NaI detector for rare event searches

Hyunsu Lee

Institute for Basic Science

Center for Underground Physics

NaI 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

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/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 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

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

ELSEVIER
Physics Letters B
Volume 433, Issues 1–2, 6 August 1998, Pages 150-155

1998

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

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

NaI(Tl) for rare event searches : Dark Matter

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⊞ Show more

DAMA/LIBRA

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PICO-LON

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ANAIS

1998

Physics Letters B
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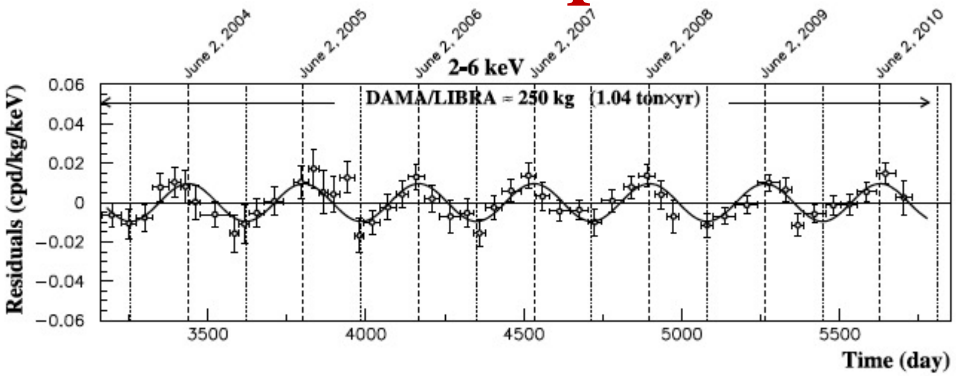
COSINE

Annual modulation signal from DAMA/LIBRA

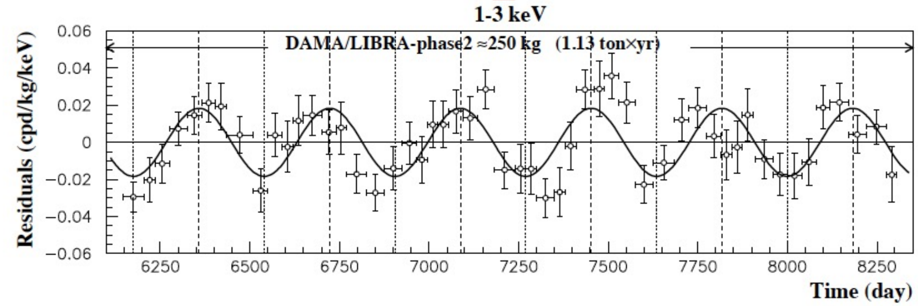
Phase1 experiment



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

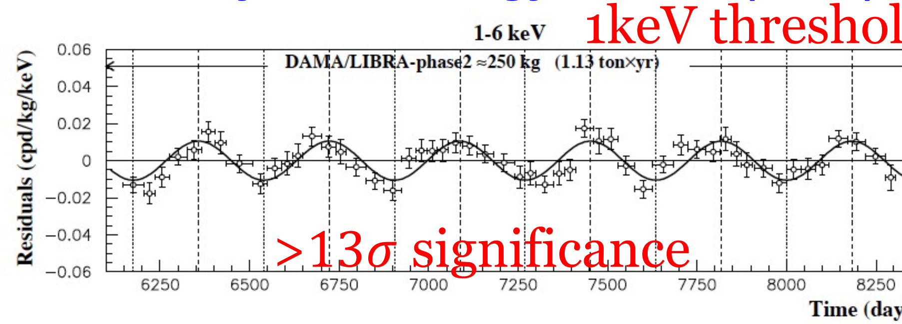
2keV threshold

Phase2 experiment



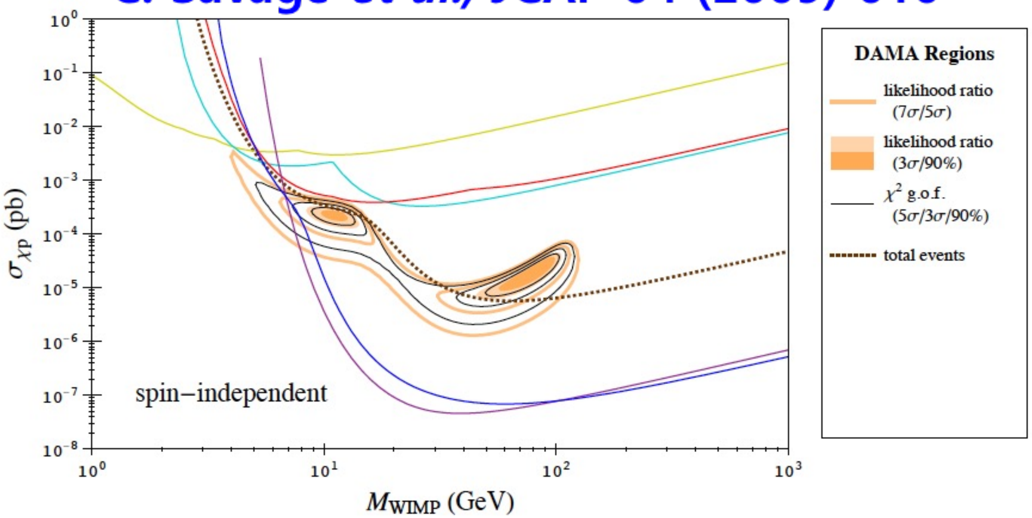
Nucl. Phys. At. Energy 19, 307 (2018)

1keV threshold

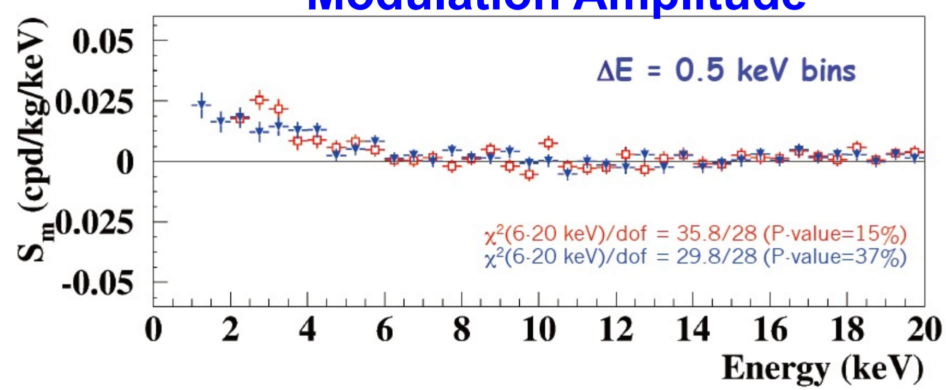


>13σ significance

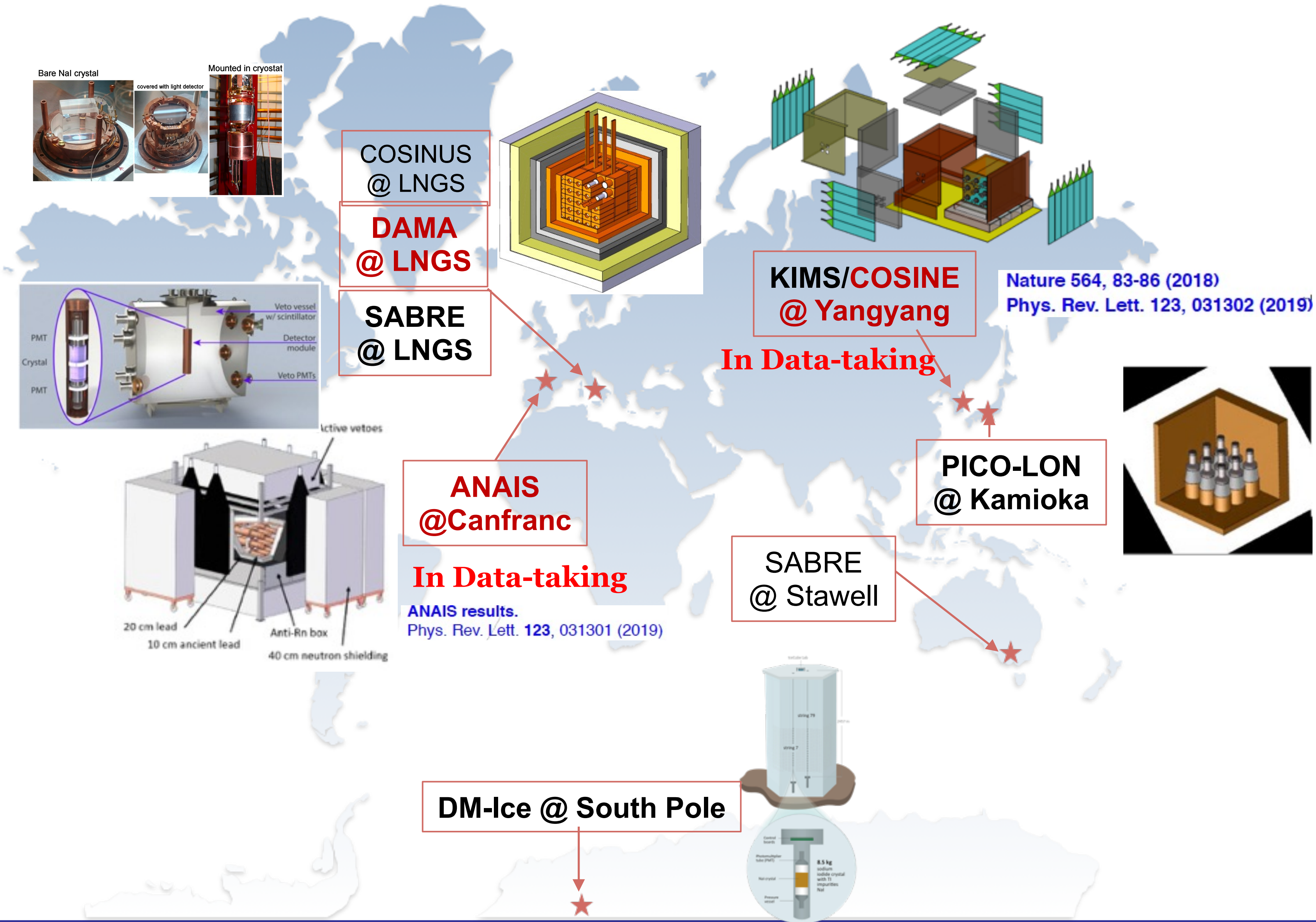
C. Savage *et al.*, JCAP 04 (2009) 010



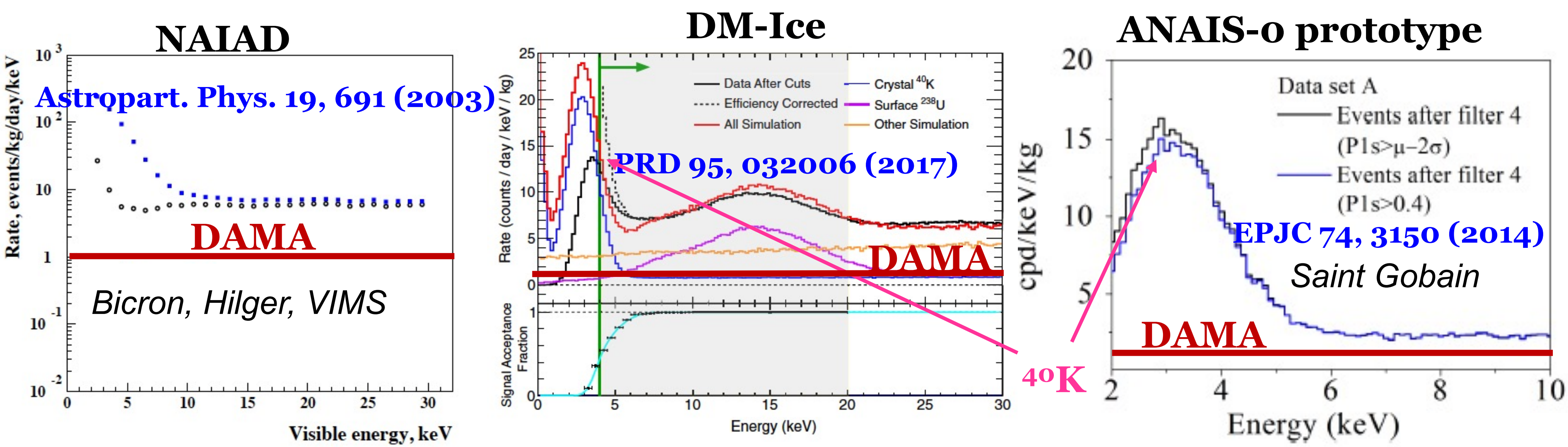
Modulation Amplitude



Global NaI(Tl) efforts



Why it is so hard to reproduce DAMA?

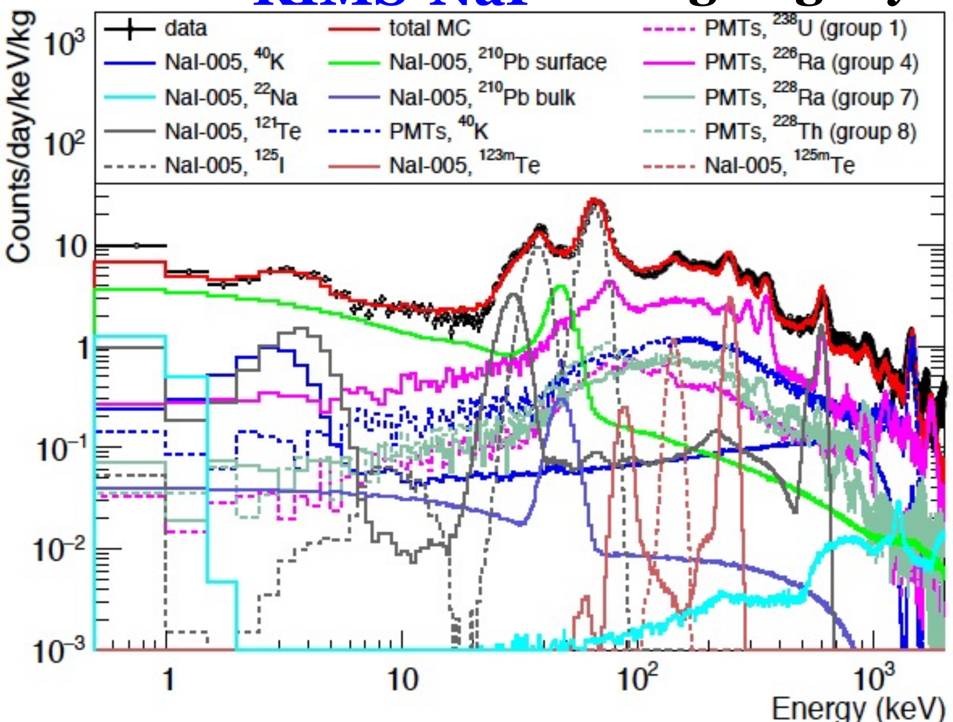


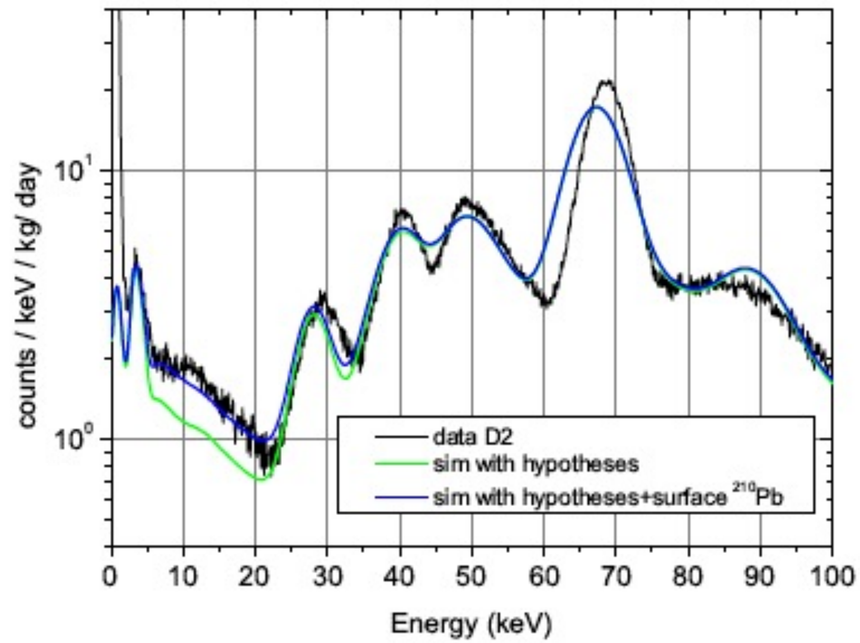
- No other experiments achieve the low-background rate of NaI(Tl)
- Saint-Gobain lost the technique for low-background NaI(Tl) crystals
  - ❖ Confidential contraction between DAMA and Saint-Gobain was finished already

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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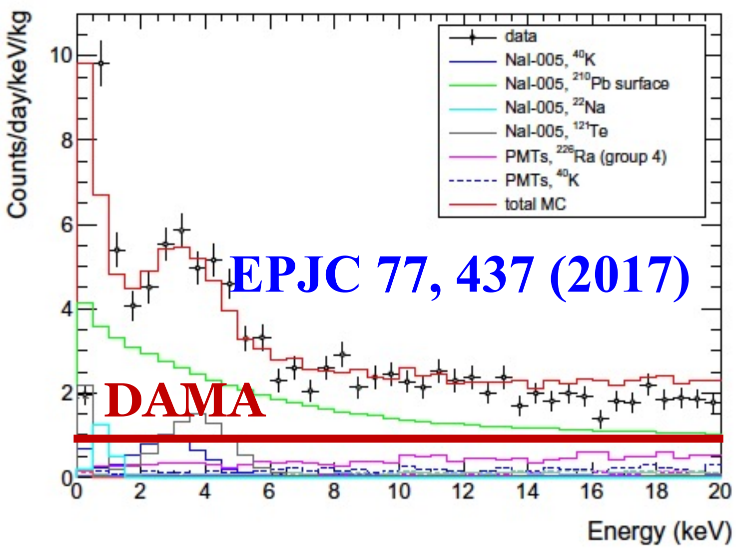
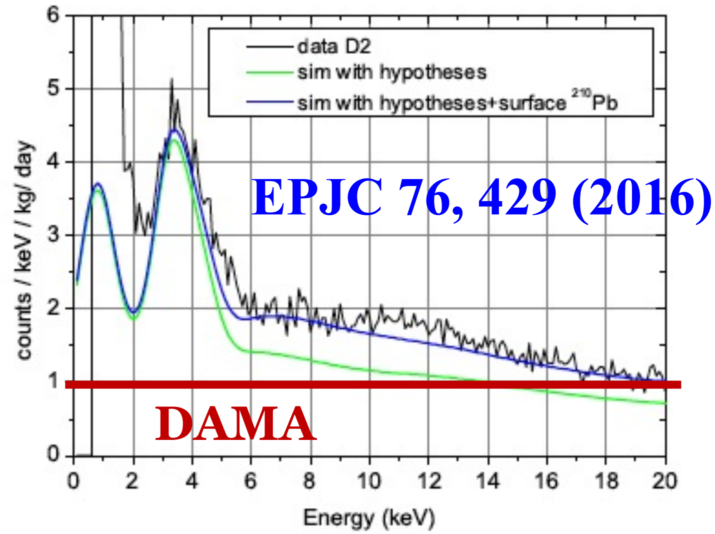




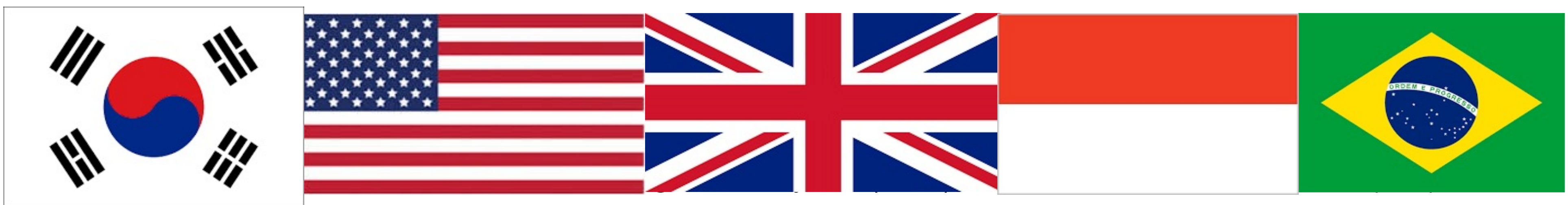
COSINE-100 **ANAIS-112**

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 (Since 2015)

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



YangYang(Y2L) Underground Laboratory

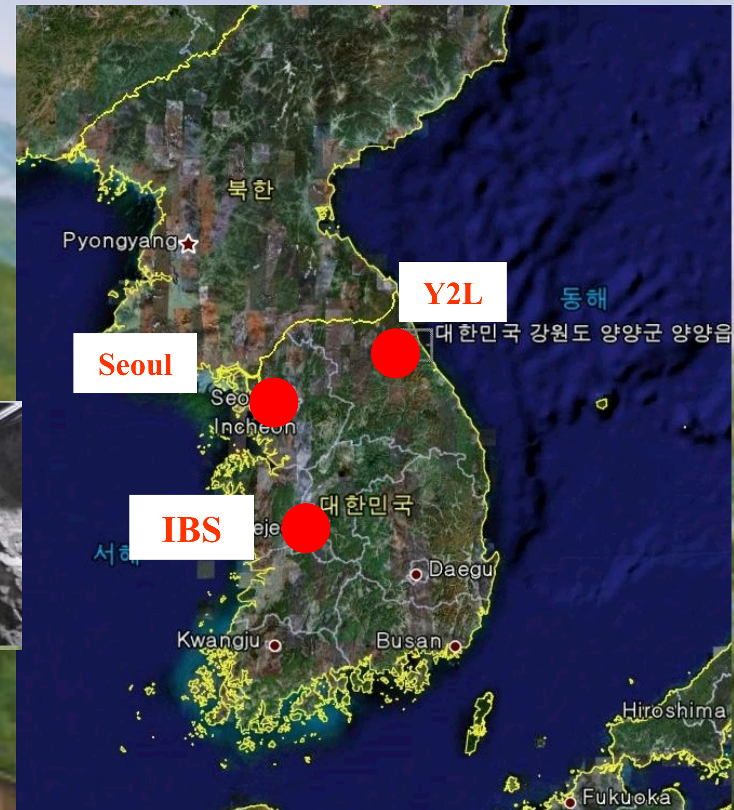
(Upper Dam) YangYang Pumped

Storage Power Plant

1000m

700m

(Power Plant)

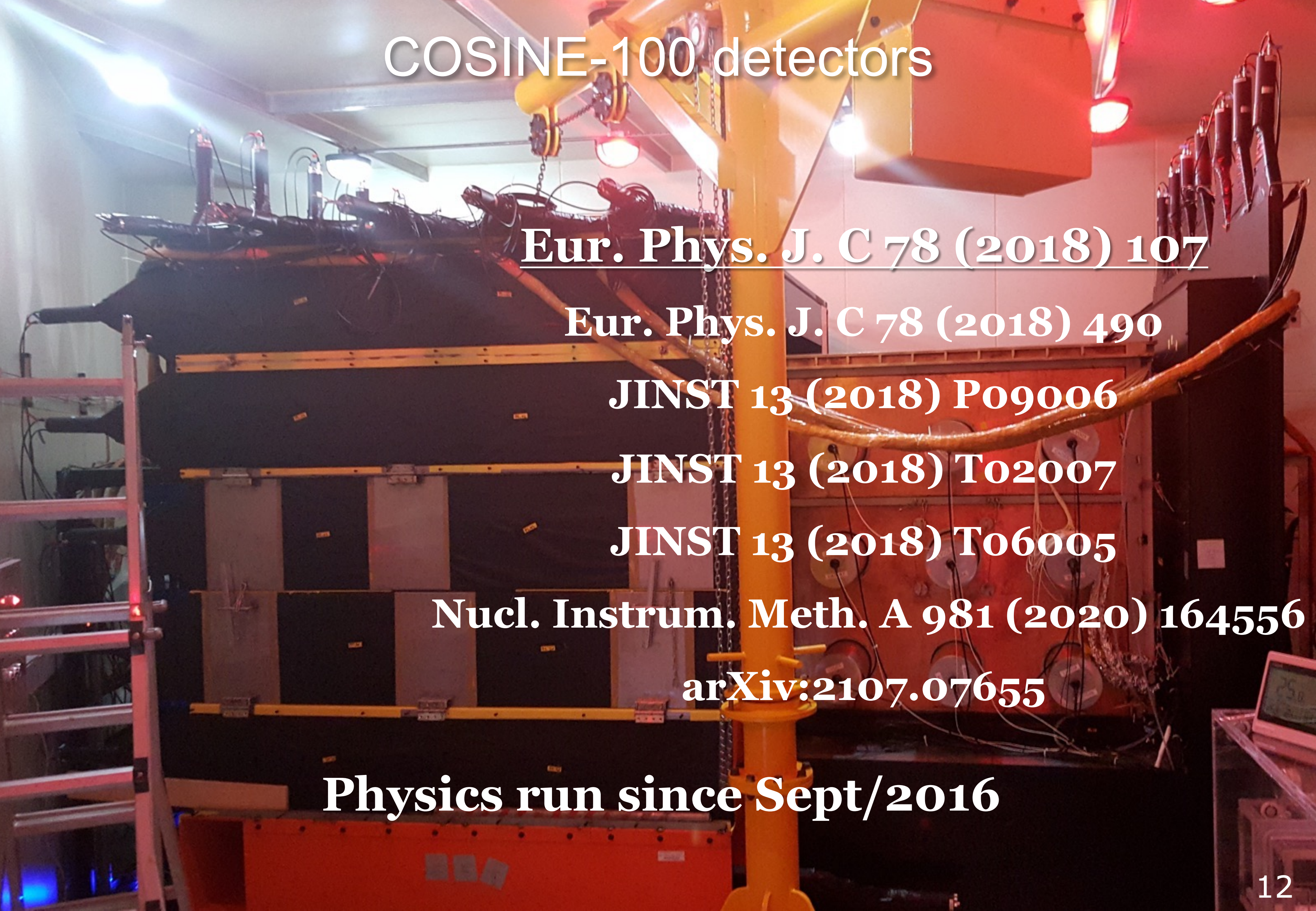


KIMS/COSINE (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)

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

COSINE-100 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

arXiv:2107.07655

Physics run since Sept/2016

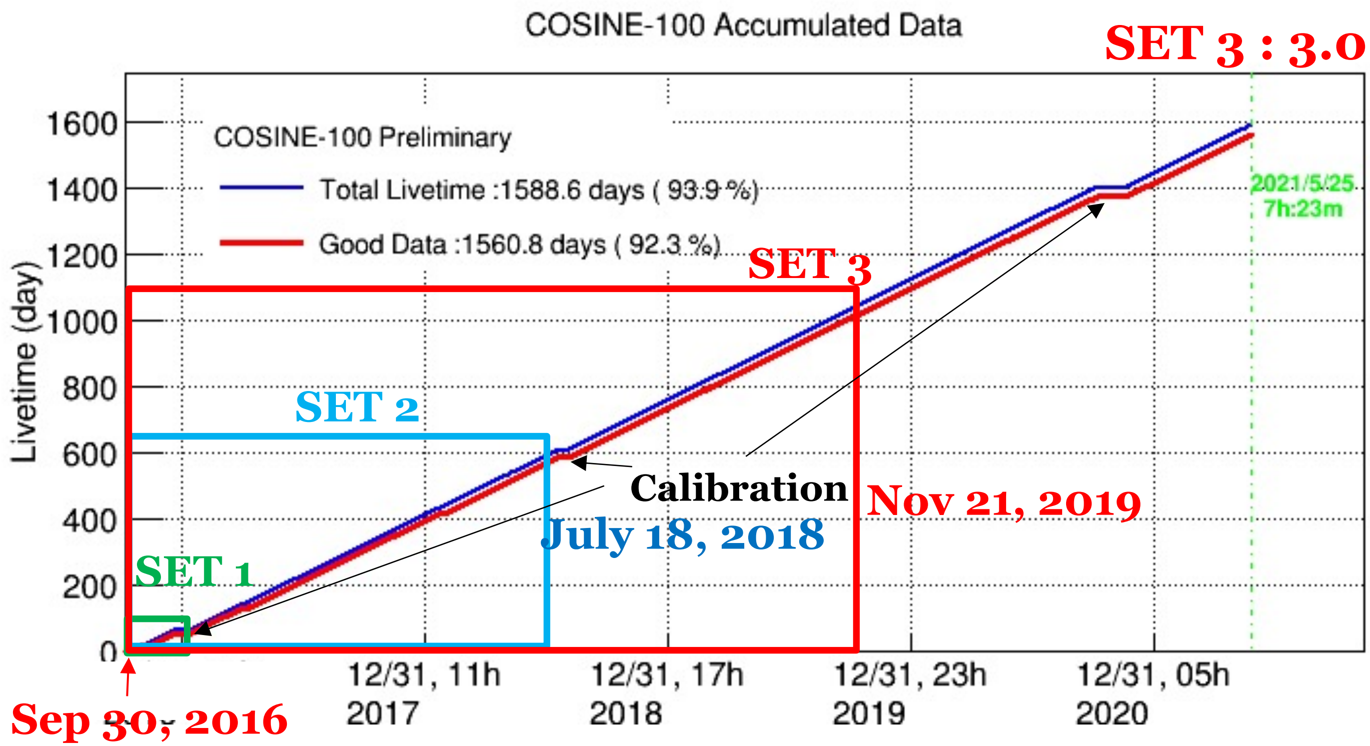
COSINE-100 operation

- **Total Exposure of COSINE-100**

SET 1 : 59.5 days

SET 2 : 1.7 years

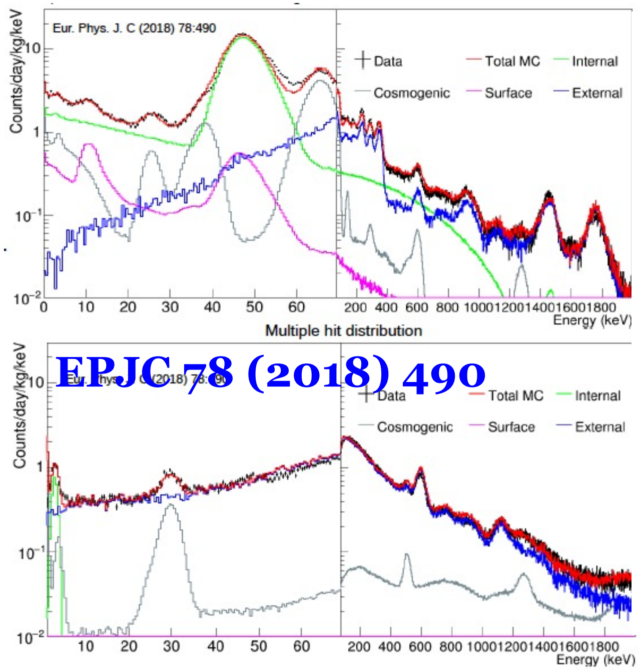
SET 3 : 3.0 years



- **Stable operation from Sep. 2016 for about 4.5 years**
  - **~94 % physics data**
  - **~92 % good quality data**

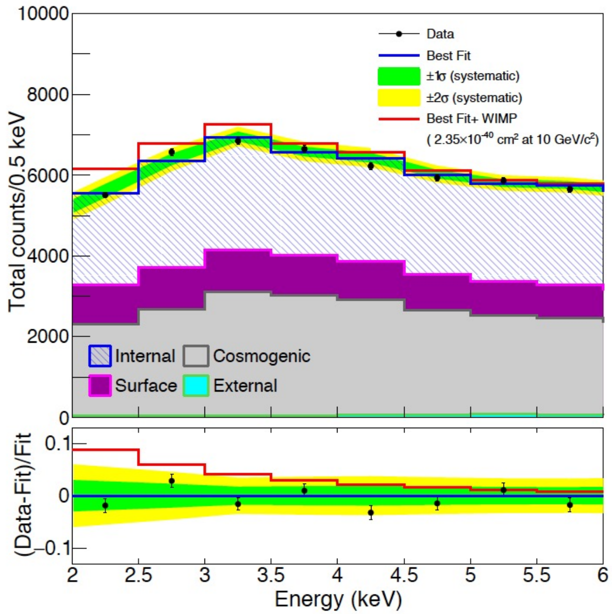
COSINE-100 Physics results (2 keV threshold)

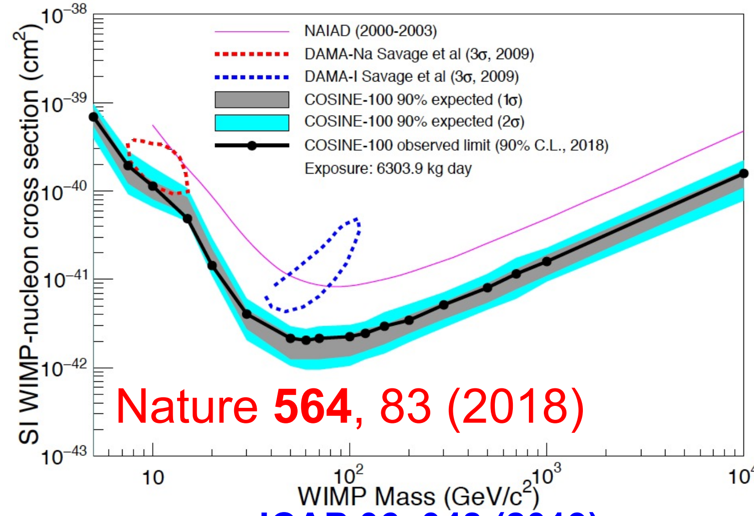
Background modeling (59.5 days)



EPJC 78 (2018) 490

WIMP Search (59.5 days)





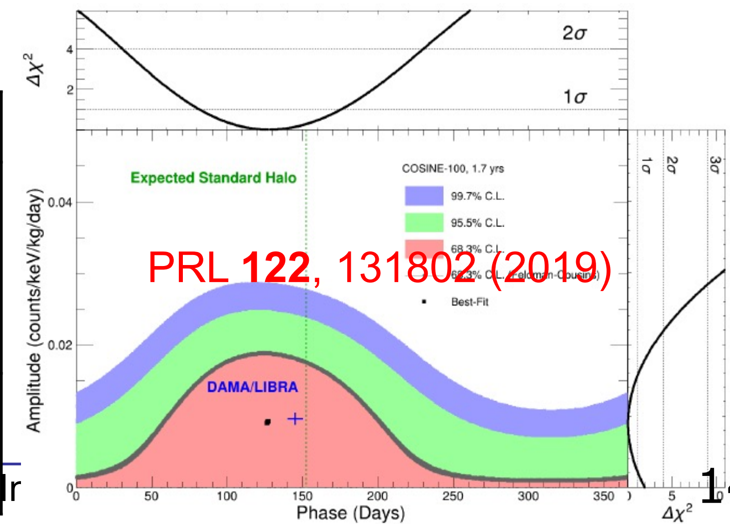
Nature **564**, 83 (2018)

JCAP 06, 048 (2019)

JCAP 11, 008 (2019)

Annual Modulation analysis (**1.7** years)

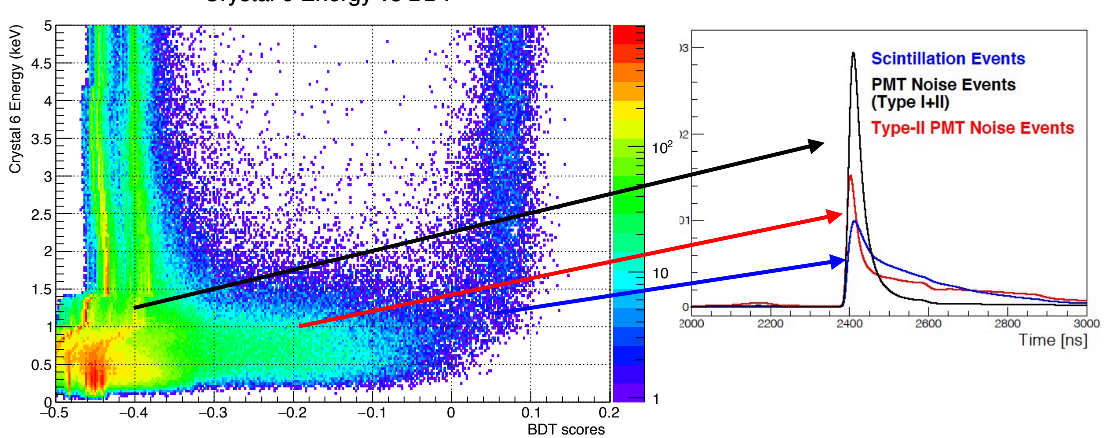
Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	**0.0083 ± 0.0068**	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5



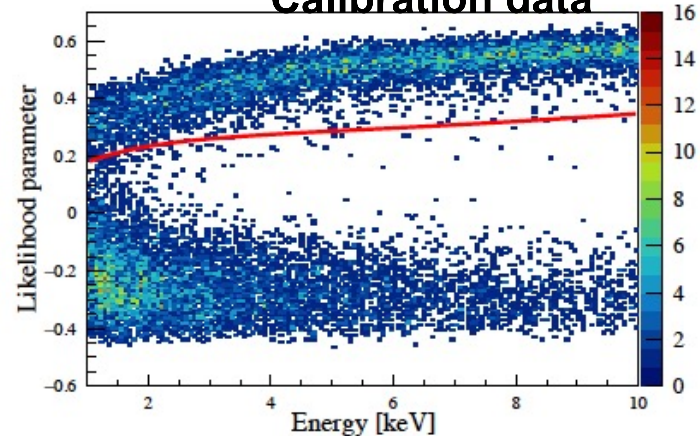
PRL **122**, 131802 (2019)

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

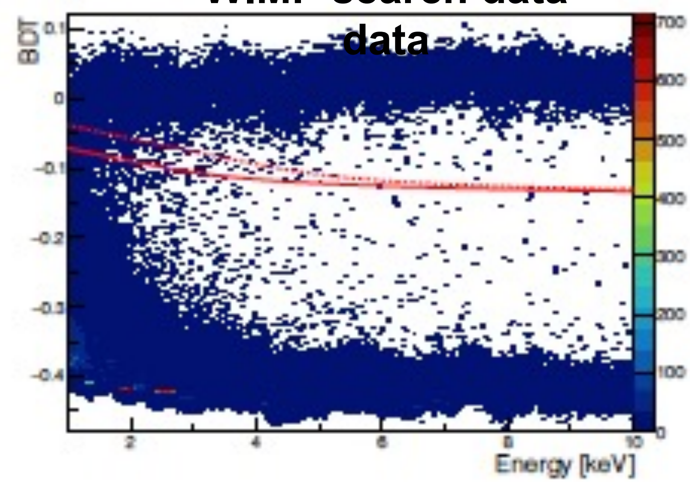


Calibration data



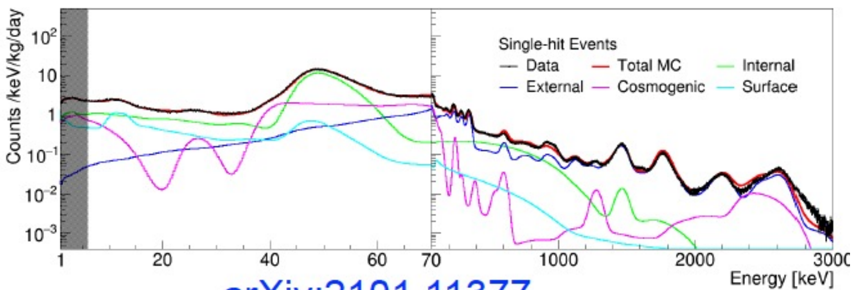
Astropart. Phys 130, 102581 (2021)

WIMP search data

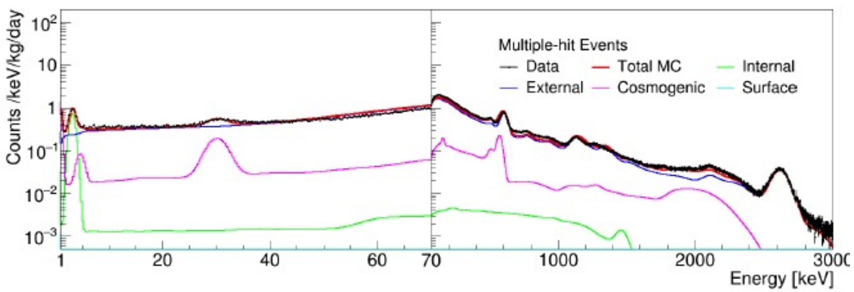


- Develop new likelihood parameter based on the pulse shape of the signals and the noises

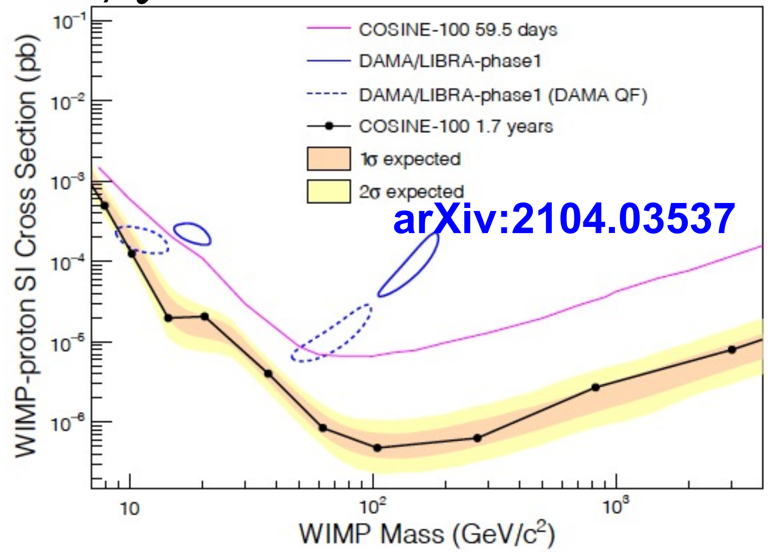
COSINE-100 results with 1keV threshold



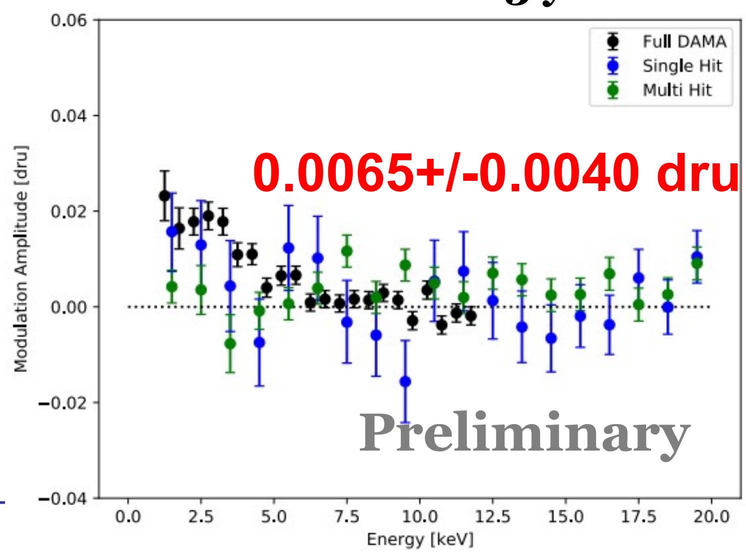
arXiv:2101.11377



1.7 years data



Annual modulation with 3 years data

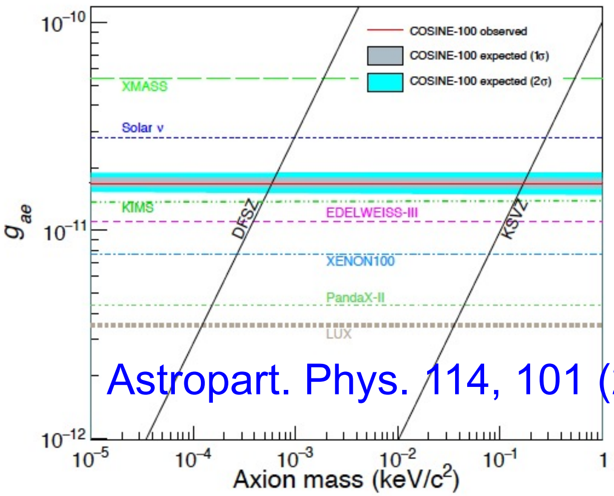


1-6 keV **Preliminary**

COSINE-100	$\mathbf{0.0065 \pm 0.0040}$
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

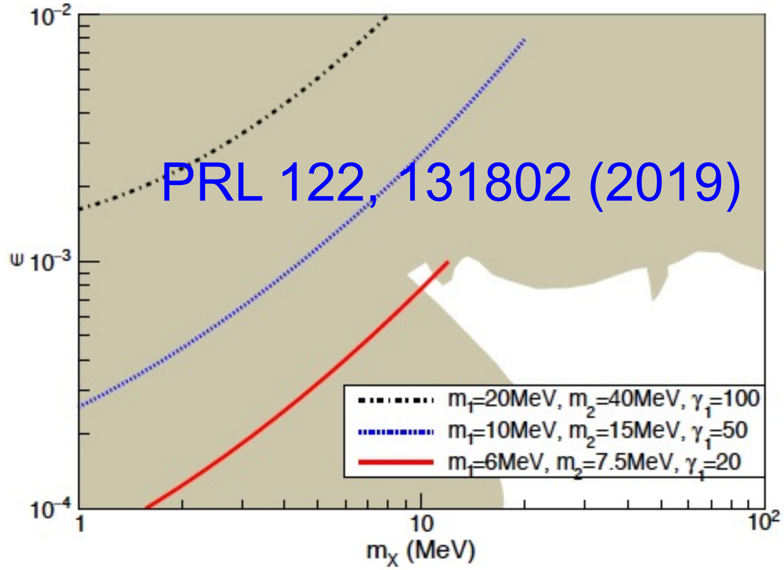
Other analyses

Solar Axion



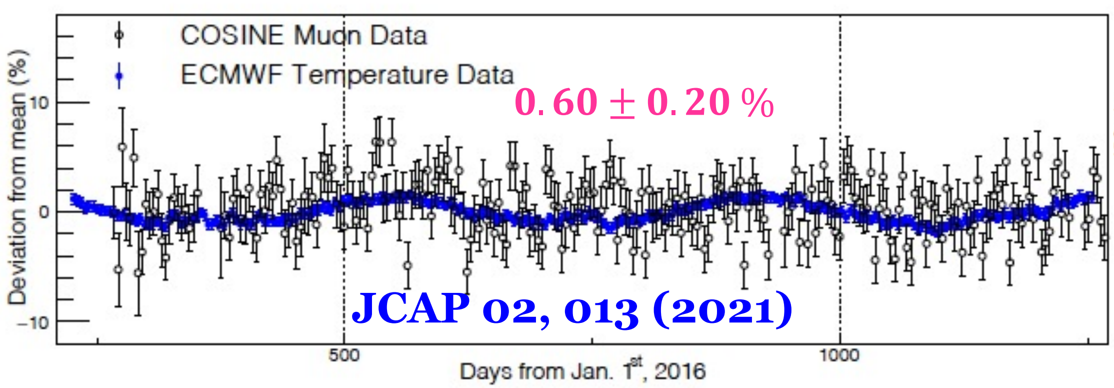
Astropart. Phys. 114, 101 (2020)

Inelastic boosted dark matter



PRL 122, 131802 (2019)

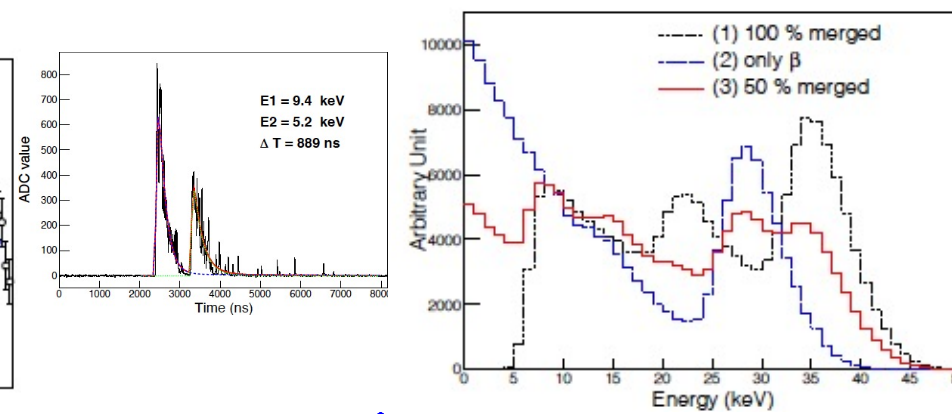
Annual modulation of muon rate



0.60 ± 0.20 %

JCAP 02, 013 (2021)

New isomers in ^{228}Ac



arXiv:2103.02809

COSINE-200 crystal development

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

Powder purification performance

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

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

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

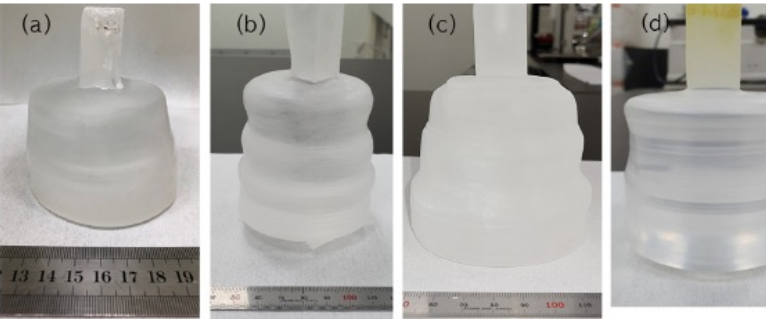

Purification factory ~ 70 kg powder load


Test grower ~ 1kg ingot


Full size grower ~ 100 kg ingot

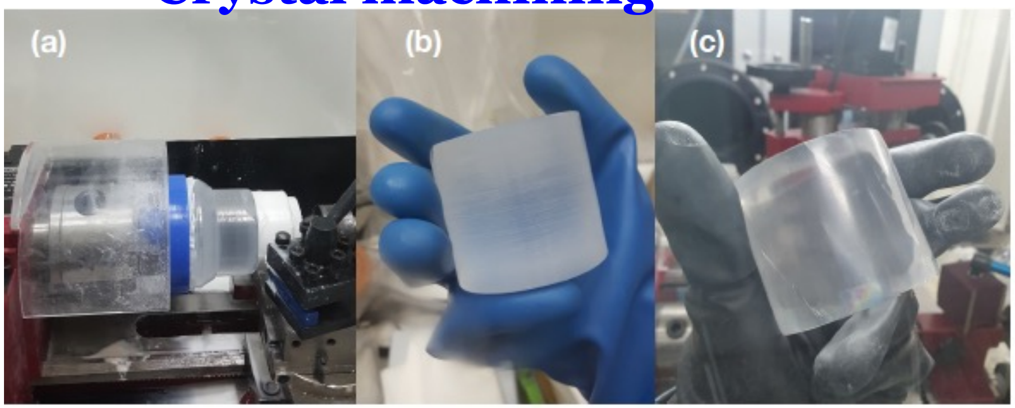
Our grown crystals

Crystal ingots



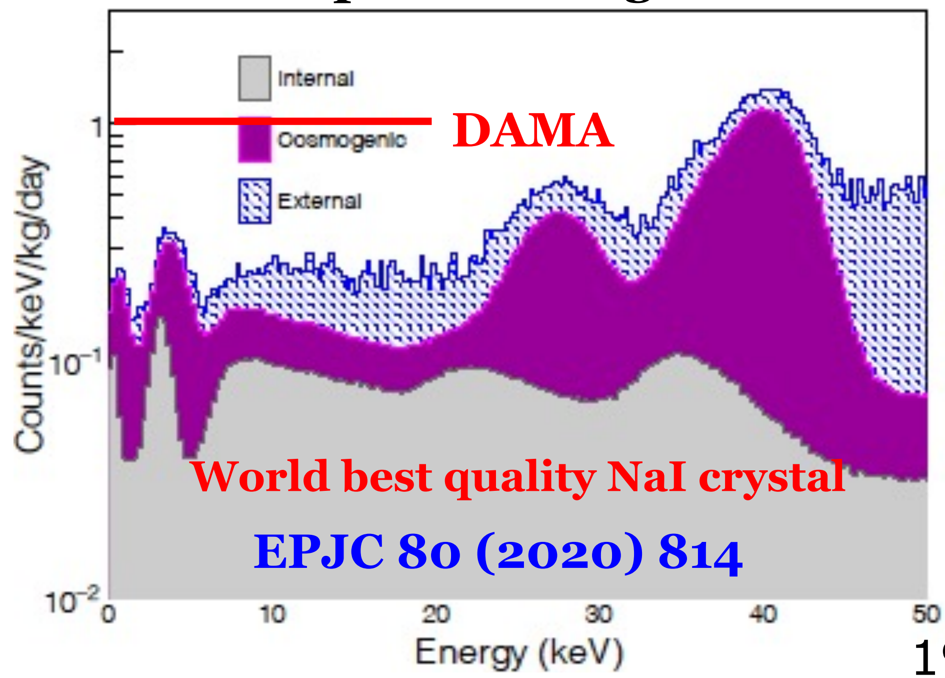
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/k
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

Crystal machining



Detector assembly

Expected background



World best quality NaI crystal

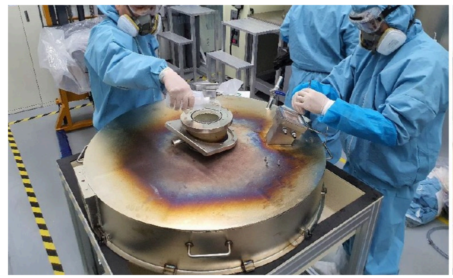
EPJC 80 (2020) 814

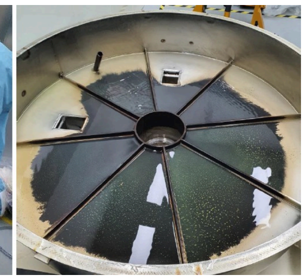
A proof of principle for low background NaI

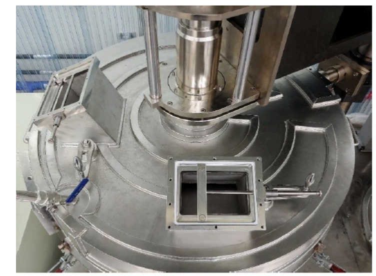
Full size grower

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

First run







Third run

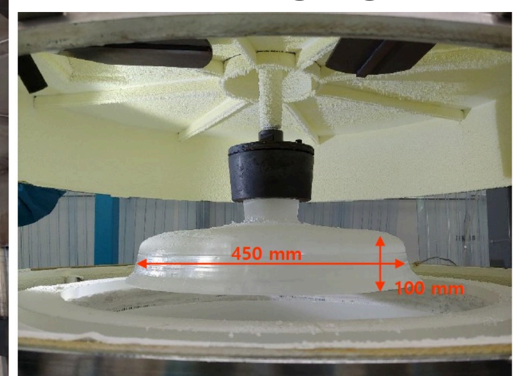
~200 kg powder

<Powder charging>

Seed holder

<Seed & holder>

~50 kg ingot

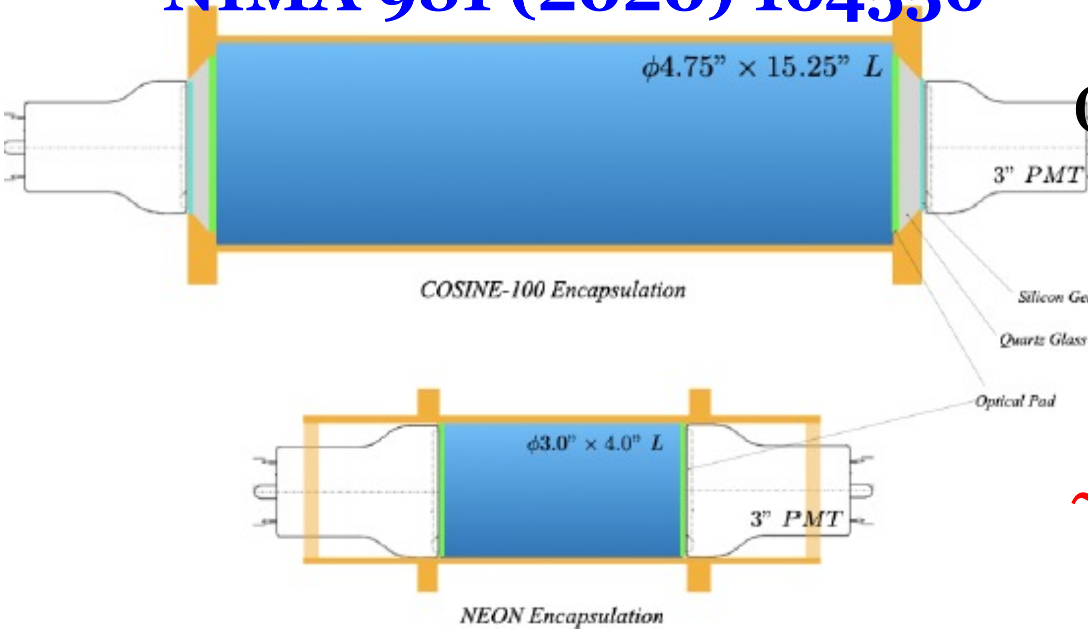


<Crystal dimension>

- **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

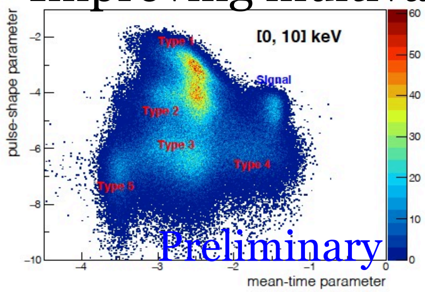
(NPE=number of photoelectrons)

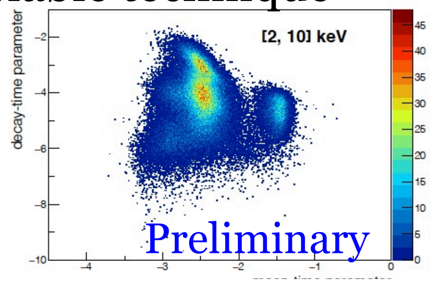
~23 NPE/keV

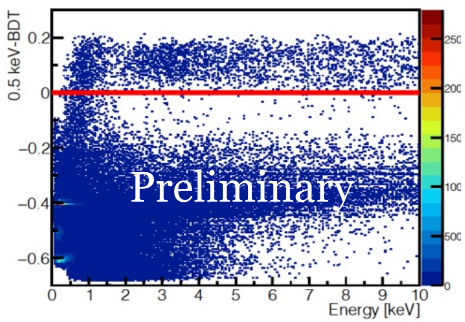
- Direct attachment of NaI(Tl) to PMTs
- ~50 % increased light yield was observed
- This technique can be applied for COSINE-200 detector assembly

Efforts for low-threshold NaI(Tl) detectors

Improving multivariable technique



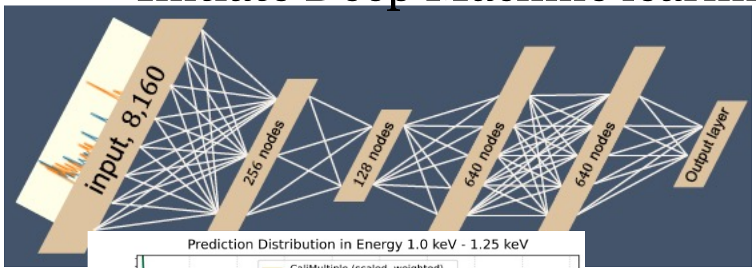


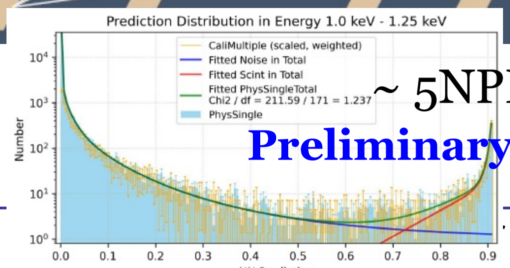


Multiple-hit

~ 0.5 keV (7 NPE) threshold achievable!!

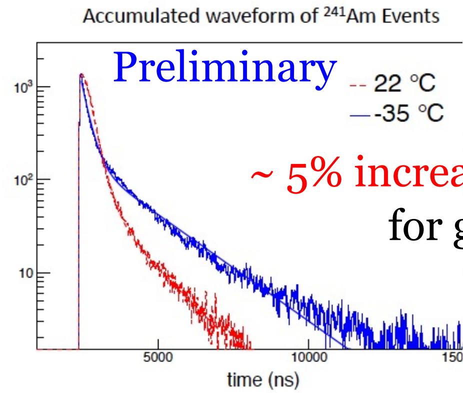
Initiate Deep Machine learning



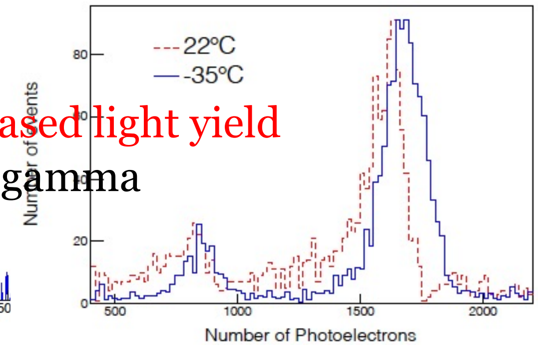


~ 5NPE threshold?

Low temperature measurement

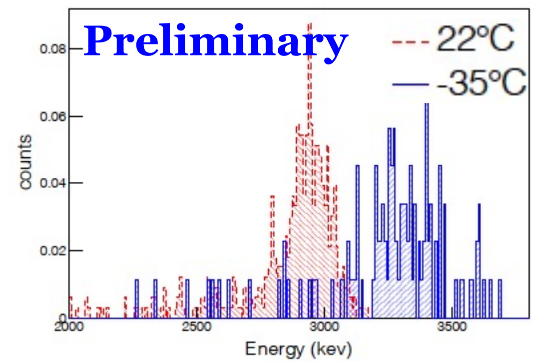


Am-241 measurement



~ 5% increased light yield for gamma

Po-210 alpha measurement



Alpha quenching increased ~ 10 %

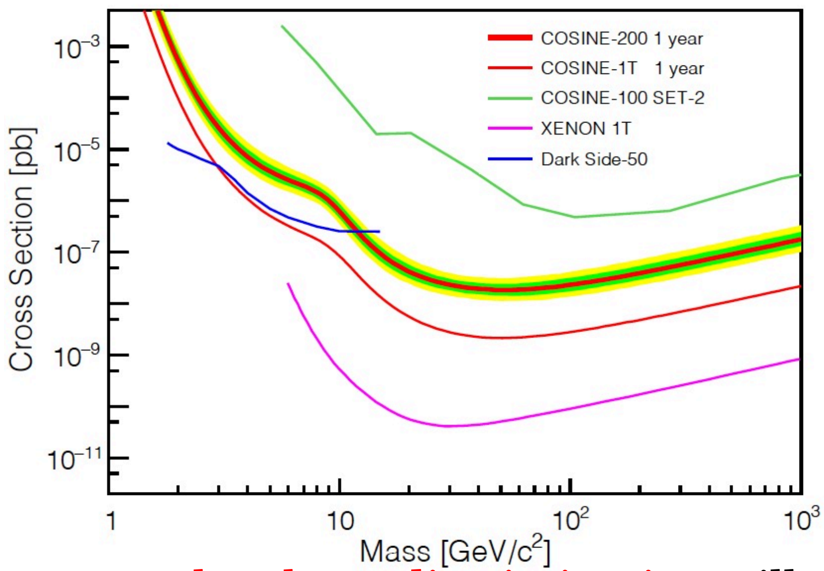
Neutron quenching measurement is under preparation

Consider -30°C operation of COSINE-200

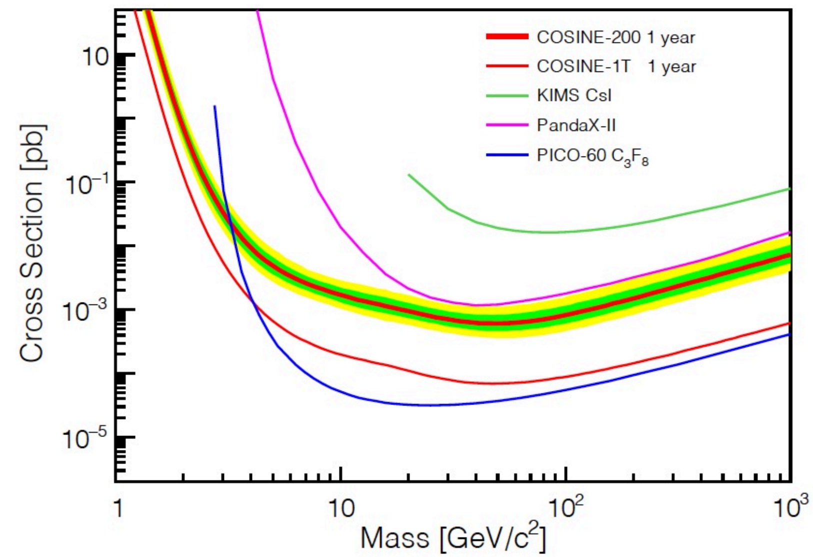
COSINE-200 sensitivity

- Assuming light yield ~ 22 NPE/keV (5NPE threshold)
- 10% increased quenching factor was assumed

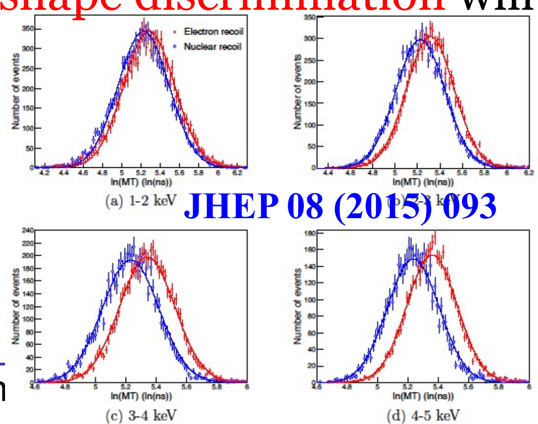
WIMP-nucleon spin-independent



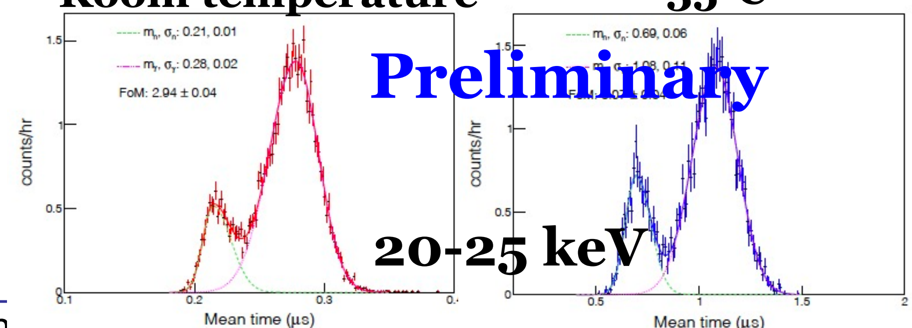
WIMP-proton spin-dependent



Pulse shape discrimination will enhance dark matter detection sensitivity significantly



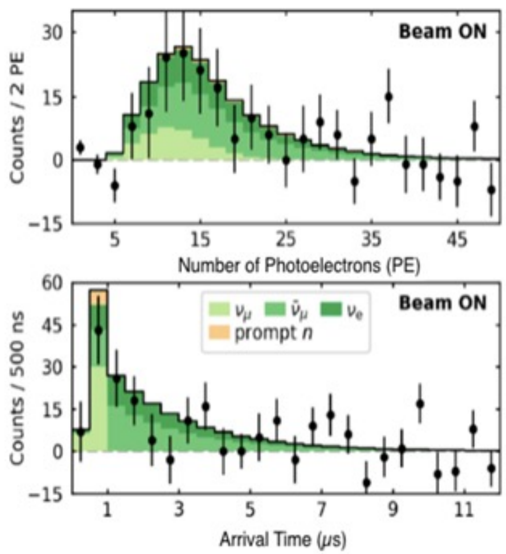
Room temperature -35°C



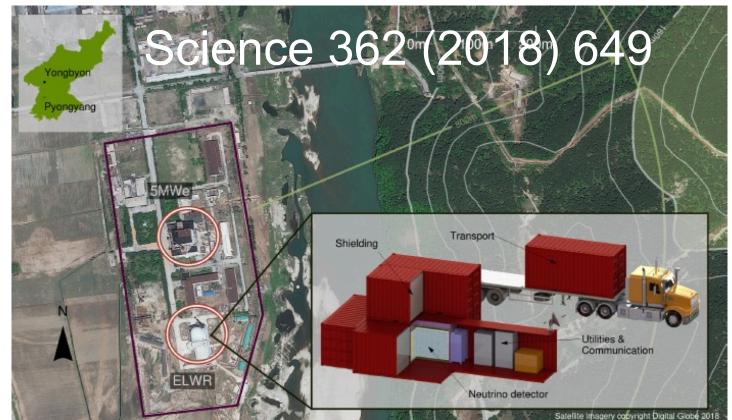
Possibility to detect CEνNS in reactor

- 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

Science **357**, 1123 (2017)



Science 362 (2018) 649



NEON Collaboration

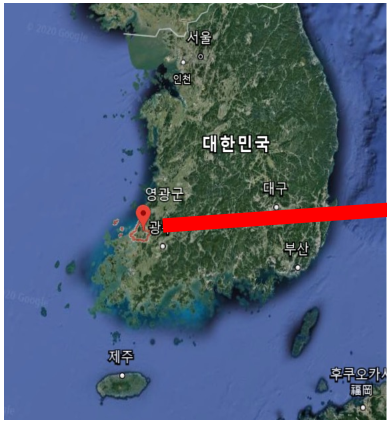
~ 15 people who are all active members of COSINE-100 and/or NEOS

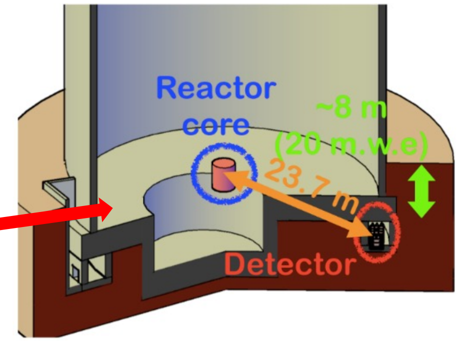
Aim to observe CEνNS from reactor $\bar{\nu}_e$ using NaI(Tl) detector

Can take an advantage of COSINE-100 and NEOS experiences

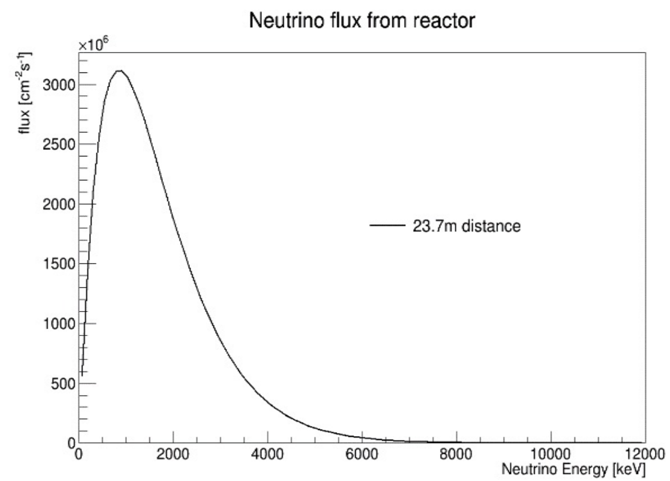
Hanbit nuclear power plant

Tendon Gallery of Hanbit Nuclear Power Plant (Yeonggwang)





- Good relation with company
  - NEOS site – unit 5 (Maintenance May~Oct 2020)
  - NEON site – unit 6 (Maintenance Jan~May 2021)
- 2.8 GW thermal power
- Tendon gallery is ~24 m far from reactor core
  - Environmental conditions were well known from NEOS experiment



Neutrino($\bar{\nu}_e$) flux at NEON site : 7.1×10^{12} **cm^{-2}s^{-1}**

Construction of the NEON detector (Nov/2020)

Nov/12 **Nov/13**

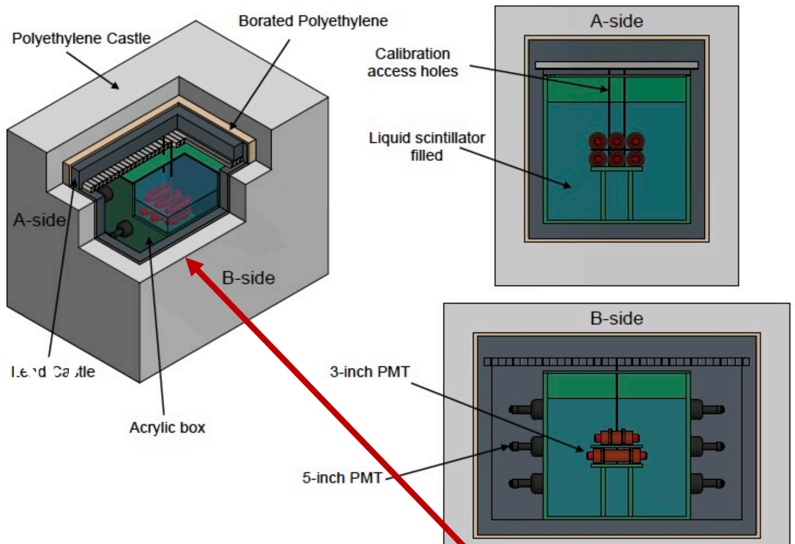
Nov/19 **Nov/20**

Nov/26

Dec/7/2020

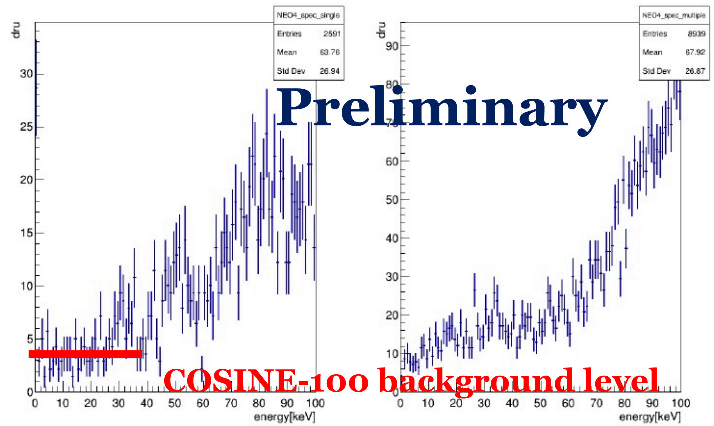
NEON status

Detector is onsite since Dec/2020



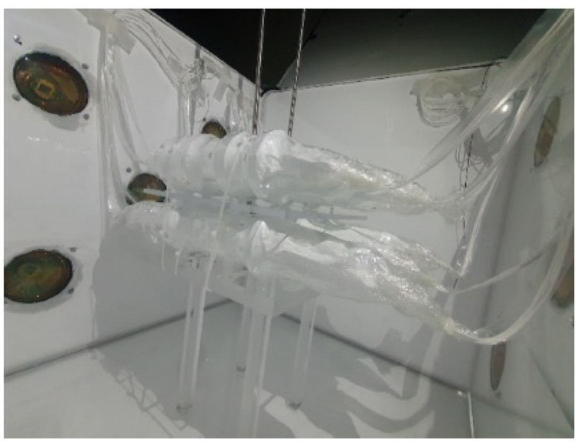
Reactor data

Single-hit **Multiple-hit**

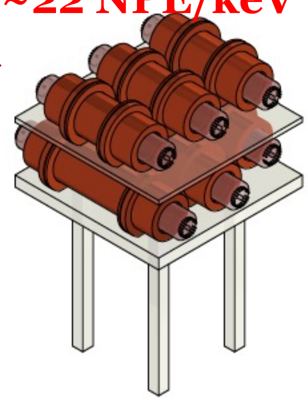


Reactor on from May/22, 2021

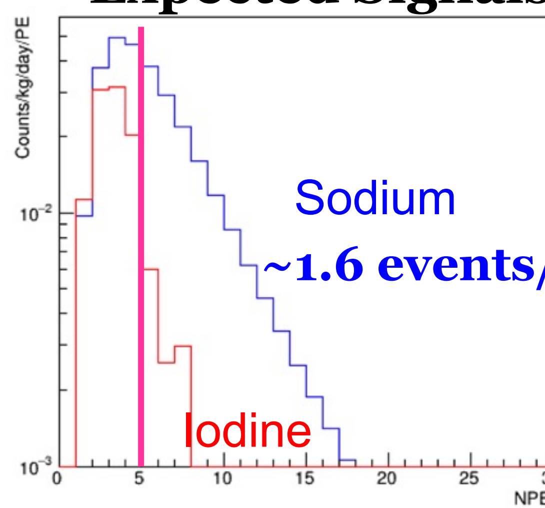
~ 15 kg NaI(Tl) crystals (six units)



~22 NPE/keV



Expected Signals



~1.6 events/day/15 kg

~ 4 σ observation sensitivity with 2 years operation

Issues on low-energy nuclear recoil calibration

~18.2 NPE/keV

Scattering angle (deg)	Sim. Na recoil energy (keV_{nr})	Observed recoil energy (keV_{ee})	Quenching factor
18.2	2.9 ± 0.7	<0.65	<0.22
24.9	5.7 ± 0.7	0.76 ± 0.4	0.133 ± 0.018
31.1	8.8 ± 1.2	1.13 ± 0.5	0.129 ± 0.014
32.2	9.1 ± 1.2	1.46 ± 0.5	0.162 ± 0.012
41.1	14.3 ± 2.4	2.21 ± 0.9	0.159 ± 0.019
41.3	15.0 ± 1.4	2.36 ± 0.8	0.160 ± 0.010
47.9	19.4 ± 1.6	3.21 ± 1.0	0.168 ± 0.009
54.4	24.9 ± 2.4	4.10 ± 1.5	0.171 ± 0.010
59.1	29.0 ± 1.9	5.36 ± 1.9	0.188 ± 0.008
64.6	33.3 ± 2.8	6.19 ± 2.1	0.191 ± 0.011
74.2	43.0 ± 2.2	8.53 ± 2.7	0.204 ± 0.008
84.0	51.8 ± 2.6	10.59 ± 4.5	0.207 ± 0.010

PRC 92, 015807 (2015)

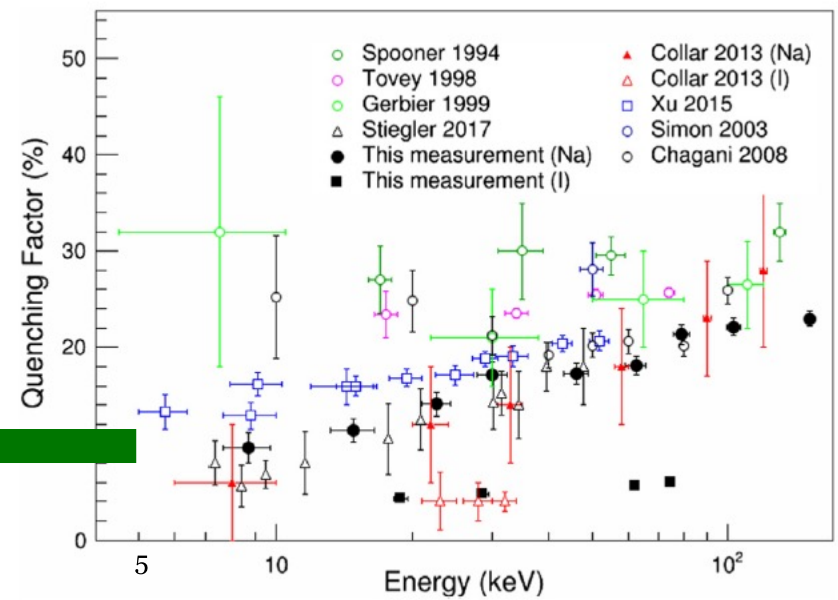
~14 NPE/keV

Nuclei	Scattering angle (degree)	E_{ee} (keV)	E_{nr} (keV)	Quenching factor (%)
Na	13.2	<0.5	5.8 ± 1.0	
	16.4	0.83 ± 0.07	8.7 ± 1.3	9.6 ± 1.6
	21.3	1.68 ± 0.04	14.8 ± 1.6	11.3 ± 1.2
	26.6	3.20 ± 0.05	22.7 ± 2.0	14.1 ± 1.3
	31.0	5.17 ± 0.07	30.1 ± 2.2	17.2 ± 1.3
	38.2	7.97 ± 0.09	46.1 ± 2.8	17.3 ± 1.1
	45.0	11.4 ± 0.1	62.6 ± 3.2	18.1 ± 0.9
	51.3	16.8 ± 0.2	78.9 ± 3.6	21.3 ± 1.0
	59.0	22.7 ± 0.2	102.7 ± 4.1	22.1 ± 0.9
	74.7	34.7 ± 0.3	151.6 ± 5.0	22.9 ± 0.8

Astropart. Phys. 108, 50 (2019)

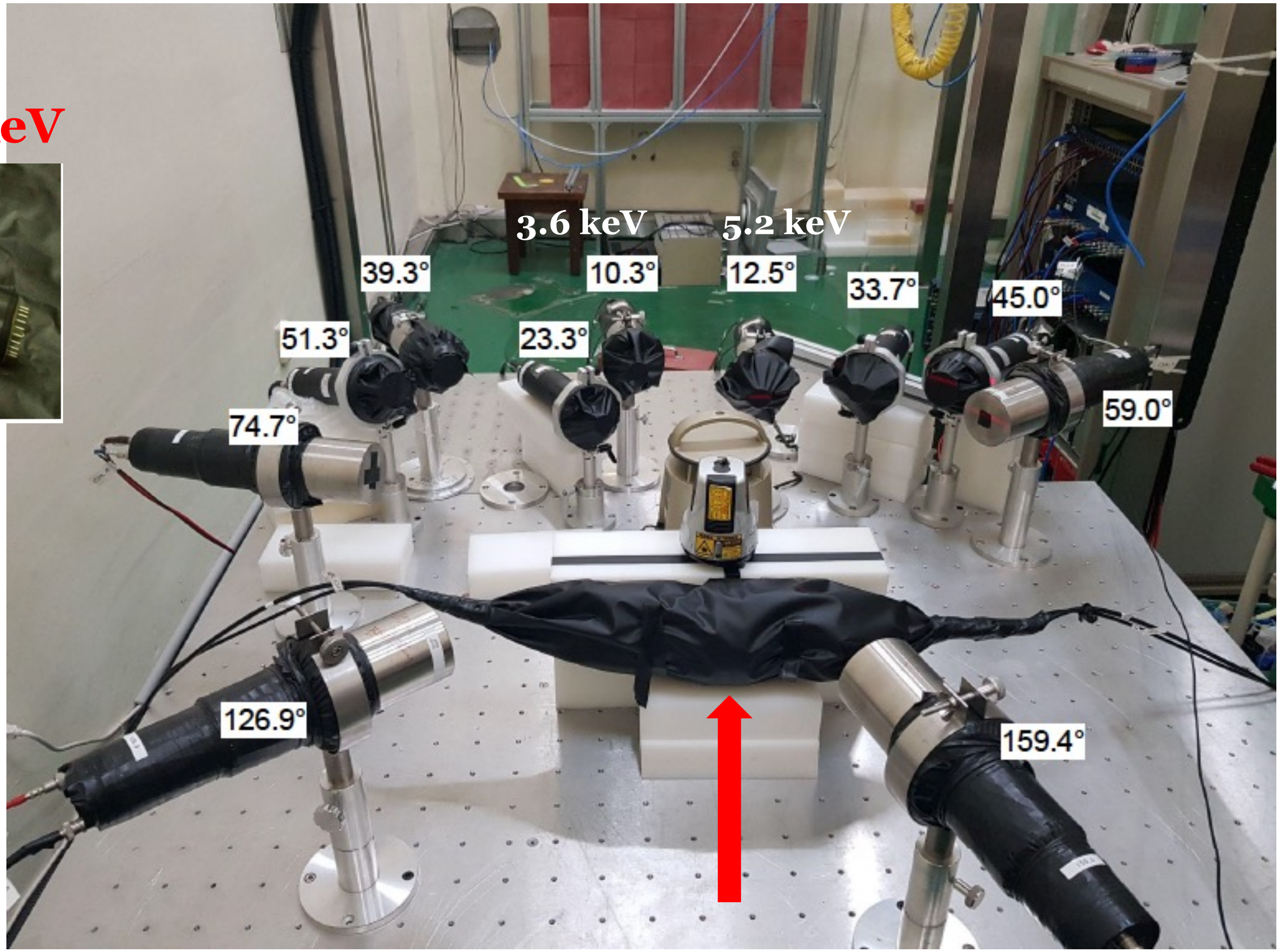
Need to measure below 5 keV_{nr}

< 0.5 keV_{ee}



New setup for neutron calibration

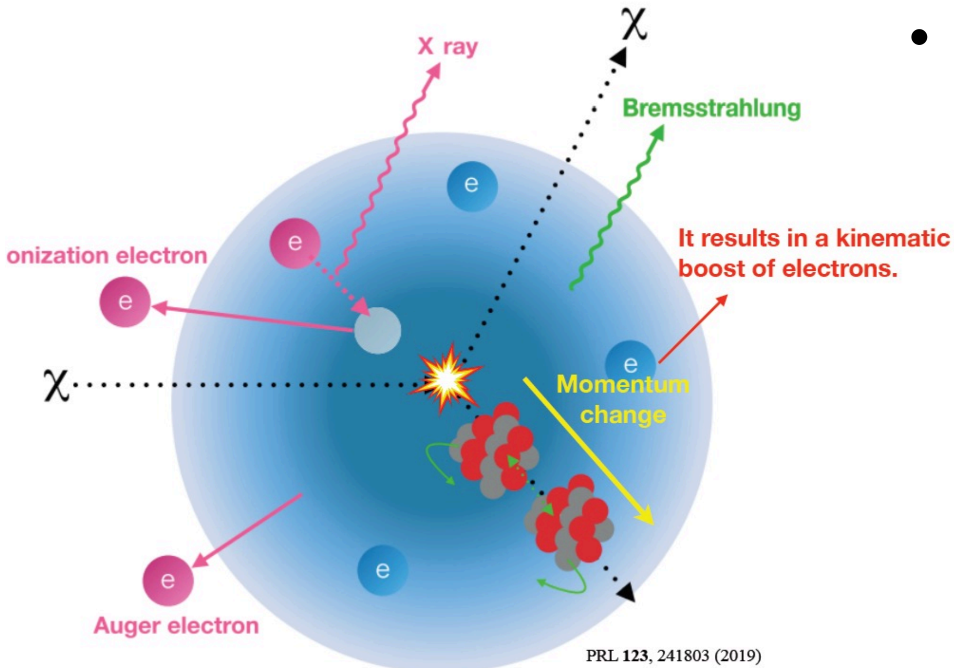
~25 NPE/keV



2.45 MeV neutron from DD generator

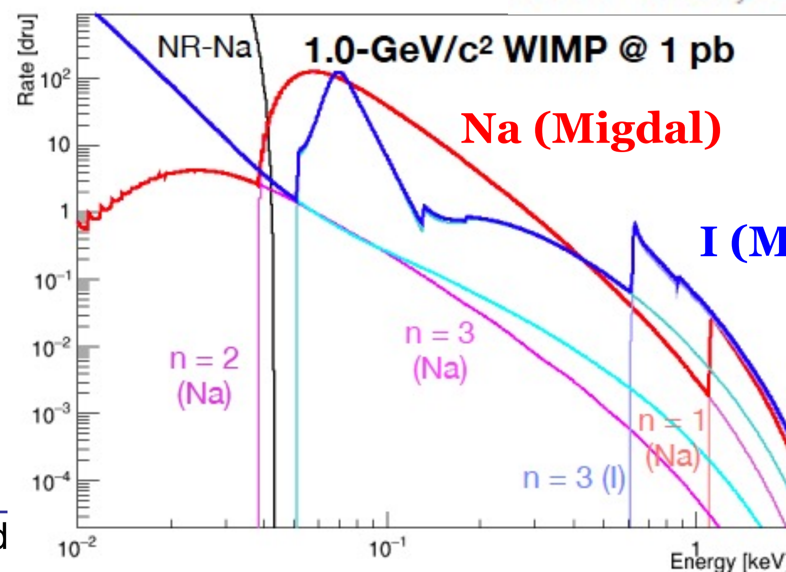
Migdal effect for low energy nuclear recoil

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

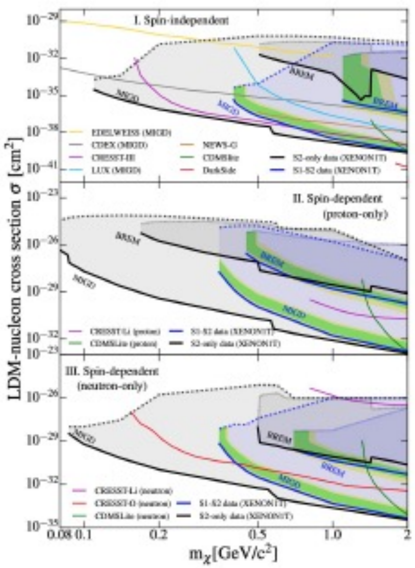


- Although electron recoil energy should be smaller than total nuclear recoil energy, such electron recoil do not have quenched
  - ❖ Na nuclear recoil has only 10% quenching

JHEP 2018, 194 (2018)



Migdal is new era for low-mass dark matter

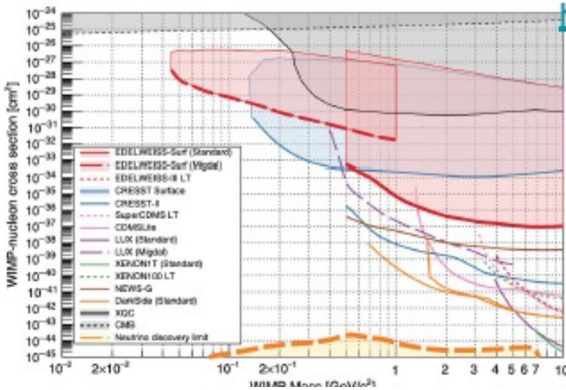


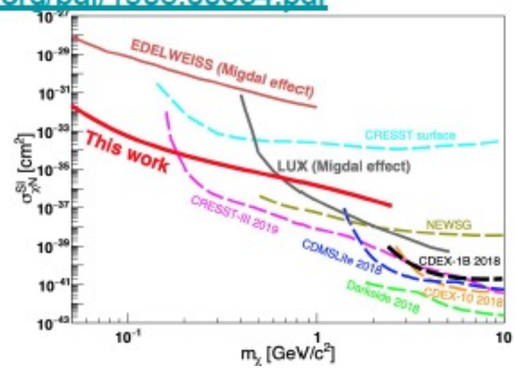
LUX (Xenon)
"Results of a Search for Sub-GeV Dark Matter Using 2013 LUX Data"
https://arxiv.org/pdf/1811.11241.pdf PRL 122,131301 (2019)

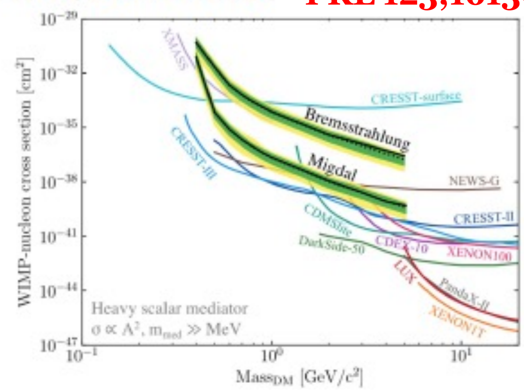
XENON1T (Xenon)
"A Search for Light Dark Matter Interactions Enhanced by the Migdal effect or Bremsstrahlung in XENON1T"
https://arxiv.org/pdf/1907.12771.pdf PRL 123,241803 (2019)

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)

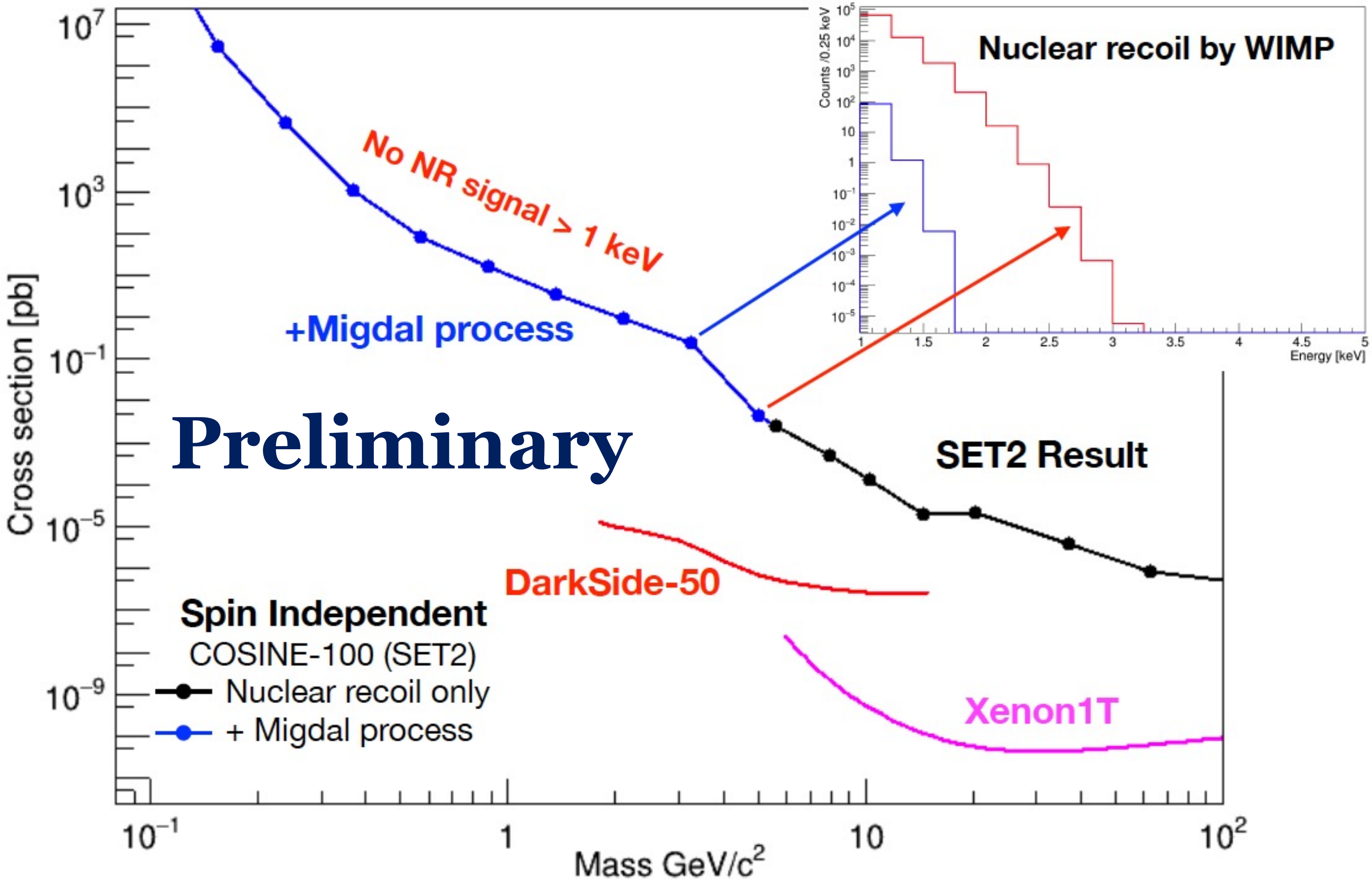
CDEX-1B (Germanium)
"Constraints on Spin-Independent Nucleus Scattering with sub-GeV Weakly Interacting Massive Particle Dark Matter from the CDEX-1B Experiment at the China Jin-Ping Laboratory" PRL 123,161301 (2019)
https://arxiv.org/pdf/1905.00354.pdf







COSINE-100 limit with Migdal effect



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

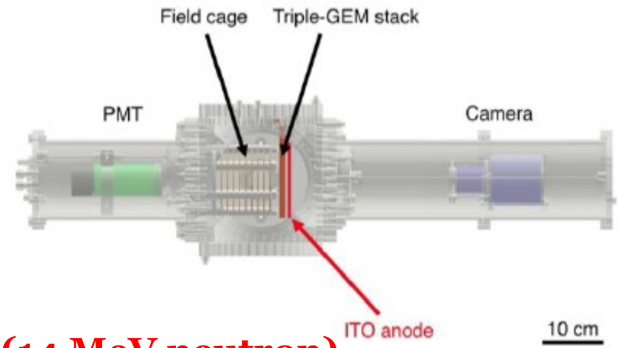
University of New Mexico D. Loomba

University of Oxford H. Kraus

University of Sheffield V. Kudryavtsev

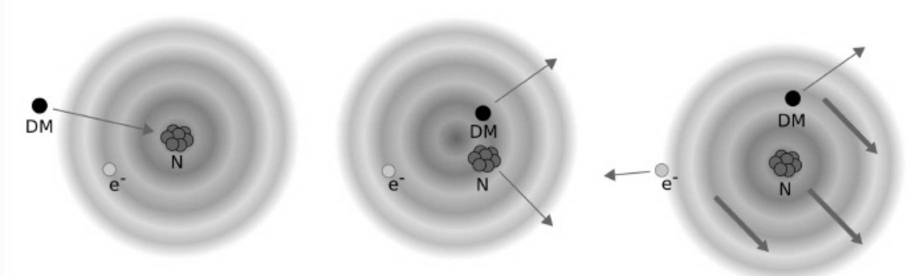
11

High pressure gas detector

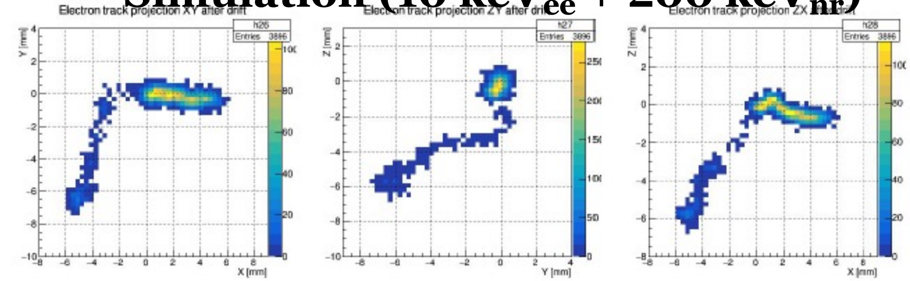


DT generator (14 MeV neutron)

- Measure tracks of both nuclear and electron recoils

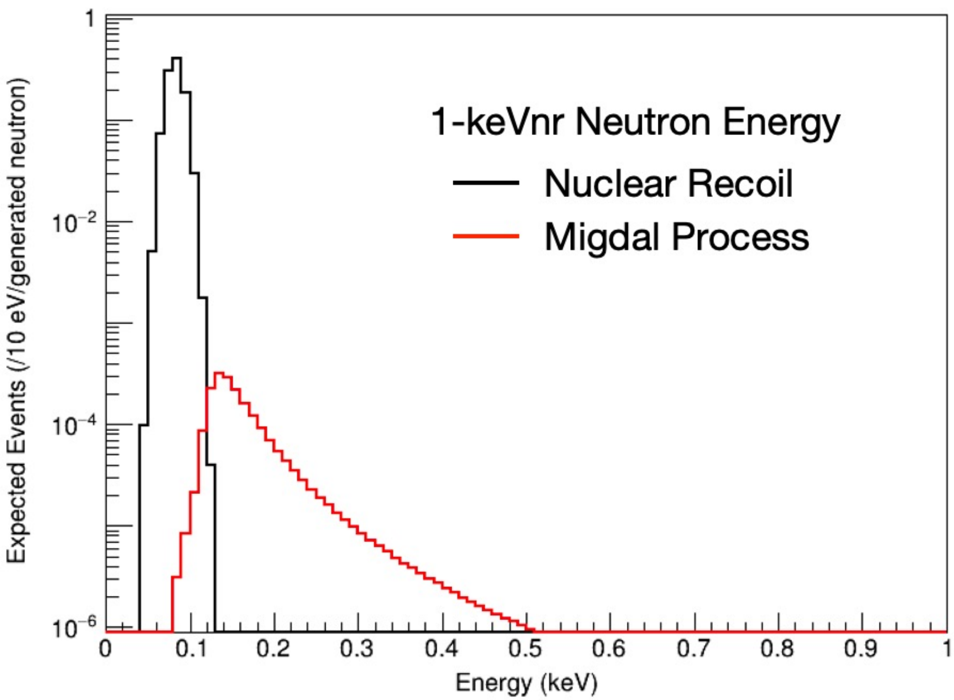


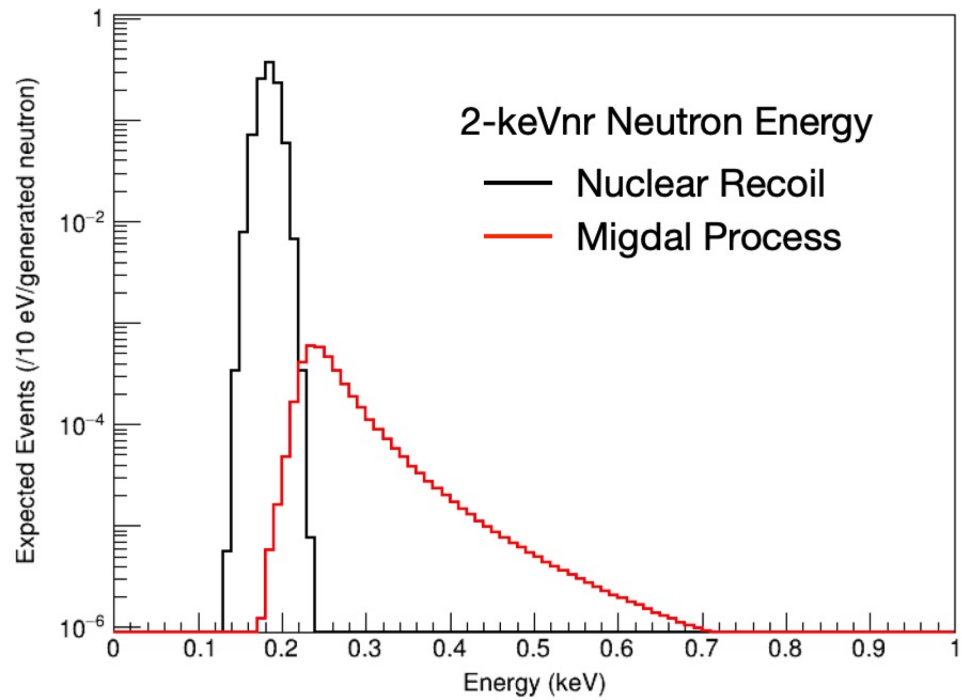
Simulation (10 keV$_{ee}$ + 200 keV$_{nr}$)



Migdal effect in NaI using neutron generator?

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



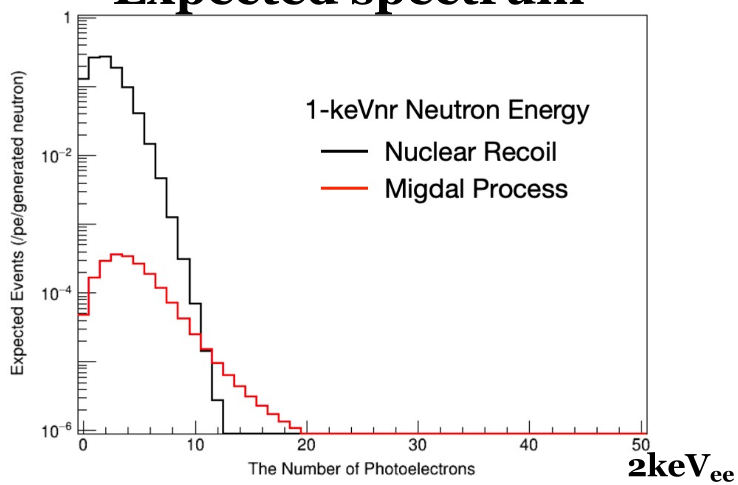


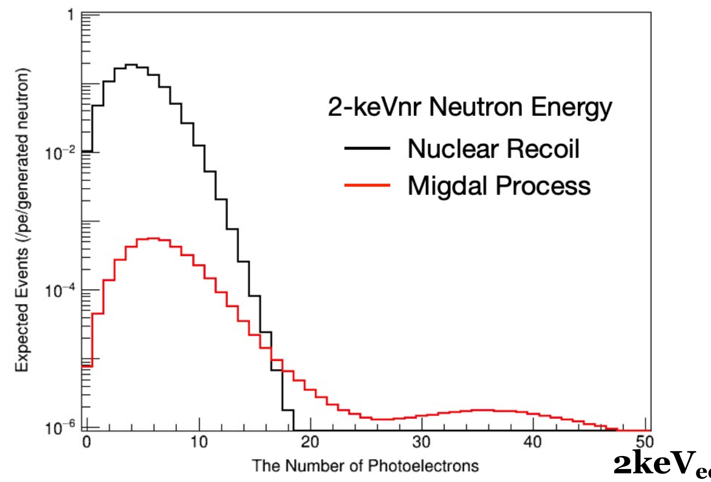
- No resolution here

Migdal effect in NaI using neutron generator?

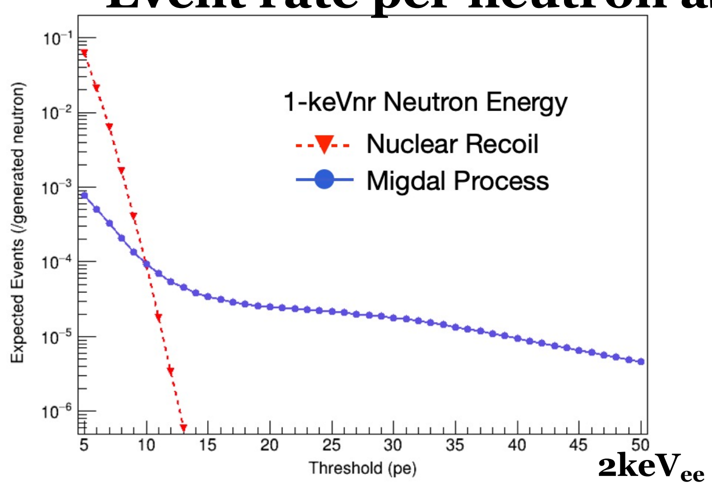
- 25 NPE/keV light yield, Poisson statistics for resolution

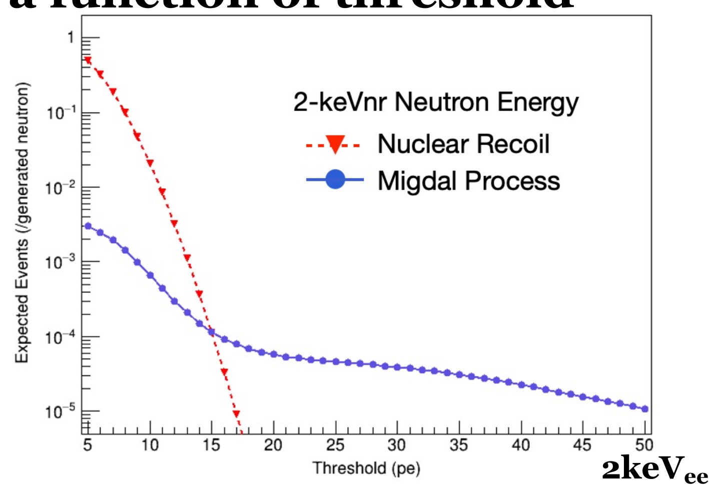
Expected spectrum





Event rate per neutron as a function of threshold



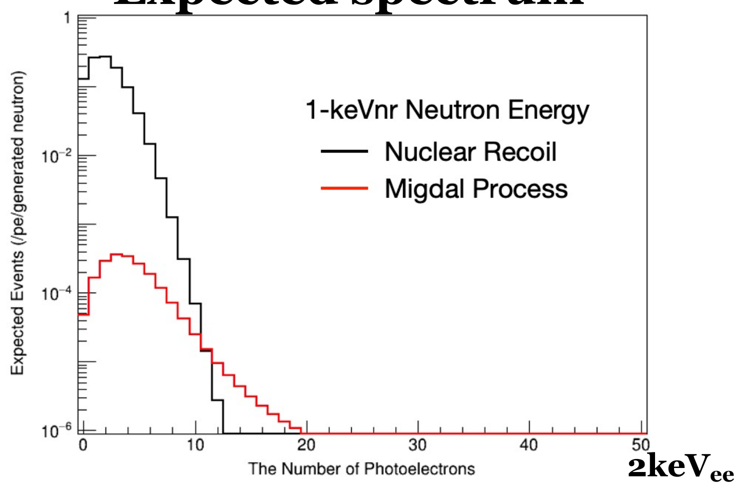


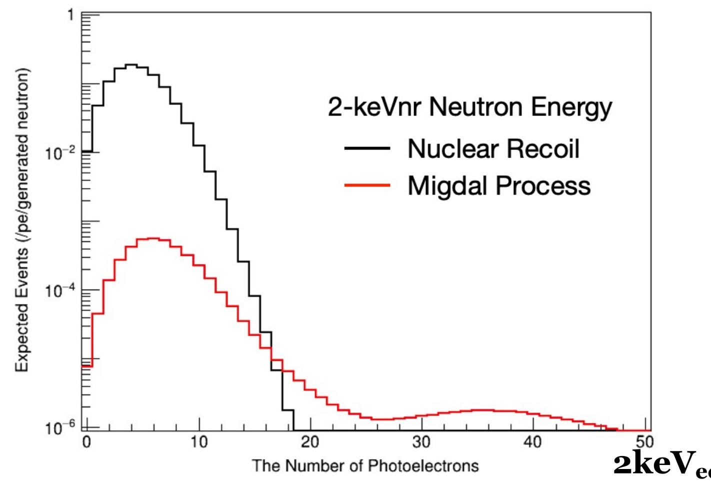
To get 100 Migdal events, we need ~ 10^6 nuclear recoils in 1-2 keV energy (5-8^o angles)

Migdal effect in NaI using neutron generator?

- 25 NPE/keV light yield, Poissonian statistics for resolution

Expected spectrum

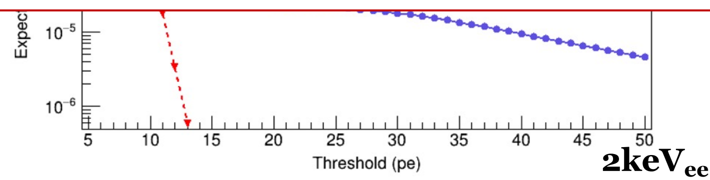


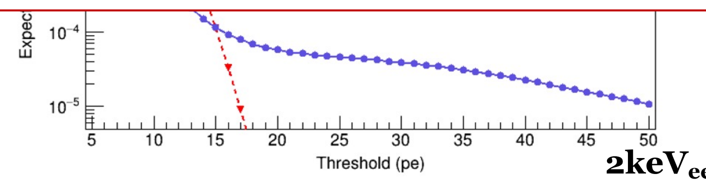


In current quenching factor setup, one neutron tagging detector require more than year measurement.

This can be reduced if we covered all solid angles

Q) background?





To get 100 Migdal events, we need ~ 10^6 nuclear recoils in 1-2 keV energy (5-8^o angles)

Other neutron sources?

10th International Particle Accelerator Conference IOP Publishing
Journal of Physics: Conference Series **1350** (2019) 012066 doi:10.1088/1742-6596/1350/1/012066

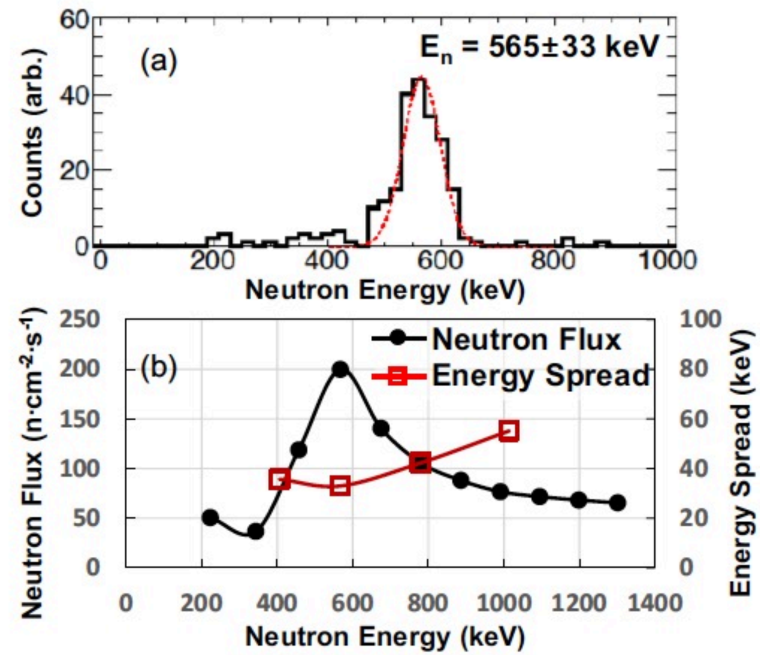
Characterization Study of Fast Neutron Sources Based on Proton Accelerators at KOMAC

P. Lee[1], J.J. Dang[1], H.S. Kim[1], H.J. Kwon[1], S.H. Lee[1]

Y.S. Cho[2]

[1]Korea Multi-purpose Accelerator Complex, Korea Atomic Energy Research In
Gyeongju-si, Republic of Korea
[2]Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

E-mail: pilsoolee@kaeri.re.kr



- KIGAM tandem accelerator is now in KOMAC
- KOMAC developed low-energy neutron source irradiating 2 MeV proton to LiF target
- This is pulsed beam (low background)
- Larger scattering angles (11-17^{o} angles)

We asked to use this low-energy neutron for quenching factor measurement

Other neutron sources?

10th International Particle Accelerator Conference IOP Publishing
Journal of Physics: Conference Series **1350** (2019) 012066 doi:10.1088/1742-6596/1350/1/012066

Characterization Study of Fast Neutron Sources Based on Proton Accelerators at KOMAC

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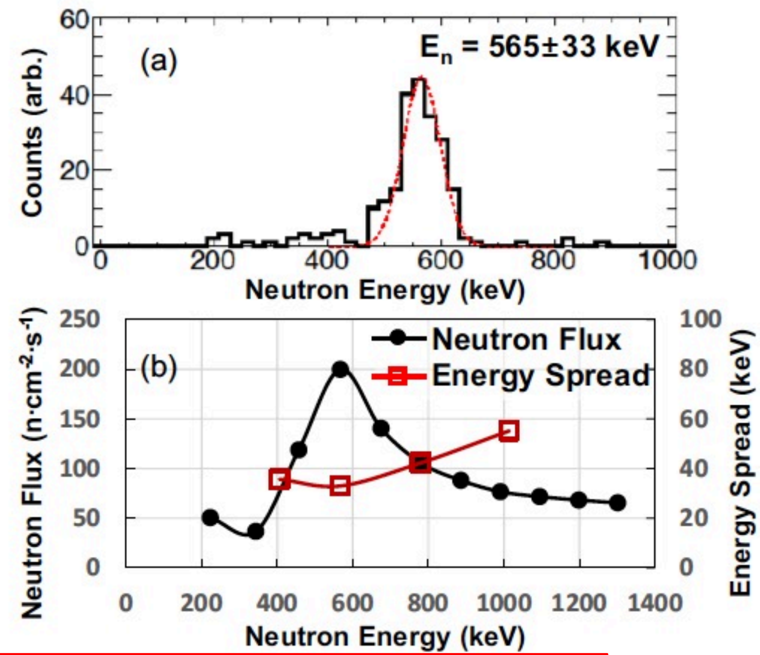
Y.S. Cho[2]

[1]Korea Multi-purpose Accelerator Complex, Korea Atomic Energy Research Ir
Gyeongju-si, Republic of Korea
[2]Korea Atomic Energy Research Institute, Daejeon, Republic of Korea

E-mail: pilsoolee@kaeri.re.kr



- KIGAM tandem accelerator is now in KOMAC
- KOMAC developed low-energy neutron source irradiating 2 MeV proton to LiF targ
- Thi ... low- ... ching
- Lar

Feasibility studies based on geant4 simulation is just started.

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

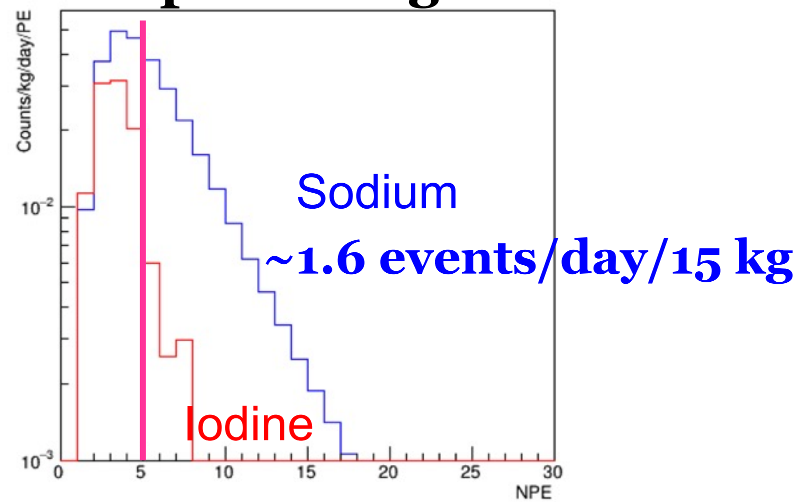
- World-leading scientific applications are developed
  - Dark matter
  - CEvNS
  - Migdal effect?

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

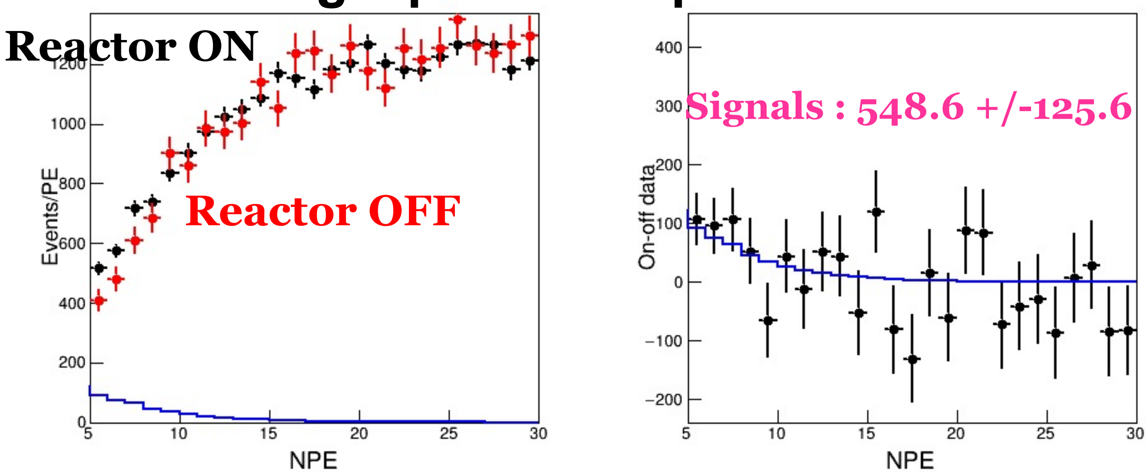
Sensitivity

- Flat background ~5 dru
- Detector mass = 15 kg
- Reactor on data = **365 days**
- Reactor off data = **100 days**
- Light yield = 22 NPE/keV
- Trigger and selection efficiency
- Threshold = 5 NPE

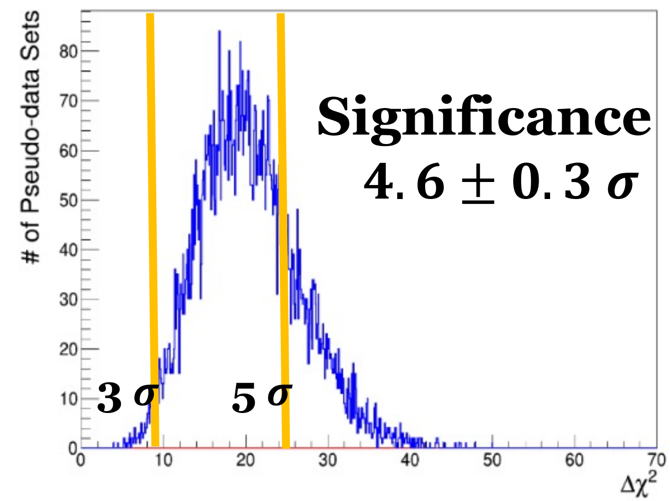
Expected Signals



Single pseudo experiment



10,000 Pseudo experiments



Strategy of NEON experiment

2019	2020	2021	2022	2023	2024	2025
		Detector development				
			NEON-phase 1			
					NEON-phase 2	

- NEON-phase1 (~2023)
  - ❖ ~15 kg commercial crystals (< 10 dru background)
  - ❖ Demonstration of detector performance and observe CEνNS with > 3σ

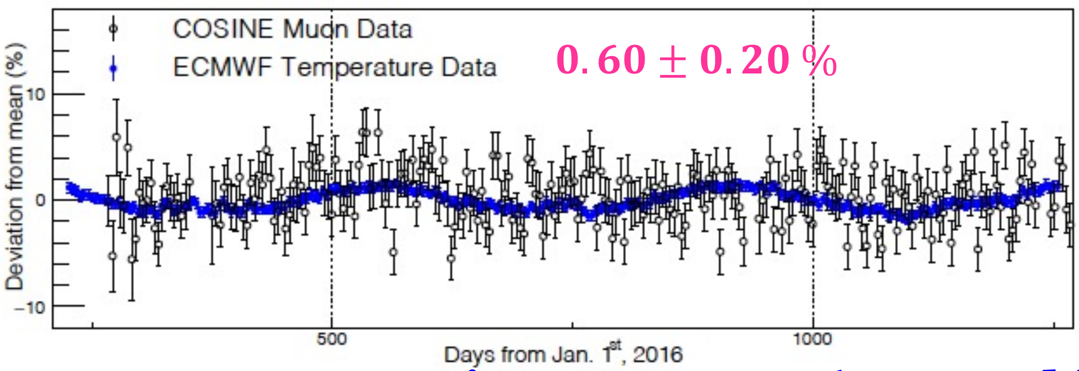
- NEON-phase2 (~2025)
  - ❖ ~100 kg purified crystals (<1dru background)
  - ❖ Precision measurement and explore new physics interaction

EPJC 80 (2020) 814

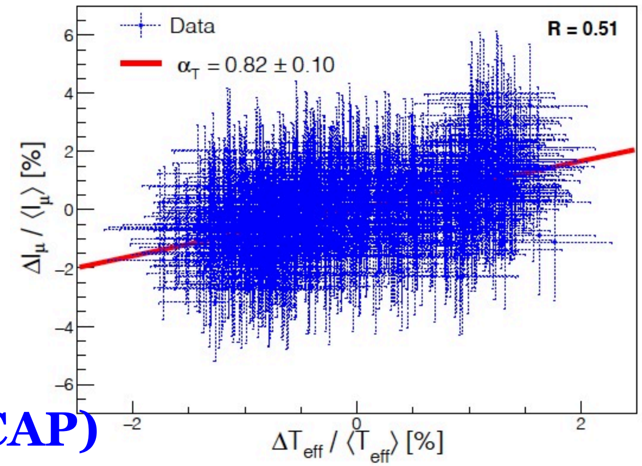

<Body growth>

Muon modulation (3 years data)

Annual modulation of muon rate

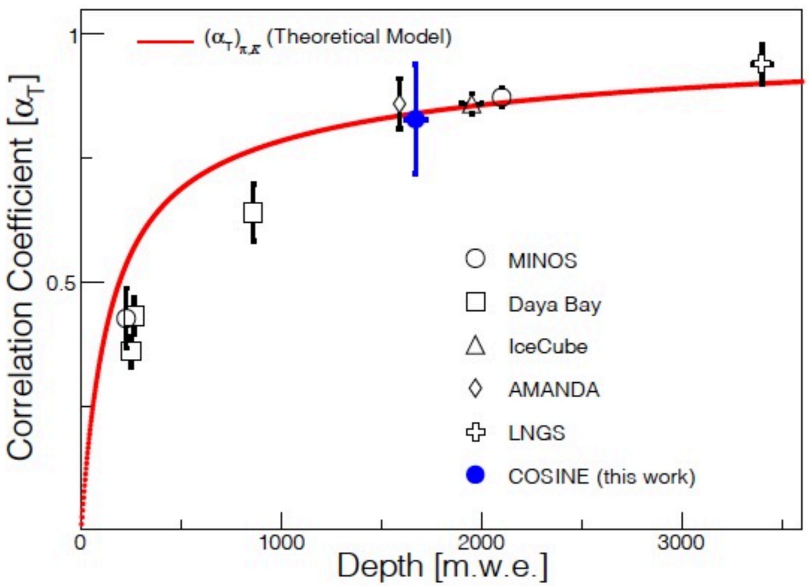


Correlation with T_{eff}



arXiv:2005.13672 (accepted in JCAP)

Annual modulation of muon rate



Diurnal modulation