NaI detector for dark matter and neutrino searches

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Institute for Basic Science
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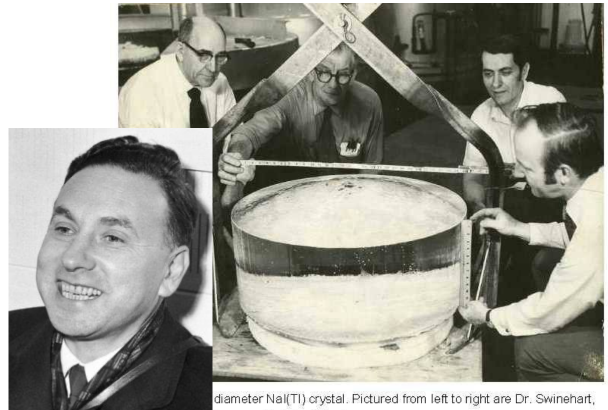
IBS and KMI Joint Workshop, August 3-5 2022

NaI(Tl) crystal 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



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

Discovered by Robert Hofstadter in 1948

Properties	From Saint-Gobain
Density [g/cm³]	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 dark matter searches

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

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 47, NUMBER 2 FEBRUARY 1993

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

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

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 dark matter searches

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⊞ Show more

DAMA/LIBRA

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PICO-LON

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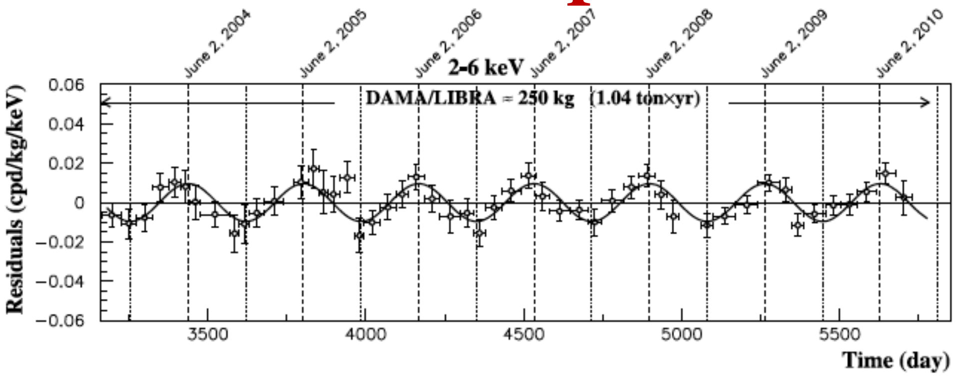
COSINE

Annual modulation signal from DAMA/LIBRA

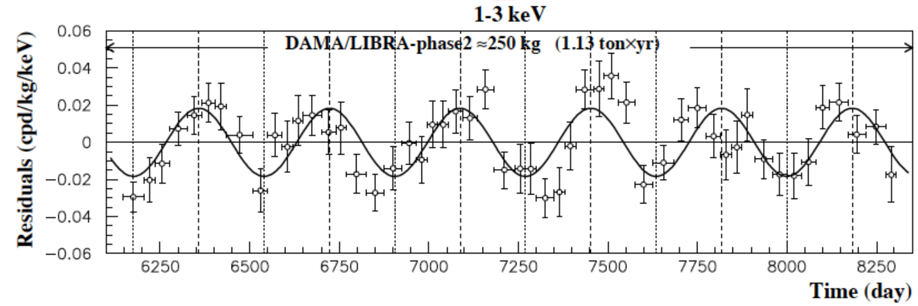
Phase1 experiment



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

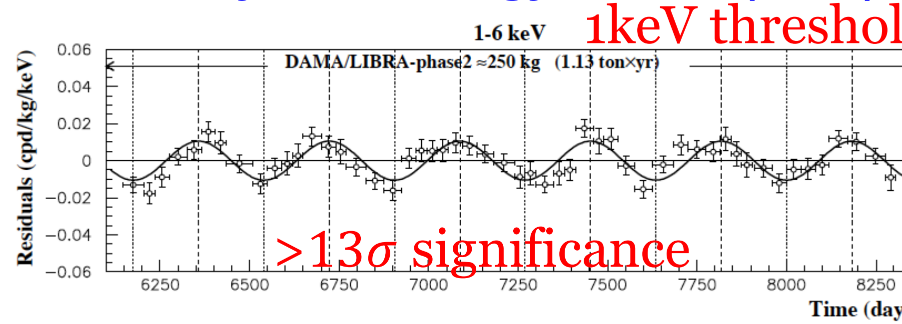
2keV threshold

Phase2 experiment



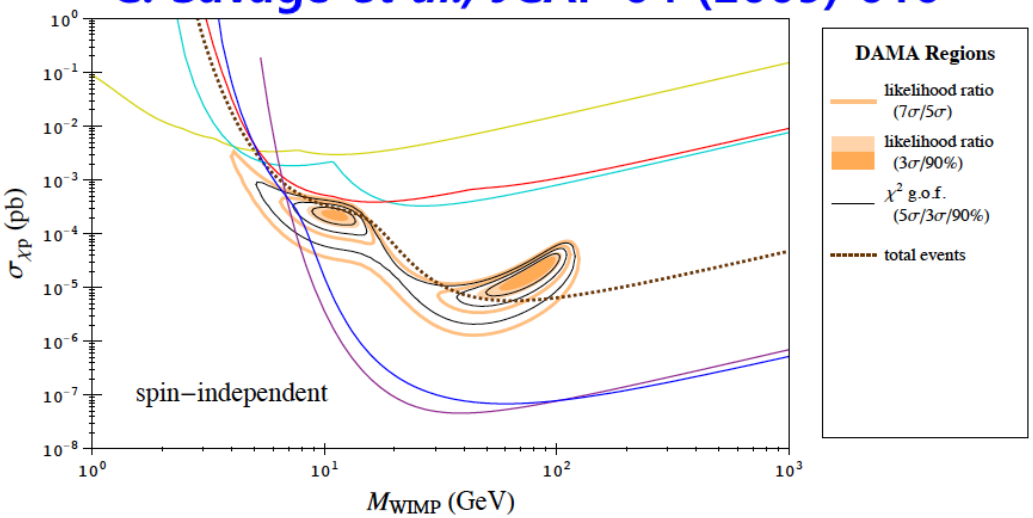
Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold



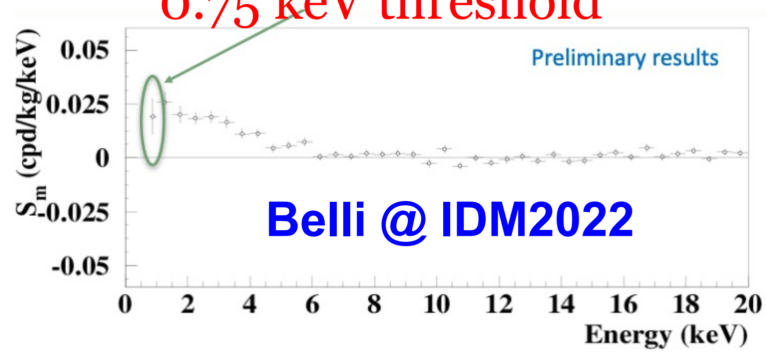
>13σ significance

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



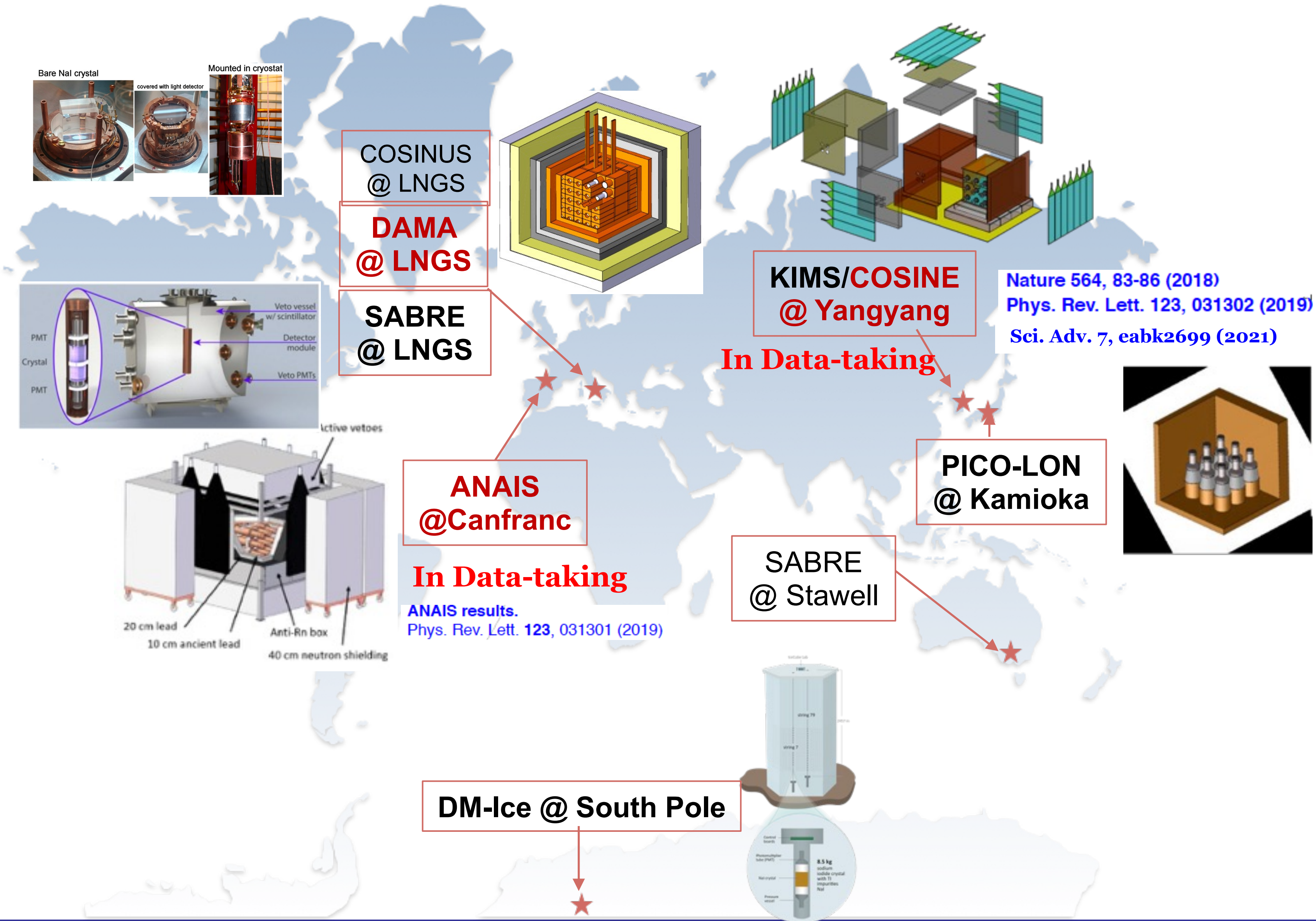
Modulation Amplitude

0.75 keV threshold

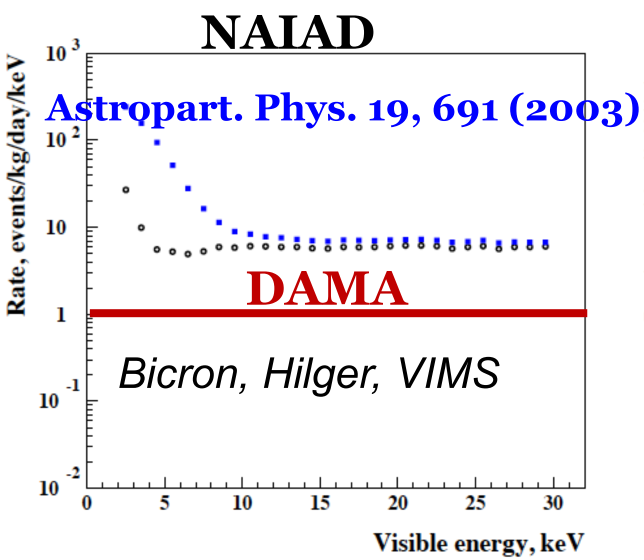


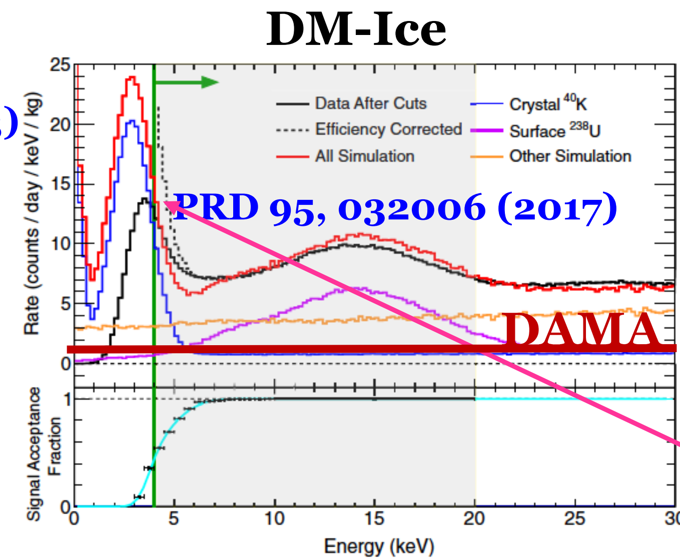
Belli @ IDM2022

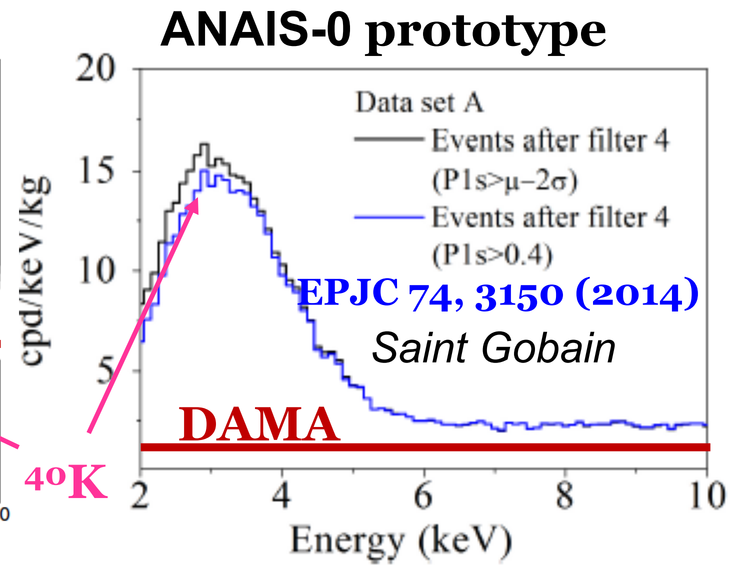
Global NaI(Tl) efforts



Why it is so hard to reproduce DAMA?





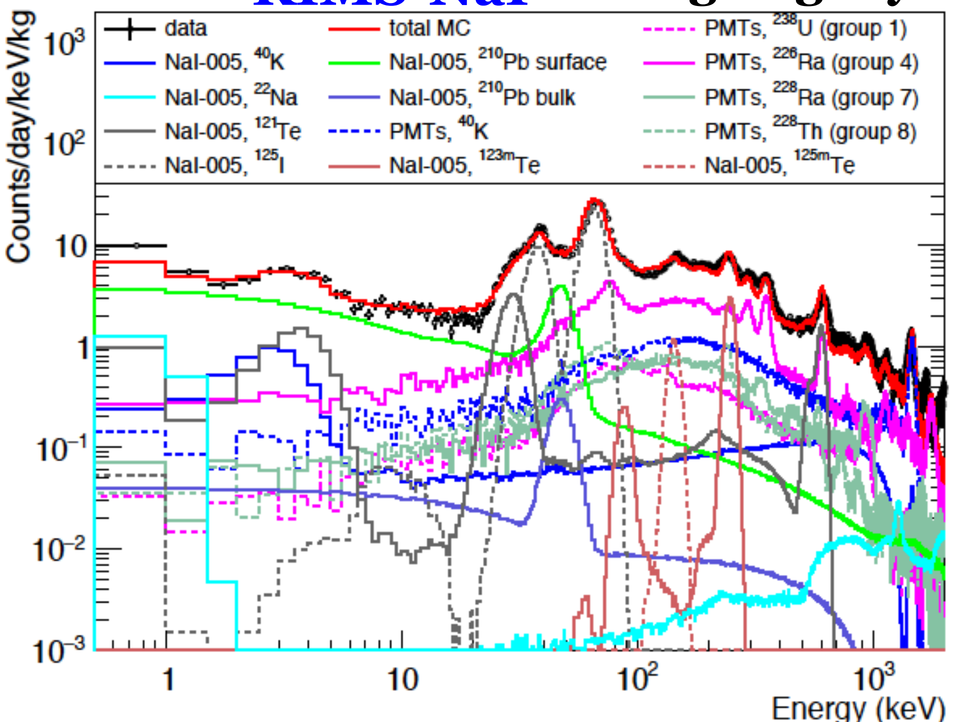


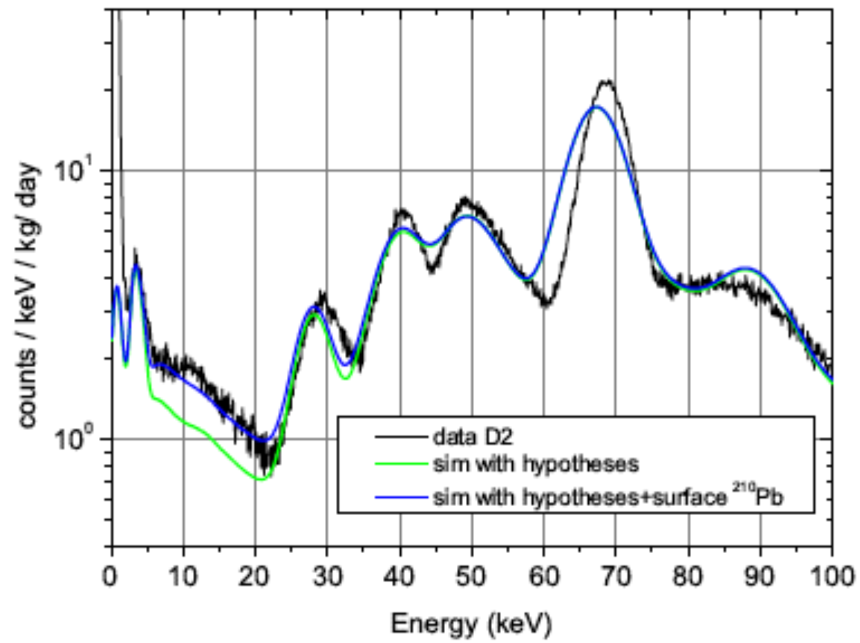
- No other experiments achieve the low-background rate of NaI(Tl)
- Saint-Gobain lost the technique for low-background NaI(Tl) crystals
  - ❖ Confidential contraction between DAMA and Saint-Gobain was finished already

NaI(Tl) development with Alpha Spectra (AS)

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

KIMS-NaI **High light yield ~ 15 PE/keV** **ANAIS**





Astropart. Phys. 62, 249 (2015)

EPJC 76, 185 (2016)

EPJC 77, 437 (2017)

NIMA 103, 851 (2017)

NIMA, 742, 197 (2014)

JCAP 1502, 046 (2015)

EPJC 76, 429 (2016)

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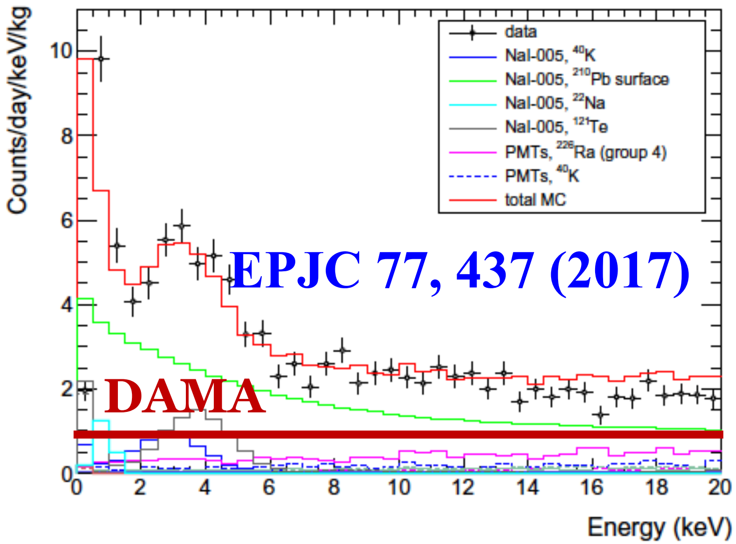
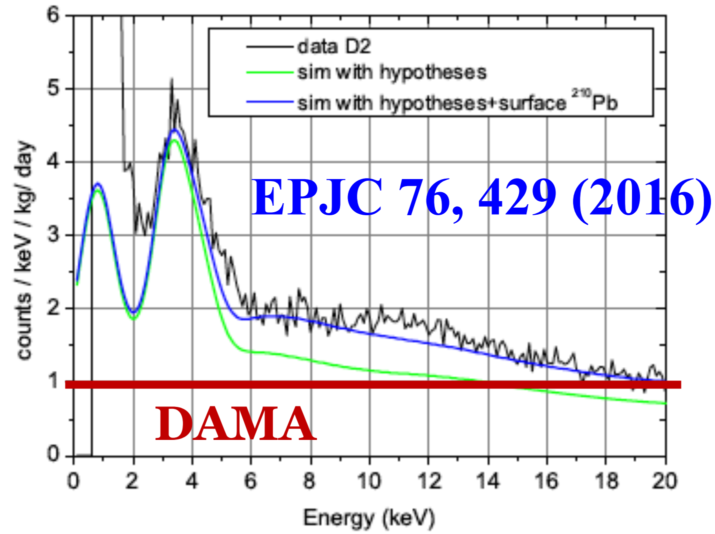




➡ **COSINE-100** ➡ **ANAIS-112**

2-4 times larger than DAMA

- 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

5 countries

14 institutes
~50 members

KIMS + DM-ICE = COSINE

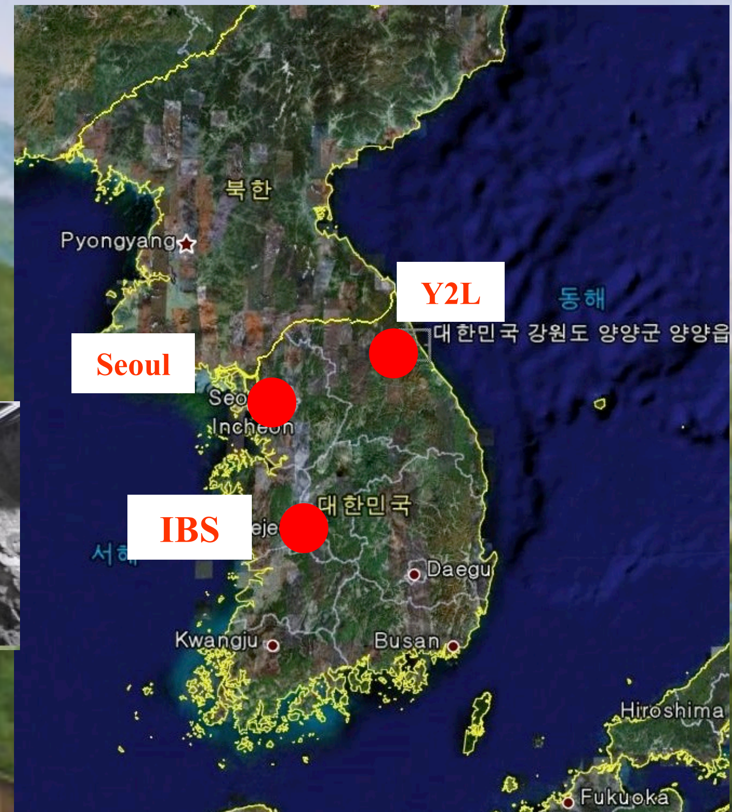
YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

1000m

700m

(Power Plant)



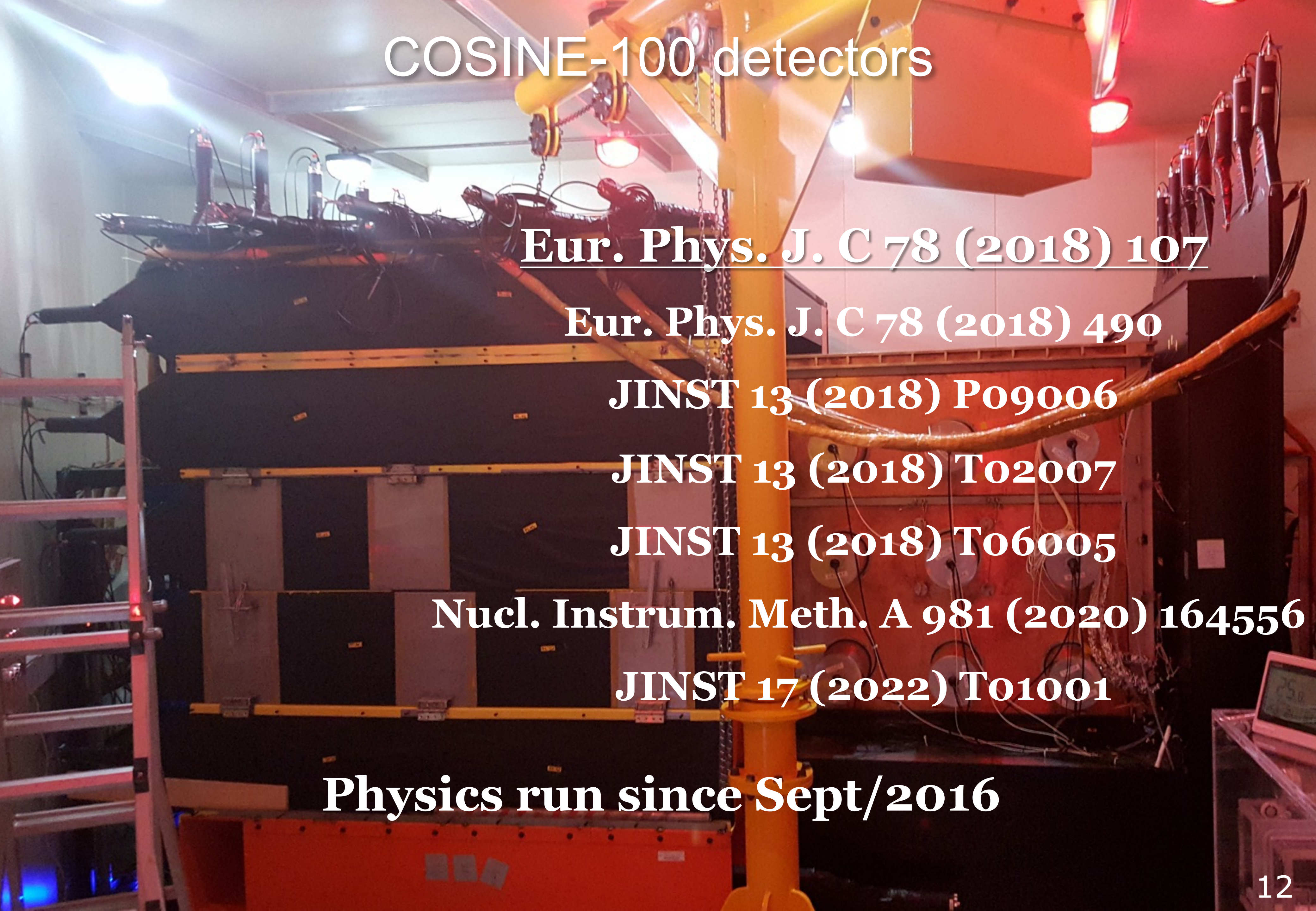
양양양수발전소

KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

COSINE-100 detectors



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

Eur. Phys. J. C 78 (2018) 490

JINST 13 (2018) P09006

JINST 13 (2018) T02007

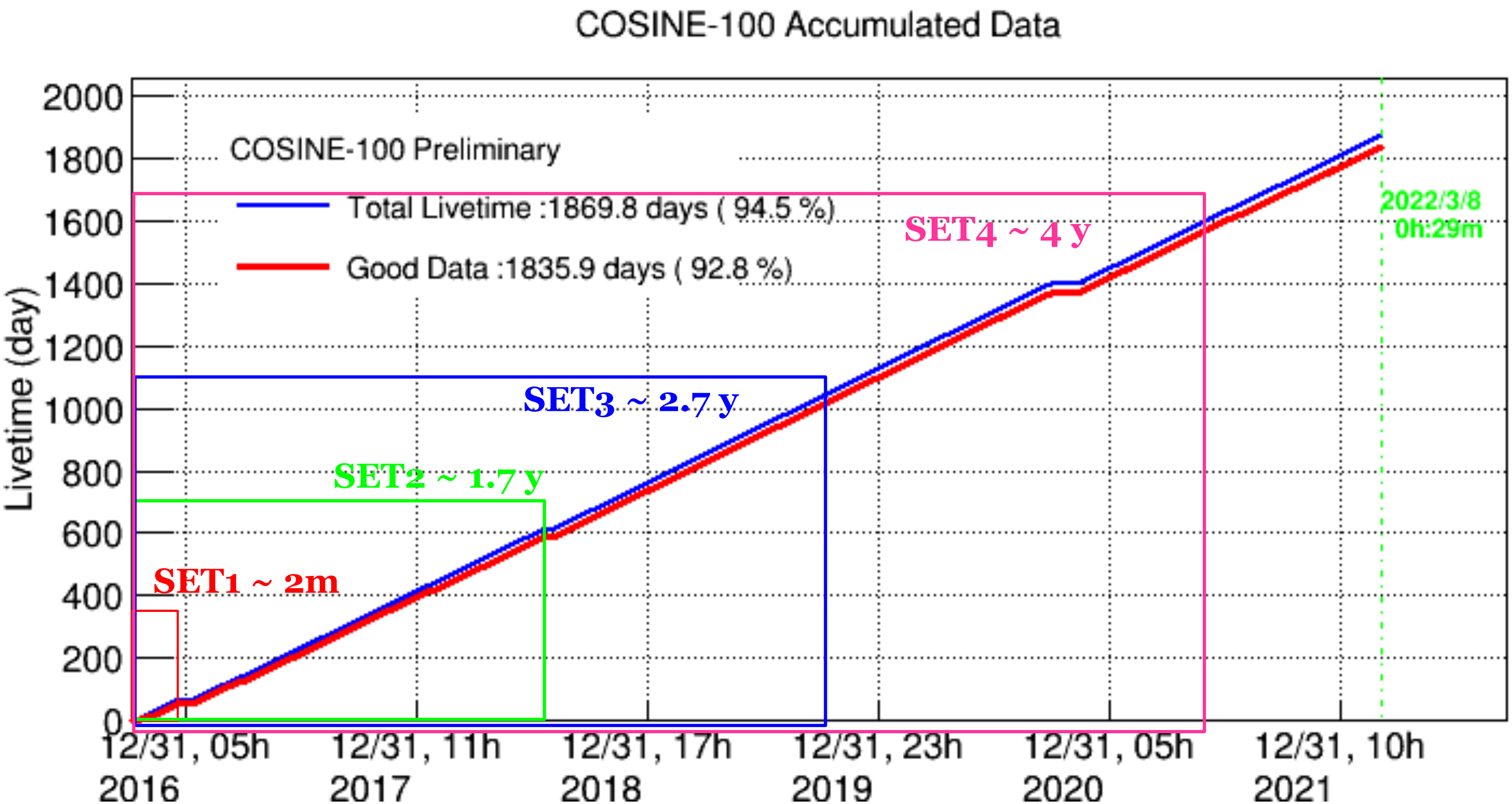
JINST 13 (2018) T06005

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

JINST 17 (2022) T01001

Physics run since Sept/2016

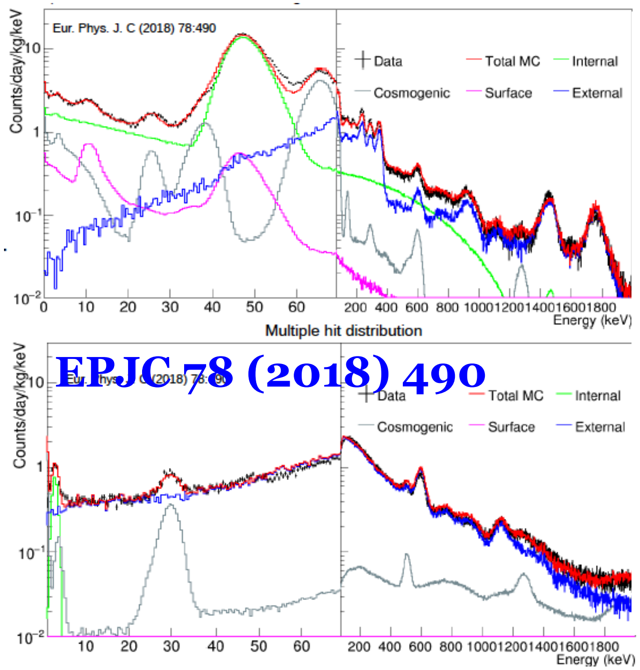
COSINE-100 data exposure



- **Stable operation from Sep. 2016 for about 5.5 years**
  - **~94.5 % live time (physics data)**
  - **~93 % good quality physics data (~5 years data)**

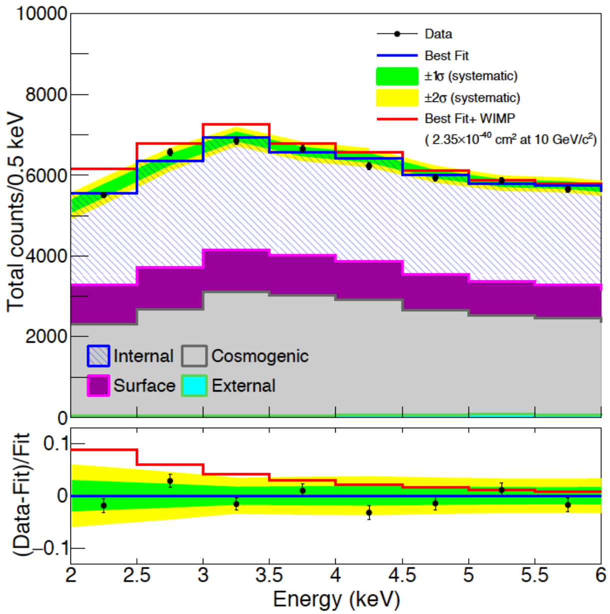
COSINE-100 Physics results (2 keV threshold)

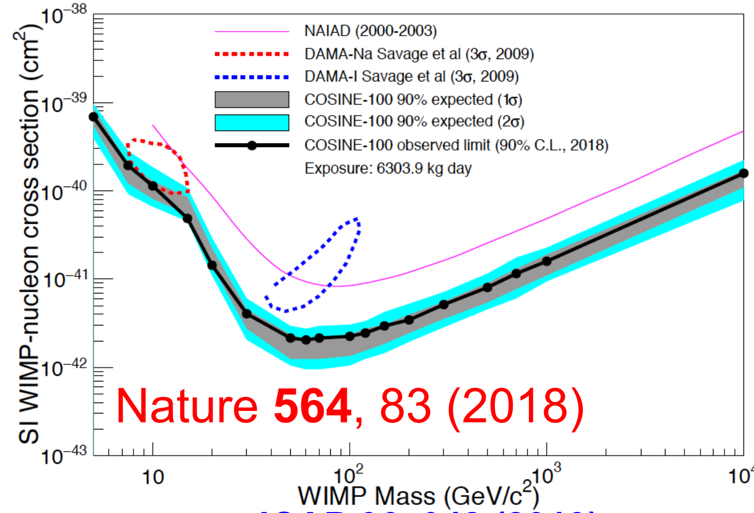
Background modeling (59.5 days)



EPJC 78 (2018) 490

WIMP Search (59.5 days)





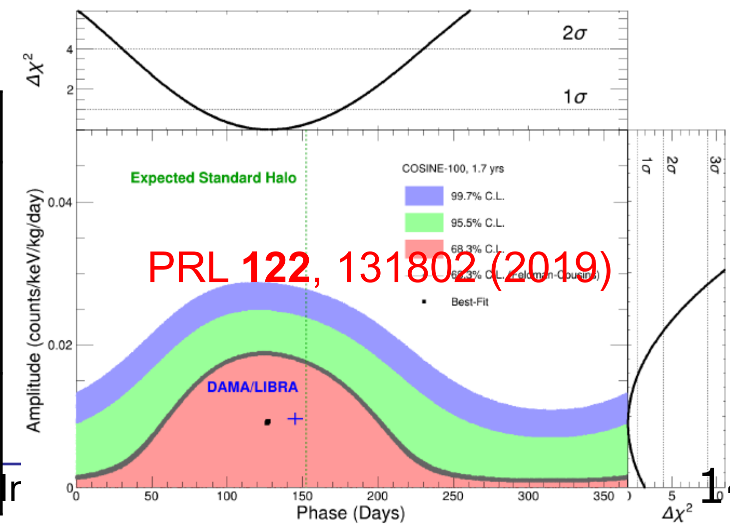
Nature **564**, 83 (2018)

JCAP 06, 048 (2019)

JCAP 11, 008 (2019)

Annual Modulation analysis (**1.7** years)

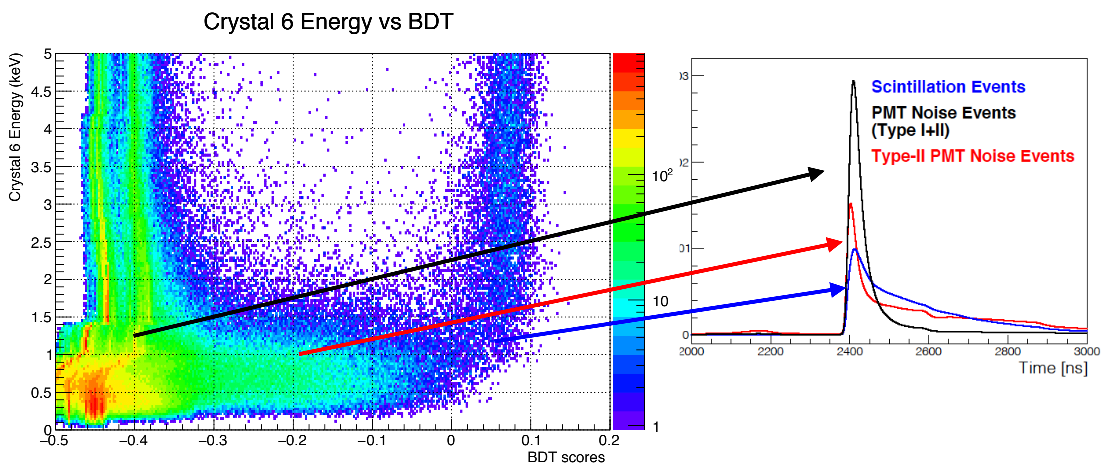
Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	**0.0083 ± 0.0068**	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5



PRL **122**, 131802 (2019)

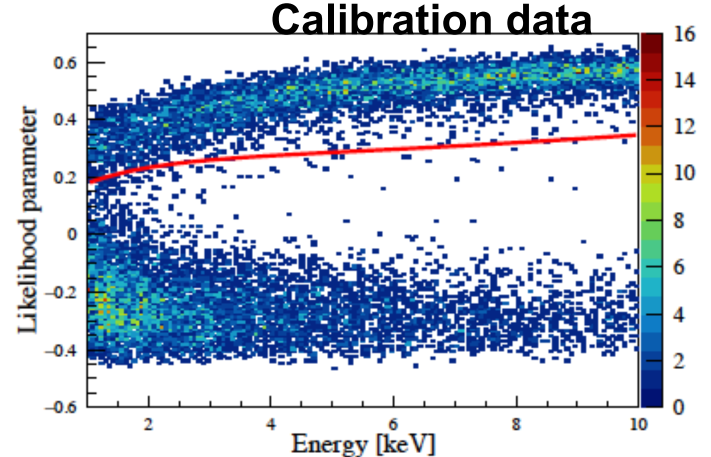
Event selection

- Two-fold trigger can reach to 0.15 keV trigger threshold
- PMT-induced noise significantly contribute for <2 keV
- Multivariable machine learning technique applied to reduce analysis threshold to 1 keV



- Develop new likelihood parameter based on the pulse shape of the signals and the noises

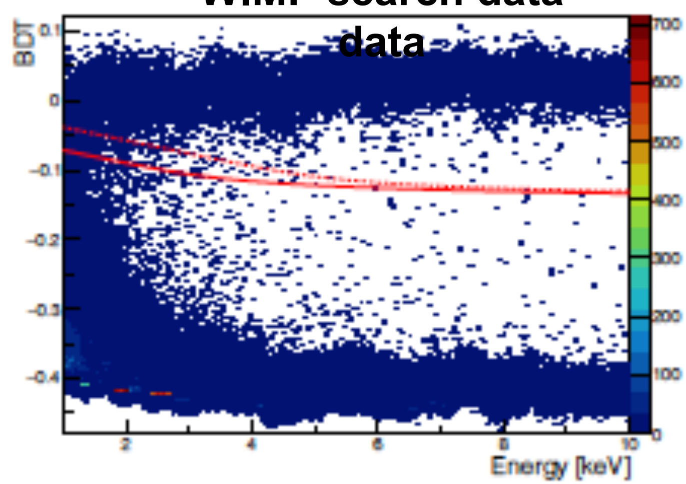
Calibration data



Astropart. Phys 130, 102581 (2021)

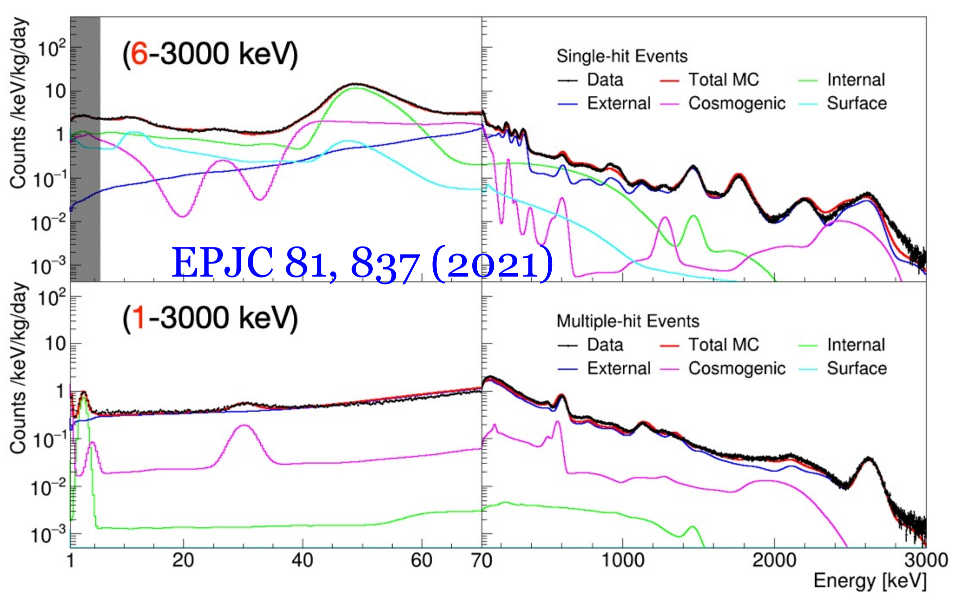
WIMP search data

data



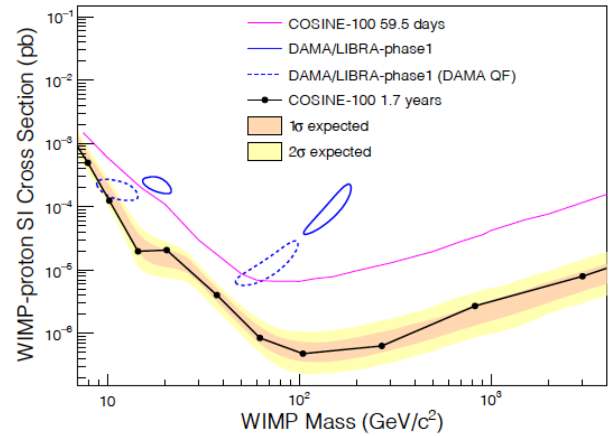
Updated results with 1keV threshold

Background modeling



EPJC 81, 837 (2021)

1.7 years data

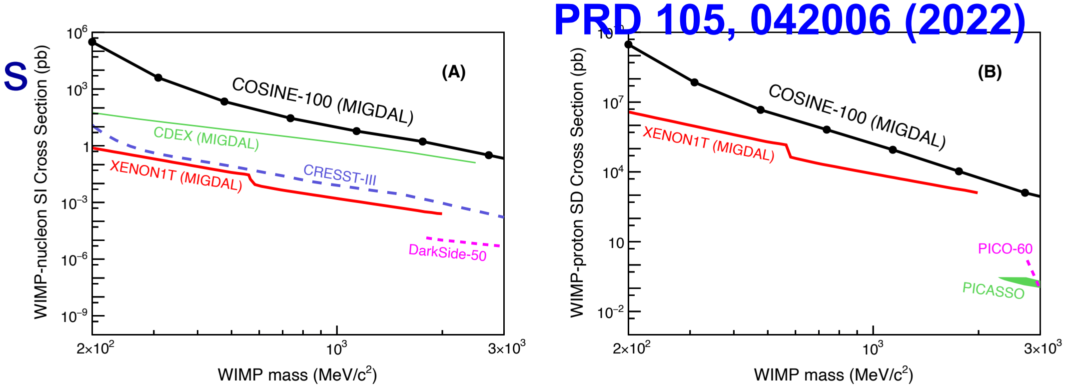


Sci. Adv. 7, eabk2699 (2021)

- Migdal effect
  - Nuclear recoil → Boost of electrons → Secondary radiation
  - Because of nuclear recoil quenching, large visible energy
  - Sub-GeV DM search

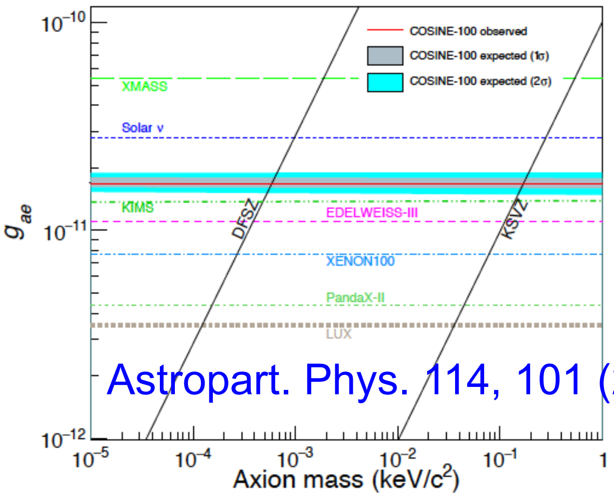
Low-mass search with Migdal effect

PRD 105, 042006 (2022)



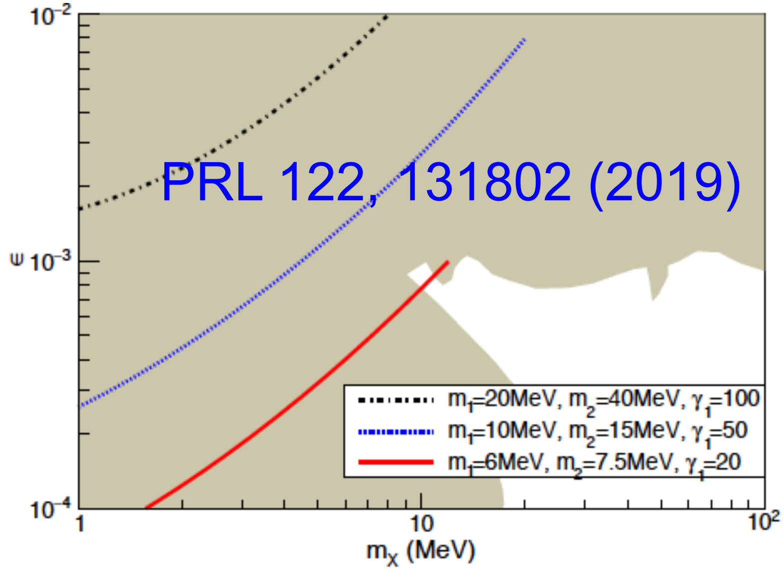
Other searches

Solar Axion



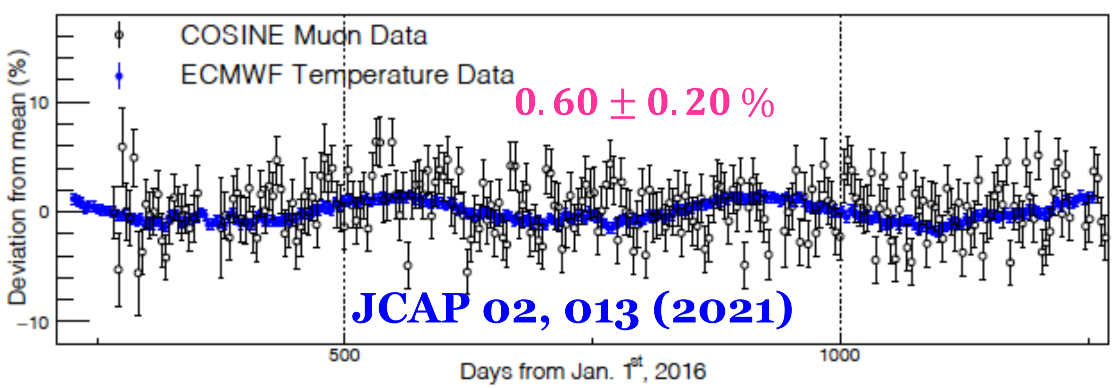
Astropart. Phys. 114, 101 (2020)

Inelastic boosted dark matter



PRL 122, 131802 (2019)

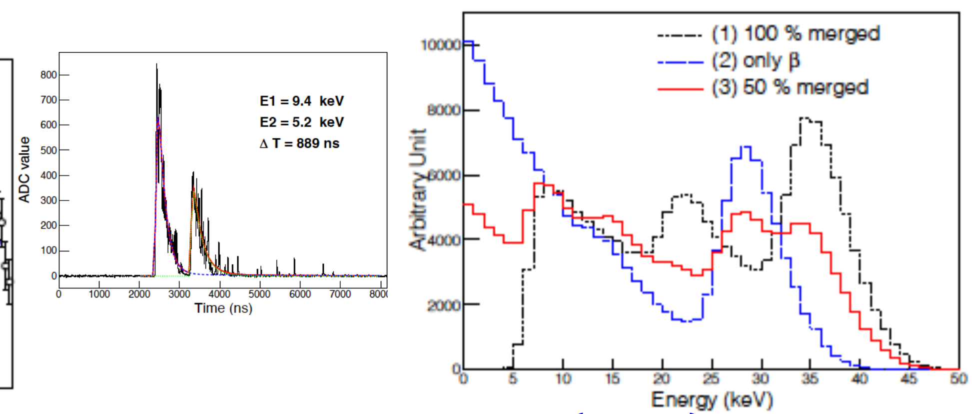
Annual modulation of muon rate



0.60 ± 0.20 %

JCAP 02, 013 (2021)

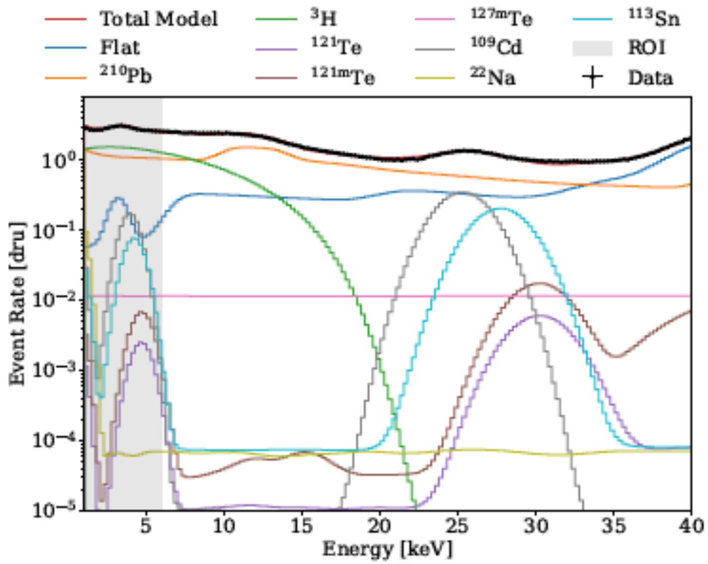
New isomers in ^{228}Ac



EPJC 81, 746 (2021)

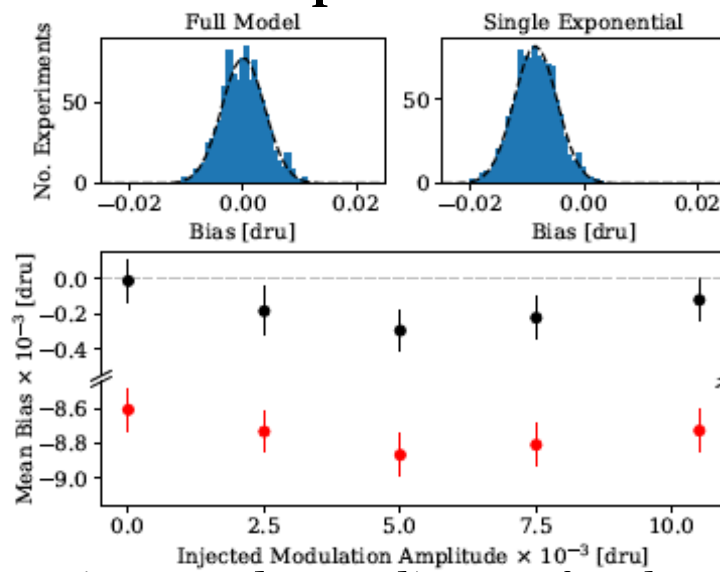
Annual modulation (3 years data)

Time dependent background modeling



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

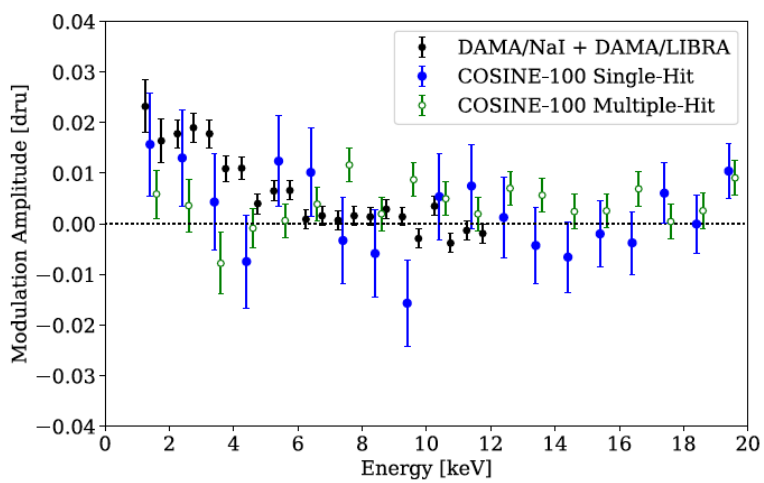
Pseudo experiment



Full model

Single exponential

arXiv:2111.08863



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

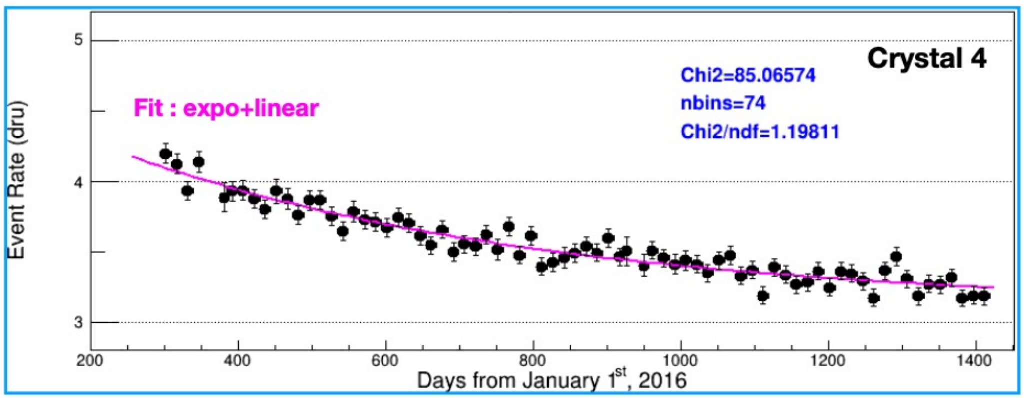
JHEP 20, 137 (2020)

Idea of time-dependent background as an explanation of DAMA signals

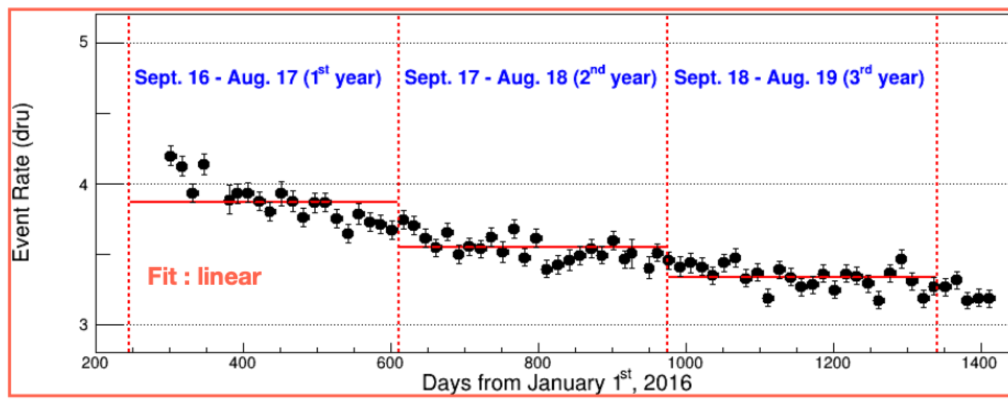
DAMA/LIBRA claimed that there is no time-dependent background in their data

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

Single exponential model (reference)

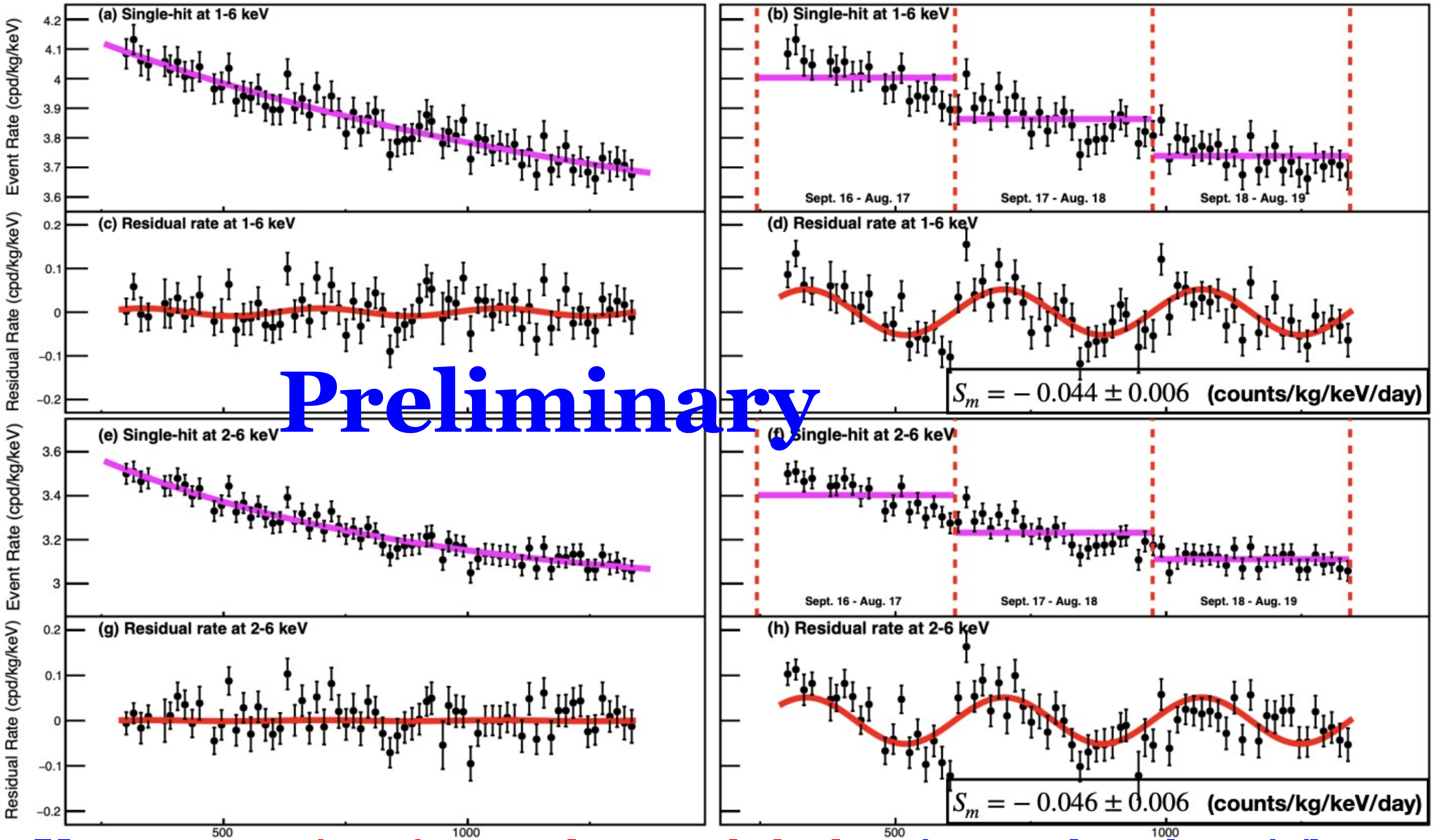


DAMA/LIBRA's method



Results from the COSINE-100 data

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

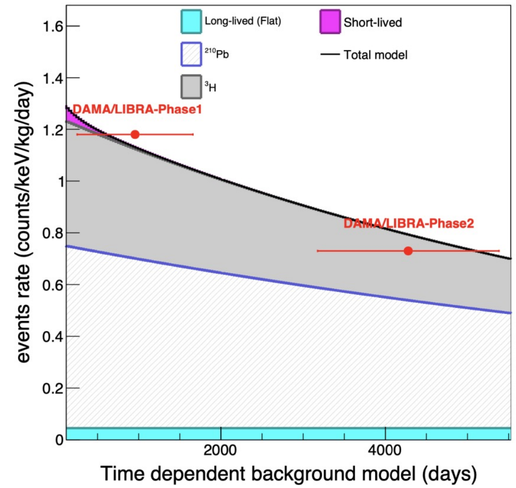


Very strong (~7σ) negative modulation (opposite phase) from the COSINE-100 data using DAMA/LIBRA's method

Pseudo data for the DAMA/LIBRA

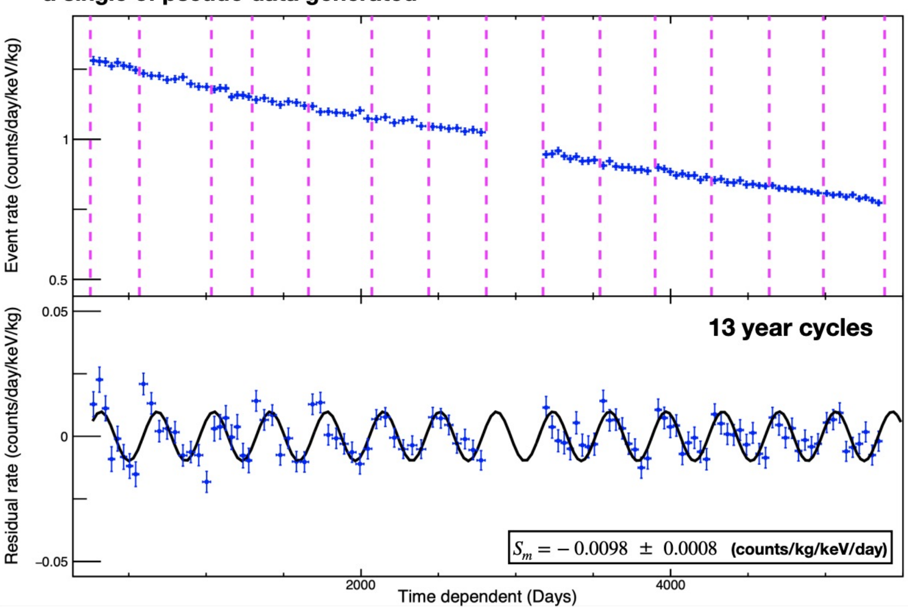
Assuming same background composition between COSINE-100 and DAMA

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	

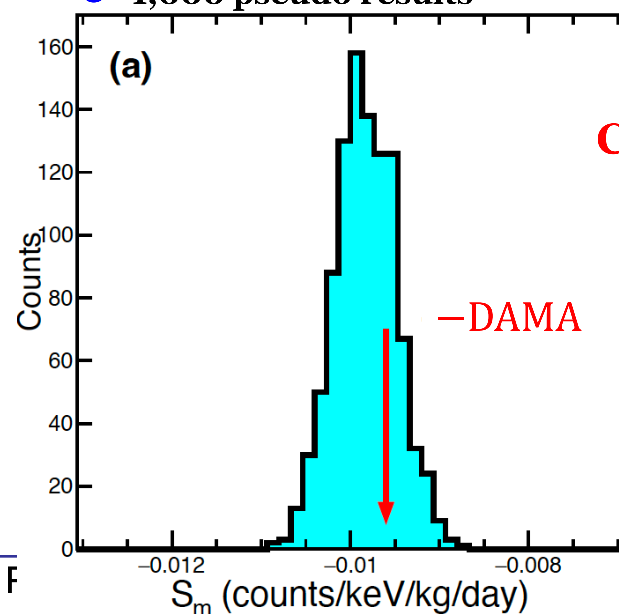


Preliminary

a single of pseudo data generated



1,000 pseudo results



Consistent modulation amplitude

Opposite phase

COSINE-200 crystal development

- 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

Powder purification performance

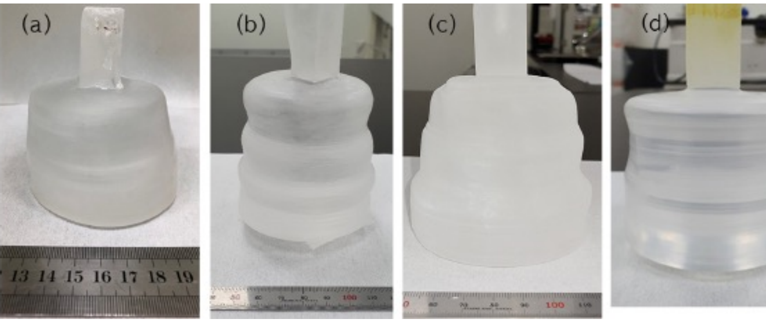
K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)

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

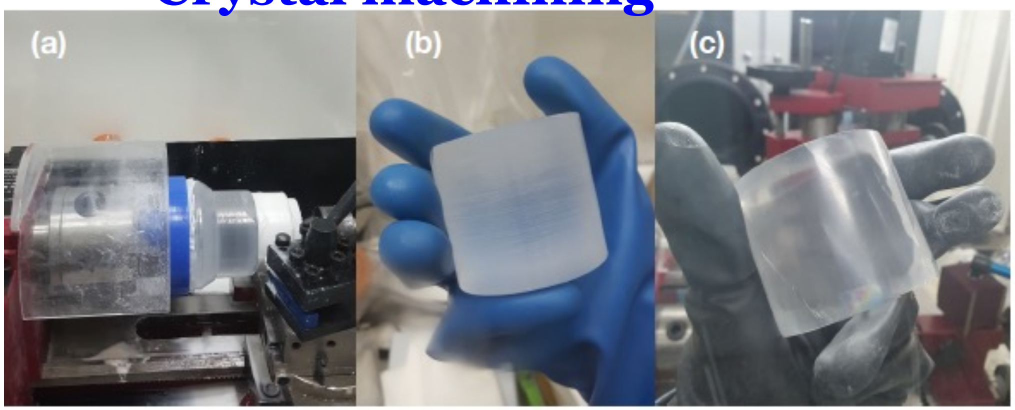
Our grown crystals

Crystal ingots



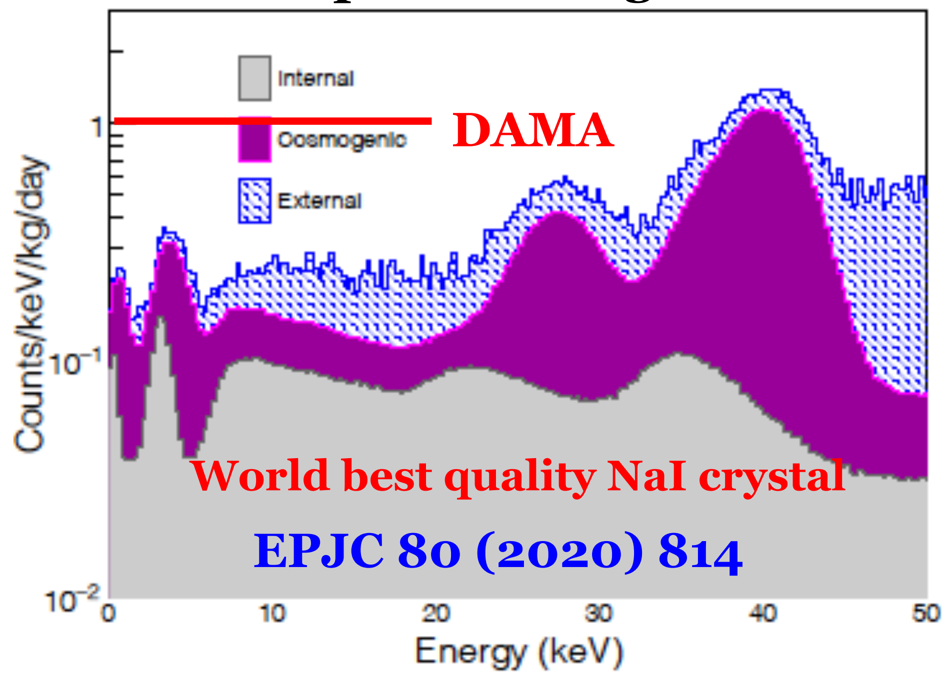
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

Expected background

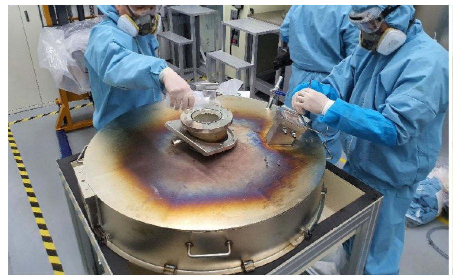


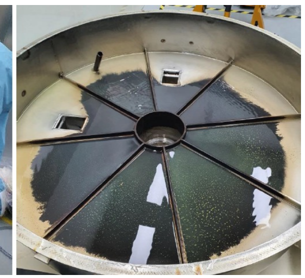
A proof of principle for low background NaI

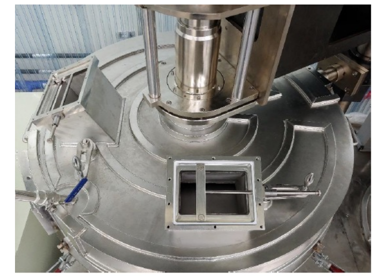
Full size grower

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

First run







Third run

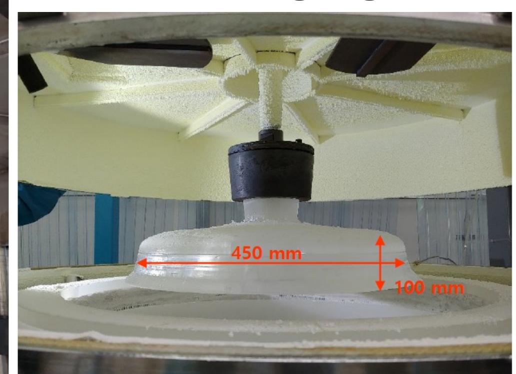
~200 kg powder

<Powder charging>

Seed holder

<Seed & holder>

~50 kg ingot

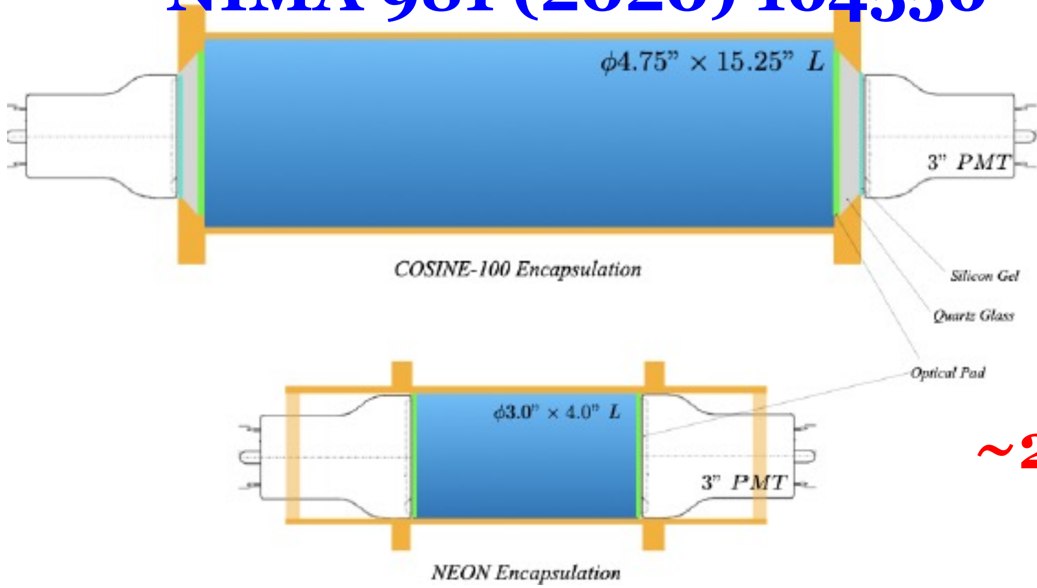


<Crystal dimension>

- **First test run**
  - **Found some issues and improved the system**
- **Third run**
  - **Successful seeding and grow ~10cm ingot**

Novel technique of crystal encapsulation

NIMA 981 (2020) 164556



15 NPE/keV

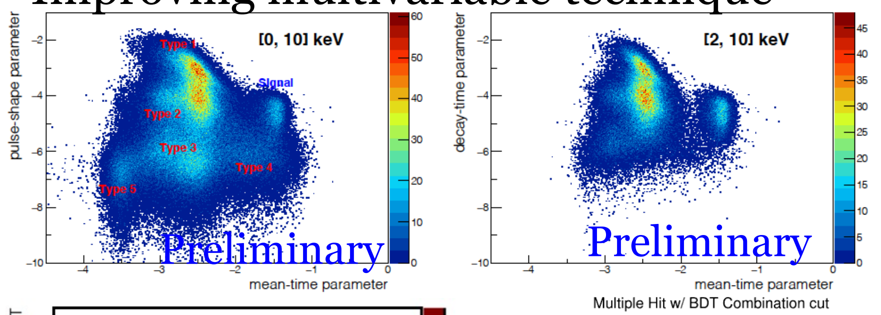
(NPE=number of photoelectrons)

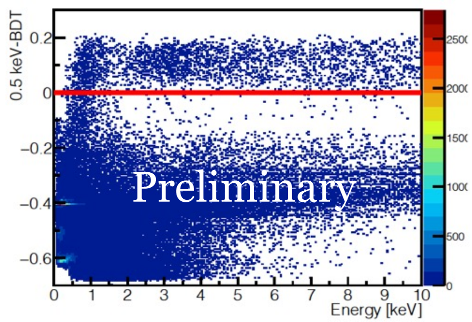
~23 NPE/keV

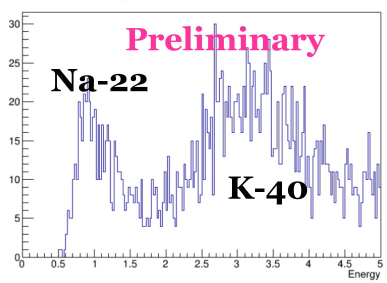
- Direct attachment of NaI(Tl) to PMTs
- ~50 % increased light yield was observed
- This technique can be applied for COSINE-200 detector assembly

Efforts for low-threshold NaI(Tl) detectors

Improving multivariable technique

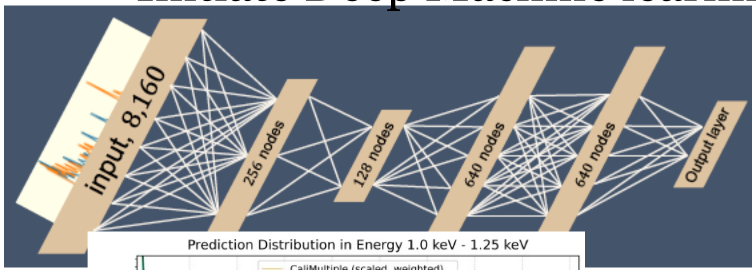


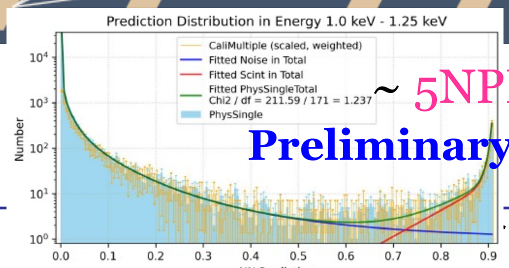




~ 0.5 keV (7 NPE) threshold achievable!!

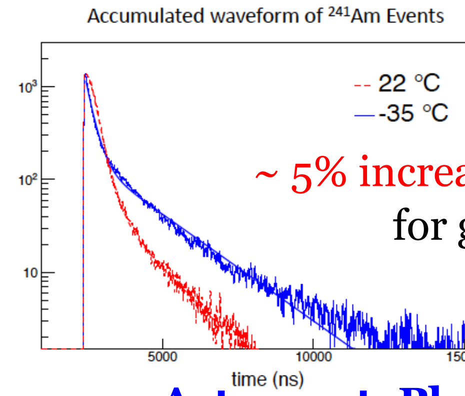
Initiate Deep Machine learning



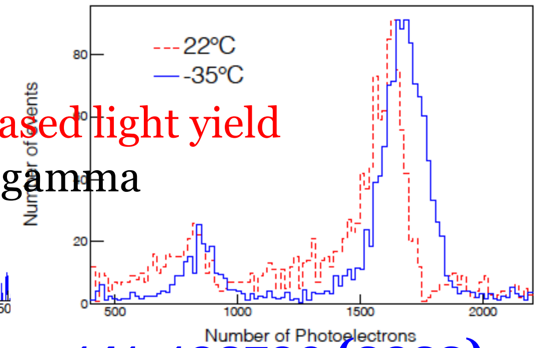


~ 5NPE threshold?

Low temperature measurement



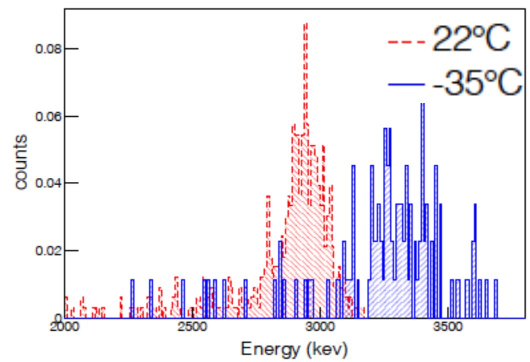
Am-241 measurement



~ 5% increased light yield for gamma

Astropart. Phys. 141, 102709 (2022)

Po-210 alpha measurement



Alpha quenching increased ~ 10 %

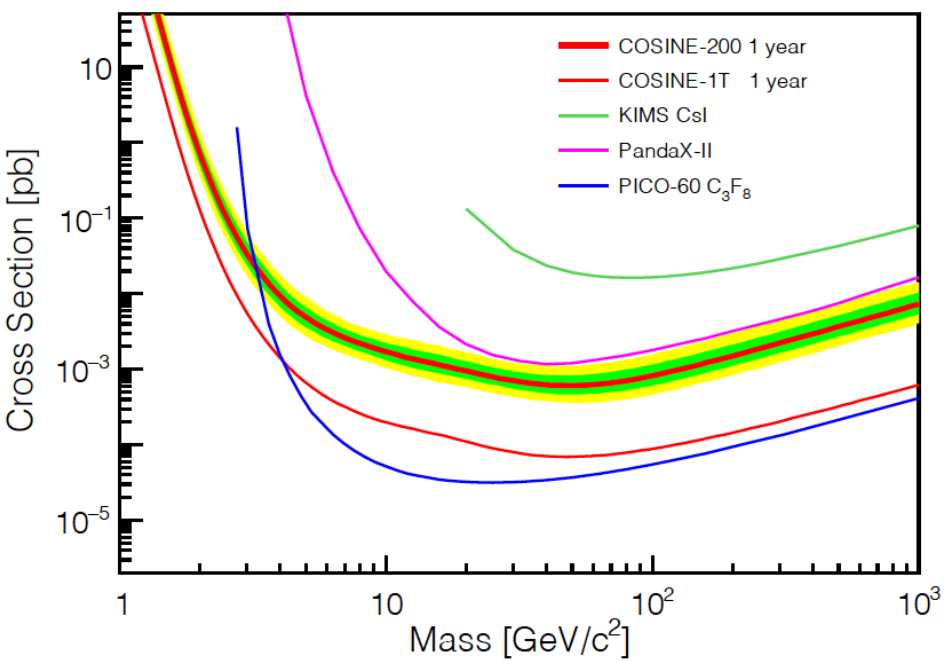
Neutron quenching measurement is under preparation

Consider -30°C operation of COSINE-200

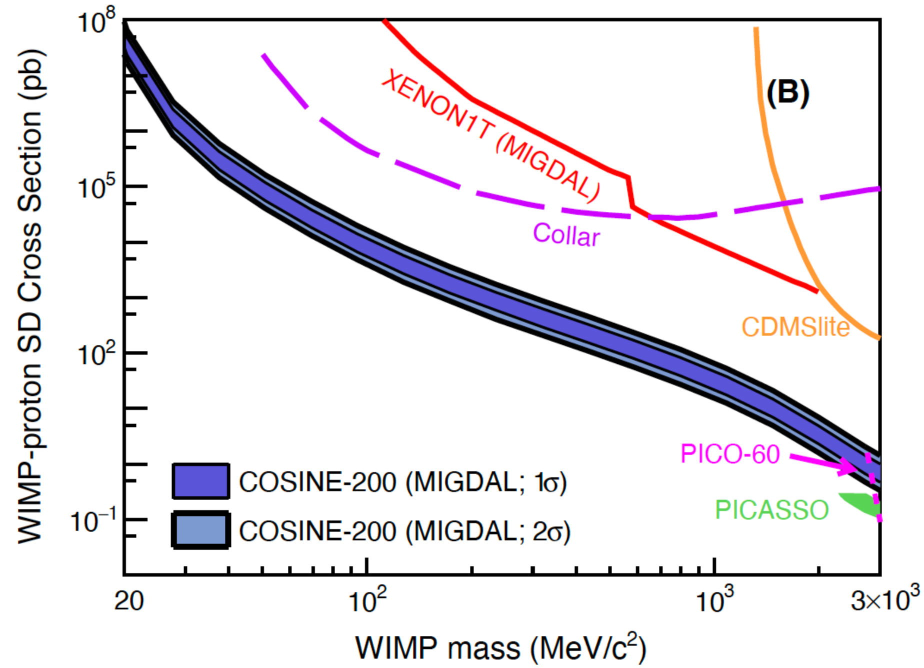
COSINE-200 sensitivity

- 200 kg x 1 year data are assumed (22 NPE LY, 5 NPE threshold)
- Both sodium and iodine are proton odd

WIMP-proton spin-dependent



Low mass search with Migdal



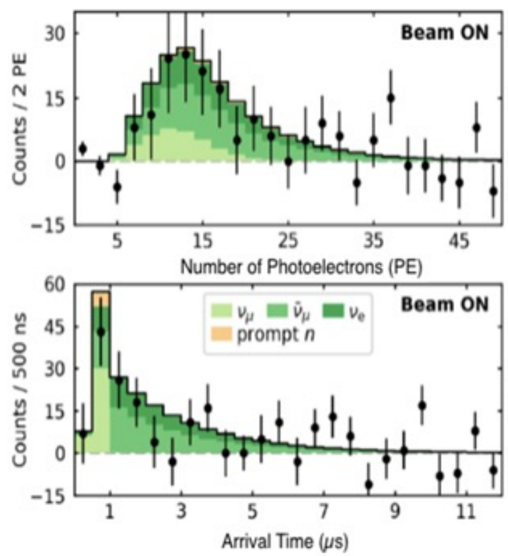
- Can be world best sensitive detector for low-mass WIMP-proton spin-dependent interaction

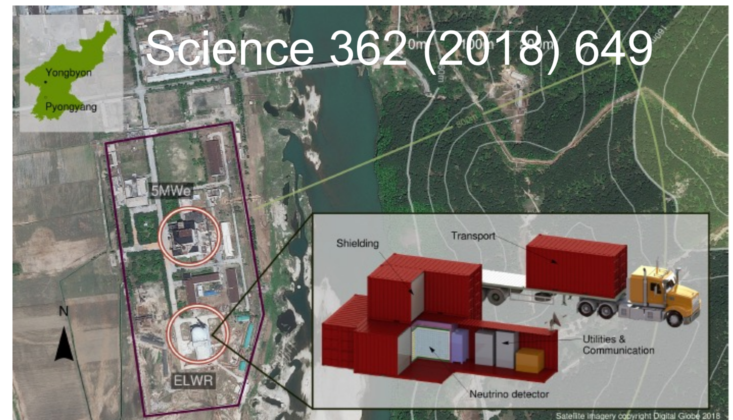
CEνNS

- Coherent Elastic ν Nucleon Scattering (CEνNS)
  - ❖ Predicted at 1974
  - ❖ First observation at 2017 using spallation neutron source (~ 30 MeV neutrino)
  - ❖ However, CEνNS with reactor neutrino (~3 MeV) is not
    - ❑ A lot of scientific and technological application

COHERENT collaboration

Science **357**, 1123 (2017)





NEON Collaboration

~ 16 members who are all active members of COSINE-100 and/or NEOS

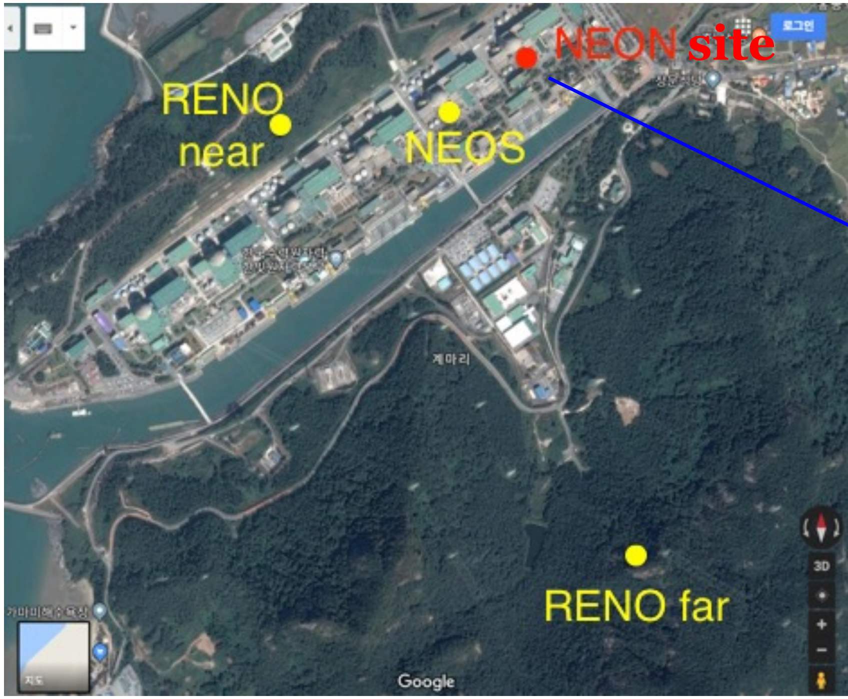
Aim to observe CEνNS from reactor $\bar{\nu}_e$ using NaI(Tl) detector

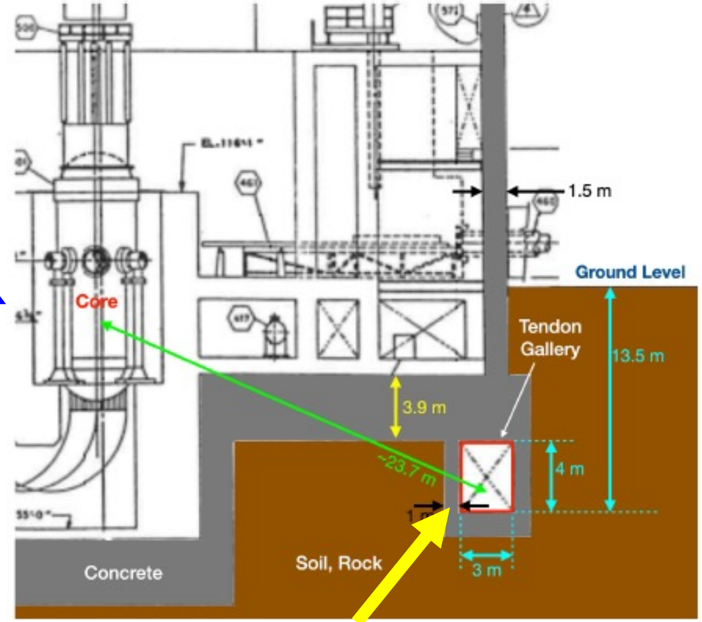
Can take an advantage of COSINE-100 and NEOS experiences

High quality NaI(Tl) development

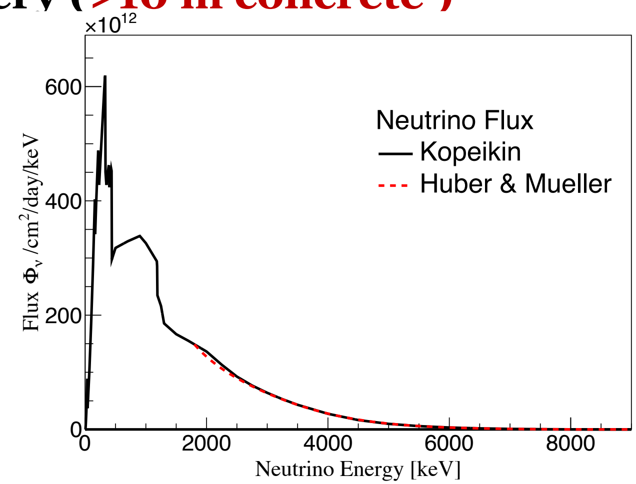
Short baseline reactor neutrino

Hanbit nuclear power plant





Tendon gallery (>10 m concrete)



- Good relation with company
- 2.8 GW thermal power
- Tendon gallery is ~24 m far from reactor core
  - ❖ Environmental conditions were well known from NEOS experiment

$$\phi_{\bar{\nu}} = 8.09\times10^{12}\ /cm^2/s$$

Construction of the NEON detector (Nov/2020)

Nov/12 (2020) **Nov/13**

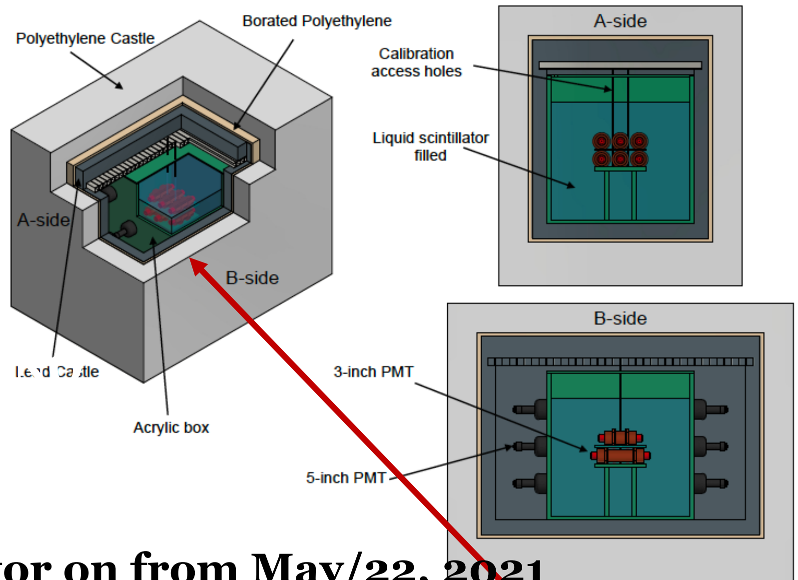
Nov/19 **Nov/20**

Nov/26

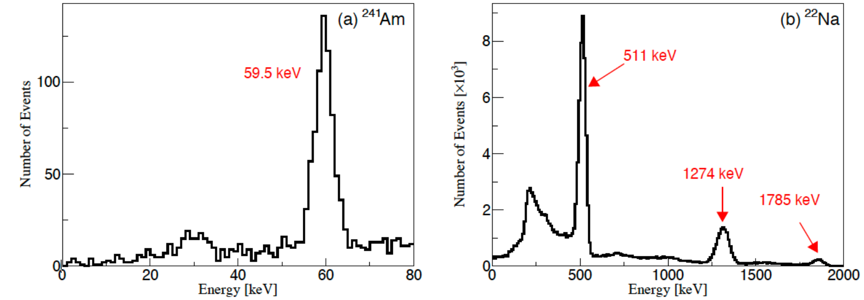
Dec/7/2020

NEON detector

Detector is onsite since Dec/2020

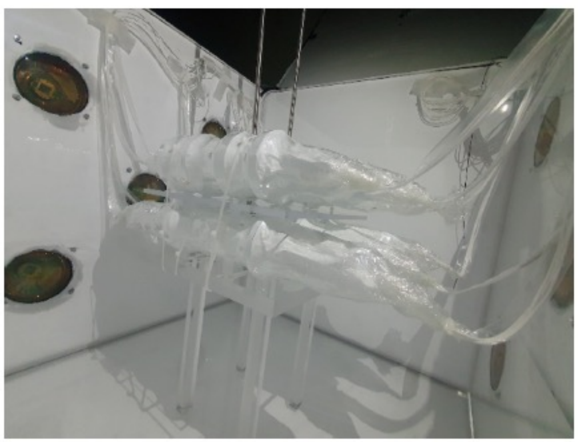


Calibration

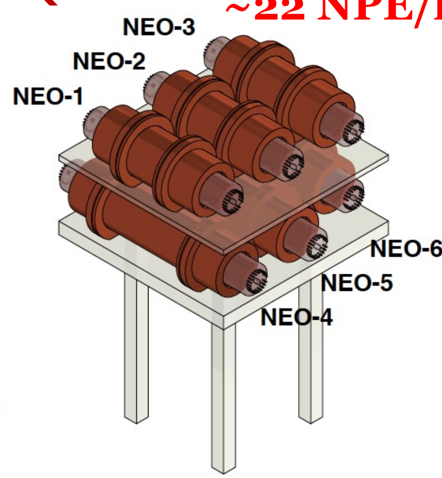


Reactor on from May/22, 2021

~ 13.5 kg NaI(Tl) crystals (commercial quality)

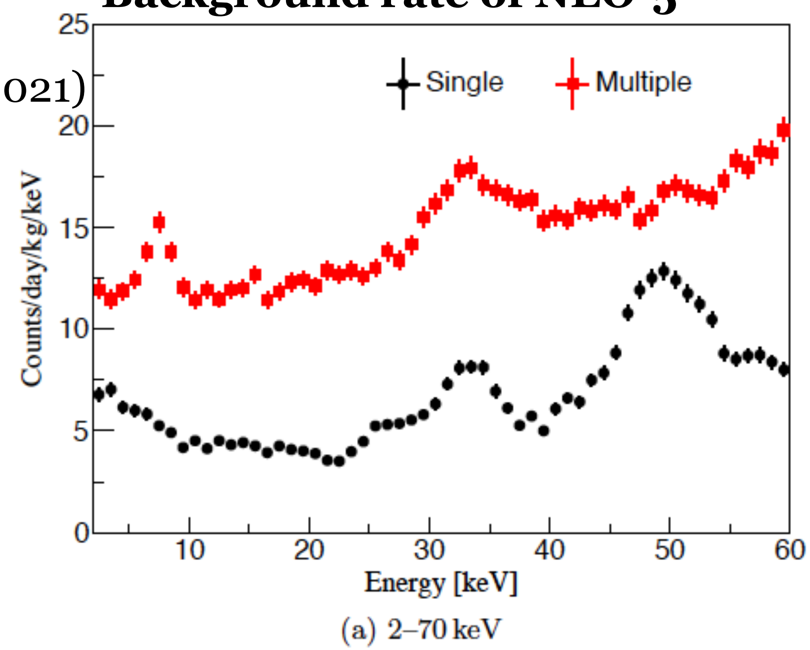


~22 NPE/keV



Background rate of NEO-5

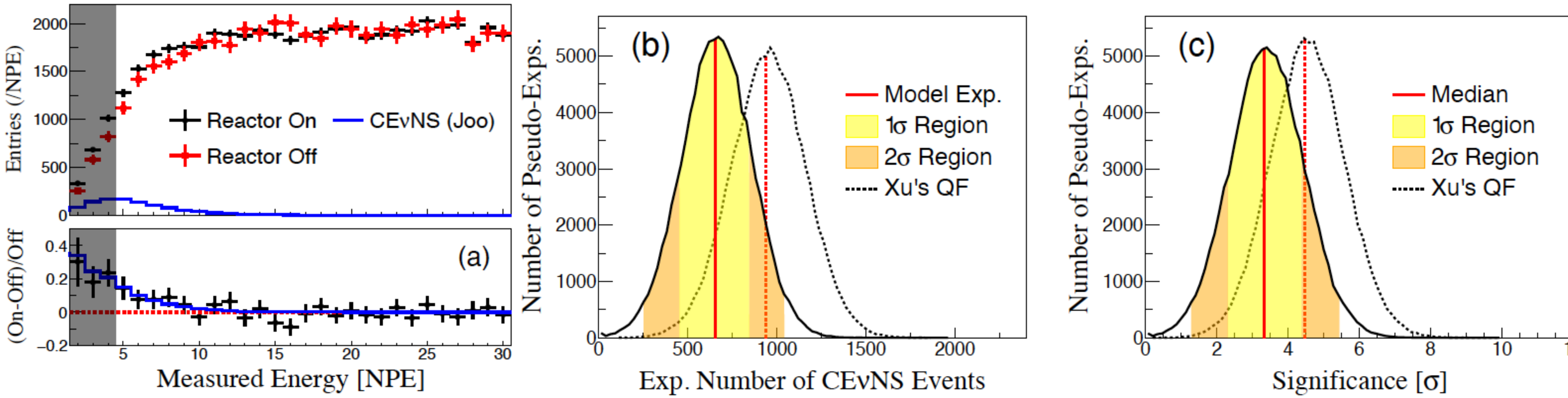
Oct~Nov (2021)



~ 6 counts/kg/keV/day at 2-6 keV

(~2 times higher background than COSINE-100)

Detection sensitivity

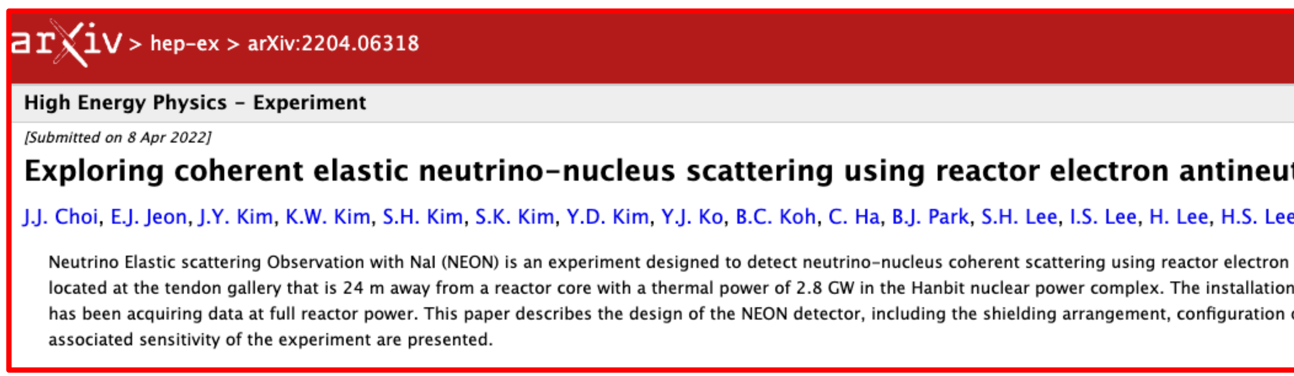


Assumption

- 7 counts/kg/day/keV flat background
- 13.3 kg mass of detector
- 365 days reactor on data
- 100 days reactor off data
- 22 NPE/keV light yield
- 5 NPE energy threshold

More than 3 σ significance

arXiv:2204.06318


arXiv > hep-ex > arXiv:2204.06318

High Energy Physics – Experiment

[Submitted on 8 Apr 2022]

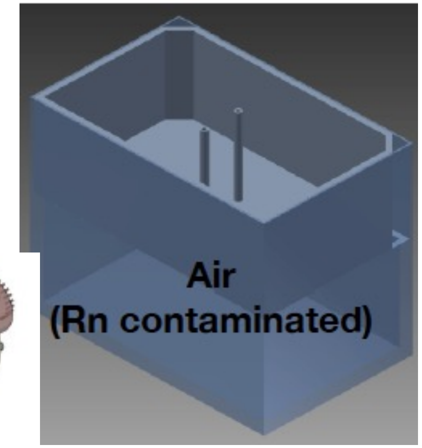
Exploring coherent elastic neutrino-nucleus scattering using reactor electron antineu

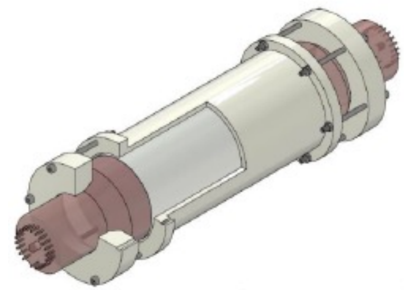
J.J. Choi, E.J. Jeon, J.Y. Kim, K.W. Kim, S.H. Kim, S.K. Kim, Y.D. Kim, Y.J. Ko, B.C. Koh, C. Ha, B.J. Park, S.H. Lee, I.S. Lee, H. Lee, H.S. Lee

Neutrino Elastic scattering Observation with NaI (NEON) is an experiment designed to detect neutrino-nucleus coherent scattering using reactor electron
located at the tendon gallery that is 24 m away from a reactor core with a thermal power of 2.8 GW in the Hanbit nuclear power complex. The installation
has been acquiring data at full reactor power. This paper describes the design of the NEON detector, including the shielding arrangement, configuration
associated sensitivity of the experiment are presented.

Upgrade of NEON-phase2 encapsulation

- A few issues on the NEON phase-1 were observed
  - ❖ Air leak in detector encapsulation
    - ❑Continuous decrease of light yield
  - ❖ Rn contamination on acrylic box
    - ❑Large background

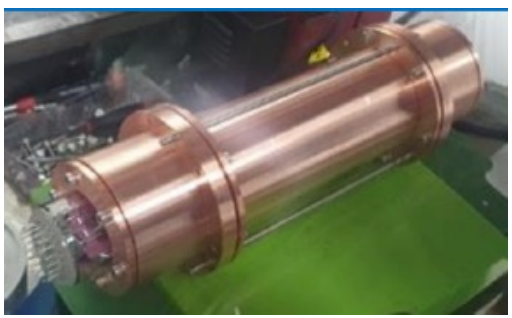




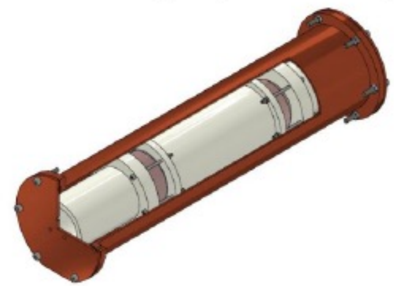
Inside of copper(Teflon frame)

- New crystal encapsulation

Phase-1



Phase-2



Copper shield with crystal

Phase-2 starts April/2022

Immerse NEON detectors inside LS without acrylic box

NEO-1 and NEO-2 are replaced with 8” crystals (now **total 16.5 kg**)

NEON schedule

2019	2020	2021	2022	2023	2024	2025
Detector development						
	NEON-10					
				NEON-100		

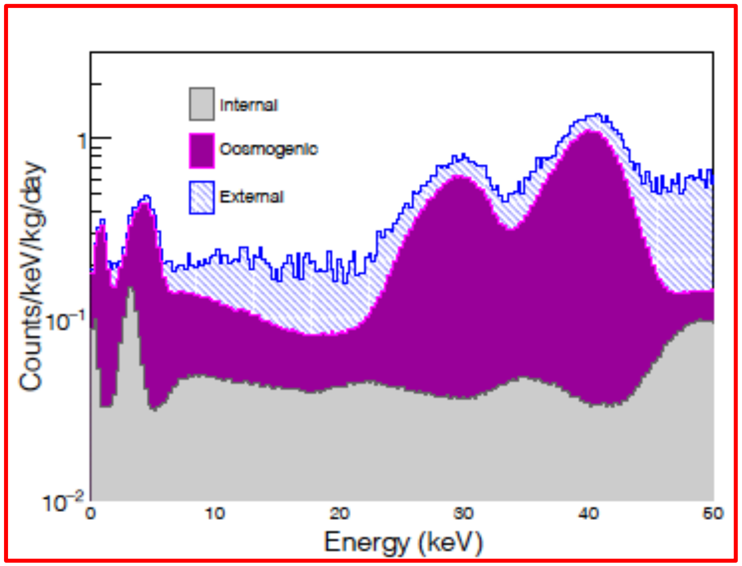
- NEON-10 (~2023)
  - ❖ ~15 kg commercial crystals (<10 counts/kg/day/keV background)
  - ❖ Reactor on: May 2021 ~ Sep 2022, Dec 2022~
  - ❖ Demonstration of detector performance and observe CEνNS with > 3σ
- NEON-100 (~2025)
  - ❖ ~100 kg purified crystals (<1 counts/kg/day/keV background)
  - ❖ Precision measurement and explore new physics interaction

NEON schedule

2019	2020	2021	2022	2023	2024	2025
Detector development						
	NEON-10					
				NEON-100		

EPJC 80, 814 (2020)

<Body growth>



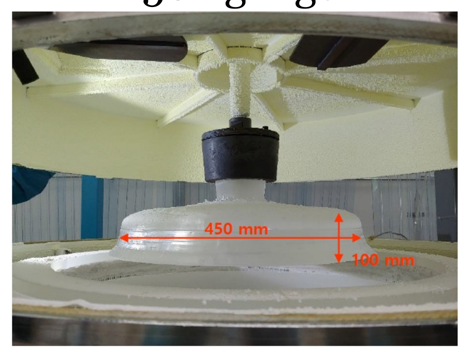
Need to grow 100 kg ingot

Top view

Full size grower @ CUP

Side view

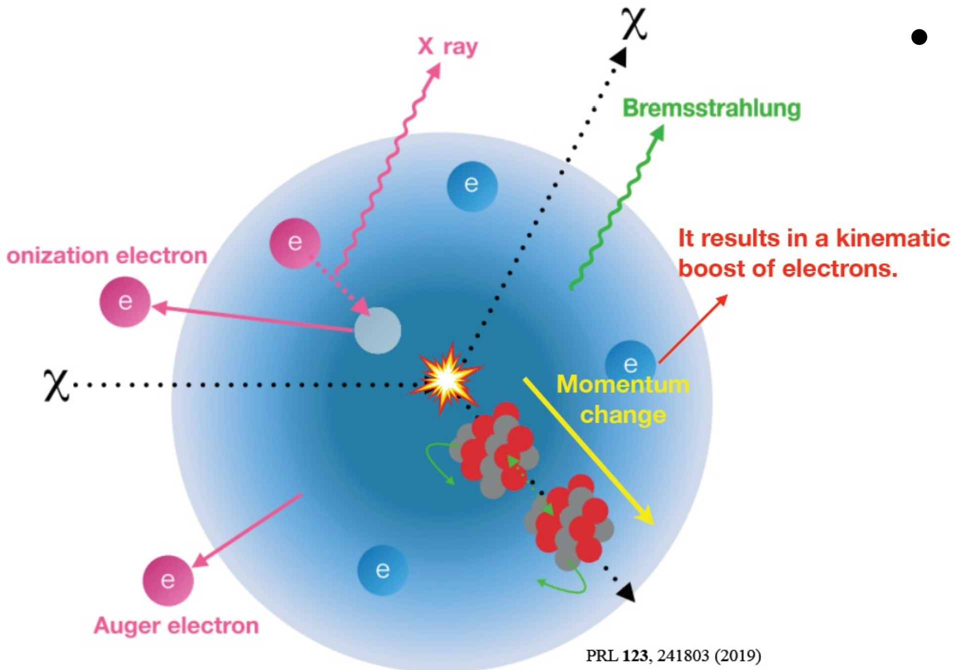
~50 kg ingot



<Crystal dimension>

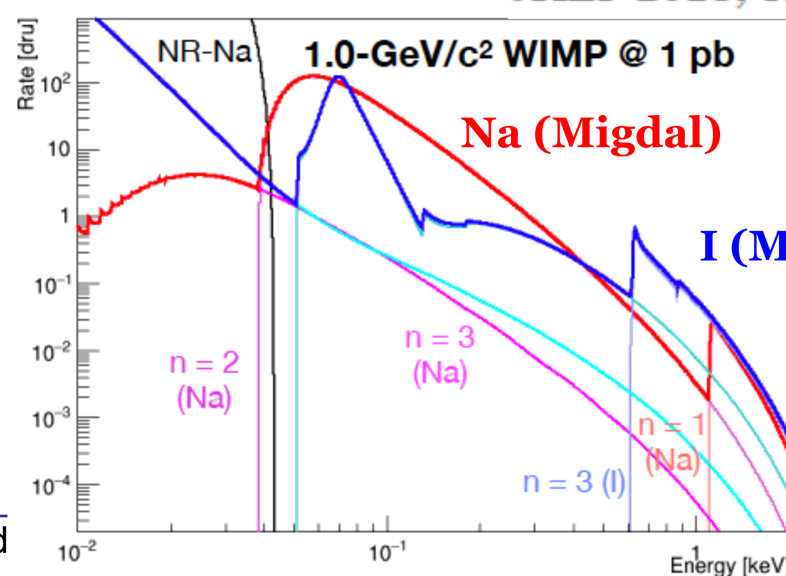
Migdal effect for low energy nuclear recoil

- Nuclear recoil can induce orbital electron excitation called as Migdal effect with very low probability (10^{-3})

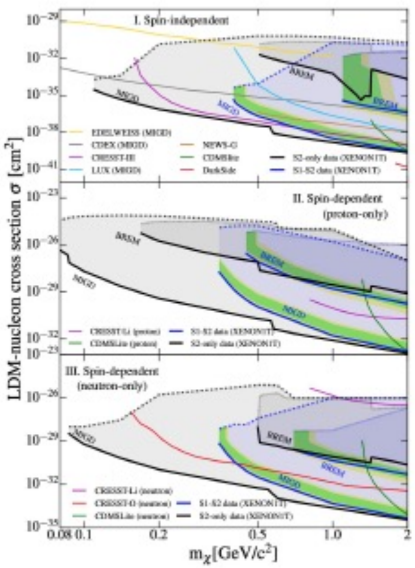


- Although electron recoil energy should be smaller than total nuclear recoil energy, such electron recoil do not have quenched
  - ❖ Na nuclear recoil has only 10% quenching

JHEP 2018, 194 (2018)



Migdal is new era for low-mass dark matter

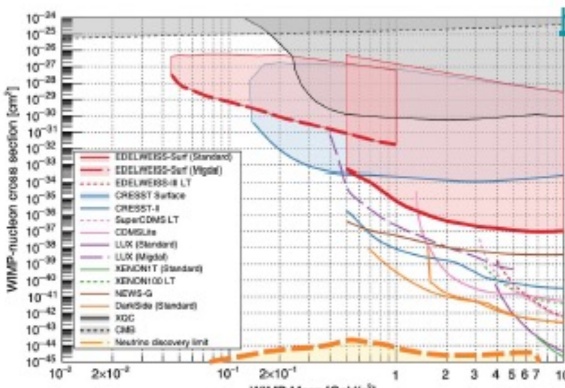


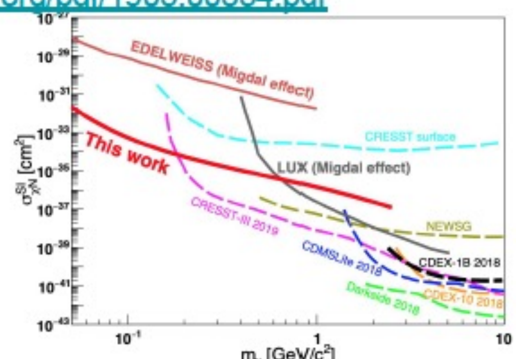
LUX (Xenon)
"Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data"
https://arxiv.org/pdf/1811.11241.pdf **PRL 122,131301 (2019)**

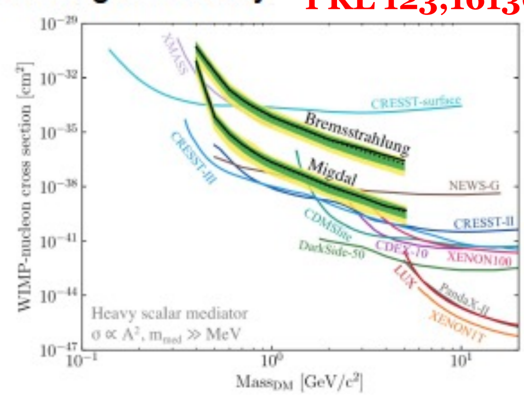
XENON1T (Xenon)
"A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T"
https://arxiv.org/pdf/1907.12771.pdf **PRL 123,241803 (2019)**

EDELWEISS (Germanium)
"Searching for low-mass dark matter particles with a massive Ge bolometer operated above-ground"
https://arxiv.org/abs/1901.03588 **PRD 99, 082003 (2019)**

CDEX-1B (Germanium)
"Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory" **PRL 123,161301 (2019)**
https://arxiv.org/pdf/1905.00354.pdf







COSINE-100 (NaI) **PRD 105,042006 (2022)**
"Searching for low-mass dark matter via the Migdal effect in COSINE-100"

Observation of Migdal effect?

MIGDAL Collaboration

CERN (GDD) F. Brunbauer, F. Garcia (HIP), E. Oliveri, L. Ropelewski, L. Scharenberg, R. Veenhof

Coimbra-LIP E. Asamar, I. Lopes, F. Neves, V. Solovov

Imperial College London H. Araujo, J. Borg, T. Marley, M. Nakhostin, T. Sumner,

King's College London C. McCabe

STFC (ISIS) C. Cazzaniga, C. Frost, M. Kastriotou; **(PPD)** S. Balashov, C. Brew, M. Van der Grinten, A. Khazov, P. Majewski; **(TD)** Project Engineer

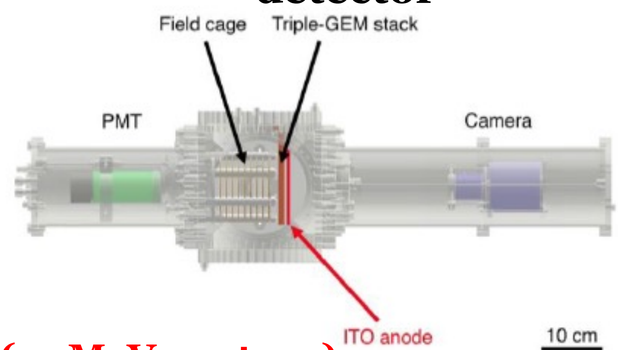
Royal Holloway University of London A. Kaboth

University of New Mexico D. Loomba

University of Oxford H. Kraus

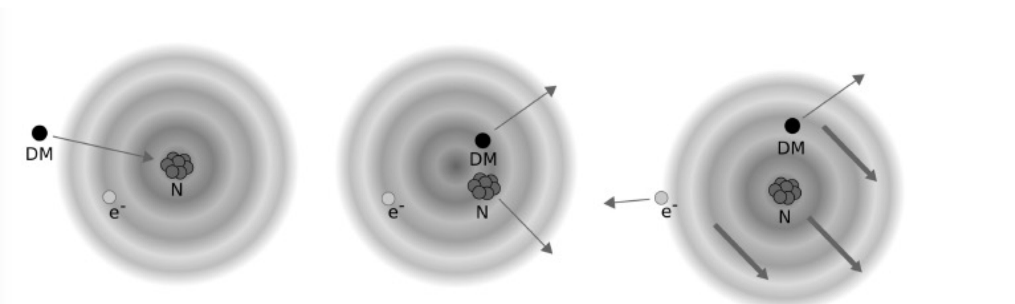
University of Sheffield V. Kudryavtsev

High pressure gas detector

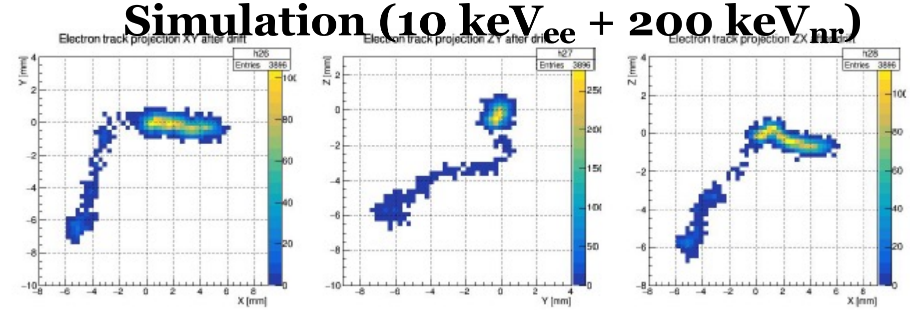


DT generator (14 MeV neutron)

- Measure tracks of both nuclear and electron recoils

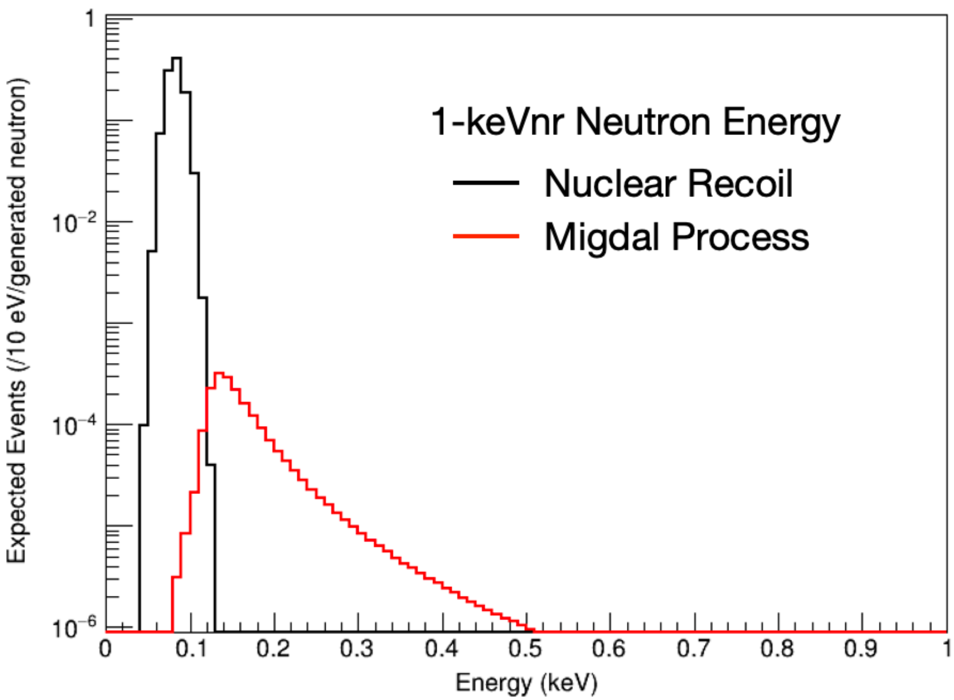


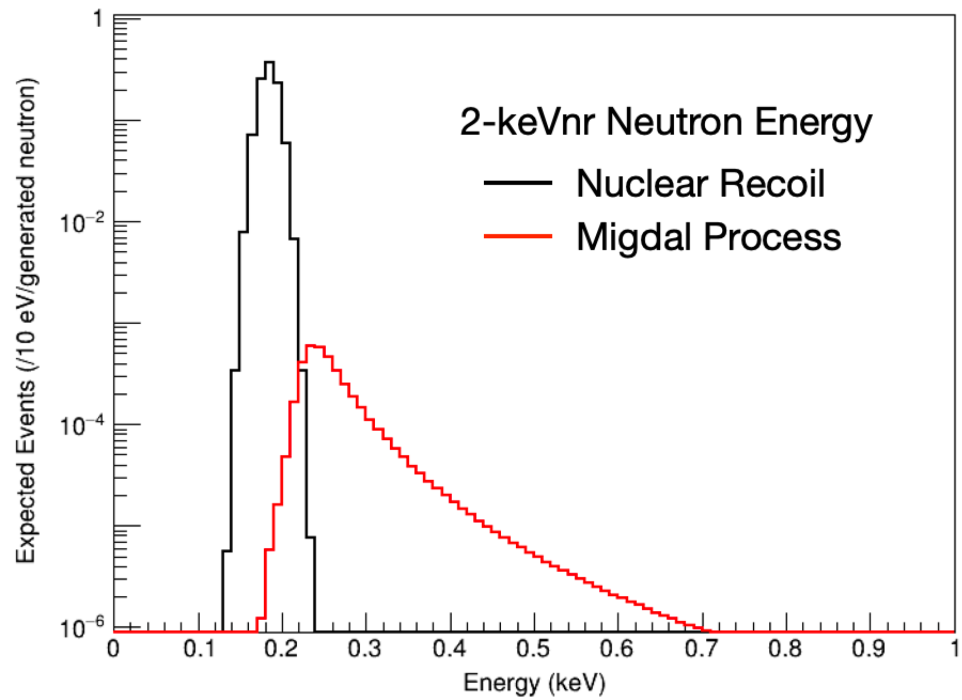
Simulation (10 keV_{ee} + 200 keV_{nr})



Migdal effect in NaI using neutron generator?

- 1~2 keV nuclear recoil energies seems to be very good





- No resolution here

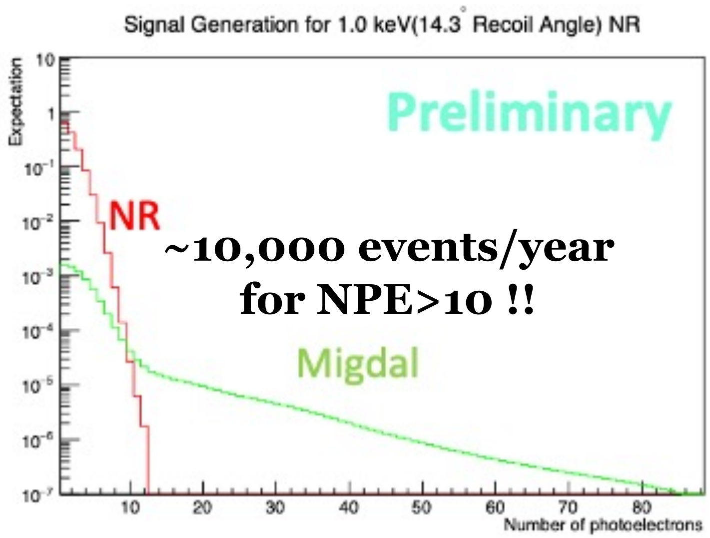
Low-energy neutron sources?

- We have DD neutron generator 10^9 n/s with 2.5 MeV
  - 1-2 keV recoils corresponds to angle of 5-8° angles to the beam direction
  - Currently operated at KRISS

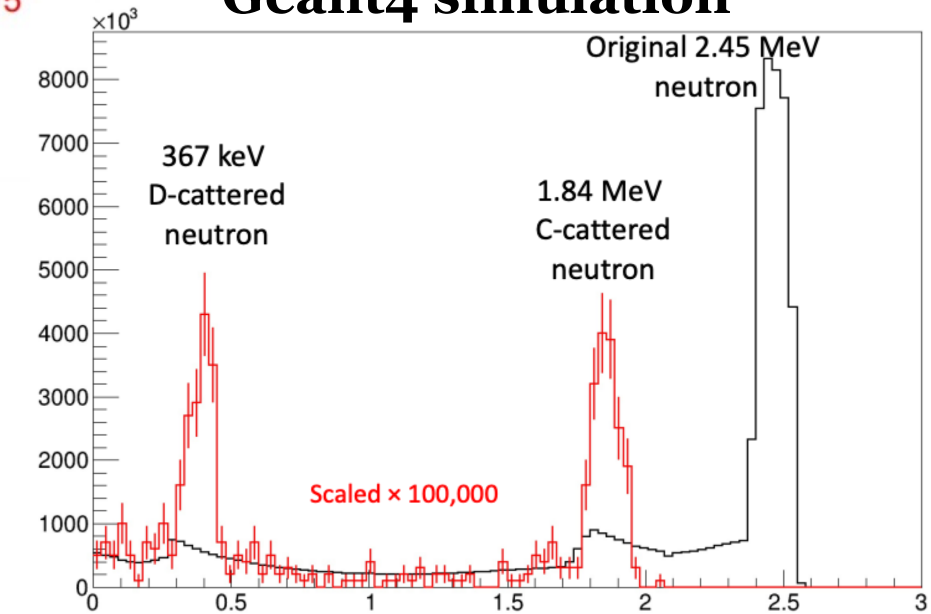
2.5 MeV neutron scattered to deuteron can make O(100 keV) neutrons

NIMA 851, 68 (2017)

- 14~20° angles



Geant4 simulation



Neutron flux ~ 1/60

It will be installed at IBS HQ this year

Summary & Conclusion

- NaI(Tl) crystals have been developed for dark matter search experiments in Korea
  - More than 20 years questions from DAMA/LIBRA

- Korea (KIMS/COSINE) is the world-leading group in the NaI(Tl) detector for rare event searches

- World-leading scientific applications are developed
  - Dark matter
  - CEvNS
  - Migdal effect?

Stay tuned for more exciting results to come from COSINE and NEON experiments!