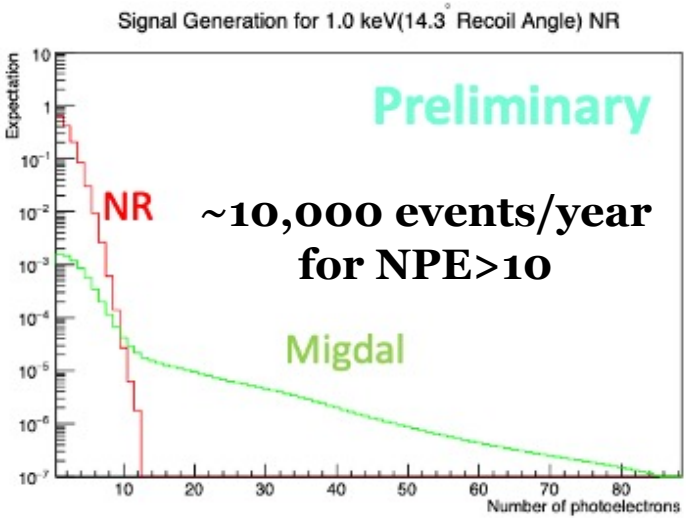




No resolution

- If we cover all solid angle of 14~20°

Poisson statistics

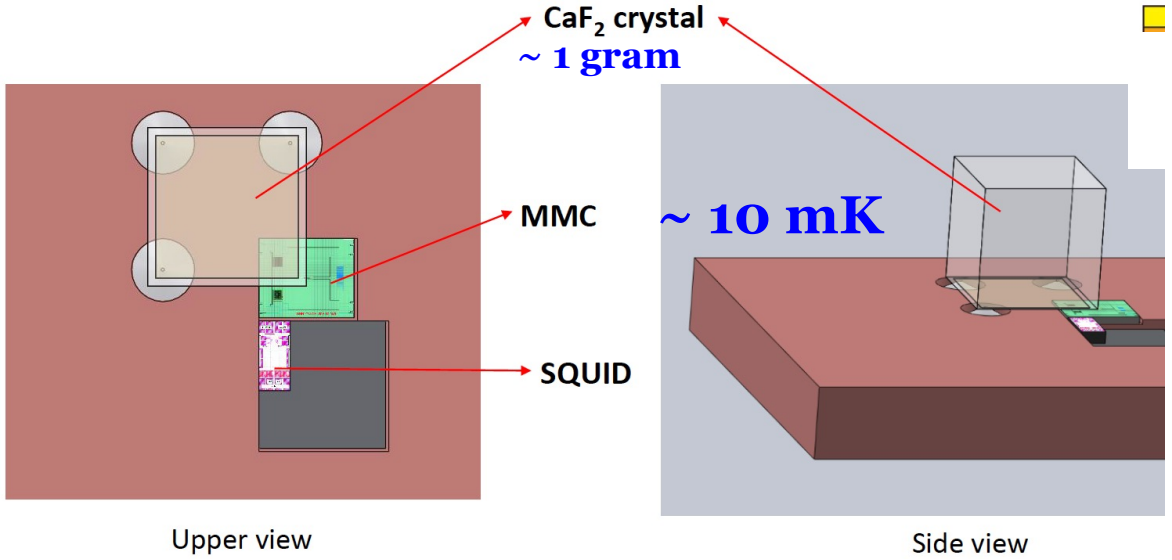


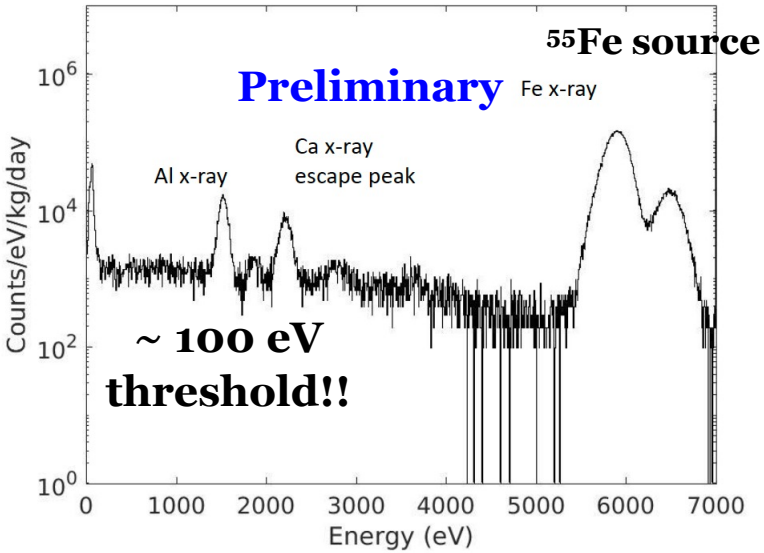
Assuming 25 NPE/keV and 2 cm x 2cm crystal

Feasibility will be tested with a few tagging detector

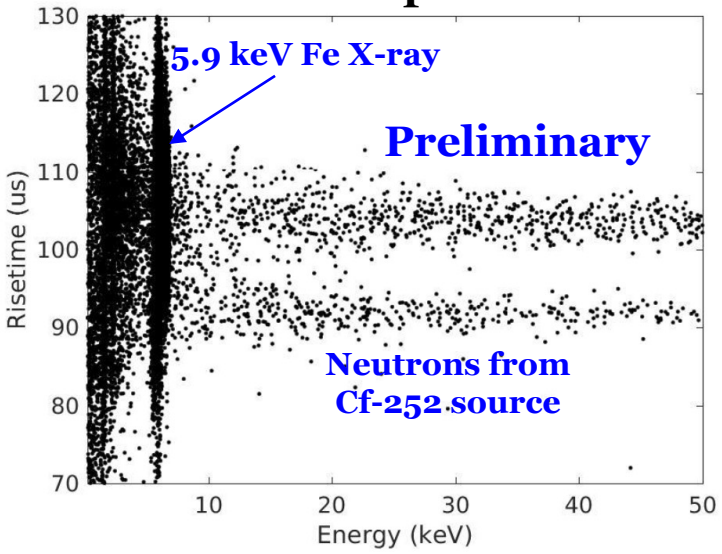
Low temperature bolometer for low-mass dark matter

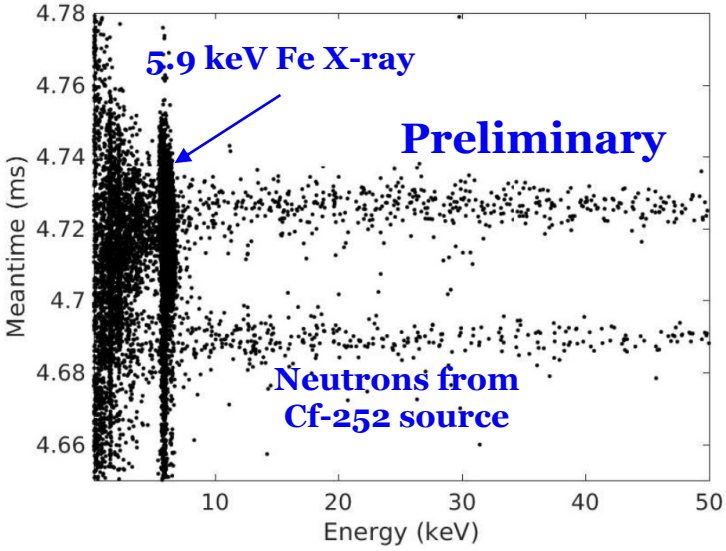
- CaF_2 crystal with MMC (Metallic magnetic calorimeter)





Pulse shape discrimination of the nuclear recoil events





Summary & Conclusion

- Main activity of IBS-CUP on dark matter is to reproducing DAMA/LIBRA with NaI(Tl) crystals
- Eventually, low-background and high light yield NaI(Tl) crystals techniques are developed by ourself
- NaI(Tl) detectors have a great potential for low-mass dark matter
  - Spin-dependent WIMP-proton interaction
  - Migdal process
- R&D of cryogenic bolometer technology for low-mass dark matter is started

The 1st Yemilab Workshop

Oct 15 – 18, 2022
High-1 Resort
Asia/Seoul timezone

https://indico.ibs.re.kr/event/531

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Oct 15 – 18

Jeongson, Korea

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- Timetable
- Registration
- Participant List
- Venue
- Accommodation
- LOC
- Covid Situation
- Visa & Entrance to Korea

Contact

sunny.seo@ibs.re.kr

Welcome to the 1st Yemilab Workshop!

Yemilab is the first deep underground lab dedicated to science in Korea and its construction was successfully finished recently. To celebrate the kick-off of the Yemilab, we are organizing this workshop and cordially invite world experts in underground physics. New ideas, technologies, or perspectives will be shared in this workshop.

Anyone who is curious or excited about Yemilab is very welcome to join us!

No registration fee.

Free meals for all in-person participants who register **by Sept. 24 (F)**.

- 10/15 (Sat): Arrival, Registration, Reception
- 10/16 (Sun): Yemilab Tour, Banquet
- 10/17(M)-18(Tu): Physics Workshop